Nonperturbative QCD in pp scattering at the LHC

IX Simpósio Latino Americano de Física de Altas Energias
SILAFAE

Jochen Bartels,
Hamburg University and Universidad Técnica Federico Santa Maria

- Introduction: the transverse distance scale
- Total cross section, elastic scattering
- BFKL and recent developments
- multiple interactions
- saturation
- diffraction

Not covered: heavy ion collisions (AAS or pA)
At the LHC we are looking for new physics (mostly) at large momentum scales which allows to use ‘hard QCD’:

- parton densities,
- partonic subprocesses,
- jets
- ...

But: there is another class of final states which

1) has large cross section:
   - total cross section is about 100 mb
   For comparison:
     - cross sections of hard processes are smaller:
       - Typical jet cross section at the LHC: $10 - 100 \, \mu b$
       - Higgs cross section: $\mathcal{O}(pb)$
2) are fully or partly nonperturbative
Perturbative vs. nonperturbative QCD: relevant scale is the transverse distance

time, longitudinal direction

long extension along incoming direction

transverse plane

\[ T(s, t) \sim is \int d^2 b e^{i\vec{q} \cdot \vec{b}} A(s, \vec{b}), \quad t = -\vec{q}^2 \]

\[ \sigma_{\text{tot}} = \frac{1}{s} \text{Im} T(s, 0) \sim \int d^2 b A(s, \vec{b}) \]

\[ R^2(s) = R_A^2 + R_B^2 + \alpha' \ln s \]

long formation time

wee parton cloud

A

B

nonperturbative
short distance - long distance:

static potential:

\[ V(\vec{r}) \]

short distance: coulomb potential

large distance: linear potential, string tension

short distance: dipole-dipole: BFKL

long distance: hadron-hadron: Pomeron

no finite radius, cloud grows with power of energy

hadron size \( r_{A,B} \), Pomeron slope
• hard processes confined to small regions

• total cross section, elastic scattering probes all distances

• most processes lie in between; in particular:

  BFKL searches start in small regions, but are sensitive to large distances

  multiple interactions and saturation explore the interface

  hard diffraction is sensitive to small and large distances

• each final state has its own way to exhibit large distance effects

• Total cross section, elastic scattering
• BFKL and recent developments
• multiple interactions
• saturation
• diffraction
Total cross section, elastic scattering

Sizes of soft cross section:

- total cross section: 98 mb
- elastic cross section: 24.8 mb
- single diffractive cross section: 14.16 mb
- double diffractive cross section: 8.8 mb
- inelastic cross section: 70 mb

Forward direction has large cross sections: theory wanted!
Fig. 2: The new TOTEM data demonstrate the continuation of the trends from earlier measurements, and indicate the high precision of the TOTEM experiment.
Theory/models for total cross section: \( \sigma_{tot} = 98.3 \text{mb} \)

Block, Halzen: Fit of formula (95.4)
\[
\sigma_{tot} = 90.281 \left( \ln \frac{\nu}{m} \right)^2 - 1.44 \ln \frac{\nu}{m} + 37.2 + 37.1 \left( \frac{\nu}{m} \right)^{-0.5}
\]

Donnachie, Landshoff: Regge pole, soft plus hard (soft alone: \( \sigma_{tot} \approx 91 \text{mb} \))
\[
\sigma_{tot} = c_1 s^{\alpha_{P,\text{soft}}(0)-1} + c_2 s^{\alpha_{P,\text{hard}}(0)-1} \quad (98)
\]
\[
\text{soft: } \alpha_{P,\text{soft}}(t) = 1.093 + \alpha' + 0.25t \quad \text{hard: } \alpha_{P,\text{hard}}(t) = 1.362 + \alpha' + 0.1t
\]

Eikonal ansatz for elastic cross section

Tel Aviv (Gotsman, Levin, Maor) (98.6)
Durham (Martin, Khoze, Ryskin) (96.4)

Pomeron graphs
Elastic cross section: dip structure

(a) The first TOTEM data on differential cross-section of elastic p+p scattering at $\sqrt{s} = 7$ TeV, measured in the momentum transfer range of $0.36 \leq |t| \leq 2.5$ GeV$^2$.

(b) When compared to predictions of different models, the TOTEM elastic scattering $d\sigma/dt$ data show a strong discriminative power.

Fig. 1: TOTEM elastic scattering $d\sigma/dt$ data measurements at $\sqrt{s} = 7$ TeV.
Comparison with $p\bar{p}$ (although at different energies): signal for the Odderon?

Simplest explanation: three gluon exchange (Donnachie, Landshoff: ISR data) = beginning of Odderon (analogue of BFKL)
Small-size dipole scattering: BFKL

Elastic scattering of two small dipoles

\[ \text{Im } T_{\gamma^* \gamma^*} = \sum \text{sum over gluon production} \]

Important properties:

- growth with energy:
  \[ \sigma_{\gamma^* \gamma^*}^{\text{tot}} \sim S \omega_{BFKL}, \quad \omega_{BFKL} = \alpha_s \frac{4N_c \ln 2}{\pi} + O(\alpha_s^2) \]

- strong growth in transverse direction
More remarkable properties of the BFKL Pomeron:

1) unitarity:
   nonlinear equations
   bootstrap equation

\[ \text{Im} T_{2\rightarrow 2} = \sum_n \int d\Omega_n |T_{2\rightarrow n}|^2 \]

2) Beginning of a 2+1 dim field theory, with reggeized gluons as d.o.f.

3) In LO: two-dimensional conformal invariance (Moebius invariance):
   connection with N=4 SYM (=most symmetric gauge theory),
   integrability, theory might be solvable

4) Electroweak theory, gravity:
   high energy behavior vs. renormalizibility
How to test this calculation:

1) $\gamma^*\gamma^*$ collisions in electron-positron scattering (LEP)
2) Mueller-Navelet jets in pp-scattering (Tevatron, LHC)

---

ok, not fully convincing

---

HERA, forward jets

LHC, Mueller-Navelet

wait for data

---
Comments on BFKL-related activities for the LHC:

1) NLO available: BFKL, jet vertex, numerical analysis
2) Angular decorrelation as BFKL signal

3) BFKL energy dependence: use different machine energies
Jet-gap-jet (hard color singlet exchange)

\[ \frac{d\sigma^{pp}}{dx_1 dx_2 dE_T^2} = S f(x_1, E_T) f(x_2, e_T) \frac{d\sigma^{qq\rightarrow JJ}}{dE_T^2}(\eta, E_T) \]

Survival factor S: (other chains, radiation?)
Modelled by Monte Carlo

BFKL needs all conformal spins

Cox, Forshaw, Lonnblad; Enberg, Ingelman, Motyka; Royon

Monday, December 10, 12
New formulation of BFKL (HERA): discrete Regge poles

BFKL equation is often written as evolution equation

\[ \frac{\partial}{\partial y} \psi(y, k) = \int d^2k' K_{BFKL}(k, k') \psi(y, k') \]

where kernel has continuous eigenvalue spectrum.

Instead: boundary conditions at infrared plus asymptotic freedom lead to discrete spectrum. Quasiclassical picture:

Eigenvalues and wave functions are sensitive to changes at turning points in UV region

Fit to HERA data. Signal of new physics?
Multi-Parton Interactions (MPI)

Inclusive cross section vs. underlying event:

Inclusive cross section

- Remnant
- Partons (quarks, gluons)
- Final state radiation
- Hadronization

Pictures have slightly different meaning:

- Event → cross section involves summation
- Cancellations (collinear factorization, AGK)

Important consistency check!
Important question: where is diffraction (rapidity gaps)?

Soft diffraction:

BUT: second, third... chain may fill the gap, less diffraction

Sum over chains and all rescattering effects:

lowers the probability of rapidity gaps
(semi)hard diffraction: add new contribution

As in soft diffraction: additional chains fill the gap.

Leaves the eikonal approximation!
Double parton cross sections:

\[ d\sigma = \sum_{i_1 i_2} \int dx_1 dx_2 f_{i_1}(x_1, \mu) d\tilde{\sigma}_{i_1 i_2 \rightarrow 2\text{jet}}(x_1, x_2; \mu; p_1, Y_1, p_2, Y_2) f_{i_2}(x_2, \mu) \]

single parton (no rescattering)

\[ d\sigma^{DP} = \frac{m}{\sigma_{\text{eff}}} \sum_{i_1, j_1, i_2, j_2} \int dx_1 dy_1 dx_2 dy_2 H_{i_1 j_1}(x_1, y_1, \mu_a, \mu_b) \]

\[ d\tilde{\sigma}_{i_1 i_2 \rightarrow \text{jet}}(x_1, y_1, \mu_a; p_1, Y_1) d\tilde{\sigma}_{j_1 j_2 \rightarrow \text{jet}}(y_2, y_2, \mu_b; p_2, Y_2) H_{i_2 j_2}(x_2, y_2, \mu_a, \mu_b) \]

correction: double parton (no rescattering)
Cross sections have been calculated (e.g. double J/Psi)

Theoretical questions being addressed:

Evolution of double parton densities:
• double DGLAP misses transverse dependence
• corrections: correlations, splitting

• Higher twist suppression: only after integration over jet momenta
Saturation

Saturation was first discussed in the context of small-\(x\) gluon densities at HERA, later on it started to play a major role in ion collisions (color glass condensate)

\[
Q_s^2 = Q_0^2 \left( \frac{1}{x} \right)^\lambda
\]

Saturation scale \(Q_s \approx 1\)GeV at \(x = 10^{-5}\)

Evidence in ep scattering:
- geometric scaling
- successful models for \(F_2\)
- ratio of diffractive to total cross section
Saturation at the LHC (in pp): larger kinematic region

Potential signals:
• $\langle pt \rangle, \langle n \rangle$?
• Ridge effect?
• Drell Yan in forward region

much more in AA and pA: larger saturation scale
Ridge effect in pp and pA collisions: two particle correlation, azimuthal correlations

Saturation is a strong candidate:
- strong field: high density
- low $p_T$: saturation momentum
  \[ x = 10^{-5} \rightarrow Q_s \approx 1\text{GeV} \]
- angular correlation: need extra ingredient
\[ p = q \]

Form factor effect

\[ |p-k| \approx |q-k| \approx Q_s: \quad \overrightarrow{p} = \overrightarrow{q} \]

Saturation form factor effect

Difference between pp and pA is in the details of saturation
Diffractive/rapidity gap processes

Central exclusive production (CEP): forward spectrometer

Topic of intense discussion

Experimental aspects: clean signal, precise mass determination
Theoretical ingredients: parton densities, Sudakov factor, suppression rules, survival probability

Needed: NLO calculation of hard subprocess

\[ \sigma(pp \to p + H + p) \sim \left( \frac{S^2}{B^2} \right) \left[ N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x'_1, Q_t^2, \mu^2) f_g(x_2, x'_2, Q_t^2, \mu^2) \right]^2 \]
Higgs Boson: cross section predictions

Cross section \( \sim \) fbs, i.e. roughly 4 orders of mag. lower than inclusive case (price paid for exclusivity).

CEP of a CP-odd Higgs suppressed by \( \sigma(0^-)/\sigma(0^+) \sim 1/100 \rightarrow \) with just a few signal events, the Higgs quantum numbers can be determined (does not rely on coupling to weak bosons).
Recent developments:

- Diphoton seen at Tevatron
- double meson states, resonances
- $\chi_c$ production

\[
W_{\gamma\gamma} \leq 1.8 \text{ TeV}
\]

Two photon physics:

Learn about CEP dynamics

Figure 1: Feynman diagrams for the signal (triple gauge couplings on the left, quartic on the right)

VV-scattering: unitarity problem
Conclusions

Fundamental problem in ‘nonperturbative high energy QCD’: understand the transition and the large distance region

small  ➡  large transverse distance region

Small: BFKL, DGLAP  Large: total, elastic cross section (Pomeron)

most final states sensitive to both, e.g.

• multiple interactions
• saturation
• diffraction

their study provides the necessary theoretical help