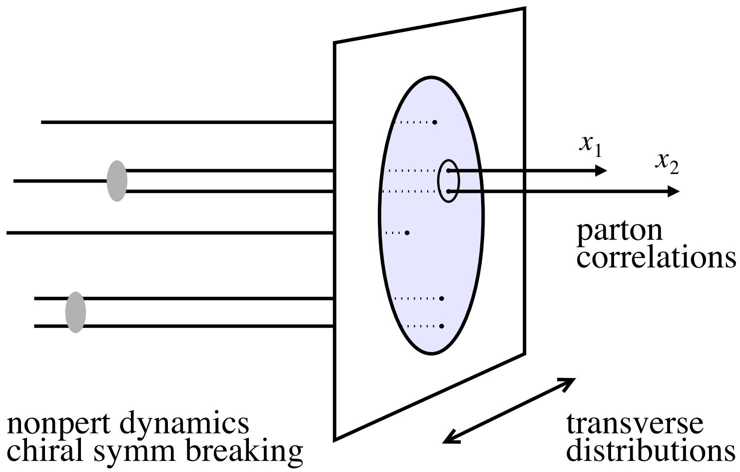
Transverse geometry and hard-soft correlations in high-energy pp collisions

C. Weiss (JLab), Hard-Soft Correlations, Clermont-Ferrand U., 24-July-18



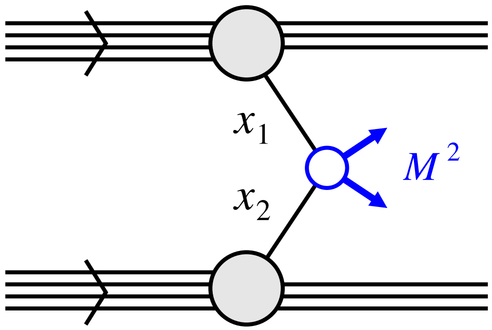
Nucleon structure

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

Underlying Event / MPI in pp

- Nucleon structure in QCD
  - Partonic wave function
  - Physical characteristics
- Transverse distribution of partons
  - GPDs and exclusive processes in $ep/\gamma p$
  - Transverse geometry in pp
  - Hard-soft correlations
  - Multiparton interactions
- Fluctuations and correlations
  - Fluctuations and diffraction in ep
  - Parton correlations
  - Effects on pp

Nucleon structure: Hard processes in pp



- Factorization of cross section

  Separate $k_T^2 \sim \mu^2(\text{soft}) \longleftrightarrow M^2$

  $\sigma \; = \; f_1(x_1, \mu^2)\, f_2(x_2, \mu^2) \; \times \; \sigma_{\text{hard}}(\mu^2, M^2)$

  One-body densities of partons PDFs

- Underlying event characteristics

  Many observables: Hadron number distributions, p_T, energy flow, . . .

  Hard-soft correlations

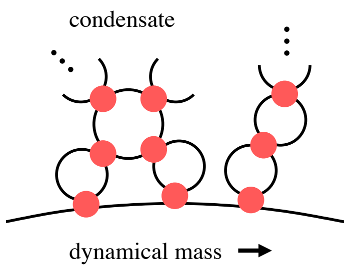
- Proton as dynamical system

  Partonic wave function (scale μ^2)

  Physical properties: Spatial distributions, fluctuations, parton correlations, . . .

  Formulated as generalizations of PDFs. Measurable in $ep/\gamma p$.

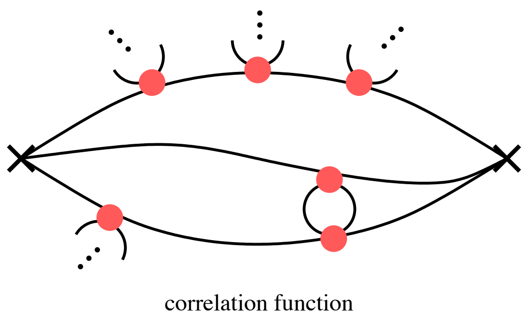
Nucleon structure: Parton picture



- Vacuum fluctuations

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

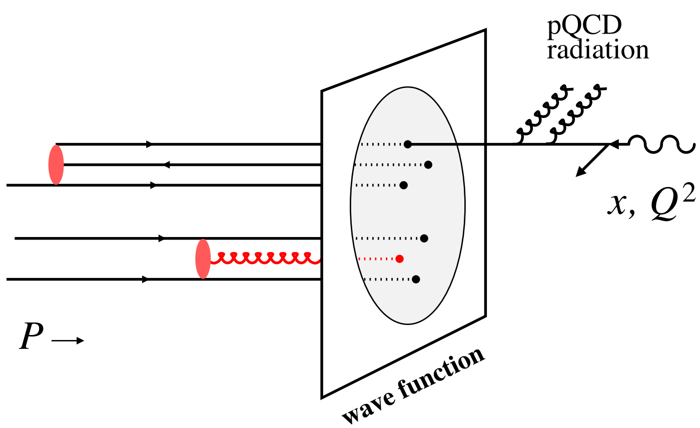
  Chiral symmetry breaking: $\bar{q}q$ condensate, dynamical mass generation, π as collective mode



- Slow–moving nucleon $P \sim \mu_{\mathrm{vac}}$

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

  No concept of "particle content"



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

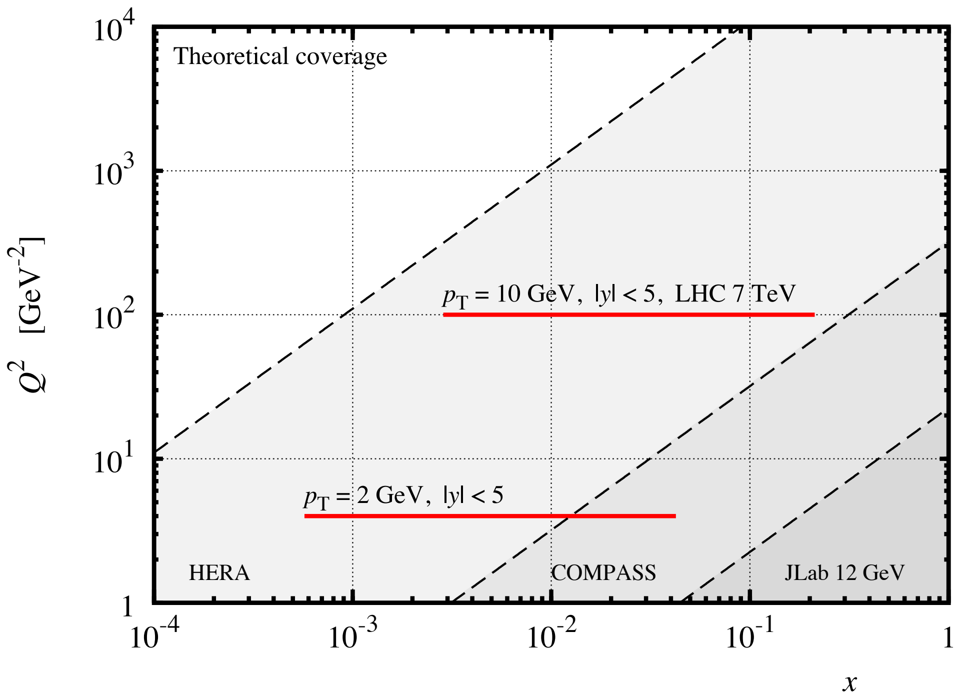
  Closed system: Wave function description
  Feynman, Gribov. Alt: Light–front quantization

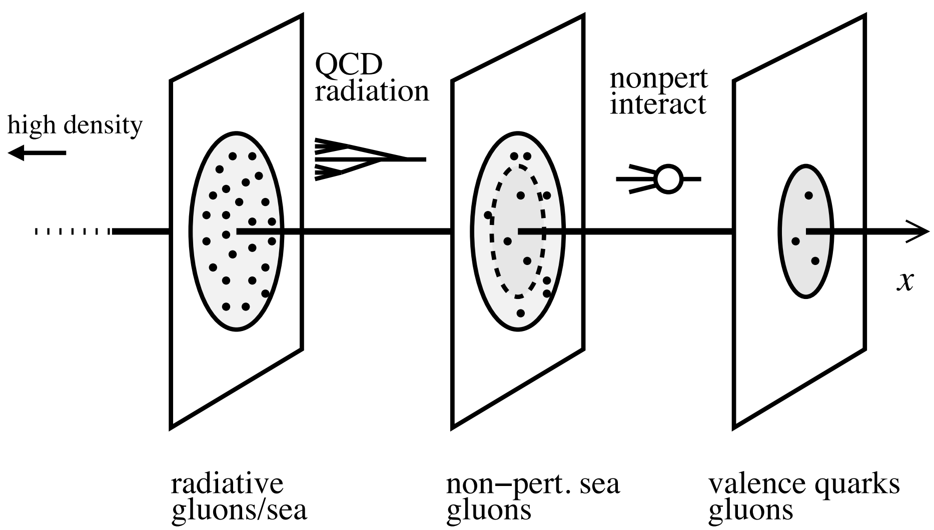
  Components with different particle number

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

  QCD: UV divergences, renormalization, scale dependence $\leftrightarrow$ factorization

Nucleon structure: Many–body system





- Components of system

$x > 0.1$	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

Number densities incl. spin/flavor — PDFs

Transverse spatial distributions — GPDs

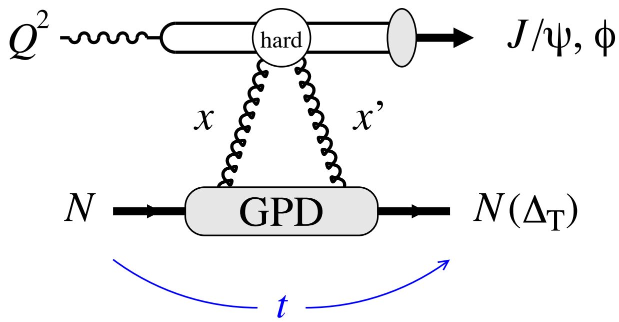
Orbital motion, ang. momentum — TMDs

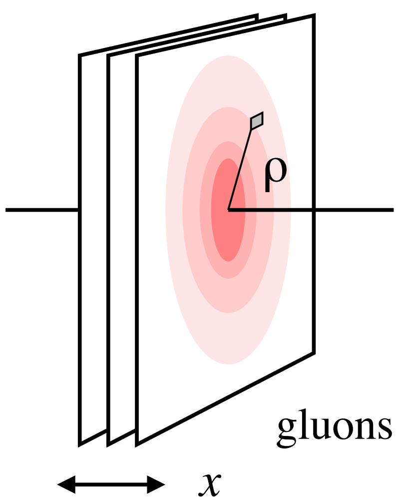
Quantum fluctuations: Dispersion

Multiparton correlations — MPDs, GPDs

Densities with operator definition $\langle N | \, \mathrm{QCD–Op} \, | N \rangle$
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 $Q^2 \gg \mu^2_{\mathrm{had}} \sim |t|$
  Collins, Frankfurt, Strikman 96

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

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

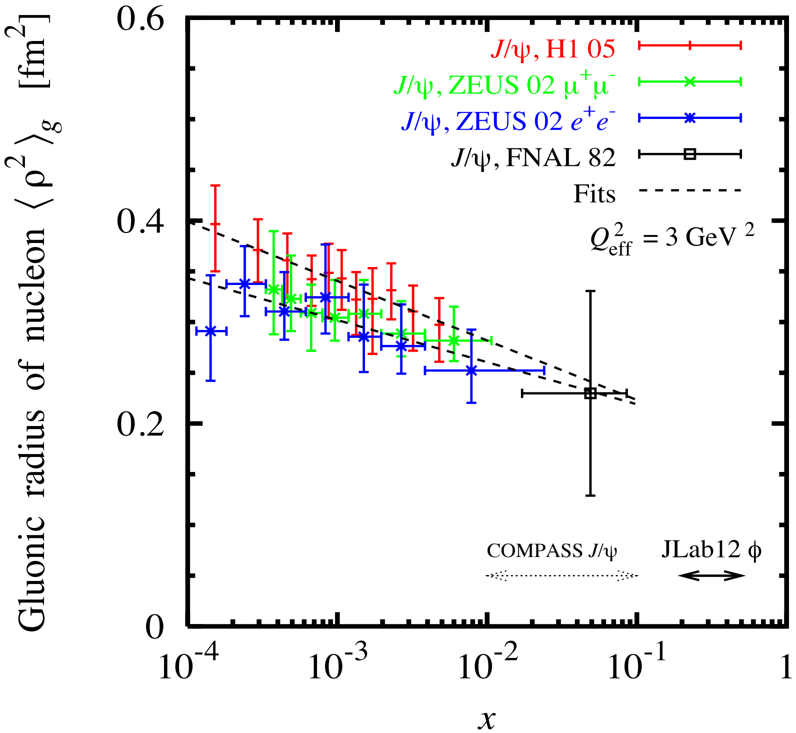
- Transverse spatial distribution of partons $x' = x$

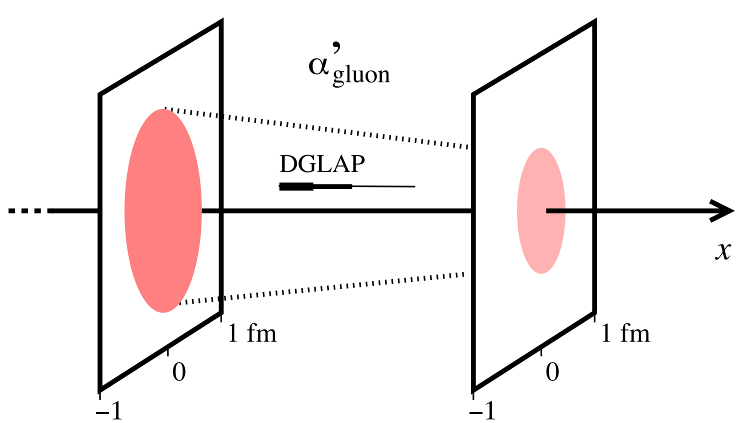
  $$f(x, \boldsymbol{\rho}) = \int \frac{d^2 \Delta_T}{(2\pi)^2} \, e^{-i \boldsymbol{\rho} \boldsymbol{\Delta}_T} \; \mathrm{GPD}(x, t) \quad \text{2D Fourier}$$

  Tomographic image of nucleon at fixed x, changes with x and Q^2

- Large x: Quark GPDs, polarization, $x' \neq x$
  JLab12: DVCS, meson production

Transverse distributions: Gluons





- Transverse distribution of gluons

  Exclusive J/ψ at HERA, also ϕ, ρ
  Large x: FNAL, COMPASS, JLab12 ϕ

  Transverse profile from relative t–dep.

  Gluonic radius from slope $\langle \rho^2 \rangle_g = 2B_{\text{excl}}$

- Important observations

  Gluonic radius $\langle \rho^2 \rangle_g$ much smaller than soft nucleon radius $\sim 1\,\text{fm}^2$

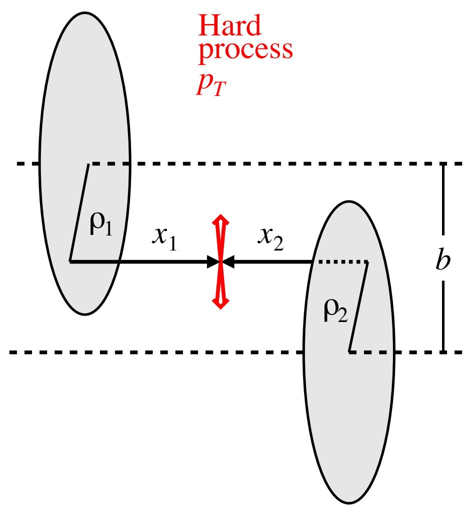
  Grows with effective Regge slope $\alpha'_g \approx 0.14\,\text{GeV}^{-2} < \alpha'_{\text{soft}}$
  Parametrization available: Frankfurt, Strikman, CW 10

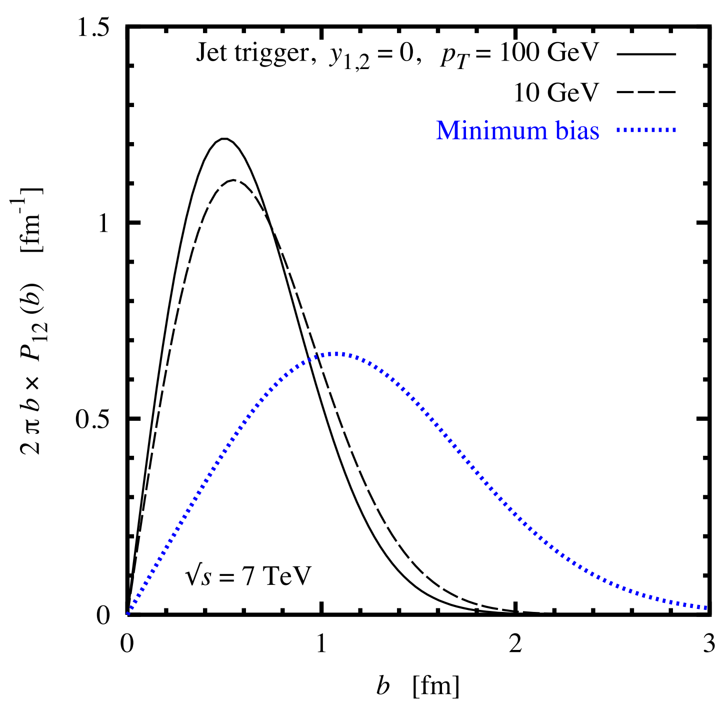
- Q^2 dep. from DGLAP evolution

  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
  FSW04

Transverse distributions: Applications to pp





- Hard process from parton-parton collision

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

- Cross section as function of pp impact par

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

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

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

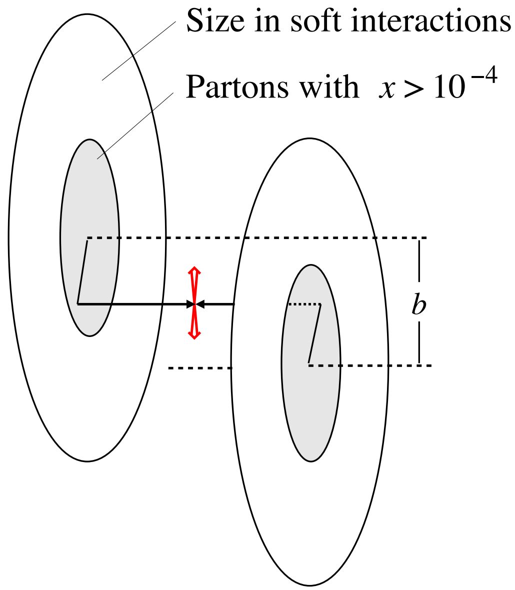
- New information available

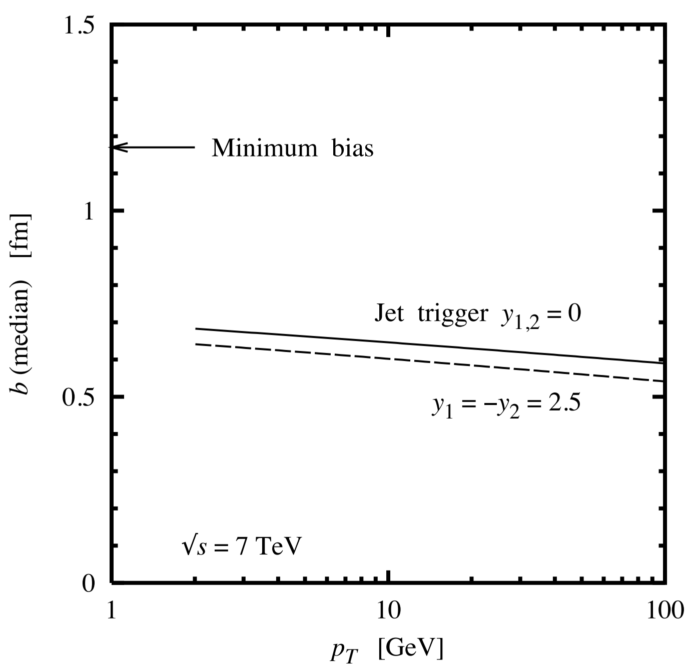
  Model spectator interactions depending on b
  Underlying event

  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

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

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

two scales!

- Two classes of pp collisions

FSW04/10

Peripheral: Most of inelastic cross section

Central: High probability for hard process

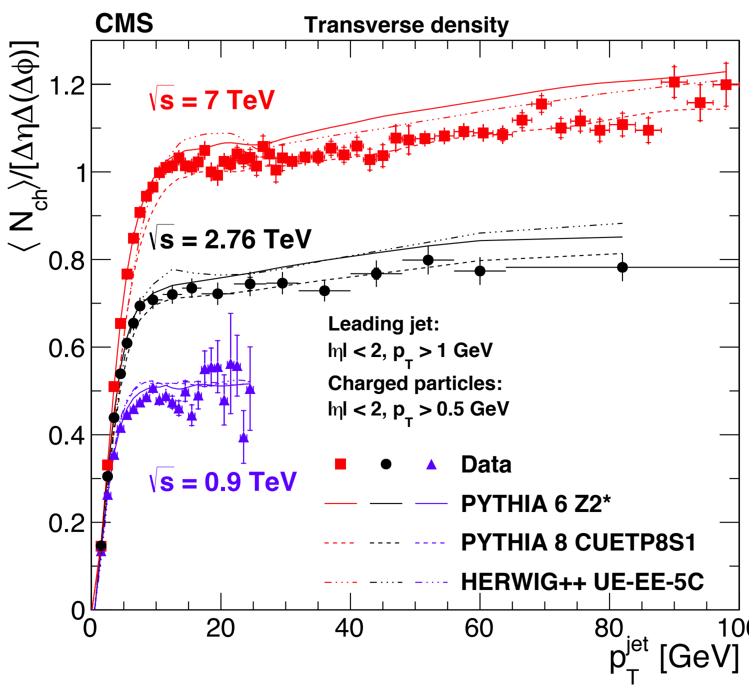
- Hard processes select central collisions

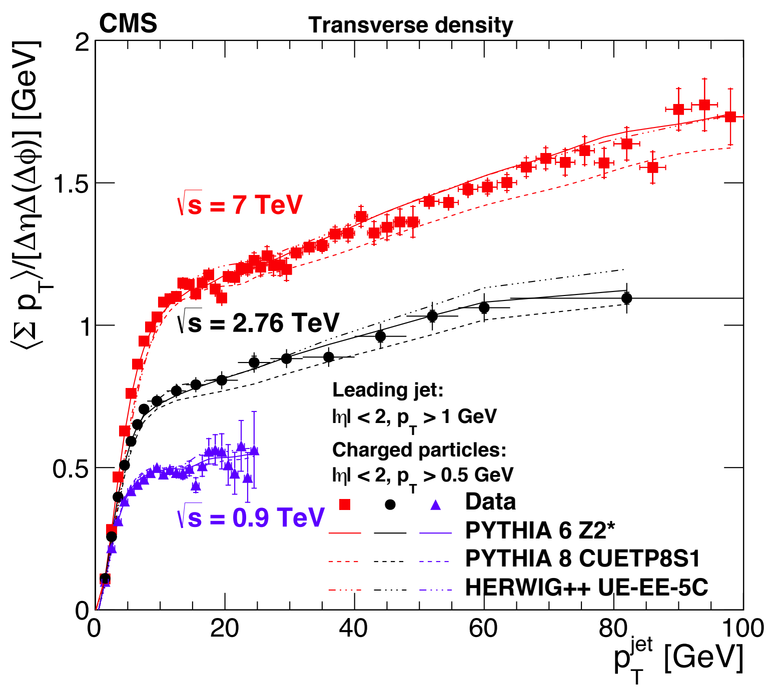
Underlying event in hard processes very different from min. bias collisions

Geometric correlations: Hard process $\leftrightarrow$ centrality $\leftrightarrow$ event chars

New tests of dynamical mechanisms in particle production

Transverse distributions: Hard-soft correlations

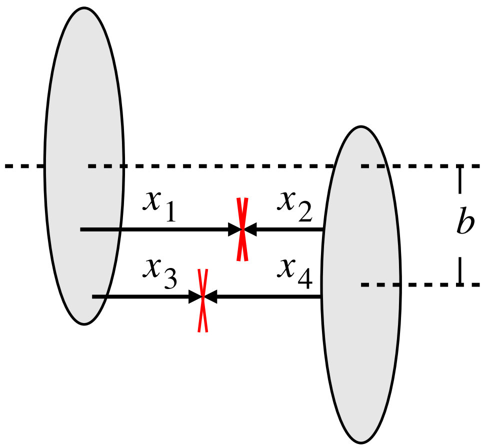




CMS underlying event analysis, JHEP 1509 (2015) 137

- Underlying event activity as function of trigger p_T^{jet}
- $p_T^{\mathrm{jet}} \sim$ few GeV: No hard process, collisions mostly peripheral, low activity
- $p_T^{\mathrm{jet}} \gtrsim 10$ GeV: Hard process, collisions central, high activity.
  Little changes with further increase of p_T^{jet} because collision already central
- Geometric correlations — impact parameter as "hidden variable"

Transverse distributions: MPI



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

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

- Double collision rate parametrized by σ_{eff}^{-1}

- Mean field approximation

  Calculable from transverse distributions

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

  Reference prediction

  $\langle\rho^2\rangle_g(x \sim 0.1)$ gives $\sigma_{\text{eff}} \sim 34$ mb

- Enhancement observed

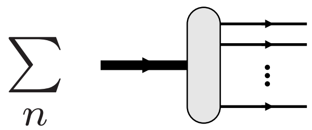
  CDF/D0 3jet $+\ \gamma$ rate about $2\times$ larger than mean field

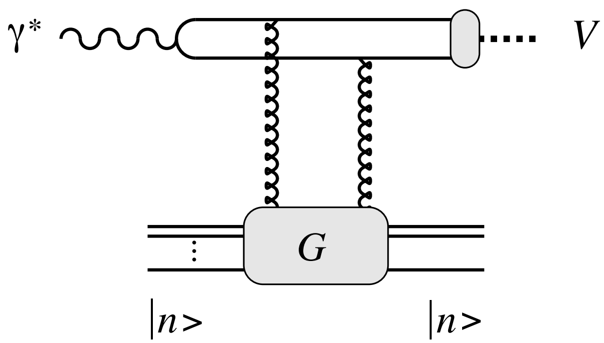
  LHC MPI results $\rightarrow$ this meeting

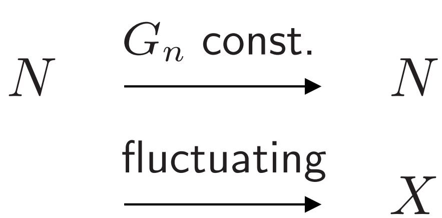
  Dynamical explanation? Correlations beyond MF

- Transverse distributions of partons determine mean field expectation for MPI

Quantum fluctuations: Parton densities







- Nucleon quantum many-body system

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

  High-energy process intercepts instantaneous configurations, interactions "frozen"

  Inclusive DIS measures average parton density

  Fluctuations of parton density and transverse size?
  Fundamental property of many-body system
  Frankfurt, Strikman, Treleani, CW, PRL **101**:202003, 2008

- Fluctuations of gluon density

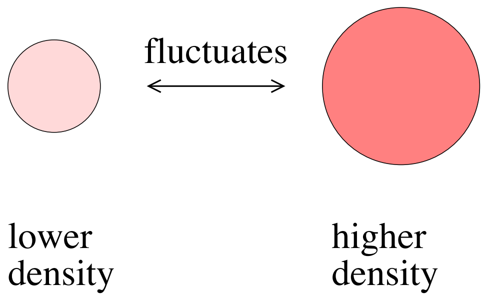
  Hard diffractive processes at small x

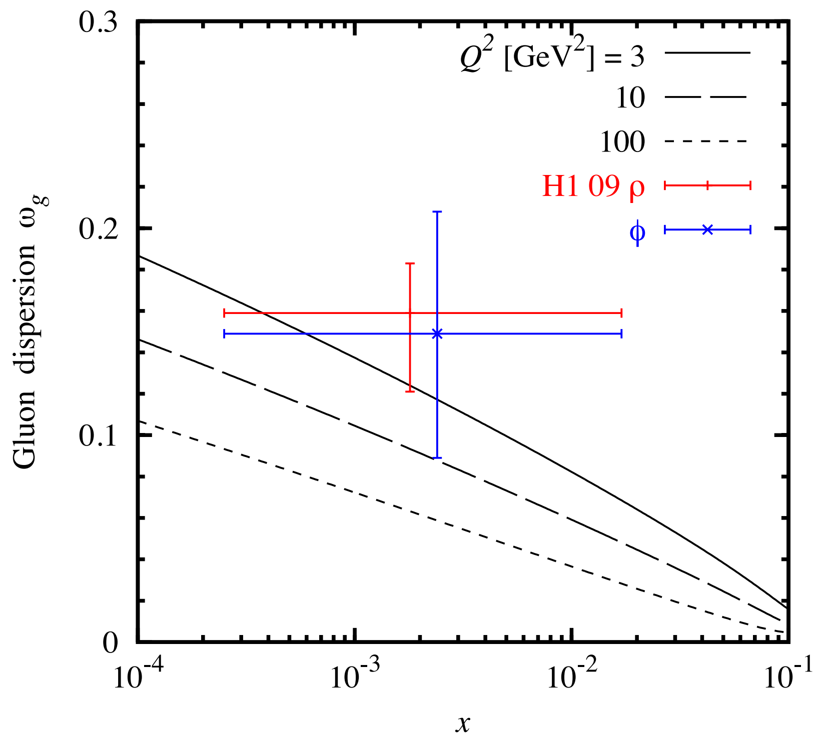
  Amplitude diagonal in partonic states $|n\rangle$, proportional to configurations's gluon density G_n

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

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

Quantum fluctuations: Sizes and MPI





- Scaling model Close et al. 83: EMC effect

  Fluctuations of size change effective scale of non-pert gluon density μ^2(gluon) $\propto R^{-2}$

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

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

  Roughly consistent with HERA data

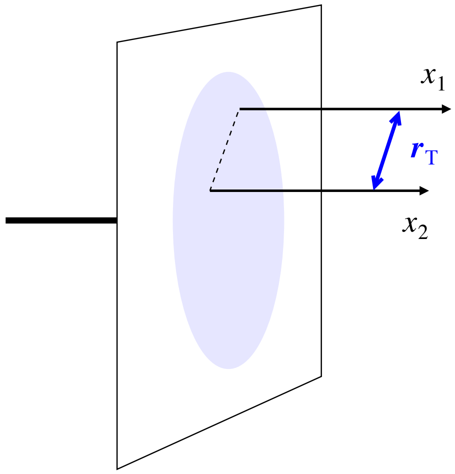
- Fluctuation effect on MPI

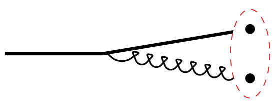
  Small effect of gluon density fluctuations
  $\omega_g < 0.1$ at Tevatron

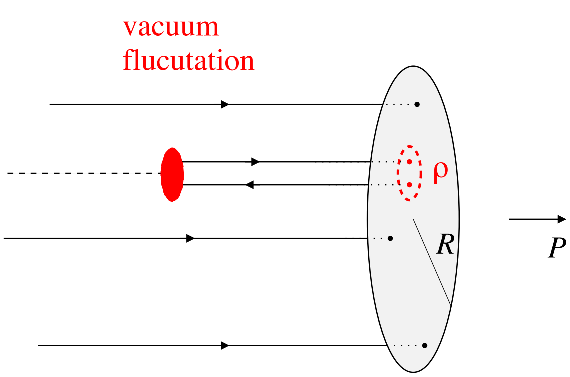
  Moderate enhancement from size fluctuations
  $\sigma_{\text{eff}}\,(\text{fluct}) \;\approx\; (1 - \omega_\sigma/2)\; \sigma_{\text{eff}}\,(\text{mean field})$
  ∼10-15% at Tevatron

  Fluctuation effect on MPI small, cannot explain experimental rates

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

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

  Subtleties: UV divergences, renormalization, mixing

- Perturbative and non-perturbative correlations

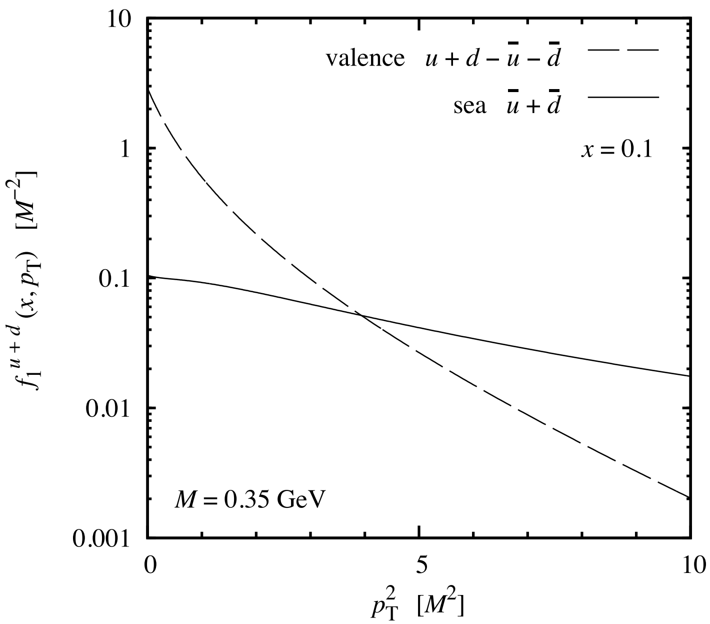
  DGLAP evolution: Active parton from perturbative splitting, partner within range $r_T \sim \mu^{-1}$

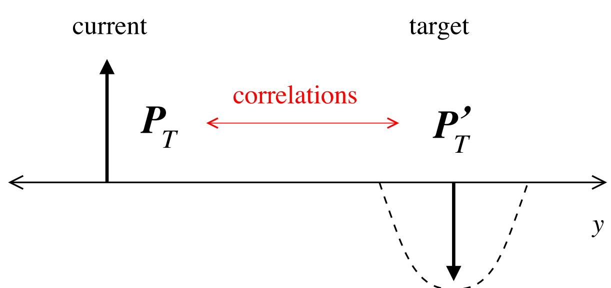
  Chiral symmetry breaking: Nonperturbative $q\bar{q}$ pairs with transverse size $\ll 1$ fm
  Schweitzer, Strikman, CW 12. Cf. Shuryak 82; Diakonov, Petrov 84

- Effect on MPI

  Perturbative correlations can explain observed enhancement beyond mean field
  Review Blok, Strikman 17

Parton correlations: Dynamical model





- Model of nonperturbative correlations
  Schweitzer, Strikman, CW 12

  Chiral quark-soliton model: Dynamical quark mass, semiclassical approximation in large–N_c limit
  Diakonov, Petrov, Polylitsa 88

  Sea quark transverse momenta up to $p_T \sim \mu_{\chi\mathrm{SB}}$
  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
  $W \sim$ few GeV to avoid DGLAP radiation. COMPASS, EIC

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

Summary

- Nucleon as dynamical system

  Quantum many-body system, wave function description

  Information from $ep/\gamma p$ and non-perturbative theoretical approaches

- Transverse geometry essential aspect of pp collisions

  Transverse distribution of partons from $ep/\gamma p$ (GPDs)

  Hard processes select central pp collisions

  Geometric correlations explain UE characteristics

- 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$15%
Parton correlations	theoretical models, future tests in ep? JLab12, EIC	substantial enhancement from pert correlations

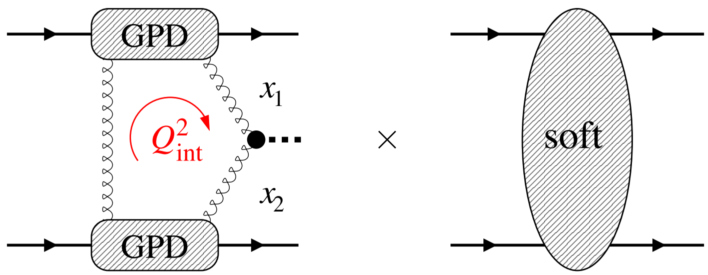
- Potential interest in nucleon structure community

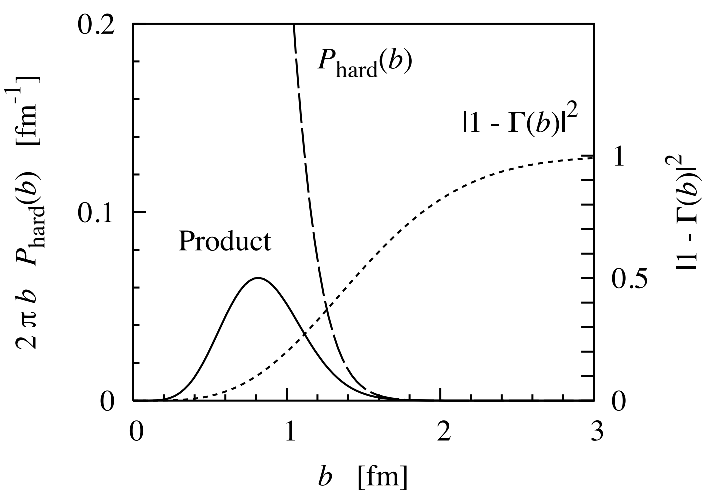
  Connections to exclusive processees (GPDs), semi–inclusive DIS (TMDs), higher twist

  Study of parton correlations “next step” after one-body densities

Supplementary material

Diffraction: Rapidity gap survival





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

- 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 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

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

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