Average transverse energy density for pions, kaons, ϕ-mesons and Ω-hyperons in the most central A+A collisions at RHIC and LHC

O.M. Shaposhnikova[1,2], A.A.Marova[2], G.A. Feofilov[2]
[1]Lomonosov Moscow State University
[2]Federal State Budgetary Educational Institution of Higher Education "Saint-Petersburg State University", Saint Petersburg, 199034 Russia

LUHEP SPb SU

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Interesting strangeness

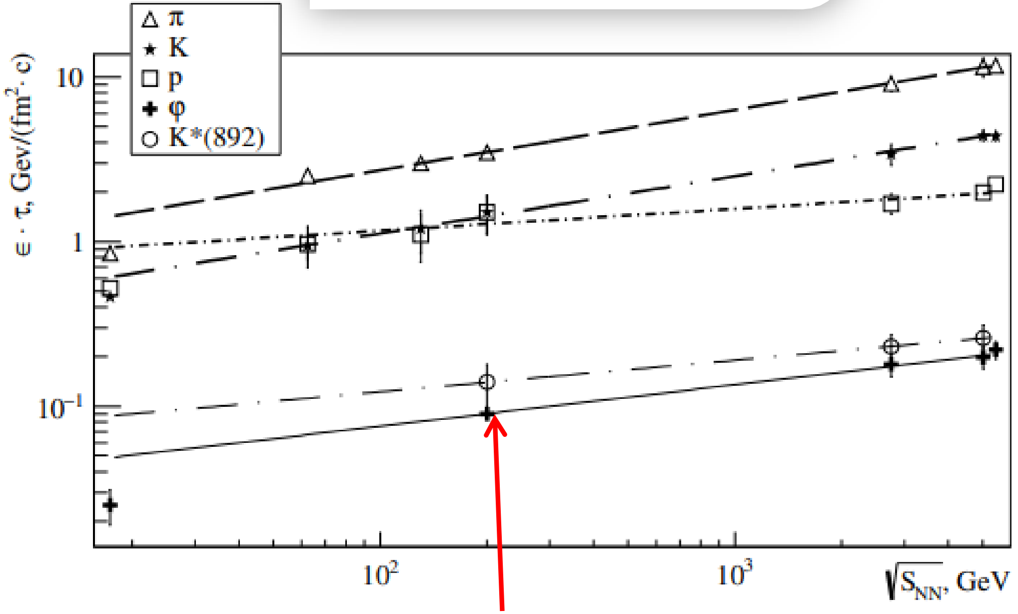
Hadrons with (multiple) strange quarks

Small hadronic cross section	Sensitive to dynamics of the medium	Can be easily reconstructed and identified in experiment!

→ Systematic study of medium properties!

$$\varepsilon \cdot \tau = \frac{dE_{\perp}}{dy} \frac{1}{S_{\perp}}$$

[2]



φ -meson (1020)

The lightest meson with hidden flavor. Contains only strange quarks.

[1]

→ A dramatic increase prediction in the φ -meson after the formation of the quark-gluon plasma (QGP).

No increase in the strangeness of fi-mesons output is observed.

добавить вывод как на следующем слайде - наблюдение

добавить определние бьоркеновской энергии

[1] - Asher Shor , PHYSICAL REVIEW LETTERS, 25.70.Np, 12.35.Ht, 21.65 (1985)

[2] - O. Shaposhnikova et al., 2024, Vol. 55, No. 4, pp. 1134–1139.

Transverse energy

S⊥ – площадь поперечного сечения двух сталкивающихся ядер.

$$\varepsilon \cdot \tau = \frac{dE_\perp}{dy} \frac{1}{S_\perp}$$

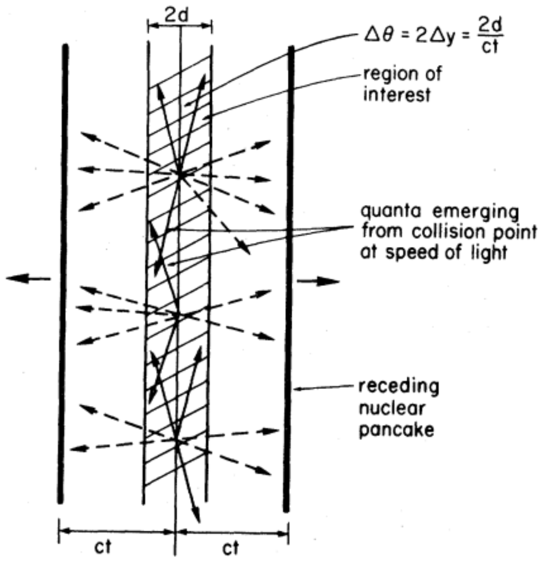
E⊥ – полная поперечная энергия

τ - время образования

$$\frac{d < E_\perp >}{dy} = < m_\perp > \frac{dN}{dy}$$

[1]

$$< m_\perp > = \sqrt{m^2 + < p_\perp >^2}$$



Мы интересуемся зависимостями для отдельных заряженных частиц

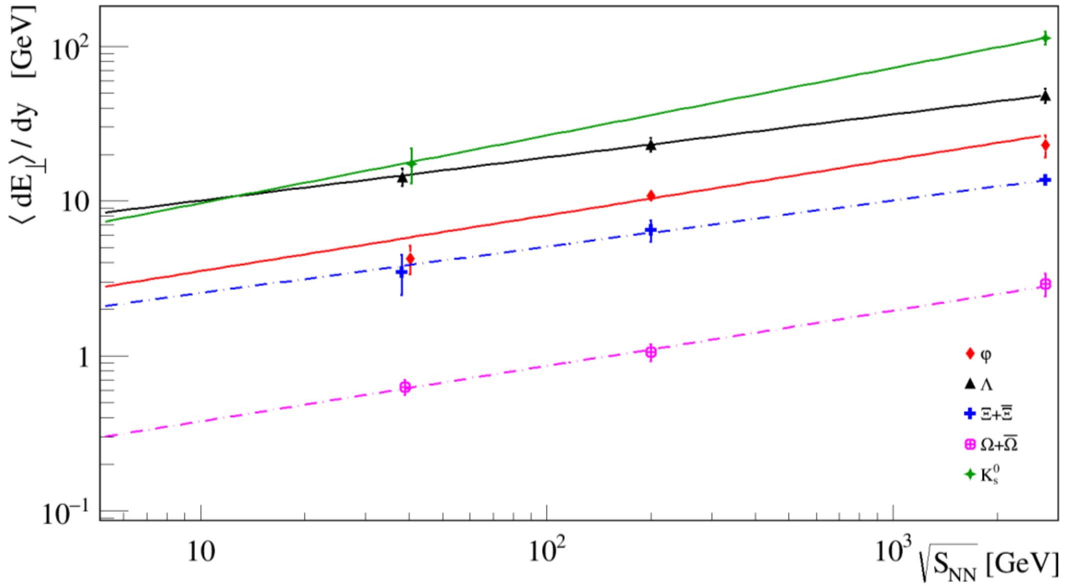
π, K, ϕ, Ω…...

События берутся в самой центральной области быстрот.

[1] – Abelev et al.(RHIC Collaboration), PHYSICAL REVIEW C 79, 034909 (2009)
[2] - J. D. Bjorken, Phys. Rev. D 27, 140 (1983)

$\langle dE_\perp/dy \rangle_{particles}$, |γ|<0.5, 0-5%

$\langle dE_\perp/dy \rangle = Q \cdot (\sqrt{S_{NN}})^n$



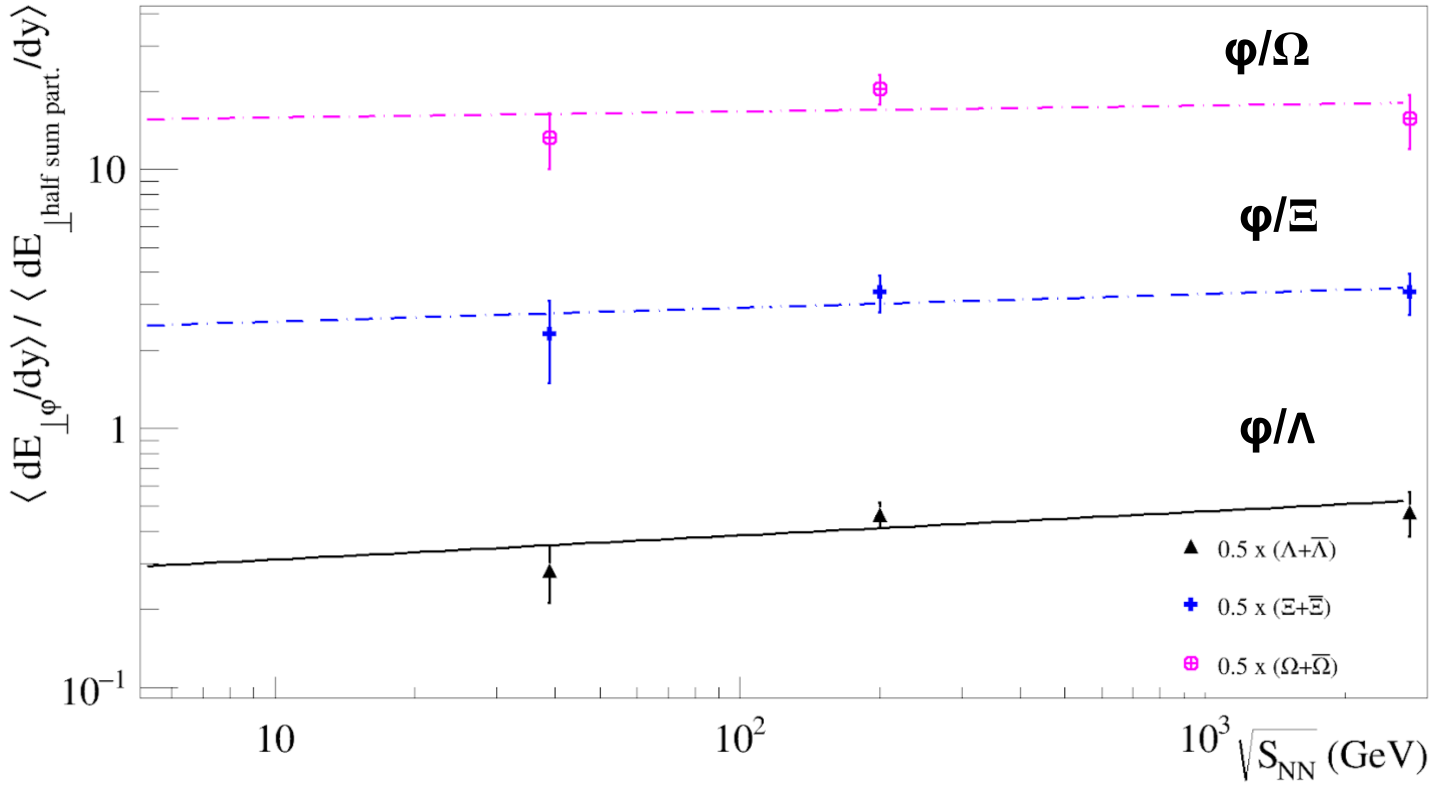
Transverse energy density at midrapidity for various particles in central 0-5% in A+A collisions [1]

Particles	n
φ	0.36±0.04
$\Xi^+ + \Xi^-$	0.30±0.05
Λ	0.28±0.04
$\Omega^+ + \Omega^-$	0.39±0.08
K_0^s	0.44±0.06

- **Our result: the slopes of the transverse energies of different particles are strangely similar in the collision energy range √SNN ~ 39 GeV –2.76 TeV.**

[1] O.Shaposhnikova et al., report at ICPPA-2024, to be published

$\langle dE_{\perp}/dy \rangle_{\varphi} / \langle dE_{\perp}/dy \rangle_{particles}$, $|\gamma|<0.5$, 0-5% [1]



- **Our main result in [1]: the ratious of transverse energy of various particles with strangeness remain constant in the collision energy range $\sqrt{S_{NN}} \sim$ 39 GeV –2.76 TeV.**

[1] O.Shaposhnikova et al., report at ICPPA-2024, to be published

Motivation

Ratios of particles with and without strangeness and with different masses.

$$\varphi, \pi, K, \Omega$$

Particle	Кварковый состав	m, MeV	τ, c	S
π	udd	139	$2.6*10^{-8}$	0
K	$u\bar{s}, \bar{u}s$	495	$1,24*10^{-8}$	0
φ	$s\bar{s}$	1020	$1.54*10^{-22}$	1
Ω	sss	1670	$8.21*10^{-11}$	1.5
Ξ	dss	1321	$2.9*10^{-10}$	0.5
Λ	uds	1116	$2.6*10^{-10}$	0.5

Sources of experimental data used

39 Gev

Particle	π[1]	K[1]	φ [2]	Ω[3]
dN/dy	184±0.07	28± 0,02	3.38±0.48	0.165±0.017
$< p_\perp >$ [Gev/c]	0.414 ± 0.019	0.606 ± 0.0002	0.69±0.08	*

200 Gev

Particle	π[4]	K[4]	φ [5]	Ω[3]
dN/dy	325± 25	50.4± 6.3	7.7±0.3	0.26±0.04
$< p_\perp >$ [Gev/c]	0.4 ± 0.03	0.7-0.8 ± 0.05	0.97±0.02	*

2760 Gev

Particle	π[7, 8]	K[7, 8]	φ [9]	Ω[10]
dN/dy	733± 53	109± 9	13.8±1.8	0.595 ±0.03
$< p_\perp >$ [Gev/c]	0.518 ± 0.019	0.72 ± 0.027	1.31±0.07	*

[1] –Adamczyk L. et al. (STAR Collab.), Phys.Rev.C 96 (2017) 044904, 2017
[2] - Adamczyk L. et al. (STAR Collab.), Phys.Rev.C 93 (2016) 021903, 2016.
[3] - J. Adams et al., (STAR Collab.), Phys.Rev.Lett. 98 (2007) 062301, 2007.
[4] - B.I.Abelev et al. (ALICE Collab.), Phys. Rev. C79, 034909(2009).
[5] - J. Adams et al. (STAR Collab.) Phys. Rev. C71:064902,2005
[6] - J. Adams et al. (STAR Collab), PRL 98, 062301 (2007)
[7] - B.I.Abelev et al. (ALICE Collab.), Phys. Rev. C 88, 044910 (2013).
[8] - C. Loizides, J. Nagle, and P. Steinberg, SoftwareX 1-2 (2015) 13–18
[9] - B.I.Abelev et al. (ALICE Collab.), Phys. Rev. C 91, 024609(2015)
[10] - B.I.Abelev et al. (ALICE Collab.), Phys.Lett.B 728 (2014) 216-227, 2014.
[11] - ALICE Collaboration, Physics Letters B 728 (2014)

*** - <pt> ---** we obtained average values using pt spectra from Hepdata [6,11]

We estimate the systematic error to be about 10%.

Calculating the average $p_\perp$

The Levy function:

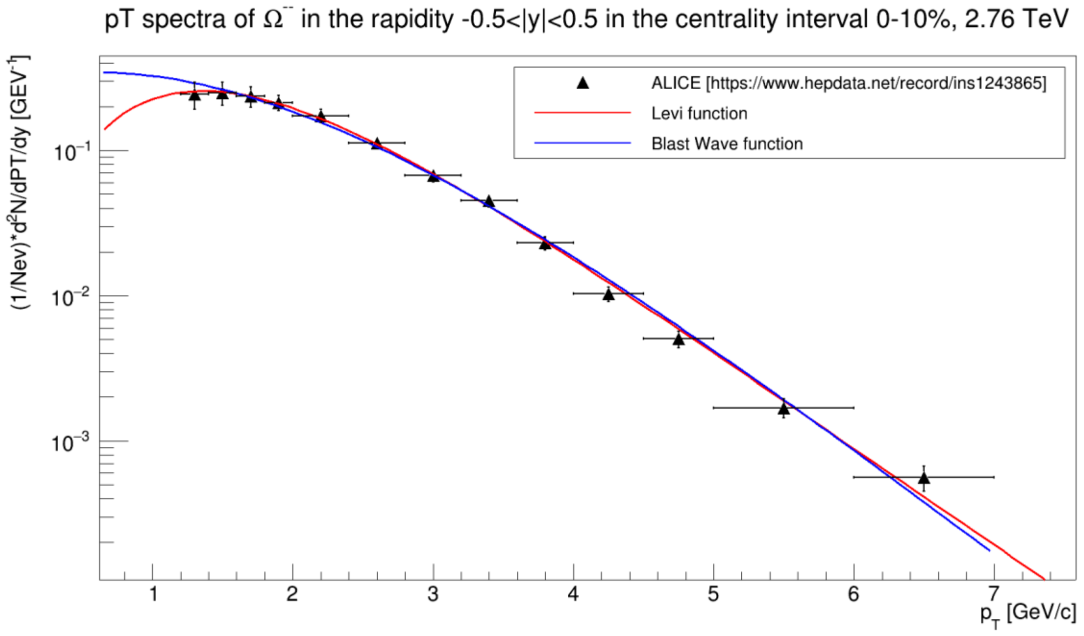
$$f_L(p_\perp) = \frac{norm \cdot (n-1)(n-2)}{nT(nT + m_0(n-2))} \cdot p_\perp \left(1 + \frac{\sqrt{{m_0}^2 + {p_\perp}^2} - m_0}{nT}\right)$$

n, T, and m_0 - fitting parameters

Average transverse momentum:

$$< p_\perp > = \frac{\int_a^b f(p_\perp) p_\perp dp_\perp}{\int_a^b f(p_\perp) dp_\perp}$$

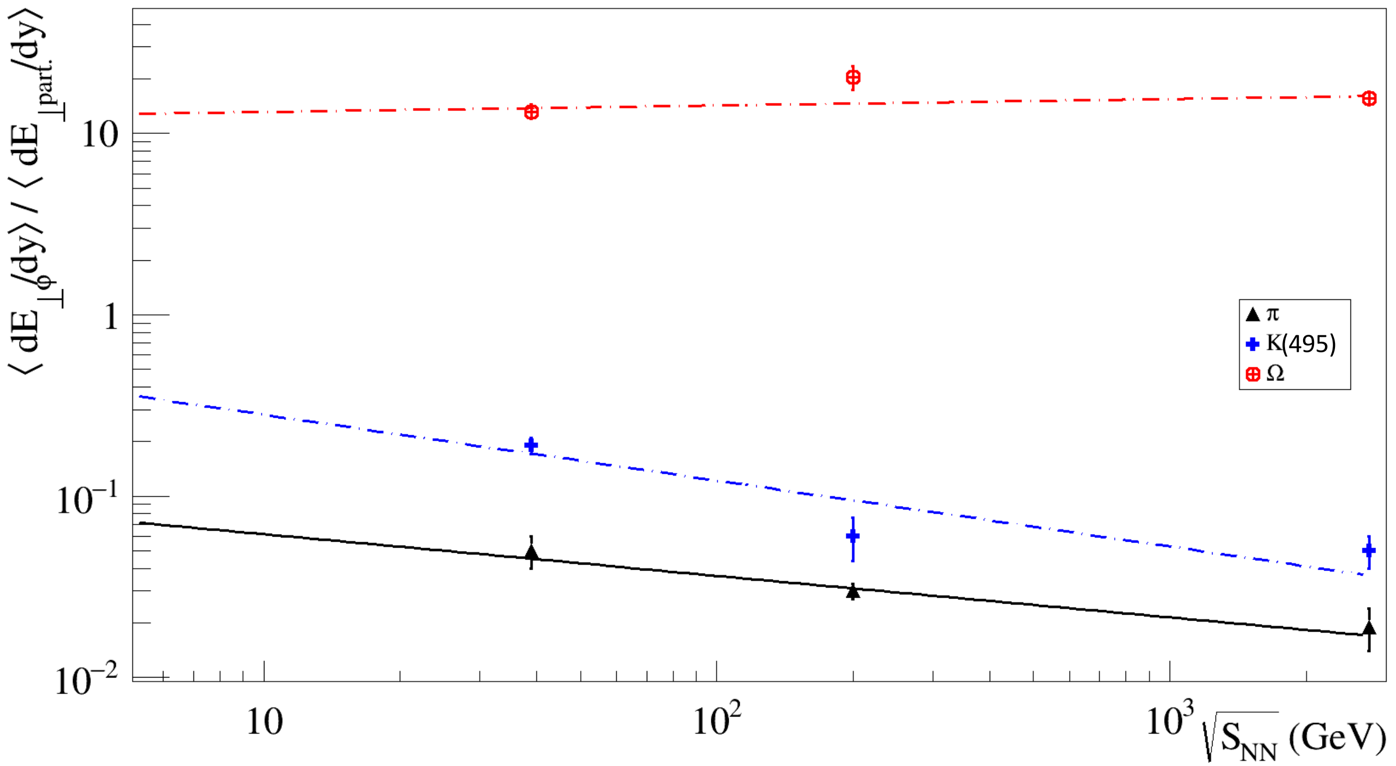
a and b are extended intervals over the entire range of $p_\perp$



To estimate systematic errors we used the blast-wave function.

Ссылка на работу где описано

New results



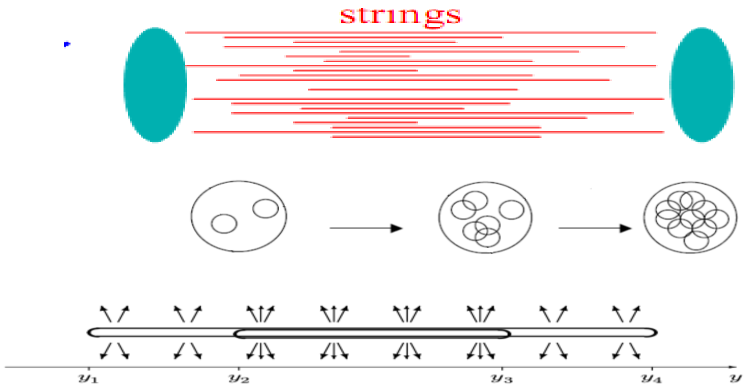
$$\langle dE_{\perp}/dy \rangle = Q * (\sqrt{S_{NN}})^n$$

Particles	*n*
π	*-0.23±0.09*
K	*-0.36±0.08*
Ω	*0.04±0.03*

PRELIMINARY RESULTS

The ratious of transverse energy of various particles with strangeness or without remain constant in the collision energy range √SNN ~ 39 GeV –2.76 TeV.

Some theoretical approaches:
Multi-Pomeron Exchange Model (EPEM)[1]
with string fusion[2]



-- Quark-gluon strings as tubes of color fields between partons of colliding nuclei

-- Formation of clusters and fusion in case of high density

--Hadronisation

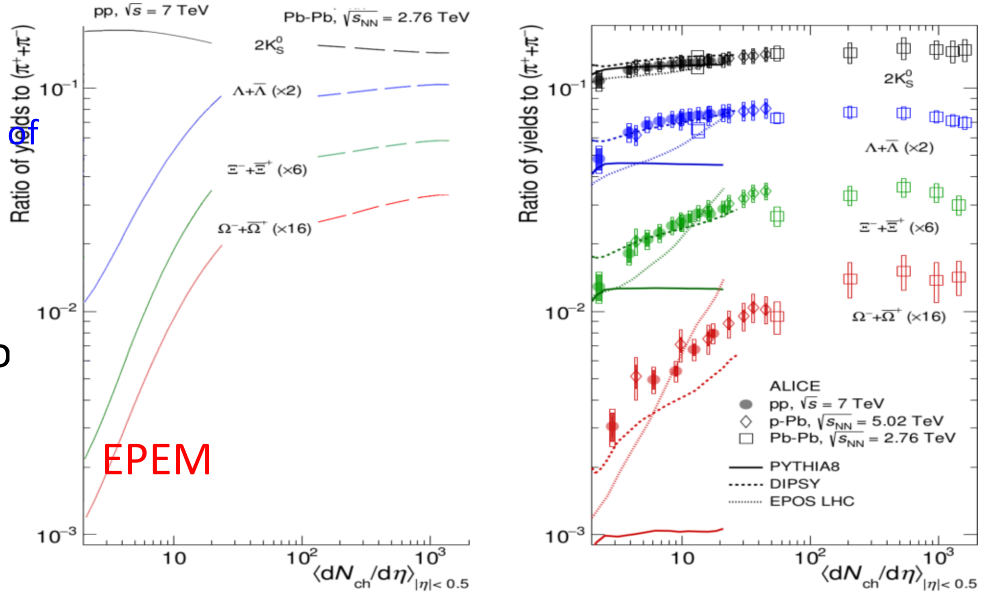
$$g_\nu \exp\left(-\frac{\pi\left(p_t{}^2 + m_\nu{}^2\right)}{n^\beta t}\right)$$

Schwinger mechanism of production o particles species of type *ν* production mass m_ν, momentum p_t *and* spin – S_ν,

$$g_\nu = 2S_\nu + 1$$

Here,
n - number of Pomerons,
t- string tension,
β – model collective parameter

DOI:10.1038/NPHYS/4111



- The model [1] qualitatively describes exp. ratios[3] of yields to pions in p+p to p+Pb and Pb+Pb at 2.76 TeV

[1] V.Kovalenkro, et al.,*Universe* **2022**, *8*(4), 246.
[2] Amelin, N.S.; Braun, M.A.; Pajares, C. String fusion and particle production at high-energies: Monte Carlo string fusion model. Z. Phys. C 1994, 63, 507–516
[3] ALICE Collab.,Nature Physics,v. 13, 535-539 (2017), DOI:10.1038/NPHYS/4111

See also Talk by Vladimir Kovalenko 03/07/2025, 11:25 ,Section 4

Calculation t_{eff} basing on the work [1]

$$\frac{dN}{dy} \sim (2S_\mu + 1) \cdot \exp\left(-\frac{\pi(p_t^2 + m_\mu^2)}{t_{eff}}\right)$$

$$\frac{<\frac{dE_\varphi}{dy}>}{<\frac{dE_\Omega}{dy}>} = \frac{\frac{dN_\varphi}{dy} < m_T >_\varphi}{\frac{dN_\Omega}{dy} < m_T >_\Omega} = \frac{(2S_\varphi + 1)}{(2S_\Omega + 1)} \cdot \frac{< m_T >_\varphi}{< m_T >_\Omega} \exp\left(\frac{\pi(< m_T >_\Omega{}^2 - < m_T >_\varphi{}^2)}{t_{eff}}\right) = R$$

$$t_{eff} = \frac{\pi(< m_T >_\Omega{}^2 - < m_T >_\varphi{}^2}{\ln\left(\frac{R(2S_\Omega + 1) < m_T >_\Omega}{(2S_\varphi + 1) < m_T >_\varphi}\right)}$$

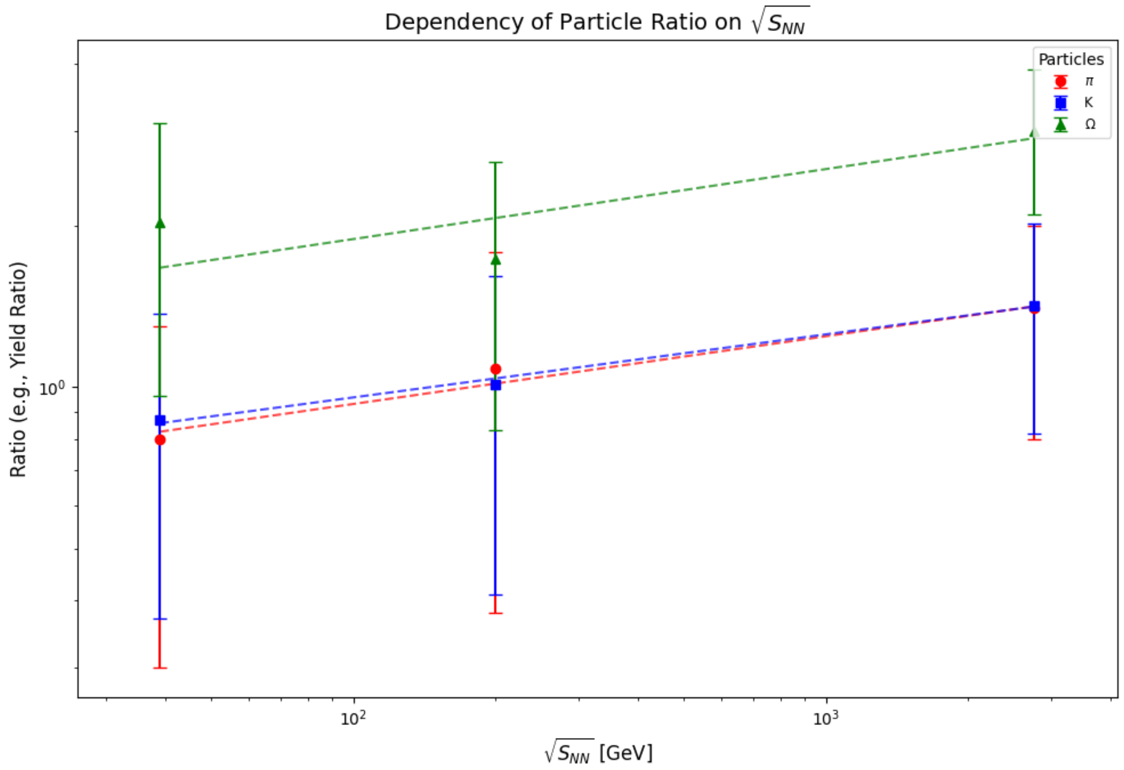
The error of t_{eff} include the error in the mean R.

[1] V.Kovalenkro, et al., Multipomeron Model with Collective Effects for High-Energy Hadron Collisions, *Universe* **2022**, *8*(4), 246.

Effective string tension (preliminary)

t_{eff} ,GeV^2

Particles/ $\sqrt{S_{NN}}$	π	K	Ω
39 GeV	0.8 ±0.5	0,87 ±0.5	2.03 ± 1.07
200 GeV	1.08 ±0.7	1.01 ±0.6	1.73 ± 0.9
2760 GeV	1.4 ±0.6	1.42 ±0.6	3.0 ± 0.9



Preliminary:
t_{eff} weakly increases with $\sqrt{s_{NN}}$ and it is found to be close to ~ 1 GeV^2 in case of φ/π transverse energy ratio and ~ 2 GeV^2 in case of φ/Ω transverse energy ratio

Ω

Conclusions

1. Ratios of mean transverse energies in the most central class of collisions for φ -meson and *π* -meson, K-meson, and *Ω* -hyperon are found to be different but practically constant in the range from √ sNN = 39 GeV to √ sNN = 2760 TeV.

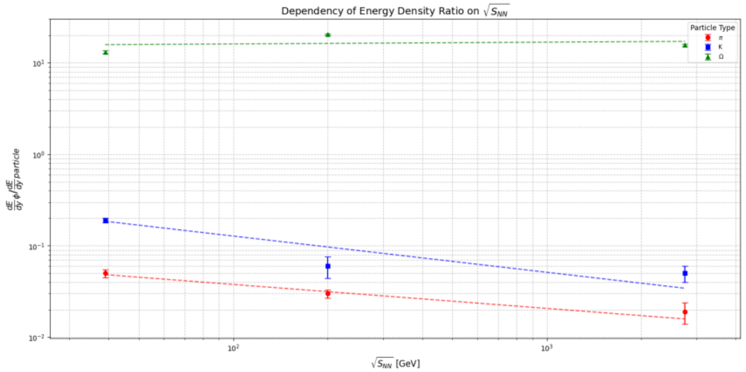
Multipomeron exchange model with collective effects of string fusion is used to analyze the obtained dependence. In this study, we obtain the string tension coefficient t_{eff}
and note its rather weak increase with increasing energy.

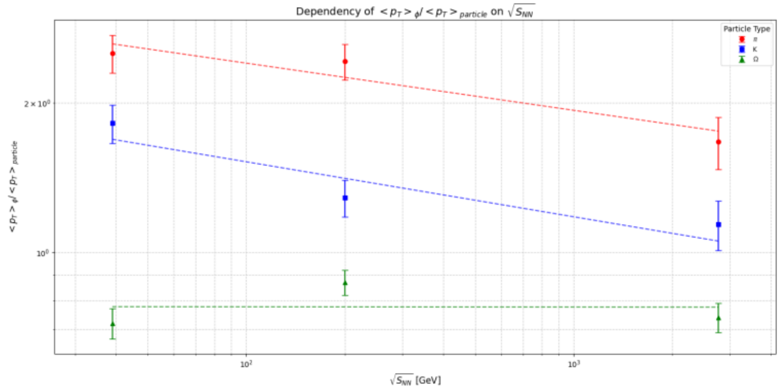
3. It is planned to consider also the mean transverse energies for protons and lambda-hyperons, as particles with the mass closest to the φ –meson mass

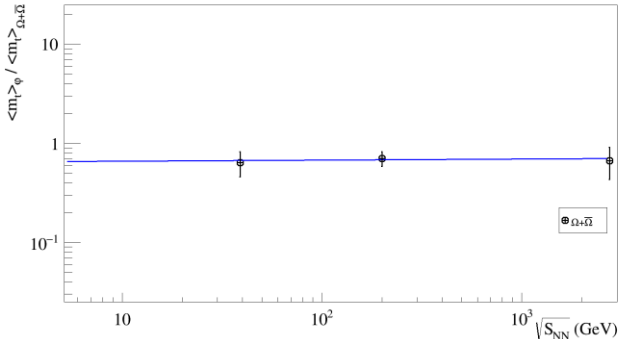
4. We will continue the analysis of such types of ratios of mean transverse energies of particles within this Multipomeron exchange model and with other models, taking into account the obtained relations.

Back-up

Back-up Back-up Back-up Back-up Back-up Back-up Back-upvvvvvvv Back-up


Dependency of Energy Density Ratio on $\sqrt{S_{NN}}$
Particle Type
π
K
Ω
$\sqrt{S_{NN}}$ [GeV]

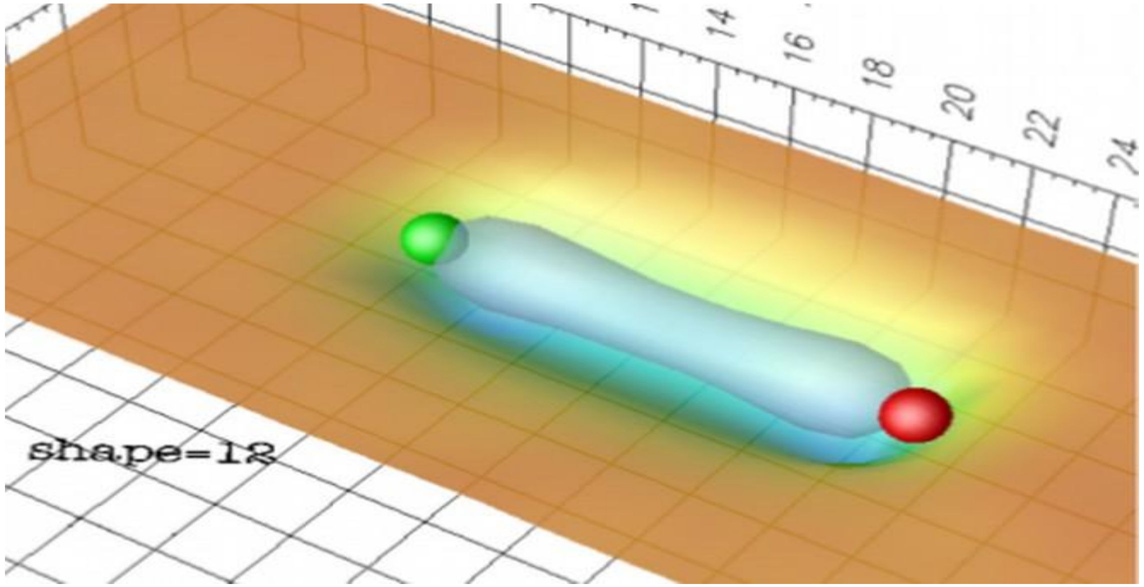

Dependency of $<p_T>_\phi / <p_T>_{particle}$ on $\sqrt{S_{NN}}$
Particle Type
π
K
Ω
$<p_T>_\phi / <p_T>_{particle}$
$\sqrt{S_{NN}}$ [GeV]

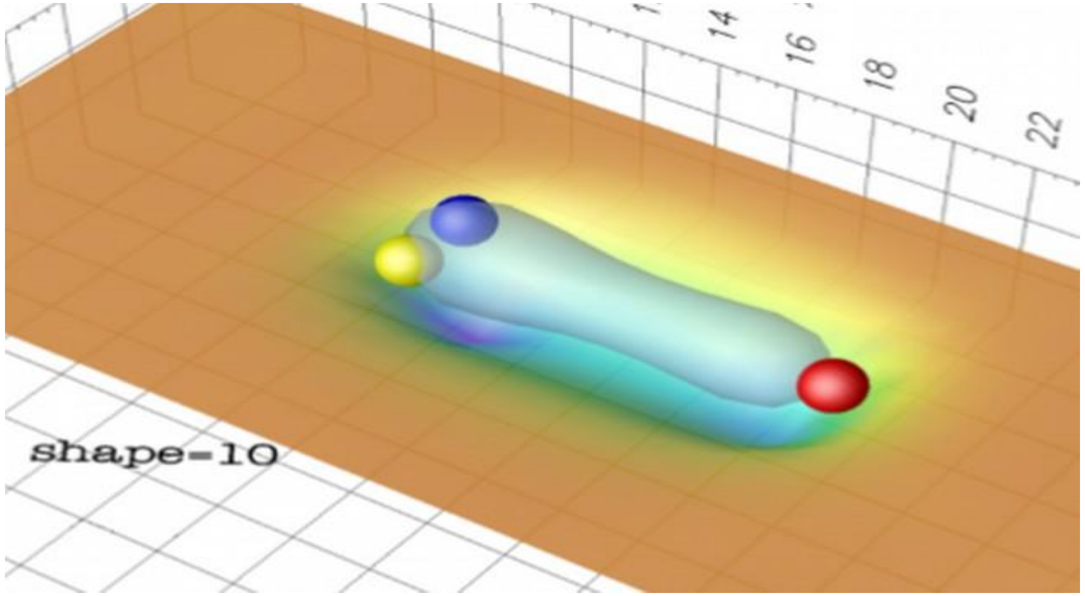

$<m_t>_\phi / <m_t>_{\Omega+\bar{\Omega}}$
$\Omega+\bar{\Omega}$
$\sqrt{S_{NN}}$ (GeV)

Cluster of fused quark-gluon strings and Schwinger-like formula

Множественное рождение частиц в мягкой области

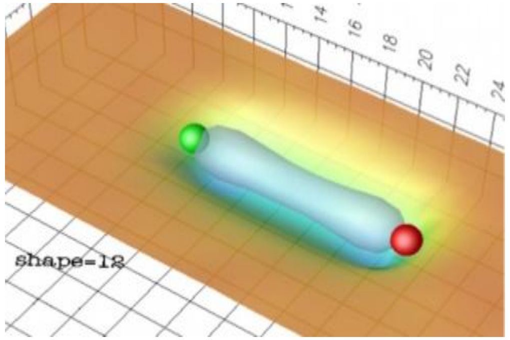
- Более 90% адронов в высокоэнергетических столкновениях рождаются в мягкой области (диапазон поперечных импульсов 0 < pt< 1 – 1.5 ГэВ/*c*)
- Невозможность применения теории возмущения КХД → полуфеноменологические подходы
- Кварк-глюонные струны – трубки цветового поля, образующиеся между партонами снаряда и мишени





F. Bissey, et. al., Phys. Rev. D 80, 114506 (2009)

Two theoretical models



Cluster of fused quark-gluon strings (Schwinger-like formula)

$$Y_\nu \sim \sum_\mu M_{\mu\nu}\cdot(2S_\mu+1)\cdot\exp\left(-\frac{\pi\left(p_t^2+m_\mu^2\right)}{t_{\text{eff}}}\right)$$ [1]

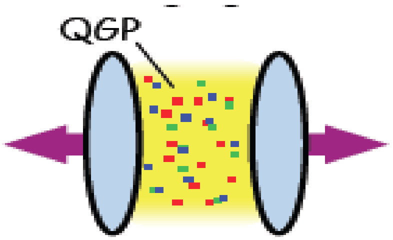
t_{eff} is the effective string tension

S_μ is the spin of a particle of the type μ

$M_{\mu\nu}$ is the effective branching matrix

исано

[1] – Kovalenko et al. “Multipomeron Model with Collective Effects for High-Energy Hadron Collisions”, Universe 2022, 8, 246.



Thermal model

Temperature: **T = 169 MeV**

Degeneracy factor: $\mathbf{g_m}$

Фактор вырождения **g** для частицы **m** учитывает все возможные внутренние степени свободы, которые могут влиять на её состояние.

Fugasity:

$$\lambda_m = \exp\left(\frac{\mu_m}{T}\right)$$

$$\mu_m = B\mu_B + Q\mu_Q + S\mu_S$$

Зарядовый и странный потенциалы малы по сравнению с барионным -> $\mu_m = \mu_B$ -> $\lambda_\varphi = 1$

Формула, используемая в модели SHGM:

$$\left(\frac{dE_m}{dy}\right)_{y=0} = \frac{g_m V \lambda_m}{(2\pi)^2} \int \frac{m_T^3\, dm_T}{\left[\exp\left(\frac{m_T}{T}\right)\right]}.$$

$$\frac{g_\Omega}{g_\varphi} = \frac{\left. e^{\frac{-m_{T\varphi}}{T}(m_{T\varphi}{}^3 T + 3m_{T\varphi}{}^2 T^2 + 6m_{T\varphi} T^3 + 6T^4)} \right|_{\sqrt{m_\varphi{}^2 + p_{T_1}{}^2}}^{\sqrt{m_\varphi{}^2 + p_{T_2}{}^2}}}{\left. e^{\frac{-m_{T\Omega}}{T}(m_{T\Omega}{}^3 T + 3m_{T\Omega}{}^2 T^2 + 6m_{T\Omega} T^3 + 6T^4)} \right|_{\sqrt{m_\Omega{}^2 + p_{T_1}{}^2}}^{\sqrt{m_\Omega{}^2 + p_{T_2}{}^2}}} \cdot \frac{1}{10} \cdot \frac{1}{e^{\mu_B/T}}$$

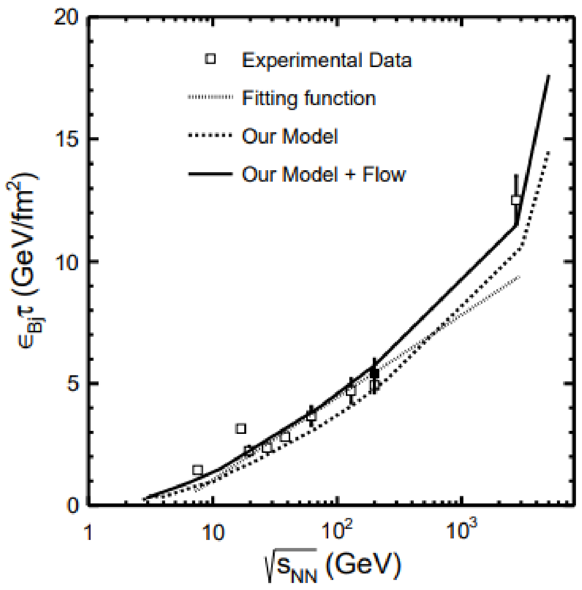
$\frac{g_\Omega}{g_\varphi}$ зависит только от μ_B

$\sqrt{S_{NN}}$ [GeV]	$\frac{g_\Omega}{g_\varphi}$
200	3.86±0.17
2760	3.87±0.25

[1] - Swatantra Kumar Tiwari , Raghunath Sahoo, Eur. Phys. J. A (2018) 54: 39

Thermal model

$$\left(\frac{dE_m}{dy}\right)_{y=0} = \frac{g_m V \lambda_m}{(2\pi)^2} \int \frac{m_T^3\, dm_T}{\left[\exp\left(\frac{m_T}{T}\right)\right]}.$$



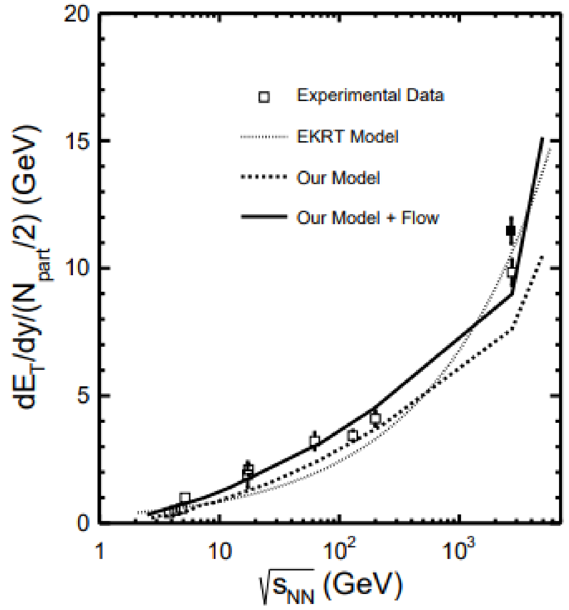


Table 2: Temperature and Baryon Chemical Potential extracted after fitting the particle ratios for various centrality at $\sqrt{s_{NN}}$ = 200 GeV and 2.76 TeV. Most-central, mid-central and peripheral are defined in the text for both energies.

Centrality	$\sqrt{s_{NN}}$ = 200 GeV		$\sqrt{s_{NN}}$ = 2.76 TeV	
	T (MeV)	μ_B (MeV)	T (MeV)	μ_B (MeV)
Most-central	169	23.5	169	1.7
Mid-central	168.5	17	168.5	1.0
Peripheral	168	5.5	168	0.5

[1] - Swatantra Kumar Tiwari , Raghunath Sahoo, "Transverse Energy per Charged Particle in Heavy-Ion Collisions: Role of Collective Flow", Eur. Phys. J. A (2018) 54: 39

Thermal model: dN/dy

Baryon

$$\left(\frac{dN_i}{dy}\right)_{th} = \frac{g_i V \lambda_i}{(2\pi^2)} \left[\left((1-R) - \lambda_i \frac{\partial R}{\partial \lambda_i}\right) \int_0^\infty \frac{m_T^2 \, cosh y \, dm_T}{\left[exp\left(\frac{m_T \, cosh y}{T}\right) + \lambda_i\right]} - \lambda_i (1-R) \int_0^\infty \frac{m_T^2 \, cosh y \, dm_T}{\left[exp\left(\frac{m_T \, cosh y}{T}\right) + \lambda_i\right]^2}\right].$$

Meson

$$\left(\frac{dN_m}{dy}\right)_{th} = \frac{g_m V \lambda_m}{(2\pi^2)} \int_0^\infty \frac{m_T^2 \, cosh y \, dm_T}{\left[exp\left(\frac{m_T \, cosh y}{T}\right) - \lambda_m\right]}.$$

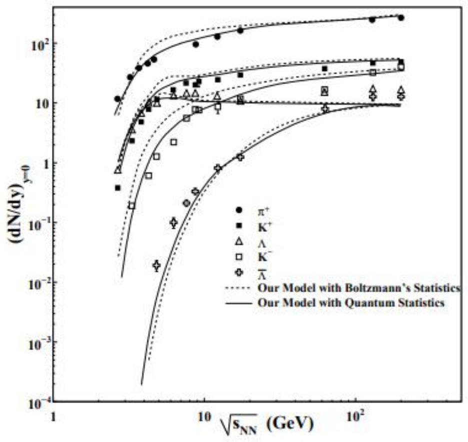


FIG. 3: Variation of rapidity distributions of various hadrons with respect to $\sqrt{s_{NN}}$ at midrapidity. Lines show our model calculation. Symbols are the experimental data [9, 49, 50].

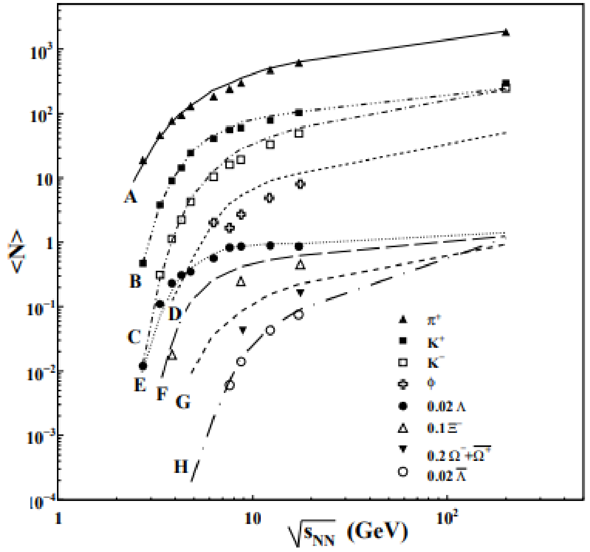


FIG. 2: Variations of total multiplicities of π^+, K^+, K^-, ϕ, Λ, Ξ^-, $(\Omega^- + \bar{\Omega}^+)$, and $\bar{\Lambda}$ with respect to center-of-mass energy predicted by our model. Experimental data measured in central $Au-Au/Pb-Pb$ collisions [31–47] have also been shown for comparison. In this figure, A, B, C, D, E, F, G, and H represent the multiplicities of π^+, K^+, K^-, ϕ, Λ, Ξ^-, $(\Omega^- + \bar{\Omega}^+)$, and $\bar{\Lambda}$, respectively.

$$\frac{dN_i}{dy} = \int_{-\eta_{max.}}^{\eta_{max.}} \left(\frac{dN_i}{dy}\right)_{th} (y-\eta) \, d\eta,$$

The resulting rapidity spectra of ith hadron, after incorporation of the flow velocity in the longitudinal direction is [11, 12]:

[2] - S. K. Tiwari ∗ , P. K. Srivastava, and C. P. Singh, “The effect of flow on Hadronic Spectra in an Excluded-Volume Model”, J. Phys. G : Nucl. Part. Phys. 40, 045102 (2013)