Two component model for hadron production in high energy collisions

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Outline

• Introduction
  – Charge particle spectra and phenomenology

• Phenomenological model

• Predictions of the model
  – Inclusive cross-sections and transverse momentum spectra
  – Pseudorapidity distributions

• Heavy-ion collisions in a two component model
Charge Particle Spectra and the Fit Function

Differential Invariant Cross-Section

\[ E \frac{d^3 \sigma}{d^3 p} = \frac{d^3 \sigma}{d\phi dy dp_T dp_T} \Rightarrow \frac{d^2 \sigma}{\pi dy dp_T} \]

\( p_T \) – transverse momentum, \( y \) - rapidity

The widely used Tsallis approximation

\[ \frac{d^2 \sigma}{\pi dy \left( p_T^2 \right)} = \frac{A}{\left( 1 + \frac{E_{T\text{kin}}}{T \times N} \right)^N} \]

\[ E_{T\text{kin}} = \sqrt{p_T^2 + m^2} - m \]

8000 points from 300 data-sets from 18 collider experiments have been fitted using this approach
Differential Invariant Cross-Section

\[ \frac{E \, d^3 \sigma}{d^3 p} = \frac{d^3 \sigma}{d\phi dy p_T dp_T} \Rightarrow \pi \, dyd (p_T^2) \]

\( p_T \) – transverse momentum, \( y \) - rapidity

The widely used Tsallis approximation

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\[ E_{T\text{kin}} = \sqrt{p_T^2 + m^2} - m \]

8000 points from 300 data-sets from 18 collider experiments have been fitted using this approach

Traditional approaches **DO NOT** provide reasonable Description of the experimental data
Differential Invariant Cross-Section

\[
\frac{d^3 \sigma}{d^3 p} = \frac{d^3 \sigma}{d \phi dy dp_T dp_T} \Rightarrow \frac{d^2 \sigma}{\pi dy d(p_T^2)}
\]

\( p_T \) – transverse momentum, \( y \) - rapidity

The widely used Tsallis approximation

\[
\frac{d^2 \sigma}{\pi dy (p_T^2)} = \frac{A}{(1 + \frac{E_{Tkin}}{T* N})^N}
\]

\( E_{Tkin} = \sqrt{p_T^2 + m^2} - m \)

\( \propto \frac{1}{(E_{Tkin}^N)^{\frac{1}{n}}} \)

\( \propto e^{-E_{Tkin}^{kin}/T} \)

8000 points from 300 data-sets from 18 collider experiments have been fitted using this approach

Traditional approaches DO NOT provide reasonable Description of the experimental data

New approach is introduced: A sum of exponential & power-law terms

\[
\frac{d^2 \sigma}{\pi dy(dp_T^2)} = A_1 \exp(-E_{Tkin}/T_e) + \frac{A_2}{(1 + \frac{p_T^2}{T^2 N})^N}
\]
Comparison of pp and γγ Spectra

\[ \frac{d^2\sigma}{\pi dy(dp_T^2)} = A_1 \exp(-E_{T\text{kin}}/T_e) + \frac{A_2}{(1 + \frac{p_T^2}{T^2N})^N} \]

pp-collisions have large exponential term contribution

γγ-interactions are described by the power-law only
Phenomenological model

Two contributions to hadron production

1. Radiation of hadrons by valence quarks
   These partons exist long before the interaction and considered as a thermalized statistical state
   Boltzmann-like exponential distribution

2. Fragmentation of virtual partons exchanged between colliding partonic systems into mini-jets.
   power-law spectrum (typical for pQCD)
Energy dependences

Charged particle densities $d\sigma/d\eta$ grow with energy $\sim s^{\Delta}$:

- **Power-law**: $\Delta \approx 0.25$
  - the pQCD (BFKL) pomeron after the resummation of the NLL corrections.

- **Exponent**: $\Delta \approx 0.15$
  - strongly affected by absorptive corrections.

Mean transverse momenta $<p_T>$

- **Power-law**: $\sim s^{0.05}$
  - growth of the typical transverse momenta of mini-jets

- **Exponent**: constant
Multiplicity dependences

Charged particle densities $d\sigma/d\eta$:
Charge multiplicity is proportional to the number of pomerons involved.
→ the contribution from the **power-law** component (mini-jets) grows faster than that from the **exponential** one

Mean transverse momenta $<p_T>$
- **Power-law**: Within the Regge theory the higher multiplicity events have a larger number, $n$, of 'cut' pomerons ($N_{ch} \sim n$). Accounting for mini-jet contribution the $<p_T>$ should increase with $N_{ch}$ since another way to enlarge multiplicity is to produce mini-jets with larger $E_T$.
- **Exponent**: constant
Pseudorapidity distributions

Hadrons produced via the **mini-jet fragmentation** should be concentrated in the central rapidity region ($\eta \sim 0$), while those coming from the **proton fragmentation** are expected to dominate at high values of $\eta$ due to non-zero momenta of the initial partons along the beam-axis.

**Gaussian distribution** for Double Pomeron Exchange (DPE) events

**Sum of THREE Gaussians** for Minimum Bias (MB) events in pp-collisions

→ existence of plateau in a pseudorapidity distribution
Scaling of distributions

Data on pseudorapidity distributions measured under the same experimental conditions by the UA5 Detector.
Predictions for LHC-energies

$\langle p_T \rangle$ as a function of multiplicity

Very good agreement between the predictions and the available experimental data from LHC
Heavy-ion collisions

Two component approach allows two extract the thermal production of charged particle production in heavy-ion collisions from the whole statistical ensemble

1. Collective flow is taken into account
2. Data from RHIC and LHC are combined in terms of energy density

1. $\varepsilon \sim T^4 + B$
2. $T_C \sim 150$ MeV
Summary

- Universality of charged particle production in high energy collisions has been observed.
- Phenomenological model for hadroproduction was introduced.
- Transverse momentum and pseudorapidity distributions have been studied in terms of this model.
- Prediction on charge particle production at LHC-energies have been made.
- Good agreement between the predictions and the available experimental data has been found.
- Introduced model already tested on DIS-data from H1 Collaboration (H1-prelim-13-032): paper in progress
- Further tests using CMS-data at 14 TeV are approaching

Thank you for your attention!
More information in the papers:
(or simply look at http://inspirehep.net/author/profile/A.A.Bylinkin.1)

[1] Systematic studies of hadron production spectra in collider experiments
   A.Bylinkin and A.Rostovtsev, Phys.Atom.Nucl. 75 (2012) 999-1005,

[2] Anomalous behavior of pion production in high energy particle collisions

[3] Universality of identified hadron production in pp-collisions

[4] Hydrodynamic extension of a two component model for hadroproduction in heavy-ion
   collisions. A.Bylinkin, N.Chernyavskaya and A.Rostovtsev
   arxiv:1405.3055 [hep-ph], Accepted by Phys.Rev.C

   A.Bylinkin and M.Ryskin, arXiv:1404.4739

   A.Bylinkin and A.Rostovtsev, arXiv:1404.7302

[7] An analysis of charged particles spectra in events with different charged

[8] A variation of the charged particle spectrum shape as function of rapidity in high

**Origin of the thermal component**

*Confinement is associated with an event horizon for colored particles.*

The quantum effects then produce the thermal spectra of hadrons, similar to the Hawking evaporation of black holes or Unruh radiation. The color string stretching between the colored fragments in a high energy collision contains the longitudinal chromoelectric field. This field decelerates the colored fragments producing a Rindler event horizon. Quantum fluctuations in the vicinity of the event horizon then result in the thermal production.

\[ Q_s^2(s; \pm \eta) = Q_s^2(s_0; \eta = 0) \left( \frac{s}{s_0} \right)^{\lambda/2} \exp(\pm \lambda \eta); \]

\[ Q_s = T, \ T_e = Q_s/2\pi \]
Why the new approach matches the data better?

Systematic defects in the data description using traditional approach

Experimental data divided over the values of the fit function in corresponding points

Tsallis fit

\[
\frac{d\sigma}{dE_T^2} = \frac{A}{(1 + \frac{E_{T\text{kin}}}{T \times N})^N}
\]

New approach

\[
A_1 \exp(-E_{T\text{kin}}/T_e) + \frac{A_2}{(1 + \frac{P_T}{T^2 N})^N}
\]

\[\chi^2/\text{n.d.f.} = 288/44 \quad \chi^2/\text{n.d.f.} = 87/25\]

\[\chi^2/\text{n.d.f.} = 54/42 \quad \chi^2/\text{n.d.f.} = 22/23\]

New approach provides much better description of the data.
Type of produced particle

QCD-fluctuations are democratic to quark flavour while valence quark radiation can't produce heavy flavours

**Prediction:** Kaon (and $J/\psi$) spectra should have less exponential contribution than pion

$$R = \frac{\text{Power-law}}{\text{Exp} + \text{Power-law}}$$

$J/\psi$ spectra CDF $\sqrt{s} = 1.96$ TeV

<table>
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<th>Experiment</th>
<th>$\sqrt{s}$ [GeV]</th>
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<tr>
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<td>STAR 200</td>
<td></td>
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<tr>
<td>ALICE 900</td>
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</tbody>
</table>
R Value

The relative contribution of exponential and power-law terms can be calculated by integrating each term by transverse momentum from 0 to the upper bound of the kinematical region

\[ \int_0^\infty \frac{A}{(1 + \frac{P_T^2}{T_N})^N} dP_T^2 = \frac{ANT}{N - 1} \]

\[ A_e \int_0^\infty \exp(-E_{T\text{kin}}/T_e) dP_T^2 = A_e(2mT_e + 2T_e^2) \]

\[ R = \frac{ANT}{ANT + A_e(2mT_e + 2T_e^2)(N - 1)} \]
What is in $\gamma p$-collision?

Particles produced at the proton side of the event should carry similarity to $pp$-collisions.

Particles produced at the photon side of the event should carry similarity to $\gamma\gamma$-collisions.
DIS at HERA is the unique possibility to study such transition in hadroproduction dynamics.
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**Event kinematics is defined by**

- $\sqrt{s}$ — ep centre-of-mass energy
- $Q^2$ — photon virtuality
- $x$ — Bjorken variable
- $y$ — inelasticity
- $W$ — photon-proton system mass $[M_x]$
1. Reduced proton beam energy
   \( E_p = 460 \text{ GeV} \) \( \sqrt{s} = 225 \text{ GeV} \)

2. High values of inelasticity
   \( 0.35 < y < 0.8 \)

3. Low photon virtuality
   \( 5 < Q^2 < 10 \text{ GeV}^2 \)

Measurements are performed in \( \gamma p \) centre-of-mass system \( (P_T^*, \eta^*) \)

\[ \eta^* = -\ln \tan(\theta^*/2) \]

\( \eta^* < 0 \) — proton direction

7 \( \eta^* \) bins \( 0 < \eta^* < 3.5 \)
Measured cross-sections

Charged particle spectra $0 < \eta^* < 0.5$

Large exponential contribution

H1 Preliminary

$\frac{d^2\sigma_{pp}}{dp_T^2 d\eta^*} \text{ [pb/(GeV/c)^2]}$

$10^6$

$10^3$

$10^1$

$10^{-1}$

$10^{-2}$

$p_T^* \text{ [GeV/c]}$

H1 data

Fit

Exp

Power

Charged particle spectra $1.5 < \eta^* < 2.0$

Small exponential contribution

H1 Preliminary

$\frac{d^2\sigma_{pp}}{dp_T^2 d\eta^*} \text{ [pb/(GeV/c)^2]}$

$10^6$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^{-1}$

$p_T^* \text{ [GeV/c]}$

H1 data

Fit

Exp

Power
Power-law term contribution

\[ R = \frac{\text{Power-law}}{\text{Exp} + \text{Power-law}} \]

First precise measurement in DIS

Transition between two hadroproduction contributions is observed with approaching the proton fragmentation region

As it is qualitatively predicted by the model
Power-law term contribution

Transition between two hadroproduction contributions is observed with approaching the proton fragmentation region

As it is qualitatively predicted by the model
Results: Comparison with MC

Both DJANGOH and RAPGAP fail to describe the shape of the $P_T^*$ spectra in the central region.