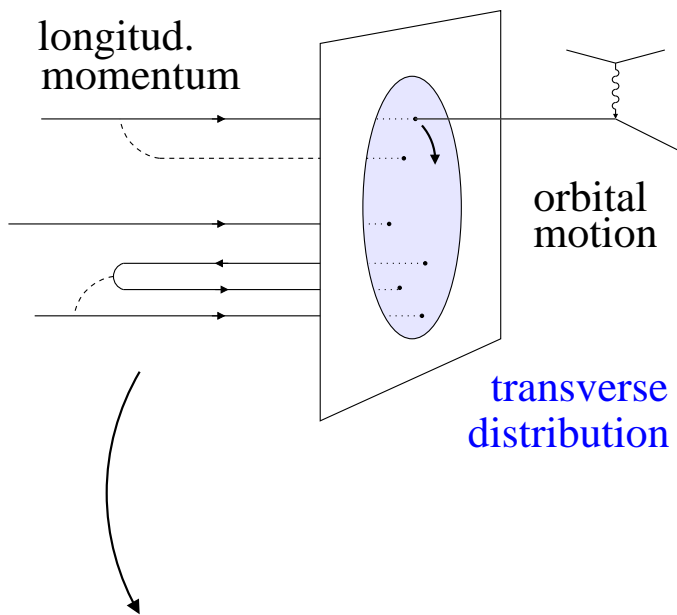


# 3D imaging of proton and nuclei with EIC

## Progress report on deep exclusive reaction program

C. Weiss (JLab), EIC Advisory Committee Meeting, JLab, 02–Nov-09



- Gluon imaging

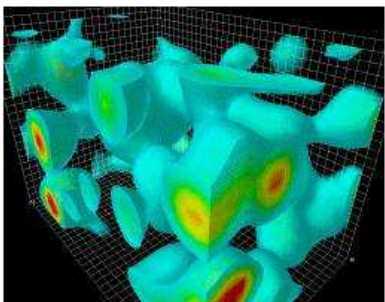
Physics of non-perturbative glue  
Exclusive  $J/\psi$  and  $\phi$  production  
Importance for  $pp$ @LHC, small  $x$   
Nuclear gluons

- Quark imaging

Sea quarks: QCD vacuum, chiral dynamics  
Exclusive meson production, DVCS  
Polarization

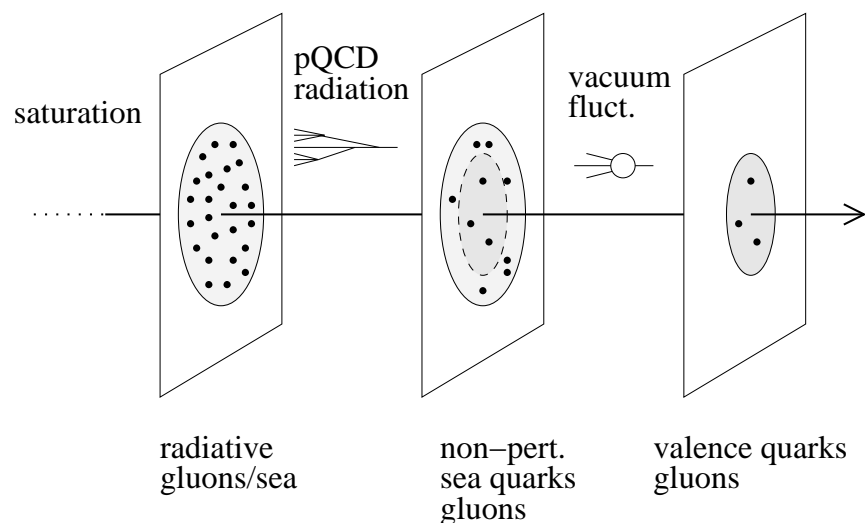
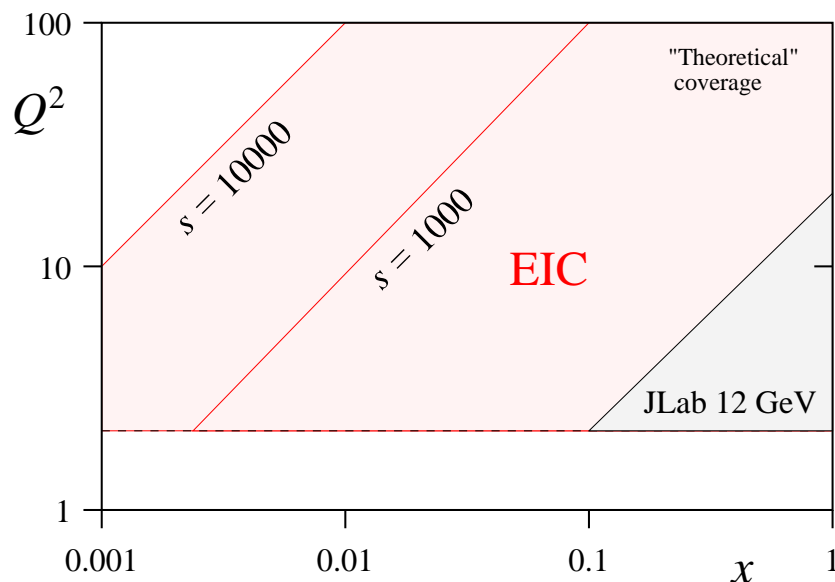
- Meson/baryon structure

Excited states  $N \rightarrow N^*$ , diffraction  
Longitudinal correlations  $\xi \neq 0$   
Orbital motion



Dynamics!

# Nucleon structure: Landscape



- Nucleon in QCD many-body system

Different components, effective dynamics

- Components probed in  $ep$  scattering

JLab 12 GeV    valence quarks

EIC    sea quarks, gluons,  
 $Q^2$  dependence

- Physical properties

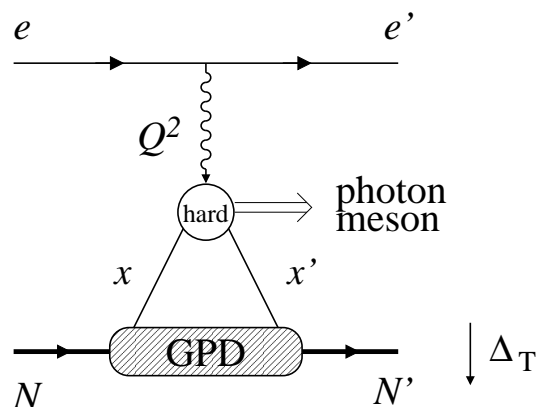
Parton densities

Transverse spatial distributions: GPDs \*

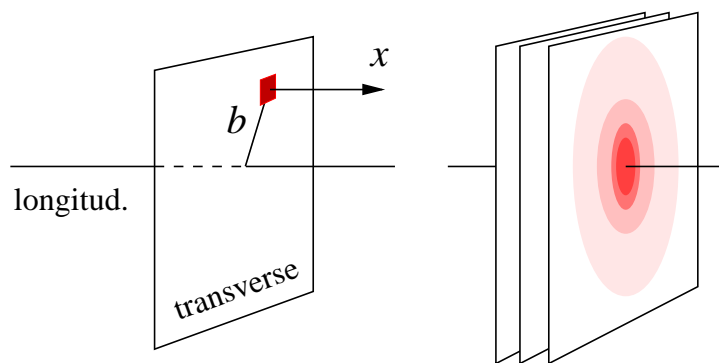
Orbital motion: TMDs, angular momentum

Correlations: “Higher twist”

# Nucleon structure: Transverse imaging



Fourier



- Transverse imaging of nucleon through high- $Q^2$  exclusive processes  $N(e, e' M) N'$

GPDs ( $x' = x$ ): Form factors of partons with longitudinal momentum fraction  $x$

Transverse spatial distribution of partons: Tomographic images of nucleon at fixed  $x$  Burkardt

→ Fundamental, process-independent

→ Twist-2, calculable in lattice QCD

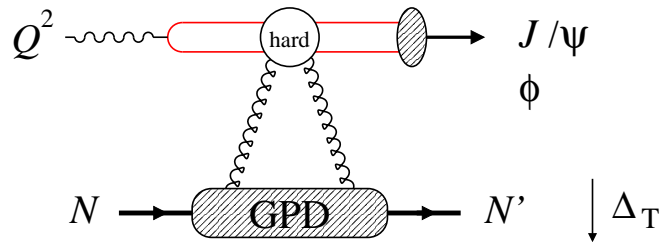
- JLab 12 GeV: Valence quark GPDs through  $N(e, e' \gamma) N' +$  spin observables

Transverse distributions of valence quarks

Longitudinal correlations  $x' \neq x$

Much more interesting information:  
Gluons! Sea quarks! Spin/flavor

# Glueon imaging: Probes and dynamics



- Glueon imaging through exclusive  $J/\psi$  and  $\phi$  ( $Q^2 > 10 \text{ GeV}^2$ )

Clean channels!

Transverse distribution directly from  $\Delta_T$ -dependence

- Physical interest

Valence gluons – dynamical origin?

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

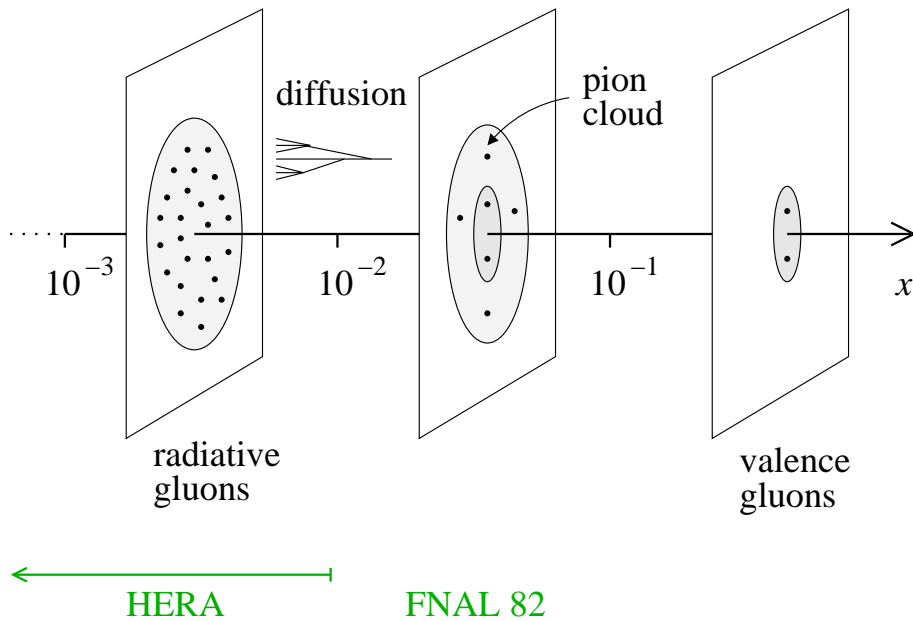
Diffusion in QCD radiation

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

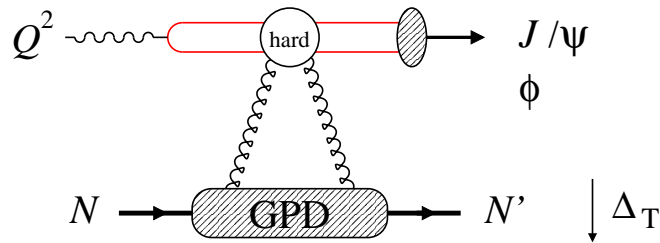
- Existing data

Transverse area  $x < 0.01$  HERA

Larger  $x$  poorly known FNAL 82, ...



# Glueon imaging: Valence gluons



- EIC: Precise gluon imaging through exclusive  $J/\psi$  and  $\phi$

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

- Needed for imaging

Full  $t$ -distribution  $\rightarrow$  Fourier

Non-exponential? Power-like at  $|t| > 1 \text{ GeV}^2$ ?

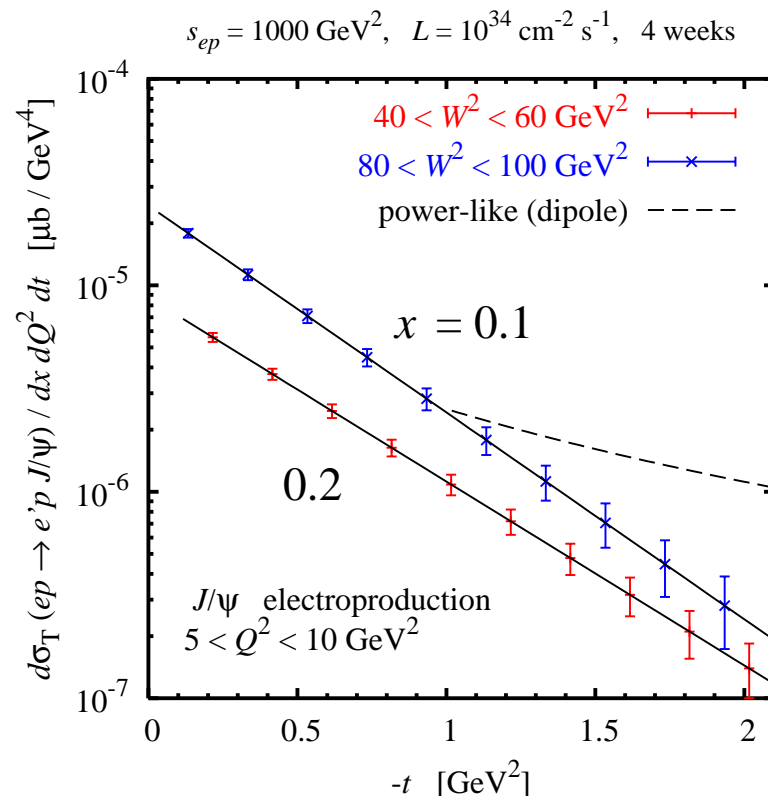
Electroproduction with  $Q^2 > 10 \text{ GeV}^2$ :

Test of reaction mechanism, different channels

- Machine requirements

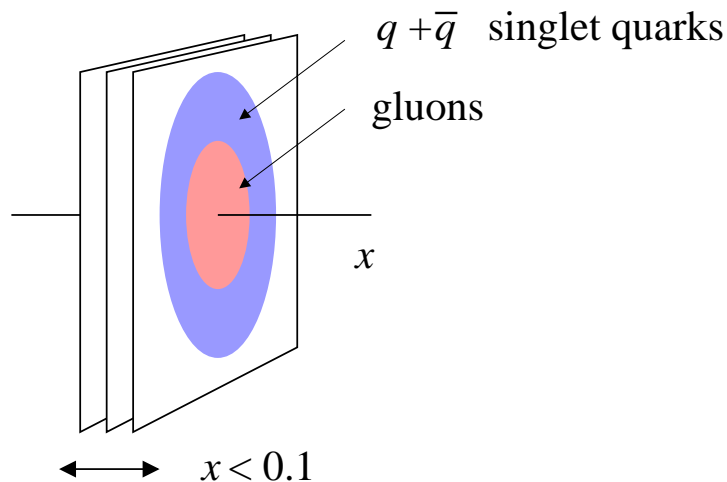
Recoil detection for exclusivity,  $t$ -measurements

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



First gluonic images of nucleon at large  $x$ !

# Gluon imaging: Gluon vs. quark size



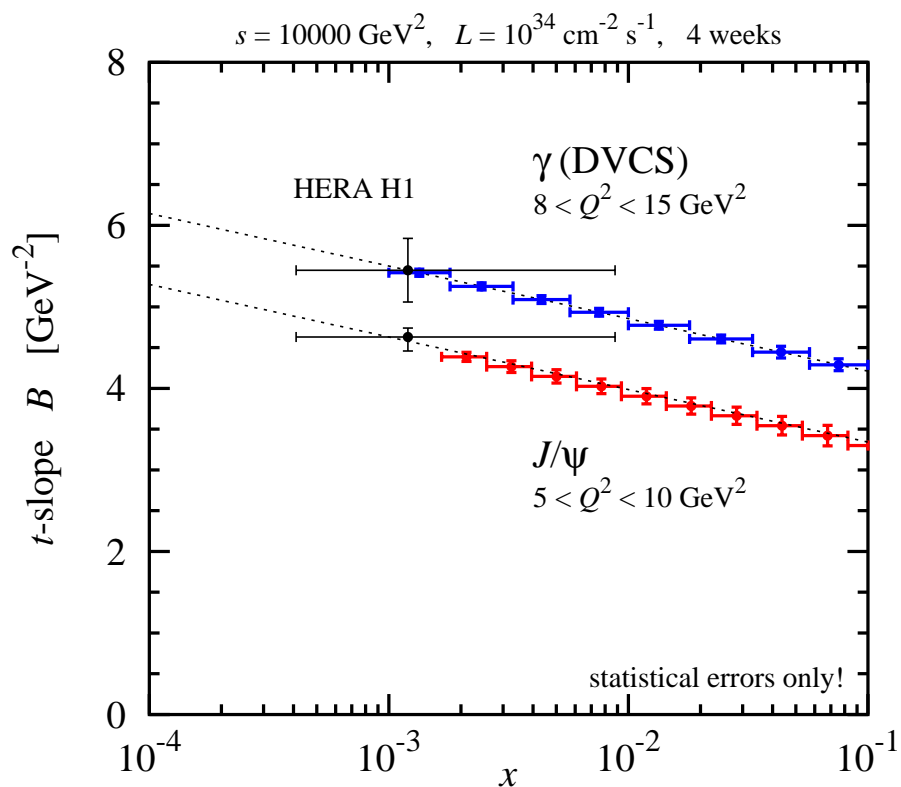
- Do singlet quarks and gluons have the same transverse distribution?

Hints from HERA:

$$\text{Area}(q + \bar{q}) > \text{Area}(g)$$

Dynamical models predict difference:  
Pion cloud, constituent quark picture

No difference assumed in present  
 $pp$  MC generators for LHC!



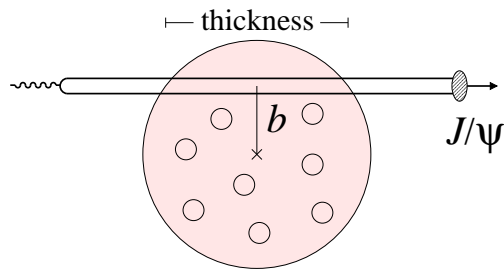
- EIC: Gluon size from  $J/\psi$ , singlet quark size from DVCS

$x$ -dependence: Quark vs. gluon diffusion in wave function

Detailed analysis: LO  $\rightarrow$  NLO Müller et al.

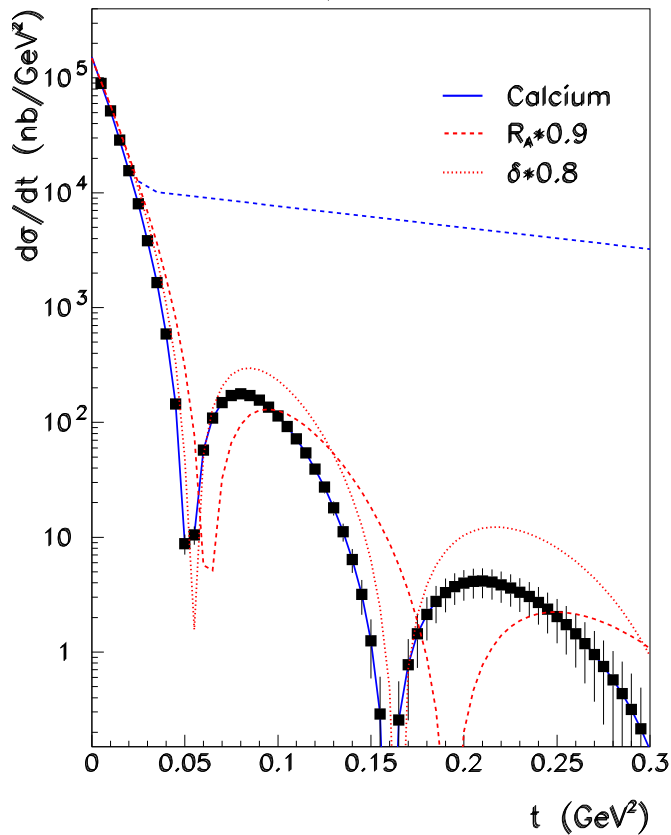
Detailed differential images of nucleon's partonic structure

# Glueon imaging: Nuclei



$$\gamma^* A \rightarrow J/\psi A$$

$$Q^2 = 0$$



Caldwell, Kowalski, arXiv:0909.1254

- Transverse distribution of gluons in nuclei from coherent  $J/\psi$  production

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

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

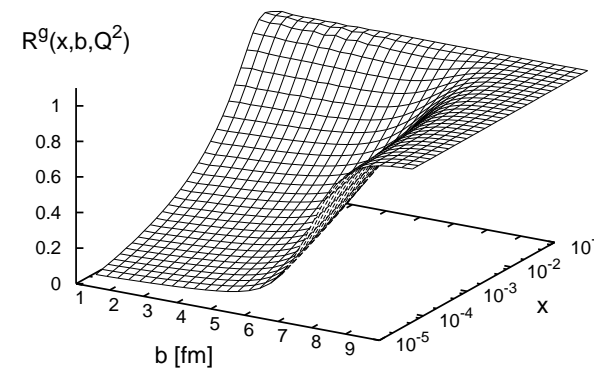
Theoretical predictions [Goetze, Guzey, Siddikov 09](#)

- Experimental challenges

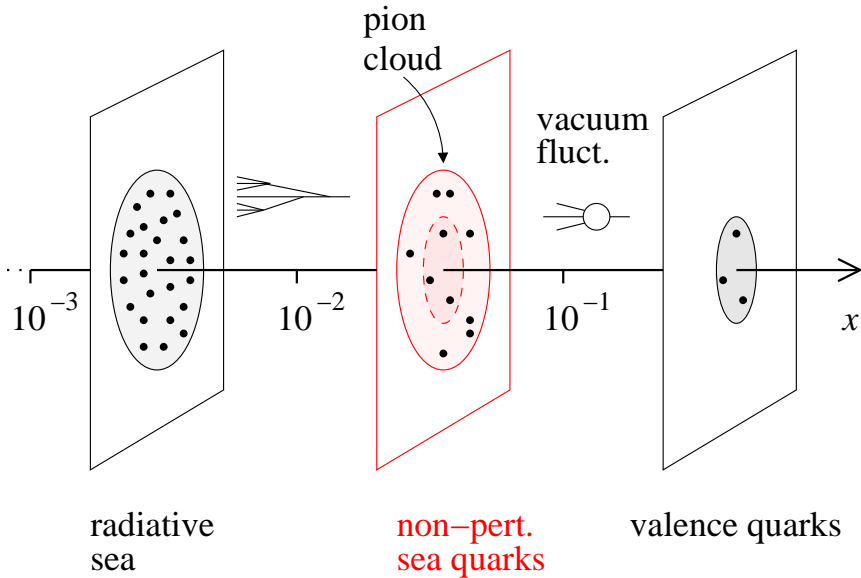
Detection at very low  $t \sim (\text{few fm})^{-2}$

Beam optics: Intrinsic  $k_T$

Veto nuclear breakup, excitations (theory)



# Quark imaging: Exclusive meson production



- Transverse distribution of non-perturbative sea quarks

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

Longitudinal polarization  $q_+ \leftrightarrow q_-$

→ QCD vacuum structure

→ Chiral dynamics, “pion cloud”

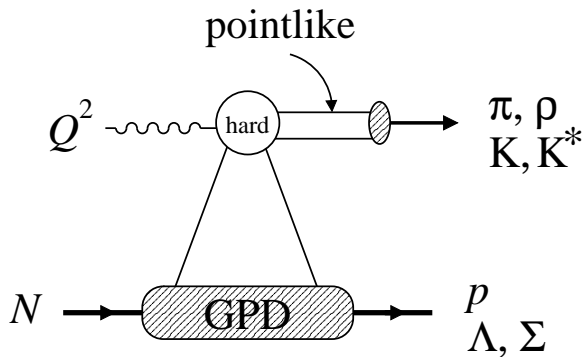
- Exclusive meson production

$$\gamma^* N \rightarrow M + B$$

Requires  $Q^2 > 10 \text{ GeV}^2$  for dominance of “pointlike” configurations → pQCD

Meson quantum numbers select spin/flavor component of GPD

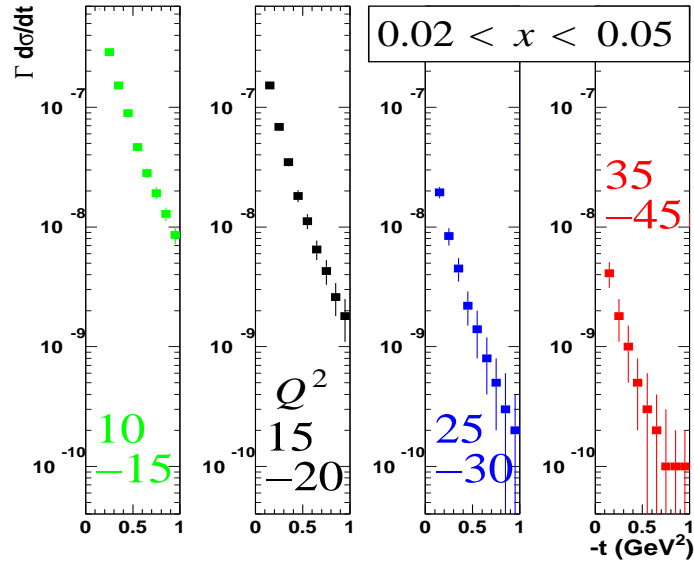
Information about meson wave function:  
Size, flavor structure



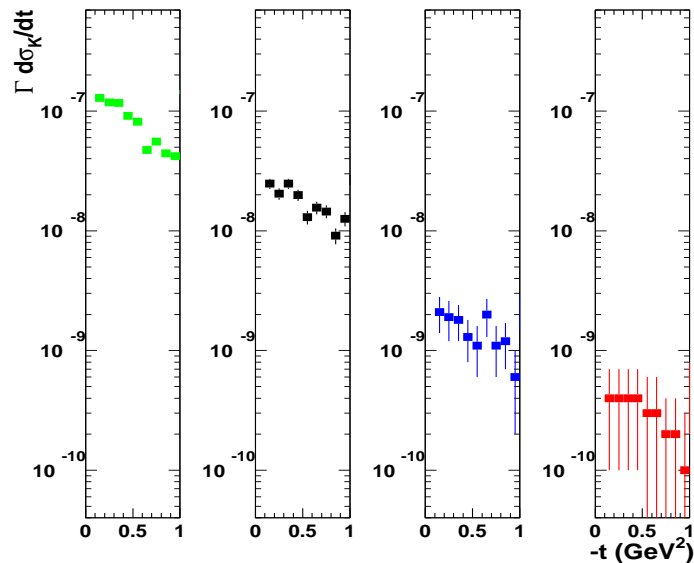


# Quark imaging: Sea quarks

$$ep \rightarrow e'\pi^+ n$$



$$ep \rightarrow e'K^+ \Lambda$$



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

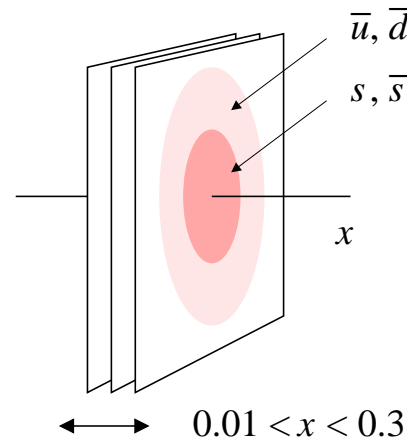
→  $\pi N$  or  $K \Lambda$  components in nucleon?  
 → QCD vacuum fluctuations?

- EIC: Exclusive  $\pi$  and  $K$  production

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

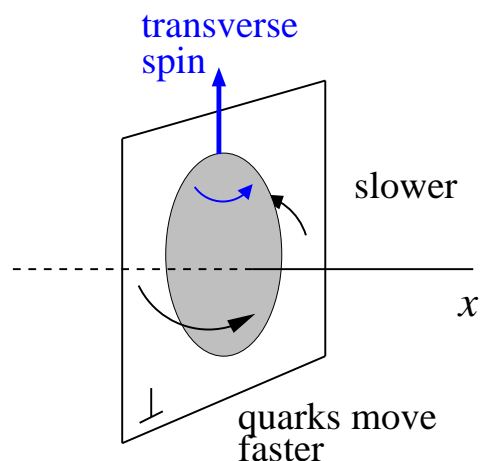
Kinematic reach in  $Q^2, x$

Recoil detection for exclusivity,  $t$ -distributions



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

# Quark imaging: Polarization



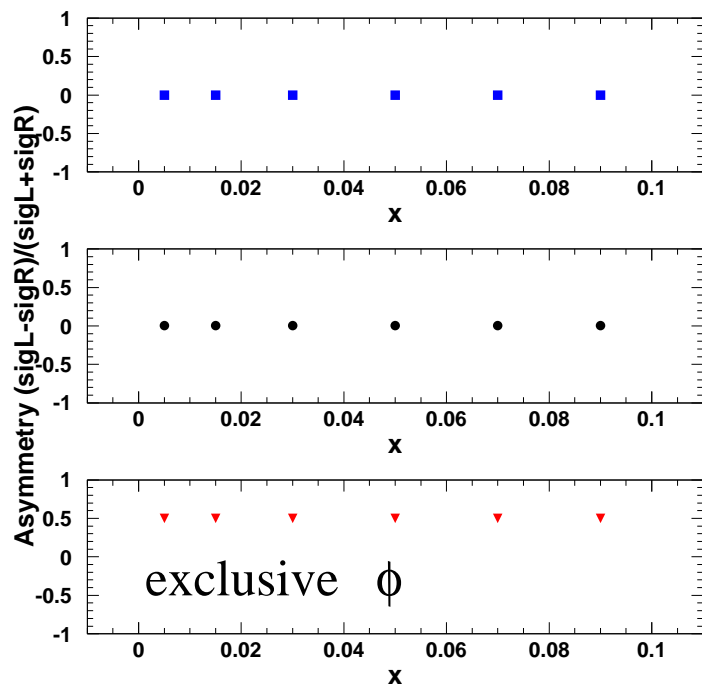
- Deformation of transverse distributions by transverse polarization of nucleon

Helicity-flip GPD, cf. Pauli FF

- EIC: Exclusive  $\rho$  and  $\phi$  production with transversely polarized beam

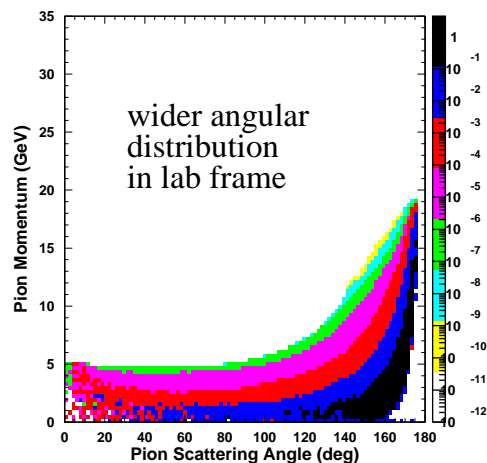
Excellent statistics at  $Q^2 > 10 \text{ GeV}^2$

Transverse polarization natural for collider

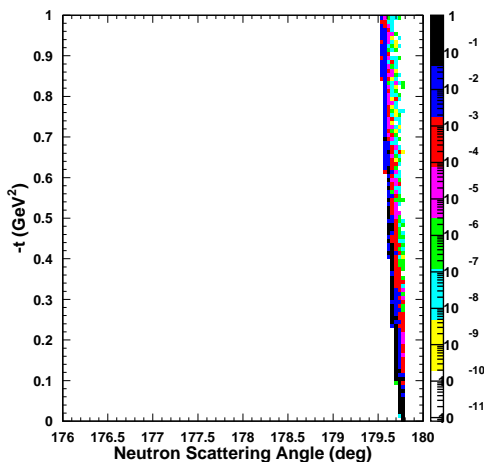
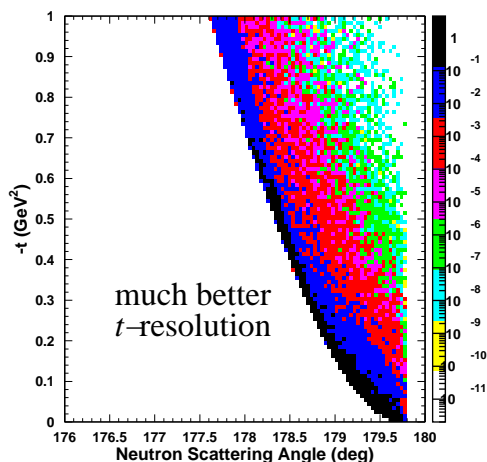
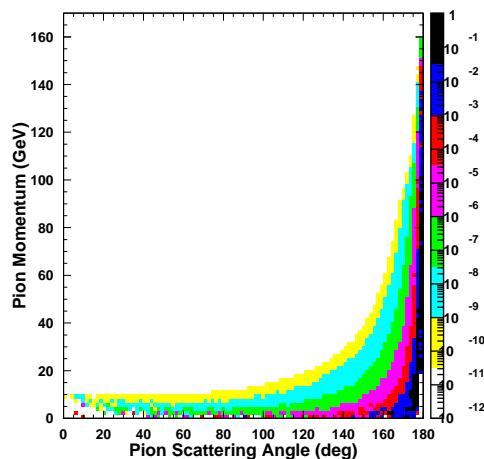


# Exclusive processes: Why lower energies

5 on 30 GeV



10 on 250 GeV



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

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

- Lower-energy, symmetric collider

→ Wider  $\pi^+$  angular distribution:  
Detection, angular resolution

→ Wider recoil  $n$  distribution:  
 $t$ -resolution

- Detector simulations in progress

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

# Exclusive processes: Beyond transverse imaging

- Longitudinal correlations in nucleon

GPDs at  $x' \neq x$ : Correlated  $q\bar{q}$  pairs in nucleon  
→ QCD vacuum structure, relativistic nature of nucleon

EIC: Reveal correlations through exclusive meson,  $\gamma$  at  $x > 0.1$ ,  
 $Q^2$  dependence

. . . needs kinematic coverage way beyond JLab 12 GeV

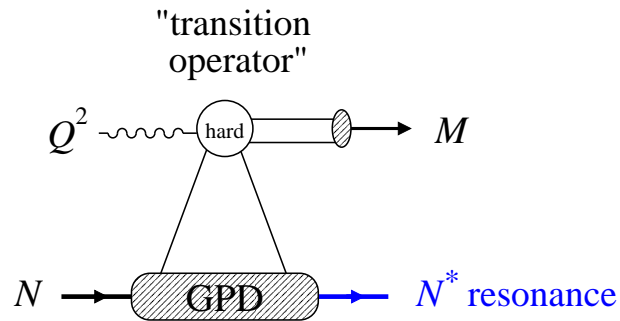
- Orbital motion of quarks/gluons

TMDs and orbital motion from semi-inclusive DIS:  
Major component of EIC program

Connection with GPDs: Unintegrated distributions, Ji sum rule

. . . should be discussed together!

# Exclusive processes: Baryon/meson structure



- $N^*$  resonance excitation through hard exclusive process

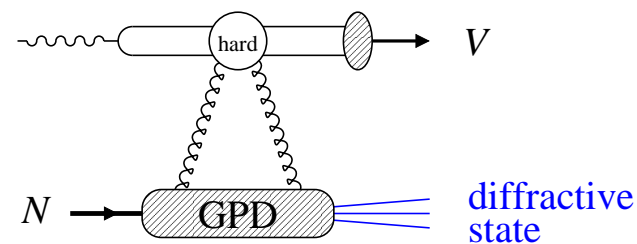
QCD factorization: Hard process as transition operator Frankfurt, Strikman, Polyakov

New quantum numbers!

- New probes of meson structure

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

“Exotics” from QCD counting rules



- 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!

# Summary

- High-luminosity  $ep/eA$  collider offers unique capabilities for gluon and quark imaging through exclusive processes
  - Fundamental QCD structure of nucleon/nuclei, non-perturbative dynamics
  - Visualization, 3D images
  - Synergy with lattice QCD: GPD moments
  - Essential input for  $pp$ @LHC, small- $x$

... Potential to become “golden experiment”
- Challenging experiments: Low rates, differential measurements, exclusivity,  $t$ -resolution, etc.
  - Driver of accelerator/detector requirements
  - Need to control systematics!
- Explore other interesting aspects of exclusive processes: Longitudinal correlations, meson structure, diffraction, ...