Nucleon Tomography with 0-jettiness

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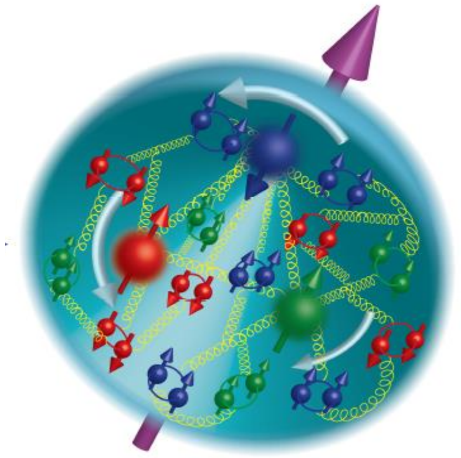
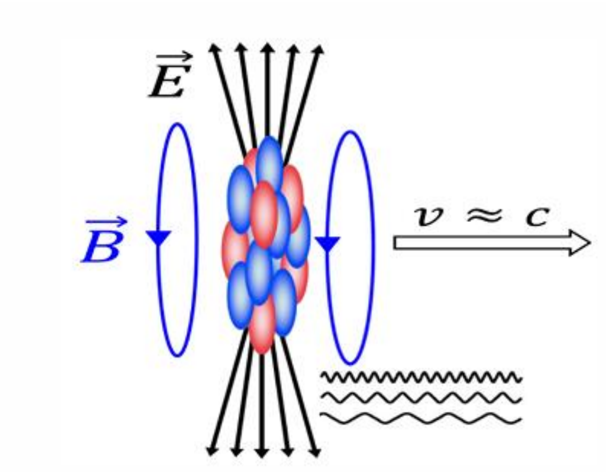
arXiv:2410.13781
Phys.Rev.D 106 (2022) 3, 034025
Phys.Rev.D 107 (2023), 054004

The International Conference on Symmetry Breaking Phenomena in Quantum Field Theory

Outline

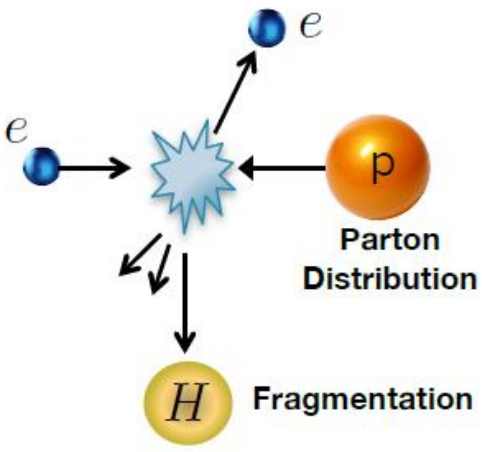
- **Introduction to Nucleon Tomography**
- **Nucleon Tomography with 0-jettiness**
- **Azimuthal Asymmetries in Ultraperipheral Heavy-Ion Collisions**



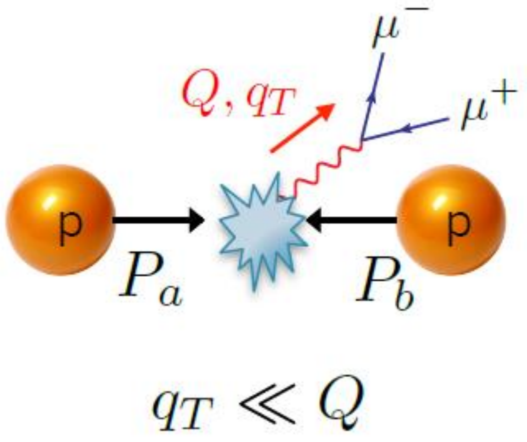


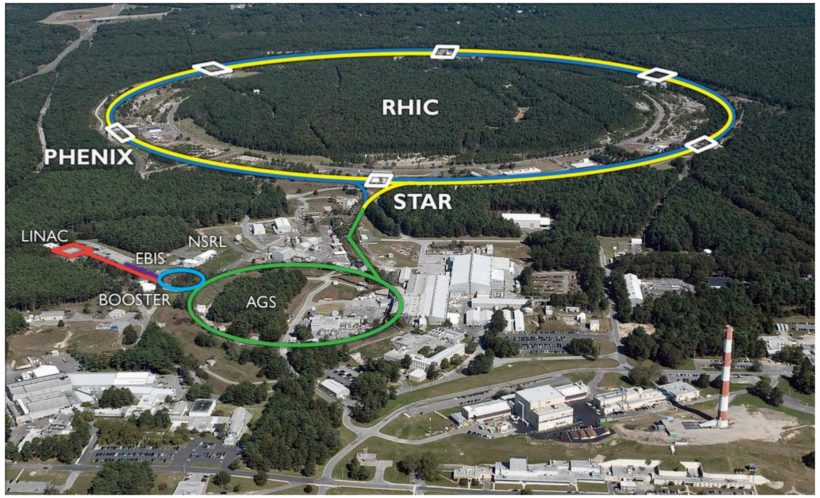
Nucleon Tomography : a fundamental quest

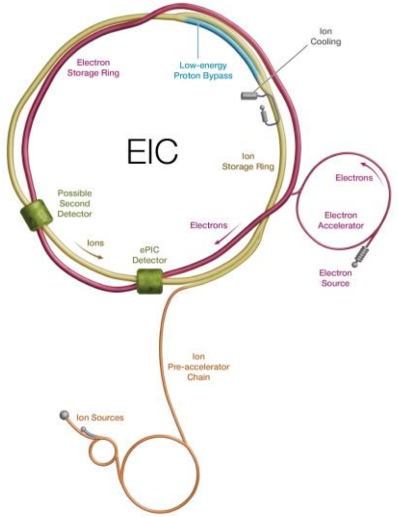
Semi-Inclusive DIS



Drell-Yan



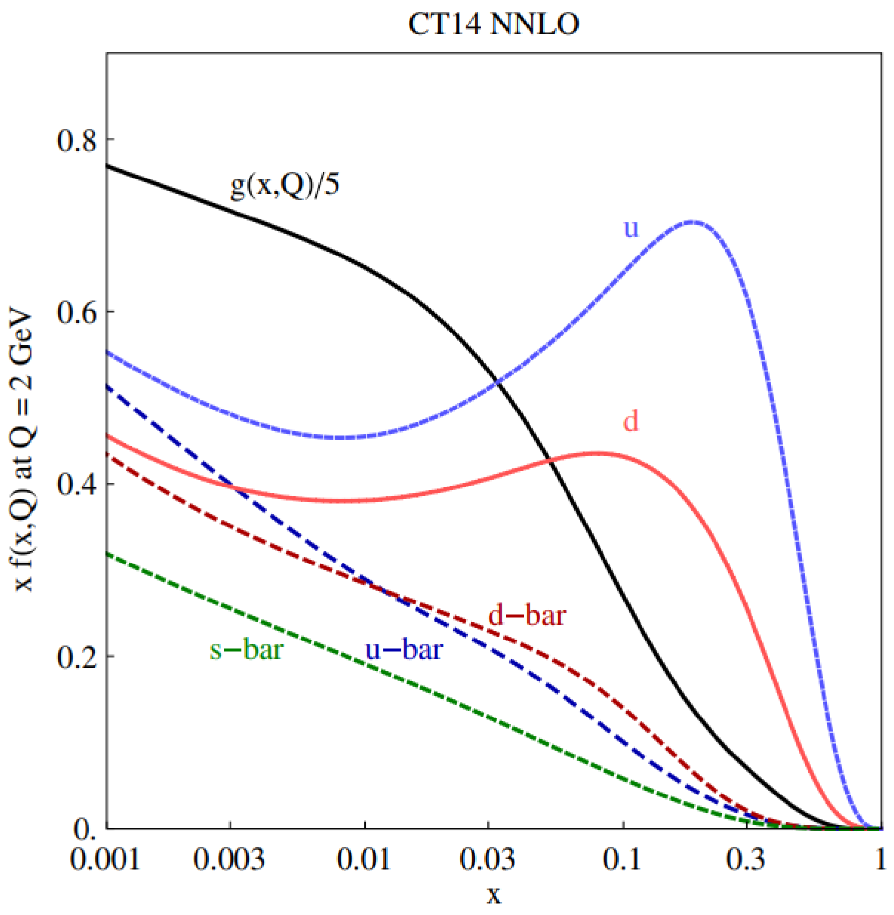


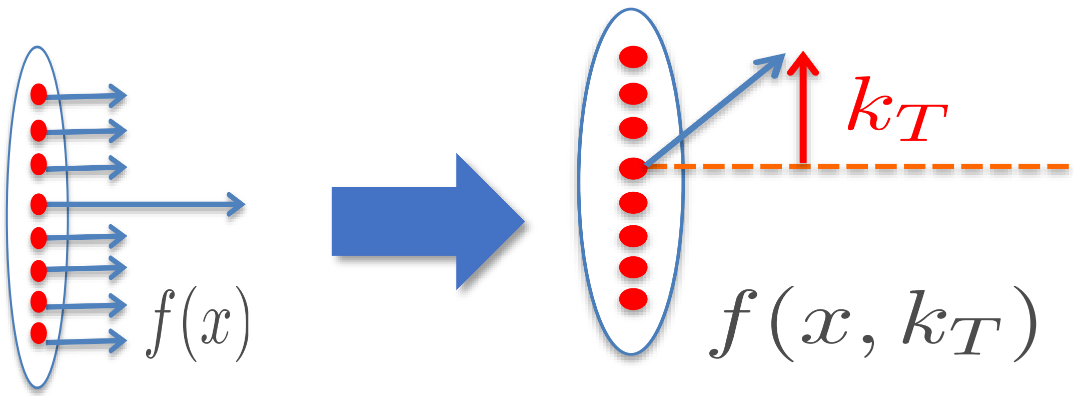


Proton structure: encoded in PDFs

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

Nucleon Tomography : a fundamental quest





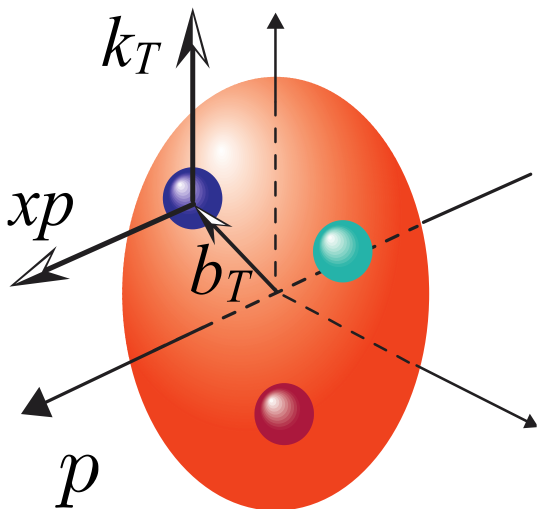
Longitudinal motion only

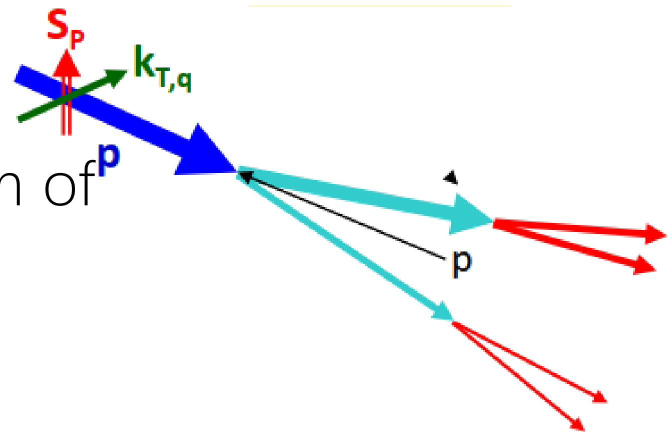
Longitudinal + transverse motion

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

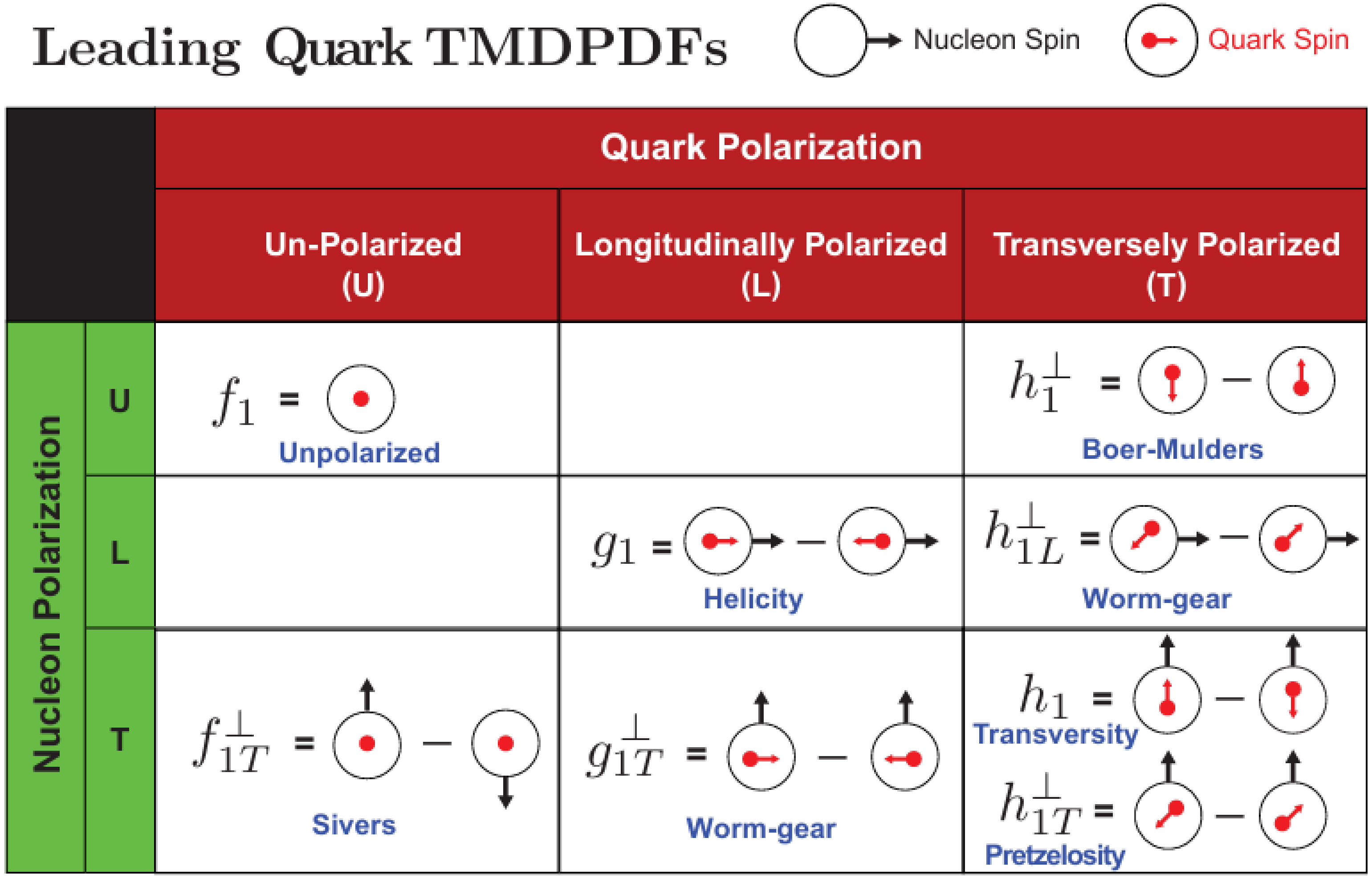
TMDs: center piece of nucleon structure

- 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
- Information on the color glass condensate —a unique form of nuclear matter at small x
- QCD factorization

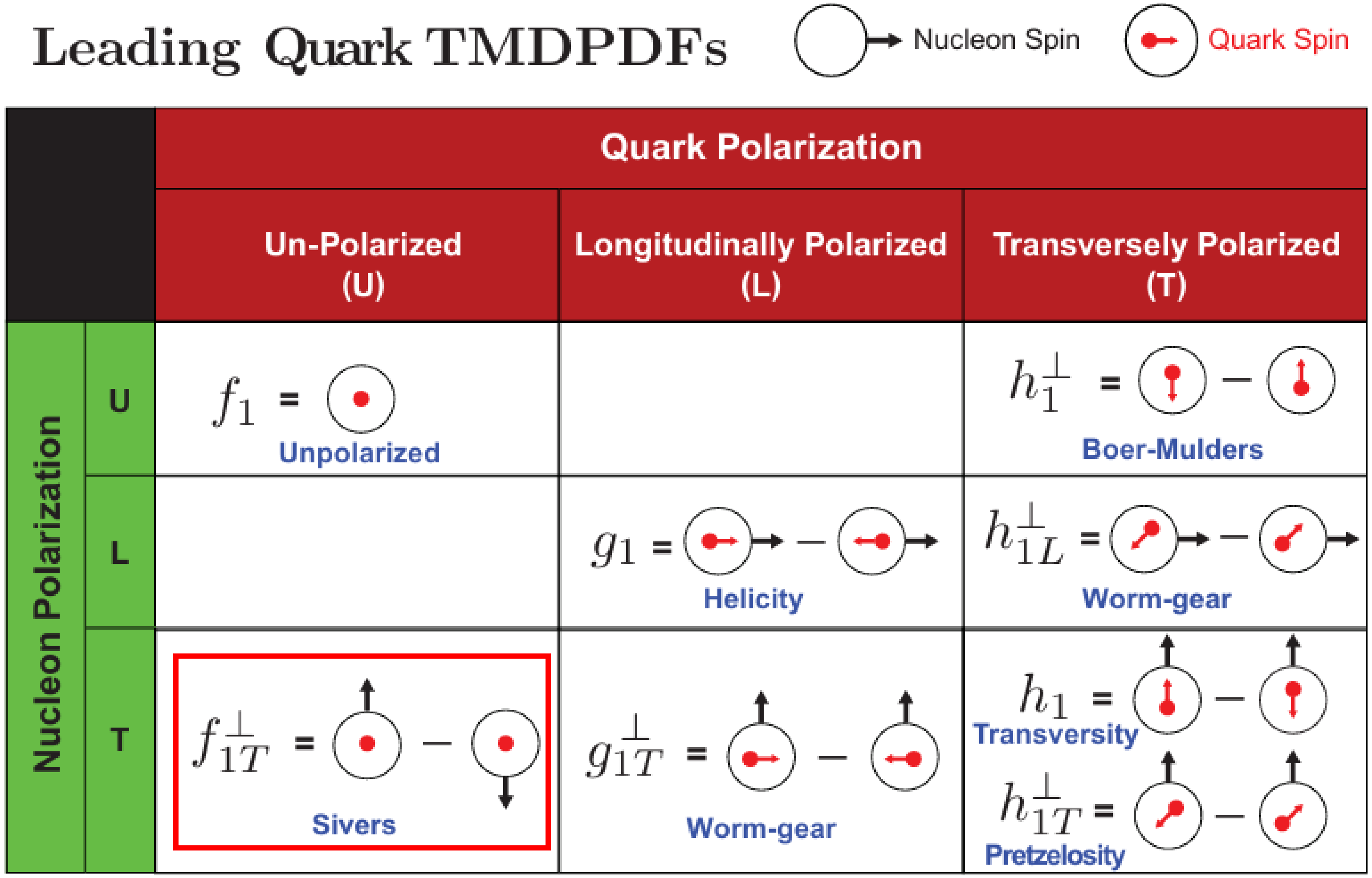




TMDs: center piece of nucleon structure



TMDs: center piece of nucleon structure

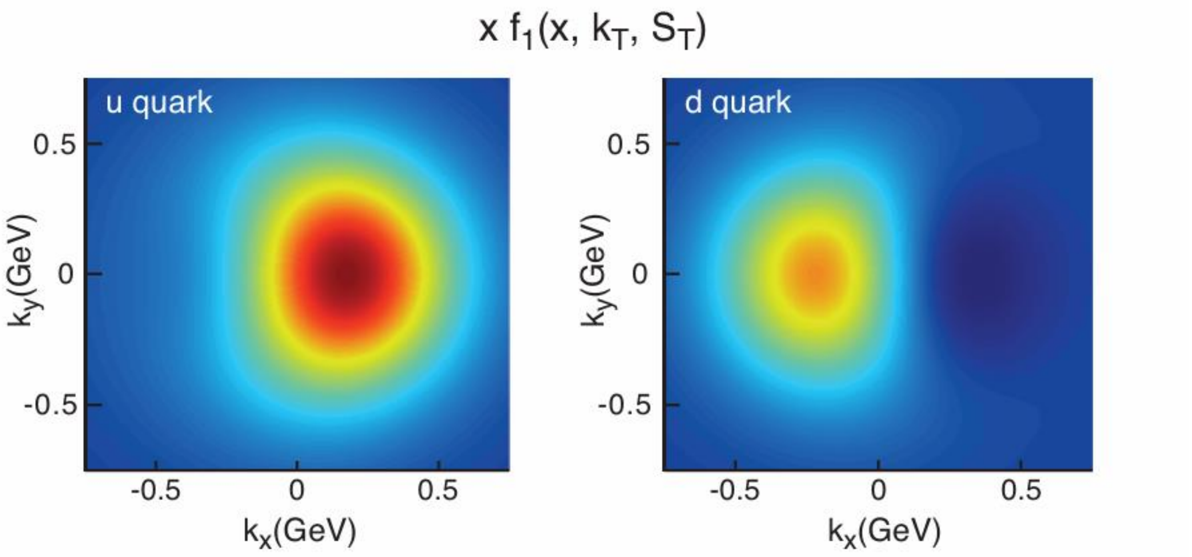


One example: Sivers function

- 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



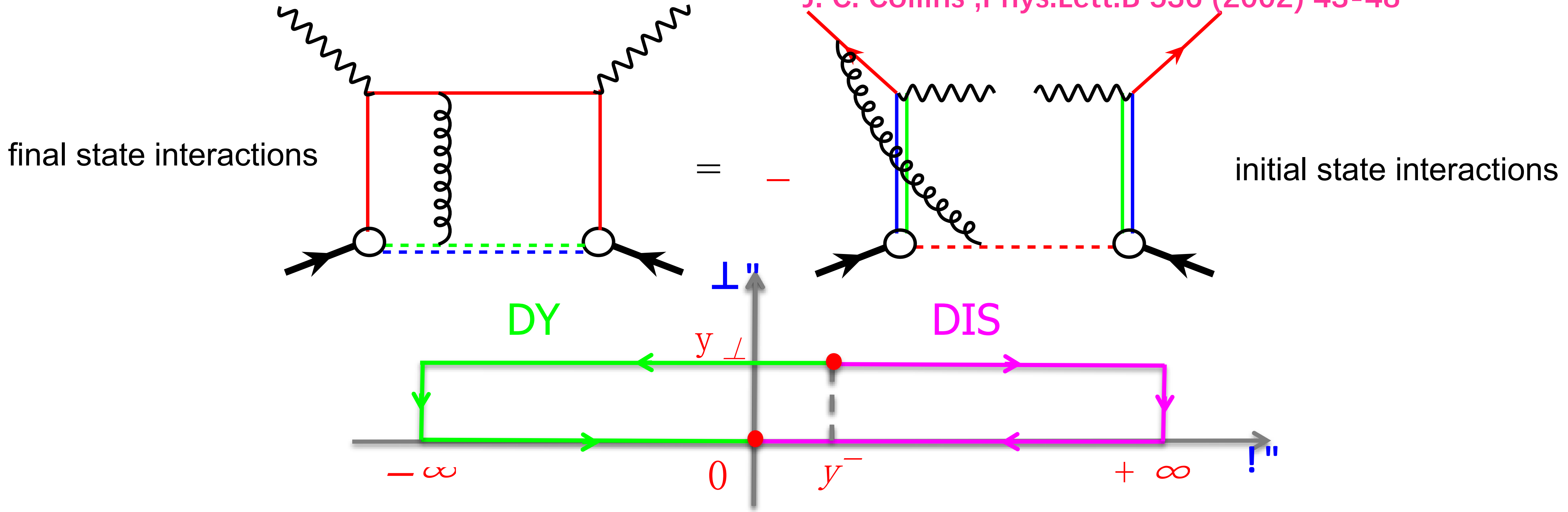
A.Accardi et al.Eur.Phys.J.A 52 (2016) 9, 268

- 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



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

Sivers function: history

- 1990: introduced by D. Sivers, to describe the large single spin asymmetry measured in inclusive hadron production in p+p collisions at Fermilab
- 1993: J. Collins shows Sivers function has to vanish due to time-reversal invariance
- 2002: Brodsky, Hwang, Schmidt performed an explicit model calculation, showed the existence of the Sivers function
- 2002: Original proof missed the gauge link (needed to properly define gauge invariant distribution), once added, found Sivers function in SIDIS is opposite to that in Drell-Yan

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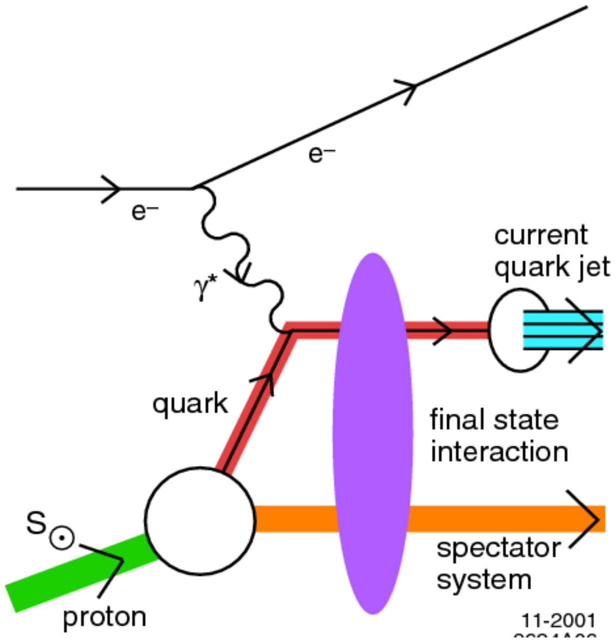
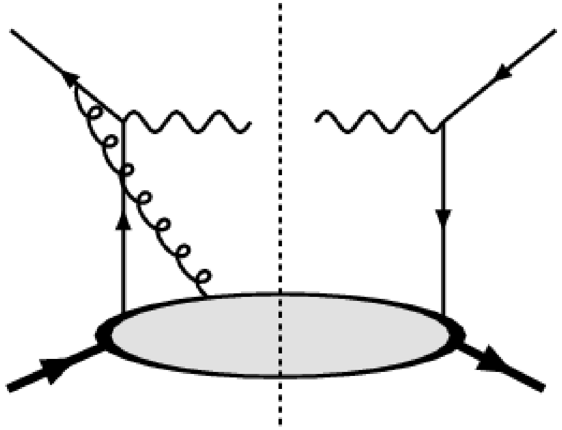
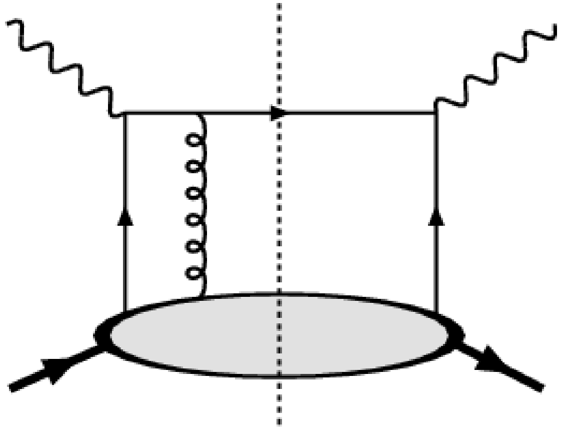




ISI



FSI

$$\text{Sivers}|_{DY} = -\text{Sivers}|_{DIS}$$

Sivers Function and Qiu-Sterman Function

- Qiu-Sterman Function

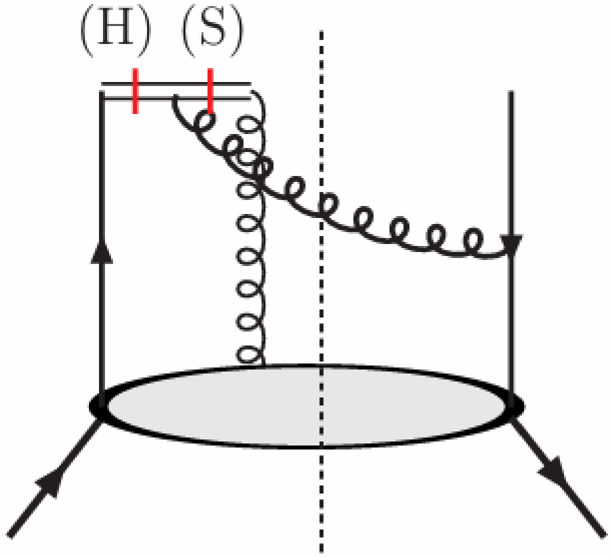
$$T_F(x_2, x_2') \equiv \int \frac{d\zeta^- d\eta^-}{4\pi} e^{i(x_2 P^+ \eta^- + (x_2' - x_2) P_B^+ \zeta^-)} \epsilon_\perp^{\beta\alpha} S_{\perp\beta} \times \langle PS | \overline{\psi}(0) \mathcal{L}(0, \zeta^-) \gamma^+ g F_\alpha{}^+(\zeta^-) \mathcal{L}(\zeta^-, \eta^-) \psi(\eta^-) | PS \rangle$$

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

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

- Sivers function at large kt

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



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

Sivers Function and Qiu-Sterman Function

- Qiu-Sterman Function

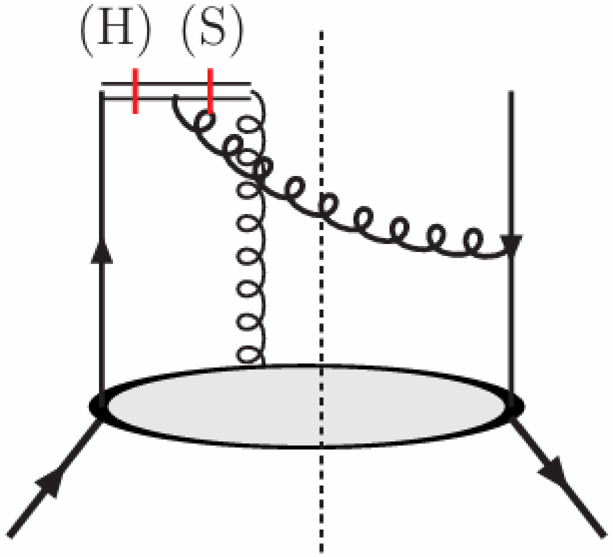
$$T_F(x_2, x_2') \equiv \int \frac{d\zeta^- d\eta^-}{4\pi} e^{i(x_2 P^+ \eta^- + (x_2' - x_2) P_B^+ \zeta^-)} \epsilon_\perp^{\beta\alpha} S_{\perp\beta}$$
$$\times \langle PS | \overline{\psi}(0) \mathcal{L}(0, \zeta^-) \gamma^+ g F_\alpha{}^+(\zeta^-) \mathcal{L}(\zeta^-, \eta^-) \psi(\eta^-) | PS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

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

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

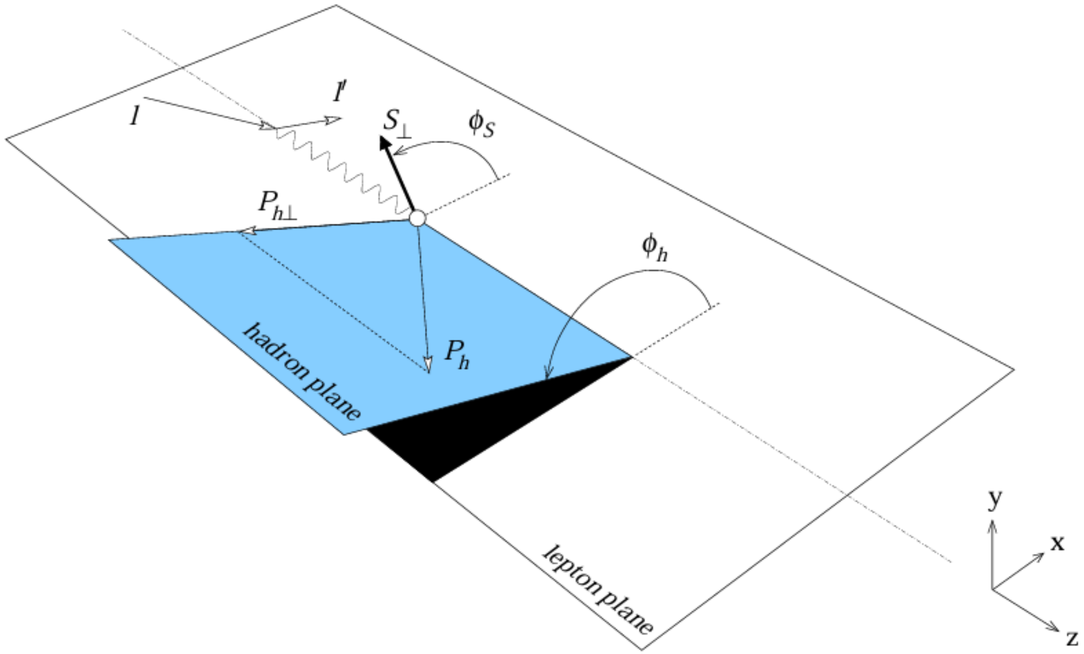
- Sivers function in small b limit

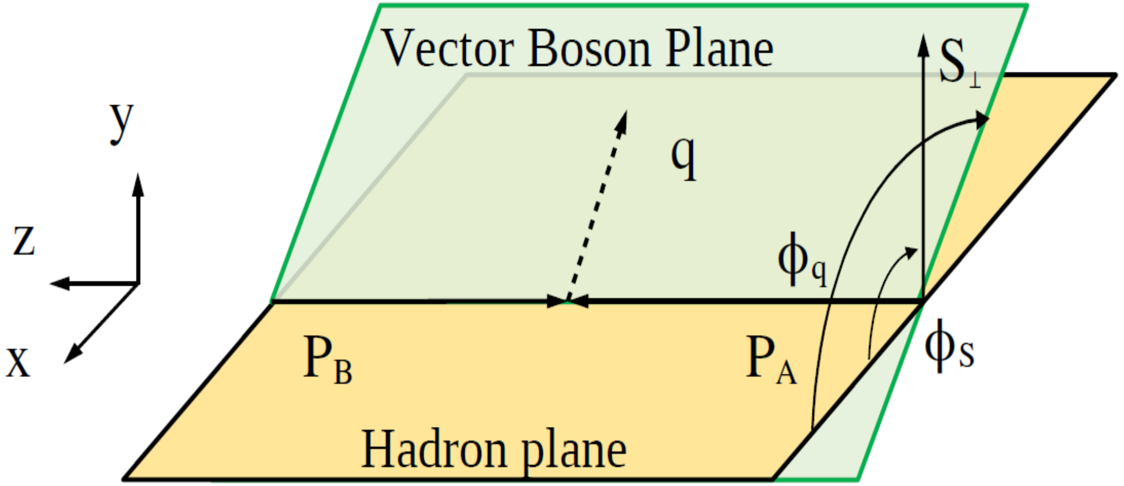
$$\tilde{f}_{1T}^{\alpha}(z,b) = \frac{\alpha_s}{2\pi}\left(\frac{-ib_\perp^\alpha}{2}\right)\left\{\left(-\frac{1}{\epsilon} + \ln\frac{c_0^2}{b^2\mu^2}\right)\mathcal{P}^T_{qg\to qg} \otimes T_F(z)\right.$$
$$-\delta(1-\xi) T_F(x,x) C_F \ln\frac{c_0^2}{b^2\mu^2} - \frac{1}{2N_c} T_F(x,x)(1-\xi)$$
$$\left.+\delta(1-\xi)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



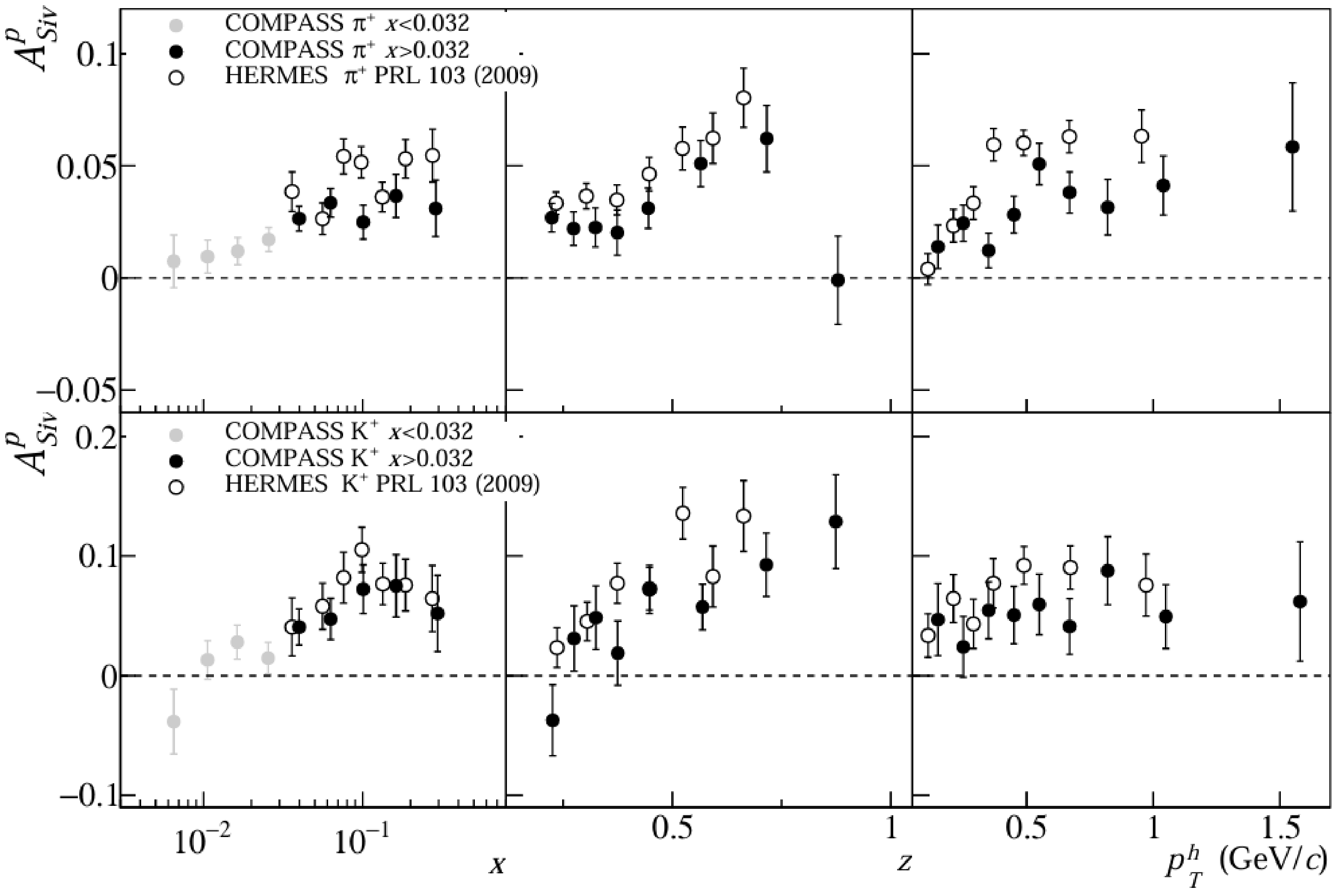
$$\mathcal{P}^T_{qg\to qg} \otimes T_F(z) = \int \frac{dx}{x}\left\{T_F(x,x)\left[C_F\left(\frac{1+\xi^2}{1-\xi}\right)_+ - C_A\delta(1-\xi)\right]\right.$$
$$\left.+\frac{C_A}{2}\left(T_F(x,z)\frac{1+\xi}{1-\xi} - T_F(x,x)\frac{1+\xi^2}{1-\xi}\right)\right\},$$

Transverse single spin asymmetries



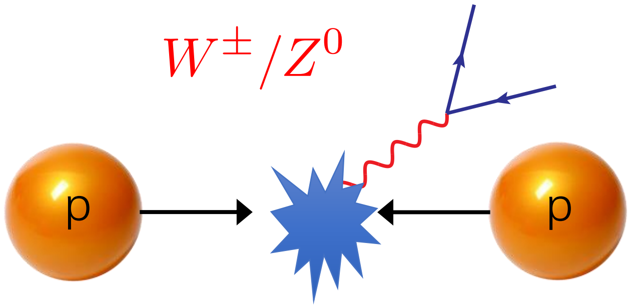


Transverse single spin asymmetries in SIDIS

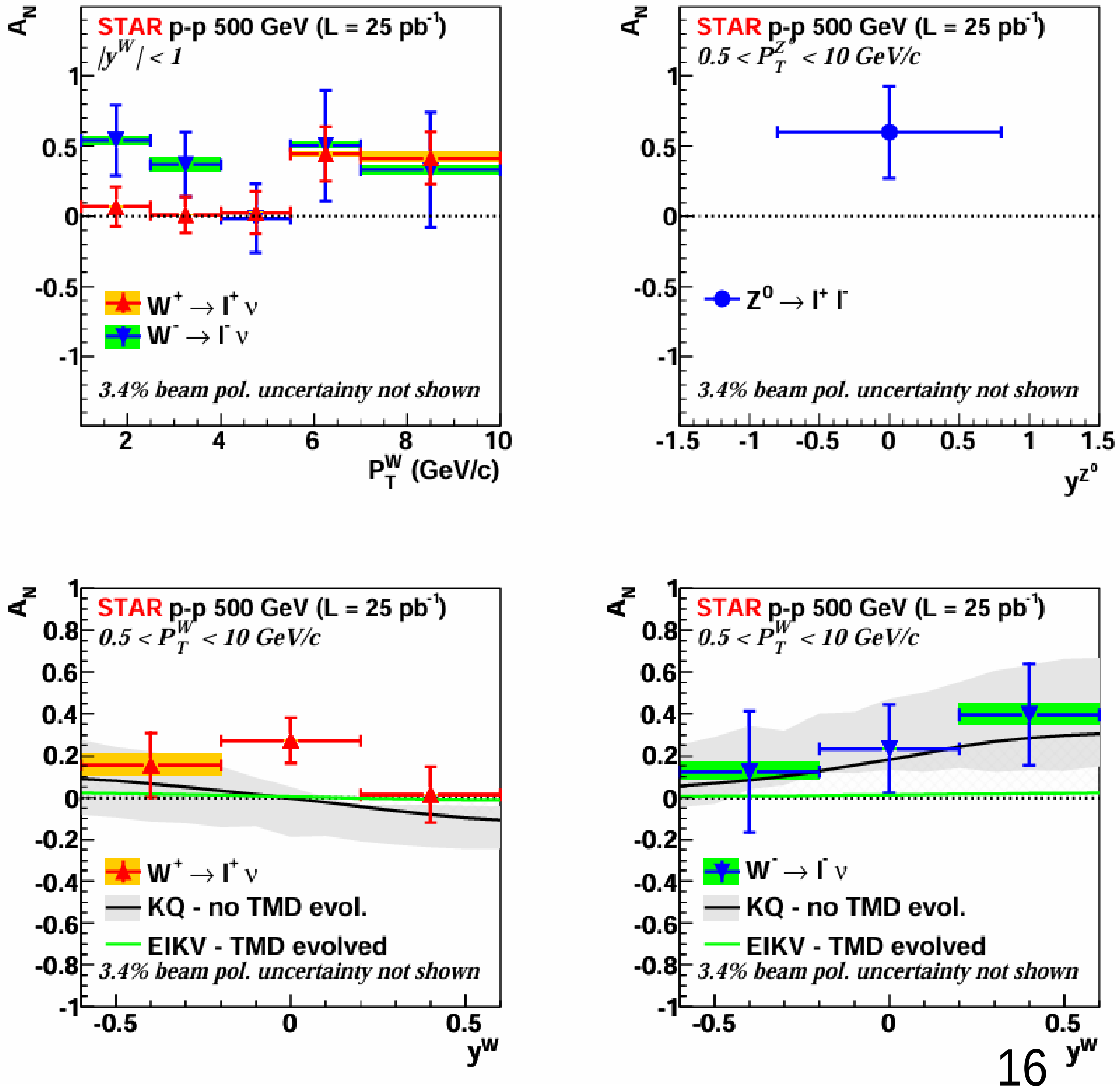


COMPASS
Phys. Lett. B744 (2015) 250
HERMES
Phys. Rev. Lett. 103 (2009) 152002

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 factor

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

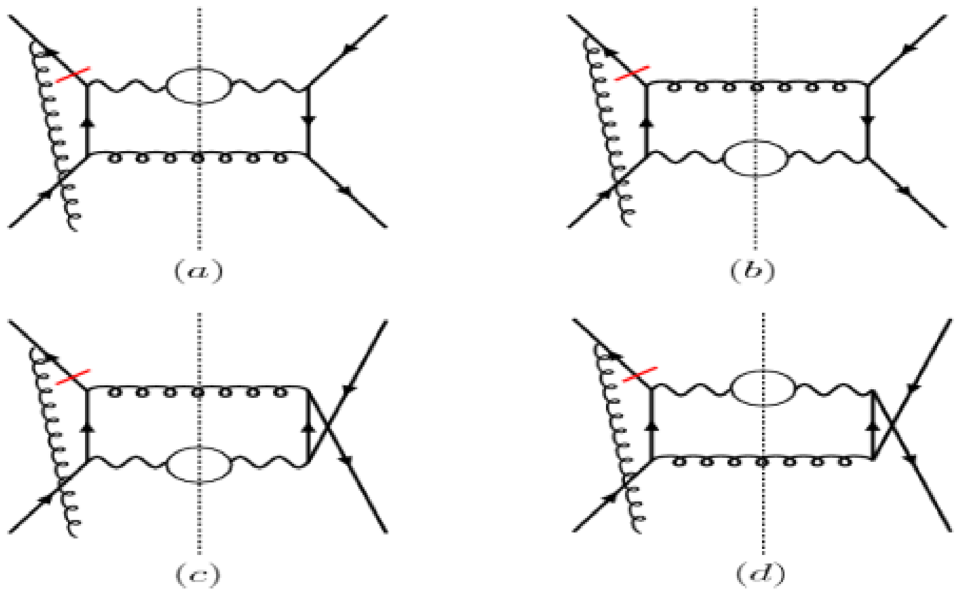
Phenomenogical applications of the QCD resummation to the transverse momentum spectrum have been very successful

Resummation

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

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

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

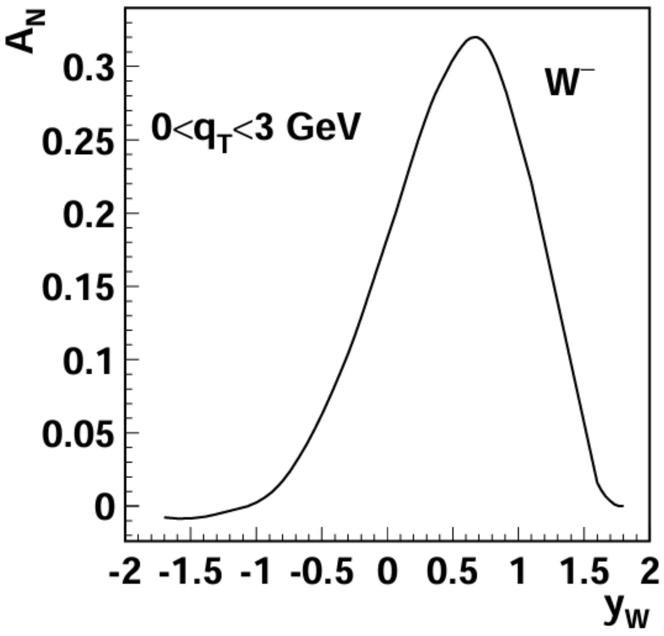


$$S_{UT}(Q^2,b) = \int_{C_1^2/b^2}^{C_2^2Q^2}\frac{d\mu^2}{\mu^2}\left[\ln\left(\frac{C_2^2Q^2}{\mu^2}\right)A_{UT}(C_1;g(\mu)) + B_{UT}(C_1,C_2;g(\mu))\right],$$

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

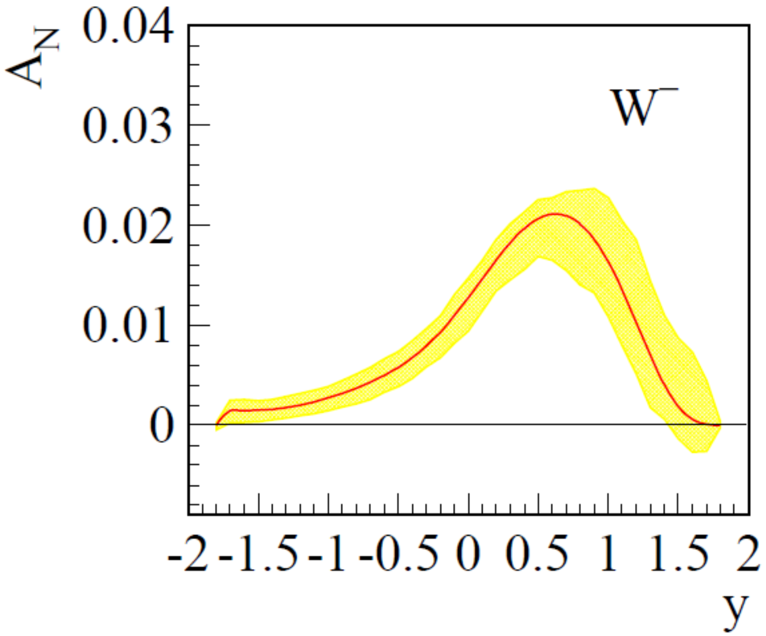
TMD evolution effect

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.

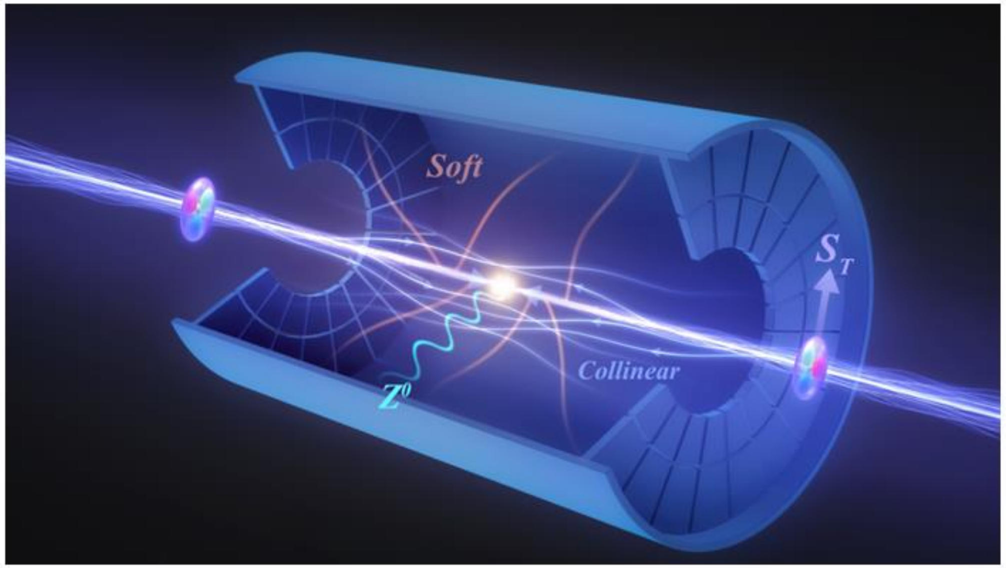
How to enhance the asymmetry?

Our solution: 0-jettiness veto method

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

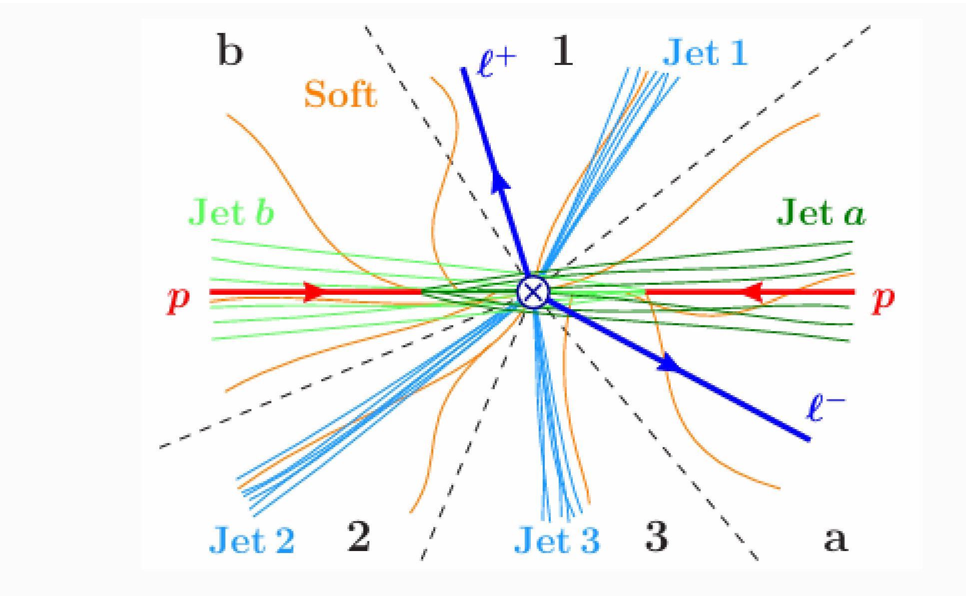
$$\tau < \tau_0$$

S. Fang, S. Lin, D. Y. Shao, and J. Zhou, Phys.Rev.Lett. 136 (2026) 2, 021901



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

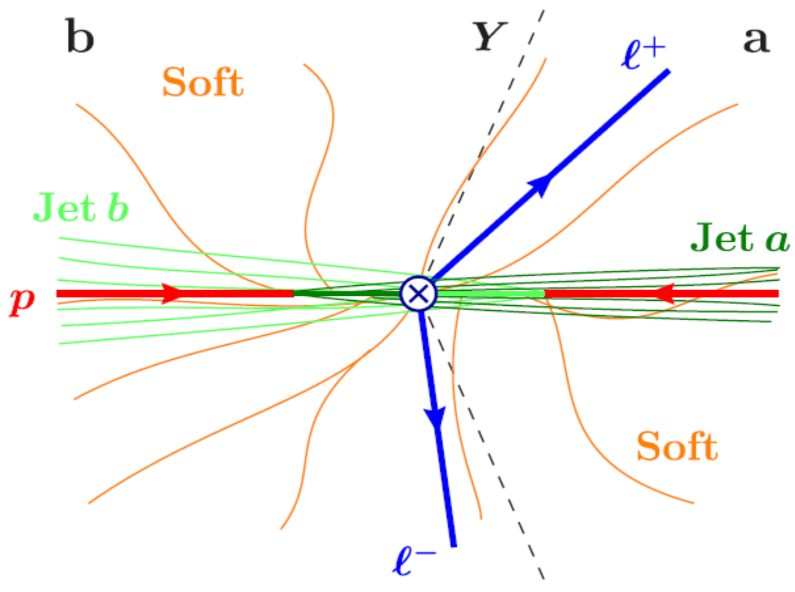
- For electroweak Drell-Yan processes, the 0-jettiness variable is defined as

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

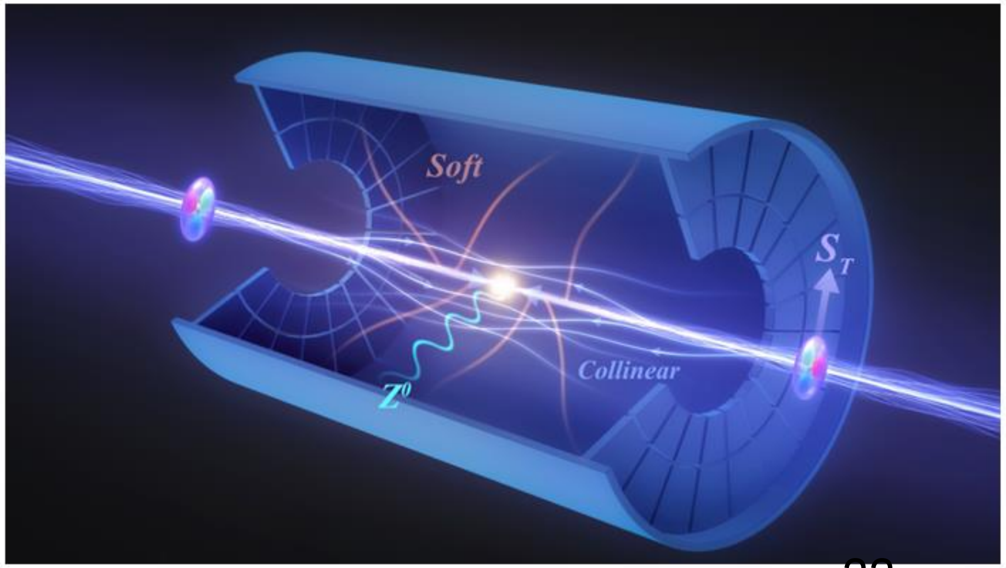
The sum runs over all particles i (excluding the gauge boson) with momentum l_i

$$\tau < \tau_0$$

- 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.



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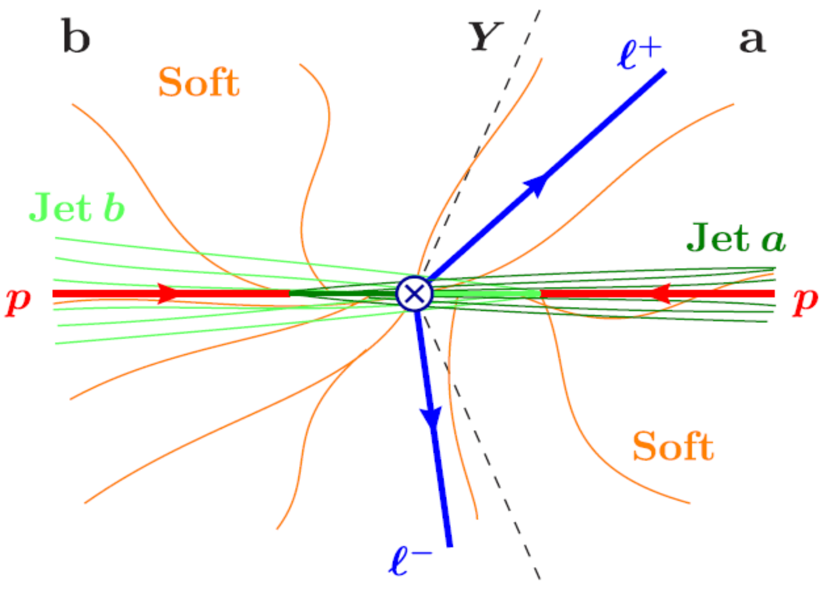
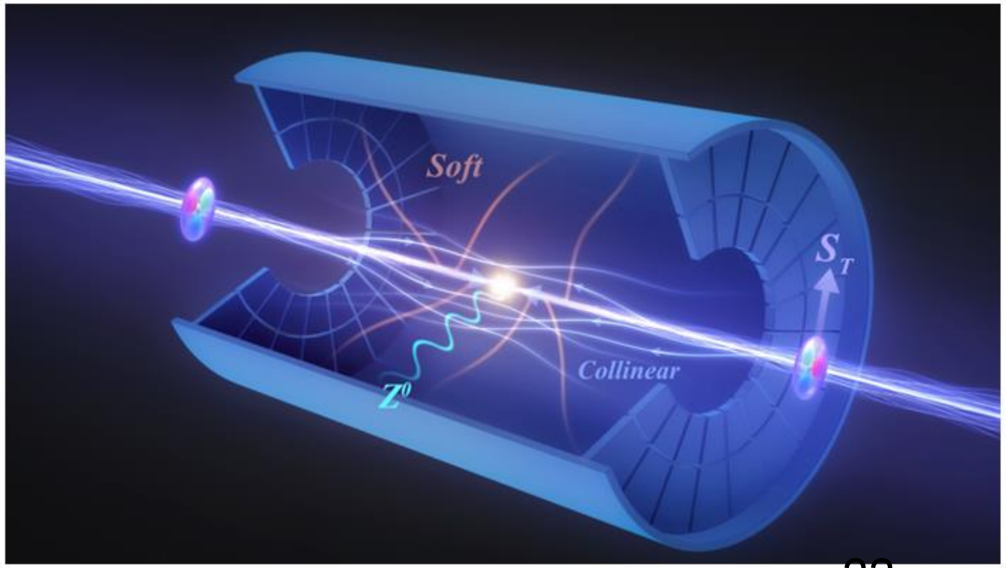
$$\tau < \tau_0$$

- 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: $\ln\frac{Q^2}{q_\perp^2}$ $\quad$ $\ln\frac{1}{\tau_0}$

- The modified Sudakov factor with vetoes:

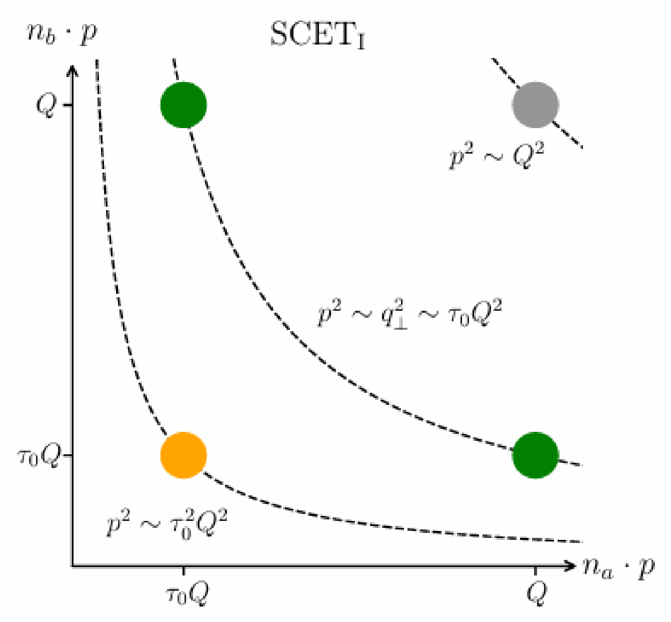
$$\frac{C_F}{\pi}\left[\int_{\mu_b^2}^{t}\frac{d\mu^2}{\mu^2}\left(2\ln\frac{t}{\mu^2}-\frac{3}{2}\right)-\int_{\mu_b^2}^{\tau_0 t}\frac{d\mu^2}{\mu^2}\ln\frac{\tau_0 t}{\mu^2}+\int_{t}^{Q^2}\frac{d\mu^2}{\mu^2}\left(\ln\frac{Q^2}{\mu^2}-\frac{3}{2}\right)+\int_{\tau_0 t}^{t}\frac{d\mu^2}{\mu^2}\ln\frac{\mu^2}{\tau_0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

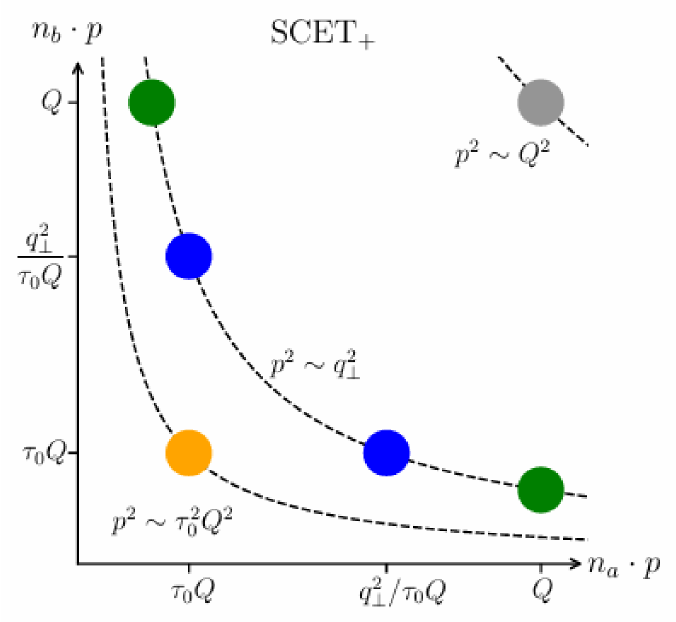
- The standard Sudakov factor:

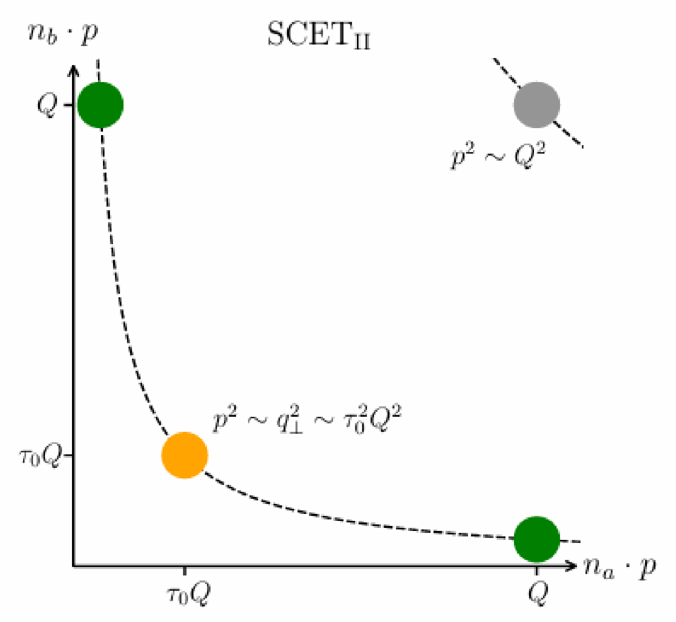
$$\frac{C_F}{\pi}\int_{\mu_b^2}^{Q}\frac{d\mu^2}{\mu^2}\left(\ln\frac{Q}{\mu^2}-\frac{3}{2}\right)\alpha_s(\mu)$$

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.

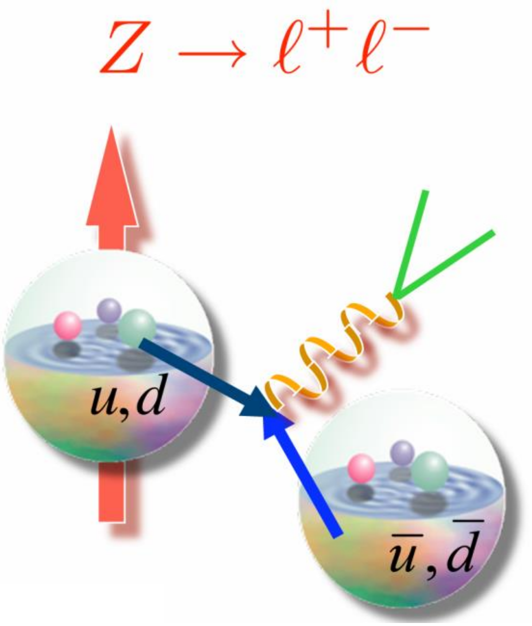






$\tau_0^2 Q^2 \ll q_\perp^2 \sim \tau_0 Q^2 \ll Q^2$ $\quad$ $\tau_0^2 Q^2 \ll q_\perp^2 \ll \tau_0 Q^2 \ll Q^2$ $\quad$ $\tau_0^2 Q^2 \sim q_\perp^2 \ll \tau_0 Q^2 \ll Q^2;$

Impact of 0-jettiness on spin asymmetries



- Unpolarized:

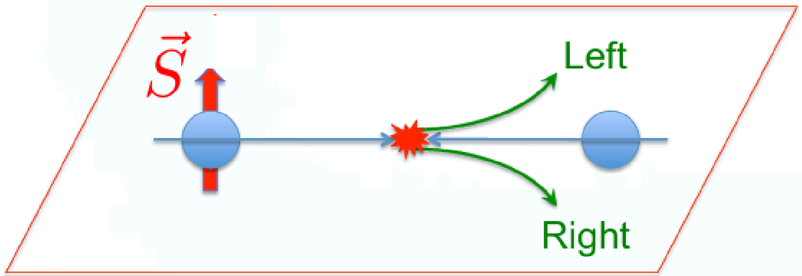
$$\frac{d\sigma_{UU}}{dy\, d^2\vec{q}_\perp} = \sigma_0 \sum_{q,q'} |V_{qq'}|^2 \int_0^\infty \frac{b\, db}{2\pi} J_0(b\, q_\perp) \times f_q(x_q, \mu_b) f_{q'}(x_{q'}, \mu_b) e^{-S_{\rm P}(b)} ,$$

- Transversely-polarized:

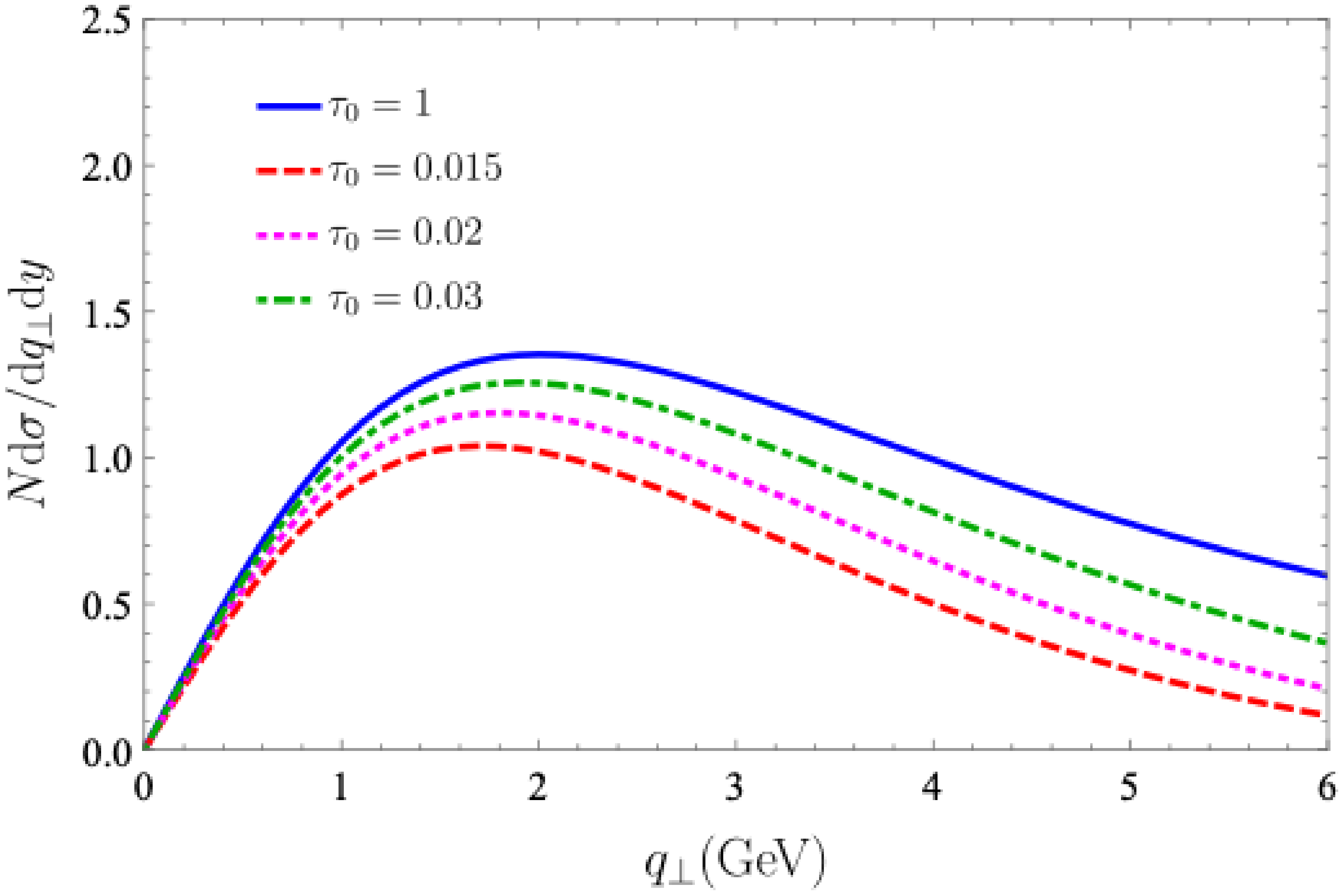
$$\frac{d\sigma_{UT}(S_\perp)}{dy\, d^2\vec{q}_\perp} = -\sin(\phi_q - \phi_S)\, \sigma_0 \int_0^\infty \frac{b^2\, db}{4\pi} J_1(b\, q_\perp) \times \sum_{q,q'} |V_{qq'}|^2 T_{F,q}(x_a, x_a, \mu_b) f_{q'}(x_b, \mu_b) e^{-S_{\rm P}(b)} .$$

- SSA:

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



Numerical results

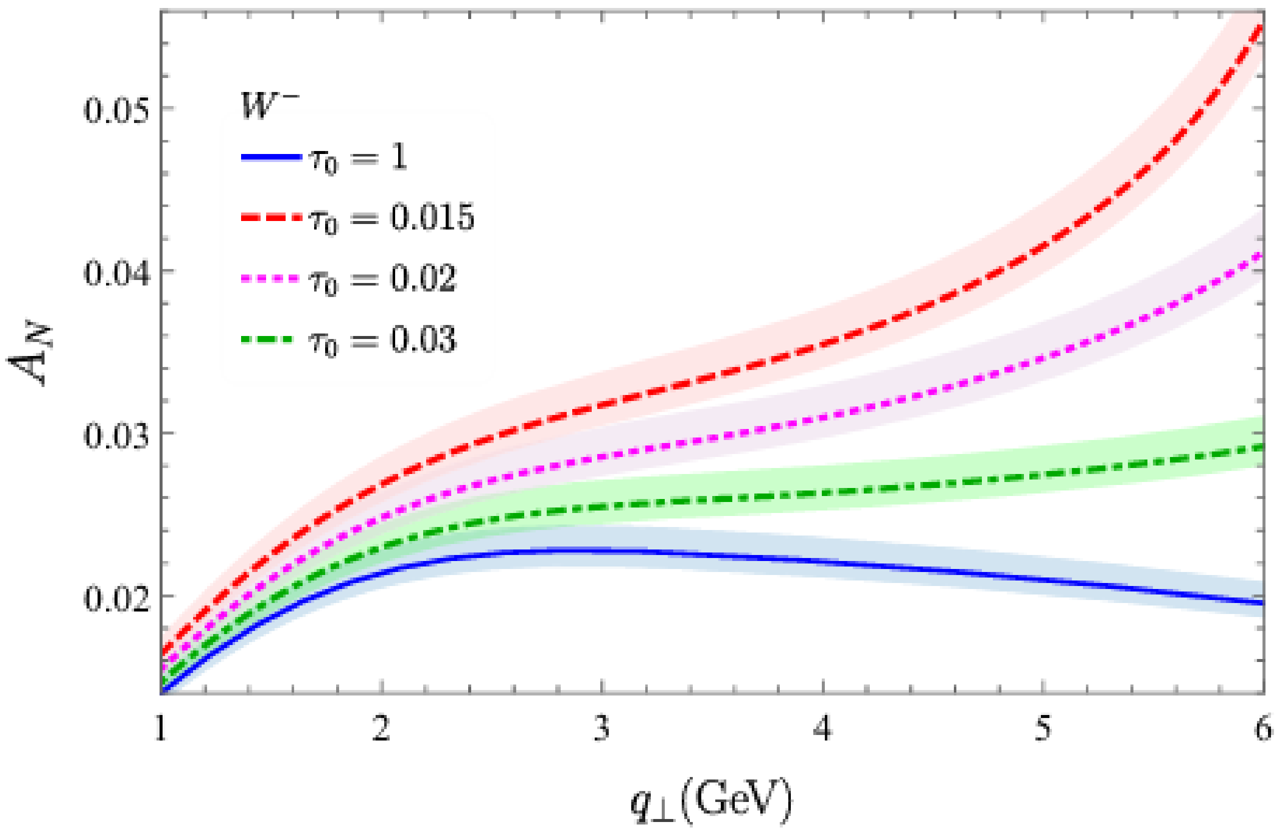


The normalized unpolarized cross section for W⁻ production at RHIC energy

The enhanced asymmetries

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

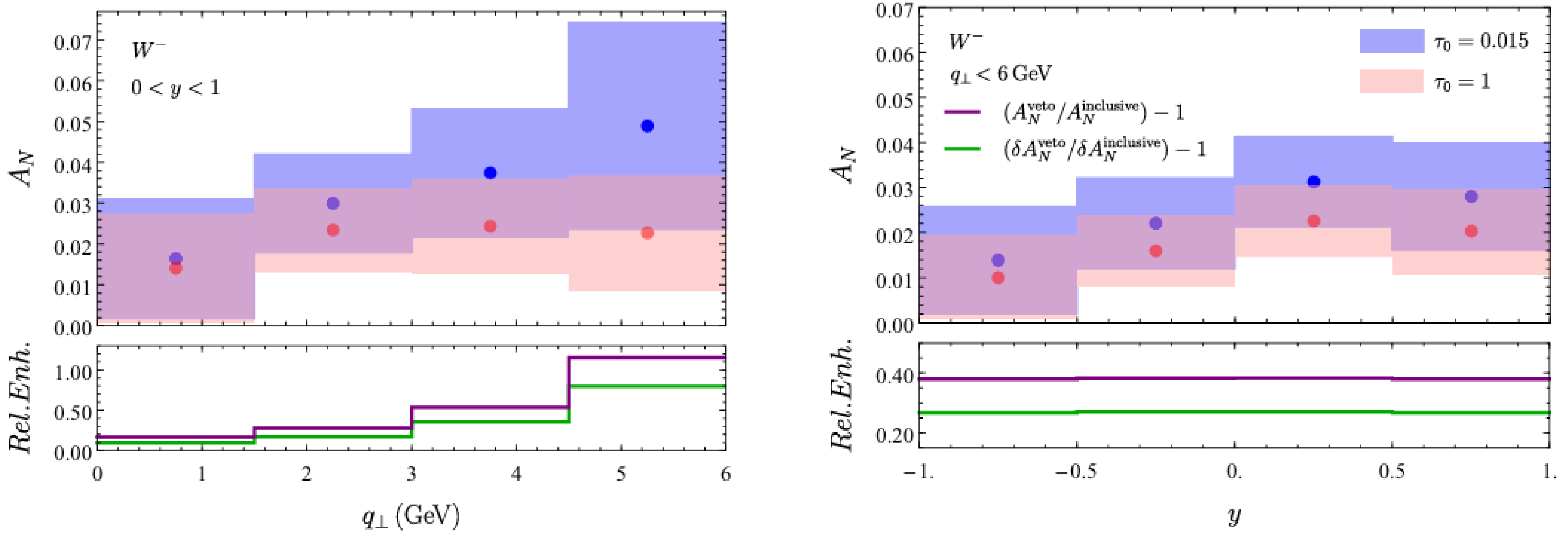


Statistical uncertainties

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

$\mathcal{L} = 780\mathrm{pb}^{-1}$

$P = 53\%$

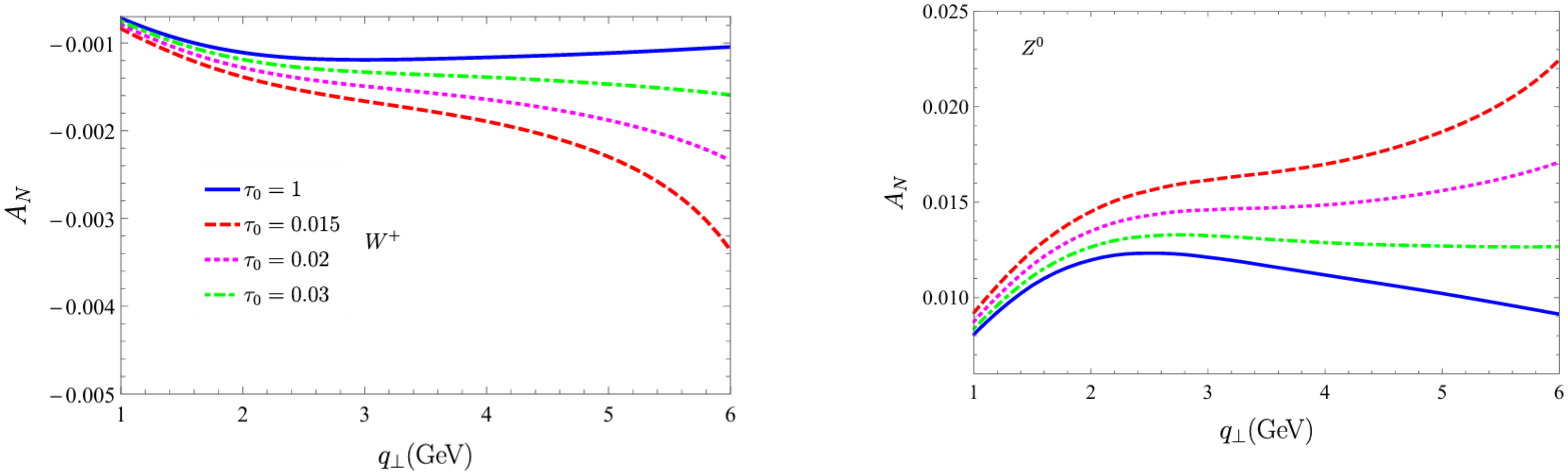


Implementing a 0-jettiness veto can significantly enhance the sensitivity of SSA measurements to the predicted sign flip of the Sivers function, thereby offering a more robust avenue for testing fundamental TMD dynamics in polarized collisions.

The enhanced asymmetries

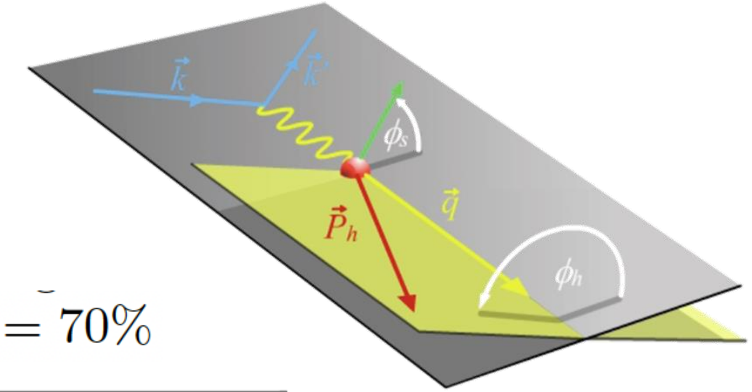
$$\tau \equiv \frac{2}{Q^2}\sum_i \min\{p_a \cdot l_i, p_b \cdot l_i\} = \sum_i \frac{|\vec{l}_{\perp,i}|}{Q} e^{-|y_i - y|}$$

$$\tau < \tau_0$$



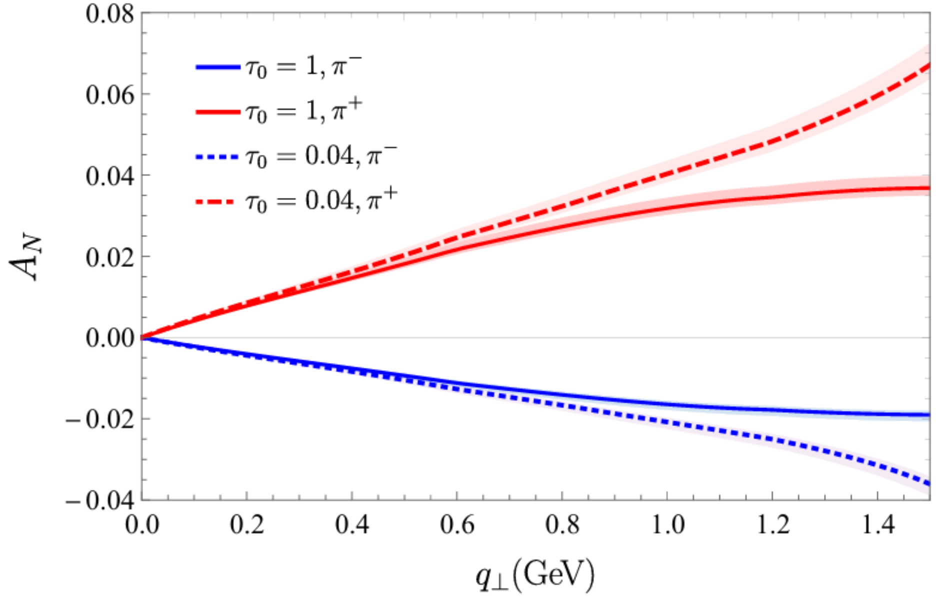
Implementing a 0-jettiness veto can significantly enhance the sensitivity of SSA measurements to the predicted sign flip of the Sivers function, thereby offering a more robust avenue for testing fundamental TMD dynamics in polarized collisions.

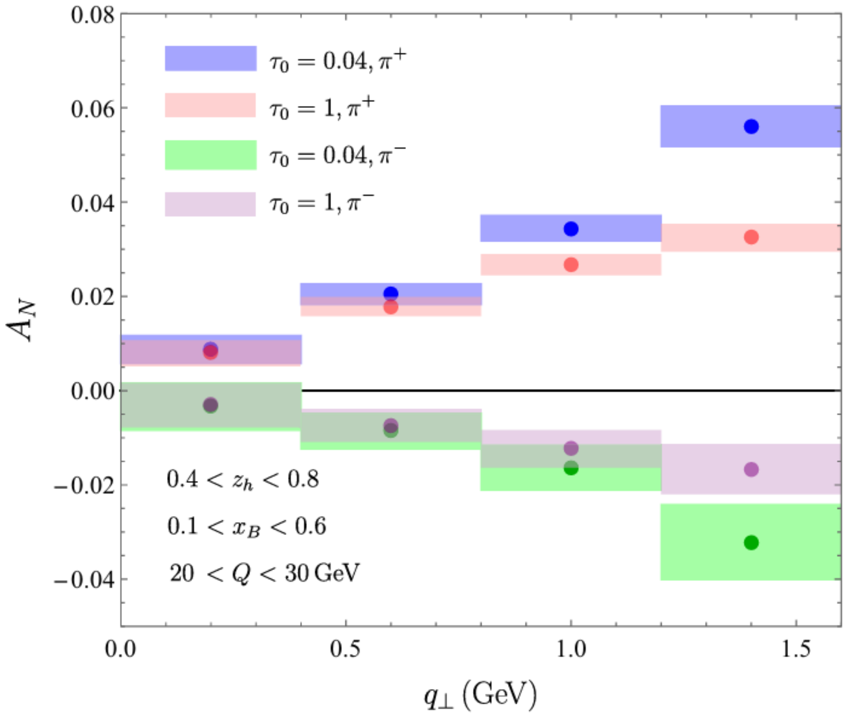
Single spin asymmetry in SIDIS



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

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

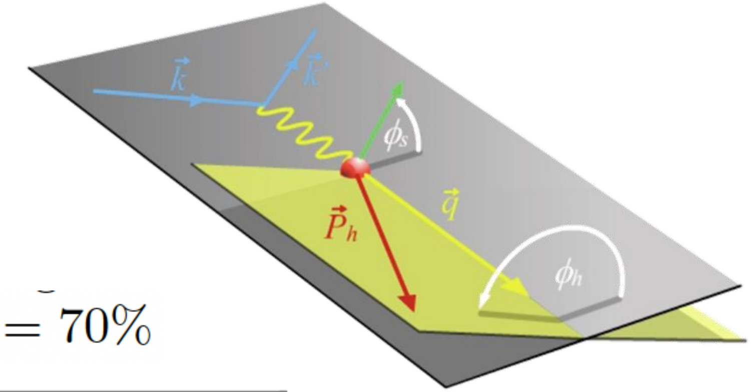




The results show that the asymmetries are enhanced at moderately large pion transverse momentum when the veto is applied

Single spin asymmetry in SIDIS

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



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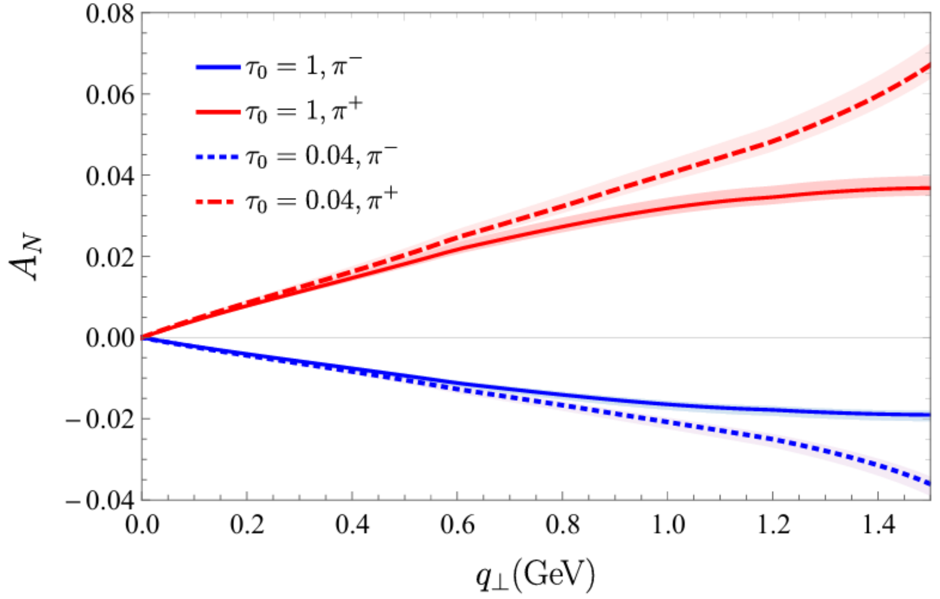
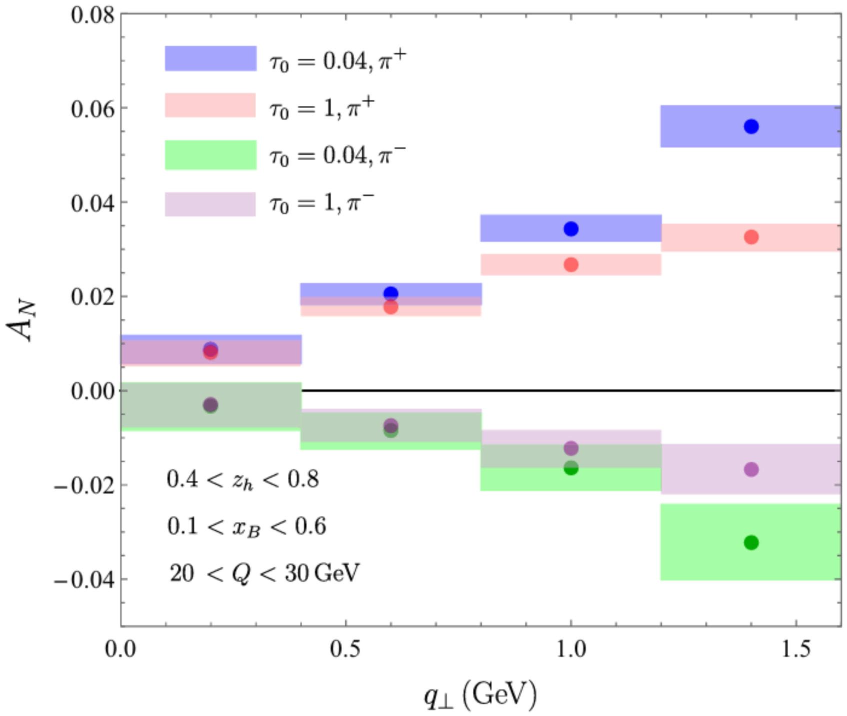


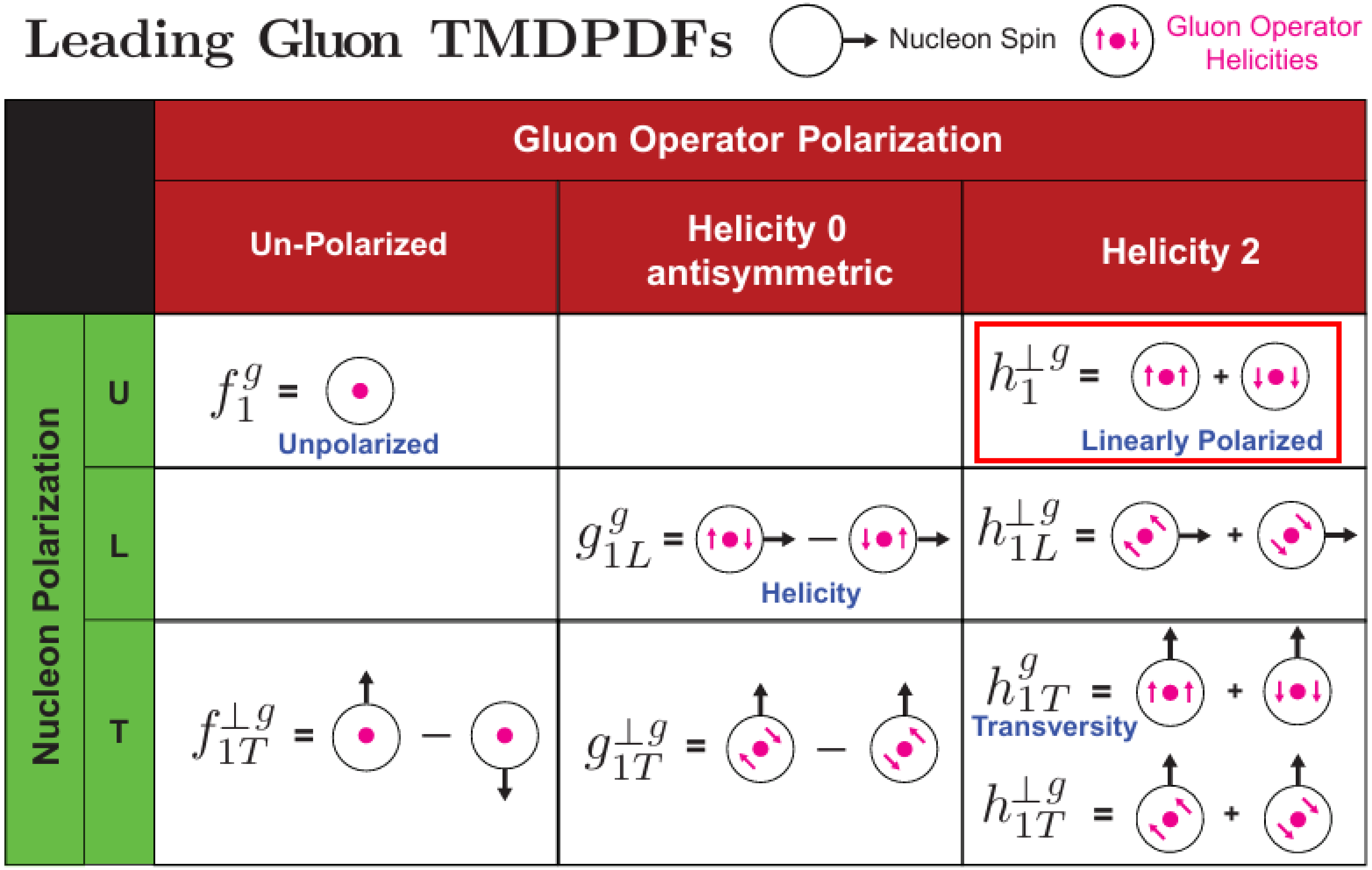


The error bands for the π^+ vetoed and inclusive cases show no overlap for $q_\perp \gtrsim 1$ GeV, confirming a measurable improvement in sensitivity.

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 $W^{\pm}/Z^{0}$ 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.

Gluon TMDs



Leading Gluon TMDPDFs
Nucleon Spin
Gluon Operator Helicities
Gluon Operator Polarization
Un-Polarized
Helicity 0 antisymmetric
Helicity 2
Nucleon Polarization
U
L
T
f_1^g =
Unpolarized
$h_1^{\perp g}$ =
Linearly Polarized
g_{1L}^g =
Helicity
$h_{1L}^{\perp g}$ =
$f_{1T}^{\perp g}$ =
$g_{1T}^{\perp g}$ =
h_{1T}^g =
Transversity
$h_{1T}^{\perp g}$ =

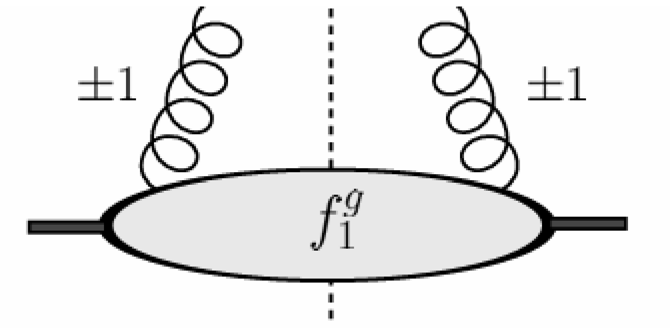
Gluon TMDs

$$\frac{1}{xP^+}\int \frac{dy^- d^2 y_T}{(2\pi)^3} e^{ik\cdot y}\langle P, S_T|2\mathrm{Tr}\left[F^{\mu}_{+T}(0)U F^{\nu}_{+T}(y)U'\right]|P, S_T\rangle$$

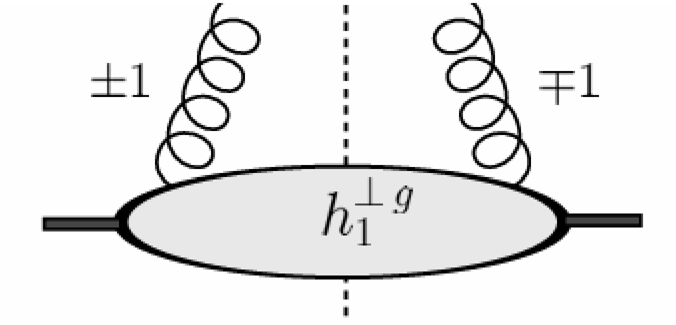
$$= \delta_T^{\mu\nu} f_1^g + \left(\frac{2k_T^\mu k_T^\nu}{k_\perp^2} - \delta_T^{\mu\nu}\right) h_1^{\perp g}$$

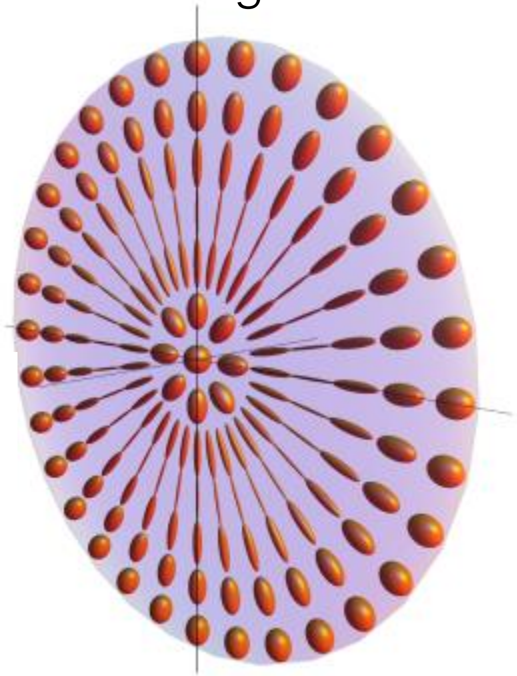
For $h_1^{\perp g} > 0$ gluons prefer to be polarized along kT

Unpolarized



linearly-polarized



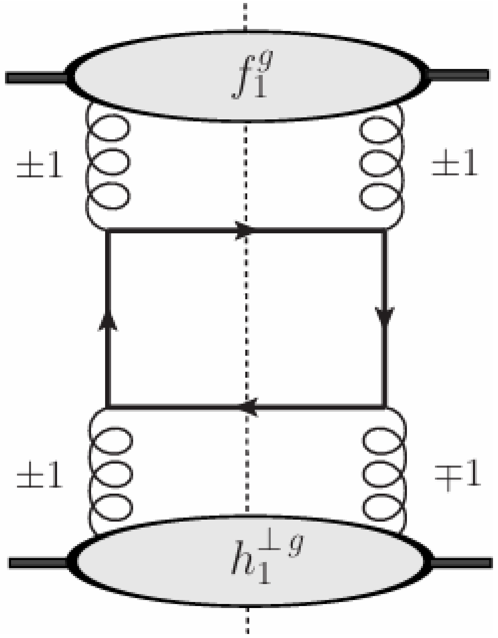


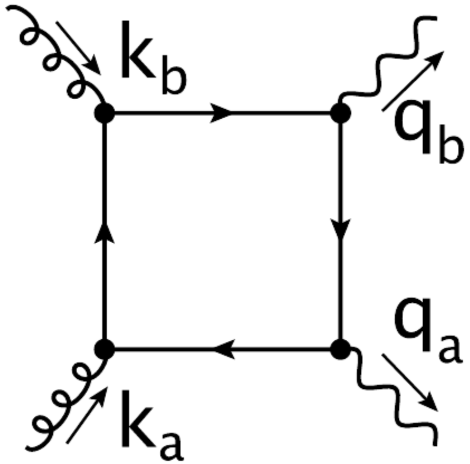
an interference between ±1 helicity gluon states

Linearly-polarized Gluon

D. Boer, S. J. Brodsky, P. J. Mulders, and C. Pisano
Phys.Rev.Lett. 106 (2011) 132001

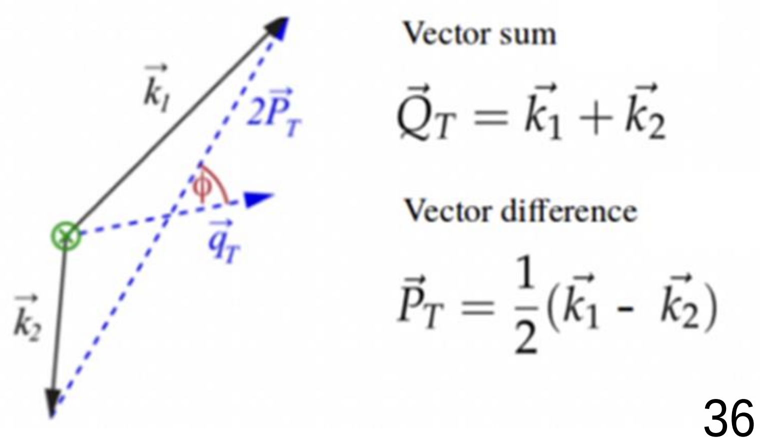
J.-W. Qiu, M. Schlegel, and W. Vogelsang
Phys.Rev.Lett. 107 (2011) 062001



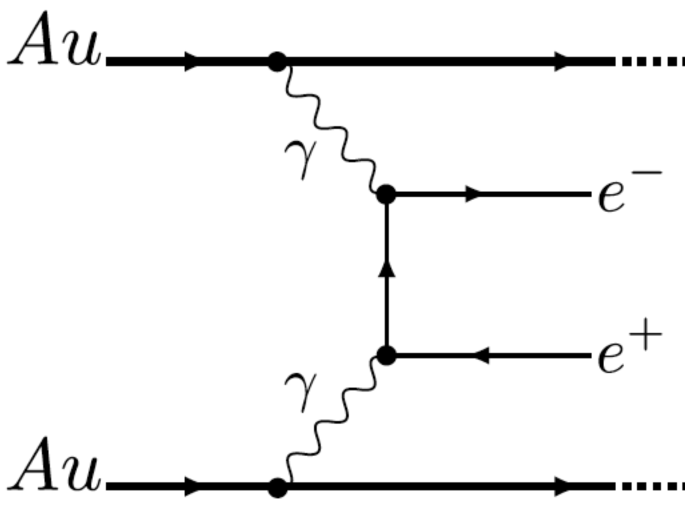


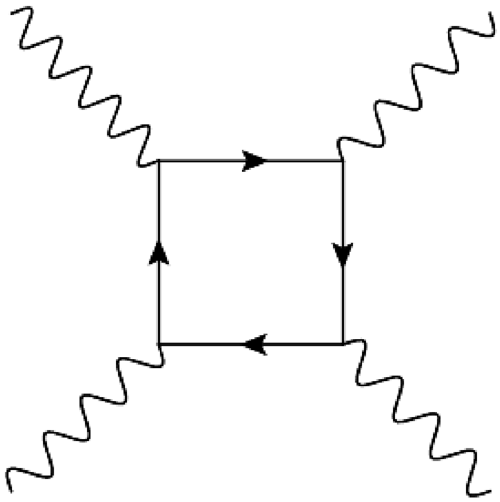
$$f_1^g \otimes h_1^{\perp g} \quad \Longrightarrow \quad \langle \cos 2\phi \rangle$$

$$h_1^{\perp g} \otimes h_1^{\perp g} \quad \Longrightarrow \quad \langle \cos 4\phi \rangle$$



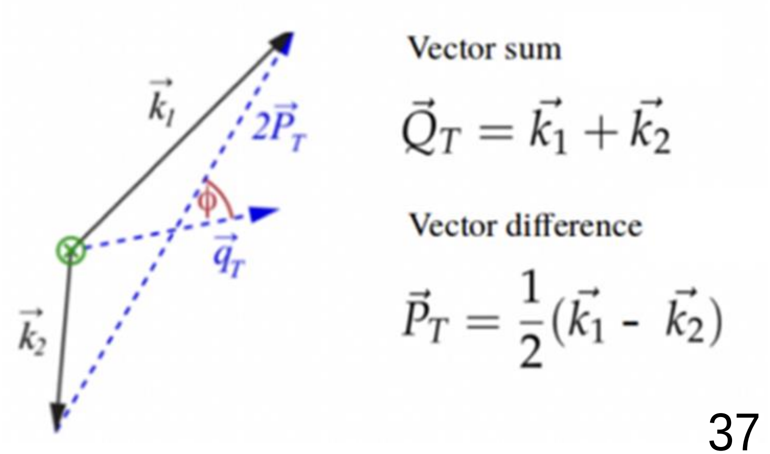
Linearly-polarized Photon



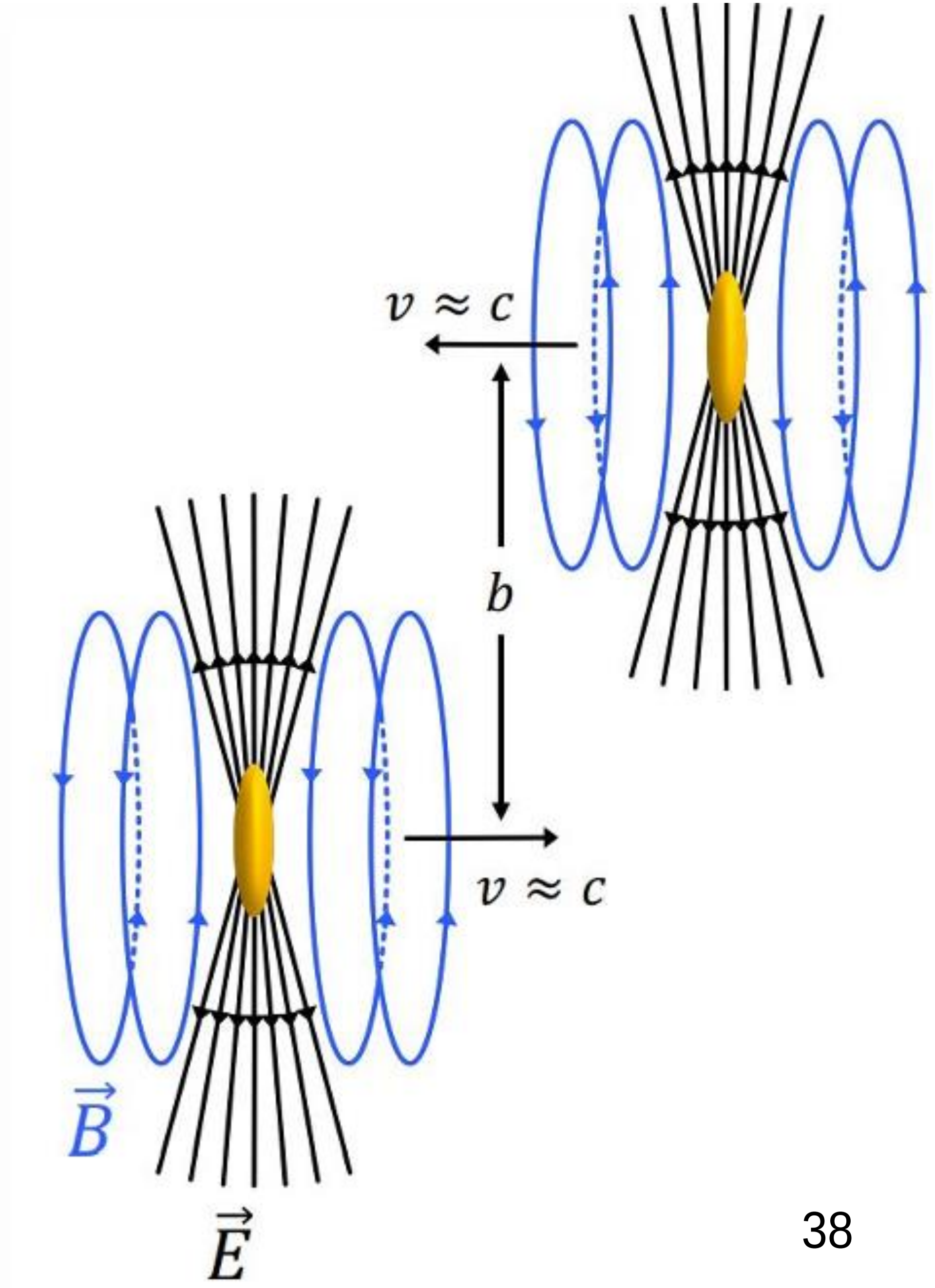


$$f_1^g \otimes h_1^{\perp g} \implies \langle \cos 2\phi \rangle$$

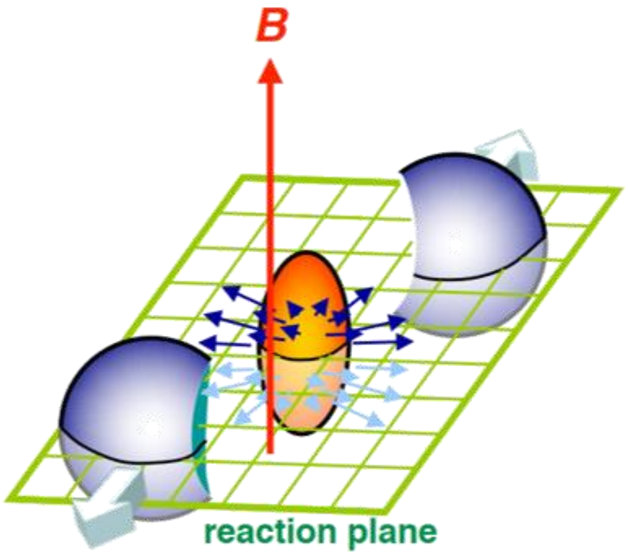
$$h_1^{\perp g} \otimes h_1^{\perp g} \implies \langle \cos 4\phi \rangle$$

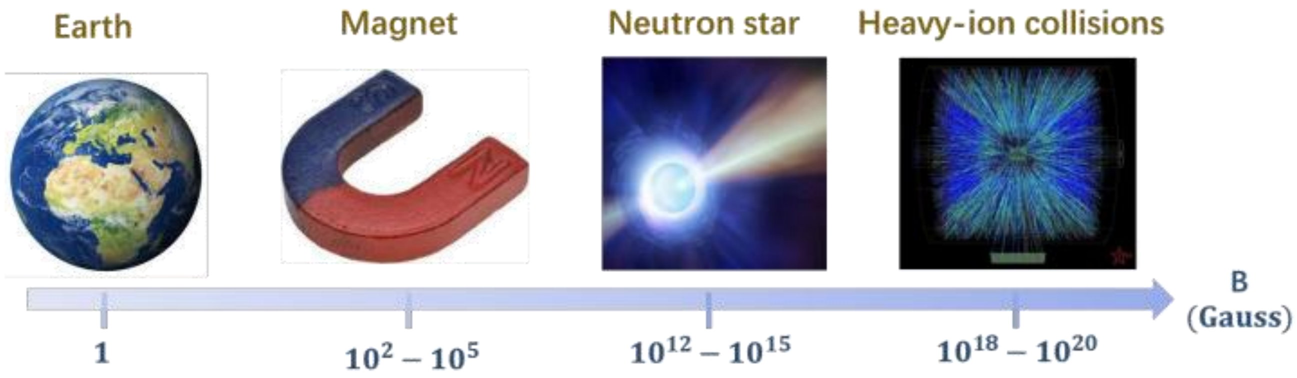


Azimuthal Asymmetries in Ultraperipheral Heavy-Ion Collisions



Strong EB fields in HIC





- $eB \sim \gamma Z \alpha v / b_T^2 \sim 10^{18}\mathrm{Gauss}$

  $\sqrt{s_{NN}} = 200\mathrm{GeV}$ Au+Au

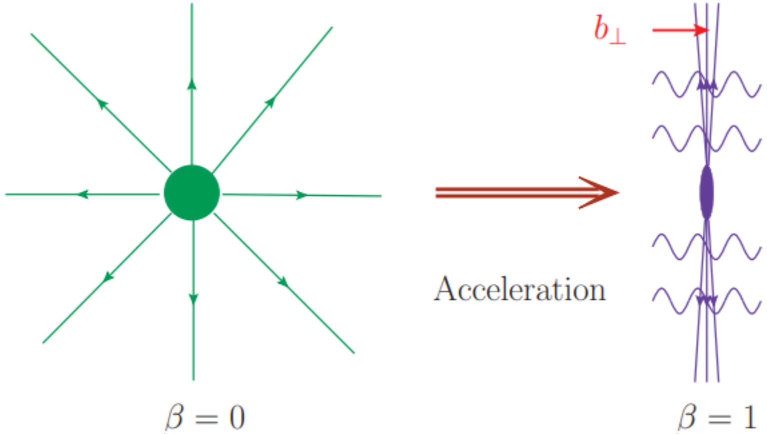
D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys. A 803, 227 (2008)

L. McLerran and V. Skokov, Nucl. Phys. A 929, 184 (2014)

……

Equivalent Photon Approximation

Ultra-relativistic charged particle produce highly Lorentz contracted electromagnetic field

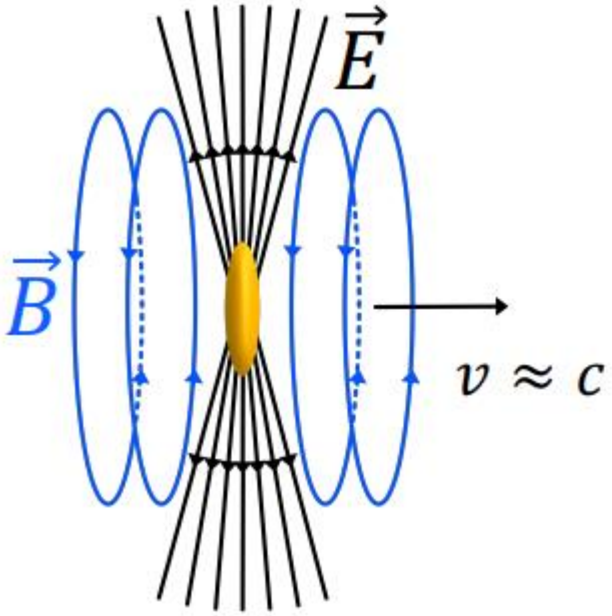


Equivalent Photon Approximation

Classical EM ⇔ Quasi-real photons

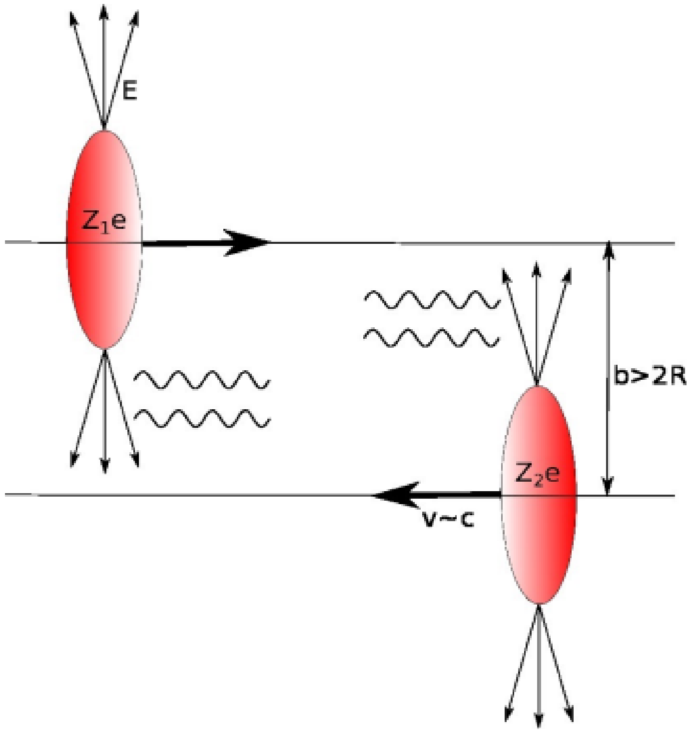
Equivalent Photon Approximation

Due to the large flux of quasi-real photon,the cross-section can be enhanced by the Ze



$$n(\omega) = \frac{4Z^2\alpha_e}{\omega}\int \frac{d^2k_\perp}{(2\pi)^2}k_\perp^2\left[\frac{F(k_\perp^2+\omega^2/\gamma^2)}{(k_\perp^2+\omega^2/\gamma^2)}\right]^2$$

Ultraperipheral Collisions(UPC)



UPC: the impact parameter is larger than 2 times the radius of a nucleus

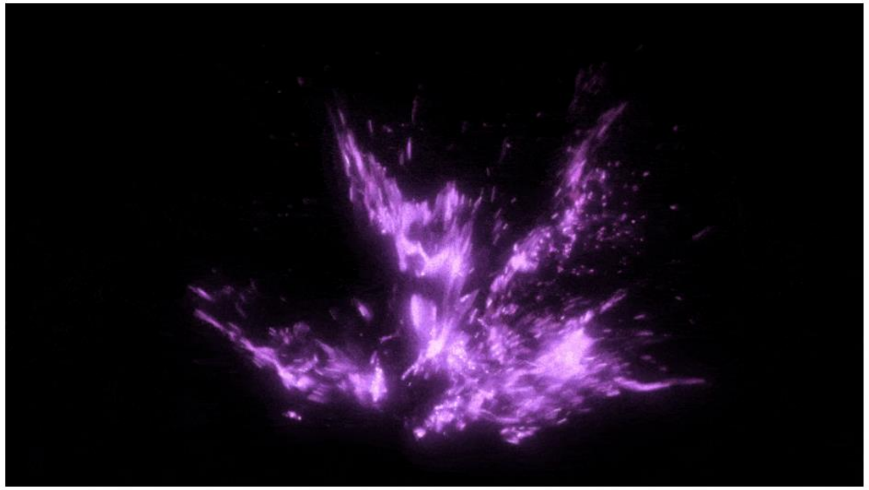
Clean background

Azimuthal modulation in dilepton photoproduction

Scientists Generate Matter Directly From Light – Physics Phenomena Predicted More Than 80 Years Ago

TOPICS: Antimatter Atomic Physics Brookhaven National Laboratory DOE Popular

By BROOKHAVEN NATIONAL LABORATORY JULY 30, 2021

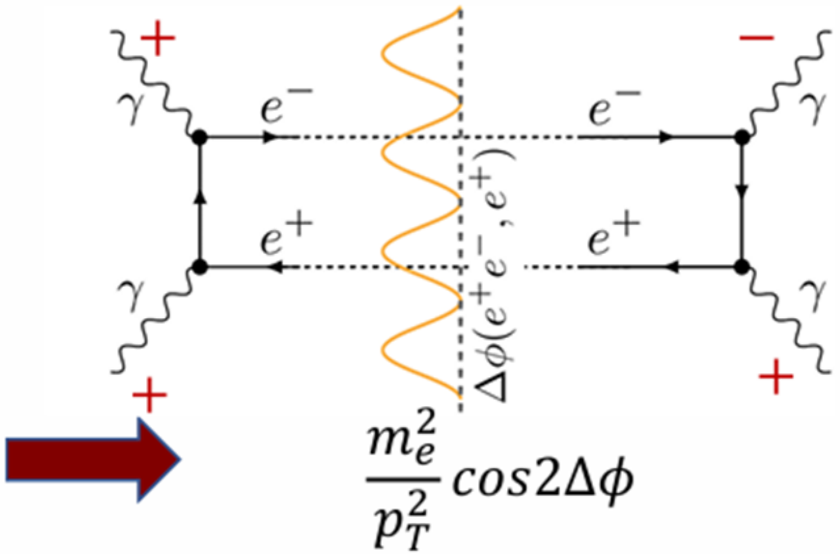


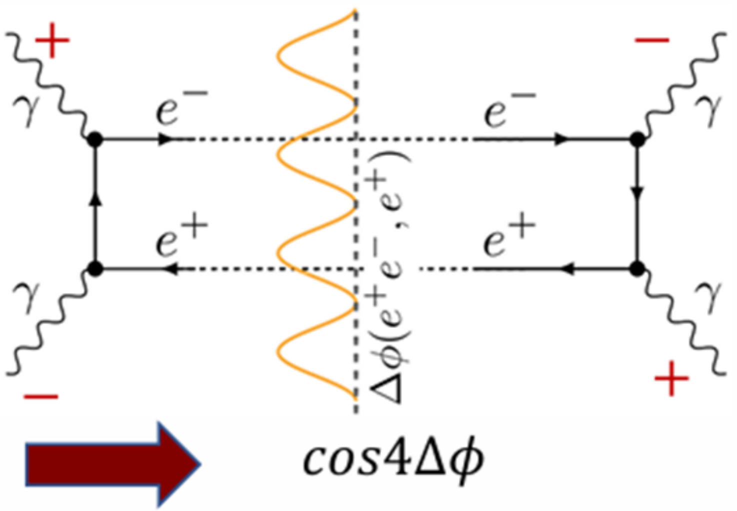
R.J. Wang, S. Lin, S.Pu,Y.F. Zhang, Q. Wang,Phys.Rev.D 106 (2022) 3, 034025

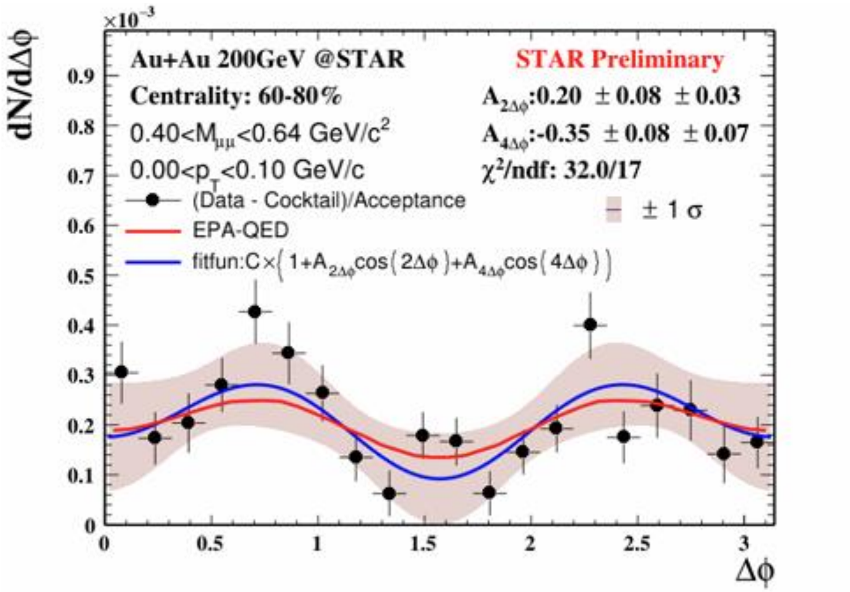
S. Lin,R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

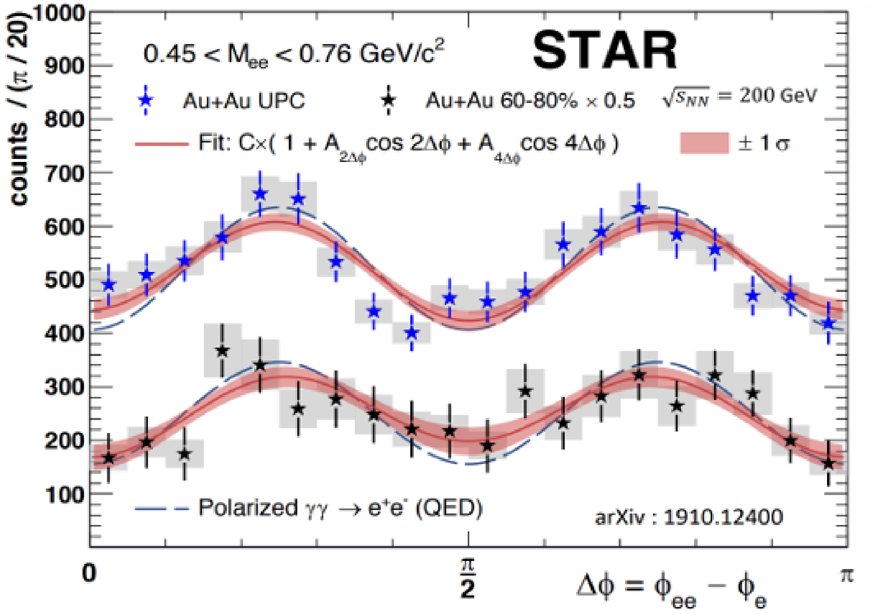
Azimuthal modulation in dilepton photoproduction

C. Li, J. Zhou and Y. J. Zhou, PLB 795, 576 (2019) ;PRD 101 (2020) 3, 034015









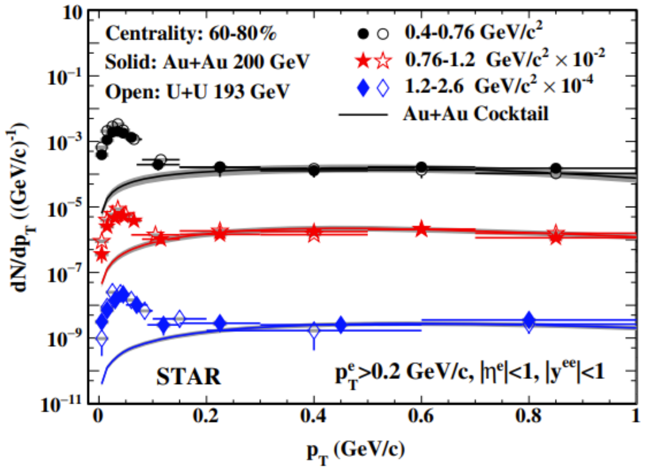
Peripheral Collisions

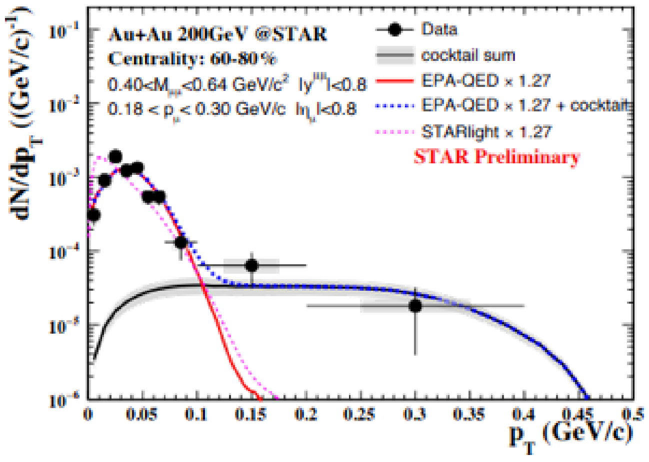
- $\gamma\gamma \rightarrow l^{+}l^{-}$ processes have been measured in peripheral collisions ($b < 2R_A$)

STAR, J. Adam et al., Phys. Rev. Lett. 121, 132301 (2018), 1806.02295.

ATLAS, M. Aaboud et al., Phys. Rev. Lett. 121, 212301 (2018), 1806.08708.

ALICE, Sebastian Lehner et al., PoS LHCP2019 (2019) 164, 1909.02508.

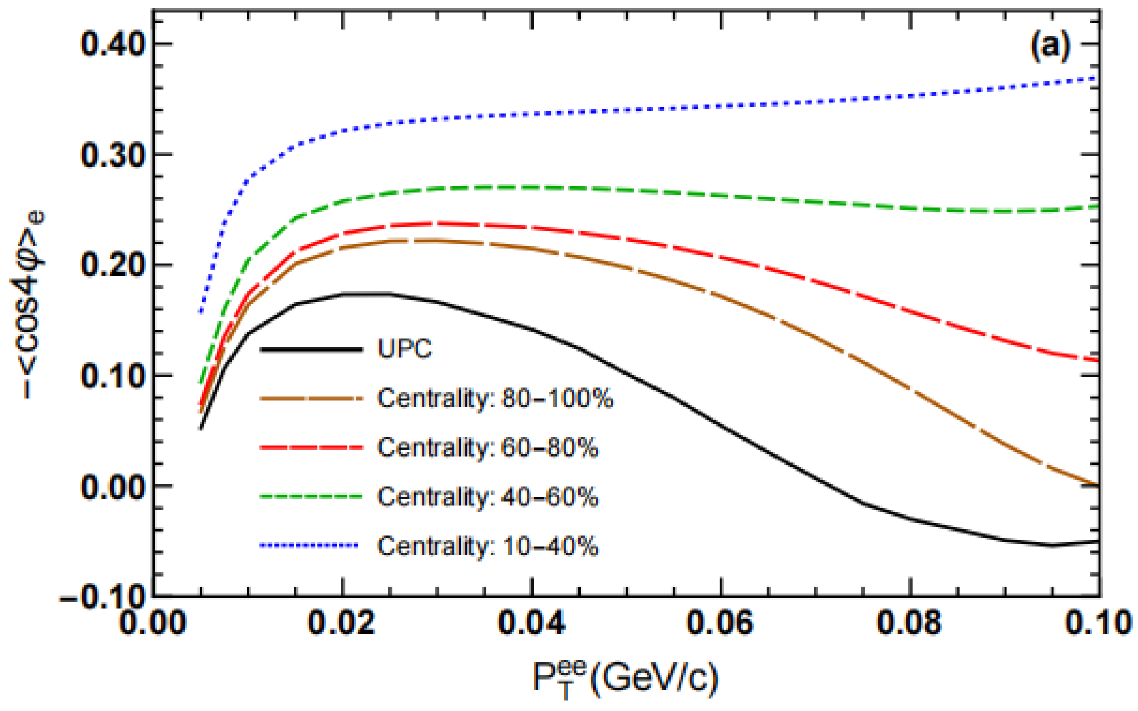


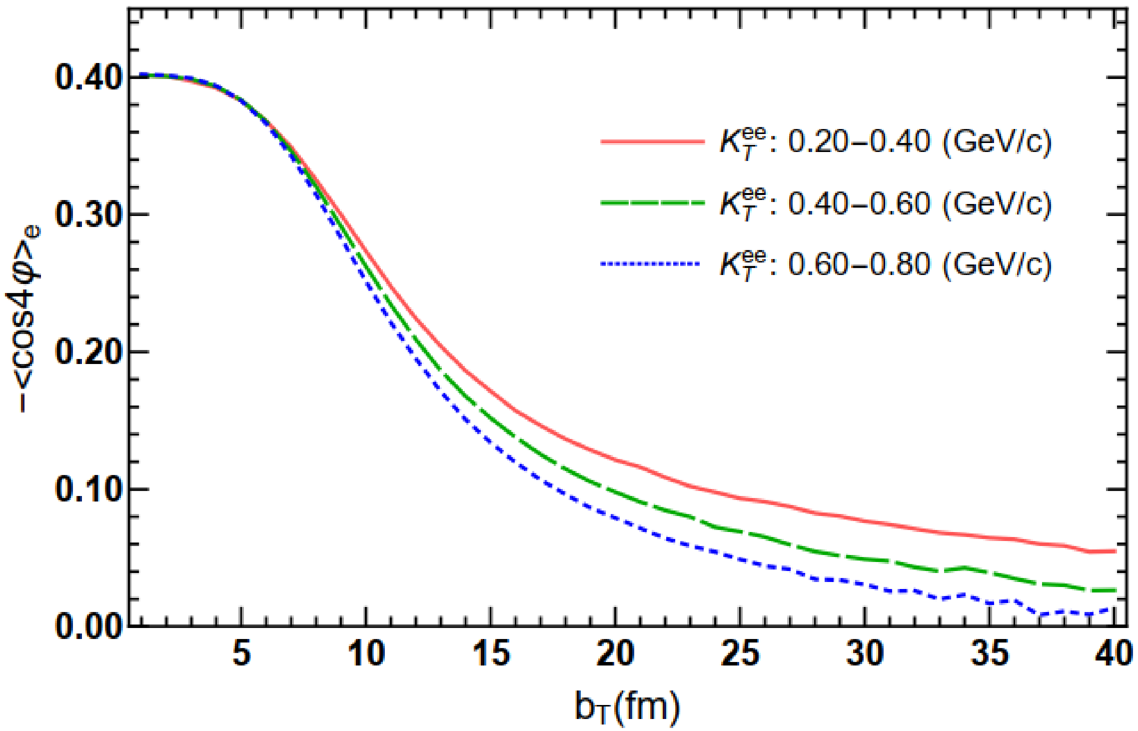


Excess above hadronic production has been observed at low transverse momentum of dileptons (P_T^{ee})

Azimuthal modulation in dilepton photoproduction

R.J. Wang, S. Lin, S.Pu,Y.F. Zhang, Q. Wang, Phys.Rev.D 106 (2022) 3, 034025





Azimuthal modulation in dilepton photoproduction

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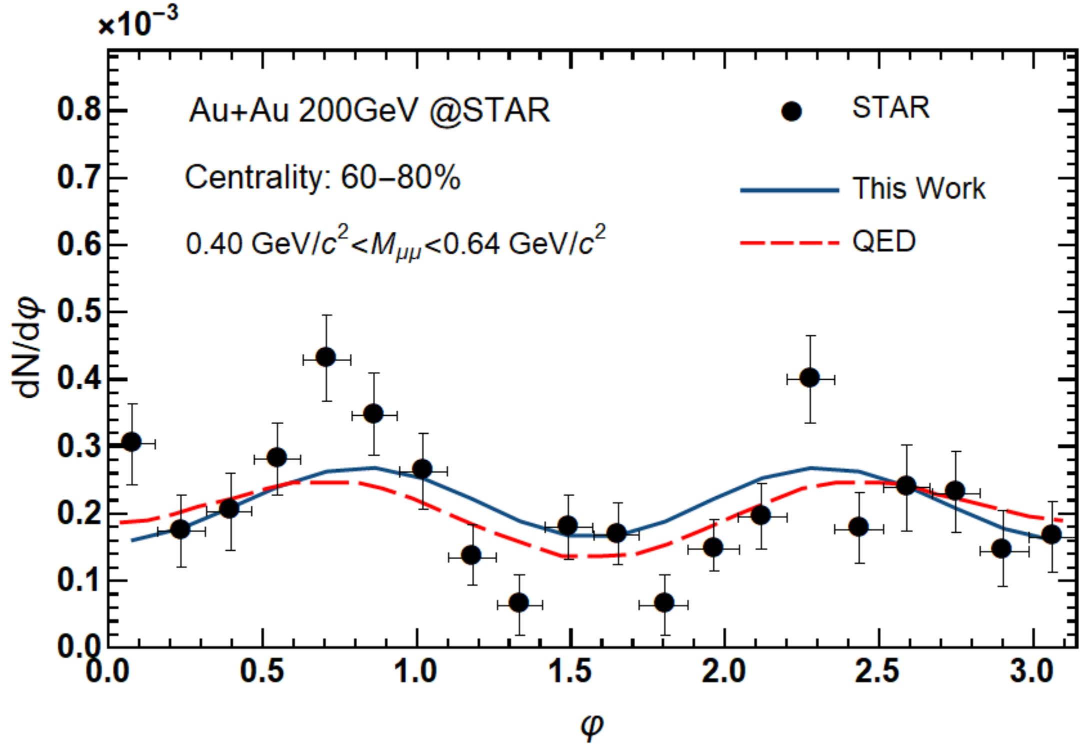

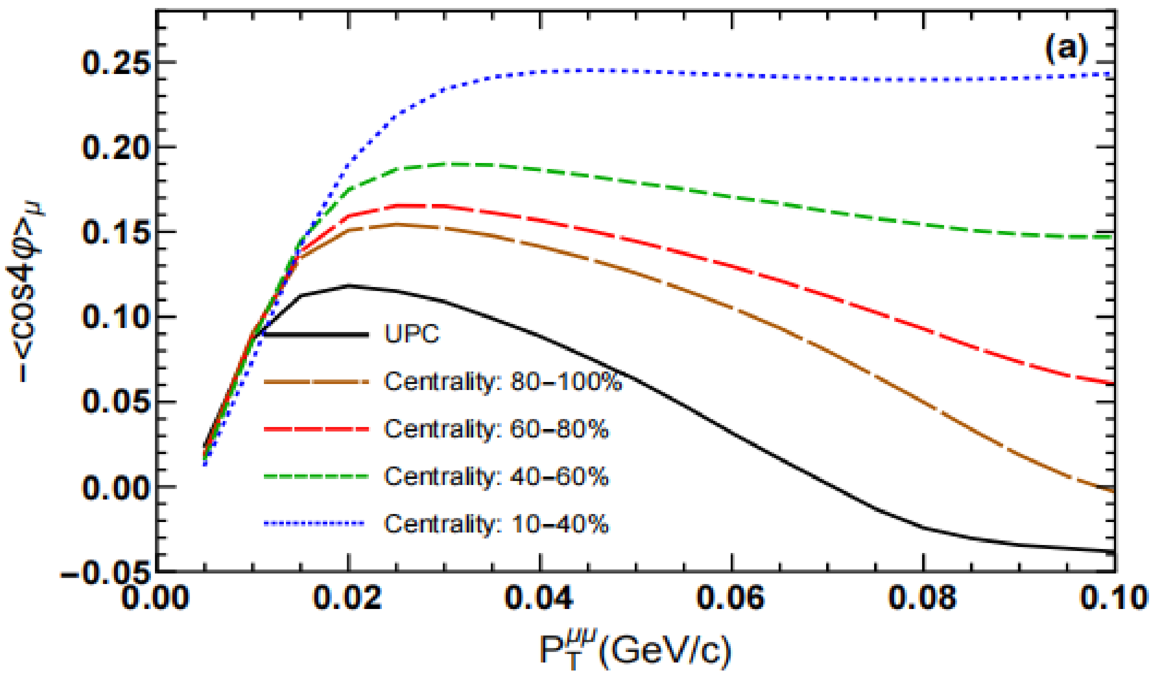

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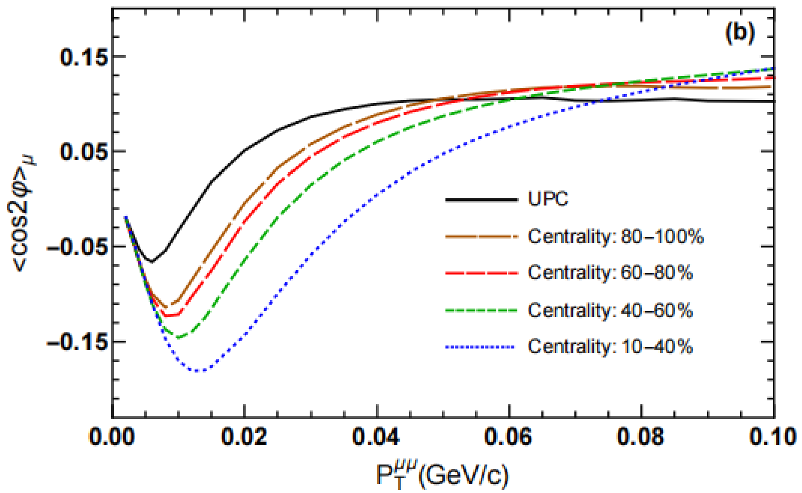
R.J. Wang, S. Lin, S.Pu,Y.F. Zhang, Q. Wang，Phys.Rev.D 106 (2022) 3, 034025



The $\cos 2\varphi$ modulations of $\mu^+\mu^-$ are higher than e^+e^- case.

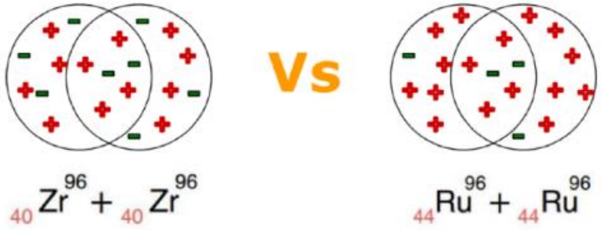
C. Li, J. Zhou and Y. J. Zhou, PLB 795, 576 (2019) ;PRD 101 (2020) 3, 034015
D.Y. Shao, C. Zhang, J. Zhou, Y.J. Zhou, PRD 107 (2023) 3, 036020

$$\frac{d\sigma_0}{d^2q_\perp d^2P_\perp dy_1 dy_2 d^2b_\perp} = A_0 + A_2\cos 2\phi + A_4\cos 4\phi$$

$$A_2 = \int [d\mathcal{K}_\perp] \frac{8\boxed{m^2}P_\perp^2}{(P_\perp^2+m^2)^2}\cos\left(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}\right)\cos\left(\phi_{k'_{1\perp}} + \phi_{k'_{2\perp}} - 2\phi\right)$$

Azimuthal modulation in dilepton photoproduction

- Can nuclear structure information be reflected in the photoproduction in isobar collision ?



(a)	R_c	d_c	R_n	d_n
Ru	5.083 fm	0.477 fm	5.093 fm	0.488 fm
Zr	4.977 fm	0.492 fm	5.022 fm	0.538 fm

(b)	R_c	d_c	R_n	d_n
Ru	5.083 fm	0.477 fm	R_c^{Ru}	d_c^{Ru}
Zr	4.977 fm	0.492 fm	R_c^{Zr}	d_c^{Zr}

Charge density distribution → F

Mass density distribution → $\int_{b_{min}}^{b_{max}} db_T$

The lepton pair photoproduction is calculated with the charge density distribution, while the centrality is defined from the Glauber model with the nuclear mass density.

S. Lin,R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

Azimuthal modulation in dilepton photoproduction

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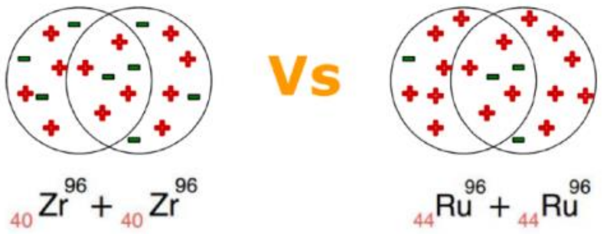

Charge density distribution → F

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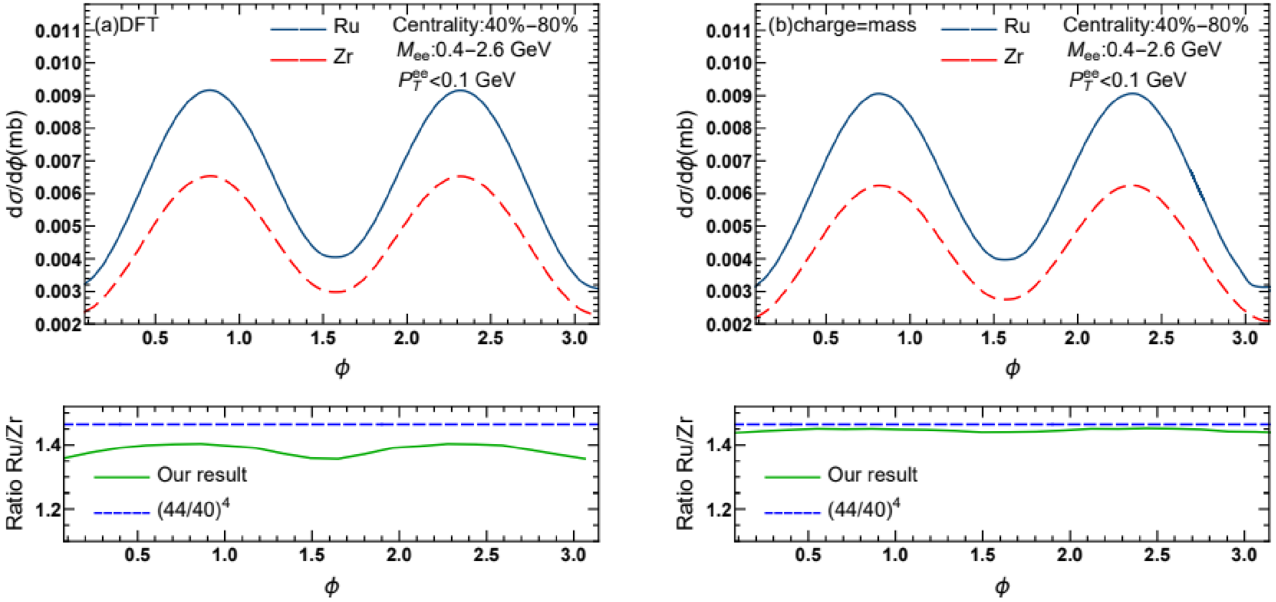

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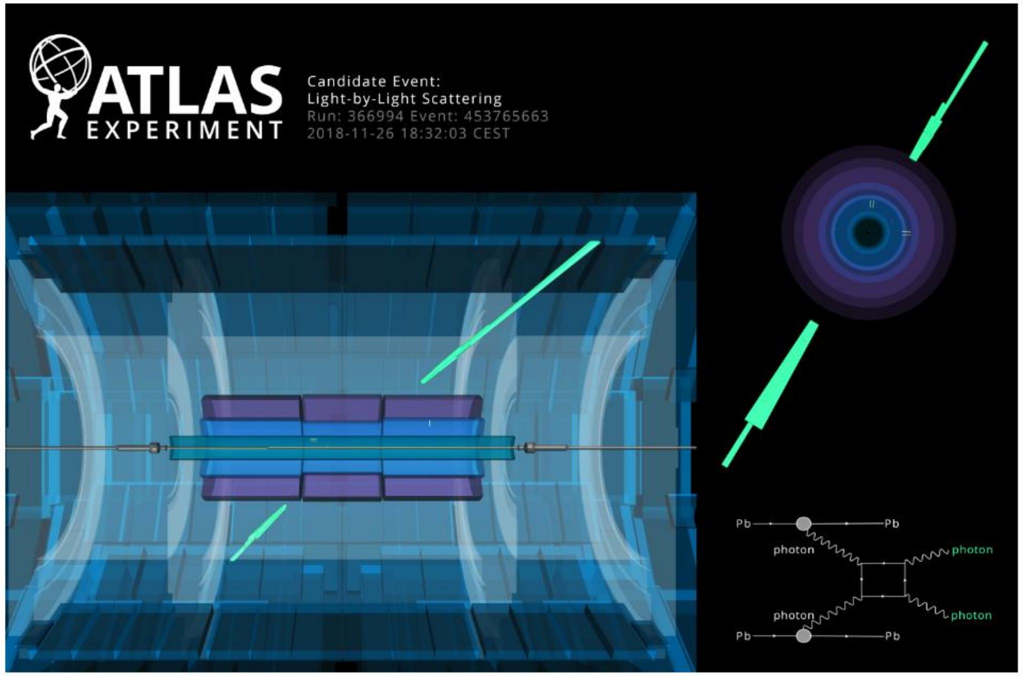
S. Lin,R.J. Wang, J.F. Wang, H.J. Xu, S. Pu and Q. Wang, Phys.Rev.D 107 (2023), 054004.

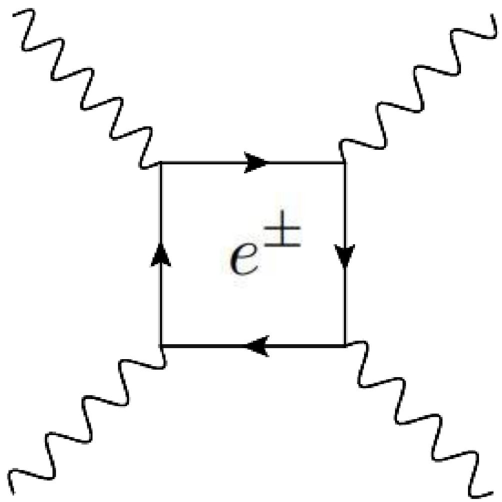
Azimuthal modulation in light-by-light scattering



Yu Jia, Shuo Lin, Jian Zhou, Ya-jin Zhou,arXiv:2410.13781

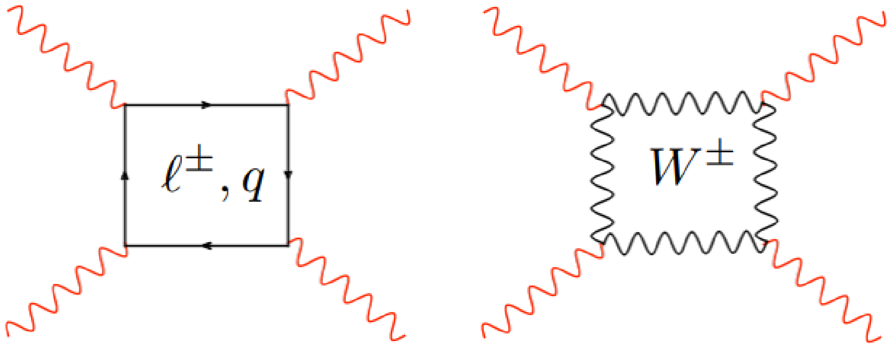
Light-by-light scattering：A Long-Researched Topic

- Initially predicted based on Dirac theory. **Halpern 1933**
- Low frequency limit Euler-Heisenberg Lagrangian
  Heisenberg, Euler and Kockel 1935-36
- High frequency limit **Akhieser, Landau and Pomeranchuk 1936**
- The first complete LO calculation in QED **Karplus & Neuman 1951**

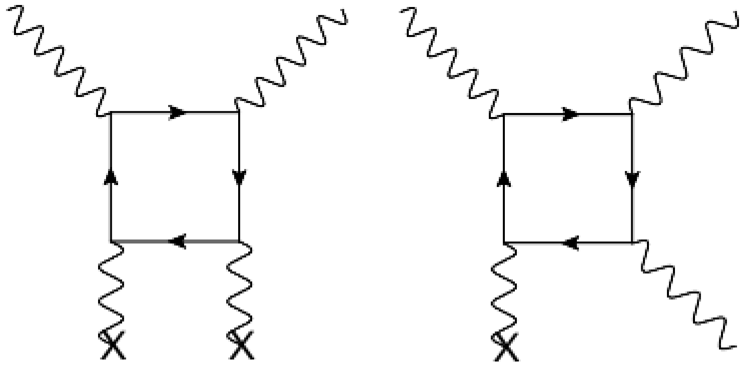


Light-by-light scattering： Connections to Many Topics

- One of the most fascinating processes in Standard Model
- Strong field related phenomena
- The anomalous magnetic moments
- A playground to search for new physics.



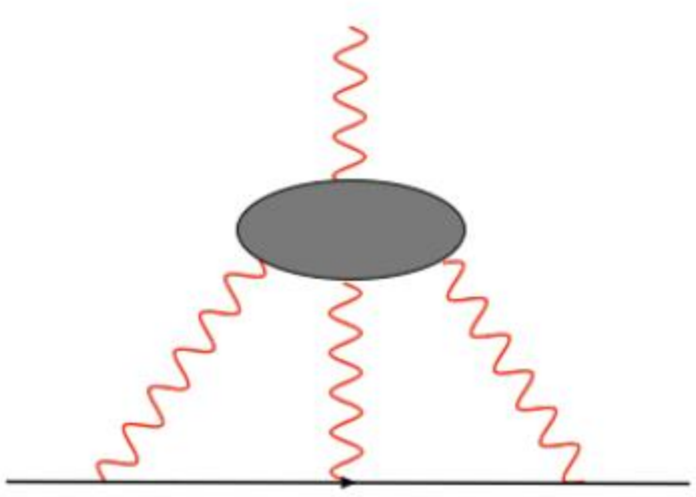
Delbrück scattering Photon splitting

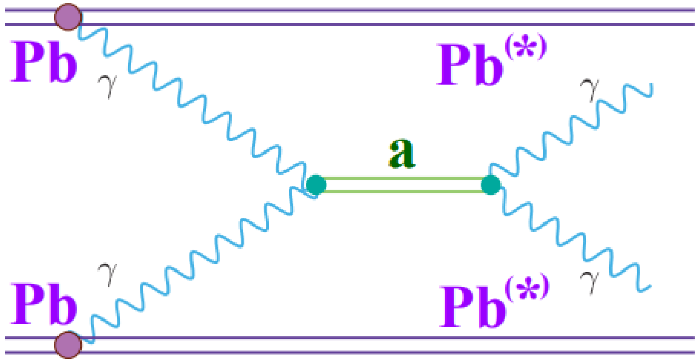


Each cross denotes external field legs, e.g., an atomic Coulomb field or a strong background magnetic field.

Light-by-light scattering： Connections to Many Topics

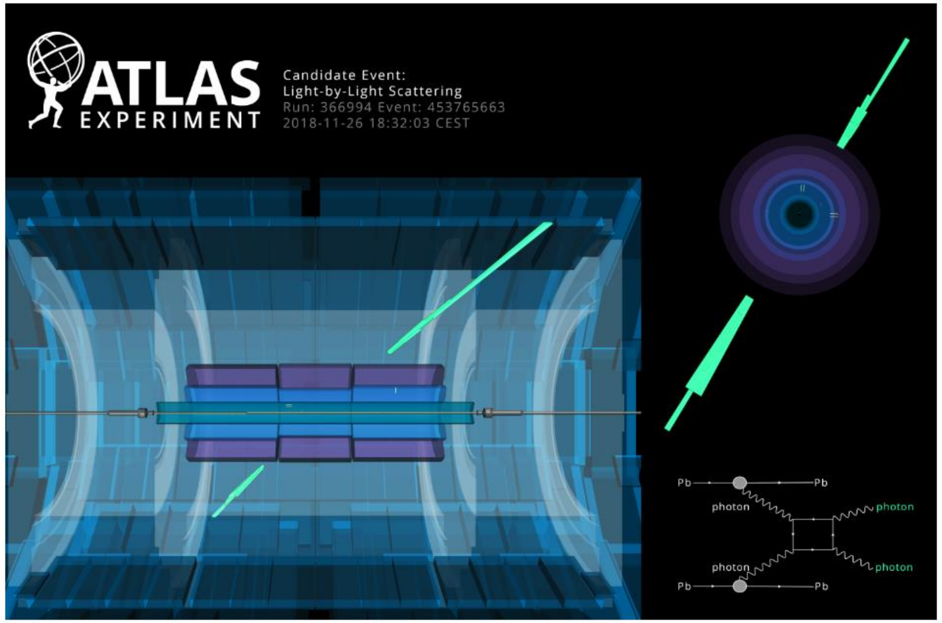
- One of the most fascinating processes in Standard Model
- Strong field related phenomena
- The anomalous magnetic moments
- A playground to search for new physics.

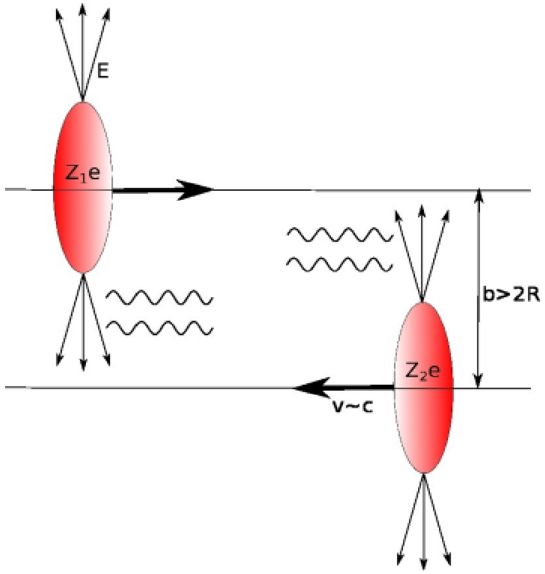




Experimental measurement

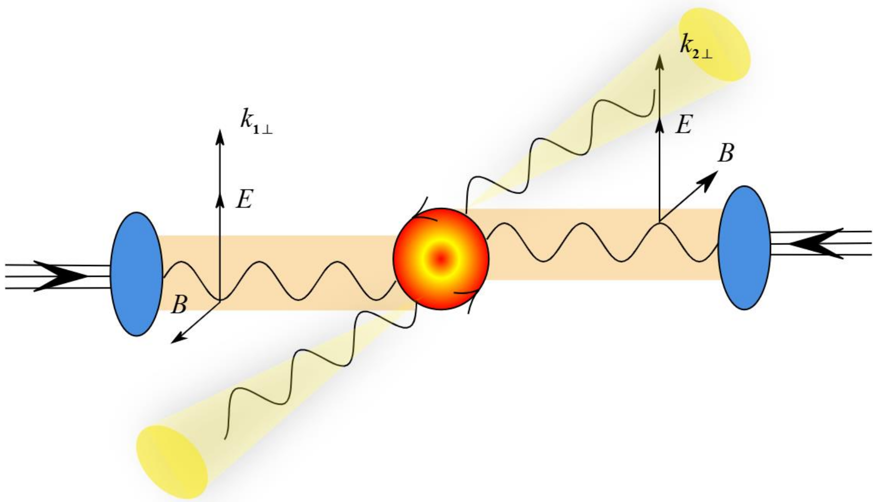
M. Aaboud et al. (ATLAS), Nature Phys. 13, 852 (2017), 1702.01625.
A. M. Sirunyan et al. (CMS), Phys. Lett. B 797, 134826 (2019), 1810.04602.
G. Aad et al. (ATLAS), Phys. Rev. Lett. 123, 052001 (2019), 1904.03536.
G. Aad et al. (ATLAS), JHEP 03, 243 (2021), [Erratum: JHEP 11, 050 (2021)], 2008.05355.





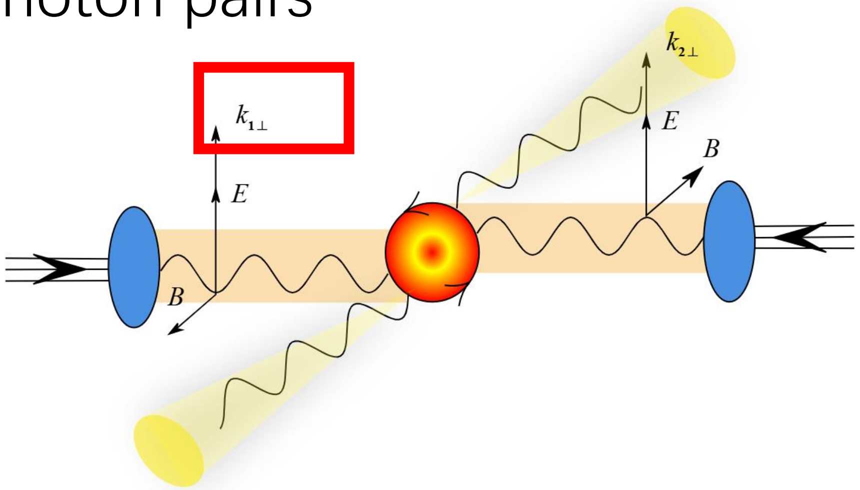
Joint dependence of kt & bt

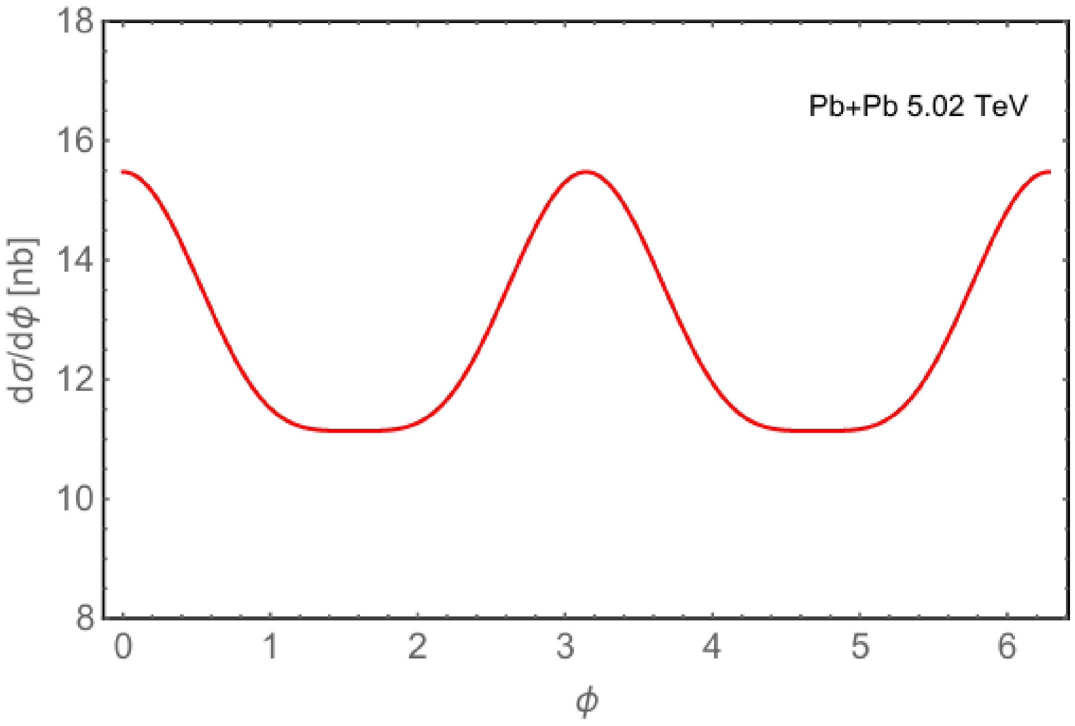
$$\frac{d\sigma}{d^2\boldsymbol{p}_{1\perp} d^2\boldsymbol{p}_{2\perp} dy_1 dy_2 d^2\boldsymbol{b}_\perp}$$
$$= \frac{1}{32\pi^2 Q^4} \int d^2\boldsymbol{k}_{1\perp} d^2\boldsymbol{k}_{2\perp} \frac{d^2\boldsymbol{k}'_{1\perp}}{(2\pi)^2} \delta^2(\boldsymbol{q}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_{2\perp})$$
$$\times\ e^{i(\boldsymbol{k}_{1\perp} - \boldsymbol{k}'_{1\perp})\cdot \boldsymbol{b}_\perp} \Big\{ \cos(\phi_1 - \phi_2)\cos(\phi'_1 - \phi'_2)|M_{++}|^2$$
$$+\ \cos(\phi_1 + \phi_2)\cos(\phi'_1 + \phi'_2)|M_{+-}|^2$$
$$-\ \cos(\phi_1 + \phi_2)\cos(\phi'_1 - \phi'_2) M_{++} M^*_{+-}$$
$$-\ \cos(\phi_1 - \phi_2)\cos(\phi'_1 + \phi'_2) M_{+-} M^*_{++} \Big\}$$
$$\times\ \mathcal{F}(x_1, \boldsymbol{k}^2_{1\perp})\, \mathcal{F}^*(x_1, \boldsymbol{k}'^2_{1\perp})\, \mathcal{F}(x_2, \boldsymbol{k}^2_{2\perp})\, \mathcal{F}^*(x_2, \boldsymbol{k}'^2_{2\perp}),$$



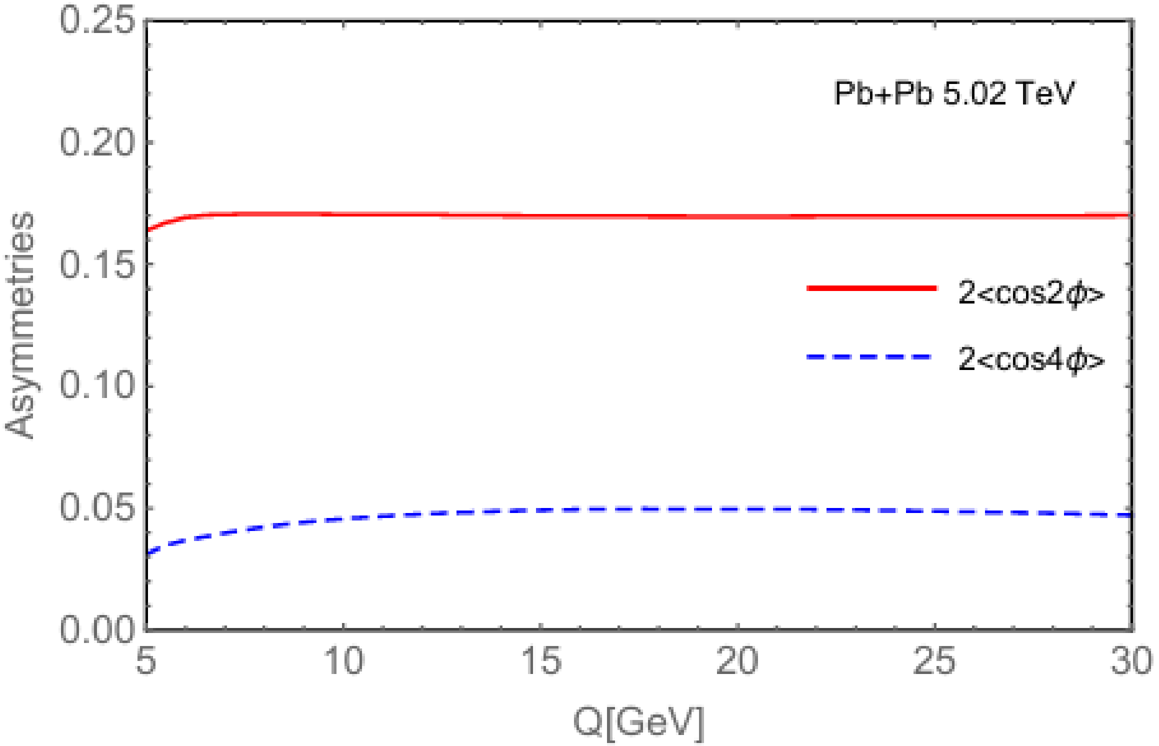
Azimuthal modulation

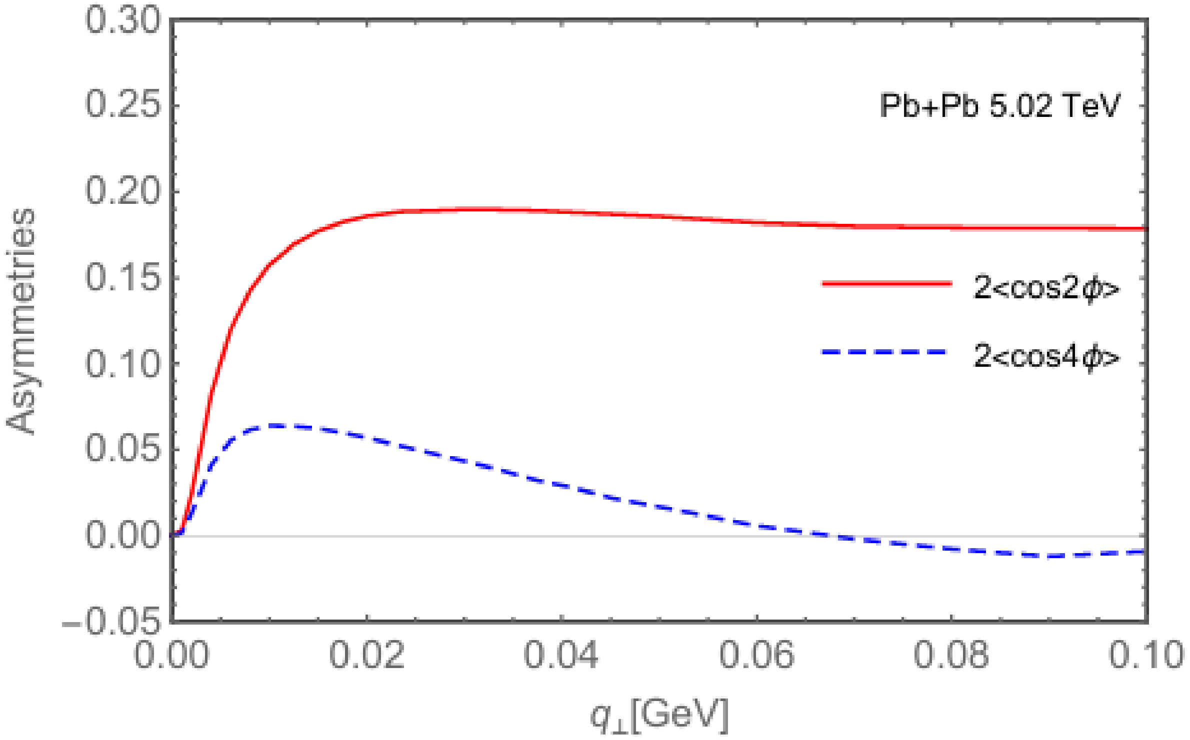
The linear polarization of initial photons
→azimuthal asymmetry of final photon pairs





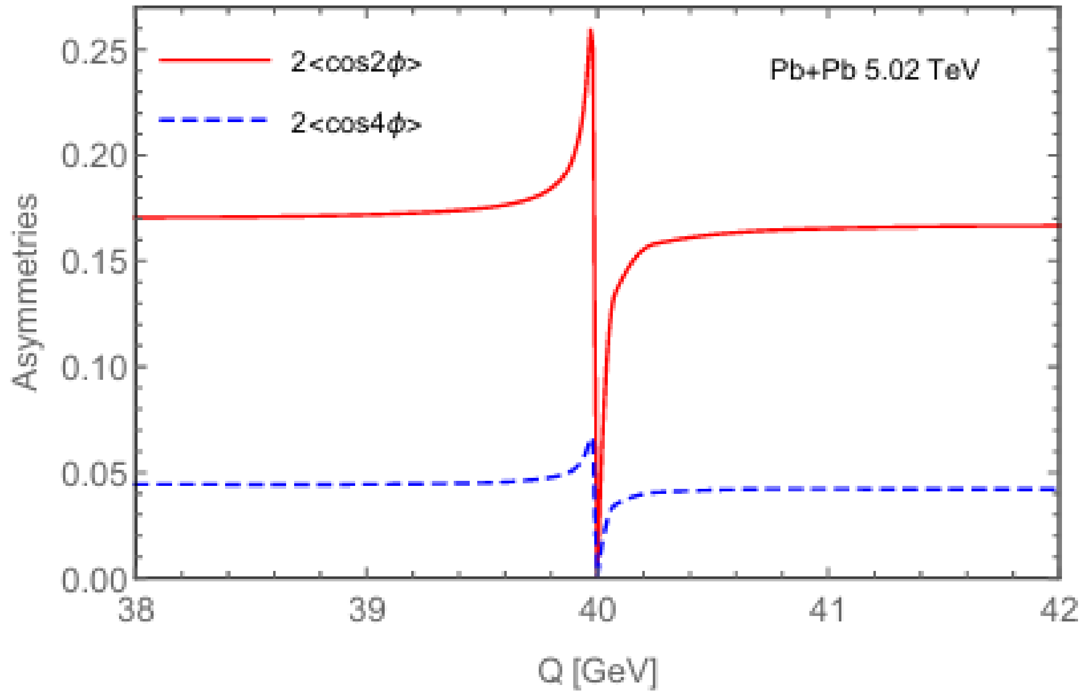
Azimuthal modulation





Azimuthal modulation

$$\frac{1}{f}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$$



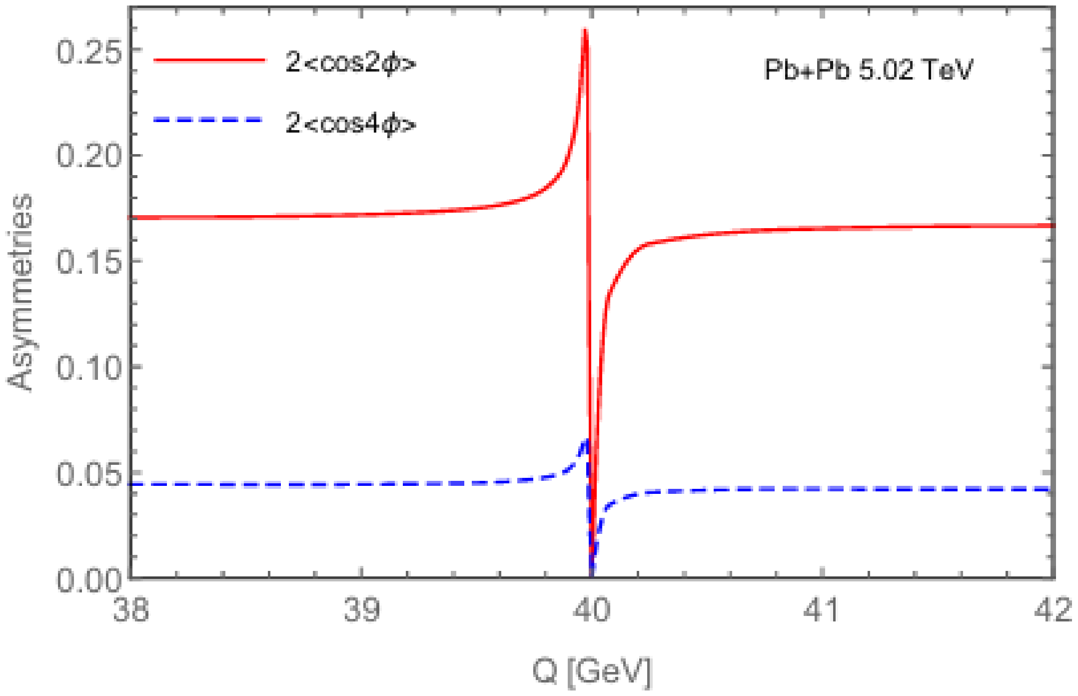
Axion-like particle

Unlike the SM continuum, which shows a relatively stable azimuthal modulation, the NP resonant contribution gives rise to a highly nontrivial invariant-mass dependence of the azimuthal asymmetry.

Azimuthal modulation could be a valuable new observable for new physics.

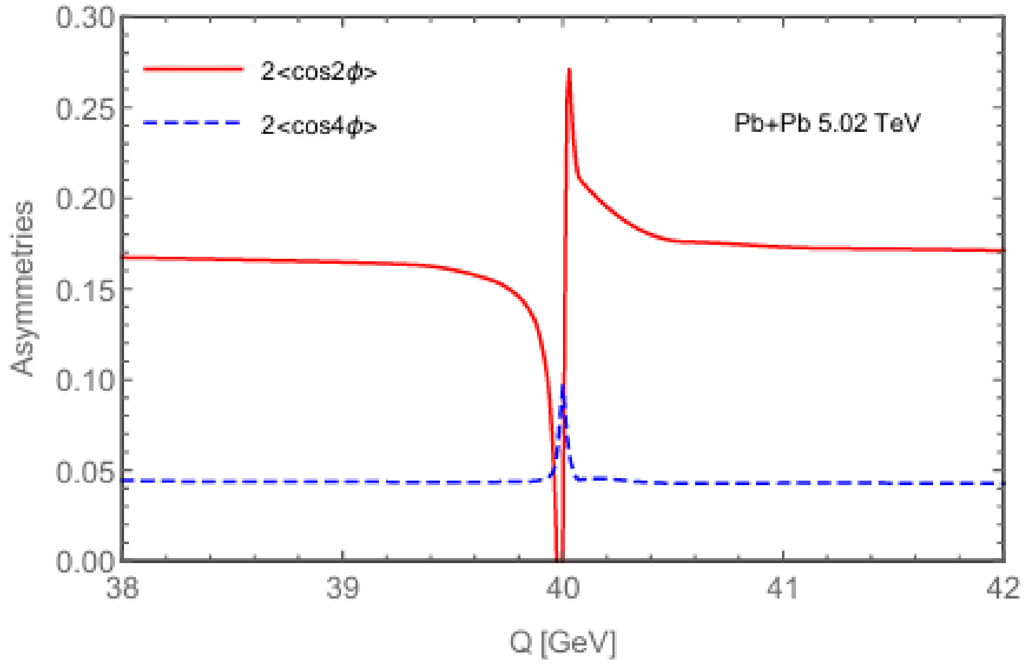
Azimuthal modulation

$$\frac{1}{f}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$$



Axion-like particle

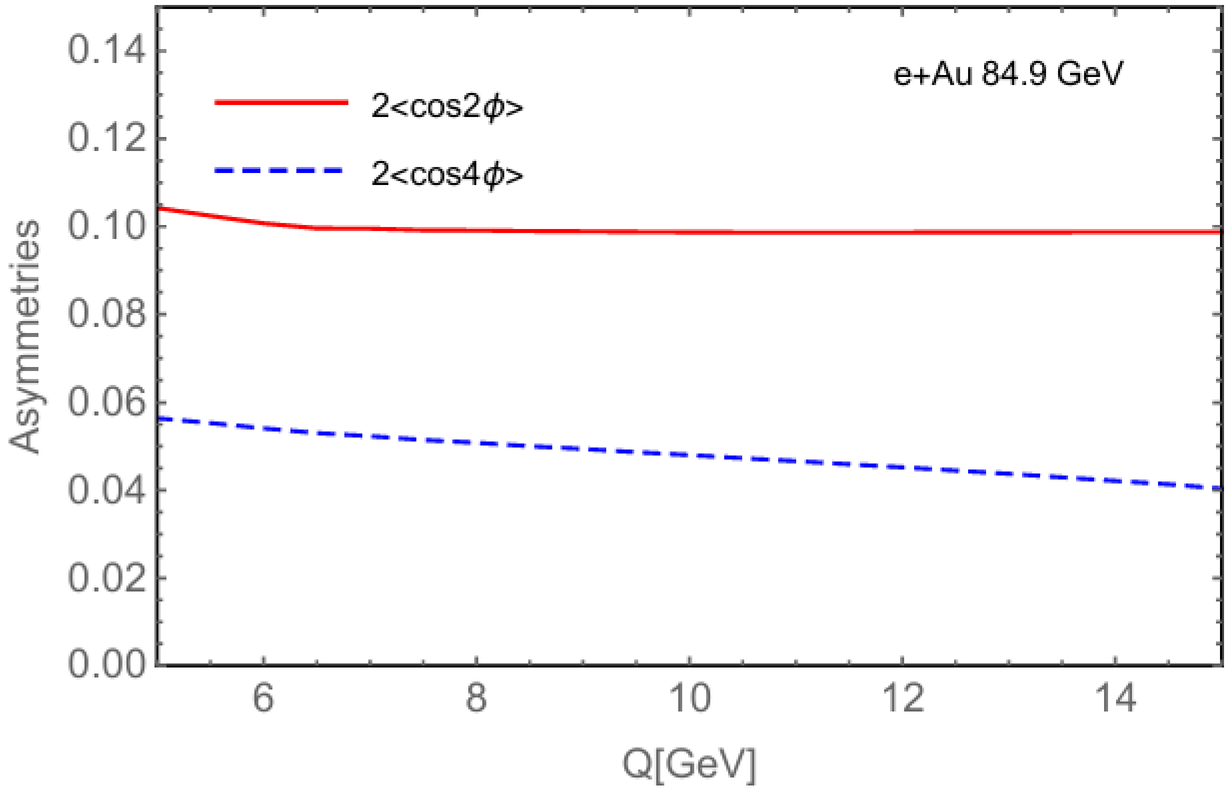
$$g_{G\gamma}\left(-F_{\mu\rho}F^{\rho}_{\nu}+\frac{1}{4}\eta^{\mu\nu}(F_{\rho\sigma})^2\right)G_{\mu\nu}$$

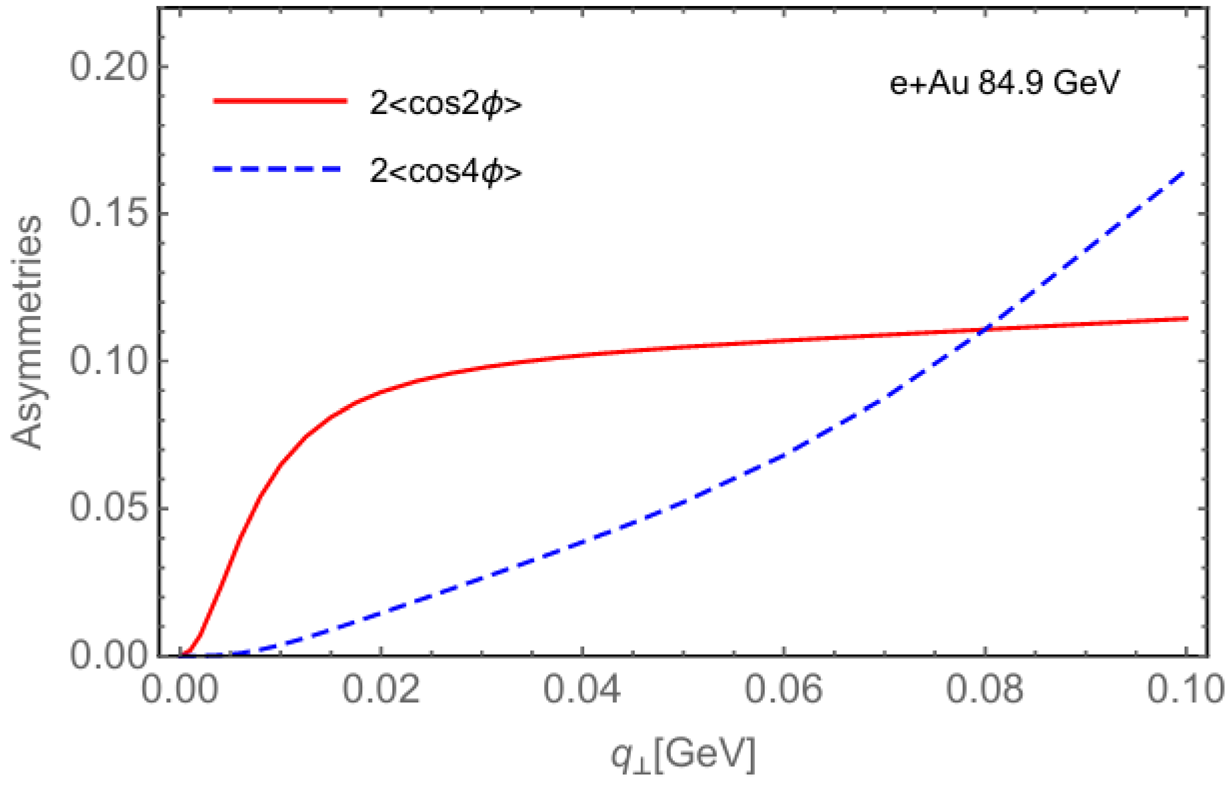


massive graviton

Azimuthal modulation could be a valuable new observable for new physics.

Light-by-light scattering： Prediction for the EiC





Summary

- light-by-light scattering is a fundamental process for many interesting questions.
- We show that the linear polarization of incident photons generates a sizable cos2ϕ-type azimuthal modulation, which awaits the test in future LHC and EIC/EicC experiments.
- Azimuthal modulation could be a valuable new observable for new physics.

Summary

- Understanding the nucleon structure remains one of the central topics in hadron physics.

- UPCs exhibit rich azimuthal asymmetry structures and abundant polarization-dependent phenomena.

Thanks for your attention!

Back up

SCET$_\text{I}$ regime

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

- **Factorization formula:**

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

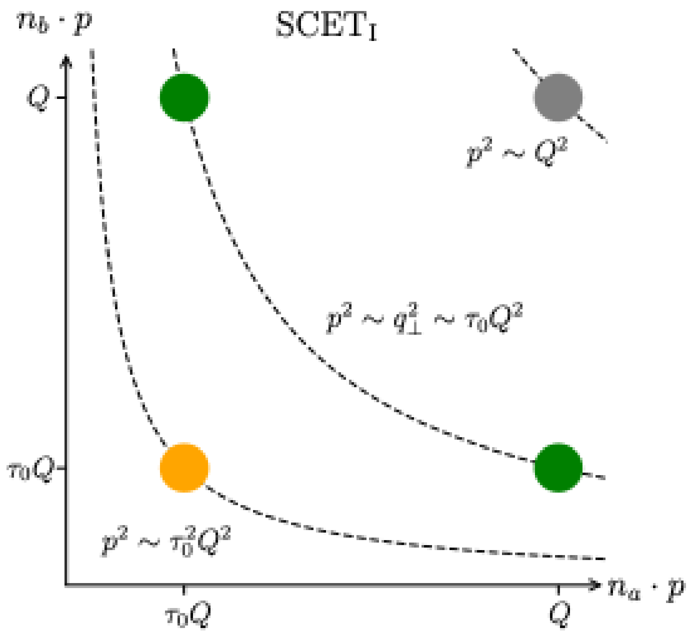
$$\frac{d\sigma_\text{I}(\tau_0)}{dy\, d^2\vec{q}_\perp} = \sigma_0 H(Q,\mu) \sum_{q,q'} C_{qq'} \int_0^{\tau_0 Q} d\mathcal{T} \int \frac{e^{s\mathcal{T}} ds}{2\pi i} \int_0^\infty \frac{b\, db}{2\pi} J_0(b\, q_\perp) \mathcal{B}_{q/p}(s/Q, x_q, b, \mu) \mathcal{B}_{q'/p}(s/Q, x_{q'}, b, \mu) \mathcal{S}(s,\mu),$$

- **RGEs:**

$$\gamma_\mathcal{B}^q(s/Q,\mu) = -2\Gamma_\text{cusp}^q(\alpha_s) \ln \frac{Q}{\mu^2 s e^{\gamma_E}} + \gamma_\mathcal{B}^q(\alpha_s),$$

$$\gamma_\mathcal{S}^q(s,\mu) = 2\Gamma_\text{cusp}^q(\alpha_s) \ln \frac{1}{\mu^2 s^2 e^{2\gamma_E}} + \gamma_\mathcal{S}^q(\alpha_s),$$

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

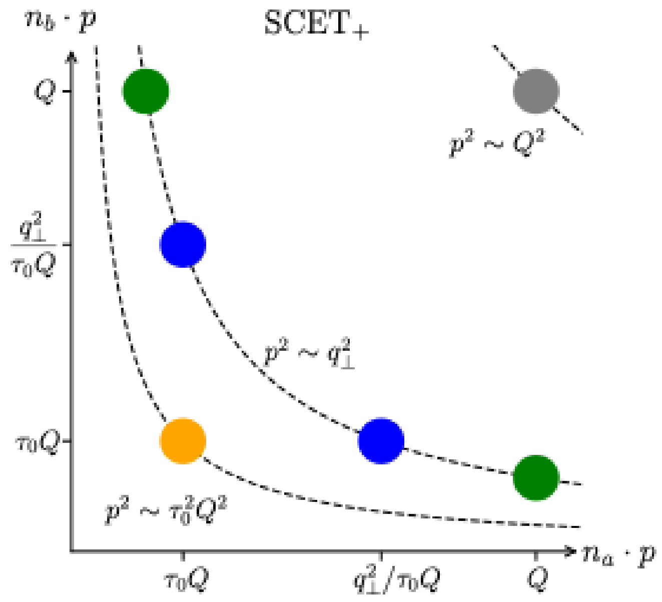


- **Scale choice:** $\mu_H^\text{I} \sim Q\,, \qquad \mu_\mathcal{B}^\text{I} \sim \sqrt{\tau_0} Q\,, \qquad \mu_\mathcal{S}^\text{I} \sim \tau_0 Q\,.$

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

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



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

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

SCET$_{II}$ regime

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

Procura, Waalewijn, Zeune '14

- **Factorization formula:**

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

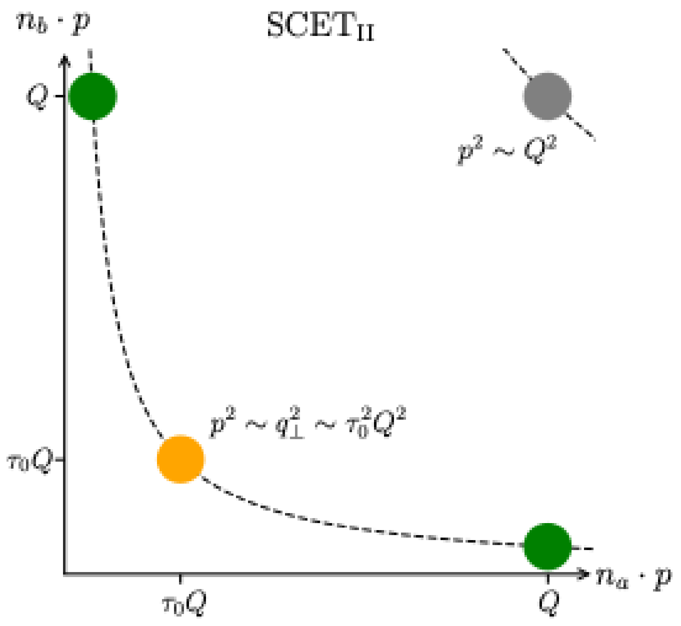
- **RGEs:**

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

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

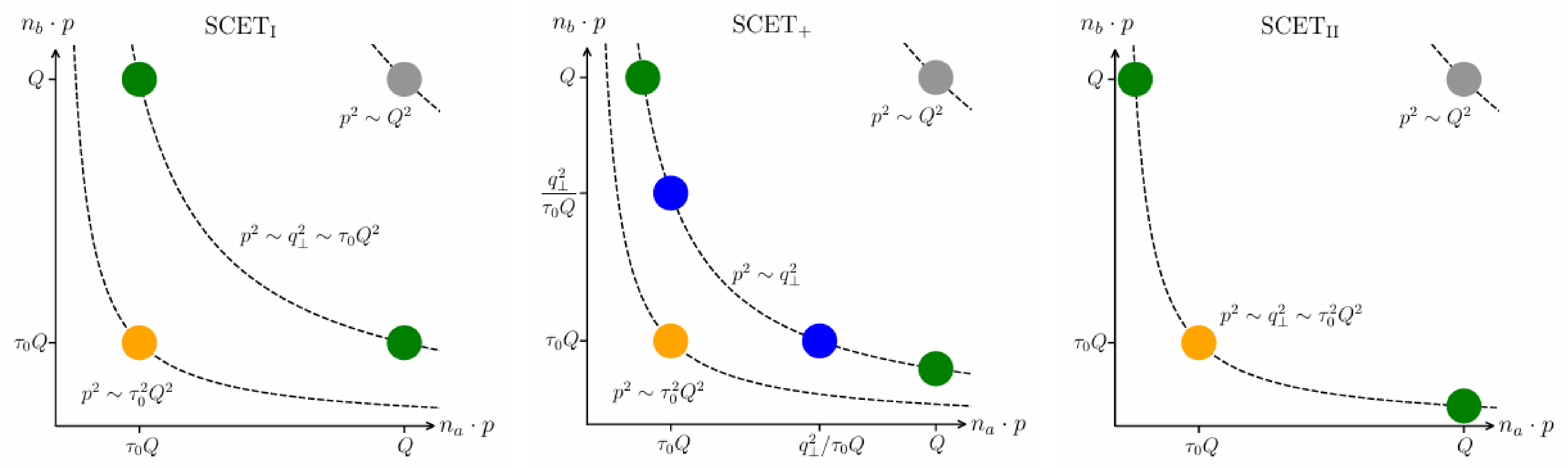
$$\gamma_S^q(\mu,\nu) = 2\Gamma_{\rm cusp}^q(\alpha_s) \ln \frac{\mu^2}{\nu^2} + \gamma_S^q(\alpha_s),$$

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



- **Scale choice:** $\mu_H^{II} \sim Q,\quad \mu_B^{II} \sim \mu_b,\quad \mu_S^{II} \sim \mu_b,$

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



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

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

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

Theoretical uncertainty

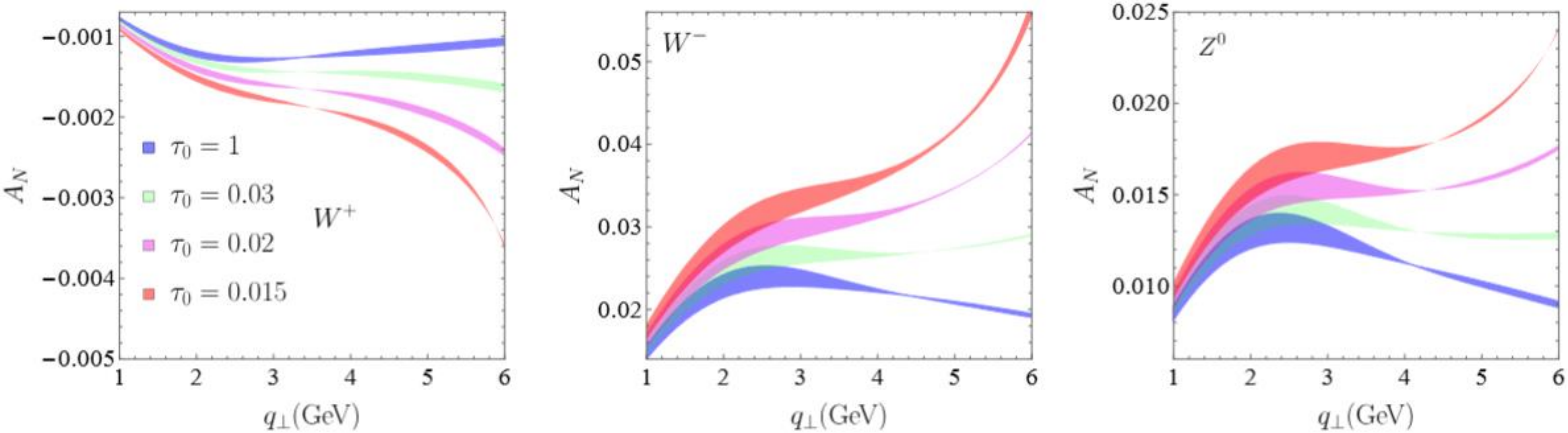


FIG.c: The SSAs for W^+, W^-, and Z^0 production in polarized pp collisions at the RHIC energy $\sqrt{s} = 500$ GeV and rapidity $y = 0$, shown as functions of $q_\perp$ for various values of τ_0. The upper and lower edges of the band correspond to the results obtained using the non-perturbative inputs in the main text and those from [1308.5003], respectively.

Theoretical uncertainty

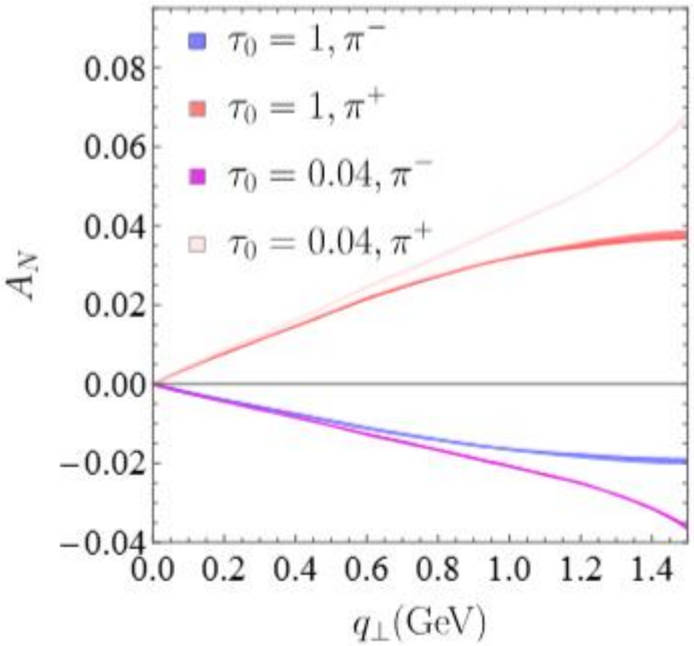


FIG.d: The SSAs for π^+ and π^- production in SIDIS process at $z_h = 0.5$, $x_B = 0.2$, $Q = 25\,\mathrm{GeV}$ and $\sqrt{s} = 100\,\mathrm{GeV}$ are plotted as a function of pions' transverse momentum $q_\perp$. The upper and lower edges of the band correspond to the results obtained using the non-perturbative input in the main text and those from [1401.5078], respectively.

Resumption

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.