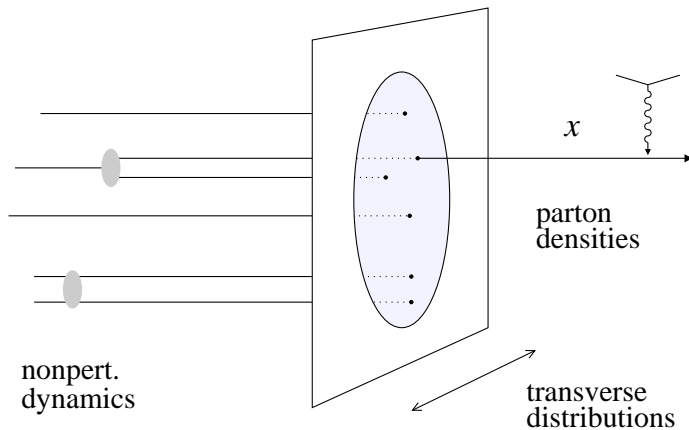


Generalized parton distributions: Low-energy nucleon structure in pp@LHC

C. Weiss (Jefferson Lab), NPPD Conference, Glasgow, 04-Apr-11



- Parton picture of nucleon

Slow vs. fast nucleon in QCD

Physical properties

- Transverse distribution of partons

Charge density

Elastic form factors

low-energy eN

Quark/gluon distributions

Exclusive processes

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

HERMES, COMPASS, JLab 12 GeV
HERA, EIC

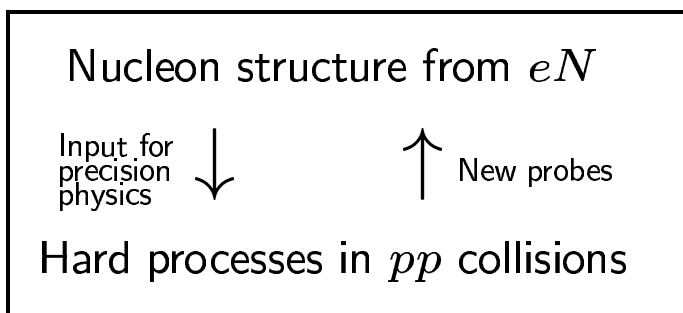
- Transverse structure in pp collisions

Geometry of parton-parton processes

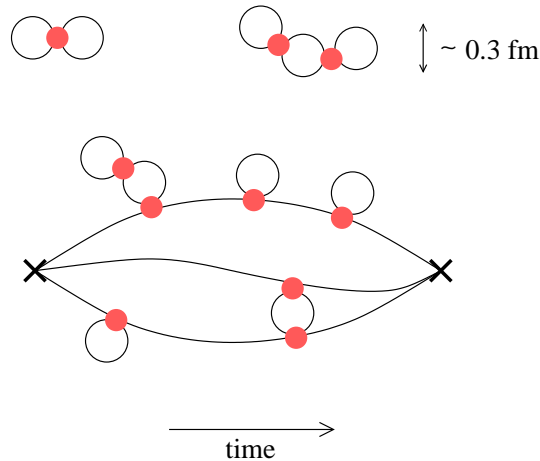
Spectator interactions, underlying event

ATLAS, CMS

Multiparton correlations CDF, D0



Parton picture: Nucleon structure in QCD



- QCD vacuum not empty

Strong gluon fields of size $\mu_{\text{vac}}^{-1} \ll 1 \text{ fm}$

Condensate of $\bar{q}q$ pairs

- Nucleon at rest

$t \rightarrow i\tau$ statistical mechanics Lattice
 $\langle N|O|N \rangle$ from correlation functions

No concept of “particle content!”

- Fast-moving nucleon $P \gg \mu_{\text{vac}}$

Closed system: Wave function description,
 components with different particle number

Feynman, Gribov

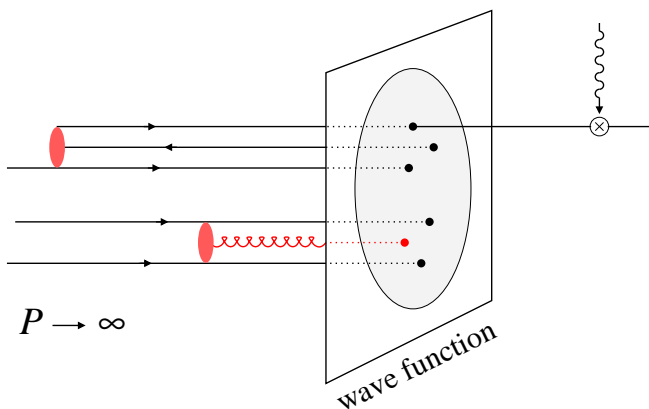
Short-distance probe: “Snapshot”

- Physical properties

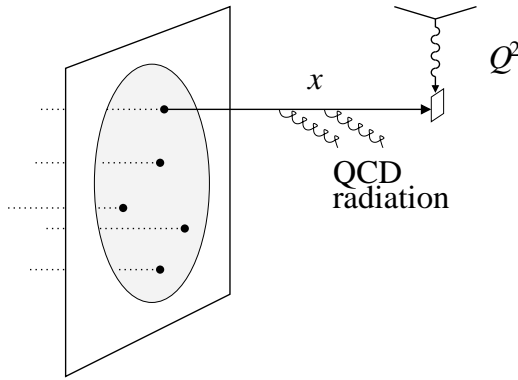
Number densities $f(x)$

Transverse spatial distributions

Correlations



Parton picture: Number densities

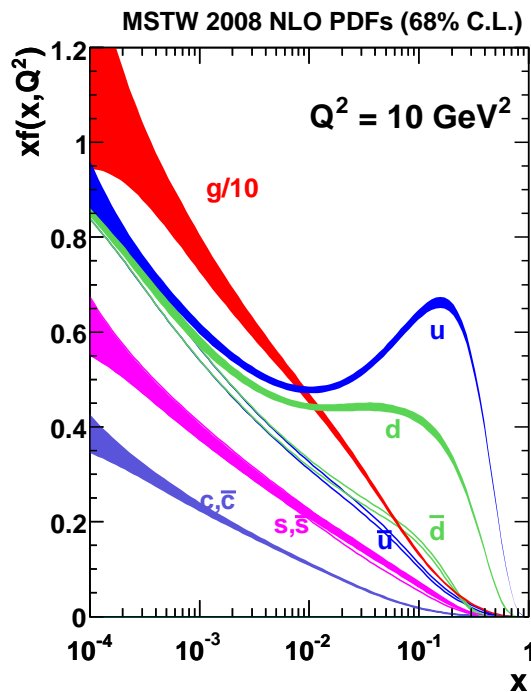


- Deep-inelastic processes $Q^2 \gg 1 \text{ GeV}^2$

$f(x|Q^2)$ longitudinal momentum densities
 Q^2 dependence from QCD radiation

Factorization theorem: Process-independent,
 $\langle N | \text{twist-2} | N \rangle$ QCD operator definition

→ Non-perturbative methods, lattice



- Parton densities from global fits

Much progress, controlled errors

Martin, Stirling, Thorne, Watt 09;

Gluck, Jimenez-Delgado, Reya 08;

CTEQ10, . . .

Open questions: $s \neq \bar{s}$, \bar{u}/\bar{d} , $x \rightarrow 1$

LHC, JLab 12 GeV

Basic particle content of nucleon in QCD

What about transverse distributions?

Transverse structure: Charge density

- Elastic form factors Low-energy eN scattering \rightarrow K. De Jager

$$\text{Local current } \langle N | J_\mu | N \rangle \sim F_{1,2}(t)$$

$$\text{Transverse momentum transfer } |t| = \Delta^2$$

- Transverse charge density Soper 76, Miller 07

$$\rho(b) = \int \frac{d^2\Delta}{(2\pi)^2} e^{-i\Delta b} F_1(-\Delta^2) \quad \text{2D Fourier}$$

Cumulative charge of constituents
at transverse position b

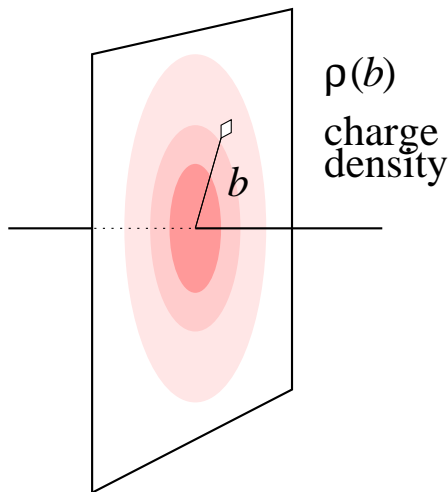
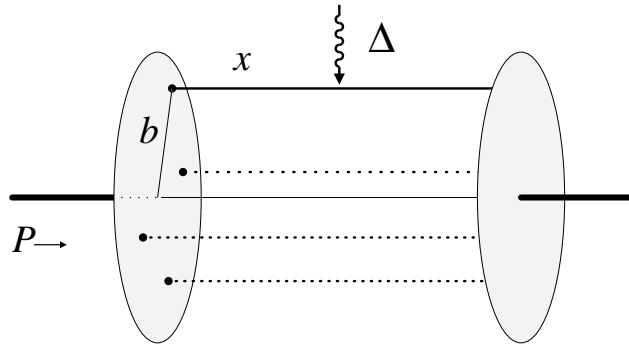
Integrates over x , counts only $q - \bar{q}$

- New insight in nucleon structure

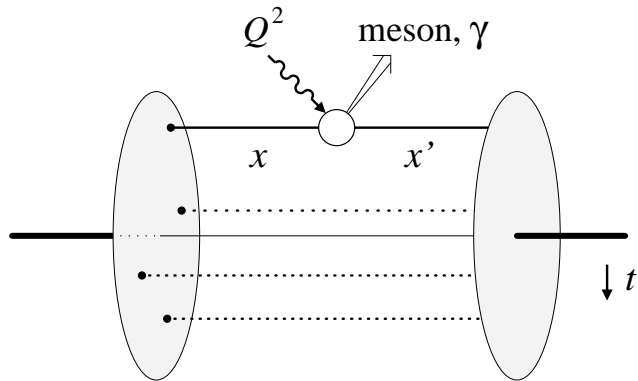
Neutron negative at $b = 0$, d quarks at center

Yukawa tail $e^{-m_\pi b}$ from chiral dynamics,
visible only at $b > 2$ fm Strikman, CW PRC82 (2010) 042201

What about quarks, gluons, x -dependence?



Transverse structure: Quarks and gluons



- Hard exclusive processes $\gamma^* N \rightarrow M + N$

$Q^2 \gg 1 \text{ GeV}^2$ probes single quark/gluon

$|t|$ small leaves nucleon intact

- Generalized parton distribution $F(x, t|Q^2)$

D. Müller et al. 94; Ji 96; Radyushkin 96

Form factor of partons with momentum x
 $x' \neq x$ in exp. kinematics

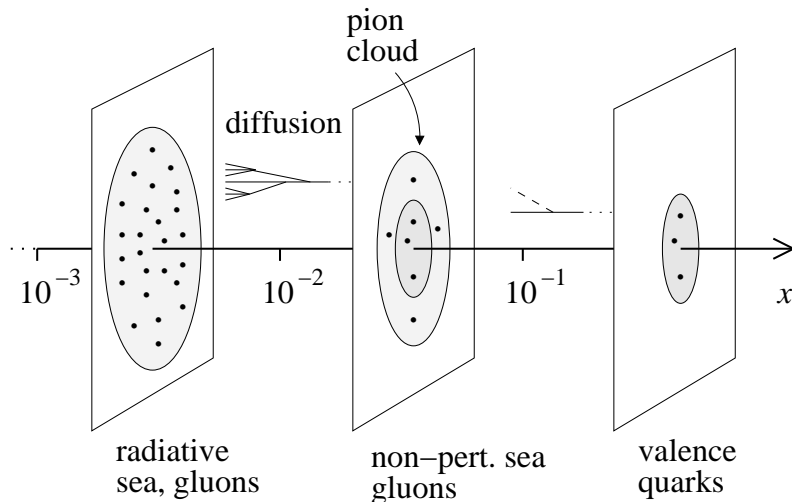
Factorization theorem: Process-independent,
 $\langle N' | \text{twist-2} | N \rangle$ operator definition

- Transverse spatial distribution of partons

$$f(x, b) = \int \frac{d^2 \Delta}{(2\pi)^2} e^{-i\Delta b} F(x, -\Delta^2)$$

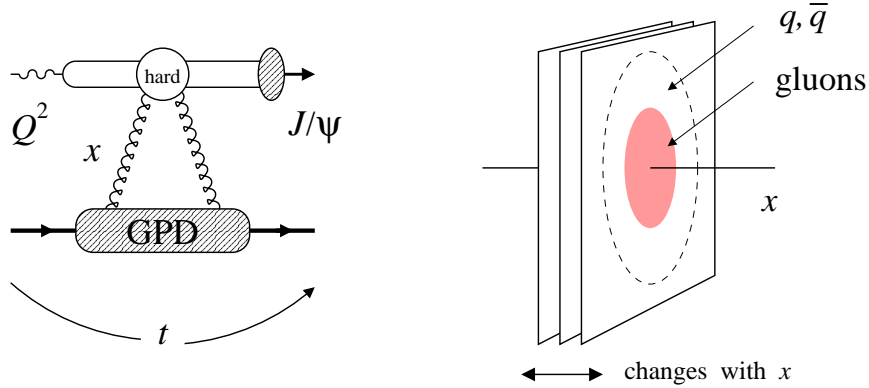
Tomographic image of nucleon at fixed x, Q^2

New window on dynamics! → M. Guidal



3D view of nucleon's partonic structure

Transverse structure: Gluons

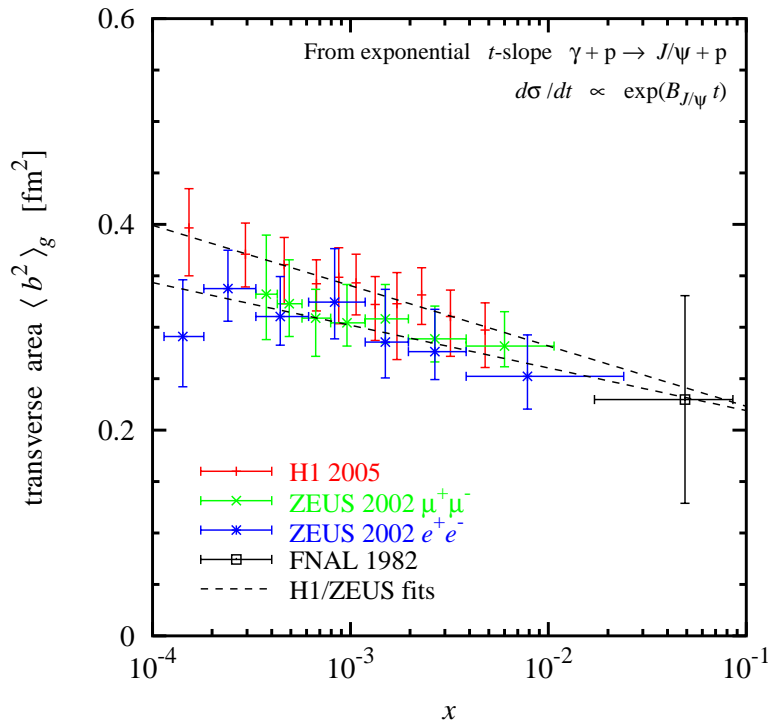


- Exclusive production $\gamma^* N \rightarrow J/\psi + N$
also ϕ, ρ

Clean probe of gluon GPD

Reaction mechanism and universality tested at HERA

Transverse distribution from $d\sigma/dt$



- Transverse gluon image of nucleon

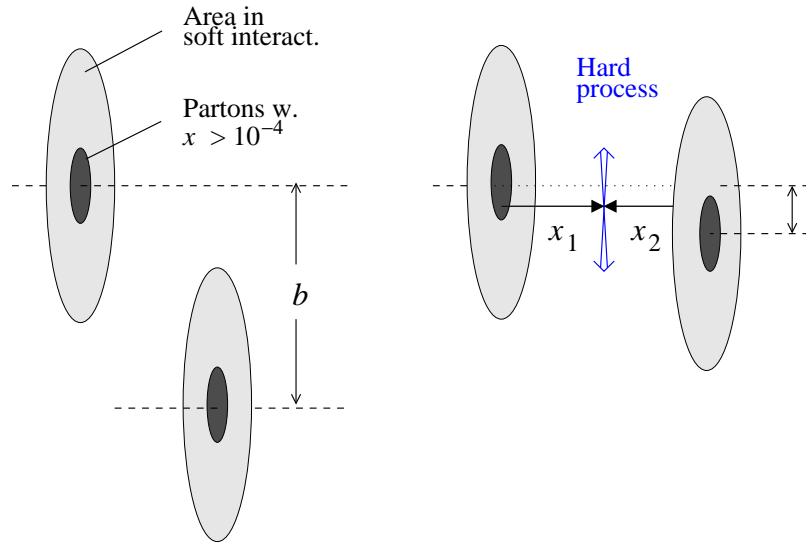
Gluons concentrated at center
 $\langle b^2 \rangle_g(x \sim 10^{-2}) < \langle b^2 \rangle_{\text{charge}}$

Radius grows slowly with decreasing x

$\alpha'_g \ll \alpha'_p = 0.25 \text{ GeV}^{-2}$

Gribov diffusion in wave function

Proton–proton: Transverse geometry



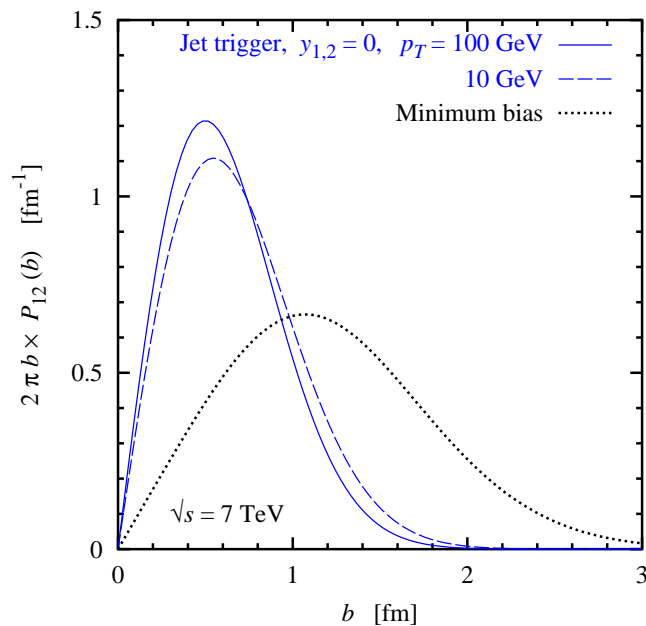
- Two different sizes

$$R^2(\text{soft}) \gg R^2(\text{partons } x > 10^{-4})$$

Hard parton–parton processes require central pp collisions

- Trigger on high- p_T particle selects central pp collisions!

Impact parameter dependence of cross section calculable with transverse distributions from ep
Frankfurt, Strikman, CW 04; PRD83 (2011) 054012



- Proton impact parameter governs spectator interactions

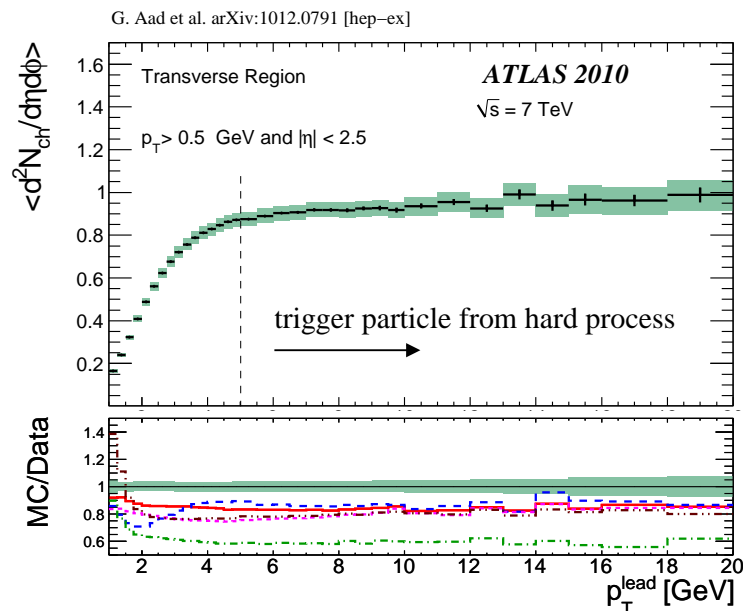
“Underlying event” in hard processes

Geometric correlations:

High- p_T trigger \rightarrow centrality \rightarrow event char’s

Model-independent! Many applications!

Proton–proton: Geometric correlations



- Transverse multiplicity

Min-bias trigger	mostly peripheral	low multiplicity
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High- p_T trigger	central	high multiplicity p_T -independent
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Reveals minimum p_T for hard production

Benchmarks for MC. Also: Rapidity dependence, energy flow, . . .

- Multiple hard processes

Geometric probability calculable from transverse parton distributions

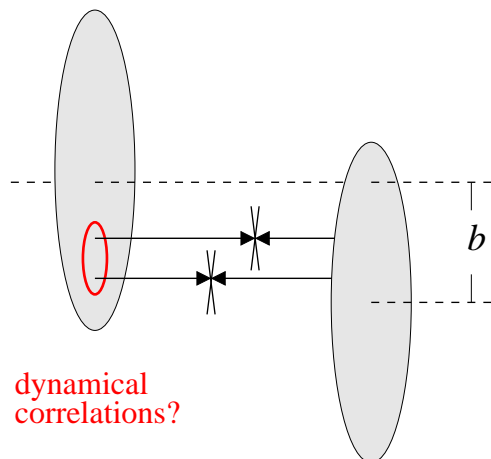
Dynamical correlations?

Tevatron CDF 3 jet + γ show enhancement

High rates expected at LHC:

Background to new particle production

New field of study! MPI@LHC 2010



- Exclusive diffraction $pp \rightarrow p + H + p$

Gap survival probability

Hard process \leftrightarrow soft spectator interactions

Summary

- Transverse spatial distribution of partons key concept in nucleon structure

3D view of nucleon in QCD

New insights into non-perturbative dynamics

- Input to analysis of high-energy pp collisions with hard processes

Transverse geometry explains many features of underlying event New data coming!

Model-independent approach sets benchmarks for detailed MC studies

Multiparton processes can probe dynamical correlations

- Future $eN/\mu N$ programs exploring transverse nucleon structure

JLab 12 GeV

High- t form factors → K. De Jager

GPDs in valence region → M. Guidal

COMPASS

GPDs through Compton, J/ψ

Electron-Ion Collider

Sea quark and gluon imaging