Partonic structure of hadrons from low to high transverse-momentum

QCD EVOLUTION

19-23 May 2025
Jefferson Lab

Leonard Gamberg
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U.S. DEPARTMENT OF ENERGY | Office of Science

with (JAM Collaboration)
- Paul Anderson, Nobuo Sato, Wally Melnitchouk, Richard Whitehill, Xiaochao Zheng

PennState Berks

Outline

- Discussion of *unpolarized observables in* SIDIS @ *LP* & @ *NLP*
- In particular the *NLP* observables (a subtle discussion)
  - $F_{UU,L}$ and R_{SIDIS} **of interest to JLab TMD program 11 GeV, 22 GeV …**
  - $F_{UU}^{\cos\phi_h}$
- Factorization frameworks
  - **Collinear P_T**
  - **TMD**

1. Challange of Factorization at next to leading power (NLP) in the hard scale
2. $\Longrightarrow$ *Matching* "low" (TMD) to "high" (collinear) transverse momentum spectrum q_T or P_{hT}
3. Discussion … power counting

Importance of NLP Factorization & TMDs

- Importance of NLP "TMD-like" observables underscored while suppressed by $(M/Q)^n$ wrt LP observables

  ◉ NLP/SLP TMDs as sizable as leading-power in situations where Q not that large…
  e.g. the kinematics of fixed-target experiments

- Their understanding is required for a complete description of "benchmark processes" SIDIS, DY & e^+e^-…

- Of interest to probe physics of quark-gluon-quark correlations, only recently explored beyond α_s

- Experimental info SIDIS on effects related to subleading TMDs available DESY/Zeus, Fermi-LAB, HERMES, COMPASS, JLab
- Opportunity for EIC with its large kinematical coverage, for 11 GeV SoLID TMD program & for further groundbreaking progress in this area

  ◉ **NB: Iff factorization can be established beyond "tree level" @ next to leading order**
  -Global analysis in terms of NLP TMDs

Challenges of *NLP* TMDs

NLP TMD observables challenging in comparison to the current state-of-the-art of LP observables

Treatments in the literature are mostly limited to a tree-level formalism until recently

***First studies beyond tree level :** "Matches & Mis-matches" Bacchetta et al. JHEP 2008, Chen et al. PLB 2017

More recently

A.P. Chen, J.P. Ma, PLB (2017)
Bacchetta et al. PLB 2019
MIT group, Gao, Ebert, Stewart JHEP 2022
Gamberg, Kang, Shao, Terry, Zhao arXiv: e-Print:221.13209
Vladimirov, Rodini, Scimemi, Moos, JHEP 2021, 2022, JHEP 2023, PRD 2024
Balitsky 2023 rapidity TMD evolution

- In arXiv: e-Print:221.13209 present a systematic procedure for stress testing TMD factorization for DY & SIDIS at NLP using CSS formalism which addresses disagreements in the literature

- **The observable** $F_{UU,L}$ **&** $R_{SIDIS} = \frac{\sigma_L}{\sigma_T} \sim \frac{F_{UU,L}}{F_{UU,T}}$

  Feynman "Photon-Hadron Phys." 1972, Ravndal, PLB 1973

- **The observable** $\langle \cos\phi \rangle$ **Georgi & Cahn, PRL 1978, PLB 1978**

  Critique of the perturbative QCD calculation of azimuthal dependence in leptoproduction emphasize importance intrinsic k_T the early days/birth of TMD physics

R_{SIDIS} Is there a TMD formalism?

- The best known of these (& relatively not well understood) the ratio of longitudinal and transverse cross section (SIDIS) longitudinal and transverse photon: power supressed $(M/Q)^2$

Feynman 1972 "Photon Hadron Interactions" & Ravndal PLB 1973:

$$R = \frac{\sigma_L}{\sigma_T} = \frac{4\left(m^2 + \langle p_\perp^2 \rangle\right)}{Q^2} \qquad \Longrightarrow \qquad \frac{F_{UU,L}}{F_{UU,T}}$$

where $\langle p_\perp^2 \rangle$ is the intrinsic parton transverse momentum

… often assumed that $F_{UU,L}$ is negligible at low transverse momentum details see Cahn 1989 PRD

20^{th} century interpretation from collinear inclusive DIS physics

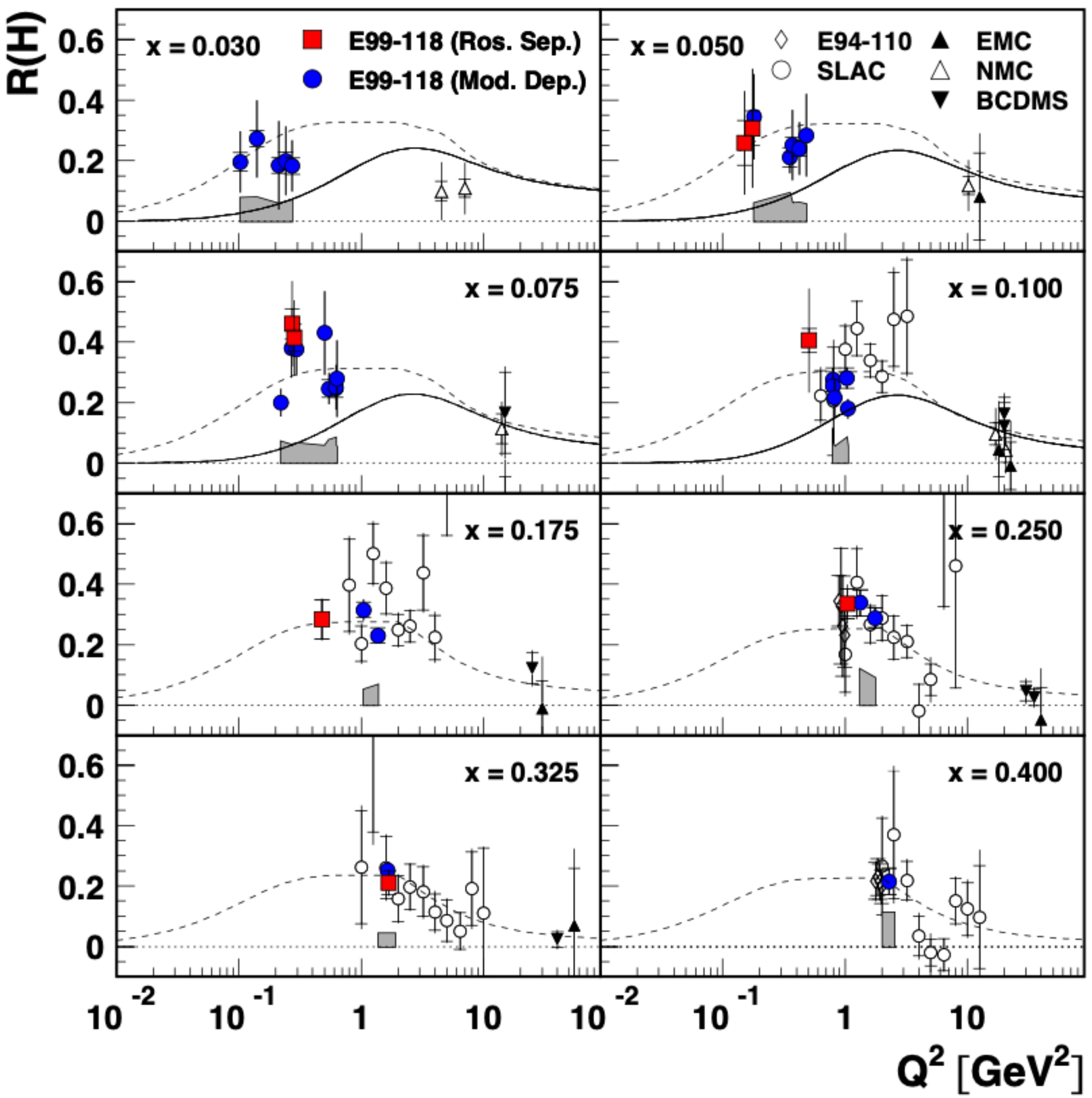
Recall inclusive *C.S.* expressed in terms of σ_T and σ_L or structure functions

$F_L(F_2 \,\&\, F_1)$ & $F_T(F_1)$,

i.e via absorption of transverse and longitudinal photons

$$R = \frac{\sigma_T}{\sigma_L} = \frac{F_L}{F_T} = \frac{1}{2xF_1}\left\{F_2\left(1+\frac{4x^2M^2}{Q^2}\right) - 2xF_1\right\}$$

JLab exp. (E99-118) Prl 2007



- Zero in the scaling limit $\lim_{Q^2\to\infty} R \approx \frac{4x^2M^2}{Q^2} \to 0,$
- However pQCD result $\{F_2 - 2xF_1\} \sim \frac{\alpha_s(Q)}{2\pi} C_2(F)\, x$

Comparison of the values of $R(x, Q^2)$ for hydrogen from the JLab exp. (E99-118) to results of other exps.

21st century interpretation from DIS to SIDIS)

$$R = \frac{\sigma_L}{\sigma_T} \to \frac{F_{UU,L}}{F_{UU,T}}$$

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\,\frac{y}{2\,(1-\varepsilon)}\left\{F_{UU,T} + \varepsilon\,F_{UU,L} + \quad \ldots\right.$$

TMD observable for ??

$$F_{UU,T} = C[f_1 D_1]\ ,$$

$$F_{UU,L} = C[\,.\,?\,.\,]$$

$$\mathcal{C}\big[wfD\big] = \sum_a x\,e_a^2 \int d^2\boldsymbol{p}_T\,d^2\boldsymbol{k}_T\,\delta^{(2)}\big(\boldsymbol{p}_T - \boldsymbol{k}_T + \boldsymbol{q}_T\big)\,w(\boldsymbol{p}_T,\boldsymbol{k}_T)\,f^a(x,p_T^2)\,D^a(z,k_T^2)$$

Mulders & Tangerman 1995 Bacchetta et al. JHEP 2007

Context TMD Correlator at tree level "twist 4"

K. Goeke, A. Metz, M. Schlegel PLB 2005

NNLP:

$$\Phi^{[\gamma^-]} = \frac{M^2}{(P^+)^2}\left[f_3(x,\vec{k}_T^2) - \frac{\varepsilon_T^{ij} k_{Ti} S_{Tj}}{M} f_{3T}^{\perp}(x,\vec{k}_T^2)\right]$$

Correlator at tree level @ "twist" 4

previously of academic interest

factorization is at best unexplored

LP & NLP :

$$\Phi^{[\gamma^+]} = f_1(x,\vec{k}_T^2) - \frac{\varepsilon_T^{ij} k_{Ti} S_{Tj}}{M} f_{1T}^{\perp}(x,\vec{k}_T^2),$$

$$\Phi^{[\gamma^i]} = \frac{M}{P^+}\left[\frac{k_T^i}{M}\left(f^{\perp}(x,\vec{k}_T^2) - \frac{\varepsilon_T^{jk} k_{Tj} S_{Tk}}{M} f_T^{\perp\prime}(x,\vec{k}_T^2)\right) + \quad \ldots\right.$$

Leading Quark TMDPDFs Nucleon Spin Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^{\perp}$ = − Boer-Mulders
L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Worm-gear
T	$f_{1T}^{\perp}$ = − Sivers	$g_{1T}^{\perp}$ = − Worm-gear	h_1 = − Transversity; $h_{1T}^{\perp}$ = − Pretzelosity

Subleading Quark TMDPDFs

Nucleon Polarization	Quark Chirality: Chiral Even	Quark Chirality: Chiral Odd
U	$f^{\perp}$, $g^{\perp}$	e , h
L	$f_L^{\perp}$, $g_L^{\perp}$	e_L, h_L
T	f_T, $f_T^{\perp}$, g_T, $g_T^{\perp}$	e_T, $e_T^{\perp}$, h_T, $h_T^{\perp}$

Context TMD Correlator at tree level "twist 4"

NNLP:

NNLP: some discussion in Bacchetta et al.
Matches and mismatches JHEP 2008
& recent discussion w/ M. Cerruti

$$F_{UU,L} = \frac{4M^2}{Q^2}\,\mathcal{C}\left[\frac{\boldsymbol{p}_T^2}{M^2} f_1 D_1\right]$$

Correlator at tree level @ "twist" 4
previously of academic interest
factorization ~~is at best unexplored~~

$+ \quad \ldots$

Leading Quark TMDPDFs — Nucleon Spin — Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = − Boer-Mulders
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Subleading Quark TMDPDFs

Nucleon Polarization	Quark Chirality: Chiral Even	Quark Chirality: Chiral Odd
U	$f^\perp,\ g^\perp$	$e\ ,\ h$
L	$f_L^\perp,\ g_L^\perp$	$e_L,\ h_L$
T	$f_T,\ f_T^\perp,\ g_T,\ g_T^\perp$	$e_T,\ e_T^\perp,\ h_T,\ h_T^\perp$

R_{SIDIS} NLP TMDs?

Bacchetta & Cerruti *MAP*
Eur. Phys. J. A (2024) 60:173

R_{sidis} esitmate sizable contribution up to 20%

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\frac{y}{2(1-\varepsilon)}\left\{F_{UU,T} + \varepsilon F_{UU,L} + \right.$$

- ε ratio of longitudinal and transverse photon flux ...

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}, \qquad \gamma^2 \equiv \frac{4M^2x^2}{Q^2}$$

- Findings demonstrate $F_{UU,L}$ can't be ignored
  substantial & essential for an accurate interpretation of $F_{UU,T}$ which is associated with leading twist TMDs.

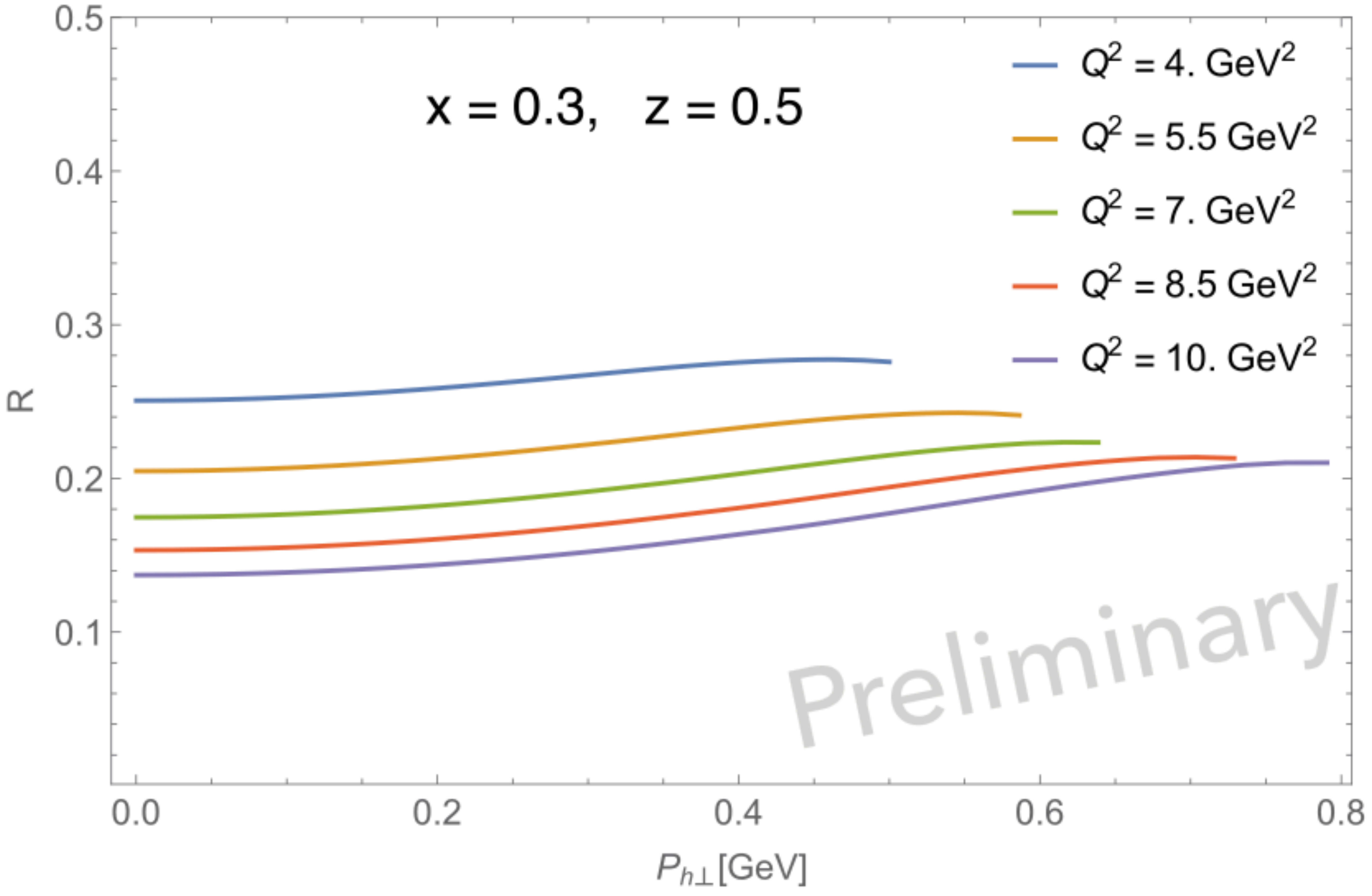


Fig. 18 Estimate of $R_{\rm SIDIS} = F_{UU,L}/F_{UU,T}$ versus the hadron transverse momentum $P_T\,(P_{hT})$ at fixed values of x and z and for different values of Q^2, compatible with JLab22 kinematics, using MAP22 TMD analysis [134]

- ***What is the physics here?!***

•*What is the physics here ?*

Power behavior $F_{UU,L}$ & $F_{UU,T}$

Low

$q_T \ll Q$

$$F_{UU,T} = \mathcal{C}\big[f_1 D_1\big]$$

$$F_{UU,L} = \mathcal{O}\left(\frac{M^2}{Q^2}, \frac{q_T^2}{Q^2}\right) \longrightarrow F_{UU,L} = \frac{4M^2}{Q^2}\, \mathcal{C}\left[\frac{\boldsymbol{p}_T^2}{M^2}\, f_1 D_1\right]$$

Bacchetta & Cerruti *MAP*

Hi

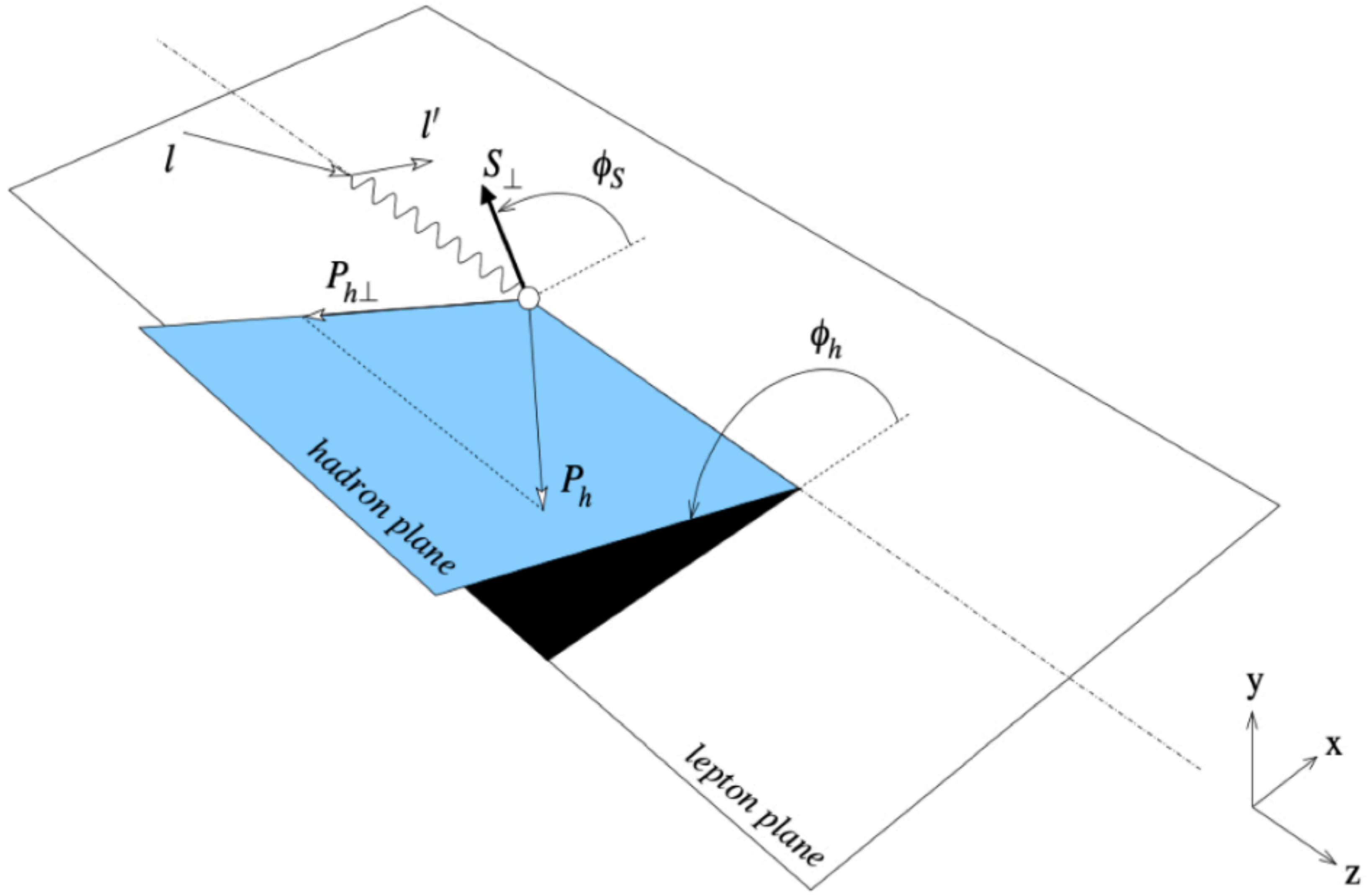
$q_T \gg M$

$$F_{UU,T} \sim \frac{1}{q_T^2}\, \alpha_s\, \mathcal{F}\big[f_1 D_1\big]\,,$$

$$F_{UU,L} \sim \frac{1}{Q^2}\, \alpha_s\, \mathcal{F}\big[f_1 D_1\big]$$

SIDIS "benchmark processes" TMD Factorization & $P_\perp$ Collinear Factorization

- TMD: applicable $\Lambda_{QCD} \sim P_{h\perp} \ll Q$ Collinear: applicable $P_{h\perp} \sim Q \gg \Lambda_{QCD}$
- $P_{h\perp} \sim \mathbf{k}_T$ or $\mathbf{p}_T$ intrinsic transverse momentum partons CS described via TMDs
- $P_{h\perp} \gg \mathbf{k}_T$ or $\mathbf{p}_T$ generated transverse momentum in the final state as perturbative radiation & non-perturbative structure is given by collinear pdfs & FFs



$$E'E_h \frac{d\sigma_{ep\to e'hX}}{d^3l' d^3P_h} \approx \hat{\sigma}_{eq\to e'q'} \otimes f_1 \tilde{\otimes} D_{h/q'}.$$

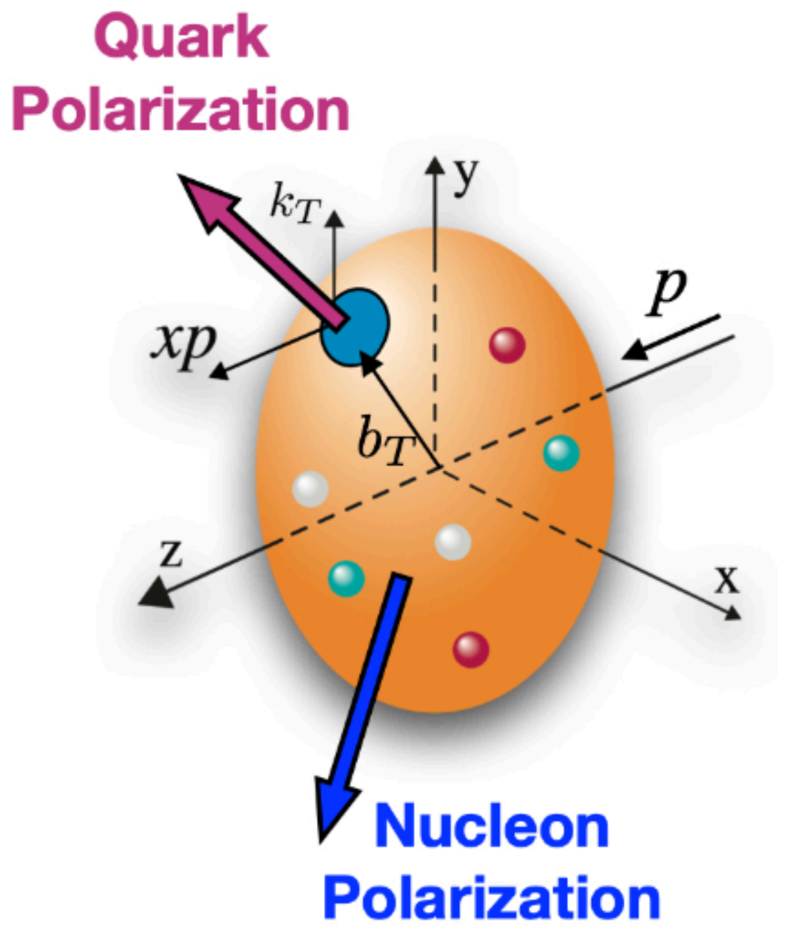
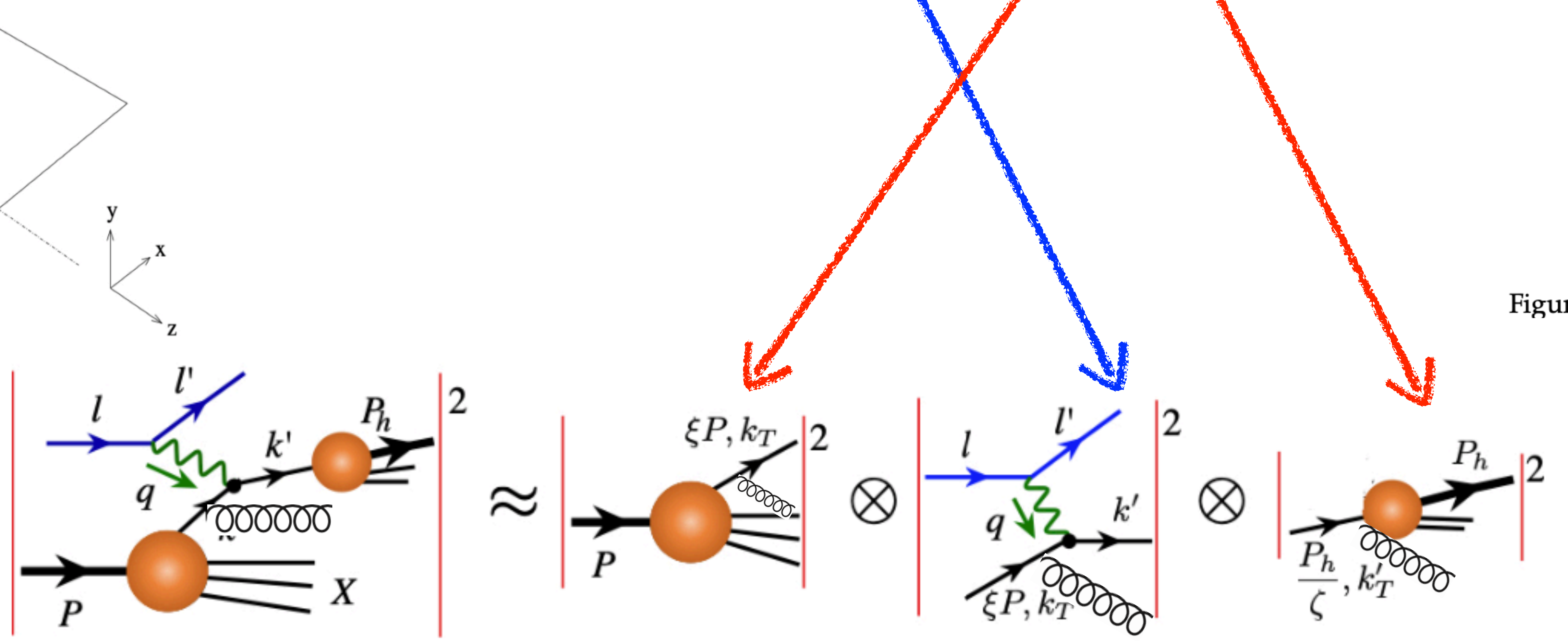


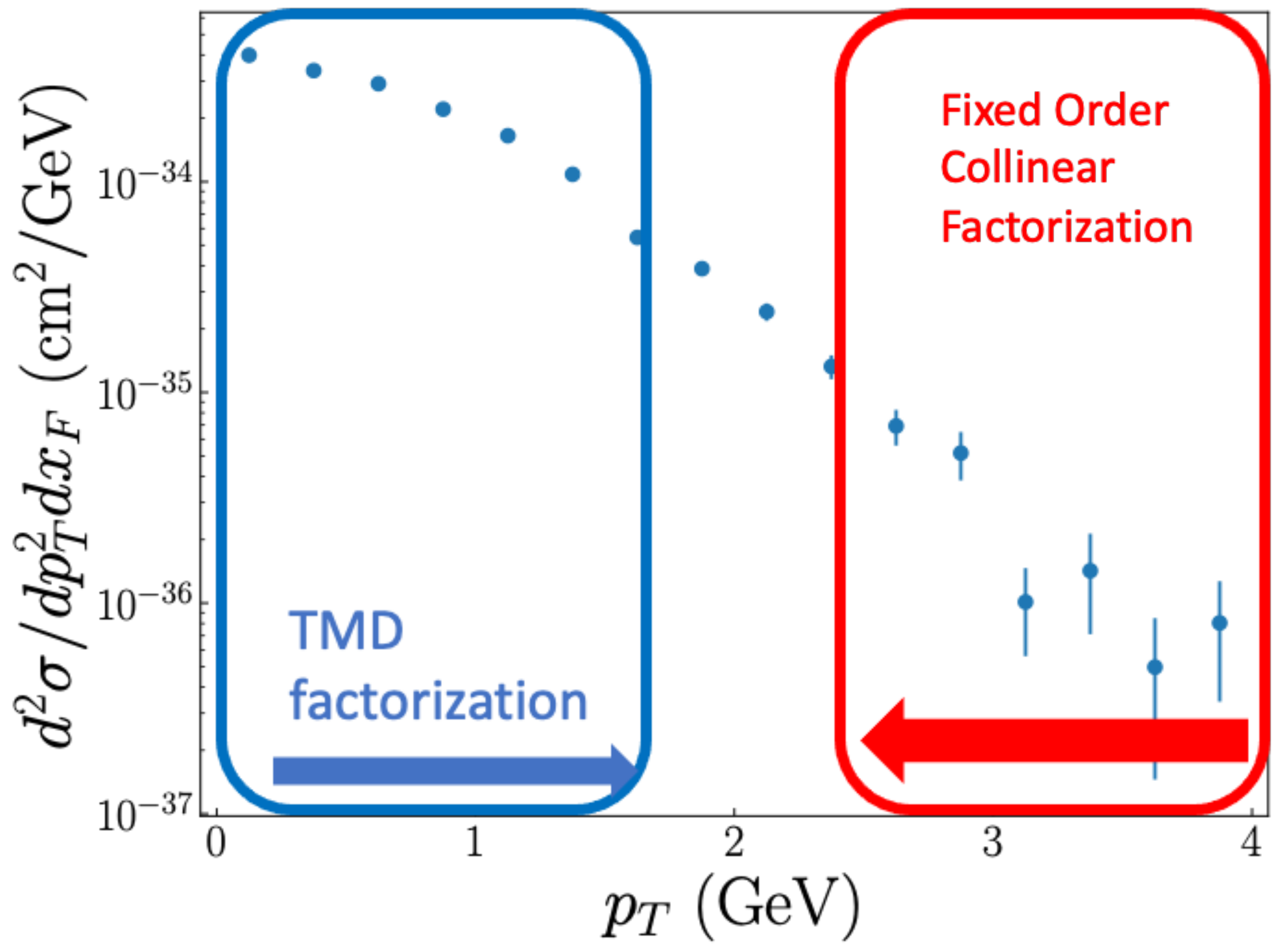
Figure 1.1: Illustration of the mo-
spin variables probed
on distributions.

$\sigma_{\rm SIDIS} \propto$



Can we learn about power corrections $F_{UU,L}$ of R_{SIDIS} @ large $q_T \approx P_{hT}/z$

- Factorization & Matching unpolairzed Colins/Soper/Sterman NPB 1985, Collins Collins, Gamberg, Prokudin, Rogers, Sato, Wang 2016 PRD
- Bacchetta, Boer, Diehl, Mulders JHEP (2008) Ji, Qiu, Vogelsang Yuan PRL. 97,(2006); Phys. Rev. D 73 (2006)



- **<u>Cross section in terms of different "regions"</u>**
- W valid for $q_T \sim k_T \ll Q$ TMD factorization
- FO valid for $k_T \ll p_T \sim Q$ Collinear factorization
- AY subtracts d.c. & in principle,

  $AY \to W$, $p_T \to \infty$ and $AY \to FO, p_T \to 0$

$$\frac{d\sigma(m \lesssim q_T \lesssim Q, Q)}{dy dq^2 dp_T^2} = W(p_T, Q) + FO(p_T, Q) - AY(p_T, Q) + O\left(\frac{m}{Q}\right)^c$$

“Matching” is much more nuanced @ *NLP & NNLP*

Opportunity to learn about low $q_T \sim M$ from large $q_T \sim Q$

Power counting/behavior $F_{UU,L}$ & $F_{UU,T}$

Low

$q_T \ll Q$

$$F_{UU,T} = \mathcal{C}\big[f_1 D_1\big]$$

$$F_{UU,L} = \mathcal{O}\left(\frac{M^2}{Q^2}, \frac{q_T^2}{Q^2}\right)$$

Large

$q_T \gg M$

$$F_{UU,T} \sim \frac{1}{q_T^2}\,\alpha_s\,\mathcal{F}\big[f_1 D_1\big]\,,$$

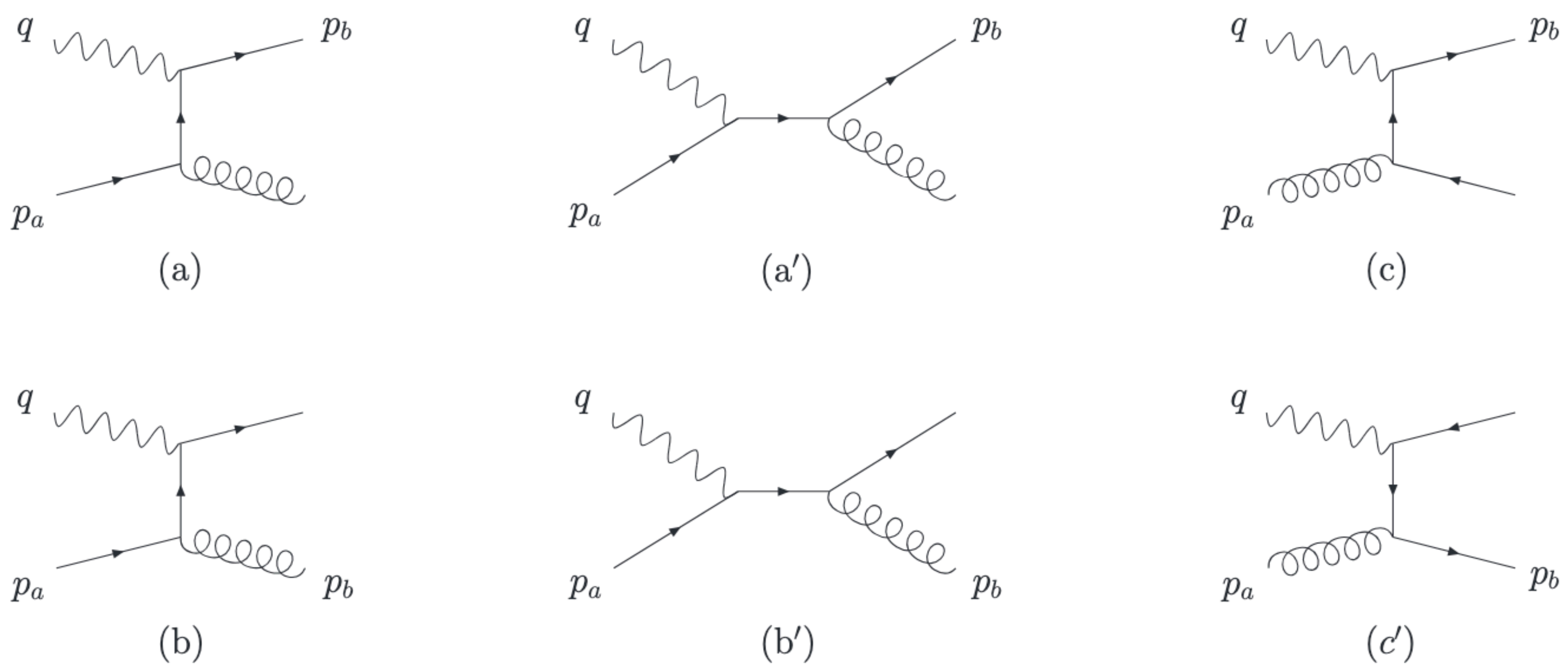
$$F_{UU,L} \sim \frac{1}{Q^2}\,\alpha_s\,\mathcal{F}\big[f_1 D_1\big]$$

For large $q_T \sim P_{hT}/z$ well established for Leading POWER

- @ large P_T , $F_{UU,L} = 2\, F_{UU}^{\cos 2\phi_h}$ — Bacchetta et al. JHEP 2008 "Matches & Mis-matches":
  in principle hard gluon raditation — "collinear P_T factorization applies CSS 1985
  Catani et al. 1997-2015, Nadolsky, Vogelsang Koike NPB 2005… many others

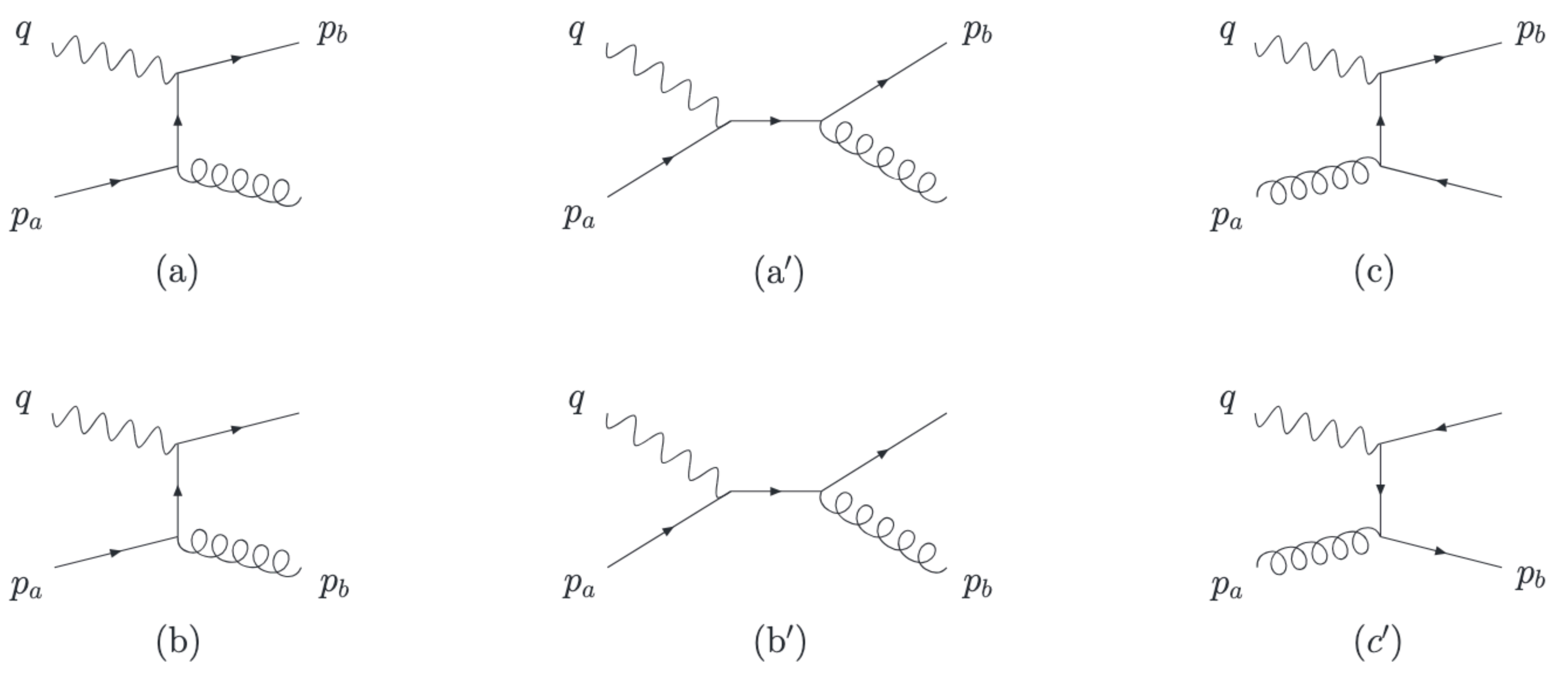
$$F_{UU,T} = \frac{1}{Q^2}\frac{\alpha_s}{(2\pi z)^2}\sum_a x\, e_a^2 \int_x^1 \frac{d\hat{x}}{\hat{x}} \int_z^1 \frac{d\hat{z}}{\hat{z}}\, \delta\!\left(\frac{q_T^2}{Q^2} - \frac{(1-\hat{x})(1-\hat{z})}{\hat{x}\,\hat{z}}\right)$$

$$\times \left[f_1^a\!\left(\frac{x}{\hat{x}}\right) D_1^a\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* q\to qg)} + f_1^a\!\left(\frac{x}{\hat{x}}\right) D_1^g\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* q\to gq)} + f_1^g\!\left(\frac{x}{\hat{x}}\right) D_1^a\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* g\to q\bar{q})} \right]$$



Opportunity R_{SIDIS} & large P_T

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\,\frac{y}{2\,(1-\varepsilon)}\,\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$



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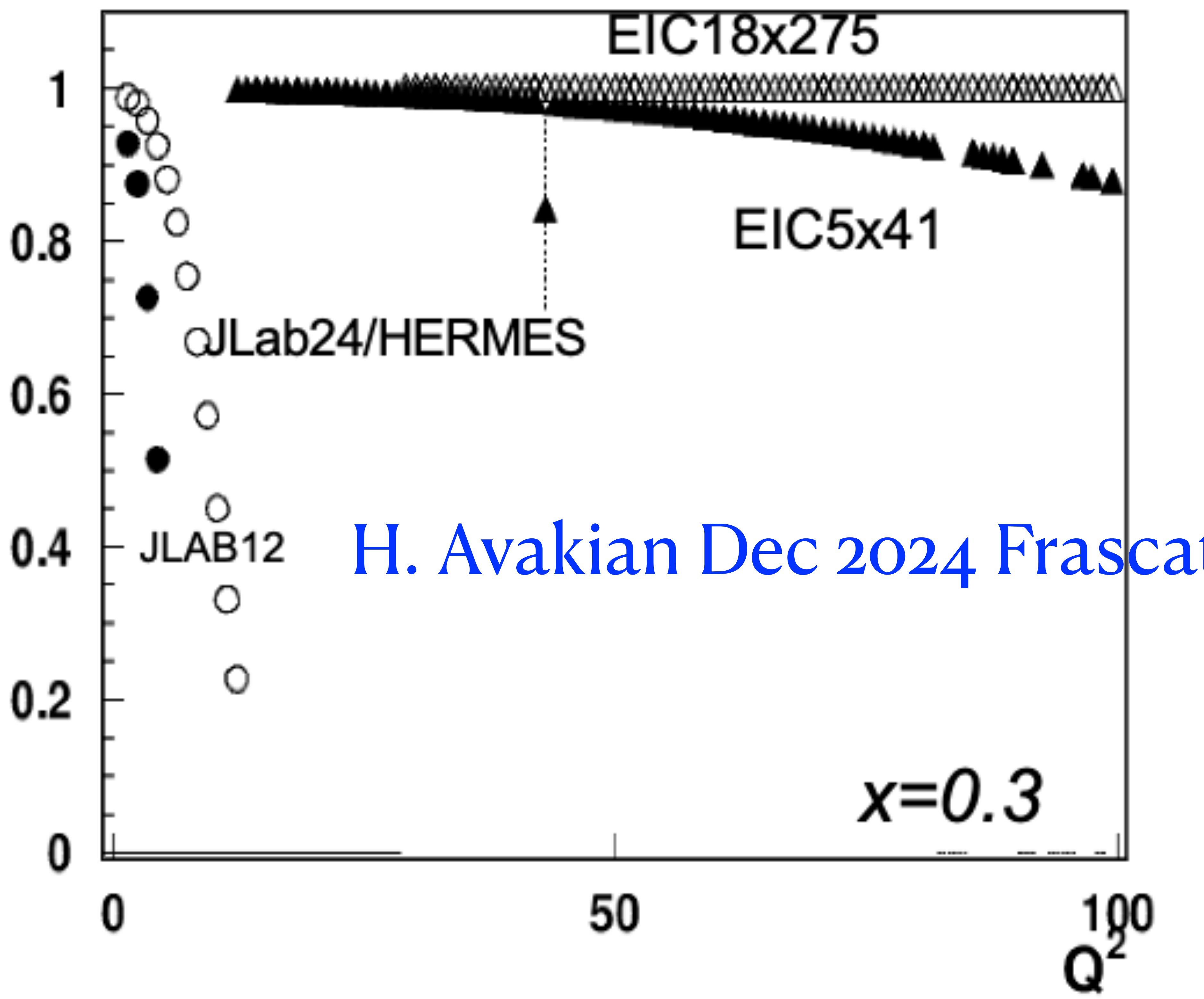


H. Avakian Dec 2024 Frascati

Power behavior $F_{UU,L}$ & $F_{UU,T}$ at $M \ll q_T \ll Q$

$$F_{UU,T} = \frac{1}{Q^2}\frac{\alpha_s}{(2\pi z)^2}\sum_a x\, e_a^2 \int_x^1 \frac{d\hat{x}}{\hat{x}} \int_z^1 \frac{d\hat{z}}{\hat{z}}\, \delta\!\left(\frac{q_T^2}{Q^2} - \frac{(1-\hat{x})(1-\hat{z})}{\hat{x}\,\hat{z}}\right)$$
$$\times \left[f_1^a\!\left(\frac{x}{\hat{x}}\right) D_1^a\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* q\to qg)} + f_1^a\!\left(\frac{x}{\hat{x}}\right) D_1^g\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* q\to gq)} + f_1^g\!\left(\frac{x}{\hat{x}}\right) D_1^a\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* g\to q\bar{q})} \right]$$

Asymptotic region

$$F_{UU,T} = \frac{1}{q_T^2}\frac{\alpha_s}{2\pi^2 z^2}\sum_a x\, e_a^2 \Big[f_1^a(x)\, D_1^a(z)\, L\!\left(\frac{Q^2}{q_T^2}\right) + f_1^a(x)\,\big(D_1^a \otimes P_{qq} + D_1^g \otimes P_{gq}\big)(z)$$
$$+ \big(P_{qq}\otimes f_1^a + P_{qg}\otimes f_1^g\big)(x)\, D_1^a(z) \Big]$$

$$F_{UU,L} = \frac{2}{Q^2}\frac{\alpha_s}{2\pi^2 z^2}\sum_a x\, e_a^2 \Big[f_1^a(x)\, D_1^a(z)\, L\!\left(\frac{Q^2}{q_T^2}\right) + f_1^a(x)\,\big(D_1^a \otimes P''_{qq} + D_1^g \otimes P''_{gq}\big)(z)$$
$$+ \big(P''_{qq}\otimes f_1^a + P''_{qg}\otimes f_1^g\big)(x)\, D_1^a(z) \Big]$$

$$L\!\left(\frac{Q^2}{q_T^2}\right) \equiv C_F\left[2\ln\!\left(\frac{Q^2}{q_T^2}\right) - 3\right]$$

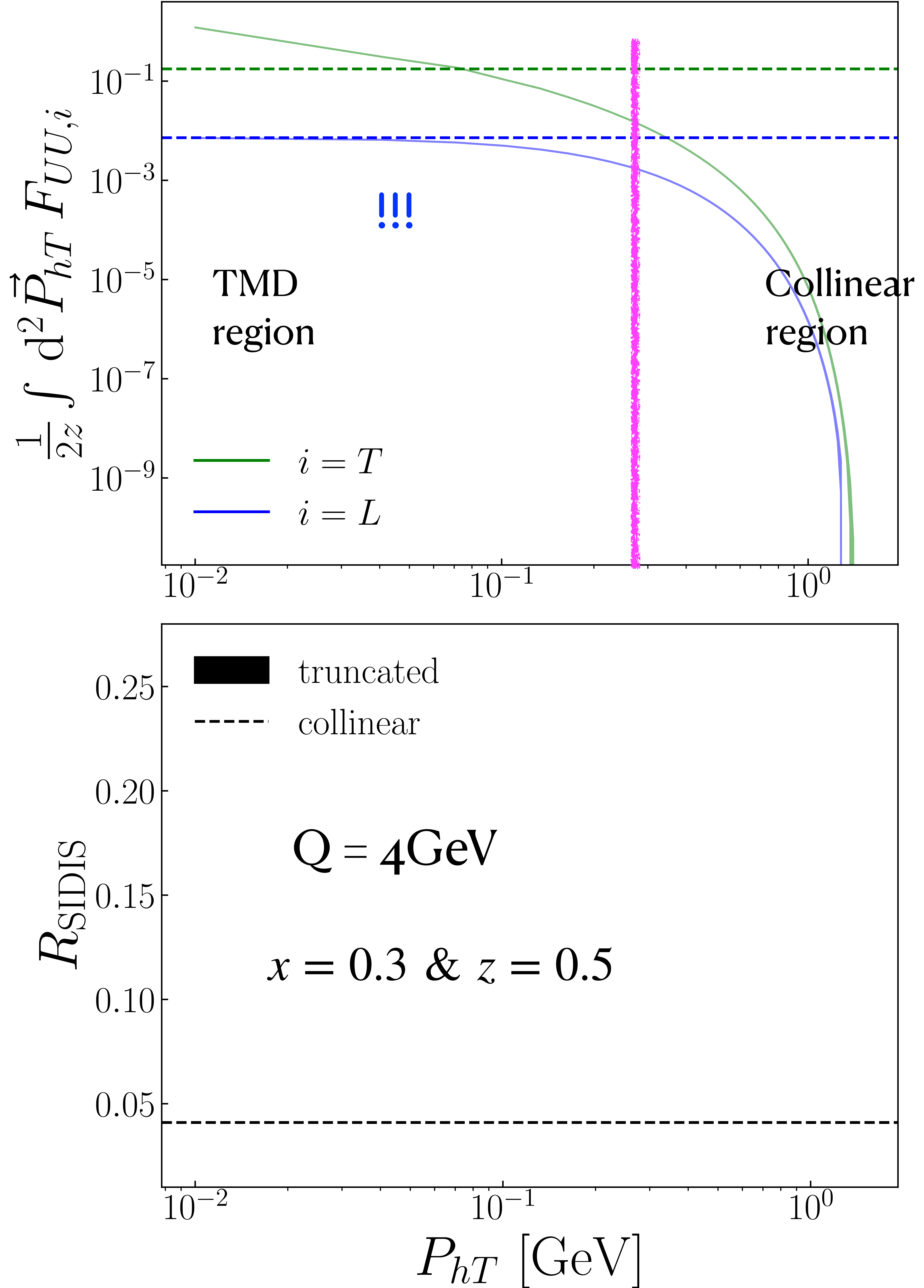
Large to intermidate to low q_T regions
Colliner SIDIS vs. truncated moments

$$\int_{P^2_{hT\,\mathrm{min}}/z^2}^{q^2_{T\,\mathrm{max}}} F(x, z, Q^2, P_{hT})$$

$F_{UU,L}$ truncated moment converges “P_T integrable”

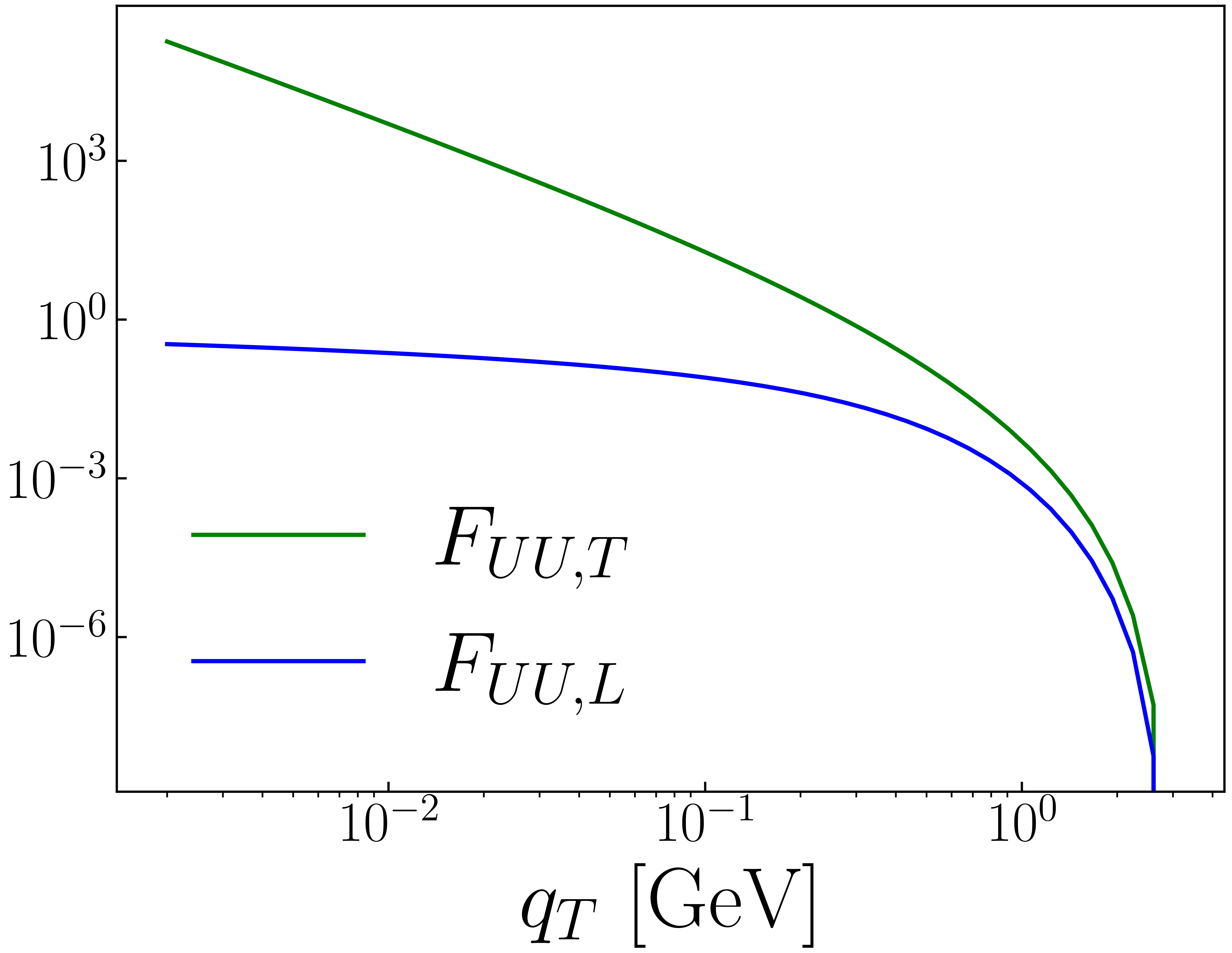
- Small power corrections ?
- Small TMD contribution ?

$F_{UU,T}$ truncated moment as expected diverges



Intermidate region to low q_T region

$\bullet F_{UU,T}(x, z, q_T, Q) \quad \& \quad F_{UU,L}(x, z, q_T, Q)$



R_{SIDIS} & $\sigma_L \sim F_{UU,L}$ at large p_T

$$\frac{d\sigma}{dx\,dy\,dz\,dq_T^2\,d\varphi} = \frac{\pi\alpha^2 yz}{4Q^2}\Big[\underbrace{\overset{\sigma_L}{\sinh^2\vartheta F_{UU,L}} - \overset{\sigma_T}{\frac{1}{2}(2+\sinh^2\vartheta) F_{UU,T}}}_{\sigma_0} - \underbrace{\sinh 2\vartheta F_{UU}^{\cos\varphi}}_{\sigma_1}\cos\varphi + \underbrace{\frac{1}{2}\sinh^2\vartheta F_{UU}^{\cos 2\varphi}}_{\sigma_2}\cos 2\varphi\Big]$$

e.g.

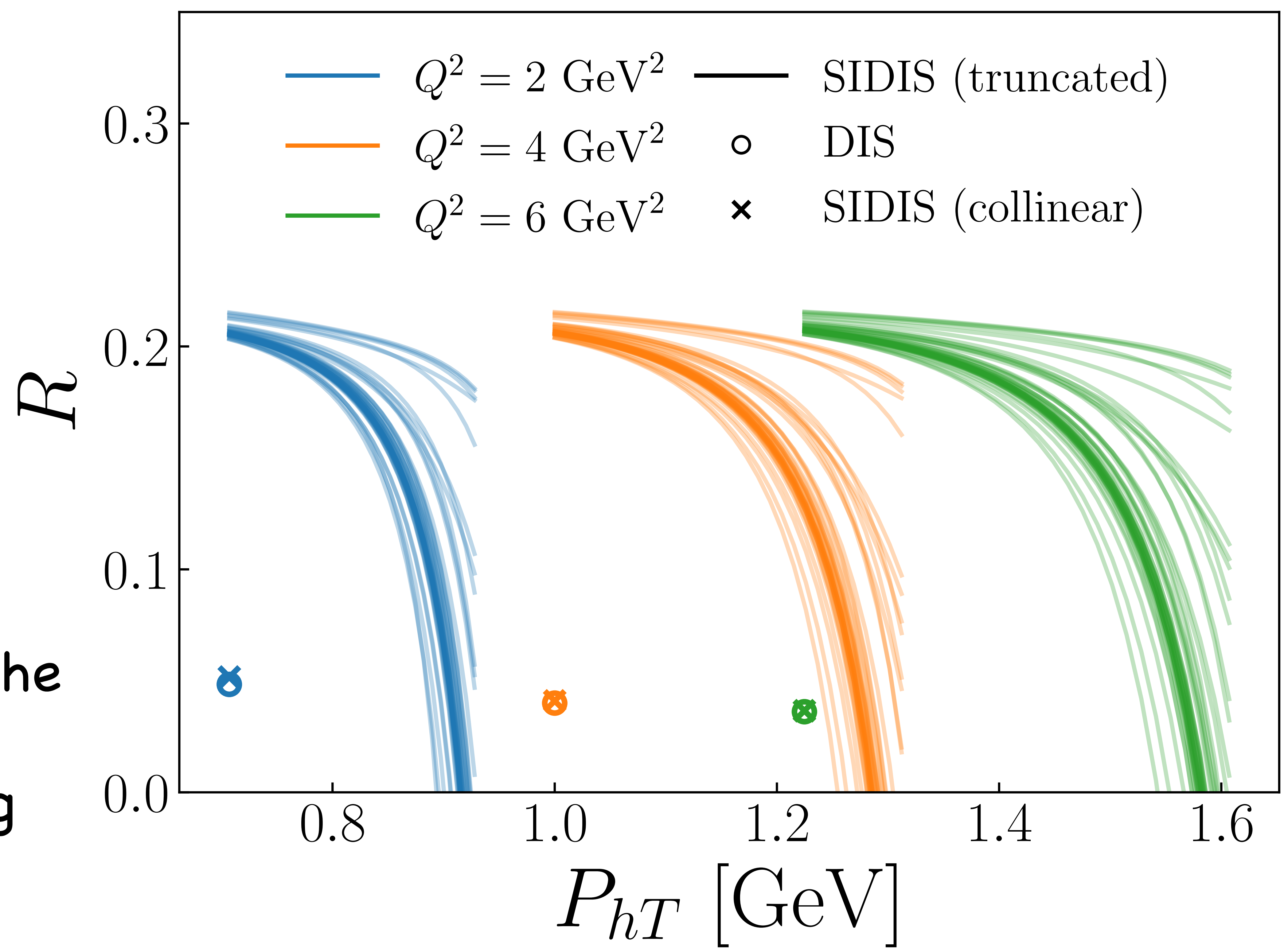
$$F_{UU,T} = \frac{1}{Q^2}\frac{\alpha_s}{(2\pi z)^2}\sum_a x\, e_a^2 \int_x^1 \frac{d\hat{x}}{\hat{x}}\int_z^1 \frac{d\hat{z}}{\hat{z}}\,\delta\Big(\frac{q_T^2}{Q^2} - \frac{(1-\hat{x})(1-\hat{z})}{\hat{x}\,\hat{z}}\Big)$$
$$\times\Big[f_1^a\Big(\frac{x}{\hat{x}}\Big) D_1^a\Big(\frac{z}{\hat{z}}\Big) C_{UU,T}^{(\gamma^* q\to qg)} + f_1^a\Big(\frac{x}{\hat{x}}\Big) D_1^g\Big(\frac{z}{\hat{z}}\Big) C_{UU,T}^{(\gamma^* q\to gq)} + f_1^g\Big(\frac{x}{\hat{x}}\Big) D_1^a\Big(\frac{z}{\hat{z}}\Big) C_{UU,T}^{(\gamma^* g\to q\bar{q})}\Big]$$

$$R_{SIDIS} = \frac{F_{UU,L}}{F_{UU,T}}$$

Nb:SIDIS truncated moments

$$\int_{P_{hT\,\min}^2/z^2}^{q_{T\,\max}^2} F(x,z,Q^2,P_{hT})$$

Jlab 11 GeV $x = 0.3$ & $z = 0.5$



Nb: Bands are generated by computing the observable on subset of JAM replicas (from recent W+charm analysis) & taking the mean ± standard deviation

R_{SIDIS} & $\sigma_L \sim F_{UU,L}$ at large p_T

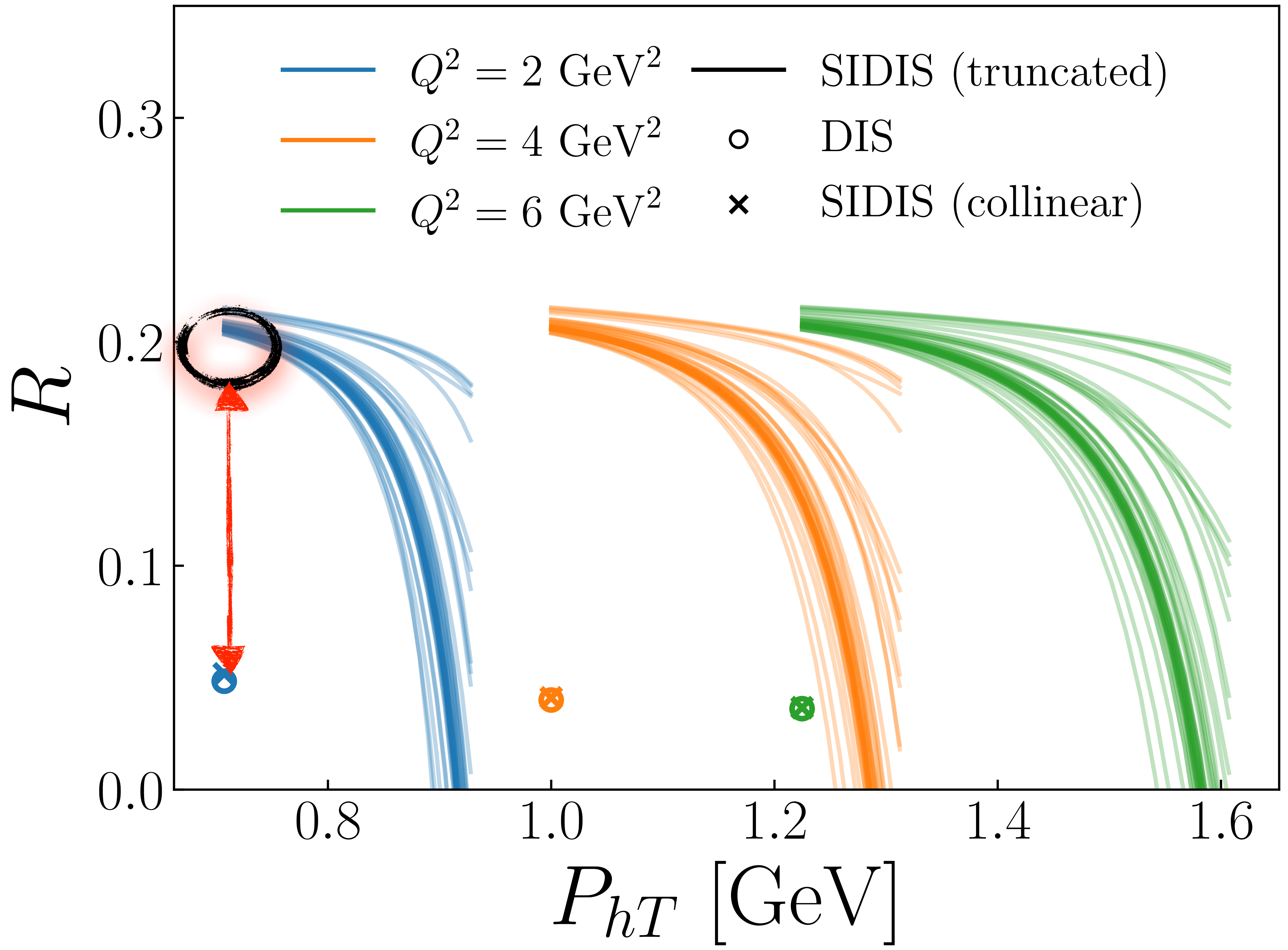
$$\frac{d\sigma}{dx\,dy\,dz\,dq_T^2\,d\varphi} = \frac{\pi\alpha^2 yz}{4Q^2}\Big[\underbrace{\overset{\sigma_L}{\sinh^2\vartheta F_{UU,L}} - \frac{1}{2}(2+\sinh^2\vartheta)\overset{\sigma_T}{F_{UU,T}}}_{\sigma_0} - \underbrace{\sinh 2\vartheta F_{UU}^{\cos\varphi}}_{\sigma_1}\cos\varphi + \underbrace{\frac{1}{2}\sinh^2\vartheta F_{UU}^{\cos 2\varphi}}_{\sigma_2}\cos 2\varphi\Big]$$

e.g.

$$F_{UU,T} = \frac{1}{Q^2}\frac{\alpha_s}{(2\pi z)^2}\sum_a x e_a^2 \int_x^1 \frac{d\hat{x}}{\hat{x}}\int_z^1 \frac{d\hat{z}}{\hat{z}}\,\delta\left(\frac{q_T^2}{Q^2} - \frac{(1-\hat{x})(1-\hat{z})}{\hat{x}\hat{z}}\right)$$
$$\times\left[f_1^a\left(\frac{x}{\hat{x}}\right)D_1^a\left(\frac{z}{\hat{z}}\right)C_{UU,T}^{(\gamma^* q\to qg)} + f_1^a\left(\frac{x}{\hat{x}}\right)D_1^g\left(\frac{z}{\hat{z}}\right)C_{UU,T}^{(\gamma^* q\to gq)} + f_1^g\left(\frac{x}{\hat{x}}\right)D_1^a\left(\frac{z}{\hat{z}}\right)C_{UU,T}^{(\gamma^* g\to q\bar{q})}\right]$$

$$R_{SIDIS} = \frac{F_{UU,L}}{F_{UU,T}}$$

Jlab 11 GeV $\quad x = 0.3$ & $z = 0.5$

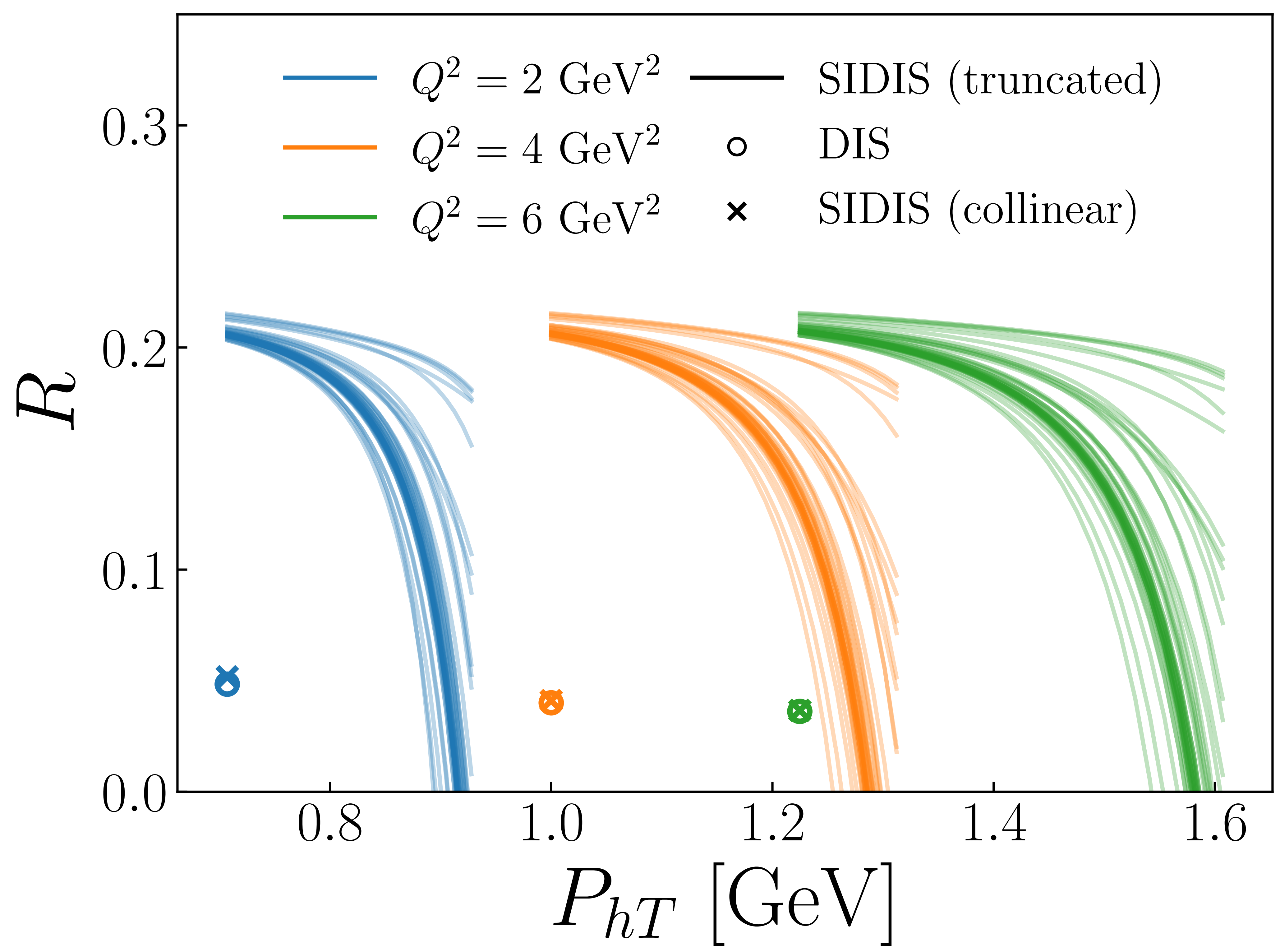


Comments:

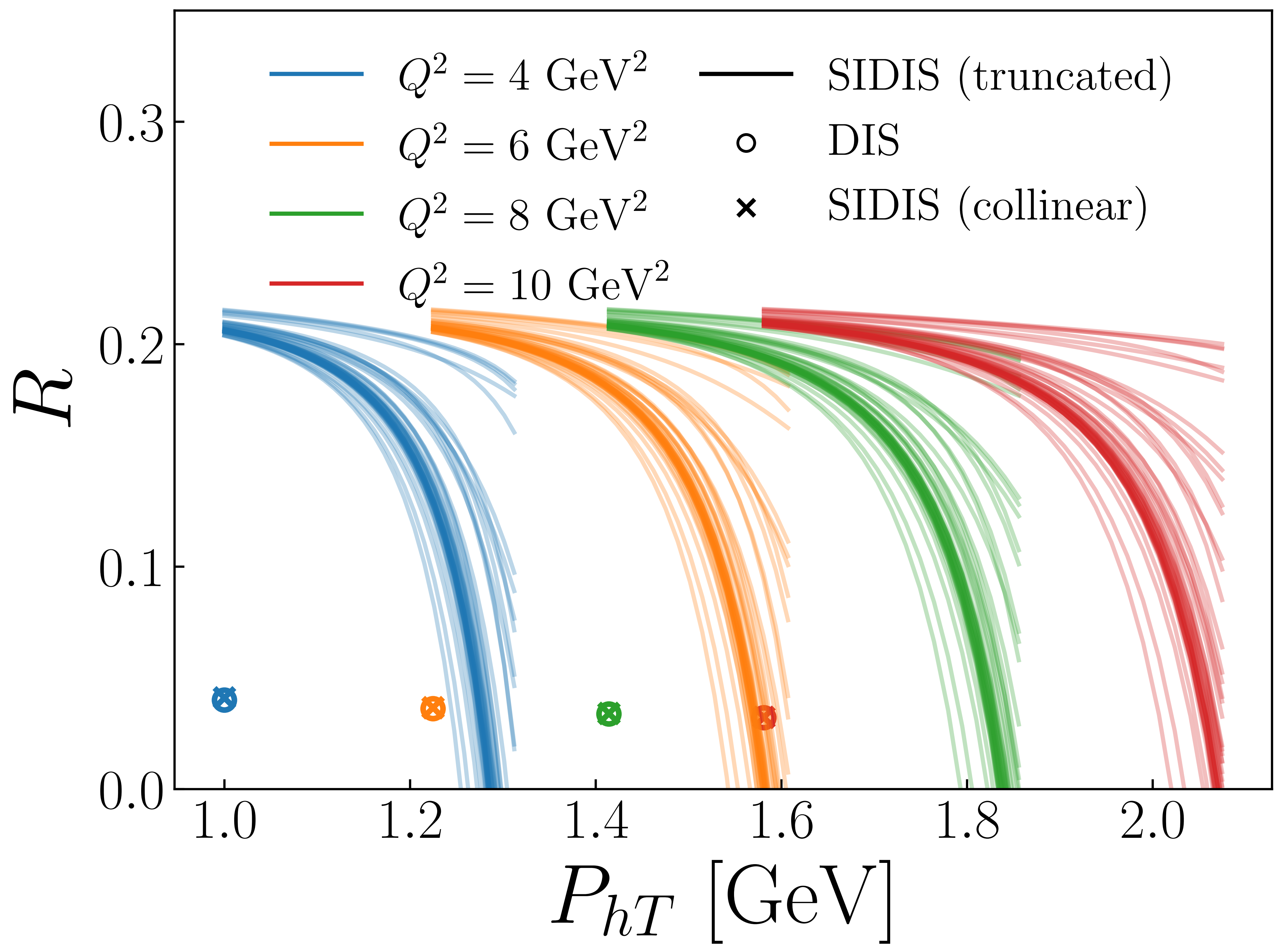
- Truncated moment is sig. larger than P_T integrated SIDIS—indication of
- power corrections ?
- TMD contribution ?

R_{SIDIS} & $\sigma_L \sim F_{UU,L}$ at large p_T

Jlab 11 GeV $x = 0.3$ & $z = 0.5$



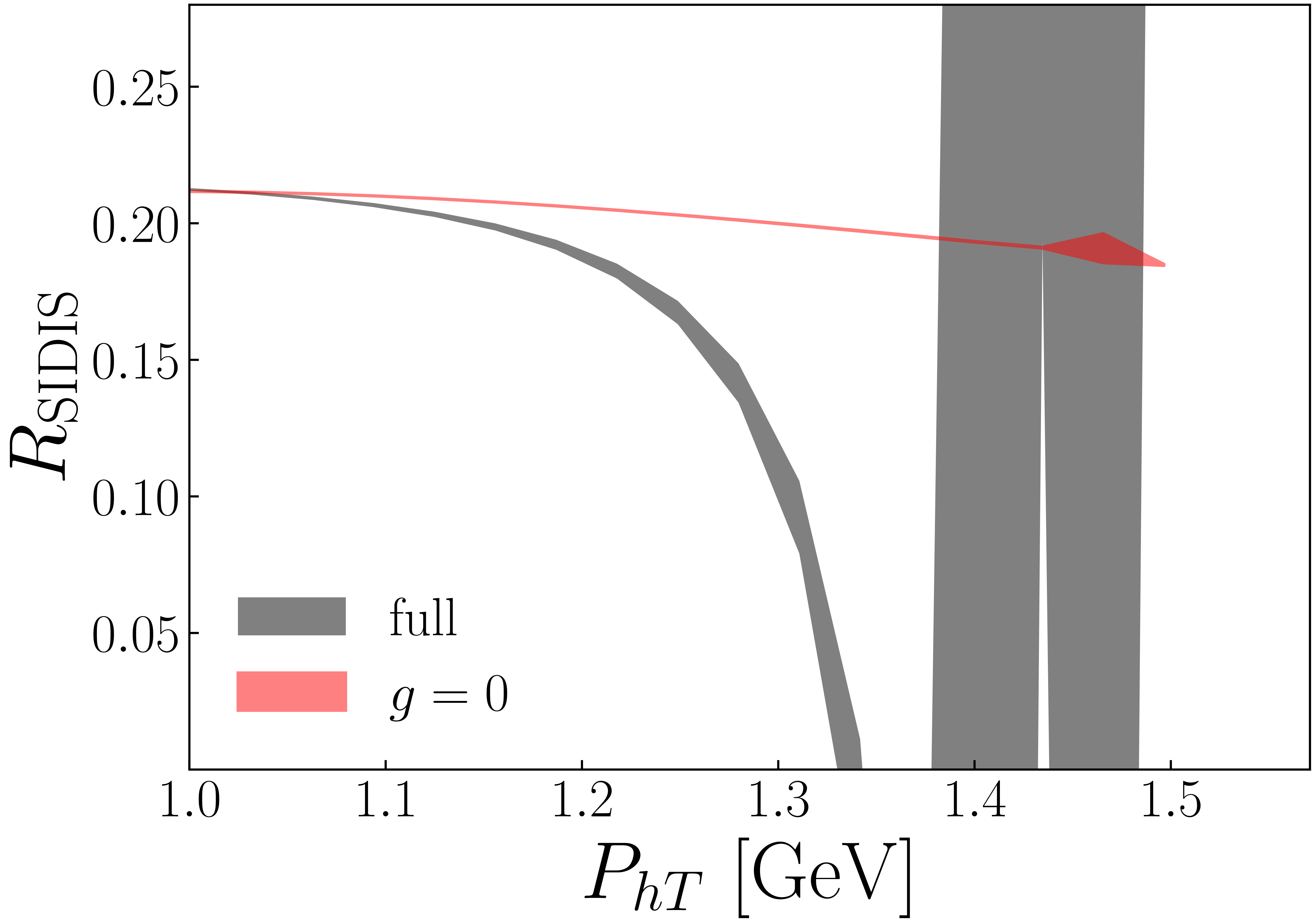
Jlab 22 GeV $x = 0.3$ & $z = 0.5$



R_{SIDIS} & $\sigma_L \sim F_{UU,L}$ at large p_T

- gluon contribute large uncertainty @ hi-x (see delta function)
- $g \to 0$ ie gluon PDF set to zero
- Rsidis can be useful to pin down the g @ $lg\ x$

$$\text{FO} = \sum_q e_q^2 \int_{\frac{q_T^2}{Q^2}\frac{xz}{1-z}+x}^{1} \frac{d\xi}{\xi - x} H(\xi)\ \boldsymbol{f}_q(\xi,\mu)\ \boldsymbol{d}_q(\zeta(\xi),\mu) + O(\alpha_S^2) + O(m^2/q^2)$$



+ **Attention**: $\left(\frac{q_T^2}{Q^2}\frac{xz}{1-z} + x\right) < \xi < 1$
+ **large q_T probes large ξ in PDFs**
+ Can be useful in collinear global fits

The observable $\langle \cos\phi \rangle$

No assumption of mechanism

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\frac{y}{2\,(1-\varepsilon)}\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}\right.$$

$$\int d\sigma^{(1)}\,\cos\phi = \int d^2P_T\,\cos\phi\,\frac{d\sigma}{dx_H\,dy\,dz_H\,d^2P_T}$$

SIDIS Kinematics dictionary

$$Q^2 = -q^2\,,\quad \mathbf{P}_T = \mathbf{P}_{2T}\,,\quad \phi,$$

$$x_H = \frac{Q^2}{2P_1\cdot q}\,,\quad y = \frac{P_1\cdot q}{P_1\cdot k_1}\,,\quad z_H = \frac{P_1\cdot P_2}{P_1\cdot q}\,,$$

and the parton variables

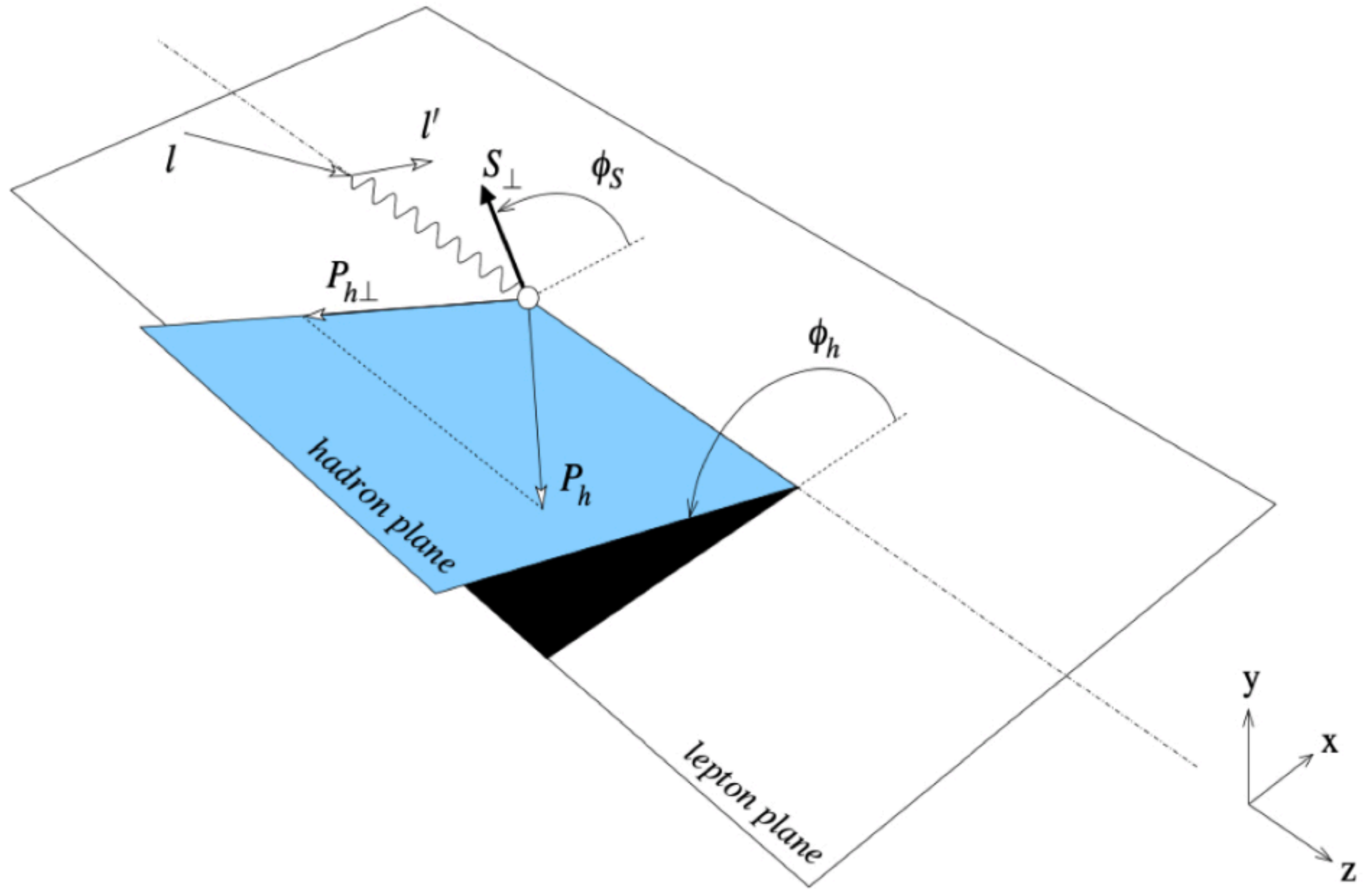
$$x = \frac{x_H}{\xi} = \frac{Q^2}{2p_1\cdot q}\,,\quad z = \frac{z_H}{\xi'} = \frac{p_1\cdot p_2}{p_1\cdot q}.$$

TMDs @ "twist-3 " NLP

The beginning of TMD physics? $\langle \cos\phi \rangle$

- **<u>Georgi Politzer, PRL 1978</u>** "Measurement $\langle \cos\phi \rangle$ provides clean test of predictions of PQCD

~12-15% …clean test of QCD "…since such effects would not arise as a result of limited transverse momentum associated with confined quarks…"



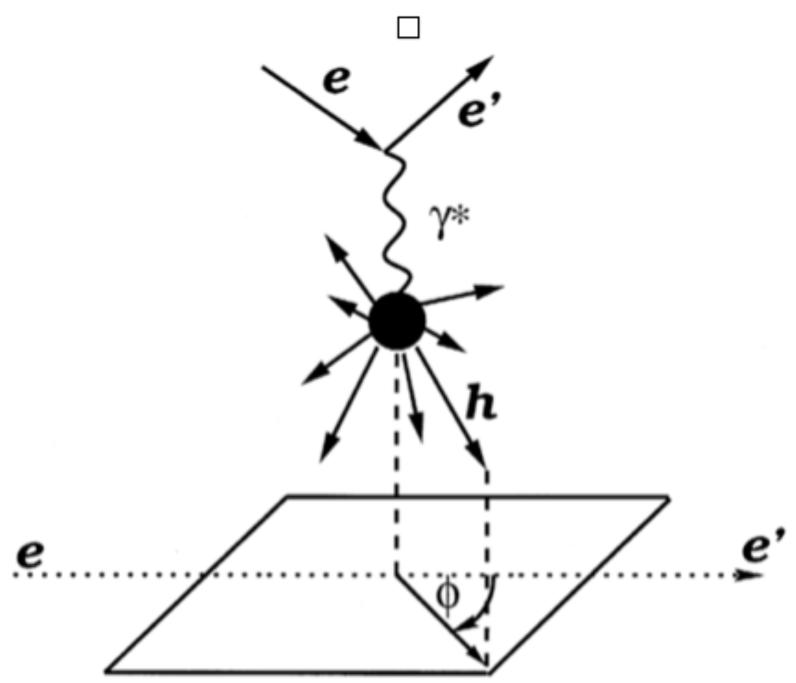
- **<u>Cahn, PLB 1978, (& earlier paper by Ravndal, PLB 1972)</u>**
  Critique QCD calculation of azimuthal dependence
  emphasize importance intrinsic $\boldsymbol{k_T}$ …

"…Results cast doubt on the utility of such azimuthal asymmetry as a clean test of quantum chromodynamics " (i.e. of G&P 78)

Clean tests of QCD ?

PHYSICAL REVIEW LETTERS

VOLUME 40 — 2 JANUARY 1978 — NUMBER 1



Clean Tests of Quantum Chromodynamics in μp Scattering

Howard Georgi

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

and

H. David Politzer

California Institute of Technology, Pasadena, California 91125

(Received 25 October 1977)

Hard gluon bremsstrahlung in μp scattering produces final-state hadrons with a large component of momentum transverse to the virtual-photon direction. Quantum chromodynamics can be used to predict not only the absolute value of the transverse momentum, but also its angular distribution relative to the muon scattering plane. The angular correlations should be insensitive to nonperturbative effects.

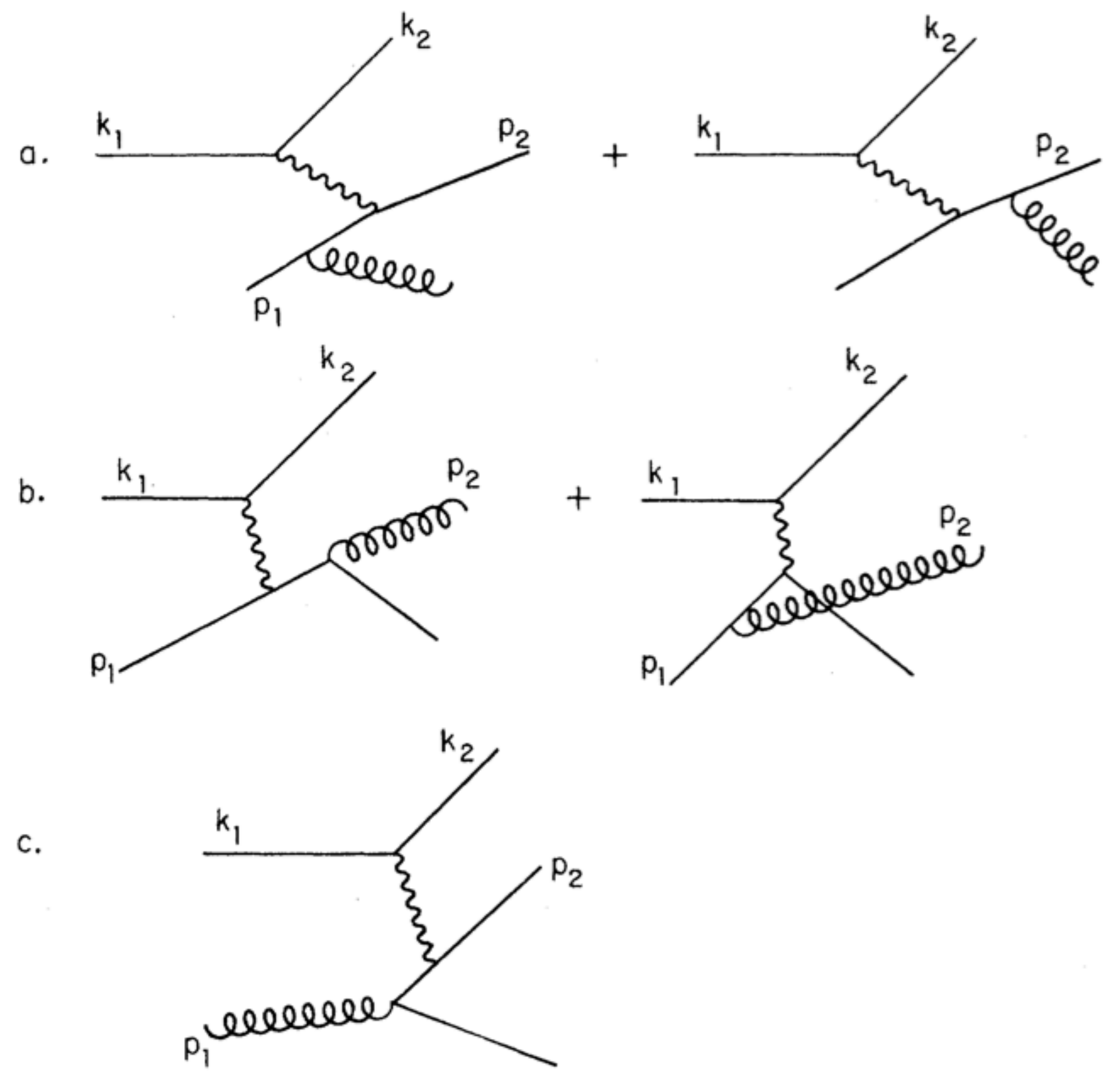


FIG. 1. Diagrams contributing to semi-inclusive μ-parton scattering to first order in α_s. k (p) denotes muon (parton) momentum. The wavy line is a virtual photon. The curly line is a gluon.

Pert. QCD $\quad \alpha_s = g^2/4\pi$

$$\langle \cos\varphi \rangle_{ep} = -\frac{\alpha_s}{2}\kappa\sqrt{1-z}\,\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

Cahn intrinsic k_T

Volume 78B, number 2,3 PHYSICS LETTERS 25 September 1978

AZIMUTHAL DEPENDENCE IN LEPTOPRODUCTION: A SIMPLE PARTON MODEL CALCULATION☆

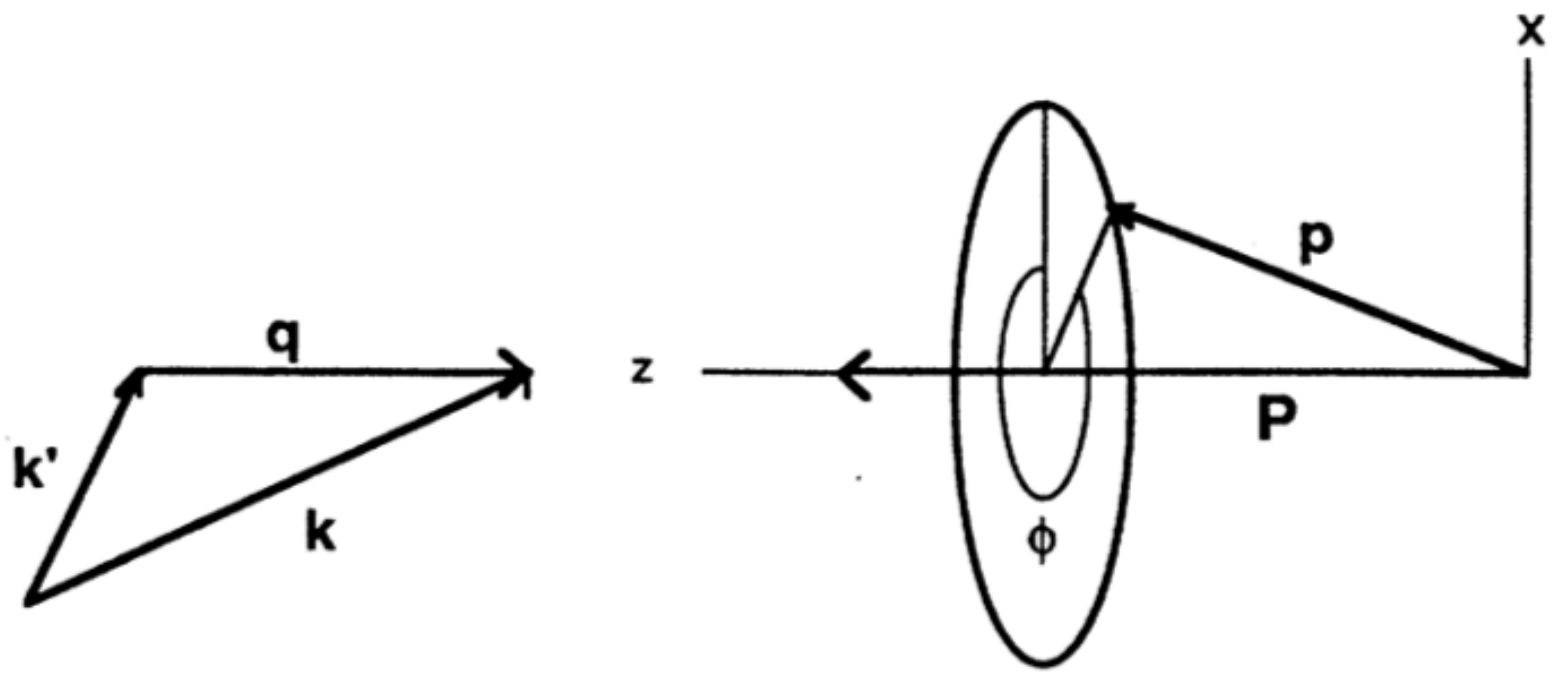
Robert N. CAHN
Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

Received 5 June 1978

Simple parton model argument allowing for transverse momentum in Mandelstam variables...

Semi-inclusive leptoproduction, $\ell + p \to \ell' + h + X$, is considered in the naive parton model. The scattered parton shows an azimuthal asymmetry about the momentum transfer direction. Simple derivations for the effects in ep, νp and $\bar{\nu}$p scattering are given. Reduction of the asymmetry due to fragmentation of partons into hadrons is estimated. The results cast doubt on the utility of such azimuthal asymmetry as a clean test of quantum chromodynamics.

$$\sigma_{ep} \propto \hat{s}^2 + \hat{u}^2 \propto \left[1 - \frac{2p_\perp}{Q}\sqrt{1-y}\,\cos\phi\right]^2 + (1-y)^2\left[1 - \frac{2p_\perp}{Q\sqrt{1-y}}\cos\phi\right]^2$$



NLP ! $\frac{p_\perp}{Q}$

$$\langle \cos\phi \rangle_{ep} = -\left[\frac{2p_\perp}{Q}\right]\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

Cahn intrinsic k_T

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\,\frac{y}{2\,(1-\varepsilon)}\,\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$

TMD Collaboration

Preprints: JLAB-THY-23-3780, LA-UR-21-20798, MIT-CTP/5386

TMD Handbook

Renaud Boussarie[1], Matthias Burkardt[2], Martha Constantinou[3], William Detmold[4], Markus Ebert[4,5], Michael Engelhardt[2], Sean Fleming[6], Leonard Gamberg[7], Xiangdong Ji[8], Zhong-Bo Kang[9], Christopher Lee[10], Keh-Fei Liu[11], Simonetta Liuti[12], Thomas Mehen[13], Andreas Metz[3], John Negele[4], Daniel Pitonyak[14], Alexei Prokudin[7,16], Jian-Wei Qiu[16,17], Abha Rajan[12,18], Marc Schlegel[2,19], Phiala Shanahan[4], Peter Schweitzer[20], Iain W. Stewart[4], Andrey Tarasov[21,22], Raju Venugopalan[18], Ivan Vitev[10], Feng Yuan[23], Yong Zhao[24,4,18]

10 - Subleading TMDs

L. Gamberg, A. Metz, I. Stewart

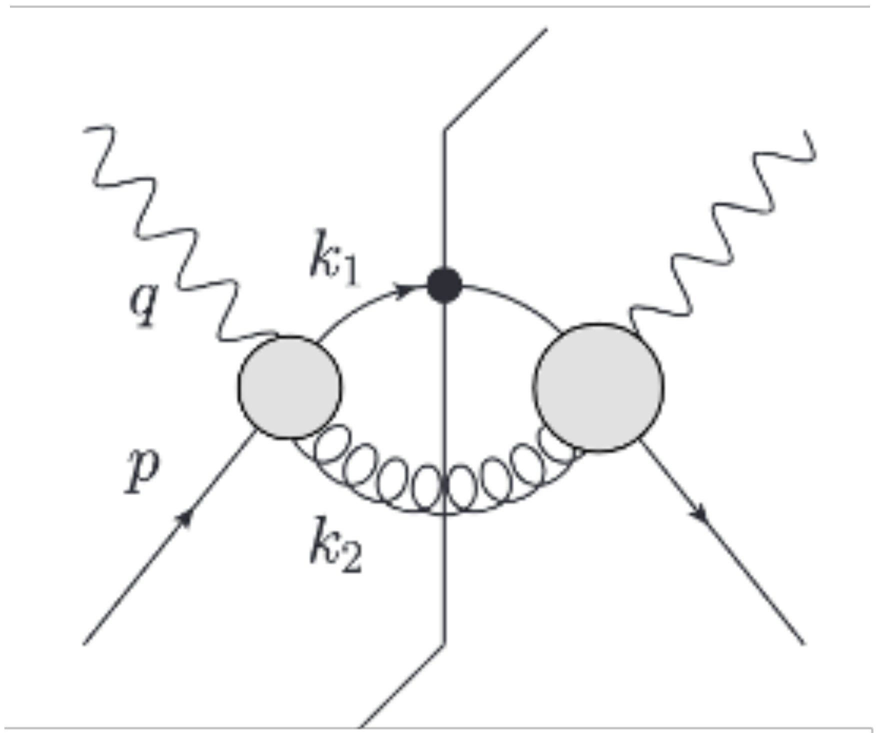
Subleading Quark TMDPDFs

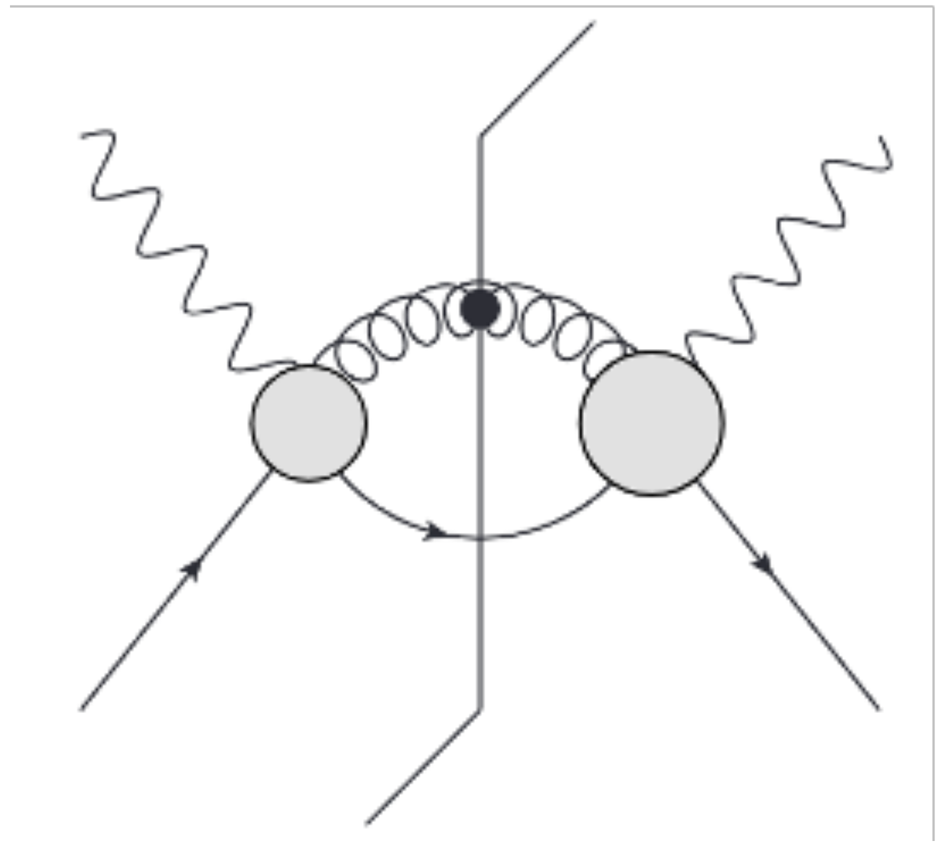
Nucleon Polarization	Quark Chirality: Chiral Even	Quark Chirality: Chiral Odd
U	$f^{\perp}$, $g^{\perp}$	e , h
L	$f_L^{\perp}$, $g_L^{\perp}$	e_L, h_L
T	f_T, $f_T^{\perp}$, g_T, $g_T^{\perp}$	e_T, $e_T^{\perp}$, h_T, $h_T^{\perp}$

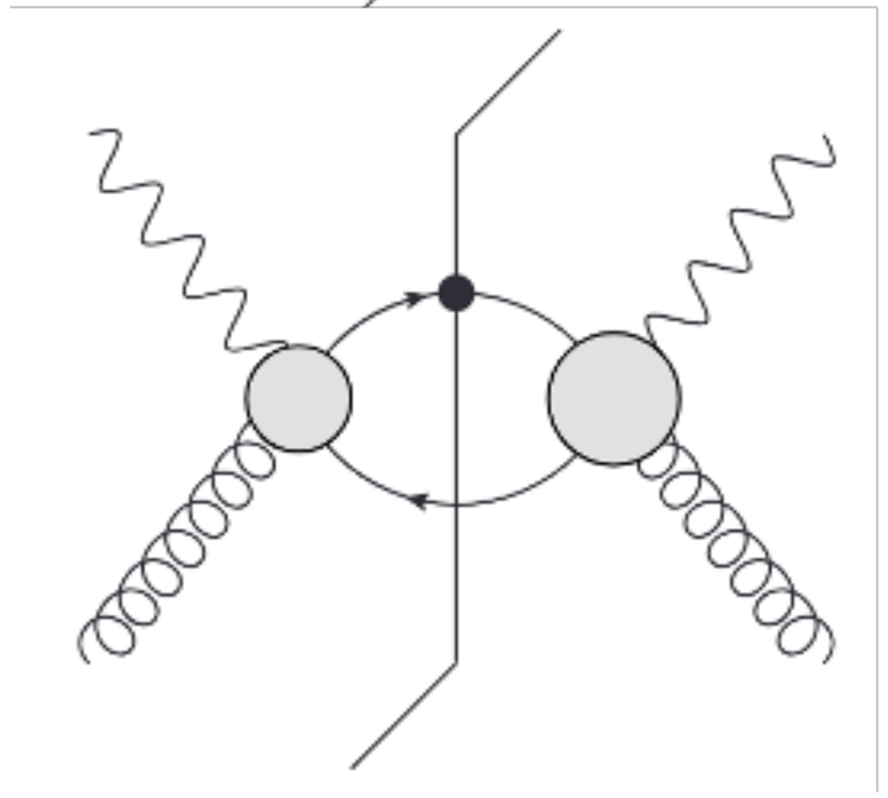
However again large q_T angular modulation $\cos\phi_h$ effect & $\cos 2\phi_h$

$$F_{UU,T} = \frac{1}{Q^2}\,\frac{\alpha_s}{(2\pi z)^2}\sum_a x\, e_a^2 \int_x^1 \frac{d\hat{x}}{\hat{x}} \int_z^1 \frac{d\hat{z}}{\hat{z}}\,\delta\!\left(\frac{q_T^2}{Q^2} - \frac{(1-\hat{x})(1-\hat{z})}{\hat{x}\,\hat{z}}\right)$$

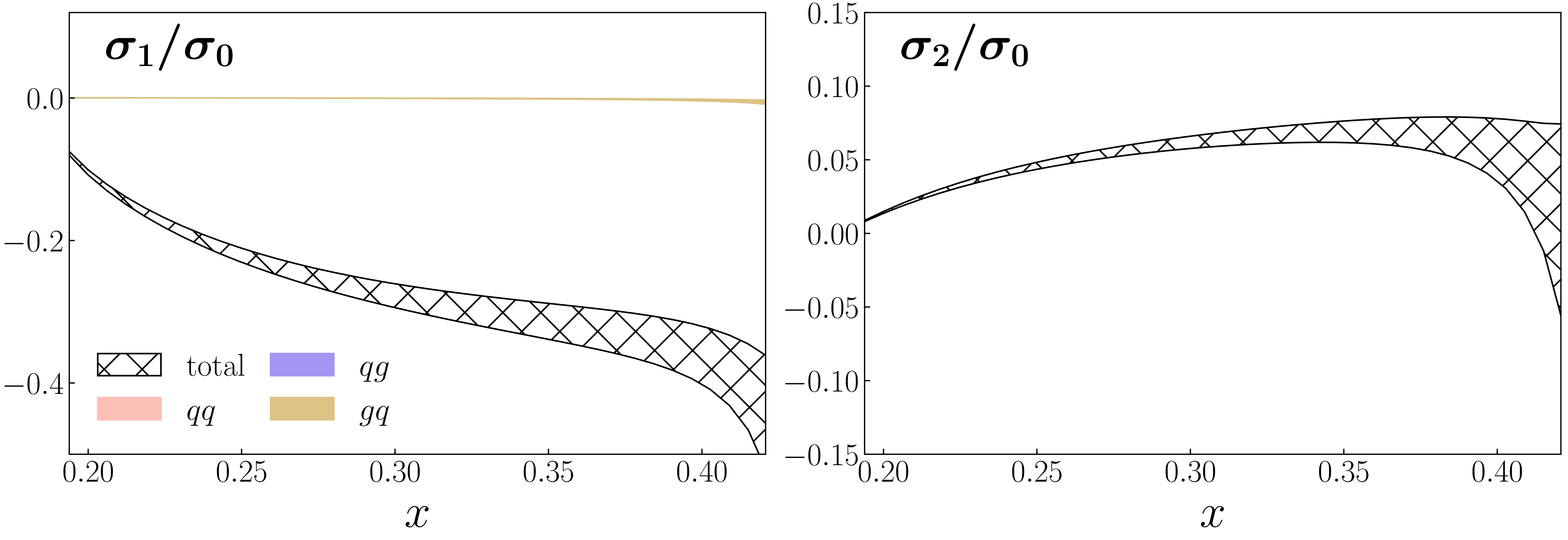
$$\times \left[f_1^a\!\left(\frac{x}{\hat{x}}\right) D_1^a\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* q\to qg)} + f_1^a\!\left(\frac{x}{\hat{x}}\right) D_1^g\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* q\to gq)} + f_1^g\!\left(\frac{x}{\hat{x}}\right) D_1^a\!\left(\frac{z}{\hat{z}}\right) C_{UU,T}^{(\gamma^* g\to q\bar{q})} \right]$$





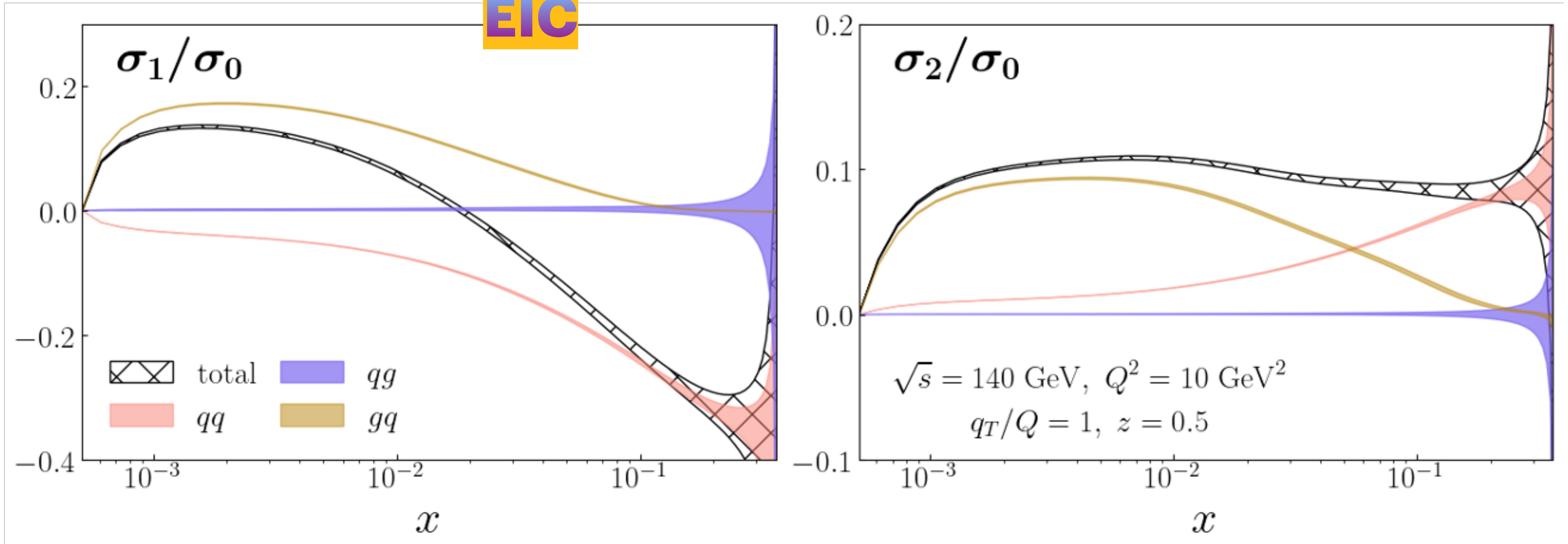


11 GeV



σ_1/σ_0
σ_2/σ_0
0.0
−0.2
−0.4
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
0.20
0.25
0.30
0.35
0.40
x
total
qg
qq
gq

EIC



σ_1/σ_0
σ_2/σ_0
0.2
0.0
−0.2
−0.4
0.1
−0.1
10^{-3}
10^{-2}
10^{-1}
x
total
qg
qq
gq
$\sqrt{s} = 140$ GeV, $Q^2 = 10$ GeV^2
$q_T/Q = 1$, $z = 0.5$

Summary

We explore NLP $(M/Q)^n$ contributions in large q_T and TMD regions via power counting and factorization theorems

- NLP factorization based on *"TMD formalism"*

  —extend the tree level Amsterdam formalism and beyond leading order

  CSS, Ji Ma Yuan, Abyat Rogers, framework vs. SCET and Background Field Methods
- Considier R_{SIDIS} & revisit "Cahn effect" & matching related to early importance intrinsic $\boldsymbol{k}_T$
  - *"Intrinsic"NLP TMDs related thru EOM in terms "kinematic" & "dynamical"*
- Consider RG consistency of matching to collinear factorization & issues of resummation
  - Bacchetta, Boer, Diehl, Mulders JHEP 2008, Bacchetta et al. PLB 2019
- Report progress in this <u>*necessary condition*</u> NLP factorization (not yet sufficient)

- In doing so, we provide the basis for performing global analysis & phenomenology of one the earliest observables used to study intrinsic 3-D momentum structure of the nucleon—Opportunity for Jlab, EIC, COMPASS study of transverse momentum nucleon structure

Thank You