Imaging partons in the proton: the potential of EIC

M. Diehl

Deutsches Elektronen-Synchroton DESY

Orsay, 6 December 2012

HELMHOLTZ GEMEINSCHAFT

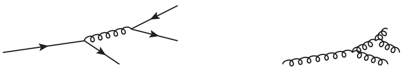
DESY

Two views of the proton:

- three quarks (spectroscopy, quark models)
- many quarks, antiquarks, gluons (high-energy processes, $\mathcal{L}_{\text{QCD}}$)

How are these two pictures and the underlying concepts related?

- simple (and often quoted) picture of nucleon:
  - three quarks at low resolution scale
  - gluons and sea quarks generated by perturbative splitting



but: PDF fits of Glück, Reya et al. show that this is too simple

- must have gluons and sea quarks at nonperturbative scales

How can we understand their dynamical origin in QCD?
How do they relate to the valence quarks?

What is the dynamical origin of sea quarks and gluons in QCD? How do they relate to the valence quarks?

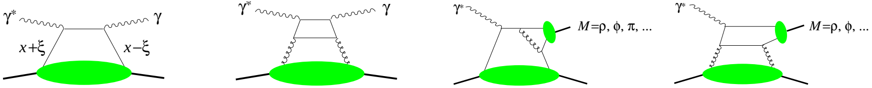
$\rightsquigarrow$ explore and quantify features of quarks, antiquarks and gluons in the proton that are suitable to guide theory

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

How to obtain images at the femtometer scale?

Access to transverse position: exclusive processes

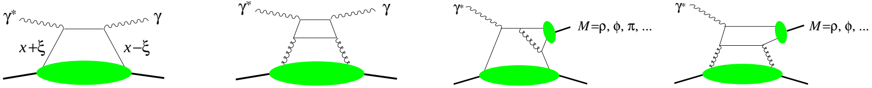
- DVCS and meson production ⇝ generalized parton distrib's



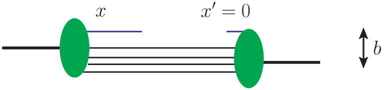
- similar theory as for usual parton densities
  have factorization proofs, evolution in resolution scale Q
- longit. mom. transfer ⇝ two parton mom. fractions $x \pm \xi$
  - at LO in α_s measure GPD$(x, \xi = x, \mathbf{\Delta})$
  - in general x "smeared" around ξ
- separate dependence on x and ξ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

Access to transverse position: exclusive processes

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



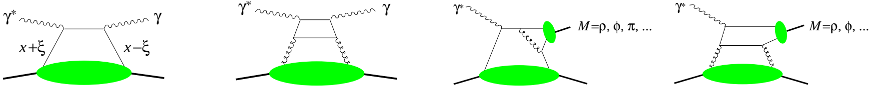
- '1st stage' imaging: amplitude $\xrightarrow{\text{Fourier}}$ GPD$(x, \xi = x, \boldsymbol{b})$



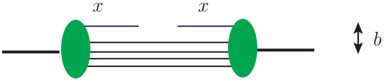
  - no probability interpretation
    but $\boldsymbol{b}$ = well defined transverse distance

Access to transverse position: exclusive processes

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



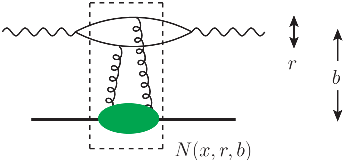
- '2nd stage': GPD$(x, \xi = x, \boldsymbol{b}) \;\rightarrow\;$ GPD$(x, \xi = 0, \boldsymbol{b})$



  - 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 s



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 perturb. calc.
  - GPD formal'm: all x, large Q limit, predicts Q dependence
  - in double limit of large Q and small x approaches equivalent

Apples, oranges, and other fruits

mind the difference:

$4\,\frac{\partial}{\partial t}\log G(t)\Big|_{t=0} = \langle r_x^2 + r_y^2\rangle$ squared radius of a disk

$6\,\frac{\partial}{\partial t}\log G(t)\Big|_{t=0} = \langle r_x^2 + r_y^2 + r_z^2\rangle$ squared radius of a sphere

form factor	distribution	$\langle b^2\rangle$
F_1^p	$\sum_q e_q\,(q-\bar{q})$	$(0.67\,\mathrm{fm})^2$
G_E^p		$(0.72\,\mathrm{fm})^2 = (0.67\,\mathrm{fm})^2 + \kappa_p/m_p^2$

- in form factor integral parton distributions have average $x \sim 0.2$
- J/Ψ photoproduction at HERA: generalized gluon dist. at $x = 10^{-3}$
  $\rightsquigarrow \langle b^2\rangle = (0.57$ to $0.60\,\mathrm{fm})^2$
- mix of sea quarks and gluons from DVCS:
  $\rightsquigarrow \langle b^2\rangle = (0.65 \pm 0.02\,\mathrm{fm})^2$ at $\langle x\rangle = 1.2\times 10^{-3}$, $\langle Q^2\rangle = 8\,\mathrm{GeV}^2$

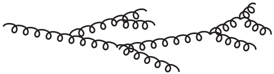
numbers: G_E and F_1 from Particle Data Group 2012; J/Ψ from H1, hep-ex/0510016 and ZEUS, hep-ex/0201043; DVCS from H1, arXiv:0709.4114

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 $\langle b^2 \rangle \propto \text{const} + 4\alpha' \log \frac{1}{x}$ Gribov diffusion

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

  much smaller than in soft hadronic procs.

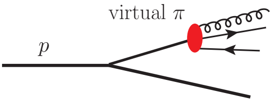
  value for valence and sea quarks? interplay with gluons?

- 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 $x \lesssim m_\pi/m_p$

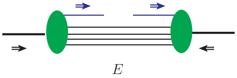
requires precise measurem'ts at low $\boldsymbol{\Delta}$



How does the nucleon spin spin arise at microscopic level?

Which role do orbital angular momentum and spin-orbit correlations play in the nucleon?

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 $E(x, \xi = 0, \boldsymbol{\Delta})$

  - connection to orbital angular momentum via $\boldsymbol{b} \times \boldsymbol{p}$
    $\rightsquigarrow$ Ji's angular momentum sum rule
  - 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

Dynamics of spin-orbit correlations

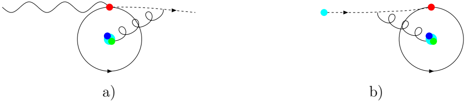


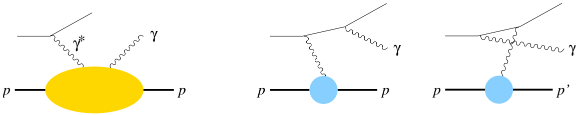
figure: M Burkardt

- 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

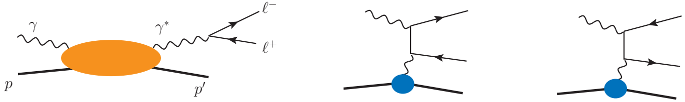
  test experimentally for different x and diff't parton species
- both E and Sivers dist'n exist for quarks and gluons
  could become sizeable at small x by parton splitting,
  provided that are not small at low scale/low $\boldsymbol{k}$

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)
    → 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
- close analog: timelike Compton scattering (TCS)



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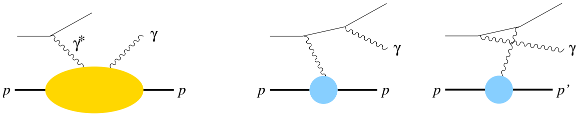
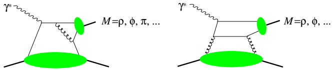


  - at tree level $\frac{4}{9}u + \frac{1}{9}d + \frac{1}{9}s + \frac{4}{9}c$
    gluons via evolution and higher orders in α_s
- meson production
  - many channels, separation of quark flavors and gluons
  - theory more involved: meson wave fct.
    NLO and $1/Q$ corrections
    can be large



- pioneering measurements at H1, ZEUS, HERMES, JLab
  $\rightarrow$ first glimpses of parton imaging
- JLab 12 GeV will investigate high x region
  COMPASS will give more insight into sea quark region
- photoproduction (J/Ψ, Υ, γ^*) at high energy:
  ultraperipheral collisions at LHC
- but full exploration will need a dedicated new facility

Experimental requirements

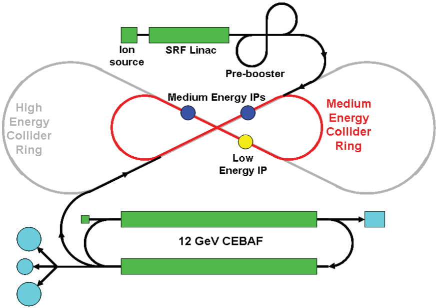
- rare processes, need multi-dimensional binning (x_B, Q^2, t)
  to get full physics information $\rightarrow$ high luminosity
- study and use evolution effects
  $\rightarrow$ large lever arm in Q^2 at given x_B
- exclusive final state $\rightarrow$ hermetic detector
  scattered proton at small angles
  acceptance from small to large t crucial for imaging
- spin observables $\rightarrow$ e and p polarization

The Electron Ion Collider project

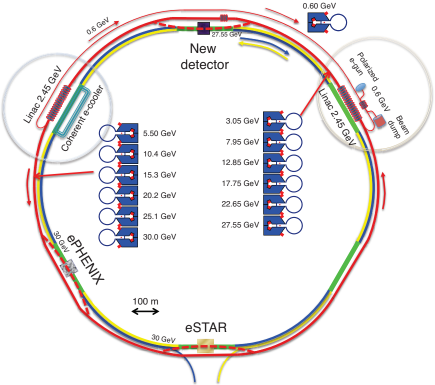
- e^- on protons and on light to heavy nuclei
- high polarization of e^- ($\sim 80\%$)
  and of p ($\gtrsim 70\%$, longit. and transv.)
- variable c.m. energy
  (staged approach with subsequent energy upgrade)
- high luminosity $\sim 10^{33} \div 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  integrated luminosity $\sim 10 \div 100\,\mathrm{fb}^{-1}$
- near hermetic detector

All plots in the following are from the EIC White Paper (2012)
to appear on arXiv soon

The Electron Ion Collider: two designs



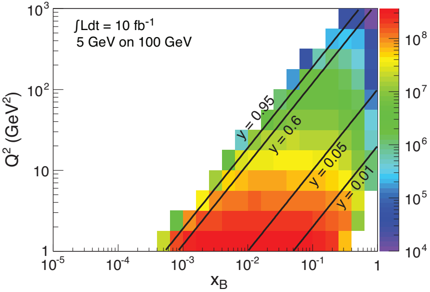
ELIC at JLab
add proton/ion ring to CEBAF e^- beam



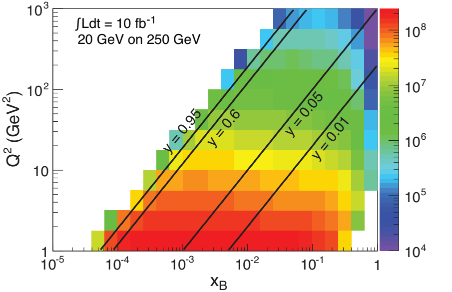
eRHIC at BNL
add e^- LINAC to existing RHIC complex

Kinematic reach and fine binning

event numbers for inclusive DIS



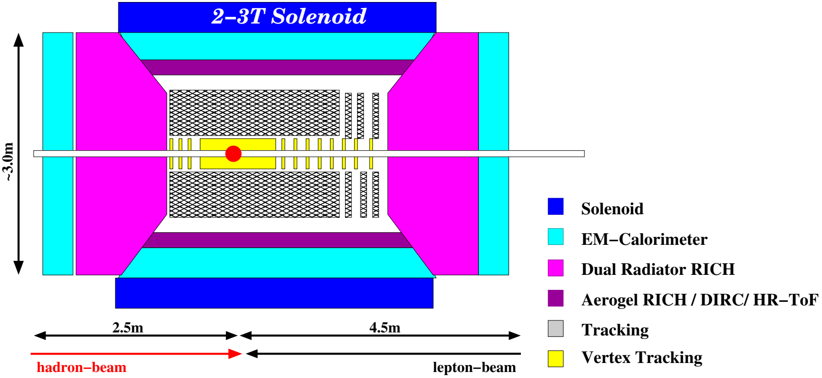
$\sqrt{s} = 45\,\mathrm{GeV}$, stage I



$\sqrt{s} = 140\,\mathrm{GeV}$, stage II

plots: E C Aschenauer

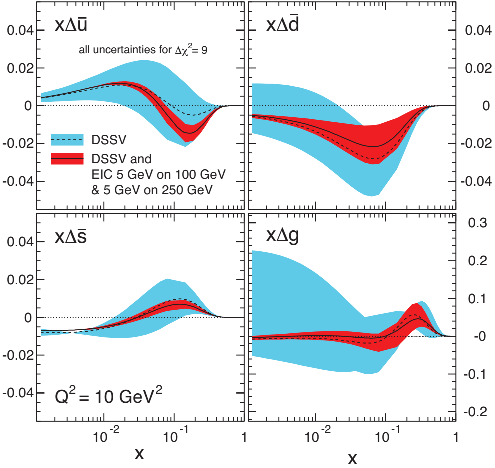
Schematic view of an EIC detector



- large acceptance in η
- good PID and vertex resolution
- detection of low-angle protons, neutrons, electrons
  $\rightsquigarrow$ integration of detector in IR design

Science highlights of EIC (a selection)

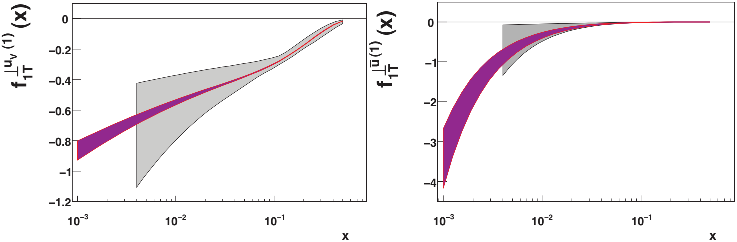
- polarized parton densities: gluon, flavor separated q and $\bar{q}$ down to small x



plot: Aschenauer, Sassot, Stratmann arXiv:1206.6014

Science highlights of EIC (a selection)

- transverse-momentum dependent distributions
  transv. mom. ⊗ spin ⊗ flavor



- first moment of Sivers function for $u - \bar{u}$ (left) and $\bar{u}$ (right)
  grey band: fit of present data
  pink band: including semi-inclusive $\pi^{\pm}$ prod'n at EIC

plot: A Prokudin

Science highlights of EIC (a selection)

- imaging of quarks and gluons in the proton → this talk

eA collisions

- physics of high gluon densities → talk by C Marquet
- nuclear quark and gluon densities down to low x
- hadronization in cold nuclear medium

Parton imaging with an Electron-Ion Collider

work done by/with

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

for the EIC White Paper (2012)

A study of DVCS

- simulated DVCS data based on a model for GPDs

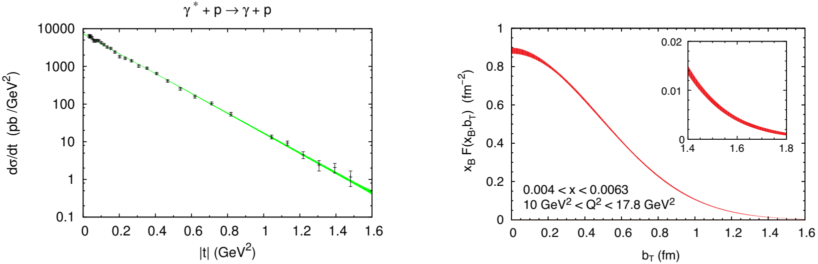
  K. Kumerički, D. Müller, K. Passek-Kumerčki 2007
  gives good description of HERA DVCS data

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

  should be good approx. for small x_B
- include cuts for acceptance
  assume proton detection in Roman pots for
  $|t| > (0.175\,\mathrm{MeV})^2$
- 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

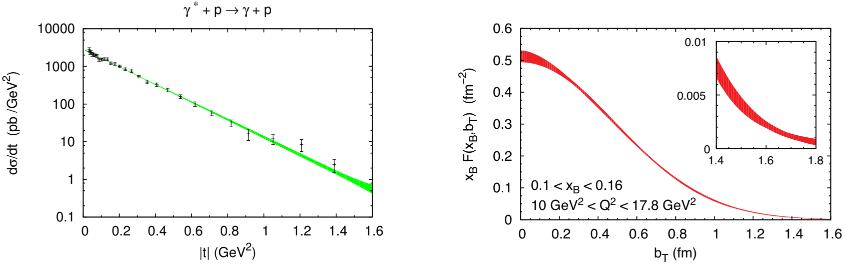
$E_e = 20\,\text{GeV}$, $E_p = 250\,\text{GeV}$ with $10\,\text{fb}^{-1}$ for $|t| < 1\,\text{GeV}^2$ and $100\,\text{fb}^{-1}$ for $|t| > 1\,\text{GeV}^2$



- 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

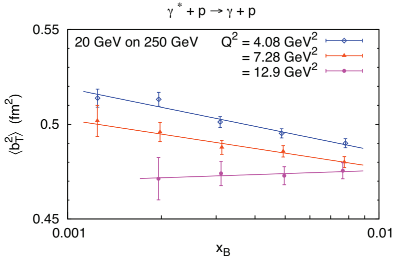
$E_e = 5\,\mathrm{GeV}$, $E_p = 100\,\mathrm{GeV}$ with $10\,\mathrm{fb}^{-1}$



- high-quality imaging for both low and high energies

Imaging: first stage

$E_e = 20\,\mathrm{GeV}, E_p = 250\,\mathrm{GeV}$ with $10\,\mathrm{fb}^{-1}$ for $|t| < 1\,\mathrm{GeV}^2$ and $100\,\mathrm{fb}^{-1}$ for $|t| > 1\,\mathrm{GeV}^2$



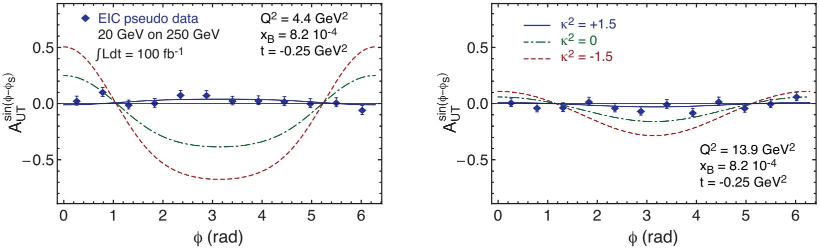
- resolve combined correlation of $\langle \boldsymbol{b}^2 \rangle$ with x_B and Q^2
  - shrinkage: $\langle \boldsymbol{b}^2 \rangle = 2B = 2B_0 + 4\alpha' \log \frac{1}{x}$ with $d\sigma/dt \propto e^{Bt}$
  - B and α' change with Q^2 due to evolution
- high luminosity and low syst. err. crucial for revealing these effects

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 where

$$E^a(x,\xi,t=0) = \kappa^a \, H^a(x,\xi,t=0)$$

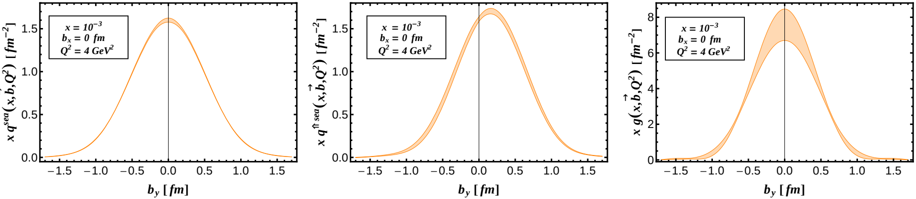
at scale $Q = 2\,\text{GeV}$
$a =$ sea quarks, gluons



plots: Dieter Müller

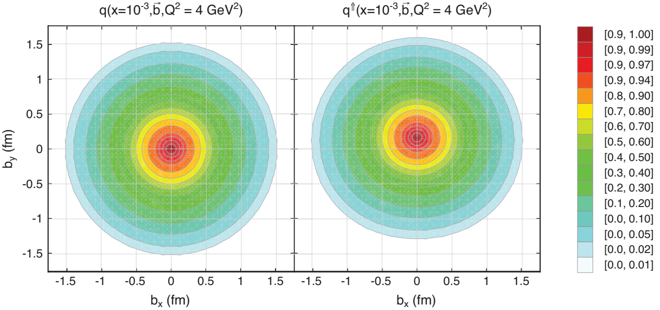
Imaging: second stage

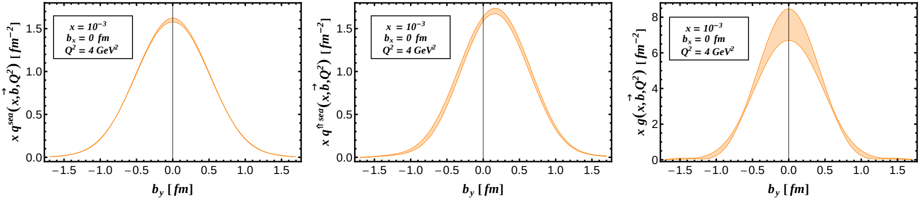
- fit $d\sigma/dt$ and $A_{UT}^{\sin(\phi-\phi_S)}$ to GPD model ansatz (17 free parameters)
- extrapolate to $\xi = 0$ and Fourier transform $\to b$ space densities
- assume known values $q(x), g(x)$ for H^q, H^g at $\xi = 0, t = 0$
  forward limits of E^q, E^g unknown



plots: Dieter Müller

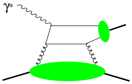
- excellent reconstruction of H^{sea} and E^{sea}
  good reconstruction of H^g from scaling violation in $d\sigma/dt$
  errors on E^g very large (not shown)



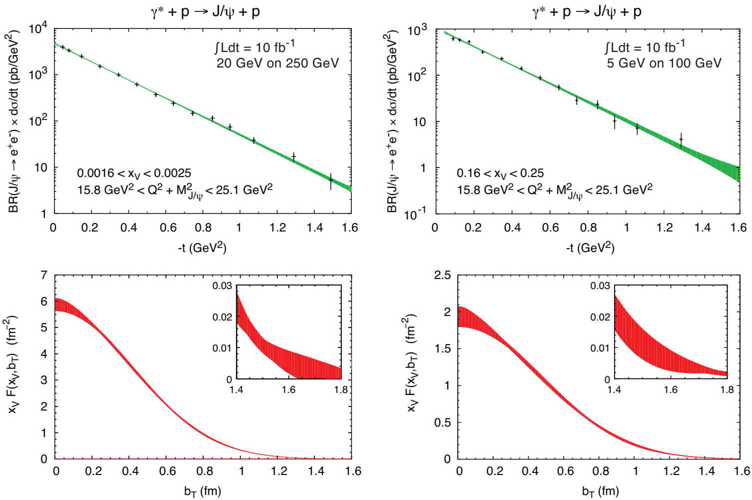


plots: Dieter Müller

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:
  - theory more stable
  - 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
- generate pseudo-data using a version of Pythia
  tuned to J/Ψ data from H1 and ZEUS



- precise measurements possible in electroproduction
- can scan spatial distribution of gluons over two orders of magnitude in momentum fraction

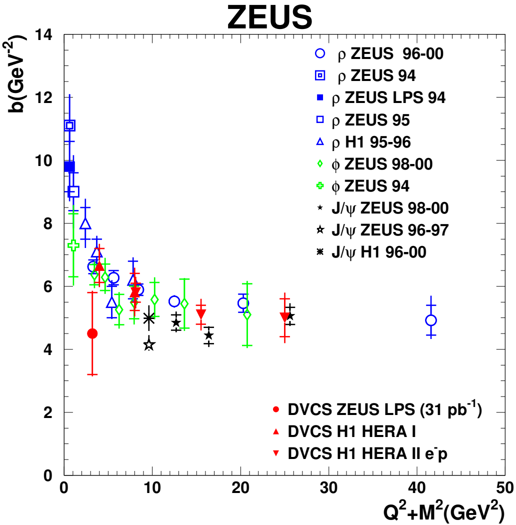
Conclusions

- exclusive processes $\to$ 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
  $\to$ expect excellent capabilities with foreseen characteristics of accelerator and detector

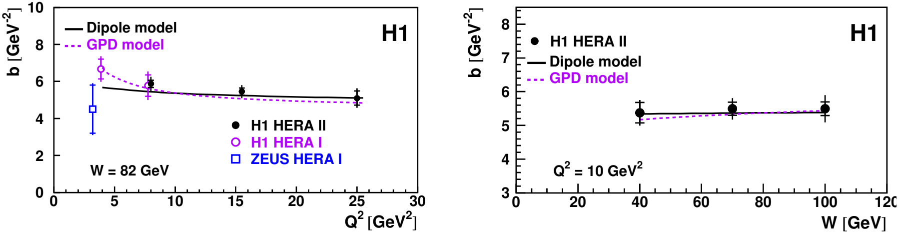
Backup plots

H1 and ZEUS results on t dependence of DVCS and J/Ψ production

t slopes in DVCS and meson production (ZEUS, arXiv:0812.2517)



t slope in DVCS (H1, arXiv:0907.5289)



t dependence in J/Ψ production (H1, hep-ex-0510016)