Imaging partons with exclusive scattering processes

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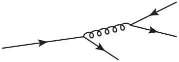
Context and goals

Hadrons and nuclei $\overset{?}{\leftrightarrow}$ quarks, antiquarks, gluons

- $q, \bar{q}, g$ only manifest at short distance/short times
  $\rightsquigarrow$ 'snapshots' of a strongly interacting system
  rather than 'structure' in a static sense
- several difficult and interesting aspects:
  confinement, gluon self coupling, chiral symmetry breaking
  highly relativistic system, parton number not conserved
- aim: study quantitatively
  how hadrons and nuclei 'look like'/behave at parton level
  how partons interact inside hadrons and nuclei
  1. to make progress in understanding QCD dynamics
     measurements $\leftrightarrow$ physical picture $\leftrightarrow$ theory
  2. in some cases: use to improve quantitative description of $pp/pA/AA$ collisions

Dynamics at short vs. long distances

- hard processes involve both short and long distance dynamics (inevitably have hadrons in initial and final state)
- parton splitting



  - important aspect of dynamics in several contexts
  - evolution eqs. in resolution scale (DGLAP) or in rapidity (BFKL, BK, etc)
  - perturbative calculations, largely well understood
- simplest (and often quoted) picture of nucleon:
  - three quarks at low resolution scale
  - gluons and sea quarks generated by perturbative evolution

  but PDF fits of Glück, Reya et al. show that this is too simple
- must have gluons and sea quarks at nonperturbative scales
  - different behavior of s vs. $\bar{s}$, $\bar{u}$ vs. $\bar{d}$
  - role of pion/kaon fluctuations (connected with chiral dynamics)

Some questions

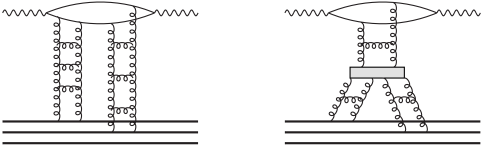
- how are quarks, antiquarks and gluons spatially distributed in a nucleon?
- how does this distribution change with momentum fraction x?
  $\rightarrow$ difference between "valence" and "sea quarks"?
- distribution at large transverse distances?
  $\rightarrow$ confinement, chiral dynamics
- connection between transv. spatial distribution and transv. momentum of partons?
- what is the role of spin and orbital angular momentum?

Nuclei

- coherent hard scattering on nucleus ⇝ spatial parton distr'n
  general theme: deviation from "independent nucleon approx."

$$f_{q/A}(x,b) = f_{q/N}(.\,,.) \otimes f_{N/A}(.\,,.)$$

- nontrivial effects in saturation dynamics



scattering on gluons from different nuclei

merging of gluon chains from different nuclei

- to which extent are measurements feasible?
  can be expect measurably large nontrivial effects?
  is this valuable for interpreting heavy ion collisions?

How to obtain images at the femtometer scale?

Prolog: transverse momentum vs. position

- variables related by 2d Fourier transforms, e.g.
  - proton states $|p^+, \boldsymbol{b}\rangle = \int d^2\boldsymbol{p}\, e^{-i\boldsymbol{b}\boldsymbol{p}}\, |p^+, \boldsymbol{p}\rangle$ with $p^+ = p^0 + p^3$

fully relativistic description: localize only in 2 dimensions
in 3d can only localize object within its Compton wavelength

- in matrix elements

$$\langle p'^+, \boldsymbol{b}'| \cdots |p^+, \boldsymbol{b}\rangle = \int d^2\boldsymbol{p}'\, d^2\boldsymbol{p}\, e^{i(\boldsymbol{b}'\boldsymbol{p}' - \boldsymbol{b}\boldsymbol{p})} \langle p'^+, \boldsymbol{p}'| \cdots |p^+, \boldsymbol{p}\rangle$$

$$\boldsymbol{b}'\boldsymbol{p}' - \boldsymbol{b}\boldsymbol{p} = \tfrac{1}{2}(\boldsymbol{b}' + \boldsymbol{b})(\boldsymbol{p}' - \boldsymbol{p}) + \tfrac{1}{2}(\boldsymbol{b}' - \boldsymbol{b})(\boldsymbol{p}' + \boldsymbol{p})$$

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

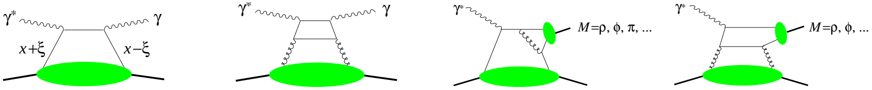
works in same way for position $\boldsymbol{b}$ and momentum $\boldsymbol{k}$ of partons

- 'average' transv. mom. and position not Fourier conjugate
  $\rightarrow$ get different information from distributions in $\boldsymbol{b}$ and $\boldsymbol{k}$

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

Access to transverse position: exclusive processes

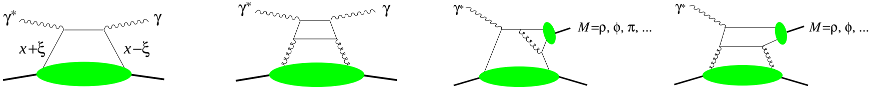
- DVCS and meson production ⇝ generalized parton distrib's



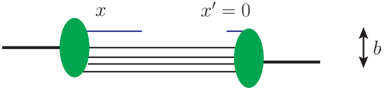
- similar theory as for usual parton densities
  have factorization proofs, evolution in resolution scale Q
- longit. mom. transfer ⇝ two parton mom. fractions $x \pm \xi$
  - at LO in α_s measure GPD$(x, \xi = x, \boldsymbol{\Delta})$
  - in general x "smeared" around ξ
- separate dep'ce on x and ξ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

Access to transverse position: exclusive processes

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



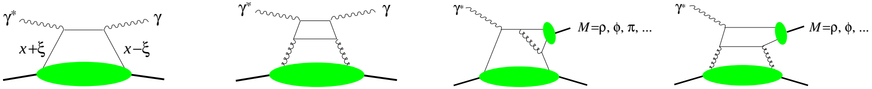
- '1st stage' imaging: amplitude $\overset{\text{Fourier}}{\rightarrow}$ GPD$(x, \xi = x, \boldsymbol{b})$



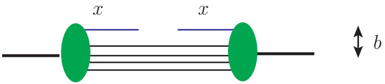
no probability interpretation, but $\boldsymbol{b}$ = well defined transverse distance

Access to transverse position: exclusive processes

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



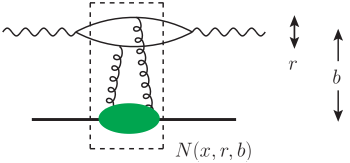
- '2nd stage': GPD$(x, \xi = x, \boldsymbol{b}) \rightarrow$ GPD$(x, \xi = 0, \boldsymbol{b})$



  - density interpretation: GPD$(x, \xi = 0, \boldsymbol{b}) = f(x, \boldsymbol{b})$
  - access only via α_s effects $\rightsquigarrow$ Q^2 dependence
  - presently unclear how strongly extrapolation to $\xi = 0$ will depend on theoretical assumptions

Small x formulation: the dipole representation

- amplitude $N(x, \boldsymbol{r}, \boldsymbol{b})$ for scattering of dipole on target naturally in b space



  Fourier transf. gives $\boldsymbol{r} \to \boldsymbol{k}$ of quark, $\boldsymbol{b} \to \boldsymbol{\Delta}$ of target

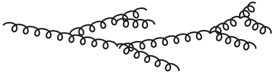
- valid for small x (empirically $\lesssim 10^{-2}$)
  "x" and "ξ" do not appear as independent variables
- comparison with collinear (= GPD) formalism:
  - dipole formalism: small x limit, predicts x dependence
    large Q limit not taken, require Q large enough for pert. calc.
  - GPD form.: all x, large Q limit, predicts Q dependence
  - in double limit of large Q and small x approaches equivalent

Some knowns, unknowns and predictions

- lattice calculations (moments $\int dx\, x^n f(x, \boldsymbol{b})$ with $n = 0, 1, 2$) find significant correlation between $\boldsymbol{b}$ and x

  average x in moments ~ 0.2 to 0.4

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

  for gluons $\alpha' \sim 0.15\,\text{GeV}^{-2}$ from HERA J/Ψ prod'n

  much smaller than in soft hadronic procs.

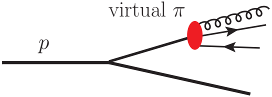
  value for valence and sea quarks? interplay with gluons?

- at large b prediction from chiral dynamics — M Strikman, C Weiss

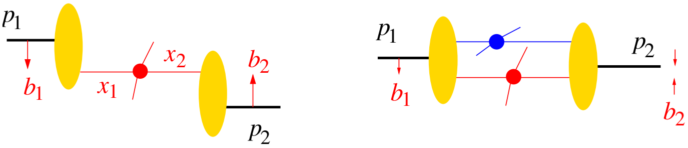
  $f(x, b) \sim e^{-\kappa b}/b$ with $\kappa \sim 2m_\pi = (0.7\,\text{fm})^{-1}$

sets in for $x \lesssim m_\pi / m_p$

requires precise measurem'ts at low Δ_T



Aside: multi-parton interactions in hadron-hadron collisions

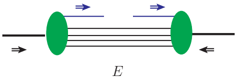


- hard inclusive process, e.g. $pp \to \text{jet jet} + X$
  - no impact parameter dependence
    integrate over b_1 and b_2 independently
- secondary soft or hard interactions
  - do not affect inclusive cross section, but change event structure
    will affect many analyses at LHC
  - sensitive to transverse distance between partons
    but this distance not directly related to final-state variables
- information from GPDs can help description of mult. interactions
  - b dependence and its interplay with momentum fraction x

How does the nucleon spin spin arise at microscopic level?

What is the role played by orbital angular momentum and spin-orbit correlations?

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 polarization asymmetry
  parton dist's in proton polarized 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 $\boldsymbol{b} \times \boldsymbol{p}$
  - 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

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

Spin and orbital angular momentum

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

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

$$e^a(x) = \int d^2b\, e^a(x, b^2) = E^a(x, \xi = 0, \Delta_T = 0)$$

- other definitions of angular momentum exist
  much disc. in literature: Jaffe, Manohar '90; . . . ; Wakamatsu '11
  to my mind, non-uniqueness of "o.a.m." reflects character of the system under study:
  - quarks and gluons interact
  - gauge fields contain phys. and unphys. d.o.f.

Dynamics of spin-orbit correlations

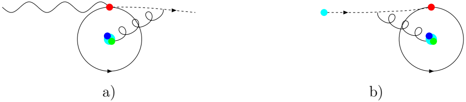


figure: M Burkardt

- chromodynamic lensing:
  transverse shift in $\boldsymbol{b}$ space (described by E)
  $\rightarrow$ transverse shift in $\boldsymbol{k}$ (described by Sivers distribution)
  - generated by gluon exchange, opposite signs for SIDIS and DY
  - no calculation in full QCD (is highly nonperturbative)
    but explicitly seen in model calculations

  test experimentally for different x and diff't parton species

- both E and Sivers dist'n exist for quarks and gluons
  could become sizeable at small x by parton splitting,
  provided that are not small at low scale/low $\boldsymbol{k}$

Parton imaging with an EIC

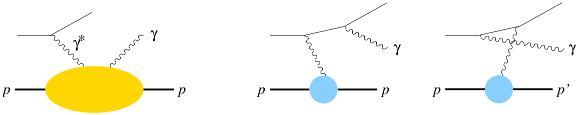
work done for preparation of the EIC white paper

with E. C. Aschenauer, S. Fazio, D. Müller, K. Kumerički, F. Sabatié

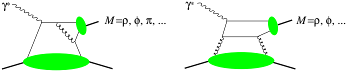
plots are preliminary

Exclusive processes

- deeply virtual Compton scattering (DVCS)
  - best theory control: NNLO, twist three, target mass corr's
    D. Müller et al., V. Braun and A. Manashov
  - interference with Bethe-Heitler process (calculable)
    $\rightarrow$ phase of Compton amplitude



  - at tree level $\frac{4}{9}u + \frac{1}{9}d + \frac{1}{9}s + \frac{4}{9}c$
    gluons via evolution and higher orders in α_s



- meson production
  - many channels, separation of quark flavors and gluons
  - theory more involved: meson wave fct.
    NLO and $1/Q$ corrections can be large

Experimental requirements

- rare processes, need for multi-dimensional binning (x_B, Q^2, t)
  $\rightarrow$ high luminosity
- study and use evolution effects
  $\rightarrow$ large lever arm in Q^2 at given x_B
- exclusive final state $\rightarrow$ hermetic detector
  scattered proton at small angles $\rightarrow$ Roman pots
  acceptance from small to large t crucial for imaging
- spin observables $\rightarrow$ e and p polarization
- e^+ beam would be very beneficial
  to extract interference of DVCS and Bethe-Heitler
  but is not as essential as previous points

A study of DVCS

- simulated DVCS data based on a model for GPDs

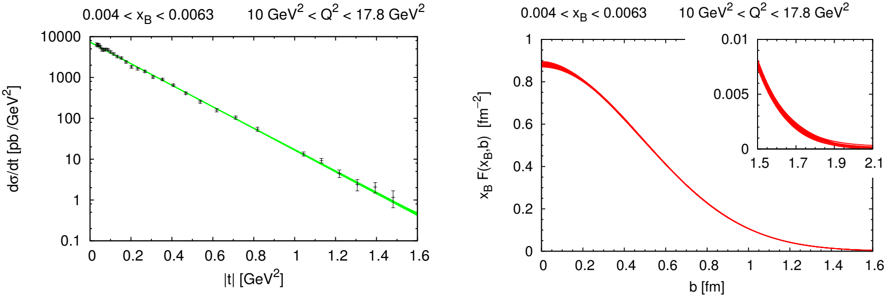
  K. Kumerički, D. Müller, K. Passek-Kumerčki 2007

  give good description of DVCS data of H1 and ZEUS

  concentrate on distributions
  H (unpol. parton in unpol. proton)
  and E (unpol. parton in transverse pol. proton)

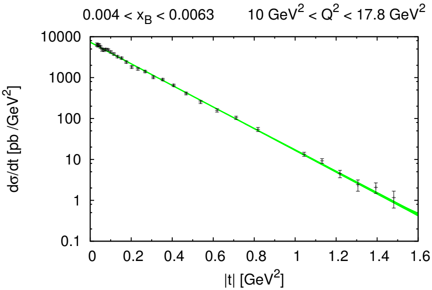
- include cuts for acceptance
  - for Roman pots assume $(0.175\,\mathrm{MeV})^2 < |t| < 0.88\,\mathrm{GeV}^2$
    requires careful integration into accelerator lattice
  - for $|t| > 1\,\mathrm{GeV}^2$ detect recoil proton in main detector
- smear events for expected resolution in t, Q^2, x_B
- assume systematic errors of 5%
- not shown: overall uncertainty from luminosity measurement

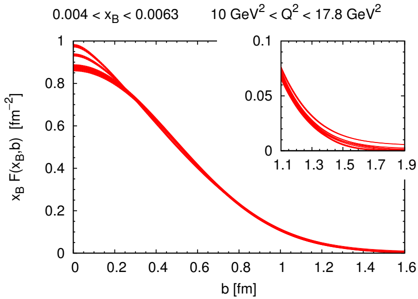
Imaging: first stage



- extract Compton cross sect. by subtracting Bethe-Heitler cross sect. with assumed uncertainty of 3%
- Fourier transform Compton amplitude (obtained from $d\sigma_{\gamma^* p \to \gamma p}/dt$)
- bands: parametric error from fitting $d\sigma/dt$ and from different extrapolations for large and small t

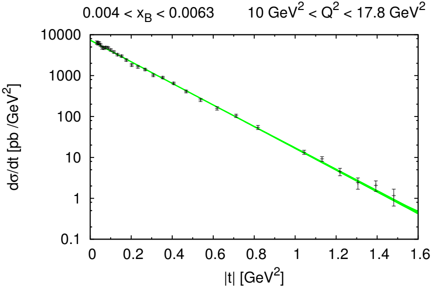
Imaging: first stage

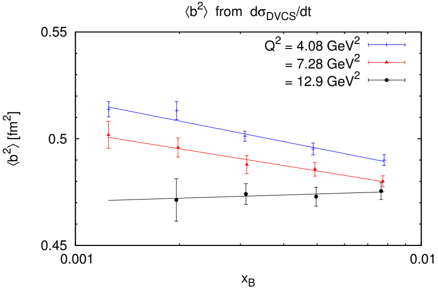




- clear loss of quality if go e.g. from $(0.175\,\mathrm{MeV})^2 < |t| < 1.5\,\mathrm{GeV}$ to $(0.300\,\mathrm{MeV})^2 < |t| < 0.88\,\mathrm{GeV}^2$

Imaging: first stage





- resolve combined correlation of $\langle \boldsymbol{b}^2 \rangle$ with x_B and Q^2
  - shrinkage: $\langle \boldsymbol{b}^2 \rangle = 2B = 2B_0 + 4\alpha' t$ with $d\sigma/dt \propto e^{Bt}$
  - B and α' changes with Q^2 due to evolution
    never seen experimentally so far, but different α' measured in different processes

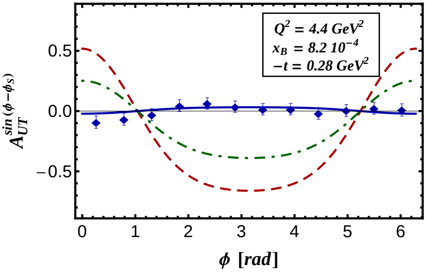
Polarization: access to E

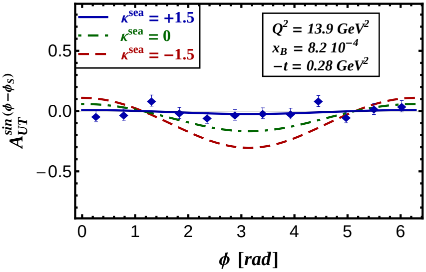
- $d\sigma/dt$ mainly sensitive to H
- transverse proton spin asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$ receives contributions from H and E
- generate data with model

$$E^a(x,\xi,t) = \kappa^a(t)\, H^a(x,\xi,t)$$

at scale $Q = 2\,\mathrm{GeV}$

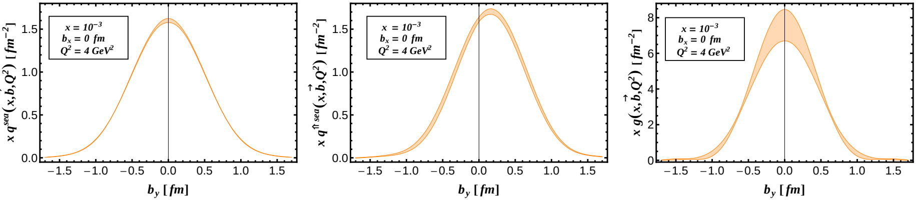
$a =$ sea quarks, gluons



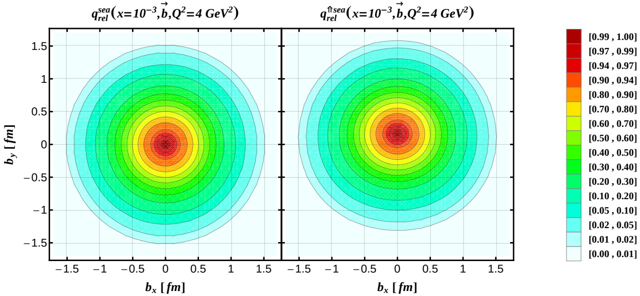


Imaging: second stage

- fit $d\sigma/dt$ and $A_{UT}^{\sin(\phi-\phi_S)}$ to GPD model ansatz (17 free parameters)
- extrapolate to $\xi = 0$ and Fourier transform $\to b$ space densities
- assume known values $q(x), g(x)$ for H^q, H^g at $\xi = 0, t = 0$
  forward limits of E^q, E^g unknown



- excellent reconstruction of H^{sea} and E^{sea}
  good reconstruction of H^g from scaling violation in $d\sigma/dt$
  errors on E^g very large (not shown)


$q_{rel}^{sea}(x=10^{-3},\vec{b},Q^2=4\ GeV^2)$
$q_{rel}^{\Uparrow sea}(x=10^{-3},\vec{b},Q^2=4\ GeV^2)$
b_y [fm]
b_x [fm]
[0.99 , 1.00]
[0.97 , 0.99]
[0.94 , 0.97]
[0.90 , 0.94]
[0.80 , 0.90]
[0.70 , 0.80]
[0.60 , 0.70]
[0.50 , 0.60]
[0.40 , 0.50]
[0.30 , 0.40]
[0.20 , 0.30]
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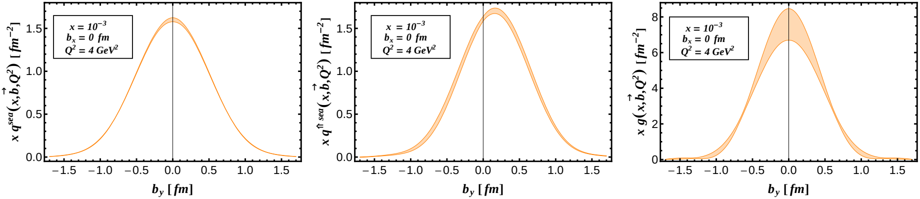
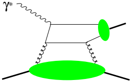
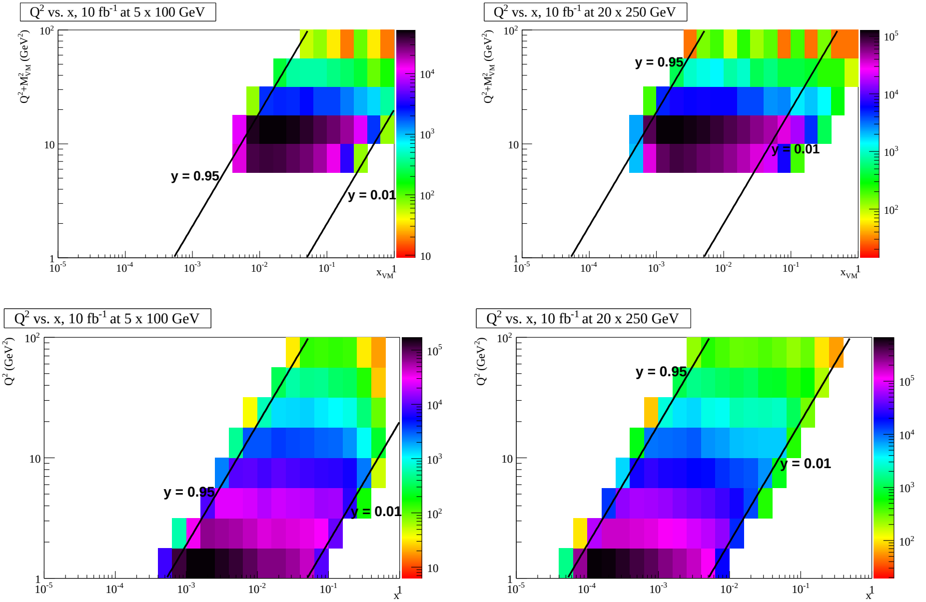

$x\ q^{sea}(x,\vec{b},Q^2)$ [fm^{-2}]
$x\ q^{\Uparrow sea}(x,\vec{b},Q^2)$ [fm^{-2}]
$x\ g(x,\vec{b},Q^2)$ [fm^{-2}]
$x = 10^{-3}$
$b_x = 0\ fm$
$Q^2 = 4\ GeV^2$
b_y [fm]

Focus on gluons: J/Ψ production



- $\gamma^* p \to J/\Psi p$
- wave function approx. non-relativistic (not too unknown)
- charm provides hard scale
  $\to$ can compute photo- and electroproduction
- finite Q^2: can compute both σ_L and σ_T at leading order in $1/Q$
  measurable via decay $J/\Psi \to \ell^+\ell^-$ $\rightsquigarrow$ extra handle for theory
- transverse target asymmetry sensitive to E^g (not studied yet)

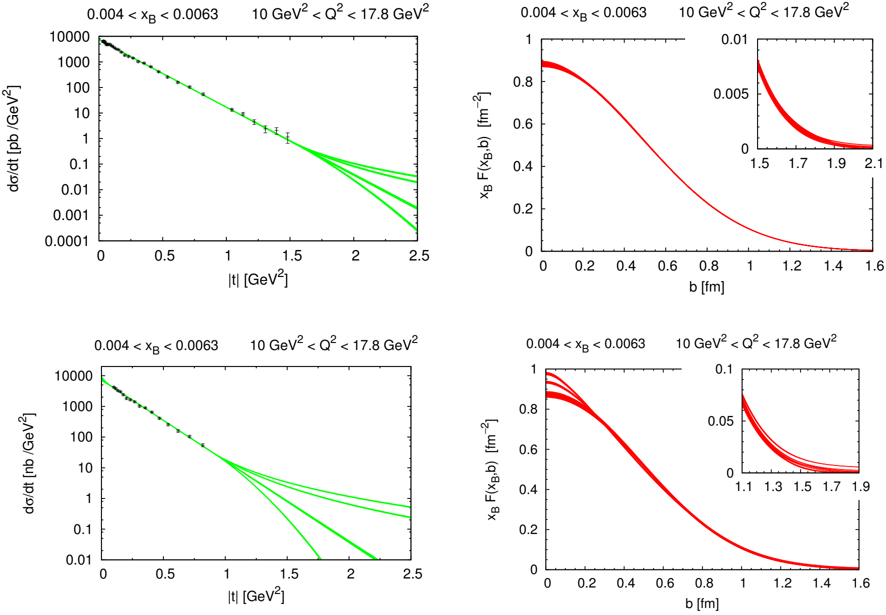
- generate data using version of Pythia
  tuned to J/Ψ data from H1 and ZEUS
- next slide: plots for event numbers of J/Ψ production (top row)
  and DVCS (bottom row)


Q^2 vs. x, 10 fb^-1 at 5 x 100 GeV
Q^2+M^2_VM (GeV^2)
y = 0.95
y = 0.01
x_VM
Q^2 vs. x, 10 fb^-1 at 20 x 250 GeV
Q^2+M^2_VM (GeV^2)
y = 0.95
y = 0.01
x_VM
Q^2 vs. x, 10 fb^-1 at 5 x 100 GeV
Q^2 (GeV^2)
y = 0.95
y = 0.01
x
Q^2 vs. x, 10 fb^-1 at 20 x 250 GeV
Q^2 (GeV^2)
y = 0.95
y = 0.01
x

Conclusions

- exclusive processes $\rightarrow$ images of quarks, antiquarks and gluons in transverse plane
- images can provide insight into important aspects of hadron structure and parton dynamics
- study of imaging in ep collisions at EIC
  $\rightarrow$ expect excellent capabilities with foreseen characteristics of accelerator and detector

Backup plots


0.004 < x_B < 0.0063
10 GeV^2 < Q^2 < 17.8 GeV^2
dσ/dt [pb /GeV^2]
|t| [GeV^2]
x_B F(x_B,b) [fm^-2]
b [fm]
dσ/dt [nb /GeV^2]