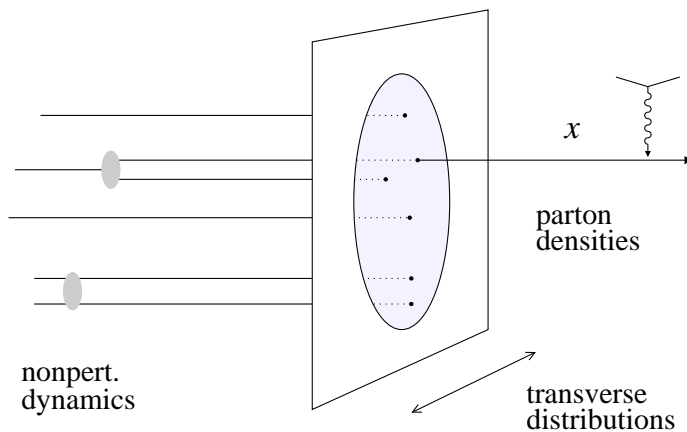# Transverse nucleon structure and final states in pp collisions at LHC

C. Weiss (Jefferson Lab), DIS2011 "QCD and hadronic final states," 12–Apr–11

nonpert. dynamics

x

parton densities

transverse distributions

Nucleon structure from eN

Input for precision physics ↓   ↑ New probes

Hard processes in pp collisions

- Transverse distribution of partons

  Hard exclusive processes in ep, generalized parton distributions

  Gluons from J/ψ HERA, EIC

- Parton–parton processes in pp

  Impact parameter dependence of cross section
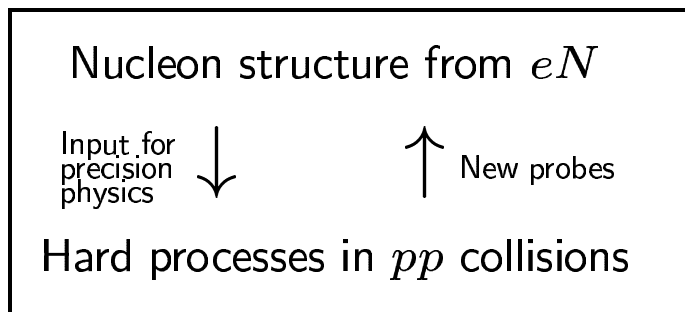
  Central vs. peripheral collisions

- Implications for final states

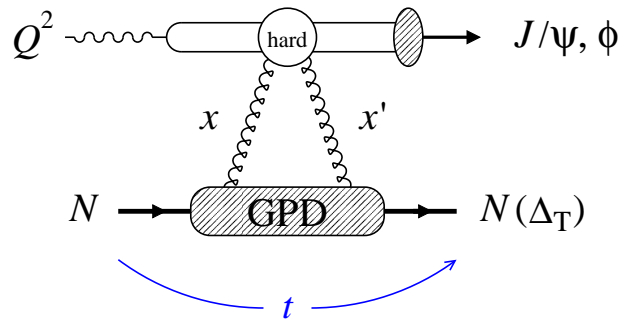 Underlying event: Transverse multiplicity, forward energy flow   ATLAS, CMS 2011

  Multiparton processes: Dynamical correlations?   CDF, D0, LHC

  Rapidity gap survival in exclusive diffraction $pp \to p + H + p$

Transverse distributions: Exclusive processes

- Hard exclusive processes $\gamma^* N \to M + N$
  $Q^2, M^2 \gg$ hadronic scale, $|t|$ small

  QCD factorization theorem
  Collins, Frankfurt, Strikman 96

  GPDs: Gluonic form factor of nucleon
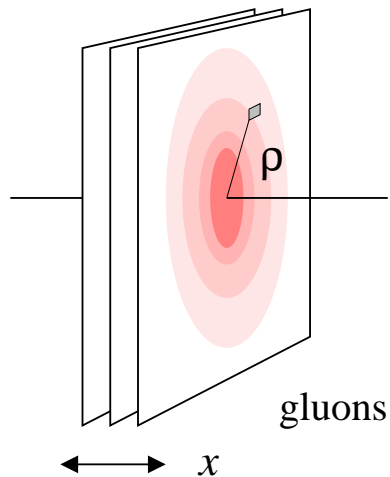 universal, process–independent
  Müller et al. 94, Ji 96, Radyushkin 96

  Operator definition $\langle N' | \, \text{twist-2} \, | N \rangle$,
  renormalization, non-pert. methods

- Transverse spatial distribution of gluons $\quad x' = x$

$$G(x, \rho) = \int \frac{d^2 \Delta_T}{(2\pi)^2} \, e^{-i\boldsymbol{\rho}\boldsymbol{\Delta}_T} \, \text{GPD}(x, t = -\boldsymbol{\Delta}_T^2)$$
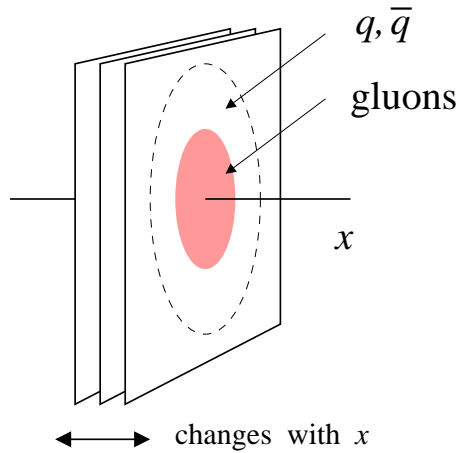
  Tomographic image of nucleon at fixed x,
  changes with x and Q^2

- Large x: Quark GPDs, polarization,
  longitudinal momentum transfer $x' \neq x$
  JLab12: DVCS, meson production
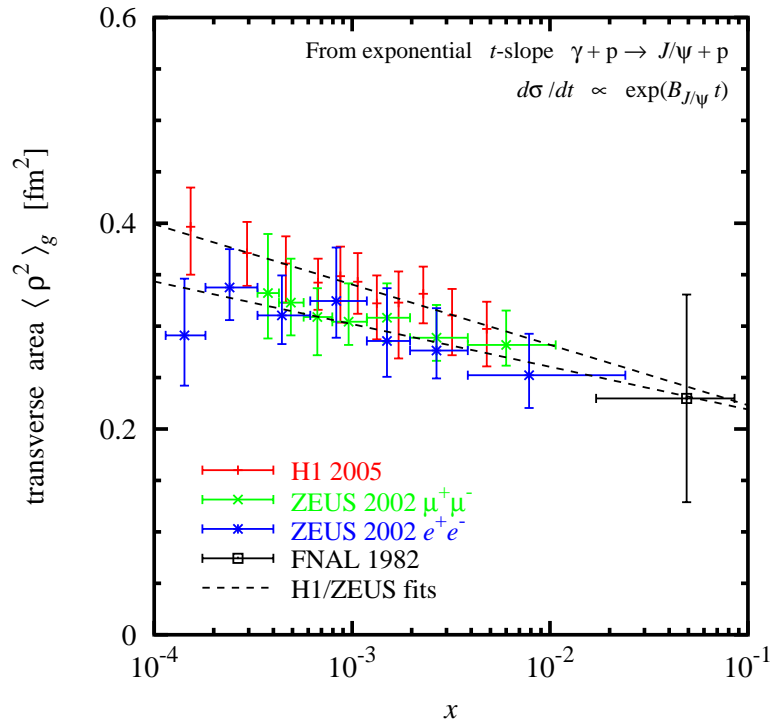
Transverse distributions: Gluons from J/ψ

$q, \bar{q}$

gluons

x

changes with x

- Exclusive process $\gamma^* N \to J/\psi + N$

  also ϕ, ρ

  Gluon GPD at $x \sim m_\psi^2/W^2$, $\quad Q^2 \sim 3\,\mathrm{GeV}^2$

  Reaction mechanism, universality tested at HERA   H1, ZEUS

  Transverse profile from relative t–dependence

From exponential t-slope $\gamma + p \to J/\psi + p$

$d\sigma/dt \propto \exp(B_{J/\psi}\, t)$

transverse area $\langle \rho^2 \rangle_g$ [fm^2]

H1 2005
ZEUS 2002 $\mu^+\mu^-$
ZEUS 2002 e^+e^-
FNAL 1982
H1/ZEUS fits

x

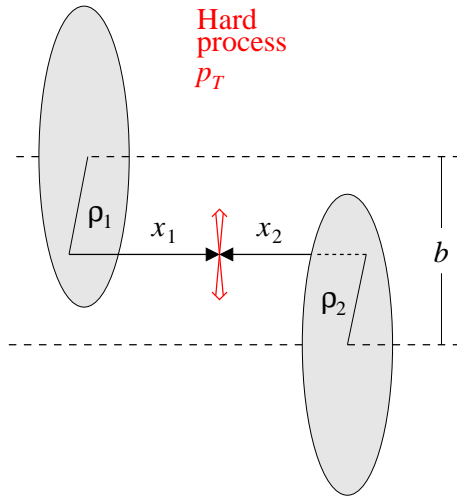- Transverse gluonic size of nucleon

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

  Radius grows slowly with decreasing x
  $\alpha'_g \ll \alpha'_P = 0.25\,\mathrm{GeV}^{-2}$
  Gribov diffusion suppressed by hard scale

  Q^2 dependence from DGLAP evolution calculable, weak   FSW, PRD69 (2004) 114010
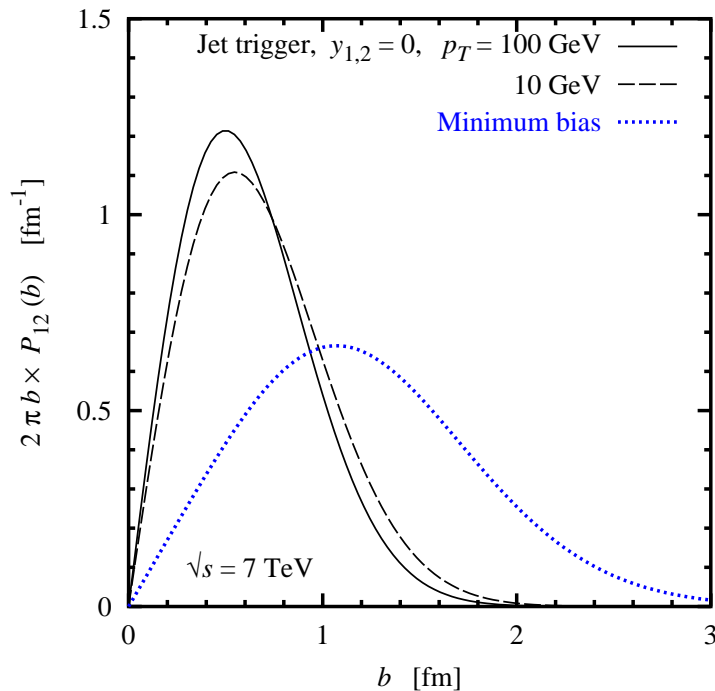
Proton–proton: Impact parameter dependence

Hard
process
p_T

ρ_1 x_1 x_2

ρ_2

b

- Hard process from parton–parton collision

  Local in transverse space $p_T^2 \gg$ (transv. size)$^{-2}$

- Cross section as function of pp impact parameter b

$$
\sigma_{12}(b) = \int d^2\rho_1 \, d^2\rho_2 \, \delta(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2)
$$
$$
\times \, G(x_1, \rho_1) \, G(x_2, \rho_2) \, \sigma_{\mathrm{parton}}
$$
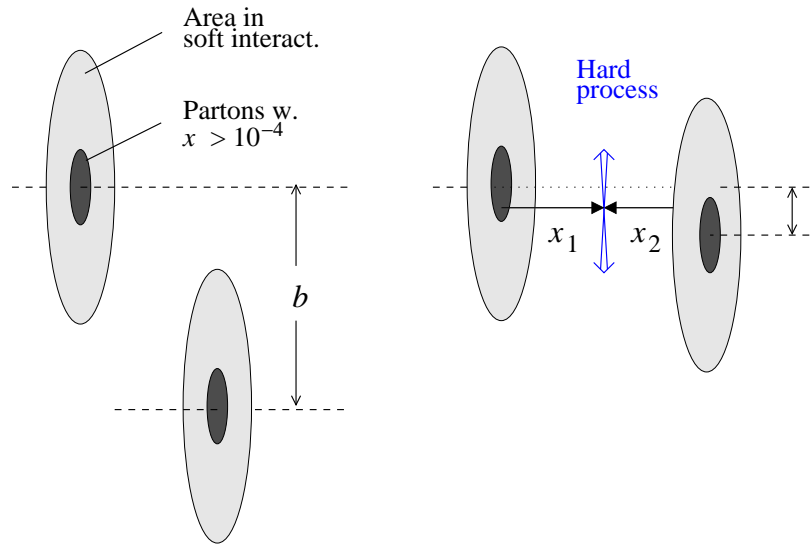
Calculable from known transverse distributions
Integral $\int d^2 b$ reproduces inclusive formula

Normalized distribn $P_{12}(b) = \sigma_{12}(b)/[\int \sigma_{12}]$
FSW, PRD83 (2011) 054012

- New information!

  Spectator interactions and underlying event

  Multiple hard processes

  Gap survival in diffraction

Jet trigger, $y_{1,2} = 0$, $p_T = 100$ GeV ———
10 GeV – – –
Minimum bias ········

$\sqrt{s} = 7$ TeV

$2\pi\, b \times P_{12}(b)$ [fm^{-1}]

b [fm]

Final states: Underlying event

Area in
soft interact.

Partons w.
$x > 10^{-4}$

Hard
process

x_1 x_2

b

- 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 jet
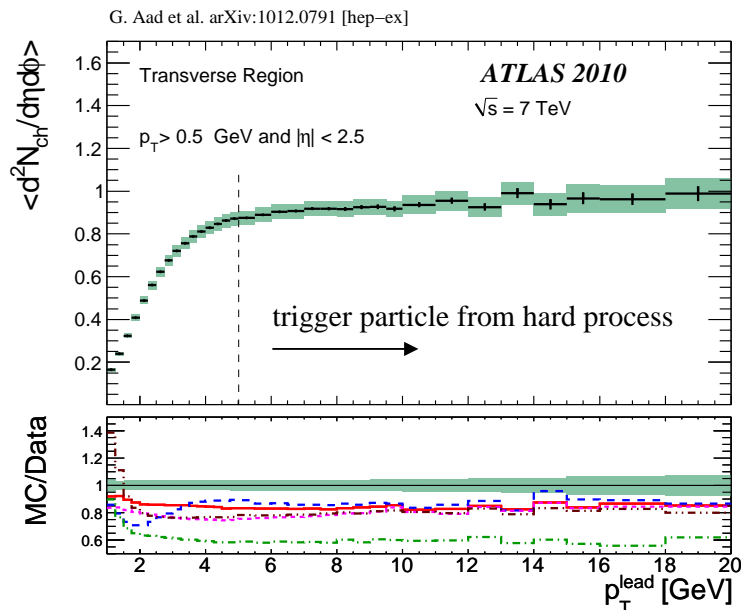selects central pp collisions!

- Geometric correlations

High–p_T trigger $\to$ central collisions
$\to$ event characteristics

Example: Transverse multiplicity
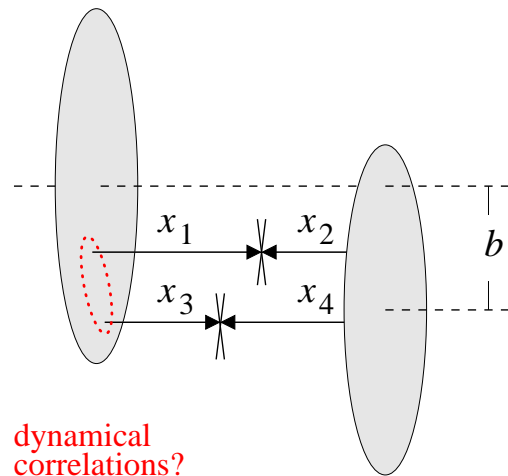Also: Rapidity dependence, energy flow, . . .

Reveals minimum p_T where hard production
mechanism dominates   FSW, PRD83 (2011) 054012

Model–independent! Benchmarks for
detailed MC simulations

G. Aad et al. arXiv:1012.0791 [hep–ex]

$\langle d^2 N_{ch}/d\eta d\phi \rangle$

Transverse Region

ATLAS 2010
$\sqrt{s}$ = 7 TeV

p_T > 0.5 GeV and $|\eta|$ < 2.5

trigger particle from hard process

MC/Data

p_T^{lead} [GeV]

CMS: Similar results

Final states: Multiparton processes

dynamical
correlations?

$$\frac{\sigma(12;34)}{\sigma(12)\sigma(34)} = \frac{1}{\sigma_{\text{eff}}}$$

$$\times \frac{f(x_1, x_3)f(x_2, x_4)}{f(x_1)f(x_2)f(x_3)f(x_4)}$$

- Double collision rate parametrized by $1/\sigma_{\text{eff}}$

  Mean field $\sigma_{\text{eff}} = \pi R_{13}^2$ avg distance btw collision points.
  Calculable from transverse distributions

  $$\sigma_{\text{eff}}^{-1} \text{ (mean field)} = \int d^2 b \, P_{12}(b) \, P_{34}(b)$$

  Enhancement compared to mean field expectation
  indicates dynamical correlations

- Data suggest substantial correlations

  CDF 3 jet $+ \gamma$ rate two times larger than
  mean field with $\langle \rho^2 \rangle (x \sim 0.1)$

  Possible explanation: Short–distance scale in
  QCD vacuum from chiral symmetry breaking
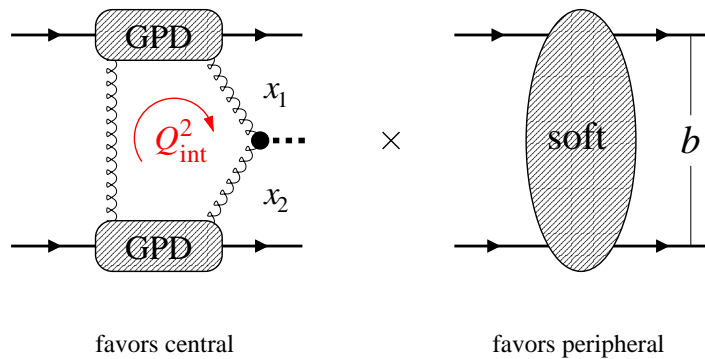 FSW, Annalen Phys. 13 (2004)

- LHC: High rates for multijet events

  Background to new physics processes

  Detailed studies of parton correlations
  New field of study. Great interest! MPI@LHC 2010 Glasgow

Final states: Gap survival in diffraction

favors central   favors peripheral

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

- **Central exclusive diffraction**

  Heavy system produced in hard two–gluon exchange

  Concurrent soft spectator interactions must not produce particles
 Khoze, Martin, Ryskin 97+

- **Survival probability S^2**

  Mean–field S^2 calculable from transverse gluon distn and pp elastic amplitude
  Model–independent, pure transverse geometry
  FHSW PRD75 (2007) 054009

  Basic suppression by factor $\sim 30 - 40$ from elimination of scattering at small b $\sqrt{s} = 14$ TeV

  Additional suppression by factor $> 2 - 3$ from dynamical correlations, black–disk regime
  Effect specific to LHC, marginal at Tevatron.
  Requires detailed modeling
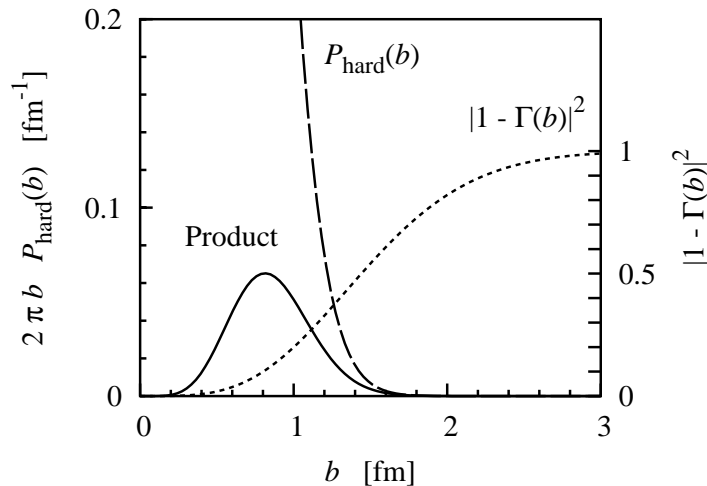
- **Diffraction pattern in p_{T1}, p_{T2}**
  Experimental tests: CMS/TOTEM or LHC420
  STAR pp2pp @ $\sqrt{s} = 500$ GeV

Summary

- Transverse spatial distribution of partons essential input in analysis of pp collisions with hard processes

    Fundamental twist–2 characteristic, GPD

    Measurable in hard exclusive processes in $ep/\gamma p$ Future data: COMPASS, JLab 12, EIC/LHeC

    Impact parameter dependence of cross section for parton–parton processes in pp calculable from independently measured input

- Hard processes require/select central pp collisions

    Geometric correlations: High–p_T trigger $\rightarrow$ central collisions $\rightarrow$ event characteristics
    Seen in CMS/ATLAS underlying event data!

    Model–independent predictions, benchmarks for detailed MC simulations

- Multiparton processes in pp

    Transverse geometry essential for identifying dynamical correlations

    High rates expected at LHC, background for new physics processes

    New field of nucleon structure: "Next step" after one–body parton densities