Theory Perspectives on Electromagnetic Hadron Physics

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Deutsches Elektronen-Synchrotron DESY

EINN2023, Paphos, Cyprus, 31 October 2023

HELMHOLTZ

DESY.

Topics at this meeting (incomplete)

electroweak precision measurements

$(g-2)_\mu$

dark matter searches

QCD phase diagram

nucleon spin

PDFs

spectroscopy

TMDs

nuclear effects

GPDs

generalised polarisabilities

form factors

dispersion relations

fragmentation functions

jets

EIC

lattice

machine learning

CEBAF

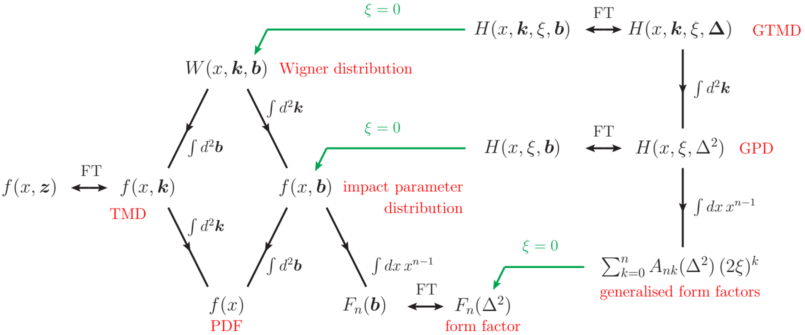
AMBER

quantum computing

too diverse and too many topics to review in this talk
will focus on a subset of closely related topics

apologies if your favourite subject / publication / plot is missing

Mapping the structure of the nucleon

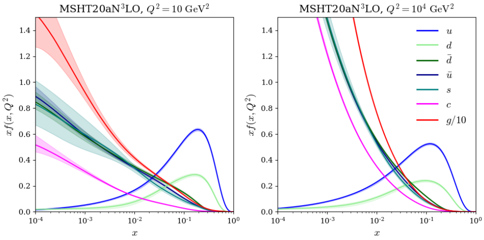


- here focus on PDFs, TMDs, GPDs, and (generalised) form factors

more on the relation between different functions → backup slides

PDFs: not the end of a story

J McGowan et al
arXiv:2207.04739



- study of PDFs has become an area of precision physics
  driven by the needs of interpreting measurements at LHC and elsewhere
  uncertainty estimates are a major undertaking → talk P Nadolsky (Wed)
- but important aspects remain poorly known
  - large x behaviour
  - strangeness (s and $\bar{s}$) distributions
  - gluon at small x
  - important intrinsic charm component? → talk G Magni (Wed)
  - polarised distributions
    esp. sea quarks and gluon at small x → talk W Vogelsang (today)
  - nuclear distributions, esp. at small x

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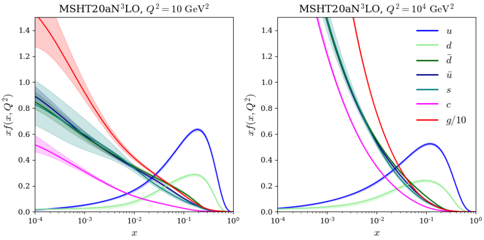
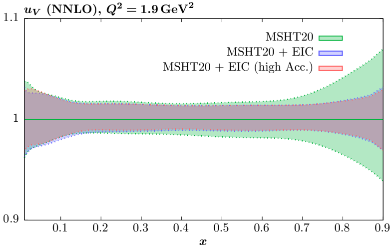


- EIC expected to be a game changer for polarised and nuclear PDFs but may even be valuable for unpolarised PDFs in proton

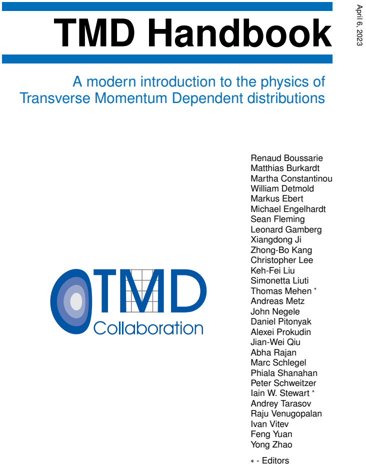


PDF uncertainty w.r.t. MSHT20 central fit

impact study for inclusive DIS at EIC
N Armesto et al, arXiv:2309.11269

Transverse parton momentum: TMDs

new: comprehensive review
arXiv:2304.03302, 471 pages


April 6, 2023

TMD Handbook

A modern introduction to the physics of
Transverse Momentum Dependent distributions

Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

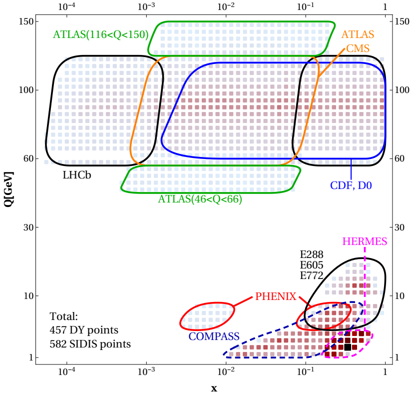
* - Editors

TMD Collaboration

talks by
V Moos, L Gamberg, P Zurita (today)
C Riedl (Wed)
A Metz (Thu)

TMDs

- distributions $f_a(x, \boldsymbol{k}_T; \text{scales})$ in longitudinal and transverse momentum
- vigorous programme of fits to data (for unpolarised distributions) pushing theory to higher perturbative orders



- strong complementarity in Q^2 and p_T reach between SIDIS ($\ell N \to \ell + h + X$) and Drell-Yan ($pp \to \ell^+ \ell^- + X$)

← plot: data used in SV19 fit

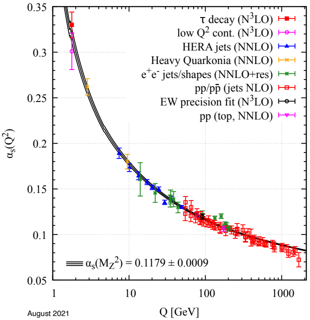
I Scimemi, A Vladimirov arXiv:1912.06532

- SIDIS involves fragmentation functions

→ talk R Seidl (Thu)

TMDs

- distributions $f_a(x, \boldsymbol{k}_T; \text{scales})$ in longitudinal and transverse momentum
- theory challenges: higher perturbative orders
  - needed to match precision of current and future data
  - some terms accompany large logs in exponent $\to$ amplified impact
  - at scales of a few GeV, α_s is not so small



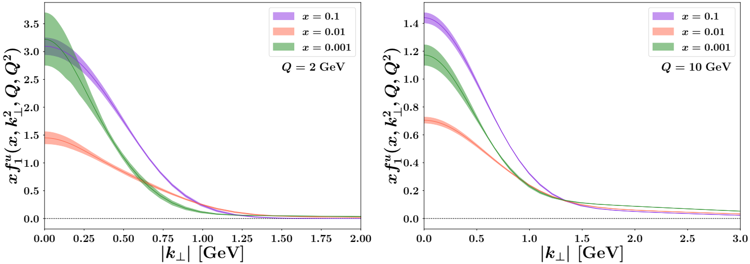
plot: Review of Particle Physics

TMDs

- distributions $f_a(x, \boldsymbol{k}_T; \text{scales})$ in longitudinal and transverse momentum
- theory challenges: power corrections
  Ebert, Gao, Stewart 2021; Vladimirov, Moos, Scimemi 2021; Rodini, Vladimirov 2023; . . . ; talk L Gamberg
  - p_T/Q terms: angular asymmetries, new distributions
  - $(p_T/Q)^{2n}$ corrections to angular independent terms

TMDs: scale evolution

- scale dependence of TMDs very different from PDF evolution
  no cross talk between different x values, no quark $\leftrightarrow$ gluon transitions
- instead: dependence on two scales μ and ζ
  roughly speaking:
  $\mu \sim$ cutoff in virtuality
  $\zeta \sim$ cutoff in rapidity
  of partons included in the distribution



A Bacchetta et al, arXiv:2206.07598 (MAP22 fit)

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  $\mu \sim$ cutoff in virtuality
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  of partons included in the distribution
- evolution equations: $f_a(x, \boldsymbol{k}_T; \mu, \zeta) \xrightarrow{\text{Fourier trf.}} f_a(x, \boldsymbol{b}_T; \mu, \zeta)$

$$\frac{d}{d\ln\mu} f_a(x, \boldsymbol{b}_T; \mu, \zeta) = \left[\gamma_{K,a}(\mu) \ln \frac{\mu}{\sqrt{\zeta}} + \gamma_a(\mu)\right] f_a(x, \boldsymbol{b}_T; \mu, \zeta)$$

$$\frac{d}{d\ln\sqrt{\zeta}} f_a(x, \boldsymbol{b}_T; \mu, \zeta) = K_a(\boldsymbol{b}_T; \mu)\, f_a(x, \boldsymbol{b}_T; \mu, \zeta)$$

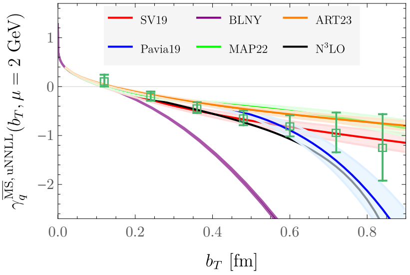
$\gamma_{K,a}, \gamma_a =$ anomalous dimensions, known to high orders

$K_a(\boldsymbol{b}_T; \mu) =$ Collins-Soper kernel: non-perturbative at large b_T

TMDs: Collins-Soper kernel

$$\frac{d}{d\ln\sqrt{\zeta}}\, f_a(x, \boldsymbol{b}_T; \mu, \zeta) = K_a(\boldsymbol{b}_T; \mu)\, f_a(x, \boldsymbol{b}_T; \mu, \zeta)$$

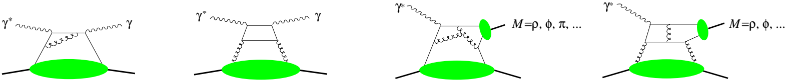
- K_q and K_g defined in terms of Wilson lines and the vacuum
  $\rightsquigarrow$ fundamental functions with high degree of universality
- new development: extract from lattice simulations
  e.g. Shu et al 2023; Chu et al (LPC coll.) 2023; Avkhadiev et al 2023
- impressive agreement between lattice and recent TMD fits:



A Avkhadiev et al, arXiv:2307.12359

$\gamma_q^{\overline{\text{MS}}}\big|_{\text{plot}} = K_q\big|_{\text{here}}$

Nucleon tomography: GPDs



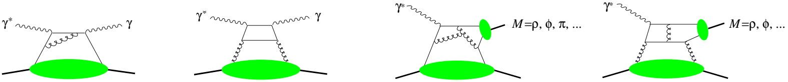
- principle:

  exclusive processes $\longrightarrow$ scattering amplitudes
  $\longrightarrow$ hard scattering$(x, \xi, Q/\mu) \underset{x}{\otimes}$ GPDs$(x, \xi, t; \mu)$ using factorisation
  $\longrightarrow$ GPDs$(x, \xi, t; \mu)$
  $\longrightarrow$ impact parameter distributions after Fourier trf. from $\boldsymbol{\Delta}_T \to \boldsymbol{b}_T$

- vigorous experimental programme ongoing at JLab
  would receive strong boost with e^+ beams at CEBAF
  flagship programme at the EIC

  $\to$ talks by S Niccolai and A Hobart (today)

Nucleon tomography: GPDs



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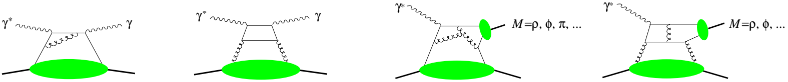
- theory: new processes proposed and studied
  - $\gamma p \to \gamma\gamma\, p$ at large $M_{\gamma\gamma}$
    sensitive to $q - \bar{q}$, computation pushed to NLO
    O Grocholski et al, 2021, 2022
  - $\gamma N \to \gamma\pi\, N'$, $\gamma N \to \gamma\rho\, N'$ at large $M_{\gamma\,\text{meson}}$
    G Duplančić et al, 2022, 2023; Z Yu, J-W Qiu 2023; and earlier work
  - new calculation of double DVCS $(ep \to e\,\ell^+\ell^-\,p)$: K Deja et al, 2023
    pioneering work in 2002, 2003

Nucleon tomography: GPDs



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- α_s corrections

  why bother? → see page 8

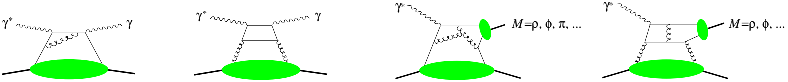
  - DVCS at NNLO → talk by V Braun (Wed)
  - public GPD evolution code → talk by V Bertone (Wed)

- how to reconstruct GPDs from scattering amplitudes?

  new studies of the "deconvolution problem" V Bertone et al 2021 E Moffat et al 2023

  $\rightsquigarrow$ need wide Q^2 coverage and several processes with good theory control

Nucleon tomography: GPDs



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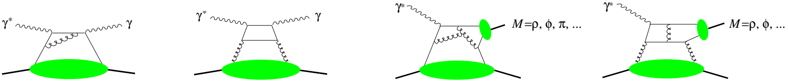
  $\longrightarrow$ impact parameter distributions after Fourier trf. from $\boldsymbol{\Delta}_T \to \boldsymbol{b}_T$

- kinematic power corrections in DVCS
  - corrections in powers of $\sqrt{-t}/Q$ and m/Q
  - extend validity of factorisation regime $(-t \ll Q^2)$

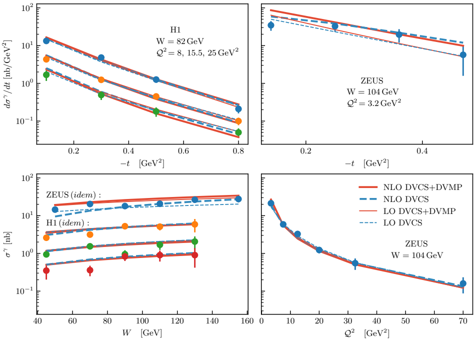
    crucial for imaging since smallest accessible distances $\propto 1/\sqrt{|t|_{\text{max}}}$

  new results by V Braun, A Manashov 2023

Nucleon tomography: GPDs



- new combined analysis of DVCS and ρ^0 production data from HERA
  M Čuić, G Duplančić, K Kumerički, K Passek-K, arXiv:2310.13837
  finds that a common description is possible at NLO, but not at LO



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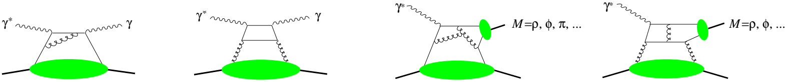

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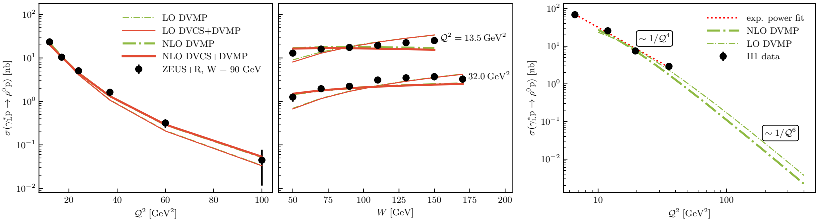

fit DVCS for $Q^2 > 5\,\mathrm{GeV}$ and ρ production for $Q^2 > 10\,\mathrm{GeV}$
8 fit parameters plus 3 parameters fitted to HERA DIS data

Nucleon imaging: form factors

- Q: "Why bother with form factors when we have GPDs?"
  - $F(t)$ much simpler than $H(x, \xi, t)$
    can use form factors to constrain GPD extractions
  - much simpler dependence on renormalisation scale μ
  - much larger reach in momentum transfer t
    no condition $|t| \ll Q^2$ as for GPD extraction

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  - flavour decomposition of form factors requires high precision
    strong cancellations between different contributions

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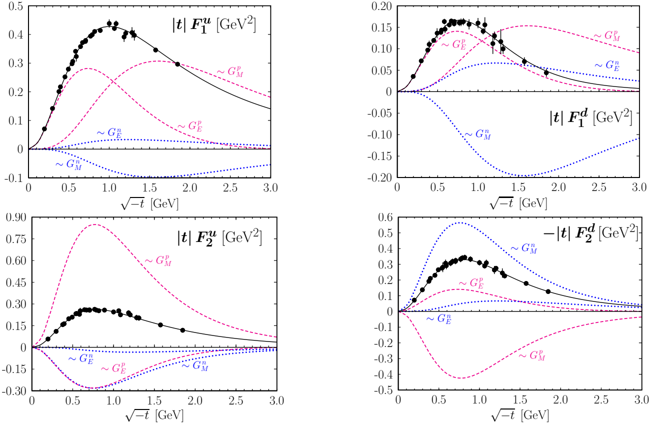

interpolated form factor data and flavour decomposition: MD, P Kroll arXiv:1302.4604

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  A: yes and no. Many outstanding issues:
  - flavour decomposition of form factors requires high precision
    strong cancellations between different contributions
  - theoretical challenges for extracting form factors from data:
    – two-photon exchange → opportunities with e^+ beams at CEBAF
    – nuclear corrections for neutron form factors
  - strange form factors G_M^s, G_E^s still very poorly known
    small at low t, hard to measure and to calculate on the lattice
  - axial form factor is known very poorly from experiment

  lattice calculations → talks by S Bacchio and D Pekfou (today)

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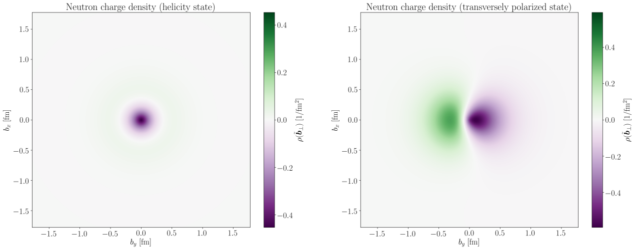
- theory interpretation:
  form factors $\rightarrow$ two- vs. three-dimensional densities
  subject $>$ 10 years old; new theory work: A Freese, G Miller 2021, 2023

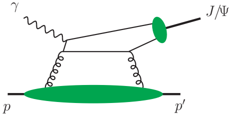


A Freese, G Miller
arXiv:2302.09171

Form factors of the energy-momentum tensor (EMT)

aka "gravitational form factors", but gravitation cannot tell quarks from gluons

- proposal: heavy quarkonium production ($V = J/\Psi, \Upsilon$)
  $\gamma p \to V\, p$ or $ep \to eV\, p$ near threshold
  $\leftrightarrow$ gluon part of EMT form factors
  several papers by D Kharzeev et al; X Ji; Y Hatta; ...



  - experimental results $\to$ talk by S Joosten (today)

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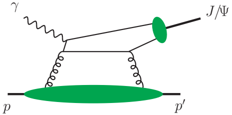

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  - **but** this result is obtained only with **rough** approximations
  - detailed analyses Y Guo, X Ji, Y Liu 2021 and P Sun, X-B Tong, F Yuan 2022
    - factorisation in terms of GPDs remains valid at threshold
    - use lowest-order approximations in M_N/M_V and α_s
      rather poor for J/Ψ, better for Υ
    - need further approximations for 'GPDs $\to$ EMT form factors'
      more detail $\to$ backup slides

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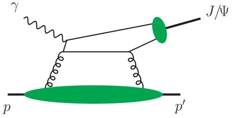

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    rather poor for J/Ψ, better for Υ
  - need further approximations for 'GPDs $\to$ EMT form factors'
    more detail $\to$ backup slides
- my personal conclusion:
  - we cannot claim to "extract" EMT form factors from this process
  - but we may have "high sensitivity" to the EMT form factors
    within a more comprehensive analysis

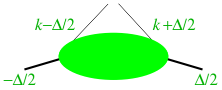
Summary

- significant progress and activity in a wide range of areas
- complementarity between experimental facilities and energy ranges and between experiment, phenomenology, lattice
- push towards precision in many different areas
  precision is not just a goal itself:
  it often is prerequisite to obtaining reliable quantitative results
- looking forward to hearing more at this meeting

TMDs, GPDs, Wigner functions here take $\xi = 0$, can generalise to $\xi \neq 0$

- impact parameter distribution $f_q(x, \boldsymbol{b})$ is not related to TMD $f_q(x, \boldsymbol{k})$ by a Fourier transform:

$$
\begin{aligned}
f(x, \boldsymbol{b}) &\propto \varphi^*(x, \boldsymbol{b})\, \varphi(x, \boldsymbol{b}) \\
&\propto \int d^2\boldsymbol{\Delta}\; e^{-i\boldsymbol{\Delta b}} \int d^2\boldsymbol{k}\; \psi^*(x, \boldsymbol{k} + \tfrac{1}{2}\boldsymbol{\Delta})\, \psi(x, \boldsymbol{k} - \tfrac{1}{2}\boldsymbol{\Delta}) \\
&\propto \int d^2\boldsymbol{\Delta}\; e^{-i\boldsymbol{\Delta b}}\, H(x, \boldsymbol{\Delta}) \\
f(x, \boldsymbol{k}) &\propto \psi^*(x, \boldsymbol{k})\, \psi(x, \boldsymbol{k})
\end{aligned}
$$



with wave functions $\varphi(x, \boldsymbol{b}) \underset{\text{FT}}{\longleftrightarrow} \psi(x, \boldsymbol{k})$

- Fourier transform of TMD:

$$
\begin{aligned}
f(x, \boldsymbol{z}) \propto \int d^2\boldsymbol{k}\; e^{i\boldsymbol{kz}}\, f(x, \boldsymbol{k}) &\propto \int d^2\boldsymbol{k}\; e^{i\boldsymbol{kz}}\, \psi^*(x, \boldsymbol{k})\, \psi(x, \boldsymbol{k}) \\
&\propto \int d^2\boldsymbol{b}\; \varphi^*(\boldsymbol{b} - \tfrac{1}{2}\boldsymbol{z})\, \varphi(\boldsymbol{b} + \tfrac{1}{2}\boldsymbol{z})
\end{aligned}
$$

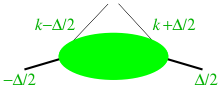
TMDs, GPDs, Wigner functions

here take $\xi = 0$, can generalise to $\xi \neq 0$

- impact parameter distribution $f_q(x, \boldsymbol{b})$
  is not related to TMD $f_q(x, \boldsymbol{k})$ by a Fourier transform:

$$\begin{aligned} f(x,\boldsymbol{b}) &\propto \varphi^*(x,\boldsymbol{b})\, \varphi(x,\boldsymbol{b}) \\ &\propto \int d^2\boldsymbol{\Delta}\; e^{-i\boldsymbol{\Delta b}} \int d^2\boldsymbol{k}\; \psi^*(x,\boldsymbol{k}+\tfrac{1}{2}\boldsymbol{\Delta})\, \psi(x,\boldsymbol{k}-\tfrac{1}{2}\boldsymbol{\Delta}) \\ &\propto \int d^2\boldsymbol{\Delta}\; e^{-i\boldsymbol{\Delta b}}\, H(x,\boldsymbol{\Delta}) \end{aligned}$$

$$f(x,\boldsymbol{k}) \propto \psi^*(x,\boldsymbol{k})\, \psi(x,\boldsymbol{k})$$



with wave functions $\varphi(x,\boldsymbol{b}) \underset{\text{FT}}{\longleftrightarrow} \psi(x,\boldsymbol{k})$

- GTMDs and Wigner functions:

$$H(x,\boldsymbol{k},\boldsymbol{\Delta}) \propto \psi^*(x,\boldsymbol{k}+\tfrac{1}{2}\boldsymbol{\Delta})\, \psi(x,\boldsymbol{k}-\tfrac{1}{2}\boldsymbol{\Delta})$$

$$W(x,\boldsymbol{k},\boldsymbol{b}) \propto \int d^2\boldsymbol{\Delta}\; e^{-i\boldsymbol{\Delta b}}\, \psi^*(x,\boldsymbol{k}+\tfrac{1}{2}\boldsymbol{\Delta})\, \psi(x,\boldsymbol{k}-\tfrac{1}{2}\boldsymbol{\Delta})$$

$W =$ phase space distribution, generates probability distributions

$$f(x,\boldsymbol{b}) = \int d^2\boldsymbol{k}\; W \quad \text{and} \quad f(x,\boldsymbol{k}) = \int d^2\boldsymbol{b}\; W$$

Quarkonium near threshold: from GPDs to EMT form factors

argument and plots from Y Guo, X Ji, Y Liu, arXiv:2103.11506

- factorisation in terms of gluon GPDs ($F_g = H_g$ or E_g):

$$\mathcal{A}(\gamma p \to V p) \propto \frac{1}{2\xi} \int_{-1}^{1} dx \left[\frac{1}{\xi + x - i\epsilon} + \frac{1}{\xi - x - i\epsilon} \right] F_g(x, \xi, t)$$

- Taylor expansion around $\xi = 1$ gives

$$\mathcal{A}(\gamma p \to V p) \propto \sum_{n=0}^{\infty} \frac{1}{\xi^{2n+2}} \int_{-1}^{1} dx\, x^{2n}\, F_g(x, \xi, t)$$

  - $n = 0$ term: lowest Mellin moment gluon GPDs $\leftrightarrow$ EMT form factors
  - even at $\xi = 1$ have sum over all terms
    must assume that higher moments are smaller than leading ones

Quarkonium near threshold: from GPDs to EMT form factors

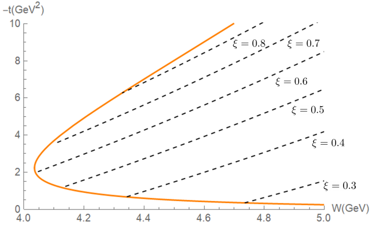
argument and plots from Y Guo, X Ji, Y Liu, arXiv:2103.11506

- Taylor expansion around $\xi = 1$ gives

$$\mathcal{A}(\gamma p \to V p) \propto \sum_{n=0}^{\infty} \frac{1}{\xi^{2n+2}} \int_{-1}^{1} dx\, x^{2n}\, F_g(x, \xi, t)$$

  - $n = 0$ term: lowest Mellin moment gluon GPDs $\leftrightarrow$ EMT form factors
  - even at $\xi = 1$ have sum over all terms
    must assume that higher moments are smaller than leading ones

- near threshold $\xi = 1 - \mathcal{O}(M_N / M_V)$



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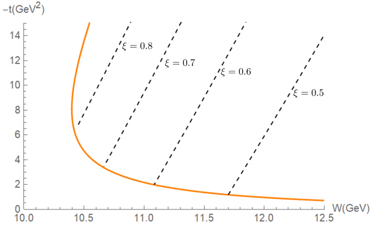

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