Role of string collectivity and semihard process in multiplicity-dependent transverse momentum and the strangeness enhancement

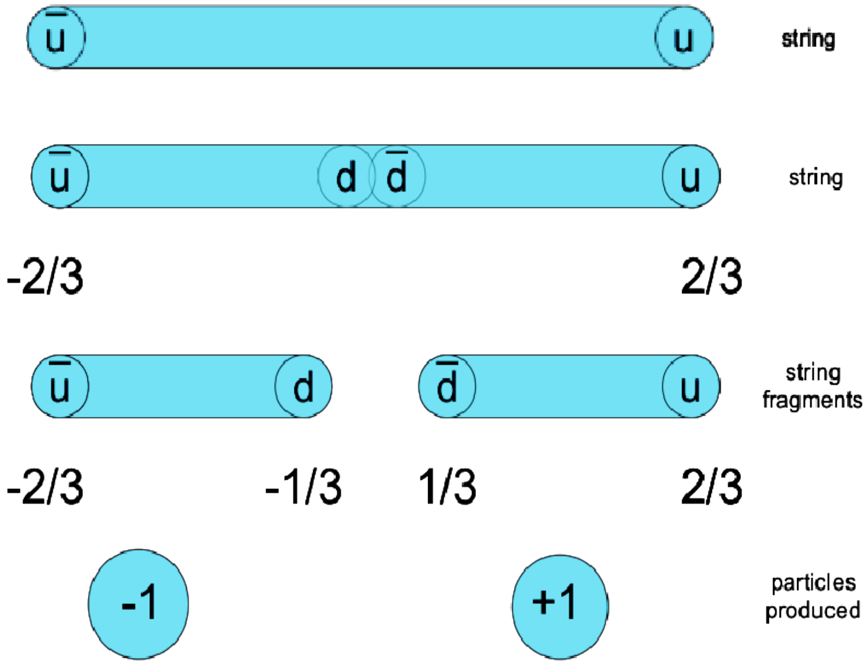
Vladimir Kovalenko
Saint Petersburg State University

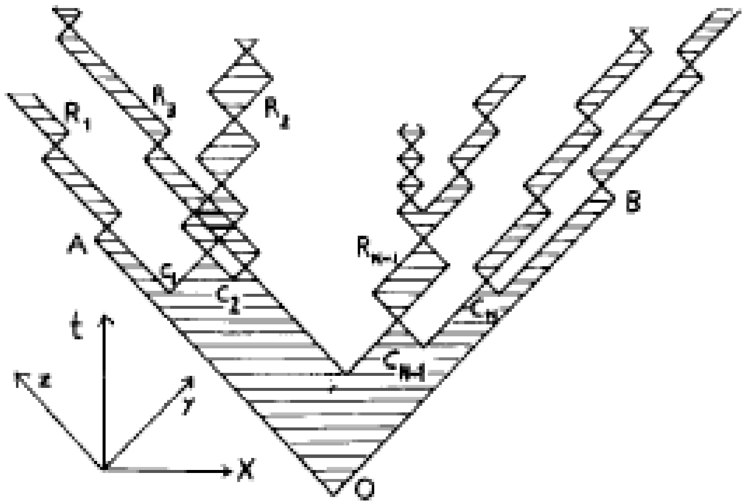
COST Workshop on Interplay of hard and soft QCD probes for collectivity in heavy-ion collisions

from 25 February 2019 to 1 March 2019
Lund university

Overview

- The soft QCD processes is not described by usual perturbation theory
- The model of quark-gluon strings, stretched between projectile and target partons – semiphenomenological approach to the multiparticle production

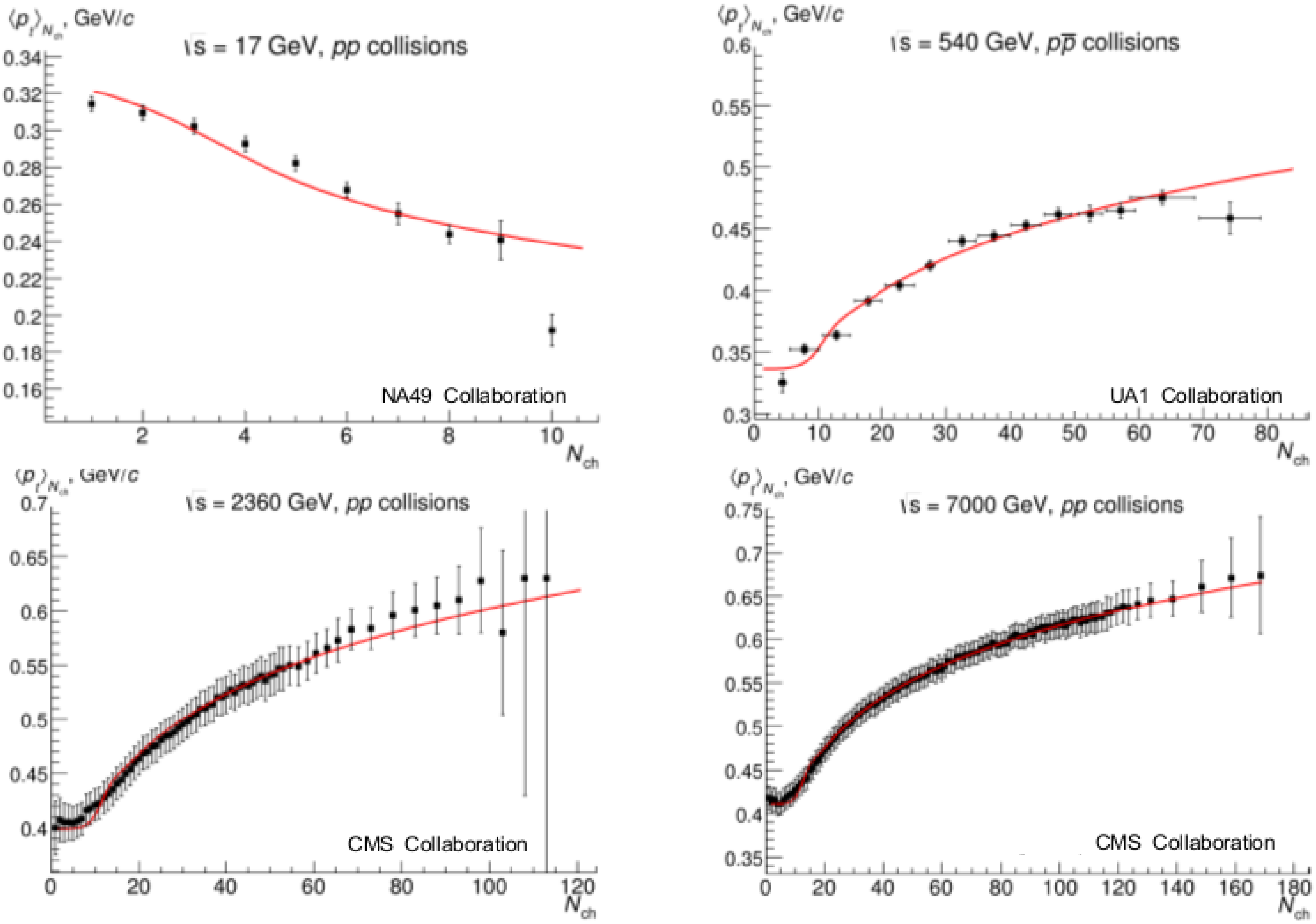




Space-time evolution and fragmentation of AMOR string

[1] Y. Nambu, “Strings, Monopoles and Gauge Fields”, Phys. Rev. D 10, 4262 (1974).
[2] X. Artru and G. Mennessier, Nucl Phys B 70 (1974) 93 “String Model and Multiproduction”
[3] A. Capella and J. Tran Thanh Van, “Long Range Rapidity Correlations in Hadron - Nucleus Interactions”, Phys. Rev. D 29, 2512 (1984).
[4] A. Kaidalov and K. Ter-Martirosian, “Pomeron as Quark-Gluon Strings and Multiple Hadron Production at SPS Collider Energies”, Phys. Lett. B 117, 247–251 (1982).
[5] K. Werner, Phys. Rep. 232, 87—299 (1993).

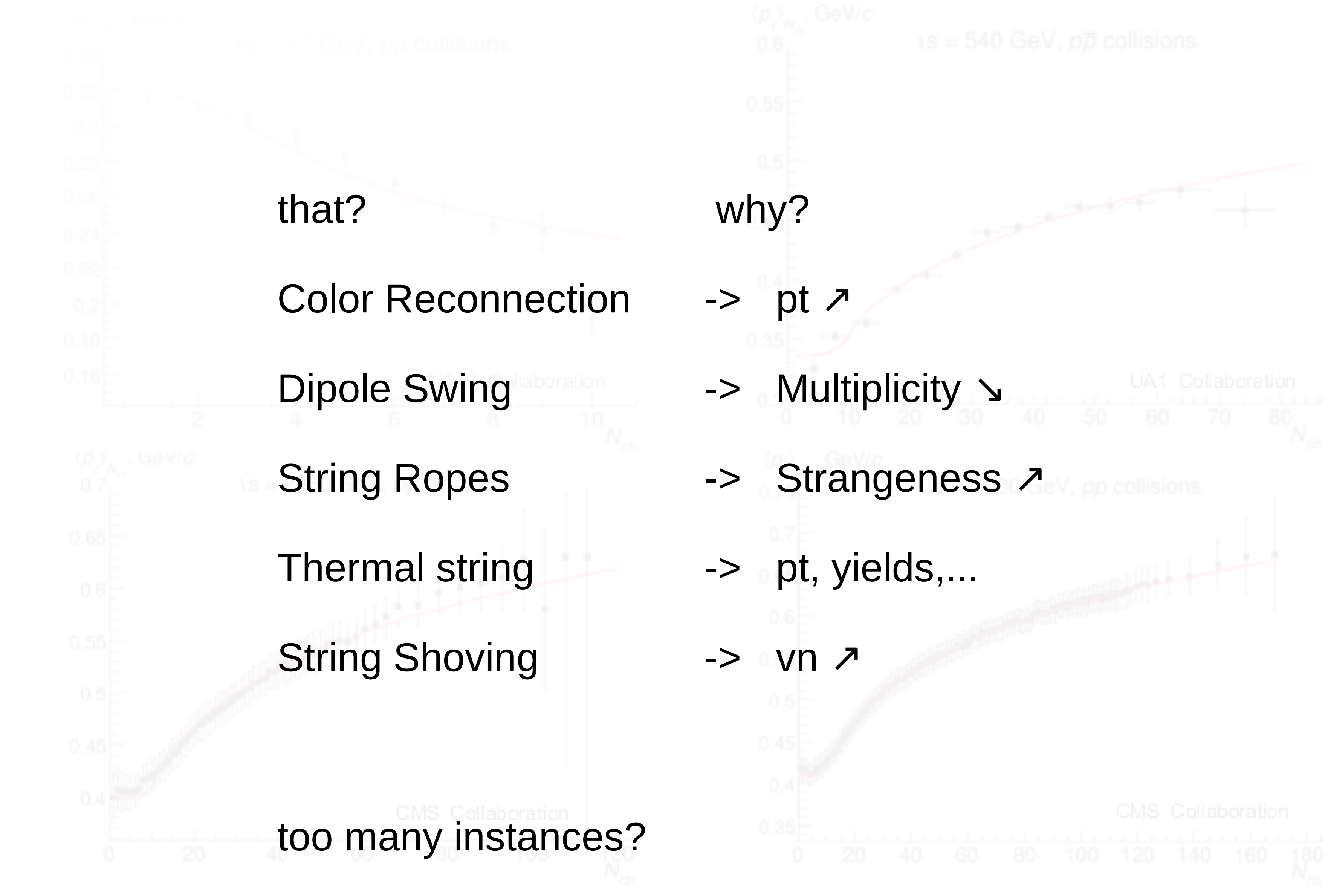
p_t-N_{ch} correlations



Experimental data:

[6] T. Anticic et al. (NA49 Collaboration), Phys. Rev. C 70 (2004) 034902.
[7] G. Arnison et al. (UA1 Collaboration), Phys. Lett. B 118 (1982) 167.
[8] V. Khachatryan et al. (CMS Collaboration), JHEP 1101 (2011) 079.

String collectivity?



that?		why?
Color Reconnection	->	pt ↗
Dipole Swing	->	Multiplicity ↘
String Ropes	->	Strangeness ↗
Thermal string	->	pt, yields,...
String Shoving	->	vn ↗

too many instances?

Experimental data:

[6] T. Anticic et al. (NA49 Collaboration), Phys. Rev. C 70 (2004) 034902.

[7] G. Arnison et al. (UA1 Collaboration), Phys. Lett. B 118 (1982) 167.

[8] V. Khachatryan et al. (CMS Collaboration), JHEP 1101 (2011) 079.

String fusion

$$Q^2(n) = \left(\sum_{i=1}^{n} \overrightarrow{Q_i}(1) \right)^2 = \sum_{i=1}^{n} Q_i^2(1) + \sum_{i \neq j} \overrightarrow{Q_i}(1) \cdot \overrightarrow{Q_i}(1)$$

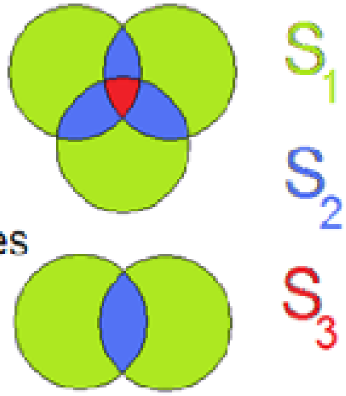
$$\langle Q^2(n) \rangle = n Q^2(1)$$

overlaps

SFM

$C = \{S_1, S_2, \ldots\}$

S_k – area covered k-times



String fusion mechanism predicts:

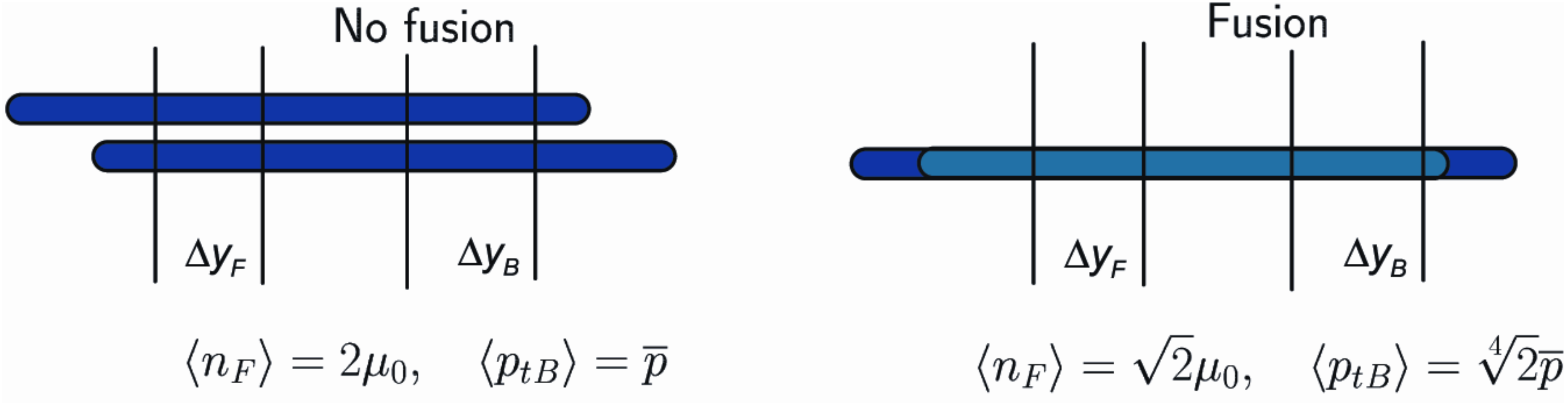
– decrease of multiplicity
– increase of p_T
– growth of p_T with multiplicity in pp, pA and AA collisions
– growth of strange particle yields
– cumulative particle production
– forward-backward correlations
….

$$\langle \mu \rangle_k = \mu_0 \sqrt{k} \frac{S_k}{\sigma_0} \qquad \langle p_t^2 \rangle_k = p_0^2 \sqrt{k} \qquad \langle p_t \rangle_k = p_0 \sqrt[4]{k}$$

S_k – area, where k strings are overlapping, σ_0 single string transverse area,
μ_0 and p_0 – mean multiplicity and transverse momentum from one string

[9] M. A. Braun, C. Pajares, Nucl. Phys. B 390 (1993) 542.
[10] M. A. Braun, R. S. Kolevatov, C. Pajares, V. V. Vechernin, Eur. Phys. J. C 32 (2004) 535.
[11] N.S. Amelin, N. Armesto, C. Pajares, D. Sousa, Eur.Phys.J.C22:149-163 (2001), arXiv:hep-ph/0103060
[12] G. Ferreiro and C Pajares J. Phys. G: Nucl. Part. Phys. 23 1961 (1997)

String fusion and forward-backward correlations



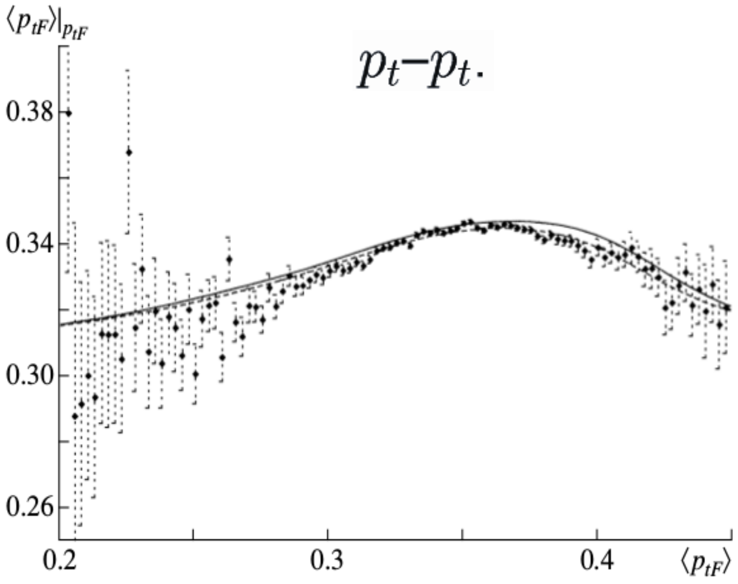
$$\langle n_F\rangle = 2\mu_0, \quad \langle p_{tB}\rangle = \overline{p}$$

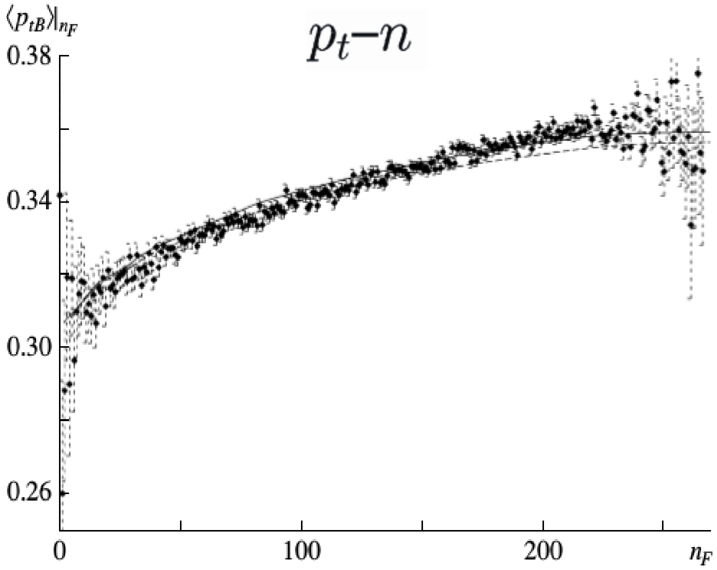
$$\langle n_F\rangle = \sqrt{2}\mu_0, \quad \langle p_{tB}\rangle = \sqrt[4]{2}\,\overline{p}$$

correlations n–n, p_t–p_t. p_t–n

Intensive observable – event mean transverse momentum:

$$p_{tF(B)} = \frac{p_{t1} + \ldots + p_{tn_{F(B)}}}{n_{F(B)}}$$





SPS, PbPb

[13] V. V. Vechernin, R. S. Kolevatov, Phys. Atom. Nucl. 70 (2007) 1858; V. V. Vechernin, R. S. Kolevatov, Phys. Atom. Nucl. 70 (2007) 1797

experimental data:
[14] C. Alt et al. (NA49 Collaboration) and G. A. Feofilov et al. (SPbSU group), in Proc. Relativistic Nuclear Physics and Quantum Chromodynamics, (JINR, Dubna), Vol. 1, p. 222 (2005).

Mean pt forward-backward correlations

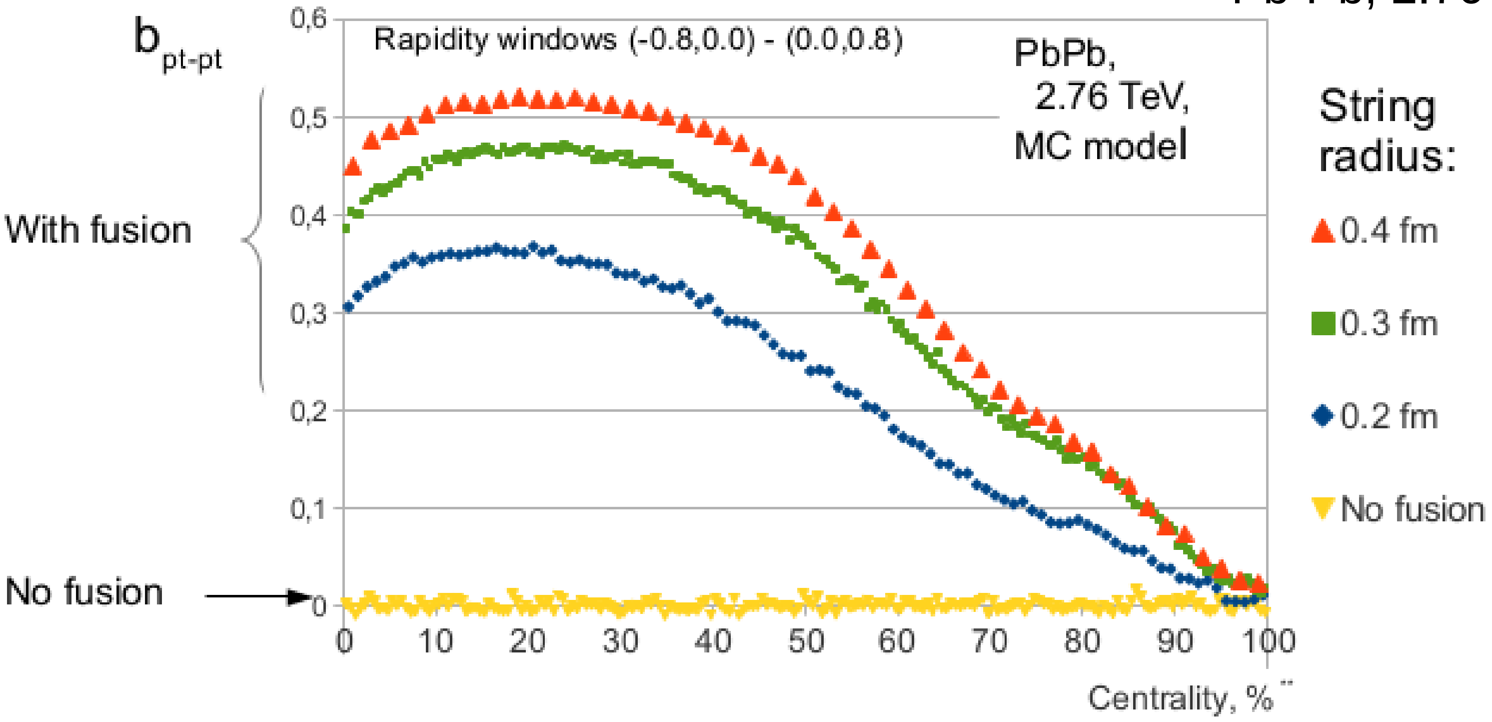
correlation coefficient

$$b=\frac{\langle F\,B\rangle-\langle F\rangle\langle B\rangle}{\langle F^2\rangle-\langle F\rangle^2}$$

$$B\,,F\,,\rightarrow p_t=\frac{1}{n}\sum_{i=1}^{n}p_{ti}$$

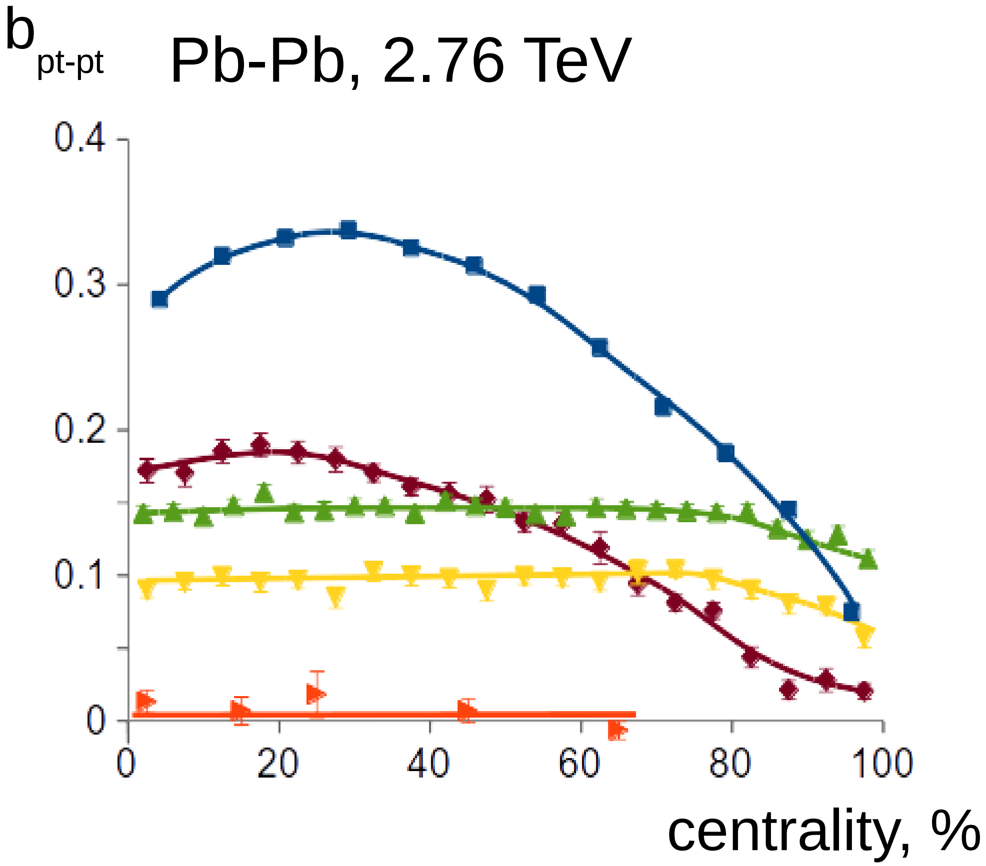
p_t–p_t.

Pb-Pb, 2.76 TeV

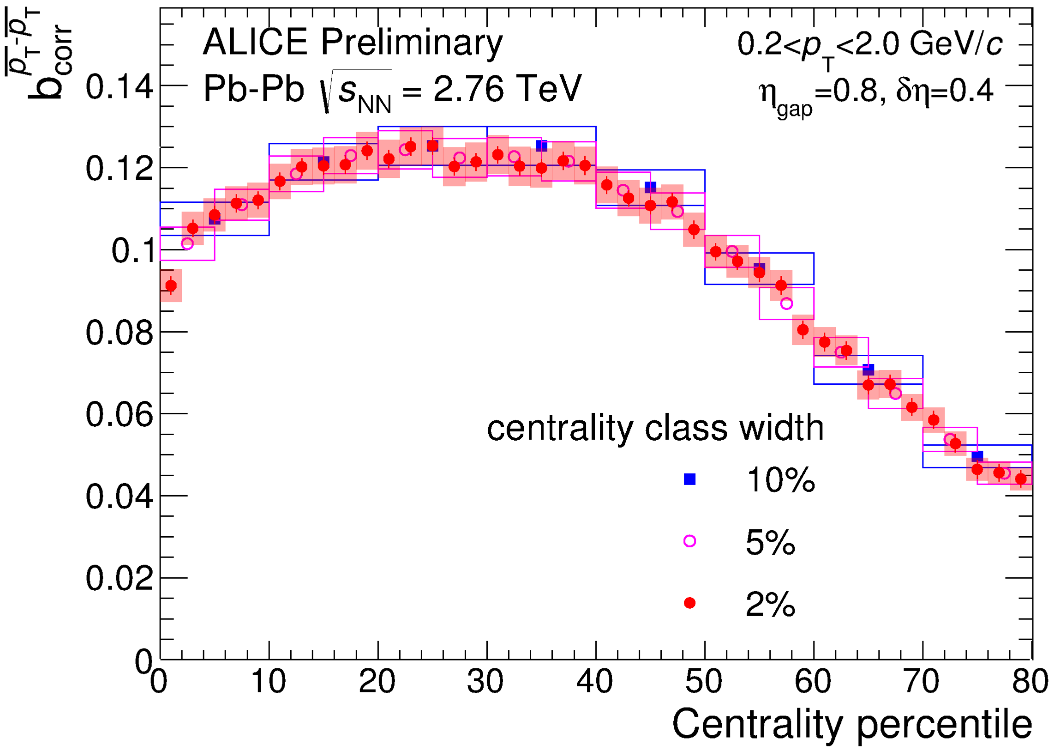


[15] V. Kovalenko, V. Vechernin. EPJ Web of Conferences 66, 04015 (2014), arXiv:1308.6618 [nucl-th] (2013)

Mean pt forward-backward correlations



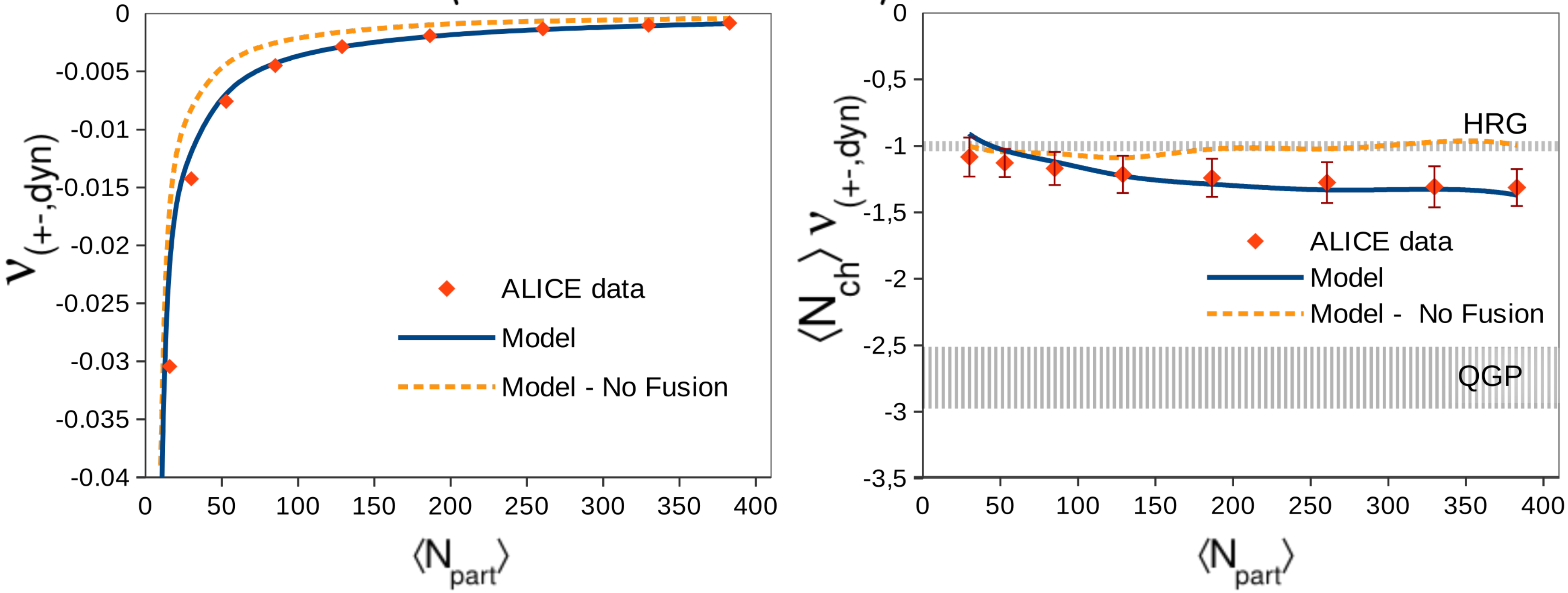
[16] Vladimir Kovalenko, Vladimir Vechernin, J. Phys. Conf. Ser. 798, 012053 (2017), arXiv:1611.07274 [nucl-th]



[17] I. Altsybeev, KnE Energ.Phys. 3 (2018) 304-312, arXiv:1711.04844 [nucl-ex]

charge fluctuations

$$\nu_{\text{dyn}} = \left\langle \left(\frac{N_+}{\langle N_+\rangle} - \frac{N_-}{\langle N_-\rangle} \right)^2 \right\rangle - \left(\frac{1}{\langle N_+\rangle} + \frac{1}{\langle N_-\rangle} \right)$$

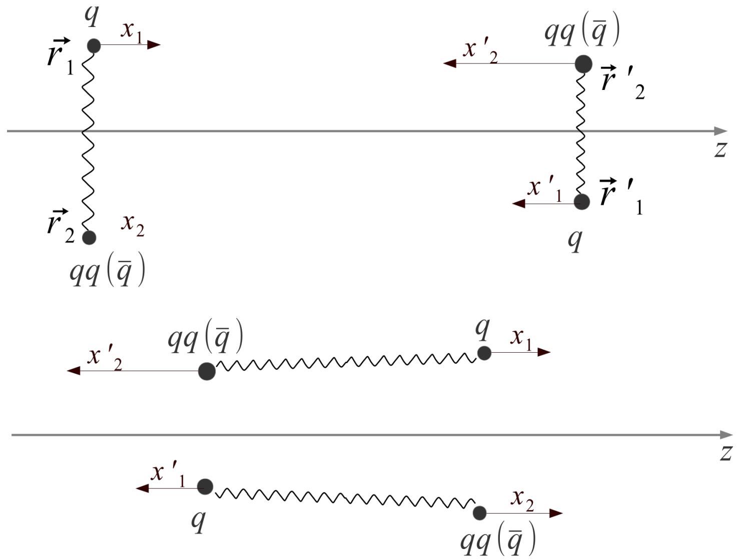


- String fusion improves the description of the centrality dependence of dynamical net-charge fluctuation.
- Scaling variable $\langle N_{ch}\rangle\, \nu_{(+-,dyn)}$ decreases with centrality towards the level of QGP estimation (which is in agreement with experiment)

In case of no fusion, it remains constant at the level of HRG

[18] Vladimir Kovalenko, arXiv:1811.08819 [nucl-th]

Monte Carlo model



- Partonic picture based on dipole interaction
- Energy and angular momentum conservation in the initial state
- The probability amplitude depends on transverse coordinates:

$$f=\frac{\alpha_s^2}{2}\ln^2\frac{|\vec r_1-\vec r_1'||\vec r_2-\vec r_2'|}{|\vec r_1-\vec r_2'||\vec r_2-\vec r_1'|}$$

- With confinement effects taking into account, the probability amplitude is [19,20]:

$$f=\frac{\alpha_S^2}{2}\left[K_0\left(\frac{|\vec r_1-\vec r_1'|}{r_{\max}}\right)+K_0\left(\frac{|\vec r_2-\vec r_2'|}{r_{\max}}\right)-K_0\left(\frac{|\vec r_1-\vec r_2'|}{r_{\max}}\right)-K_0\left(\frac{|\vec r_2-\vec r_1'|}{r_{\max}}\right)\right]^2.$$

- The **hardness** of the elementary collisions is defined by transverse size of dipoles:

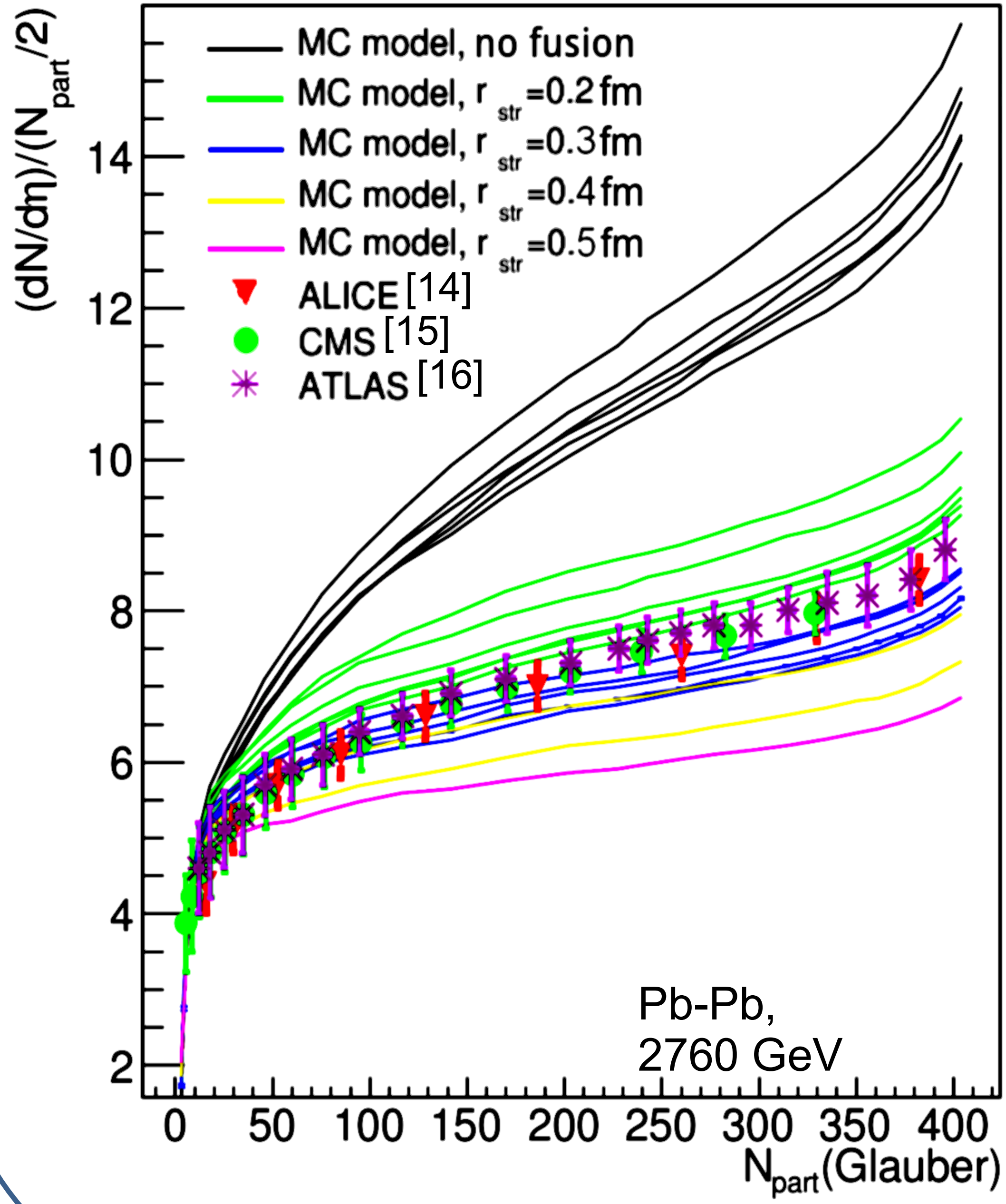
$$d_{1i}=|\vec r_1-\vec r_2|,\ d_i'=|\vec r_1'-\vec r_2'|$$

- Transverse momentum of a cluster of strings:

$$p_1^4=\sum_i^k p_{T\,str\,i}^4,\quad p_{T\,str\,i}^2=\frac{1}{d_i^2}+\frac{1}{d_i'^2}+p_0^2$$

[19] C. Flensburg, G. Gustafson, L. Lonnblad, Eur. Phys. J. (C), 60, 233–247, 2009, arXiv:0807.0325
[20] G. Gustafson, Acta Phys. Polon. B, 40, 1981–1996, 2009
[21] V. N. Kovalenko, Phys. Atom. Nucl. 76, 1189 (2013), arXiv:1211.6209 [hep-ph].
[22] V. Kovalenko, V. Vechernin, PoS (Baldin ISHEPP XXI) 077 (2012), arXiv:1212.2590 [nucl-th].
[23] V. Kovalenko and V. Vechernin, DESY Conf. Proc. 2014-04, 82 (pp. 691-694), DOI: 10.3204/DESY-PROC-2014-04/82, arXiv:1410.3884 [hep-ph]

Description of multiplicity in Pb-Pb collisions



Centrality dependence of multiplicity [22]

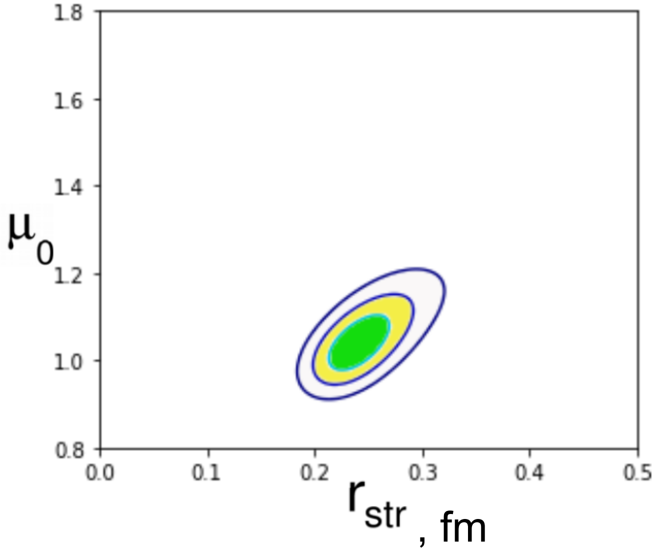
No fusion

with fusion:

r_{str}=0.2-0.3 fm

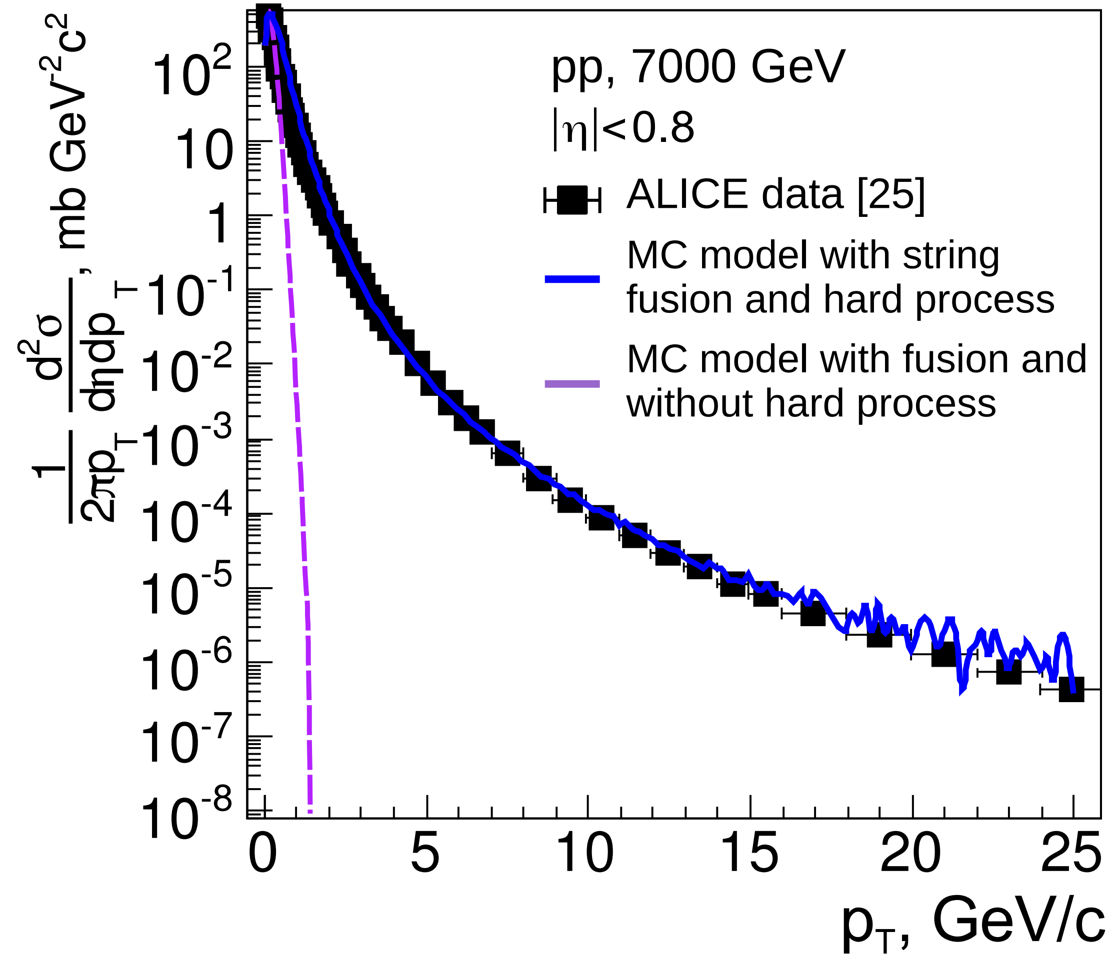
- Absence of string fusion is disfavored.
- Good description of multiplicity with $r_{str} = 0.2 - 0.3$ fm [24].

[24] V. Kovalenko, PoS(Confinement2018)235 :



Bayesian Gaussian Process posterior estimation of string radius and mean multiplicity per rapidity [24]

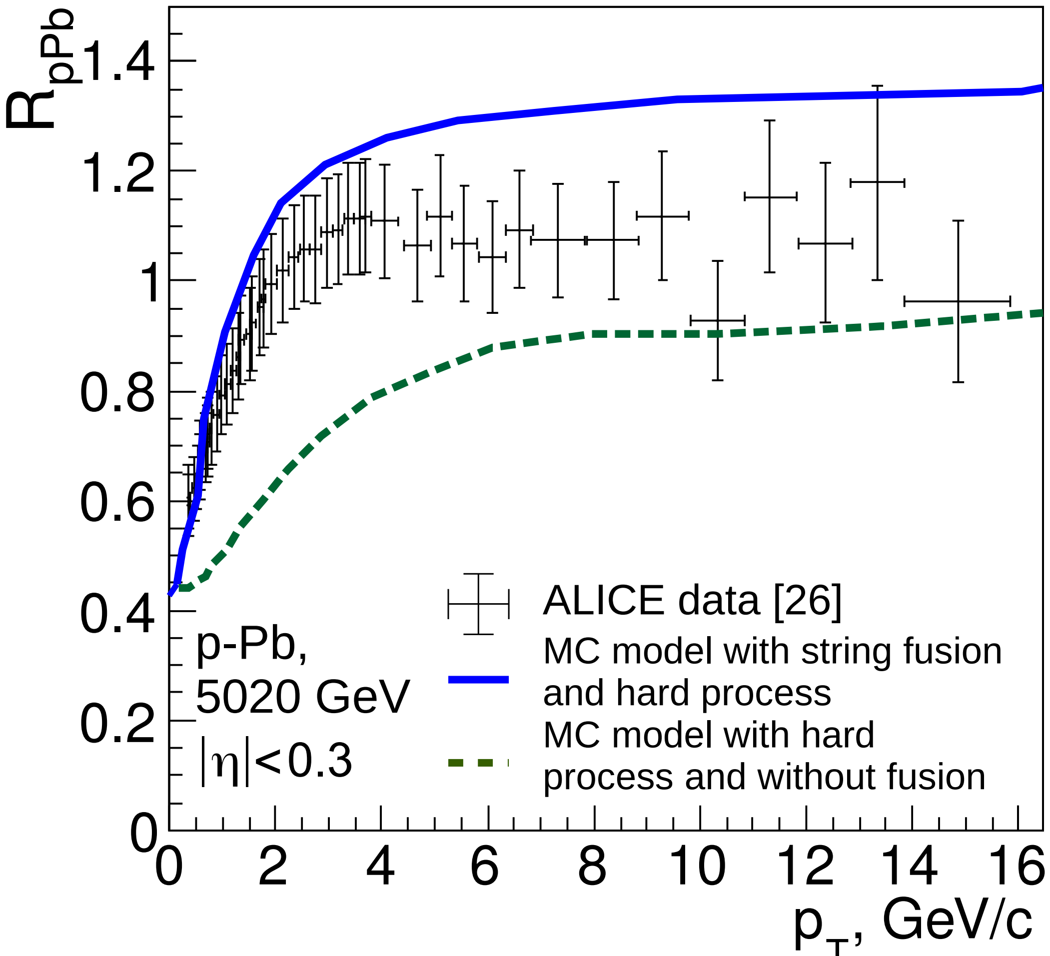
Transverse momentum distribution



- Inclusion of hard process is necessary in order to reproduce the transverse momentum spectra of charged particles in pp collisions.
- Reasonable description of transverse momentum spectra of charged particles in the MC model with string fusion and hard process included.

[25] B. Abelev, et. al. (ALICE Collaboration), Eur. Phys. J. C 73 (2013) 2662, arXiv:1307.1093 [nucl-ex].

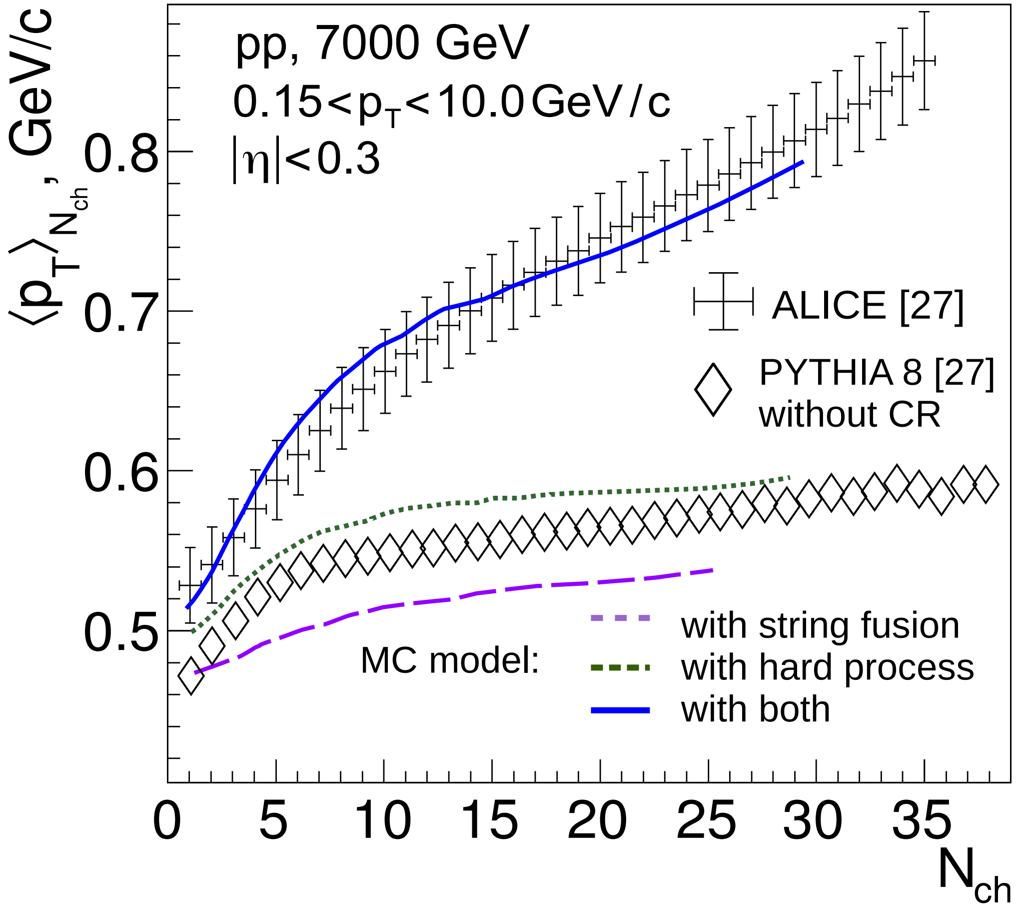
Nuclear modification factor



- Better description of nuclear modification factor in the model with string fusion.
- A slight excess (compared to unity) of the nuclear modification at high transverse momenta might be related to the absence in the model of the parton energy loss, which could be relevant at the LHC energies in p-A collisions

[26] B. Abelev, et. al. (ALICE Collaboration), Phys. Rev. Lett. 110 (2013) 082302, arXiv:1210.4520 [nucl-ex].

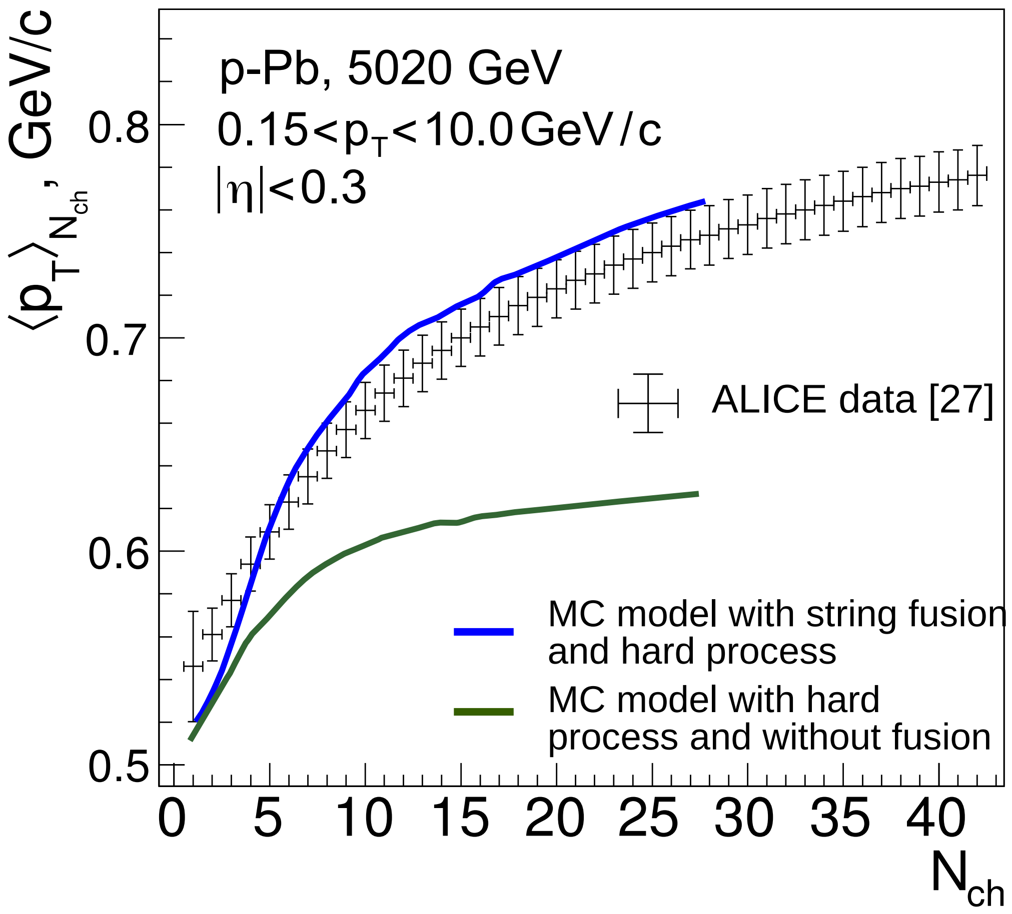
Results: pt-n correlations in pp collisions

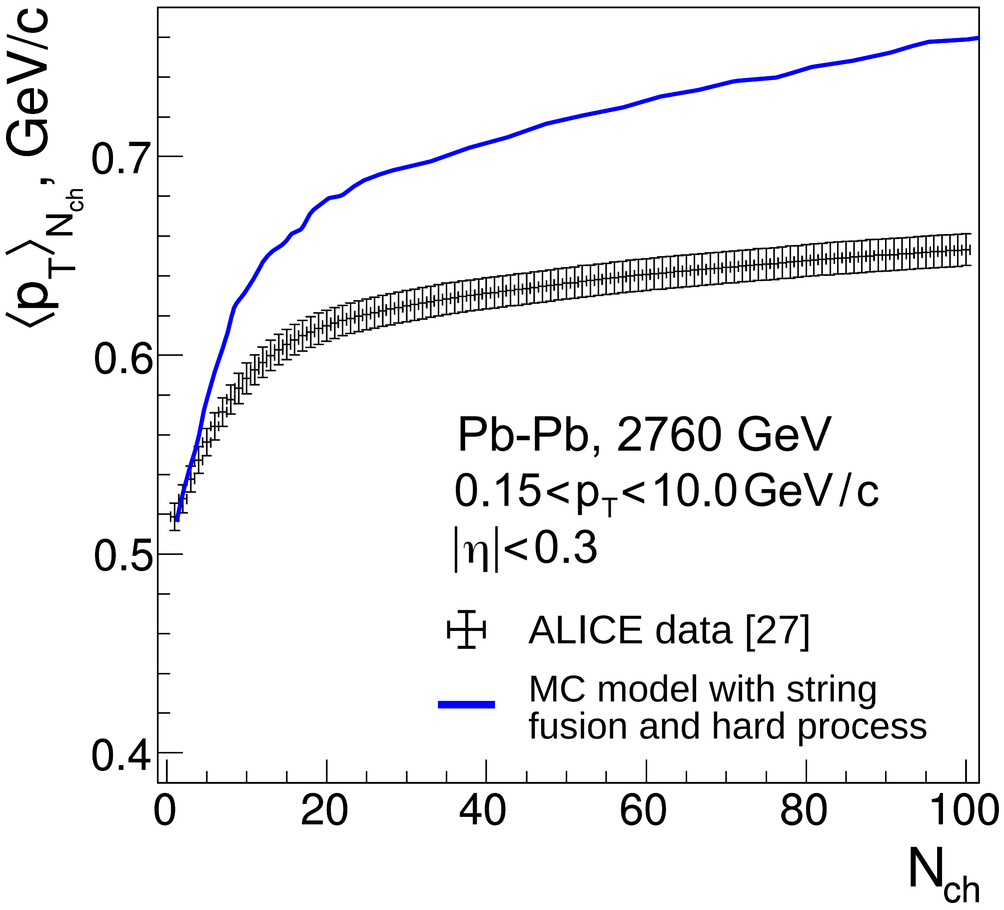


- String fusion or hard process separately are not sufficient to describe experimental correlation between transverse momentum and multiplicity.
- MC model with hard process only behaves like Pythia 8 [28] without color reconnection [29] – almost flat function with small slope
- Inclusion of both hard process and string fusion enables to describe data.

[27] B. Abelev, et al. (ALICE Collaboration). Phys. Lett. B 727 (2013) 371, arXiv:1307.1094 [nucl-ex].
[28] T. Sjöstrand, S. Mrenna, P. Skands, Comput. Phys .Commun. 178 (2008) 852-867, arXiv:0710.3820 [hep-ph].
[29] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 05 (2006) 026, arXiv:hep-ph/0603175.

Results: pt-n correlations in p-Pb and Pb-Pb





- Hard process in proton-lead collisions is not enough to describe the strong correlation between transverse momentum and multiplicity.
- MC model with both hard process and string fusion matches the data
- Contributions of string fusion and hard process to the overall correlation function are of the same order.

[27] B. Abelev, et al. (ALICE Collaboration). Phys. Lett. B 727 (2013) 371, arXiv:1307.1094 [nucl-ex].

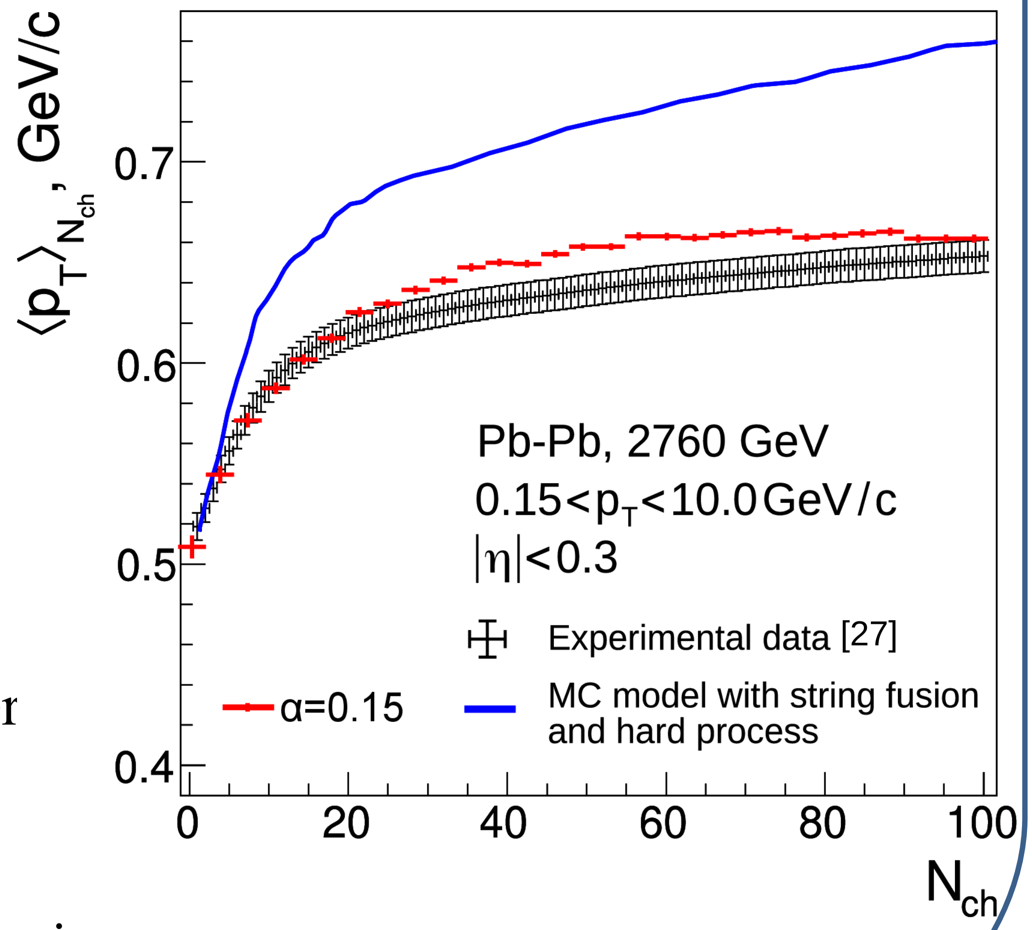
Parton energy loss

- The loss of energy of an ultra-relativistic particle is proportional to [its momentum×field] 2/3.

[30] M. A. Braun, C. Pajares, Eur. Phys. J. C 71, 1558 (2011), arXiv:1008.0245 [hep-ph]

$$\frac{dp(x)}{dx} = -0.12e^2\left(eEp(x)\right)^{2/3}$$

$$\Delta p_t = -\alpha\left(p_t * \sqrt{\eta}\right)^{2/3}\Delta x$$



- Anisotropic flows from strings:

[31] M.A. Braun, C. Pajares, V.V. Vecher Nucl. Phys. A906 (2013) 14-27

- And ridge:

[32] M.A. Braun, C. Pajares, V.V. Vechernin, Eur. Phys. J. A51 (2015) no.4, 44

Extended Multi-Pomeron model with string collectivity [33,34]

Regge-Gribov multipomeron approach

Probability of production of *n* pomerons

$$w_n = \sigma_n / \sum_{n'} \sigma_{n'},$$

where σ_n – cross section of n cut-pomeron exchange:

$$\sigma_n = \frac{\sigma_{\mathrm{P}}}{nz}\left(1 - e^{-z}\sum_{l=0}^{n-1}\frac{z^l}{l!}\right)$$

Each cut-pomeron corresponds to pair of strings

$$z = \frac{2C\gamma s^{\Delta}}{R_0^2 + \alpha' \ln(s)}$$

Values of parameters used:

$$\Delta = 0,139\,, \quad \alpha^{'} = 0,21\ \mathrm{GeV}^{-2}\,,$$

$$\gamma = 1,77\ \mathrm{GeV}^{-2}\,, \quad R_0^2 = 3,18\ \mathrm{GeV}^{-2}\,,$$

$$C = 1,5\,.$$

Probability for n strings to give N_{ch} particles:

$$P(n, N_{ch}) = \exp(-2nk\delta)\frac{(2nk\delta)^{N_{ch}}}{N_{ch}!}$$

where k – is mean multiplicity per rapidity unit from one pomeron;
δ – acceptance i.e. width of (pseudo-)rapidity interval

Schwinger mechanism of particles production from one string:

$$\left.\frac{dN_{\mathrm{ch}}}{dy\,d^2p_T}\right|_{y=0} \sim \exp\left(\frac{-\pi\left(p_t^2 + m^2\right)}{n^{\beta}t}\right)$$

[33] E. Bodnia, D. Derkach, G. Feofilov, V. Kovalenko, A. Puchkov, PoS (QFTHEP 2013) 060 (2013), arXiv:1310.1627 [hep-ph].

[34] E. O. Bodnia, V. N. Kovalenko, A. M. Puchkov, G. A. Feofilov, AIP Conf. Proc. 1606, 273-282 (2014), arXiv:1401.7534 [hep-ph].

Extended Multi-Pomeron model with string collectivity

$$\rho(N_{ch}, p_t) =$$

Probability distribution

$$= \frac{C_w}{z}\sum_{n=1}^{\infty}\frac{1}{n}\left(1-\exp(-z)\sum_{l=0}^{n-1}\frac{z^l}{l!}\right)\times$$

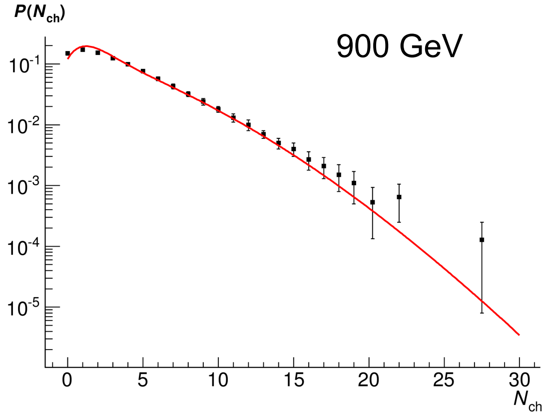
Probability of production of *n* pomerons

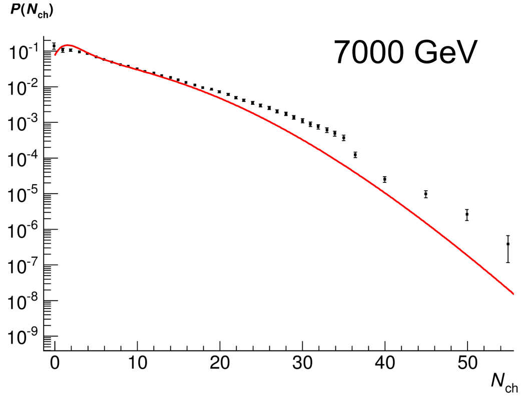
$$\times \exp(-2nk\delta)\frac{(2nk\delta)^{N_{ch}}}{N_{ch}!}\times$$

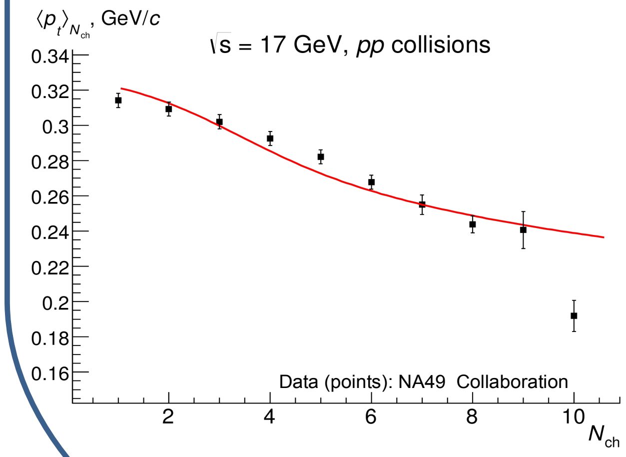
Poisson distribution of the charged particles from 2*n* string

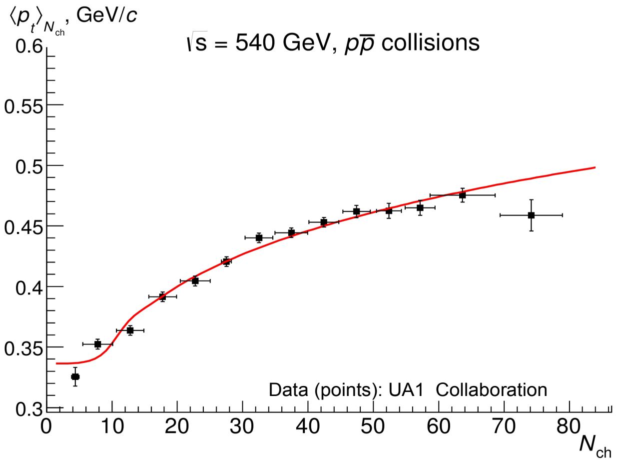
$$\times \frac{1}{n^{\beta}t}\ \exp\left(-\frac{\pi p_t^2}{n^{\beta}t}\right)$$

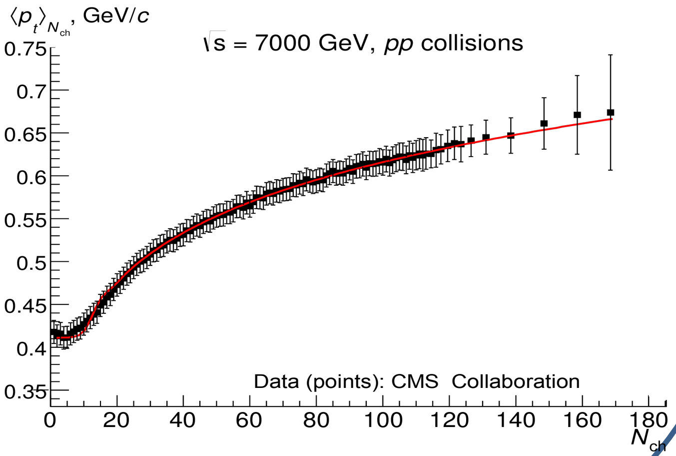
Modified Schwinger mechanism











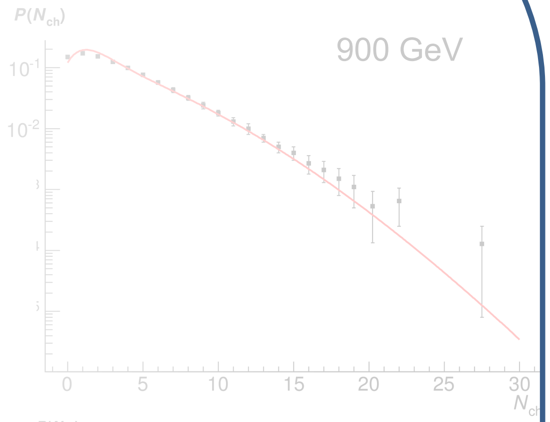
Extended Multi-Pomeron model with string collectivity

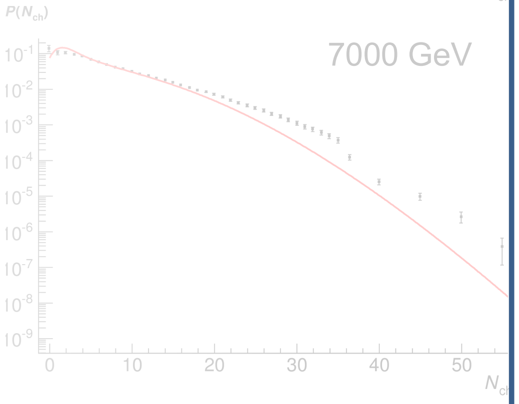
$\rho(N_{ch}, p_t) =$ Probability distribution

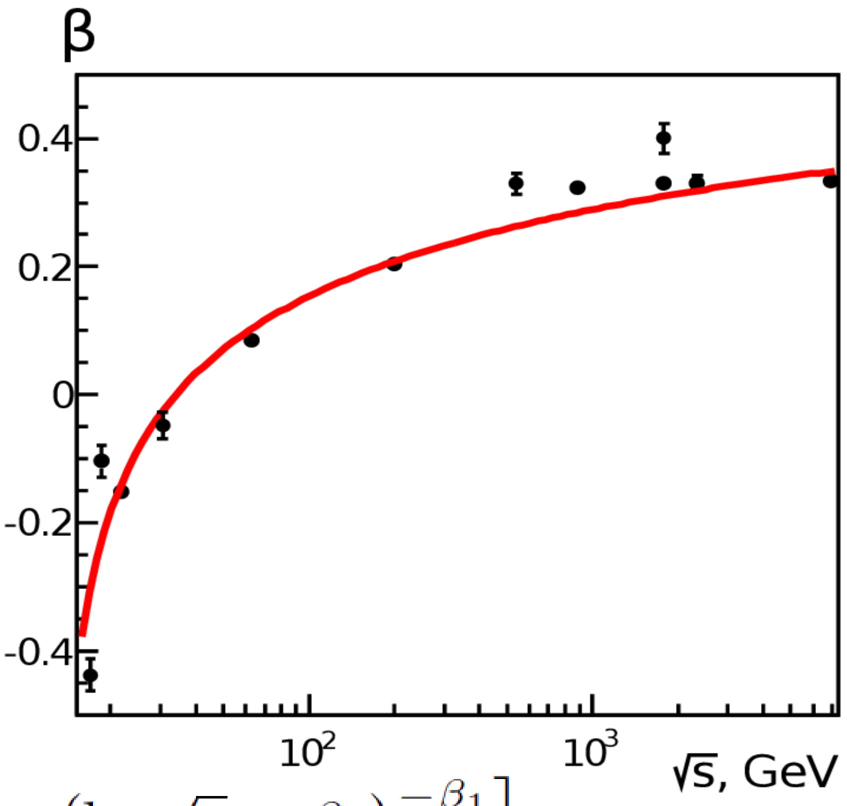
$= \frac{C_w}{z}\sum_{n=1}^{\infty}\frac{1}{n}\left(1-\exp(-z)\sum_{l=0}^{n-1}\right.$

$\times \exp(-2nk\delta)\frac{}{N_{ch}}$

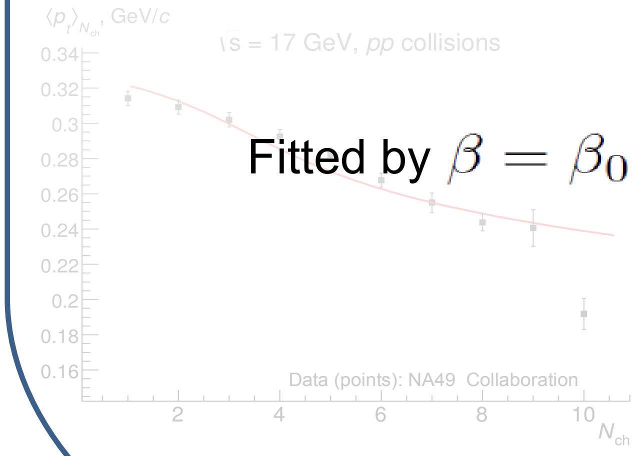
$\times \frac{1}{n^{\beta}t}\exp\left(-\frac{\pi}{n}\right.$

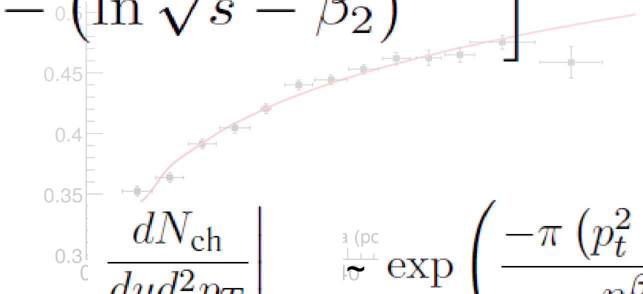


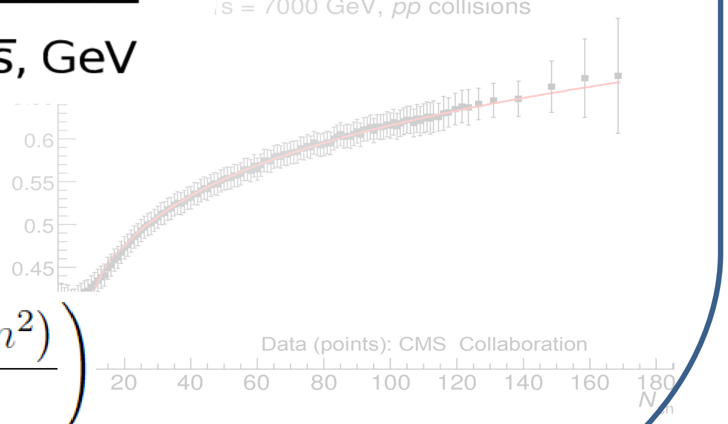




Fitted by $\beta = \beta_0\left[1-\left(\ln\sqrt{s}-\beta_2\right)^{-\beta_1}\right]$







$$\left.\frac{dN_{ch}}{dy\,d^2p_T}\right|_{y=0} \sim \exp\left(\frac{-\pi\left(p_t^2+m^2\right)}{n^{\beta}t}\right)$$

Particle differentiation

- Schwinger mechanism of particle production:

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

- take all light hadrons and correct for their cascade decays (feed down)

then

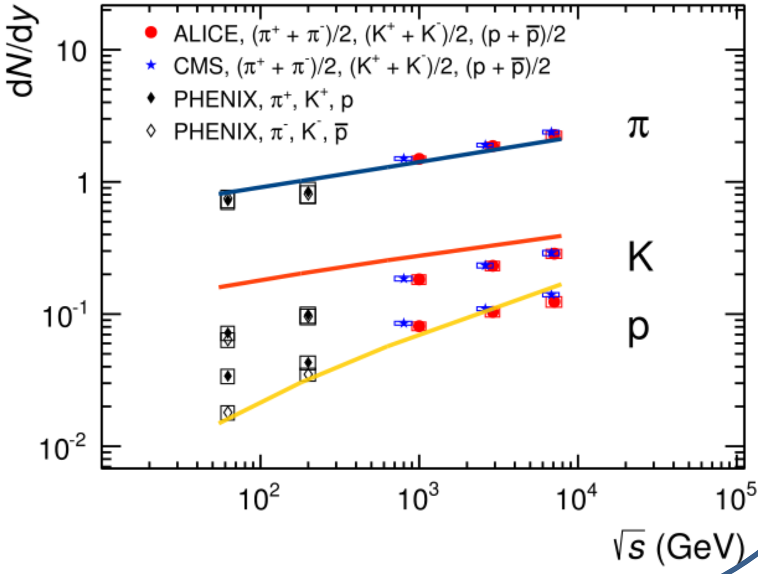
$$Y_\nu \sim \sum_\mu M_{\mu\nu}\cdot\left(2S_\mu+1\right)\cdot\exp\left(\frac{\pi\left(p_t^2+m_\mu^2\right)}{n^\beta t}\right),$$

where S_μ – spin of particle type μ

$M_{\mu\nu}$ – effective branching ration matrix, i.e.
the yield of particles from cascade decays of a particle μ

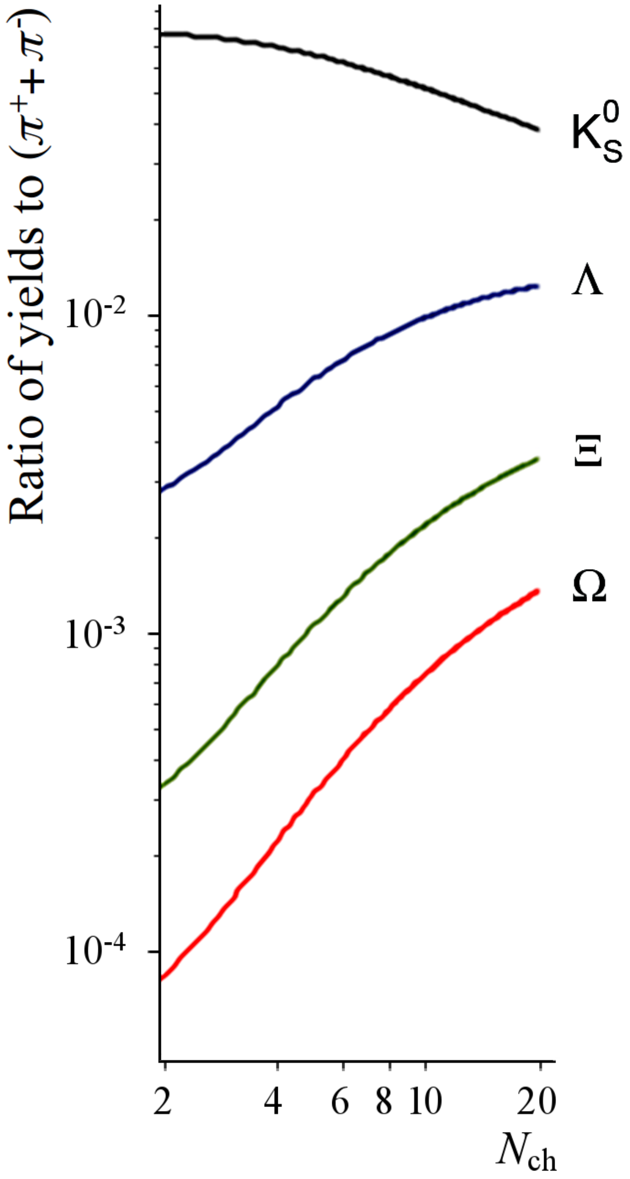
- The mass spectrum and the effective branching ration is extracted from Therminator 2 particle decayer (M. Chojnacki, et al, Comput. Phys. Commun. 183, 746 (2012), arXiv:1102.0273 [nucl-th])

[36] G. Feofilov, V. Kovalenko, A. Puchkov, arXiv:1710.08895 [hep-ph]
[37] G. Feofilov, V. Kovalenko, A. Puchkov, EPJ Web Conf. 171 (2018) 18003, arXiv:1711.00842 [nucl-th]

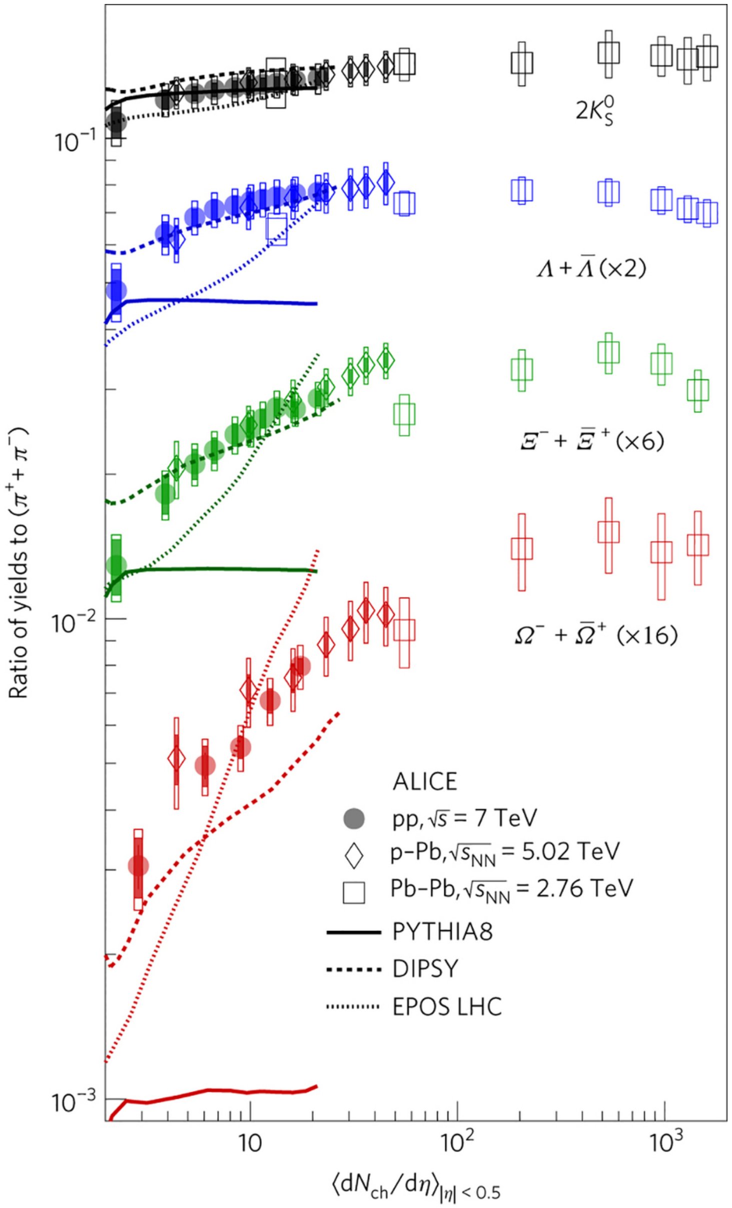


Experimental data – summary plot [38] J. Adam, et al (ALICE collaboration) Eur. Phys. J. C 75, 226 (2015)

Multi-strange production

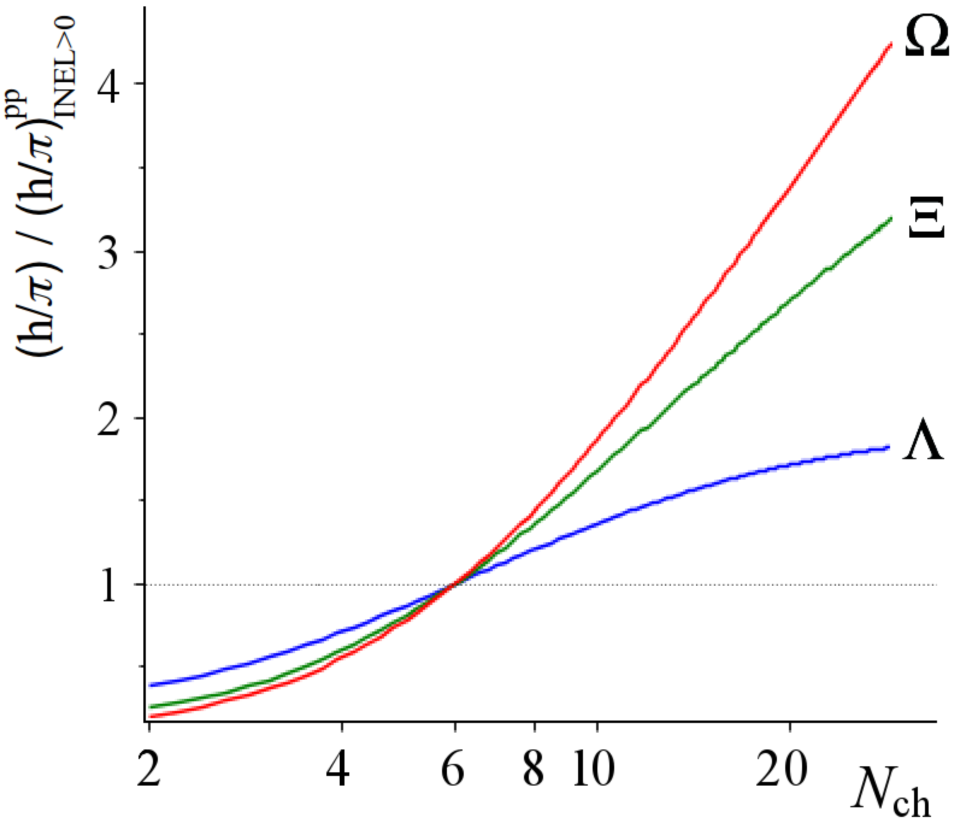


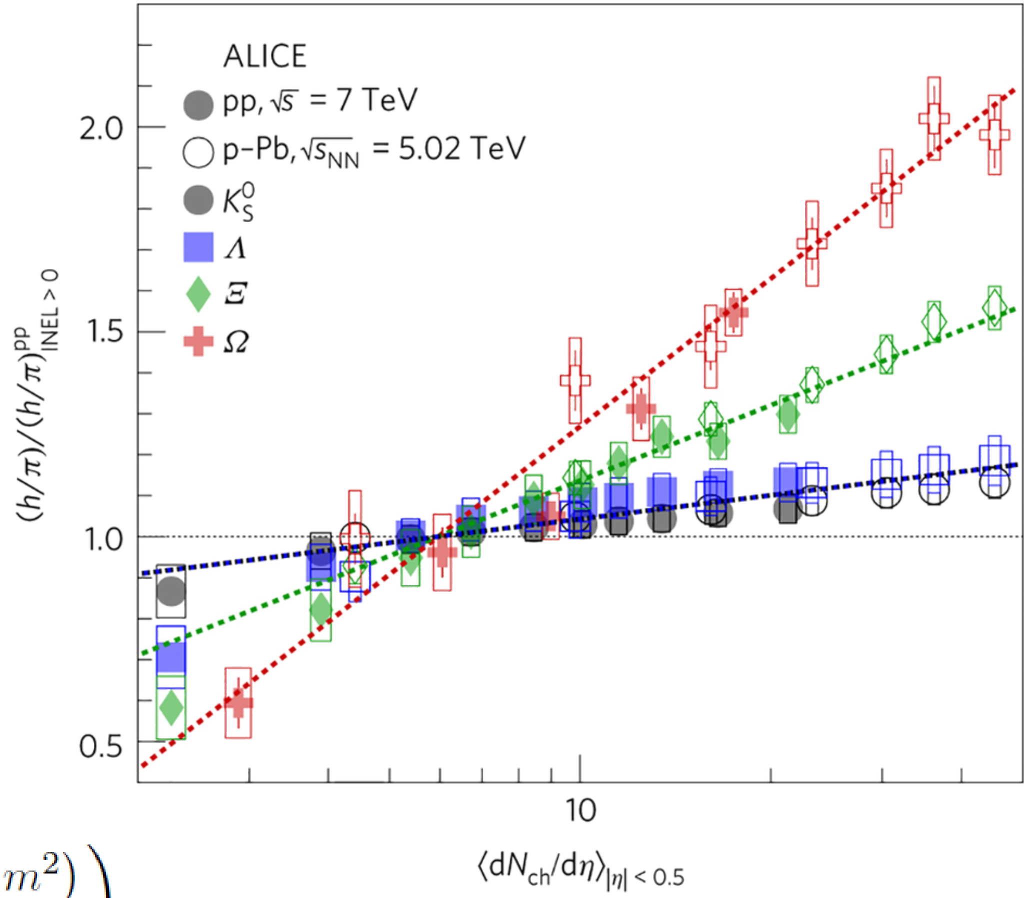
[36] G. Feofilov, V. Kovalenko, A. Puchkov, arXiv:1710.08895 [hep-ph]



[38] J. Adam, et al (ALICE Collaboration), Nature Physics 13, 535–539 (2017), arXiv:1606.07424 [nucl-ex]

Multi-strange production: relative yields





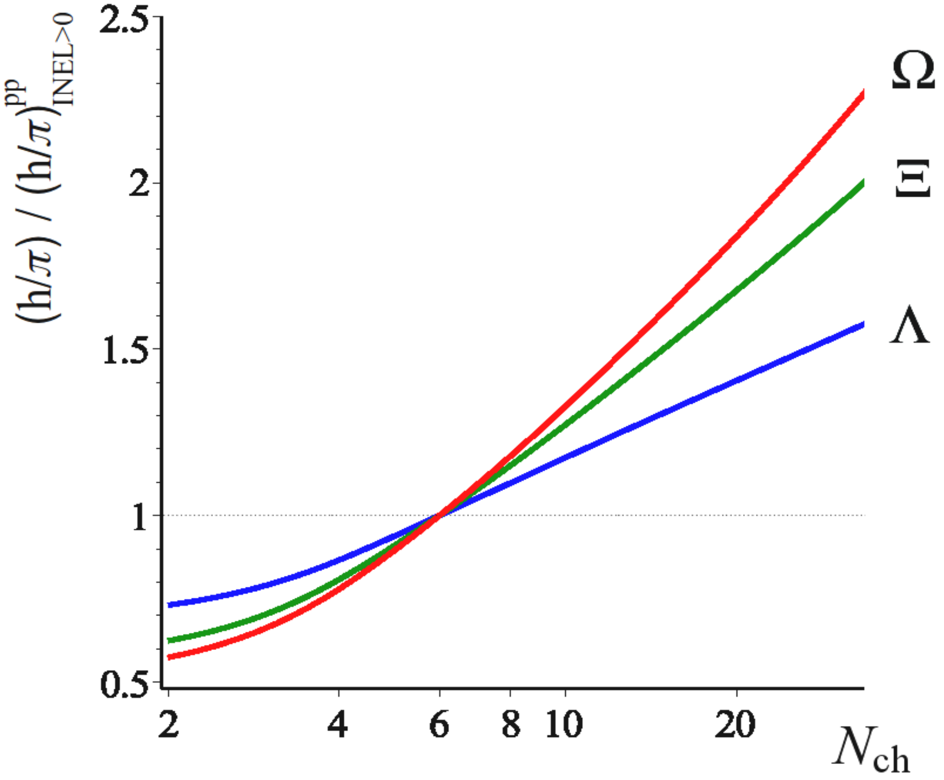
β=0.343

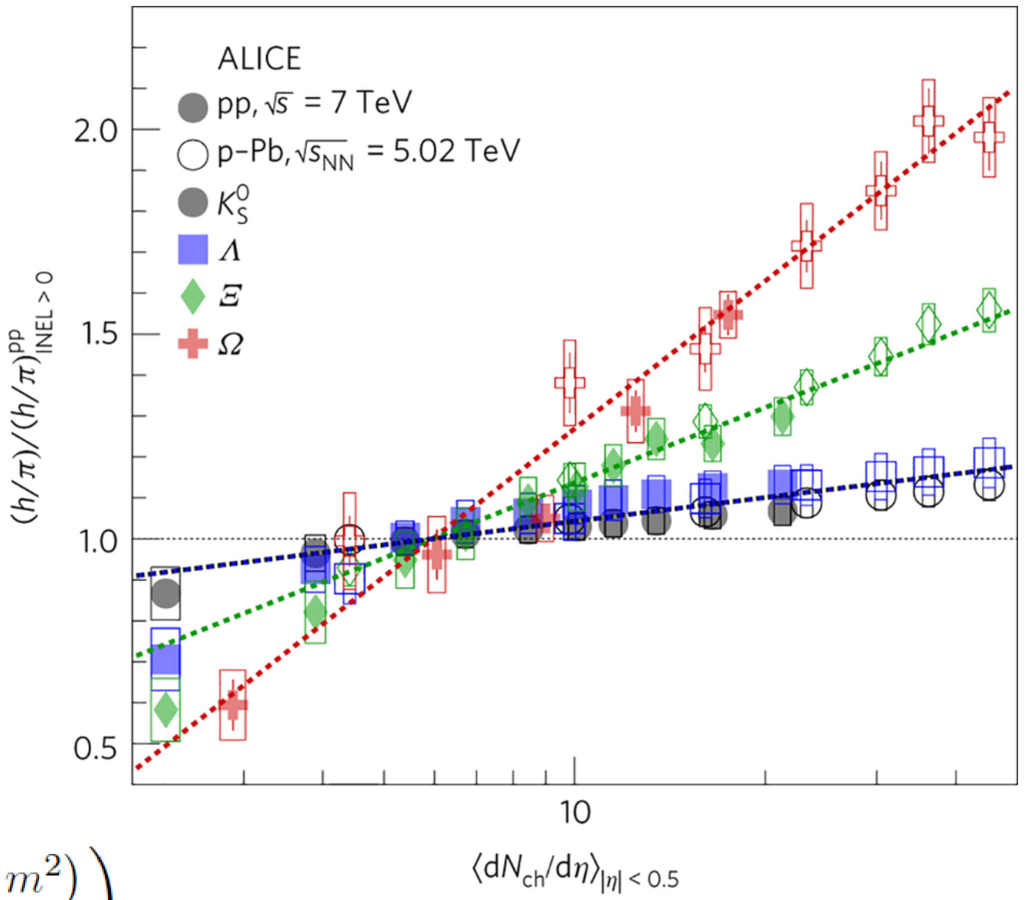
$$\left.\frac{dN_{ch}}{dy\,d^2p_T}\right|_{y=0} \sim \exp\left(\frac{-\pi\left(p_t^2+m^2\right)}{n^{\beta}t}\right)$$

[36] G. Feofilov, V. Kovalenko, A. Puchkov, arXiv:1710.08895 [hep-ph]

[38] J. Adam, et al (ALICE Collaboration), Nature Physics 13, 535–539 (2017), arXiv:1606.07424 [nucl-ex]

Multi-strange production: relative yields



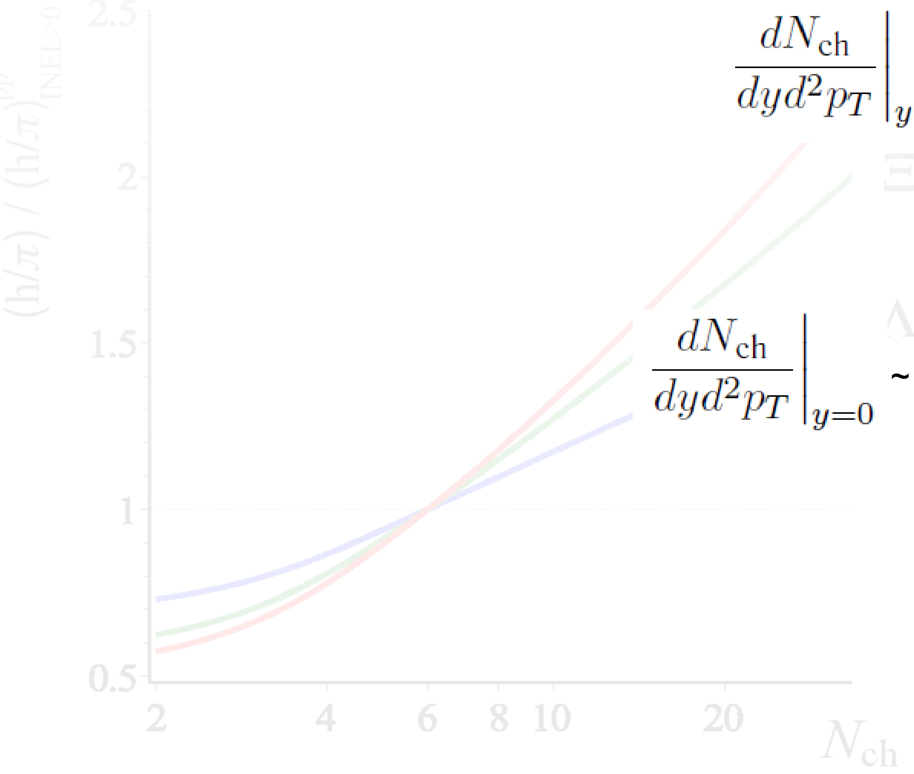


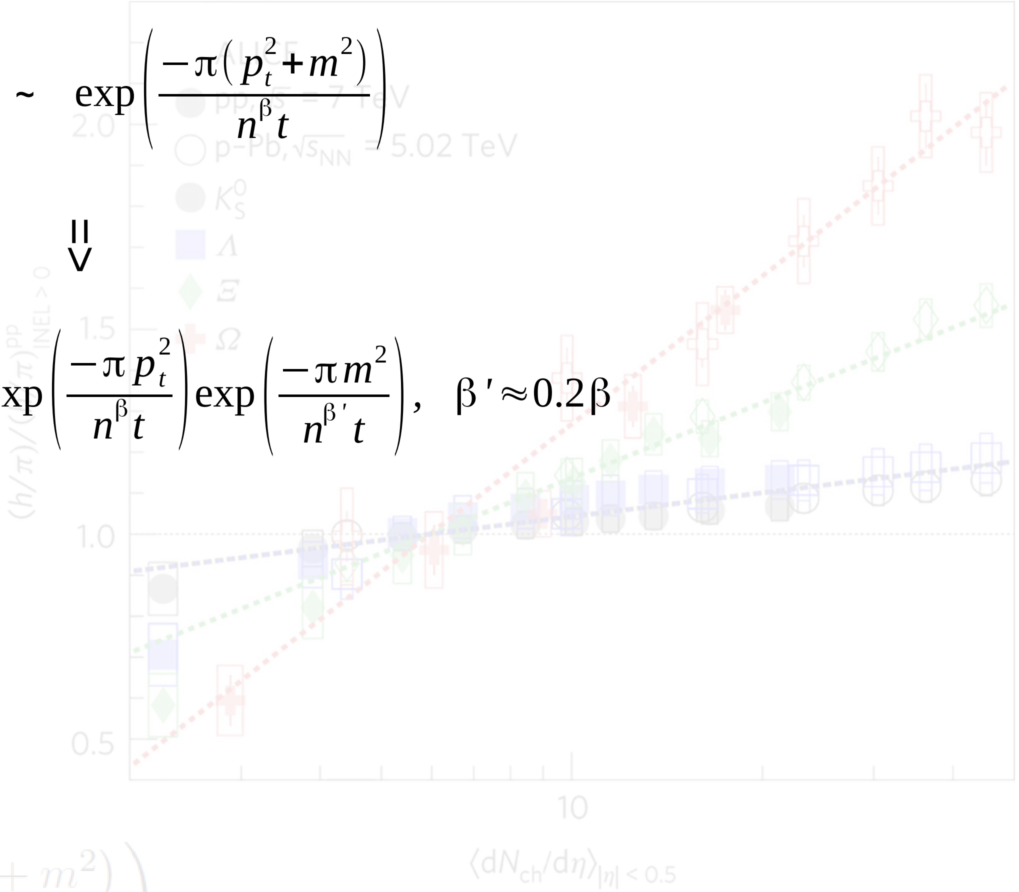
β=0.069

$$\left.\frac{dN_{\mathrm{ch}}}{dy\,d^2p_T}\right|_{y=0} \sim \exp\left(\frac{-\pi\,(p_t^2+m^2)}{n^\beta t}\right)$$

[38] J. Adam, et al (ALICE Collaboration), Nature Physics 13, 535–539 (2017), arXiv:1606.07424 [nucl-ex]

Multi-strange production: relative yields





$$\left.\frac{dN_{\rm ch}}{dy\,d^2p_T}\right|_{y=0} \sim \exp\left(\frac{-\pi\left(p_t^2+m^2\right)}{n^\beta t}\right)$$

$$\Downarrow$$

$$\left.\frac{dN_{\rm ch}}{dy\,d^2p_T}\right|_{y=0} \sim \exp\left(\frac{-\pi\, p_t^2}{n^\beta t}\right)\exp\left(\frac{-\pi\, m^2}{n^{\beta'} t}\right), \quad \beta'\approx 0.2\beta$$

β=0.069

- Possible other ways:
  - replace Gaussian function with exponential (thermal)
  - try to put quark masses instead of hadron masses
  - apply fully thermal model

ration), Nature Physics 13, 535–539 (2017), arXiv:1606.07424 [nucl-ex]

Summary and outlook

- String fusion mechanism allows to describe the multiplicity dependence of transverse momentum, strangeness enhancement, as well as many other collective features of pp, pA and AA collisions.
- There are several major mechanisms that contribute to the transverse momentum as a function of multiplicity:
  - Hardness of the elementary collision, responsible for the whole transverse momentum scale.
  - String collectivity (fusion), which multiplicatively enhances the $\langle p_T \rangle - N_{ch}$ correlation function.
  - In AA collisions - parton energy loss possibly.
- String collectivity effect, responsible for strangeness enhancement corresponds only part of the transverse momentum enhancement
- For more detailed study of these effects one should study extensively the correlations involving strangeness, transverse momentum, charges etc...