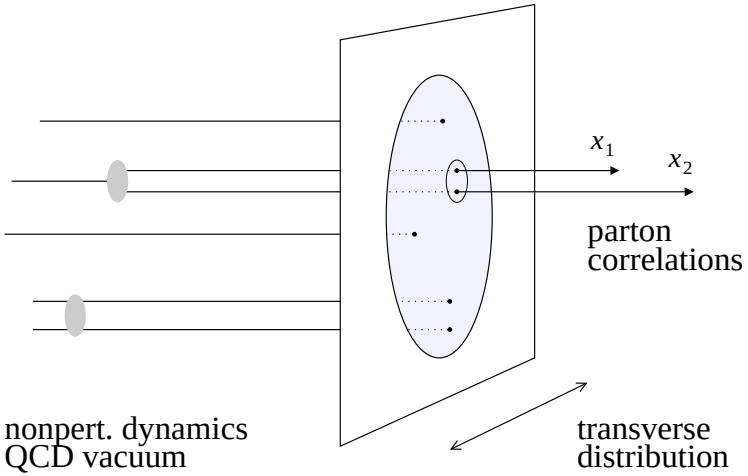
Nonperturbative nucleon structure and MPI

C. Weiss (JLab), MPI@TAU, Tel Aviv University, 15–Oct–12



- Partonic wave function of nucleon

  Non-perturbative QCD vacuum

  Physical properties: Spatial distributions, fluctuations, correlations

- Transverse distribution of partons

  GPDs from exclusive $ep/\gamma p$
  HERA, COMPASS, HERMES, JLab12

  Hard vs. soft pp interactions

  Importance for MPI

- Quantum fluctuations

  Gluon dispersion from diffractive ep HERA

- Parton correlations

  Short–distance scale $\rho \sim 0.3\,\mathrm{fm}$

  Effect on MPIs

  Connections: Intrinsic p_T in ep/pp, higher twist, exclusive mesons

Perturbative QCD
Multijet processes, radiation

↓

MPI

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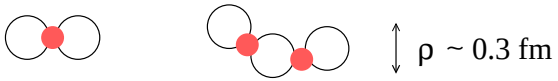
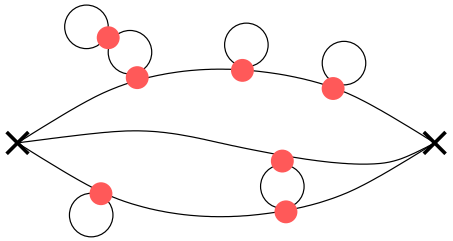
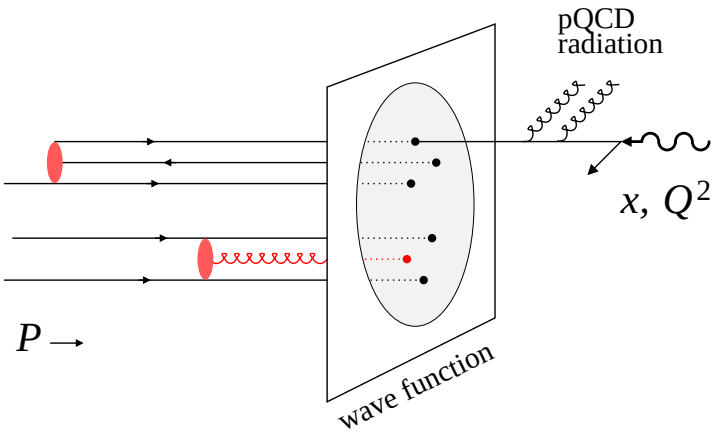
Nucleon structure
Parton densities, spatial distributions, quantum fluctuations, correlations, . . .

Nucleon structure: Parton picture







- QCD vacuum not empty

  Strong gluon fields of size $\rho \ll 1\,\mathrm{fm}$

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

- Nucleon at rest

  $t \to i\tau$ statistical mechanics Lattice, analytic methods
  $\langle N|O|N\rangle$ from correlation functions

  No concept of "particle content!"

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

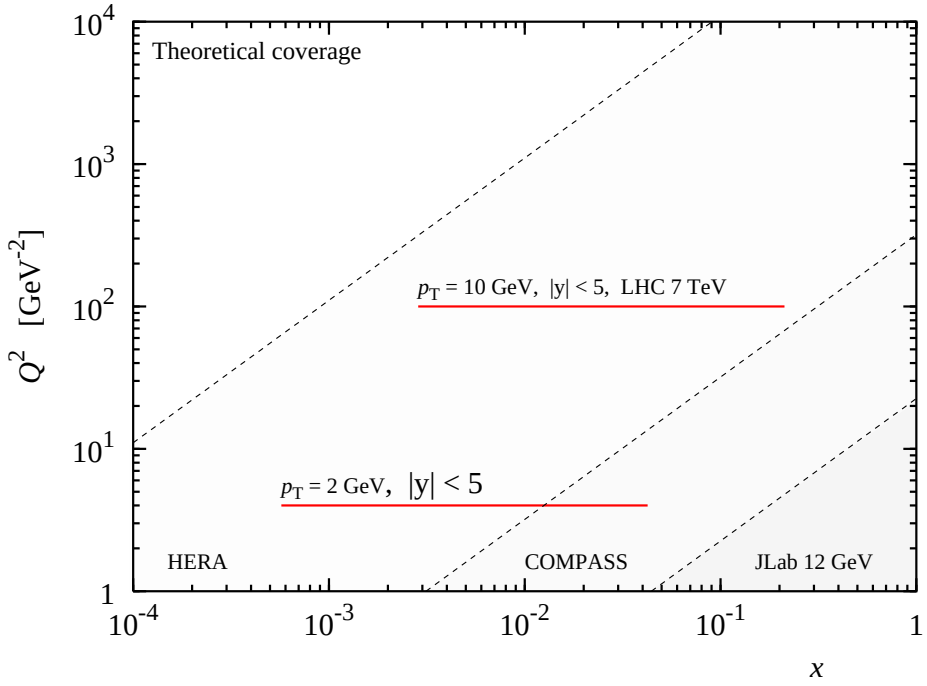
  Closed system: Wave function description
  Gribov, Feynman. Alt: Light–front quantization

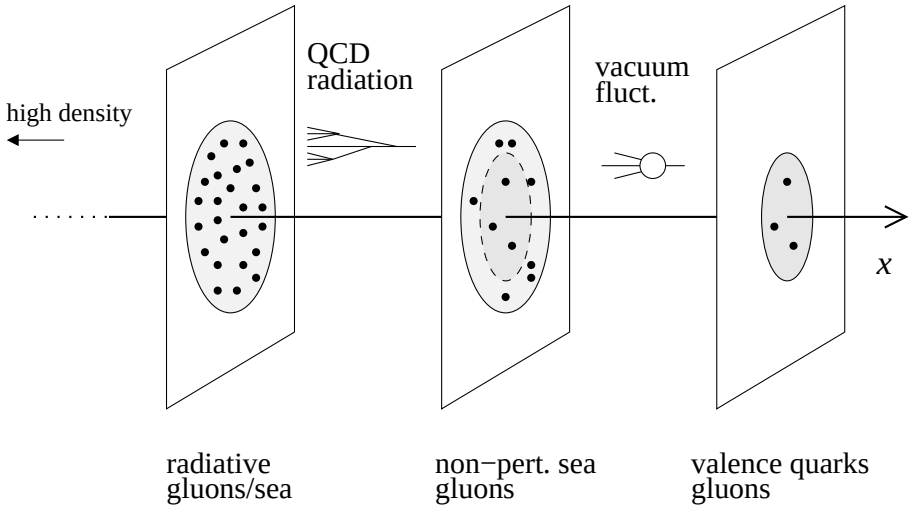
  Components with different particle number

  Many–body system: Constituents, interactions, spatial structure, orbital motion, . . .

  Hard process "snapshot" w. resolution $1/Q^2$
  Separation of short– and long–distance interactions: Factorization
  pQCD radiation in leading–log approximation: Scale dependence

Nucleon structure: Many–body system





- Components probed predominantly

  $x > 0.1$ — Valence quarks: Source, quantum numbers
  Also gluons!

  $\sim 10^{-1..2}$ — Sea quarks, gluons: Quantum numbers
  Generated by non–pert. interactions

  $x < 10^{-2}$ — Gluons, singlet sea:
  Radiatively generated

- Physical properties

  Particle number densities,
  incl. spin/flavor — PDFs

  Transverse spatial distributions — GPDs

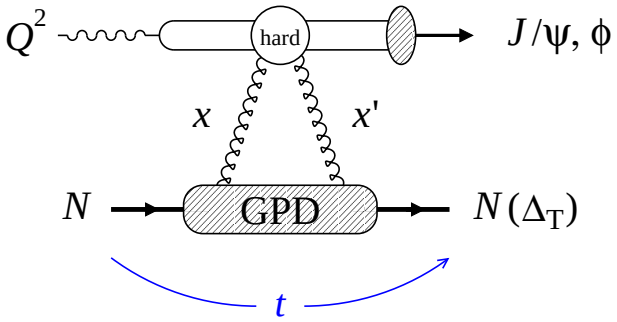
  Orbital motion, ang. momentum — TMDs

  Quantum fluctuations: Dispersion

  Multiparton correlations — MPDs, GPDs

Densities with operator definition $\langle N|\,\mathrm{QCD\text{–}Op}\,|N\rangle$
Calculable with non–perturbative methods
Scale dependence from RNG equation.

Transverse distributions: Exclusive processes



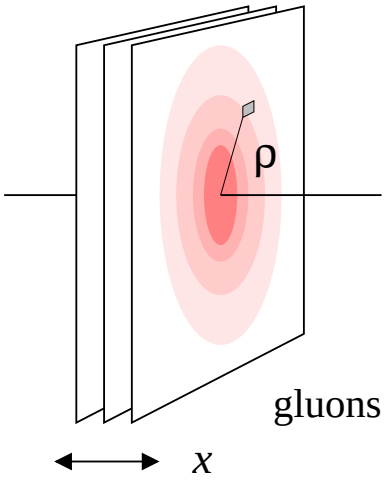
- Hard exclusive meson production

  Meson produced in small–size $q\bar{q}$ configuration

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

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

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



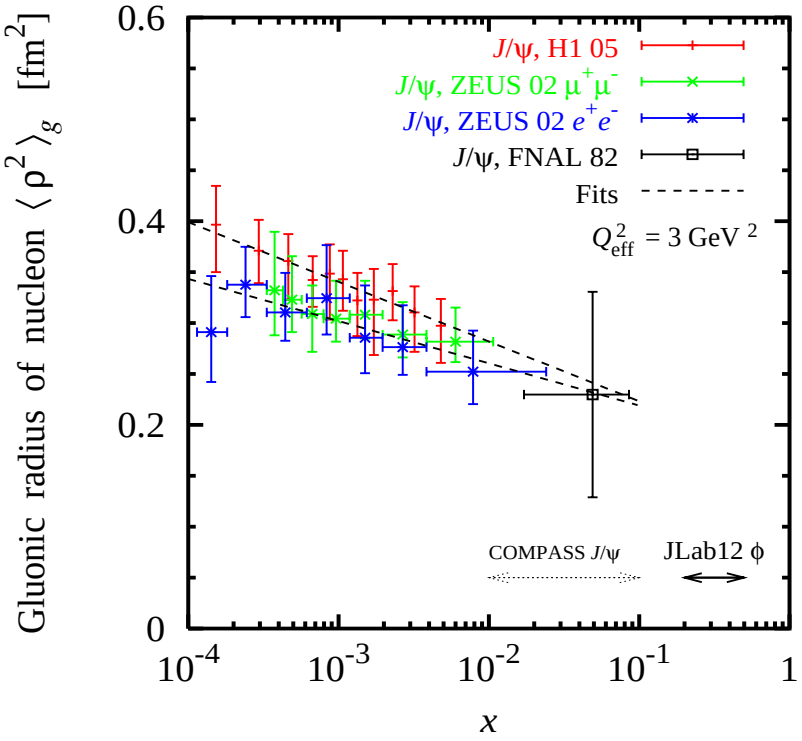
- Transverse spatial distribution of gluons $x' = x$

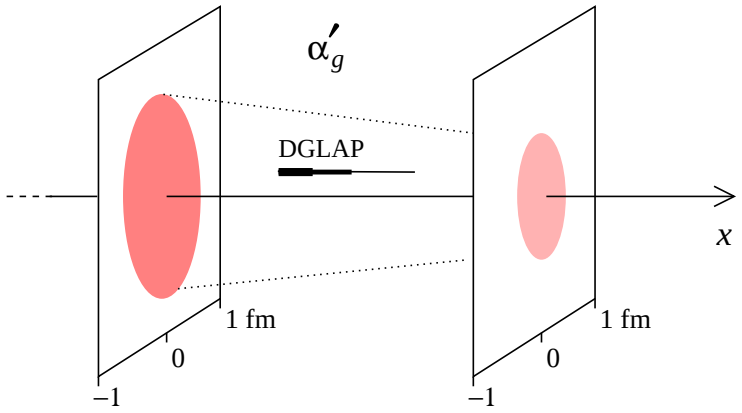
$$G(x,\rho) = \int \frac{d^2\Delta_T}{(2\pi)^2}\, e^{-i\boldsymbol{\rho}\boldsymbol{\Delta}_T}\, \mathrm{GPD}(x,t)$$ 2D Fourier

  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 distributions: Gluons





- Transverse distribution of gluons

  Exclusive J/ψ photo/electroproduction
  FNAL. HERA also ϕ, ρ. Large x JLab12 ϕ

  Transverse profile from relative t–dep.

  Average size from slope $\langle \rho^2 \rangle_g = 2B_{J/\psi}$
  Finite–size corrections

- Important observations

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

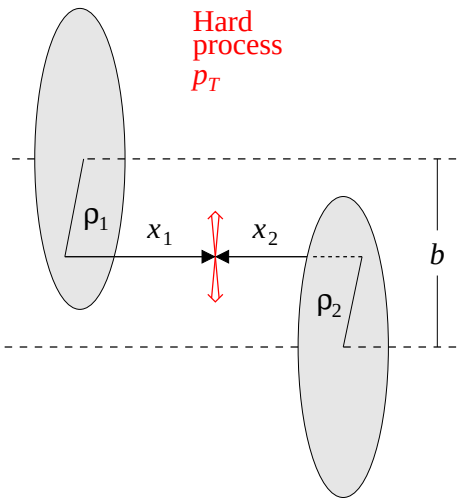
  Grows with effective Regge slope $\alpha'_g \approx 0.14\,\mathrm{GeV}^{-2} < \alpha'_{\rm soft}$
  Parametrization available: Frankfurt, Strikman, CW 10

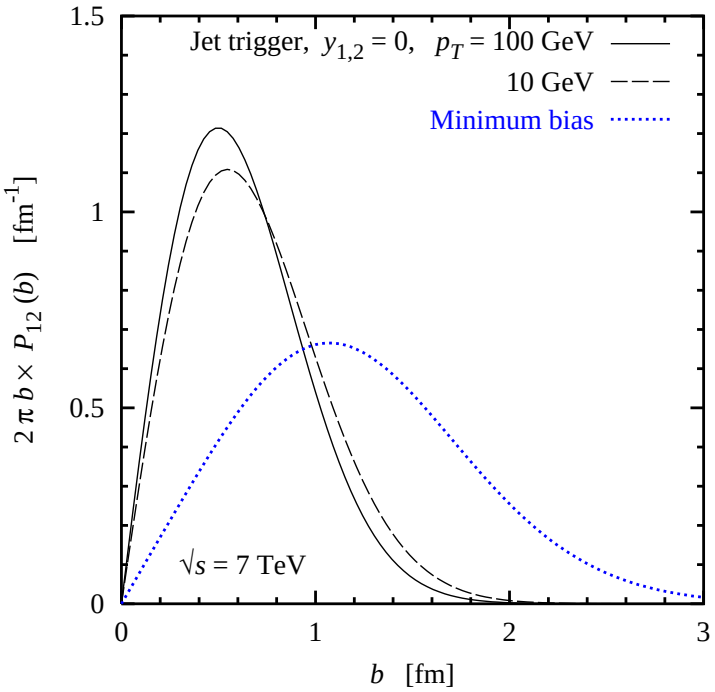
- Q^2 dep. from DGLAP evolution FSW04

  Partons decay locally in transverse space

  Size changes because initial partons at $x_0 > x$ sit at smaller transv. distances
  Small effect at $Q^2 >$ few GeV^2

Transverse distributions: Applications to 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 param

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

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

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

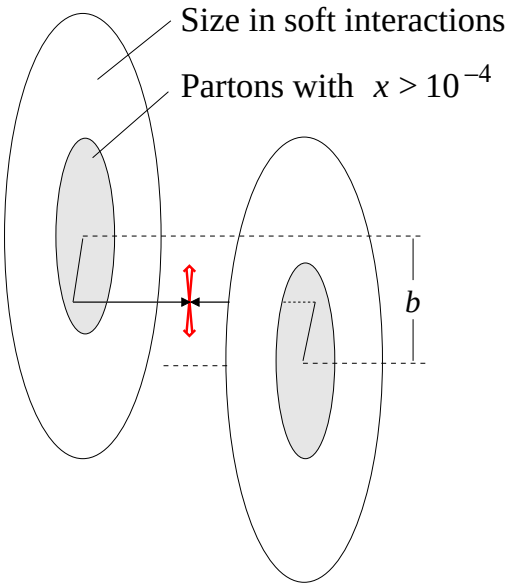
- New information available

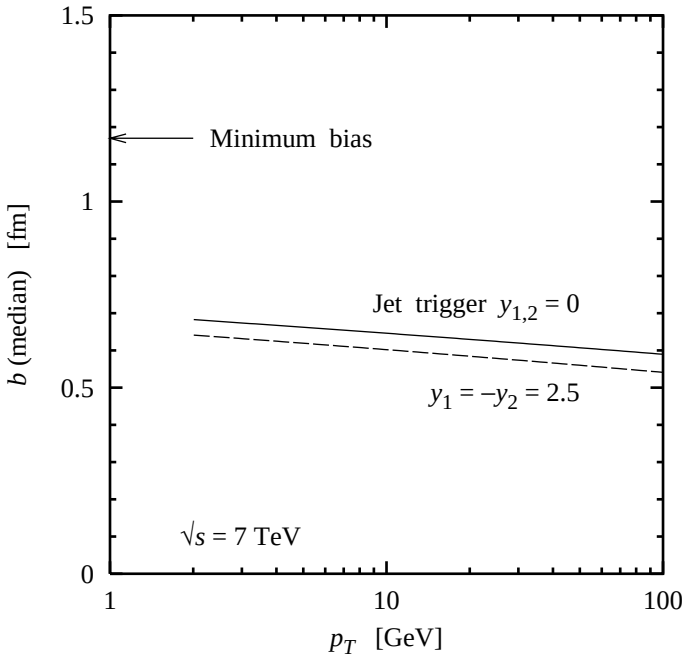
  Model spectator interactions depending on b
  Underlying event

  Predict probability of multiple hard processes
  Dynamical correlations? FSW04

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

Transverse distributions: Hard vs soft interactions





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

$$\sigma^{pp}_{\text{soft inel}}(b) \;=\; 1 - |1 - \Gamma(s,b)|^2$$

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

- Two classes of pp collisions

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

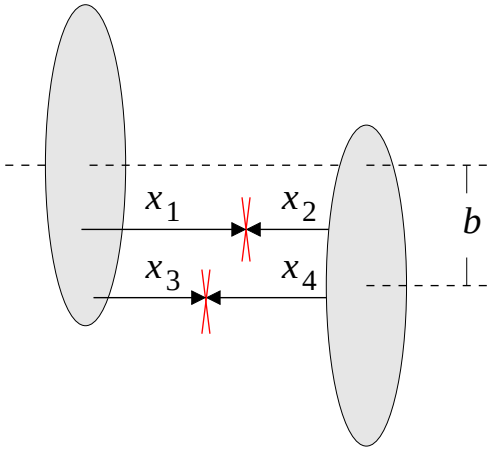
- Hard processes select central collisions
  → Talk Strikman

  Underlying event very different from min. bias

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

  New tests of dynamical mechanisms
  in particle production

Transverse distributions: MPIs



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

- Double collision rate parametrized by $\sigma_{\rm eff}^{-1}$

  Mean field $\sigma_{\rm eff} = \pi R_{13}^2$ avg distance btw collisions
  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 $ep/\gamma p$

  Mean field as reference prediction

- Observed enhancement

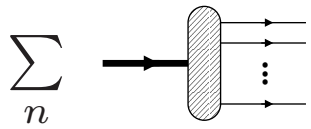
  CDF/D0 3jet + γ rate two times larger than mean field with $\langle\rho^2\rangle(x \sim 0.1)$

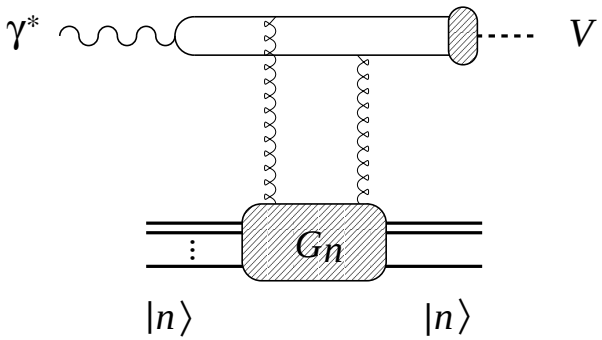
  LHC results → Talks at this meeting

  Dynamical explanation? Substantial correlations?

Transverse spatial distribution determines basic mean–field expectation of MPI rate

Quantum fluctuations: Parton densities





$$N \xrightarrow{G_n \text{ const.}} N$$

$$\xrightarrow[\text{fluctuating}]{} X$$

- Nucleon quantum many–body system

  Partonic wave function has components with different particle number, transverse size, etc.

  High–energy processes intercept instantaneous configurations "interactions frozen"

  Fluctuations well–known in soft interactions:
  Cross section distribution $P(\sigma)$, diffractive dissociation

  Fluctuations of parton density and transverse size?
  Frankfurt, Strikman, Treleani, CW, PRL **101**:202003, 2008
  Fundamental interest, affects MPI

- Fluctuations of gluon density

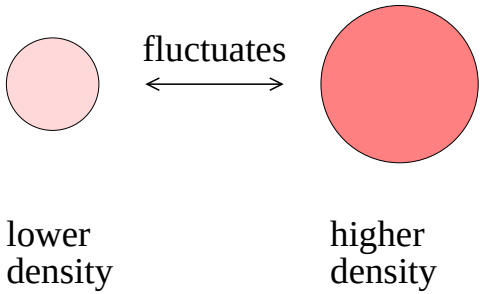
  Hard diffractive processes at small x

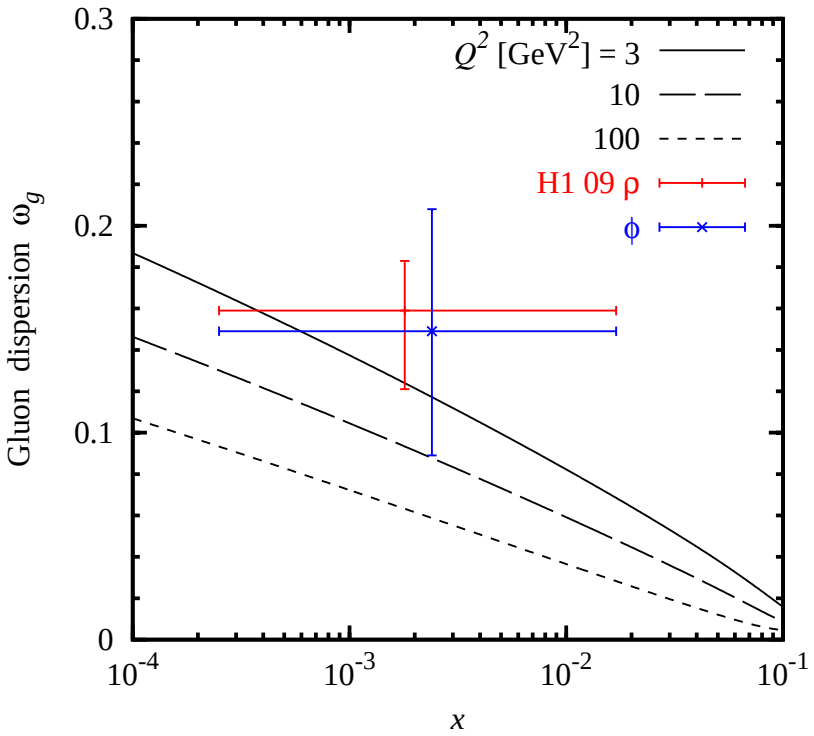
  Amplitude diagonal in partonic states $|n\rangle$, proportional to configurations's gluon density G_n

  Fluctuations of G_n lead to dissociation
  cf. soft diffraction: Good, Walker 60, Miettinen, Pumplin 78

$$\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \left.\frac{d\sigma/dt\ (\gamma^* N \to V X)}{d\sigma/dt\ (\gamma^* N \to V N)}\right|_{t=0}$$

Quantum fluctuations: Sizes and MPI





- Scaling model Close et al. 83: EMC effect

  Fluctuations of nucleon size change effective scale of non-perturbative gluon density
  $\mu^2(\text{gluon}) \propto R^{-2}$

  Size distribution from soft cross section fluctuations $\omega_\sigma \sim 0.25$ at $\sqrt{s} = 20\,\text{GeV}$

  Gluon density fluctuations change with x, Q^2
  DGLAP evolution

  Consistent with HERA data
  Large uncertainties

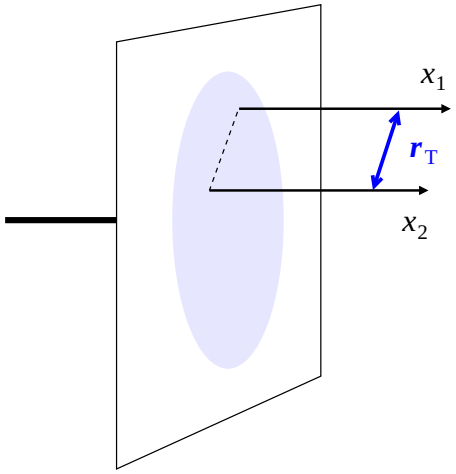
- Fluctuations in MPI

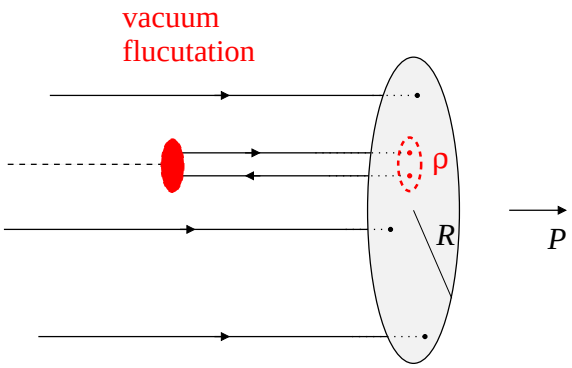
  Small effect of gluon density fluctuations
  $\omega_g < 0.1$ at Tevatron

  Moderate enhancement from size fluctuations
  $\sigma_{\text{eff}}\,(\text{fluct}) \approx (1 - \omega_\sigma/2)\,\sigma_{\text{eff}}\,(\text{mean field})$

Fluctuations cause moderate enhancement of MPI, ∼10-15% at Tevatron

Parton correlations: QCD vacuum structure





- Parton correlations in nucleon

  How is the probability to find a parton influenced by having other parton nearby?
  Fundamental property of many–body system: Condensed matter, nuclei

  Multiparton distributions
  Blok, Dokshitzer, Frankfurt, Strikman 10; Diehl, Ostermeier, Schafer 11
  Subtleties: UV divergences, renormalization, mixing with higher–twist ops

  $$\langle N |\, O_{\rm tw2}(x_1, \boldsymbol{r}_{1T})\; O_{\rm tw2}(x_2, \boldsymbol{r}_{2T})\; | N \rangle_{\boldsymbol{r}_{1T}-\boldsymbol{r}_{2T}=\boldsymbol{r}_T}$$

- Non–perturbative QCD vacuum

  Short–distance scale $\rho \sim 0.2$–0.3 fm from dynamical chiral symmetry breaking
  Shuryak 82; Diakonov, Petrov 84. Size of $q\bar{q}$ pairs in vacuum condensate, measured in Lattice QCD. Euclidean $\rightarrow$ Minkowski?

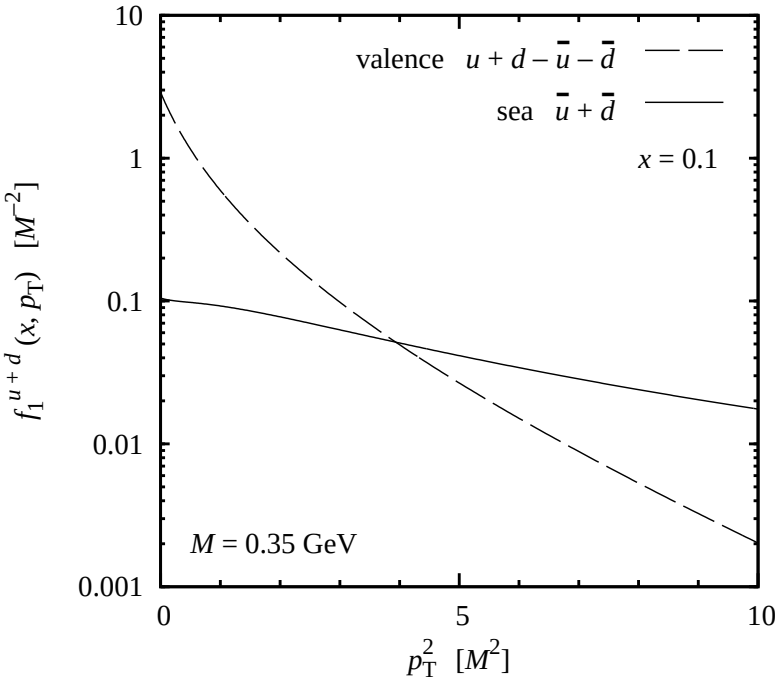
  Parton short–range correlations: Sea quarks in correlated pairs + nonperturbative gluon field
  Schweitzer, Strikman, CW, arXiv:1210.1267

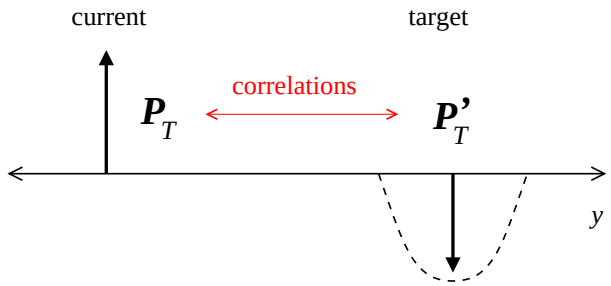
- Enhancement of MPI

  Non-pert. correlations could account for Tevatron results
  Frankfurt, Strikman, CW04

  Primordial vs. DGLAP–induced correlations?
  Challenge to separate! $\rightarrow$ Discussion

Parton correlations: Dynamical model





- Model of nonperturbative correlations
  Schweitzer, Strikman, CW 12

  Chiral constituent quarks as effective degrees of freedom at momenta $|p^2| < \rho^{-2}$
  Dynamica mass $M \sim$ 0.3–0.4 GeV. Diakonov, Eides 83

  Large–N_c limit: Semiclassical approximation
  Chiral quark–soliton model. Diakonov, Petrov, Polylitsa 88

  Sea quark transverse momenta up to $p_T \sim \rho^{-1}$
  Qualitativey different from valence quarks $p_T \sim R^{-1}$

  Correlated $q\bar{q}$ pairs in nucleon wave function:
  Spin/flavor structure, σ/π quantum numbers

- Signals in deep–inelastic lepton scattering

  P_T distributions in semi-inclusive DIS
  incl. spin asymmetries, particle correlations. JLab12, COMPASS

  Particle correlations between current and target fragmentation regions
  Moderate energies $W \sim$ few GeV avoid DGLAP radiation.
  COMPASS, EIC

  Exclusive meson production at large x
  Knockout of correlated $q\bar{q}$ pair. JLab12

Quark correlations from DIS . . . new field!

Summary

- Partonic wave function encodes non-perturbative QCD

  Dynamical system, not MC generator!

  Much information from $ep/\gamma p$ and non–perturbative theoretical approaches

- Nucleon properties determining MPI rates

Transverse distributions	reasonably well known, more data expected COMPASS, JLab12, EIC	mean–field expectation
Density/size fluctuations	rough estimates	moderate enhancement $\sim 20\%$ at Tevatron
Parton correlations	theoretical models, future tests in ep	possibly substantial enhancement, perturbative $\leftrightarrow$ non-perturbative?

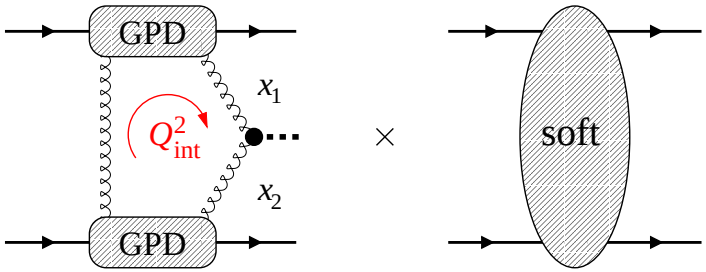
- Great potential interest in nucleon structure community

  Connections to exclusive processees (GPDs), semi–inclusive DIS (TMDs), higher twist

  Parton correlations "next step" after one–body densities

Supplementary material

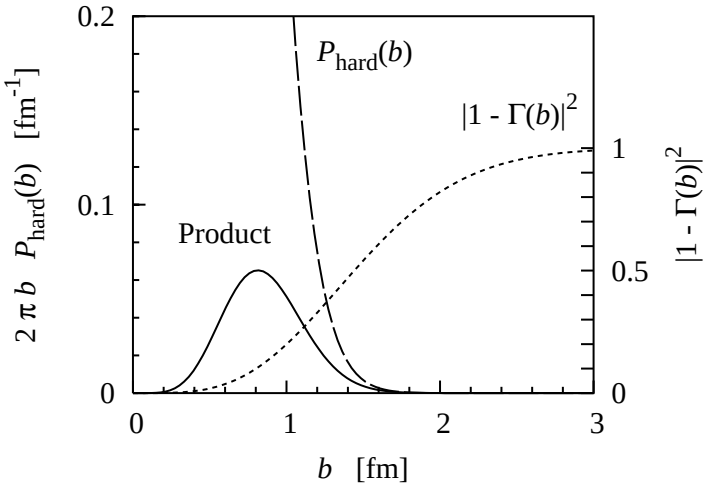
Diffraction: Rapidity gap survival



- 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