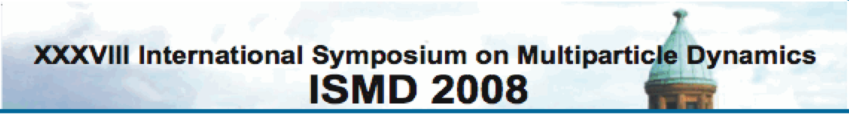

NEW SCALING BEHAVIOR of LOW-p_T HADRON PRODUCTION in PROTON-(ANTI)PROTON COLLISIONS at RHIC and TEVATRON

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Czech Republic

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- Motivation & goals
- z-Scaling in inclusive hadron production
  (ideas, definitions, properties,…)
- New properties of z-scaling:
  – flavor independence & saturation at low z
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- Kinematics of constituent subprocesses
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Motivation & 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 hadron matter (phase transitions, quark-gluon plasma, …)
- complementary restrictions for theory (nonperturbative QCD, Standard Model, ...)

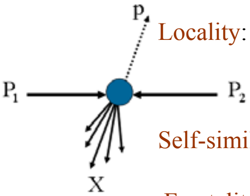
Analysis of new pp & $\bar{p}p$ data obtained at RHIC & Tevatron.

Study of new properties of z-scaling:

flavor independence and saturation at low z.

z-Scaling

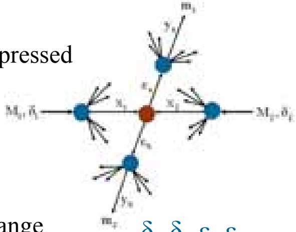
Principles & properties of hadron interactions at high energies:



Locality: collisions of hadrons and nuclei are expressed via interactions of their constituents (partons, quarks and gluons,...).

Self-similarity: interactions of the constituents are mutually similar.

Fractality: the self-similarity over a wide scale range.



$\delta_1,\delta_2,\varepsilon_a,\varepsilon_b$

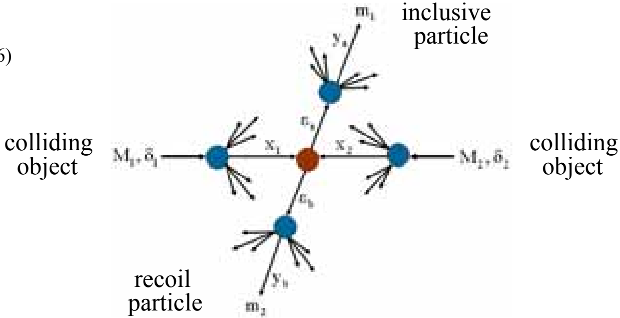
z-Scaling hypothesis:

$s^{1/2}, p_T, \theta_{cms}$ — Inclusive particle distributions can be described in terms of kinematical characteristics of the constituent subprocesses. — x_1, x_2, y_a, y_b

$Ed^3\sigma/dp^3$ — Inclusive cross sections of particles depend in a self-similar way on a single scaling variable z. — $\Psi(z)$

Locality of hadron interactions

M.T. & I.Zborovský
Part.Nucl.Lett.312(2006)
PRD75,094008(2007)
arXiv:0809.1033



Constituent subprocess

$$(x_1M_1) + (x_2M_2) \Rightarrow (m_1/y_a) + (x_1M_1+x_2M_2+m_2/y_b)$$

Kinematical condition (4-momentum conservation law):

$$(x_1P_1+x_2P_2-p/y_a)^2 = M_X^2$$

Recoil mass: $M_X = x_1M_1+x_2M_2+m_2/y_b$

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.

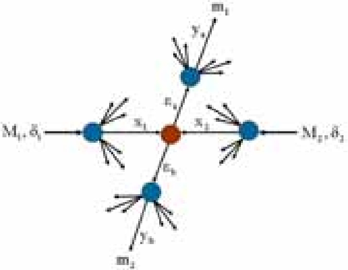
z is a fractal measure attributed to any inclusive reaction:

$$z(\Omega) \rightarrow \infty \text{ if resolution } \Omega^{-1} \rightarrow \infty$$

Scaling variable z

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

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



- Ω^{-1} is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction
- $s_\perp^{1/2}$ 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 $\Omega^{-1}(x_1,x_2,y_a,y_b)$

$$\Omega=(1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\varepsilon_a}(1-y_b)^{\varepsilon_b}$$

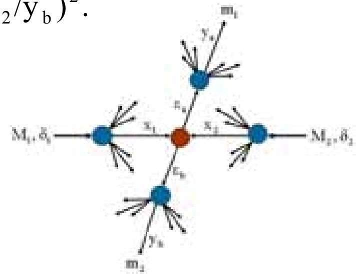
$\delta_1,\delta_2,\varepsilon_a,\varepsilon_b$ - structural parameters

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

$$(x_1P_1+x_2P_2-p/y_a)^2=(x_1M_1+x_2M_2+m_2/y_b)^2.$$

Extremum conditions:

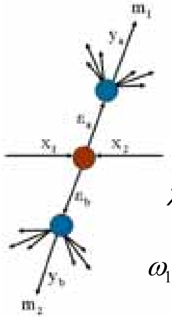
$$\begin{cases} \partial\Omega/\partial x_1\,|_{y_a=y_a(x_1,x_2,y_b)}=0 \\ \partial\Omega/\partial x_2\,|_{y_a=y_a(x_1,x_2,y_b)}=0 \\ \partial\Omega/\partial y_b\,|_{y_a=y_a(x_1,x_2,y_b)}=0 \end{cases}$$



$pp/p\bar{p}$: $\delta_1=\delta_2\equiv\delta$, $\varepsilon_a=\varepsilon_b\equiv\varepsilon_F$, $m_1=m_2$

Transverse kinetic energy $s_\perp^{1/2}$ consumed on production of m_1 & m_2

$$s_\perp^{1/2} = \underbrace{y_a(s_\lambda^{1/2} - M_1\lambda_1 - M_2\lambda_2) - m_1}_{\text{energy consumed on production of } m_1} + \underbrace{y_b(s_\chi^{1/2} - M_1\chi_1 - M_2\chi_2) - m_2}_{\text{energy consumed on production of } m_2}$$



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

$$\lambda_{1,2} = \kappa_{1,2}/y_a + \nu_{1,2}/y_b$$

$$\kappa_{1,2} = \frac{(P_{2,1}p)}{(P_2P_1)}, \quad \nu_{1,2} = \frac{M_{2,1}m_2}{(P_2P_1)}$$

$$\chi_{1,2} = (\mu_{1,2}^2 + \omega_{1,2}^2)^{1/2} \mp \omega_{1,2}$$

$$\mu_{1,2}^2 = \alpha^{\pm 1}(\lambda_1\lambda_2 + \lambda_0)\frac{1 - \lambda_{1,2}}{1 - \lambda_{2,1}}$$

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

$$\lambda_0 = \bar{\nu}_0/y_b^2 - \nu_0/y_a^2$$

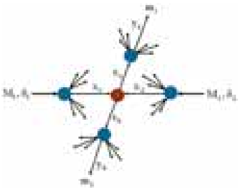
$$\xi^2 = (\lambda_1\lambda_2 + \lambda_0)/[(1-\lambda_1)(1-\lambda_2)]$$

$$\bar{\nu}_0 = \frac{0.5m_2^2}{(P_1P_2)}, \quad \nu_0 = \frac{0.5m_1^2}{(P_1P_2)}$$

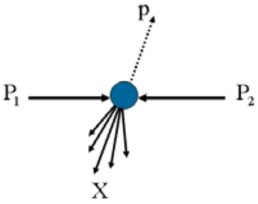
$$s_\lambda = (\lambda_1 P_1 + \lambda_2 P_2)^2$$

$$s_\chi = (\chi_1 P_1 + \chi_2 P_2)^2$$

Scaling function Ψ(z)



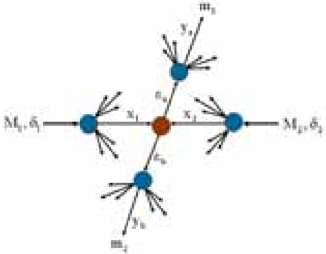
$$\Psi(z) = \frac{\pi \cdot s}{(dN/d\eta) \cdot \sigma_{inel}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3}$$



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

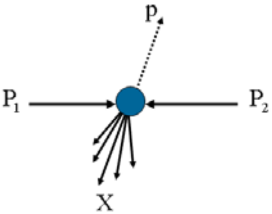
The variable z and the function Ψ(z) are expressed via momenta and masses of the colliding and produced particles, multiplicity density, and inclusive cross section.

Normalization of $\Psi(z)$



$$\int_0^\infty \Psi(z)dz = 1$$

$$z \to \alpha_F z, \quad \Psi \to \alpha_F^{-1} \Psi$$



$$\Psi(z) = \frac{\pi \cdot s}{(dN/d\eta) \cdot \sigma_{inel}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3} \Longleftrightarrow \int E \frac{d^3\sigma}{dp^3} dy d^2p_\perp = \sigma_{inel} \cdot N$$

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

Properties of z-scaling

- Energy independence of $\Psi(z)$ ($s^{1/2} > 20$ GeV)
- Angular independence of $\Psi(z)$ ($\theta_{cms} = 3^0$-90^0)
- Multiplicity independence of $\Psi(z)$ ($dN_{ch}/d\eta$=1.5-26.)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high z ($z > 4$)
- Flavor independence of $\Psi(z)$ (π,K,φ,Λ,..,D,J/ψ,B,Υ,…)
- 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.

Flavor independence of Ψ(z) in pp

STAR

J.Adams et al., Phys.Lett.B616,8(2005)

J.Adams et al., Phys.Lett. B637,161(2006)

B.I.Abelev et al., Phys.Rev.C75,064901(2007)

ISR

B.Alper et al., Nucl.Phys.B100,237(1975)

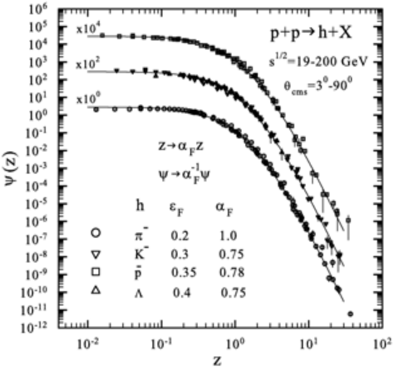
K.Guettler et al., Phys.Lett.B64,111(1976)

Nucl.Phys.B116,77(1976)

(low p_T)

M.G.Albrow et al., Nucl.Phys.B56,333(1973)

(small angles)



MT & I.Zborovský
arXiv:0809.1033[hep-ph]

ε_F, α_F independent of $s^{1/2}$,p_T,θ_{cms}

$\Psi(z) \sim z^{-\beta}$ at low and high z

- Energy independence of Ψ(z)
- Angular independence of Ψ(z)
- The shape of Ψ(z) is the same for different hadrons (π,K,$\bar{p}$,Λ)

Flavor independence of $\Psi(z)$ in pp at RHIC

STAR

J.Adams et al., PRL92,092301(2004)

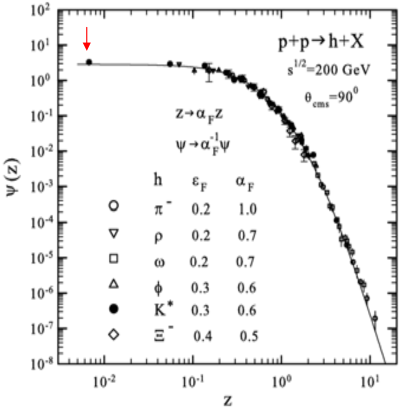
J.Adams et al., PLB612,181(2005)

J.Adams et al., PRC71,064902(2005)

B.I.Abelev et al., PRC75,064901(2007)

PHENIX

S.S.Adler et al., PRC75,051902(2007)



ε_F, α_F independent of $s^{1/2}$, p_T, θ_{cms}

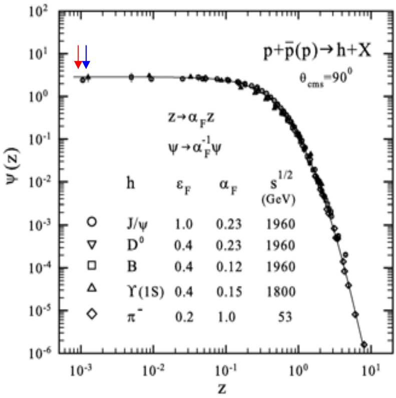
$\Psi(z) \sim z^{-\beta}$ at low and high z

- The shape of $\Psi(z)$ is the same for different hadrons ($\pi, K, \rho, \omega, \varphi, \Xi$)

K^* p_T=100 MeV/c

Flavor independence of Ψ(z) in $\bar{p}p$ at Tevatron

CDF
D.Acosta et al., PRL88,161802(2002)
D.Acosta et al, PRL91,241804(2003)
D.Acosta et al., PRD71,032001(2005)



ε_F, α_F independent of $s^{1/2}$, p_T, θ_{cms}

$\Psi(z) \sim z^{-\beta}$ at low and high z

	p_T(MeV/c)
J/ψ	125
Υ	290

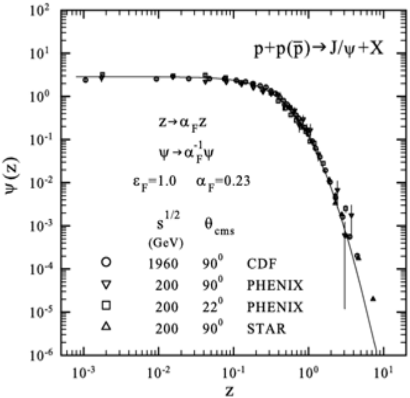
- Energy independence of Ψ(z)
- The shape of Ψ(z) is the same for different hadrons (D,B,J/ψ,Υ)

J/ψ production at RHIC and Tevatron

CDF
D.Acosta et al.,
PRD71,032001(2005)

PHENIX
A.Adare et al.,
PRL98,232002(2007)

STAR
Z.Tang et al.,
QM2008,Jaipur,India
arXiv:0804.4846



ε_F, α_F
independent
of $s^{1/2}$,p_T,θ_{cms}

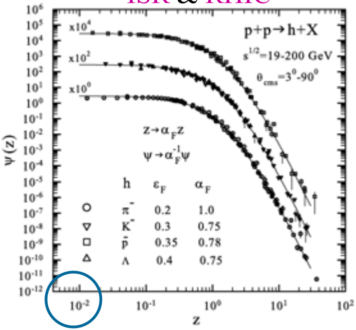
$\Psi(z) \sim z^{-\beta}$
at low and high z

- Energy and angular independence of $\Psi(z)$
- Flavor independence of $\Psi(z)$ (solid line for $\pi,\ldots\Upsilon$)

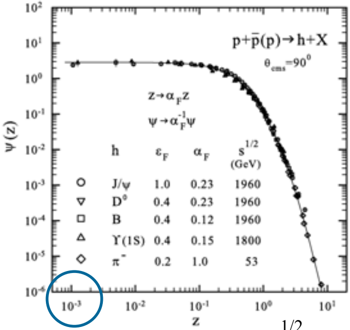
Saturation of Ψ(z) at low z

$-d\ln\Psi/d\ln z = \beta$

ISR & RHIC



ISR& Tevatron



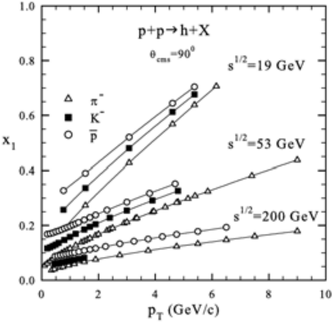
For z<0.1 the slope parameter β ≈ 0, $\quad z \approx \dfrac{s_\perp^{1/2}}{(dN_{ch}/d\eta|_0)^c}$.

Soft self-similar processes are governed by thermodynamics (multiplicity density, specific heat c, entropy,..)

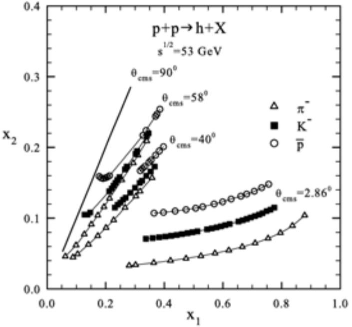
Kinematics of constituent subprocess

Fractions x_1,x_2 vs. p_T, θ_{cms}, $s^{1/2}$

ISR & RHIC



ISR & RHIC

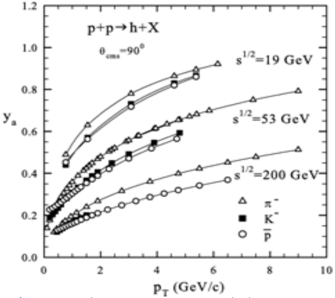


- x_1,x_2 increase with p_T and decrease with $s^{1/2}$.
- $x_1 = x_2$ at $\theta_{cms}=90^0$; $x_1 >> x_2$ at small $\theta_{cms}=2.86^0$.
- Scale dependence of z is given by various p_T, θ_{cms}, $s^{1/2}$.

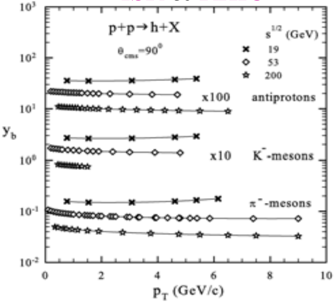
Kinematics of constituent subprocess

Fractions y_a, y_b vs. p_T, $s^{1/2}$

ISR & RHIC



ISR & RHIC

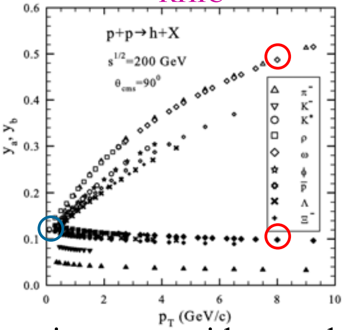


- y_a increases with p_T ⇒ energy losses decrease with p_T.
- y_a decrease with $s^{1/2}$ ⇒ energy losses increase with $s^{1/2}$.
- y_b is flat with p_T ⇒ weak dependence of M_X on p_T.
- $y_b \ll y_a$ for $p_T > 1$ GeV/c ⇒ inclusive particle is balanced by a high multiplicity recoil system M_X.

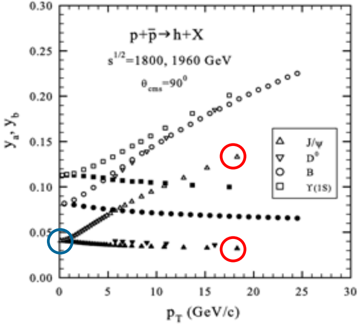
Kinematics of constituent subprocess

Fractions y_a, y_b vs. p_T , $s^{1/2}$

RHIC



Tevatron



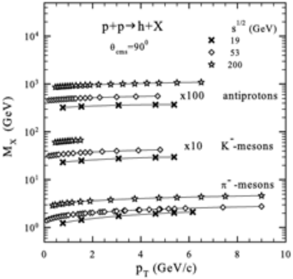
- y_a increases with p_T and decreases with $s^{1/2}$.
- y_b is flat with p_T and decreases with $s^{1/2}$; $y_b << y_a$ at high p_T.
- $y_b \approx y_a$ at low p_T $\Rightarrow$ $M_X \approx m_2/y_b \approx m_1/y_a$.
- Anomaly small y_a for $J/\psi \Rightarrow$ extra large energy losses for J/ψ.

Kinematics of constituent subprocess

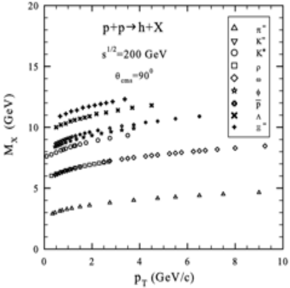
Recoil mass M_X vs. p_T , $s^{1/2}$

$$M_X = x_1 M_1 + x_2 M_2 + m_2/y_b$$

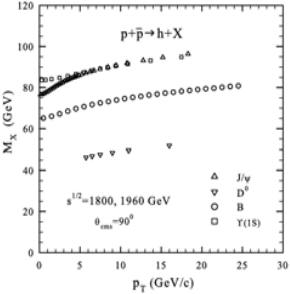
ISR & RHIC



RHIC



Tevatron



- M_X increases with p_T and $s^{1/2}$.
- M_X increases with hadron mass ($\pi, K, \rho, \omega, \varphi, \Lambda, \Xi, D, B, \Upsilon$).
- Extra large $M_X^{J/\psi}$ ($\approx M_X^{\Upsilon}$) $\Rightarrow$ extra high recoil multiplicity for J/ψ.

Summary

- Analysis of new RHIC and Tevatron data on inclusive cross sections of hadrons ($\pi, K, \rho, \omega, \varphi, \bar{p}, \Lambda, \Xi, B, D, J/\psi, \Upsilon$) produced in pp and $p\bar{p}$ collisions was performed in z-presentation.
- New properties of z-scaling - flavor independence and saturation at low z (low p_T), were established.
- A microscopic scenario of hadron interactions at a constituent level was proposed.
- Extra large energy losses & M_X in J/ψ production were found.
- z-Scaling reflects self-similarity, locality, and fractality of hadron interactions at the constituent level.
- The approach is useful for searching for new physics phenomena in particle production at RHIC, Tevatron, and LHC.

Thank You for Your Attention