Forward Physics and Cosmic Rays: Introduction

Convenors: M. Grothe, F. Hautmann and S. Ostapchenko
I. Introduction to 11 talks in Forward Physics and Cosmic Rays session:

- LHC experimental results [5]
- Auger [1]
- HERA [1]
- Theory [4]

◊ With the advent of the LHC, forward physics becomes largely a new field both from theory and experiment standpoints.

↓

II. Introduction to key themes from forward-region phenomenology
Particle production in the forward region at hadron colliders:

\[ p \rightarrow \text{hadrons} \rightarrow p \]

small polar angles, i.e. large rapidities

◊ Historically:

• fairly specialized subject: e.g., measurements of \( \sigma(\text{total}) \) and \( \sigma(\text{elastic}) \)
  
  • dominated by soft, small-\( p_T \) processes

◊ At the LHC:

• forward processes involve both soft and hard production
  
  • phase space opening up for large \( \sqrt{s} \) \( \Rightarrow \) multiple-scale processes
  
  • unprecedented coverage of large rapidities (calorimeters + proton taggers)
  
  \[ \Rightarrow \]

• forward high-\( p_T \) production

• central production of high \( p_T \) + forward protons
Measurements of forward particle production (soft and hard) at the LHC serve as input to Monte Carlo models of high-energy showers in cosmic ray physics.

- Fixed target collision in air with $10^{17}$ eV corresponds to pp interaction at LHC.
LHC experimental results

◊ **A)** Forward physics via main detectors + forward calorimeters:
  - Low-$x$ physics via LHC-b [J. Anderson]
  - Forward particle production + energy flow: CMS [S. Cerci]
  - Forward particle production + energy flow: LHC-f [L. Bonechi]

◊ **B)** ‘Vetoes on forward detectors’:
  - LHC Diffraction [S. Navin]

◊ **C)** Physics with near beam proton taggers:
  - TOTEM

Future physics:
  - High-luminosity diffraction and $\gamma$ physics
  - Central exclusive production and discovery physics
NOTE:

♦ Nearly all above topics imply **new experimental areas**: prime start-up physics subjects

♦ **Theoretical issues**: LHC is to a large extent a QCD machine; LHC forward physics is dominated by QCD at small $x$.

   ⇓

   • Factorization at small $x$
   • Evolution / parton showering beyond collinear ordering
   • High-density effects and parton saturation

♦ **Phenomenology**: How well do current Monte Carlo generators simulate LHC final states in the forward region?
Not only LHC physics…: The Cosmic Ray / Collider connection

[talk by G. Rodriguez]

R. Engel, 2010
Inputs from HERA: Diffraction in DIS and photoproduction

[talk by R. Polifka]

- new diffractive fits with HERAII data
- diffractive jet photo- and lepto-production
- diffractive $F_L^{(D)}$

+ further new results coming up from HERA analyses
OUTLINE

- Forward region $\Rightarrow$ multiple-scale, small-$x$ physics

  $\Rightarrow$ Evaluation of QCD theoretical predictions in multi-scale regime:

  - Perturbative QCD resummations?
  
  - Corrections beyond single parton scattering?
  
  - Theory tools to treat hard and soft interactions?
II. High-$p_T$ production in the forward region

- multiple hard scales
- asymmetric parton kinematics $x_A \to 1$, $x_B \to 0$

◊ Are fixed-order QCD calculations reliable in the forward region?
◊ Are perturbative QCD resummations to be performed?

[talks by Anderson, Lykasov, Deak]
Forward jet production as a multi-scale problem

- summation of high-energy logarithmic corrections long recognized to be necessary for reliable QCD predictions
  ⇒ BFKL calculations

  *Mueller & Navelet, 1987; Del Duca et al., 1993; Stirling, 1994; Colferai et al., arXiv:1002.1365*

- Large logarithmic corrections are present both in the hard scale and in the rapidity interval

  \[ \text{rapidity} \quad \text{BFKL} \quad k_T – \text{factorization} \quad \rightarrow \text{collinear} \]

  \[ \rightarrow \text{Both kinds of log contributions can be summed consistently to all orders of perturbation theory via QCD factorization at fixed } k_T \]
Forward jets:

- High-energy factorization at fixed transverse momentum

\[
\frac{d\sigma}{dQ_t^2 \, d\phi} = \sum_a \int \Phi_{a/A} \otimes \frac{d\hat{\sigma}}{dQ_t^2 \, d\phi} \otimes \phi_{g^*/B}
\]

needed to resum consistently both logs of rapidity and logs of hard scale

Deak, Jung, Kutak & H, JHEP 09 (2009) 121

Figure 1: Factorized structure of the cross section.

- \(\phi_a\) near-collinear, large-\(x\); \(\phi_{g^*}\) \(k_\perp\)-dependent, small-\(x\)
- \(\hat{\sigma}\) off-shell continuation of hard-scattering matrix elements
FULLY EXCLUSIVE MATRIX ELEMENTS: BEHAVIOR AT LARGE $k_T$

$Q_t = \text{final-state transverse energy (in terms of two leading jets } p_t \text{'s)}$

$k_t = \text{transverse momentum carried away by extra jets}$

- dynamical cut-off at $k_t \sim Q_t$, set by higher-order radiative effects
- non-negligible terms from finite $k_t$ tail
- $C_F C_A$ contribution to $qg$ dominates at high energies $s/Q_t^2 \gg 1$
Multiple parton interactions

Multi-jet production by (left) multiple parton chains; (right) single parton chain.

- modeled by shower Monte Carlo generators
  
  *Sjöstrand & Skands, 2006; Gieseke et al., 2008*

◊ Do multiple parton interactions become non-negligible in hard processes at forward rapidities?
FORWARD-CENTRAL JET CORRELATIONS

- polar angles small but far enough from beam axis
- measure correlations in azimuth, rapidity, $p_T$

\[ p_\perp \gtrsim 20 \text{ GeV}, \Delta \eta \gtrsim 4 \div 6 \]
1 central + 1 forward jet: 
particle and energy flow in the inter-jet and outside regions
Cross section as a function of the azimuthal difference $\Delta \phi$ between central and forward jet for different rapidity separations

[Deak et al., in progress]

MC models:
- **CASCADE**: non-collinear radiative corrections to single parton chain
- **PYTHIA**: multiple parton interactions, no corrections to collinear approximation
Transverse energy flow in the inter-jet region

- higher mini-jet activity in the inter-jet region from corrections to collinear ordering
Transverse energy flow in the outside region

- at large (opposite) rapidities, full branching well approximated by collinear ordering
- higher energy flow only from multiple interactions
Diamond Energy flow due to minijets ($E_T > 5$ GeV) ⇒ reduced IR sensitivity ⇒ ‘tune’ (semi-)hard interaction component

Diamond Particle spectra will serve similar purpose

Diamond Distribution in $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ also potentially useful ($\leftrightarrow$)
Figure 5: $\Delta R$ distribution of the central ($|\eta_c| < 2$, left) and forward jets ($3 < |\eta_f| < 5$, right) for $E_T > 10$ GeV (upper row) and $E_T > 30$ GeV (lower row). The prediction from the $k_\perp$ shower (CASCADE) is shown with the solid blue line; the prediction from the collinear shower (PYTHIA) including multiple interactions and without multiple interactions is shown with the red and purple lines. $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$, where $\Delta \phi = \phi_{jet} - \phi_{part}$, $\Delta \eta = \eta_{jet} - \eta_{part}$.
FURTHER QUESTIONS

♠ What are the implications of higher mini-jet activity in the between region for vector boson fusion search channels?

♠ Could one include multi-parton interactions in a complete parton factorization picture?

♠ Could one achieve a unified understanding of forward hard processes including DIS? \[\rightarrow\] prospects for future LHeC, EIC

- Note:

- neither Pythia Monte Carlo nor NLO calculations are able to describe forward jet HERA data

A concept underlying several talks:

**III. UNINTEGRATED (OR TRANSVERSE MOMENTUM DEPENDENT) PARTON DISTRIBUTIONS**

- Gustafson [shower Monte Carlo]
- Enberg [uses of u-pdfs in diffraction]
- Deak [in High-\(p_T\) session]
- Cherednikov [theory developments]

\[ p = (p^+, m^2 / 2 p^+, 0_\perp) \]

\[ \tilde{f}(y) = \langle P \mid \bar{\psi}(y) \gamma^+ \tilde{\psi}(0) \mid P \rangle, \quad y = (0, y^-, y_\perp) \]

correlation of quark fields (‘dressed’ with gauge links) at distances \(y, y_\perp \neq 0\)
**A) Single-scale hadron scattering.** E.g., DIS structure functions

- necessarily sensitive to long timescales, BUT

\[ \sigma \text{ can be written as } \sigma(Q, m) = C(Q, \text{ parton momenta } > \mu) \otimes f(\text{ parton momenta } < \mu, m) \]

\[ \text{in "infinite-momentum" frame, } \delta t_{\text{scatter}} \ll \tau_{\text{parton}} \]

\[ \text{Pdf's: } f(x, \mu) = \int \frac{dy^-}{2\pi} e^{-ixp^+y^-} \tilde{f}(y) \]

\[ \tilde{f}(y) = \langle P | \overline{\psi}(y) V_y^+(n) \gamma^+ V_0(n) \psi(0) | P \rangle, \quad y = (0, y^-, 0) \]

\[ V_y(n) = \mathcal{P} \exp \left( ig_s \int_{0}^{\infty} d\tau \ n \cdot A(y + \tau n) \right) \quad \text{correlation of parton fields at lightcone distances} \]
Renormalization group invariance ⇒

\[
\frac{d}{d \ln \mu} \sigma = 0 \quad \Rightarrow \quad \frac{d}{d \ln \mu} \ln f = \gamma = - \frac{d}{d \ln \mu} \ln C
\]

↔ DGLAP evolution equations [Altarelli-Parisi Dokshitzer Gribov-Lipatov]

\[
f = f_0 \times \exp \int \frac{d\mu}{\mu} \gamma(\alpha_s(\mu))
\]

↑ resummation of \((\alpha_s \ln Q/\Lambda_{QCD})^n\) to all orders in PT

Note: expansions \(\gamma \simeq \gamma^{(LO)} (1 + b_1 \alpha_s + b_2 \alpha_s^2 + \ldots)\)

\[
C \simeq C^{(LO)} \left(1 + c_1 \alpha_s + c_2 \alpha_s^2 + \ldots\right)
\]

give LO, NLO, NNLO, ... logarithmic corrections
Multiple-scale hard scattering at LHC energies

\[ s \gg q_1^2 \gg \cdots q_n^2 \gg \Lambda \]

- more complex, potentially large corrections to all orders in \( \alpha_s \), \( \sim \ln^k (q_i^2 / q_j^2) \)

\[ e.g. \; \gamma \simeq \gamma^{(LO)} \left( 1 + c_1 \alpha_s + \cdots + c_{n+m} \alpha_s^m (\alpha_s L)^n + \cdots \right), \; L = \text{“large log”} \]

\[ \rightarrow \text{yet summable by QCD techniques that} \]
\[ \triangleright \text{generalize renormalization-group factorization} \]
\[ \triangleright \text{extend parton correlation functions off the lightcone} \]
\[ \Rightarrow \text{unintegrated (or TMD) pdf’s} \]
Examples:

- **Sudakov form factor** $S'$:

  \[
  S' = p_A + p_B - k^+ k^- (a) \quad \quad \quad \quad (b)
  \]

  \[
  \Rightarrow \frac{\partial S}{\partial \eta} = K \otimes S \quad \text{CSS evolution equations} \quad [\text{Collins-Soper-Sterman}]
  \]

  \[
  \leftarrow \text{resums } \alpha_s^n \ln^m \frac{M}{p_T}
  \]

- **High-energy resummation**: $s \gg M^2 \gg \Lambda_{QCD}^2$

  \[
  \diamond \text{energy evolution: BFKL equation} \quad [\text{Balitsky-Fadin-Kuraev-Lipatov}]
  \]

  \[
  \leftrightarrow \text{corrections down by } 1/\ln s \text{ rather than } 1/M
  \]
IV. FROM QCD TO MONTE CARLO EVENT GENERATORS

• Factorizability of QCD $x$-sections $\rightarrow$ probabilistic branching picture
  
  ◊ A) QCD evolution by “parton showering” methods:
  
  $d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \alpha_S(q^2) P(z) \Delta(q^2, q_0^2)$
  
  $\rightarrow$ collinear, incoherent emission

  ◊ B) Soft emission $\rightarrow$ interferences $\rightarrow$ ordering in decay angles:
  
  $\rightarrow$ gluon coherence for $x \sim 1$

  ◊ C) Gluon coherence for $x \ll 1 \Rightarrow$ corrections to angular ordering:
  
  $\rightarrow$ MC based on $k_\perp$-dependent unintegrated pdfs and MEs
COHERENCE IN HIGH-ENERGY LIMIT

Soft vector-emission current from external legs →

- leading IR singularities

\[ \text{[J.C. Taylor, 1980; Gribov-Low (QED)]} \]

- fully appropriate in single-scale hard processes

\[ \text{Dokshitzer, Khoze, Mueller and Trojan, RMP (1988); Webber, A. Rev. Nucl. Part. (1986)} \]

\[
\text{multi-scale: } s = q_1^2 \gg \cdots \gg q_n^2 \gg \Lambda^2
\]

\[ \text{[e.g.: LHC final states with multi-jets]} \]

\[ \Downarrow \]

▷ internal emissions non-negligible

▷ current also factorizable at high-energy:

\[
|M^{(n+1)}(k, p)|^2 = \left\{ [M^{(n)}(k + q, p)]^\dagger [J^{(R)}]^2 M^{(n)}(k + q, p) - [M^{(n)}(k, p)]^\dagger [J^{(V)}]^2 M^{(n)}(k, p) \right\} \ . \ \text{BUT...} \]

\[ \Rightarrow \]
\[ J \text{ depends on total transverse momentum transmitted} \]
\[ \Rightarrow \text{matrix elements and pdf at fixed } k_\perp \text{ ("unintegrated"}) \]

- virtual corrections not fully represented by $\Delta$ form factor
  \[ \Rightarrow \text{modified branching probability } P(z, k_\perp) \text{ as well} \]

\[ \textbf{K}_\perp\text{-DEPENDENT PARTON BRANCHING} \]

\[ G(x, k_T, \mu) = G_0(x, k_T, \mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \Theta(\mu - zq) \]
\[ \times \Delta(\mu, zq) \mathcal{P}(z, q, k_T) G(x/z, k_T + (1 - z)q, q) \]

\[ \text{Sudakov unintegr. splitting} \]

\[ \alpha \]

\[ \alpha_1 \]

\[ \text{CCFM evolution equation} \]
[talks by Deak, Monte Carlo implementations CASCADE, LDC, ... Gustafson]
Unintegrated (TMD) pdf’s are key ingredient for different types of QCD resummations

also relevant to fully take account of coherence effects in parton showers at high energy

possibly, more natural framework to push theory towards soft $p_T$ physics and to treat diffraction

[talk by Enberg]
In summary...

♣ Exciting new results from the LHC

♣ Impact on cosmic rays physics → Auger results

♣ Continuing stream of inputs from HERA

♣ Many new, challenging physics issues

... should make for an enjoyable session and interesting times ahead!