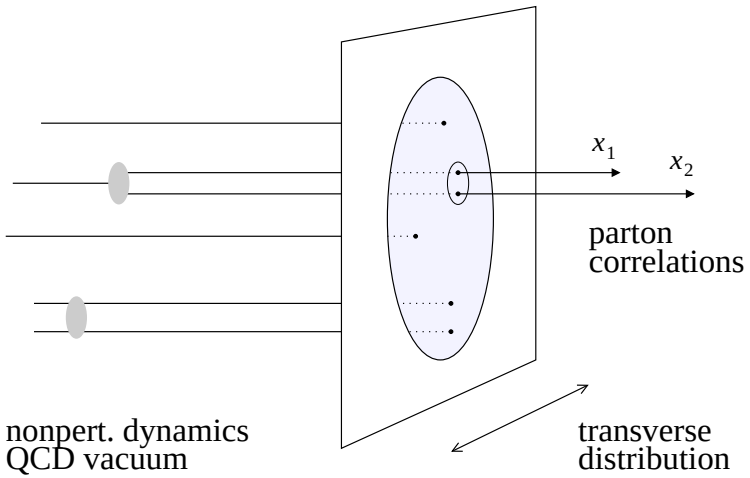
Non-perturbative nucleon structure and multiparton interactions

C. Weiss (JLab), MPI@LHC 2010, Glasgow, 29–Nov–10



- Nucleon structure in QCD

  Non-pert short-distance scale ~ 0.3 fm

  Many–body system: Wave function, densities, correlations

- Transverse distribution of partons

  Exclusive processes in $ep/\gamma p$ and GPDs
  HERA, COMPASS

  Hard processes in pp

  Hard vs. soft interactions

- Multiparton processes CDF, LHC

  Mean-field: Transverse geometry

  Correlations: QCD vacuum structure

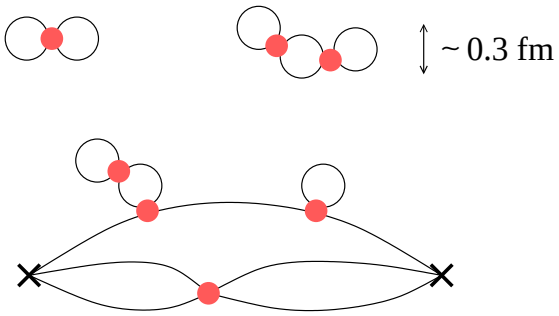
  Connections: Higher twist in DIS, intrinsic k_T, . . .

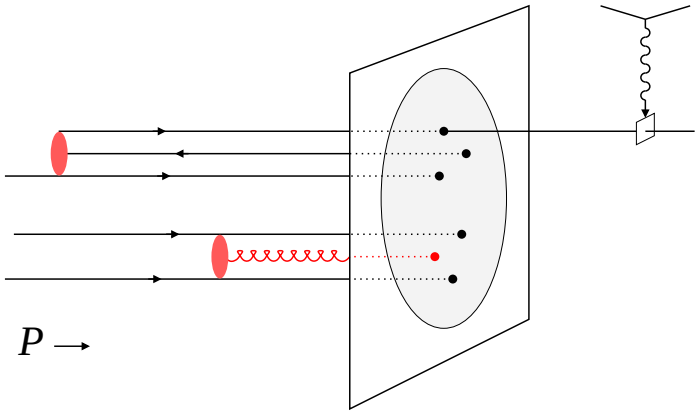
Nucleon structure

Input for precision physics ↓ ↑ New probes complement $ep/\gamma p$

Multiparton processes in pp

Nucleon structure: Parton picture





- QCD vacuum not empty

  Strong non-perturbative gluon fields
  of size $\rho \sim 0.2 - 0.3\,\mathrm{fm}$
  Lattice QCD simulations

  $\bar{q}q$ pair condensate, π as collective excitation

- Slow–moving nucleon $P \sim \rho^{-1}$

  $\langle N|O|N\rangle$ from Euclidean correlation functions
  $\rightarrow$ lattice, analytic methods

  No concept of "particle content!"

- Fast–moving nucleon $P \gg \rho^{-1}$

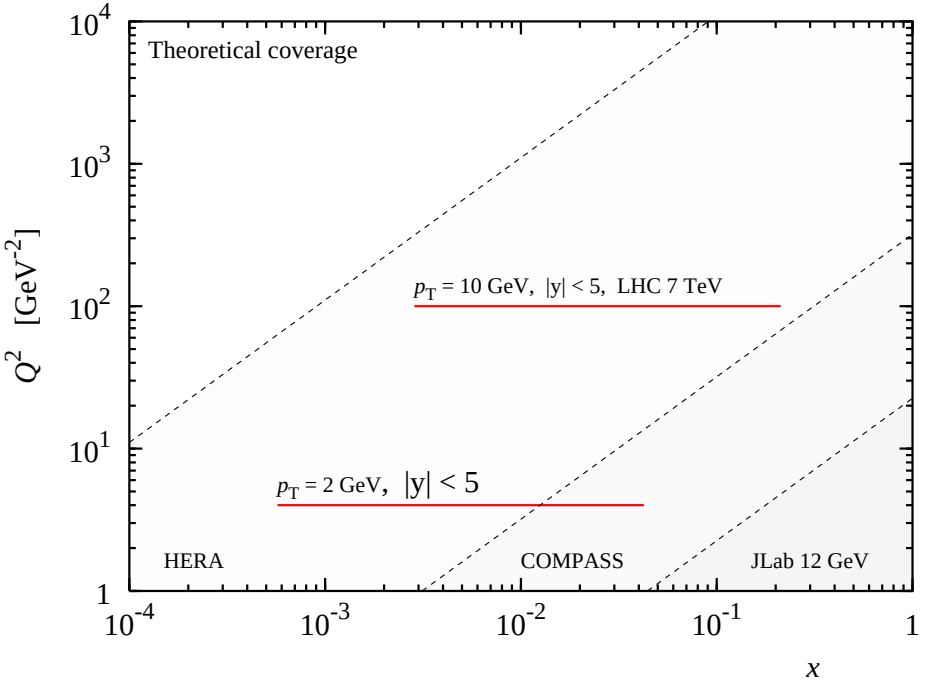
  Closed system: Wave function description
  Gribov, Feynman

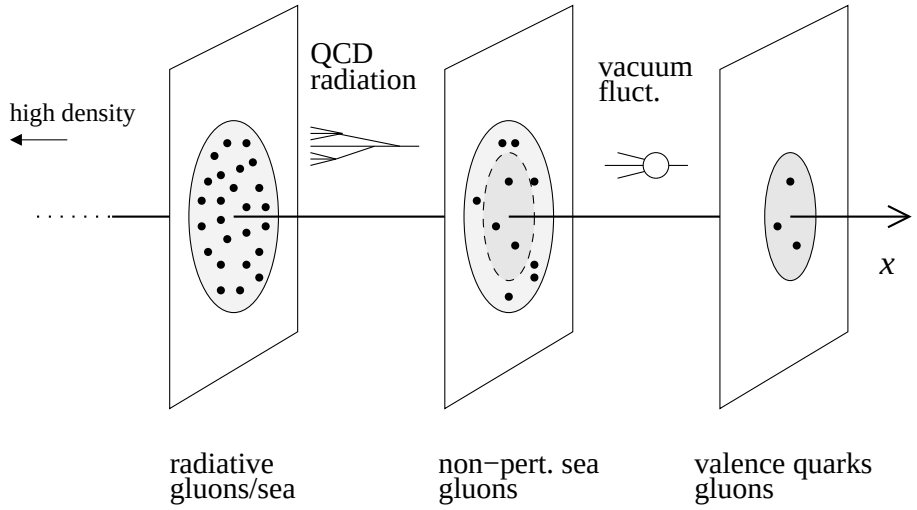
  Components with different particle number

  Hard process: "Snapshot" with
  spatial resolution $1/Q^2$

  pQCD radiation: Scale dependence

Nucleon structure: Many–body system





- Nucleon many–body system

  Different components of wave function, effective dynamics

  "Face" changes with excitation energy and resolution scale!

- Physical properties

  Longitudinal momentum densities
  incl. flavor, spin

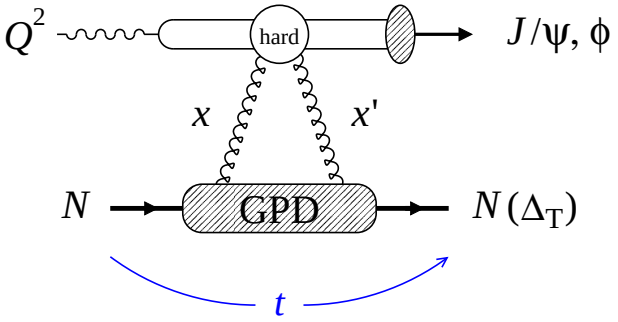
  Transverse spatial distributions ←

  Multiparton correlations: ←
  Transverse, longitudinal

  Orbital motion: Transverse momenta, polarization effects

  Quantum fluctuations: Dispersion

Transverse distribution: Exclusive processes

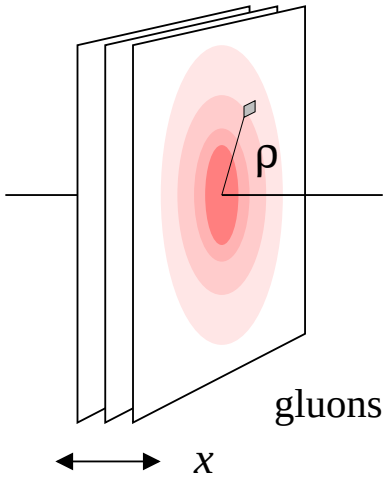


- $Q^2, M^2 \gg$ hadronic scale: Meson produced in small–size configuration

  QCD factorization theorem $Q^2_{\rm eff} \gg |t|$
  Collins, Frankfurt, Strikman 96

  GPDs: Gluonic form factor of nucleon, universal, process–independent Ji 96, Radyushkin 96

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



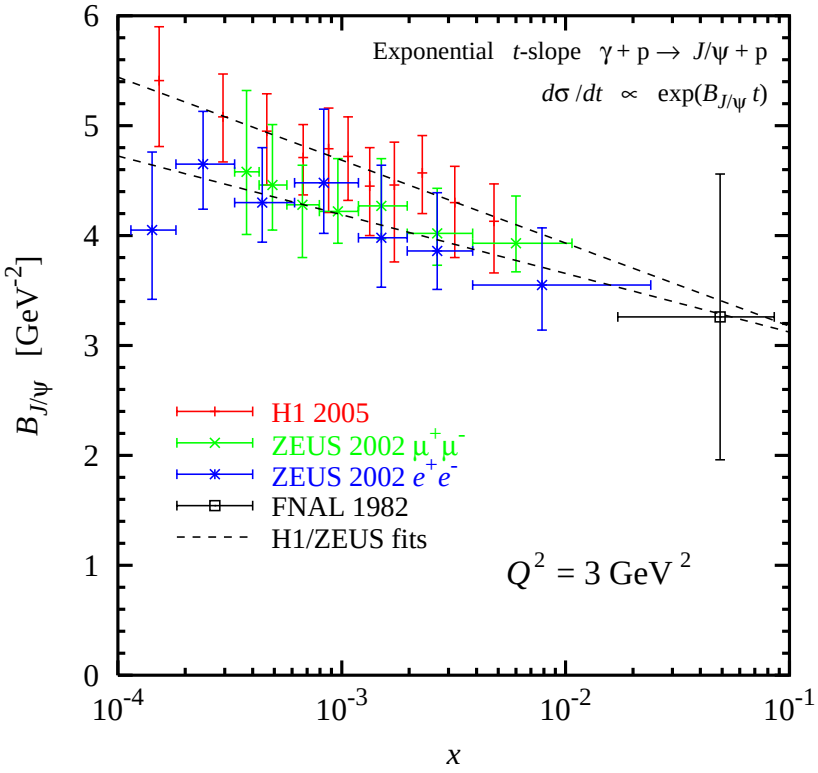
- Transverse spatial distribution of gluons $x' = x$

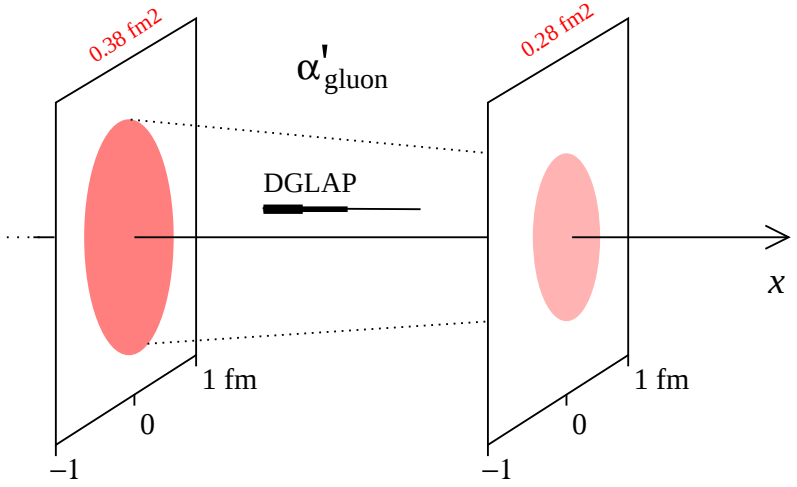
$$G(x,\rho) = \int \frac{d^2\Delta_T}{(2\pi)^2}\, e^{-i\boldsymbol{\rho}\boldsymbol{\Delta}_T}\, \mathrm{GPD}(x,t)$$ 2D Fourier

  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 distribution: Gluons from J/ψ





- Transverse distribution of gluons from exclusive J/ψ (also ϕ, ρ)
  HERA, FNAL

  Transverse profile from relative t–dep.

  Average size from slope
  $\langle \rho^2 \rangle_g = 2B_{J/\psi}$ – finite–size corr.

- Interesting observations

  Average gluonic size $\langle \rho^2 \rangle_g$ much smaller than soft nucleon size $\sim 1\,\mathrm{fm}^2$

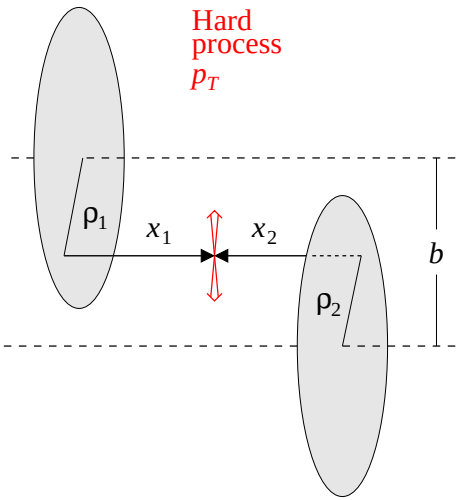
  Grows with effective Regge slope
  $\alpha'_g \approx 0.14\,\mathrm{GeV}^{-2} < \alpha'_{\mathrm{soft}}$
  Parametrization available: Frankfurt, Strikman, CW 10

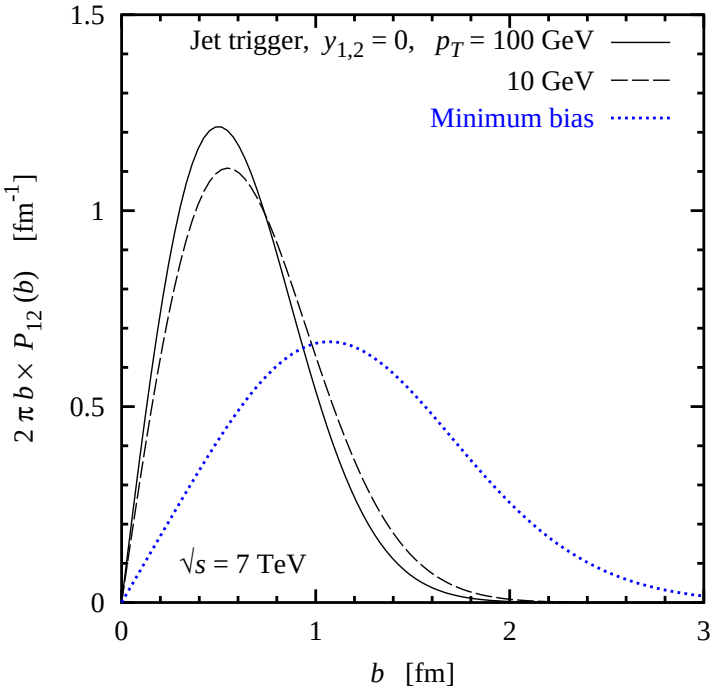
- Q^2 dep. from DGLAP evolution FSW04

  Partons decay locally in transverse space

  Size changes because initial partons at $x_0 > x$ sit at smaller transv. distances
  Small effect

Transverse distribution: Hard processes in pp





- 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

$$\sigma_{12}(b) = \int d^2\rho_1\, d^2\rho_2\, \delta(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) \times G(x_1, \rho_1)\, G(x_2, \rho_2)\, \sigma_{\rm parton}$$

  Calculable from known transverse distributions
  Integral $\int d^2b$ reproduces inclusive formula

  Normalized distribn $P_{12}(b) = \sigma_{12}(b)/[\int \sigma_{12}]$

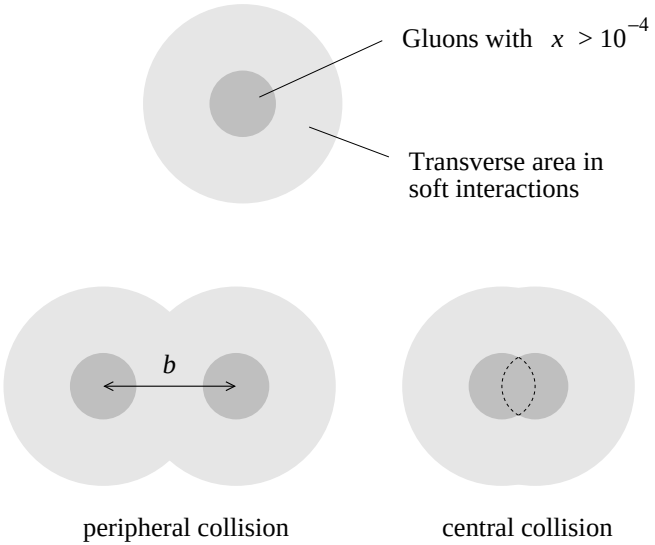
- New information available

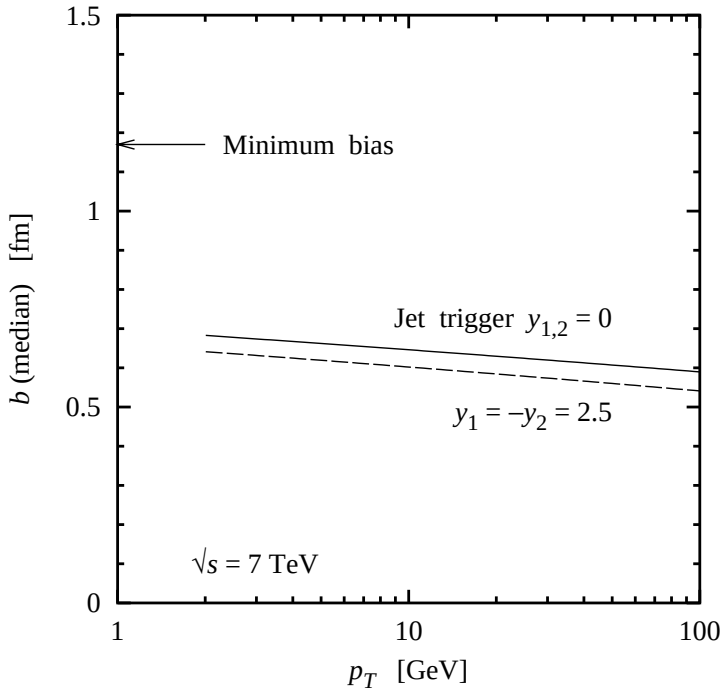
  Model spectator interactions depending on b

  Predict probability of multiple hard processes
  Dynamical correlations? FSW04

  Diffraction: Gap survival probability
  Determined largely by transverse geometry FHSW 07

Transverse distribution: Hard vs. soft interactions





- Transverse size in soft interactions from pp elastic amplitude + unitarity

$$\sigma^{pp}_{\text{soft inel}}(b) \;=\; 1 - |1 - \Gamma(s,b)|$$

$$R^2(\text{soft}) \;\gg\; \langle\rho^2\rangle_g(x > 10^{-4})$$ "Two–scale picture"

- Two classes of pp collisions

  Peripheral: Most of inelastic cross section
  Central: High probability for hard process

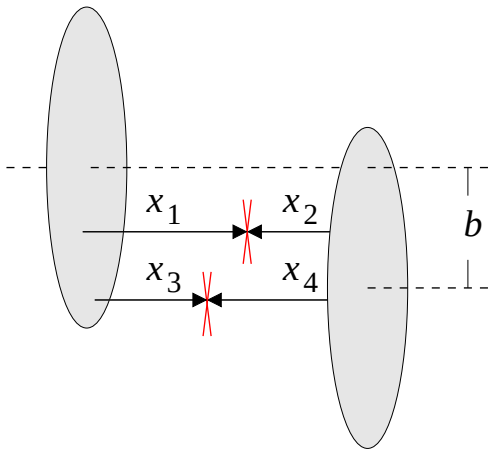
- Hard processes select central collisions

  Event structure very different from min. bias

  Geometric correlations:
  Hard process → centrality → event chars
  E.g. transverse multiplicity → Talk Frankfurt

  New tests of dynamical mechanisms in particle production

Multiparton processes: Transverse geometry



$$\frac{\sigma(12;34)}{\sigma(12)\sigma(34)} = \frac{1}{\sigma_{\rm eff}} \times \frac{f(x_1,x_3)f(x_2,x_4)}{f(x_1)f(x_2)f(x_3)f(x_4)}$$

- Double collision rate parametrized by $1/\sigma_{\rm eff}$
  → Talks Blok, Treleani

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

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

  Numerically stable. Convolution becomes simple product of
  t–dependent gluon form factors measured in exclusive $ep/\gamma p$

  Enhancement compared to mean field expectation
  indicates dynamical correlations

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

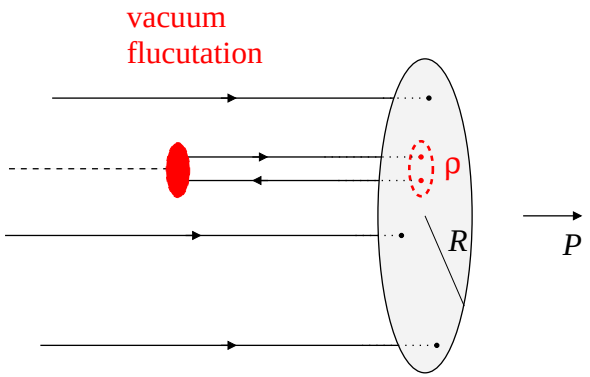
  Substantial correlations! Dynamical explanation?

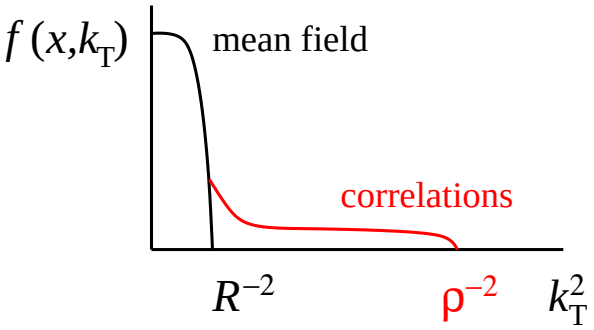
- LHC: High rates for multijet events

  Background to new physics processes

  Detailed studies of parton correlations
  New field of study. Great interest!

Multiparton processes: Dynamical correlations





- QCD vacuum structure implies non-perturbative parton correlations Cf. short–range NN correlations in nuclei

  Dynamical scale $\rho \ll R$ from chiral symm. breaking
  Euclidean → Minkowski?

  CDF data consistent with transverse lumps of size $\rho \sim 0.3\,\mathrm{fm}$ FSW04

- Theoretical challenges

  Primordial vs. DGLAP–induced correlations?

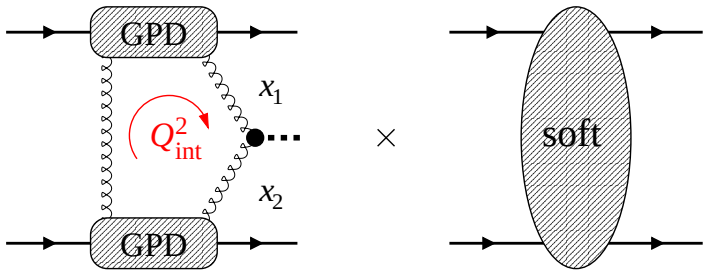
  Operator definition of multiparton distributions?
  Hope to learn more at this meeting!

- Connections with other DIS observables

  Intrinsic $k_T \sim \rho^{-1}$ in semi-inclusive DIS and single–spin asymmetries

  Higher–twist effects in inclusive DIS $\langle k_T^2 \rangle \sim \rho^{-2}$
  Balla, Polyakov, CW 97; Sidorov, CW 05

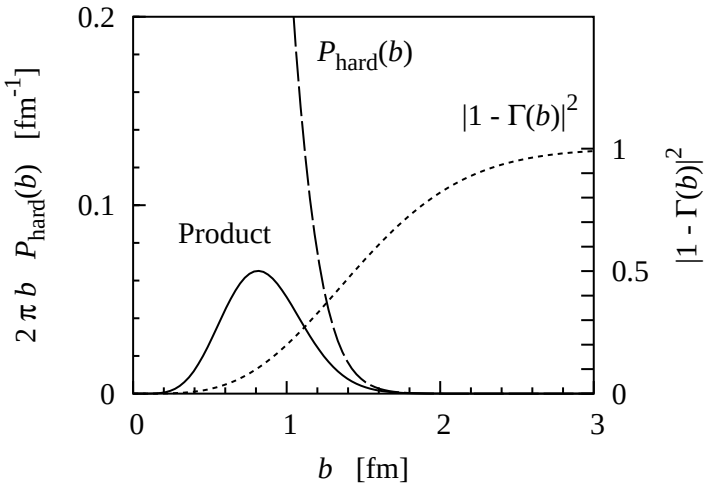
Diffraction: Rapidity gap survival



- Central exclusive diffraction → Talk Martin

  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 FHSW06

  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
  Requires detailed modeling

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

- Diffraction pattern in p_{T1}, p_{T2}

  Experimental tests: CMS/TOTEM or LHC420
  STAR pp2pp @ $\sqrt{s} = 500$ GeV

Summary

- Parton picture of nucleon structure relates non-perturbative dynamics with observables in hard processes

- 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

  Governs underlying event, multiparton rates, gap survival in diffraction, . . .

  New ways of testing reaction dynamics in pp@LHC

- Indications of strong non-perturbative parton–parton correlations in nucleon

  "Imprint" of QCD vacuum on partonic structure

  CDF data show enhancement by factor ~ 2 compared to mean field

  Affects rate of multiparton processes in pp@LHC

  New opportunities for nucleon structure studies "Next step" after one–body densities