Non-perturbative nucleon structure and multiparton interactions

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• Nucleon structure in QCD
  Non-pert short-distance scale $\sim 0.3$ 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
  Mean-field: Transverse geometry
  Correlations: QCD vacuum structure
  Connections: Higher twist in DIS, intrinsic $k_T$, . . .
Nucleon structure: Parton picture

- **QCD vacuum not empty**
  
  Strong non-perturbative gluon fields of size $\rho \sim 0.2 - 0.3$ fm
  
  Lattice QCD simulations
  
  $\bar{q}q$ pair condensate, $\pi$ 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 $Q^2_{\text{eff}} \gg |t|$  
Collins, Frankfurt, Strikman 96

GPDs: Gluonic 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 $x' = x$

$$G(x, \rho) = \int \frac{d^2 \Delta_T}{(2\pi)^2} e^{-i\rho \Delta_T} \text{GPD}(x, t)$$  
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 $J/\psi$

- Transverse distribution of gluons from exclusive $J/\psi$ (also $\phi, \rho$)
  
  Transverse profile from relative $t$–dep.

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

- Interesting observations
  
  Average gluonic size $\langle \rho^2 \rangle_g$ much smaller than soft nucleon size $\sim 1 \text{ fm}^2$

  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
Transverse distribution: Hard processes in $pp$

- 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 parameter $b$

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

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

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

- 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

\[
\sigma_{\text{soft inel}}^{pp}(b) = 1 - |1 - \Gamma(s, b)|
\]

\[
R^2(\text{soft}) \gg \langle \rho^2 \rangle_g(x > 10^{-4}) \quad \text{"Two-scale picture"}
\]

- 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 \( \rightarrow \) centrality \( \rightarrow \) event chars
E.g. transverse multiplicity \( \rightarrow \) Talk Frankfurt

New tests of dynamical mechanisms in particle production
Multiparton processes: Transverse geometry

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

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

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

  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 $+ \gamma$ 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 $\rightarrow$ Minkowski?
  - CDF data consistent with transverse lumps of size $\rho \sim 0.3$ 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
  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

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

- 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 $\sim 2$ compared to mean field
  Affects rate of multiparton processes in pp@LHC
  New opportunities for nucleon structure studies  
  “Next step” after one–body densities