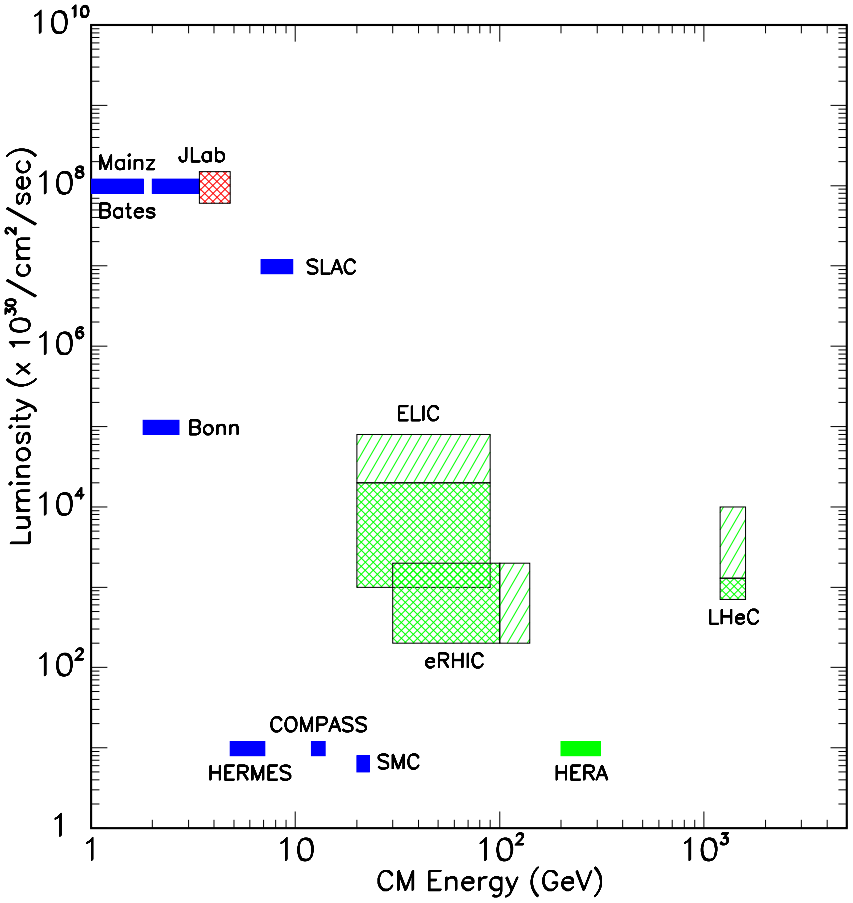
Exclusive processes and nucleon structure

C. Weiss (JLab), EIC Workshop Rutgers, 14–Mar–2010



Luminosity	low-rate processes
Energy	x, Q^2 coverage
Detection	exclusivity, resolution

- Nucleon structure in QCD

  Quark/gluon transverse distributions, correlations, orbital motion

- High–Q^2 exclusive processes and GPDs

  Reaction mechanism and tests

  Large vs. small x

- Exclusive processes from 12 GeV to EIC

  DVCS: GPDs from dispersion analysis

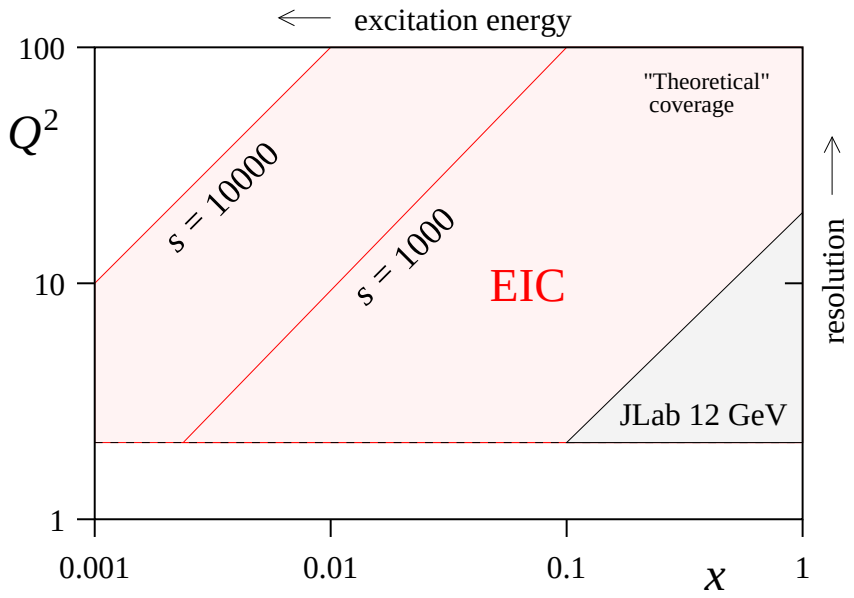
  Meson production: Quark imaging

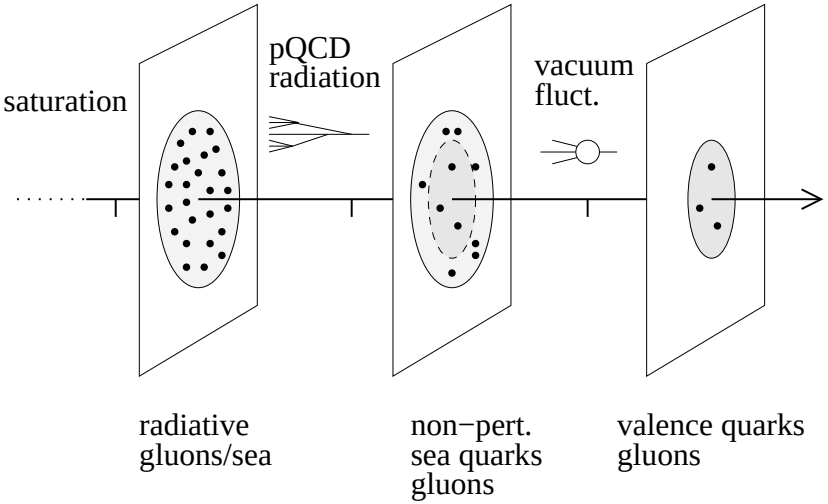
  $J/\psi, \phi$: Gluon imaging

  N^* and meson structure

  Nuclei: Color transparency, shadowing, coherent processes

Nucleon structure: Landscape





- Nucleon in QCD many–body system

  Partonic picture: Different components, effective dynamics

  Correspondence with rest frame picture: Euclidean QCD, lattice, instantons

- Components probed in ep scattering

  JLab 12 GeV — Valence region: $3q, 5q$

  EIC — Sea quarks, gluons, Q^2 dependence

- Physical properties

  Parton densities

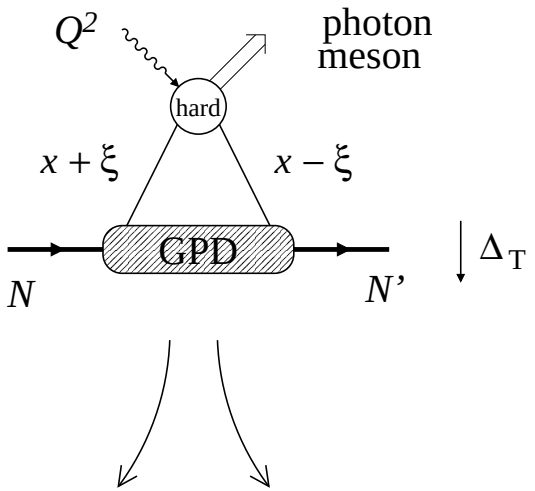
  Transverse spatial distributions

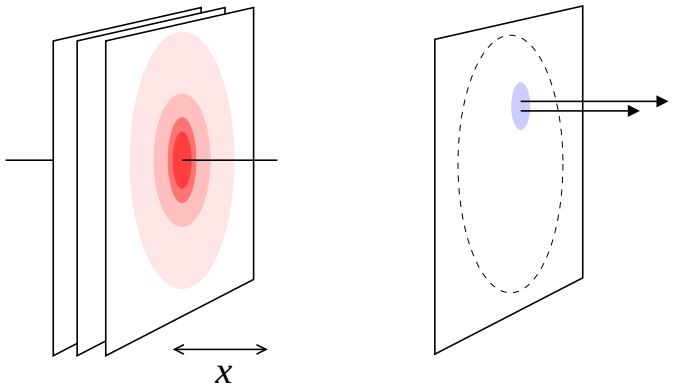
  Orbital motion, angular momentum

  Correlations

  + nuclear modifications

Exclusive processes: GPDs





Transverse density
$\xi = 0$

$q\bar{q}$ correlations
$x < \xi$

- $Q^2 \gg$ hadronic size^{-2}: Reaction pointlike, partonic mechanism

  QCD factorization theorem
  GPDs universal, process–independent
  Müller etal. 94; Brodsky etal. 94; Collins etal. 96; Radyushkin 96, Ji 96

- Nucleon structure from GPDs

  $\xi = 0$ Transverse spatial distribution of
  of partons with longitudinal momentum x → Miller

  $|x| < \xi$ $q\bar{q}$ correlations in nucleon

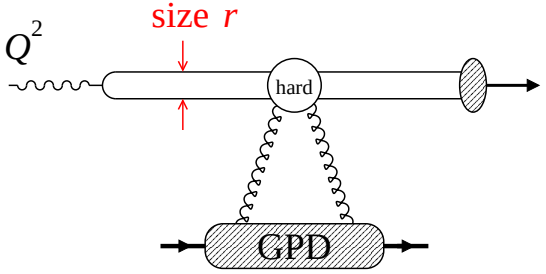
  Moments Form factors of local twist–2 operators
  EM tensor, angular momentum → Schweitzer

- Test reaction mechanism!

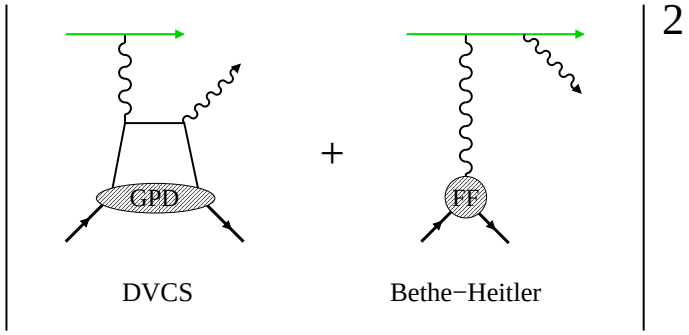
  Model–independent features: Universality,
  Q^2 scaling, kinematic dependences, . . .

  Finite–size corrections: Theory estimates
  Frankfurt et al 96, Kroll, Goloskokov 05+

Exclusive processes: Large vs. small x

	$x \ll 0.1$	$x > 0.1$
Cross sections	Gluon/singlet quark $J/\psi, \phi, \rho^0, \gamma$ large vs. non-singlet quarks ρ^+, π, K small	Valence quark dominance $\rho^+ \approx \rho^0, \phi \ll \rho^0$ → Guidal
GPD interpretation	Skewness small $\xi \ll 1$ theoretically controlled $t \approx -\Delta_\perp^2$ Transverse imaging	Skewness sizable, non-perturbative $t = f(\xi, \Delta_\perp)$, $t_{\min}$ large Transverse structure + longitudinal correlations
Higher twist	 Space–time picture: Dipole model HT ∼ finite dipole size Successful phenomenology incl. absolute cross sections HERA	"Knockout" of $q\bar{q}$ pair Sudakov suppression

DVCS: Observables and analysis



$$\text{Re DVCS} = \int_{\text{Dispersion}} \text{Im DVCS} + \text{D–Term}$$

$$\text{Im DVCS} \overset{\text{LT}}{\sim} H(\xi,\xi;t)$$

measurable!

- Interference BH–DVCS allows one to access DVCS at amplitude level

HERMES, JLab	DVCS $\times$ BH	from σ(pol), $\sigma(e^{\pm})$
HERA	$\lvert\text{DVCS}\rvert^2$	from σ(unpol)

- Reaction mechanism

  JLab Hall A cross sections show Q^2 scaling, higher twist $\sim M_V^2/Q^2$ → Munoz Camacho

  HERA: Q^2–scaling, t–slopes

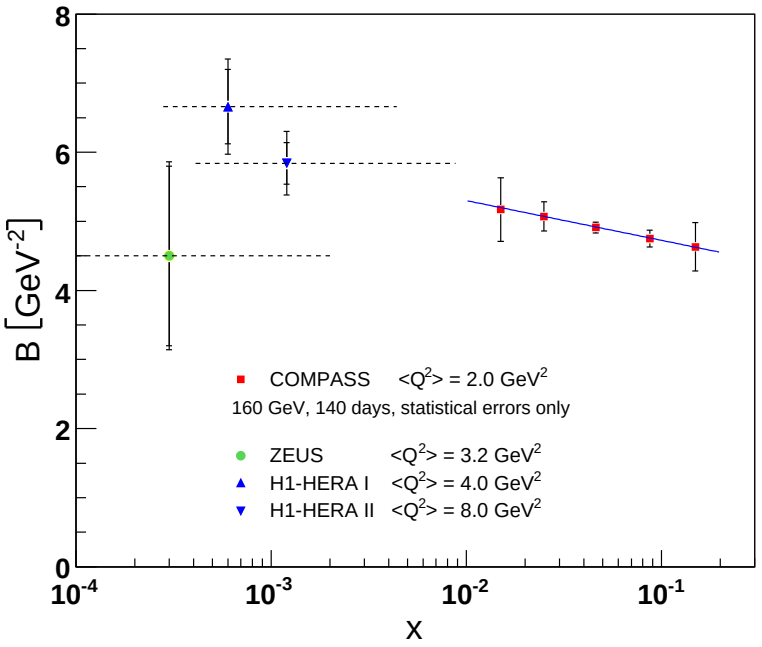
- Theory analysis

  Leading–twist analysis developed at NLO
  Müller et al.

  Successful HERA phenomenology, $R =$ DVCS/DIS

  Dispersion relations for hard exclusive amplitudes: Minimize model dependence
  Frankfurt et al. 97, Teryaev et al. 05+; Müller etal. 07; Diehl et al. 07

DVCS: Future facilities



- JLab 12 GeV: Valence quark GPDs through spin observables, p/D → Munoz Camacho
- COMPASS: DVCS at $0.01 < x < 0.1$
  Re DVCS from $\mu^{\pm}$ Projections Schoeffel 09
- EIC: Great opportunities!
  Need to quantify impact on GPD analysis
  Simulations: Sandacz, Horn, Hyde

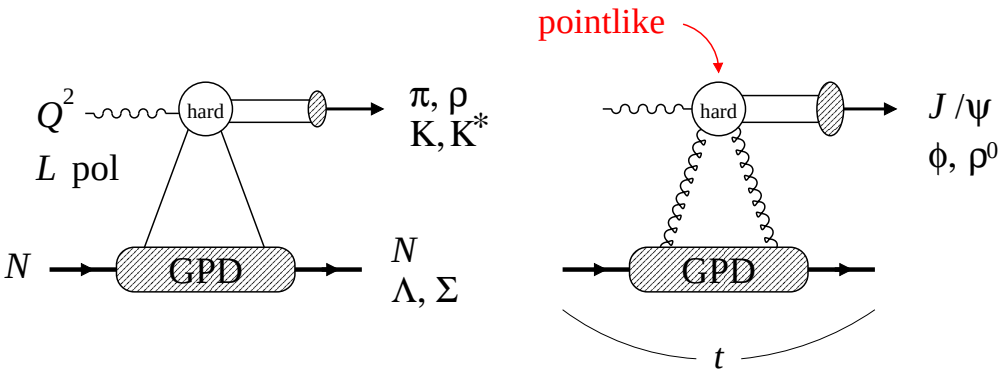
- Topics for discussion

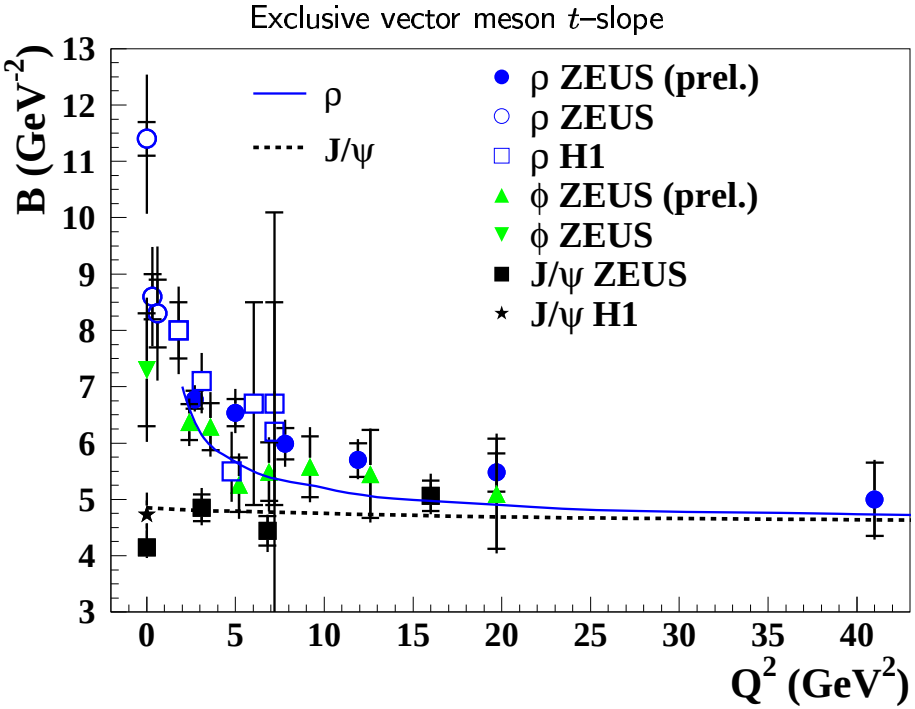
Reaction mechanism: What do we need in order to separate leading and higher twist?

Dispersion analysis: Do we need more data at smaller x or better accuracy at larger x?

Neutron DVCS: What can be done with forward tagging?

Meson production: Mechanism





- Requires $Q^2 > 10\,\mathrm{GeV}^2$ for pointlike process

  HERA: t–slope independent of Q^2, universality

  JLab 6 GeV: Mechanism not yet fully understood → Guidal

- Meson selects definite charge/spin/flavor component of GPD

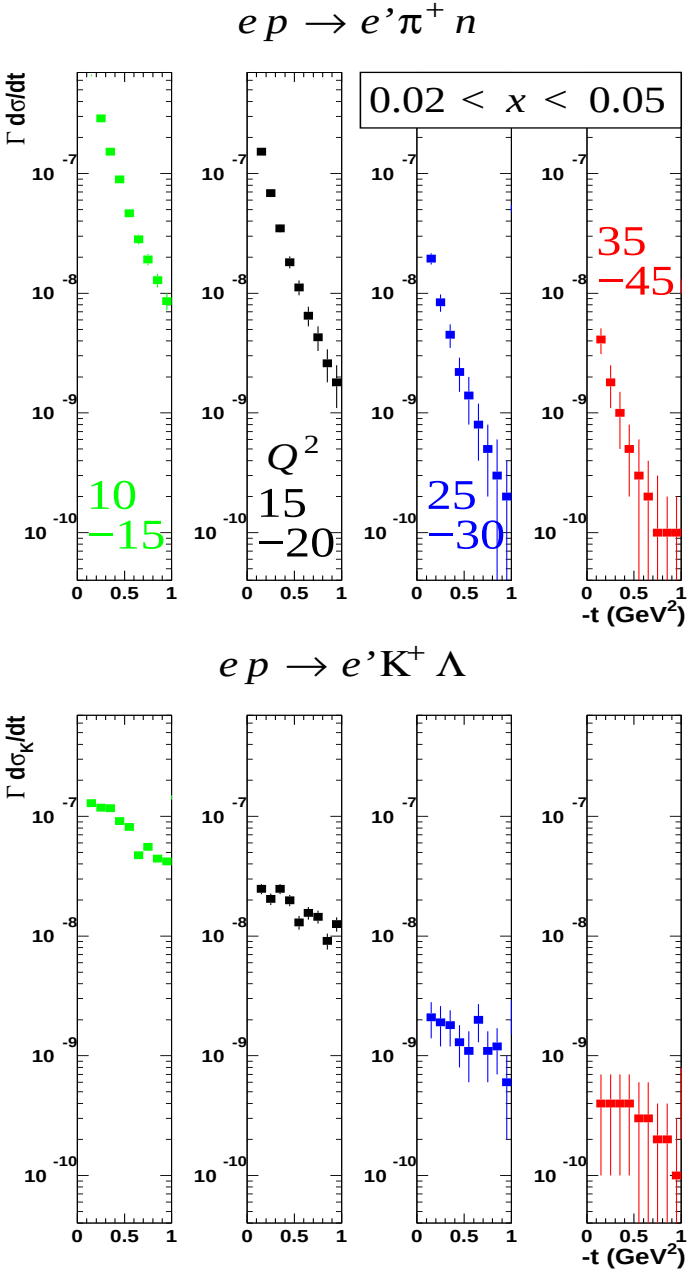
$J/\psi, \phi$	gluon
ρ^0	gluon + singlet q
ρ^+, K^*	non-singlet q
π, K, η	non-singlet Δq

- Nucleon structure interest

  Transverse imaging of quarks and gluons

  Spin/flavor structure

Meson production: Quark imaging



EIC simulation T. Horn et al. 09

- Do strange and non-strange sea quarks have the same transverse distribution?

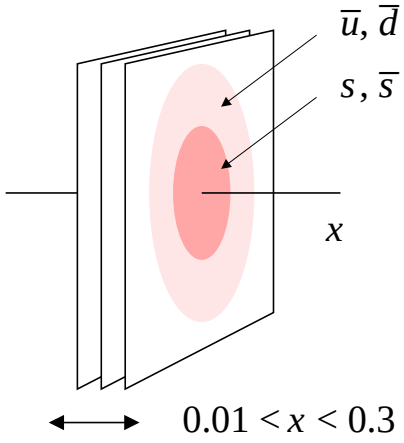
  → πN or $K\Lambda$ components in nucleon?
  → QCD vacuum fluctuations?

- EIC: Exclusive π and K production → Horn

  High luminosity for low rates,
  differential measurements in x, t, Q^2

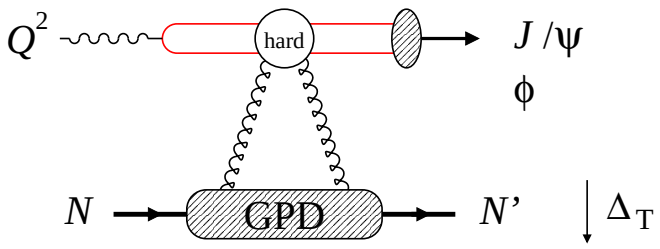
  Kinematic reach in Q^2, x

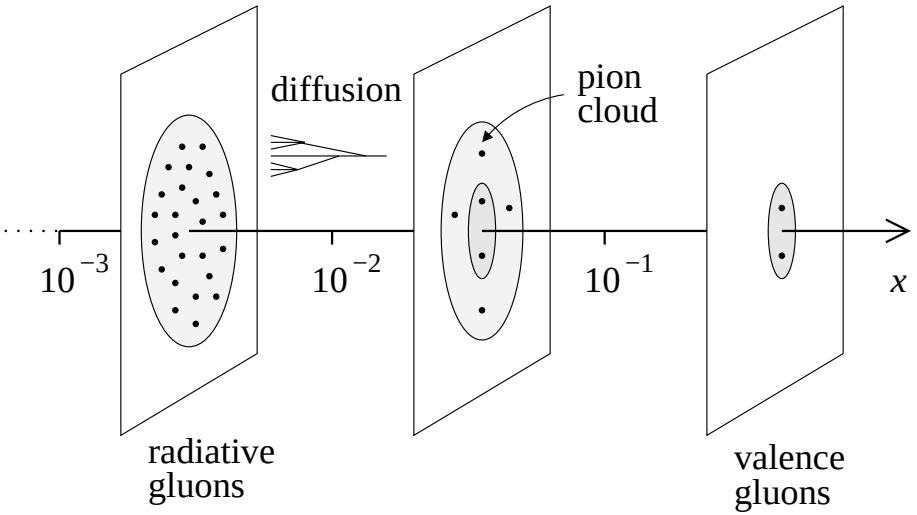
  Recoil detection for exclusivity, t–distributions



. . . many more examples!

Meson production: Gluon imaging





HERA FNAL 82

- Gluon imaging through exclusive J/ψ and ϕ ($Q^2 > 10\,\mathrm{GeV}^2$)

  Clean channels!

  Transverse distribution directly from Δ_T–dependence

- Physical interest → Vogt, Strikman

  Valence gluons – dynamical origin?

  Chiral dynamics at $b \sim 1/M_\pi$

  Diffusion in QCD radiation

  Input for pp@LHC MC, small–x physics

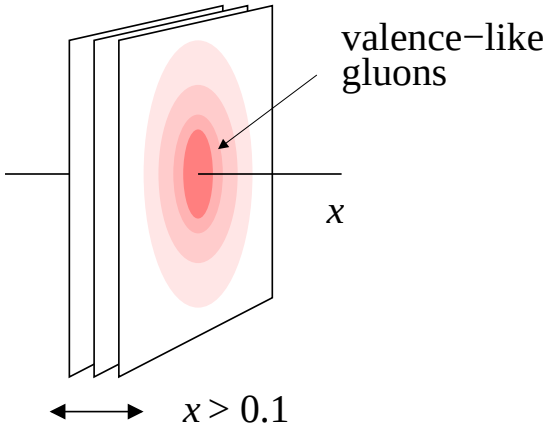
- Existing data and plans

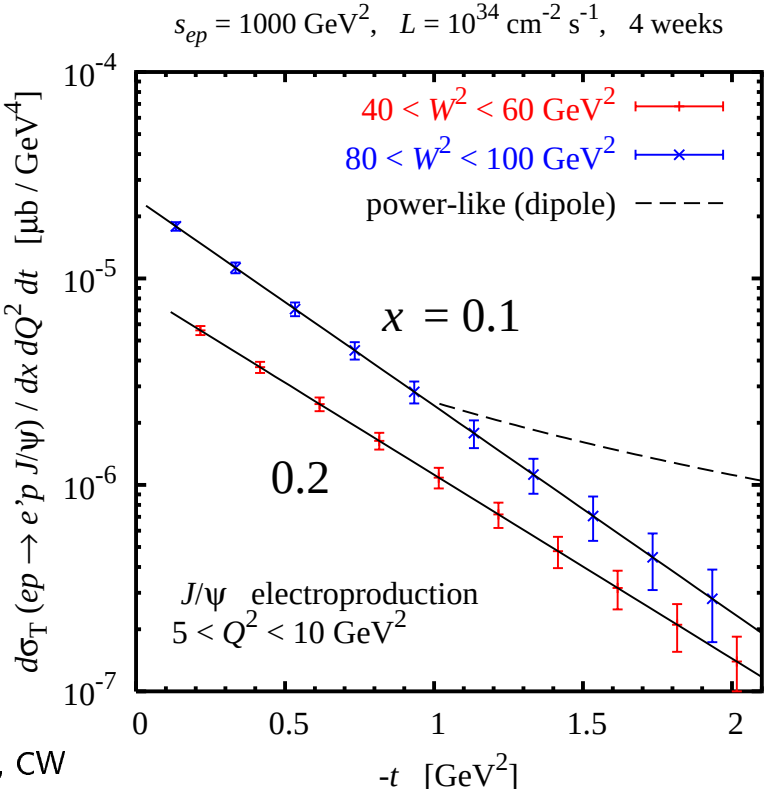
  Transverse area $x < 0.01$ HERA

  Larger x poorly known FNAL 82, ...

  JLab 12 GeV: Exclusive ϕ, J/ψ near threshold → Chudakov

Meson production: Valence gluons





Hyde, CW

- EIC: Transverse imaging of valence gluons through exclusive $J/\psi, \phi$
- Needed for imaging

  Full t–distribution $\rightarrow$ Fourier
  Non-exponential? Power–like at $|t| > 1\,\mathrm{GeV}^2$?

  Electroproduction with $Q^2 > 10\,\mathrm{GeV}^2$:
  Test reaction mechanism, compare different channels, control systematics

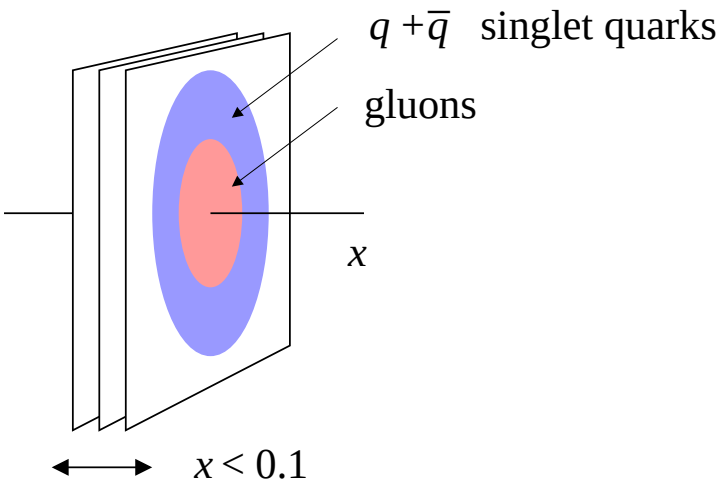
- Experimental requirements

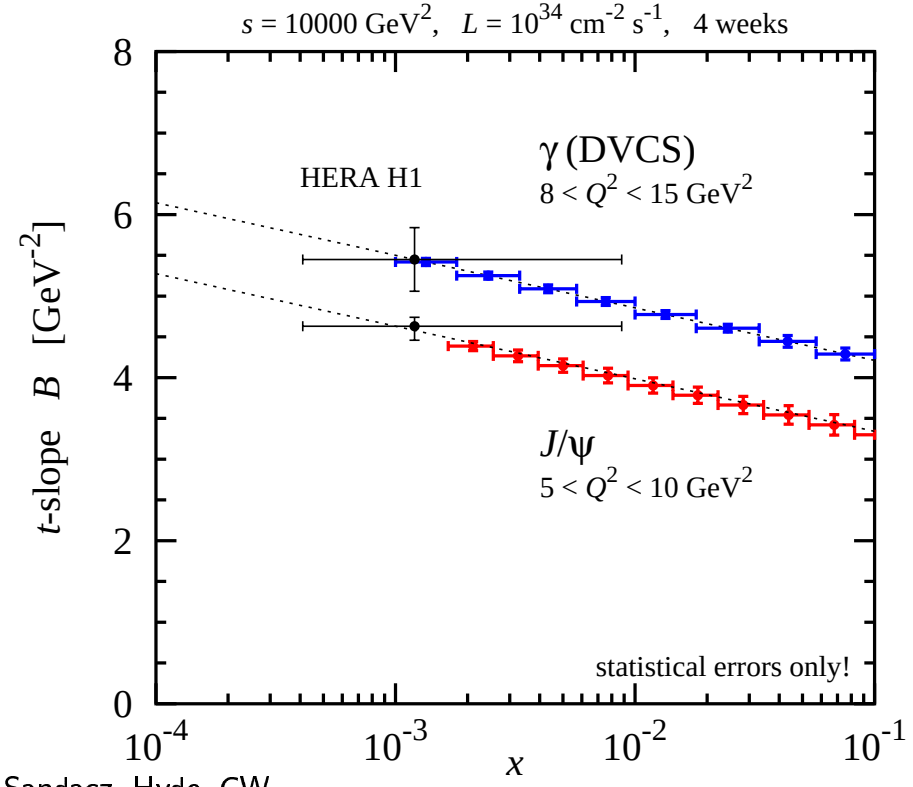
  Recoil detection for exclusivity, t–measurements

  Luminosity $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $x > 0.1$, electroproduction, high–t

First gluonic images of nucleon at large x!

Meson production: Gluon vs. quark size





Sandacz, Hyde, CW

- Do singlet quarks and gluons have the same transverse distribution?

  Hints from HERA:
  Area$(q + \bar{q})$ > Area(g)

  Difference expected from chiral dynamics:
  Pion cloud Strikman, CW 09

  No difference assumed in present pp MC generators for LHC!

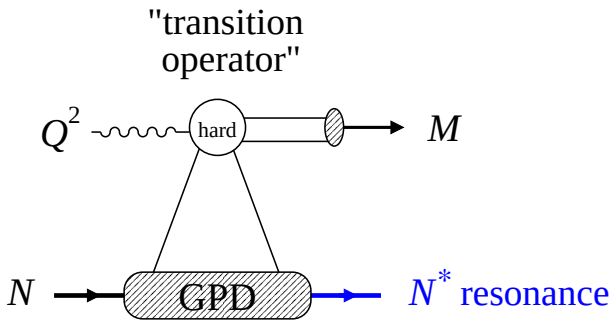
- EIC: Gluon size from J/ψ, singlet quark size from DVCS

  x–dependence: Quark vs. gluon diffusion in wave function

  Detailed analysis: LO → NLO Müller et al.

Detailed differential images of nucleon's partonic structure

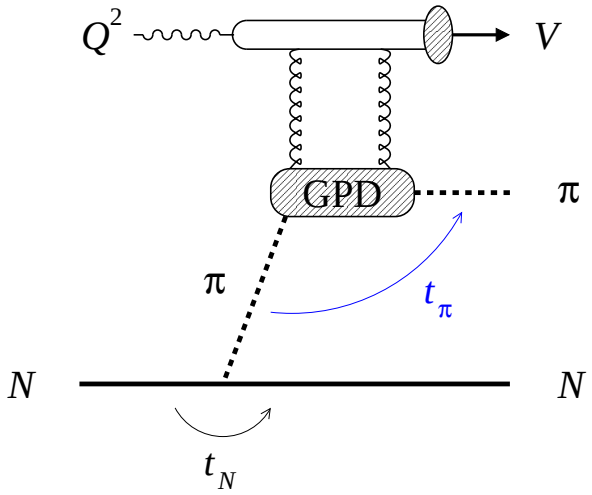
Meson production: N^* and meson structure



- N^* resonance excitation through hard exclusive process

  QCD factorization: Hard process as transition operator Frankfurt, Strikman, Polyakov

  New quantum numbers!



- New probes of meson structure

  Meson size $\leftrightarrow$ Q^2 dependence, flavor structure

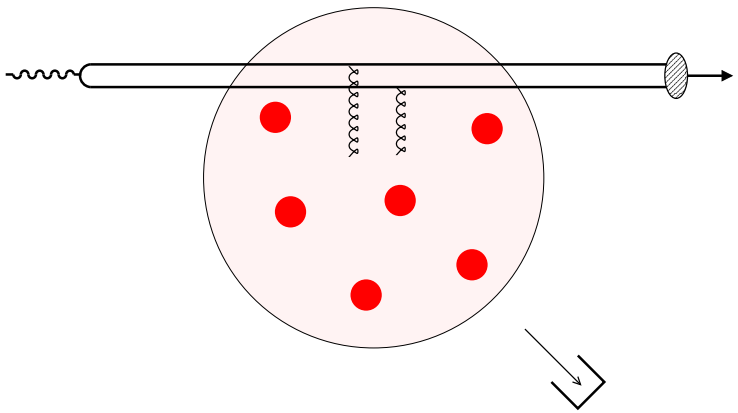
  "Exotics" from QCD counting rules

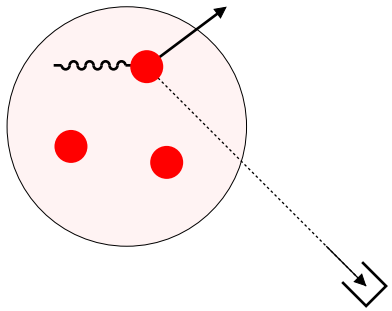
- Pion GPDs from "knockout" processes → Girod

  Requires $x \ll M_\pi/M_N \sim 0.1$ for quasi–real pion

  Kinematics with $p_T(\pi) \gg p_T(N)$ suppresses production on nucleon Strikman, CW 04

Exclusive processes with nuclei





- QCD factorization = Color Transparency

  Nuclei as filter for small–size configurations

  Explore longitudinal direction $R_A \leftrightarrow l_{\rm coh}$

- Coherent processes: Nuclear GPDs

  Fundamental quark/gluon distributions
  in nucleus, matter vs. charge radii → Liuti

  Shadowing as function of impact parameter → Guzey

  Requires detection at very low $t \sim$ (few fm)$^{-2}$
  Intrinsic k_T from beam optics
  Veto nuclear breakup, excitations

- Quasi–elastic processes: Neutron structure

  Neutron GPDs, medium modifications

  Requirements similar as for
  spectator tagging in inclusive DIS → Keppel, Hyde

Summary

- High–luminosity EIC offers many exciting opportunities to explore QCD structure of nucleon and nuclei with exclusive processes

  DVCS over wide kinematic range

  Valence/sea quark imaging with meson production

  Gluon imaging with J/ψ and ϕ

  Fundamental quark/gluon distributions in nuclei from coherent scattering

- Many processes require/favor lower energy, more symmetric collider $s \sim 1000\,\text{GeV}^2$ Cf. detailed process simulations

- "Next step" for nuclear physics after JLab 12 GeV