GPDs and transverse geometry in high-energy pp collisions

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- Hard processes in $pp$
  Inclusive cross section, factorization
  Event observables, hard-soft correlations

- Transverse distribution of partons
  GPDs and exclusive processes in $ep/\gamma p$

- Transverse geometry in $pp$ collisions
  Hard-soft correlations
  Multiparton interactions

- Exclusive diffraction $pp \rightarrow p + H + p$
  Rapidity gap survival probability

GPDs from $ep/\gamma p$

Input for analysis $\downarrow$ New probes?
Underlying event / MPI in $pp$

Based on work with L. Frankfurt, M. Strikman 2004–
**Hard processes in pp**

- **Inclusive cross section**
  
  Separate \( k_T^2 \sim \mu^2\text{(soft)} \leftrightarrow M^2 \)
  
  \[ \sigma = f_1(x_1, \mu^2) f_2(x_2, \mu^2) \times \sigma_{\text{hard}}(\mu^2, M^2) \]
  
  PDF same as in \( ep \)

- **Underlying event characteristics**
  
  Many observables: Particle number distributions, average \( p_T \), energy flow, . . .

  Soft interactions mostly

- **Hard-soft correlations**
  
  How does underlying event depend on hard process and its variables?
  
  UE with hard processes \( \leftrightarrow \) UE with min bias trigger? Change with \( x_1, x_2, M^2 \)?

  Interest: Understand strong interaction dynamics in collision, facilitate search for rare hard processes through cuts

  No strict factorization, additional assumptions needed

*Here: Approach based on transverse geometry. Limited information, but model-independent. Very useful!*
• Intuitive picture

Partonic wave function: Superposition of configurations with different particle number, spatial size, etc.

\[ \text{PDF}(x) = \sum_{\text{configs}} \text{[parton with } x\text{]} \quad \text{one-body density} \]

Underlying event ↔ interactions of spectators

• Hard process kinematics

\[ x_1 x_2 = \frac{M^2}{s} \]

\[ M^2 = 4p_T^2 \quad \text{back-to-back dijet} \]

Typical \( x \)-values \(~10^{-1}–10^{-3}\)
HERA/COMPASS/EIC region
Transverse distributions: Exclusive processes

- Hard exclusive meson production
  
  Meson produced in small–size $q\bar{q}$ configuration

  QCD factorization theorem $Q^2 \gg \mu_{\text{had}}^2 \sim |t|$

  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 partons $x' = x$

  $f(x, \rho) = \int \frac{d^2 \Delta_T}{(2\pi)^2} e^{-i\Delta_T \rho} \text{GPD}(x, t)$ 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 $J/\psi$ at HERA, also $\phi$, $\rho$
  Large $x$: FNAL, COMPASS, JLab12 $\phi$

  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
  $\alpha'_g \approx 0.14 \text{ GeV}^{-2} < \alpha'_\text{soft}$

- $Q^2$ 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 $Q^2 > \text{few GeV}^2$

Transverse geometry in pp: Hard processes

- 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

\[
\sigma_{12}(b) = \int d^2\rho_1 \, d^2\rho_2 \, \delta(b - \rho_1 + \rho_2) \\
\times G(x_1, \rho_1) \, G(x_2, \rho_2) \, \sigma_{\text{parton}}
\]

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 geometry in pp: Soft interactions

- pp elastic scattering amplitude

\[ A(s, t) = \frac{is}{4\pi} \int d^2b \ e^{-i\Delta_T b} \Gamma(s, b) \]

impact parameter representation \((t = -\Delta_T^2)\)

Data ISR, Tevatron, LHC; empirical parametrizations

- Cross sections

\[
\sigma_{el}(s) \sim |A|^2 = \int d^2b \ |\Gamma(s, b)|^2 \quad \text{elastic}
\]

\[
\sigma_{tot}(s) \sim \text{Im} \ A = \int d^2b \ 2 \text{Re} \ \Gamma(s, b) \quad \text{total}
\]

\[
\sigma_{in}(s) = \int d^2b \ [2 \text{Re} \ \Gamma - |\Gamma|^2] \quad \text{inelastic}
\]

Normalized \(b\)-distributions

- Impact parameter distn in min bias events
**Transverse geometry in pp: Hard vs soft**

- **Transverse proton size in soft interactions much larger than in hard processes**
  \[
  R^2_{\text{soft}} \gg \langle \rho^2 \rangle_g(x > 10^{-4}) \quad \text{two scales!}
  \]

- **Two classes of \( pp \) collisions**
  - 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

Frankfurt, Strikman, CW, PRD 69, 114010 (2004) [INSPIRE]; PRD 83, 054012 (2011) [INSPIRE]
Transverse geometry in pp: Hard-soft correlations

Underlying event activity as function of trigger $p_T^{jet}$

- $p_T^{jet} \sim$ few GeV: No hard process, collisions mostly peripheral, low activity
- $p_T^{jet} \gtrsim 10$ 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”

CMS underlying event analysis, JHEP 1509 (2015) 137
Multiparton interactions: Geometry

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

- 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

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

- Enhancement observed

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

  LHC MPI results forthcoming

  Dynamical explanation? Correlations beyond MF

- Transverse distributions of partons determine mean field expectation for MPI

Frankfurt, Strikman, CW, PRD 69, 114010 (2004) [INSPIRE]
Multiparton interactions: Dynamical correlations

- 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

  \[ \langle N | O_{tw_2}(x_1, r_{1T}) \; O_{tw_2}(x_2, r_{2T}) | N \rangle_{r_{1T} - r_{2T} = r_T} \]

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

- $H$ produced in hard process
  \[ \mu_{\text{soft}}^2 \ll Q_{\text{int}}^2 \ll M^2 \]  
  \[ x_{1,2} \sim \frac{M}{\sqrt{s}} \sim 10^{-2} \]  
  Higgs at LHC

- Soft spectator interactions must not produce particles
  \[ S^2 \equiv \frac{\sigma_{\text{diff (full)}}}{\sigma_{\text{diff (no soft)}}} \]  
  Gap survival probability

- Mean-field approximation:
  \[ [V_{\text{hard}}, H_{\text{soft}}] = 0 \]  
  independent, closure of partonic states

- Amplitude calculable in terms of
  - Gluon GPD, unintegrated
  - $pp$ elastic $S$–matrix

Frankfurt, Hyde, Strikman, CW, PRD 75, 054009 (2007) [INSPIRE]
Exclusive diffraction: Gap survival probability

- Gap survival probability
  \[ S^2 = \int d^2 b \ P_{\text{hard}}(b) \ |1 - \Gamma(b)|^2 \]

- Probability for two–gluon collision favors small \( b \)
- Probability for "no inelast. interaction" favors large \( b \)

- "Blackness" of \( pp \) amplitude \( \Gamma(b) \sim 1 \) suppresses diffraction at small \( b \)

- Numerical results in mean–field approx. \( S^2 \sim 0.03 - 0.04 \) Higgs at LHC

- Parton correlations further reduce RGS probability

\( P_{\text{hard}}(b) \) : Overlap of normalized transverse gluon densities (squared)
Exclusive diffraction: $p_T$ dependence

- Gap survival probability depends on final proton transverse momenta $p_{1T}$ and $p_{2T}$

Figure: Dependence on $p_{2T}$ for fixed $p_{1T}$ in $x$-direction

Observable diffraction pattern attests to interplay of hard and soft interactions

Calculable from GPDs and $pp$ elastic amplitude

Frankfurt, Hyde, Strikman, CW, PRD 75, 054009 (2007) [INSPIRE]
Applications and extensions

- Centrality trigger for pp collisions
  
  Hard process at $x_{1,2} \sim 10^{-1} - 10^{-2}$ selects central pp collisions

  Small-$x$ gluon density in central pp collision comparable to heavy nucleus:
  Black-disk regime in leading parton interactions, observables in forward particle production

- Quantum fluctuations of gluon density

  Defined/quantified in context of collinear factorization

  Measured in diffractive VM production $ep \rightarrow e + V + X$(low-mass) \hspace{1cm} HERA, EIC

  Influences MPI, rapidity gap survival in pp

- Parton correlations in $ep$ scattering

  Nonperturbative correlations between sea quarks due to chiral symmetry breaking

  Observable in hadron correlations between current and target fragmentation regions of DIS at intermediate energies ($W^2 \sim 30$ GeV$^2$, $Q^2 \sim 2$–3 GeV$^2$) \hspace{1cm} EIC
Summary

- pp collisions characterized by interplay between hard and soft interactions
  
  Correlations between hard process and event observables
  Proton structure beyond 1-body parton densities

- Transverse geometry essential aspect of pp collisions
  
  Transverse distribution of partons from ep/γp (GPDs)
  Hard processes select central pp collisions
  Geometric correlations explain underlying-event characteristics
  Baseline estimate of MPI rates from geometry and mean-field approximation
  Baseline estimate of gap survival probability in central exclusive diffraction

- Synergies with EIC physics program
  
  Conceptual connections
  
  ep input for next-level analysis of pp collisions: Fluctuations, correlations
  Highest available energies in pp at LHC
Supplementary material
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*

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

- **Scaling model**
  
  Fluctuations of size change effective scale of non-pert 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 $x, Q^2$ 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 $\sigma_{\text{eff}}(\text{fluct}) \approx (1 - \omega_\sigma/2) \sigma_{\text{eff}}(\text{mean field}) \sim 10-15\%$ at Tevatron

  Fluctuation effect on MPI small, cannot explain experimental rates
Parton correlations: Observables in $ep$

- Model of nonperturbative correlations
  Schweitzer, Strikman, CW 12

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

  Sea quark transverse momenta up to $p_T \sim \mu_{\chi_{SB}}$
  Different from valence quarks $p_T \sim R^{-1}$

  Correlated $q\bar{q}$ pairs in nucleon wave function:
  Spin/flavor structure, $\sigma/\pi$ 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