GPDs in high–energy ep and pp scattering

C. Weiss (JLab), Ecole Polytechnique, 27–Jun–08

- Explore nucleon structure — JLab 12 GeV, EIC

  Quark core, pion cloud, polarization
  Small–x diffusion, α', . . .

- Understand ep at small x — HERA, EIC

  Dipole picture
  Unitarity limit: "Black–disk regime"

- Model pp with hard processes — LHC, Tevatron, RHIC

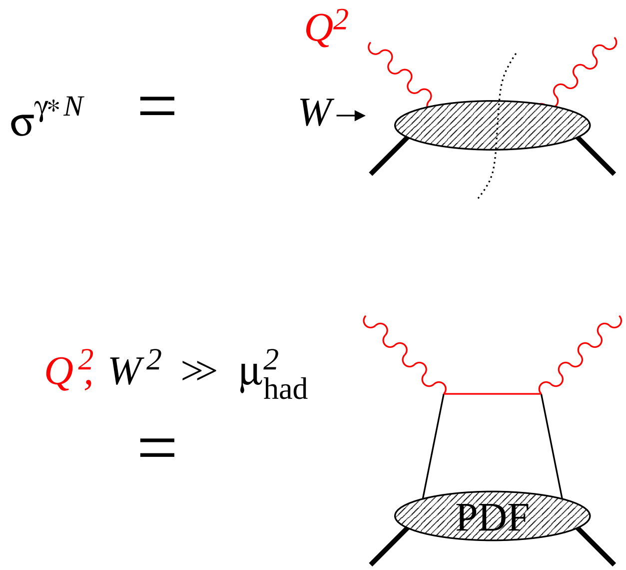
  Impact parameter dependence
  Central vs. peripheral collisions
  Exclusive diffraction $pp \to p + H + p$, . . .

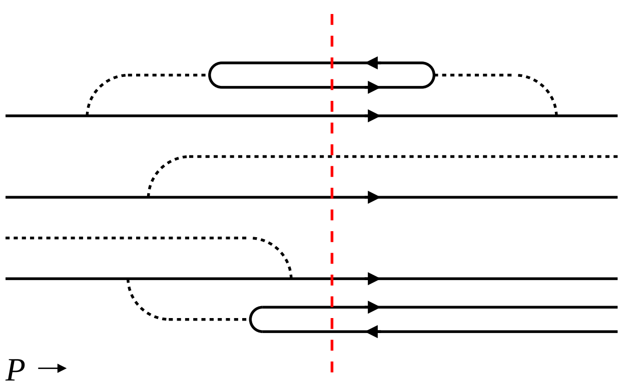
Transverse distribution of quarks/gluons in nucleon

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

longitud. momentum	transverse position

Factorization: Inclusive ep scattering





- Factorization of amplitude

Quark subprocess	short distance $\sim 1/Q$
Parton distribution in nucleon (PDF)	long distance $\sim 1/\mu_{\text{had}}$

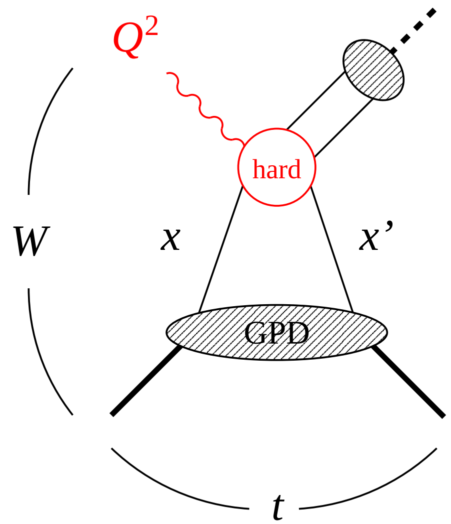
- PDF as matrix element of QCD operator

$$\langle p|\, \bar{\psi}(0) \ldots \psi(z)\, |p\rangle_{z^2=0} \quad \leftrightarrow \quad f(x)$$

- Space–time interpretation:
  Density of quarks with longitudinal momentum fraction x in wave function of fast–moving nucleon ($P \gg \mu_{\text{had}}$)

  [Concept: Gribov 70's]

Factorization: Exclusive processes in ep

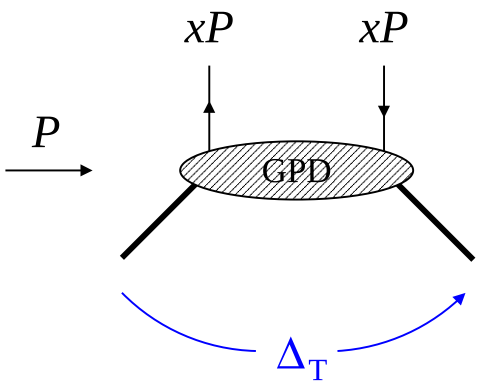


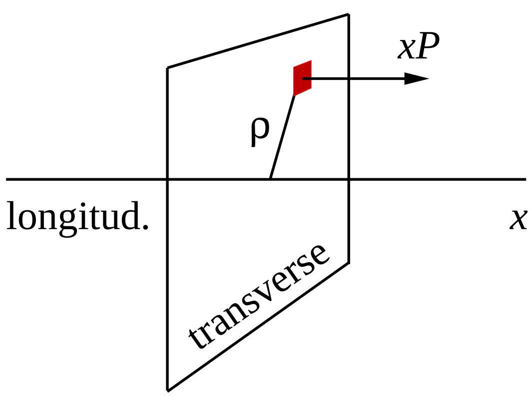
$\gamma^* p$	$\rightarrow$	$\gamma + p$	Deeply virtual Compton
$\gamma^*_L p$	$\rightarrow$	$\rho + p$	Vector meson
		$J/\psi + p$	Heavy $\bar{Q}Q$ (gluon GPD)
		$\pi + N$	pseudoscalar

- Meson/γ produced in reaction with quasi-free parton in target
- GPD $H(x, x', t)$ combines properties of parton distribution and elastic FF
- Factorization implies
  - GPDs universal, process–independent
  - Leading $1/Q^2$ power behavior

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

GPDs: Transverse spatial distribution of partons





[Burkardt 02; Diehl 02]

- Transverse coordinate representation ($x' = x$)

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

FF of partons with mom. xP — transverse spatial distribution

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

longitud. momentum density

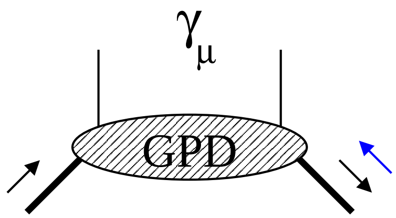
- Transverse size of nucleon (x–dep.)

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

$$\boxed{\text{“Tomographic image” of nucleon at fixed } x}$$

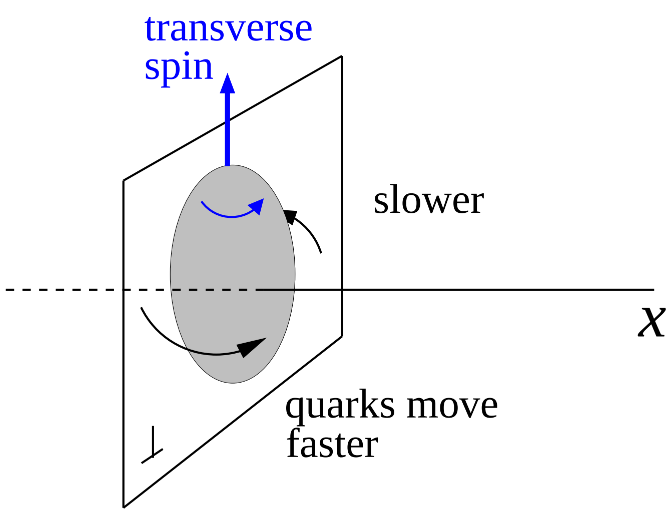
GPDs: Polarization in quark distributions

Quarks unpolarized:



$=$ H, Dirac — E Pauli

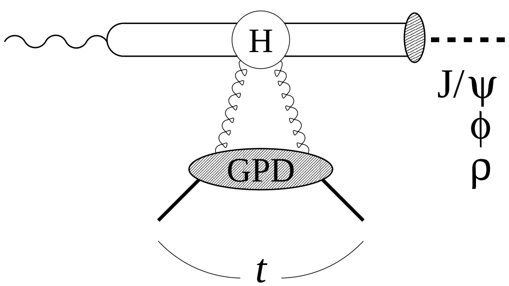
polarized: $\gamma_\mu\gamma_5$ — $\tilde{H}$, axial — $\tilde{E}$ pseudoscalar

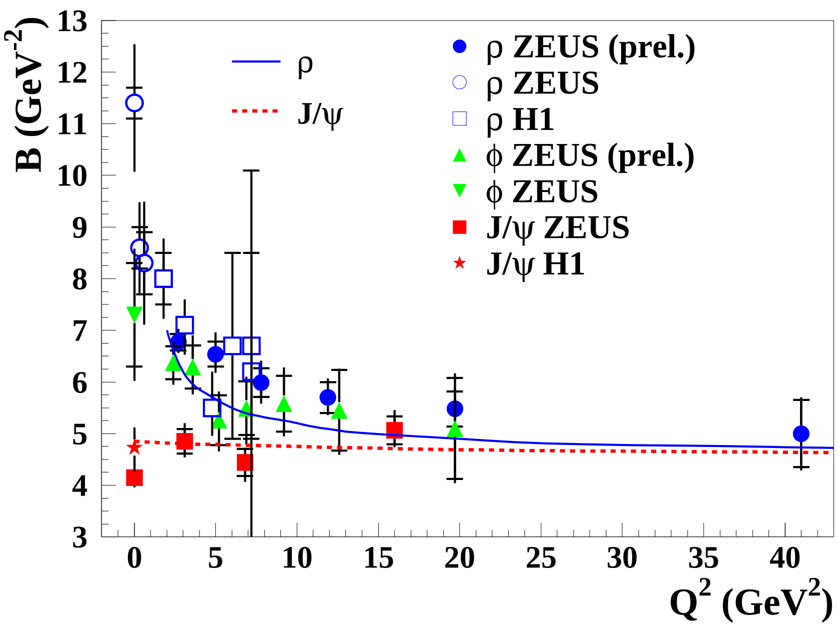


- $E(x)$: Distortion of longitudinal motion of quarks due to transverse nucleon spin [Burkardt 03]

$\rightarrow$ JLab 12 GeV exp. program

GPDs: Transverse gluon distribution from J/ψ





[Summary HERA 05 data by A. Levy]

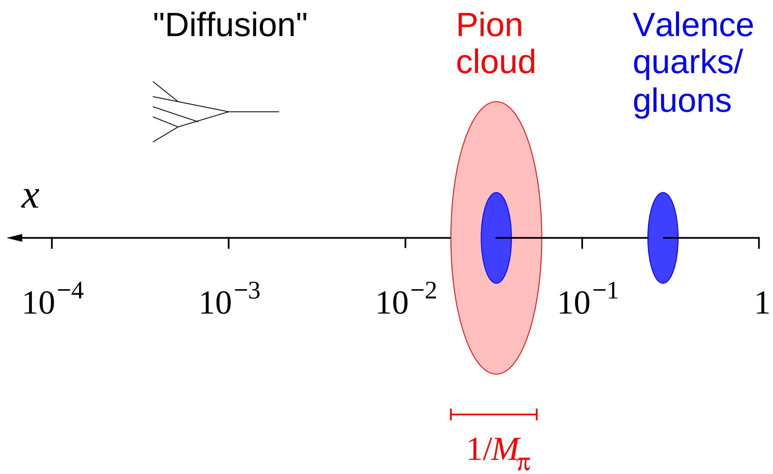
- Test of factorization:
  Universality of t–slopes at high Q^2

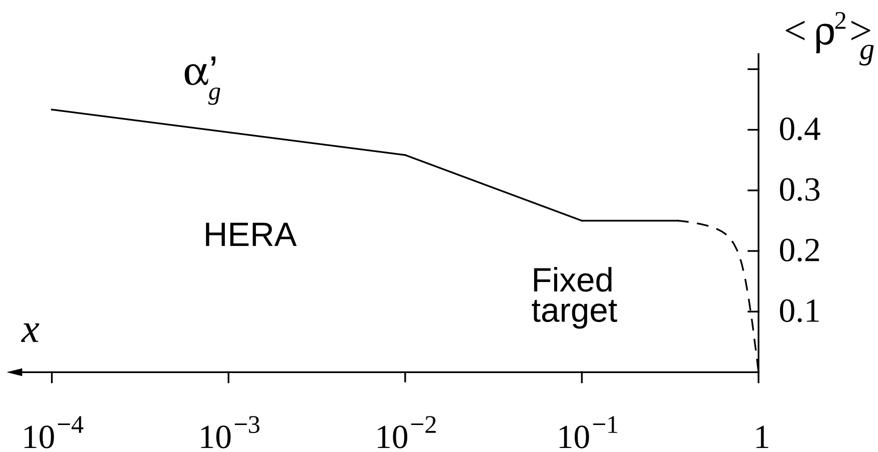
- Spatial distribution from
  t–dependence (unnormalized)

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

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

GPDs: Gluonic transverse size of nucleon

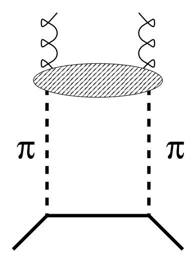




(Scale $Q^2 \approx 3$ GeV^2)

- Gluonic transverse size increases with decreasing x

- Pion cloud at $x < M_\pi / M_N$



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

"Yukawa tail"

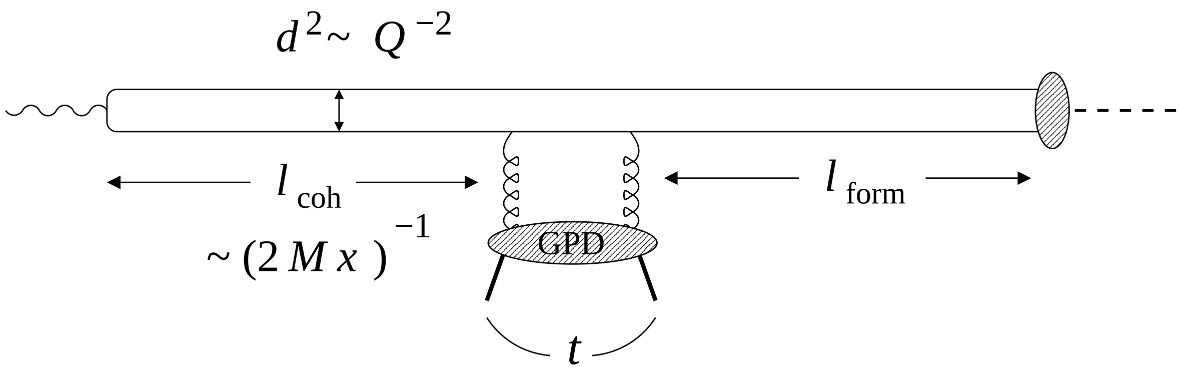
[Strikman, CW 03]

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

[DGLAP: Frankfurt, Strikman, CW 03]

Small x: GPDs and dipole picture

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



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

$$A^{dp} \quad \propto \quad d^2\, \alpha_s\, x\, G(x, t \,|\, Q^2_{\mathsf{eff}})$$

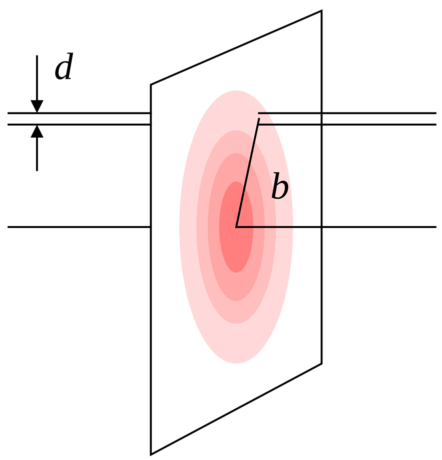
Scale $Q^2_{\mathsf{eff}} \approx \pi^2\, d^{-2}$

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

- Diagonal approximation $x = x'$ in GPD
  [Frankfurt et al. 97; Shuvaev et al. 99]

Small x: Impact parameter representation



- Dipole–proton interaction probes local transverse gluon density $G(x, \boldsymbol{b})$

- Impact parameter representation of dipole–proton scattering amplitude

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

profile function

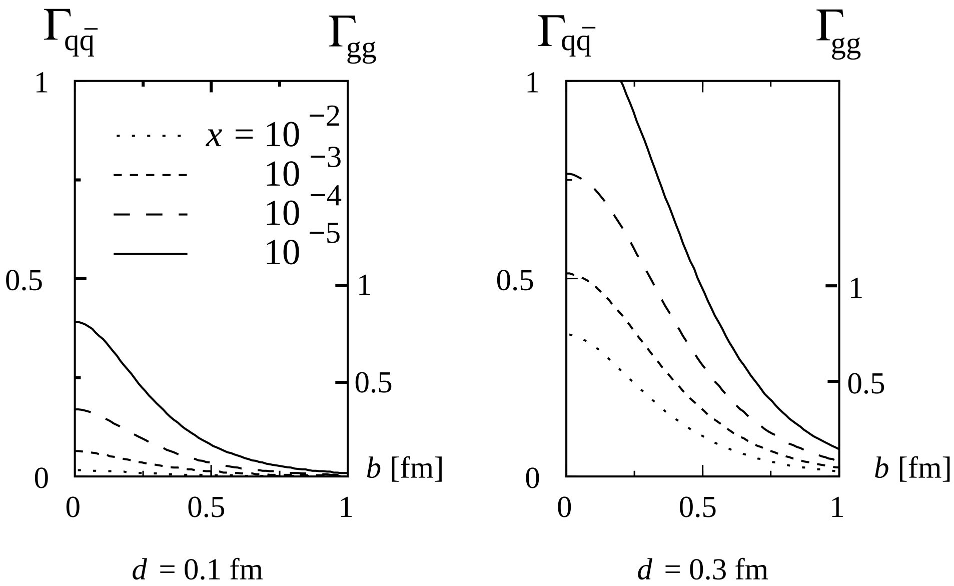
$$\frac{d\sigma^{dp}_{\text{inel}}}{d^2b} \;=\; 1 - |1 - \Gamma^{dp}|^2$$

Probability of inelastic scattering

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

Model–independent formulation of unitarity limit in hard interactions

Small x: Approach to black–disk regime



- Γ^{dp} evaluated with LO gluon density + spatial distribution

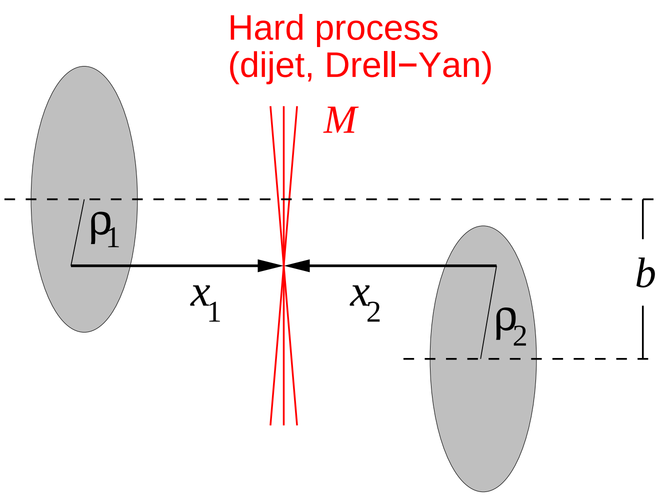
  $\rightarrow$ BDR not reached for $\bar{q}q$ dipoles at HERA

  $\rightarrow$ Definitely reached for gg dipoles in central pp scattering at LHC

- Here BDR reached because of large non-perturbative gluon density (chiral symmetry breaking) and "usual" DGLAP evolution
  . . . no need for $\log(1/x)$ enhanced radiation [cf. Color Glass Condensate]

[Frankfurt, Guzey, Strikman 02; FS + CW 03–05; FS + Rogers 03]

pp: Impact parameter dependence



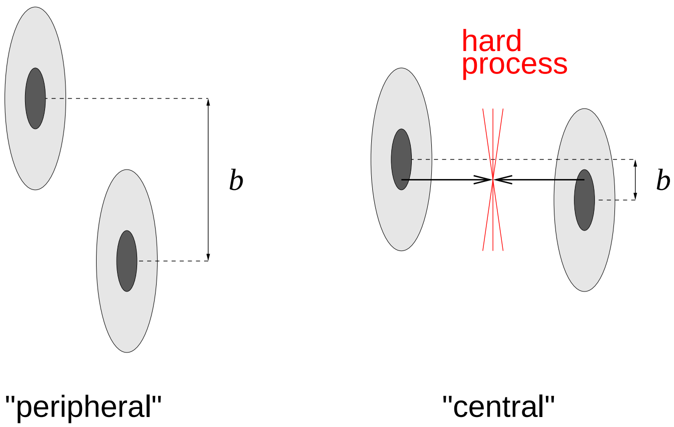
$$P_{\text{hard}}(b) \;\propto\; \int d^2\rho_1\, d^2\rho_2 \;\times\; \delta(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) \;\times\; f(x_1, \boldsymbol{\rho_1})\, f(x_2, \boldsymbol{\rho_2})$$

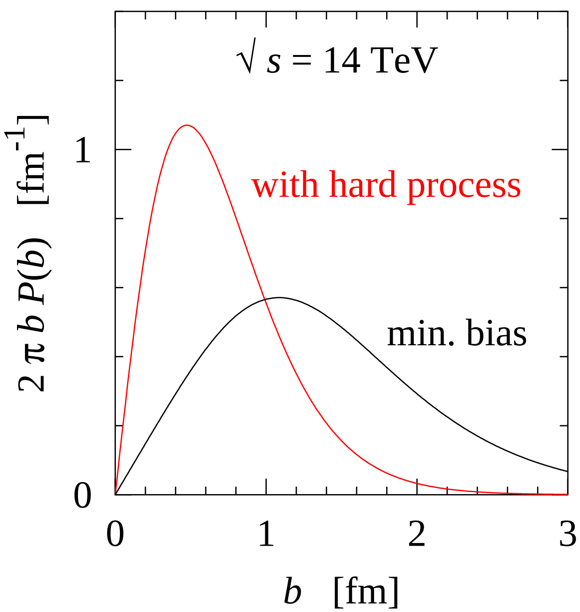
- Hard process: $x_{1,2} = \dfrac{M}{\sqrt{s}}\, e^{\pm y}$
- Local on scale of soft interactions: $M^2 \gg R^{-2}$(hadron)
- Calculate probability as function of pp impact parameter b in terms of $f(x, \boldsymbol{\rho})$ known from ep

$\rightarrow$ Spectator interactions
$\rightarrow$ Global event characteristics
$\rightarrow$ Diffraction (rapidity gap survival)

"Control" transverse geometry even though b not observable!

pp: Hard process selects central collisions





- Different transverse sizes in hard and soft interactions:

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

$$\sim 0.3 - 0.4\,\text{fm}^2 \qquad \sim 0.8 - 1.0\,\text{fm}^2$$

from excl. J/ψ $\qquad$ pp elastic

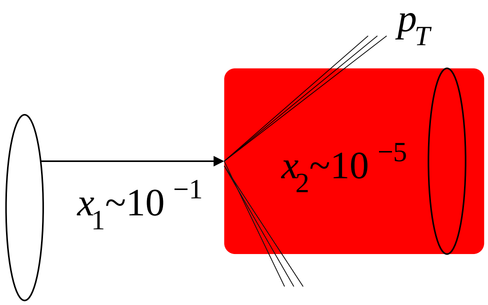
"Two–scale picture"

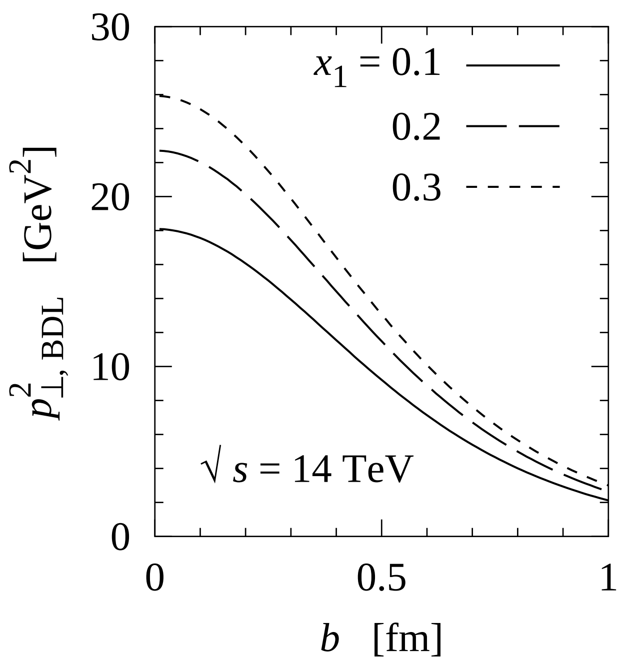
- Hard processes (e.g. dijets) as trigger on central collisions

. . . Numerous applications!

[Frankfurt, Strikman, CW 03]

pp: Black–disk limit in hard spectator interactions



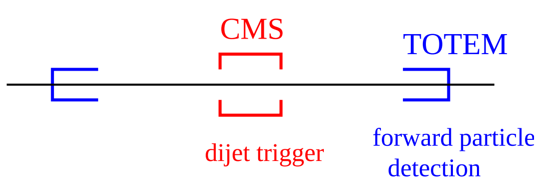


- Central collisions: Hard interactions of large–x_1 spectators with small–x_2 gluons approach black–disk limit

- Max. p_T estimated using dipole model

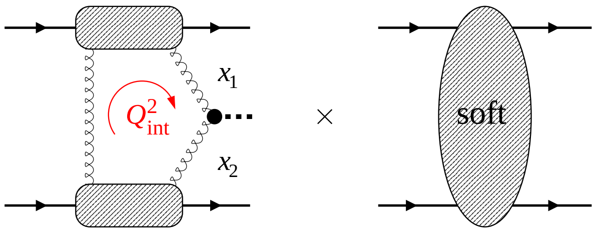
- Qualitative changes in forward particle production: Large $p_\perp$, energy loss, . . .

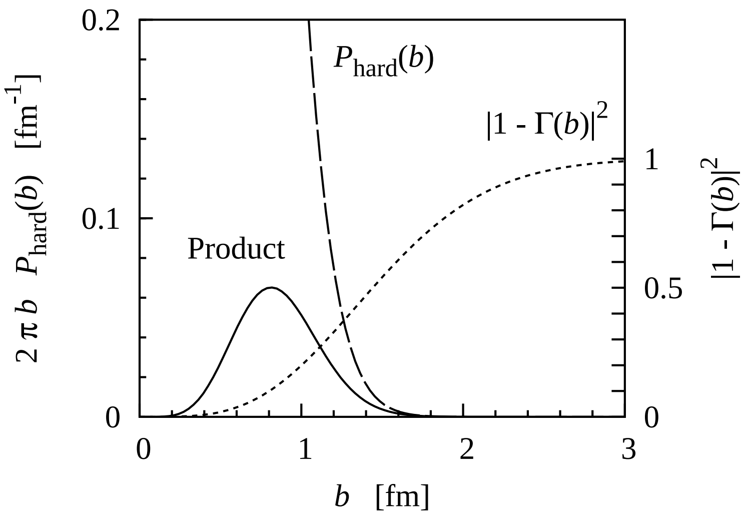
- Can be studied with LHC detectors



[Frankfurt, Strikman, CW 03/04]

Diffraction: Gap survival in $pp \to p + H + p$





[Frankfurt, Hyde, Strikman, CW 07]

- Heavy particle produced in hard process (2–gluon exchange)
  $x_{1,2} \sim 10^{-2}$ Higgs at LHC [Khoze et al. 97]

- Soft spectator interactions must not destroy rapidity gaps!

- Gap survival probability

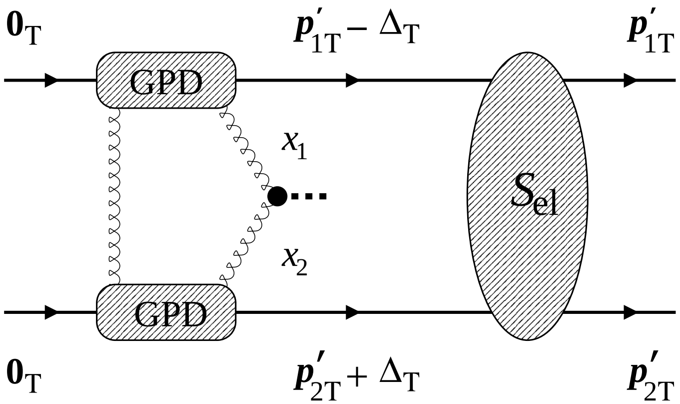
$$S^2 = \int d^2b \, P_{\mathrm{hard}}(b) \, |1 - \Gamma^{pp}(b)|^2$$

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

calculable, model–independent

Suppression of small b from "blackness" of pp scattering

Diffraction: p_T dependence



$$T_{\text{diff}}(\boldsymbol{p}_{1\mathrm{T}}, \boldsymbol{p}_{2\mathrm{T}}) \propto \int d^2\Delta_\mathrm{T}$$
$$\times\, H_g(x_1, \boldsymbol{p}_{1\mathrm{T}} - \boldsymbol{\Delta}_\mathrm{T})$$
$$\times\, H_g(x_2, \boldsymbol{p}_{2\mathrm{T}} + \boldsymbol{\Delta}_\mathrm{T})$$
$$\times\, \underbrace{S_{\text{el}}(\boldsymbol{\Delta}_\mathrm{T})}_{1 + iT_{\text{el}}}$$

- Amplitude computed in terms of

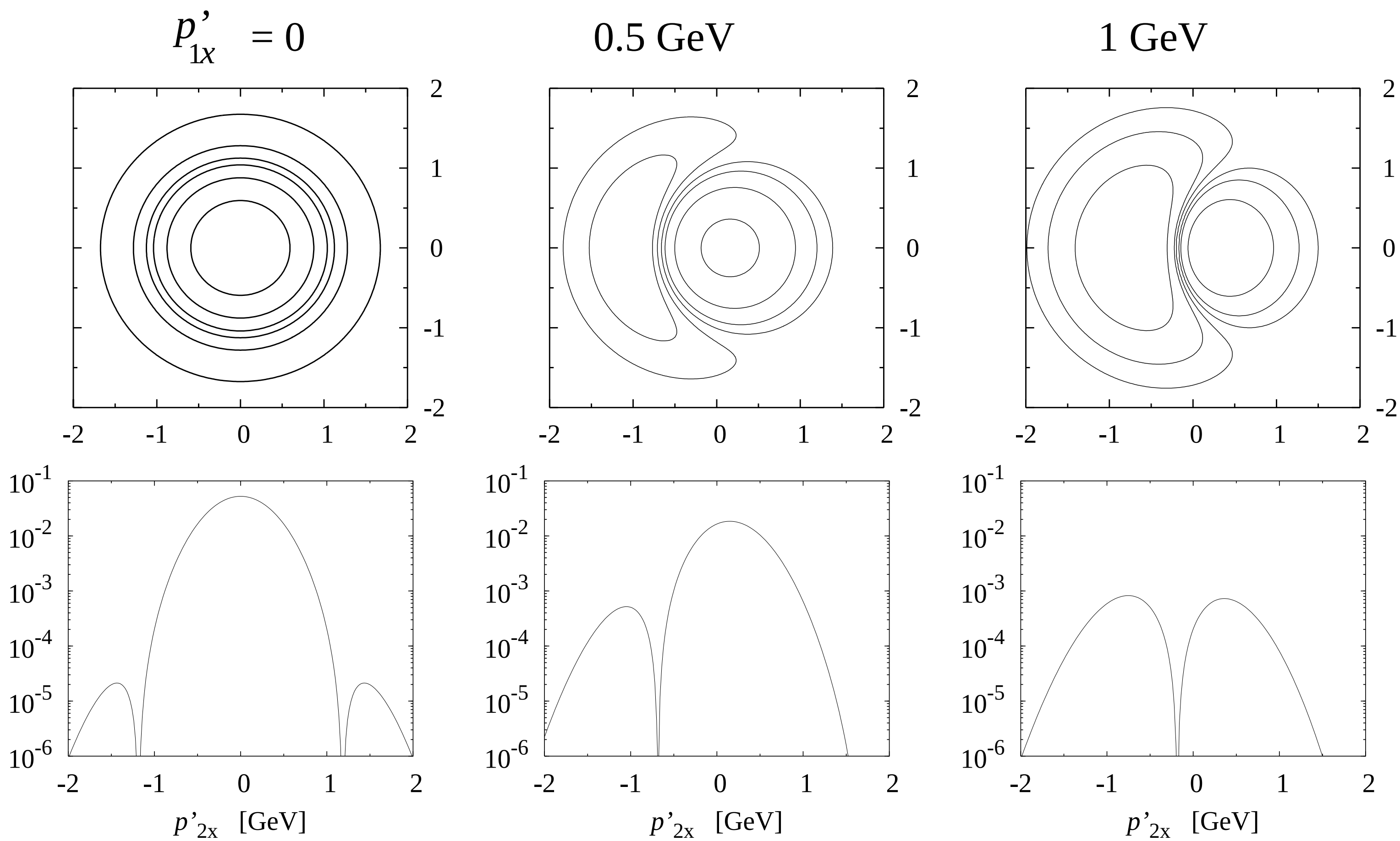
Gluon GPD	t–dep.	$\sim R^2(\text{hard})$
pp elastic S–matrix	t–dep.	$\sim R^2(\text{soft})$

- Diffractive minimum

$$\left.\begin{array}{rl} \text{“elementary” amp.} & 1 \\ \text{“absorbed” amp.} & T_{\text{el}} \end{array}\right\} \begin{array}{l} \text{destructive} \\ \text{interference} \end{array}$$

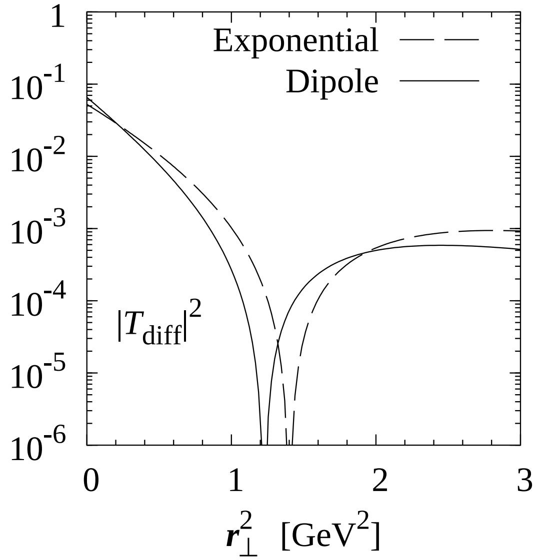
- Coordinate representation: Diffraction of wave packet from “hole” $1 - \Gamma(b)$

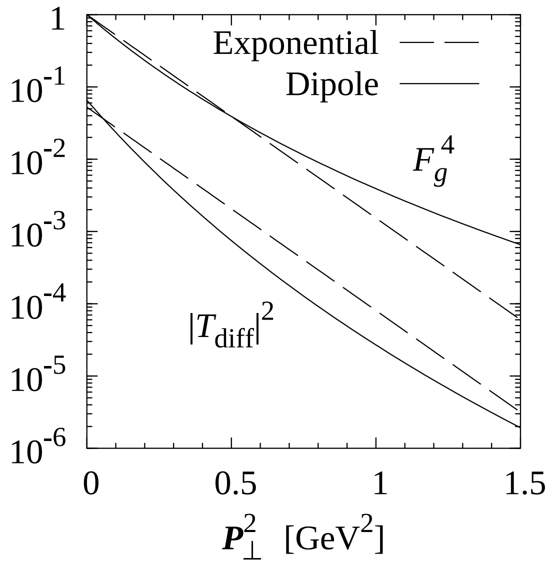
Diffraction: p_T dependence



- Pattern determined by two scales $R^2(\text{hard}) \ll R^2(\text{soft})$
- Entangled dependence on $\boldsymbol{p}_{1\mathrm{T}}$ and $\boldsymbol{p}_{2\mathrm{T}}$

Diffraction: Disentangling p_{T}





- Define CM and relative momentum

$$\begin{aligned} \boldsymbol{P}_{\mathrm{T}} &= (\boldsymbol{p}_{1\mathrm{T}} + \boldsymbol{p}_{2\mathrm{T}})/2 \\ \boldsymbol{r}_{\mathrm{T}} &= \boldsymbol{p}_{1\mathrm{T}} - \boldsymbol{p}_{2\mathrm{T}} \end{aligned}$$

- $\boldsymbol{r}_{\mathrm{T}}$ dependence has diffractive minimum: R^2(soft) and R^2(hard)

- $\boldsymbol{P}_{\mathrm{T}}$ dependence sensitive to t–dependence of gluon GPD: R^2(hard) only

$\boxed{\text{Test reaction mechanism and two–scale picture}}$

Diffraction: Beyond the mean–field approximation

- Mean–field approximation:

$$\left.\begin{array}{l}\text{Parton density } G(x, \boldsymbol{\rho}) \\ \text{Spectator interactions } \Gamma(s, \boldsymbol{b})\end{array}\right\} \quad \begin{array}{l}\text{independent, determined by} \\ \text{“average” configurations}\end{array}$$

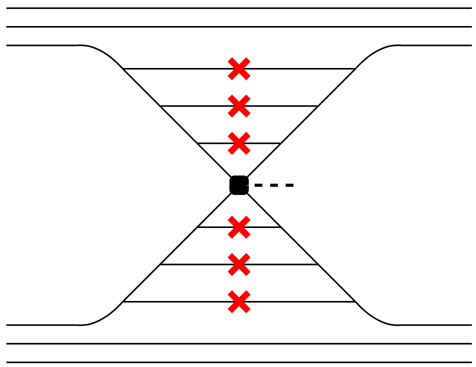
- Several effects lead to correlations between parton density and spectator interactions

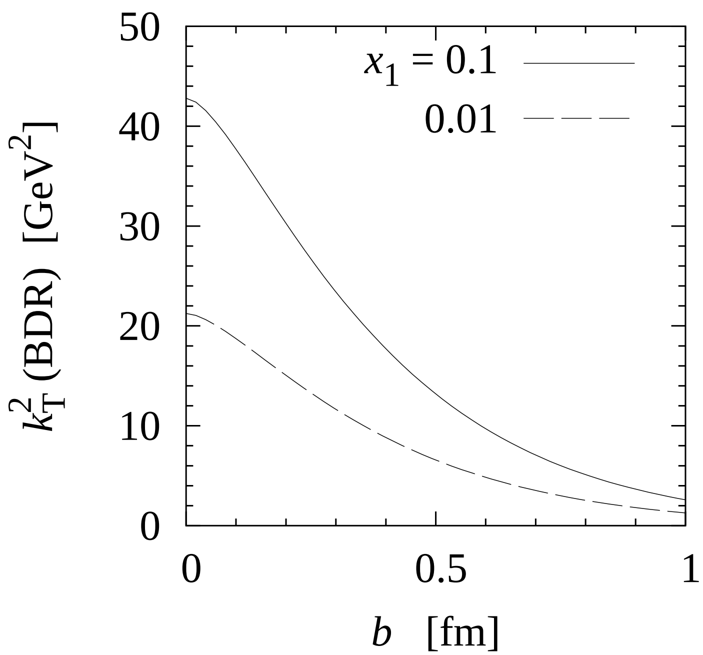
$\rightarrow$ lower RGS probability S^2

$\rightarrow$ steeper $\boldsymbol{p}_{1\mathrm{T}}, \boldsymbol{p}_{2\mathrm{T}}$ dependence

[FHSW, arXiv:0710.2942 arXiv:0708.3106; in progress]

Diffraction: Hard spectator interactions





- Parent partons ($k^2 \sim$ few GeV^2) experience absorptive interactions with small–x gluons in other proton

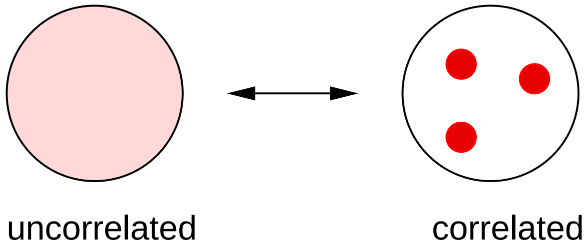
  "Black–Disk Regime"

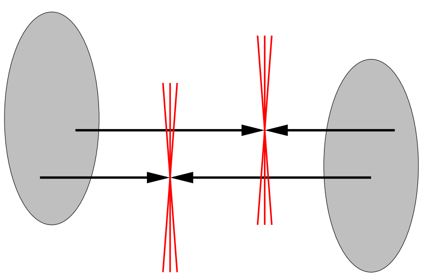
- Use estimate of "critical" k_T^2 from dipole model

- Effect reduces RGS probability at LHC by at least factor 2 . . . much weaker effect at Tevatron

- Larger impact parameters $\rightarrow$ steeper p_{1T}, p_{2T} dependence!

Outlook: Transverse correlations of partons





- GPDs single–particle distributions
  Next step: Two–particle correlations

- Fermilab CDF data on 3 jet + photon compatible with strong transverse correlations of size $\rho \sim 0.3\,\text{fm}$
  [Frankfurt, Strikman, CW 04]

  . . . Constituent quarks?

  cf. Instanton liquid picture of QCD vacuum [Diakonov, Petrov 84]

- Correlations could substantially modify rapidity gap survival in diffraction
  [Frankfurt, Hyde, Strikman, CW 07]

Summary

$\boxed{ep}$

- Future precision measurements of exclusive channels with EIC could substantially improve knowledge of transverse nucleon structure at intermediate and small x

- Transverse structure essential for understanding approach to black–disk regime (unitarity limit, saturation)

$\boxed{pp}$

- pp collisions with hard processes much more central than min.bias; very different final–state properties
$\rightarrow$ Include transverse structure in MC generators!

- Possible to probe t–dependence of GPDs in p_T dependence of central exclusive diffraction

GPDs as unifying concept $ep \leftrightarrow pp$