Joint Institute for Nuclear Research
Strangeness in Quark Matter
06 July - 11 July 2015
SQM DUBNA 2015

Self-similarity of strangeness production in pp collisions at RHIC

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- z-Scaling (ideas, definitions,…)
- Properties of data z-presentation
- Self-similarity of strange particle production in pp collisions at RHIC
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- Summary

Motivation & Goals

Search for new symmetries in Nature

Systematic analysis of inclusive cross sections of particle production in pp, pA and AA collisions to search for general features of structure, interaction and fragmentation over a wide scale range

z-Scaling as a new scaling in high energy physics

Development of z-scaling approach for description of processes with strange particle production in inclusive reactions and verification of self-similarity principle

Analysis of new RHIC data on strange particle spectra in pp collisions

The suggested approach can be used to study

- Origin of strangeness
- Symmetry of constituent interactions at small scales
- Similarity and difference of u,d,s,c,b,t quark fragmentation
- Strangeness as probe to search for new physics
- pp is a reference frame for pA and AA physics

Fundamental principles and symmetries

"Fundamental symmetry principles dictate the basic laws of physics, control the structure of matter, and define the fundamental forces in Nature."

Leon M. Lederman

Self-similarity is a property of physical phenomena and the principle to construct theories.

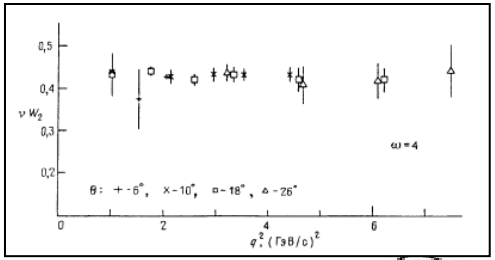
Self-similarity

- A self-similar object is exactly or approximately similar to a part of itself (i.e. the whole has the same shape as one or more of the parts).
- Self-similarity is a typical property of fractals.
- Scale invariance is an exact form of self-similarity where at any magnification there is a smaller piece of the object that is similar to the whole.

Dimensionless dynamical function vs. self-similarity parameter

- Drag force vs. Reynolds number $Re = \rho VD/\eta$ — hydrodynamics
- Friction force vs. Mach number $Ma = v/c$ — aerodynamics
- Structure function $F(x)$ vs. Bjorken variable $x = -q^2/2(pq)$ — deep-inelastic scattering

……………



Self-similarity: z-scaling

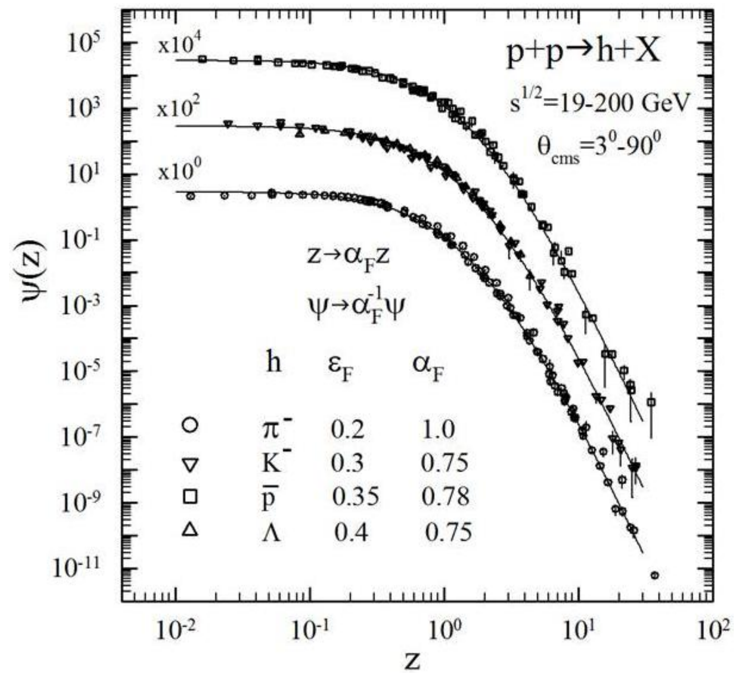
Inclusive cross sections of
π^-, K^-, $\bar{p}$, Λ
in pp collisions

FNAL:
PRD 75 (1979) 764

ISR:
NPB 100 (1975) 237
PLB 64 (1976) 111
NPB 116 (1976) 77
(low p_T)
NPB 56 (1973) 333
(small angles)

STAR:
PLB 616 (2005) 8
PLB 637 (2006) 161
PRC 75 (2007) 064901

Saturation at low z



Power law at high z

Energy scan of spectra
at U70, ISR, S$\bar{p}$pS, SPS, HERA,
FNAL(fixed target),
Tevatron, RHIC, LHC

MT & I.Zborovsky
T.Dedovich
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)
J. Phys.G: Nucl.Part.Phys. 37,085008(2010)
Int.J.Mod.Phys.A27,1250115(2012)
J.Mod.Phys.3,815(2012)

- Energy & angular independence
- Flavor independence (π, K, $\bar{p}$, Λ)
- Saturation for $z < 0.1$
- Power law $\Psi(z)\sim z^{-\beta}$ for high $z > 4$

Scaling – "collapse" of data points onto a single curve.
Universality classes – hadron species (ε_F, α_F).

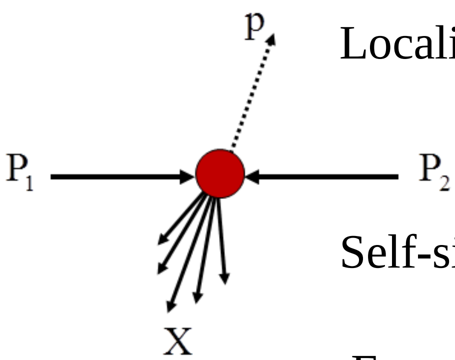
Properties of Ψ(z) in pp collisions

- Energy independence of Ψ(z) ($s^{1/2} > 20$ GeV)
- Angular independence of Ψ(z) ($\theta_{cms}=3^0$-90^0)
- Multiplicity independence of Ψ(z) ($dN_{ch}/d\eta=1.5$-26)
- Saturation of Ψ(z) at low z ($z < 0.1$)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high z ($z > 4$)
- Flavor independence of Ψ(z) (π,K,φ,Λ,..,D,J/ψ,B,ϒ,…, top)

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

z-Scaling

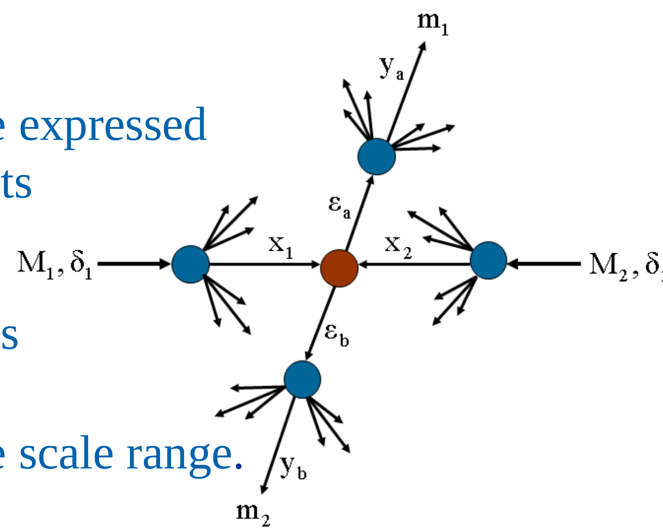
Principles: locality, self-similarity, fractality



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: self-similarity is valid over a wide scale range.



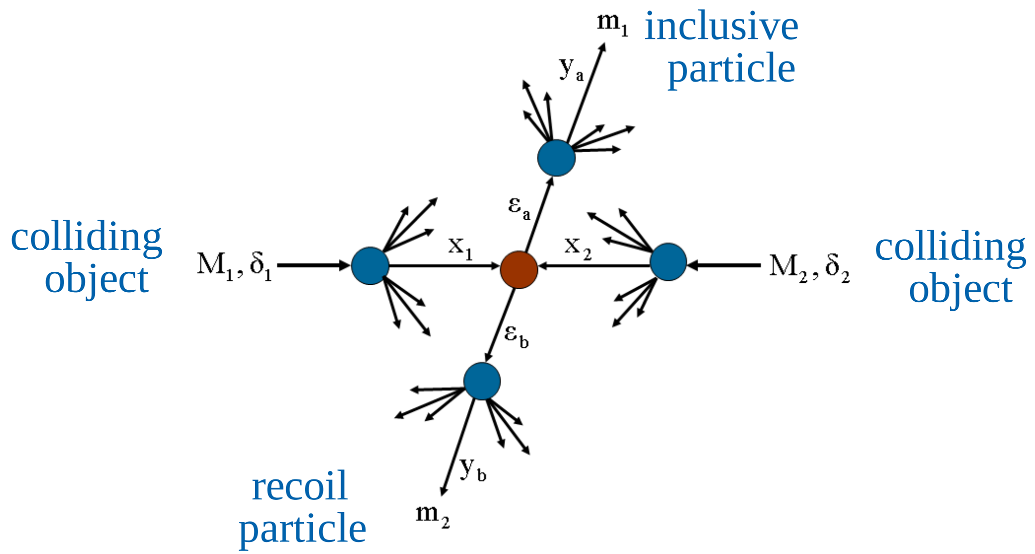
Hypothesis of z-scaling :

$s^{1/2}$, p_T, θ_{cms} — Inclusive particle distributions can be described in terms of constituent sub-processes and parameters characterizing bulk properties of the system. — x_1, x_2, y_a, y_b $\delta_1, \delta_2, \varepsilon_a, \varepsilon_b, c$

$Ed^3\sigma/dp^3$ — Scaled inclusive cross section of particles depends in a self-similar way on a single scaling variable z. — $\Psi(z)$

Locality

Collisions of colliding objects
are expressed via interactions of their constituents



Momentum conservation law for constituent sub-process

$$(x_1 P_1 + x_2 P_2 - p/y_a)^2 = M_X^2$$

Recoil mass

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

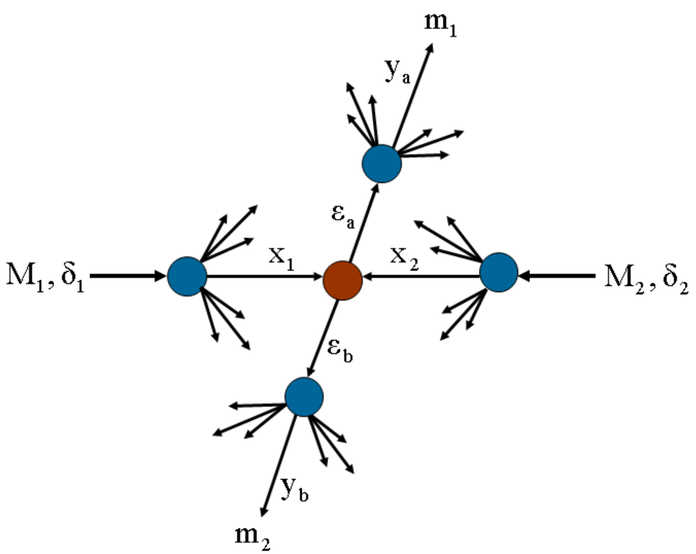
Self-similarity

Interactions of constituents are mutually similar

Self-similarity parameter

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

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



- Ω^{-1} is the minimal resolution at which a constituent sub-process can be singled out of the inclusive reaction
- $s_\perp^{1/2}$ is the transverse kinetic energy of the sub-process 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)

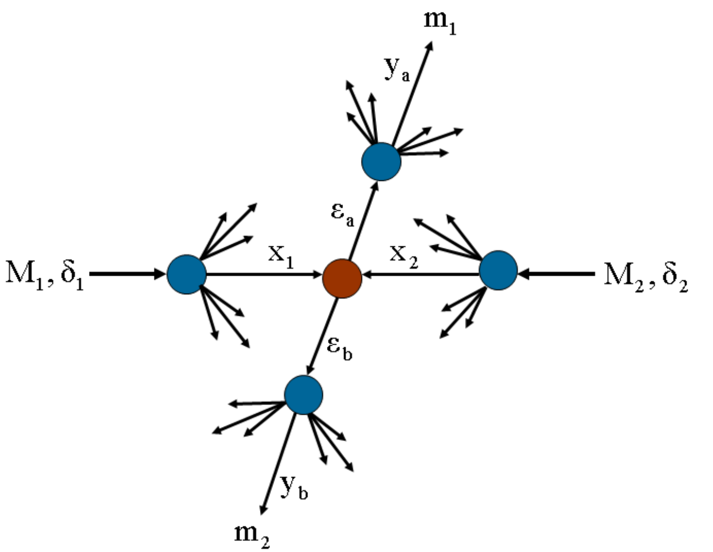
Fractality

Self-similarity over a wide scale range

Fractal measure

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

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



Ω is relative number of configurations containing a sub-process with fractions x_1, x_2 , y_a, y_b of the corresponding 4-momenta

δ_1, δ_2, ε_a, ε_b are parameters characterizing structure of the colliding objects and fragmentation process, respectively

$\Omega^{-1}(x_1, x_2, y_a, y_b)$ characterizes resolution at which a constituent sub-process can be singled out of the inclusive reaction

The fractal measure z diverges as the resolution Ω^{-1} increases.

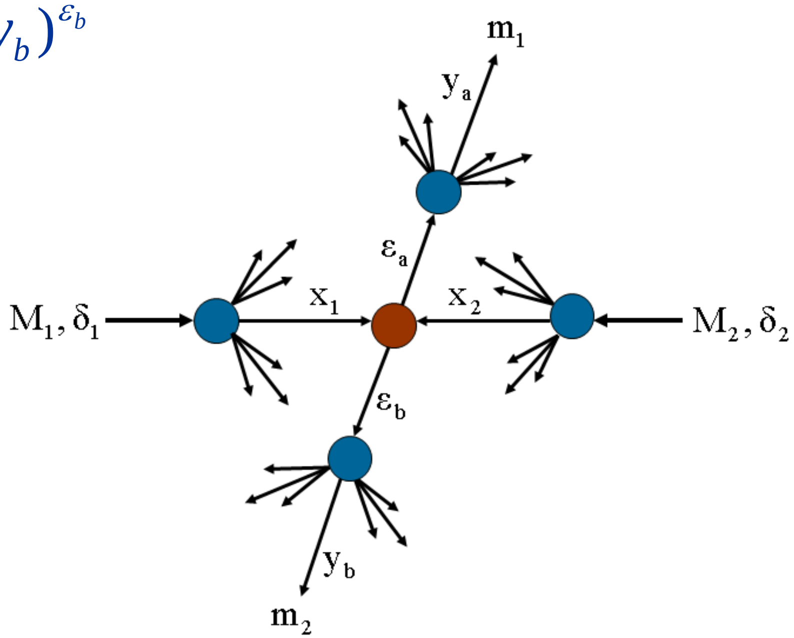
$$z(\Omega)|_{\Omega^{-1}\to\infty} \to \infty$$

Momentum fractions x_1, x_2, y_a, y_b

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 with respect to all constituent sub-processes taking into account 4-momentum conservation law:

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

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



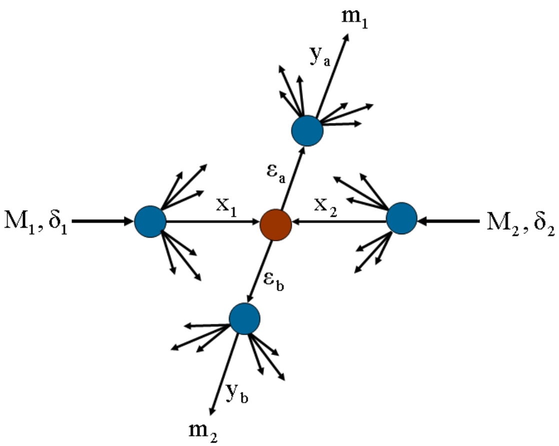
Momentum conservation law

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

Recoil mass

$$M_X = x_1M_1+x_2M_2+m_2/y_b$$

Scaling function $\Psi(z)$



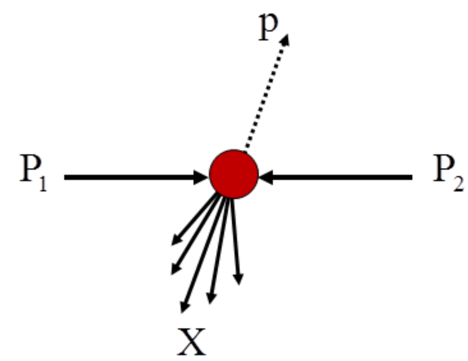
Normalization condition

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

Scale transformation

$$z \to \alpha_F z \qquad \Psi(z) \to \alpha_F^{-1}\Psi(z)$$

preserves the normalization condition



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

- σ_{in} - the inelastic cross section
- <N> - the average multiplicity
- $dN/d\eta$ - the multiplicity density
- $J(z,\eta;p_T^2,y)$ - the Jacobian
- $Ed^3\sigma/dp^3$ - the inclusive cross section

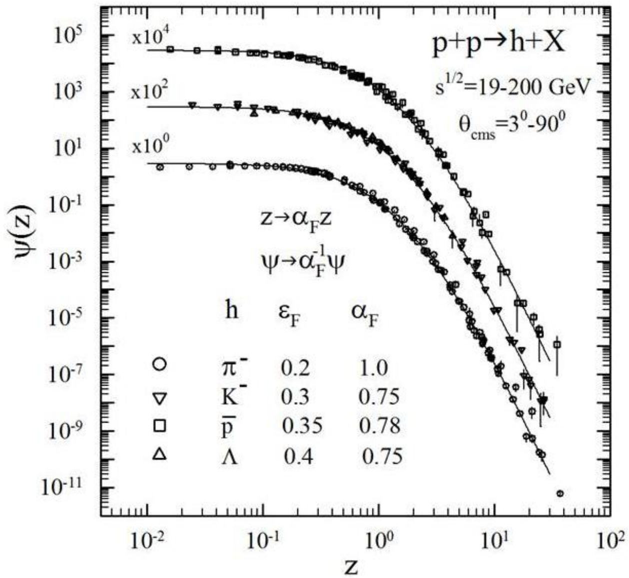
The scaling function $\Psi(z)$ is probability density to produce the inclusive particle with the corresponding z.

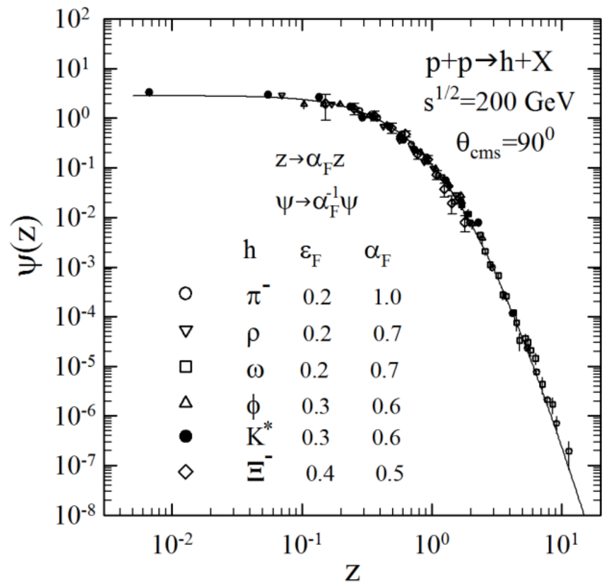
Self-similarity at RHIC

Flavor independence of scaling function

M.T. & I.Zborovský
Int.J.Mod.Phys.
A24,1417(2009)

π^-, ρ, ω, ϕ, K^*, Λ, Ξ, J/ψ





STAR:
PRL 92 (2004) 092301
PLB 612 (2005) 181
PRC 71 (2005) 064902
PRC 75 (2007) 064901

PHENIX:
PRC 75 (2007) 051902

- Energy independence
- Angular independence
- Flavor independence
- Saturation for $z < 0.01$

- Power law $\Psi(z) \sim z^{-\beta}$ at large z
- ε_F, α_F independent of p_T, $s^{1/2}$

Self-similarity of particle production with various flavor content.

Recent data from RHIC

STAR

PHENIX

K^-

- ○ (yellow) PRD 19 (1979) 764
- ● (red) PRD 19 (1979) 764
- ○ PRD 19 (1979) 764
- ◆ (green) NPB 100 (1975) 237
- ▽ PRD 40 (1989) 2777
- ◆ NPB 100 (1975) 237
- ◇ NPB 100 (1975) 237
- ★ PRC 75 (2007) 064901
- ☆ PRL 108 (2012) 072302

K^*

- □ PRC 84 (2011) 064909
- △ NPB 203 (1982) 27
- ☆ PRC 71 (2005) 064902
- ★ PRC 71 (2005) 064902
- ○ PRC 90 (2014) 054905

K^0_S

- △ PRD 20 (1979) 37
- ○ PLB 61 (1976) 309
- □ ZPC 12 (1982) 217
- ▽ PRD 83 (2011) 052004
- ★ PRC 75 (2007) 064901
- ☆ PRL 108 (2012) 072302

φ

- □ PLB 491 (2000) 59
- △ NPB 203 (1982) 27
- ○ PRD 83 (2011) 052004
- ▽ PRD 83 (2011) 052004
- ☆ PLB 612 (2005) 181

○	K^0_S	PRC 75 (2007) 064901
○	K^0_S	PRL 108 (2012) 072302
◇	K^-	PRC 75 (2007) 064901
◇	K^-	PRL 108 (2012) 072302
▽	K^*	PRC 71 (2005) 064902
△	K^*	PRC 90 (2014) 054905
□	ϕ	PRD 83 (2011) 052004
□	ϕ	PRD 83 (2011) 052004
☆	Λ	PRC 75 (2007) 064901
●	Ξ^-	PRC 75 (2007) 064901
■ (red)	Ω	PRC 75 (2007) 064901
■ (green)	Σ^*	PRL 97 (2006) 132301
● (yellow)	Λ^*	PRL 97 (2006) 132301

Self-similarity of K^- production in pp

Self-similarity parameter

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

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

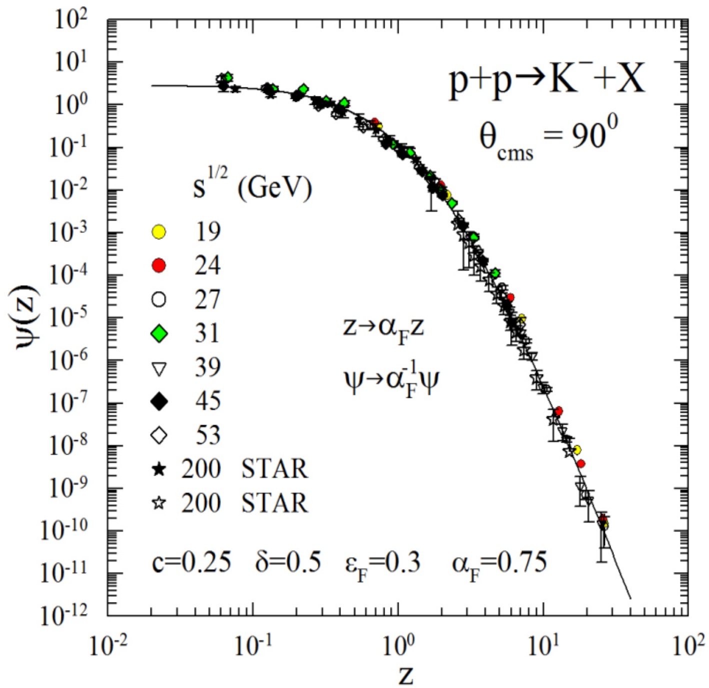
$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c - "specific heat" of bulk matter
- δ - proton fractal dimension
- ε_F - fragmentation fractal dimension

Scaling function

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

"Collapse" of data onto a single curve



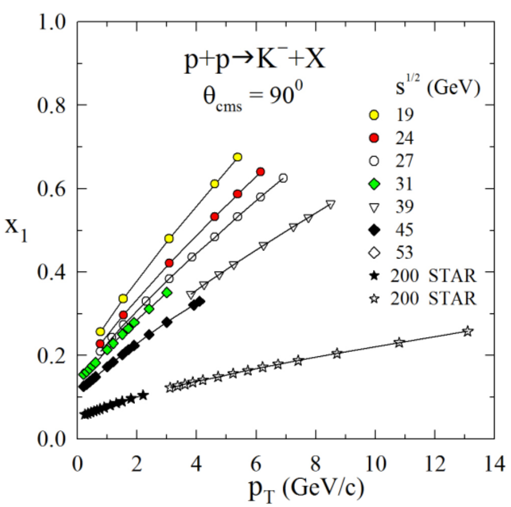
- Energy independence of $\Psi(z)$
- Centrality independence of $\Psi(z)$
- Power law at high z
- Saturation at low z

Universality: the same shape of Ψ both for K^- and π^- (solid line)

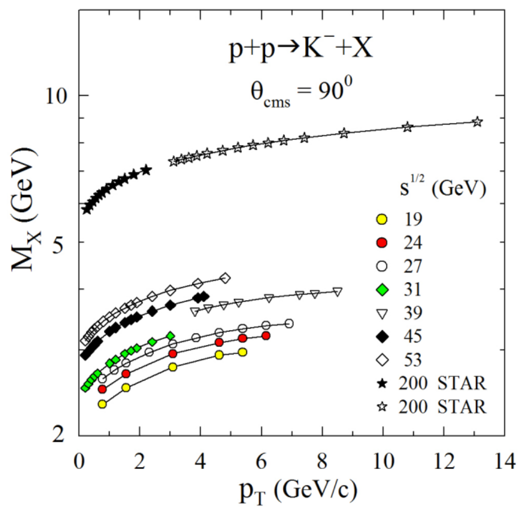
Sub-process of K^- production in pp

Constituent level of particle production in terms of

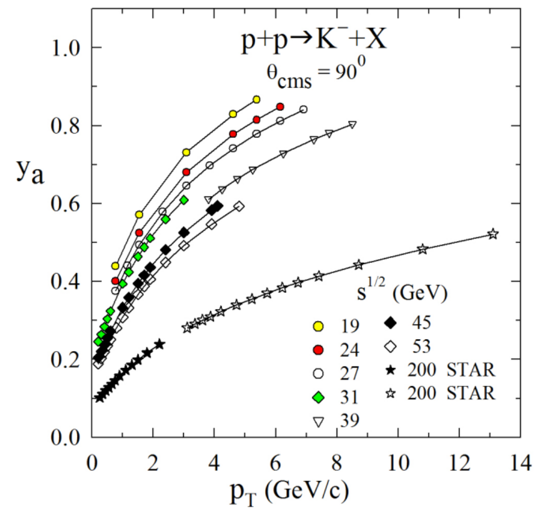
Momentum fraction



Recoil mass



Energy loss $\Delta E/E \sim (1-y_a)$



Momentum fraction

- increases with p_T
- decreases with $\sqrt{s_{NN}}$

Recoil mass

- increases with p_T
- increases with $\sqrt{s_{NN}}$

Constituent energy loss

- decreases with p_T
- increases with $\sqrt{s_{NN}}$

Self-similarity of K^0_S production in pp

Self-similarity parameter

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

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

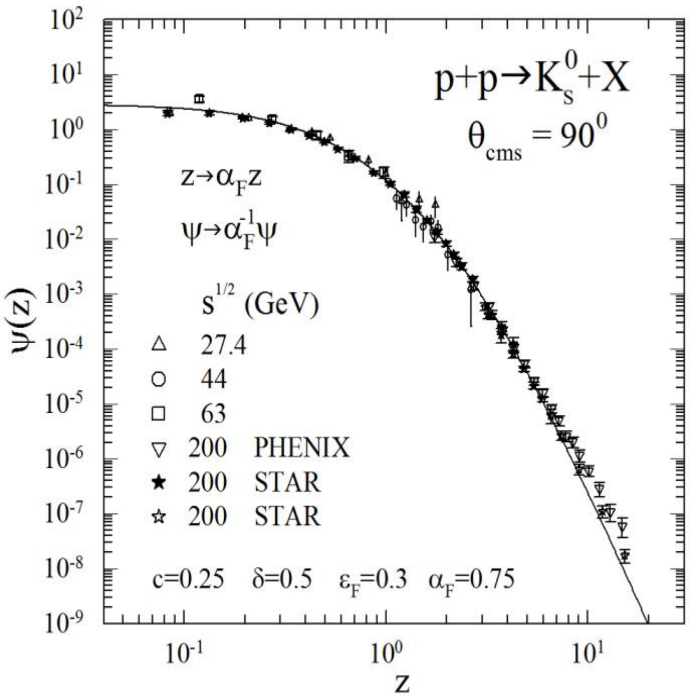
$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c - "specific heat" of bulk matter
- δ - proton fractal dimension
- ε_F - fragmentation fractal dimension

Scaling function

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

"Collapse" of data onto a single curve



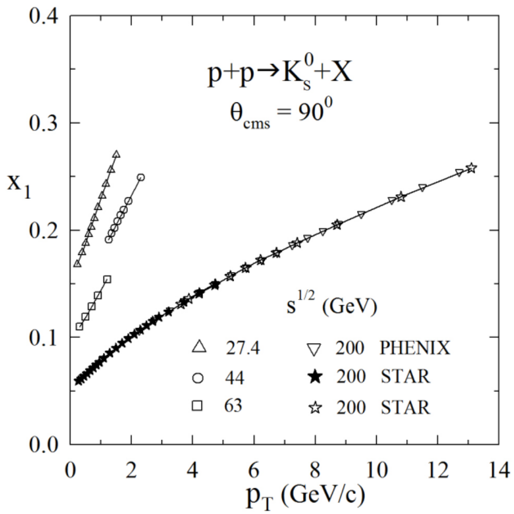
- Energy independence of $\Psi(z)$
- Centrality independence of $\Psi(z)$
- Power law at high z
- Saturation at low z

Universality: the same shape of Ψ both for K^0_S and π^- (solid line)

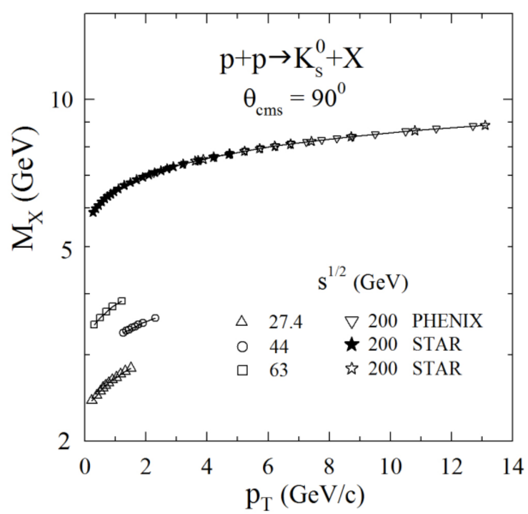
Self-similarity of K^0_S production in pp

Constituent level of particle production in terms of

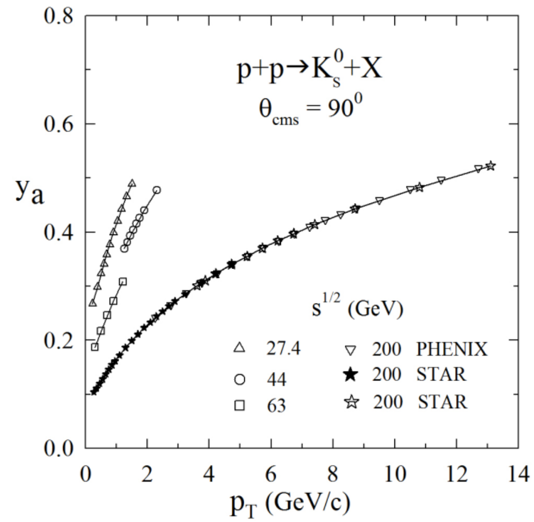
Momentum fraction



Recoil mass



Energy loss $\Delta E/E \sim (1-y_a)$



Momentum fraction

- increases with p_T
- decreases with $\sqrt{s_{NN}}$

Recoil mass

- increases with p_T
- increases with $\sqrt{s_{NN}}$

Constituent energy loss

- decreases with p_T
- increases with $\sqrt{s_{NN}}$

Self-similarity of $K^*(892)$ production in pp

Self-similarity parameter

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

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

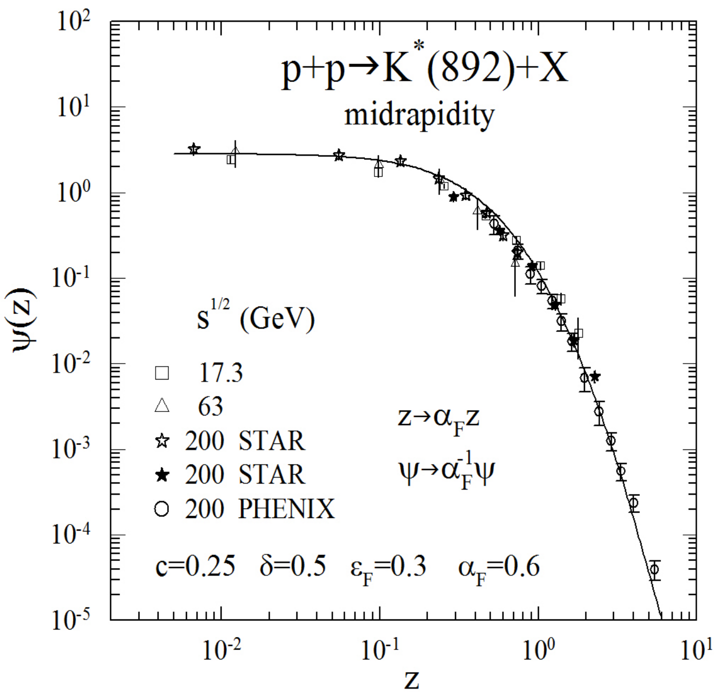
$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c - "specific heat" of bulk matter
- δ - proton fractal dimension
- ε_F - fragmentation fractal dimension

Scaling function

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

"Collapse" of data onto a single curve



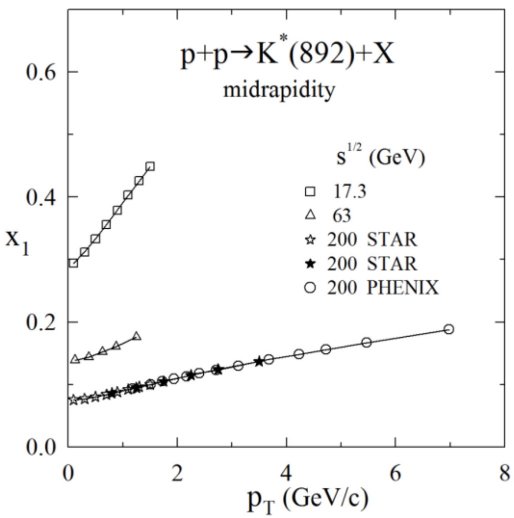
- Energy independence of $\Psi(z)$
- Centrality independence of $\Psi(z)$
- Power law at high z
- Saturation at low z

Universality: the same shape of Ψ both for K^* and π^- (solid line)

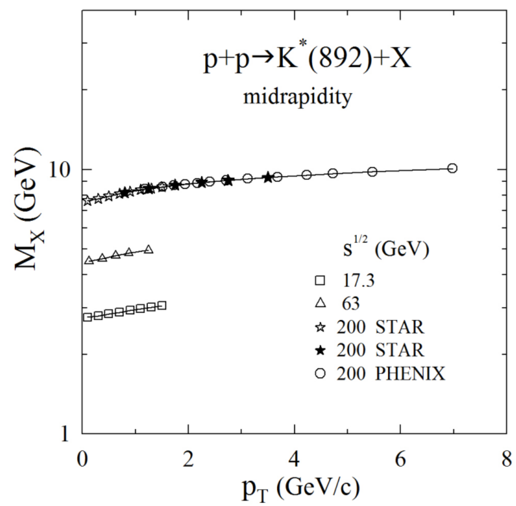
Self-similarity of $K^*(892)$ production in pp

Constituent level of particle production in terms of

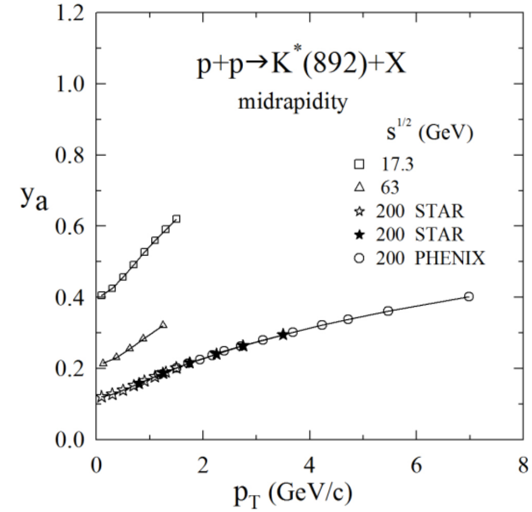
Momentum fraction



Recoil mass



Energy loss $\Delta E/E \sim (1-y_a)$



Momentum fraction

- increases with p_T
- decreases with $\sqrt{s_{NN}}$

Recoil mass

- increases with p_T
- increases with $\sqrt{s_{NN}}$

Constituent energy loss

- decreases with p_T
- increases with $\sqrt{s_{NN}}$

Self-similarity of φ production in pp

Self-similarity parameter

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

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

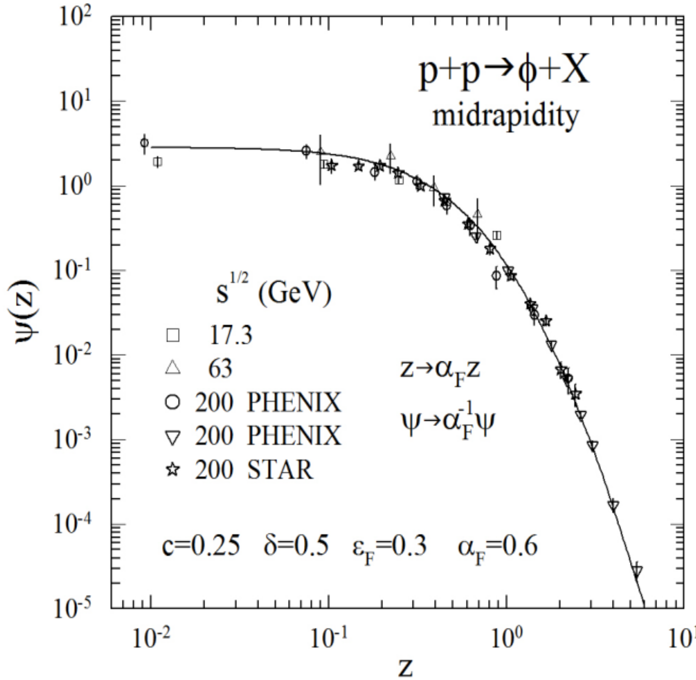
$$\Omega = (1-x_1)^\delta (1-x_2)^\delta (1-y_a)^{\varepsilon_F} (1-y_b)^{\varepsilon_F}$$

- $dN_{ch}/d\eta|_0$ - multiplicity density
- c - "specific heat" of bulk matter
- δ - proton fractal dimension
- ε_F - fragmentation fractal dimension

Scaling function

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

"Collapse" of data onto a single curve



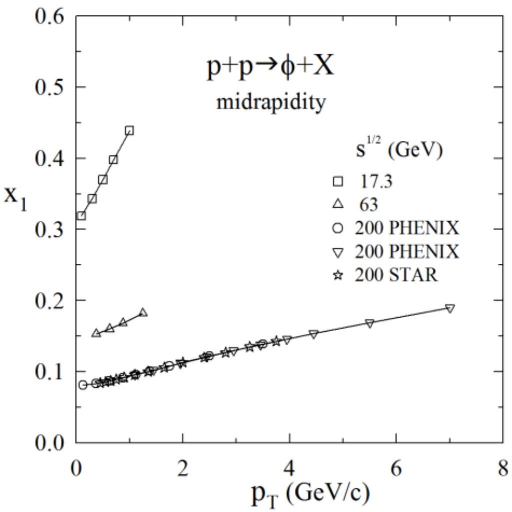
- Energy independence of Ψ(z)
- Centrality independence of Ψ(z)
- Power law at high z
- Saturation at low z

Universality: the same shape of Ψ both for φ and π^- (solid line)

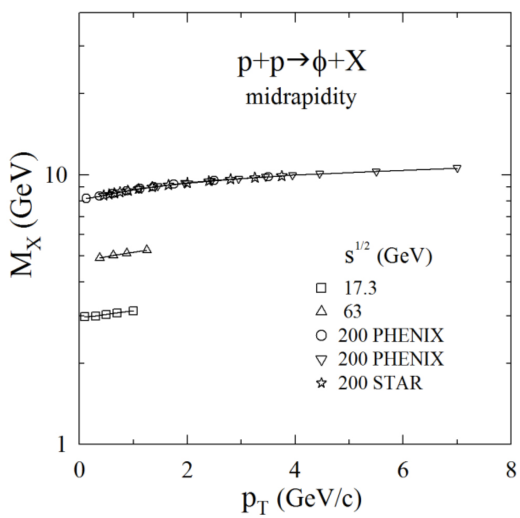
Self-similarity of φ production in pp

Constituent level of particle production in terms of

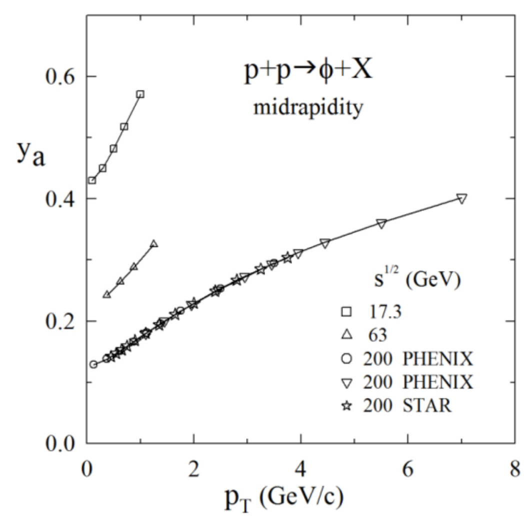
Momentum fraction



Recoil mass



Energy loss $\Delta E/E \sim (1-y_a)$



Momentum fraction
- increases with p_T
- decreases with $\sqrt{s_{NN}}$

Recoil mass
- increases with p_T
- increases with $\sqrt{s_{NN}}$

Constituent energy loss
- decreases with p_T
- increases with $\sqrt{s_{NN}}$

Self-similarity of strangeness production in pp

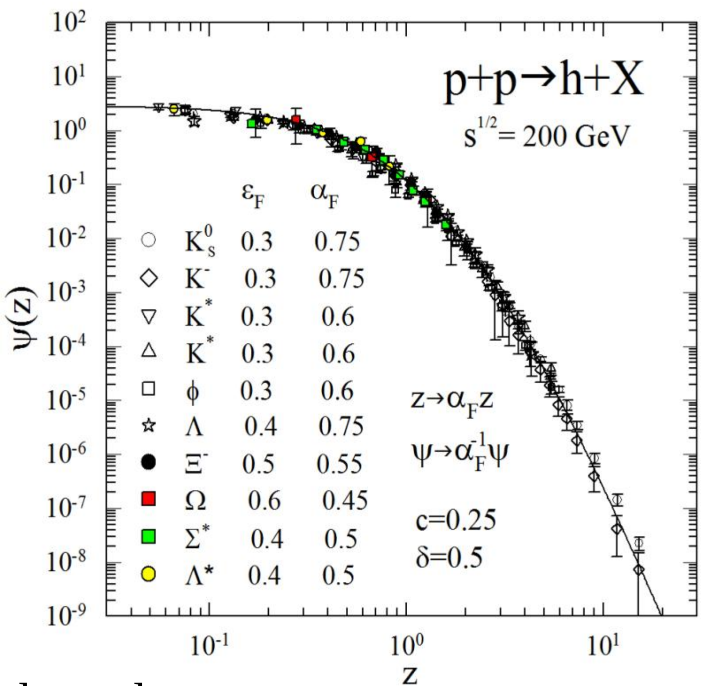
Universality: flavor independence of the scaling function

M.T.& I.Zborovský
Int.J.Mod.Phys.
A24,1417(2009)

K^0_S, K^-, K^*, ϕ, Λ, Ξ, Ω, Σ^*, Λ^*

Solid line for π^- meson is a reference frame

$\varepsilon_\pi = 0.2, \quad \alpha_\pi = 1$



STAR:
PRL 92 (2004) 092301
PRL 97 (2006) 132301
PLB 612 (2005) 181
PRC 71 (2005) 064902
PRC 75 (2007) 064901
PRL 108 (2012) 072302

PHENIX:
PRC 75 (2007) 051902
PRD 83 (2011) 052004
PRC 90 (2014) 054905

- Energy independence
- Angular independence
- Flavor independence
- Saturation for $z < 0.01$

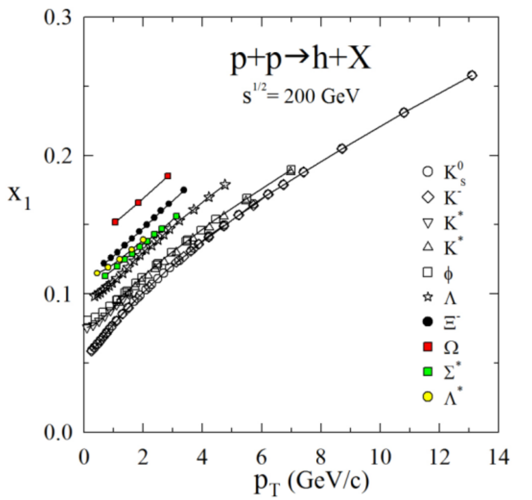
- Power law $\Psi(z) \sim z^{-\beta}$ at large z
- ε_F, α_F independent of p_T, $s^{1/2}$

Self-similarity of strangeness production in pp

K^0_S, K^-, K^*, ϕ, Λ, Ξ, Ω, Σ^*, Λ^*

Constituent level of particle production in terms of

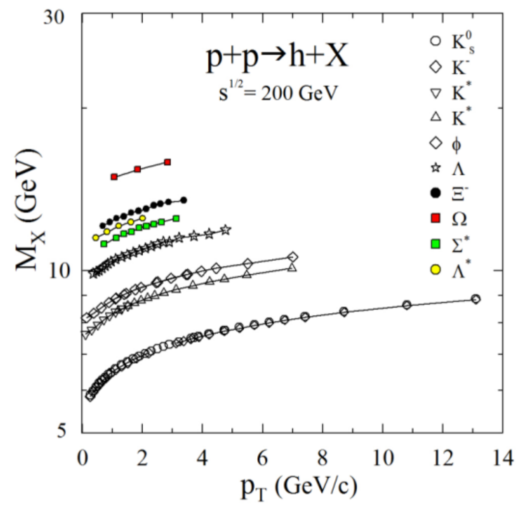
Momentum fraction



The more strangeness, the larger momentum fraction

$$x_1^{\Omega} > x_1^{\Xi} > x_1^{\Sigma} > x_1^{K}$$

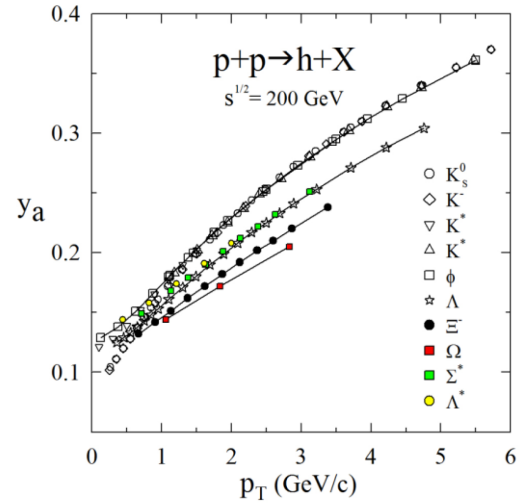
Recoil mass



The more strangeness, the larger recoil mass

$$M_X^{\Omega} > M_X^{\Xi} > M_X^{\Sigma} > M_X^{K}$$

Energy loss $\Delta E/E \sim (1-y_a)$



The more strangeness, the larger energy loss

$$\varepsilon_{\Omega} > \varepsilon_{\Xi} > \varepsilon_{\Sigma} > \varepsilon_{K}$$

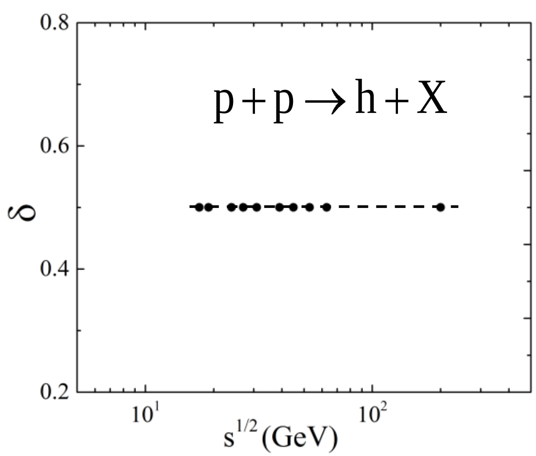
Self-similarity dictates the properties of constituent sub-process.

Model parameters: δ, ε_F , c

Parameters δ, ε_F , c are found from
the scaling behavior of Ψ as a function of self-similarity variable z

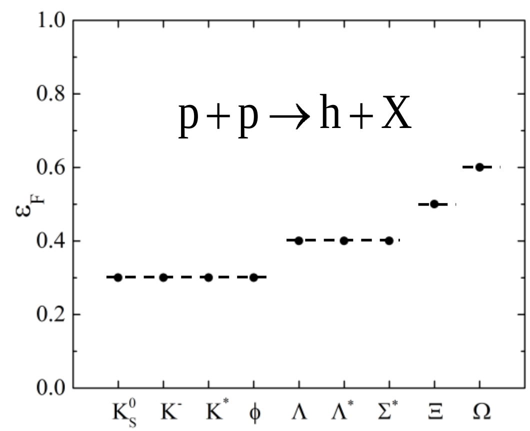
Proton fractal dimension

δ



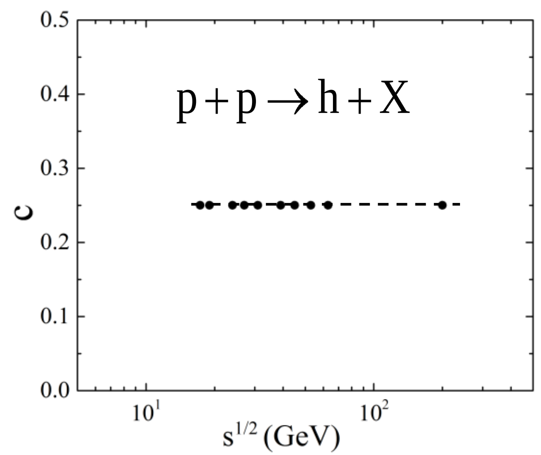
Fragmentation dimension

ε_F



"Specific heat"

c



- δ, ε_F , c are independent of $\sqrt{s}$, p_T
- ε_F depends on flavor

A discontinuity and strong correlation of the model parameters could give indication on new physics in pp collisions:
Search for phase transition, critical point …. with strange probes.

Summary & Outlook

- New data on transverse momentum spectra of strange hadrons produced in p+p collisions at RHIC in mid-rapidity region were analyzed in the z-scaling approach.
- Self-similarity of strangeness production in p+p collisions over a wide kinematical range was found.
- Constituent energy loss as a function of collision energy and transverse momentum of different strange particles was estimated.
- The energy independence of fractal dimensions and "specific heat" was confirmed.

Specific features of constituent sub-process with strange particles found in the z-scaling approach can be sensitive to critical phenomena in Strange Quark Matter created in pp, pA and AA collisions.

Discontinuity of z-scaling parameters would be manifestation of these phenomena .

Joint Institute for Nuclear Research

XV International conference

Strangeness in Quark Matter

6 July - 11 July 2015 Dubna, Russia

Thank you for your attention !

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TOPICS

STRANGENESS and heavy QUARK production in nuclear collisions
Hadronic INTERACTIONS
Bulk MATTER PHENOMENA associated with strange and HEAVY quarks
Strangeness in astrophysics
OPEN questions and NEW developments

Satellite Meetings:

Summer School "Dense Matter" 29 June-11July 2015
Roundtable "Physics at NICA" 5 July 2015

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