GPDs and exclusive processes in ep/eA scattering

Ch. Weiss (Jefferson Lab), EIC Workshop, BNL, July 17–22, 2006

3D quark/gluon structure of nucleon

$$f(x, \vec{\rho})$$

longitud. momentum — transverse position

- Quark/gluon imaging of proton

  Gluon from $J/\psi, \phi, \rho$ $\leftarrow$ HERA

  Gluon GPD $\leftrightarrow$ dipole picture

- Exclusive processes in eA

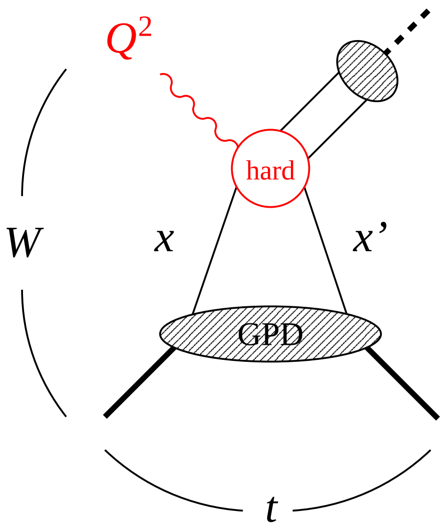
  Coherence length $\leftrightarrow$ nuclear size

- GPDs in pp with hard processes

  Control "transverse geometry"
  Unitarity limit in central pp $\rightarrow$ LHC
  Diffractive scattering

Hard exclusive processes in ep: Factorization

[Müller et al. 94; Brodsky et al. 94; Collins et al. 96; Radyushkin 96, Ji 96]

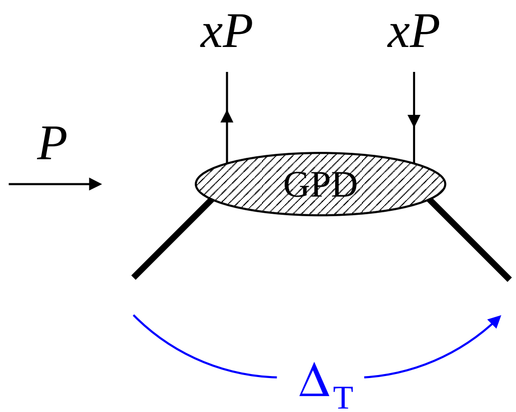


- γ^* reacts with quasi-free parton emitted/absorbed by target

- Generalized parton distribution $H(x, x', t)$ universal (process–independent)!

$\gamma^* p$	$\to$	$\gamma + p$	Deeply virtual Compton scattering
$\gamma_L^* p$	$\to$	$\rho + p$	Vector meson production
		$J/\psi + p$	Heavy quarkonium $\to$ gluon GPD
		$\pi + p$	pseudoscalar

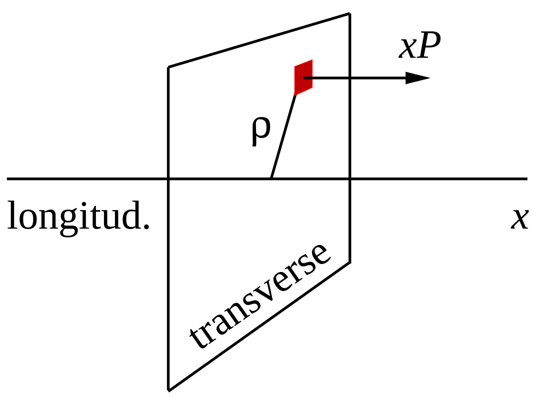
Transverse spatial distribution of partons [Burkardt 02; Diehl 02]



$$H(x,t) \quad = \quad \int d^2\rho \;\, e^{-i\vec{\Delta}_T\cdot\vec{\rho}} \;\, q(x,\rho)$$

form factor of quarks with longitudinal momentum xP

transverse spatial distribution



$$\int d^2\rho \; q(x,\rho) \;=\; q(x)$$

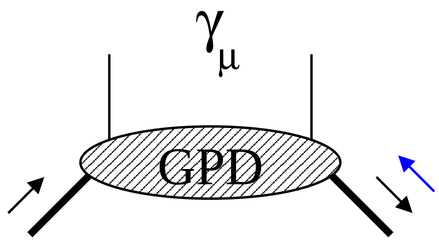
total quark density

$$\langle \rho^2 \rangle_q \;=\; 4 \, \frac{\partial}{\partial t} \; \frac{H(x,t)}{H(x,t=0)}$$

transv. size of nucleon, x–dependent!

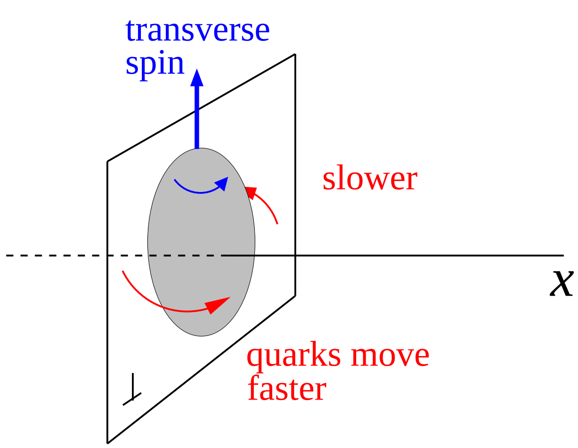
Quark distributions: Polarization

Quarks unpolarized:



$=$ H, Dirac — E Pauli

polarized: $\gamma_\mu \gamma_5$ — $\tilde{H}$, axial — $\tilde{E}$ pseudoscalar



$E(x)$: Distortion of longitudinal motion of quarks due to transverse spin [Burkardt 03]

Also: Operator relations (sum rules), QCD evolution, . . .

Towards quark/gluon imaging of the proton

- Strong differences between channels: Cross sections, energy dependence

$J/\psi, \phi$	$\longleftrightarrow$	ρ^0, γ	$\longleftrightarrow$	π, K, ρ^+
gluons		gluons + sing. quarks		non-sing. quarks

- DVCS at large x: Helicity components of quark GPDs from spin asymmetries in $ep \to ep\gamma$ [HERMES, JLab 6 and 12 GeV]

  $\rightarrow$ Talks by F. Ellinghaus, H. Avakian, A. Sandacz

- Factorization asymptotic statement . . . Need experimental tests of reaction mechanism (Q^2, W, t–dependence) and solid theory estimates of higher–twist

- Plenty of interesting information local in x, t
  . . . no "fixation" on sum rules!

Experimental requirements

- Broad range in Q^2 and W
- High luminosity . . . depends on channels $\rightarrow$ Talk by R. Ent
- Detection of recoil proton
- Accurate t–measurements for $|t| < 1\,\mathrm{GeV}^2$ $\leftarrow$ beam optics
- L/T separation . . . crucial for understanding reaction mechanism!
- Polarization (DVCS)

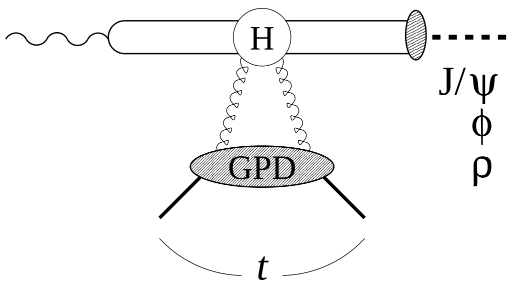
Part II

Gluon imaging of proton

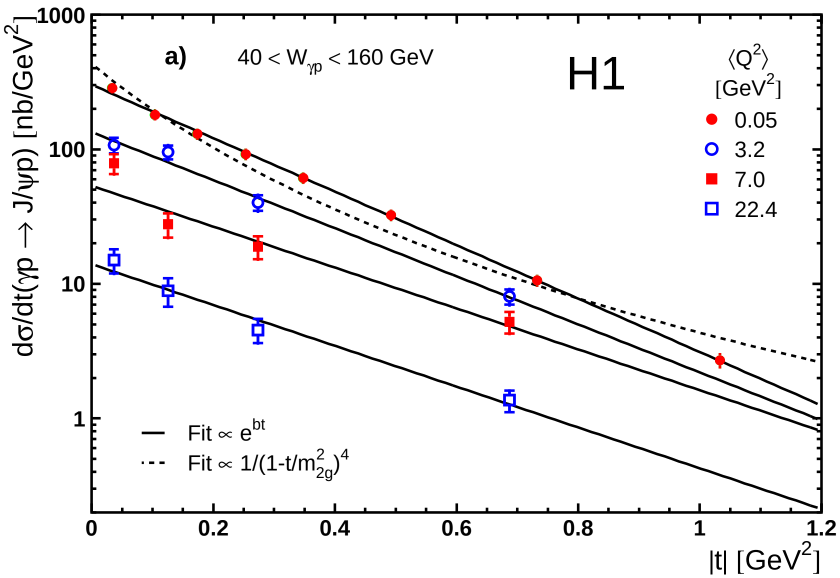
- Feasible! HERA + fixed target data
- Ideas about nucleon structure
- Related to dipole picture at small x

Review: Frankfurt, Strikman, CW, Ann. Rev. Nucl. Part. Sci. **55**, 403 (2005)

Gluon imaging of proton: J/ψ, ϕ, ρ (small x)



- "Universality" of t–slopes at high Q^2 demonstrates validity of QCD factorization



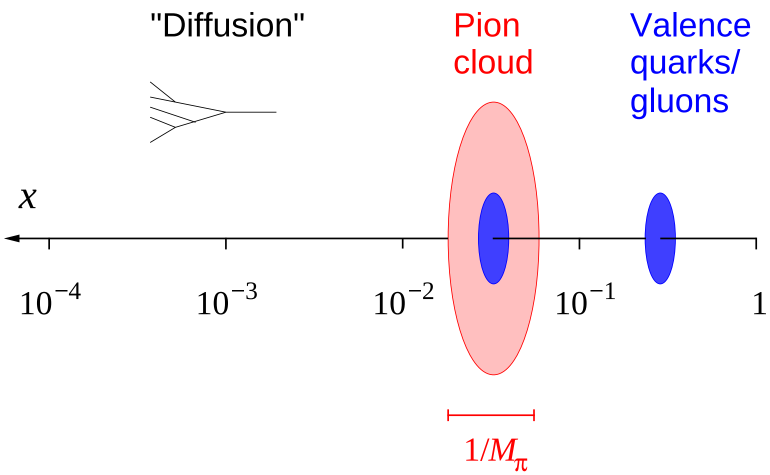
[HERA H1 2005; see also: ZEUS
. . . no recoil detection!]

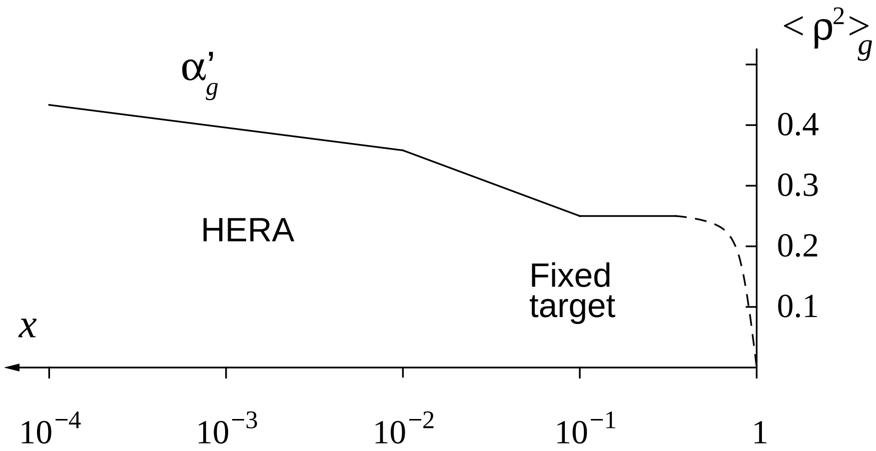
- t–dependence of differential cross section

$$\frac{d\sigma}{dt} \propto \left[\frac{H_g(x,t)}{H_g(x,0)}\right]^2 \xrightarrow{\text{FT}} \text{spatial distribution}$$

- Also: J/ψ fixed–target data [FNAL, SLAC, Cornell, CERN]

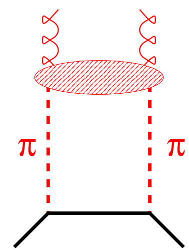
Gluonic transverse size of proton: x–dependence





(Scale $Q^2 \approx 3\,\mathrm{GeV}^2$)

- Gluonic transverse size increases with decreasing x
- Pion cloud contributes at $x < M_\pi / M_N$ [Strikman, CW 03]



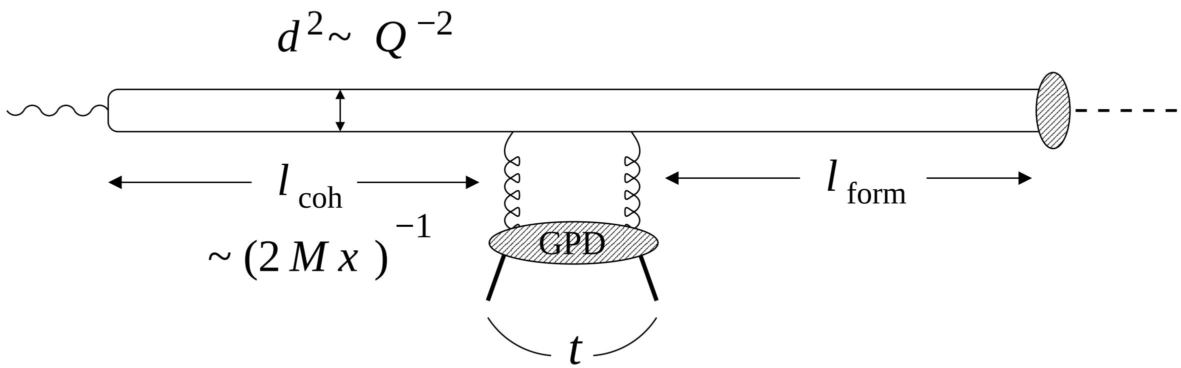
$$G(x, \rho) \sim e^{-2M_\pi \rho}$$

"Yukawa tail"

- Small x: Logarithmic growth with $\alpha'_g \ll \alpha'_{\mathrm{soft}}$ ("diffusion")

Gluon GPD and the dipole picture at small x

[Brodsky et al 94; Frankfurt, Radyushkin, Strikman 96]



Target rest frame: Scattering of small–size $q\bar{q}$ dipole from proton

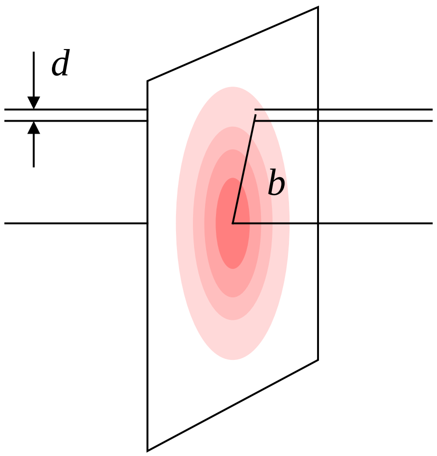
$$A^{dp} \quad \propto \quad d^2\, \alpha_s\, x\, G(x,t)$$

$$\text{Scale} \approx \pi^2\, d^{-2}$$

Dipole–proton scattering amplitude in leading $\alpha_s \log Q^2$ approximation

- QCD factorization $\leftrightarrow$ "Color transparency"
- Gluon GPD $\leftrightarrow$ "Color dipole moment" of proton
- Higher twist $\leftrightarrow$ hadronic size configurations in γ^* $\quad\rightarrow$ Talk by T. Rogers

Dipole picture in impact parameter representation



- Dipole–proton interaction probes local gluon density in transv. plane $x\,G(x, \vec{b})$

- Model–independent formulation of unitarity limit in hard interactions

$$A^{dp}(s,t) \;=\; \frac{is}{4\pi}\int d^2b\, e^{-i\vec{\Delta}_\perp \vec{b}}\,\Gamma^{dp}(s,b)$$

profile function

$\Gamma^{dp} \to 1$: "Black disc limit"

Breakdown of twist expansion

$\rightarrow$ Talk by T. Rogers

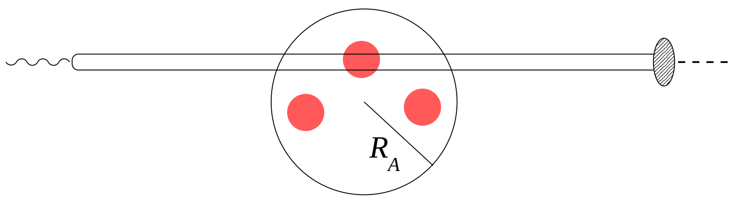
Part III

Hard exclusive processes in eA

- New studies of small–x dynamics
- GPDs as new probe of nuclear structure

  $\rightarrow$ Talk by V. Guzey

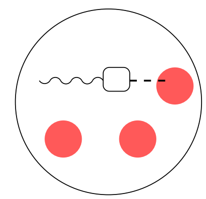
Coherence length vs. nuclear radius [with M. Strikman]



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

Color transparency ($d \ll 1$ fm)

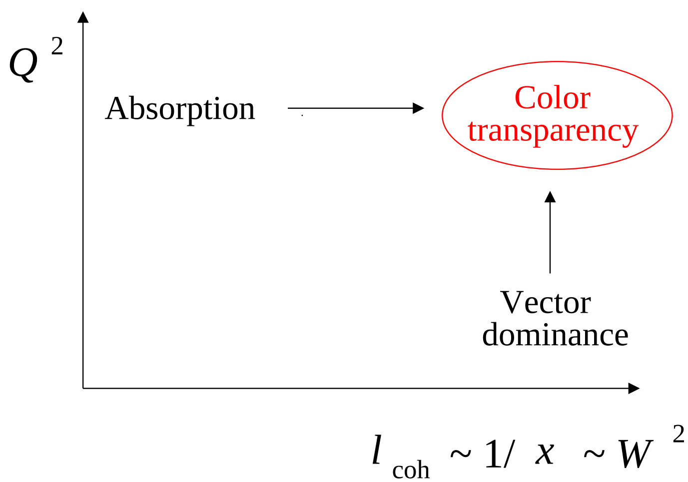
$\sigma \propto A$ (incoherent)



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

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

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



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

Coherent scattering from nuclei

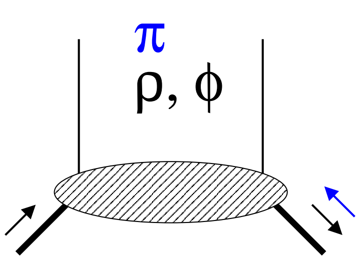
- A–dependence in color transparency regime

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

- Polarized light nuclei

^{4}He	Spin 0	"single GPD"
^{2}H	Spin 1	$\Delta S = 2$ component

- Nucleus as "detector" for quantum number transfer



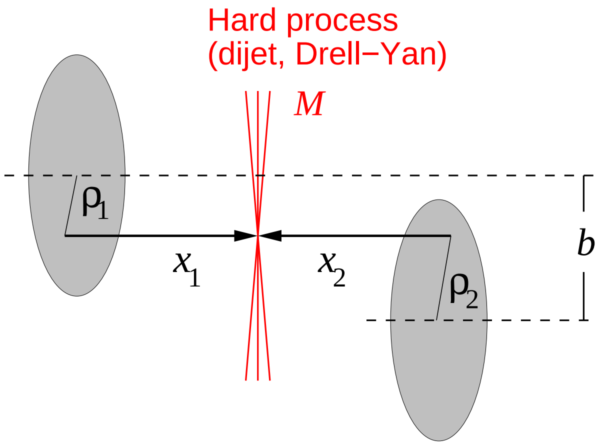
Very different propabilities for leaving nucleus intact

Part IV

GPDs in pp with hard processes

- Control transverse geometry (impact parameters)
- Trigger for central collisions
- Rapidity gap survival in diffractive scattering

Hard processes in pp: Impact parameter dependence



$pp \to M + X$

$$P_{\text{hard}}(b) \propto \int d^2\rho_1 \, d^2\rho_2 \times \delta(\vec{b} - \vec{\rho}_1 + \vec{\rho}_2) \times f(x_1, \vec{\rho_1}) \, f(x_2, \vec{\rho_2})$$

- Hard process induced by parton–parton collision

$$x_1 x_2 = M^2/s$$

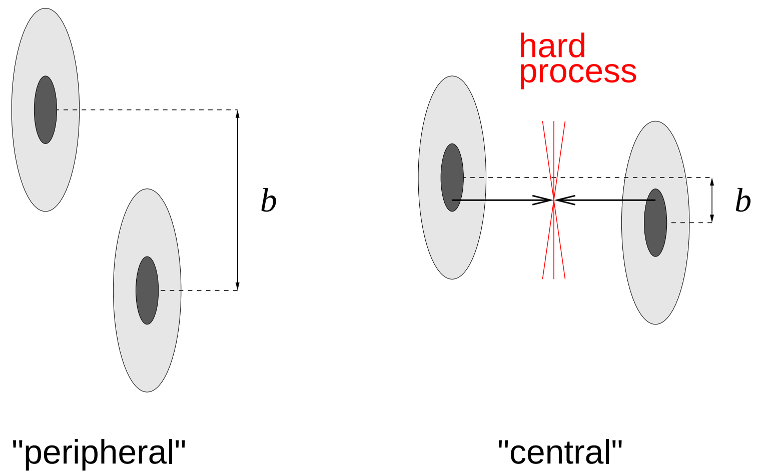
- Calculate probability as function of pp impact parameter b in terms of $f(x, \vec{\rho})$ known from ep

- "Control" impact parameter distribution even though b not observable!

$\to$ Spectator interactions

$\to$ Global event characteristics

Hard processes as "filter" for central collisions [Frankfurt, Strikman, CW 03]

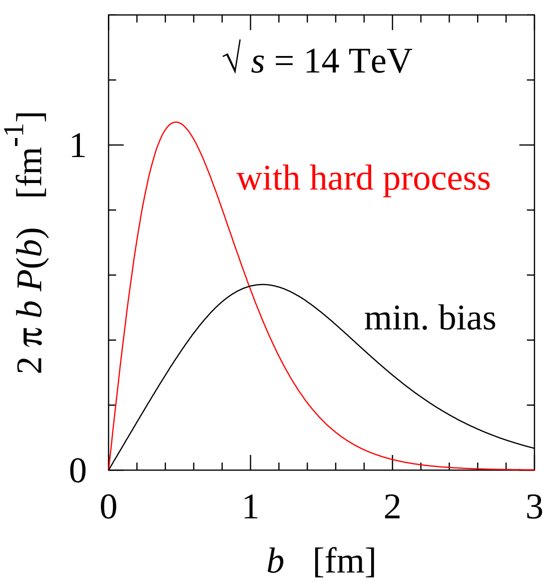


- Different transverse sizes in hard and soft interactions:

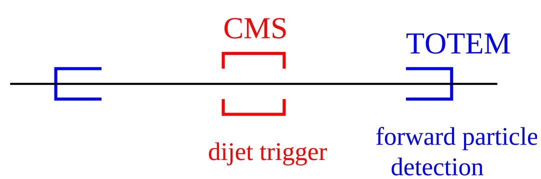
$$\langle \rho^2 \rangle \ (x \geq 10^{-2}) \quad \ll \quad R^2(\text{soft})$$

- Hard processes (e.g. dijets) as trigger on central collisions

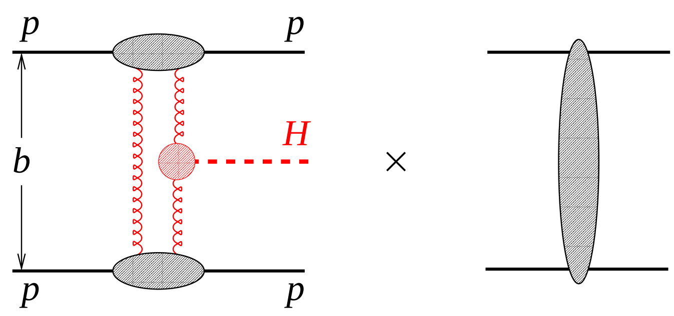
  . . . Numerous applications!

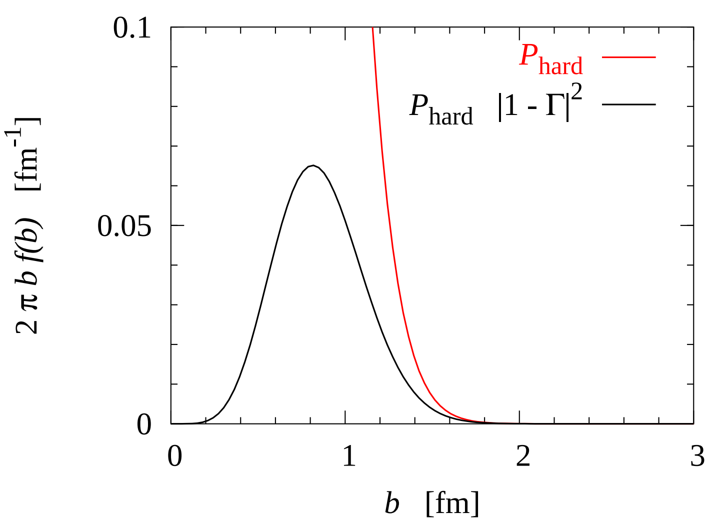


- Central collisions at LHC: Unitarity limit in spectator interactions ("black disc limit"); observable in forward particle production



Diffractive processes $pp \to p + H + p$: Rapidity gap survival





- Heavy particle produced in hard partonic process (2–gluon exchange)

- Soft spectator interactions must not destroy rapidity gaps!

- Gap survival probability

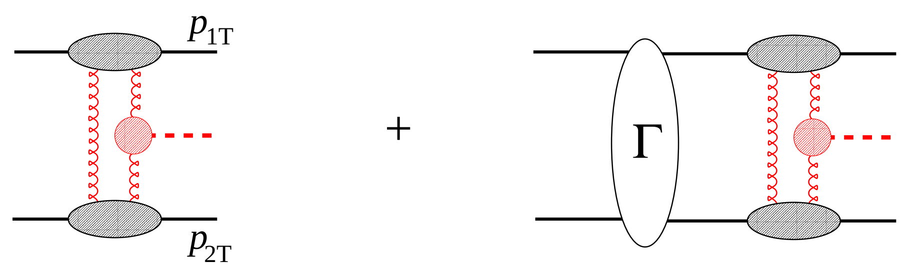
$$S^2 = \int d^2b \; P_{\text{hard}}(b) \; |1 - \Gamma(b)|^2$$

$$\approx \quad 0.03 \quad \text{(Higgs at LHC)}$$

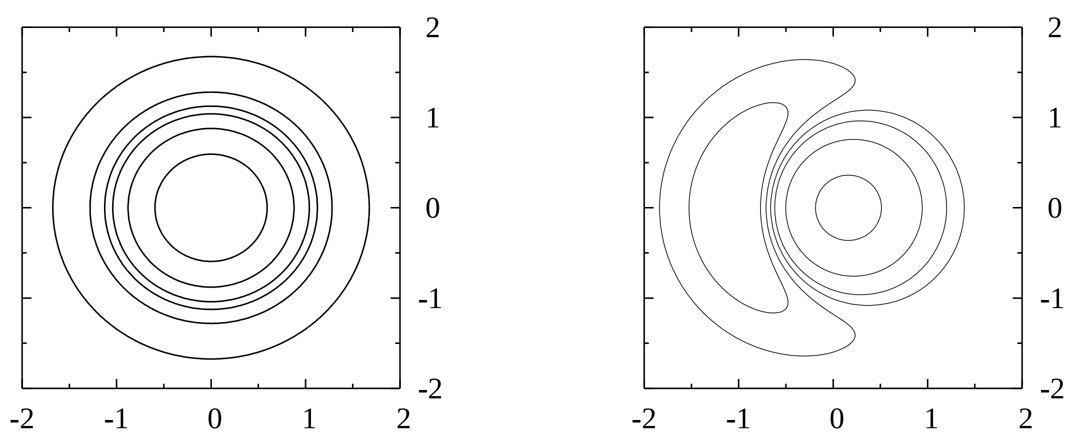
. . . calculable, model–independent!

[Frankfurt, Hyde–Wright, Strikman, CW 06]

Diffractive processes: Probing GPDs



$p'_{1x} = 0$ 0.5 GeV



- Interference between hard process alone and hard + soft rescattering
- Diffraction pattern in $\vec{p}_{T1}, \vec{p}_{T2}$
- Extract information about gluon GPD!

[Frankfurt, Hyde-Wright, Strikman, CW 06]

Summary

- ep/eA collider offers unique opportunities for quark/gluon imaging of proton and nuclei in hard exclusive processes

- Large differences between channels/kinematics: Need to carefully specify objectives!

gluons at $x < 10^{-2}$	$\longleftrightarrow$	quarks at $x > 10^{-2}$
high energy, moderate lumi		moderate energy, high lumi

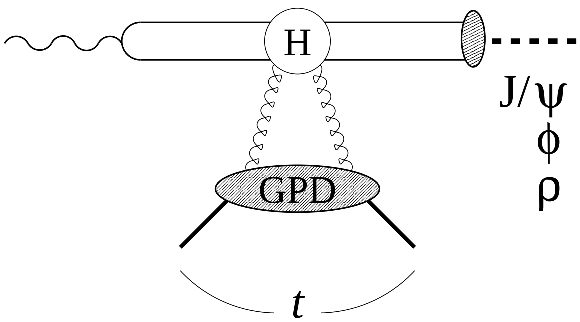
- Gluon imaging: Feasible; important for unitarity studies at smaller x

- Nuclei: New ways to explore small–x QCD and nuclear structure

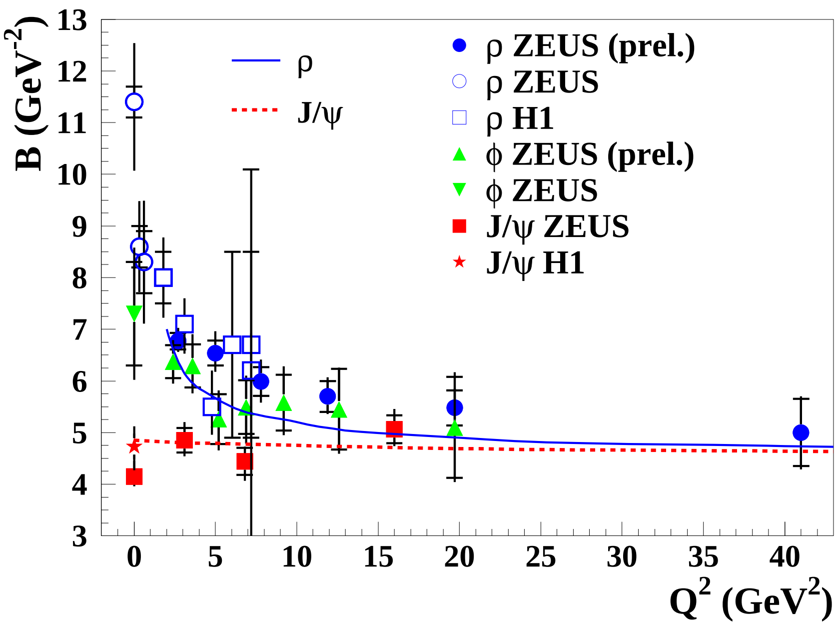
- Interesting "convergence" $ep \leftrightarrow pp$

Supplementary material

Vector meson production at HERA: Tests of factorization

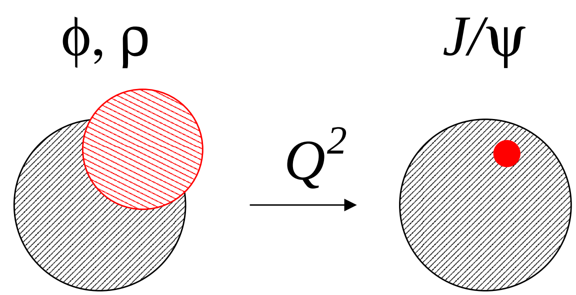


- J/ψ and ϕ, ρ (small x) probe gluon GPD



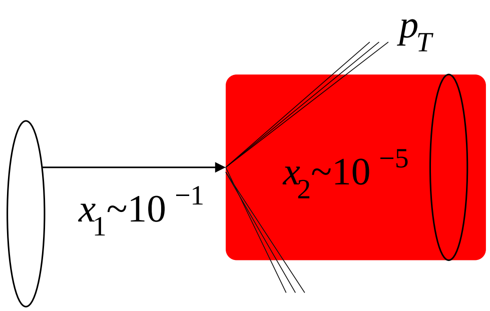
- "Universality" of t–slopes at large Q^2 shows dominance of pointlike configurations

$$\frac{d\sigma}{dt} \quad \propto \quad \left[\frac{G(x_1, x_2, t)}{G(x_1, x_2, 0)} \right]^2$$



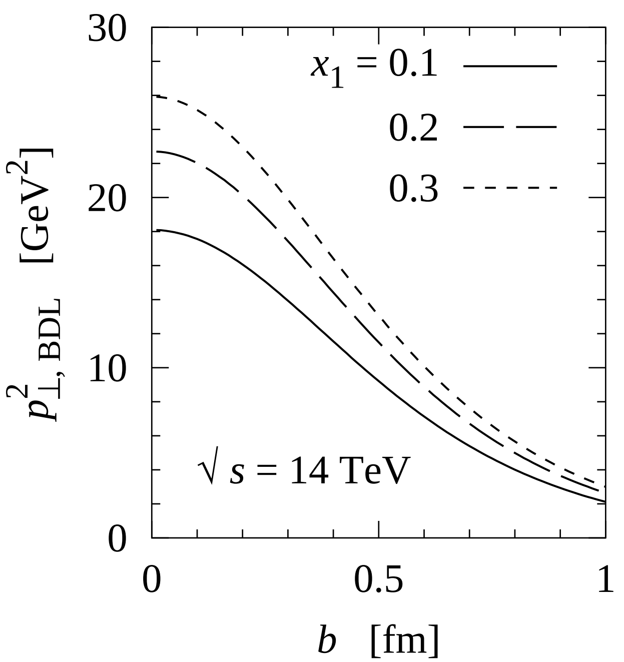
[A. Levy 05; Frankfurt, Strikman, CW 05]

Central collisions: Unitarity limit in hard spectator interactions



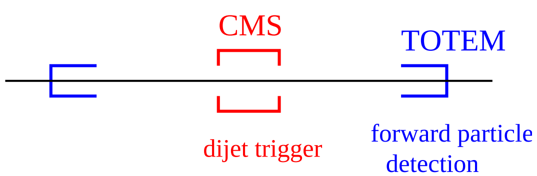
- Increase of gluon density at small x (DGLAP evolution)

- Interaction of large–x_1 spectator with small–x_2 gluons approaches "black–disk limit": $P_{\text{inel}} \to 1$



- Qualitative changes in forward particle production: Large $p_\perp$, energy loss, . . .

- Can be studied with LHC detectors



[Frankfurt, Strikman, CW 03/04]