Progress TMDs & factorization at sub-leading power

Leonard Gamberg
w/ Zhongbo Kang, Ding-Yu Shao, John Terry, Fany Zhao

arXiv: e-Print:221.13209

U.S. DEPARTMENT OF ENERGY | Office of Science

PennState Berks

Importance of *NLP* TMDs & Factorization

- Importance of NLP TMD *observables* underscored by observation that while they are suppressed by M/Q wrt *LP* observables:

  - NLP/SLP TMDs can be as sizable as leading-power TMDs in some situations, particularly when Q is not that large … not small in the kinematics of fixed-target experiments

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

- Are of interest offer a mechanism to probe physics of quark-gluon-quark correlations, provide novel information about the partonic structure of hadrons, and are largely unexplored.
  - Such correlations may be considered quantum interference effects, related to average transverse forces acting on partons inside (polarized) hadrons as well as other phenomena.

- Also, experimental information from SIDIS on effects related to subleading TMDs is & has been available
  - In the future, the EIC with its *large* kinematical coverage will be ideal for making further groundbreaking progress in this area.

  - *NB*: Iff factorization can be established beyond "tree level" leading order

Challenges of *SLP/NLP* TMDs

NLP TMD observables challenging in comparison to the current state-of-the-art of leading power observables.
Treatments in the literature are mostly limited to a tree-level formalism until recently

early studies beyond tree level : ***Bacchetta et al. JHEP 2008, Chen et al. PLB 2017*

More recently results beyond *LO*

MIT group, Gao, Ebert, Stewart JHEP 2022
Gamberg, Kang, Shao, Terry, Zhao arXiv: e-Print:221.13209
Vladimirov, Rodini, Scimemi, Moos, JHEP 2021, 2022, arXiv 2023
Balitsky 2023 rapidity only TMD evolution
See also Ch. 10 TMD handbook, e-Print:2304.03302 [hep-ph]

Various sources for power suppressed terms identified and discussed in the literature from

Tree level Studies, Mulders, Tangerman (1996), Bacchetta et al. JHEP (2007)

- This includes corrections associated to kinematic prefactors involving contractions between the leptonic and hadronic tensors, referred to as ***kinematic power corrections***.

- Another involve subleading terms in quark-quark correlators involving Dirac structures that differ from LP ones referred to as ***intrinsic power corrections***— *e.g. Cahn function* $f^{\perp}(x, k_T)$, $e(x, k_T)$ …

- Another from hadronic matrix elements of (interaction dependent) quark-gluon-quark operators, referred to ***dynamic power corrections*** multi-parton *qgq* correlators

- *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

TMD fact at NLP(incomplete)

F. Rivindal PLB 1973
Georgi Politzer PRL 1978
Cahn PLB 1978 (response to Georgi Politzer PRL 1978)
R. Tangerman, P. Mulders hep-ph/9408305 [hep-ph] (1994)
P.Mulders, R. Tangerman, NPB 461(1996)
D. Boer, P. Mulders, Phys.Rev.D 57 (1998)
L. Gamberg, D. Hwang, A Metz, M. Schlegel, PLB 639 (2006), uncanceled rapidity div. @tw3-factorization
Koike Nagashima Vogelsang SIDIS NPB 2006 Large P_T
A.Bacchetta, D. Boer, M. Diehl, P. Mulders JHEP (2008) factorization at NLP consistency checks on matching
A.P. Chen, J.P. Ma, Phys. Lett. B 768 (2017)
I. Feige, D.W. Kolodrubetz, I. Moult, I.W. Stewart, J. High Energy Phys. 11 (2017)
I. Balitsky, A. Tarasov, J. High Energy Phys. 07 (2017)
I. Balitsky, A. Tarasov, J. High Energy Phys. 05 (2018)
M.A. Ebert, I. Moult, I.W. Stewart, F.J. Tackmann, G. Vita, H.X. Zhu, J. High Energy Phys. 12 (2018)
M.A. Ebert, I. Moult, I.W. Stewart, F.J. Tackmann, G. Vita, H.X. Zhu, J. High Energy Phys. 04 (2019)
Moult, I.W. Stewart, G. Vita, arXiv:1905 .07411, 201
A. Bacchetta Bozzi, Echevarria, Pisano, Prokudin, Radici, Physics Letters B 797 (2019)
A.Vladimirov Moos, Scimemi, & S.Rodini JHEP 2022
M. Ebert A. Gao I. Stewart JHEP 06 (2022)
S. Rodini, A. Vladimirov JHEP 08 (2022)
L.Gamberg, Z.Kang, D.Shao, J.Terry, F.Zhao arXiv: e-Print:221.13209 (2022)
I.Balitsky, JHEP 03 (2023)

Also Spin Dependence
Qui Sterman collinear higher twist 1991 NLB
Boer Vogelsang DY PRD 2006

arXiv:2304.03302v1 [hep-ph] 6 Apr 2023

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

From a historical perspective it is very interesting that the subleading-power $\cos\phi_h$ azimuthal modulation of the unpolarized SIDIS cross section was important for the development of the TMD field, since one of the earliest discussions of transverse parton momenta in DIS is related to this observable [290, 291, 1237]; see also Sec. 5.1 for more details. Generally, although suppressed by Λ/Q with respect to leading-power observables, subleading TMD observables are typically not small, especially in the kinematics of fixed-target experiments. In fact, the first-ever observed SSA in SIDIS was a sizeable power-suppressed longitudinal target SSA for pion production from the HERMES Collaboration [480]. Those measurements, which triggered many theoretical studies and preceded the first measurements of the (leading-power) Sivers and Collins SSAs, were critical for the growth of TMD-related research.

[290] R. N. Cahn, *Azimuthal Dependence in Leptoproduction: A Simple Parton Model Calculation*, *Phys. Lett. B* **78** (1978) 269.

[1237] F. Ravndal, *On the azimuthal dependence of semiinclusive, deep inelastic electroproduction cross-sections*, *Phys. Lett. B* **43** (1973) 301.

[480] HERMES collaboration, A. Airapetian et al., *Observation of a single spin azimuthal asymmetry in semiinclusive pion electro production*, *Phys. Rev. Lett.* **84** (2000) 4047

TMDs @ "twist-3 " NLP-the beginning?

Some historical-context

- **Georgi Politzer, PRL 1978**
  Performed QCD analysis of *hard gluon* radiation in SIDIS to predict absolute value of final state hadron's $\boldsymbol{P_T}$, and the angular distribution relative to lepton scattering plane $\langle \cos \phi \rangle$
- ***~12-15% …effects would not arise as a result of the nonperturbative effects due to limited transverse momentum associated with confined quarks***
- **"Measurement of $\langle \cos \phi \rangle$ provide very *clean test of the perturbative predictions of QCD"***

- **Cahn, PLB 1978, (& earlier paper by Ravndal, PLB 1972)**
  Critique of the QCD calculation of azimuthal dependence in leptoproduction; emphasize importance *intrinsic* $\boldsymbol{k_T}$ …
- "We conclude that the azimuthal dependence in vector exchange interactions is inevitable since the partons have transverse momentum as a consequence of being confined and such dependence certainly does not require a special mechanism like gluon bremstrahlung"
  "…The results **(G&P78)** cast doubt on the utility of such azimuthal asymmetry as a clean test of quantum chromodynamics"

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.

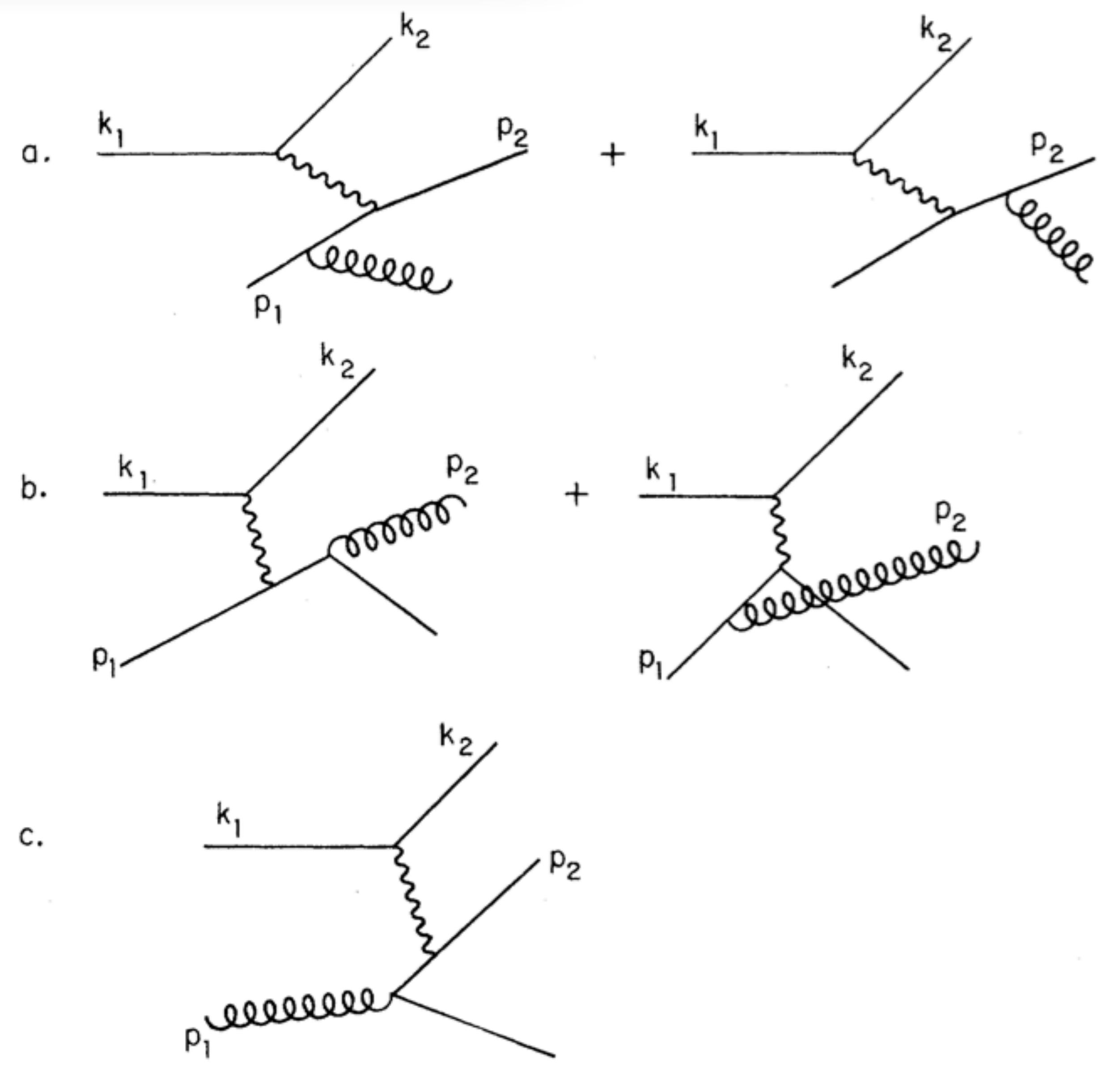


FIG. 1. Diagrams contributing to semi-inclusive μ-parton scattering to first order in α_s. k (p) denotes muon (parton) momentum. The wavy line is a virtual photon. The curly line is a gluon.

Pert. QCD

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

Cahn intrinsic k_T

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

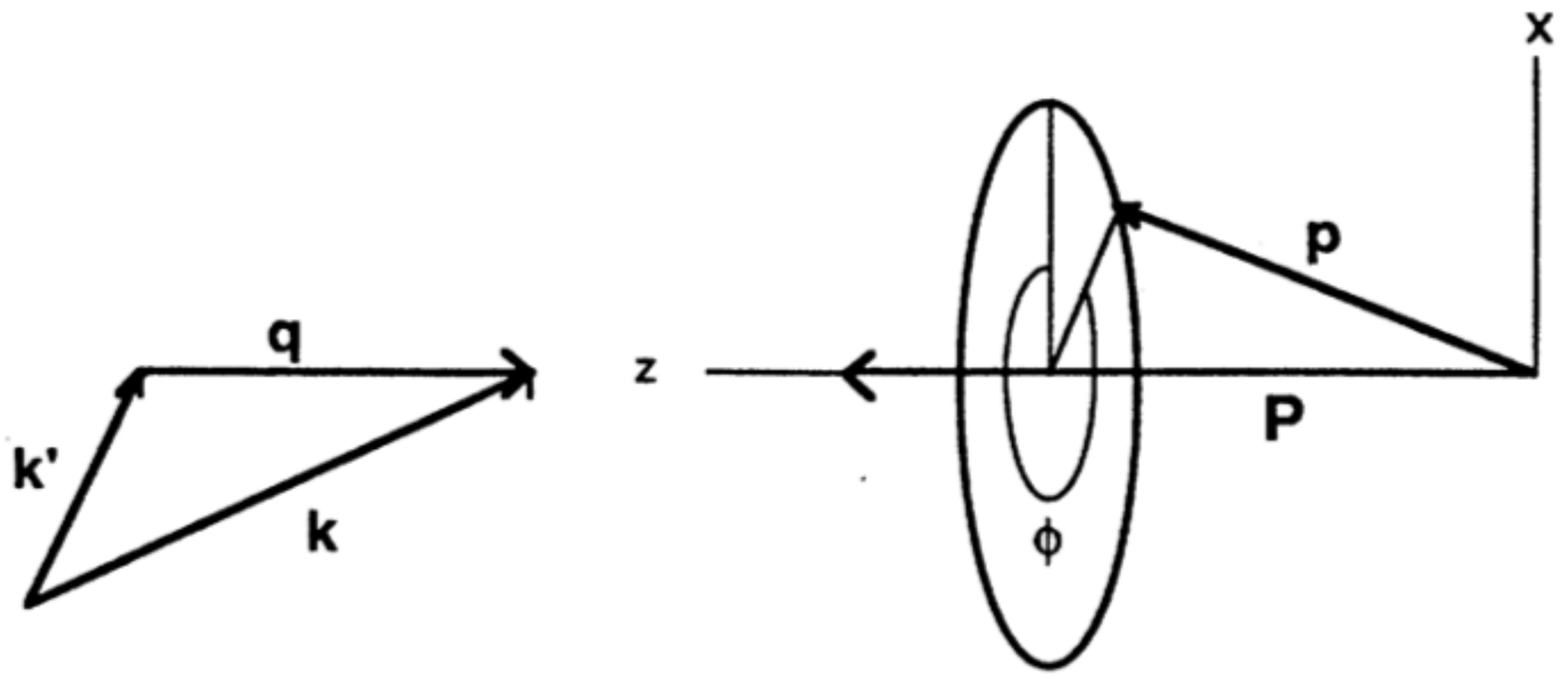
AZIMUTHAL DEPENDENCE IN LEPTOPRODUCTION: A SIMPLE PARTON MODEL CALCULATION☆

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

Received 5 June 1978

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.

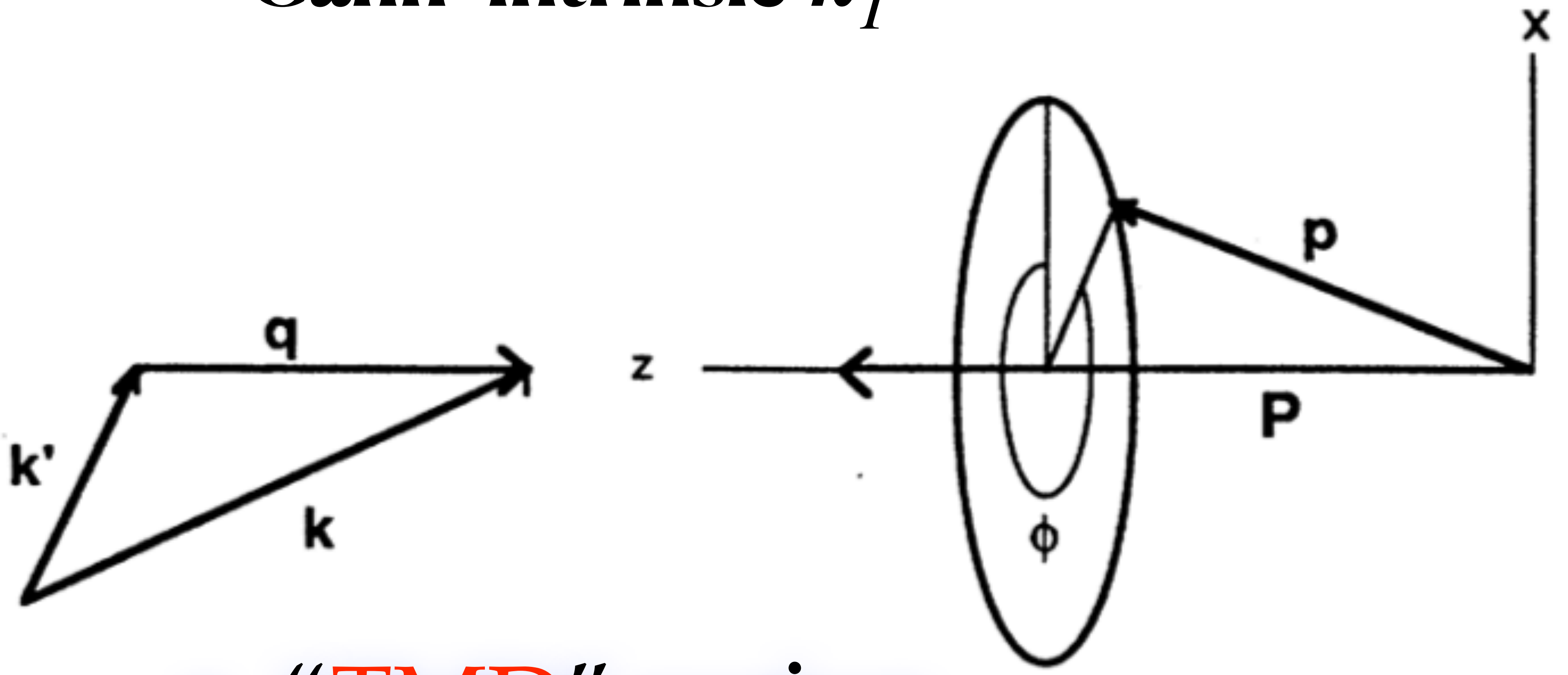


NLP

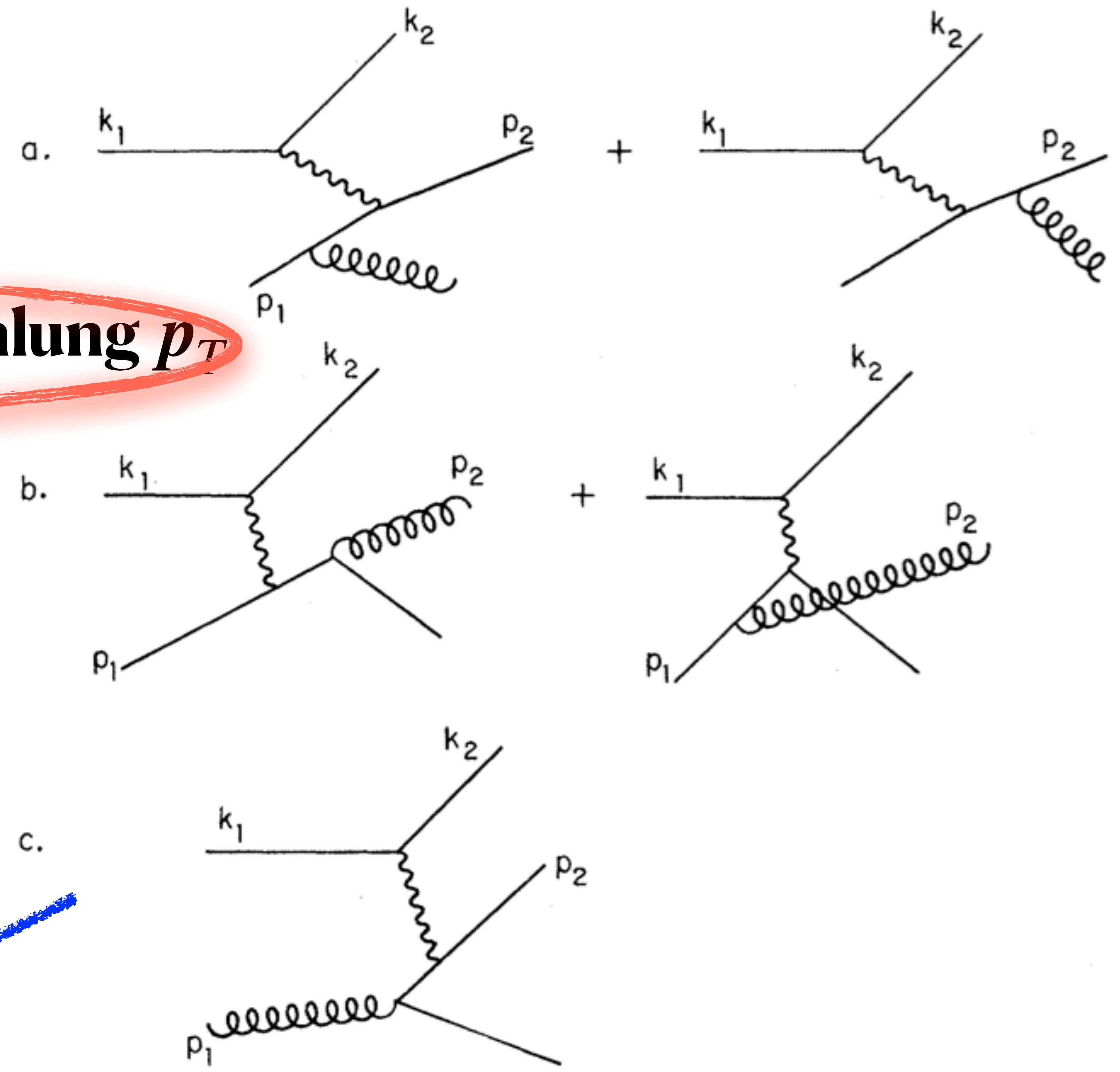
$$\langle \cos\phi \rangle_{ep} = -\left[\frac{2p_\perp}{Q}\right] \frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

Two mechanisms ? Collinear Factorization

Cahn intrinsic k_T



Georgi & Politzer
hard gluon bremsstrahlung p_T



- "TMD" region

$(p_T \sim k_T) \sim q_T \ll Q$

- "Collinear " region

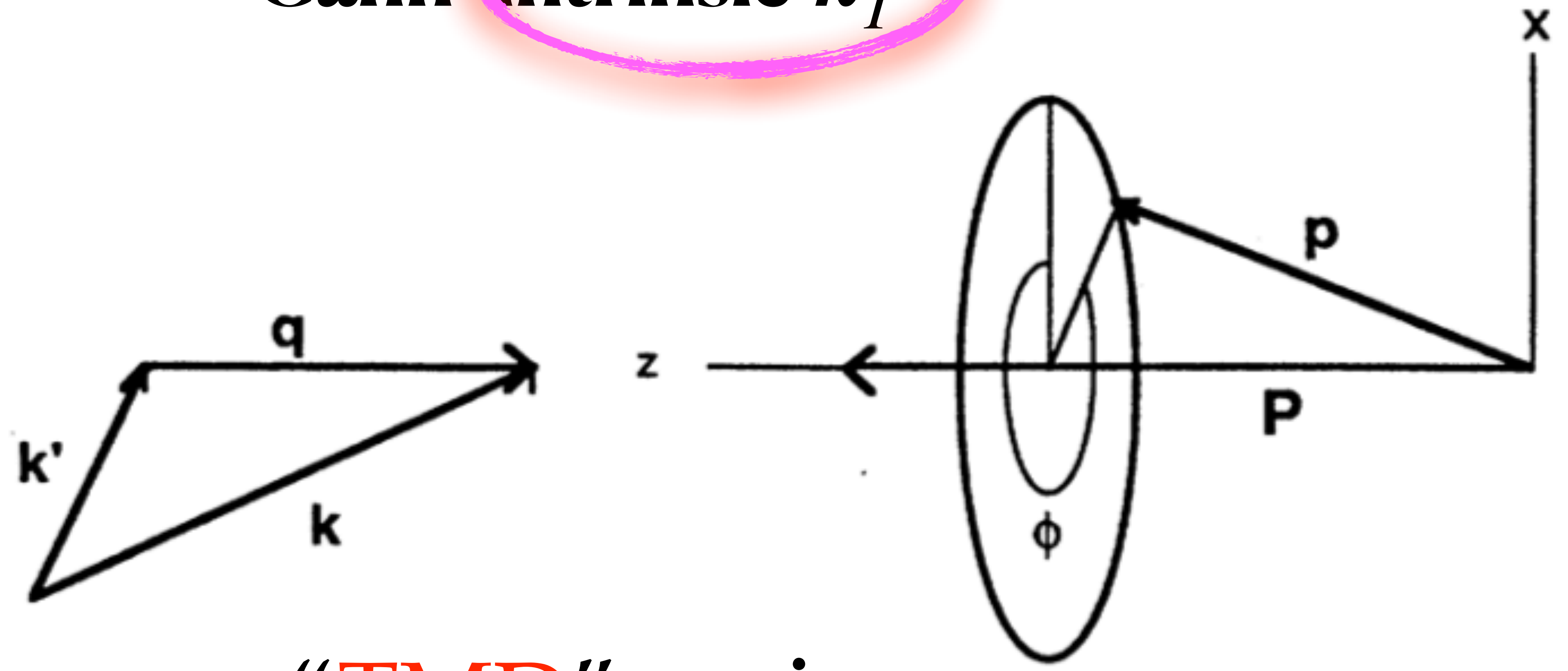
$\Lambda_{qcd} \ll q_T \sim Q$

$$\frac{d^5\sigma}{dx_{bj}\,dQ^2\,dz_f\,dq_T^2\,d\phi} = \frac{\alpha_e^2\alpha_s}{8\pi x_{bj}^2 S_{ep}^2 Q^2}\sum_k \mathcal{A}_k \int_{x_{\min}}^{1} \frac{dx}{x}\int_{z_f}^{1} \frac{dz}{z}[f\otimes D\otimes\hat{\sigma}_k \times \delta\left(\frac{q_T^2}{Q^2} - \left(\frac{1}{\hat{x}}-1\right)\left(\frac{1}{\hat{z}}-1\right)\right)$$

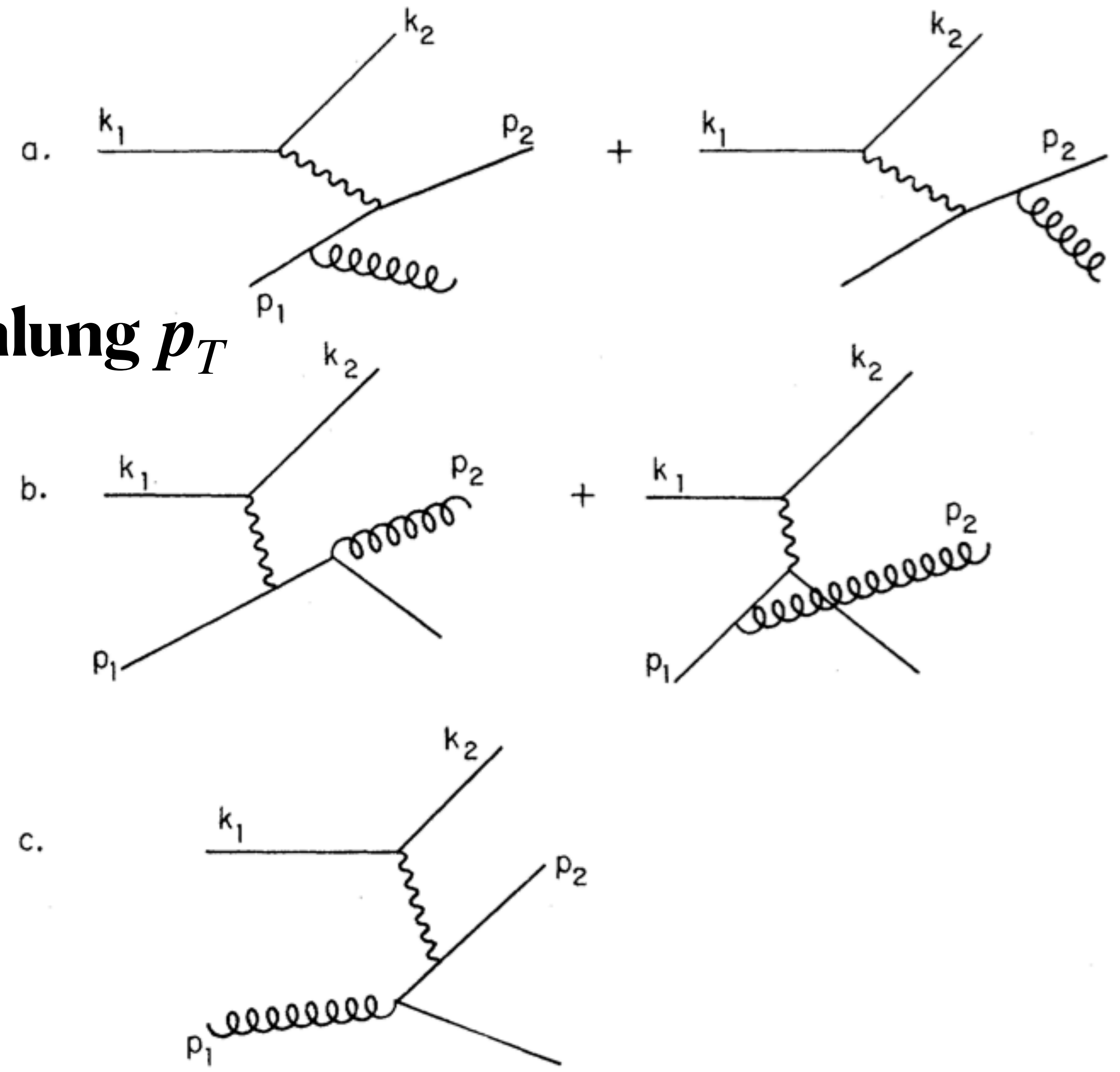
See e.g. Mendez NPB 1978, Koike, Vogelsang, Nagashima NPB 2006

Two mechanisms ? TMD Factorization

Cahn intrinsic k_T



Georgi & Politzer
hard gluon bremsstrahlung p_T



- "TMD" region

$(p_T \sim k_T) \sim q_T \ll Q$

$$\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} =$$

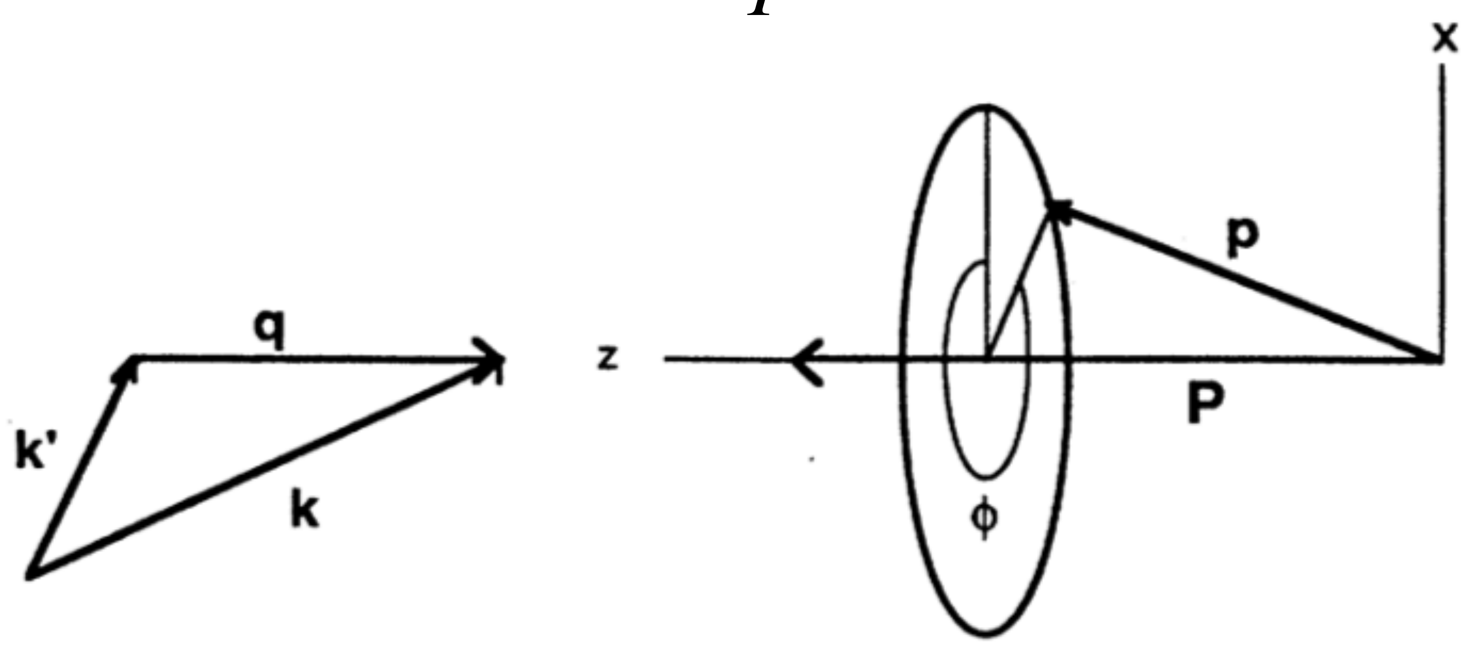
$$\frac{\alpha^2}{xyQ^2}\, \frac{y^2}{2\,(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x}\right) \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} \Big\}$$

e.g. $F_{UU}^{\cos\phi_h} \approx \frac{2M}{Q}\, \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p}_T}{M} f_1 D_1 \right]$

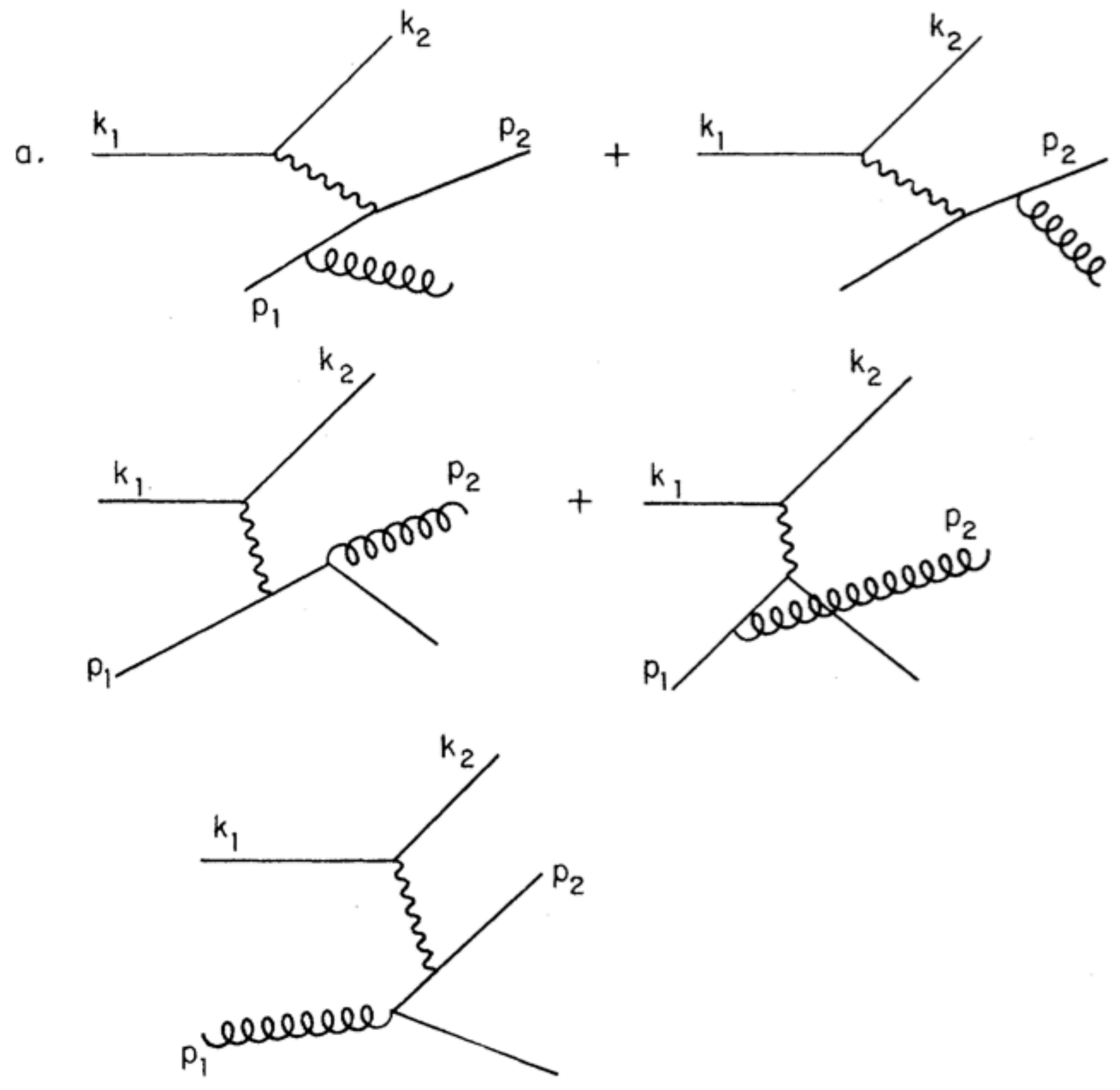
P.Mulders, R. Tangerman, NPB (1996), Bacchetta et al. JHEP 2007

Matches Factorization @ sub-leading power

Cahn intrinsic k_T

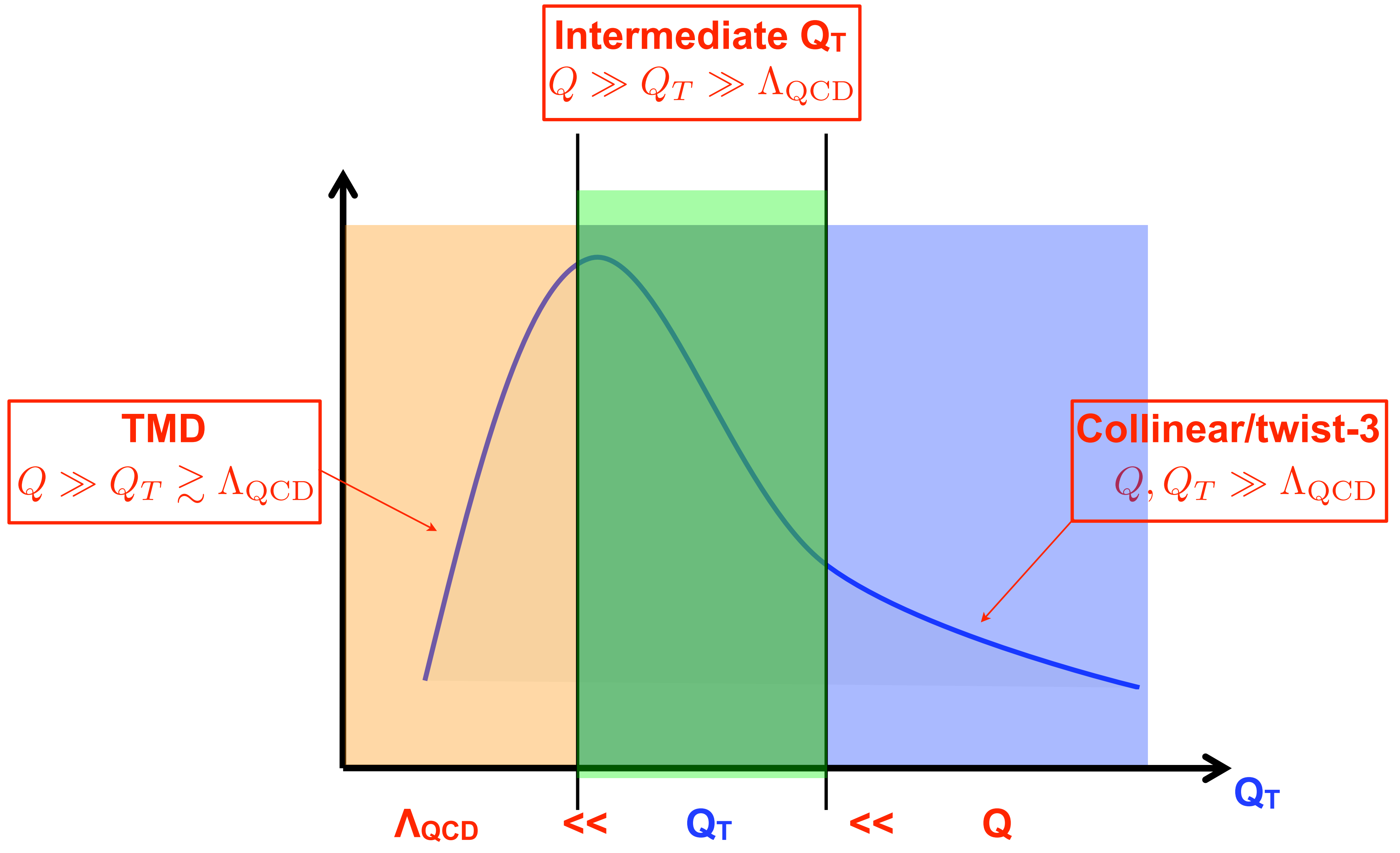


Georgi & Politzer
hard gluon bremsstrahlung p_T



- "TMD" region

$(p_T \sim k_T) \sim q_T \ll Q$



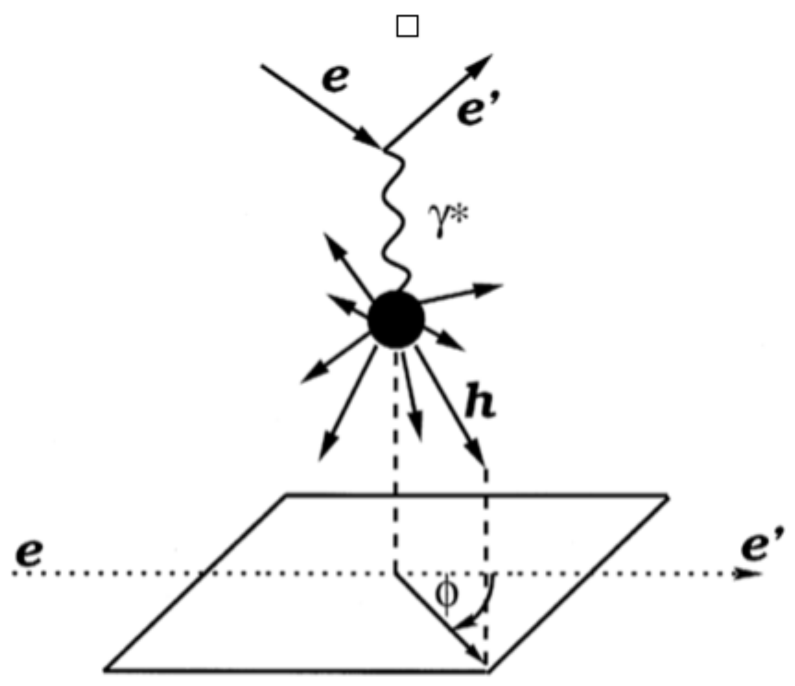
- "Collinear" region

$\Lambda_{qcd} \ll q_T \sim Q$

A comprehensive study of matching the hi & low Q_T in the overlap region in SIDIS was carried out by JHEP (2008) Bacchetta et al. where attention was given to azimuthal and polarization dependence

DATA

$$\frac{d\sigma^{ep\to ehX}}{d\phi} = \mathcal{A} + \mathcal{B}\cos\phi + \mathcal{C}\cos 2\phi + \mathcal{D}\sin\phi + \mathcal{E}\sin 2\phi$$



$\Lambda_{qcd} \ll q_T \sim Q$

"Collinear region"

EMC collaboration Phys. Lett. B 130 (1983) 118, & Z. Phys. C 34 (1987) 277

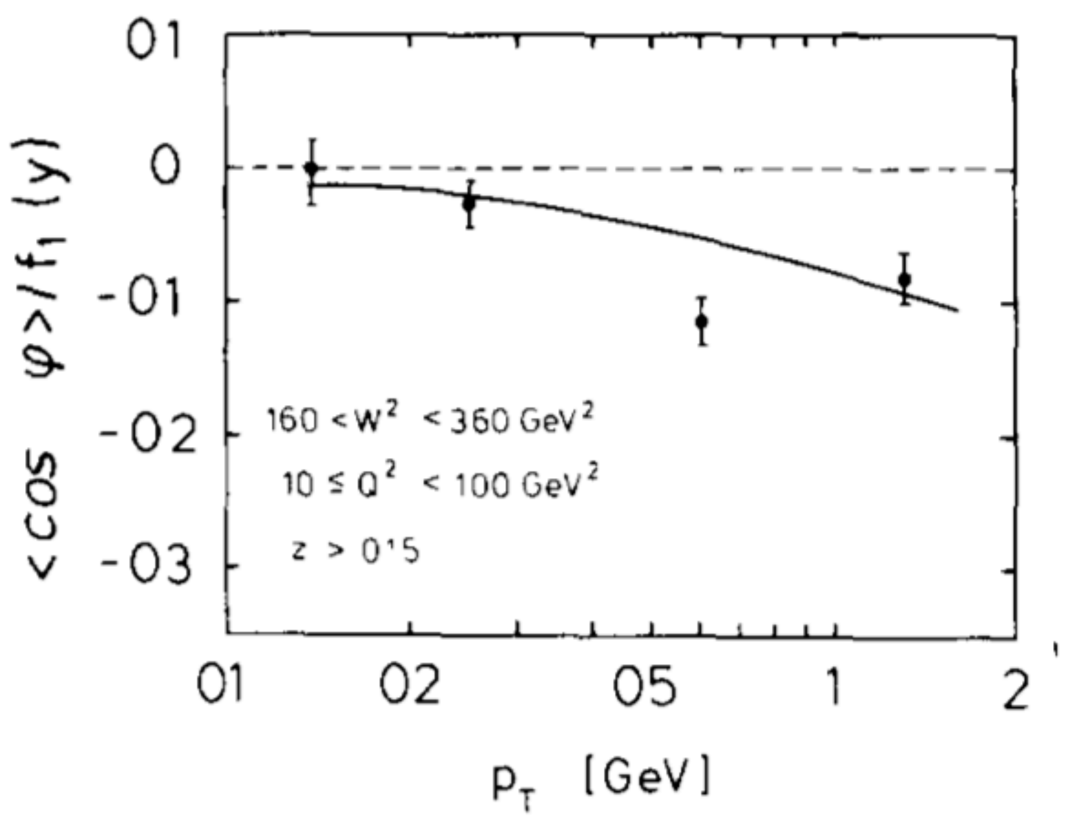
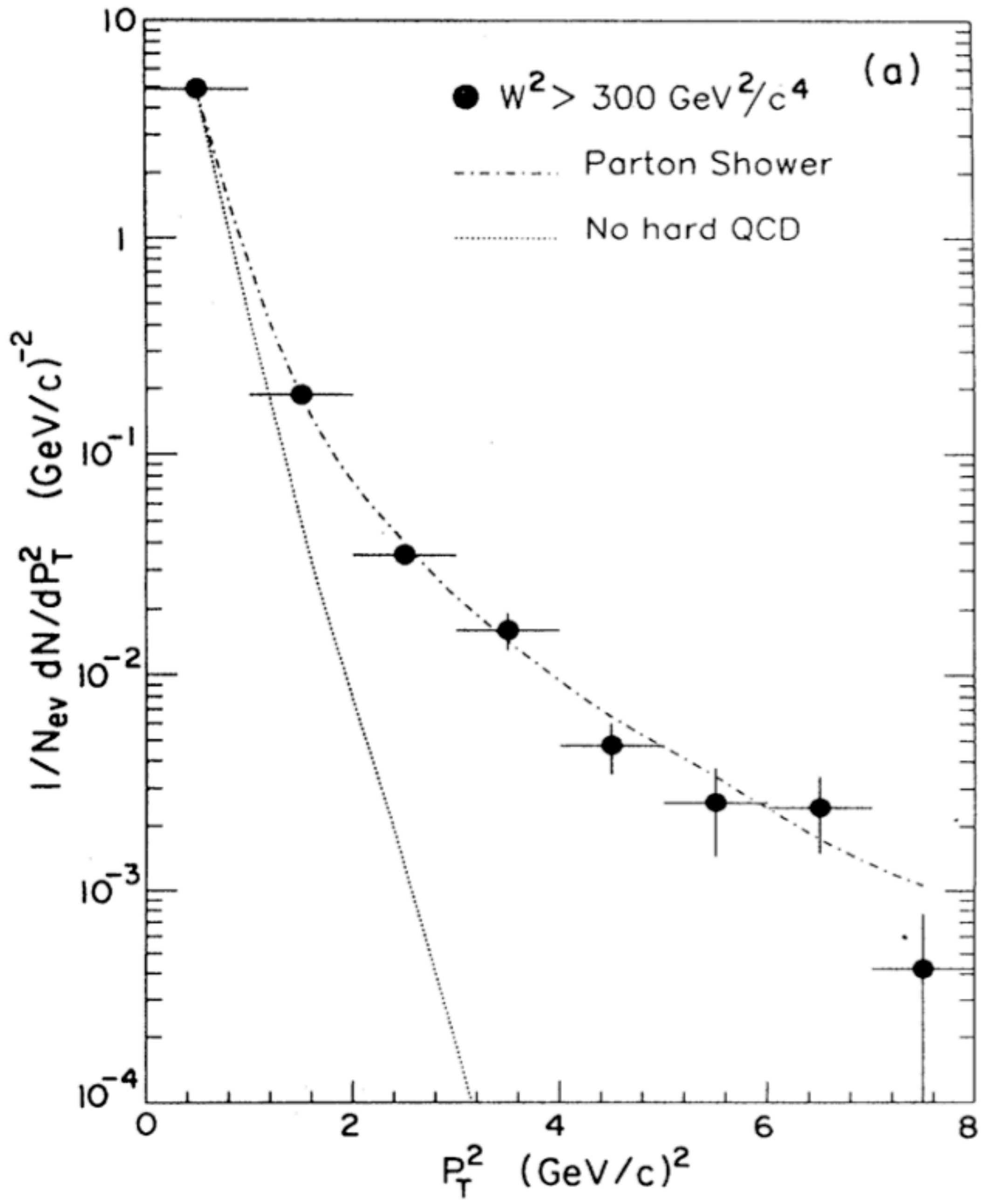


Fig 4 p_T dependence ($p_T > 50$ MeV) of cos φ moment for $160 \leqslant W^2 < 360$ GeV^2, $Q^2 > 10$ GeV^2 and $z > 0.15$ compared with model calculations described in ref [8] (statistical errors on model curve from Monte Carlo ±0 03 not shown)

E665 Phys. Rev. D 48 (1993) 5057



25 May 2000

PHYSICS LETTERS B

Physics Letters B 481 (2000) 199–212

Measurement of azimuthal asymmetries in deep inelastic scattering

ZEUS Collaboration

J. Breitweg, S. Chekanov, M. Derrick, D. Krakauer, S. Magill, B. Musgrave, A. Pellegrino, J. Repond, R. Stanek, R. Yoshida

Argonne National Laboratory, Argonne, IL, USA [1]

A. Deshpande, S. Dhawan, V.W. Hughes

Yale University, Department of Physics, New Haven, CT, USA [1]

S. Bhadra, C. Catterall, J.E. Cole, W.R. Frisken, R. Hall-Wilton, M. Khakzad, S. Menary

York University, Dept. of Physics, Toronto, Ont., Canada [31]

Received 17 March 2000; accepted 31 March 2000
Editor: W.-D. Schlatter

Abstract

The distribution of the azimuthal angle for the charged hadrons has been studied in the hadronic centre-of-mass system for neutral current deep inelastic positron–proton scattering with the ZEUS detector at HERA. Measurements of the dependence of the moments of this distribution on the transverse momenta of the charged hadrons are presented. Asymmetries that can be unambiguously attributed to perturbative QCD processes have been observed for the first time.
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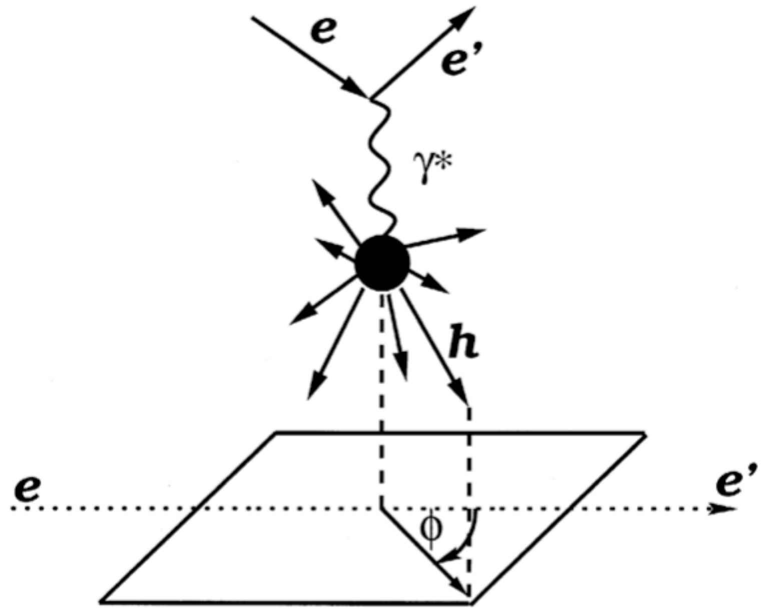


Fig. 1. Definition of the azimuthal angle ϕ. The incoming lepton is denoted by e, the scattered lepton by e', the exchanged boson by γ^* and the outgoing hadrons or partons by h. The dotted line represents the intersection of the $e-e'$ scattering plane with the transverse plane.

DATA

$\Lambda_{qcd} \ll q_T \sim Q$

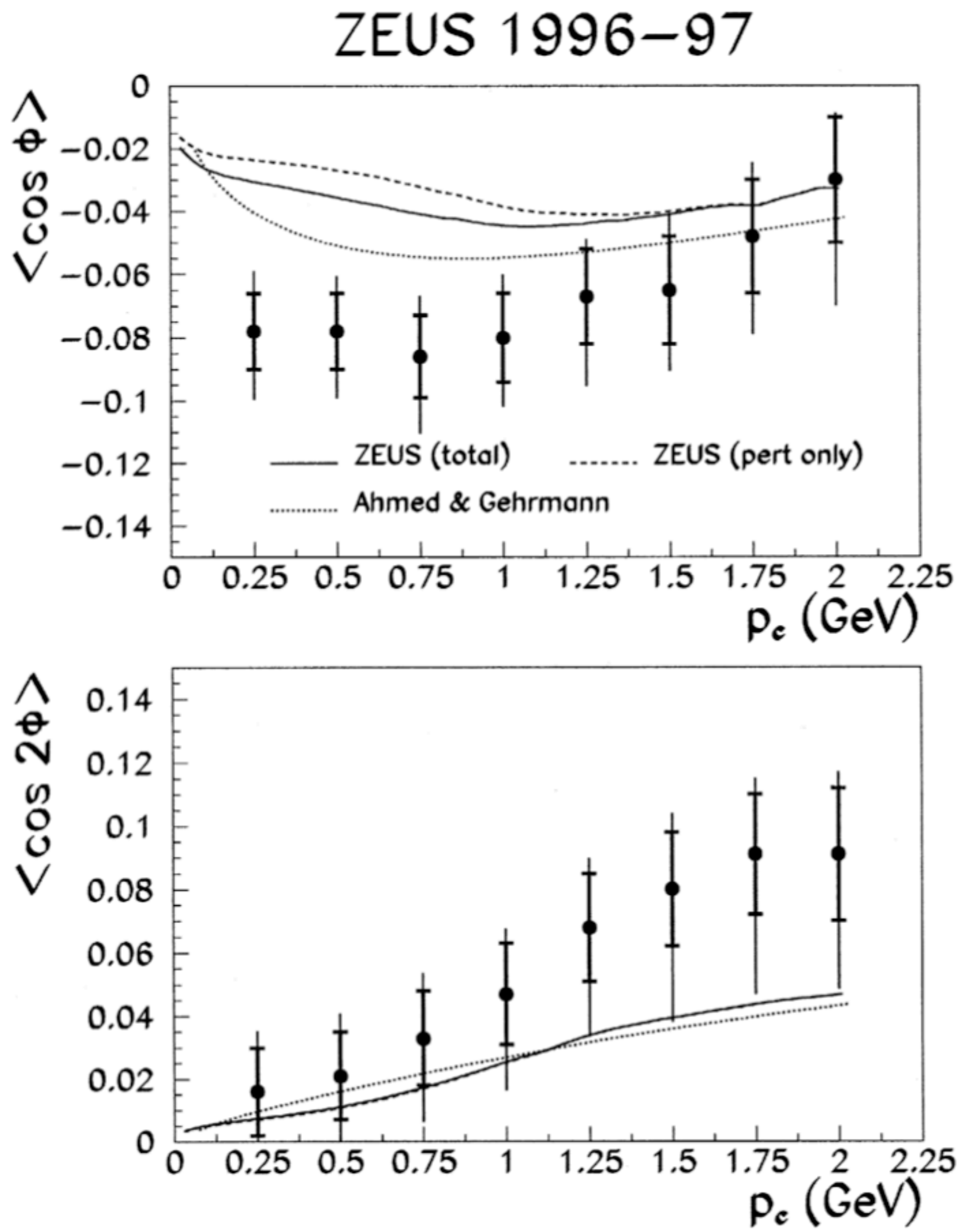
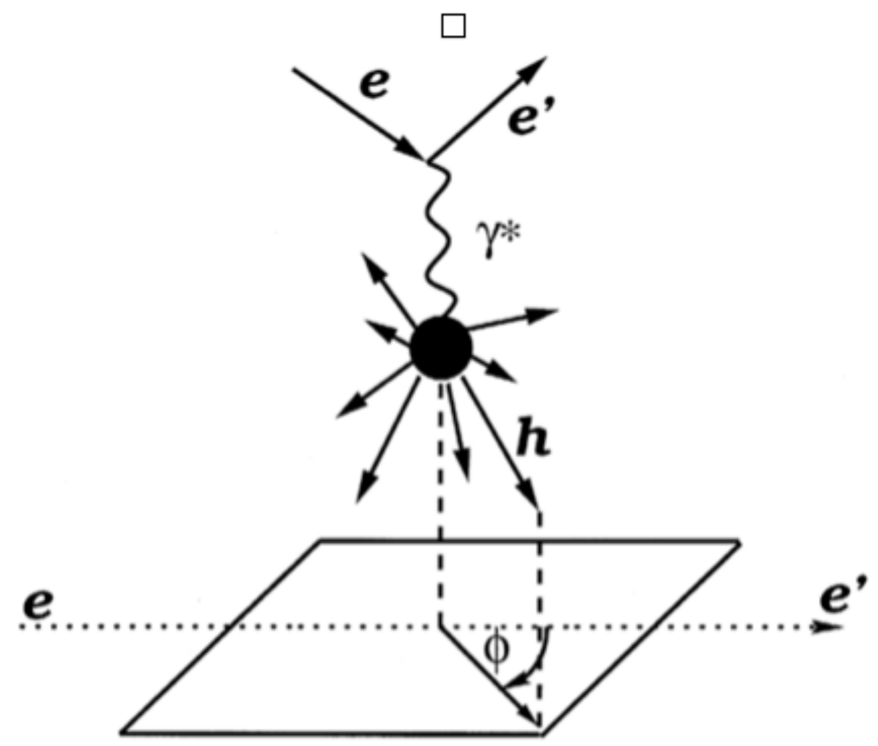


Fig. 4. The values of $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ are shown as a function of p_c in the kinematic region $0.01 < x < 0.1$ and $0.2 < y < 0.8$ for charged hadrons with $0.2 < z_h < 1.0$. The inner error bars represent the statistical errors, the outer are statistical and systematic errors added in quadrature. The lines are the LO predictions from ZEUS with perturbative and non-perturbative contributions (full line), ZEUS with the perturbative contribution only (dashed line) and Ahmed & Gehrmann (dotted line – see text for discussion). For the case of $\langle\cos 2\phi\rangle$, the ZEUS total and perturbative predictions are almost identical.

$$\frac{d\sigma^{ep\to ehX}}{d\phi} = \mathcal{A} + \mathcal{B}\cos\phi + \mathcal{C}\cos 2\phi + \mathcal{D}\sin\phi + \mathcal{E}\sin 2\phi$$

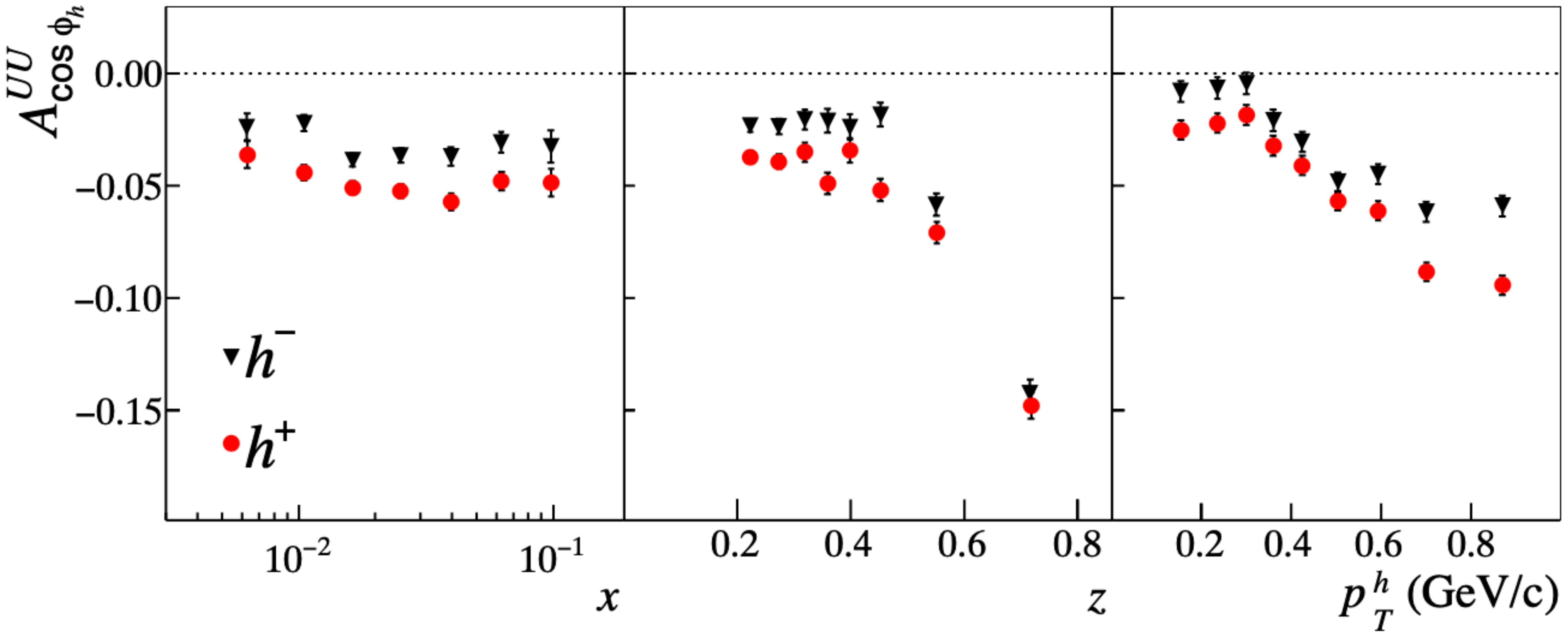


DATA

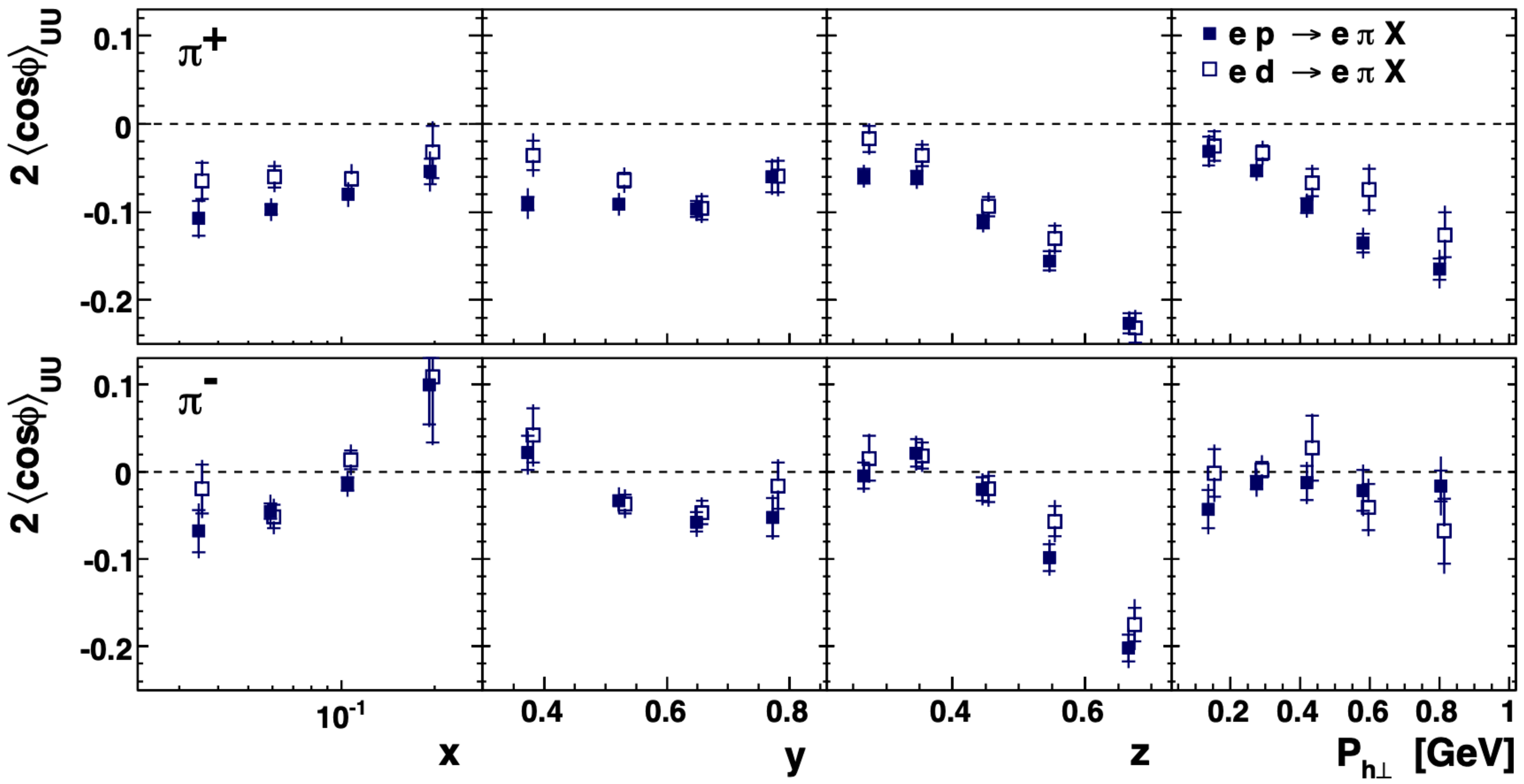
$(p_T \sim k_T) \sim q_T \ll Q$

"TMD region"

COMPASS, Nucl. Phys. B 886 (2014) 1046



HERMES, Phys. Rev. D 87 (2013) 012010



Theory/Pheno studies

$$\langle \cos\phi \rangle = \frac{\int d\sigma^{(0)} \cos\phi + \int d\sigma^{(1)} \cos\phi}{\int d\sigma^{(0)} + \int d\sigma^{(1)}}$$

Chay, S.D. Ellis, Stirling, Phys. Lett. B (1991)

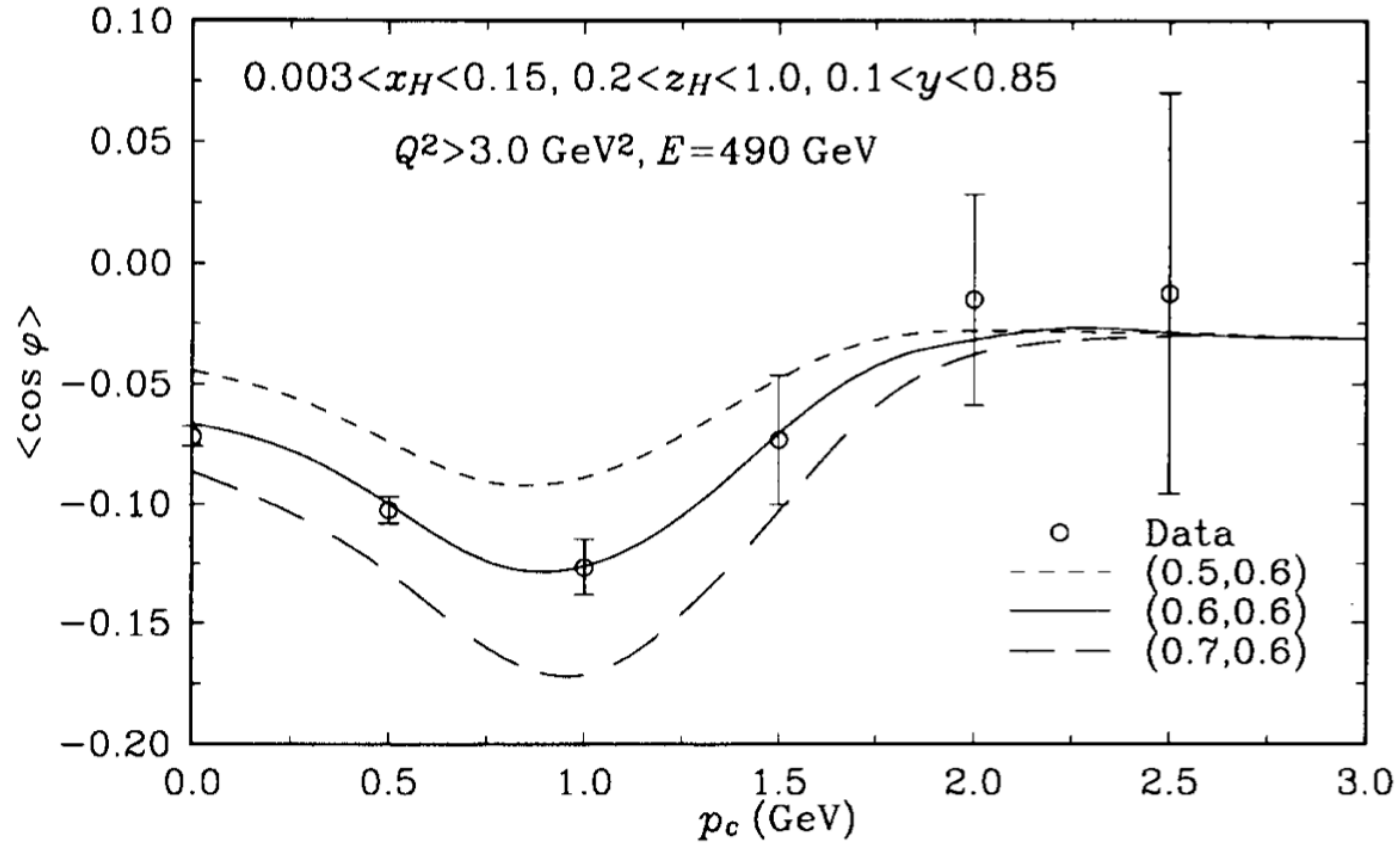
Oganessyan, Avakian, Bianchi, EPJC (1998)

$$\int d\sigma^{(0)} = 2\pi \frac{\alpha^2}{Q^2} \sum_j Q_j^2 F_j(x_H) D_j(z_H) \exp\left(-\frac{p_c^2}{b^2 + z_H^2 a^2}\right)$$
$$\times \left\{ \frac{1+(1-y)^2}{y} + 4\frac{1-y}{yQ^2}\left[\frac{a^2 b^2}{b^2+z_H^2 a^2} + \left(\frac{z_H a^2}{b^2 + z_H^2 a^2}\right)^2 (p_c^2 + b^2 + z_H^2 a^2)\right]\right\}$$

$$\int d\sigma^{(1)} \cos\phi = \int d^2 P_T \cos\phi \frac{d\sigma}{dx_H\, dy\, dz_H\, d^2 P_T}$$
$$= \frac{8}{3}\frac{\alpha_s \alpha^2}{Q^2}\frac{(2-y)\sqrt{1-y}}{y}\int_{x_H}^1 \frac{dx}{x}\int_{z_H}^1 \frac{dz}{z}\sum_j Q_j^2 (A_j + B_j + C_j)$$

$$A_j = -\sqrt{\frac{xz}{(1-x)(1-z)}}\,[xz + (1-x)(1-z)]\, F_j\left(\frac{x_H}{x}, Q^2\right) D_j\left(\frac{z_H}{z}, Q^2\right)$$

Simple addition … "double counting"



$\langle \cos\phi \rangle$ as a function of transverse momentum cutoff

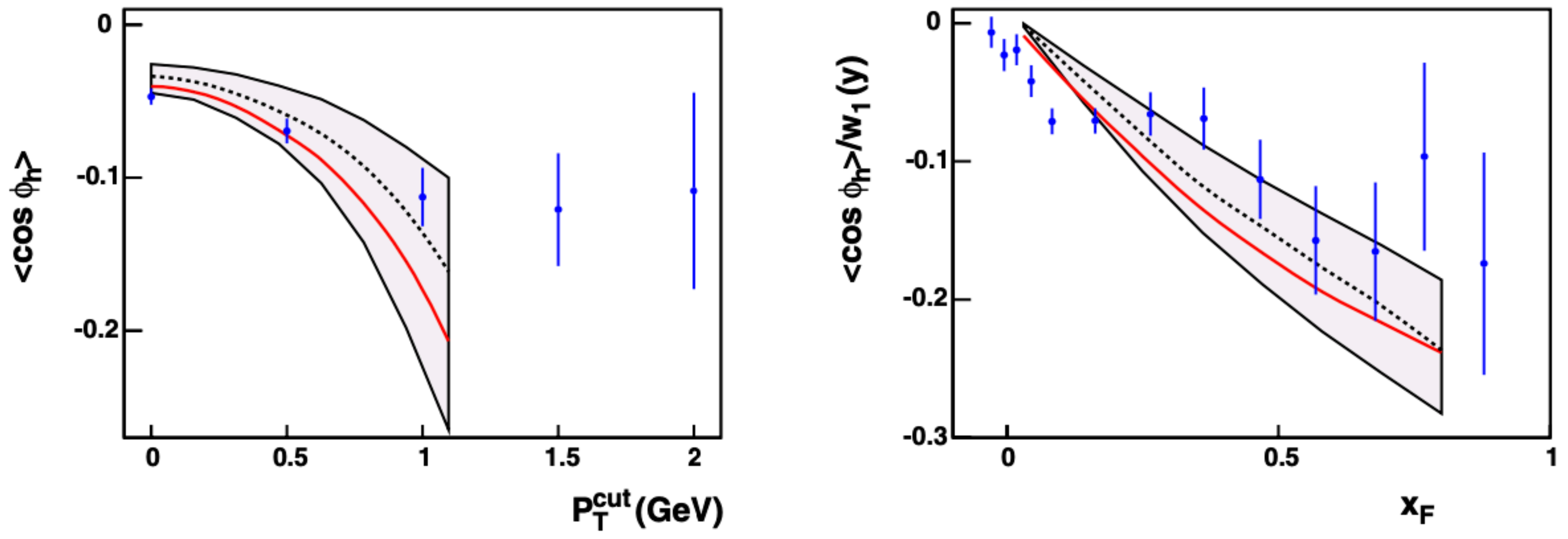
- non-perturbative Cahn-like dominate at low p_c
- negligible at large values p_c because " intrinsic transverse momentum" in distribution &. FF too small to produce effect $P_T > p_c$ (data E665 Fermi-lab).

Theory/Pheno studies

Anselmino, Boglione,D'Alesio,
Kotzinian, Murgia, Prokudin

PRD **71,** 074006 (2005)

One of the "first" TMD analysis
Role of Cahn effect in SIDIS from TMD framework
Modeling tree level result comparing w/ E665 data



$$F_{UU}^{\cos\phi_h} \approx \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\,f_1 D_1\right].$$

Wandzura Wilzeck approx in
TMD Bacchetta et al. JHEP 2007

$$\frac{d^5\sigma^{\ell p\to\ell h X}}{dx_B dQ^2 dz_h d^2\boldsymbol{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4} f_q(x_B) D_q^h(z_h)\left[1+(1-y)^2 - 4\frac{(2-y)\sqrt{1-y}\langle k_\perp^2\rangle z_h P_T}{\langle P_T^2\rangle Q}\cos\phi_h\right]\frac{1}{\pi\langle P_T^2\rangle}e^{-P_T^2/\langle P_T^2\rangle},$$

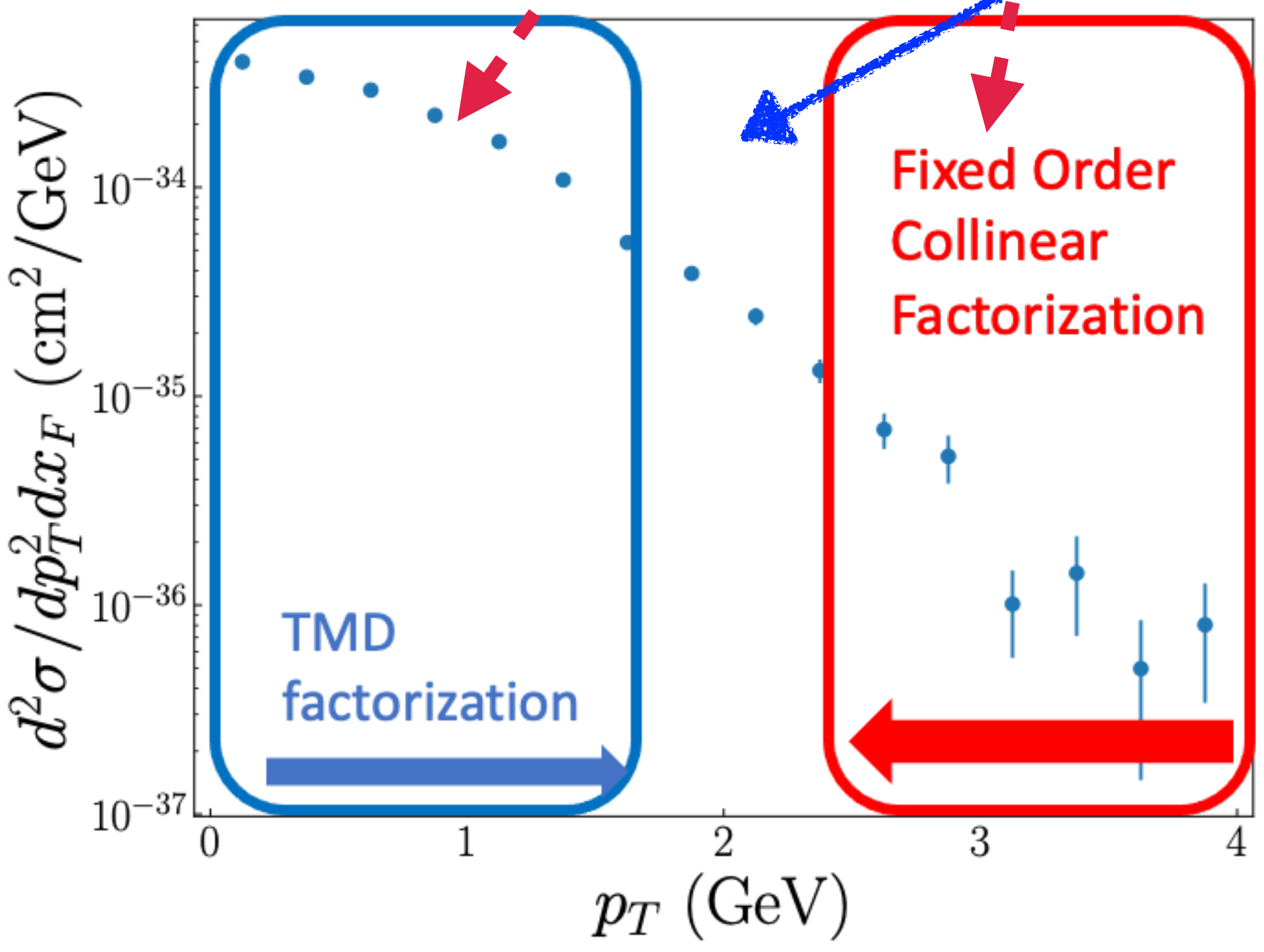
Regions and matching

Requires systematic factorization approach

NPB Collins & Soper(1982), & Sterman 1985, Collins 2011

$$\sigma(p_T) \sim W(p_T) + Y(p_T) \quad (Y = F0 - AY)$$

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

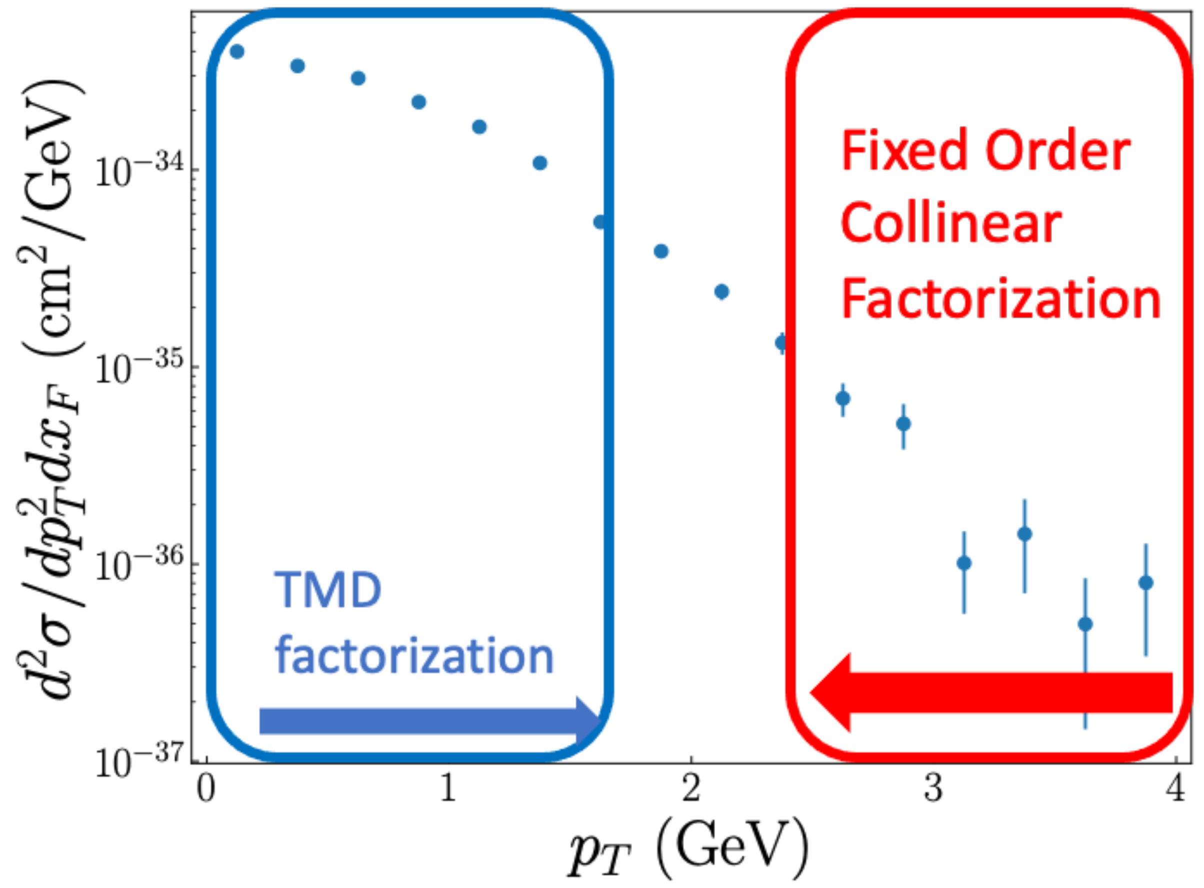


- Goal to use p_T (q_T) data over full range
- **Cross section different "regions"-"two scales"**
- W valid for $\Lambda_{QCD} \sim p_T \ll Q$ TMD factorization
- FO valid for $\Lambda_{QCD} \ll p_T \sim Q$ Collinear factorization

E615 πW Drell-Yan

Phys. Rev. D **39**, 92 (1989).

"Mis"-Matches Factorization @ sub-leading power



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

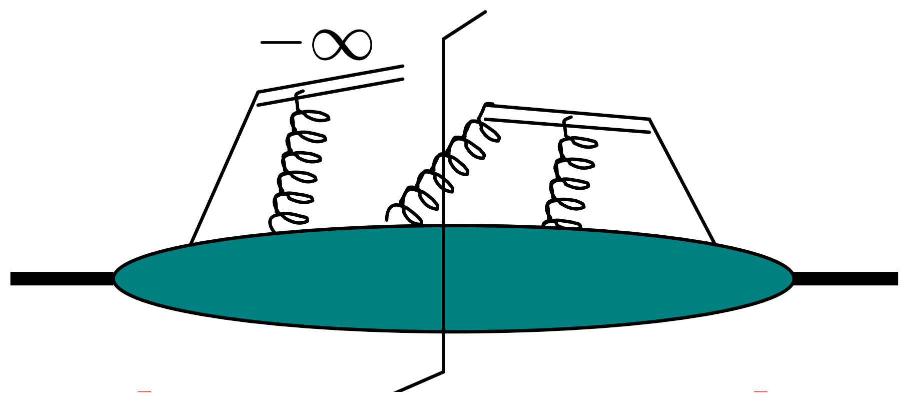
$$\langle \cos\phi \rangle = \frac{\int d\sigma^{(0)} \cos\phi + \int d\sigma^{(1)} \cos\phi}{\int d\sigma^{(0)} + \int d\sigma^{(1)}}$$

- Bacchetta, Boer, Diehl, Mulders JHEP (2008)
  Mis-match/inconsistency breakdown of factorization at NLP?

- Bacchetta Bozzi, Echevarria, Pisano, Prokudin, Radici, PLB (2019)
  "… the requirement to match the high-q_T result (4.25) for $F_{UU}^{\cos\phi_h}$ at intermediate q_T can be used as a consistency check for any framework that extends Collins-Soper factorization to the twist-three sector."

“Mis”-matches Factorization @ sub-leading power

$$\langle \cos\phi \rangle = \frac{\int d\sigma^{(0)} \cos\phi + \int d\sigma^{(1)} \cos\phi}{\int d\sigma^{(0)} + \int d\sigma^{(1)}}$$



To cure mismatch, Bacchetta et al. speculate that soft factor subtraction from LP TMD same Collins 2011 into NLP TMDs: PLB (2019)

$$\tilde{f}^{\rm sub}_{j/H}(x, b_T; \mu, y_n) = \lim_{\substack{y_A \to +\infty \\ y_B \to -\infty}} \underbrace{\tilde{f}^{\rm unsub}_{j/H}(x, b_T; \mu, y_P - y_B)} \sqrt{\frac{\tilde{S}(b_T; y_A, y_n)}{\tilde{S}(b_T; y_A, y_B)\tilde{S}(b_T; y_n, y_B)}} \times UV_{renorm}$$

$$\Updownarrow$$

$$\tilde{f}^{\rm unsub}_{j/H}(x, b_T; \mu, y_P - y_B) = \int \frac{db^-}{2\pi} e^{-ixP^+b^-} \langle P|\bar{\psi}(0)\gamma^+ \mathcal{U}_{[0,b]}\psi(b)|P\rangle\big|_{b^+=0}$$

JCC Soft factor further “repartitioned”

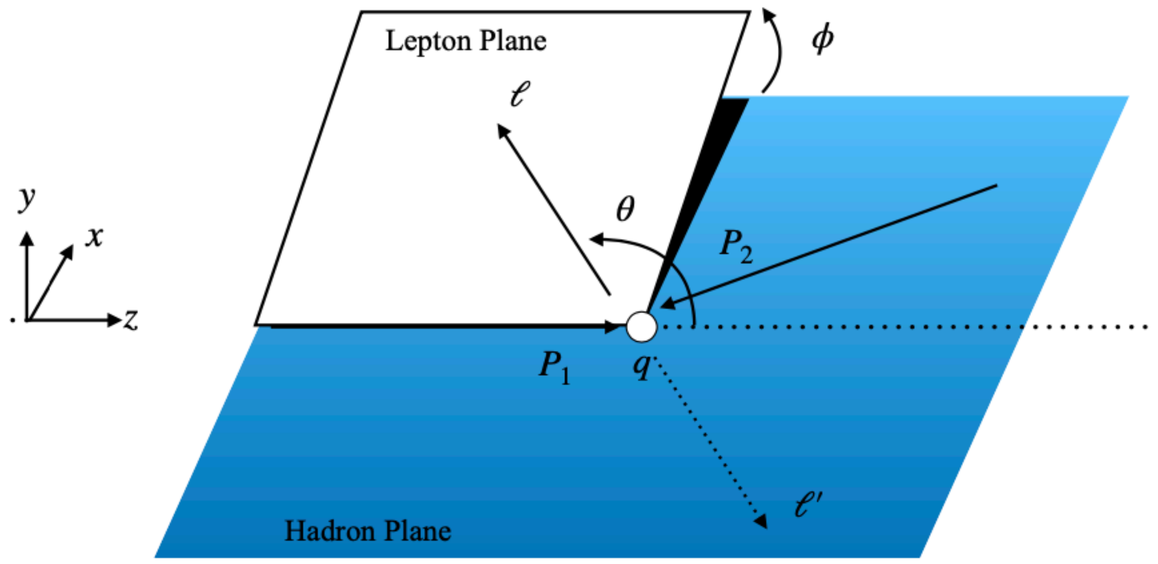
1) cancel LC divergences in “unsubtracted” TMDs
2) separate “right & left” movers i.e. full factorization
3) remove double counting of momentum regions

To understand appreciate the subtleties review
Tree level TMD & LP factorization

In reviewing will remind you about the utility of using "good and bad LC quark fields "

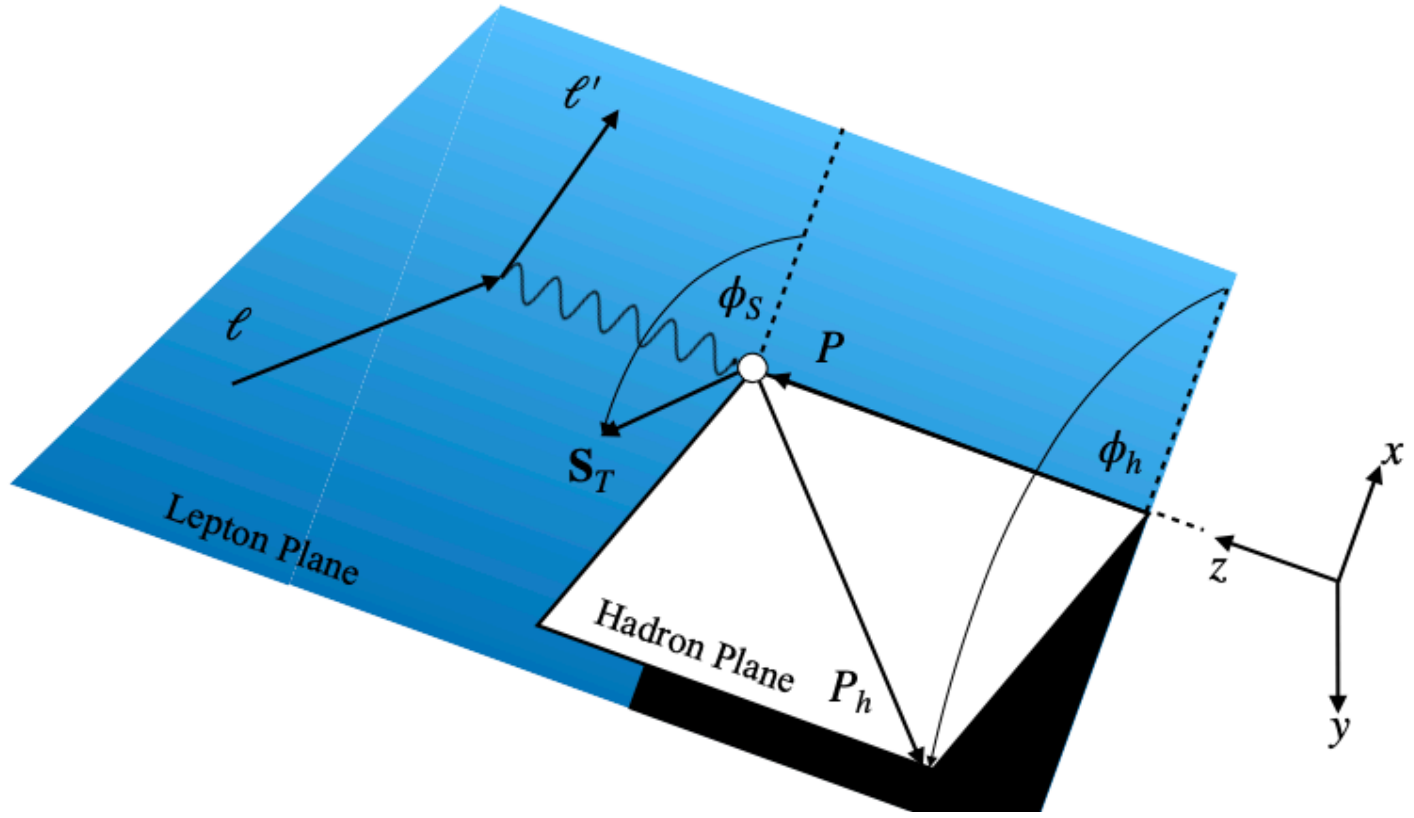
Then onto Factorization at NLO

Factorization at sub-leading power ... revisit Tree level



- "TMD" region $(p_T \sim k_T) \sim q_T \ll Q$

- Then consider factorization beyond LO and LP
  via Ji Ma Yuan 2004,Collins, Aybat & Rogers 2011
- To do this at sub-leading power—revisited tree level build RG consistency
- Develop RG and rapidity renormalization



Processes we consider

- Consider SIDIS cross section in the hadronic Breit frame
- Consider DY cross section in Gottfried Jackson lepton COM

$$\frac{d\sigma}{dx\,dy\,d\Psi\,dz\,d^2P_{h\perp}} = \kappa\frac{\alpha_{\rm em}^2}{4Q^4}\frac{y}{z}L_{\mu\nu}W^{\mu\nu}$$

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, $h_T^{\perp}$

Subleading Quark-Gluon-Quark TMDPDFs

Nucleon Polarization	Quark Chirality: Chiral Even	Quark Chirality: Chiral Odd
U	$\tilde{f}^{\perp}$, $\tilde{g}^{\perp}$	$\tilde{e}$, $\tilde{h}$
L	$\tilde{f}_L^{\perp}$, $\tilde{g}_L^{\perp}$	$\tilde{e}_L$, $\tilde{h}_L$
T	$\tilde{f}_T$, $\tilde{f}_T^{\perp}$, $\tilde{g}_T$, $\tilde{g}_T^{\perp}$	$\tilde{e}_T$, $\tilde{e}_T^{\perp}$, $\tilde{h}_T$, $\tilde{h}_T^{\perp}$

Factorization at sub-leading power … revisit Tree level

- "TMD" region $(p_T \sim k_T) \sim q_T \ll Q$

$$\frac{d\sigma}{dx\, dy\, d\Psi\, dz\, d^2P_{h\perp}} = \kappa \frac{\alpha_{\rm em}^2}{4Q^4} \frac{y}{z} L_{\mu\nu} W^{\mu\nu}$$

$$W_{\mu\nu} = \frac{1}{(2\pi)^4} \sum_X \int d^4x\, e^{-iqx} \langle P | J_\mu^\dagger(0) | h, X\rangle \langle h, X |\, J_\nu(x) | P\rangle ,$$

$$J_\mu(x) = J_\mu^{(2)}(x) + J_\mu^{(3)}(x)$$

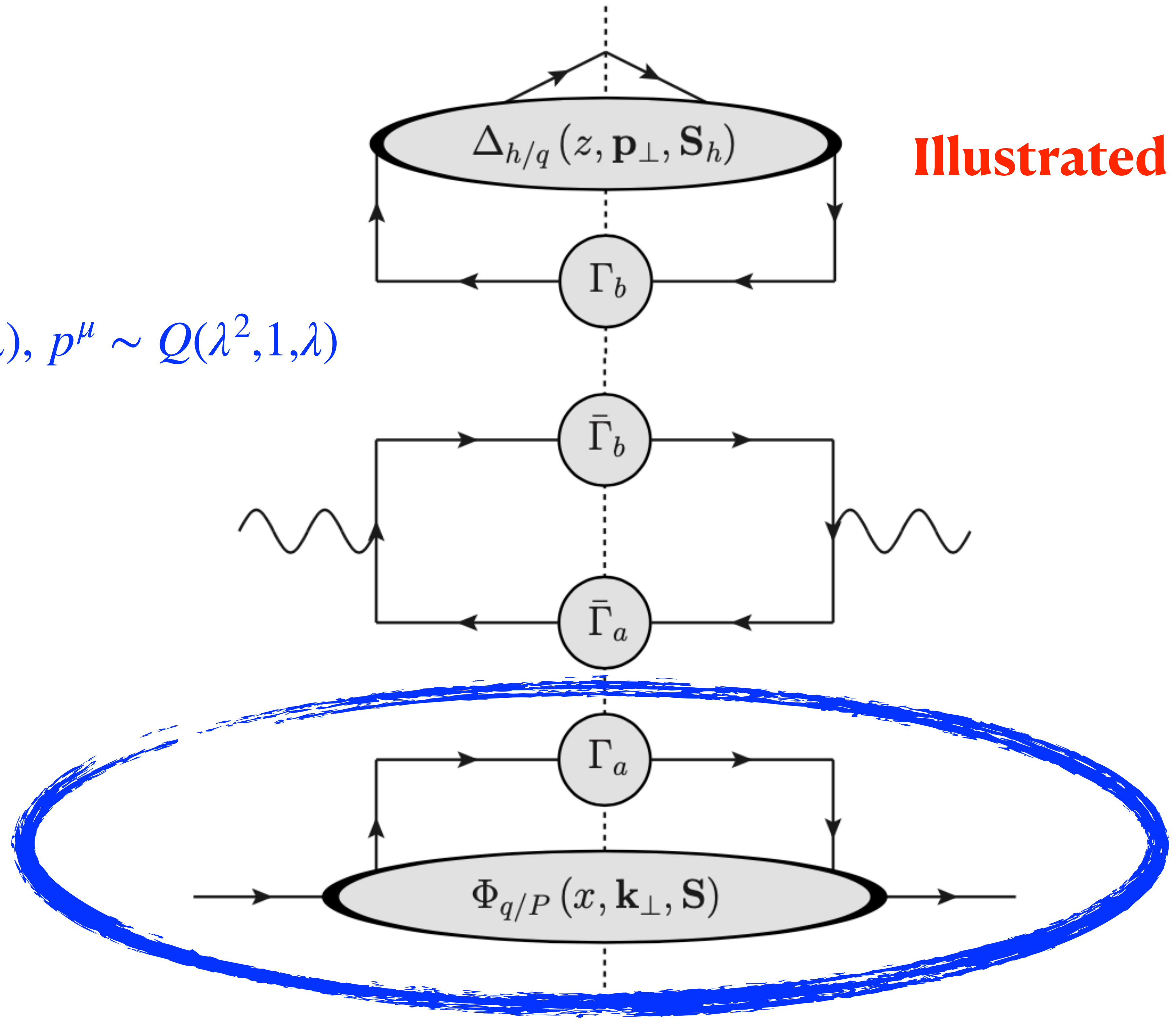
$k^\mu \sim Q(1,\lambda^2,\lambda),\ p^\mu \sim Q(\lambda^2,1,\lambda)$

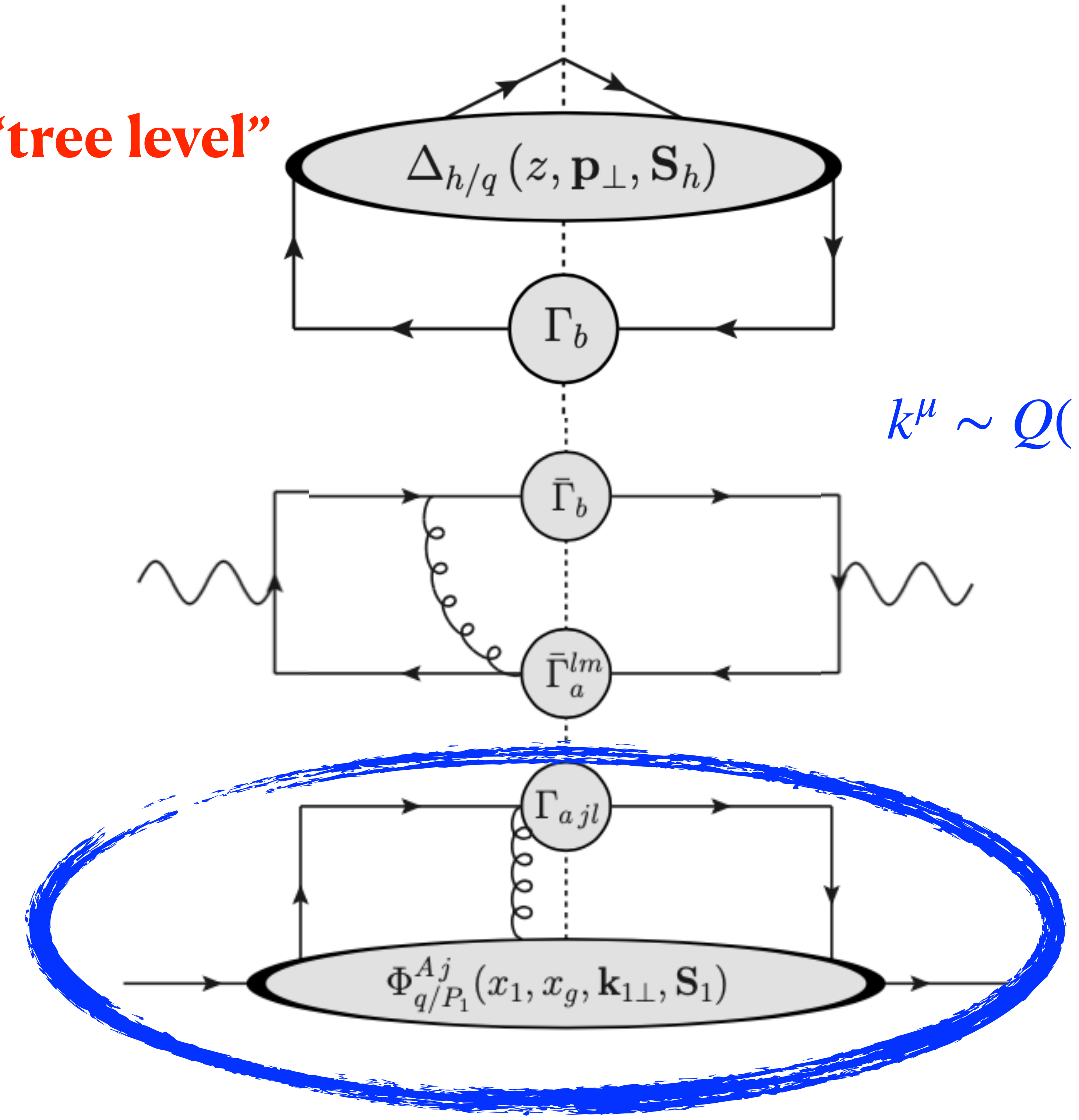
Working @ NLP, the current contains 3(!) contributions:

- One with 2 partons entering from each correlation function
- Another with 3 partons entering from one correlation function
- **& partonic kinematic power corrections-momentum scaling**

Illustrated at "tree level"

$k^\mu \sim Q(1,\lambda^2,\lambda),\ p^\mu \sim Q(\lambda^2,1,\lambda)$





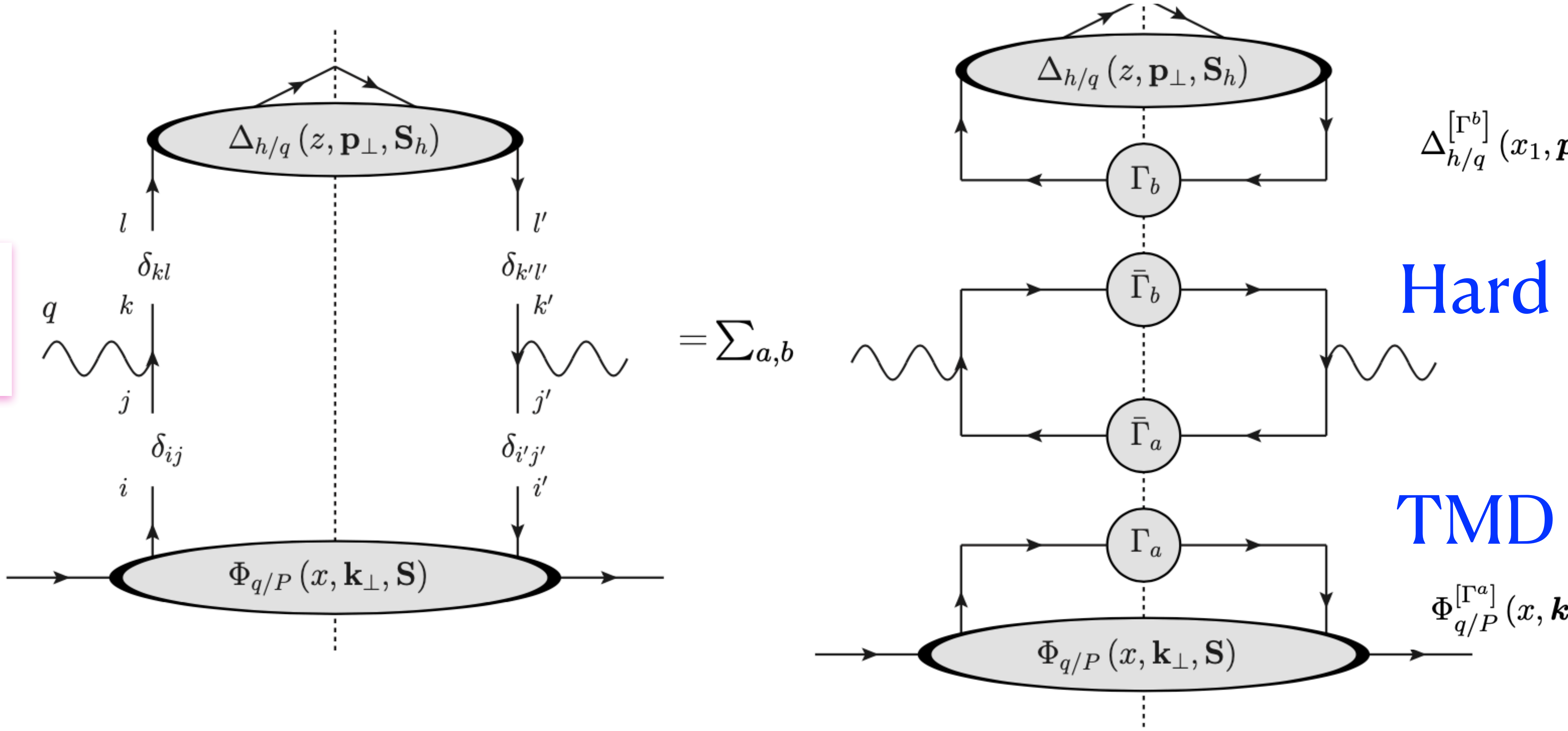
$k^\mu \sim Q(1,\lambda^2,\lambda),\ p^\mu \sim Q(\lambda^2,1,\lambda)$

Factorization at sub-leading power Tree level employ Fierz decomposition

2 parton hadronic tensor can be organized contributions @ given twist by Fierz decomposition of the quark lines

Fierz decomposition of 2 parton correlation function $\delta_{ij}\delta_{j'i'} = \sum_a \Gamma^a_{ii'}\,\bar{\Gamma}^a_{j'j}$ Illustrated in Fig.

$$\delta_{ij}\delta_{j'i'} = \sum_a \Gamma^a_{ii'}\,\bar{\Gamma}^a_{j'j}$$



$$\Delta^{[\Gamma^b]}_{h/q}(x_1, \boldsymbol{p}_\perp, \boldsymbol{S}_h) = \mathrm{Tr}\left[\Delta_{h/q}(z, \boldsymbol{p}_\perp, \boldsymbol{S}_h)\,\Gamma^b\right]$$

$$\Phi^{[\Gamma^a]}_{q/P}(x, \boldsymbol{k}_\perp, \boldsymbol{S}) = \mathrm{Tr}\left[\Phi_{q/P}(x, \boldsymbol{k}_\perp, \boldsymbol{S})\,\Gamma^a\right]$$

$$\Gamma_a \in \left\{ \underbrace{\frac{\not{n}}{4}, \frac{\not{n}\gamma^5}{4}, \frac{i}{4}\sigma^{i+}\gamma^5}_{\text{LP}}, \underbrace{\frac{1}{2}, \frac{\gamma^5}{2}, \frac{\gamma^i}{2}, \frac{\gamma^i\gamma^5}{2}, \frac{i}{2}\sigma^{ij}\gamma^5, \frac{i}{4}\sigma^{+-}\gamma^5}_{\text{NLP}} + \ldots.. \right\}$$

Factorized !!

$$W^{(2)}_{\mu\nu} = \frac{1}{N_c}\sum_{a,b}\mathrm{Tr}\left[\gamma^\mu\,\bar{\Gamma}^a\,\gamma^\nu\,\bar{\Gamma}^b\right]\mathcal{C}^{\mathrm{DIS}}\left[\Phi^{[\Gamma^a]}(x, \boldsymbol{k}_\perp, \boldsymbol{S})\;\Delta^{[\Gamma^b]}(z, \boldsymbol{p}_\perp, \boldsymbol{S}_h)\right]$$

$$\mathcal{C}^{\mathrm{DIS}}[A\,B] = \sum_q e_q^2 \int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{p}_\perp\, \delta^{(2)}(\boldsymbol{q}_\perp + \boldsymbol{k}_\perp + \boldsymbol{p}_\perp/z \times A_{q/P}(x, \boldsymbol{k}_\perp, \boldsymbol{S})\, B_{h/q}(z, \boldsymbol{p}_\perp, \boldsymbol{S}_h)$$

Next step Factorization express in terms of good and bad LC fields @ tree level

- In the formulation of the cross section/hadronic tensor in terms of the correlation function, traces of the quark correlation functions with the Γ^a operators entered, $\Phi^{\Gamma^a}(x_1, \boldsymbol{k}_T, \boldsymbol{S}) \equiv \mathrm{Tr}\left[\Phi(x_1, \boldsymbol{k}_T, \boldsymbol{S})\,\Gamma^a\right]$

  where $\Phi_{q/P_1\,jj'}(x, \boldsymbol{k}_\perp, \boldsymbol{S}) = \int \frac{d^4\xi}{(2\pi)^3} e^{ik\cdot\xi}\,\delta(\xi^+)\left\langle P, \boldsymbol{S}\left|\bar{\psi}^c_{j'}(0)\,\mathcal{U}^{\bar{n}}_{\llcorner}(0)\,\mathcal{U}^{\bar{n}\,\dagger}_{\llcorner}(\xi)\,\psi^c_j(\xi)\right|P, \boldsymbol{S}\right\rangle$

- To separate the contributions of hadronic tensor at LP & SLP, employ light-cone projections of the Dirac fields, "good" and "bad (power surpressed)" $\lambda = q_\perp/Q$ light-cone components

$$\psi^c = \chi^c + \phi^c$$

$$\chi^c(x) = \frac{\not{\bar{n}}\not{n}}{4}\psi^c(x)\,, \qquad \varphi^c(x) = \frac{\not{n}\not{\bar{n}}}{4}\psi^c(x)$$

- Upon expressing ψ^c in terms of ϕ^c and χ^c in the correlation function, four field configurations enter into the position space matrix elements,

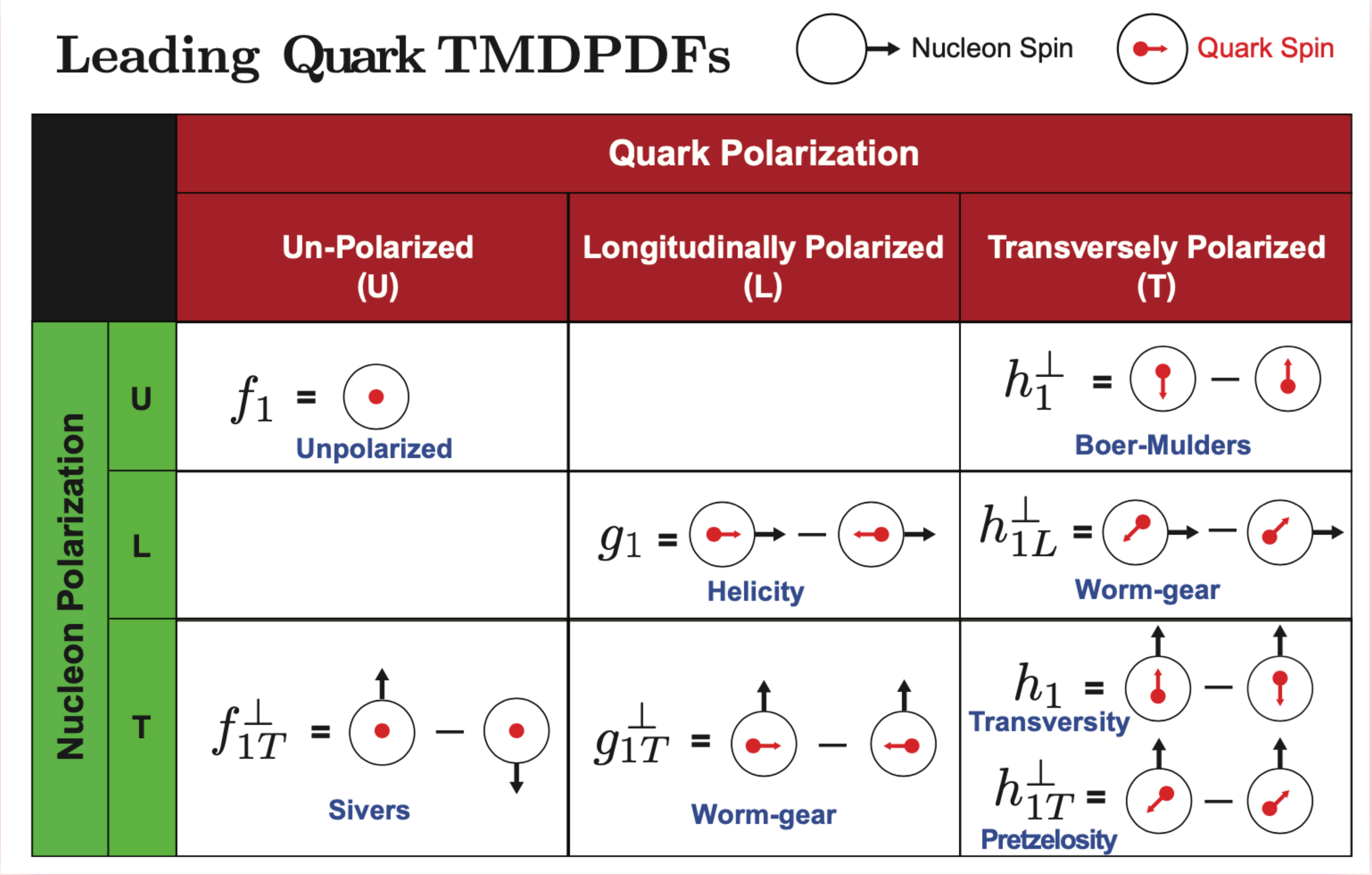
2 good twist 2 — 1 good 1 bad twist 3 — 2 bad twist 4

$$\langle P, \boldsymbol{S}|\bar{\chi}^c_{j'}\,\chi^c_j|P, \boldsymbol{S}\rangle,\ \langle P, \boldsymbol{S}|\bar{\varphi}^c_{j'}\,\chi^c_j|P, \boldsymbol{S}\rangle,\ \langle P, \boldsymbol{S}|\bar{\chi}^c_{j'}\,\varphi^c_j|P, \boldsymbol{S}\rangle,\ \text{and}\ \langle P, \boldsymbol{S}|\bar{\varphi}^c_{j'}\,\varphi^c_j|P, \boldsymbol{S}\rangle$$

By organizing the operators by their twists,
we arrive at the well known expression for the LP and NLP correlation functions

$$\Phi(x, k_T)$$

$$\Phi^{(2)}_{q/P}(x, \boldsymbol{k}_\perp, \boldsymbol{S}) = \left(f_1 - \frac{\epsilon^{ij}_\perp k_{\perp i} S_{\perp j}}{M} f^\perp_{1T}\right)\frac{\not{\bar{n}}}{4} + \left(\lambda g_{1L} - \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp}{M} g_{1T}\right)\frac{\gamma^5 \not{\bar{n}}}{4}$$
$$+ \left(S^i_\perp h_1 + \frac{\lambda k^i_\perp}{M} h^\perp_{1L} - \frac{\epsilon^{ij}_\perp k_{\perp j}}{M} h^\perp_1 - \frac{k^i_\perp k^j_\perp - \frac{1}{2} k^2_\perp g^{ij}_\perp}{M^2} S_{\perp j} h^\perp_{1T}\right)\frac{i\gamma^5 \sigma_{-i}}{4}$$



Twist 2	Twist 3	Twist 4
$\frac{1}{2}\not{n}$, $\frac{1}{4}\not{\bar{n}}$	$\frac{1}{2}, \frac{1}{2}$	$\frac{1}{2}\not{\bar{n}}$, $\frac{1}{4}\not{n}$
$\frac{1}{2}\not{n}\gamma^5$, $\frac{1}{4}\gamma^5\not{\bar{n}}$	$\frac{1}{2}\gamma^5$, $\frac{1}{2}\gamma^5$	$\frac{1}{2}\not{\bar{n}}\gamma^5$, $\frac{1}{4}\gamma^5\not{n}$
$\frac{i}{2}\sigma^{k+}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{-k}$	$\frac{1}{2}\gamma^k$, $\frac{1}{2}\gamma_k$	$\frac{i}{2}\sigma^{k-}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{+k}$
	$\frac{1}{2}\gamma^k\gamma^5$, $\frac{1}{2}\gamma^5\gamma_k$	
	$\frac{i}{2}\sigma^{kl}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{lk}$	
	$\frac{i}{4}\sigma^{+-}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{+-}$	

✦Mulders Tangerman NPB1995
✦Goeke Metz Schlegel PLB 2005
✦Bacchetta et al 2007 JHEP

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we arrive at the well known expression for the LP and NLP correlation functions

$$\Phi(x, \boldsymbol{k}_T)$$

Subleading Quark TMDPDFs

		Quark Chirality	
		Chiral Even	Chiral Odd
Nucleon Polarization	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, $h_T^\perp$

Twist 2	Twist 3	Twist 4
$\frac{1}{2}\not{n}$, $\frac{1}{4}\not{\bar{n}}$	$\frac{1}{2}, \frac{1}{2}$	$\frac{1}{2}\not{\bar{n}}$, $\frac{1}{4}\not{n}$
$\frac{1}{2}\not{n}\gamma^5$, $\frac{1}{4}\gamma^5\not{\bar{n}}$	$\frac{1}{2}\gamma^5$, $\frac{1}{2}\gamma^5$	$\frac{1}{2}\not{\bar{n}}\gamma^5$, $\frac{1}{4}\gamma^5\not{n}$
$\frac{i}{2}\sigma^{k+}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{-k}$	$\frac{1}{2}\gamma^k$, $\frac{1}{2}\gamma_k$	$\frac{i}{2}\sigma^{k-}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{+k}$
	$\frac{1}{2}\gamma^k\gamma^5$, $\frac{1}{2}\gamma^5\gamma_k$	
	$\frac{i}{2}\sigma^{kl}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{lk}$	
	$\frac{i}{2}\sigma^{+-}\gamma^5$, $\frac{i}{4}\gamma^5\sigma_{+-}$	

✦Mulders Tangerman NPB1995
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$$\begin{aligned}\Phi^{(3)}_{q/P}\left(x, \boldsymbol{k}_\perp, \boldsymbol{S}\right) = \frac{M}{P^+}\Bigg[& \left(e - \frac{\epsilon_\perp^{ij} k_{\perp i} S_{\perp j}}{M} e_T^\perp\right)\frac{1}{2} - i\left(\lambda_g e_L - \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp}{M} e_T\right)\frac{\gamma^5}{2} \\ & + \left(\frac{k_\perp^i}{M} f^\perp - \epsilon_\perp^{ij} S_{\perp j} f_T' - \frac{\epsilon_\perp^{ij} k_{\perp j}}{M}\left(\lambda_g f_L^\perp - \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp}{M} f_T^\perp\right)\right)\frac{\gamma_i}{2} \\ & + \left(g_T' S_\perp^i - \frac{\epsilon_\perp^{ij} k_{\perp j}}{M} g^\perp + \frac{k_\perp^i}{M}\left(\lambda_g g_L^\perp - \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp}{M} g_T^\perp\right)\right)\frac{\gamma^5 \gamma_i}{2} \\ & + \left(\frac{S_\perp^i k_\perp^j}{M} h_T^\perp\right)\frac{i\gamma^5 \sigma_{ji}}{4} + \left(h + \lambda_g h_L - \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp}{M} h^\perp\right)\frac{i\gamma^5 \sigma_{+-}}{4}\Bigg]\end{aligned}$$

Factorization at sub-leading power … 3 partons

- "TMD" region

$$W_{\mu\nu} = \frac{1}{(2\pi)^4} \sum_X \int d^4x\, e^{-iqx} \langle P | J_\mu^\dagger(0) | h, X \rangle \langle h, X | J_\nu(x) | P \rangle \,,$$

$$J_\mu(x) = J_\mu^{(2)}(x) + J_\mu^{(3)}(x)$$

Consider 3 partons entering from one hadron: transverse gluon leads to power suppression of order λ

$$W_{\mu\nu}^{(3)} = \frac{1}{(2\pi)^4} \int d^4x\, e^{-iqx} \left\langle P_1\,, P_2 \left| \left(J_\mu^{(3)}(0)\, J_\nu^{(2)\,\dagger}(x) + J_\mu^{(2)}(0)\, J_\nu^{(3)\,\dagger}(x) \right) \right| P_1\,, P_2 \right\rangle$$

$$W_{\mu\nu}^{(3)} = -\frac{1}{N_c C_F} \sum_q e_q^2 \int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{p}_\perp\, \delta^{(2)}\left(\boldsymbol{q}_\perp + \boldsymbol{k}_\perp + \boldsymbol{p}_\perp/z\right)$$

$$\times \left[\int dk_g^+ \,\mathrm{Tr}\left[\Phi^i_{A\,q/P_1}(x, x_g, \boldsymbol{k}_\perp, \boldsymbol{S}) \gamma^\mu \Delta_{h/q}(z, \boldsymbol{p}_\perp, \boldsymbol{S}_h) \gamma_i \frac{\not{p} - \not{k}_g}{(p-k_g)^2 + i\epsilon} \gamma^\nu \right] \right.$$

$$\left. + \int dp_g^- \,\mathrm{Tr}\left[\Delta^i_{A\,h/q}(z, z_g, \boldsymbol{p}_\perp, \boldsymbol{S}_h) \gamma^\nu \frac{\not{k} - \not{p}_g}{(k-p_g)^2 + i\epsilon} \gamma_i \Phi_{q/P}(x, \boldsymbol{k}_\perp, \boldsymbol{S}) \gamma^\mu \right] + \text{h.c.} \right]$$

Similar Fierzing algorithm
Get *factorized* Hadronic tensor

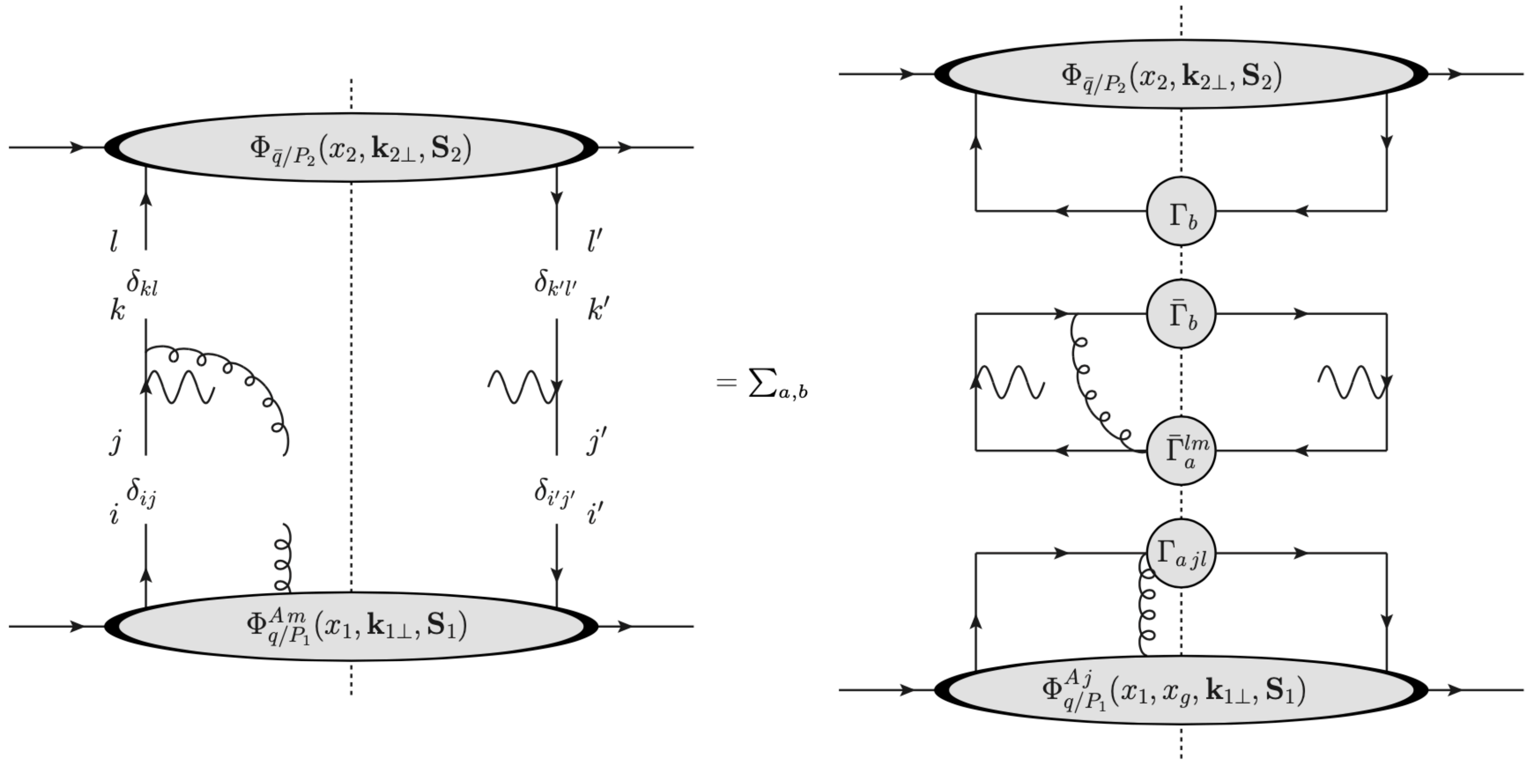


FIG. 4. Fierz decomposition of the dynamic sub-leading contribution to the cross section. In this graph, m represents a transverse Lorentz index.

DY/SIDIS tree-level diagrams relevant for sub-leading-power observables diagrams "*dynamical*" qgq contributions

$$\Phi^i_A(x, x_g, \boldsymbol{k}_\perp, \boldsymbol{S}) = \frac{1}{x_g P^+} \Phi^i_F(x, x_g, \boldsymbol{k}_\perp, \boldsymbol{S})$$

Tree level factorization sub-leading power "dynamical"

$$\Phi^i_A(x, x_g, \boldsymbol{k}_T, S)$$

SIDIS tree-level diagrams relevant for sub-leading-power observables.
diagrams "*dynamical*" contributions with

Subleading Quark-Gluon-Quark TMDPDFs

Nucleon Polarization		Quark Chirality: Chiral Even	Quark Chirality: Chiral Odd
	U	$\tilde{f}^{\perp}, \tilde{g}^{\perp}$	$\tilde{e}\,,\ \tilde{h}$
	L	$\tilde{f}_L^{\perp}, \tilde{g}_L^{\perp}$	$\tilde{e}_L, \tilde{h}_L$
	T	$\tilde{f}_T, \tilde{f}_T^{\perp}, \tilde{g}_T, \tilde{g}_T^{\perp}$	$\tilde{e}_T, \tilde{e}_T^{\perp}, \tilde{h}_T, \tilde{h}_T^{\perp}$

Generalization of
- ✦Mulders Tangerman NPB1995
- ✦ Boer Pijlman Mulders NPB 2003
- ✦Bacchetta et al 2007 JHEP

$$\begin{aligned} x_g P^+\, \Phi^i_A\left(x, x_g, \boldsymbol{k}_\perp, \boldsymbol{S}\right) = \\ \frac{xM}{2}\Bigg\{\Bigg[\left(\tilde{f}^\perp - i\tilde{g}^\perp\right)\frac{k^i_\perp}{M} - \left(\tilde{f}'_T + i\tilde{g}'_T\right)\epsilon_{\perp\, jl} S^l_\perp \\ - \left(\lambda \tilde{f}^\perp_L - \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_\perp}{M}\tilde{f}^\perp_T\right)\frac{\epsilon_{\perp\, jl}k^l_\perp}{M} - i\left(\lambda\tilde{g}^\perp_L - \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_\perp}{M}\tilde{g}^\perp_T\right)\frac{\epsilon_{\perp\, jl}k^l_\perp}{M}\Bigg]\left(g^{ij}_\perp - i\epsilon^{ij}_\perp\gamma_5\right) \\ - \left[\left(\lambda\tilde{h}^\perp_L - \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_\perp}{M}\tilde{h}^\perp_T\right) + i\left(\lambda\tilde{e}^\perp_L - \frac{\boldsymbol{k}_\perp\cdot\boldsymbol{S}_\perp}{M}\tilde{e}^\perp_T\right)\right]\gamma^i_\perp\gamma_5 \end{aligned}$$

EOMs and kinematic Suppressed Distributions

- Employ the QCD equations of motion to demonstrate the appearance of the "kinematic sub-leading distributions"

$$\frac{i\not{D}_\perp(\xi)}{in\cdot D(\xi)}\frac{\not{n}}{2}\chi^c(\xi) = \varphi^c(\xi)$$

$$\Phi^{\mathrm{int}\,[\Gamma^a]}_{q/P}(x,\boldsymbol{k}_\perp,\boldsymbol{S}) = \int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left[\langle P,\boldsymbol{S}\,|\bar{\chi}^c(0)\,\mathcal{U}^{\bar{n}}_{\mathsf{L}}(0)\,\Gamma^a\,\mathcal{U}^{\bar{n}\,\dagger}_{\mathsf{L}}(\xi)\,\varphi^c(\xi)|\,P,\boldsymbol{S}\rangle + \langle P,\boldsymbol{S}\,|\bar{\varphi}^c(0)\,\mathcal{U}^{\bar{n}}_{\mathsf{L}}(0)\,\Gamma^a\,\mathcal{U}^{\bar{n}\,\dagger}_{\mathsf{L}}(\xi)\,\chi^c(\xi)|\,P,\boldsymbol{S}\rangle\right]$$

$$\Phi^{\mathrm{int}\,[\Gamma^a]}_{q/P\,\mathrm{A}}(x,\boldsymbol{k}_\perp,\boldsymbol{S}) = \frac{1}{k^+}\int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left\langle P,\boldsymbol{S}\left|\bar{\chi}^c(0)\,\mathcal{U}^{\bar{n}}_{\mathsf{L}}(0)\,\Gamma^a\,\mathcal{U}^{\bar{n}\,\dagger}_{\mathsf{L}}(\xi)\,i\not{D}_\perp(\xi)\frac{\not{n}}{2}\chi^c(\xi)\right|P,\boldsymbol{S}\right\rangle$$

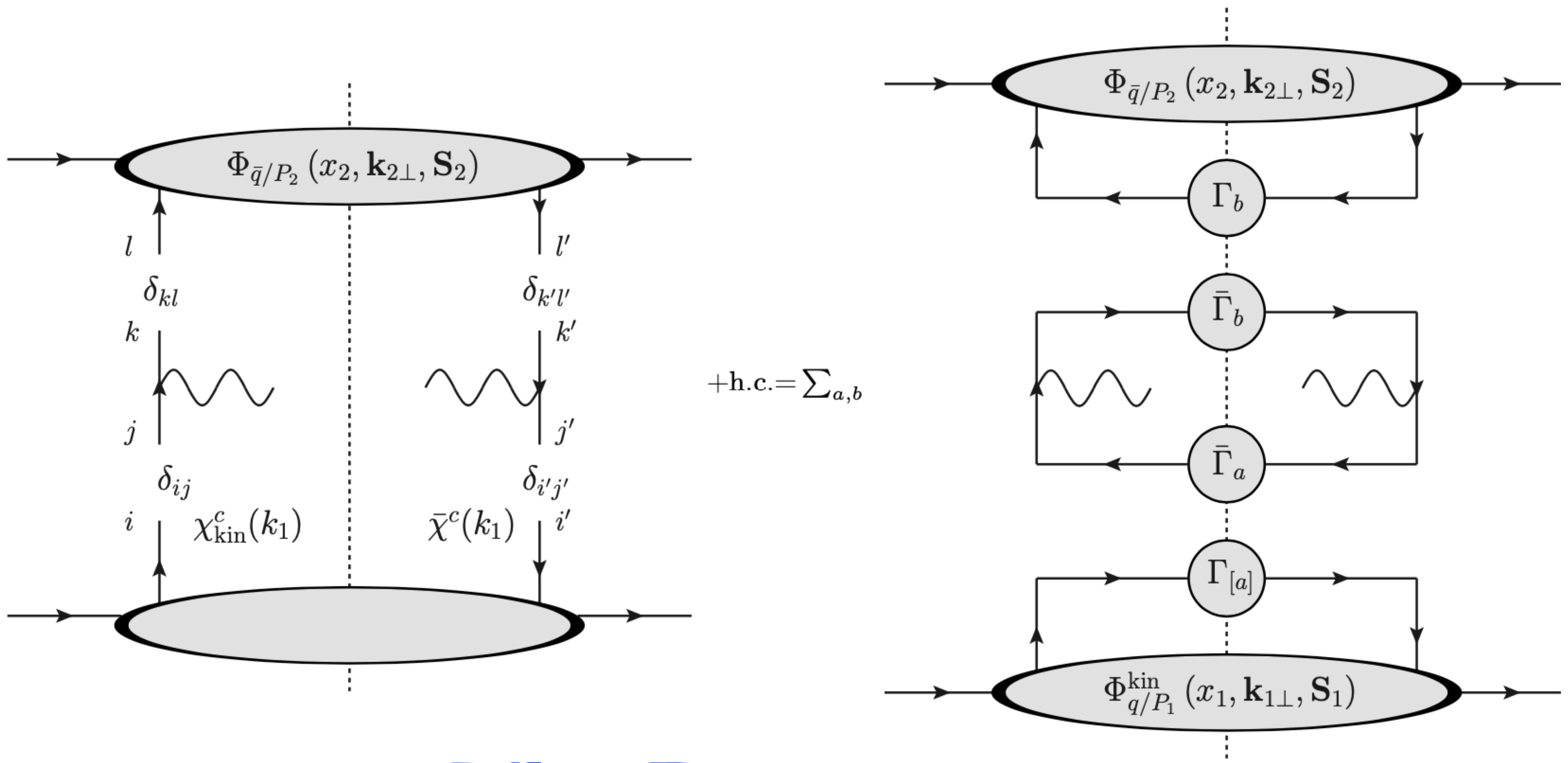
$$\Phi^{\mathrm{int}\,[\Gamma^a]}_{q/P\,\mathrm{A}}(x,\boldsymbol{k}_\perp,\boldsymbol{S}) = \frac{1}{k^+}\int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left\langle P,\boldsymbol{S}\left|\bar{\chi}^c(0)\,\mathcal{U}^{\bar{n}}_{\mathsf{L}}(0)\,\Gamma^a\,\mathcal{U}^{\bar{n}\,\dagger}_{\mathsf{L}}(\xi)\,\not{k}_\perp\frac{\not{n}}{2}\chi^c(\xi)\right|P,\boldsymbol{S}\right\rangle + \frac{ig}{k^+}\int d\eta^-\int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left\langle P,\boldsymbol{S}\left|\bar{\chi}^c(0)\,\mathcal{U}^{\bar{n}}_{\mathsf{L}}(0)\,\Gamma^a\,\mathcal{U}^{\bar{n}\,\dagger}_{\mathsf{L}}(\eta)\,F^{j+}(\eta)\,\mathcal{U}^{\bar{n}}\left(\eta^-,\xi^-;\xi^+,\boldsymbol{\xi}_\perp\right)\gamma_j\frac{\not{n}}{2}\chi^c(\xi)\right|P,\boldsymbol{S}\right\rangle$$

$$\Phi^{\mathrm{kin}}_{q/P\,jj'}(x,\boldsymbol{k}_\perp,\boldsymbol{S}) = \int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left[\langle P,\boldsymbol{S}\,|\bar{\chi}^c_{j'}(0)\,\mathcal{U}^{\bar{n}}_{\mathsf{L}}(0)\,\mathcal{U}^{\bar{n}\,\dagger}_{\mathsf{L}}(\xi)\,\chi^c_{\mathrm{kin}\,j}(\xi) + \bar{\chi}^c_{\mathrm{kin}\,j'}(0)\,\mathcal{U}^{\bar{n}}_{\mathsf{L}}(0)\,\mathcal{U}^{\bar{n}\,\dagger}_{\mathsf{L}}(\xi)\,\chi^c_j(\xi)|\,P,\boldsymbol{S}\rangle\right]$$

$$\chi^c_{\mathrm{kin}}(\xi) = \frac{\not{k}_\perp}{k^+}\frac{\not{n}}{2}\chi^c(\xi)$$

EOMs and kinematic Suppressed Distributions

- Employ the QCD equations of motion to demonstrate the appearance of the "kinematic sub-leading distributions"



$$\Phi^{\text{kin}}_{q/P\, jj'}(x, \boldsymbol{k}_\perp, \boldsymbol{S}) = \sum_a \bar{\Gamma}^a_{jj'} \int \frac{d^4\xi}{(2\pi)^3} e^{ik\cdot\xi}\, \delta(\xi^+) \left\langle P, \boldsymbol{S} \left| \bar{\chi}^c(0)\, \mathcal{U}^{\bar{n}}_{\text{L}}(0)\, \Gamma^{[a]}\, \mathcal{U}^{\bar{n}\,\dagger}_{\text{L}}(\xi)\, \chi^c(\xi) \right| P, \boldsymbol{S} \right\rangle$$

where $\Gamma^{[a]} = [\Gamma^a, \not{k}_\perp \not{n}/2k^+]$

Subleading fields and correlator(s) Summary

Three possible sub-leading field configurations. They are related through the QCD EOM

$$\varphi^c(x) = \frac{\not{n}\not{\bar{n}}}{4}\psi^c(x) \qquad \chi^c(x) = \frac{\not{\bar{n}}\not{n}}{4}\psi^c(x) \qquad \varphi^c(x) = -\frac{\not{n}}{2}\frac{\not{D}_\perp}{n\cdot D}\chi^c(x)$$

Using properties of the Wilson lines, the relevant collinear functions are given by

$$\Phi^{\text{int}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) = \int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left[\langle P,\mathbf{S}\,|\bar{\chi}^c_{j'}(0)\,\mathcal{U}^{\bar{n}}_{\llcorner}(0)\,\mathcal{U}^{\bar{n}\,\dagger}_{\llcorner}(\xi)\,\varphi^c_j(\xi)|\,P,\mathbf{S}\rangle + \text{h.c.}\right]$$

$$\Phi^{\text{dyn}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) = \frac{ig}{k^+}\int d\eta^-\int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)$$
$$\times\left[\left\langle P,\mathbf{S}\left|\bar{\chi}^c(0)\,\mathcal{U}^{\bar{n}}_{\llcorner}(0)\,\Gamma^a\,\mathcal{U}^{\bar{n}\,\dagger}_{\llcorner}(\eta)\,F^{i+}(\eta)\,\mathcal{U}^{\bar{n}}\left(\eta^-,\xi^-;\xi^+,\xi_\perp\right)\,\gamma_i\frac{\not{n}}{2}\chi^c(\xi)\right|P,\mathbf{S}\right\rangle + \text{h.c.}\right]$$

$$\Phi^{\text{kin}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) = \int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left[\left\langle P,\mathbf{S}\left|\bar{\chi}^c_{j'}(0)\,\mathcal{U}^{\bar{n}}_{\llcorner}(0)\,\frac{i\partial^i_\perp}{in\cdot D}\,\mathcal{U}^{\bar{n}\,\dagger}_{\llcorner}(\xi)\,\frac{\not{n}}{2}\gamma^\perp_i\chi^c_{\text{kin}\,j}(\xi)\right|P,\mathbf{S}\right\rangle + \text{h.c.}\right]$$

All three distributions are not required to span the NLP cross section due to EOM

$$\Phi^{\text{int}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) = \Phi^{\text{kin}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) + \Phi^{\text{dyn}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S})$$

[8]Gamberg, Kang, Shao, Terry, Zhao 2022

Subleading fields and correlator(s) Alternative

Three possible sub-leading field configurations. They are related through the QCD EOM

$$\varphi^c(x) = \frac{\not{n}\not{\bar{n}}}{4}\psi^c(x) \qquad \chi^c(x) = \frac{\not{\bar{n}}\not{n}}{4}\psi^c(x) \qquad \varphi^c(x) = -\frac{\not{n}}{2}\frac{\not{D}_\perp}{n\cdot D}\chi^c(x)$$

Using properties of the Wilson lines, the relevant collinear functions are given by

$$\Phi^{\text{int}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) = \int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left[\langle P,\mathbf{S}\,|\bar{\chi}^c_{j'}(0)\,\mathcal{U}^{\bar{n}}_{\llcorner}(0)\,\mathcal{U}^{\bar{n}\,\dagger}_{\llcorner}(\xi)\,\varphi^c_j(\xi)|\,P,\mathbf{S}\rangle + \text{h.c.}\right]$$

$$\Phi^{\text{dyn}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) = \frac{ig}{k^+}\int d\eta^- \int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)$$
$$\times\left[\left\langle P,\mathbf{S}\left|\bar{\chi}^c(0)\,\mathcal{U}^{\bar{n}}_{\llcorner}(0)\,\Gamma^a\,\mathcal{U}^{\bar{n}\,\dagger}_{\llcorner}(\eta)\,F^{i+}(\eta)\,\mathcal{U}^{\bar{n}}\left(\eta^-,\xi^-;\xi^+,\xi_\perp\right)\,\gamma_i\frac{\not{\bar{n}}}{2}\chi^c(\xi)\right|P,\mathbf{S}\right\rangle + \text{h.c.}\right]$$

$$\Phi^{\text{kin}}_{q/P\,jj'}(x,\mathbf{k}_\perp,\mathbf{S}) = \int \frac{d^4\xi}{(2\pi)^3}\, e^{ik\cdot\xi}\,\delta\left(\xi^+\right)\left[\left\langle P,\mathbf{S}\left|\bar{\chi}^c_{j'}(0)\,\mathcal{U}^{\bar{n}}_{\llcorner}(0)\,\frac{i\partial^i_\perp}{in\cdot D}\,\mathcal{U}^{\bar{n}\,\dagger}_{\llcorner}(\xi)\,\frac{\not{\bar{n}}}{2}\gamma^\perp_i\chi^c_{\text{kin}\,j}(\xi)\right|P,\mathbf{S}\right\rangle + \text{h.c.}\right]$$

All three distributions are not required to span the NLP cross section due to EOM

$$\Phi^{\text{int}}_{q/P\,jj'}\left(x,\mathbf{k}_\perp,\mathbf{S}\right) = \Phi^{\text{kin}}_{q/P\,jj'}\left(x,\mathbf{k}_\perp,\mathbf{S}\right) + \Phi^{\text{dyn}}_{q/P\,jj'}\left(x,\mathbf{k}_\perp,\mathbf{S}\right)$$

[9]Ebert, Gao, Stewart 2021

Tree level factorization sub-leading power

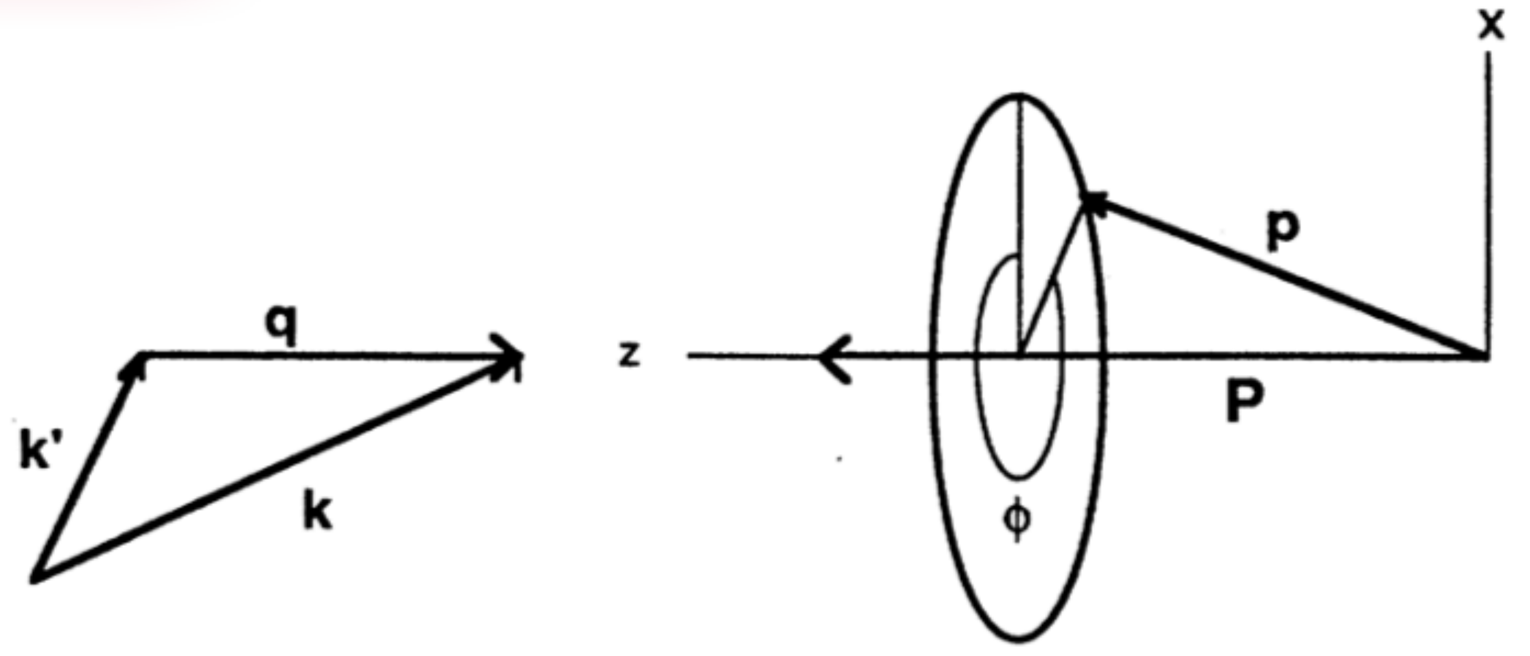
Combining these contributions and multiplying by leptonic tensor
get factorized Cahn and more .... Includes dynamical "tilde" contributions
Using "intrinsic & dynamical" basis

✦Mulders Tangerman NPB1995
✦Goeke Metz Schlegel PLB 2005
✦Bacchetta et al 2007 JHEP

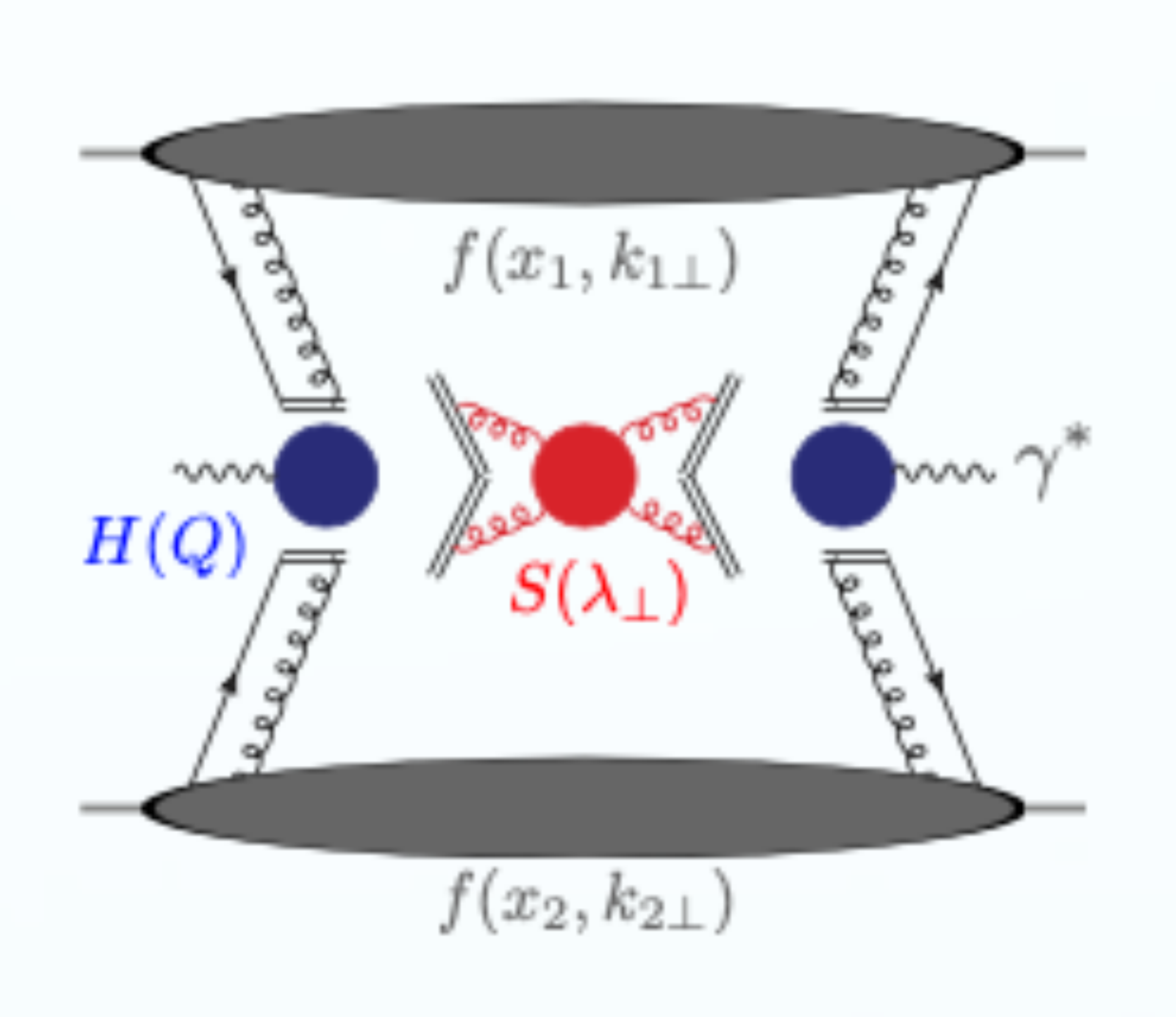
$$F^3_{\rm DIS}(x,z,\boldsymbol{P}_{h\perp}) = \mathcal{C}^{\rm DIS}\left[\frac{q_\perp}{Q} f_1\, D_1\right] - \mathcal{C}^{\rm DIS}\left[\left(x\,\frac{\boldsymbol{k}_\perp\cdot\hat{x}}{Q} f^\perp\right) D_1 - f_1\left(\frac{\boldsymbol{p}_\perp\cdot\hat{x}}{zQ} D^\perp\right)\right] - \int\frac{dx_g}{x_g}\mathcal{C}^{\rm DIS}_{\rm dyn\, x_g}\left[\left(x\,\frac{\boldsymbol{k}_\perp\cdot\hat{x}}{Q}\tilde{f}^\perp\right) D_1\right] + \int\frac{dz_g}{z_g}\mathcal{C}^{\rm DIS}_{\rm dyn\, z_g}\left[f_1\left(\frac{\boldsymbol{p}_\perp\cdot\hat{x}}{zQ}\tilde{D}^\perp\right)\right],$$

Cahn and more intrinsic k_T

Slightly different setup allows us to check RG consistency
Gamberg, Kang, Shao, Terry, Zhao arXiv: e-Print:221.13209



TMD factorization at NLO and NLP



$q_T \sim k_T \ll Q$

TMD Factorization

- ✦*Collins Soper Sterman NPB 1985*
- ✦*Ji Ma Yuan PRD PLB …2004, 2005*
- ✦*Aybat Rogers PRD 2011*
- ✦*Collins 2011 Cambridge Press*
- ✦*Echevarria, Idilbi, Scimemi JHEP 2012, …*
- ✦*SCET Becher & Neubert, 2011 EJPC*

$$\frac{d\sigma^W}{dQ^2\, dx_F\, dp_T^2} = \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2}\, e^{i\boldsymbol{p}_T\cdot\boldsymbol{b}_T}\, \tilde{W}(x_F, b_T, Q)$$

$$\tilde{W}(x_F, b_T, Q) = \sum_j H_{j\bar{j}}^{\rm DY}(Q, \mu, a_s(\mu))\, \tilde{f}_{j/A}(x_A, b_T; \zeta_A, \mu)\, \tilde{f}_{\bar{j}/B}(x_B, b_T; \zeta_B, \mu)$$

….“with resummation”….

Factorization & resummation at NLO and NLP

Beyond tree level

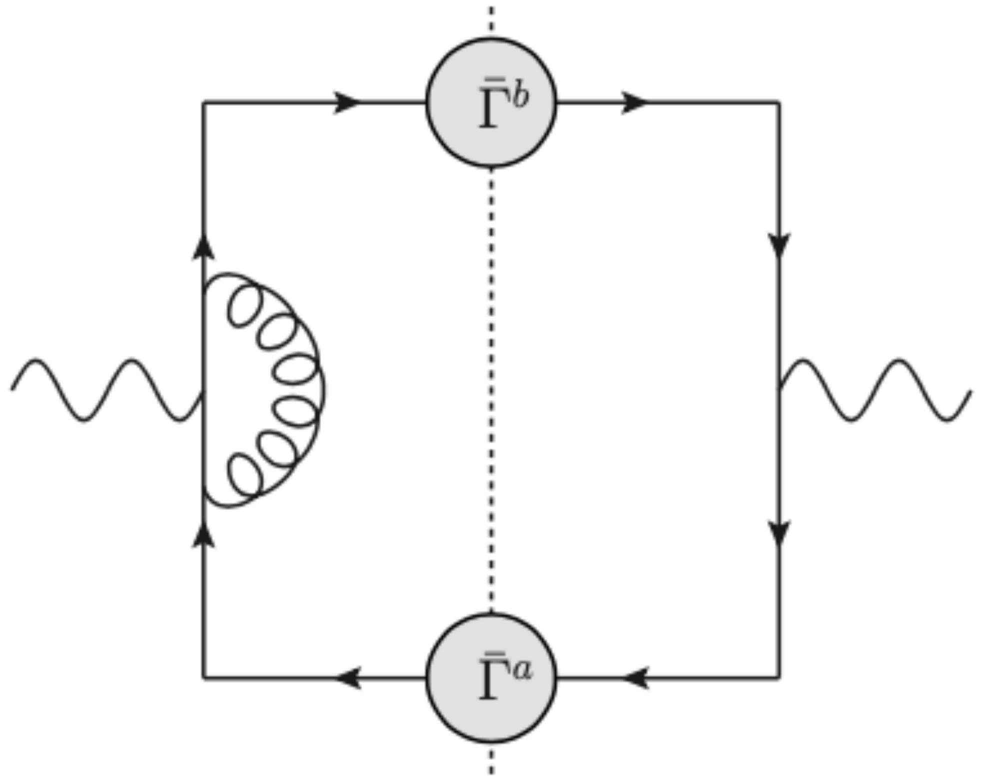
Note first attempt Bacchetta Boer Diehl Mulders JHEP 2008

- We perform one loop calculation
- & attempt to establish renormalization group consistency: Regions hard,soft,collinear

$$
\begin{aligned}
F^3_{\mathrm{DIS}}(x,z,\boldsymbol{P}_{h\perp}) = {} & H^{\mathrm{LP}}_{\mathrm{DIS}}(Q;\mu)\,\mathcal{C}^{\mathrm{DIS}}\left[\frac{q_\perp}{Q} f_1\, D_1\, \mathcal{S}^{\mathrm{LP}}\right] \\
& - H^{\mathrm{int}}_{\mathrm{DIS}}(Q;\mu)\,\mathcal{C}^{\mathrm{DIS}}\left[\left(x\,\frac{\boldsymbol{k}_\perp\cdot\hat{x}}{Q} f^\perp D_1 - \frac{\boldsymbol{p}_\perp\cdot\hat{x}}{zQ} f_1\, D^\perp\right)\mathcal{S}^{\mathrm{int}}\right] \\
& - \int \frac{dx_g}{x_g} H^{\mathrm{dyn}}_{\mathrm{DIS}}(x_g,Q;\mu)\,\mathcal{C}^{\mathrm{DIS}}\left[x\,\frac{\boldsymbol{k}_\perp\cdot\hat{x}}{Q}\tilde{f}^\perp D_1\, \mathcal{S}^{\mathrm{dyn}}\right] \\
& + \int \frac{dz_g}{z_g} H^{\mathrm{dyn}}_{\mathrm{DIS}}(z_g,Q;\mu)\,\mathcal{C}^{\mathrm{DIS}}\left[\frac{\boldsymbol{p}_\perp\cdot\hat{x}}{zQ} f_1\, \tilde{D}^\perp \mathcal{S}^{\mathrm{dyn}}\right].
\end{aligned}
$$

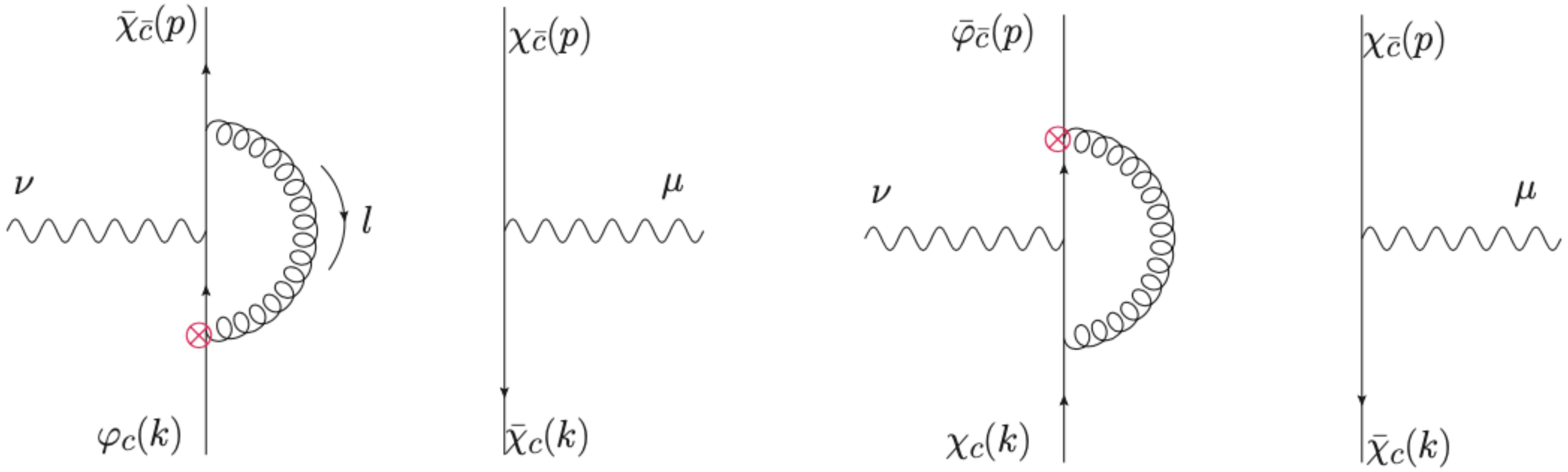
- H^{LP}, H^{int} and H^{dynam} represent LP, intrinsic NLP, and dynamic NLP hard functions.
- Additionally, S^{LP}, S^{int} and S^{dyn} denote the LP, intrinsic sub-leading power, and dynamic sub-leading power soft function
- *NB* if soft factors are different universality of TMDs breaks down. Global analysis w/ NLP observables hopeless

NLO Ingredients hard factor



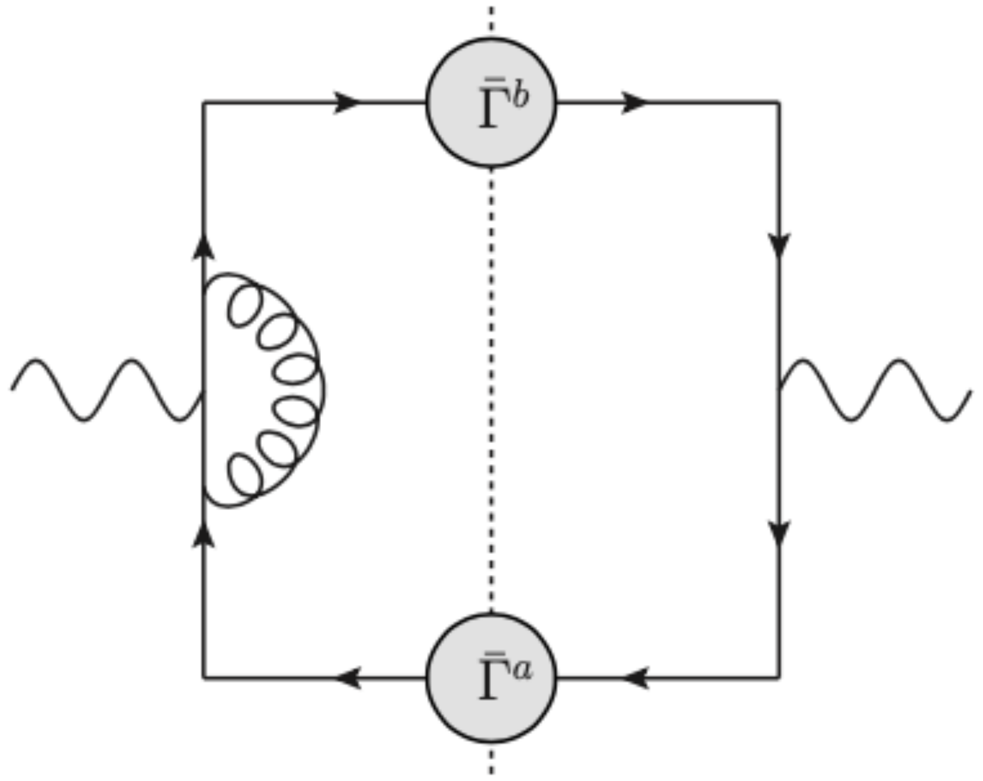
+h.c.

$$\gamma^\nu \to \gamma^\nu + \frac{\alpha_s C_F}{2\pi} F^\nu_{\mathrm{DIS}}(Q;\mu) + \mathcal{O}\left(\alpha_s^2\right)$$



$$\mathcal{M}^{\nu\,(1)}_{\mathrm{NLP}}(k,p;\mu) = \bar{\varphi}_{\bar{c}}(p) F^\nu_{\mathrm{DIS\,LP}}(Q;\mu)\,\chi_c(k) + \bar{\chi}_{\bar{c}}(p) F^\nu_{\mathrm{DIS\,LP}}(Q;\mu)\,\varphi_c(k)$$

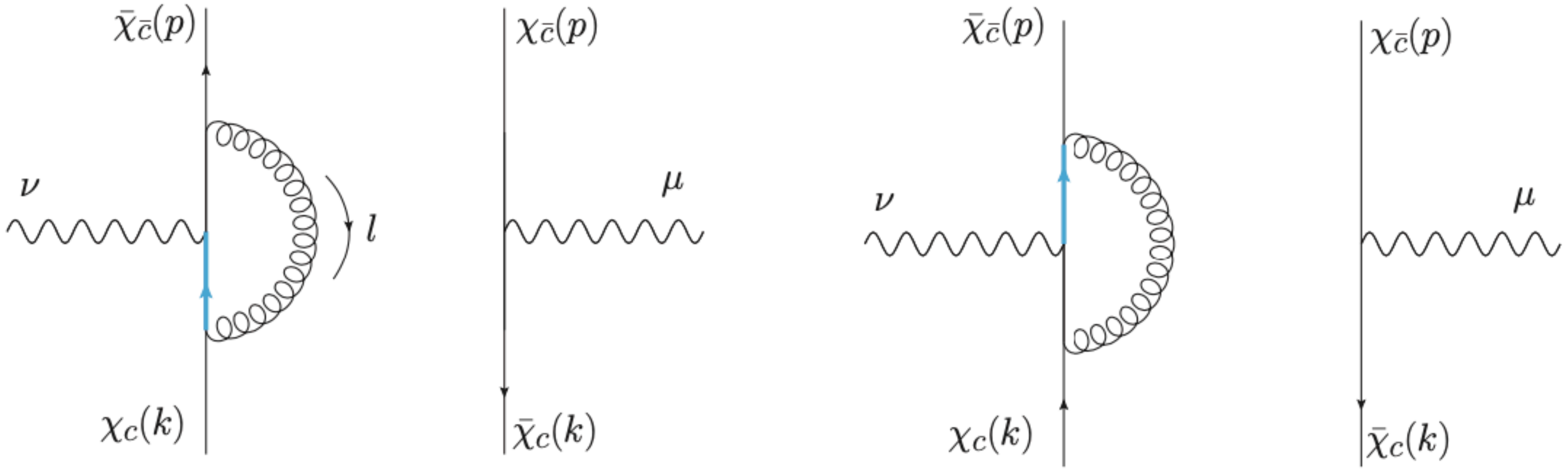
NLO Ingredients hard factor



+h.c.

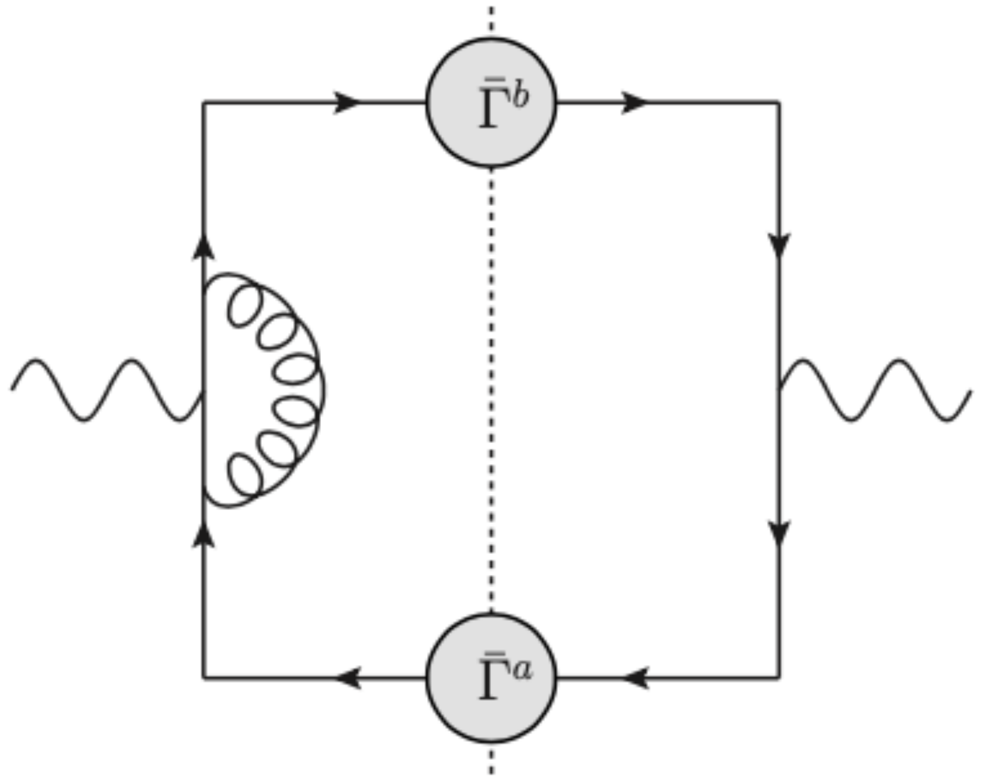
$$\gamma^\nu \to \gamma^\nu + \frac{\alpha_s C_F}{2\pi} F^\nu_{\mathrm{DIS}}\left(Q;\mu\right) + \mathcal{O}\left(\alpha_s^2\right)$$

We have found additional contributions,
we must also consider power counting
sub-leading contributions entering
from the transverse momentum of the quark propagators.



$$\begin{aligned}\mathcal{M}^{\nu\,(1)}_{\mathrm{NLP}}\left(k,p;\mu\right) = {} & \bar{\varphi}_{\bar{c}}(p)F^\nu_{\mathrm{DIS\,LP}}\left(Q;\mu\right)\chi_c(k) + \bar{\chi}_{\bar{c}}(p)F^\nu_{\mathrm{DIS\,LP}}\left(Q;\mu\right)\varphi_c(k) \\ & + \bar{\chi}_{\bar{c}}(p)F^\nu_{\mathrm{DIS\,k}}\left(k_\perp,Q;\mu\right)\chi_c(k) + \bar{\chi}_{\bar{c}}(p)F^\nu_{\mathrm{DIS\,p}}\left(p_\perp,Q;\mu\right)\chi_c(k)\end{aligned}$$

NLO Ingredients hard factor compare to LP



$+\text{h.c.}$

$$H^{(1)\,i}_{\mathrm{DIS}}(Q;\mu) = \bar{\mathcal{V}}^i_{\mu\nu}\left[\mathcal{M}^{\mu\,(1)}_{\mathrm{LP}}\mathcal{M}^{\dagger\,\nu\,(0)}_{\mathrm{LP}} + \mathcal{M}^{\mu\,(0)}_{\mathrm{LP}}\mathcal{M}^{\dagger\,\nu\,(1)}_{\mathrm{LP}}\right].$$

LP

$$\mathcal{M}^{\nu\,(1)}_{\mathrm{LP}}(k,p;\mu) = \frac{\alpha_s C_F}{2\pi}\bar{\chi}_{\bar{c}}(p)\gamma^\nu\chi_c(k)\left[\frac{3}{2\epsilon} + \frac{1}{\epsilon^2} + 2L_Q^2 - \frac{2L_Q}{\epsilon} - 3L_Q - \frac{\pi^2}{12} + 4\right]$$

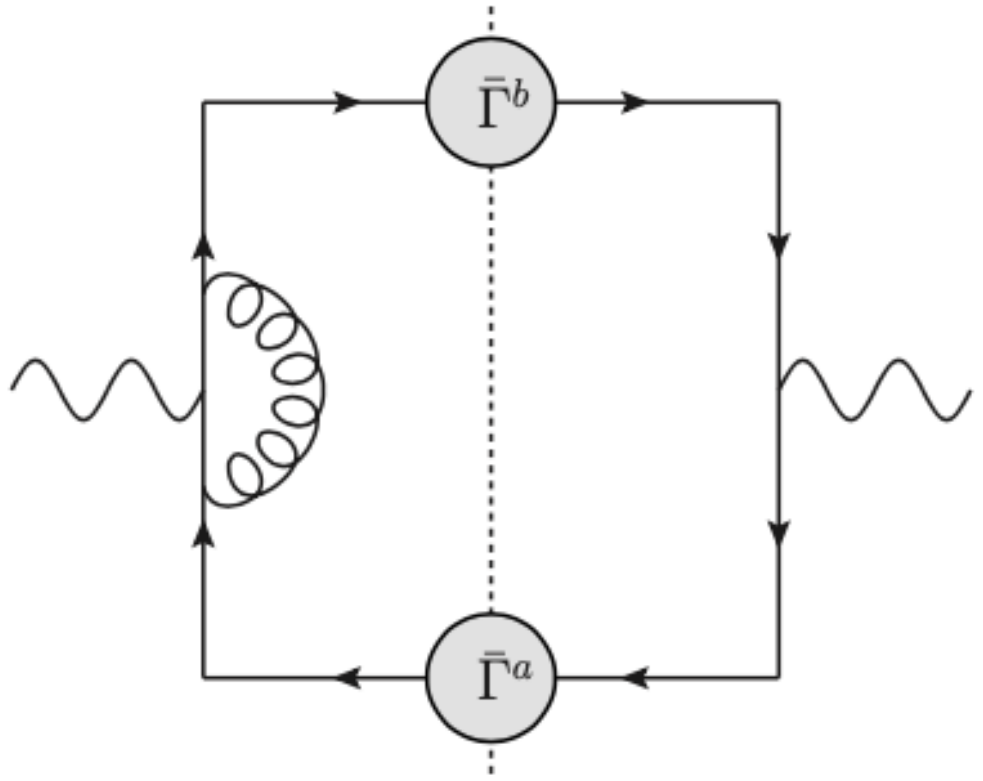
$$\hat{H}^{\mathrm{LP}}_{\mathrm{DIS}}(Q;\mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 4L_Q^2 + \frac{4L_Q}{\epsilon} + 6L_Q + \frac{\pi^2}{6} - 8\right]$$

NLP

$$\mathcal{M}^{\nu\,(1)}_{\mathrm{NLP}}(k,p;\mu) = \left(\frac{1}{\epsilon} + \frac{1}{\epsilon^2} + 2L_Q^2 - \frac{2L_Q}{\epsilon} - 2L_Q - \frac{\pi^2}{12} + \frac{7}{2}\right)\bar{\chi}_{\bar{c}}(p)\frac{\not{\bar{n}}}{2}\hat{t}^\nu\varphi_c(k) + \left(\frac{1}{\epsilon} + \frac{1}{\epsilon^2} + 2L_Q^2 - \frac{2L_Q}{\epsilon} - 2L_Q - \frac{\pi^2}{12} + \frac{7}{2}\right)\bar{\varphi}_{\bar{c}}(p)\frac{\not{n}}{2}\hat{t}^\nu\chi_c(k) + \mathrm{dyn}\,.$$

$$\hat{H}^{\mathrm{NLP}}_{\mathrm{DIS}}(Q;\mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left[-\frac{2}{\epsilon^2} - \frac{5}{2\epsilon} + \frac{4}{\epsilon}L_Q - 4L_Q^2 + 5L_Q + \frac{\pi^2}{6} - \frac{15}{2}\right]$$

NLO Ingredients hard factor



+h.c.

Using the definition of the unsubtracted (UV divergent) hard function, we obtain the subtracted hard function through multiplicative renormalization as

$$H(Q;\mu) = Z(Q;\mu)\hat{H}(Q;\mu),$$

$$H_{\rm DIS}^{\rm LP}(Q;\mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left[-4L_Q^2 + 6L_Q + \frac{\pi^2}{6} - 8\right]$$

$$H_{\rm DIS}^{\rm NLP}(Q;\mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left[-4L_Q^2 + 5L_Q + \frac{\pi^2}{6} - \frac{15}{2}\right]$$

$$Z_{\rm DIS}^{\rm LP}(Q;\mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4L_Q}{\epsilon}\right],$$

$$Z_{\rm DIS}^{\rm NLP}(Q;\mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left[-\frac{2}{\epsilon^2} - \frac{5}{2\epsilon} + \frac{4L_Q}{\epsilon}\right].$$

Since the bare operator *H* is RG invariant, the RG equation of H yields the hard anomalous dimension

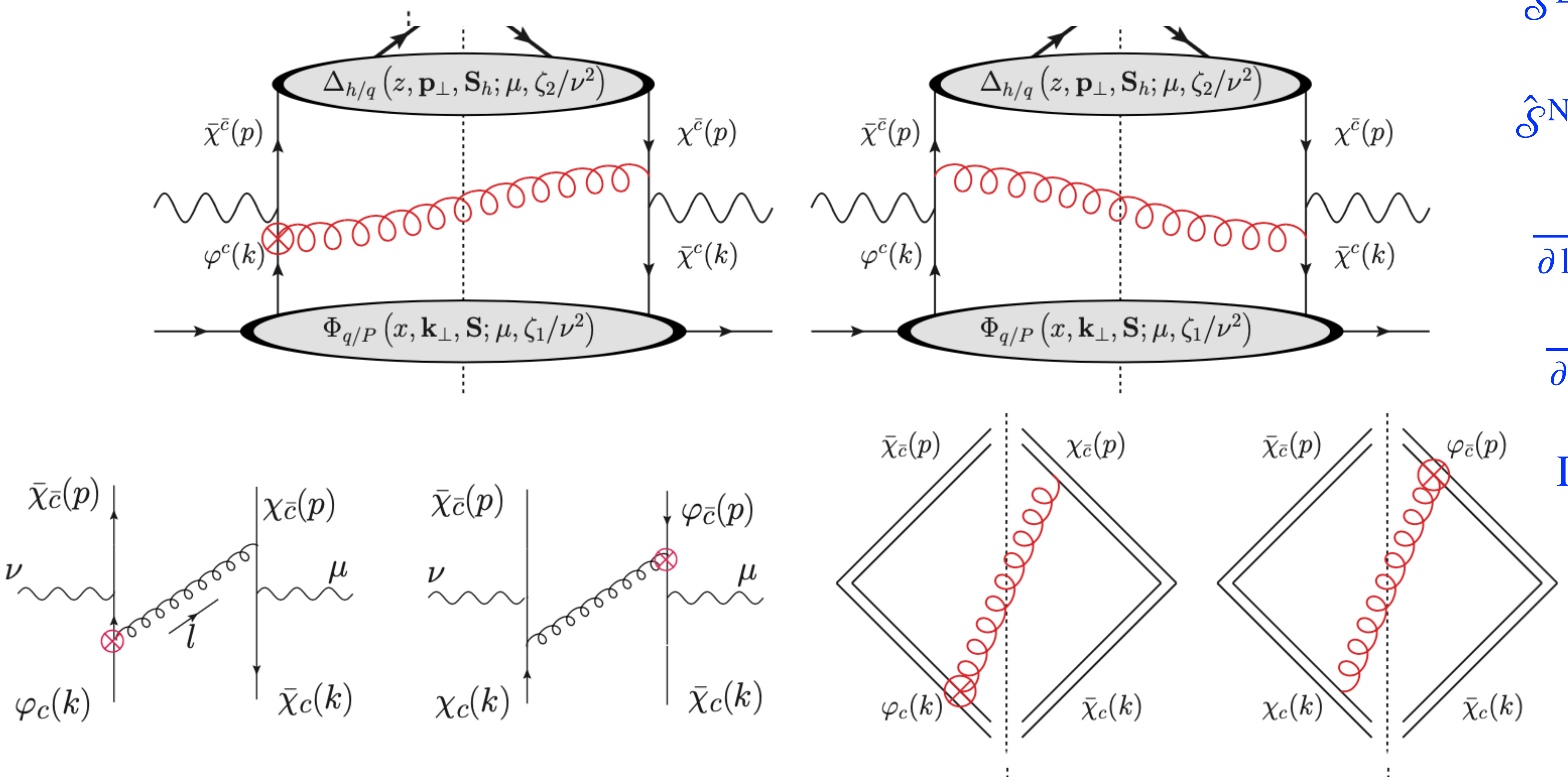
$$\Gamma_H = -\frac{\partial}{\partial \ln\mu} Z(Q;\mu),$$

$$\Gamma^{\mu}_{\rm H\,LP}(Q;\mu) = \frac{\alpha_s C_F}{\pi}\left(4L_Q - 3\right), \qquad \Gamma^{\mu}_{\rm H\,NLP}(Q;\mu) = \frac{\alpha_s C_F}{\pi}\left(4L_Q - \frac{5}{2}\right)$$

NLO Ingredients soft factor

The soft region

The soft function is generated through the emissions of soft gluons in the partonic cross section



$$\hat{\mathcal{S}}^{\rm LP}(b;\mu,\nu) = Z_{\mathcal{S}\,{\rm LP}}(b;\mu,\nu)\mathcal{S}^{\rm LP}(b;\mu,\nu$$

$$\hat{\mathcal{S}}^{\rm NLP}(b;\mu,\nu) = Z_{\mathcal{S}\,{\rm NLP}}(b;\mu,\nu)\mathcal{S}^{\rm NLP}(b;\mu,\nu)$$

$$\frac{\partial}{\partial \ln \mu}\mathcal{S}^{\rm NLP}(b,\mu,\nu) = \Gamma^{\mu}_{\mathcal{S}\,NLP}\mathcal{S}^{\rm NLP}(b,\mu,\nu)$$

$$\frac{\partial}{\partial \ln \nu}\mathcal{S}^{\rm NLP}(b,\mu,\nu) = \Gamma^{\nu}_{\mathcal{S}\,NLP}\mathcal{S}^{\rm NLP}(b,\mu,\nu)$$

$$\Gamma^{\nu}_{\mathcal{S}\,{\rm int}} = \frac{\partial}{\partial \ln \nu} Z_{\mathcal{S}\,NLP}(b;\mu,\nu)$$

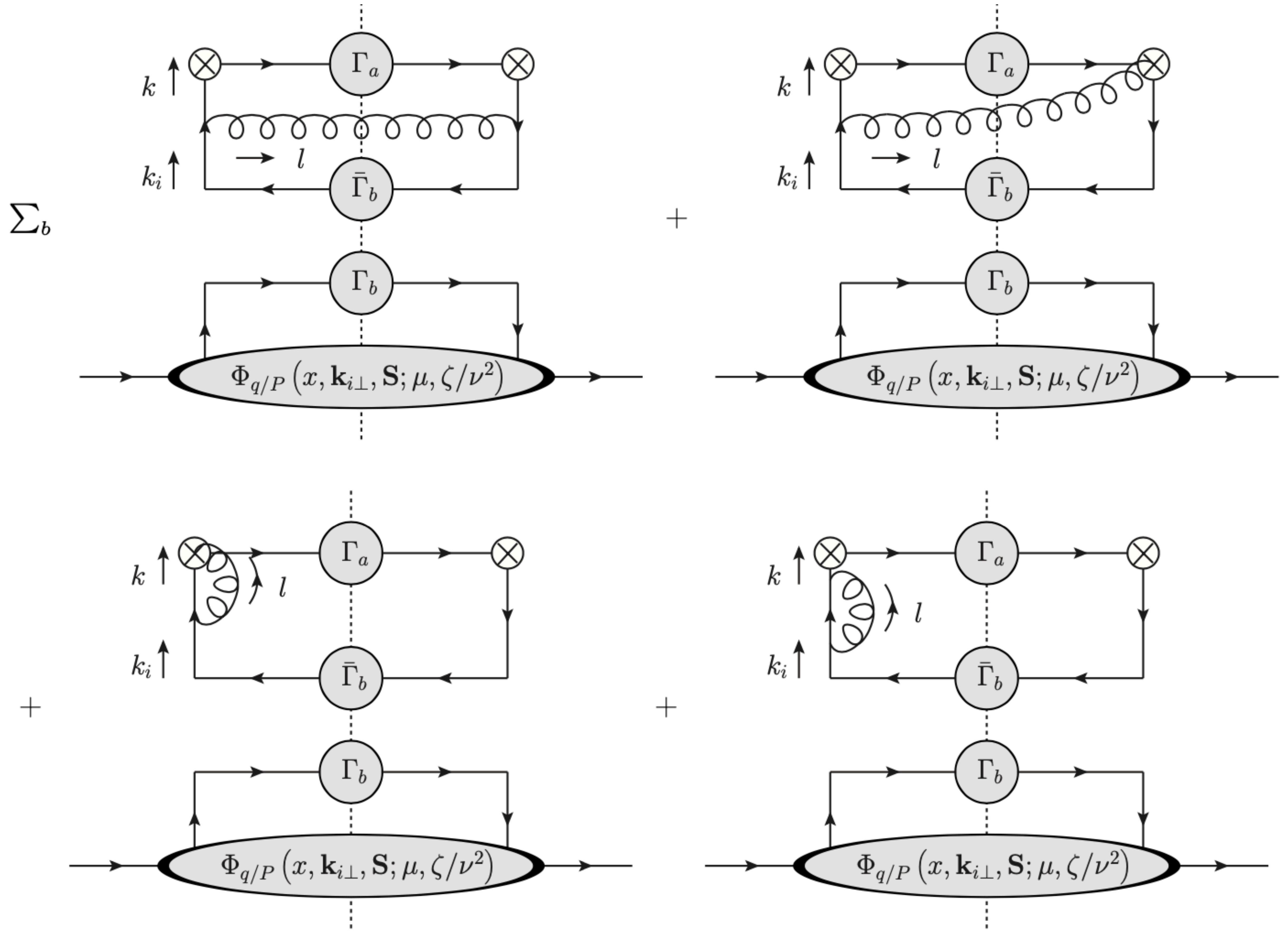
Gamberg, Kang, Shao, Terry, Zhao
arXiv: e-Print:221.13209

Soft emission from the sub-leading fields vanishes. NLO+NLP soft function is half the LP one

$$\Gamma^{\mu}_{\mathcal{S}\,{\rm int}} = \frac{1}{2}\Gamma^{\mu}_{\mathcal{S}\,{\rm LP}}\,, \qquad \Gamma^{\nu}_{\mathcal{S}\,{\rm int}} = \frac{1}{2}\Gamma^{\nu}_{\mathcal{S}\,{\rm LP}}$$

NLO Ingredients collinear factor

Diagrams associated with the evolution of the collinear region



Renormalize TMDs: soft & UV subtraction

$$\hat{\Phi}^{[\Gamma^a]}\left(x, \boldsymbol{b}, \boldsymbol{S}; \mu, \zeta/\nu^2\right) = Z_{\Gamma^a\,\Gamma^b}\left(b, \mu, \zeta/\nu^2\right)\Phi^{[\Gamma^b]0}\left(x, \boldsymbol{b}, \boldsymbol{S}; xP^+\right)$$

$$\Gamma_3^\nu = \frac{\partial}{\partial \ln \nu} Z_{NLP}(b; \mu, \nu)$$

Renormalization and TMD Evolution- $\{\zeta, \mu\}$

- Collins Soper Eq. $$\frac{\partial \ln \tilde{f}_{j/H}(x, b_T; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_T, \mu)$$

$$\tilde{K}(b_T, \mu) \equiv \frac{1}{2} \frac{\partial}{\partial y_n} \ln \frac{S(b_T, y_n, -\infty)}{S(b_T, y_n, -\infty)}$$

- RGE for C.S. kernel

$$\frac{d\tilde{K}(b_T; \mu)}{d \ln \mu} = -\gamma_k(\alpha_s(\mu))$$

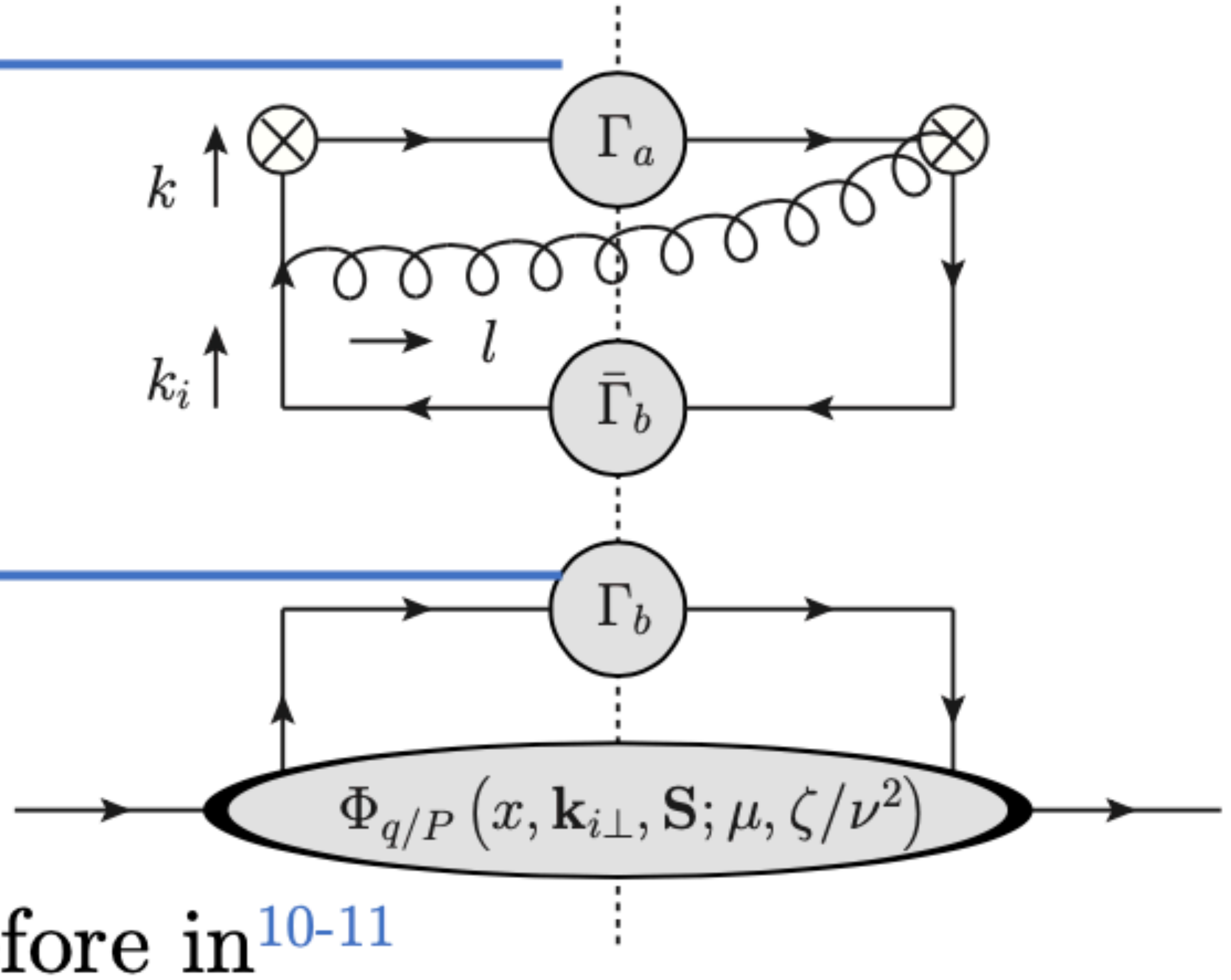
- RGE for TMD $$\frac{d \ln \tilde{f}_{j/H}(x, b_T; \mu, \zeta)}{d \ln \mu} = -\gamma_F(\alpha_s(\mu), \zeta/\mu)$$

Solve simultaneously and get evolved renormalized TMD $\rightarrow \zeta = Q^2, \quad \mu = \mu_Q \sim Q$

Anomalous dimension matrices

Evolution equations naturally enter as matrices due to mixing

$$\frac{\partial}{\partial \ln \mu}\begin{bmatrix}\Phi^{[\not n]}\\ \Phi^{[\not n\gamma^5]}\\ \Phi^{[i\sigma^{i+}\gamma^5]}\\ \Phi^{[1]}\\ \Phi^{[\gamma^5]}\\ \Phi^{[\gamma^i]}\\ \Phi^{[\gamma^i\gamma^5]}\\ \Phi^{[i\sigma^{ij}\gamma^5]}\\ \Phi^{[i\sigma^{+-}\gamma^5]}\end{bmatrix} = \mathbf{\Gamma}^{\mu}\begin{bmatrix}\Phi^{[\not n]}\\ \Phi^{[\not n\gamma^5]}\\ \Phi^{[i\sigma^{l+}\gamma^5]}\\ \Phi^{[1]}\\ \Phi^{[\gamma^5]}\\ \Phi^{[\gamma^l]}\\ \Phi^{[\gamma^l\gamma^5]}\\ \Phi^{[i\sigma^{lm}\gamma^5]}\\ \Phi^{[i\sigma^{+-}\gamma^5]}\end{bmatrix} \qquad \frac{\partial}{\partial \ln \nu}\begin{bmatrix}\Phi^{[\not n]}\\ \Phi^{[\not n\gamma^5]}\\ \Phi^{[i\sigma^{i+}\gamma^5]}\\ \Phi^{[1]}\\ \Phi^{[\gamma^5]}\\ \Phi^{[\gamma^i]}\\ \Phi^{[\gamma^i\gamma^5]}\\ \Phi^{[i\sigma^{ij}\gamma^5]}\\ \Phi^{[i\sigma^{+-}\gamma^5]}\end{bmatrix} = \mathbf{\Gamma}^{\nu}\begin{bmatrix}\Phi^{[\not n]}\\ \Phi^{[\not n\gamma^5]}\\ \Phi^{[i\sigma^{l+}\gamma^5]}\\ \Phi^{[1]}\\ \Phi^{[\gamma^5]}\\ \Phi^{[\gamma^l]}\\ \Phi^{[\gamma^l\gamma^5]}\\ \Phi^{[i\sigma^{lm}\gamma^5]}\\ \Phi^{[i\sigma^{+-}\gamma^5]}\end{bmatrix}.$$



We find operator mixing in the Collins-Soper equation. Seen before in[10-11]

$$\mathbf{\Gamma}^{\mu} = \begin{bmatrix}\Gamma_2^{\mu} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & \Gamma_2^{\mu} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & \Gamma_2^{\mu}\delta_l^i & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & \Gamma_3^{\mu} & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & \Gamma_3^{\mu} & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & \Gamma_3^{\mu}\delta_l^i & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \Gamma_3^{\mu}\delta_l^i & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{4}\Gamma_3^{\mu}\left(\delta_l^i\delta_m^j - \delta_l^j\delta_m^i\right) & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Gamma_3^{\mu}\end{bmatrix}$$

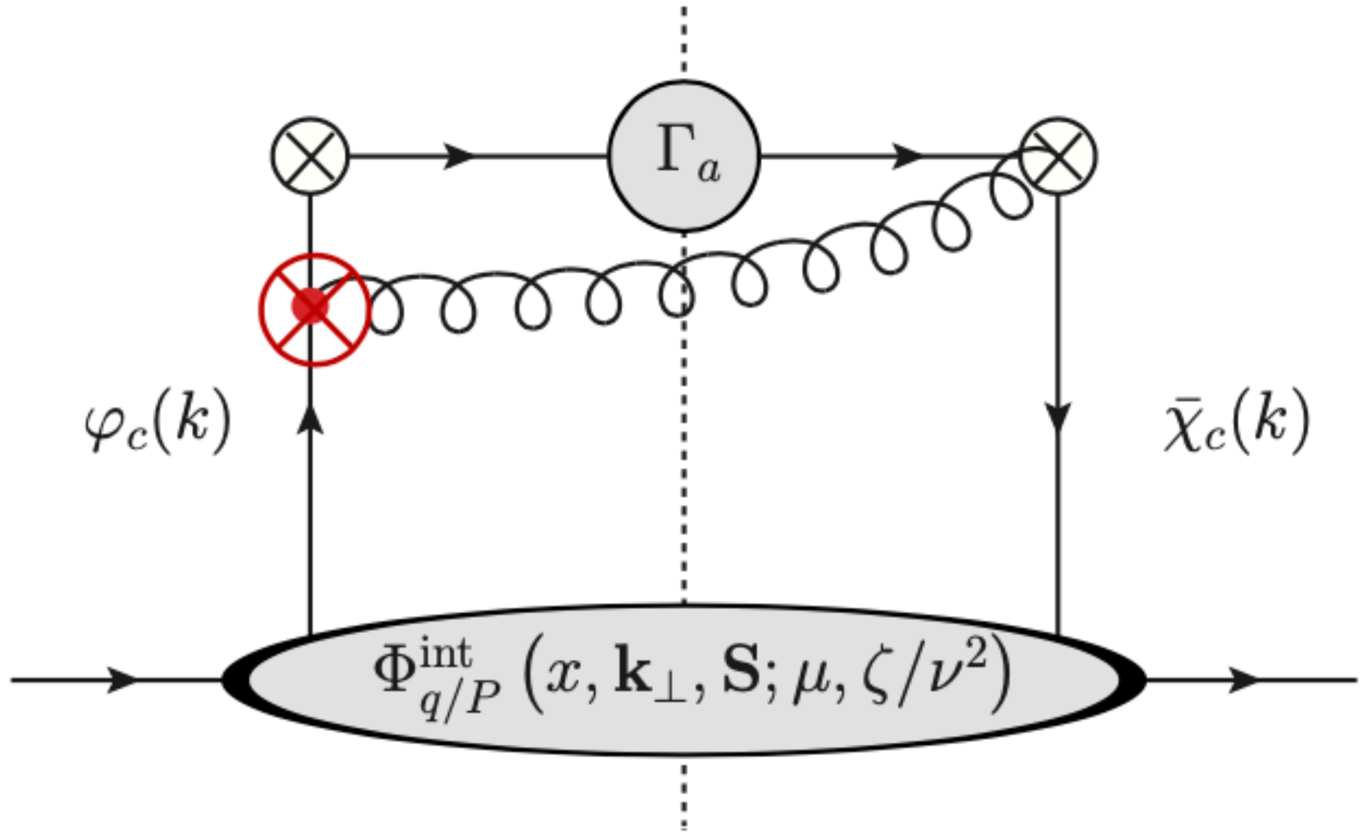
$$\mathbf{\Gamma}^{\nu} = \frac{\alpha_s C_F}{2\pi}\begin{bmatrix}2L & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 2L & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 2L\delta_l^i & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & L & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & \frac{2ib_l}{xP^+}\frac{\partial L}{\partial b^2} & 0 & L & 0 & 0 & 0 & 0\\ \frac{2ib^i}{xP^+}\frac{\partial L}{\partial b^2} & 0 & 0 & 0 & 0 & L\delta_l^i & 0 & 0 & 0\\ 0 & \frac{2ib^i}{xP^+}\frac{\partial L}{\partial b^2} & 0 & 0 & 0 & 0 & L\delta_l^i & 0 & 0\\ 0 & 0 & \frac{i}{xP^+}\frac{\partial L}{\partial b^2}\left(b^j\delta_l^i - b^i\delta_l^j\right) & 0 & 0 & 0 & 0 & L\left(\delta_l^i\delta_m^j - \delta_l^j\delta_m^i\right) & 0\\ 0 & 0 & \frac{2ib_l}{xP^+}\frac{\partial L}{\partial b^2} & 0 & 0 & 0 & 0 & 0 & L\end{bmatrix}$$

LP to LP   LP to NLP   NLP to NLP

NLO Ingredients collinear factor

Differences from LP TMDs

Study the interaction of the sub-leading fields with the Wilson lines



$$\frac{\not{n}}{2}\varphi_c(k) = 0$$

$$\Gamma_3^\nu = \frac{\partial}{\partial \ln \nu} Z_{NLP}(b;\mu,\nu)$$

Can show that these interactions vanish trivially

$$\Gamma_3^{\nu\,[\mathrm{int}]}(\mu,\nu,\zeta) = \frac{1}{2}\Gamma_2^\nu(\mu,\nu,\zeta)$$

[8]Gamberg, Kang, Shao, Terry, Zhao 2022

Necessary condition rapidity RG Consistency

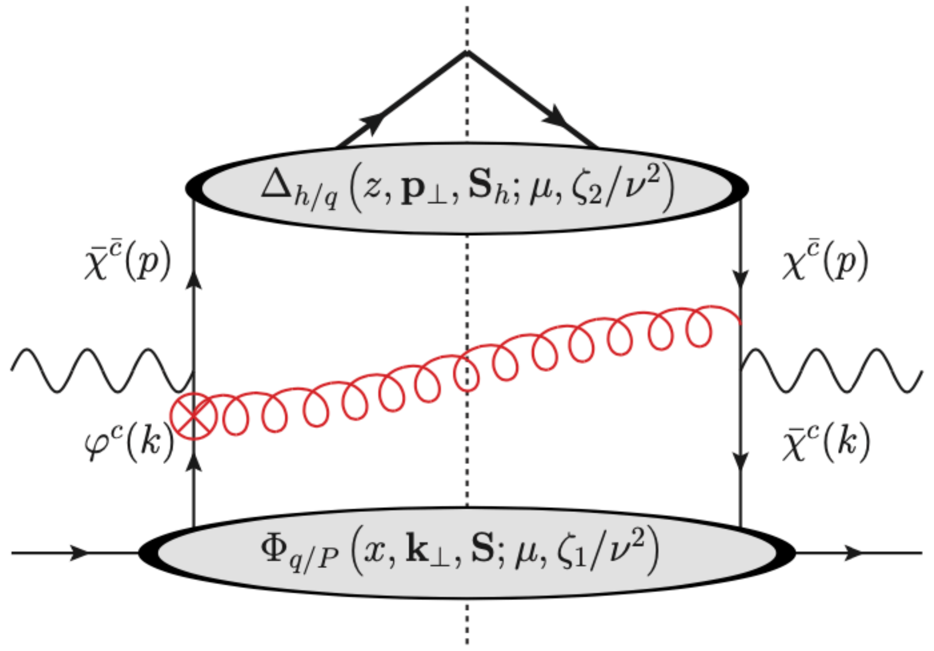
$$\frac{d\sigma}{d\ln\nu} = 0 \quad \& \quad \frac{d\sigma}{d\ln\mu} = 0$$

Leading power

$$f_1(x,b;\mu,\zeta_1) = f_1(x,b;\mu,\zeta_1/\nu^2)\sqrt{\mathcal{S}^{\rm LP}(b;\mu,\nu)}$$

$$D_1(z,b;\mu,\zeta_2) = D_1(z,b;\mu,\zeta_2/\nu^2)\sqrt{\mathcal{S}^{\rm LP}(b;\mu,\nu)}$$

$$\Gamma_2^\nu + \frac{1}{2}\Gamma_{\mathcal{S}}^\nu = 0\,, \qquad \Gamma_2^\nu + \frac{1}{2}\Gamma_{\mathcal{S}}^\nu = 0$$



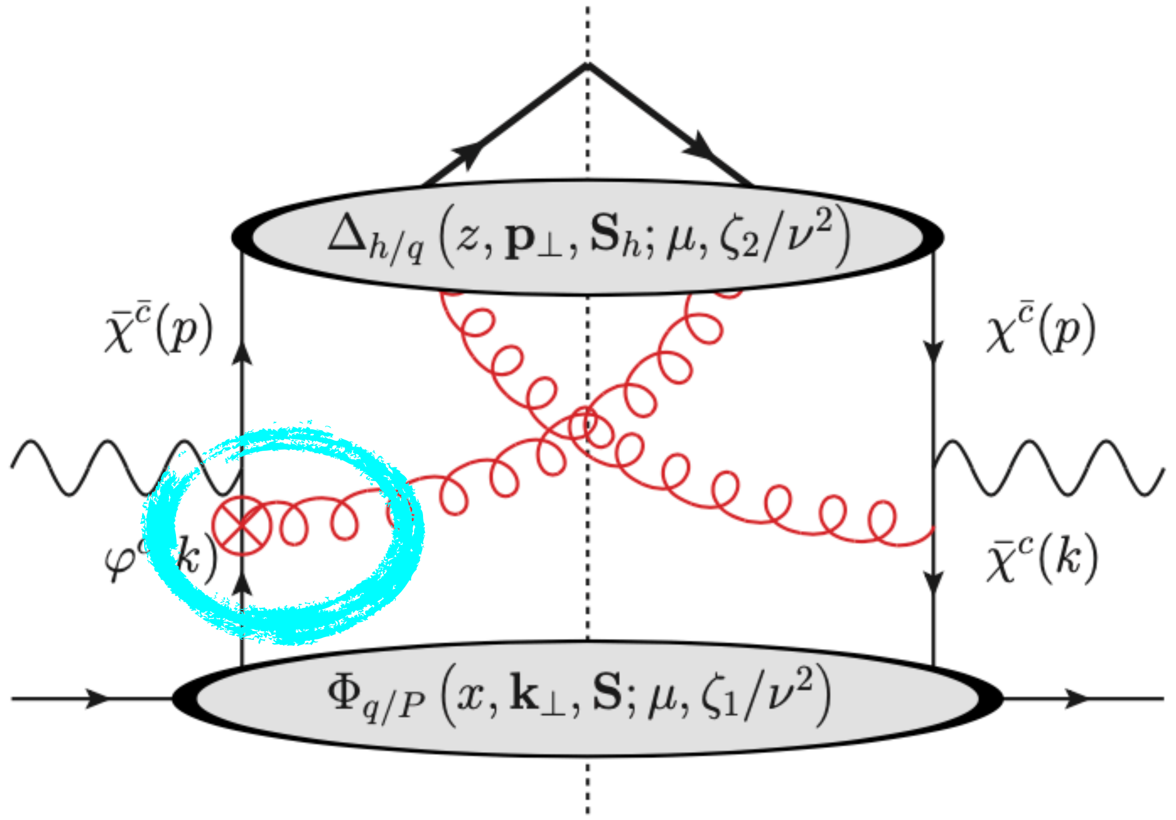
Next to leading power

$$-\,H^{\rm int}_{\rm DIS}(Q;\mu)\,\mathcal{C}^{\rm DIS}\left[\left(x\frac{\boldsymbol{k}_\perp\cdot\hat{x}}{Q}f^\perp D_1 - \frac{\boldsymbol{p}_\perp\cdot\hat{x}}{zQ}f_1 D^\perp\right)\mathcal{S}^{\rm int}\right]$$

$$ib^\mu M^2 f^{\perp\,(1)}(x,b;\mu,\zeta_1) = ib^\mu M^2 f^{\perp\,(1)}(x,b;\mu,\zeta_1/\nu^2)\sqrt{\mathcal{S}^{\rm int}(b;\mu,\nu)}$$

$$\Gamma_{3\,\rm int}^\nu + \frac{1}{2}\Gamma_{\mathcal{S}\,\rm int}^\nu = 0$$

Non-trivial result



However for cross section

$$D_1(z,b;\mu,\zeta_2) = D_1(z,b;\mu,\zeta_2/\nu^2)\sqrt{\mathcal{S}^{\rm LP}(b;\mu,\nu)} \quad \longleftrightarrow \quad \Gamma_2^\nu + \frac{1}{2}\Gamma_{\mathcal{S}\,\rm int}^\nu \neq 0 \;!!$$

$$D_1(z,b;\mu,\zeta_2) = D_1(z,b;\mu,\zeta_2/\nu)\sqrt{S^{int}}\,?? \quad \longleftrightarrow \quad \Gamma_{2\,\rm mod}^\nu + \frac{1}{2}\Gamma_{\mathcal{S}\,\rm int}^\nu = 0 \;!!$$

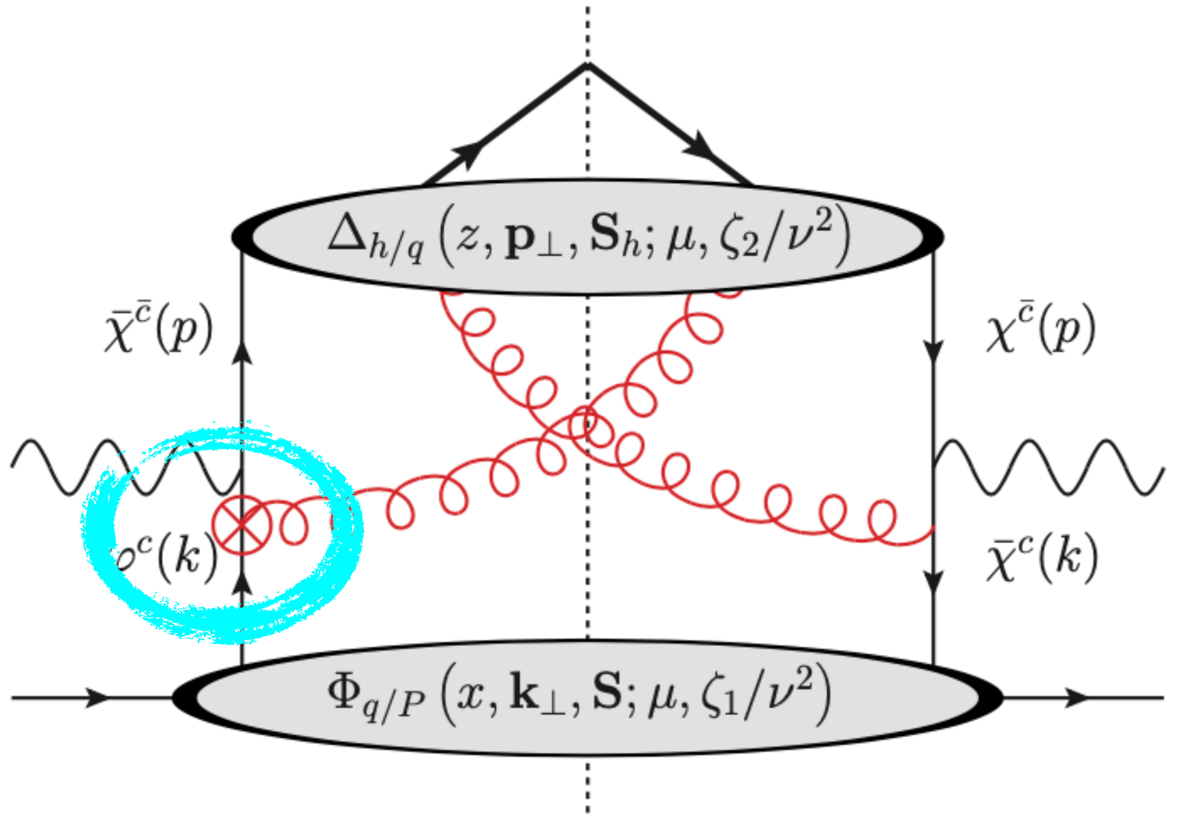
Necessary condition rapidity RG Consistency

Next to leading power $\frac{d\sigma}{d\ln\nu} = 0$ & $\frac{d\sigma}{d\ln\mu} = 0$

$$- H^{\rm int}_{\rm DIS}(Q;\mu)\, \mathcal{C}^{\rm DIS}\left[\left(x\frac{\boldsymbol{k}_\perp\cdot\hat{x}}{Q} f^\perp D_1 - \frac{\boldsymbol{p}_\perp\cdot\hat{x}}{zQ} f_1 D^\perp\right)\mathcal{S}^{\rm int}\right]$$

!!

$$\Gamma^\nu_{\mathcal{S}\,\rm int} + \Gamma^\nu_{3\,\rm int} + \Gamma^\nu_{2\,\rm mod} = 0$$



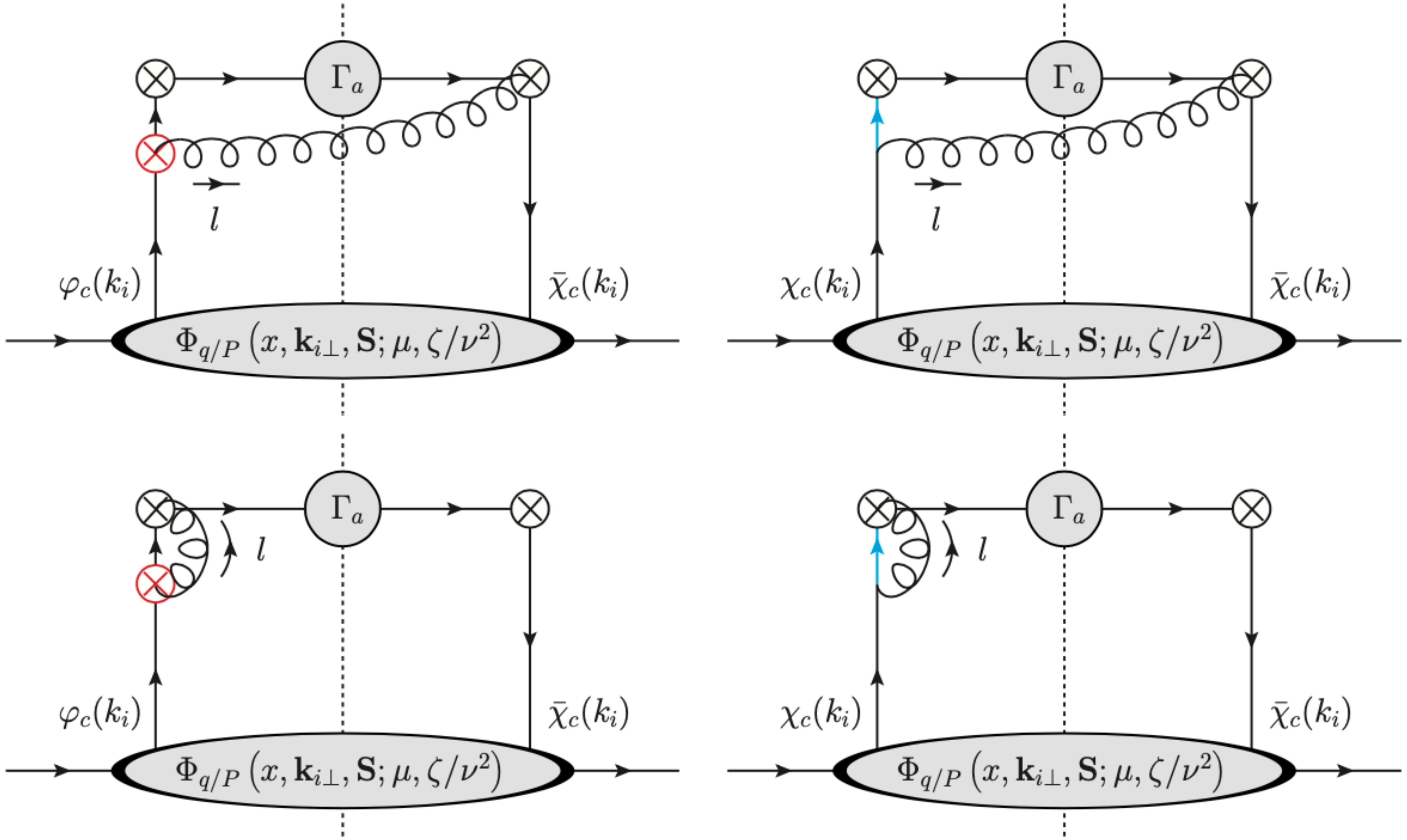
Breakdown of universality different soft function for D_1?!

$$D_1(z, b; \mu, \zeta_2) = D_1(z, b; \mu, \zeta_2/\nu)\sqrt{S^{int}}$$!!

$$D_1(z, b; \mu, \zeta_2) = D_1(z, b; \mu, \zeta_2/\nu^2)\sqrt{\mathcal{S}^{\rm LP}(b;\mu,\nu)}$$

NLP **LP**

NLO Ingredients collinear factor



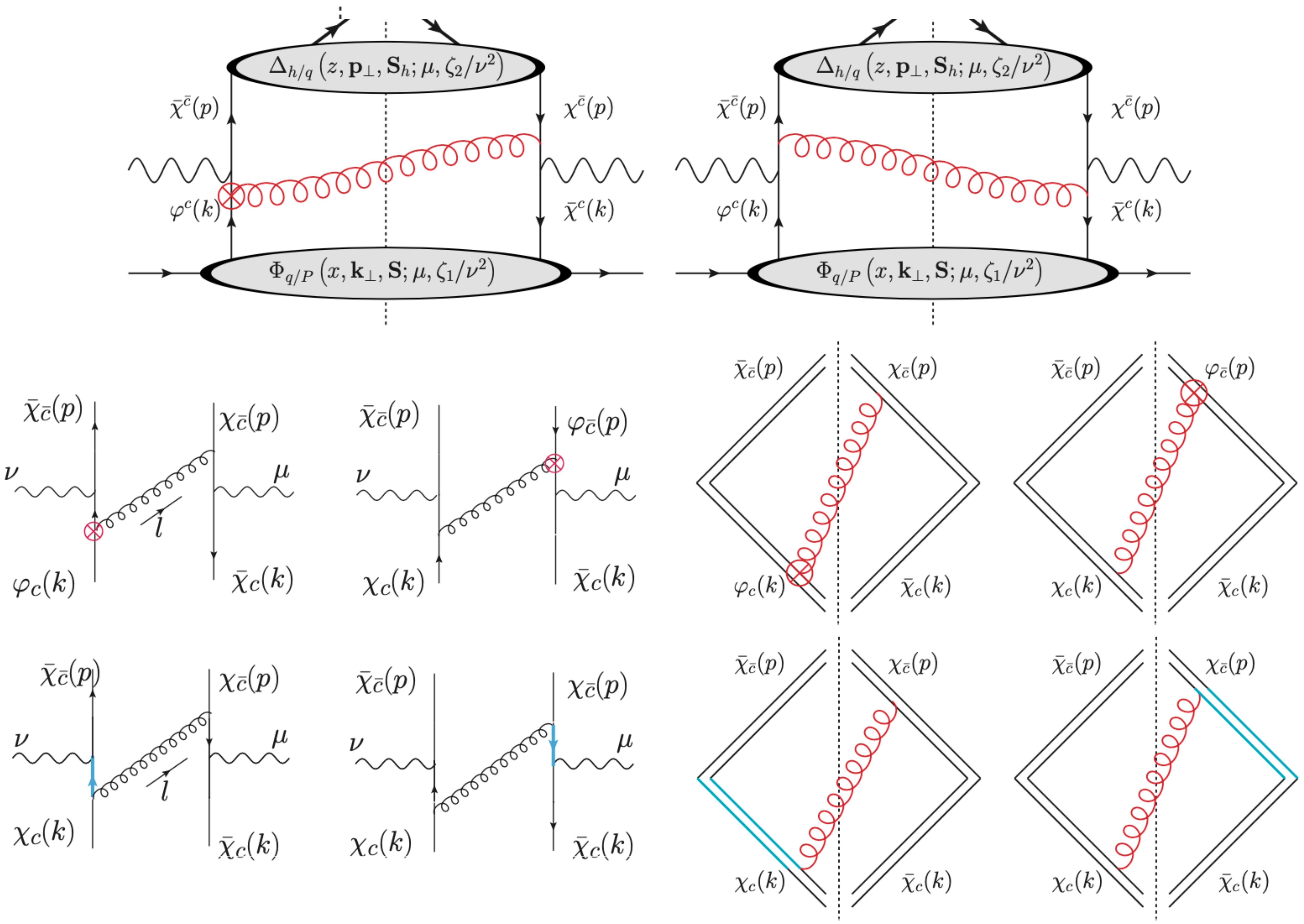
Contributions to the collinear factor from kinematic power corrections ie including the effect from the transverse momentum contributions from the transverse momentum of the quark propagators

$$\Gamma_3^{\nu\,[\mathrm{int}]}(\mu,\nu,\zeta) = \Gamma_2^{\nu}(\mu,\nu,\zeta) \qquad !!$$

NLO Ingredients soft factor

The soft region

The soft function is generated through the emissions of soft gluons in the partonic cross section



Progress Report
Stay tuned ...

Contributions to the soft factor after applying the eikonal approximation and including the effect from the transverse momentum contributions from the quark propagators.

Necessary condition RG Consistency

$$\frac{d\sigma}{d\ln\nu} = 0 \quad \& \quad \frac{d\sigma}{d\ln\mu} = 0$$

Taking into account this aforementioned modification of leading distribution by the presence of the sub- leading field, we demonstrate renormalization group consistency at one loop both RRG

$$\Gamma^{\nu}_{\mathcal{S}\,\mathrm{int}} + \Gamma^{\nu}_{3\,\mathrm{int}} + \Gamma^{\nu}_{2\,\mathrm{mod}} = 0$$

Similarly

$$\Gamma^{\mu}_{H\,\mathrm{int}} + \Gamma^{\mu}_{\mathcal{S}\,\mathrm{int}} + \Gamma^{\mu}_{3\,\mathrm{int}} + \Gamma^{\mu}_{2\,\mathrm{mod}} = 0$$

Summary

We explore sub-leading power Λ_{QCD}/Q TMDs in the context of factorization theorem

- 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
- Revisit "Cahn effect" & matching related to early picture of importance intrinsic k_T
  - *"Intrinsic"NLP TMDs related thru EOM in terms "kinematic" & "dynamical"*
- Consider RG consistency of matching to collinear factorization
  - 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 improved phenomenology of one the earliest observables used to study the intrinsic 3-D momentum structure of the nucleon—important observables EIC study of nucleon