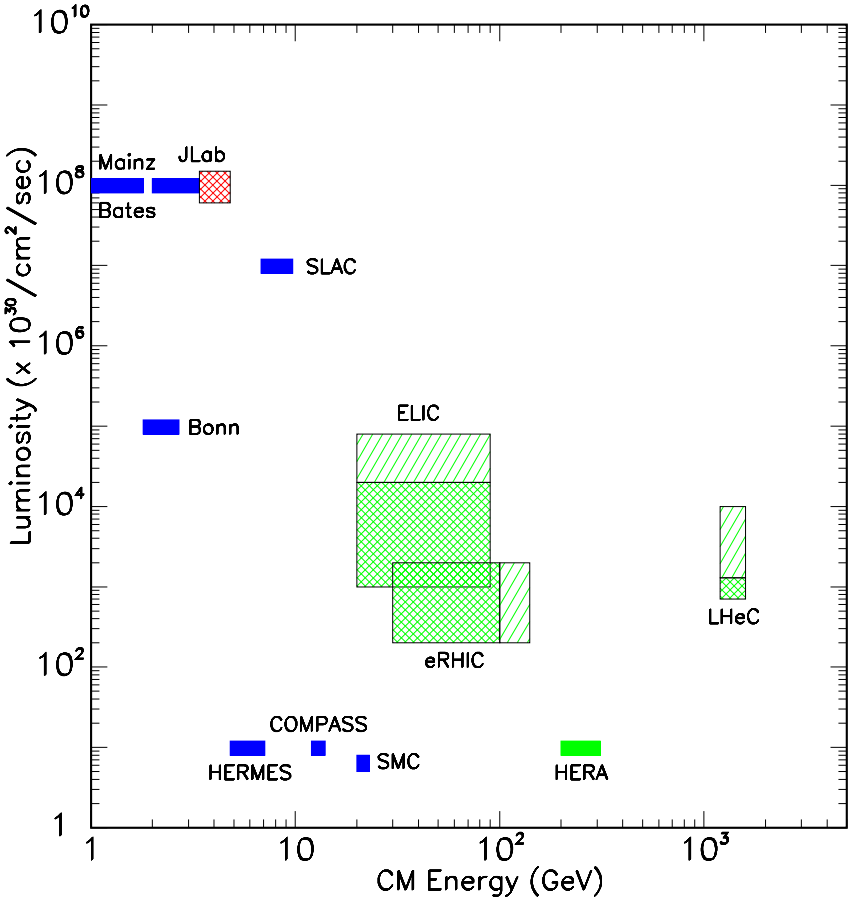
Exclusive processes with JLab 12 GeV and EIC

C. Weiss (JLab), Hard Exclusive Processes, Munich, 09–Nov–2009



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

- Exclusive processes and nucleon structure

  Physics: Transverse imaging, correlations
  Testing the reaction mechanism

- JLab 12 GeV: Valence region

  Deeply virtual Compton scattering
  Meson production

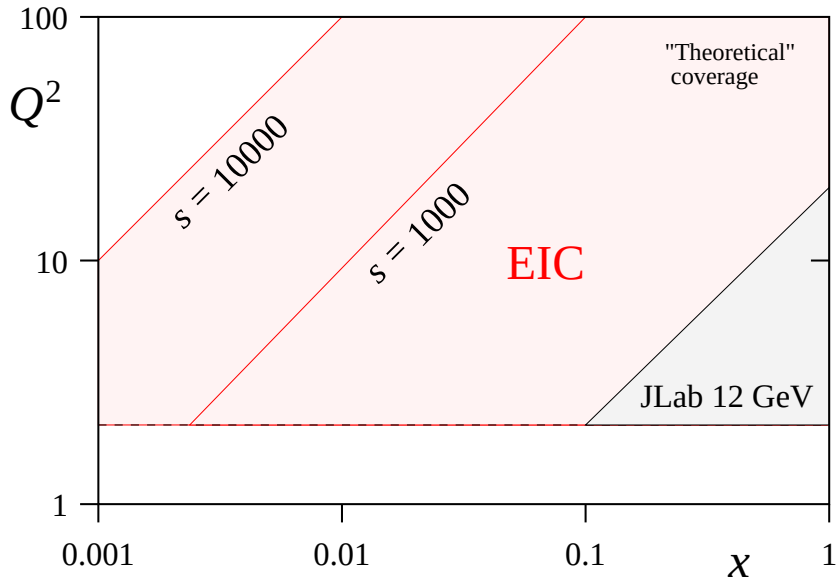
- EIC: Gluons, sea quarks, nuclei

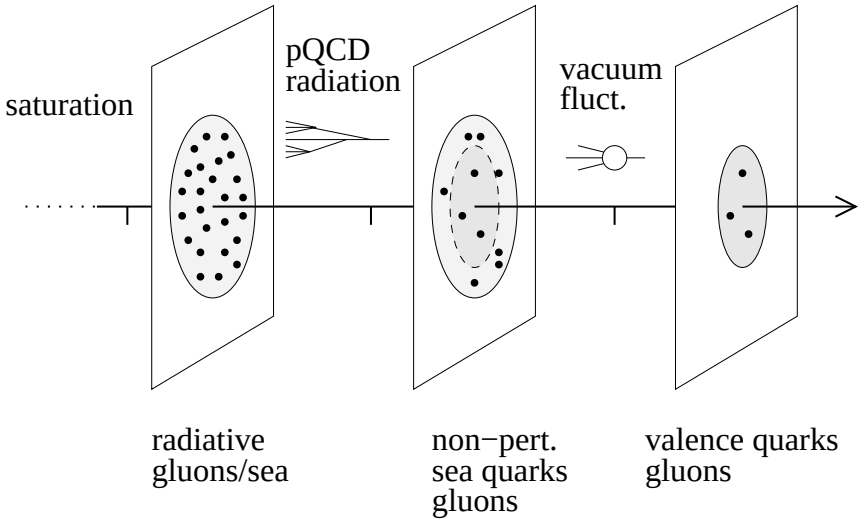
  Gluon imaging with $J/\psi, \phi$
  Sea quarks with meson production
  N^*, diffraction, meson structure
  Nuclei: New probes of shadowing, CT

- Synergies $ep \leftrightarrow pp, \pi p, \gamma p$

  Transverse geometry in pp@LHC

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

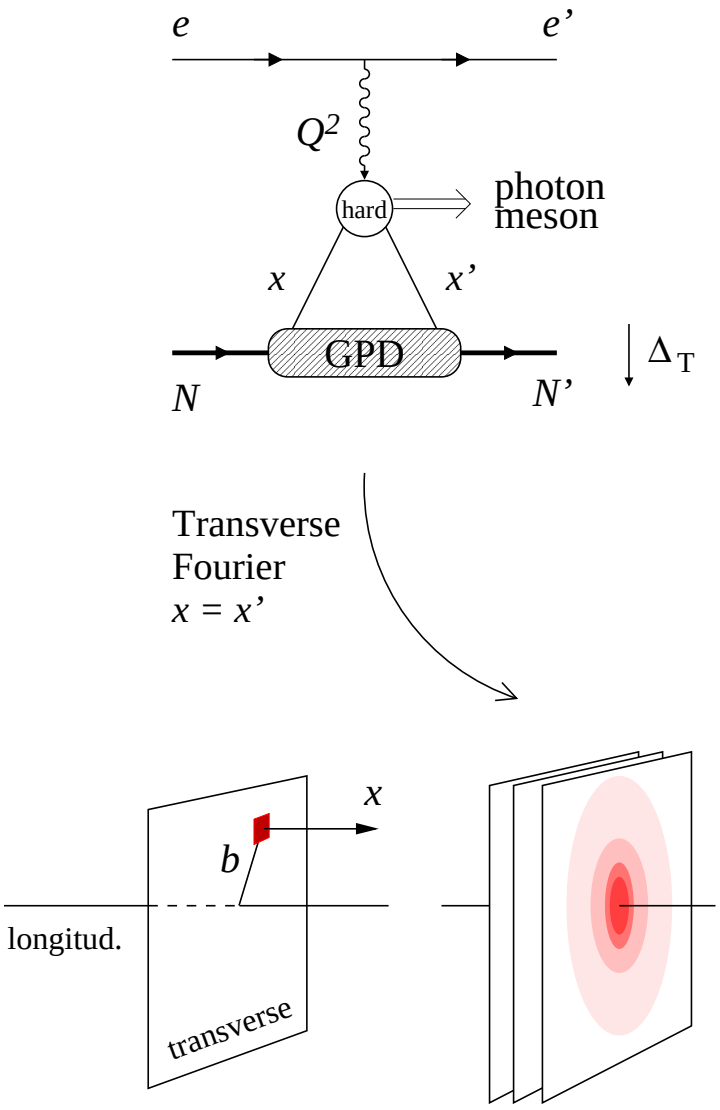
  Transverse spatial distributions

  Orbital motion, angular momentum

  Correlations: transverse, longitudinal

  $+$ nuclear modifications

Nucleon structure: Exclusive processes



- Exclusive processes at $Q^2 \gg R_{\rm had}^{-2}$: Reaction "pointlike" in transverse space, partonic mechanism

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

- Physical interest in GPDs

  $x' = x$ Transverse spatial distribution of of partons with longitudinal momentum x:
  Transverse imaging of nucleon Burkardt 00

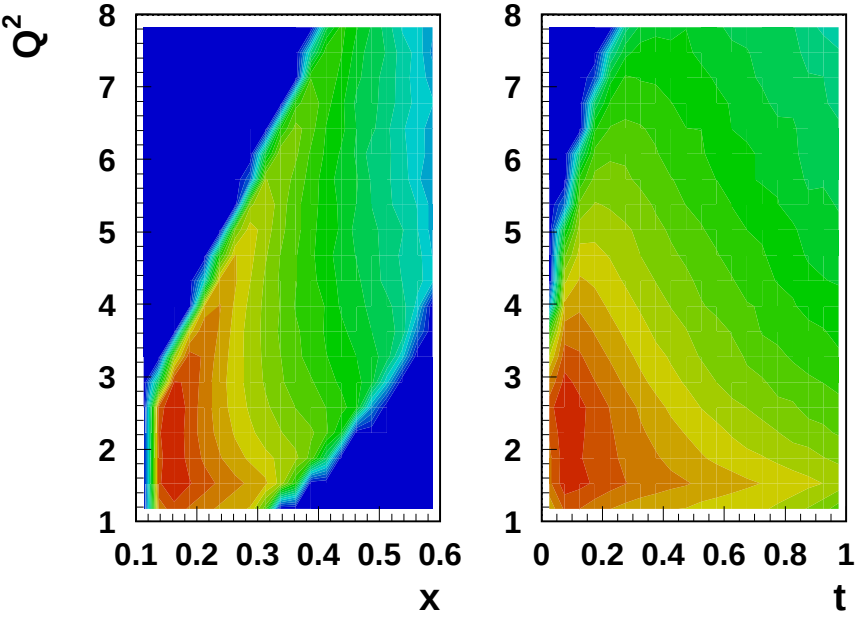
  $x' \neq x$ Longitudinal form factor:
  Correlations in wave function

  Moment x^{n-1} Form factor of local twist–2 spin–n operator: EM tensor, angular momentum
  Ji 96, Polyakov 02

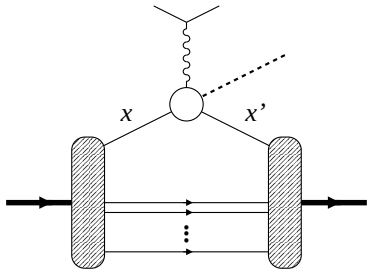
- Test reaction mechanism

  Model–independent features of small-size regime?
  Finite–size corrections?

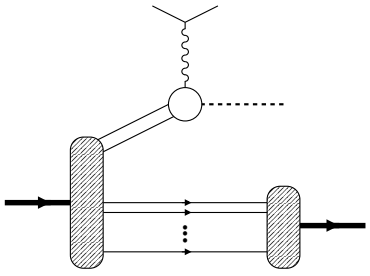
JLab 12 GeV: Exclusive processes



CLAS12 kinematic coverage $N(e, e'\gamma)N$



Scattering from q or $\bar{q}$



Knockout of $q\bar{q}$ pair

- Unique capabilities

  High luminosity $10^{37}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Hall A), 10^{35} (CLAS12) for valence region, differential measurements, spin asymmetries

  Complementarity of CLAS12 detector and magnetic spectrometers in Hall A, C

- Characteristics of valence region

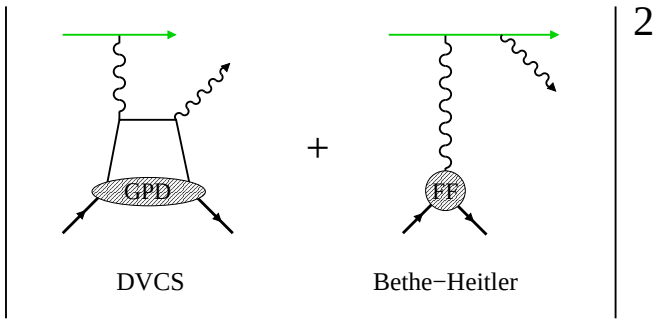
  Longitudinal momentum transfer $\xi \approx x_B/2$ substantial; $t_{\min}$ large

  Scattering from quark/antiquark and pair knockout both important . . . GPD contains both!

  Large polarization effects

- Limited kinematic coverage: How to test reaction mechanism?

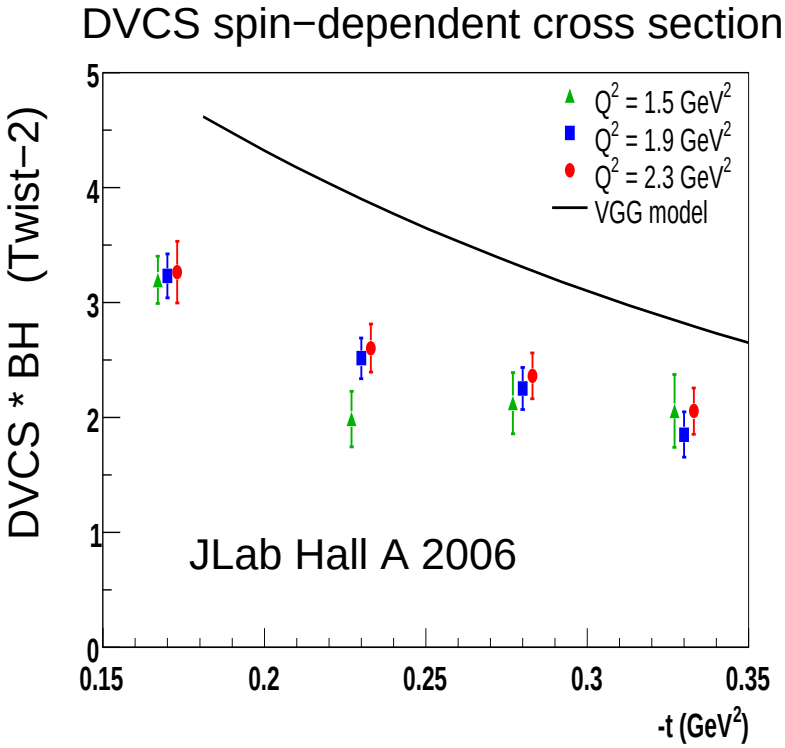
JLab 12 GeV: Deeply virtual Compton scattering



- Interference BH–DVCS in $N(e, e'\gamma)N'$ gives access to DVCS at amplitude level

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

$$\text{Re(DVCS)} \sim \int dx \frac{H(x,\xi;t)}{x-\xi}$$

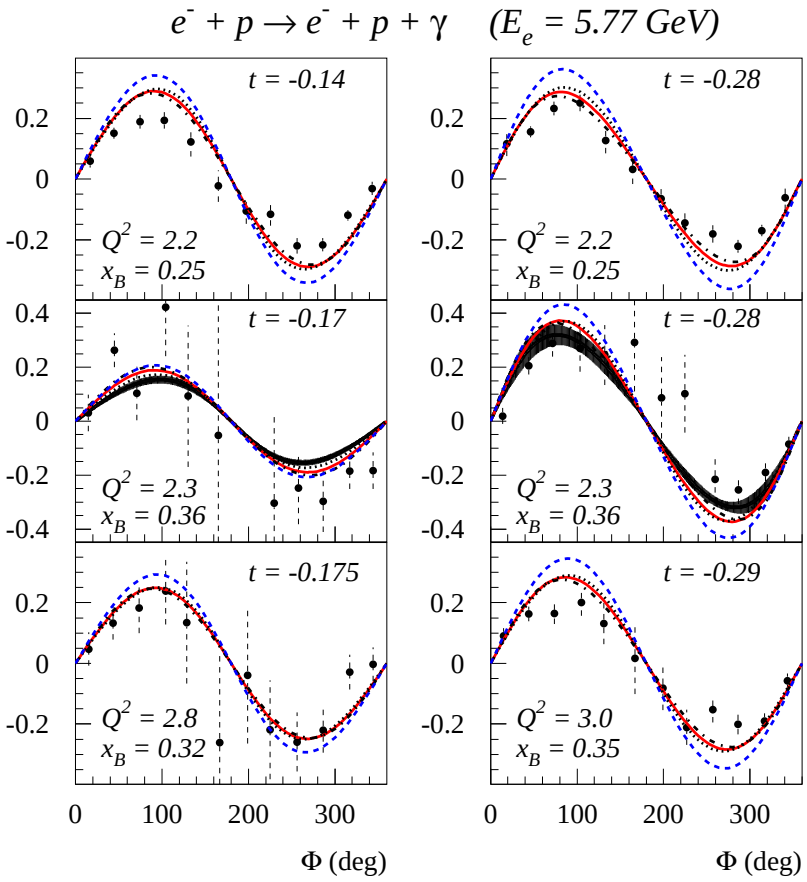


- Reaction mechanism: Hall A 6 GeV cross section measurements indicate "normal" approach to scaling

  . . . more tests needed!

- Separate GPDs $H \leftrightarrow E$ etc. through polarization observables, neutron target

JLab 12 GeV: New developments in DVCS



CLAS 6 GeV DVCS beam spin asymmetry explained by dispersion analysis with Hall A DVCS cross section + "minimal" GPD model. Vanderhaeghen, Polyakov 08

- Leading–twist analysis of DVCS: Well–developed formalism, GPD parametrizations → Talk M. Vanderhaeghen

- New development: Dispersion relations for hard exclusive amplitude

  Teryaev 05; Anikin, T. 07; Müller etal. 07; Diehl, Ivanov 07

  → Minimal model dependence!

  → Accessible information $\mathrm{Im}A \sim H(\xi, \xi; t)$ + subtraction constant D–term Polyakov, CW 99

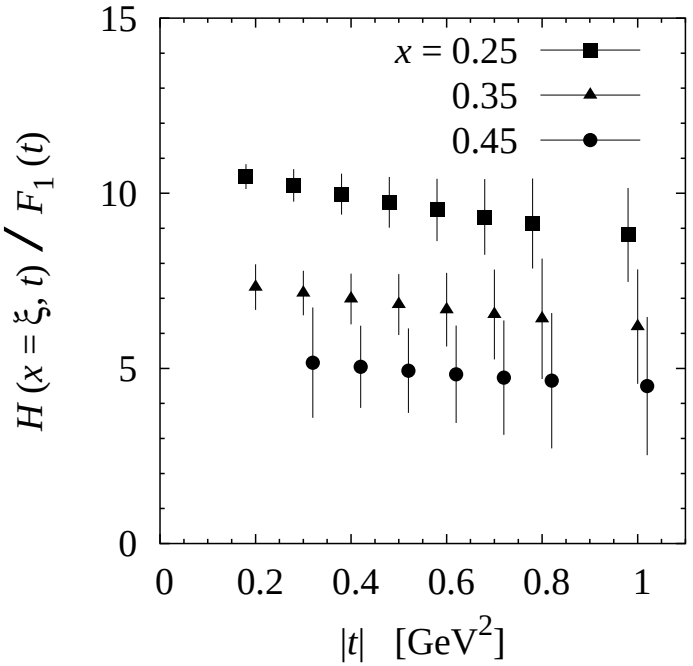
- Need dynamical models *specific* to valence region

  Finite–size, kinematic corrections?

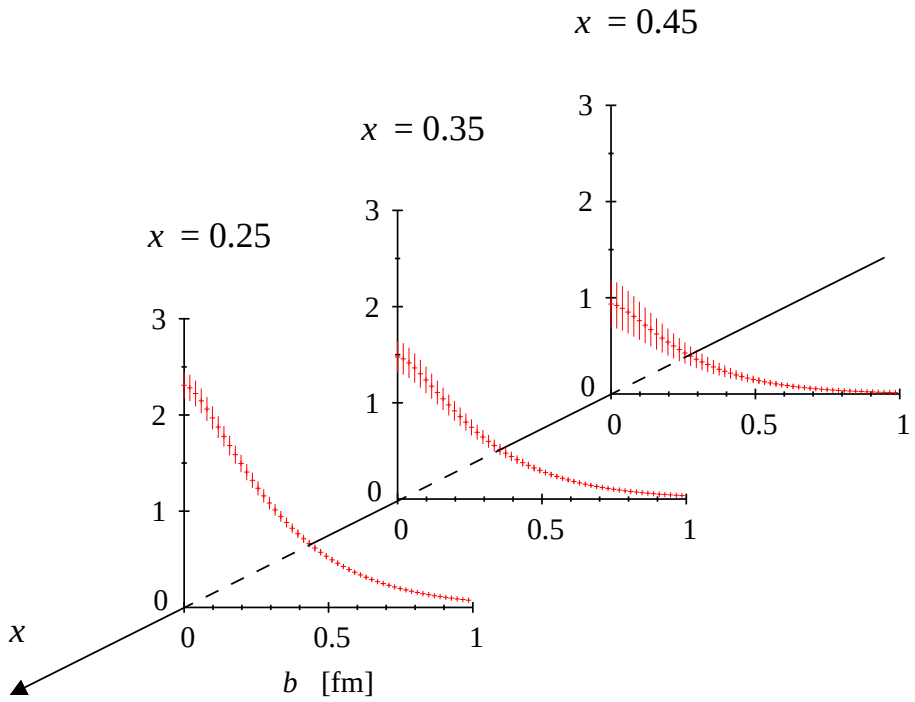
  Correlations at large x?

"Simpler" than previously thought!

JLab 12 GeV: Projected DVCS results



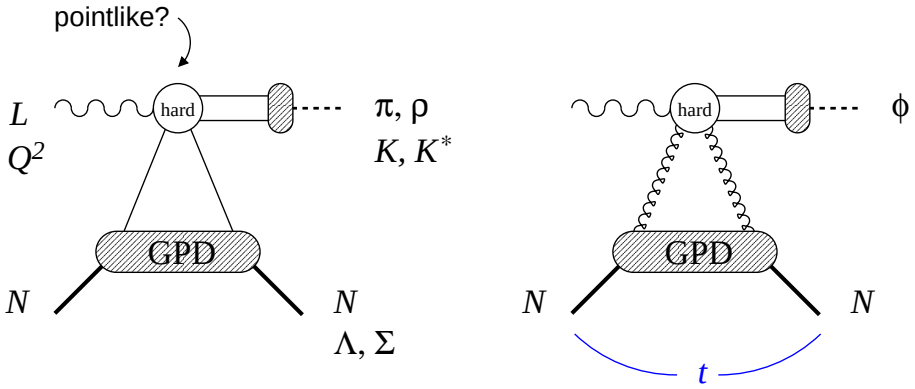
- GPD $H(x = \xi, t)$ extracted from simulated CLAS12 beam spin asymmetry

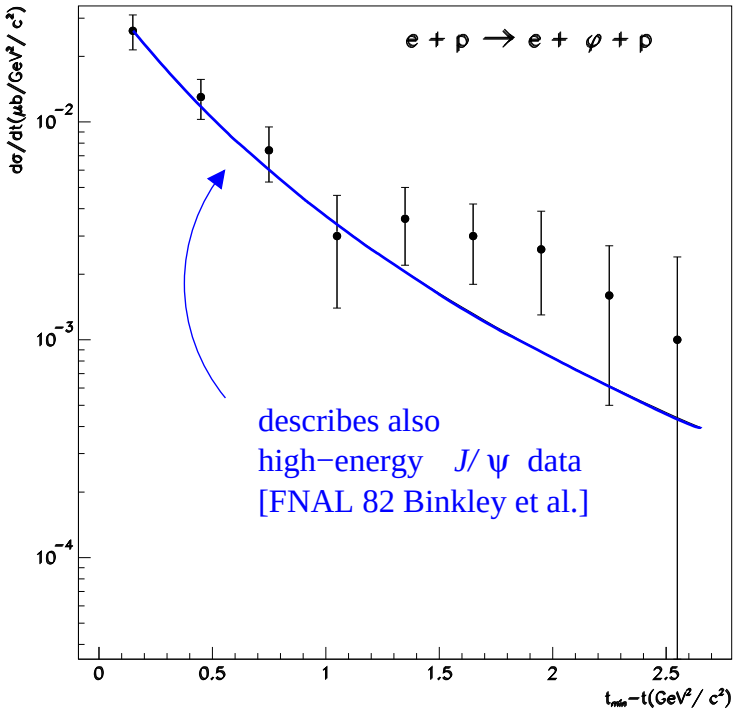


- Transverse "quark image" of nucleon in valence region (here $x = \xi$)

$\rightarrow$ Dynamical models

JLab 12 GeV: Exclusive meson production





- Reaction mechanism at $W \sim$ few GeV still poorly understood

  Role of $q\bar{q}$ pair knockout? Guidal, Morrow 08

  Large finite–size corrections at $Q^2 \sim$ few GeV^2
  Progress with theoretical calculations
  → Talk A. Levy. Kroll, Goloskokov 08/09

- Interesting: t–dependence of ϕ at 6 GeV compatible with J/ψ at higher energies

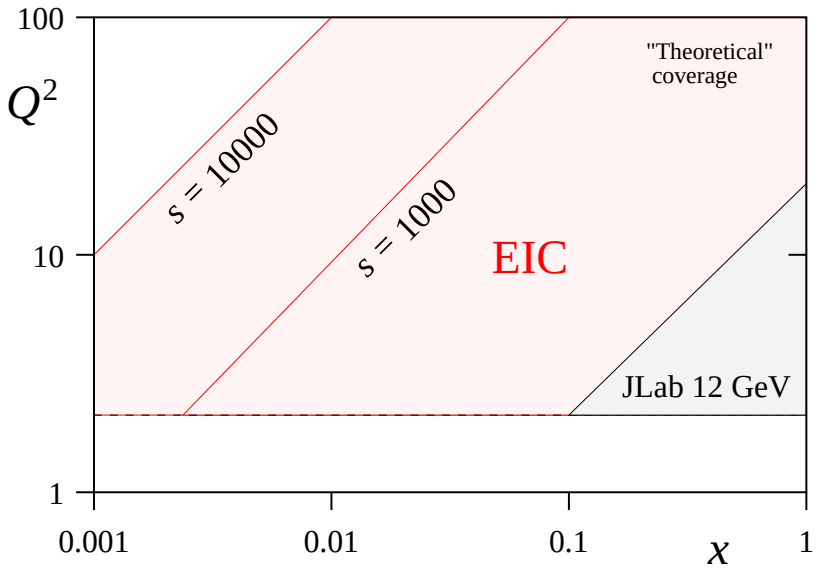
  Universality of gluon GPD!

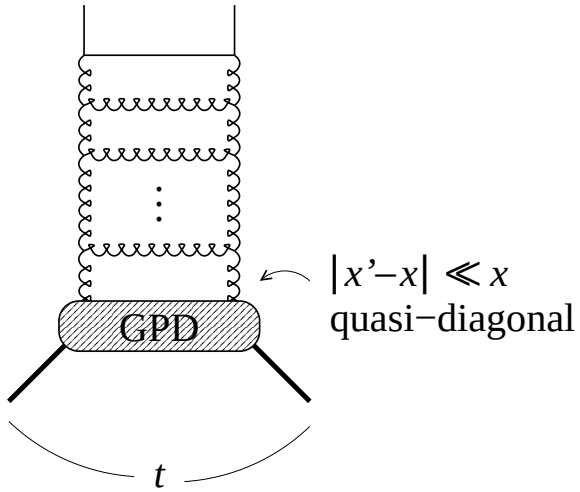
- Cross section *ratios* less affected by finite meson size

  Comparisons between channels,
  spin asymmetries many examples!

Need better understanding of reaction mechanism. . . expect progress!

EIC: Exclusive processes





- Unique capabilities

  Wide kinematic coverage at high luminonsity:
  Meson production at $Q^2 > 10\,\mathrm{GeV}^2$
  J/ψ electro/photoproduction
  Tests of reaction mechanism → Talk A. Levy

  Forward detection of recoil nucleon/nucleus

- Exclusive processes at $x < 0.1$

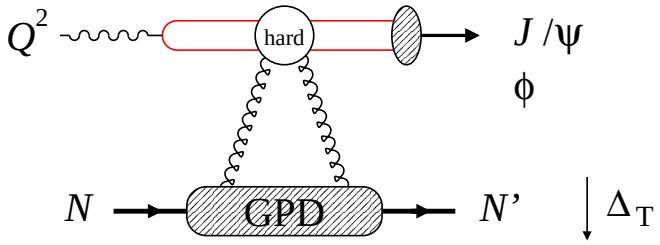
  Skewness ξ–dependence calculable
  Focus on transverse imaging!

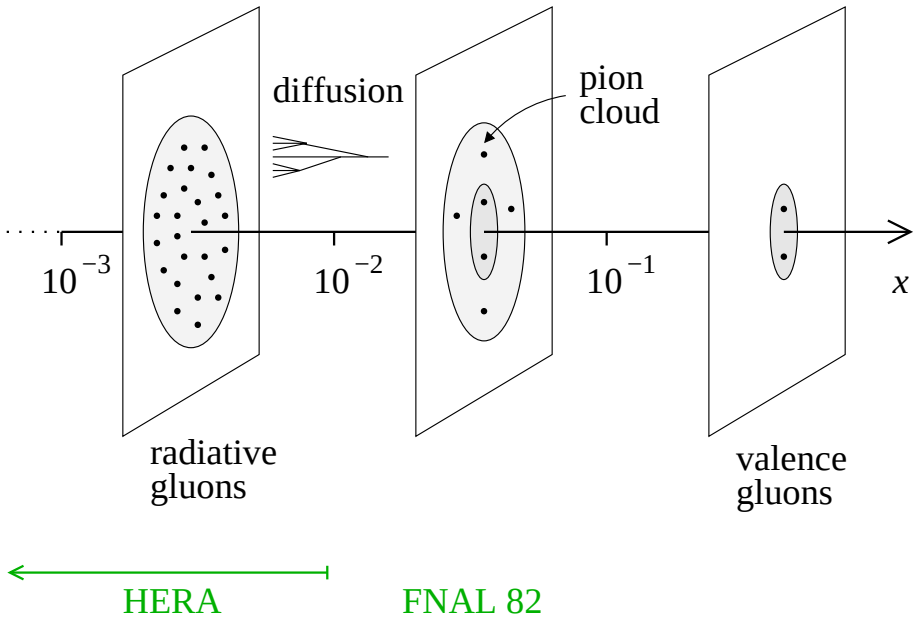
  Differences/similarities between channels

"Diffractive"	↔	"Non-diffractive"
$J/\psi, \phi, \rho^0, \gamma$		π, ρ^+, K, K^*
gluon/singlet quark		non-singlet quark GPD
large		small cross sections

  DVCS no longer "special," look at whole set!

EIC: Gluon imaging with J/ψ





- 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

  Valence gluons – dynamical origin?

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

  Diffusion in QCD radiation

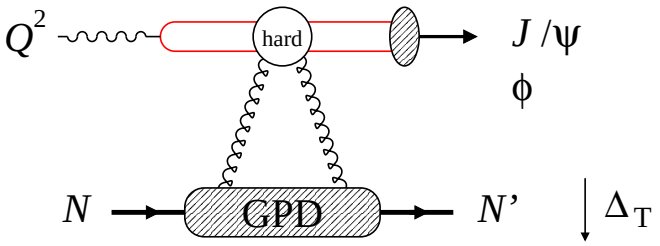
- Essential for future MC for pp@LHC, saturation $Q_s \sim$ gluons/transverse area

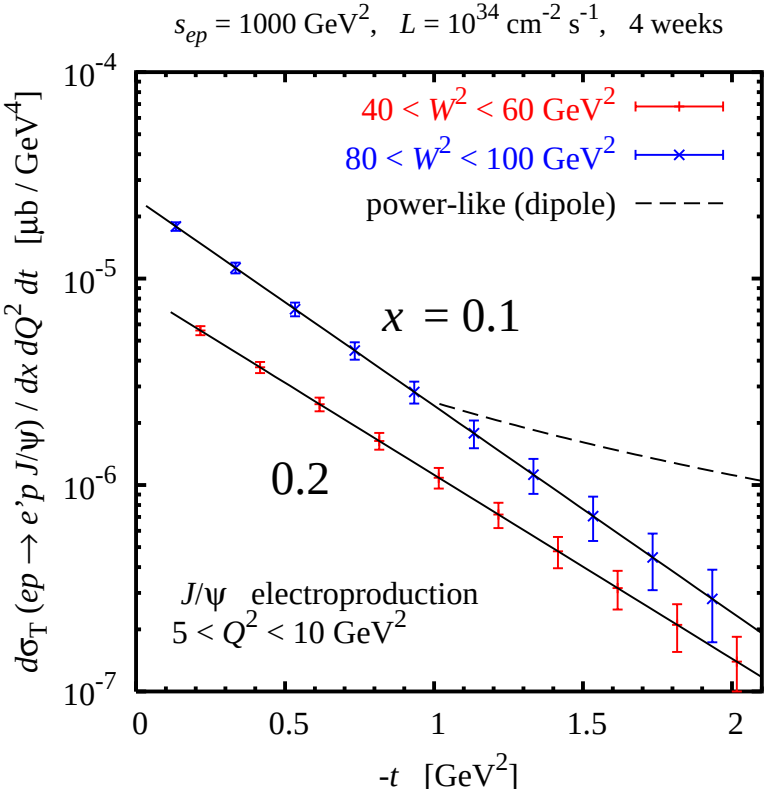
- Existing data

  Transverse area $x < 0.01$ HERA

  Larger x poorly known FNAL 82, . . .

EIC: Valence gluons





Hyde, CW

- EIC: Precise gluon imaging through exclusive J/ψ and ϕ

  $x > 0.01$: Map unkown region of non-perturbative gluons!

- 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 of reaction mechanism, different channels

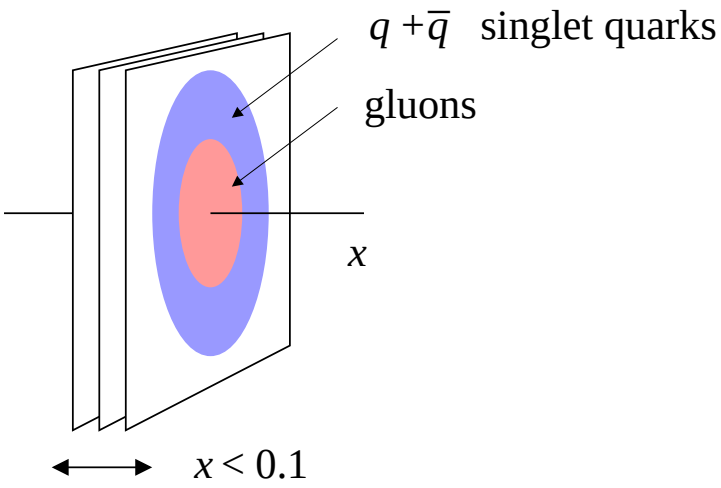
- Machine requirements

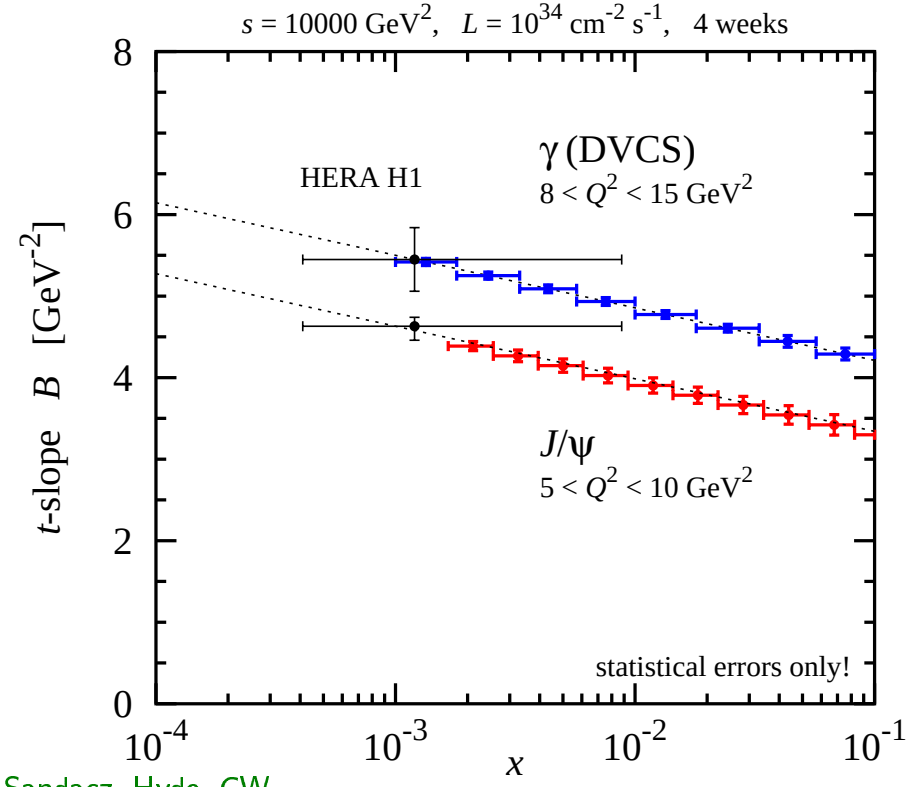
  Recoil detection for exclusivity, t–measurements

  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!

EIC: Gluon vs. singlet quark size





Sandacz, Hyde, CW

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

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

  Dynamical models predict difference:
  Pion cloud, constituent quark picture

  No difference assumed in present pp MC generators for LHC!

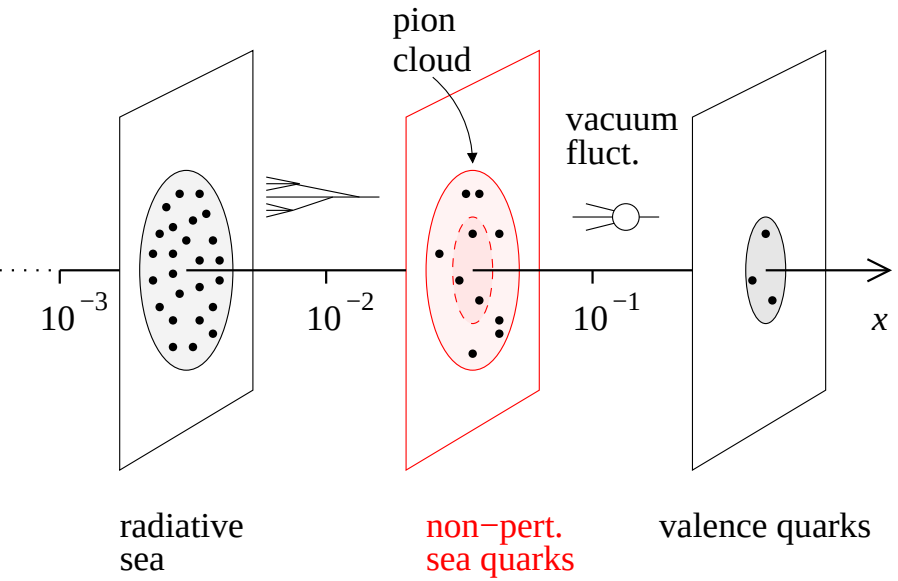
- EIC: Gluon size from J/ψ, singlet quark size from DVCS

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

  Detailed analysis: LO → NLO Müller et al.

Detailed differential images of nucleon's partonic structure

EIC: Quark imaging through meson production



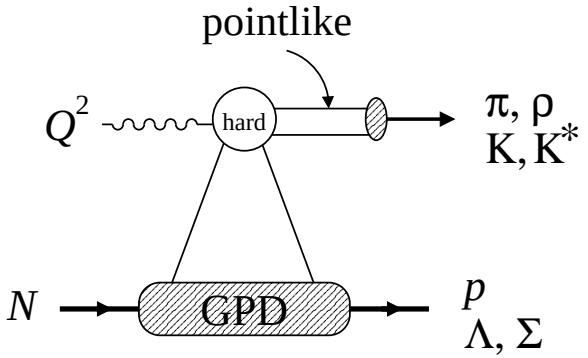
- Transverse distribution of non-perturbative sea quarks

  Flavor structure $\bar{u} \leftrightarrow \bar{d} \leftrightarrow s, \bar{s}$

  Longitudinal polarization $q_+ \leftrightarrow q_-$

  $\rightarrow$ QCD vacuum structure

  $\rightarrow$ Chiral dynamics, "pion cloud"



- Exclusive meson production $\gamma^* N \rightarrow M + B$

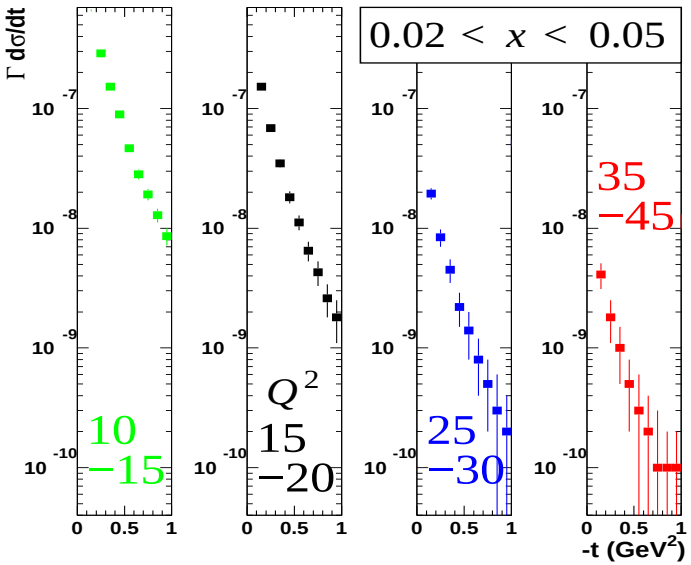
  Requires $Q^2 > 10\,\mathrm{GeV}^2$ for dominance of "pointlike" configurations $\rightarrow$ pQCD

  Meson quantum numbers select spin/flavor component of GPD

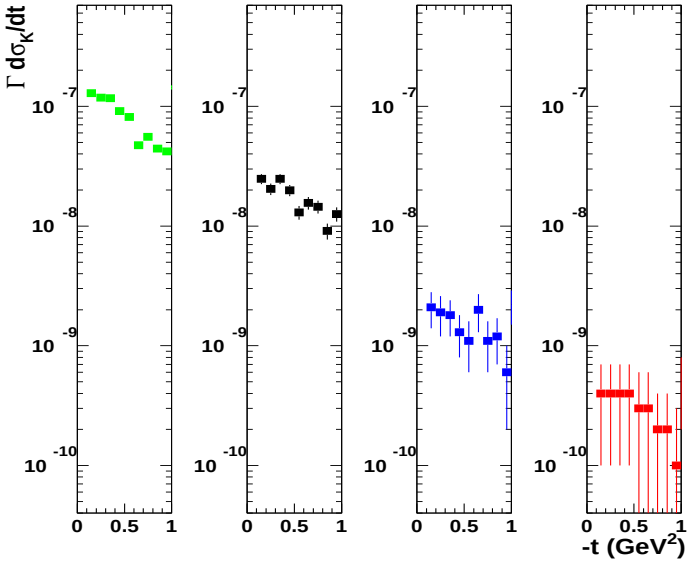
  Information about meson wave function: Size, flavor structure

EIC: Sea quark imaging

$e\,p \to e'\pi^+\,n$



$e\,p \to e'\mathrm{K}^+\,\Lambda$



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

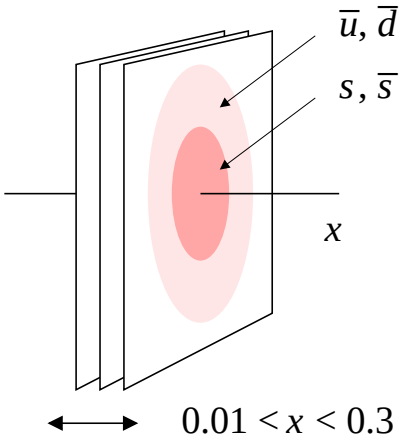
  → πN or $K\Lambda$ components in nucleon?
  → QCD vacuum fluctuations?

- EIC: Exclusive π and K production

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

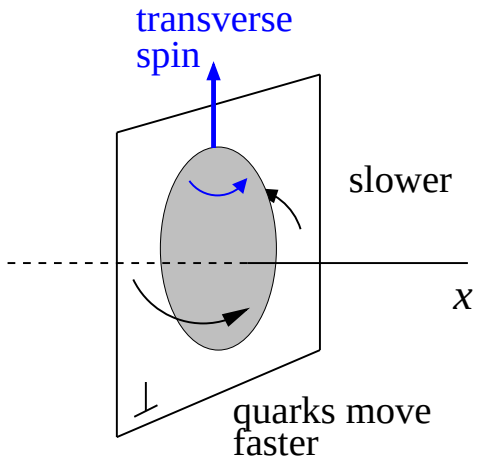
  Kinematic reach in Q^2, x

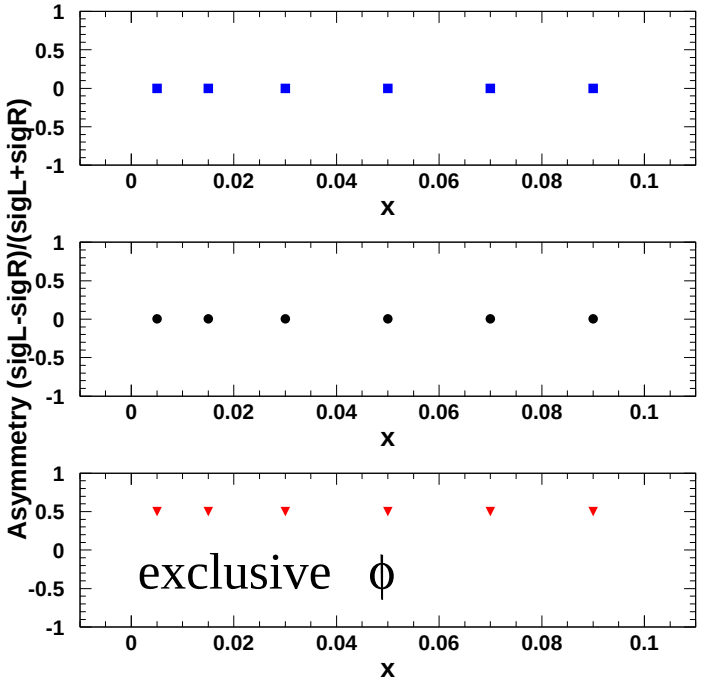
  Recoil detection for exclusivity, t–distributions



Spatial structure of non-perturbative sea – many more examples!

EIC: Transverse polarization





T. Horn, 4 on 60 GeV, L = 10^{34}cm^{-2}cm^{-1}

- Deformation of transverse distributions by transverse polarization of nucleon

  Helicity–flip GPD E, cf. Pauli FF

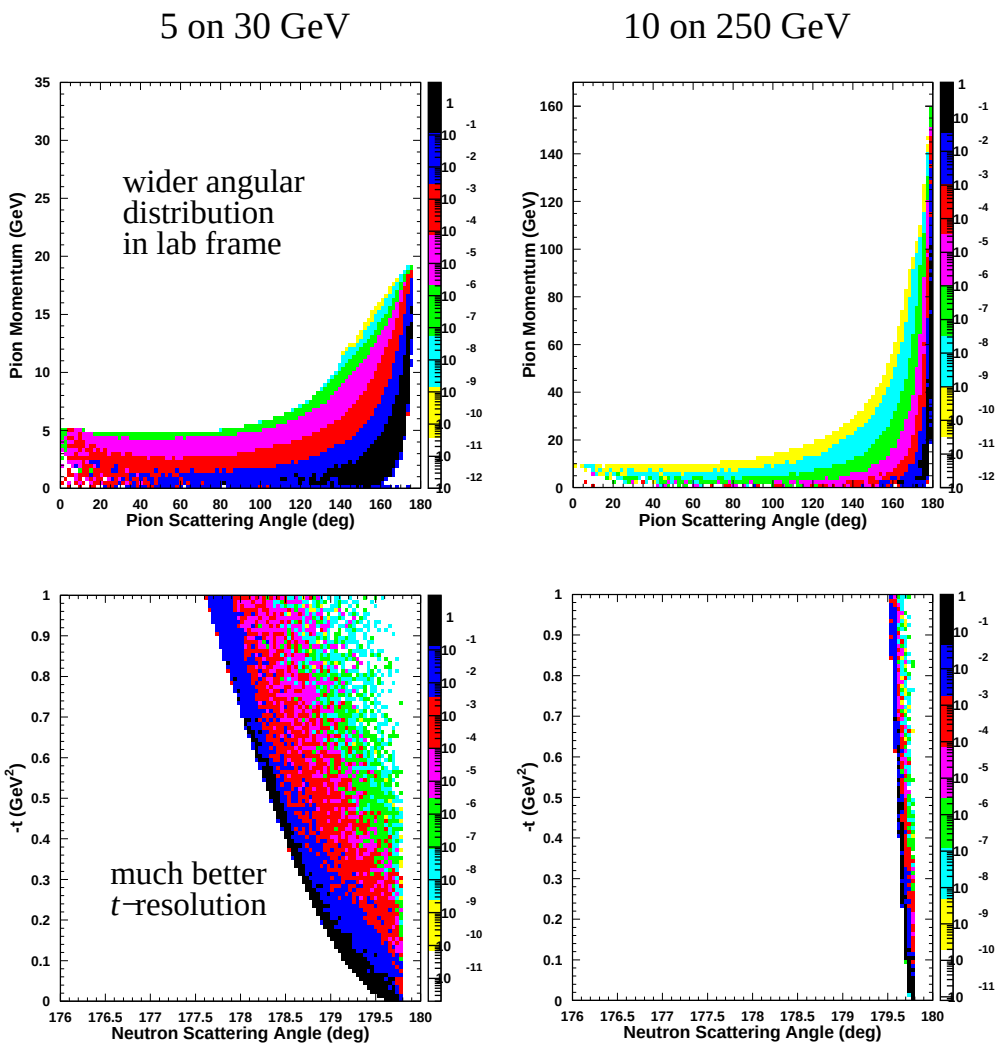
- EIC: Exclusive ρ and ϕ production with transversely polarized beam

  Excellent statistics at $Q^2 > 10\,\text{GeV}^2$

  Transverse polarization natural for collider

$$\frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} \propto \frac{\text{Im}(\mathcal{H}\mathcal{E}^*)}{|\mathcal{H}|^2 + \text{corr.}}$$

EIC: Why lower energies



T. Horn et al. 2008

- Example: Exclusive production $ep \to e'\pi^+ n$

  Physics interest $x > 0.01$:
  Non-perturbative sea quarks

- Lower–energy, symmetric collider

  $\to$ Wider π^+ angular distribution:
  Detection, angular resolution

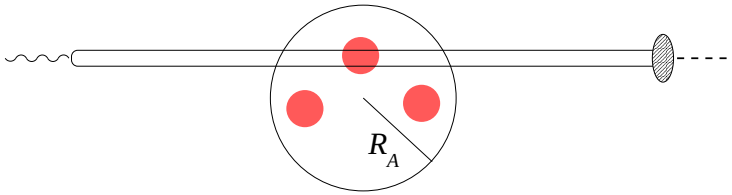
  $\to$ Wider recoil n distribution:
  t–resolution

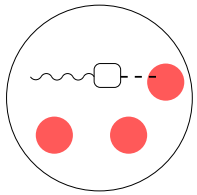
- Detector simulations in progress

Exclusive processes at $x > 0.01$: Better prospects with lower–energy, more symmetric collider!

EIC: Exclusive processes with nuclei

with M. Strikman





$l_{\text{coh}},\ l_{\text{form}} \gg R_A$

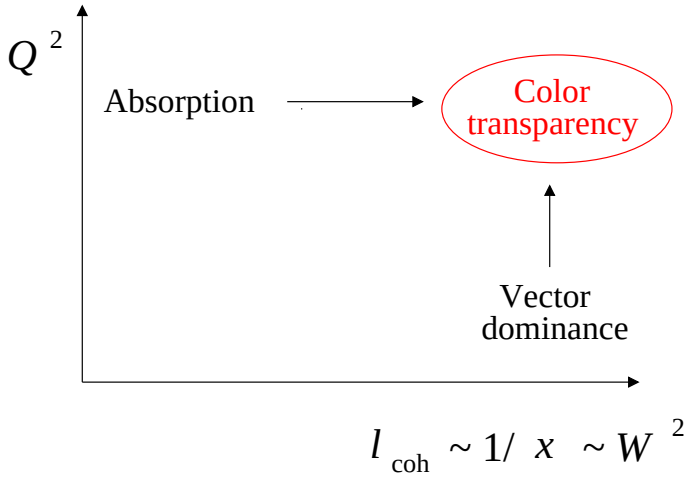
Color transparency

$\sigma \propto A$ incoherent

$l_{\text{coh}},\ l_{\text{form}} \ll R_A$

Absorption $\sigma_{\pi N}\ \rho_{\text{nuc}}\ R_A \sim 1$

$\sigma \propto A^{2/3}$



- Nucleus as "filter" for small–size configurations
- Unique way to explore longitudinal direction in high–energy scattering

EIC: Coherent scattering from nuclei

- A–dependence in color transparency regime

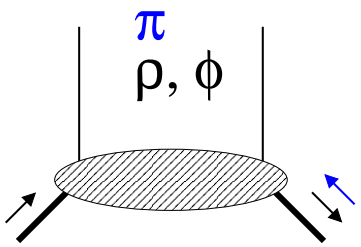
$$\frac{d\sigma}{dt}(t=0) \;\propto\; A^2, \qquad |t| \;\propto\; R_A^{-2} \;\propto\; A^{-2/3}$$

- Polarized light nuclei

  ^{4}He Spin 0 "single GPD"

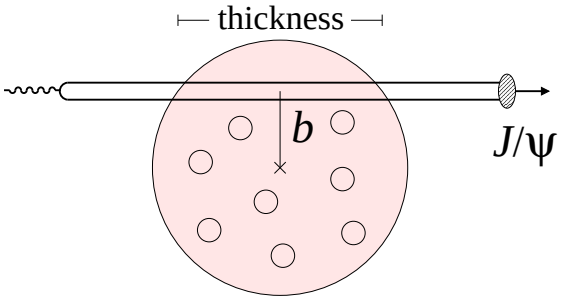
  ^{2}H Spin 1 $\Delta S = 2$ component

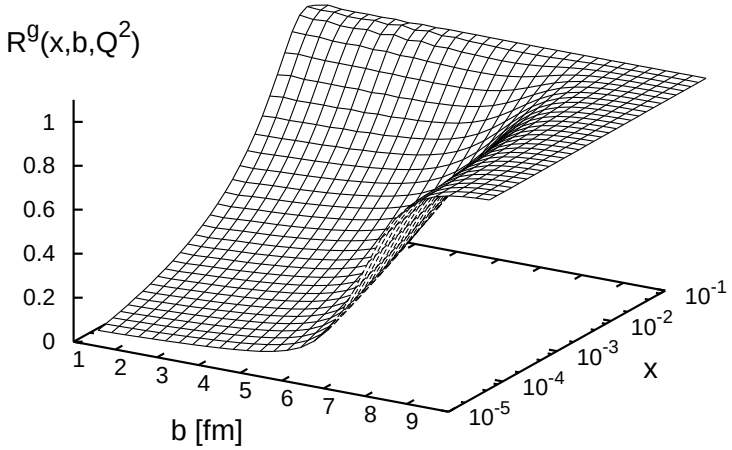
- Nucleus as "detector" for quantum number transfer



Very different propabilities
for leaving nucleus intact

EIC: Gluon imaging of nuclei





Goeke, Guzey, Siddikov 09

- Transverse distribution of gluons in nuclei from coherent J/ψ production

  Fundamental characteristic: Quark–gluon origin of nucleon–nucleon forces

  New approach to nuclear shadowing: Thickness $\leftrightarrow$ impact parameter b

  Theoretical predictions

- Experimental challenges

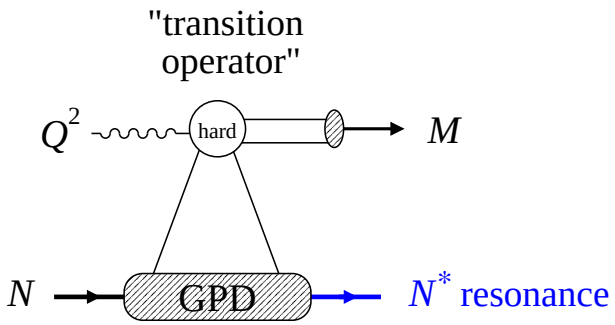
  Caldwell, Kowalski, arXiv:0909.1254

  Detection at very low $t \sim$ (few fm)$^{-2}$

  Beam optics: Intrinsic k_T

  Veto nuclear breakup, excitations (theory)

Exclusive processes: Beyond transverse imaging



- N^* resonance excitation through hard exclusive process

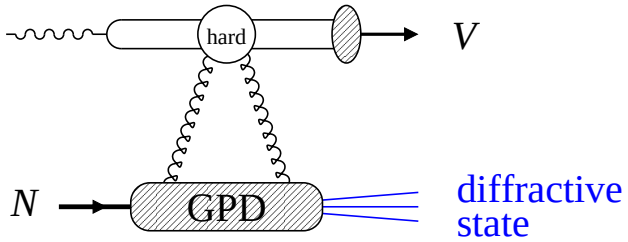
  QCD factorization: Hard process as transition operator Frankfurt, Strikman, Polyakov

  New quantum numbers!

- New probes of meson structure

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

  "Exotics" from QCD counting rules



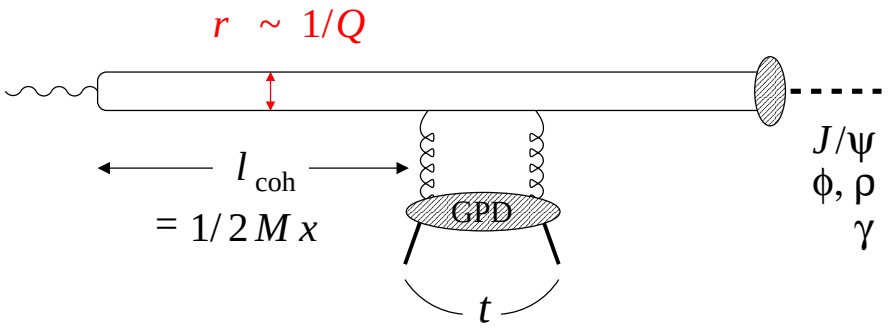
- Diffractive dissociation in exclusive vector meson production

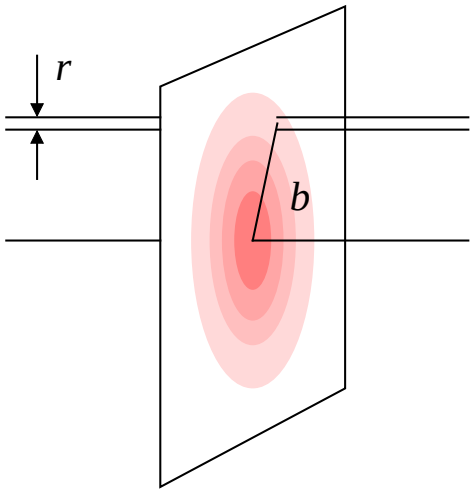
  Quantum fluctuations of gluon density: Fundamental property of many–body system

  Frankfurt, Strikman, Treleani, CW

Interesting opportunities, should be explored further!

Exclusive processes: Small–x physics





- LO QCD factorization for hard exclusive processes at small x equivalent to dipole picture

  Brodsky, Frankfurt, Gunion, Müller, Strikman 94
  Frankfurt, Radyushkin, Strikman 98

  Gluon GPD as color dipole of nucleon

  Space–time evolution, intuition

  Modeling of finite size effects

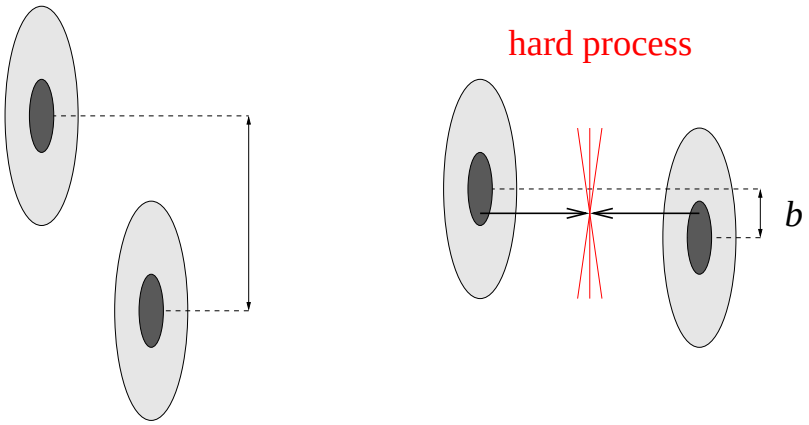
- Transverse gluon distribution essential ingredient in studies of unitarity limit/saturation at small x

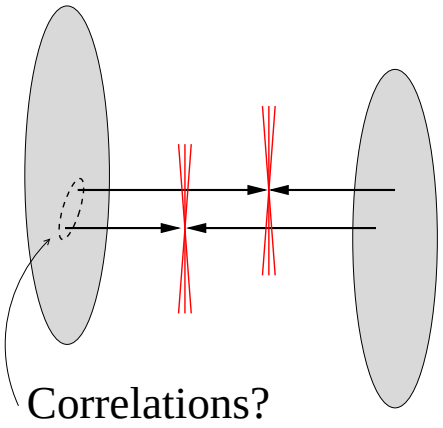
  Frankfurt, Strikman + Rogers, Guzey, CW; Kowalski, Teaney

  "Black–disk regime"

  Affects also nuclear enhancement of saturation: "Oomph factor"

Synergies $ep \leftrightarrow pp$





- Transverse distribution of partons essential ingredient in theory of high–energy pp collisions with hard processes

- Centrality dependence

  → Spectator interactions, underlying event structure

  → Hard process as trigger on central collisions Frankfurt, Strikman, CW 04

  → Rapidity gap survival in central exclusive diffraction Frankfurt, Hyde, Strikman, CW 06

- Multiple hard processes

  Geometric probability depends on transverse sizes!

  Multiparton correlations? Frankfurt, Strikman, CW 04

  High probability in pp@LHC, not included in present MC!

Summary

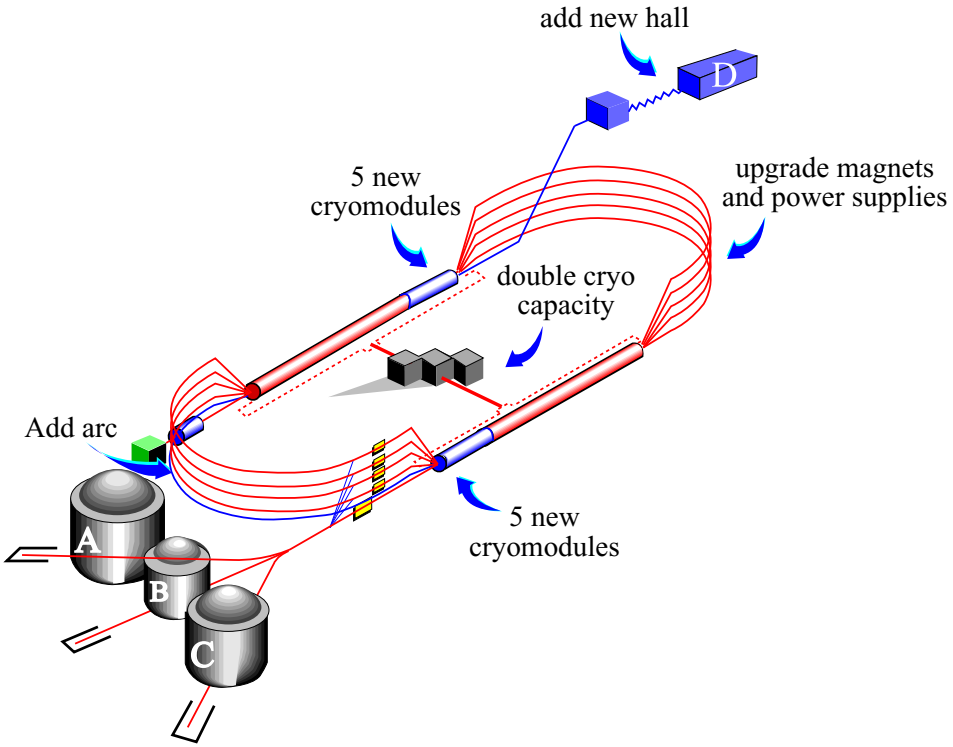
- JLab 12 GeV and EIC program provide strong and complementary capabilities for exclusive processes

- JLab 12 GeV: Need to explore/establish reaction mechanism!
  Expect progress from 6 GeV meson production data.
  Theory input essential, including dynamical models

- EIC: Great potential for gluon and sea quark imaging and nuclear physics studies. Needs more involvement . . . now is the time!

Supplementary material

JLab and 12 GeV Upgrade



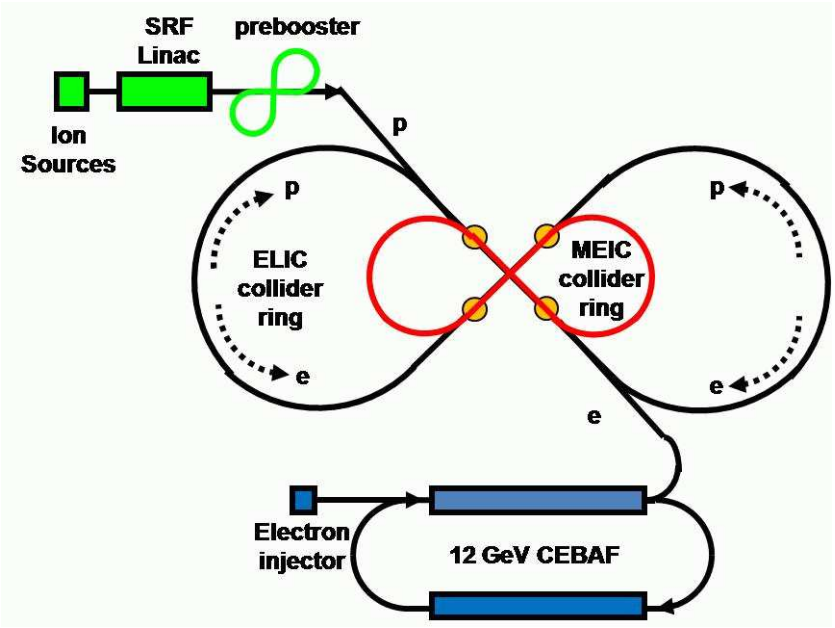
CW beam $\sim 100\,\mu A$
Present beam energy 6 GeV
Operating since 1994

- "Race track" accelerator with linacs + arcs, extensible to 24 GeV
- Uses unique superconducting RF technology + energy recovery
- Experimental halls
  - A, C Magnetic spectrometers
  - B Large acceptance CLAS
- 12 GeV Upgrade

  Double beam energy 6 $\rightarrow$ 12 GeV
  Add Hall D (γ beam, GlueX detector)
  Upgrade existing halls

DOE project (CD0 2004, CD3 2008)
Construction started, beam exp. 2013
Total cost $\sim$ 300M$

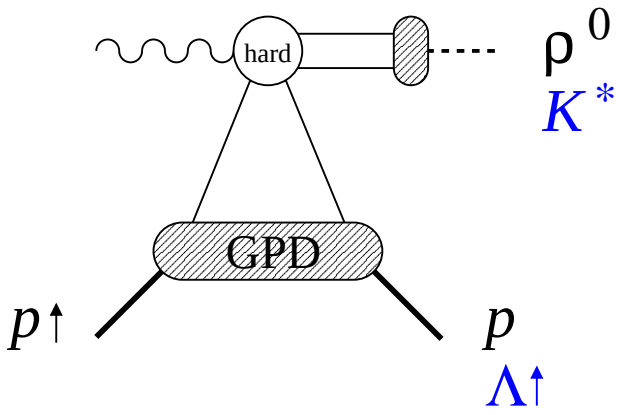
High–luminosity medium–energy EIC at JLab



- Research & development on–going, presented to EIC Advisory Committee Feb–09 and Nov–09
- Possible upgrade to high–energy ELIC with 10/250 GeV, but *distinct* medium–energy physics program!

Energy	E_e/E_p	$= 5/30 - 11/60$ GeV
	s_{ep}	$= 600 - 2600$ GeV^2
Luminosity	few $\times$ 10^{34} cm^{-2} s^{-1}	
Circumf.	$\sim$ 600 m	
Polarization, nuclear beams		

JLab 12 GeV: Cross section ratios



$$\frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} \propto \frac{\mathrm{Im}(\mathcal{H}\mathcal{E}^*)}{|\mathcal{H}|^2 + \text{corr.}}$$

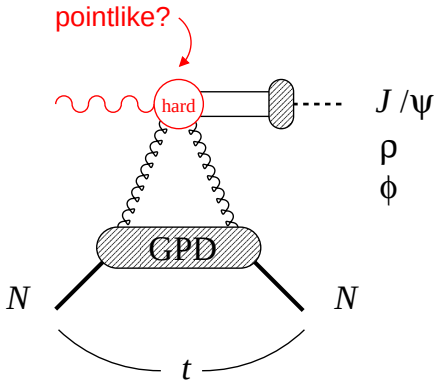
- Transverse target spin asymmetry in $\gamma_L^* p \to \rho^0 p$ sensitive to helicity–flip GPD E
- Alt: Transverse recoil polarization in $\gamma_L^* p \to K^* \Lambda$

  $SU(3)$ symmetry: $\langle \Lambda | \ldots | p \rangle \to \langle p | \ldots | p \rangle$
- Pseudoscalars π, K probe polarized GPDs

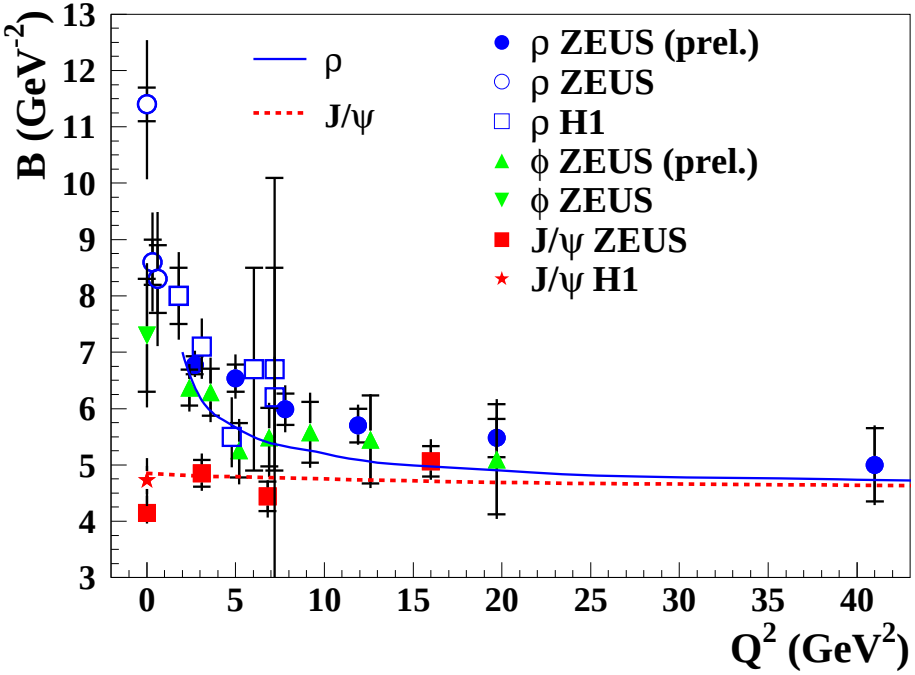
  $\tilde{H}$: Flavor structure $\Delta q, \Delta \bar{q}$

  $\tilde{E}$: "Pole term" in π^+, K^+

EIC: Meson production



Exclusive vector meson t–slope



- $Q^2 \to \infty$: Meson produced in pointlike configuration

  t–slope independent of Q^2

  Seen in HERA vector meson data!

- $Q^2 \sim$ few GeV^2: Substantial finite–size corrections (higher twist)

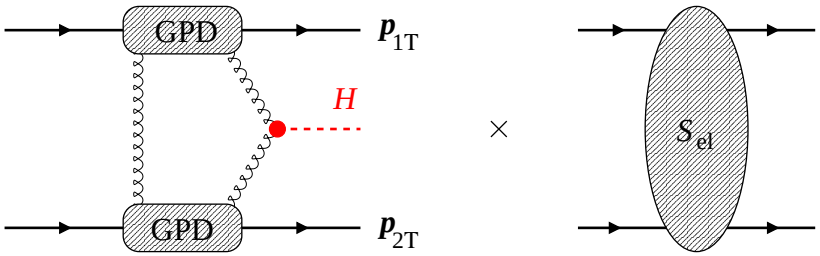
  Dynamical models w. intrinsic k_T

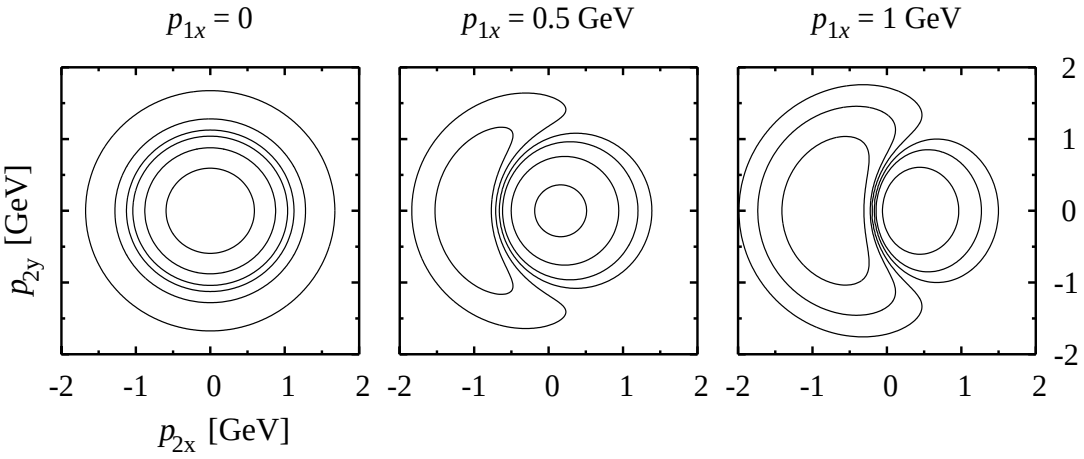
  Frankfurt et al. 96; Vanderhaeghen et al. 98; Kroll, Goloskokov 05

GPDs in pp: Central exclusive diffraction

$$pp \;\to\; p \;+\; \text{gap} \;+\; H \;+\; \text{gap} \;+\; p$$

$(=$ dijet, Higgs, $Q\bar{Q}$, ...$)$





- Hard process modified by soft spectator interactions: Rapidity gap survival

  soft $\approx$ elastic S_{el}

- Interference phenomenon:

  $S_{\rm el} = 1 + T_{\rm el}$ ← known!

- Diffraction pattern in $\boldsymbol{p}_{1T}, \boldsymbol{p}_{2T}$, observable with forward detectors:

  CMS/TOTEM at LHC
  LHC420 ($x < 0.01$)
  STAR pp2pp @ $\sqrt{s} = 500$ GeV ?

Frankfurt, Hyde-Wright, Strikman, Weiss 06