# From 12 GeV to EIC: Imaging

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

# Parton imaging: why? what? how? where?

scope of this talk

- overarching physics motivation
  concrete examples of physics accessible with parton imaging
- explain some underlying physical principles
- some comments on theory status
- some comments on specific issues at JLab@12 GeV and at EIC
- not a comprehensive overview

more information in later talks at this meeting

## Physics questions

- outstanding question in QCD: relation between

| | |
|---|---|
| $q, \bar{q}, g$ in $\mathcal{L}_{\text{QCD}}$ | constituent quarks |
| current quarks, $m_{u,d} \ll 100\,\text{MeV}$ | effective masses $m \sim 300\,\text{MeV}$ |
| manifest at small distances | spectroscopy, quark models |
| hadrons seen at high resolution | "$p = uud, n = ddu, \ldots$" |

- simplest idea: at low resolution $p = uud$
  gluons and sea quarks from perturbative parton splitting
  Parisi, Petronzio '76, Novikov et al '77; Glück, Reya '77
  is incompatible with measured parton densities
  Glück, Reya, Vogt '90 ff.; MD talk at POETIC 2018

- other scenarios
  - proton = quarks and antiquarks, gluons from evolution
    have $\bar{q}$ e.g. from meson cloud Thomas '83
    or in quark-soliton model Diakokov et al '86
  - proton $= UUD$ with "composite valence quarks" $U, D$ containing antiquarks and gluons Altarelli et al '74

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- general idea:
  seek qualitatively new and quantitatively precise information on $q, \bar{q}, g$ in hadrons at high resolution

- several lines of study:
  - partons in "valence region" $x \sim 1/3$
  - partons at large $x \gg 1/3$ $\rightsquigarrow$ JLab@12 GeV
  - sea quarks and gluons $\rightsquigarrow$ EIC
  - spin and orbital angular momentum of partons
  - distribution of partons in three dimensions $\rightsquigarrow$ imaging

# Imaging: longitudinal vs. transverse directions

- hard processes single out (at least) one spatial direction


holds both in collision c.m. and in target rest frame

- different roles played by longitud. and transv. directions
  $\rightsquigarrow$ lose manifest 3dim rotation symmetry in target rest frame
- usual parton densities: longitudinal information
  aims: achieve high precision, details of flavor structure,
  $q$ vs. $\bar{q}$, polarisation, nuclear effects
- transverse structure: much less well known
  in first instance aim to see general trends/patterns
  but may require high-precision to expose subtle effects
- new d.o.f.: orbital angular momentum (classically: $\vec{L} = \vec{r} \times \vec{p}$)

# Imaging basics: transverse momentum and transverse position

- variables related by 2d Fourier transforms, e.g. for quark field operator (in QFT) or wave function (in QM)

$$\phi(\boldsymbol{k}) = \int d^2\boldsymbol{z}\; e^{i\boldsymbol{z}\boldsymbol{k}} \psi(\boldsymbol{z})$$

display only transverse variables (boldface), omit longitudinal ones

- fully relativistic: can localise only in 2 dimensions   Soper '72; Burkardt '02
  in 3d can only localise object within its Compton wavelength
- at level of squared amplitudes/probabilities/density matrices have

$$\overline{\phi}(\boldsymbol{k})\,\phi(\boldsymbol{l}) = \int d^2\boldsymbol{y}\, d^2\boldsymbol{z}\, e^{-i(\boldsymbol{y}\boldsymbol{k}-\boldsymbol{z}\boldsymbol{l})}\; \overline{\psi}(\boldsymbol{y})\,\psi(\boldsymbol{z})$$

$$\boldsymbol{y}\boldsymbol{k}-\boldsymbol{z}\boldsymbol{l} = \tfrac{1}{2}(\boldsymbol{y}+\boldsymbol{z})(\boldsymbol{k}-\boldsymbol{l}) + \tfrac{1}{2}(\boldsymbol{y}-\boldsymbol{z})(\boldsymbol{k}+\boldsymbol{l})$$

  'average' transv. momentum $\leftrightarrow$ position difference
  transv. momentum transfer $\leftrightarrow$ 'average' position

- 'average' transv. mom. and position not Fourier conjugate
  nor are parton distributions in transv. mom. or in impact parameter
- integrate over all transv. mom. $\rightsquigarrow$ all fields at transv. position zero

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'average' transv. momentum $\leftrightarrow$ position difference

transv. momentum transfer $\leftrightarrow$ 'average' position

- full information: Wigner phase space distributions $W(x, \boldsymbol{k}, \boldsymbol{b})$

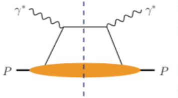
  give probabilities $\int d^2\boldsymbol{k}\, W = f(x, \boldsymbol{b})$ and $\int d^2\boldsymbol{b}\, W = f(x, \boldsymbol{k})$

  in context of parton distributions: Belitsky, Ji, Yuan '03

# Factorisation: exclusive or inclusive

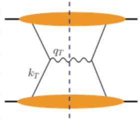
- separate dynamics into "hard probe" and "structure of target"
  nontrivial, requires hard scale $Q^2$, comes with corrections $\sim (\Lambda/Q)^k$
- exclusive processes: nucleon in final state, longitudinal and transverse momentum transfer $\rightsquigarrow$ transverse position of struck parton

- PDF factorization
  - ★ inclusive processes
  - ★ $p_T$ ~ hardest scale or unmeasured

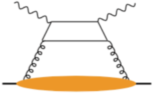



- GPD factorization
  - ★ exclusive processes
  - ★ non-forward kinematics


- TMD factorization
  - ★ inclusive
  - ★ $p_T$ « hardest scale



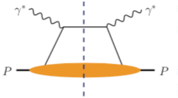

- small-x factorization
  - ★ inclusive or exclusive
  - ★ unintegrated gluon dist's



# Factorisation: exclusive or inclusive

- separate dynamics into "hard probe" and "structure of target"
  nontrivial, requires hard scale $Q^2$, comes with corrections $\sim (\Lambda/Q)^k$
- inclusive processes: parton distribution in squared amplitude,
  no mom. transfer on hadron, but can have transv. parton momentum

- PDF factorization
  - ★ inclusive processes
  - ★ $p_T$ ~ hardest scale or unmeasured

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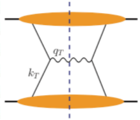


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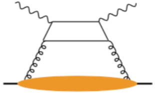


## Longitudinal momentum: moments and sum rules

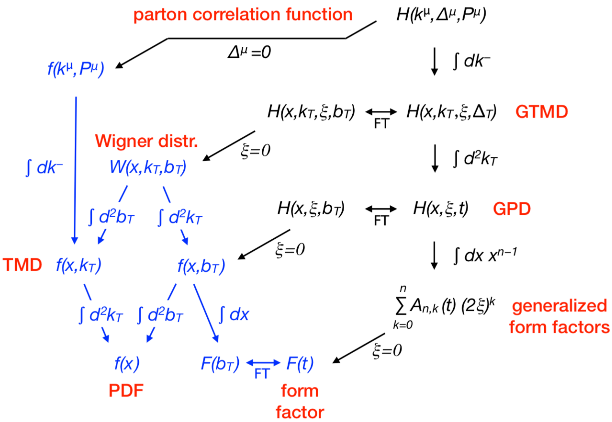
- longitudinal parton mom. fraction $\underset{\text{FT}}{\leftrightarrow}$
  $z^- = \frac{1}{\sqrt{2}}(z^0 - z^3)$ ~ long. position in frame where hadron moves fast
- parton distributions defined via

$$f(x) \sim \int dz^- \, e^{ixp^+z^-} \, \bar{\psi}\big(-\tfrac{1}{2}z^-\big) \ldots \psi\big(\tfrac{1}{2}z^-\big)$$

  display only longitudinal variables (boldface), omit transverse ones
- in moments $\int dx \, x^{n-1} f(x)$
  Fourier exponential $e^{ixp^+z^-}$ turns into $\delta(z^-)$ or its derivatives
  ⇝ local operators
- lowest moments:
  - $n = 1$, unpolarised quarks ⇝ vector current
    long. pol. quarks ⇝ axial vector current
  - $n = 2$, unpolarised quarks or gluons ⇝ energy-momentum tensor
    ⇝ momentum, angular momentum (Ji's sum rule '96)
    pressure and shear forces Polyakov '03, talk by F X Girod

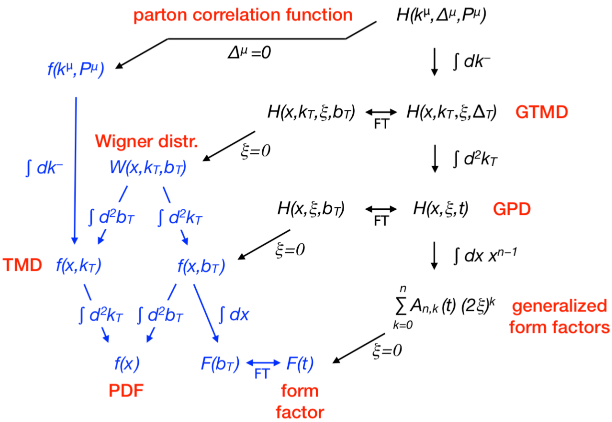
    note: gravitons couple directly to energy-momentum tensor,
    but cannot tell a quark from a gluon

# Parton correlation functions and their descendants




- graph for unpolarised partons, with polarisation even more structure
- subtleties of resolution scale dependence are understood, not shown here

# Parton correlation functions and their descendants

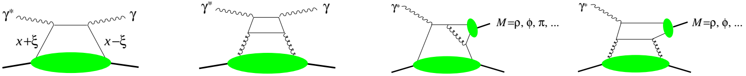



- several of these functions can be computed in lattice QCD

→ talk by M Constantinou

# Exclusive processes and GPDs: transverse position

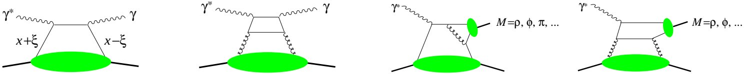
- DVCS and meson production $\rightsquigarrow$ generalised parton distrib's



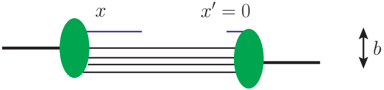

- similar theory as for usual parton densities
  have factorisation proofs, evolution in resolution scale $Q$
- longit. mom. transfer $\rightsquigarrow$ two parton mom. fractions $x \pm \xi$
  - at LO in $\alpha_s$ measure GPD$(x, \xi = x, \boldsymbol{\Delta})$
  - in general $x$ "smeared" around $\xi$
- separate dep'ce on $x$ and $\xi$ from scaling violations in $Q^2$
  - need largest possible $Q^2$ range
- imaging: measure $\boldsymbol{\Delta}$ and Fourier transform to $\boldsymbol{b}$

# Exclusive processes and GPDs: transverse position

- DVCS and meson production $\rightsquigarrow$ generalised parton distrib's



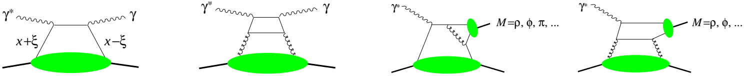

- '1st stage' imaging: amplitude $\underset{\text{FT}}{\rightarrow}$ GPD$(x, \xi = x, \boldsymbol{b})$



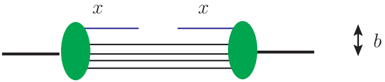

no probability interpretation, but $\boldsymbol{b}$ = well defined transverse distance

# Exclusive processes and GPDs: transverse position

- DVCS and meson production ⇝ generalised parton distrib's




- '2nd stage': GPD$(x, \xi = x, \boldsymbol{b}) \to$ GPD$(x, \xi = 0, \boldsymbol{b})$



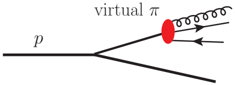

  - density interpretation: GPD$(x, \xi = 0, \boldsymbol{b}) = f(x, \boldsymbol{b})$
  - access only via $\alpha_s$ effects ⇝ $Q^2$ dependence
  - extrapolation to $\xi = 0$ depends on theoretical assumptions

## Correlations between $x$ and $\boldsymbol{b}$

- lattice calculations (moments $\int dx\, x^n f(x, b_T)$ with $n = 0, 1, 2$) find significant correlation between $b_T$ and $x$
  average $x$ in moments $\sim 0.2$ to $0.4$ $\rightsquigarrow$ size of "valence" configurations

  direct measurement in scattering experiments? $\rightsquigarrow$ JLab@12 GeV
- at large $b$ prediction from chiral dynamics — Strikman, Weiss '09
  $f(x, b) \sim e^{-\kappa b}/b$ with $\kappa \sim 2m_\pi = (0.7\,\text{fm})^{-1}$

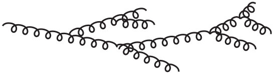
sets in for $x \lesssim m_\pi / m_p$
requires precise measurement at low $\boldsymbol{\Delta}$
first glimpse from COMPASS DVCS
full potential at EIC



# Correlations between $x$ and $\boldsymbol{b}$

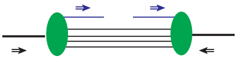
- at small $x < 0.01$ find $\langle b^2 \rangle \propto \text{const} + \alpha' \log \frac{1}{x}$

Gribov diffusion



  - for gluons $\alpha' \sim 0.15\,\mathrm{GeV}^{-2}$ from HERA $J/\Psi$ prod'n
    much smaller than in soft hadronic procs.
  - for valence quarks $(q - \bar{q})$
    get $\alpha' \sim 0.9\,\mathrm{GeV}^{-2}$ in GPD models fitted to e.m. form factors
    MD et al '04; Guidal et al '04; MD, Kroll '13
    in line with meson Regge trajectories
    direct measurement in scattering experiments?
  - value for sea quarks? cross talk with gluons?

# Spin and orbital angular momentum




- GPD $E \leftrightarrow$ nucleon helicity flip $\langle\downarrow|\mathcal{O}|\uparrow\rangle$

  $\rightsquigarrow$ interference between wave fcts. with $L^z$ and $L^z \pm 1$
  no direct relation with $\langle L^z \rangle$, but indicator of large $L^z$

- helicity flip $\leftrightarrow$ transverse polarisation asymmetry
  parton dist's in proton polarised along $x$ are shifted along $y$:

$$f^{\Uparrow}(x, \boldsymbol{b}) = f(x, b^2) - \frac{b^y}{m} \frac{\partial}{\partial b^2}\, e(x, b^2)$$

$e(x, b^2) =$ Fourier transform of $E(x, \xi = 0, \Delta_T)$

  - connection to orbital angular momentum via $\vec{b} \times \vec{p}$
  - shift known to be large for valence combinations $u - \bar{u}$, $d - \bar{d}$
    from sum rule connecting with magnetic moments of $p$ and $n$
    unknown for sea quarks and gluons

Burkardt '02, '05; Burkardt and Schnell '05

- $E$ key part of Ji's angular momentum sum rule

$$2J^q = \int dx\, x[q(x) + \bar{q}(x)] + \int dx\, x[e^q(x) + e^{\bar{q}}(x)]$$

  and its analogue for gluons

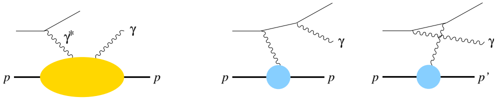
# Exclusive processes

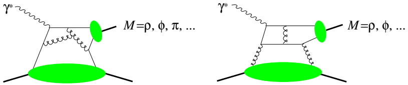
→ talk by C Hyde

- Compton scattering: deeply virtual (DVCS) or timelike (TCS)

$$ep \to ep\gamma \text{ or } \gamma p \to \ell^+\ell^- p$$

  - best theory control: NNLO, twist three, corr's in $m^2/Q^2$ and $t/Q^2$
    Müller et al., Braun and Manashov
  - interference with Bethe-Heitler process (calculable)
    → phase of Compton amplitude




- meson production
  - many channels, separation of quark flavors and gluons
  - theory more involved: meson wave fct.
    NLO and $1/Q$ corrections can be large
  - strong indications that need $Q^2 \gtrsim$ several $10\,\mathrm{GeV}^2$ to reach factorisation regime

## JLab@12 GeV and EIC

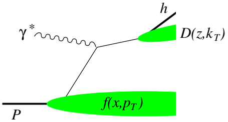
- different $x$ ranges $\rightsquigarrow$ different configurations in nucleon
- special opportunity at 12 GeV: very rare processes
  double DVCS
  - $\gamma^* p \to \gamma^* p$ measured in $ep \to e + \mu^+\mu^- + p$
  - two independent photon virtualities
    $\rightsquigarrow$ more detailed access to longitudinal kinematics
    $\rightsquigarrow$ disentangle $x$ and $\xi$ in GPDs
- special opportunities at EIC
  - high $Q^2$ $\rightsquigarrow$ greater lever arm for scale evolution,
    cleaner theory for meson production
  - production of $J/\Psi$ and $\Upsilon$ $\rightsquigarrow$ selects gluons in target
    diminished thy. uncertainty from meson wave function

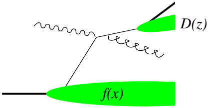
    rate estimates cf. e.g. talk by S Joosten at QCD Evolution 2018

    at 12 GeV $J/\Psi$ prod'n close to threshold $\rightsquigarrow$ dynamics not described by GPDs
- special opportunity wherever can be realised: positron beam
  DVCS beam charge asymmetry $\rightsquigarrow$ clean access to Compton amplitude
  via interference with Bethe-Heitler

# Transverse momentum dependent distributions → talk by H Gao

- theoretical description of transv. momenta in final state:
  - for small transv. momenta (or transv. momentum differences) described by transv. mom. dependent distributions etc.
  - if large then generate perturbatively = hard radiation
  - graphs for SIDIS $ep \to eh + X$:




analogous for Drell-Yan process $pp \to \ell^+\ell^- + X$

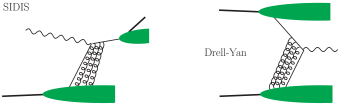
- no sharp boundary between "intrinsic" and "radiative" regimes but transition between the two interesting and practically relevant basic theory well understood, open questions remain

  cf. e.g. Bacchetta et al '08; Collins et al '16; Gamberg et al '17

- radiative corrections known at NLO, in parts also NNLO partial understanding of $1/Q$ corrections

  cf. e.g. talk by A Vladimirov at QCD Evolution 2018

# The importance of gluons "accompanying" a parton

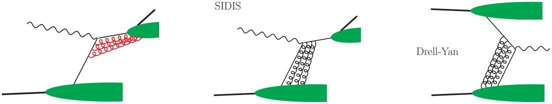



- in general, coloured objects are surrounded by gluons
  profound consequence of gauge invariance
  technically implemented in Wilson lines
- $k_T$ dep't distributions can be time reversal odd
  e.g. Sivers function: unpol. quarks in proton pol. along $x$ axis:

$$f^X(x, \boldsymbol{k}_T) = f(x, k_T^2) + \frac{k^y}{M} f_{1T}^{\perp}(x, k_T^2)$$

  Sivers fct. has opposite sign when gluons couple after quark scatters (SIDIS) or before quark annihilates (DY)
  would be zero if gluons were absent

# The importance of gluons "accompanying" a parton

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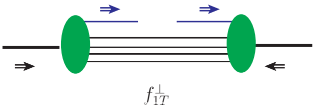
  would be zero if gluons were absent
- fragment'n fct's: similar dynamics, with important differences

# Orbital angular momentum again




- Sivers fct. $\leftrightarrow$ proton helicity flip

  $\rightsquigarrow$ interference of config's with $L^z$ and $L'_z = L^z \pm 1$
  another indicator of $L^z$

# Orbital angular momentum again

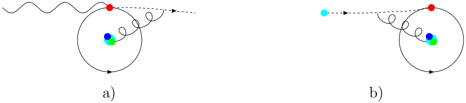



figure: M Burkardt

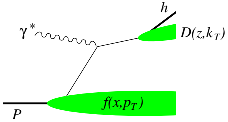
- chromodynamic lensing:
  transverse shift in $b$ space (described by $E$)
  $\rightsquigarrow$ transverse shift in $k_T$ (described by $f_{1T}^{\perp}$)
  - generated by gluon exchange, opposite signs for SIDIS and DY
  - no calculation in full QCD (is highly nonperturbative) but seen in model calculations

  should test experimentally for different $x$ and different parton species
- both $E$ and $f_{1T}^{\perp}$ exist for quarks and gluons
  could become sizeable at small $x$ by parton splitting,
  provided that are not small at low scale/low $k_T$

# JLab@12 GeV and EIC

- different $x$ ranges $\rightsquigarrow$ different configurations in nucleon
- challenge at 12 GeV: factorisation for SIDIS $ep \to eh + X$ requires

  large invariant hadronic mass: $m_X \gg$ resonance masses




$$m_X^2 = Q^2 \frac{x_B}{1-x_B}(1-z) - \frac{1}{z} P_{h\perp}^2$$

+hadron mass terms

detailed analysis: Boglione et al '17

- at EIC: several benefits from larger phase space:
  - larger $Q^2$ $\rightsquigarrow$ higher theory precision
    can study scale evolution
  - large range of hadron transv. mom. $P_{h\perp}$
    $\rightsquigarrow$ study transition between "intrinsic" and "radiative" regimes

# Wigner functions

- relatively young field, many aspects remain to be worked out
- theory tool to relate GPDs and TMDs, exhibit unifying aspects

  work by Metz et al; Hatta et al; Lorcé and Pasquini; Rajan et al
- direct measurement possible? proposal:

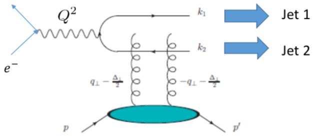
  exclusive electroproduction of dijets $ep \to e + \text{jet } 1 + \text{jet } 2 + p$

  Hatta, Xiao, Yuan '16

- access to generalised TMDs $(x, \boldsymbol{q}, \xi, \boldsymbol{\Delta})$
- open questions regarding theory

  quite sure that need $\gamma^*$, not photoproduction

  and experimental realisation
- requires EIC at high energy




plot: Y Hatta at POETIC 2018

also discussed in small-$x$ framework — Altinoluk et al '15; Boussarie et al '16

and in collinear factorisation (GPDs) — Braun, Ivanov '05

# Summary

- exclusive and semi-inclusive procs. with measured transv. momenta
  $\rightsquigarrow$ study trv. parton position and momentum in quantitative, theoretically controlled ways
- relates to deep concepts and questions in QCD
  some concrete, others more generic
  - interplay of pert. and nonpert. phenomena
    – radiatively generated vs. nonpert. sea, flavour and spin strct.
    – transition from small to large $k_T$
  - spatial distribution of partons in hadron $\leftrightarrow$ confinement
  - role of $\pi$ fluctuations $\leftrightarrow$ chiral dynamics
  - spin-orbit correlations ($k_T$ or $b_T$ vs. polarisation)
    $\rightsquigarrow$ orbital angular momentum
  - dynamics of gluons that accompany any coloured particle
    $\rightsquigarrow$ gauge symmetry, Wilson lines
- have common theory framework to interpret meas'ts at 12 GeV and at EIC
  pointed out specific differences, but see coherent science programme for the two facilities