NUCLEUS–2021

Energy and mass dependencies for the characteristics of p_T regions observed at LHC energies

Presenter : ***Professor Mais Suleymanov***

Baku State University , Azerbaijan

Time: 17:30 - 17:55 (Online)

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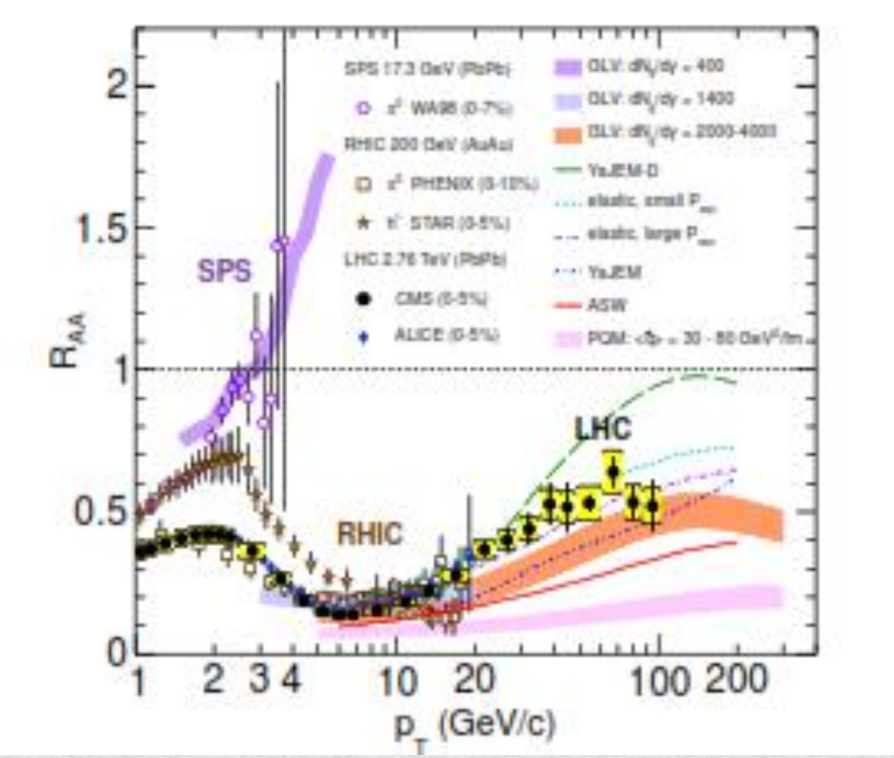
Introduction

In fact, this talk is a continuation of my previous talk given at NUCLEUS-2020 : “The meaning behind observed p_T regions at the LHC energies, some properties of the regions ” .

I want to remind you about some points of that talk.

The motivation of the research was connected with that : the evolution picture of the Nuclear Modification Factor [*CMS Collaboration. Eur. Phys. J. C (2012) 72:1945*] –



$$R_{AA} = \frac{d^2N/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}/dp_T d\eta}$$

as a function of p_T shows that in the range of p_T = 5-10 GeV/c, the suppression is stronger than before observed at the RHIC. Beyond p_T =10 GeV/c up to 20 GeV/c R_{AA} shows a rising trend, this rise continues at higher p_T, approaching a suppression factor 0.5-0.6 in the range of 40 – 100 GeV/c.

The behavior of the R_{AA} is very complex and today we are far from understanding completely this. So we tried to understand the behavior of the R_{AA} from the initial p_T distributions.

Method

For this goal the invariant differential yield of the charged particles , π^0 –,η -, K^0 - and φ-mesons as a function of p_T in *pp* and *Pb-Pb* collisions at the LHC energies were analyzed

/Mais Suleymanov, Int.J.Mod.Phys. E 27 (2018) no. 1, 1850008 ;Int.J.Mod.Phys. E28 (2019) no.10, 1950084; arXiv:nucl-ex/1710.09296; The ALICE Collaboration. Phys. Rev. C 95, 064606(2017); DOI: 10.1103/PhysRevC.95.064606

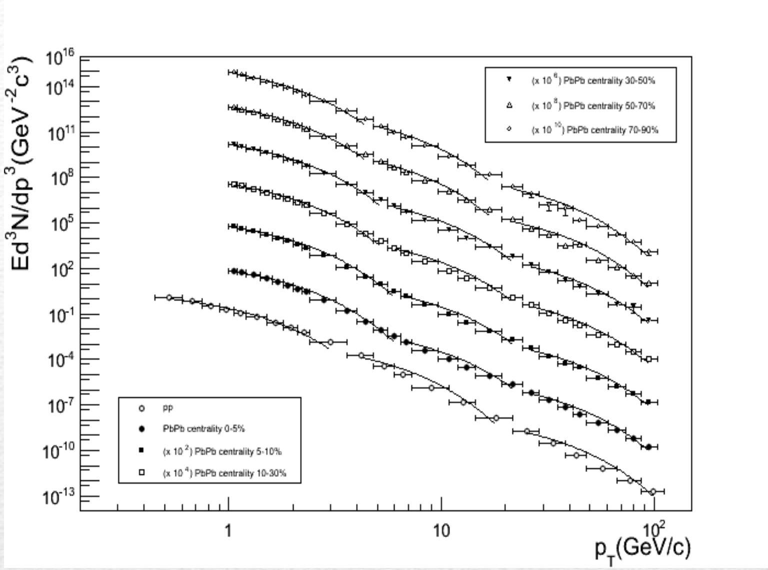
/. The published experimental data by CMS, ALICE and ATLAS collaborations were used.

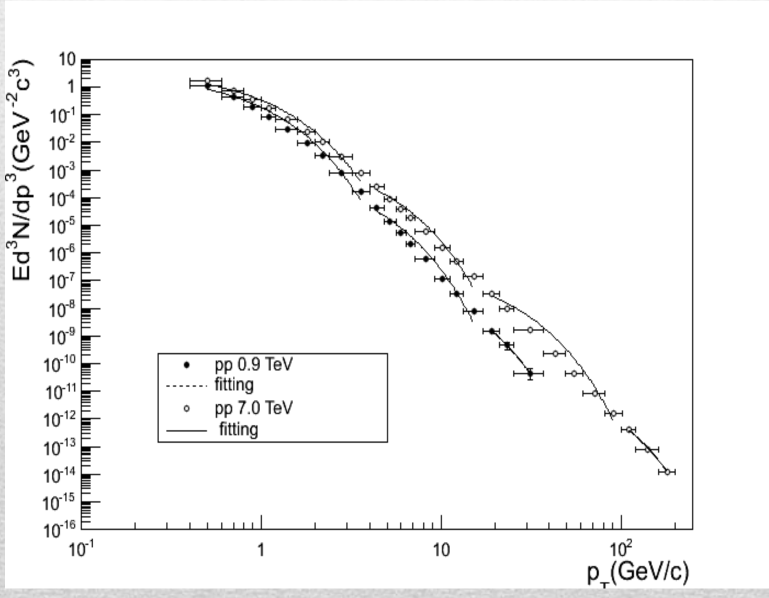
First, we fit the p_T distributions in the whole experimentally measured ranges (from the minimum measured value of p_T (p_T^{min}) to maximum one (p_T^{max})) with a simple fitting function :

$$y = a_K^c e^{-p_T b_K^c}$$

the a_K^c and b_K^c are the free fitting parameters. The index c is used to designate the type of the events (see table) and the index K represents the number of the p_T regions.

energy (TeV) / particles	0.9 pp	2.76 pp	2.76 PbPb	7	8
charged particles	3	1	2	4	5
π⁰-meson	31	11	-	41	51
η-meson	32	12	-	42	52
K⁰-meson	-	13	-	-	-
φ-meson	-	14	-	-	-



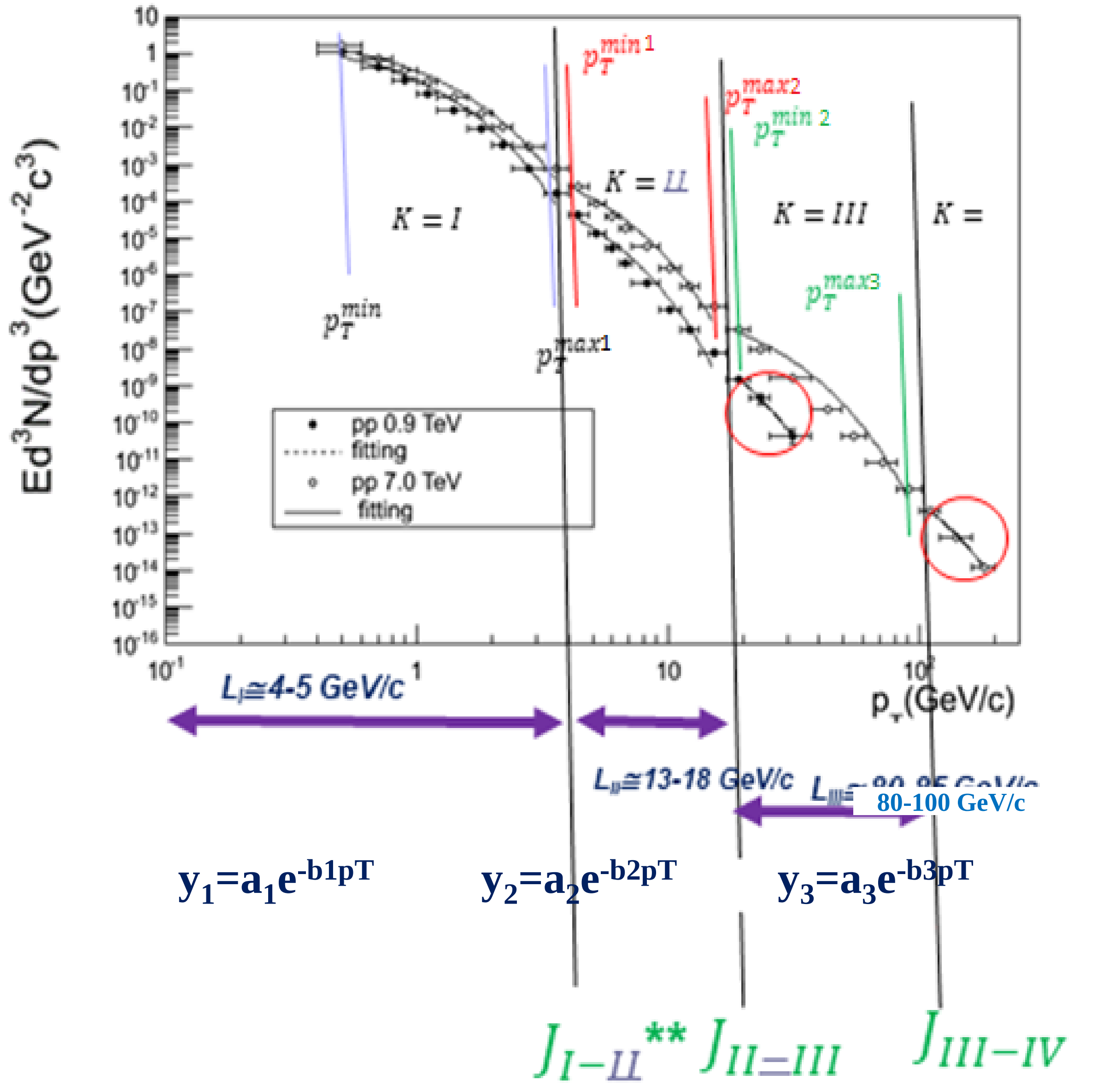


Method

This fitting attempt did not produce good fitting results and we decided to decrease the values of the p_T^{max} till getting a value of p_T^{max1} at which the best fitting results are reached. So we defined the boundary values of the p_T (from p_T^{min} to p_T^{max1}), for the first p_T region (K=I).

The rest of the distributions (from the first point after the p_T^{max1} (p_T^{min1}) till p_T^{max}) were fitted again by the same function and again to get the optimized fitting results the values of the p_T^{max} was limited to find the p_T^{max2} at which the best fitting results reached. After getting the values of the p_T^{max2} we defined the boundary values of the p_T (from p_T^{min1} to p_T^{max2}), for the second p_T region (K=II) and so on. The figure, as an example, visualizes the procedure of the getting the best fitting results.

Then using the obtained values of the maximum and minimum p_T for the best fittings in the different regions, the boundary values of p_T for the regions (J_K^c), and the lengths (L_K^c) of the regions have been defined



[c]The values of J_K^c were calculated using experimentally measured values of p_T^{min} (the value of $p_T^{min}(I)$ for the regions I was taken as $p_T^{min}(I) = 0$) and p_T^{max} as $J^c_{I-II} = (p_T^{max}(I) + p_T^{min}(II))/2$ for the region I and II, $J^c_{II-III} = (p_T^{max}(II) + p_T^{min}(III))/2$ for the region II and III and so on. The values of L_K^c were calculated as $L_I^c = J^c_{I-II}$; $L^c_{II} = J^c_{II-III} - J^c_{I-II}$ and $L^c_{III} = J^c_{III-IV} - J^c_{II-III}$ and so on.

Results

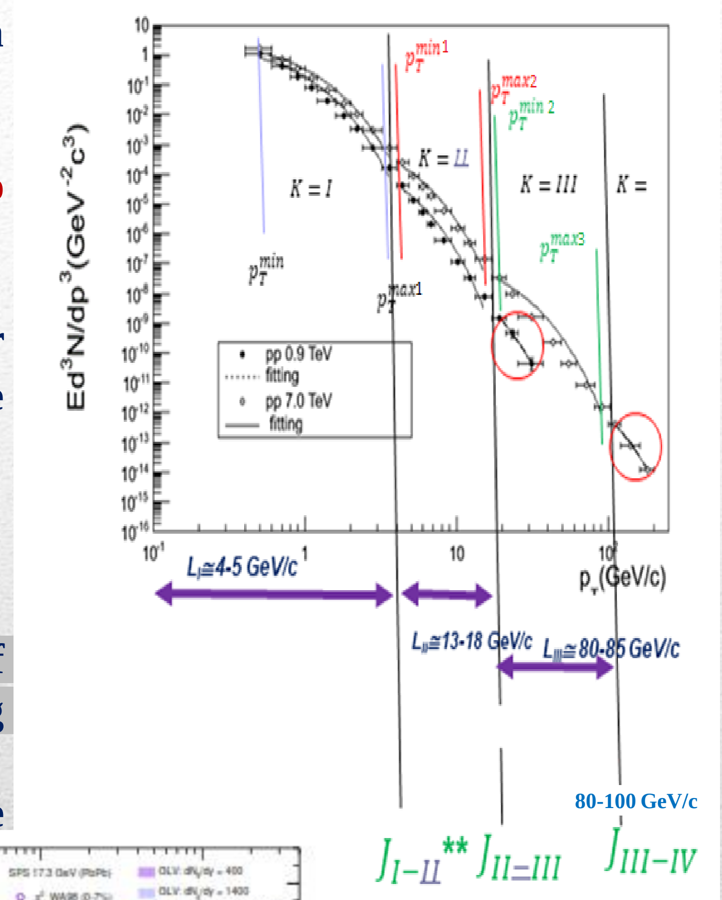
The applied method has shown that the p_T distributions contain several p_T regions (the number of regions increase with p_T).

The regions could be characterized by the lengths L_K^c and two free fitting parameters a_K^c and b_K^c.

The values of the L_K^c increase with p_T (and with *K*) and for example for the charged particles at 2.76 TeV there equations :

$$L_{III}^1 : L_{II}^1 \cong 5 \ ; \ L_{II}^1 : L_I^1 \cong 3 \ \text{(Pb–Pb)};$$
$$L_{III}^1 : L_{II}^1 \cong 5 \ ; \ L_{II}^1 : L_I^1 \cong 5 \ \text{(pp)}$$

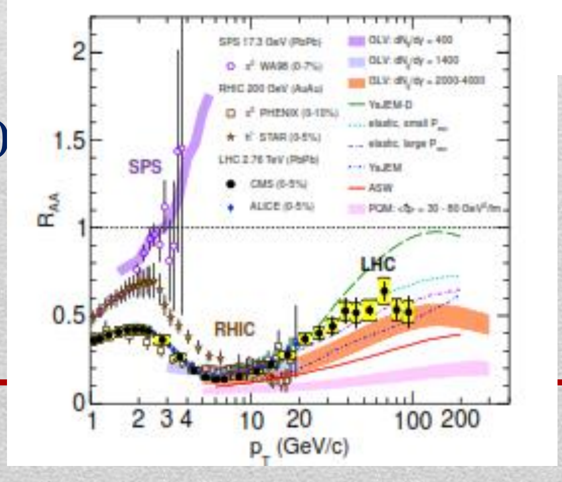
It may be due to that the observed p_T regions reflect features of fragmentation and hadronization of partons through the string dynamics.



Again one can say that for the charged particles at 2.76 TeV the regions are limited by the values of p_T :

- $< 4 - 6 \ GeV/c$ (*I* region);
- $4 - 6 \ GeV/c < p_T < 17 - 20 \ GeV/c$ (*II* region)
- $> 17 - 20 \ GeV/c$ (*III* region).

Let us note that the II region is the area where Nuclear Modification Factor has minimum for the most central heavy ion collisions- jet suppression.



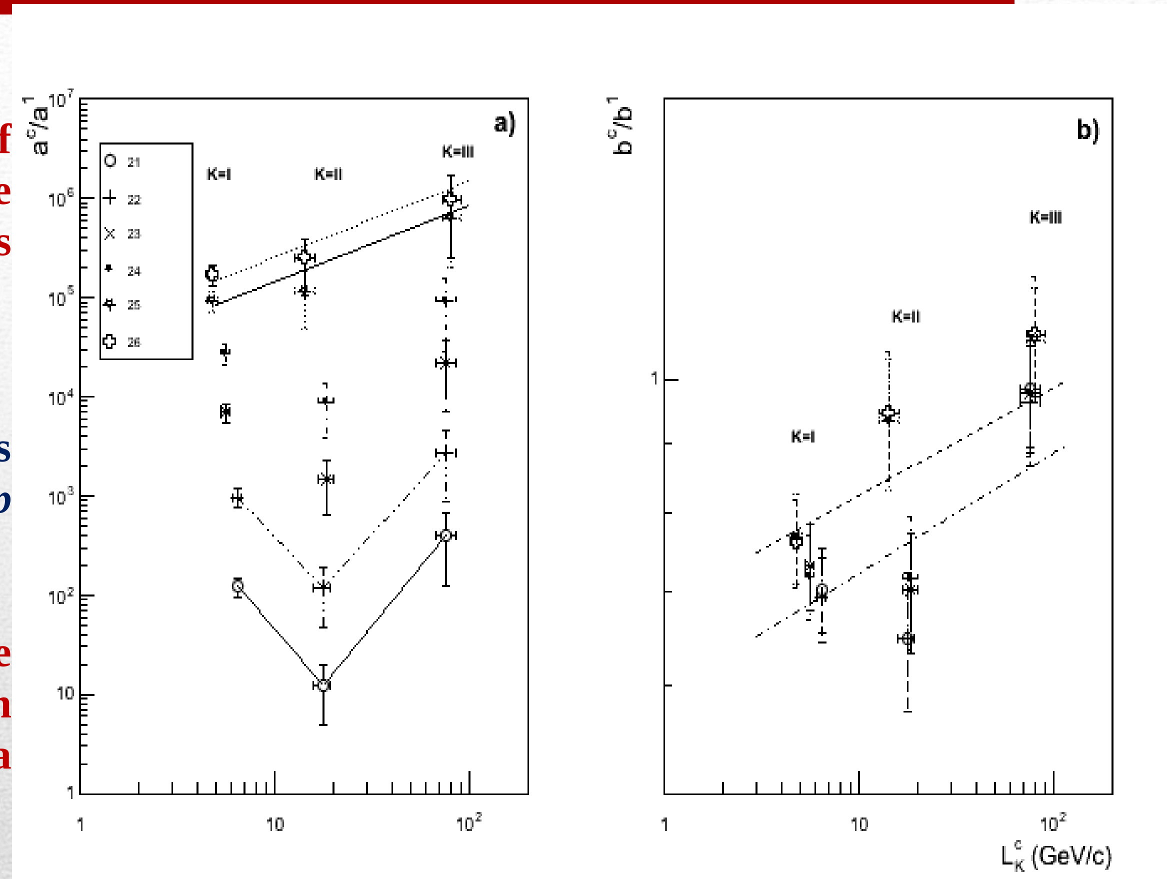
Results

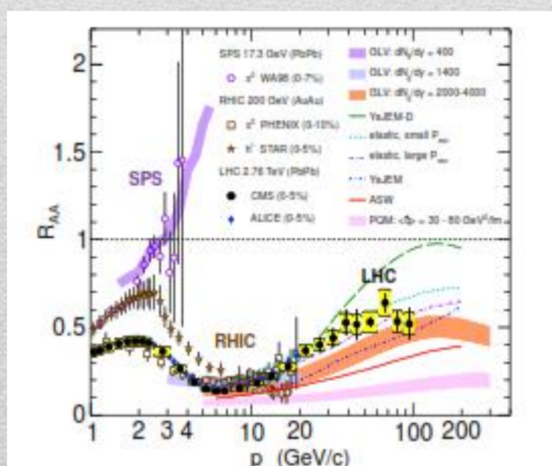
We have constructed the ratios of :

– a^c/a^1 ,here a^c and a^1 is the values of the free fitting parameters a_K^c for the most central *PbPb* and *pp* collisions respectively

- b^c/b^1, here b^c and b^1 is the values of the free fitting parameters b_K^c for the most central *PbPb* and *pp* collisions respectively .

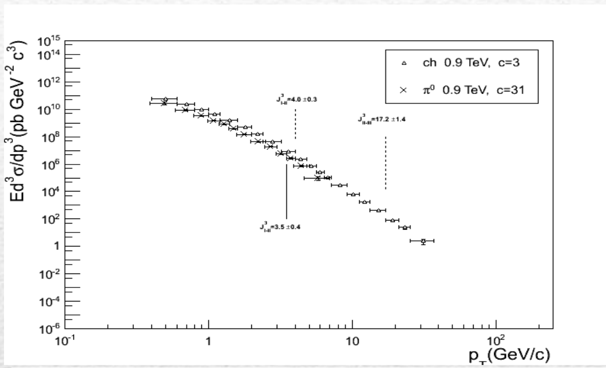
One can see that the ratios for the parameter a_K^c have the minimum values for the second p_T region - a suppression.

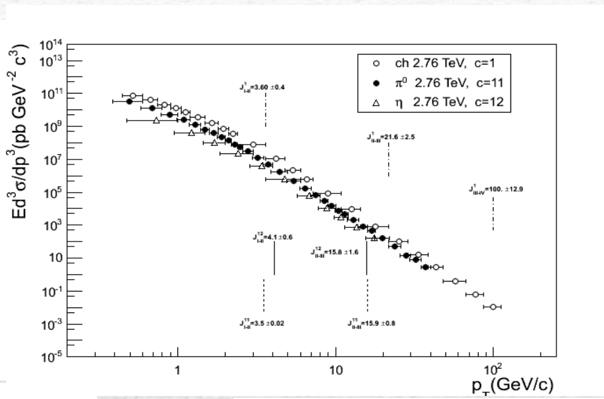


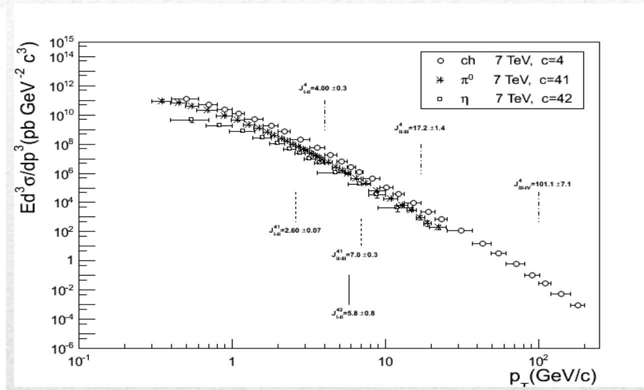


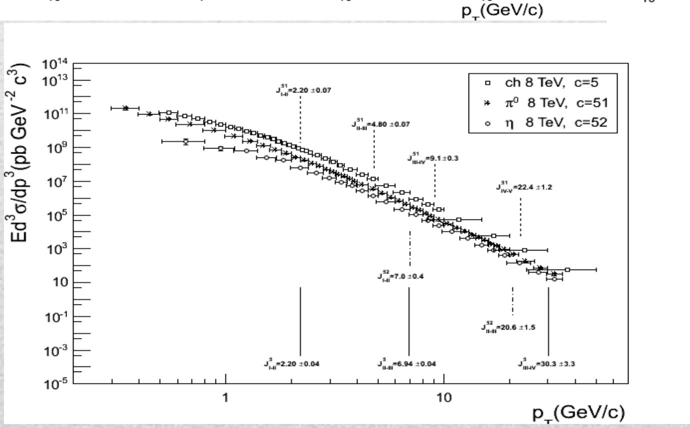
Results

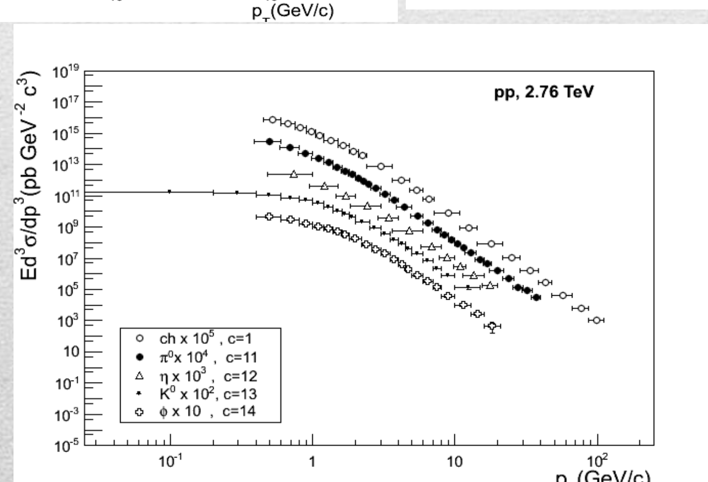
The including of the spectra of π^0- , η -, K^0- and φ - mesons to the consideration and increasing the energy of colliding particles has given new results to study some properties of the p_T regions and to get an additional information on the energy and mass dependences of the characteristics of the p_T regions: L_K^c , a_K^c and b_K^c .











The distributions were processed using same method which was applied to process the charged particles spectra.

One can say that again as in the case of the charged particles the p_T distribution data on invariant differential yield of the π^0- , η -, K^0- and φ - mesons produced in the pp collisions contained several p_T regions which could be characterized by the values of the regions' lengths and the values of the free fitting parameters a_K^c and b_K^c .

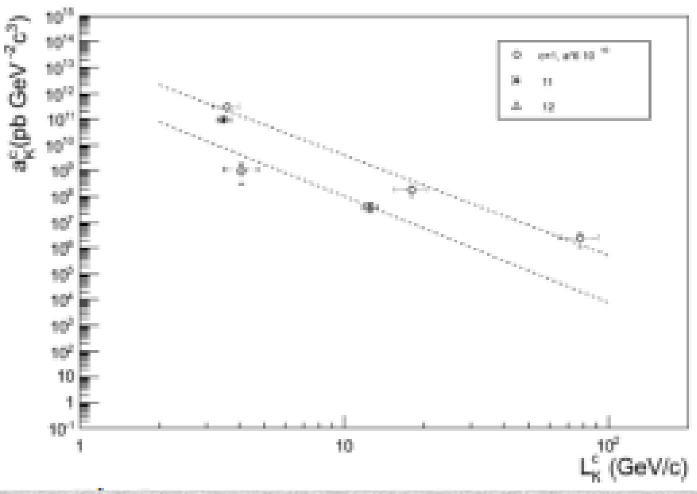
Taking into account the results coming from the papers [*Mais Suleymanov, Int.J.Mod.Phys. E 27 (2018) no. 1, 1850008 ;Int.J.Mod.Phys. E28 (2019) no.10, 1950084; arXiv:nucl-ex/1710.09296*] on the p_T distributions of the charged particles, the π^0- and η- mesons and the new data for the K^0- and φ - mesons we have analyzed the energy and mass dependences of the p_T regions' parameters to reach the arm of paper: to get an additional information on the energy and mass dependences of the characteristics of the p_T regions.

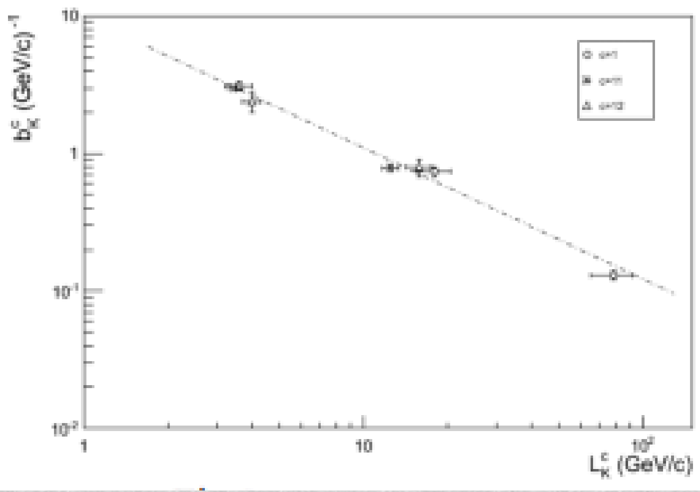
Results

The study of the L_K^c dependencies of the parameters a_K^c and b_K^c have showed that the regions can be classified into two groups depending on the values of the L_K^c, a_K^c and b_K^c; the characteristics for the first group regions don't depend on colliding energy and the type of the events (c) (though the values of a_K^c increase linearly with energy) whereas the characteristics for the second group ones show strong dependencies on the type of the events c and colliding energies . It was found that for:

- the first group of regions the lengths are 3-5 times greater than the lengths of neighboring, lower p_T regions.
- the second group of regions the lengths are 1-2 times greater than the lengths of neighboring lower p_T region.

In the framework of the string fragmentation and hadronization dynamics, this could mean that the particles in the group I of regions are produced through previous-generation strings decays into 3-5 strings while those in group II originate from previous-generation strings decays into 2 strings.





Results

The Fig. 2 shows the energy dependences of the values of L_I^c (I p_T regions' length) for the charged particles, π^0-, η-, K- and ϕ-mesons produced in the pp collisions. The lines in the figure have been drawn by hand. One can see that all points relevant to values of the L_I^c lie down on 5 lines at $L_I^c \cong 2.25; 2.55; 3.7; 5.0$; 6.4 GeV/c. The figure say us that for the considered charged particles, the energy dependence appear jump-like.

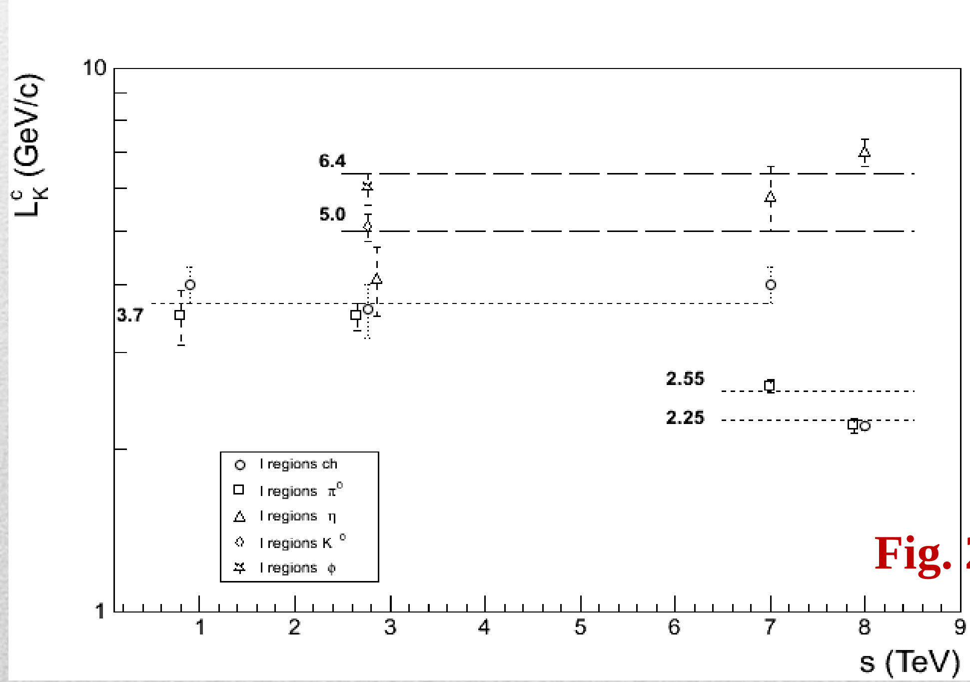


Fig. 2

Results

The energy dependences of the II p_T regions' lengths for the charged particles, π^0-, η-mesons produced in the *pp* collisions are shown in the Fig. 3.

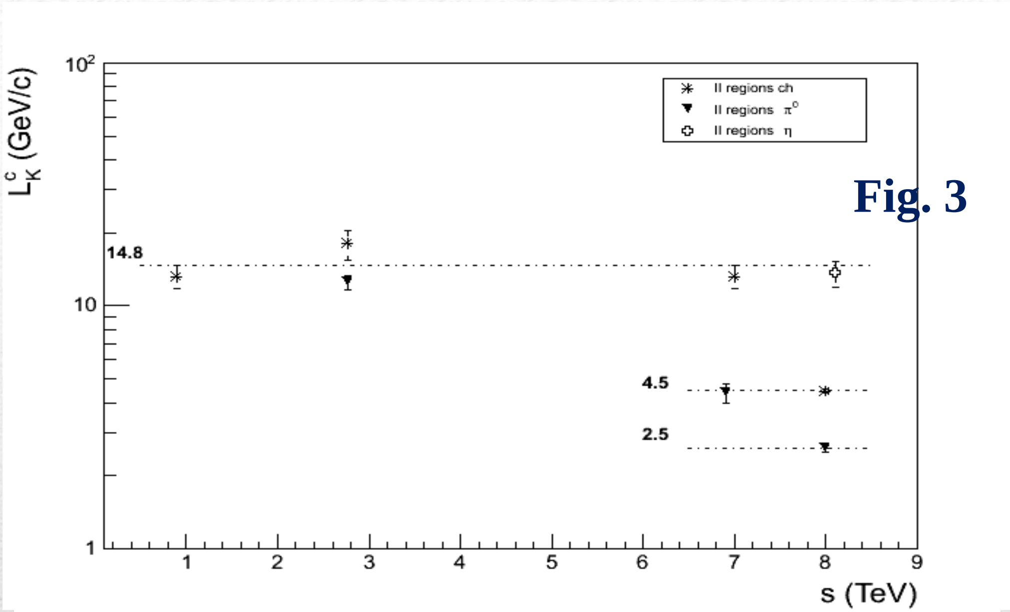


Fig. 3

The Fig. 4 shows the energy dependences of the values of the lengths for the III and IV p_T regions for the charged particles and π^0-mesons produced in the *pp* collisions.

One can say that all points relevant to values of the lengths for: the I p_T regions as a function of energy lie down on 5 lines at $L_I^c \cong 2.25; 2.55; 3.7; 5.0$; 6.4 GeV/c; the II p_T regions are approximately on 3 lines at level $L_{II}^c \cong$ 14.8; 4.5;2.5 GeV/c; the III and IV ones roughly lie down on 3 lines at $L_{III}^c \cong 80; 14.8$ and 4.5 GeV/c. The energy dependence shows jump-like changes and give clue on discrete changes with energy.

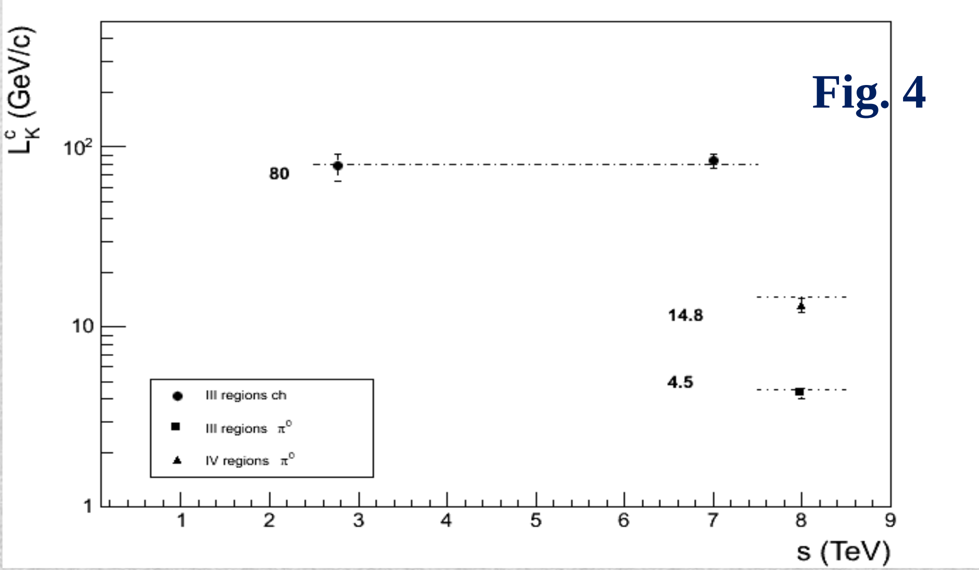


Fig. 4

One can see that wherein the lengths for the light mesons decrease and they increase for the heavy mesons.

Results

The last result is seen more cleanly from the Fig. 5 which shows the mass dependence for the values of L_K^c (in cases 2 or more points in the distributions). The lines have been drawn by hand. One can see that with mass (in the I p_T region at s = 2.76 TeV) the values of the lengths increase slowly and in the II p_T regions at s=2.76 TeV (we have had only 2 points) the values of the lengths show an independence on mass. At s = 7 TeV the values of L_K^c increase sharper than at 2.76 TeV , gets more strong at energy 8 TeV and the relation holds: $< L_\eta > : < L_{\pi^0} > \cong m_\eta : m_{\pi^0}$ (which was observed in the paper [*Int.J.Mod.Phys. E28 (2019) no.10, 1950084*]). The dependences of the lengths of p_T regions on the mass of particles and the strengthening of this dependence with increasing energy of colliding protons and the result on $< L_\eta > : < L_{\pi^0} > \cong m_\eta : m_{\pi^0}$ together with jump-like energy dependences can be arguments in favor of string theory.

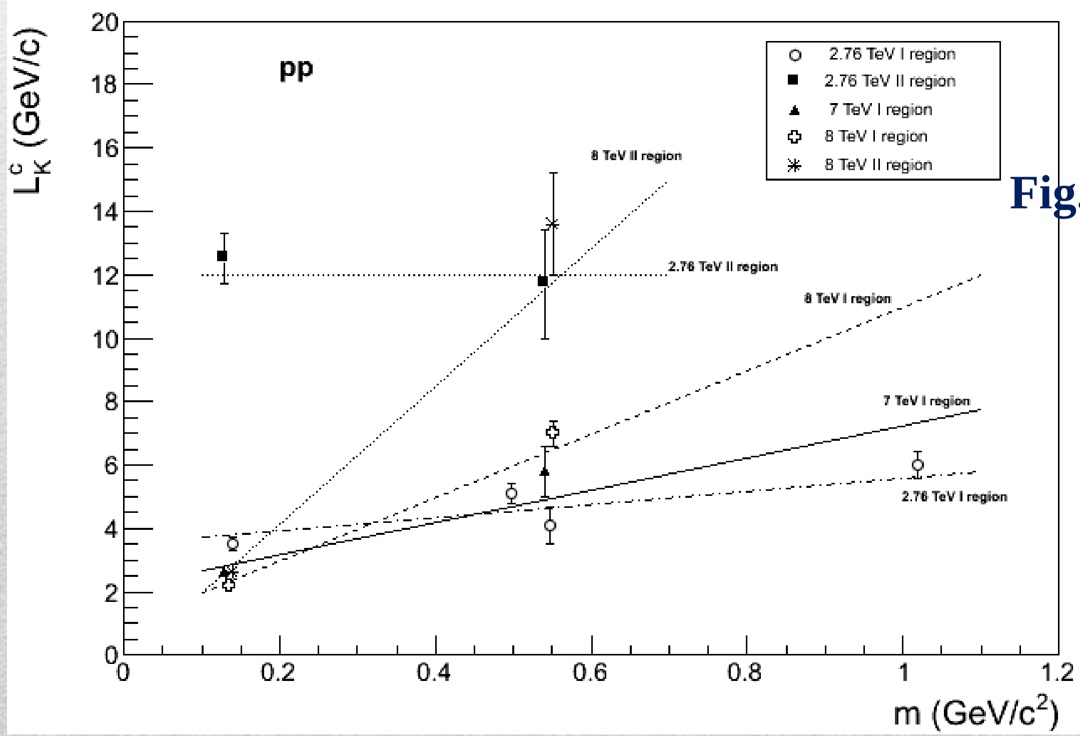


Fig. 5

Assuming that the values of the L_K^c are directly proportional to the string tension the result could be considered as evidence in favor of parton string fragmentation dynamics. Because in string theory the masses of elementary particles and their energy are defined by the intensity of string vibration and strangeness of the string stretch.

Results

The energy dependences for the parameters a_K^c (I-IV p_T regions) are shown in the Fig. 6-7.

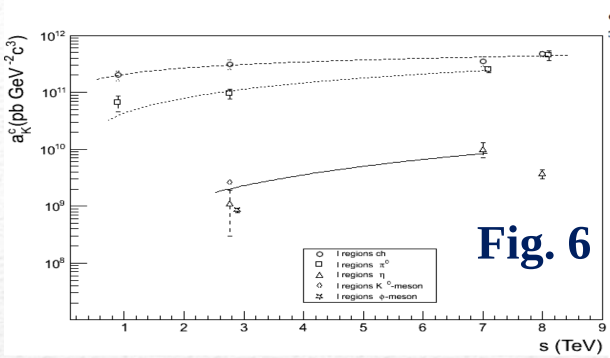


Fig. 6

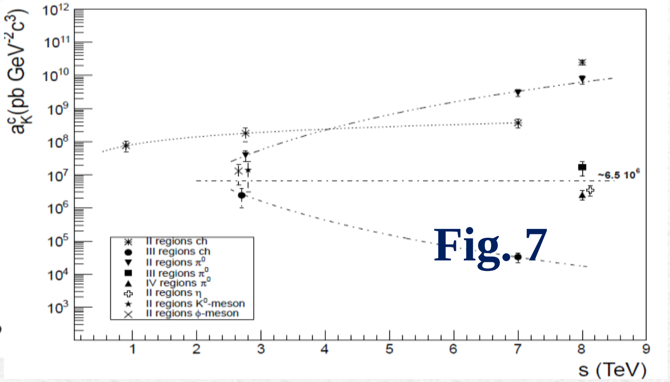


Fig. 7

The energy dependences for the parameters b_K^c are shown in the Fig. 8-9 for the p_T regions' data.

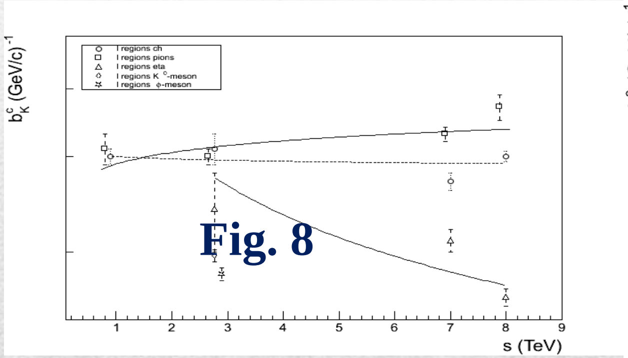


Fig. 8

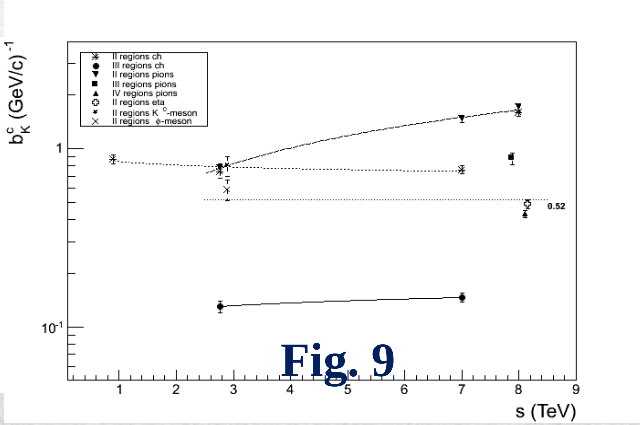
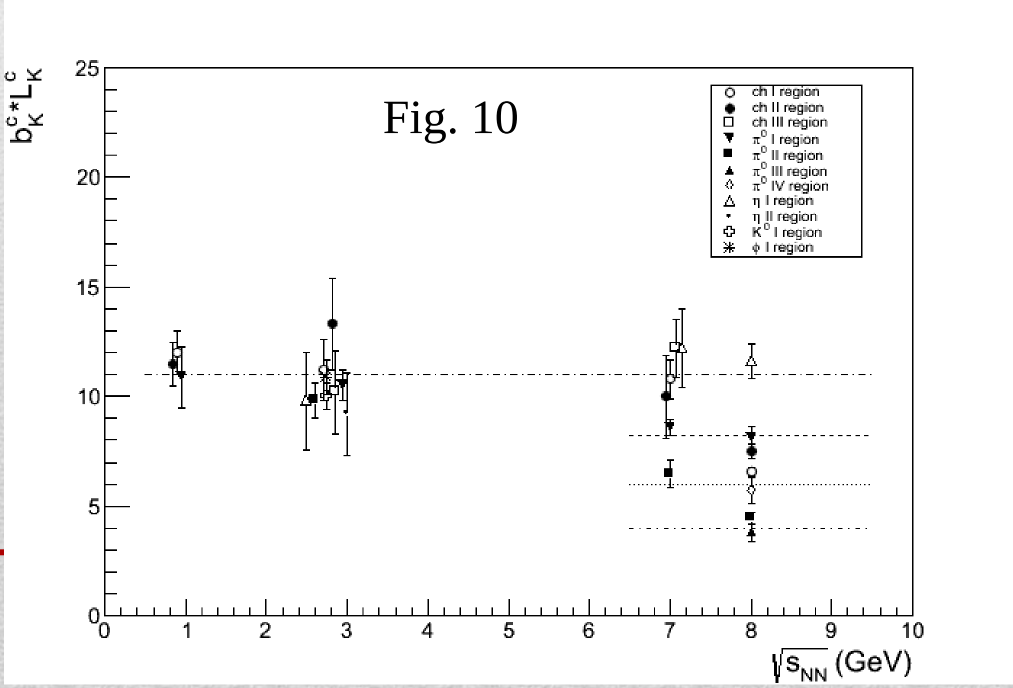


Fig. 9

One can see again that the values of a_K^c and b_K^c as a function of energy grouped around several lines and show jump-like changing with energy and again parameters a_K^c and b_K^c have showed that the regions can be classified into two groups depending on the values of the L_K^c, a_K^c and b_K^c; the characteristics for the first group regions don't depend on colliding energy and the type of the events (c) (though the values of a_K^c increase linearly with energy) whereas the characteristics for the second group ones show strong dependencies on the type of the events c and colliding energies.

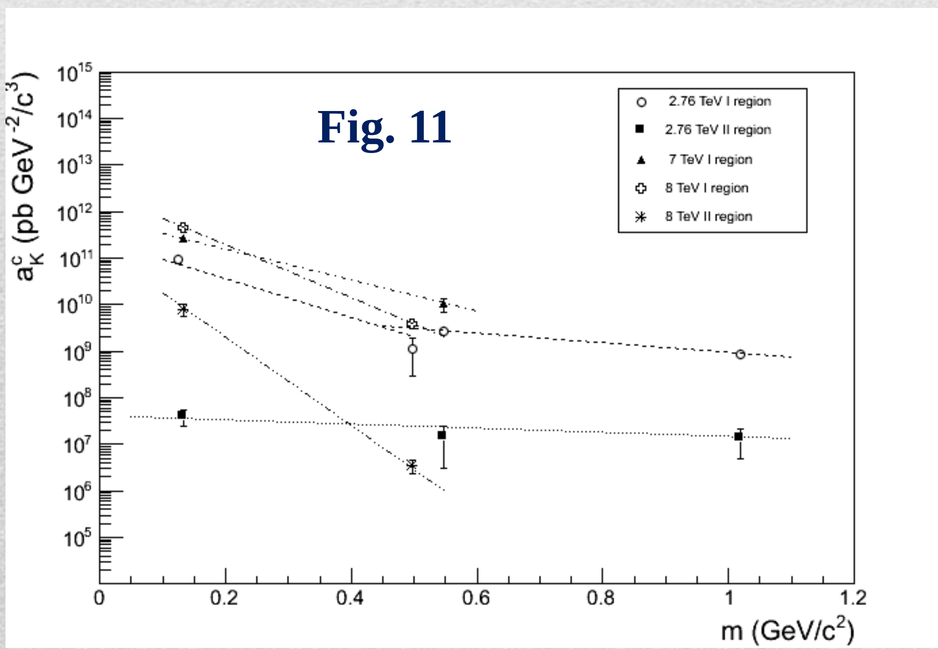
Results

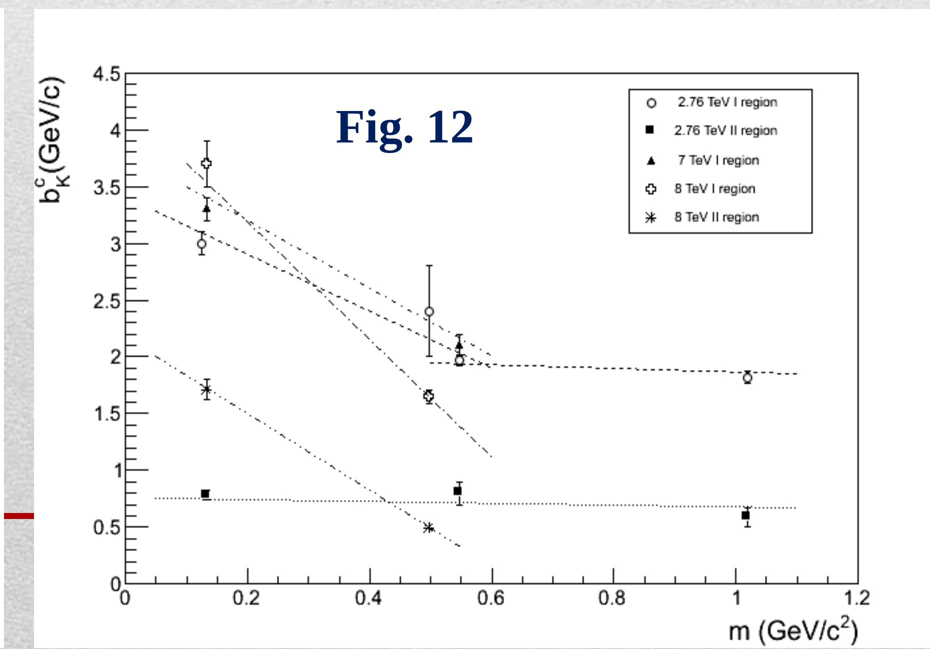
Fig. 10 shows the energy dependences, of the lengths L_K^c multiplied by the values of the free fitting parameter b_K^c in the same regions ($L_K^c * b_K^c$) for the charged particles, π^0- , η -, K^0- and φ - mesons produced in *pp* collisions at LHC energies. It can be seen that with energy, the values of $L_K^c * b_K^c$ for most of cases with remain unchanged at the level of $L_K^c * b_K^c \cong 11$. The deviations from this value begin to appear at energy of 7 TeV for charged particles and neutral pions from II p_T region. For these events the values of $L_K^c * b_K^c \cong 8$ or 6 . At energy 8 TeV, deviations get stronger and have been observed for almost all cases (with except for one case with c= 52 - for the eta mesons at 8 TeV). Now the corresponding points are on the lines at 8,6 and 4. Again one can say that with energy the values of the $L_K^c * b_K^c$ change jump-like as a signal on discrete change the values of $L_K^c * b_K^c$.



Results

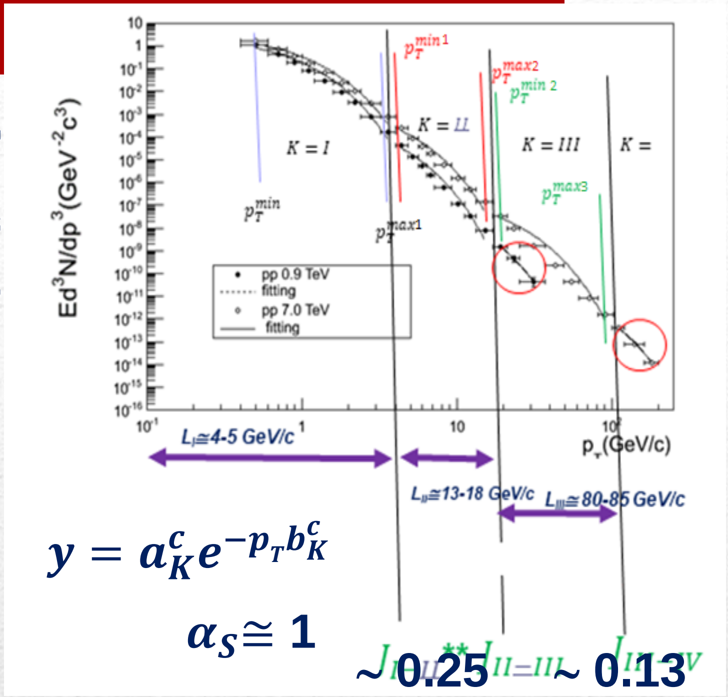
Fig. 11-12 show the mass dependence of the values of a_K^c and b_K^c for the cases when there are at least 2 defined points for the values of a_K^c and b_K^c. One can see that with mass in the I p_T region at s = 2.76 TeV the values of the parameters a_K^c and b_K^c first decrease in the interval of mass m < 500 MeV/c^2 and than almost doesn't depend on mass in the interval of m >500 MeV/c^2. But for the II p_T regions at s=2.76 the values of the parameters a_K^c and b_K^c don't depend on mass. At s=7 TeV the values the parameters a_K^c and b_K^c decrease. At a further increase the energy at 8 TeV the values of the a_K^c and b_K^c decrease sharply. So one can note that unlike parameter L_K^c the mass dependences of the parameters a_K^c and b_K^c show regime change at mass $m \cong$ 500 MeV/c^2 .





Discussion

Observation of the p_T regions for both *pp* and for Pb–Pb collisions suggests <u>that these regions could reflect the fragmentation and hadronization properties of partons.</u> The parameter b_k^c could be represented as: $b_K^c \cong \frac{1}{\tilde{p}_T}$ (here $\tilde{p}_T$ is some average p_T for parton system) and with considering $-\tilde{p}_T \cong t \cong -q^2$ (*t* is Mandelstam variable) we can write that $b_K^c \cong \frac{1}{\sqrt{q^2}}$.



$y = a_K^c e^{-p_T b_K^c}$

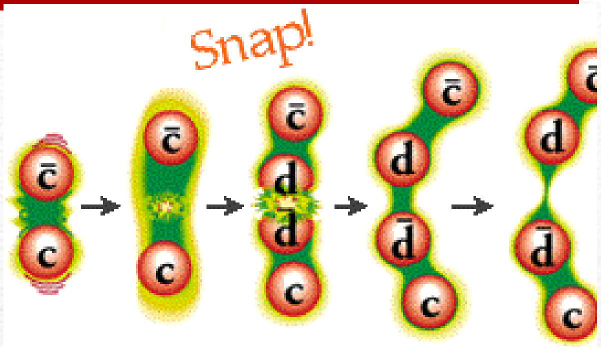
$\alpha_S \cong 1$ ~0.25 ~ 0.13

Using the expression $\alpha_S \cong \left[ln\left(\frac{q^2}{\Lambda^2}\right)\right]^{-1}$ (at Λ=0.2 GeV/c) one can get that : $\alpha_S \cong 1$ for the I region; ~ 0.25 for the II region and ~ 0.13 for the III region. The increasing of the α_s with decreasing of the p_T is <u>similar to the dependence of the α_s on p_T which is characteristics of the QCD quark string</u> : $\frac{1}{r^2} \sim Q^2 = -q^2$, in which *r* is a distance between quarks in the string

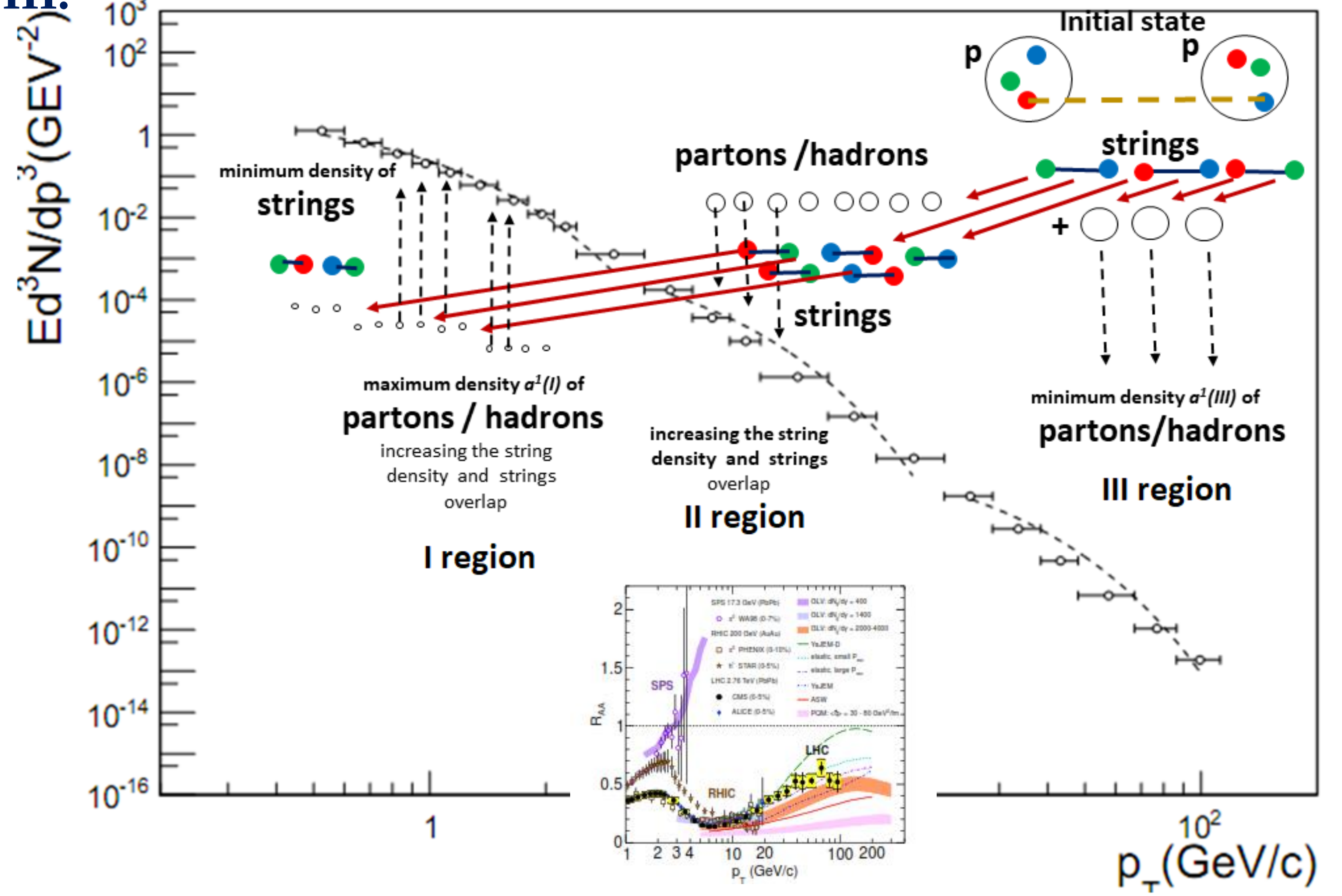
This result together with the above results on the ratios of lengths ($< L_\eta >:< L_{\pi^0} > \cong m_\eta : m_{\pi^0}$) can be clue that <u>the fragmentation and hadronization of the partons occurs through the string dynamics, and the values of the L_K^c can be related to the string tension.</u> So one can conclude that the meaning behind observed p_T regions at LHC energies could be the parton fragmentation and hadronization through parton strings.

Discussion

In this picture the region III is the domain of creation of first generation partons/strings (in our measurements) during collisions, where the most energetic hadrons /partons / strings(with highest tension) are produced and weakly modified by the medium. The region II is the one with highest density of the strings decayed from ones in region III.



In this pictures the region I is the one with the maximum number of hadrons and minimum number of strings.

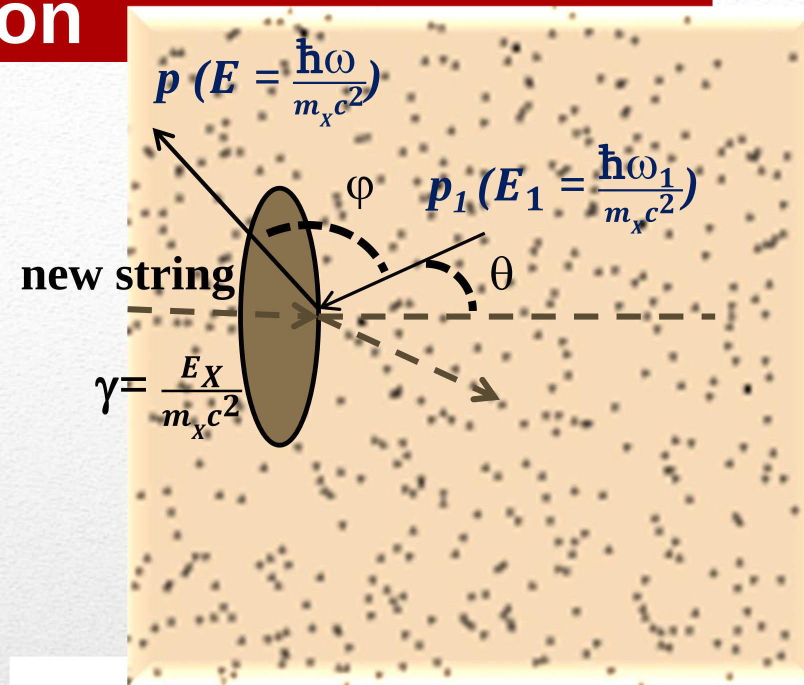


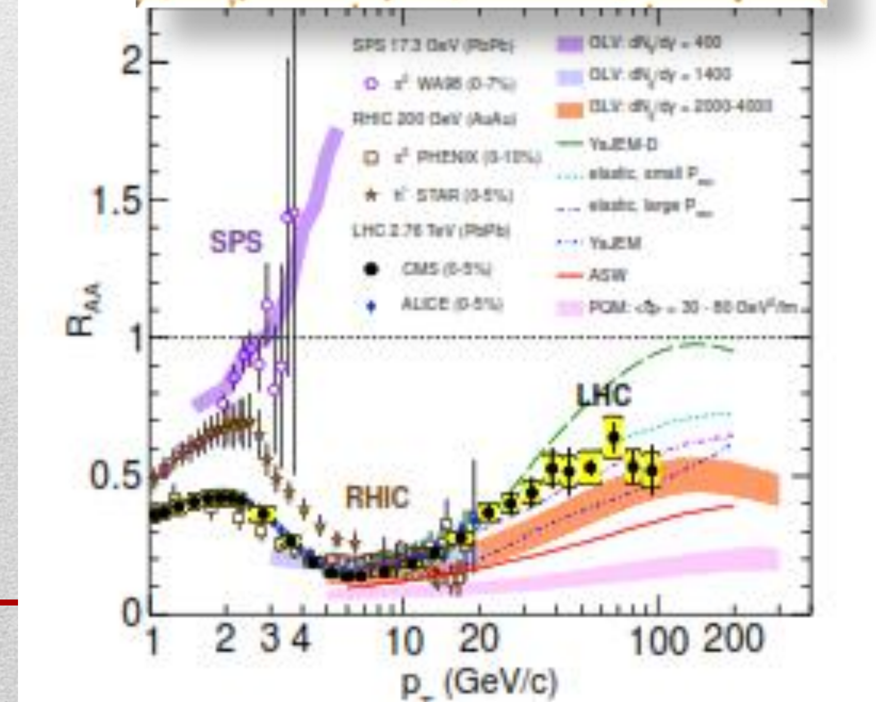
The high density causes string fusion (II region) and a collective phenomenon, which is as a result of the new string formation in the most central pp interactions. It can explain the anomalous behavior of the Nuclear Modification Factor in this region.

Discussion

In the paper [*Mais Suleymanov arXiv: nucl-ex/1710.09296*] we have discussed that the phenomena string fusion* can explain anomalous behaviour of the Nuclear Modification Factor in II region as a result of the inverse Compton effect for partons.

We support that in the case of a coherent collision of the new string with a parton which has a lower energy than the string, the parton can gain energy, resulting in its acceleration and shifting to the higher p_T region. After losing a significant part of its energy new string can decay into partons with lower energies - slowed partons in the interval of lower p_T.





CONCLUSION

- p_T distribution data from the LHC of the particles produced in *pp* and *Pb-Pb* collisions contain several p_T regions with special properties , which could be characterized by the length of the regions L_K^c and two free fitting parameters a_K^c and b_K^c;

- the study of the L_K^c dependencies of the parameters a_K^c and b_K^c and of the energy dependencies of these parameters have showed that the regions can be classified into two groups;

- the values of L_K^c, a_K^c and b_K^c as a function of energy grouped around several lines and show jump-like changing with energy;

- the lengths of the regions increase with mass of the particles and the increasing gets stronger with energy, at maximum available energy (8TeV) the ratio of lengths for η - mesons to ones for π^0—mesons become approximately equal to ratio of their mass - $< L_\eta >:< L_{\pi^0} >\cong m_\eta : m_{\pi^0}$;

- the mass dependences of the parameters a_K^c and b_K^c show regime change at mass $\cong$ 500 MeV/c^2 .

CONCLUSION

The existing of several p_T regions, the jump-like changing of the characteristics of the regions and grouping the values of the characteristics around certain lines with energy can say on discrete energy dependences for the characteristics of the regions which is characteristics of the QCD quark string .

So we could conclude that the observed p_T regions and their characteristics reflect features of fragmentation and hadronization of partons through the string dynamics.

According to the logic of string theory, the results could mean that parton strings of the very first generation (with maximum tensions T_{max} formed immediately after the collision) either hadronize or decay forming the next generation of strings with tensions $T' < T_{max}$. Some of the newly formed strings can also either hadronize other ones can decay and create strings of the next generation with tensions T "<T', etc., up to the minimum tensions T_{min} after which the string decay stops. That is, two processes occur simultaneously: string hadronization; string breaking. In an experiment, we measure the spectrum of hadrons ,we cannot have a spectrum of the strings themselves. We think the the string breaking effect might be the reason of observing several p_T regions which has a discrete nature.

Finally we want to note that in the experiment, we can see only signature of the last generations of strings, which are in the area of our p_T measurements. It is very difficult to have signature for the very first generation of strings, since for this it is necessary to have measurements for p_T in the interval up to several TeV / c.

Thank you very much

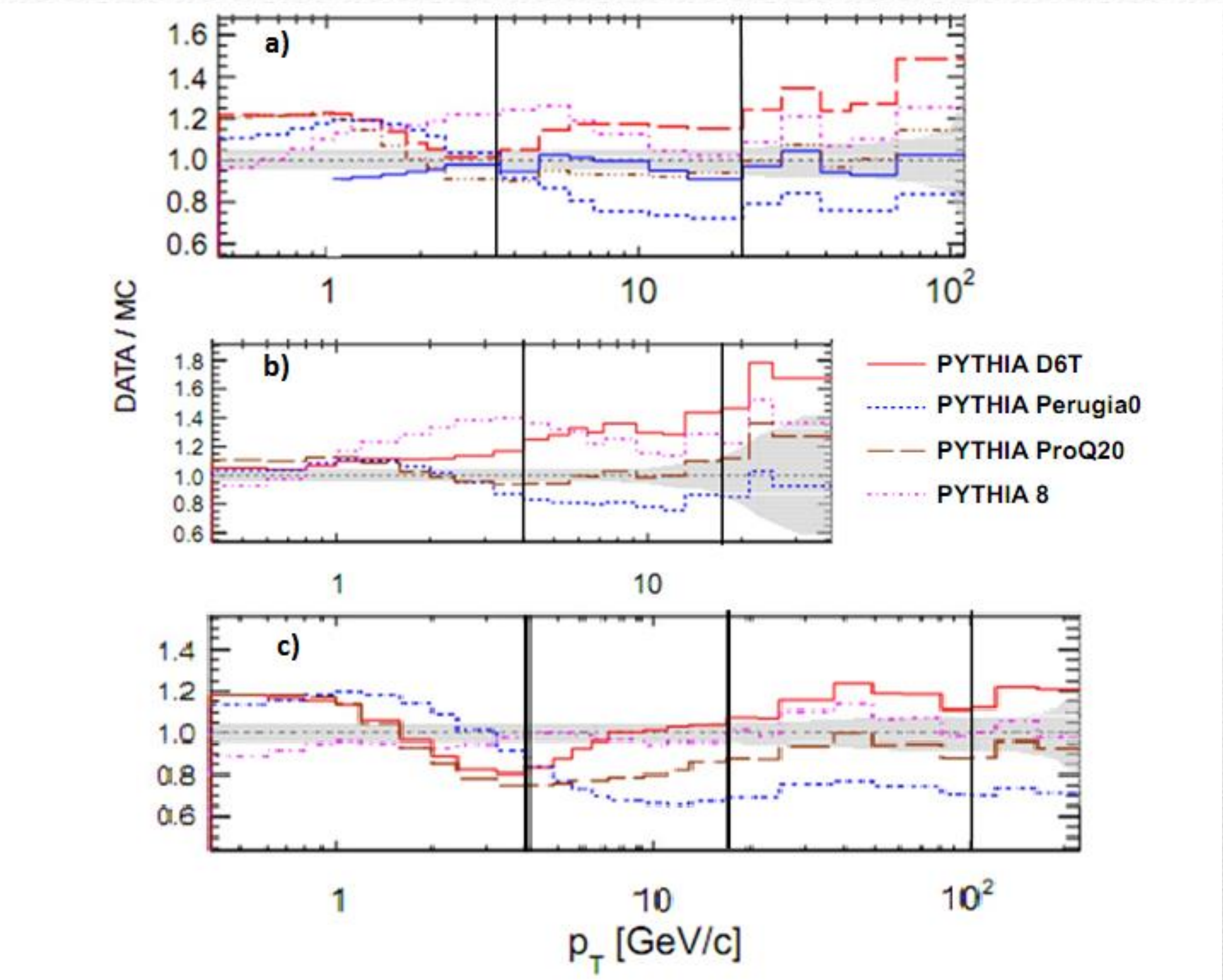


Fig.3a-c. The ratio of the measured spectrum for the *pp* collisions at: a) $\sqrt{s} = 2.76\ TeV$ (lower panel of the Fig.3a from paper [1]) ; b) $\sqrt{s} = 0.9\ TeV$ (lower panel in Fig.5a from the paper [5]); c) $\sqrt{s} = 7\ TeV$ (lower panel in Fig.5a from the paper [5]) to the predictions of the four PYTHIA tunes and to the interpolated spectrum (in Fig.3a). The grey band corresponds to the statistical and systematic uncertainties of the measurement added in quadrature.