GPD's for experts

Ch. Weiss (Jefferson Lab), QCD–N '06, June 12–16, 2006

3D quark/gluon structure of nucleon

$$f(x_1, x_2, \vec{\rho})$$

longitud. momentum — transverse position

- Vector meson production at HERA ($J/\psi, \phi, \rho$)
  - Space–time evolution
  - Tests of factorization
  - Data on t–dependence

  "Lessons" for JLab at 12 GeV future EIC

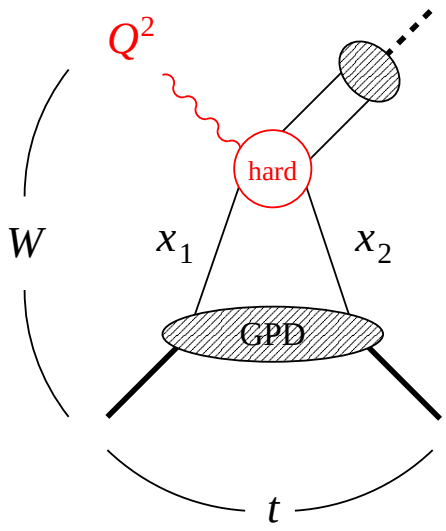
- Non-perturbative dynamics

  Pion cloud at $\rho \sim 1/M_\pi$, . . .

- High–energy pp collisions with hard processes
  - Central collisions
  - Unitarity limit
  - Diffractive Higgs production

  LHC Tevatron

- Hard exclusive processes in ep scattering: Factorization
  [D. Müller et al. 94, Brodsky et al. 94; Collins et al. 96; Radyushkin 96, Ji 96, . . .]

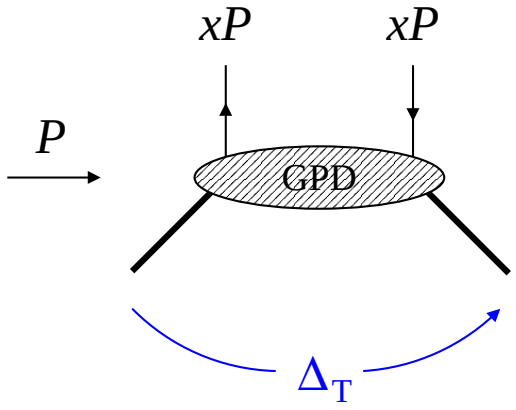


– γ^* reacts with quasi-free parton emitted/absorbed by target

– Generalized parton distribution $f(x_1, x_2, t)$ 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 (gluon distribution)

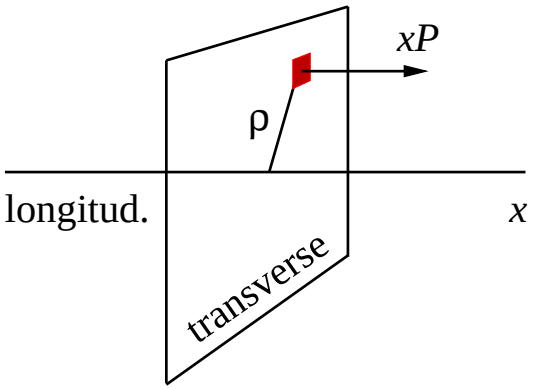
- Transverse spatial distribution of partons ($x_1 = x_2$) [Burkardt 02; Diehl 02]



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

form factor of quarks with longitudinal momentum xP

transverse spatial distribution



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

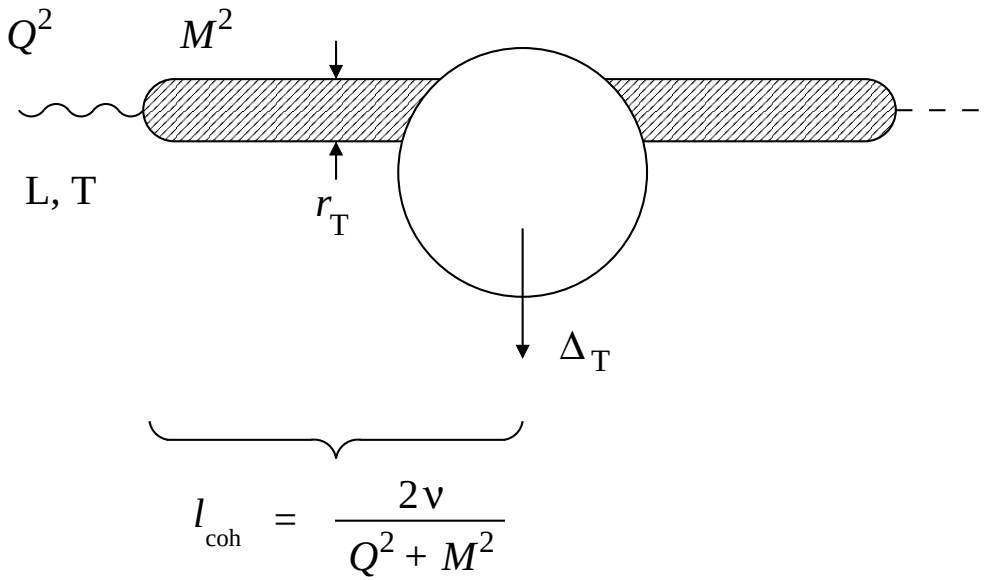
total quark density

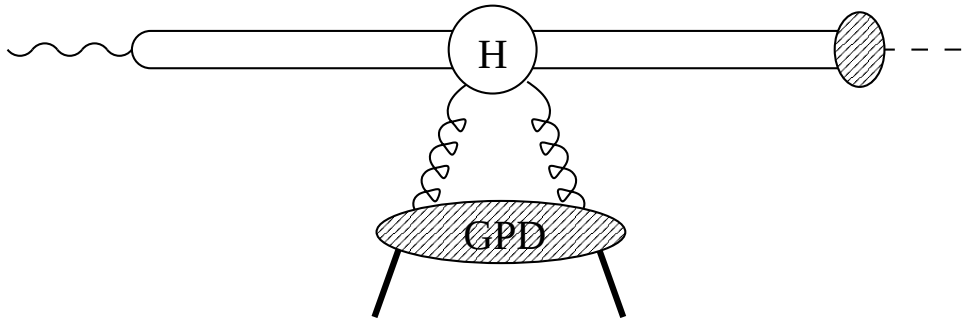
$$\langle \rho^2 \rangle \; = \; 4 \, \frac{\partial}{\partial t} \, \frac{f(x,t)}{f(x,t=0)}$$

transv. size of nucleon, x–dependent!

- Space–time evolution in target rest frame: $W^2 \gg Q^2$

  [Review: Bauer et al. 78; Brodsky et al. 94]





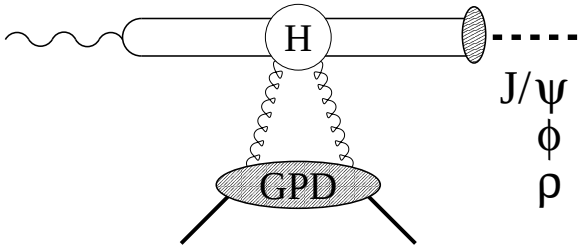
– "Mix" of configurations:
  r_T transv. size
  M^2 inv. mass

– Bjorken limit dominated by small–size configurations $r_T \sim 1/Q$ ("dipoles")

  Amp $\sim$ $r_T^2\, G(x_1, x_2; t)$

– Δ_T dependence probes transverse size of interacting system!

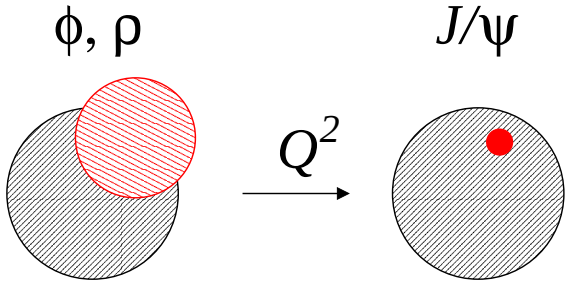
- Vector meson production at HERA: Tests of factorization

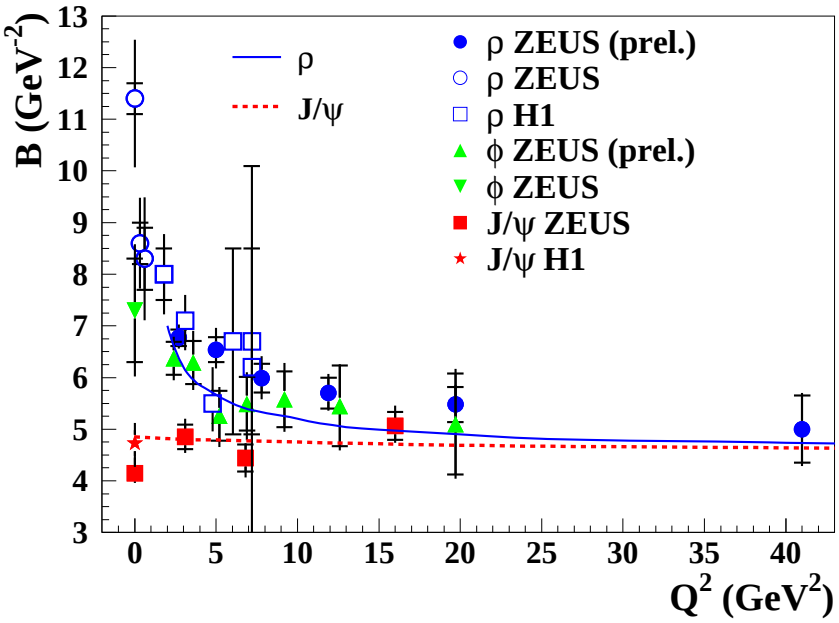


– J/ψ and ϕ, ρ (small x) probe gluon GPD

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

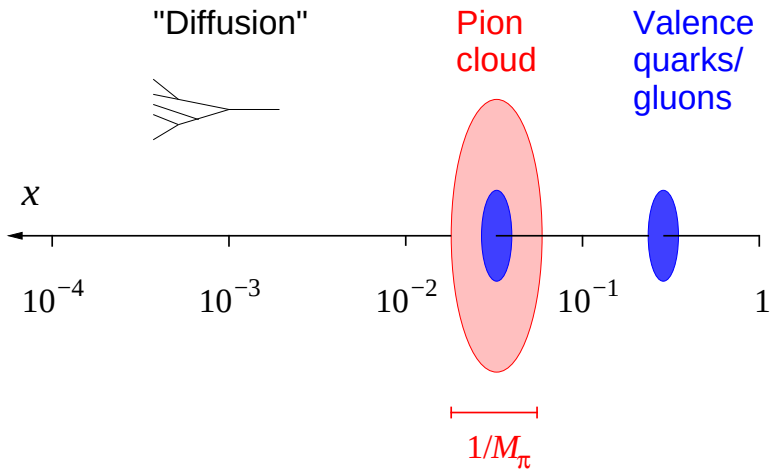
$$\frac{d\sigma}{dt} \propto \left[\frac{G(x_1, x_2, t)}{G(x_1, x_2, 0)}\right]^2$$

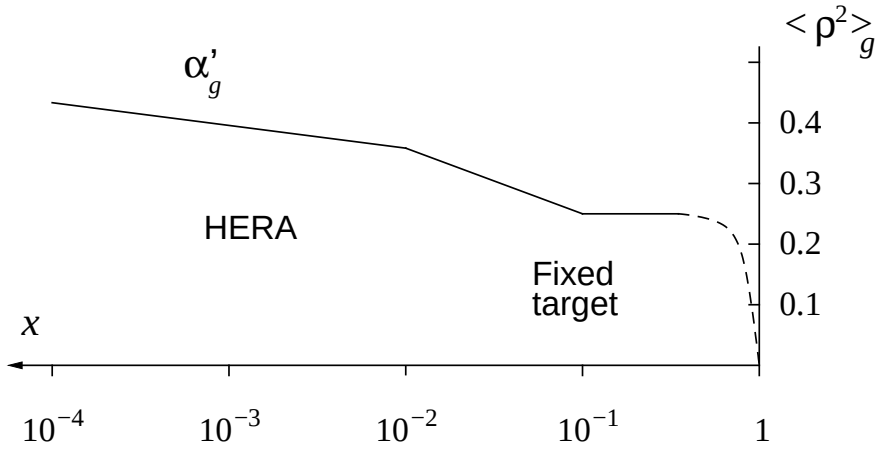




[A. Levy 05; Frankfurt, Strikman, CW 05]

- Transverse gluonic size of nucleon: x–dependence

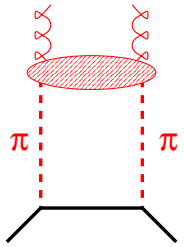




(Scale $Q^2 \approx 3\,\text{GeV}^2$)

– Gluonic transverse size increases with decreasing x

– Pion cloud contributes at $x < M_\pi/M_N$ [Strikman, CW 03]

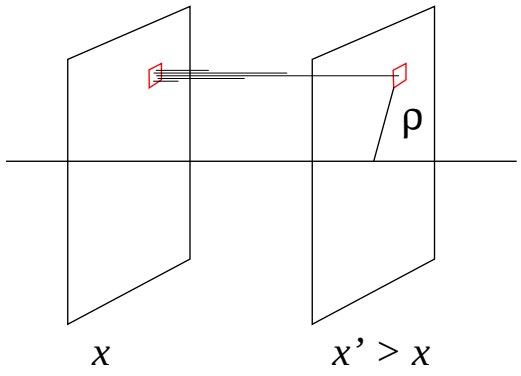


$G(x,\rho) \sim e^{-2M_\pi\rho}$

"Yukawa tail"

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

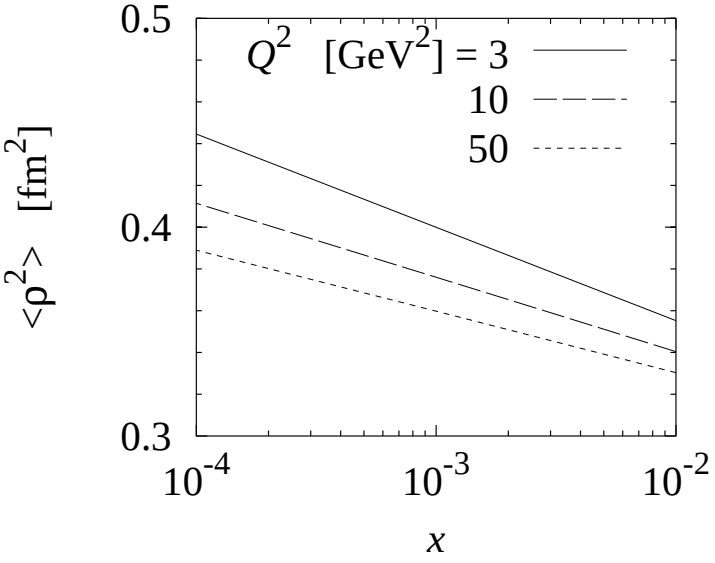
- Effect of DGLAP evolution [Frankfurt, Strikman, CW 03]

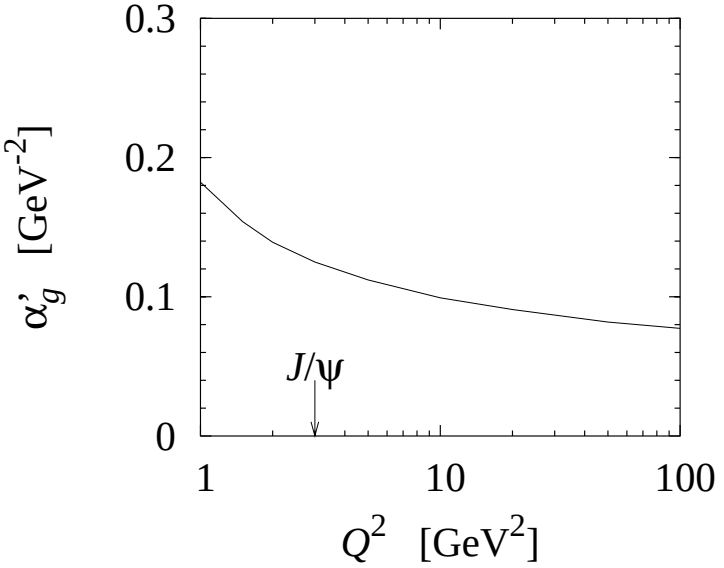


– Partons decay locally in transverse position ($Q^2 \gg 1/R_{\text{nucl}}$)

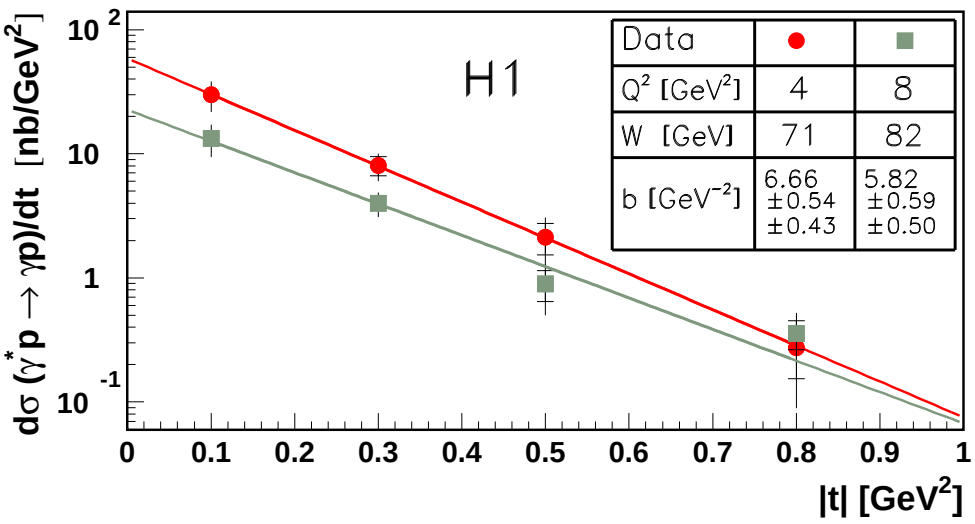
– Transverse size $\langle \rho^2 \rangle$ decreases with increasing Q^2

– Higher Q^2 slows growth of size with $\log(1/x)$: α'_g decreases





- HERA DVCS data



[H1 Collab. (Aktas et al.) 05]

– Comaprison of t–slopes

$$B(\text{DVCS}) \approx B(\rho) > B(J/\psi)$$

. . . suggests non-negligible hadronic–size contributions in DVCS!

– Evolution at small x implies

$$\langle \rho^2 \rangle_q \approx \langle \rho^2 \rangle_g$$

– Careful when using DVCS data to extract $\langle \rho^2 \rangle$

[D. Müller 06]

- Towards probing GPDs at fixed–target energies

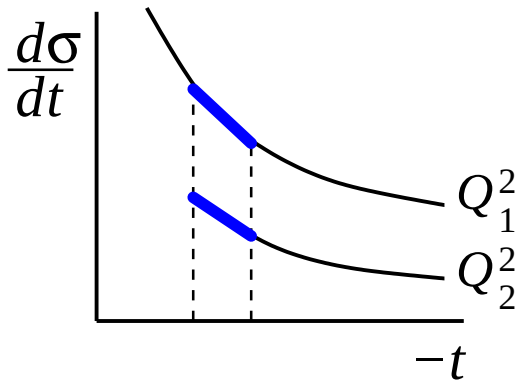
  – Need to understand space–time evolution in target rest frame

  $\Delta_{\parallel} \neq 0, \qquad l_{\text{coh}} \leq R_p$

  $\rightarrow$ Limiting behavior of GPDs ($x_{1,2} \rightarrow 0$)

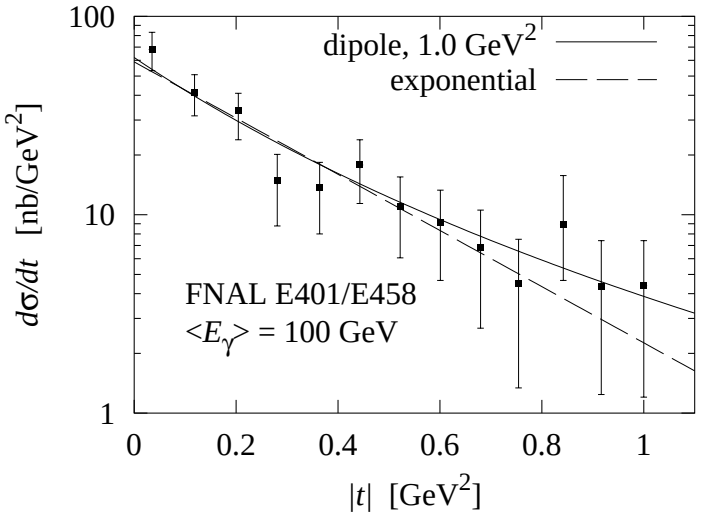
  $\rightarrow$ Physical scale of power corrections

  – Measure t–slopes and their change with Q^2 ($t_{\text{min}} \neq 0$)

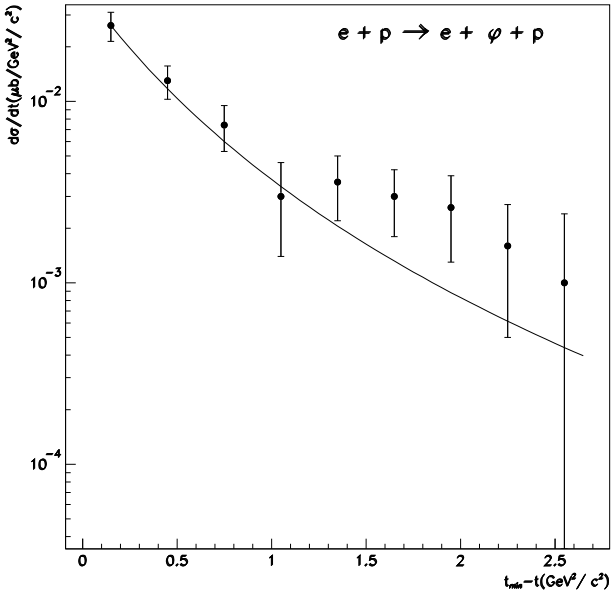


  $\rightarrow$ Transverse size of interacting configurations

  $\rightarrow$ Separate "hard" and "soft" components



[FNAL 458 (81), recoil proton det.]



[CLAS 02 Lukashin et al.]

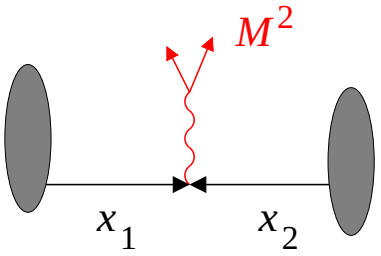
– Start from "simple" channels

$$J/\psi \quad \to \quad \phi \quad \to \quad \rho \quad \to \quad \gamma$$

gluon gluon gluon
quark

– t–dependence of gluon GPD extracted from J/ψ data consistent with CLAS ϕ data

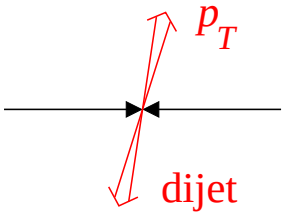
- High–energy pp collisions with hard processes



– Hard scattering process induced by parton–parton collision

$x_1 x_2 = M^2/s$

→ QCD factorization



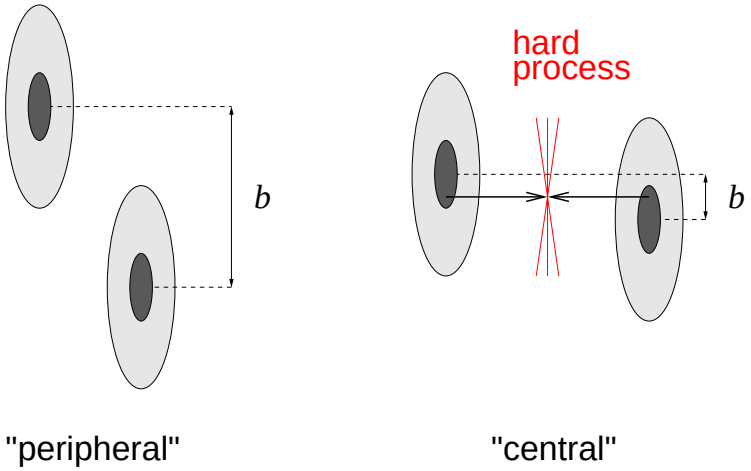
– Partonic initial state depends on soft spectator interactions (↔ hadronic final state)

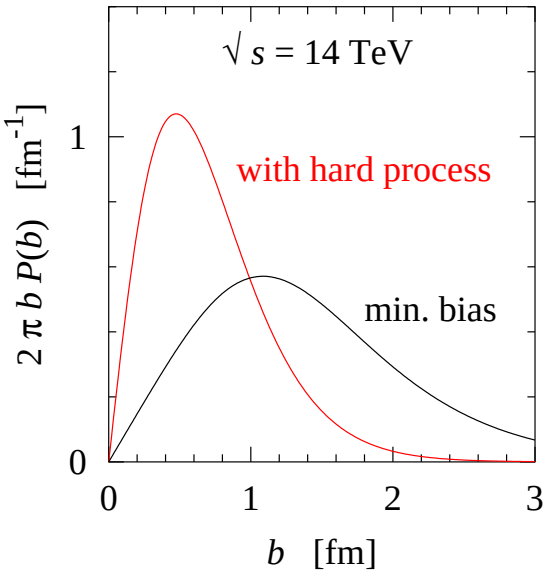
$$pp \rightarrow e^+e^- + X$$
$$\text{dijet} + X$$

– Model parton distribution in terms of transverse spatial distributions known from ep scattering

$\propto g(x_1, \rho_1)\ g(x_2, \rho_2)$

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





– Transverse radius of quarks/gluons with $x > 10^{-2}$ much smaller than radius of soft interactions

$$\langle \rho^2 \rangle_{q,g} \ll R^2_{\text{soft}}$$

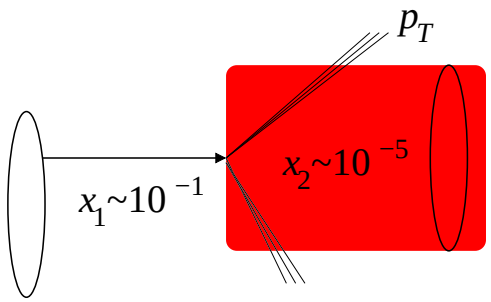
"Two–scale picture"

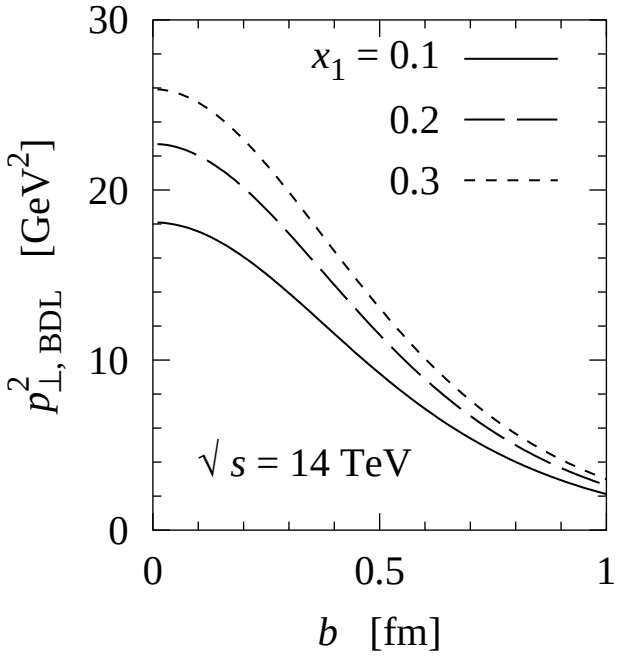
– Classification of pp collision: "Central" vs. "peripheral"

– Events with hard process are central collisions (trigger!)

– Impact parameter distribution calculable from transverse spatial distribution of gluons [← HERA]

- Central collisions: Unitarity limit in spectator interactions [FSW 03/04]



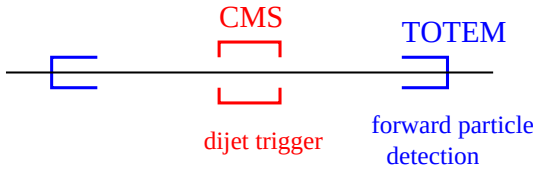


– Increase of gluon density at small x (DGLAP evolution)

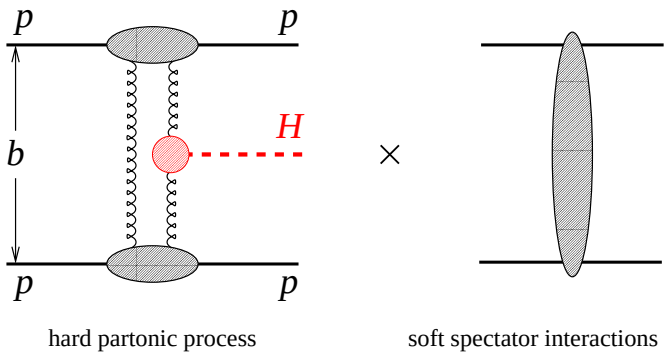
– Interaction of large–x_1 spectator with small–x_2 gluons approaches "black–disk limit": $P_{\mathrm{inel}} \to 1$

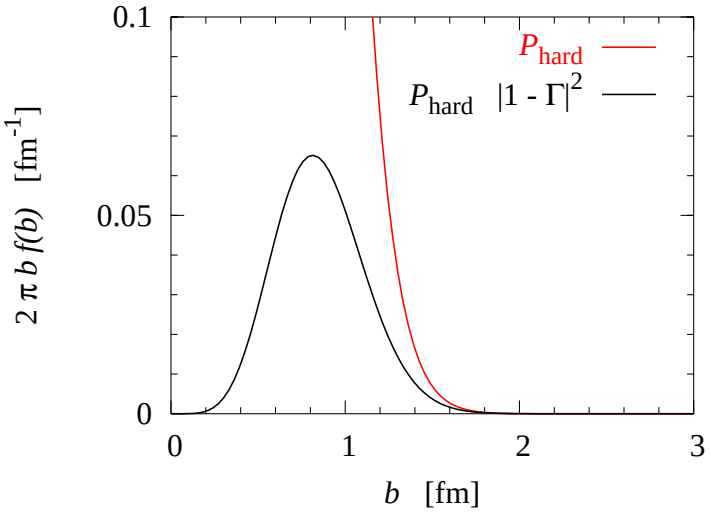
– Qualitative changes in forward particle production: Large $p_\perp$, energy loss, . . .

– Can be studied with LHC detectors



- 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

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

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

. . . calculable, model–independent!

– Observable p_T dependence probes gluon GPD!

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

Summary

- J/ψ data (HERA + fixed–target) provide information on "3D gluon density" in proton

  $\leftrightarrow$ non-perturbative dynamics

- Need to measure t–slopes and their Q^2–dependence!

  $\rightarrow$ Size of interacting configurations — test of factorization

  $\rightarrow$ Transverse structure of nucleon

- Transverse spatial distribution of partons from ep allows one to understand/control transverse geometry of high–energy pp collisions with hard QCD processes

  $\rightarrow$ Next step: Probe GPDs in pp at LHC

"3D really works!"