Spin and 3D structure: theoretical advances

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DIS2026, Bologna, 4 May 2026

HELMHOLTZ

special thanks to J Blümlein, V Braun, Y Ji, G Marinelli, M Schlegel, A Vladimirov, W Vogelsang, and F Wunder for helpful discussions or correspondence

Setting the scene

The big questions and our Cast of characters

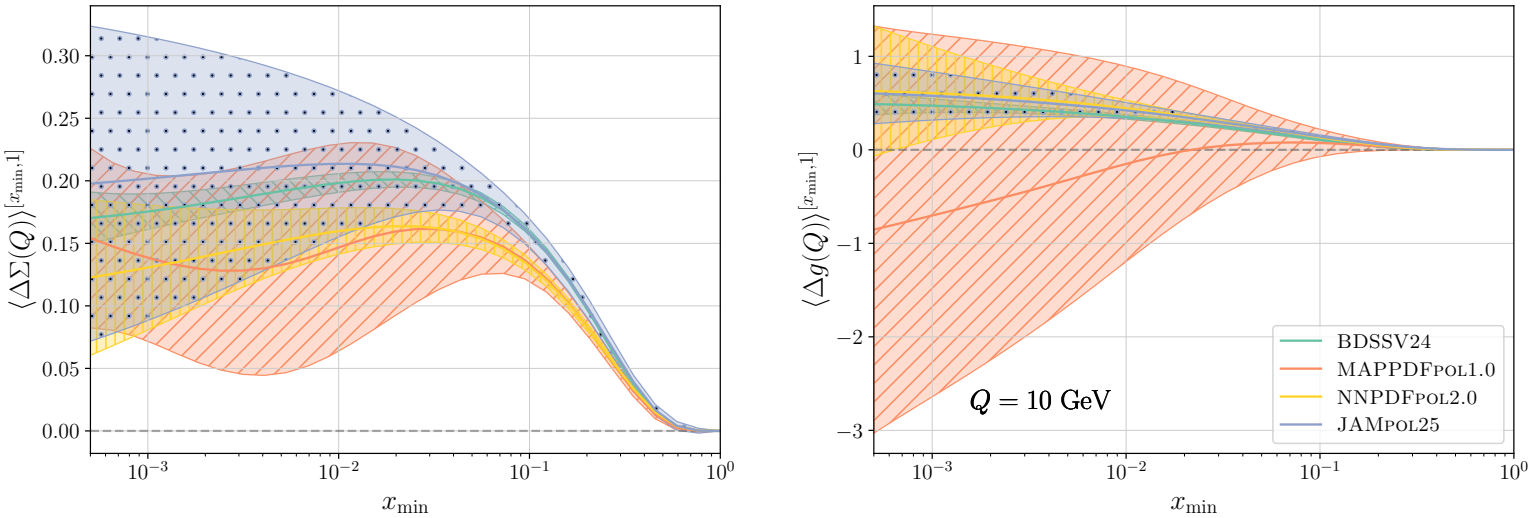
- hadron structure in 1 longitudinal + 2 transverse dimensions
  - TMDs: longit. mom. fraction x and transverse mom. k_T of partons
  - GPDs: longit. mom. fractions x, ξ and transverse mom. transfer Δ_T
    $\overset{\text{Fourier trf}}{\longrightarrow}$ transverse location b_T of partons
    $\overset{\text{sum rules}}{\longrightarrow}$ form factors of e.m. current and energy-momentum tensor
- spin and orbital angular momentum
  - polarised collinear (k_T integrated) PDFs
  - polarised TMDs (k_T) and GPDs (Δ_T) can correlate spin with orbital motion
- twist-three distributions
  - express quantum interference (scatter on one vs. two partons)
  - responsible for many spin phenomena
  - close connection with TMDs

other quantities e.g. GTMDs (x, ξ, k_T, Δ_T) or double parton distributions not discussed here for lack of time

Polarised PDFs

- first polarised PDFs at NNLO in 2024–25:
  MAPPDFPOL1.0, BDSSV24, NNPDFPOL2.0
  new NLO extraction JAMPOL25 → W Melnitchouk Wed 15:10

  contribution to proton spin of quarks or gluons with $x \geq x_{\text{min}}$:



plots from "Precision QCD with the Electron-Ion Collider", arXiv:2604.04765

- full NNLO cross sections for SIDIS computed in 2023–25
  Goyal et al, arXiv: 2312.17711, 2404.09959, 2510.18872,
  Bonino et al, arXiv:2401.16281, 2404.08597, 2506.19926, 2510.00100
  full NNLO not yet available for hadron or jet production in polarised pp

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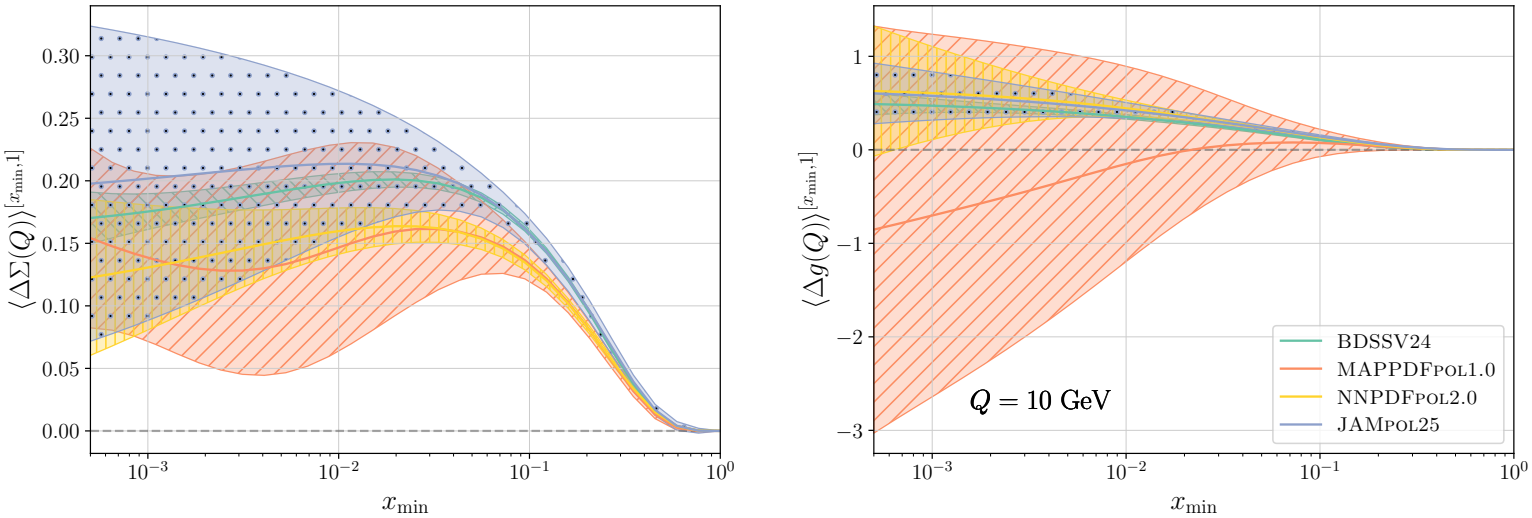


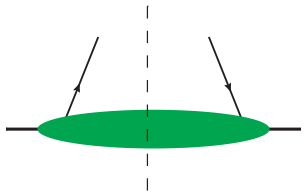
plots from "Precision QCD with the Electron-Ion Collider", arXiv:2604.04765

- available for future analyses: 3-loop heavy quark effects in inclusive DIS and 3-loop matching of PDFs across flavour thresholds
  Ablinger et al, arXiv:2509.16124, 2510.02175, 2510.09403 → backup slides

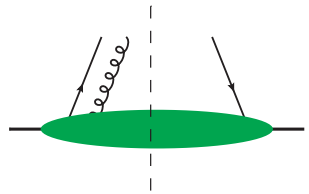
Twist three reminders and news

- contributes to observables down by one factor $1/Q$ w.r.t. leading term
  typically spin or angular asymmetries
- twist-3 distributions come in two forms:

two parton fields with subleading combination of Dirac or Lorenz indices



three parton fields: quantum interference in parton number



- 2-parton distributions of twist 3:
  - one mom. fraction x $\rightarrow$ simpler to model
  - often sufficient to describe an observable at LO
  - but: mix with 3-parton distributions under scale evolution
  - using field equations of motion can rewrite as
    terms with twist-2 distributions + terms with 3-parton distributions
    called "Wandzura-Wilczek part"

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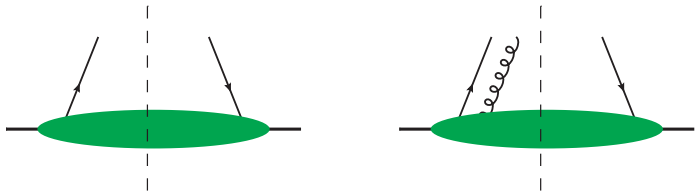


3-parton distributions:

- two mom. fractions x_1, x_2 $\rightarrow$ harder to model
- typically appear in NLO corrections
- have autonomous scale evolution fully known at LO
  recent: public evolution codes for 3-parton distributions
  Rodini, Rossi, Vladimirov arXiv:2405.01162
- new extraction from data: arXiv:2511.04294 $\rightarrow$ A Vladimirov Wed 17:25

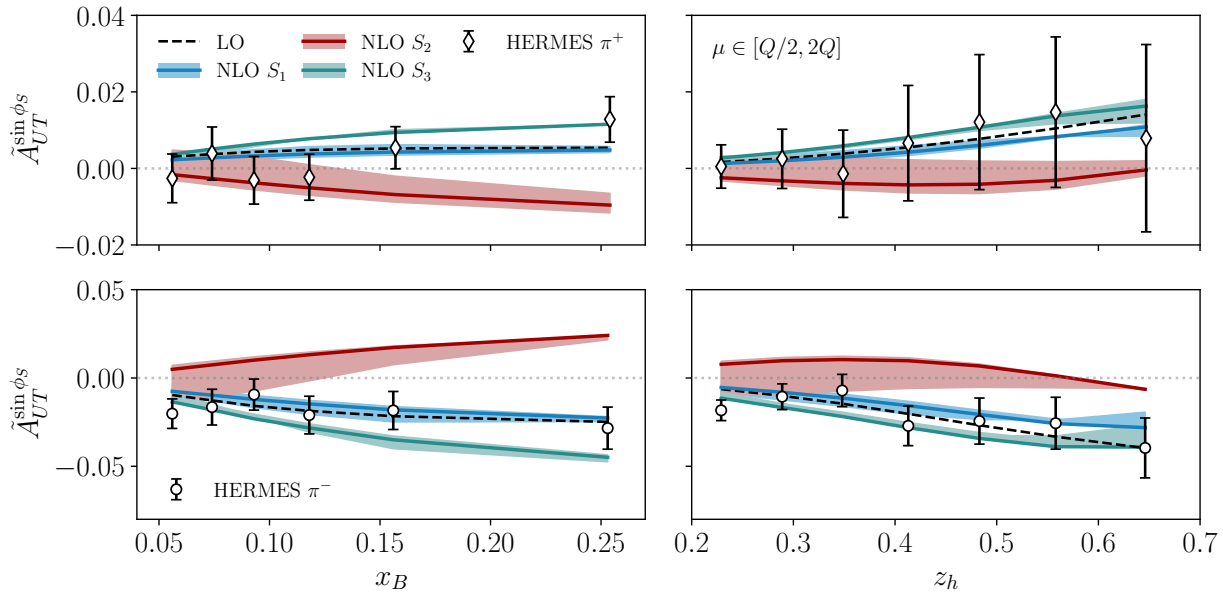
- analogous discussion for fragmentation functions (but no evolution code)

Twist three: NLO effects

Scantamburlo, Schlegel arXiv:2603.10628

$P_{h\perp}$-integrated SIDIS: transverse target spin asymmetry $A_{UT}^{\sin\phi_S}$:

- LO: transversity PDF $h_1(x)$ × twist-three fragmentation fct. $\tilde{H}(z)$
- at NLO: divergences in hard-scattering graphs correctly cancel ✓
  is important check since have no all-order factorisation theorem here
  NLO contribution from twist-3 PDF × unpol. twist-2 FF not yet included
- numerical estimate with three models for twist-3 FFs depending on z_1, z_2
  all giving same LO result, consistent with $\tilde{H}(z)$ of JAM3D (arXiv:2205.00999)



- LO: dashed curve
- NLO: three bands for 3 FF models

NLO corrections may be sizeable and even reverse sign of asymmetry

plots from arXiv:2603.10628 bands from scale variation $\mu \in [Q/2, Q]$

Twist three: more work at NLO

- Rein et al. arXiv:2503.16119

  transverse target spin asymmetry in $\ell p^\uparrow \to h X$ or $\ell p^\uparrow \to \text{jet}\, X$

  with high $P_{h\perp}$, unobserved scattered lepton

  also find that NLO contributions may be large

Transverse Momentum Distributions

- several new extractions of unpolarised TMDs in 2024-25

  see also B Pasquini's plenary at DIS 2025

  - MAP Collab. arXiv:2502.04166
    "A Neural-Network Extraction of Unpolarised Transverse-Momentum-Dependent Distributions" → A Bacchetta Tue 9:00
    use NNs to parametrise nonpert. part of TMDs in (x, b_T)
  - Kang et al. arXiv:2604.14133
    "AI-assisted modeling and Bayesian inference of unpolarized quark transverse momentum distributions from Drell-Yan data"
  - JAM Collab. arXiv:2510.13771
    "First simultaneous analysis of transverse momentum dependent and collinear parton distributions in the proton"
    fit 35 parameters for PDFs + 12 for TMDs
  - Avkhadiev et al. arXiv:2510.26489v1
    → wait a few minutes

- all analyses still reduced in scope (e.g. without SIDIS data)
  but pushing forward extraction methods in a complex environment
  $\rightsquigarrow$ important proofs of feasibility

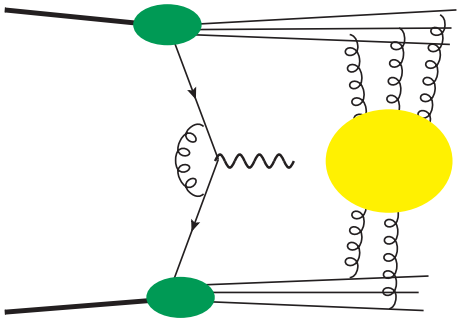
A closer look at TMDs some reminders

- variables: $f_a(x, k_T; \mu, \zeta) \overset{\text{Fourier trf}}{\longrightarrow} f_a(x, b_T; \mu, \zeta)$
  impact parameter b_T not the same as in GPDs (where $b_T \leftrightarrow \Delta_T$)
- μ dependence: $\partial f_a / \partial \ln \mu = \gamma_K(\alpha_s)\, \ln\big(\mu/\sqrt{\zeta}\big) + \gamma_a(\alpha_s)$ $\qquad (a = q, g)$
  γ_K is known at $\mathcal{O}(\alpha_s^5)$ and γ_a at $\mathcal{O}(\alpha_s^4)$
- rapidity parameter ζ specifies rapidity range of soft gluons inside the TMD

  Collins-Soper equation also called "rapidity RGE"

$$\frac{\partial}{\partial \ln \sqrt{\zeta}}\, f_a = K_a(b_T; \mu) \cdot f_a(x, b_T; \mu, \zeta)$$

- Collins-Soper kernel $K_a(b_T, \mu)$: $\qquad (a = q, g)$

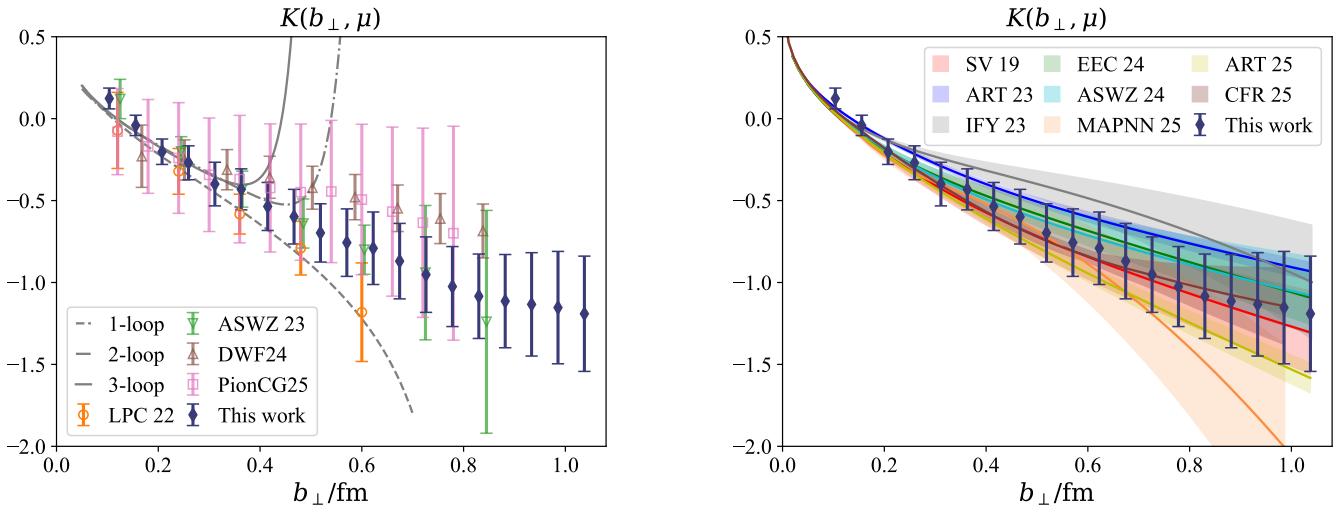


- physics: soft gluon exchange between spectator partons in DY or SIDIS process
  larger $\zeta \leftrightarrow$ more longitudinal phase space for this
- defined as VEV of Wilson line operators
  $\Rightarrow$ highly universal
  indep.t of polarisation and hadron species
  only differs between quarks and gluons

Collins-Soper kernel

$$\partial f_a / \partial \ln \sqrt{\zeta} = K_a(b_T;\mu) \cdot f_a(x, b_T;\mu,\zeta)$$

- at small b_T computed in perturbation theory up to $\mathcal{O}(\alpha_s^4)$
  at large b_T non-perturbative, lattice determinations of K_q since $\sim$ 2023
- several new studies: Bollweg et al. arXiv:2504.04625,
  Alexandrou et al. arXiv:2509.26316, Tan et al. arXiv:2511.22547
  extract from $\langle \pi | \mathcal{O}_{\text{TMD}}(b_T) | \text{vac} \rangle$ using universality of CS kernel

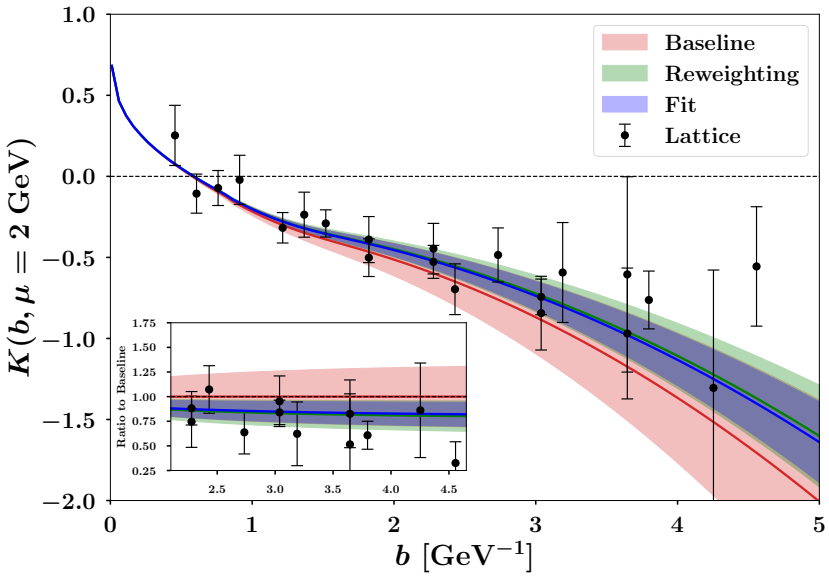


$\mu = 2\,\text{GeV}$; plots from arXiv:2511.22547

- $K(b_T) < 0$ at large b_T $\Rightarrow$ if increase ζ and hence rapidity range
  $\Rightarrow$ TMD narrower in b_T $\Rightarrow$ broader in k_T

Collins-Soper kernel

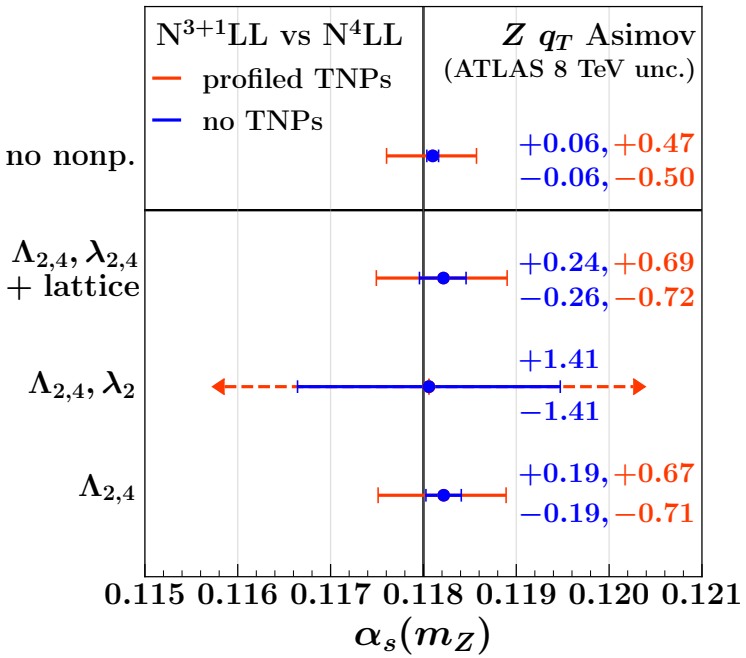
- joint determination of CS kernel from experiment and lattice data
  Avkhadiev et al. arXiv:2510.26489
  - use previous lattice data from MIT group (2023-24) and setup of MAP2025 TMD fit
  - consistent results between reweighting fitted TMDs with lattice data and joint fit experiment and lattice data
  - lattice input shifts CS kernel by $\sim 10\%$ and decreases its error by $\sim 50\%$



plot from arXiv:2510.26489 "Baseline" = without lattice, "Fit" = with lattice data

p_T spectrum in Z production: TMDs and α_s

- Cridge, Marinelli, Tackmann arXiv:2506.13874:
  study α_s sensitivity of Z p_T spectrum in pp collisions
  motivated by ATLAS α_s extraction arXiv:2309.12986
- perform various fits to pseudodata in kinematics of ATLAS 8 TeV measurement ($m_{\ell\ell} \in [80, 100]\,\text{GeV}$, $q_T \in [0, 29]\,\text{GeV}$, $Y \in [0, 3.6]$)



plot from arXiv:2506.13874

- non-perturbative parameters:
  λ_2, λ_4 for CS kernel
  Λ_2, Λ_4 for TMDs
- including these parameters in fit affects α_s uncertainty
- find poor α_s sensitivity if fit λ_2 without further constraints
  no stable fit if also include λ_4
  NB: fit has little lever arm in $\zeta = m_{\ell\ell}^2$
- much better α_s sensitivity if include lattice input for CS kernel

see also: T Cridge, WG1, Wed 16:30

SIDIS in TMD factorisation i.e. with measured $P_{h\perp} \ll Q$

- leading power: all-order factorisation proof Collins, Soper, Sterman
- $1/Q$ terms (e.g. $F^{\cos\phi_h}$): emerging full twist-3 description
  Vladimirov et al. 2021-23; Ebert, Gao, Stewart 2021; Gamberg et al. 2022
- $1/Q^2$ terms (e.g. F_L, corrections to F_T and $F^{\cos(2\phi_h)}$)
  not known whether factorisation holds or is broken
- new results for kinematic power corrections
  - capture a part of $1/Q$ and $1/Q^2$ suppressed contributions that involves the same twist-2 TMDs as the leading-power terms
  - two studies in different frameworks:
    Piloñeta, Vladimirov arXiv:2510.14496
    Balitsky, Prokudin arXiv:2601.188882
    earlier results for Drell-Yan: arXiv:2407.07277, arXiv:2404.15116
  - results differ (to be expected)

short notation for struct. fcts: $F_L \leftrightarrow \gamma_L^*$, $F_T \leftrightarrow \gamma_T^*$, with unpol. beam and target

more detail on backup slides

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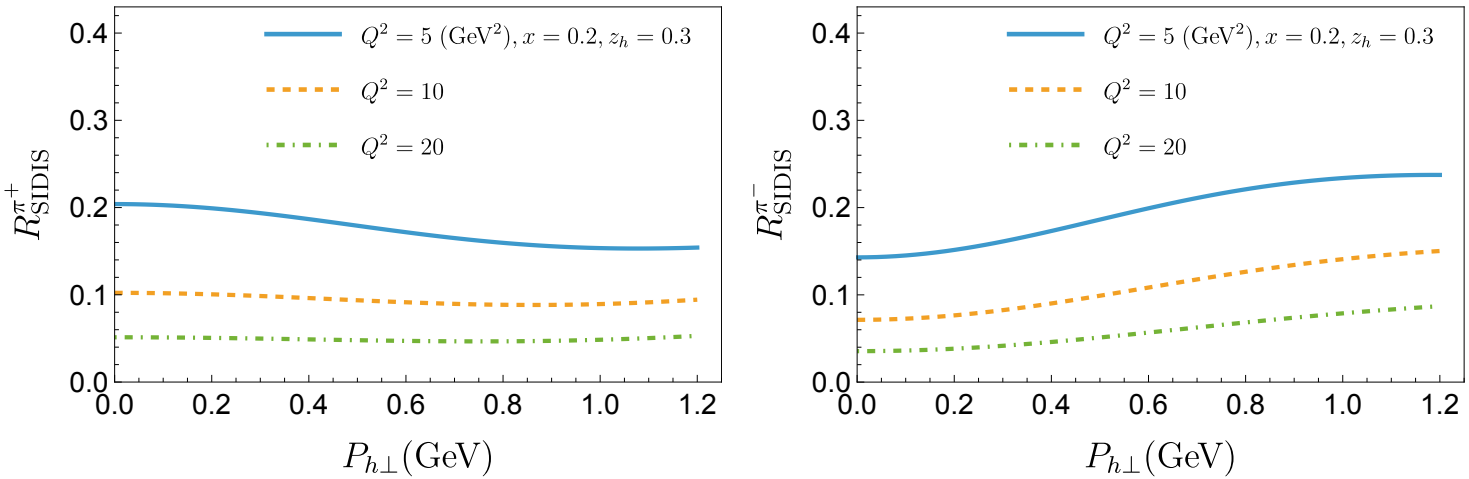
  not known whether factorisation holds or is broken
- new results for kinematic power corrections
  - estimate for $R = F_L/F_T$: sizeable although of order $1/Q^2$



plots from Balisky, Prokudin, arXiv:2601.18882

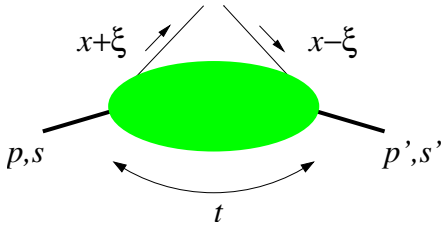
More TMD related work

headline-style no claim to completeness

- "Gluon splitting at small x: a unified derivation for the JIMWLK, DGLAP and CSS equations"
  Caucal, Iancu, Salazar, Yuan arXiv:2510.08454
- "NeoPDF: a fast interpolation library for collinear and transverse momentum-dependent parton distributions"
  Rabemananjara, arXiv:2510.05079
  use Chebyshev polynomials for accurate interpolation with moderate-size grids
- SIDIS on spin 1 targets
  Zhao et al. arXiv:2508.06134 → J Zhao Wed 10:10
  Cosyn, Weiss arXiv:2603.23699, 2603.23700
- SIDIS with jets
  Jaarsma et al. arXiv:2507.03072
- access TMDs using energy correlators
  Bhattacharya et al. arXiv:2504.10475; Cao et al. arXiv:2509.18892;
  Guo et al. arXiv:2512.15896
  Gao et al. arXiv:2509.15809 → W Li Wed 15:30

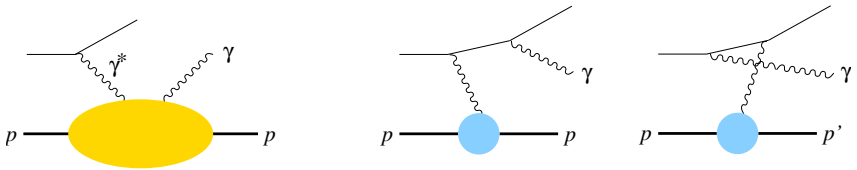
GPDs some reminders

- appear in process amplitudes, depend on



  - two momentum fraction variables x, ξ
  - invariant mom. transfer $t \leftrightarrow$ transverse. part Δ_T $\rightarrow$ impact parameter $b_T \rightsquigarrow$ parton imaging
  - scale μ: evolution kernels fully known at two loops

- theory most advanced for Compton scattering processes
  - DVCS (deeply virtual Compton scattering) : $\gamma^* p \to \gamma p$ in $\ell p \to \ell \gamma p$



Compton scattering interferes with Bethe-Heitler process

  - TCS (timelike Compton scattering) : $\gamma p \to \gamma^* p$ in $\gamma p \to \ell^+ \ell^- p$
  - double DVCS : $\gamma^* p \to \gamma^* p$ in $e p \to e \, \ell^+ \ell^- p$

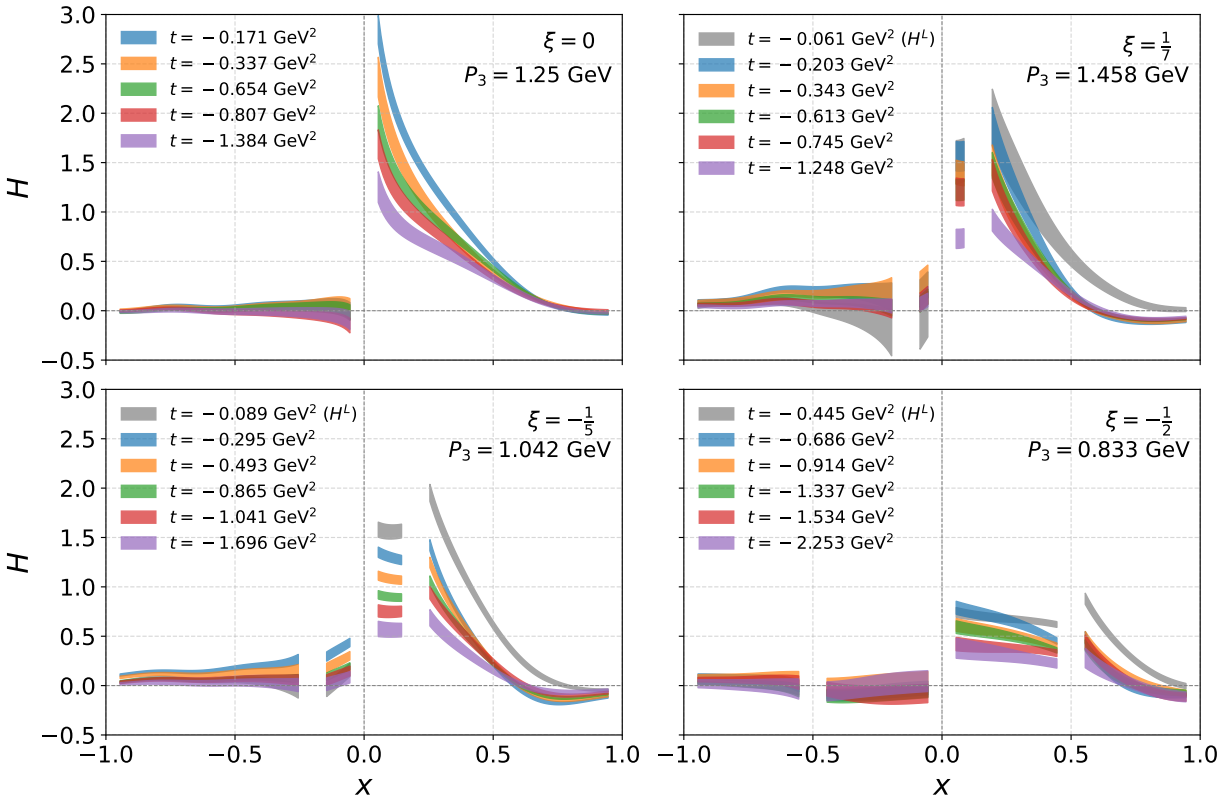
  at leading power in $1/Q$:
  - all-order factorisation theorem Collins, Freund hep-ph/9801262
  - hard scattering computed at NLO for all channels
  - full NNLO for DVCS: Braun et al. 2021-22; Y Ji, Schönleber 2023

GPDs on the lattice

- x dependence accessible with pseudo- or quasi-distributions
  new results for nonzero ξ:

  Gao et al. arXiv:2511.01818: extract x-moments up to x^4

  Chu et al. arXiv:2508.17998:

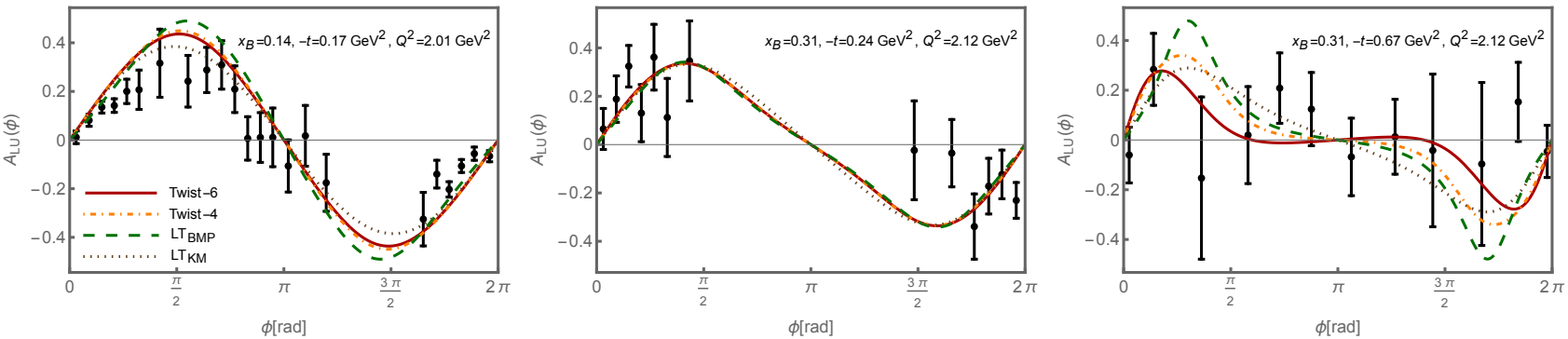


- plots show
  $H^u - H^d$
  at $\mu = 2\,\mathrm{GeV}$
- see shape in x changing with t
- method breaks down around
  $x = 0$
  $x = \pm\xi$
  $x = \pm 1$

plots from arXiv:2508.17998; $m_\pi \approx 260\,\mathrm{MeV}$, $H^L = H - \frac{\xi^2}{1-\xi^2} E$ shown at $t = t_{\mathrm{min}}$

DVCS beyond leading power in $1/Q$

- $1/Q$-suppressed amplitudes (γ_L^*) seen in angular modulations
  Schönleber, Szafron arXiv:2407.09263: all-order factorisation, including twist-3 GPDs
- new study on kinematic power corrections (involving only twist-2 GPDs) up to order $1/Q^4$ results for all helicity amplitudes with spin 1/2 hadron
  Braun, Y Ji, Manashov arXiv:2501.09185
- have corrections in $\xi m_{\text{target}}/Q$ and Δ_T/Q
  wide reach in Δ_T essential for imaging since spatial resolution $\sim 1/\Delta_{T\text{max}}$
- find $1/Q$ expansion stable up to $|t|/Q^2 \lesssim 1/4$



plots from arXiv:2501.08185 data: CLAS12 beam spin asymmetry arXiv:2211.11274

Twist 6 $\leftrightarrow 1/Q^4$, Twist 4 $\leftrightarrow 1/Q^2$, LT $\leftrightarrow 1/Q^0$ in two different reference frames

More GPD related work

headline-style no claim to completeness

- kinematic power corrections
  - for TCS on spin-0 targets Martínez-Fernández et al. arXiv:2503.02461
  - in DVCS dispersion relations Martínez-Fernández, Mezrag arXiv:2509.05059
- connection to small-x: dipole amplitudes etc.
  Kovchegov et al. arXiv:2512.10086, 2604.24629 role of ξ in BK/JIMWLK evol.
  Bhattacharya et al. arXiv:2510.02254; Benić et al. arXiv:2603.06092
- GPD models and fits to data
  Dotson et al. arXiv:2504.13289; Hechenberger et al. arXiv:2508.00817;
  Guo et al. arXiv:2509.08037; Garcia Vallejo, Sievert arXiv:2510.15838;
  Panjsheeri et al. arXiv:2511.03065; Morgado-Chávez et al. arXiv:2603.17496;
  Martínez-Fernández et al. arXiv:2604.25677 → J Wagner Wed 11:15
- exclusive dijets $ep \to e +$ dijet $+ p$ with GPDs
  Hatta, Schönleber arXiv:2511.04537; Chall et al. arXiv:2603.09686
  heavy quarks: Fucilla, Hatta arXiv:2509.05267 → M Fucilla Thu 12:35
- new choice of azimuthal angle to analyse DVCS
  Qiu, Sato, Yu arXiv:2511.20402 → backup slides

Summary — where do we stand? just a personal assessment

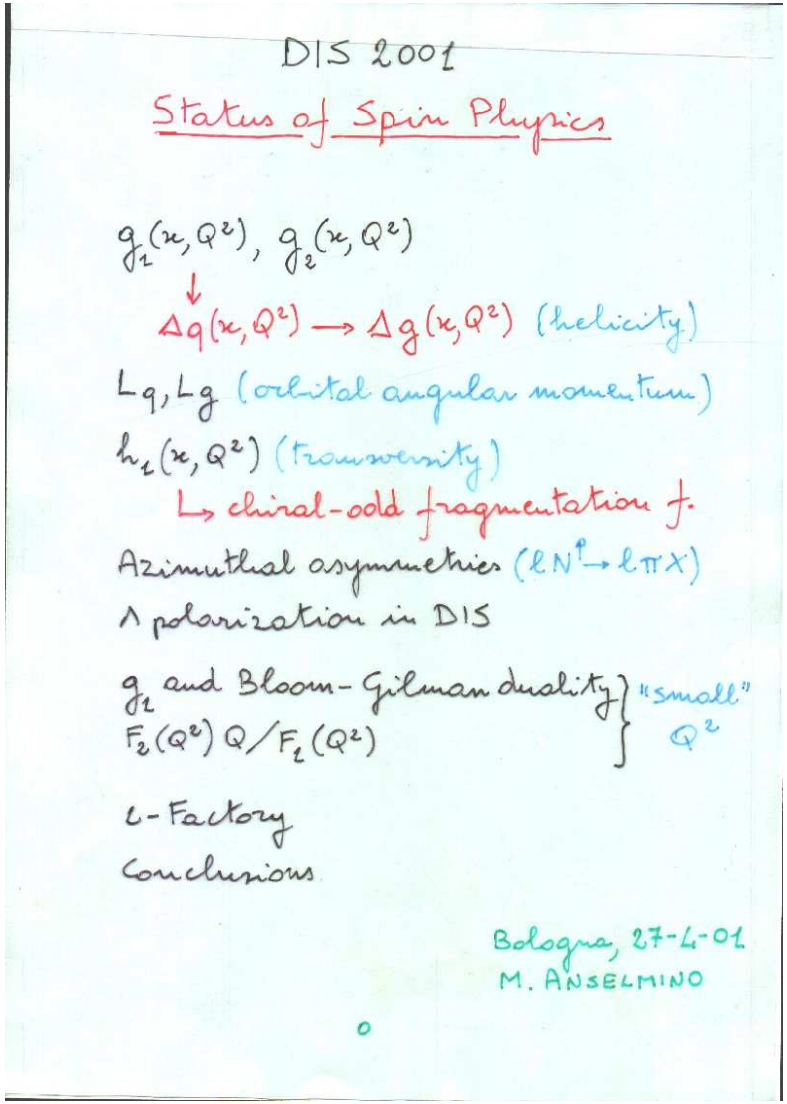
- helicity dependent PDFs: higher orders and mass effects
  moving towards full NNLO extractions, and to N^{3}LO for DIS
  EIC data will be crucial to reduce uncertainties from small x
- twist-3 distributions: new NLO results
  NLO may well be essential for stable phenomenological extractions
  important progress with numerical tools, but more work needed
  phenomenology will greatly profit from precise EIC data
- TMDs:
  unpolarised analyses $\longrightarrow$ high precision and advanced methodology
  enabled and required by precise data (esp. Z p_T from LHC)
  for polarised TMDs many studies still limited by precision of data

Summary — where do we stand? just a personal assessment

- TMDs and GPDs:
  - progress on lattice methods and simulations
    $\rightsquigarrow$ results impact phenomenology
  - new results on kinematical power corrections
    often sizeable in kinematics of current and future data
    how much of the "full result" do these corrections capture?
  - full twist-3 frameworks becoming available
    but still have very little experience with their phenomenology
  - fresh ideas for new observables, e.g. energy correlators
  - progress in relating TMDs and GPDs with small-x physics and methods

Where did we stand 25 years ago?

talk by M Anselmino at DIS 2001



DIS 2001

Status of Spin Physics

$g_1(x,Q^2)$, $g_2(x,Q^2)$

↓

$\Delta q(x,Q^2) \longrightarrow \Delta g(x,Q^2)$ (helicity)

L_q, L_g (orbital angular momentum)

$h_1(x,Q^2)$ (transversity)

↳ chiral-odd fragmentation f.

Azimuthal asymmetries ($\ell N^\uparrow \to \ell \pi X$)

Λ polarization in DIS

g_2 and Bloom-Gilman duality } "small" Q^2

$F_2(Q^2)\, Q/F_L(Q^2)$ }

e-Factory

Conclusions

Bologna, 27-4-01

M. ANSELMINO

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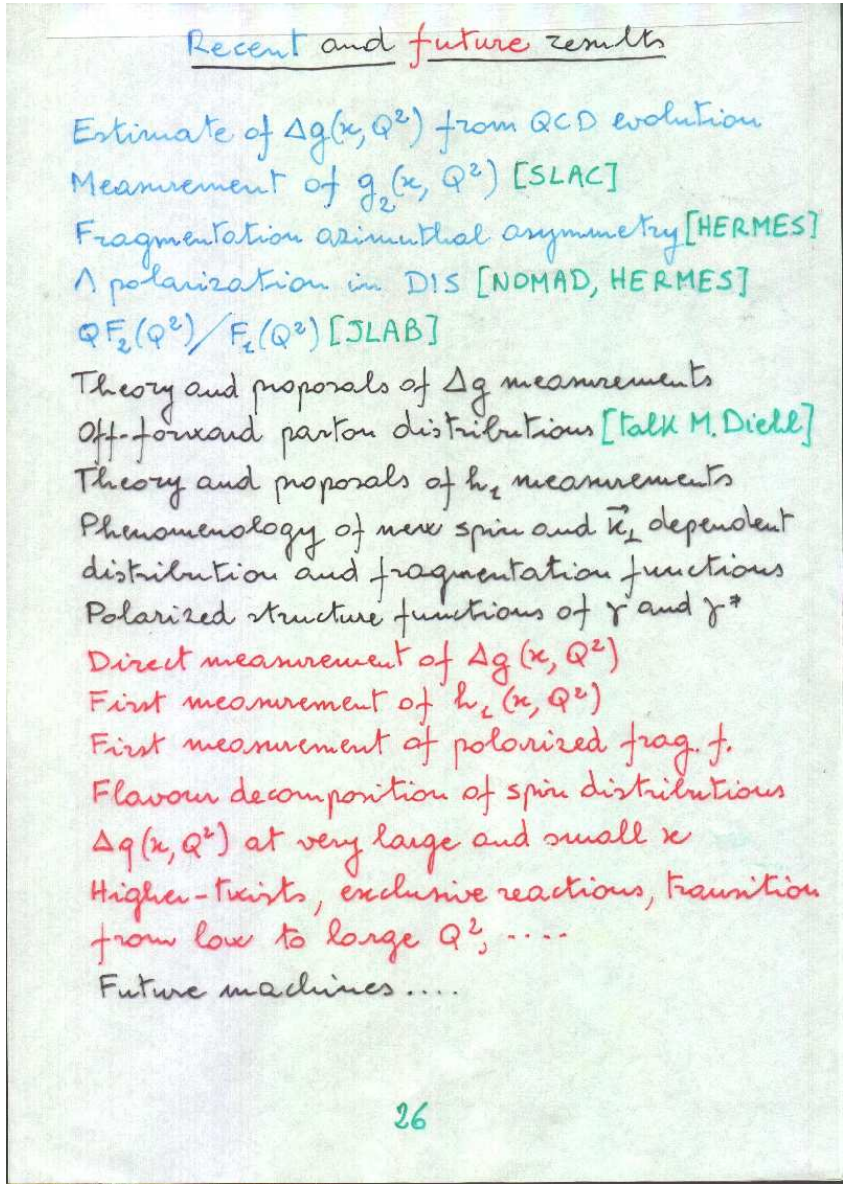


Recent and future results

Estimate of $\Delta g(x,Q^2)$ from QCD evolution

Measurement of $g_2(x,Q^2)$ [SLAC]

Fragmentation azimuthal asymmetry [HERMES]

Λ polarization in DIS [NOMAD, HERMES]

$QF_2(Q^2)/F_L(Q^2)$ [JLAB]

Theory and proposals of Δg measurements

Off-forward parton distributions [talk M. Diehl]

Theory and proposals of h_1 measurements

Phenomenology of new spin and $\vec{k}_\perp$ dependent distribution and fragmentation functions

Polarized structure functions of γ and γ^*

Direct measurement of $\Delta g(x,Q^2)$

First measurement of $h_1(x,Q^2)$

First measurement of polarized frag. f.

Flavour decomposition of spin distributions

$\Delta q(x,Q^2)$ at very large and small x

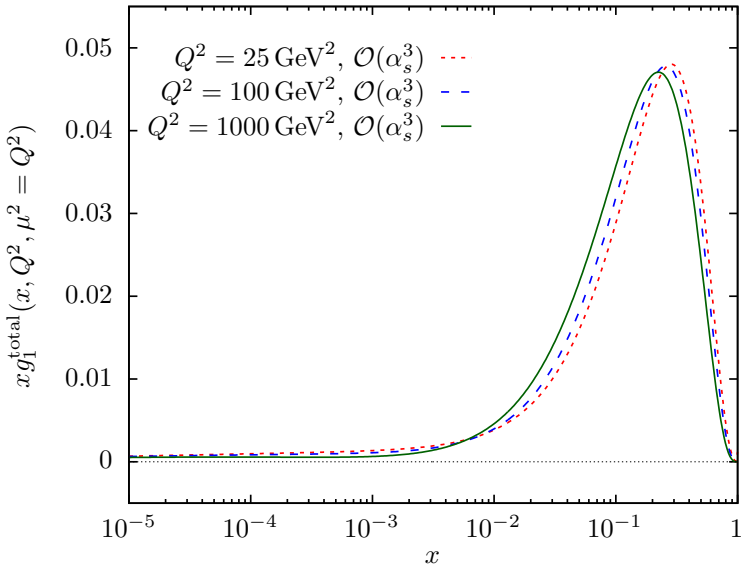
Higher-twists, exclusive reactions, transition from low to large Q^2, ...

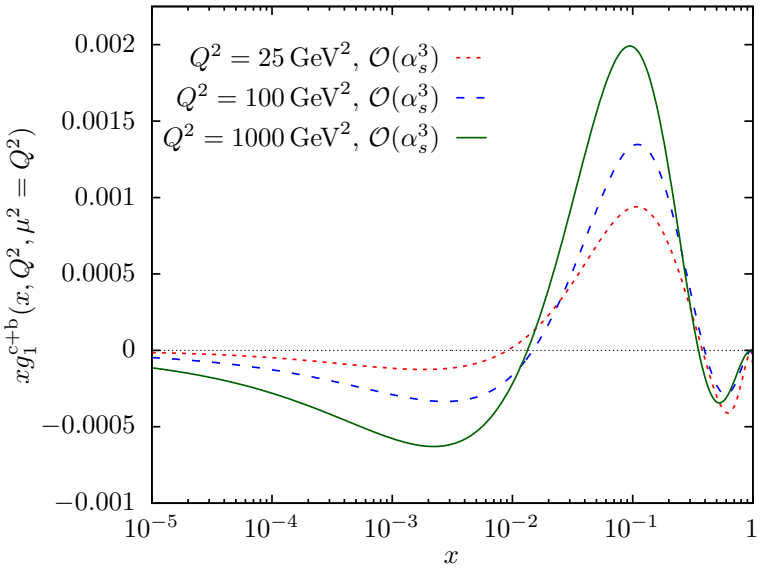
Future machines ....

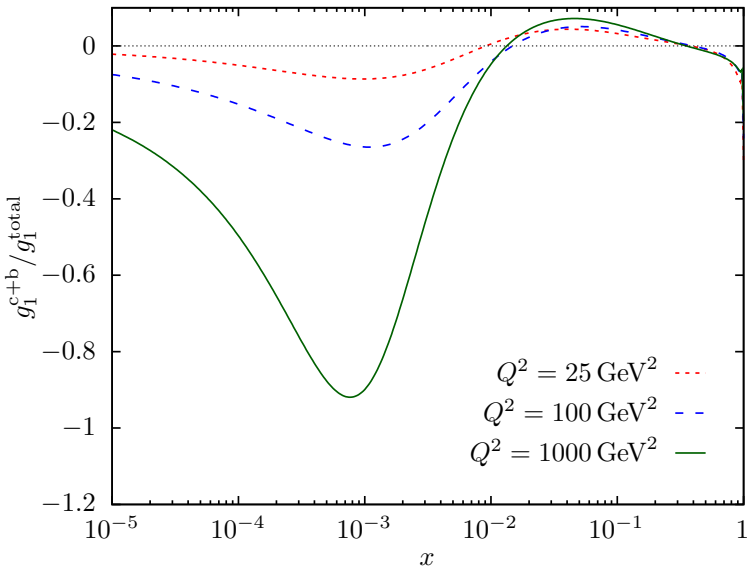
26

link: https://www.bo.infn.it/dis2001/program.html

Heavy-quark contribution to polarised structure function g_1







$g_1(x, Q^2)$ computed up to $O(\alpha_s^3)$
total and contributions from $c + b$

plots from Ablinger et al. arXiv:2509.16124

Kinematic variables and structure functions in SIDIS

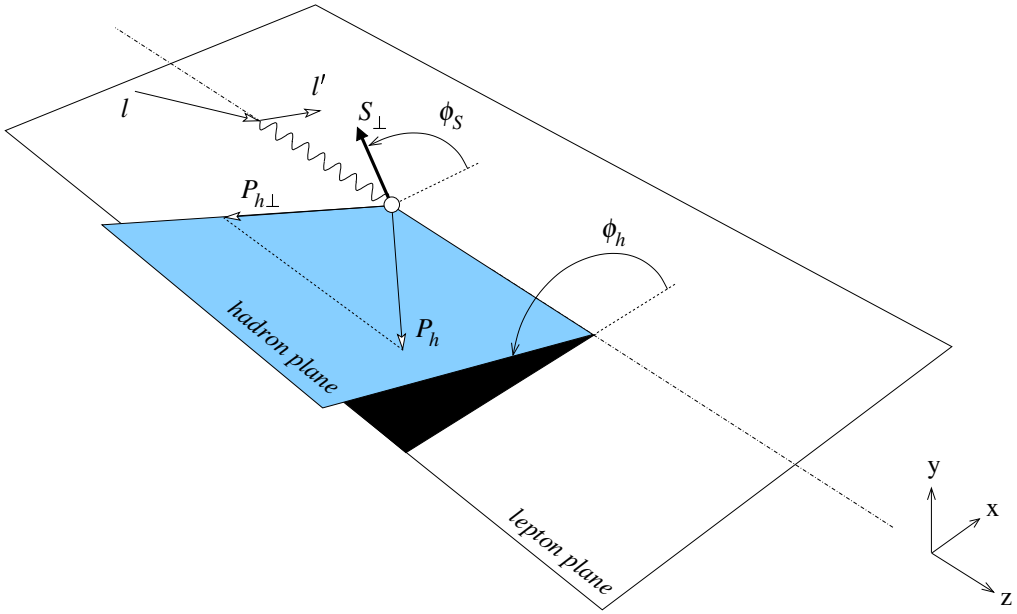


figure from: "Single-spin asymmetries: the Trento conventions" hep-ph/0410050

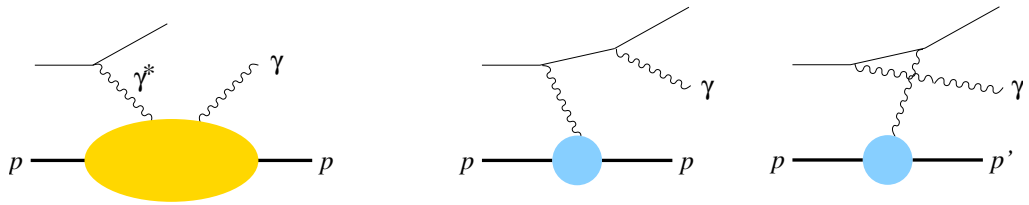
notation for SIDIS structure functions:

e.g. $F_{LT}^{\cos(\phi_h - \phi_S)}$: Longitudinal lepton and Transverse target polarisation, angular modulation with $\cos(\phi_h - \phi_S)$

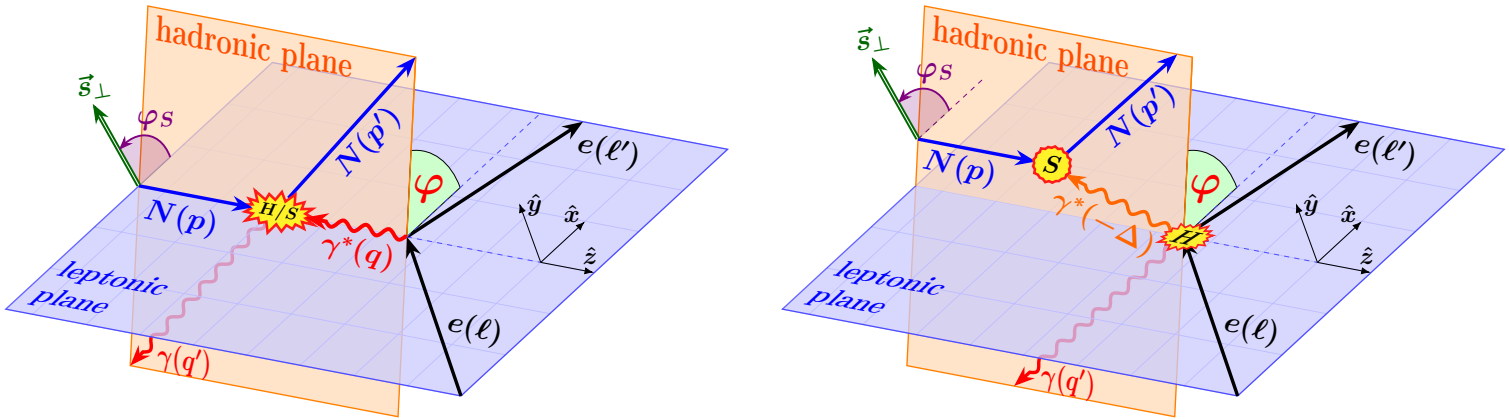
$F_{UU,T}$, $F_{UU,L}$: Unpolarised lepton and target, γ_T^* or γ_L^*

Analysis of DVCS

Qiu, Sato, Yu arXiv:2511.20402



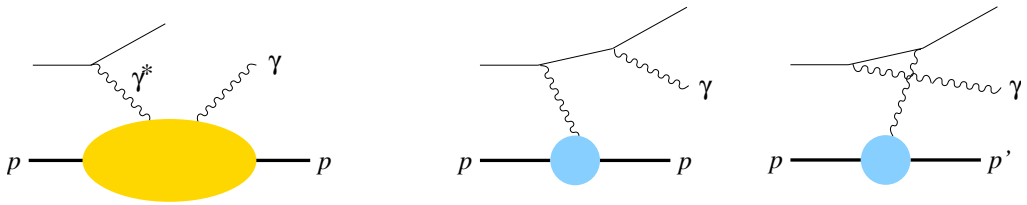
- standard set of kinematical variables include angle φ defined in $\gamma^* p$ c.m. (or equivalently in Breit frame)
  - DVCS amplitudes $\mathcal{A}(\xi, Q^2, t)$ are independent of φ ✓
  - but: complicated φ dependence of Bethe-Heitler process



figures from arXiv:2511.20402

Analysis of DVCS

Qiu, Sato, Yu arXiv:2511.20402



- proposal by Qiu et al: trade standard φ for angle ϕ defined in "SDHEP" frame (Single Diffractive Hard Exclusive process)
  - simple ϕ dependence of Bethe-Heitler process ✓

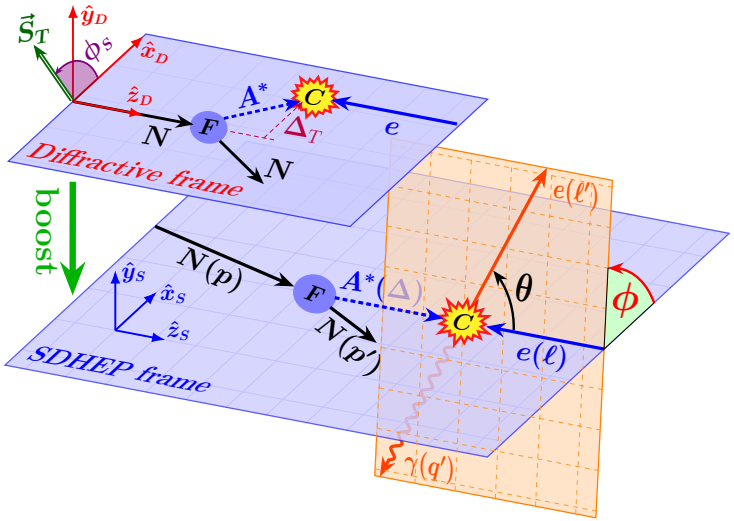


figure from arXiv:2511.20402

- DVCS amplitudes also depend on ϕ
- but dependence becomes a simple $e^{im\phi}$ in the $1/Q$ expansion
- at each step in the $1/Q$ expansion cross sect. has simple harmonic dependence with $\cos(k\phi)$, $\sin(k\phi)$ $0 \le k \le 2$ for most important terms