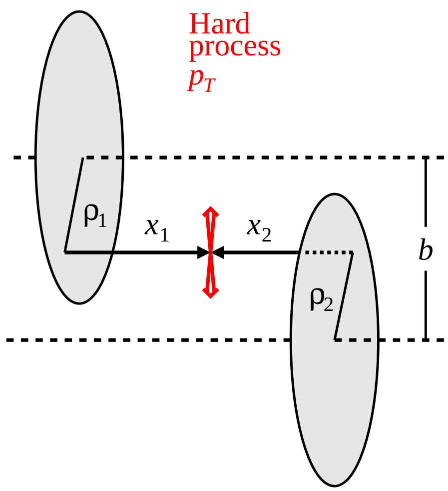
GPDs and transverse geometry in high-energy pp collisions

C. Weiss (JLab), INT Program INT-18-3, U. Washington, 04-Oct-2018
Jefferson Lab



GPDs from $ep/\gamma p$

Input for analysis ↓ ↑ New probes?

Underlying event / MPI in pp

Based on work with L. Frankfurt, M. Strikman 2004–

- 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

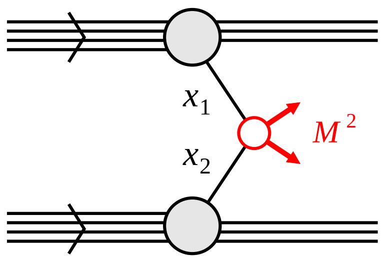
  Hard-soft correlations

  Multiparton interactions

- Exclusive diffraction $pp \to p + H + p$

  Rapidity gap survival probability

Hard processes in pp

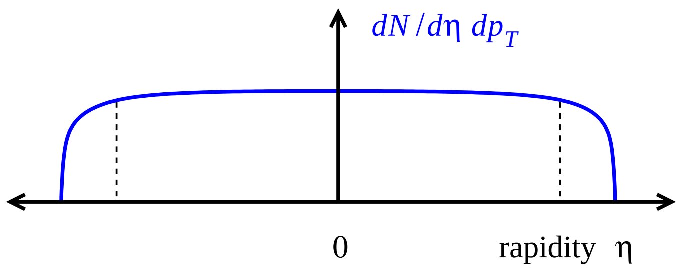


- Inclusive cross section

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

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

  PDF same as in ep



- Underlying event characteristics

  Many observables: Particle number distributions, average p_T, energy flow, . . .

  Soft interactions mostly

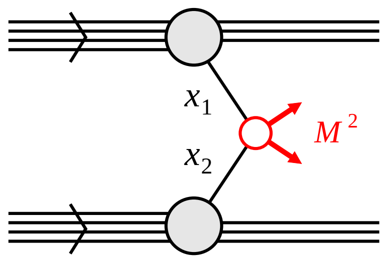
- Hard-soft correlations

  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!

Hard processes in pp

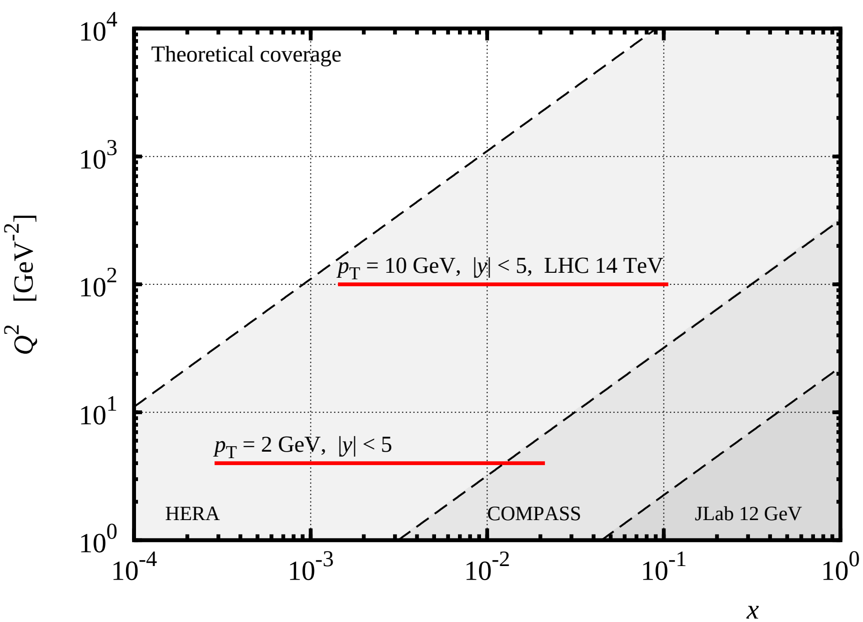


- Intuitive picture

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

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

Underlying event $\leftrightarrow$ interactions of spectators



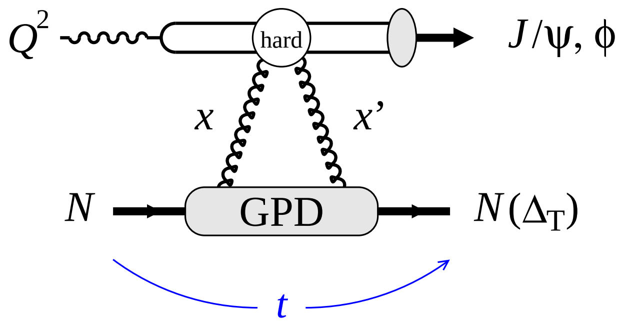
- Hard process kinematics

$$x_1 x_2 = \frac{M^2}{s}$$

$M^2 = 4p_T^2$ back-to-back dijet

Typical x-values $\sim 10^{-1}$–10^{-3}
HERA/COMPASS/EIC region

Transverse distributions: Exclusive processes



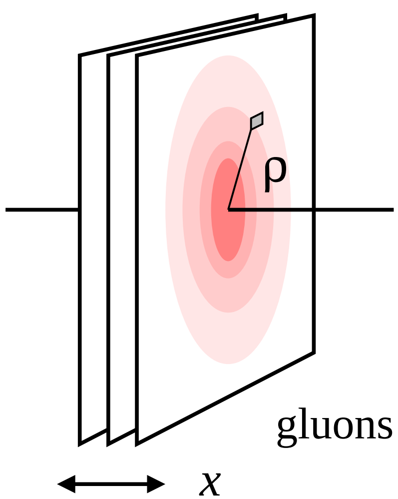
- Hard exclusive meson production

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

  QCD factorization theorem $Q^2 \gg \mu^2_{\mathrm{had}} \sim |t|$
  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



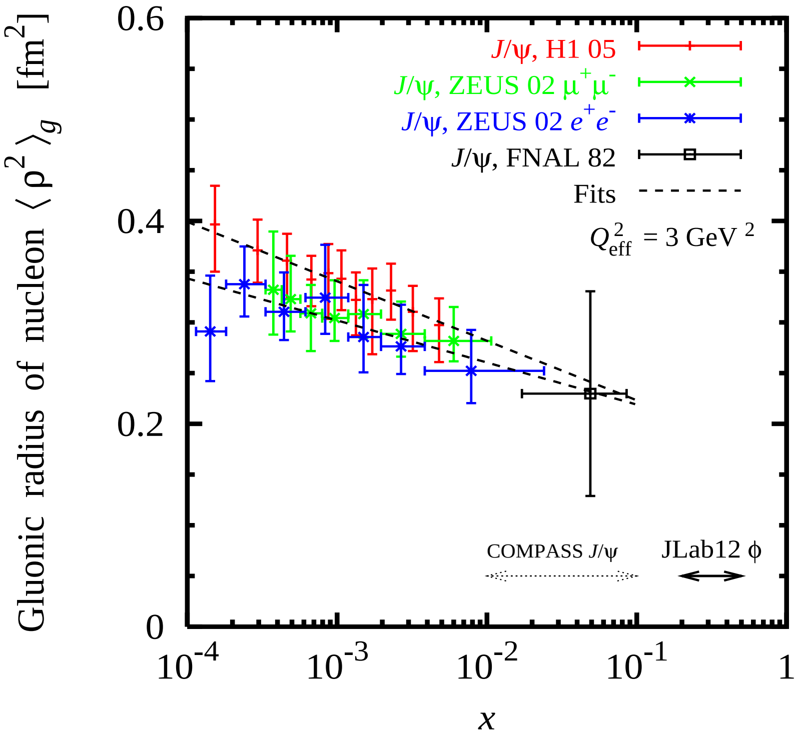
- Transverse spatial distribution of partons $x' = x$

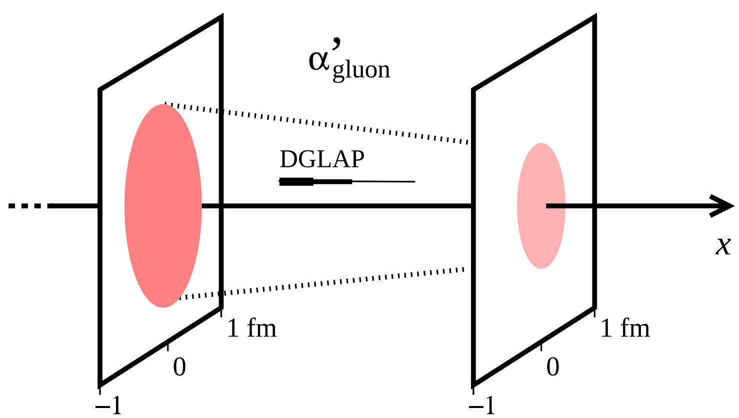
  $$f(x, \boldsymbol{\rho}) = \int \frac{d^2\Delta_T}{(2\pi)^2}\, e^{-i\boldsymbol{\Delta}_T \boldsymbol{\rho}}\, \mathrm{GPD}(x, t)$$ 2D Fourier

  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





Frankfurt, Strikman, Weiss, PRD 69, 114010 (2004) [INSPIRE]; PRD 83, 054012 (2011) [INSPIRE]

- 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 $\langle \rho^2 \rangle_g = 2B_{\rm excl}$

- Important observations

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

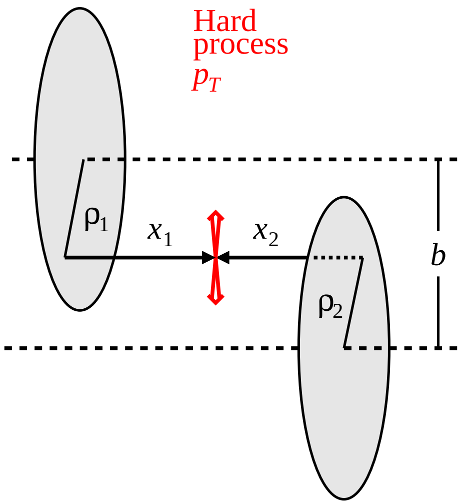
  Grows with effective Regge slope $\alpha'_g \approx 0.14\,\mathrm{GeV}^{-2} < \alpha'_{\rm soft}$

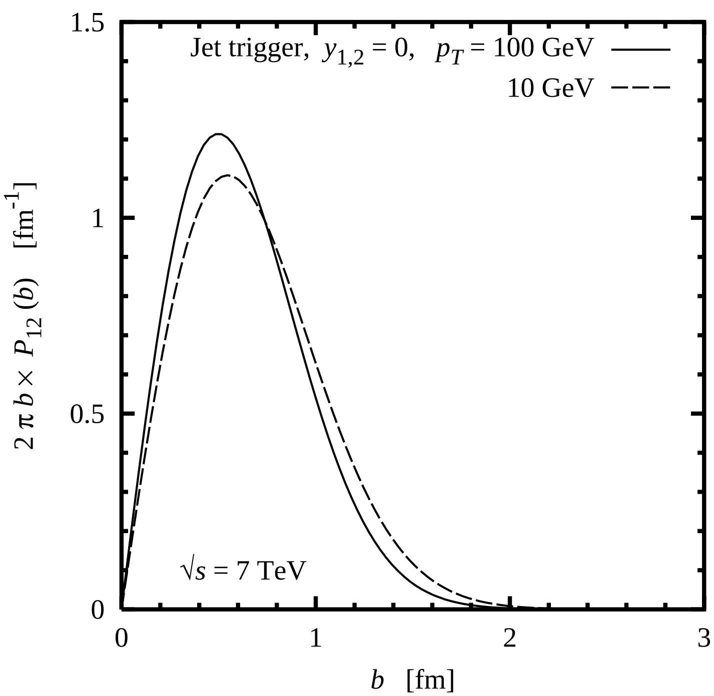
- Q^2 dep. from DGLAP evolution

  Partons decay locally in transverse space

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

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

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

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

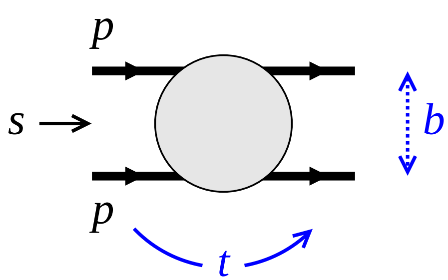
- New information available

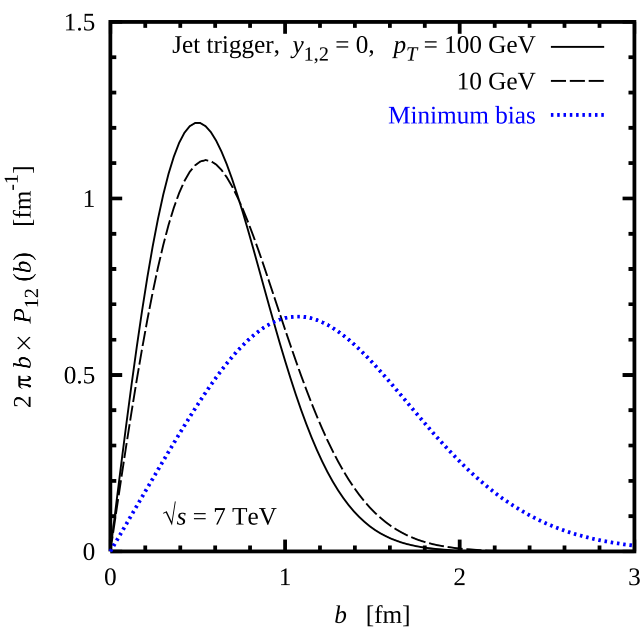
  Model spectator interactions depending on b
  Underlying event

  Predict probability of multiple hard processes
  Dynamical correlations? FSW04

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

Transverse geometry in pp: Soft interactions





- pp elastic scattering amplitude

$$A(s,t) \;=\; \frac{is}{4\pi}\int d^2b \;\; e^{-i\boldsymbol{\Delta}_T \boldsymbol{b}}\,\Gamma(s,b)$$

impact parameter representation $(t = -\boldsymbol{\Delta}_T^2)$

Data ISR, Tevatron, LHC; empirical parametrizations

- Cross sections

$$\sigma_{\rm el}(s) \;\sim\; |A|^2 \;=\; \int d^2b\,|\Gamma(s,b)|^2 \qquad \text{elastic}$$

$$\sigma_{\rm tot}(s) \;\sim\; \text{Im } A \;=\; \int d^2b\;\; 2\text{ Re }\Gamma(s,b) \qquad \text{total}$$

$$\downarrow$$

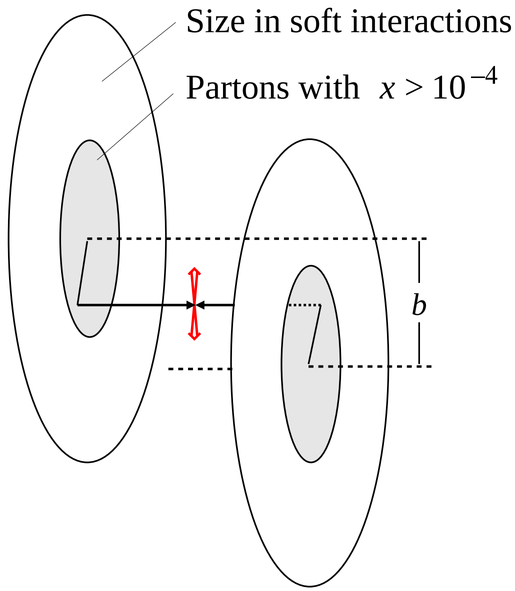
$$\sigma_{\rm in}(s) \;=\; \int d^2b\,[2\text{ Re }\Gamma - |\Gamma|^2]$$

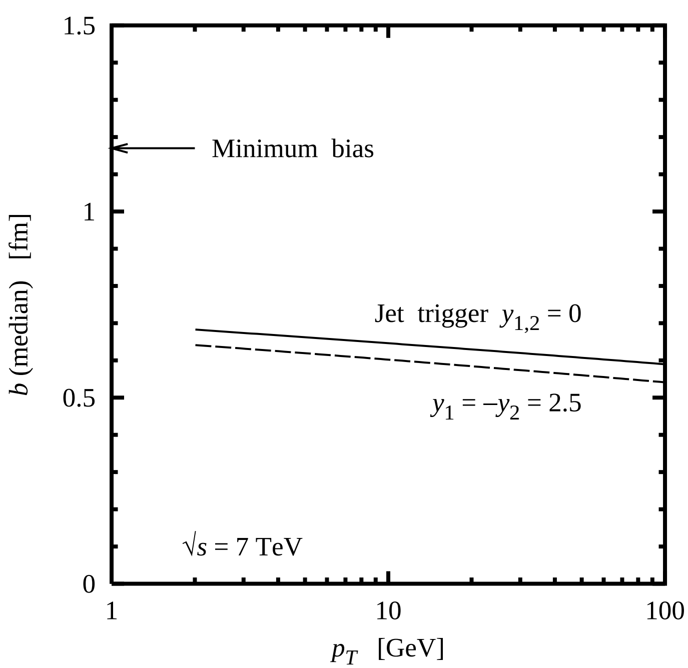
$$=\;\;\ldots\;[1 - |1-\Gamma|^2] \qquad \text{inelastic}$$

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

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

- Two classes of pp collisions

  Peripheral: Most of inelastic cross section

  Central: High probability for hard process

- Hard processes select central collisions

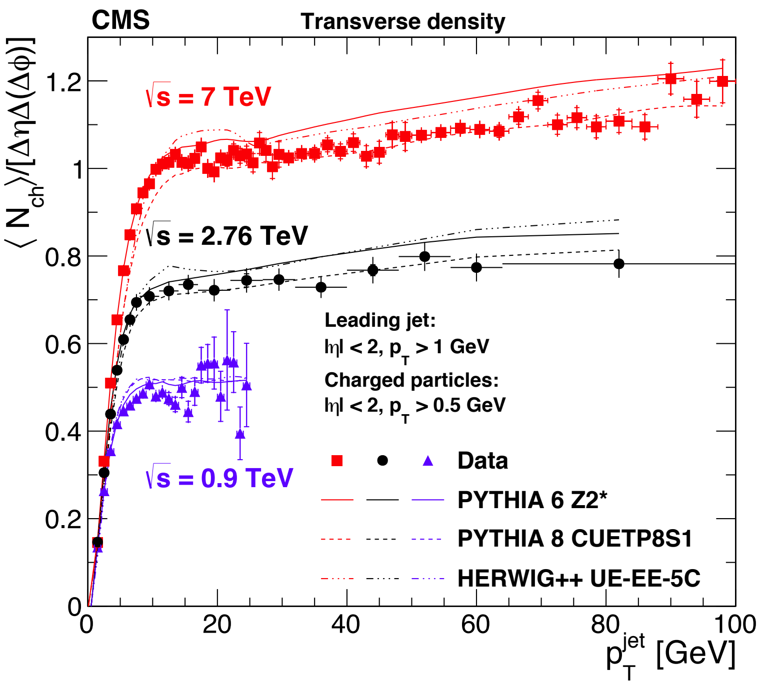
  Underlying event in hard processes very different from min. bias collisions

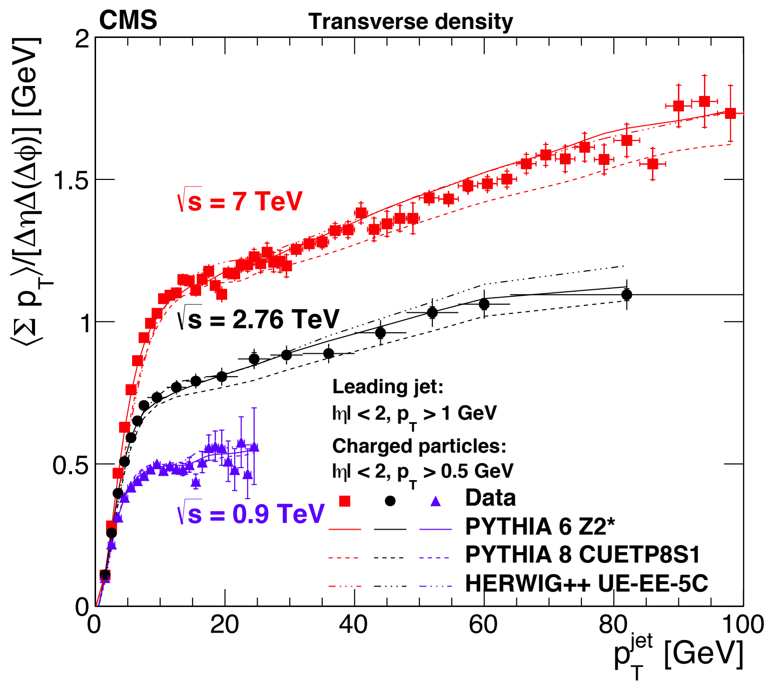
  Geometric correlations:
  Hard process $\leftrightarrow$ centrality $\leftrightarrow$ event chars

  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

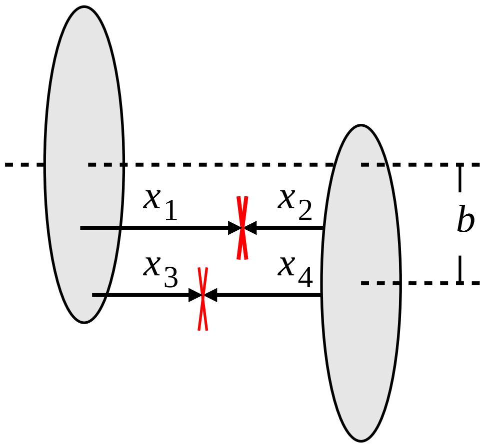




CMS underlying event analysis, JHEP 1509 (2015) 137

- 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"

Multiparton interactions: Geometry



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

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

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

- Mean field approximation

  Calculable from transverse distributions

  σ_{eff}^{-1} (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

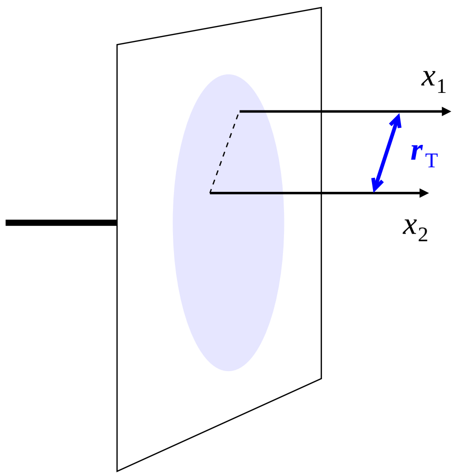
  LHC MPI results forthcoming

  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



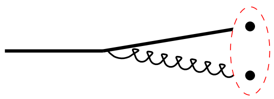
- Parton correlations in nucleon

  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

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

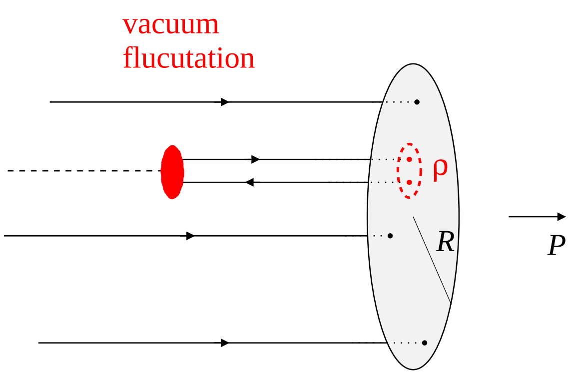
  Subtleties: UV divergences, renormalization, mixing



- Perturbative and non-perturbative correlations

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

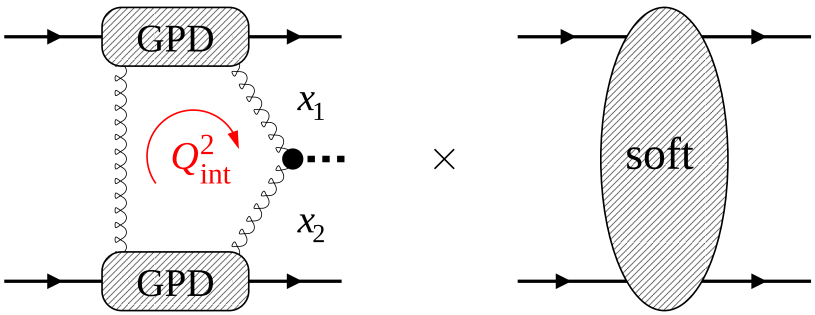
  Chiral symmetry breaking: Nonperturbative $q\bar{q}$ pairs with transverse size $\ll 1$ fm
  Schweitzer, Strikman, CW 12. Cf. Shuryak 82; Diakonov, Petrov 84

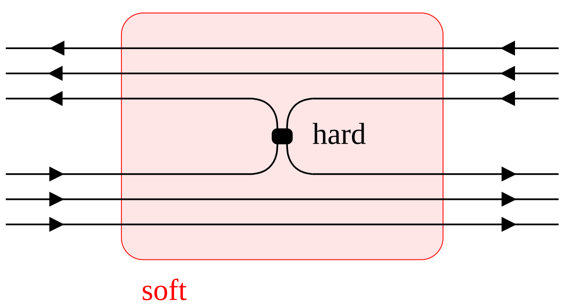


- Effect on MPI

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

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





Different time/distance scales

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

- H produced in hard process

  $\mu^2_{\text{soft}} \ll Q^2_{\text{int}} \ll M^2$ Khoze et al. 97+

  $x_{1,2} \sim \frac{M}{\sqrt{s}} \sim 10^{-2}$ Higgs at LHC

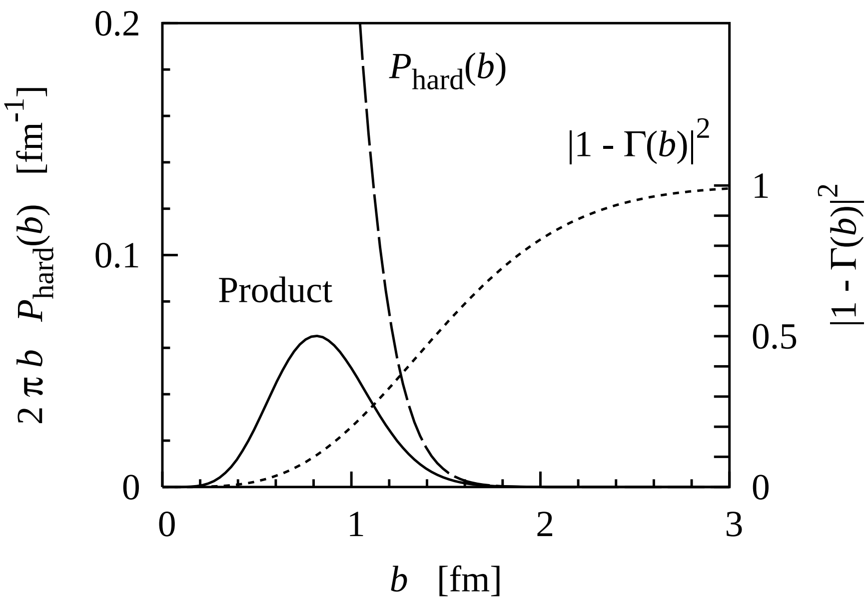
- Soft spectator interactions must not produce particles

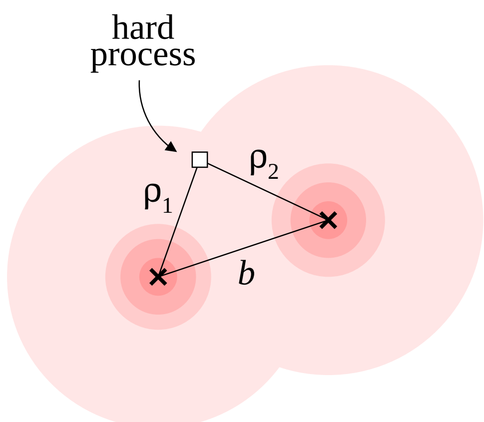
  $S^2 \equiv \frac{\sigma_{\text{diff}}(\text{full})}{\sigma_{\text{diff}}(\text{no soft})}$ Gap survival probability

- 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

Exclusive diffraction: Gap survival probability





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

- Gap survival probability

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

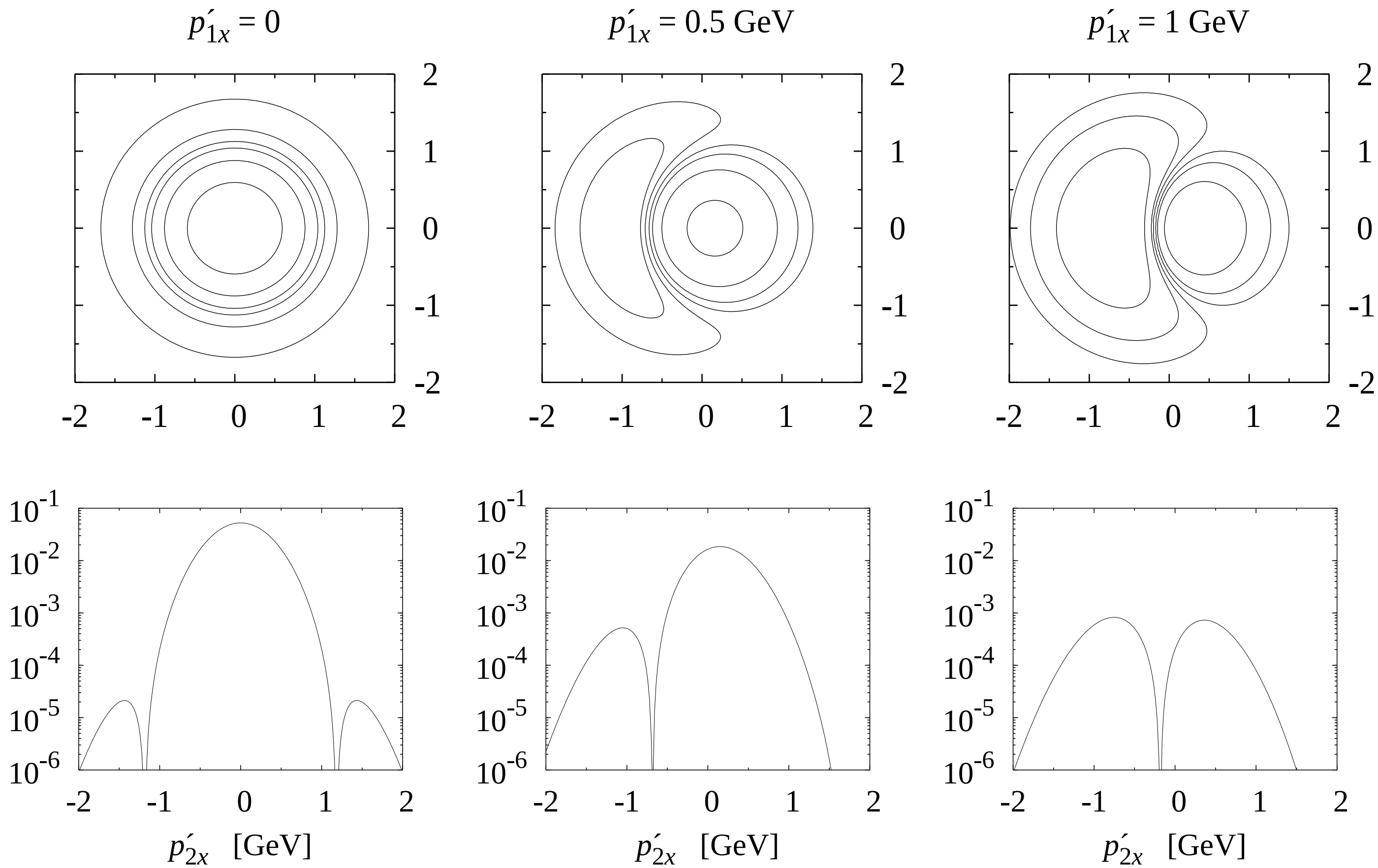
Probability for two–gluon collision	Probability for "no inelast. interaction"
favors small b	favors large b

- "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

Exclusive diffraction: p_T dependence



- Gap survival probability depends on final proton transverse momenta $\boldsymbol{p}_{1T}$ and $\boldsymbol{p}_{2T}$

  Figure: Dependence on $\boldsymbol{p}_{2T}$ for fixed $\boldsymbol{p}_{1T}$ 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) 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) 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 $ep/\gamma p$ (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

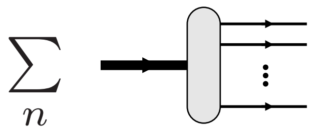
  Conceptual connections

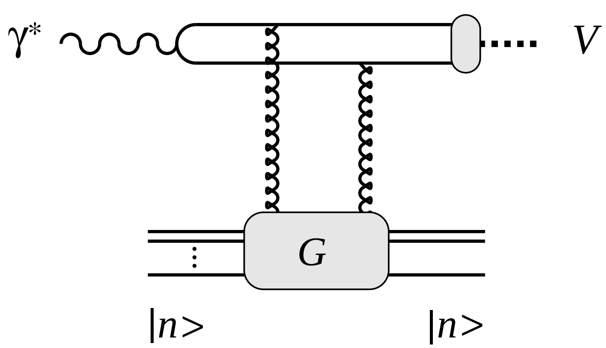
  ep input for next-level analysis of pp collisions: Fluctuations, correlations

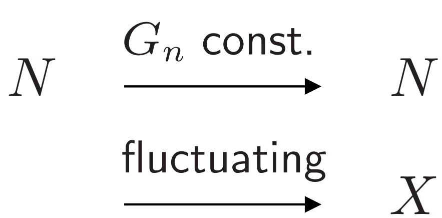
  Highest available energies in pp at LHC

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

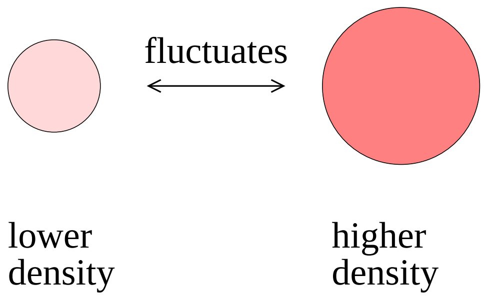
  Hard diffractive processes at small x

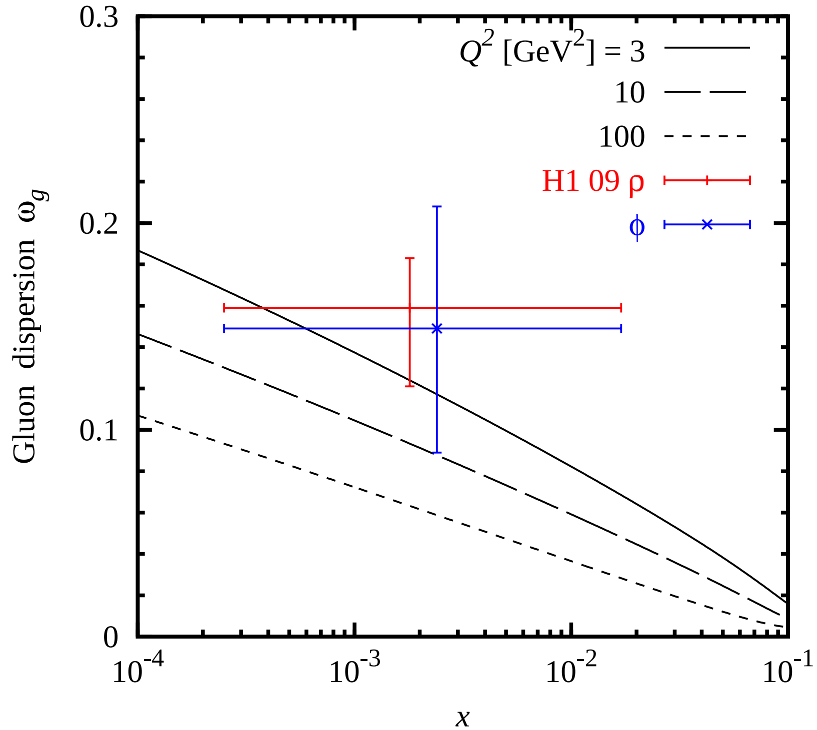
  Amplitude diagonal in partonic states $|n\rangle$, proportional to configurations's gluon density G_n

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

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

Quantum fluctuations: Sizes and MPI





- Scaling model Close et al. 83: EMC effect

  Fluctuations of 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

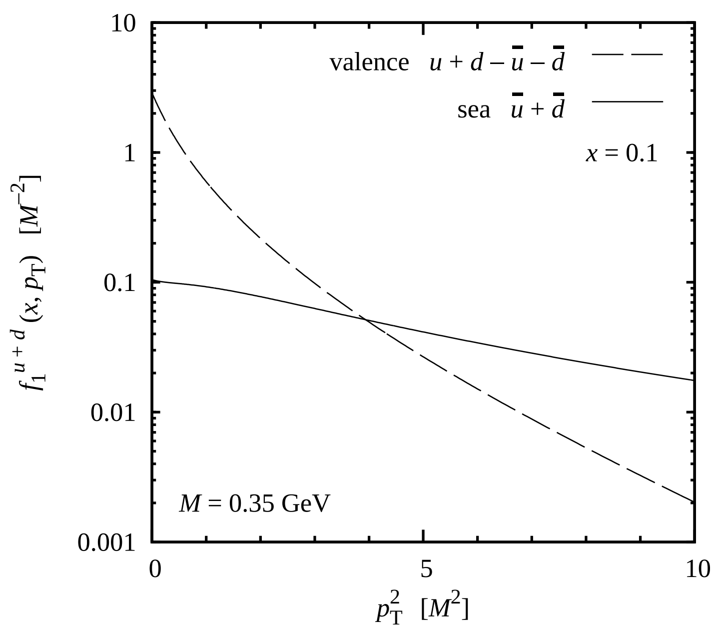
- Fluctuation effect on MPI

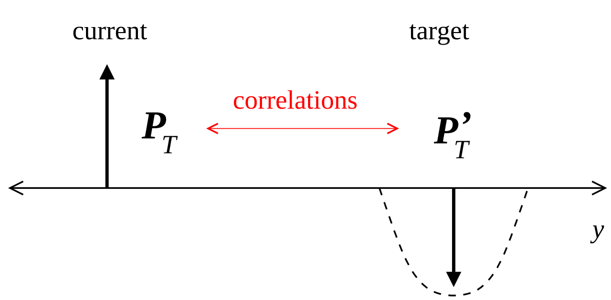
  Small effect of gluon density fluctuations
  $\omega_g < 0.1$ at Tevatron

  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: 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, Polylitsa 88

  Sea quark transverse momenta up to $p_T \sim \mu_{\chi\text{SB}}$
  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