Self-similarity of jet production & QCD

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Contents

- Introduction (motivation & goals)
- \( z \)-Scaling (ideas, definitions, properties, …)
- Tevatron, RHIC jet data & \( z \) presentation
- QCD test of \( z \)-scaling
- Conclusions
Motivations & goals

Development of a universal phenomenological description of inclusive cross sections of particles produced at high energies to search for:

- new physics phenomena in elementary processes (quark compositeness, fractal space-time, extra dimensions, ...)
- signatures of exotic state of nuclear matter (phase transitions, quark-gluon plasma, …)
- complementary restrictions for theory (nonperturbative QCD effects, Standard Model, ...)

Analysis of new experimental data on jet production at Tevatron and RHIC to verify properties and QCD test of z-scaling.
Principles & Symmetries

- Relativity (special, general, scale,…)
- Gauge invariance (U(1), SU(2), SU(3),…)
- Self-similarity (hydro & aerodynamics, point explosions, critical phenomena,…)
- Fractality (scale dependence,…)
- Locality (constituent level of interactions,…)
- ……

Guiding principles to discover new laws in Nature at small scales

<table>
<thead>
<tr>
<th></th>
<th>$s^{1/2}$ (GeV)</th>
<th>$p_T$ (GeV/c)</th>
<th>scale (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHIC (pp, AA)</td>
<td>50-500</td>
<td>~50</td>
<td>~4·10^{-3}</td>
</tr>
<tr>
<td>Tevatron ($\bar{p}p$)</td>
<td>1960</td>
<td>~500</td>
<td>~4·10^{-4}</td>
</tr>
<tr>
<td>LHC (pp, AA)</td>
<td>14000</td>
<td>~5000</td>
<td>~4·10^{-5}</td>
</tr>
</tbody>
</table>
Scaling analysis in high energy interactions

Self-similarity parameter

- $m_T = \sqrt{p_T^2 + m_0^2}$ (transverse mass)
- $x_F = \frac{p_\parallel^*}{p_{\parallel\text{max}}^*}$ (Feynman variable)
- $x_R = \frac{E^*}{E_{\text{max}}^*}$ (radial scaling variable)
- $\alpha = \frac{k_+}{p_+}$ (light-cone variable)
- $x_{Bj} = -\frac{q^2}{2(Pq)}$ (Bjorken variable)
- $n/\langle n \rangle$ (KNO variable)

- These scaling regularities have restricted range of validity
- Violation of the scaling laws can be indication of new physics

$z$-Scaling: it provides universal description of inclusive particle cross sections over a wide kinematical region
(central+fragmentation region, $p_T > 0.5$ GeV/c, $s^{1/2} > 20$ GeV)
Locality of hadron interactions

Constituent subprocess
\[(x_1M_1) + (x_2M_2) \Rightarrow (m_1/y_1) + (x_1M_1 + x_2M_2 + m_2/y_2)\]

Kinematical condition (4-momentum conservation law):
\[(x_1P_1 + x_2P_2 - p/y_1)^2 = M_X^2\]

Recoil mass: \[M_X = x_1M_1 + x_2M_2 + m_2/y_2\]
Scaling variable $z$

$$z = z_0 \cdot \Omega^{-1}$$

$$z_0 = \frac{s^{1/2}}{(dN_{ch}/d\eta|_0)^c m}$$

- $\Omega^{-1}$ is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction
- $s^{1/2}$ is the transverse kinetic energy of the subprocess consumed on production of $m_1$ & $m_2$
- $dN_{ch}/d\eta|_0$ is the multiplicity density of charged particles at $\eta = 0$
- $c$ is a parameter interpreted as a “specific heat” of created medium
- $m$ is an arbitrary constant (fixed at the value of nucleon mass)
Resolution $\Omega^{-1}(x_1, x_2, y_1, y_2)$

$\Omega = (1 - x_1)^{\delta_1} (1 - x_2)^{\delta_2} (1 - y_1)^{\epsilon_1} (1 - y_2)^{\epsilon_2}$ \quad $\delta_1, \delta_2, \epsilon_1, \epsilon_2$ - structural parameters

**Principle of minimal resolution:** The momentum fractions $x_1, x_2$ and $y_1, y_2$ are determined in a way to minimize the resolution $\Omega^{-1}$ of the fractal measure $z(\Omega)$ with respect to all constituent subprocesses taking into account the momentum conservation law

$$(x_1 p_1 + x_2 p_2 - p/y_1)^2 = (x_1 M_1 + x_2 M_2 + m_2/y_2)^2.$$ 

**Extremum conditions:**

$$\left\{ \begin{array}{l}
\frac{\partial \Omega}{\partial x_1} \bigg|_{y_1 = y_1(x_1, x_2, y_2)} = 0 \\
\frac{\partial \Omega}{\partial x_2} \bigg|_{y_1 = y_1(x_1, x_2, y_2)} = 0 \\
\frac{\partial \Omega}{\partial y_2} \bigg|_{y_1 = y_1(x_1, x_2, y_2)} = 0
\end{array} \right.$$ 

pp/$\overline{pp}$: $\delta_1 = \delta_2 \equiv \delta$, $\epsilon_1 = \epsilon_2 \equiv \epsilon_F$, $m_1 = m_2$
Self-similarity of hadron interactions

- The variable $z$ is a specific dimensionless combination of quantities characterizing particle production in high energy inclusive reactions.

  $z$ is a self-similarity parameter

- The self-similarity is connected with dropping of certain dimensional quantities out of the description of physical phenomena.

- Self-similarity of hadron interactions reflects a property that hadron constituents, their interactions, and formation of the produced particles are similar.

- Multiple interaction of the constituents is an ensemble of mutually similar individual subprocesses.

- These properties are common to various interactions of hadrons and nuclei at high energies.
Fractality of hadron interactions

- Fractality is a specific feature connected with substructure of the interacting objects (hadrons and nuclei). It is connected with self-similarity of constituent interactions over a wide scale range.

- Fractality of soft processes was investigated by A.Bialas, R.Peshchanski, I.Dremin, E.DeWolf,…

- Fractality of hard processes is reflected in the $z$-scaling via the variable $z$.

$z$ is a fractal measure attributed to any inclusive reaction:

$$z(\Omega) \to \infty \text{ if resolution } \Omega^{-1} \to \infty$$
Scaling function $\Psi(z)$

$$\Psi(z) = \frac{\pi}{(dN/d\eta) \cdot \sigma_{\text{inel}}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3}$$

- $s^{1/2}$ is the collision energy.
- $dN/d\eta$ is the pseudorapidity multiplicity density at $\eta$.
- $\sigma_{\text{inel}}$ is the inelastic cross section.
- $J(z, \eta; p_T^2, y)$ is the corresponding Jacobian (y-rapidity).
- $Ed^3\sigma/dp^3$ is the inclusive cross section.

The variable $z$ and the function $\Psi(z)$ are expressed via momenta and masses of the colliding and produced particles, multiplicity density, and inclusive cross section.
Normalization of $\Psi(z)$

The scaling function $\Psi(z)$ is probability density to produce an inclusive particle with the corresponding fractal measure $z$. 

\[ \Psi(z) = \frac{\pi \cdot S}{(dN/d\eta) \cdot \sigma_{\text{inel}}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3} \]

\[ \int_0^\infty \Psi(z) dz = 1 \]

\[ \int E \frac{d^3\sigma}{dp^3} dy d^2p_\perp = \sigma_{\text{inel}} \cdot N \]
Transverse kinetic energy $\mathbf{s}^{1/2}_\perp$

\[
\mathbf{s}^{1/2}_\perp = y_1 (\mathbf{s}_\lambda^{1/2} - \mathbf{M}_1 \lambda_1 - \mathbf{M}_2 \lambda_2) - \mathbf{m}_1 + y_2 (\mathbf{s}_\chi^{1/2} - \mathbf{M}_1 \chi_1 - \mathbf{M}_2 \chi_2) - \mathbf{m}_2
\]

energy consumed for the inclusive particle $m_1$

energy consumed for the recoil particle $m_2$

Decomposition: $x_{1,2} = \lambda_{1,2} + \chi_{1,2}$

\[
\lambda_{1,2} = \kappa_{1,2} / y_1 + \nu_{1,2} / y_2
\]

\[
\chi_{1,2} = (\mu_{1,2}^2 + \omega_{1,2}^2)^{1/2} + \omega_{1,2}
\]

\[
\omega_{1,2} = \mu_{1,2} U, \quad U = \frac{\alpha - 1}{2\sqrt{\alpha}} \xi, \quad \alpha = \frac{\delta_2}{\delta_1}
\]

\[
\xi^2 = (\lambda_1 \lambda_2 + \lambda_0) / [(1 - \lambda_1)(1 - \lambda_2)]
\]

\[
\mathbf{s}_\lambda = (\lambda_1 \mathbf{P}_1 + \lambda_2 \mathbf{P}_2)^2
\]

\[
\mathbf{s}_\chi = (\chi_1 \mathbf{P}_1 + \chi_2 \mathbf{P}_2)^2
\]
Properties of $z$-scaling

- Energy independence of $\Psi(z)$ ($s^{1/2} > 20$ GeV)
- Angular independence of $\Psi(z)$ ($\theta_{\text{cms}} = 3^0$-90$^0$)
- Multiplicity independence of $\Psi(z)$ ($dN_{\text{ch}}/d\eta=1.5$-26.)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high $z$ ($z > 4$)
- Flavor independence of $\Psi(z)$ ($\pi, K, \varphi, \Lambda, .., D, J/\psi, B, \bar{\Psi}, ..$)
- Saturation of $\Psi(z)$ at low $z$ ($z < 0.1$)

These properties reflect self-similarity, locality, and fractality of the hadron interaction at a constituent level. It concerns the structure of the colliding objects, interactions of their constituents, and fragmentation process.

Spectra of $\pi^0$ mesons in pp at RHIC

- Good agreement between NLO pQCD calculations and data
- Confirmation that pQCD can be used to extract PDFs from RHIC data
Spectra of $\pi^0$ mesons in pp at ISR & RHIC

M.T.
O.Rogachevsky
T.Dedovich
J. Phys. G26
1671 (2000)

Test of $pQCD +$ phenomenology ($PDFs, FFs, \mu_R, \ldots$)
Test of $z$-scaling + exp. uncertainties ($\sigma_{in}, dN_{ch}/d\eta, \ldots$)

Self-similarity of hadron production in pp at high energies
Jets at Hadron Colliders

Batavia, Illinois

CDF

DØ

p → p

$\sqrt{s} = 630-1960$ GeV

Upton, Long Island, New York

RHIC

p → p

$\sqrt{s} = 50-500$ GeV

CERN

ALICE

LHC

p → p

$\sqrt{s} = 14000$ GeV
Jet is a strong correlated group of particles in space-time.
Jet is a product of hard scattering of hadron constituents.
Definition of jet in experiment and theory is a basis for understanding transition mechanism from quark and gluon to hadronic degrees of freedom.
QCD evolution schemes based on DGLAP, BFKL, CCFM equations are widely used.
Large systematic errors in theoretical calculations are due to uncertainties of PDF’s and mainly to gluon distribution function.

Experimental verification and QCD test of z-scaling of jet production in hadron collisions to search for new phenomena and establish new constraints (gluons, Q^2-evolution etc.) on theory.
A typical dijet event consists of:

- hard interaction
- initial/final gluon and quark radiation
- secondary semi-hard interactions
- interaction between remnants
- hadronization
- jet formation

Model dependence on:

- Parton distribution functions
- Fragmentation functions
- Higher order corrections
- Renormalization, factorization and fragmentation scales
- QCD evolution scheme

Jet Topology

- High-$p_T$ constituent interactions are described by QCD
- Jets are copiously produced at hadron colliders
- Jets are an experimental signature of quarks and gluons

Parton distributions

Fragmentation functions

Higher order corrections

Renormalization, factorization and fragmentation scales

QCD evolution scheme
Data are in agreement with each other in the momentum range $p_T = 10 - 450$ GeV/c.

- Energy independence of $\Psi(z)$
- Power law, $\Psi(z) \sim z^{-\beta}$

Self-similarity of jet production in proton-antiproton collisions
Angular dependence of jet production in $\bar{p}p$ collisions

D. Elvira & D0 Collaboration

Angular independence of $\Psi(z)$
Power law, $\Psi(z) \sim z^{-\beta}$

Self-similarity of jet production in proton-antiproton collisions

M. T. Tokarev
August, 19-25, 2009
z-Scaling & Jets at Tevatron in Run II

- Spectra are measured up to 600 GeV/c !!!
- CDF & DØ data are described by NLO QCD
- CDF & DØ confirm z-scaling of jet production in \( \bar{p}p \)

CDF Collaboration
A. Abulencia et al.,

DØ Collaborations
J. Commin et al.,
DIS2007, April 16-20,
2007, Munich, Germany

MT & T. Dedovich
Angular independence of $\Psi(z)$

Power law, $\Psi(z) \sim z^{-\beta}$
Jet transverse spectra are measured up to 600 GeV/c

Self-similarity of jet production in proton-antiproton collisions

Angular independence of $\Psi(z)$

Power law $\Psi(z) \sim z^{-\beta}$
First jets in pp at STAR

TPC for charged hadrons+EMC for e-m showers

1) Jets reconstruction - midpoint cone algorithm (Tevatron II)
   seed energy = 0.5 GeV, cone angle R = 0.4 in $\eta$−$\phi$
   splitting/merging fraction f=0.5

2) Trigger used in this analysis - High Tower:
   $E_T > 2.4$ GeV deposited in one tower $(\Delta \eta \times \Delta \phi) = (0.05 \times 0.05)$
   + additional requirement of BBC coincidence.

3) Cuts on:
   - charged tracks $|\eta| < 1.6$ and $p_T > 0.1$ GeV/c
   - jets: $p_T$ jet > 5 GeV/c, $0.2 < \text{jet } \eta$ (det) < 0.8
   - background: $E_{\text{jet(neutral)}}/E_{\text{jet(total)}} < 0.9$ (2004)
     and < 0.8 (2003)
   - $|z$-vertex$| < 75$cm (2003) and < 60cm (2004)
   - tower $E_T > 3.5$ GeV software threshold (only 2004 cross section)

M.Miller, QM’05, NPD2005, PANIC’05, hep-ex/0604001

August, 19-25, 2009  M.Tokarev
Hard scattering at RHIC and NLO pQCD

Good agreement with NLO pQCD

pQCD should be broadly applicable at RHIC
MC results are in agreement with STAR data.
Dependence of spectra on rapidity range
\((0.2<\eta<0.8 \text{ } \& \text{ } |\eta|<1.0)\).
The slope parameter \(\beta\) of \(\Psi(z)\) is found to be
\(6.01\pm0.06\) over the range \(E_T^{\text{Jet}}=25-60\text{ GeV}\).
Sensitivity of \(\Psi(z)\) at high \(z\) to \(E_T^{\text{Jet}}(\eta^{\text{Jet}})\).

QCD test of z-scaling

- QCD is basic theory for calculations of hadron interactions in terms of quarks and gluons.
- Perturbative expansion is under control (LO, NLO, ...).
- Non-perturbative effects – PDFs, FFs, μ_R, μ_F, μ_H, are partially under control.
- Correct extrapolation in low and high (x,p_T) range is restricted by available data (e^+e^-, DIS,...).
- Additional constraints on PDFs and FFs are needed to confirm their universality (gluons, flavor, ...).
- Soft regime (multiple interactions, ...).

- A lot of data are analyzed in framework of z-presentation.
- New confirmations from RHIC and Tevatron are obtained.
- Can NLO QCD describe z-scaling in soft and hard regime?
- ......

Hadron interaction at a constituent level

\[ F^q_h(x_1, k_{1\perp}, \mu_F) \]
\[ \sigma_{qq}(x_1, x_2, k_{1\perp}, k_{2\perp}, \mu_R) \]
\[ D^h_q(z_1, p_{1\perp}, \mu_H) \]
NLO QCD ingredients

- NLO QCD jet production code
  S.D.Ellis, Z.Kunszt, D.Soper
  PRD40,2188(1989); PRL69,1496(1992); PRD46,192 (1992)

- Parton Distribution Functions
    JHEP 0207 (2002) 012
  MRST01 – A.D.Martin, R.G.Roberts, W.J.Stirling, R.S.Thorne

- Scales $\mu = c \cdot p_T$, $c = 0.5, 1., 2.$
  - Renormalization $\mu_R$
  - Factorization $\mu_F$
  - Hadronization $\mu_H$

Hadron interaction at a constituent level

$F^q_h(x_1, \mu_F)$
$\sigma_{qq}(x_1, x_2, k_{1\perp}, k_{2\perp}, \mu_R)$
$D^h_q(z_1, \mu_H)$
Jet NLO QCD spectra in $\bar{p}p$ & PDFs

- Strong dependence of spectra on energy $s^{1/2}$ at high $p_T$.
- Sensitivity to PDFs (MRST) & $\mu_R$, $\mu_F$, $\mu_H$ scales.
- NLO QCD calc. results are in agreement with available data.
- Different extrapolation of spectra predicted by NLO QCD and $z$-scaling for high transverse momenta.
Jet NLO QCD spectra in $\bar{p}p$ & PDFs

- Strong dependence of spectra on energy $s^{1/2}$ at high $p_T$.
- Sensitivity to PDFs (CTEQ) & $\mu_R, \mu_F, \mu_H$ scales.
- NLO QCD calc. results are in agreement with available data.
- Different extrapolation of spectra predicted by NLO QCD and $z$-scaling for high transverse momenta.
PDFs (CTEQ, MRST) & scales ($\mu_R, \mu_F, \mu_H$) are model dependent ingredients of QCD fit of exp. data.

z-Scaling can give additional constraints on PDFs.
z-$p_T$ plot for jet production

Kinematical regions are of more preferable for searching for new physics at RHIC, Tevatron and LHC.

Phenomena due to constituent substructure and space-time structure

Collective phenomena due to multiple jet production
Conclusions

- Results of analysis of Tevatron and RHIC data on inclusive transverse spectra of jets produced in pp and \( \bar{p}p \) collisions in \( z \)-presentation are presented.
- New confirmation of properties of \( z \)-scaling (energy and angular independence) are obtained.
- \( z \)-Scaling of jet production at high energies manifests self-similarity, locality and fractality of hadron interactions at a constituent level.
- QCD test of \( z \)-scaling is performed: \( z \)-scaling gives restriction on the asymptotic behavior of jet spectra in high-\( p_T \) region.
- The approach is useful for searching for new physics phenomena in particle production at RHIC, Tevatron, and LHC.
Thank You for Attention!