



## *String fusion effects at NICA energies*

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**Saint Petersburg State University**

### III NICA DAYS 2019

International scientific and engineering conference associated with the  
IVth MPD Collaboration Meeting

and

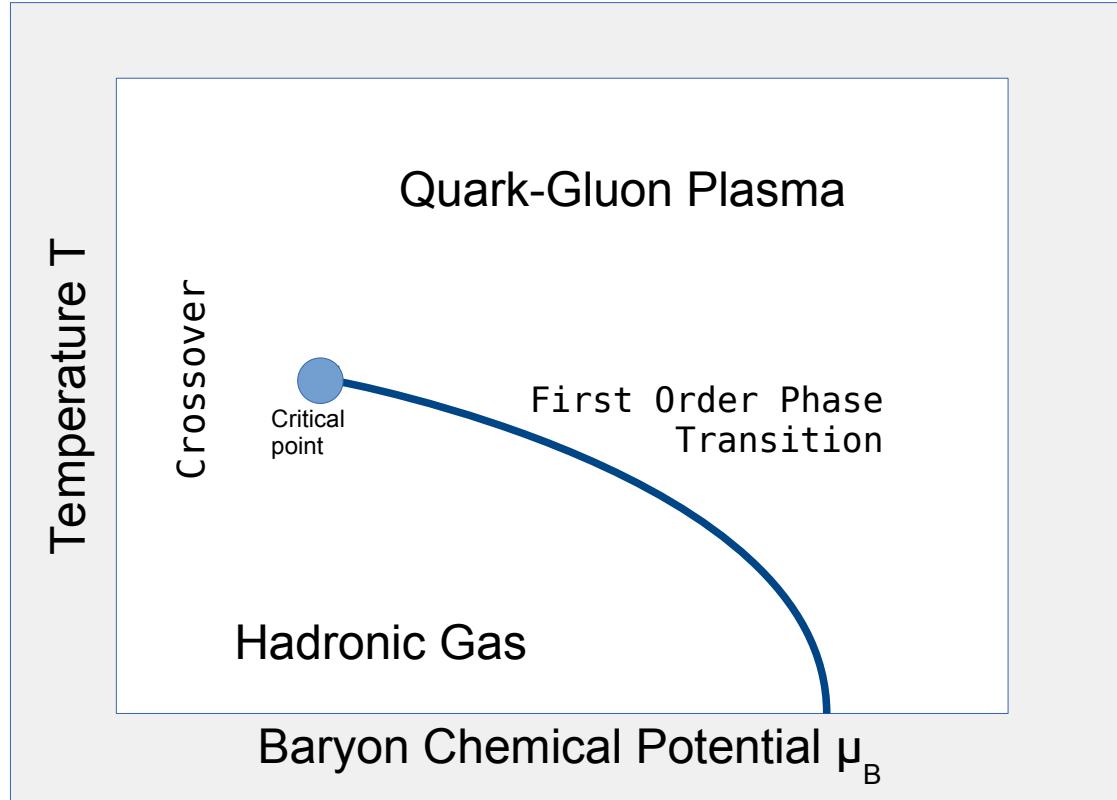
V Slow Control Warsaw 2019

**Warsaw University  
of Technology**



**21- 25 October 2019**

# QCD phase diagram and search for the critical point



$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-(2\mu_B)/T}$$

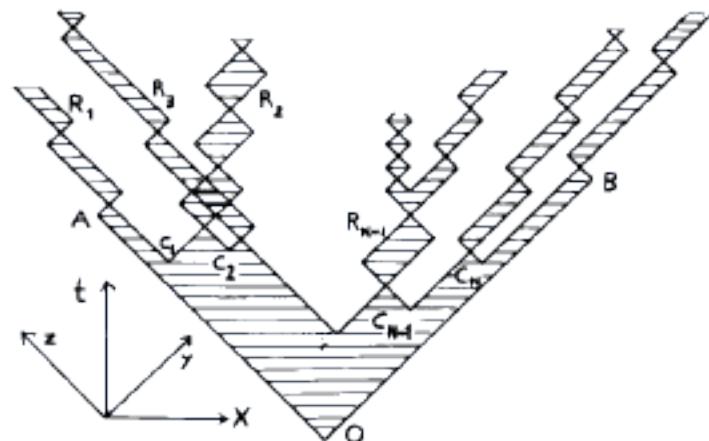
HADES, GSI	2.3 – 2.7 GeV	p+p, Au+Au, Ar+KCl, C+C
NA61, SPS, CERN	6.3 - 17.3 GeV	p+p, Be+Be, p+Pb, Ar+Ca, Xe+La, Pb+Pb, ...
CBM, FAIR, GSI	2.7 - 8.3 GeV	p, Ca, Au
RHIC BES	5 - 200 GeV	Au+Au
NICA, JINR	3 – 11 (-27) GeV	from p to Au

# QCD phase diagram studies at large baryon density

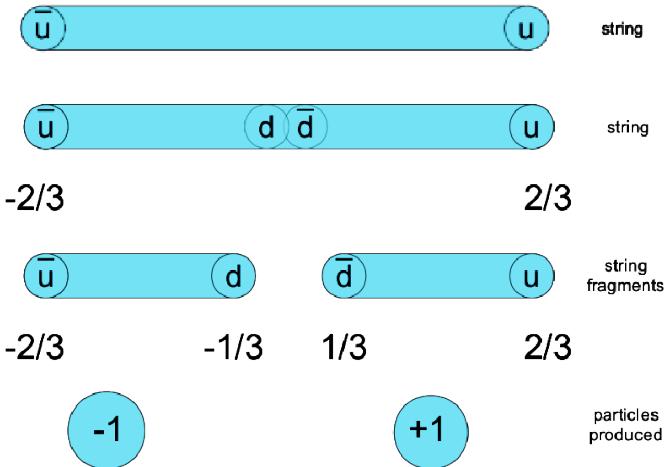
- MPD research program at NICA:  
exploration the QCD phase diagram at high baryon densities
- This includes:
  - the study of the equation-of-state of nuclear matter at high densities
  - search for the deconfinement and chiral phase transitions.
- A complex character of the evolution of a heavy-ion collision →  
it is required to study a number of experimental observables.
- The most sensitive observables, such as collective flow, correlations,  
fluctuations, require event-by event analysis. The major role plays here the  
predictions for these observables.
- Non-perturbative character of such phenomena requires  
semiphenomenological approaches
- Monte-Carlo simulations – the appropriate tool for correlation and  
fluctuation studies

# Strings – Overview

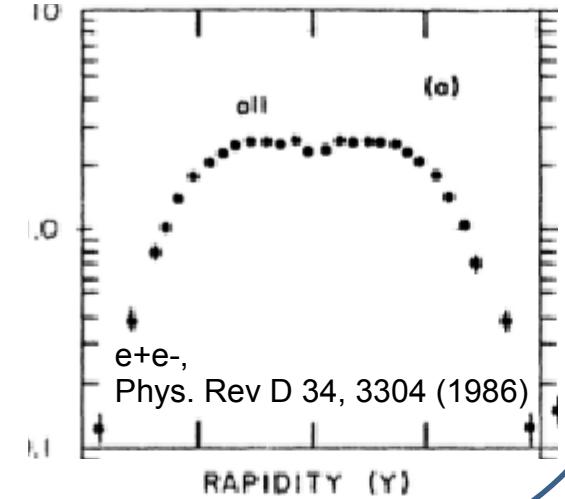
- The soft QCD processes is not described by usual perturbation theory
- The model of quark-gluon strings, stretched between projectile and target partons
  - semiphenomenological approach to the multiparticle production



X. Artru and G. Mennessier, Nucl Phys B 70 (1974) 93  
“String Model and Multiproduction”,



- Almost flat rapidity distribution from one string
- Independent particle production in each rapidity bin

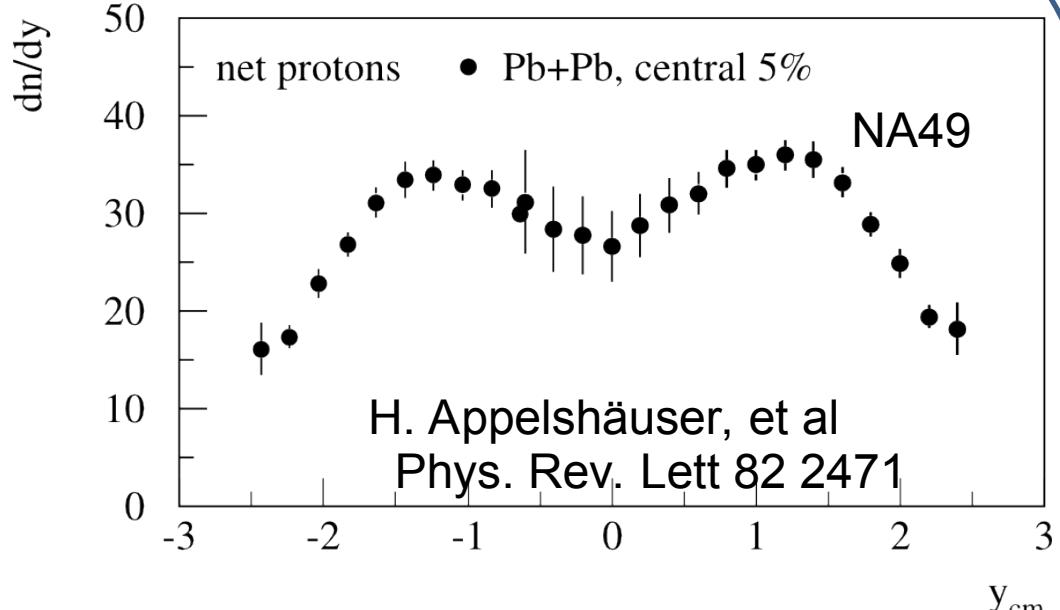
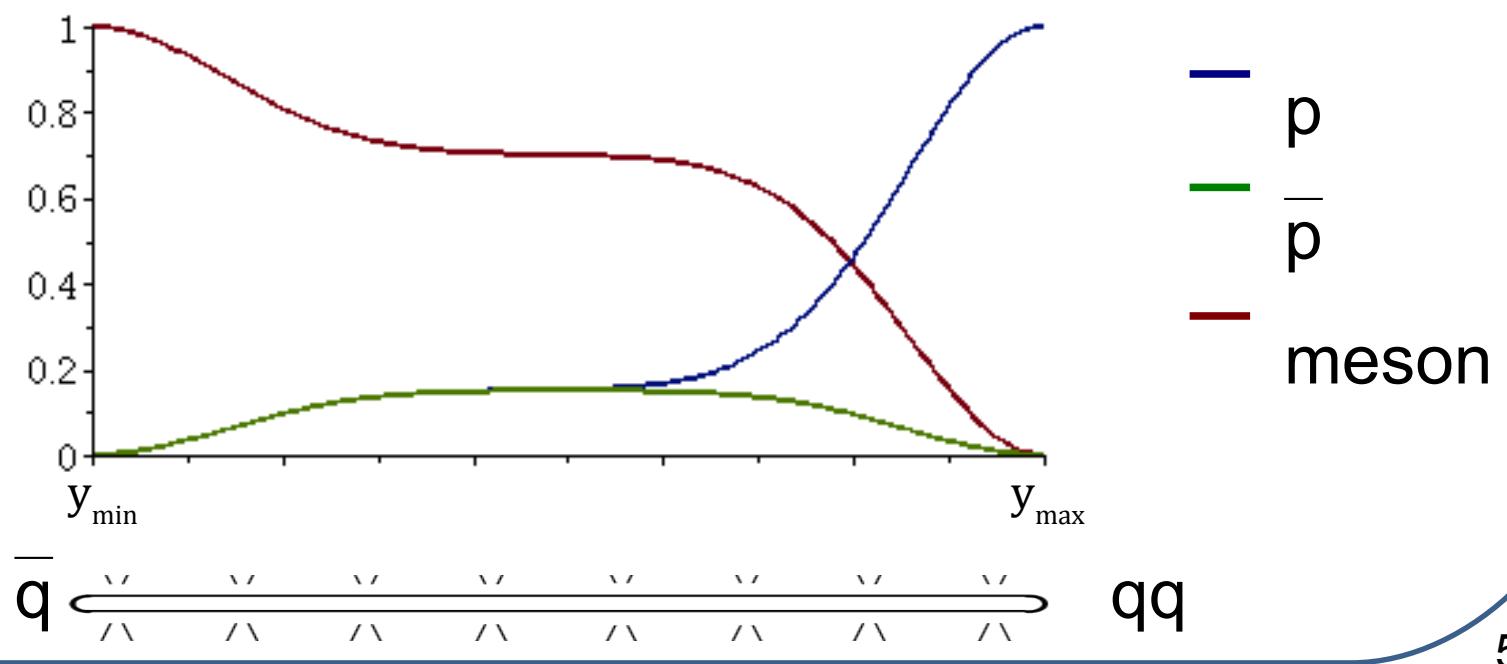


# String in rapidity space

$$\begin{aligned}\frac{\bar{p}}{p} &= \frac{e^{-(E+\mu_B)/T}}{e^{-(E-\mu_B)/T}} = \\ &= e^{-(2\mu_B)/T}\end{aligned}$$

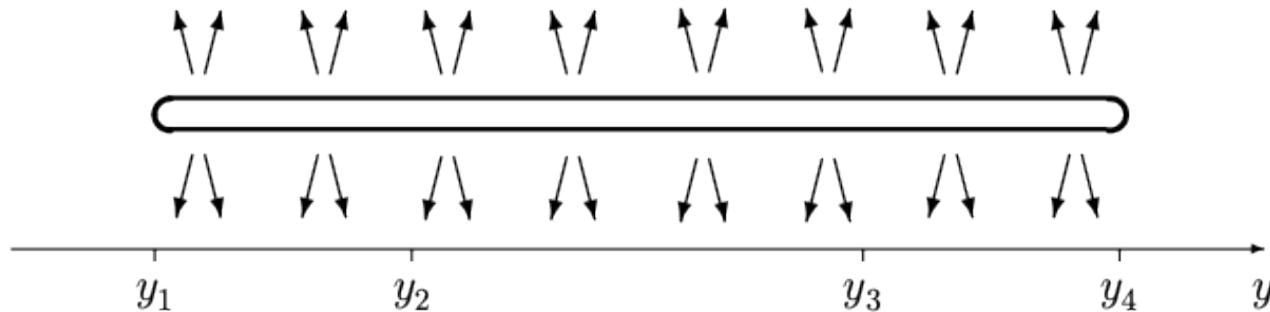
Valence string model

Particle composition from one string

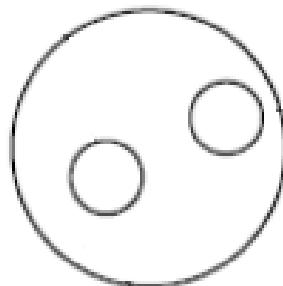
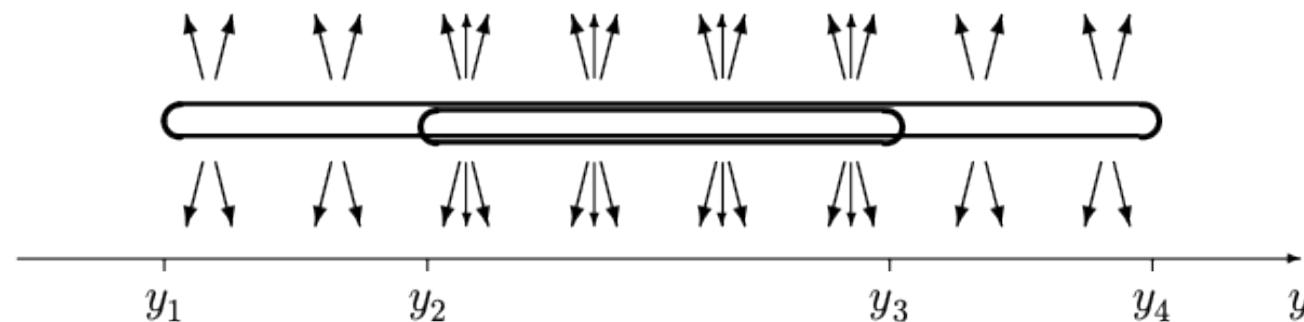


# String in rapidity space

- Each string is characterized by rapidity edges:  $y_{\min}$  to  $y_{\max}$
- Uniform rapidity distribution of produced charged particles from one string

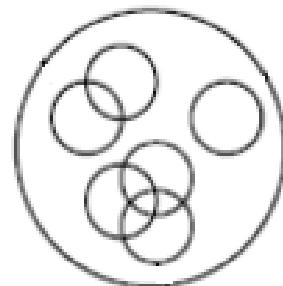


several strings can overlap

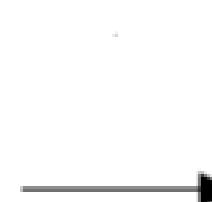


Multi-parton interactions  
heavy ions

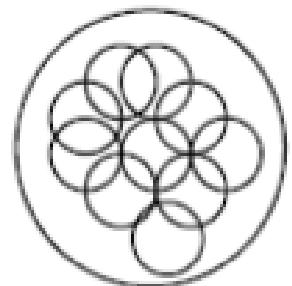
-->>>  $\text{sqrt}(s)$  increases -->>>



-->>>



-->>>



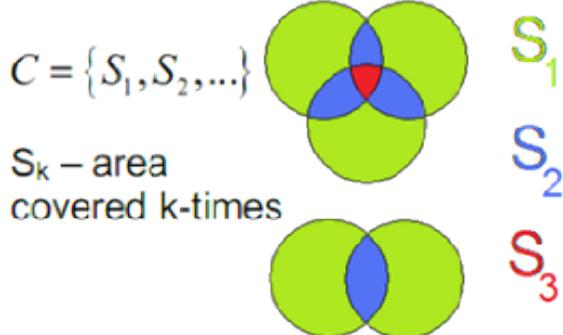
# String fusion

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

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

overlaps

SFM



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

$S_k$  – area, where  $k$  strings are overlapping,  $\sigma_0$  single string transverse area,  
 $\mu_0$  and  $p_0$  – mean multiplicity and transverse momentum from one string

M. A. Braun, C. Pajares, Nucl. Phys. B 390 (1993) 542.

M. A. Braun, R. S. Kolevatov, C. Pajares, V. V. Vechernin, Eur. Phys. J. C 32 (2004) 535.

N.S. Amelin, N. Armesto, C. Pajares, D. Sousa, Eur.Phys.J.C22:149-163 (2001), arXiv:hep-ph/0103060

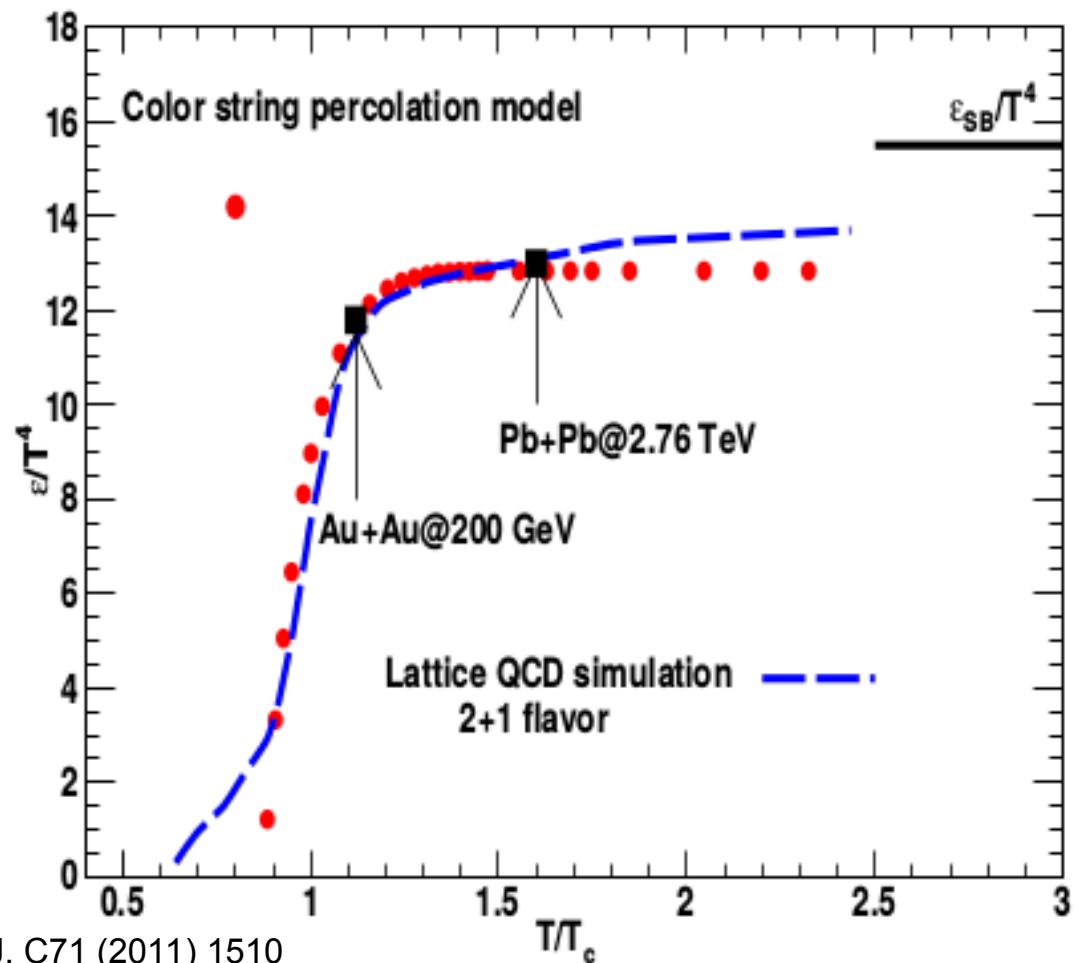
G. Ferreiro and C Pajares J. Phys. G: Nucl. Part. Phys. 23 1961 (1997)

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
- results are in a good agreement with the experiment

# String fusion

In the recent papers it was shown that the equation of state of QGP ( $\varepsilon/T^4$  as a function of  $T$ ) at zero chemical potential, obtained in the colour string percolation model is in a good agreement with the lattice results.

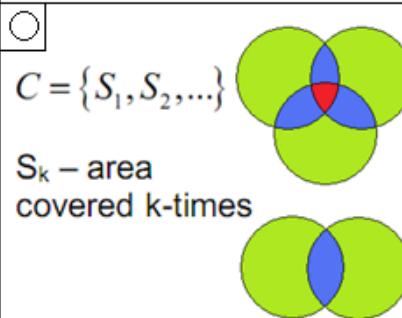
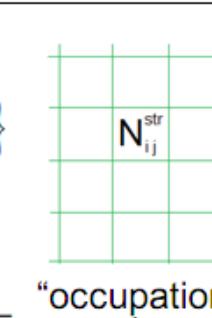


R.P. Scharenberg, B.K. Srivastava, A.S. Hirsch Eur.Phys.J. C71 (2011) 1510  
J. Dias de Deus , C. Pajares, Phys.Lett. B642 (2006) 455-458  
Brijesh K Srivastava, EP J Web of Conferences 70, 00032 (2014)

Hints of percolation transition & ridge effect...

# String fusion and finite rapidity strings

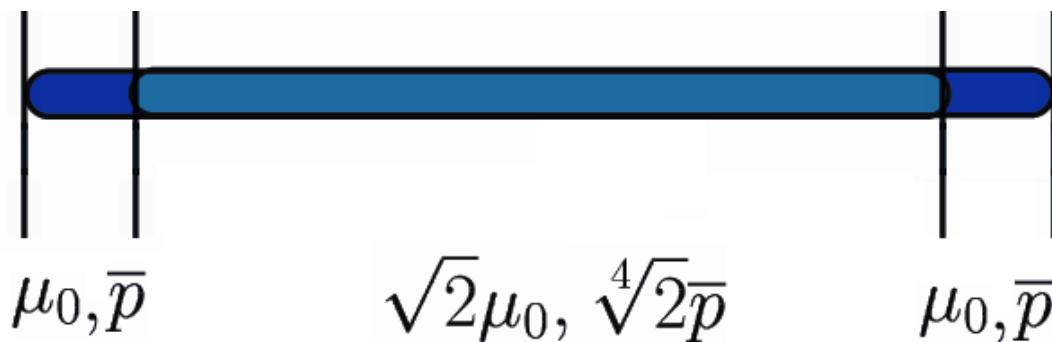
- The transverse coordinates of the centers of a string are equal to the arithmetic mean of corresponding transverse coordinates of the partons at the ends of strings
- The cellular option for string fusion is applied

	"overlaps" (local fusion)	"overlaps" (local fusion)
SFM	 <p> <math>C = \{S_1, S_2, \dots\}</math>  <math>S_k</math> – area covered k-times         </p>	 <p> <math>C = \{N_{ij}^{str}\}</math>  <math>k_{ij} = N_{ij}^{str}</math> – "occupation" numbers         </p>

V. V. Vechernin and R. S. Kolevatov, Vestn. SPb. Univ., Ser. Fiz. Khim., No. 2, 12 (2004); hep-ph/0304295.

V. V. Vechernin and R. S. Kolevatov, Vestn. SPb. Univ., Ser. Fiz. Khim., No. 4, 11 (2004); hep-ph/0305136.

- Separate processing of the rapidity intervals with different (but integer) number of rapidity strings



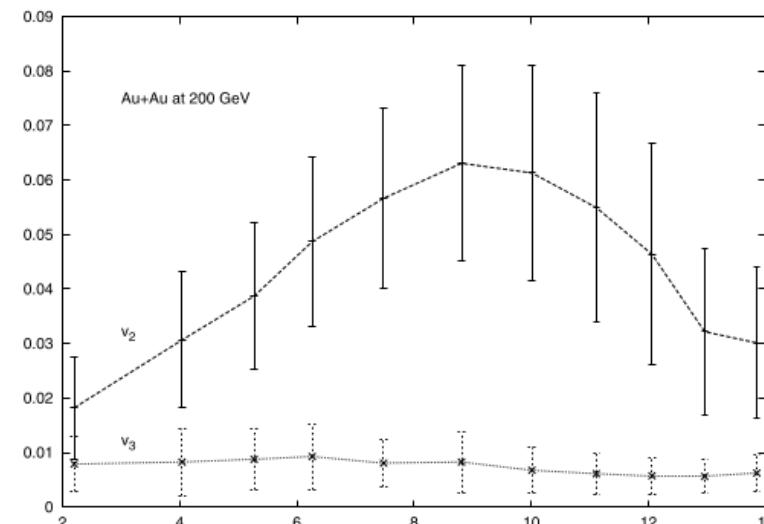
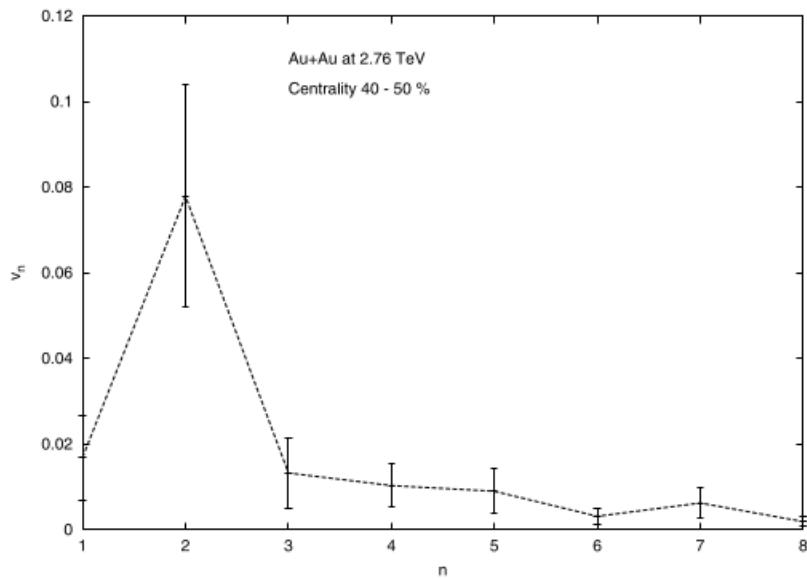
# Anisotropic flow from strings

A string fusion approach could be naturally applied for the description of the azimuthal anisotropy of particle production [1,2]

The quenching of particles travelling through the clusters of fused strings leads to non-zero flow coefficients ( $v_n$ )

The momentum loss:

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

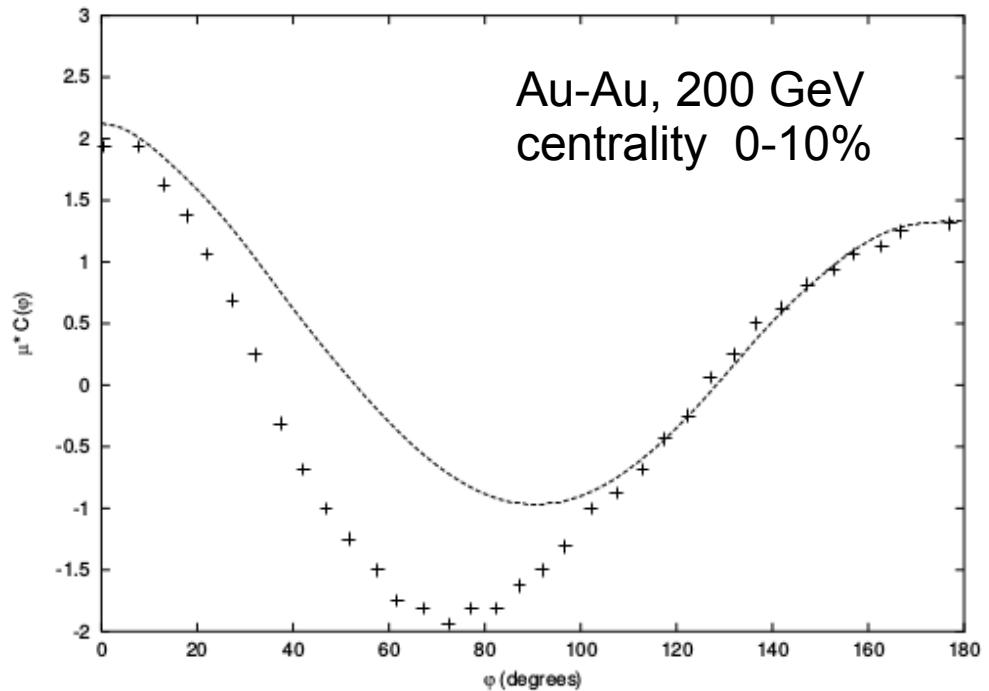
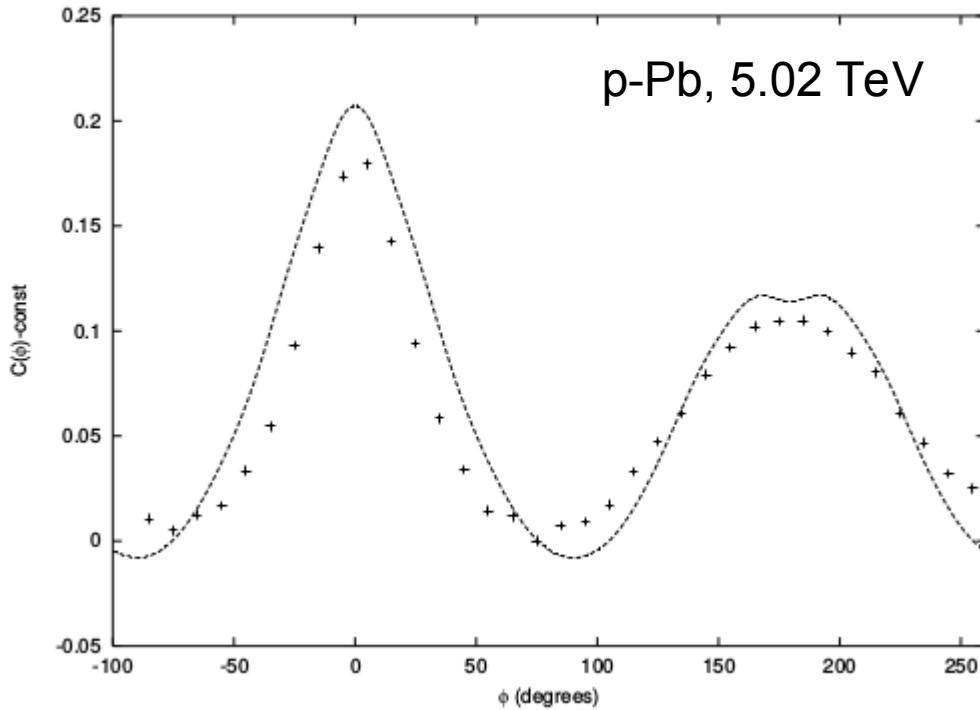


[1] M.A. Braun, C. Pajares, Eur. Phys. J. C 71 (2011) 1558.

[2] M.A. Braun, C. Pajares, V.V. Vechernin, Nuclear Physics A 906 (2013) 14–27  
10

# Ridge from strings

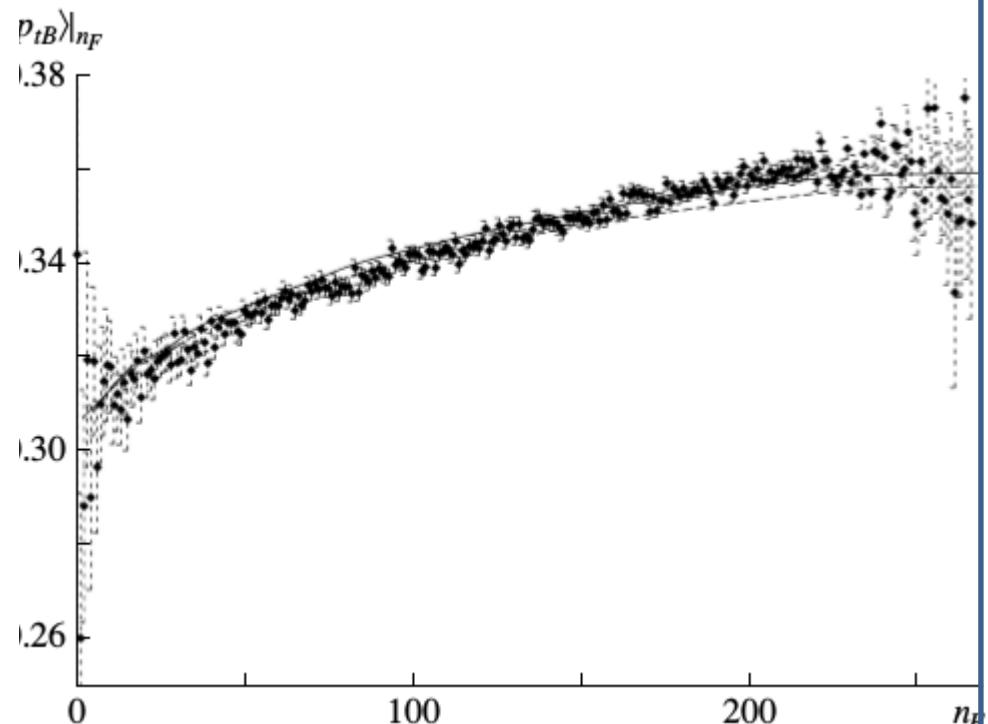
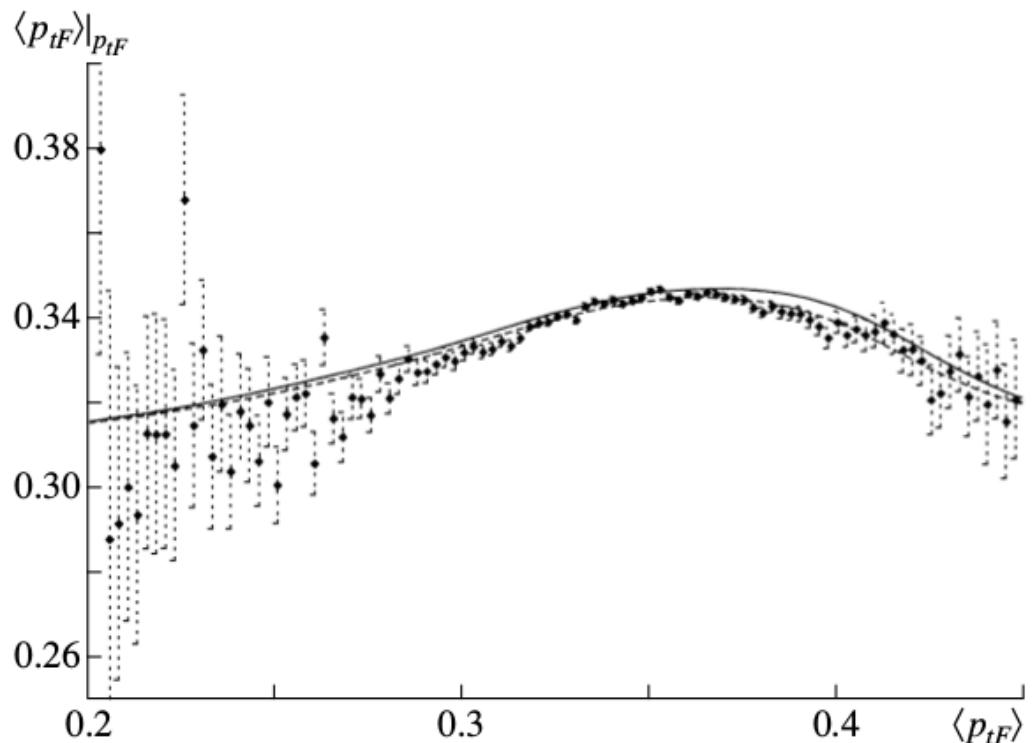
The approach allows also the calculation of ridge-like correlations



[3] M.A. Braun, C. Pajares, V.V. Vechernin, arXiv:1407.4590 [hep-ph]

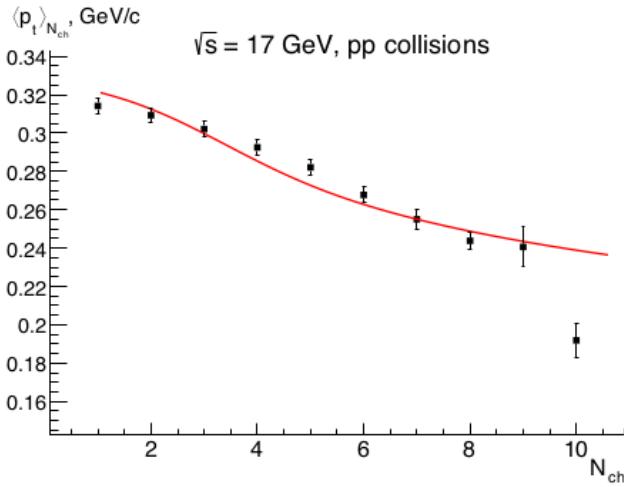
# Correlation functions at SPS energies

- pt-pt and pt-n correlations in Pb-Pb collisions at the SPS (NA49 data)  
lines - calculations in string fusion model



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

# Multi-pomeron model at SPS - NICA energies



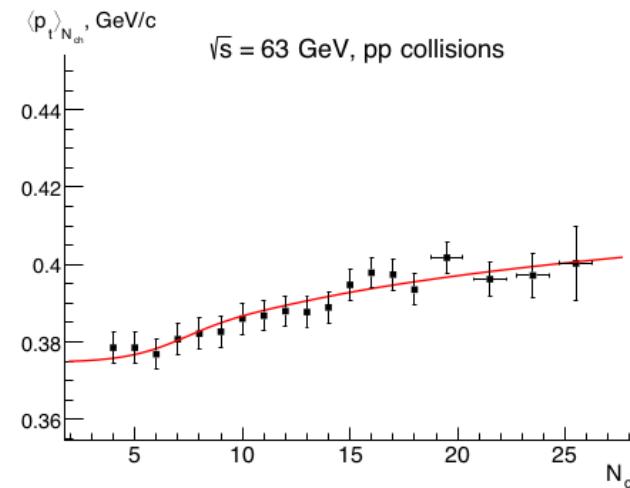
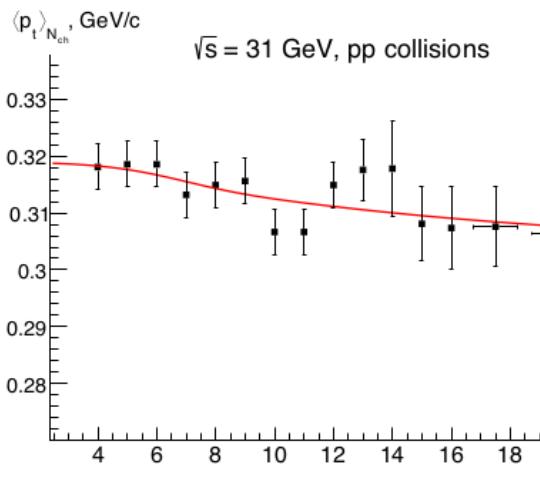
$$\begin{aligned} \rho(N_{ch}, p_t) &= \\ &= \frac{C_w}{z} \sum_{n=1}^{\infty} \frac{1}{n} \left( 1 - \exp(-z) \sum_{l=0}^{n-1} \frac{z^l}{l!} \right) \times \\ &\quad \times \exp(-2nk\delta) \frac{(2nk\delta)^{N_{ch}}}{N_{ch}!} \times \\ &\quad \times \frac{1}{n^{\beta} t} \exp\left(-\frac{\pi p_t^2}{n^{\beta} t}\right) \end{aligned}$$

Probability distribution

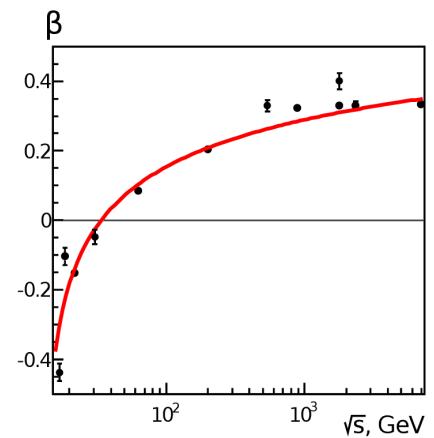
Probability of production  
of  $n$  pomerons

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

Modified Schwinger  
mechanism



E. Bodnia, et al, PoS(QFTHEP 2013)060



# Multi-pomeron model at SPS - NICA energies: strongly-intensive PT-n measure

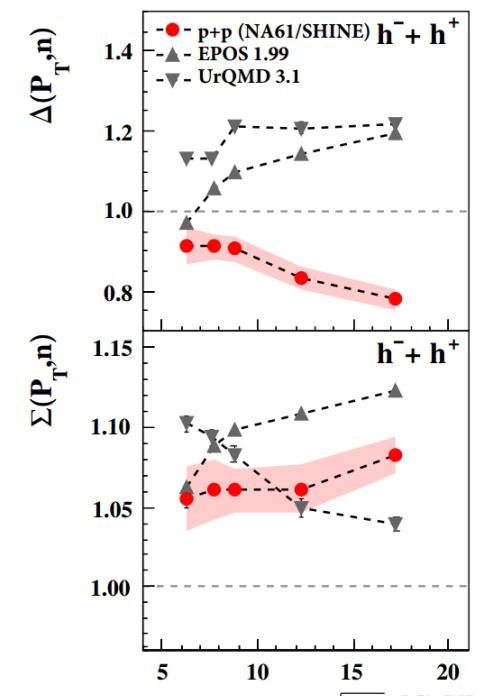
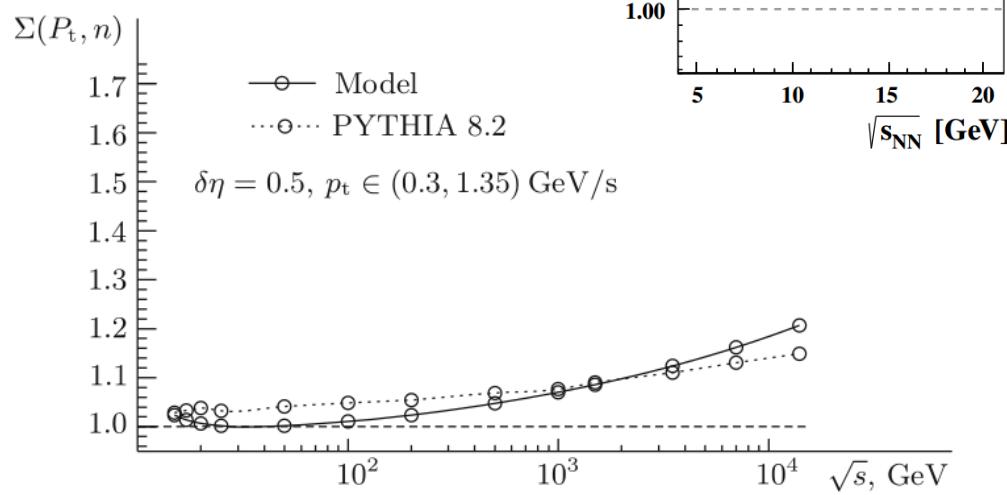
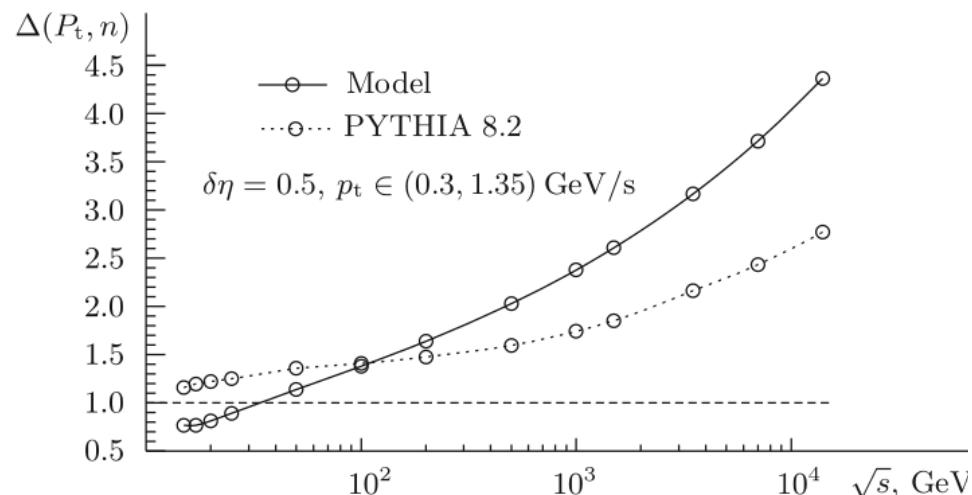
$$\Delta(P_T, n) = \frac{1}{\omega[p_T]\langle n \rangle} (\langle n \rangle \omega[P_T] - \langle P_T \rangle \omega[n])$$

$$\Sigma(P_T, n) = \frac{1}{\omega[p_T]\langle n \rangle} (\langle n \rangle \omega[P_T] + \langle P_T \rangle \omega[n] - 2\text{cov}(P_T, n))$$

$$\text{where } P_T = \sum_{i=1}^N p_{Ti}$$

$n$  - multiplicity of charged hadrons in an experimental acceptance

$\omega[p_T] = \frac{\overline{p_T^2} - \overline{p_T}^2}{\overline{p_T}}$  - scaled variance of inclusive  $p_T$  distribution



E. Andronov, V. Kovalenko, Theor. Math. Phys 200 (2019) 1282–1293

# Monte Carlo model with string fusion

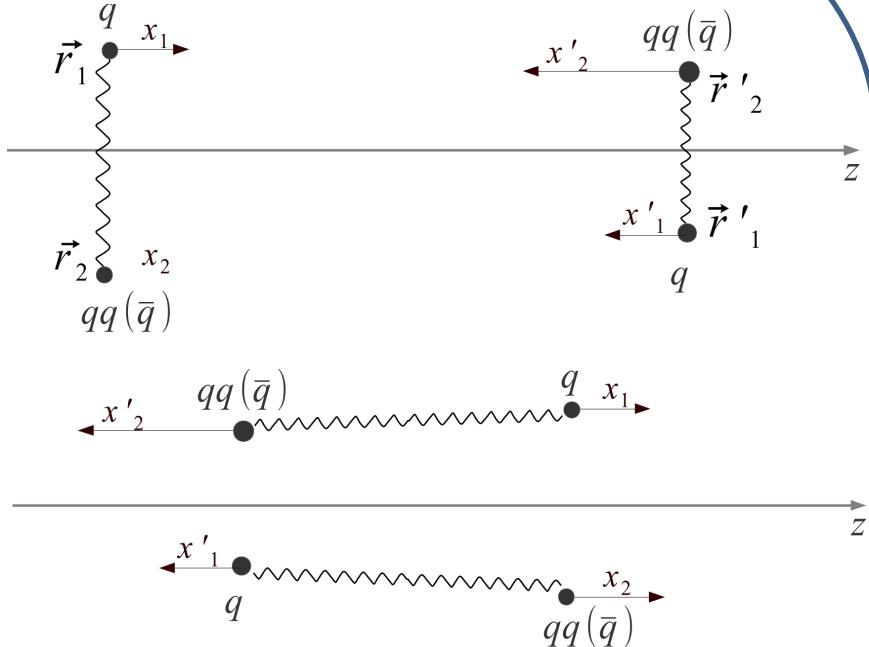
- Inclusive momentum distributions are taken from [1,2]:

$$\begin{aligned} f_u(x) &= f_{\bar{u}}(x) = C_{u,n} x^{-\frac{1}{2}} (1-x)^{\frac{1}{2}+n}, \\ f_d(x) &= f_{\bar{d}}(x) = C_{d,n} x^{-\frac{1}{2}} (1-x)^{\frac{3}{2}+n}, \\ f_{ud}(x) &= C_{ud,n} x^{\frac{3}{2}} (1-x)^{-\frac{3}{2}+n}, \\ f_{uu}(x) &= C_{uu,n} x^{\frac{5}{2}} (1-x)^{-\frac{3}{2}+n}. \end{aligned}$$

- At  $n>1$  the sea quarks and antiquarks have the same inclusive distribution as the valence quarks.
- Poisson distribution for the number of quark-antiquark (diquark) pairs is assumed with some parameter  $\lambda$
- The rapidity string edges  $y_{\min}, y_{\max}$  are determined by parton momentum fractions  $x_i$  and defined from a kinematic condition of a decay to at least two particles

[1] A.B. Kaidalov, O.I. Piskunova, Zeitschrift fur Physik C 30(1):145-150, 1986

[2] G.H. Arakelyan, A. Capella, A.B. Kaidalov, and Yu.M. Shabelski, Eur. Phys. J. C, 26(1):81-90, 2002



V. N. Kovalenko, Phys. Atom. Nucl. 76, 1189 (2013),  
arXiv:1211.6209 [hep-ph]

V. Kovalenko, V. Vechernon, PoS (Baldin ISHEPP XI)

V. Kovalenko, PoS (QFTHEP 2013) 052 (2013).

- Dipole approach for partonic picture of a nucleon in the transverse plane – Muller dipole model
  - The probability amplitude of the elementary interaction depends on transverse coordinates:

$$f = \frac{\alpha_s^2}{2} \left[ K_0 \left( \frac{|\vec{r}_1 - \vec{r}'_1|}{r_{max}} \right) + K_0 \left( \frac{|\vec{r}_2 - \vec{r}'_2|}{r_{max}} \right) - K_0 \left( \frac{|\vec{r}_1 - \vec{r}_2'|}{r_{max}} \right) - K_0 \left( \frac{|\vec{r}_2 - \vec{r}_1'|}{r_{max}} \right) \right]^2$$

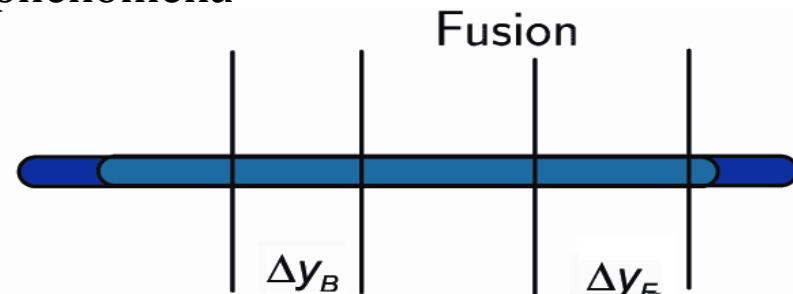
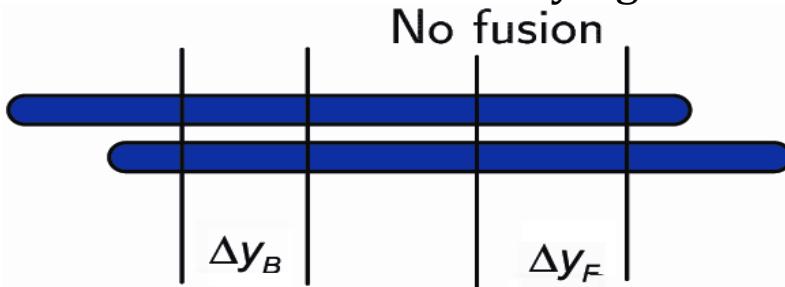
where  $K_0$  is modified Bessel function.

[3] G. Gustafson, Acta Phys. Polon. B40, 1981 (2009)

[4] C. Flensburg, G. Gustafson, and L. Lonnblad, Eur. Phys. J. (C) 60, 233 (2009)

# Long-range correlations

- Sensitive tool for studying of string fusion phenomena



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

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

Select 2 variables  
in windows:

$$F, B = \begin{cases} N_{ch} & - \text{number of charged particles in the window} \\ p_t = \frac{1}{n} \sum_{i=1}^n p_{ti} & - \text{mean (in the event!) transverse} \\ & \text{momentum of charged particles in} \\ & \text{the given window} \end{cases}$$



Three types of correlation coefficients:

n-n , pt-n, pt-pt

correlation  
function

$$f(F) = \langle B \rangle_F$$

correlation  
coefficient

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

# Forward-backward correlation coefficients and strongly intensive variable

*Long-range n-n, pt-n, pt-pt correlations b*

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

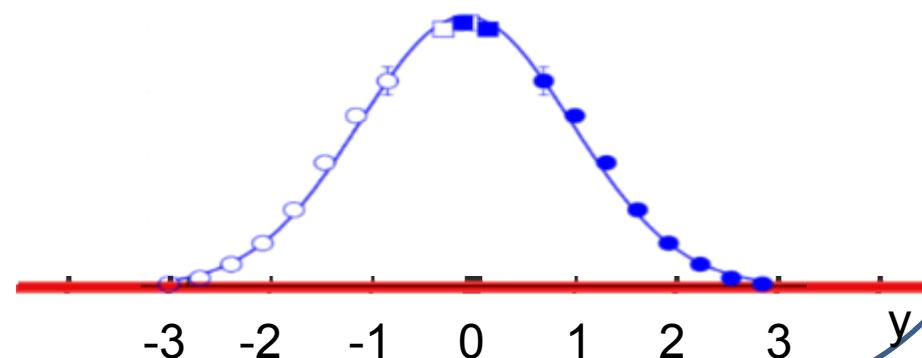
*Strongly intensive fluctuations  $\Sigma, \Delta$*

$$\Sigma[n_F, n_B] = \frac{\langle n_B \rangle \omega[n_F] + \langle n_F \rangle \omega[n_B] - 2(\langle n_B n_F \rangle - \langle n_B \rangle \langle n_F \rangle)}{\langle n_B \rangle + \langle n_F \rangle}$$

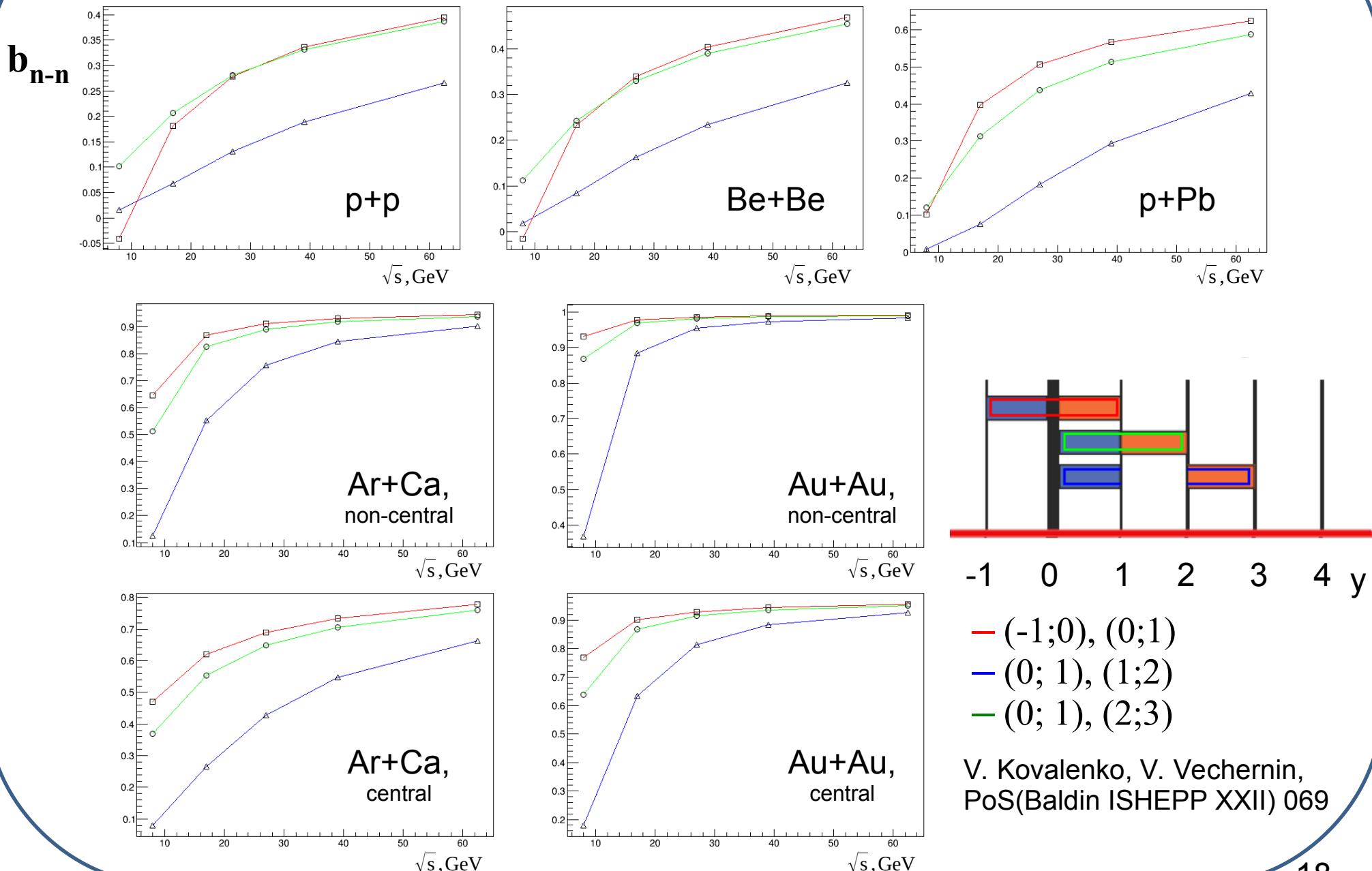
$$\Delta[A, B] = \frac{1}{C_\Delta} (\langle B \rangle \omega[A] - \langle A \rangle \omega[B])$$

*Rapidity range*  
midrapidity, forward rapidity

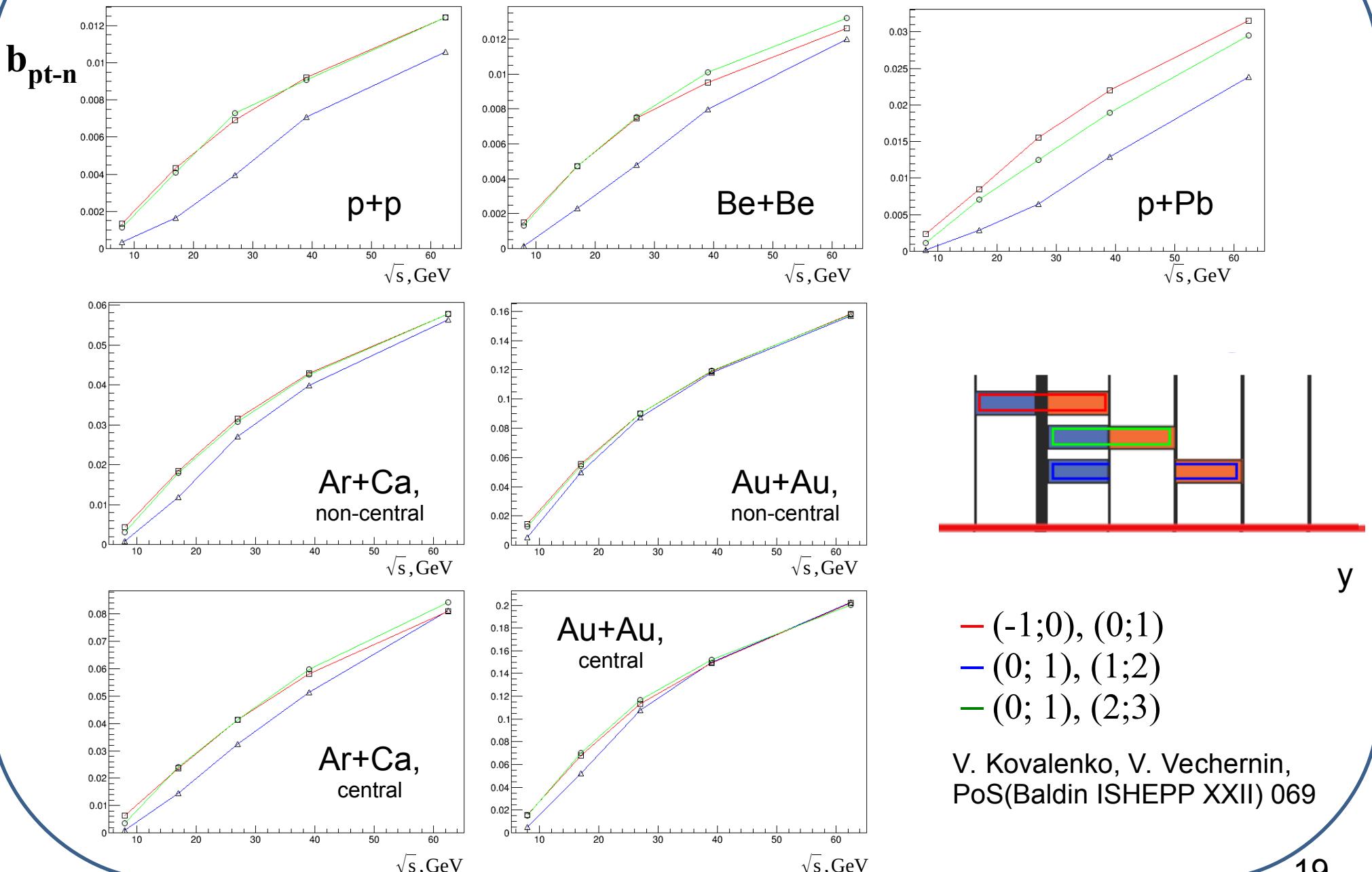
E.V.Andronov,  
Theor. Math. Phys. 185, 1383 (2015)



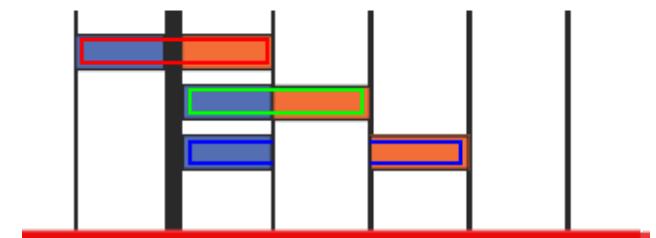
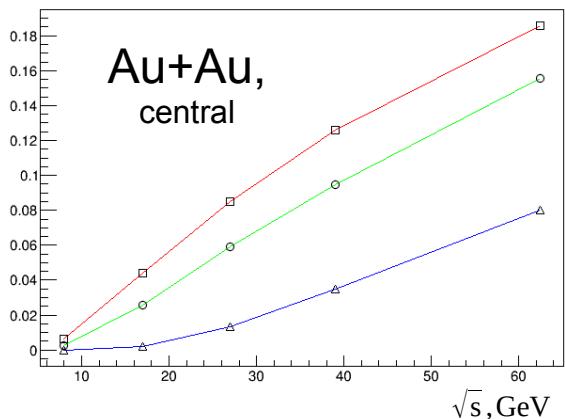
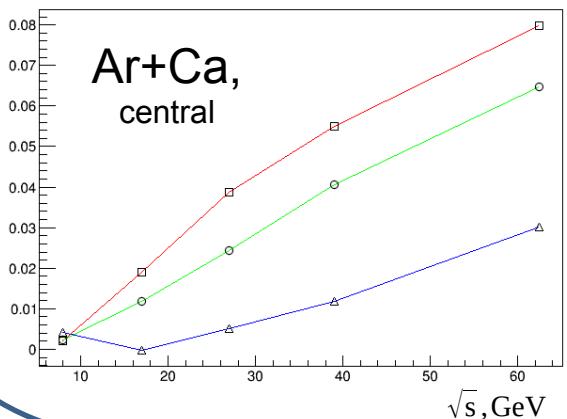
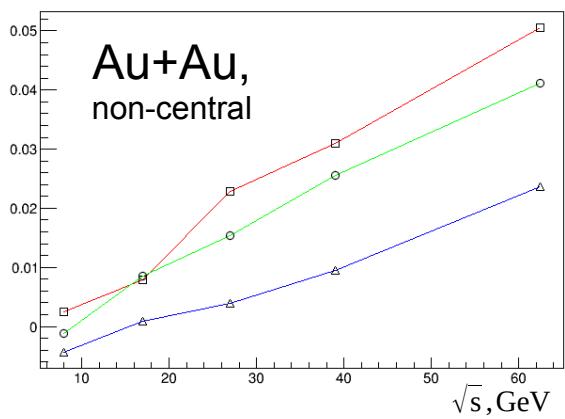
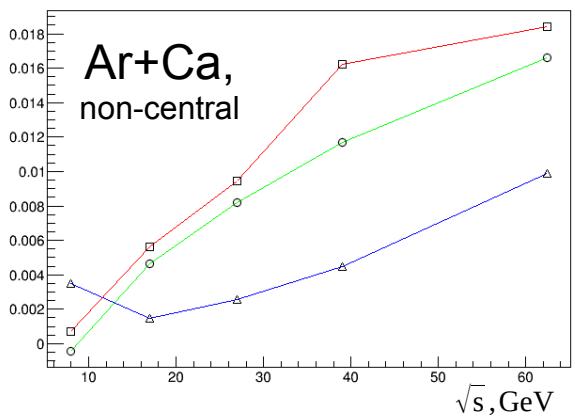
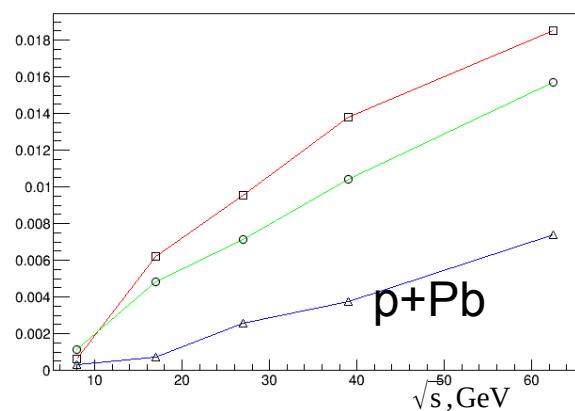
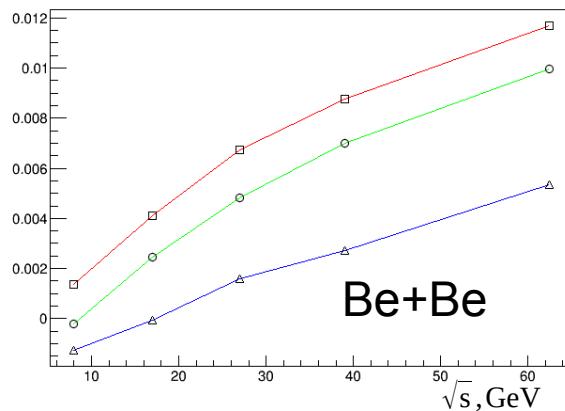
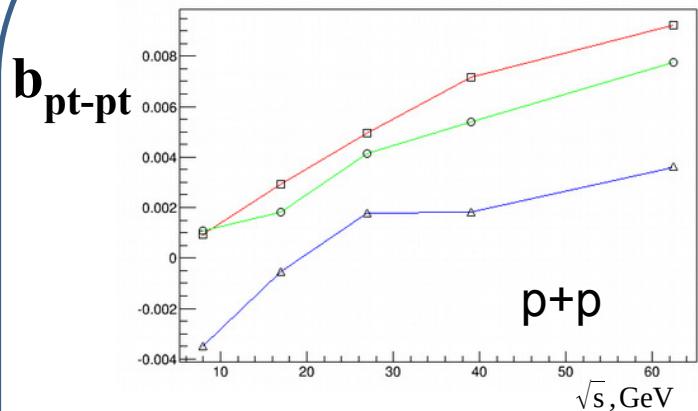
# n-n correlation coefficient in MC model with string fusion



# pt-n correlation coefficient in MC model with string fusion



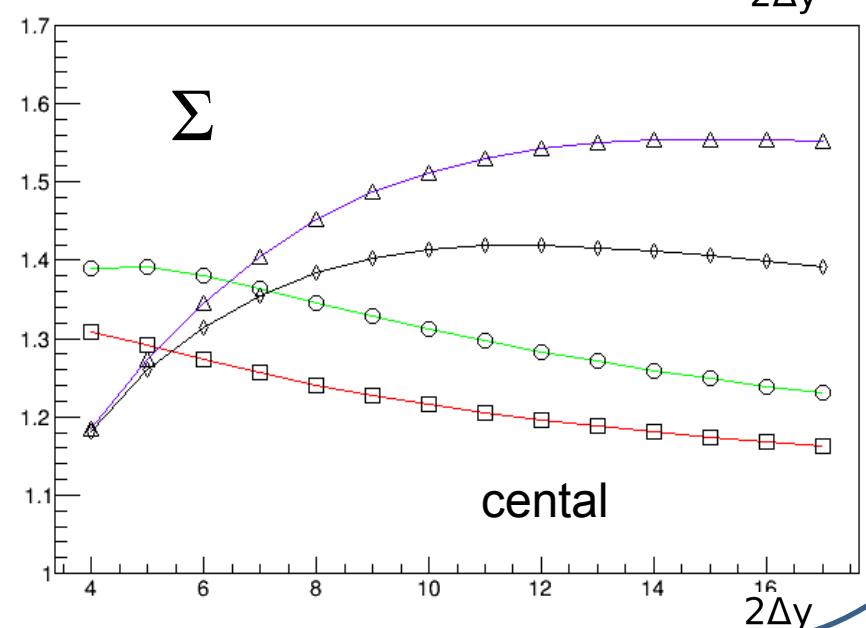
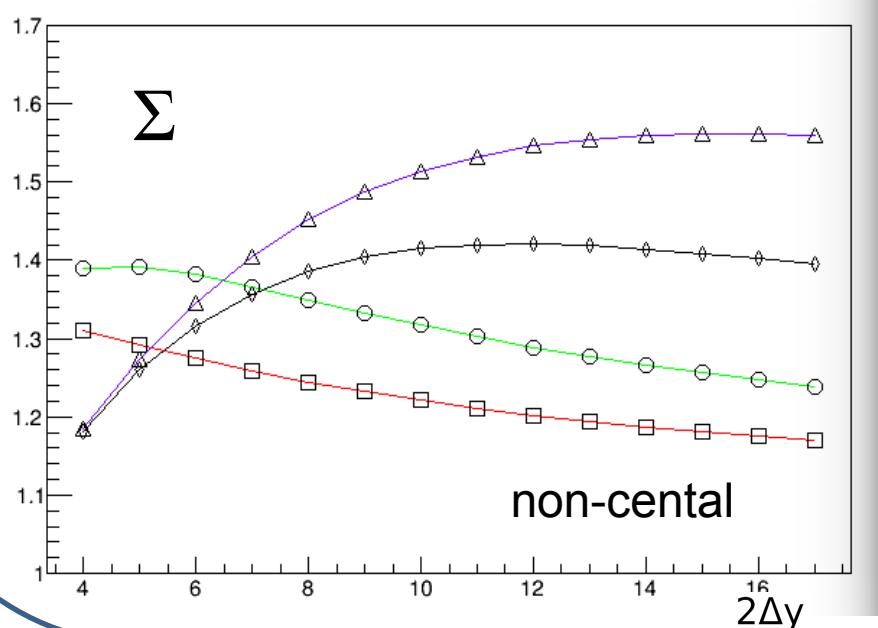
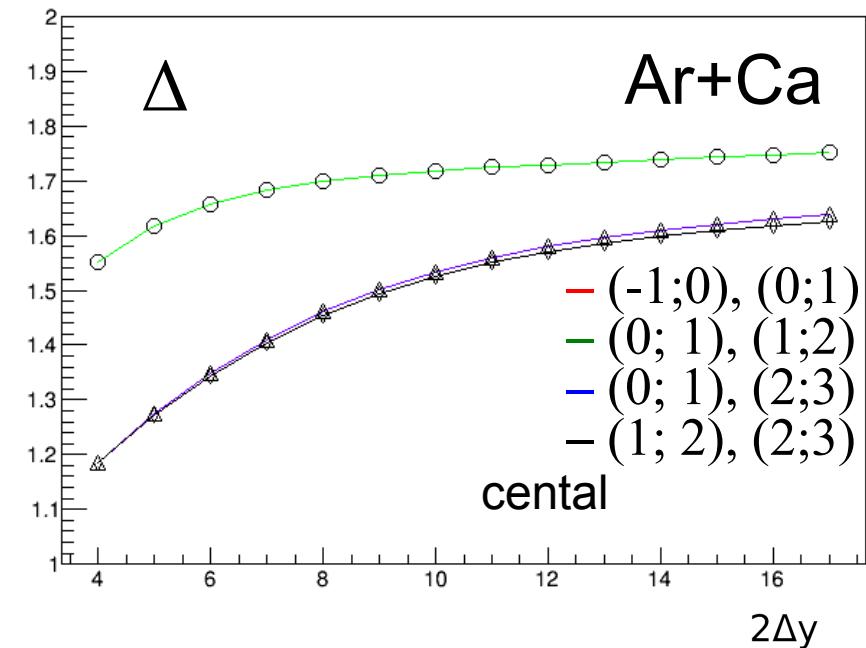
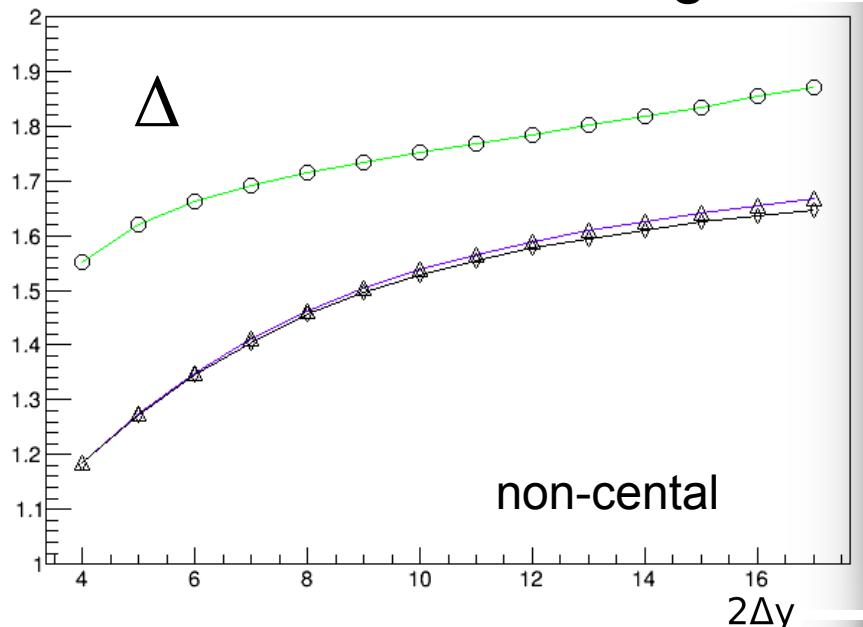
# pt-pt correlation coefficient in MC model with string fusion



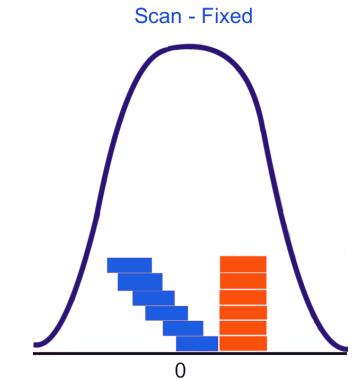
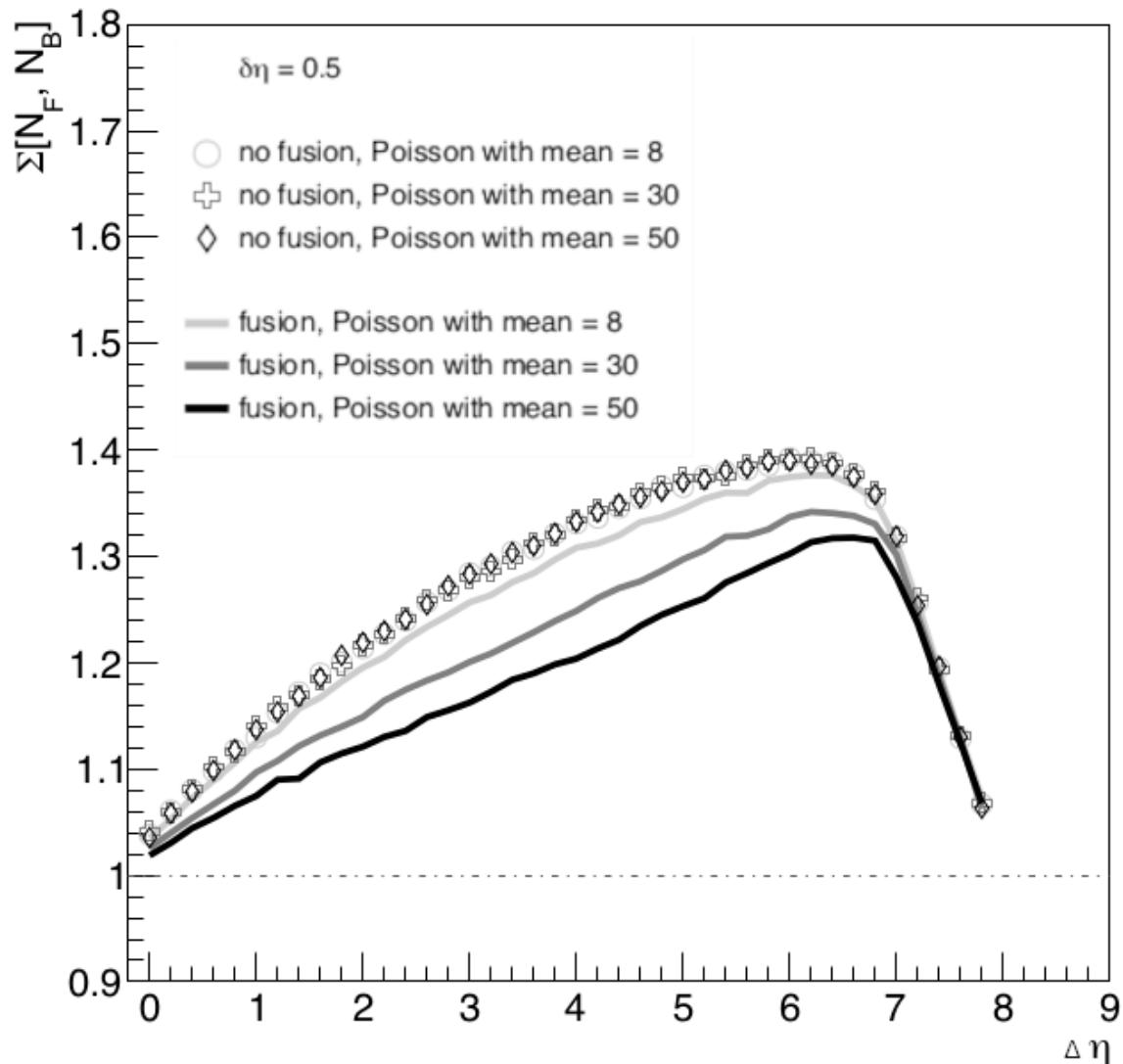
- (-1;0), (0;1)
- (0; 1), (1;2)
- (0; 1), (2;3)

V. Kovalenko, V. Vechernin,  
PoS(Baldin ISHEPP XXII) 069

# Forward-backward multiplicity strongly intensive fluctuations in MC model with string fusion



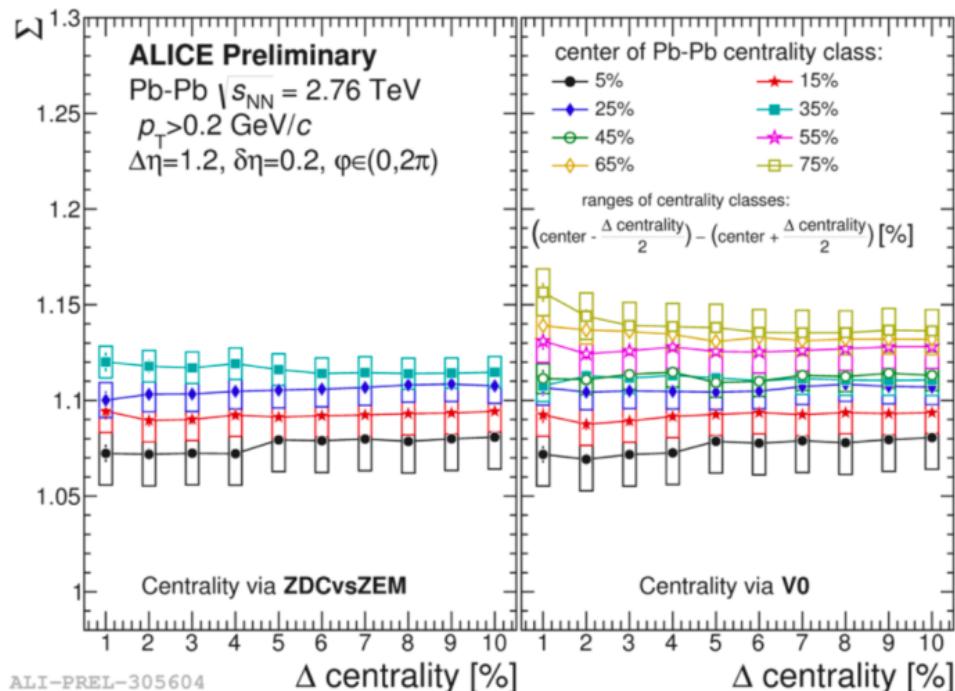
# Forward-backward multiplicity strongly intensive fluctuations in the model with strings finite in rapidity



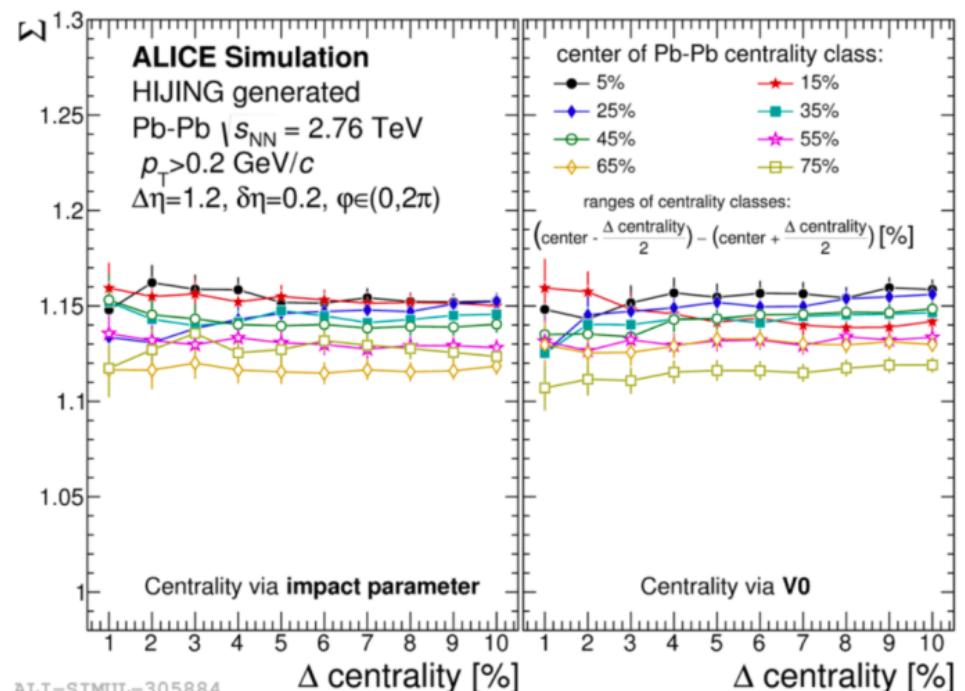
Influence  
of string  
fusion

D. Prokhorova, V. Kovalenko, Nucleus 2019, submitted to PEPAN

# Forward-backward multiplicity strongly intensive fluctuations in the model with strings finite in rapidity Experimental data at LHC energy



(a)



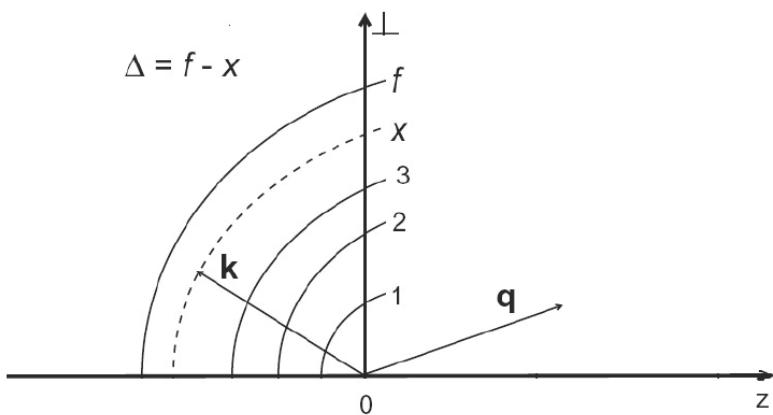
(b)

I. Sputowska, Proceedings 10, 14 (2019).

Influence of string fusion – with strings finite in rapidity  
 $\Sigma$  decreases with centrality

D. Prokhorova, V. Kovalenko, Nucleus 2019, submitted to PEPAN

# Cumulative particles production and string fusion

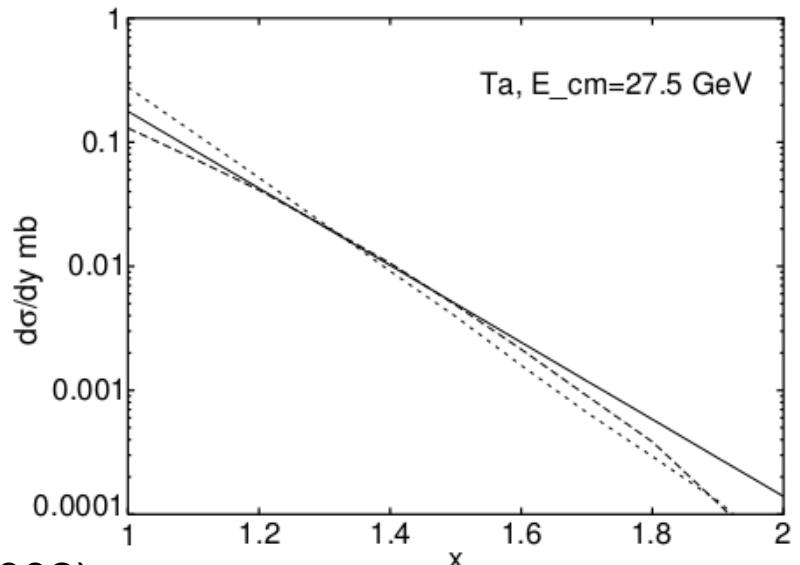


In the rest frame of fragmentating nucleus  
at large initial energy:

$$-x_F \approx x \equiv \frac{k_-}{p_-} = \frac{\sqrt{k_z^2 + \mu_\perp^2} - k_z}{m_N} > 0$$

$$x_q \equiv \frac{q_-}{p_-} = \frac{\sqrt{q_z^2 + M_\perp^2} - q_z}{m_N} > 0$$

The kinematical border is given  
by the condition:  $x + x_q = f$

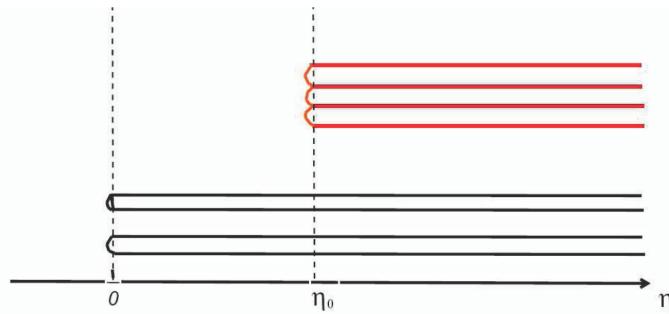


- In the string fusion picture, the fused strings share the energy comming from several nucleons, enabling particle production at  $x > 1$

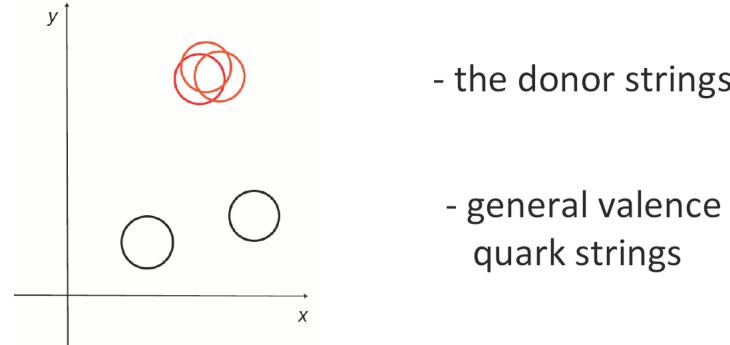
M.A. Braun, et al, Eur. Phys. J. C 25, 249–257 (2002)

- Current implementation of the string fusion for cumulative production accounts fusion of only two strings -> full implementation upcoming

# Cumulative particles production and string fusion



Rapidity distribution of the donor strings  
(in laboratory frame)

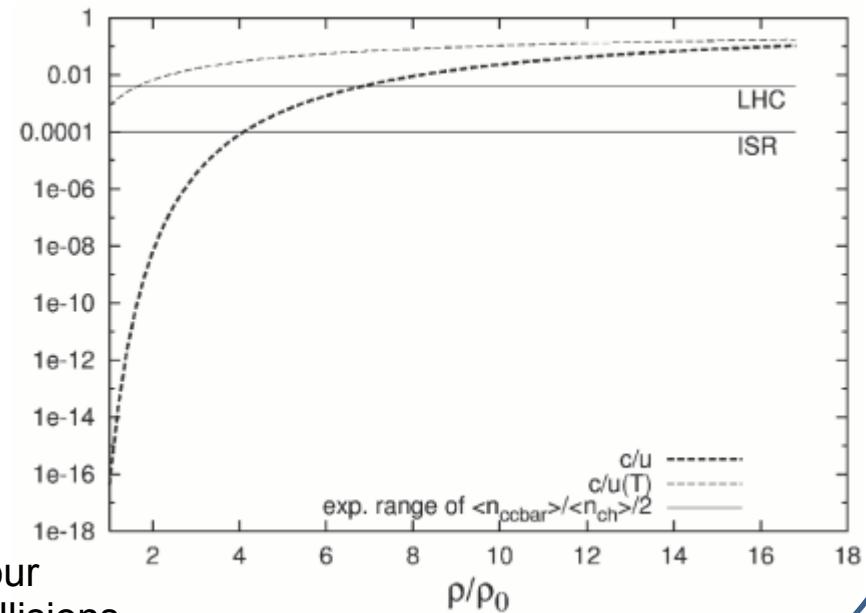


Transverse plane distribution  
of the donor strings

$$\frac{dn}{d^2p_\perp} \sim e^{-m_\perp/T}$$

- Increase of the relative strangeness and charm production with string fusion
- Positive long-range correlatinos between cumilative production and strangeness/charm

V. Vechernin, Enhanced yield of strange and heavy-flavour particles from few-nucleon clusters in high energy pA collisions,  
Strangeness in Quark Matter 2019



# Summary and outlook

- The collective effects of formation and fusion of strings are essential at NICA energies.
- They can be studied using various observables, includung:
  - Forward-backward correlations
  - Strongly intensive variables
  - Cumulative particle production
  - Production of strangeness and charm
- Areas that could be also addressed:
  - Particles spectra rations
  - Fluctuations of particle ratios
  - Baryo-chemical potential dependence
  - ... and more

# Thank you!

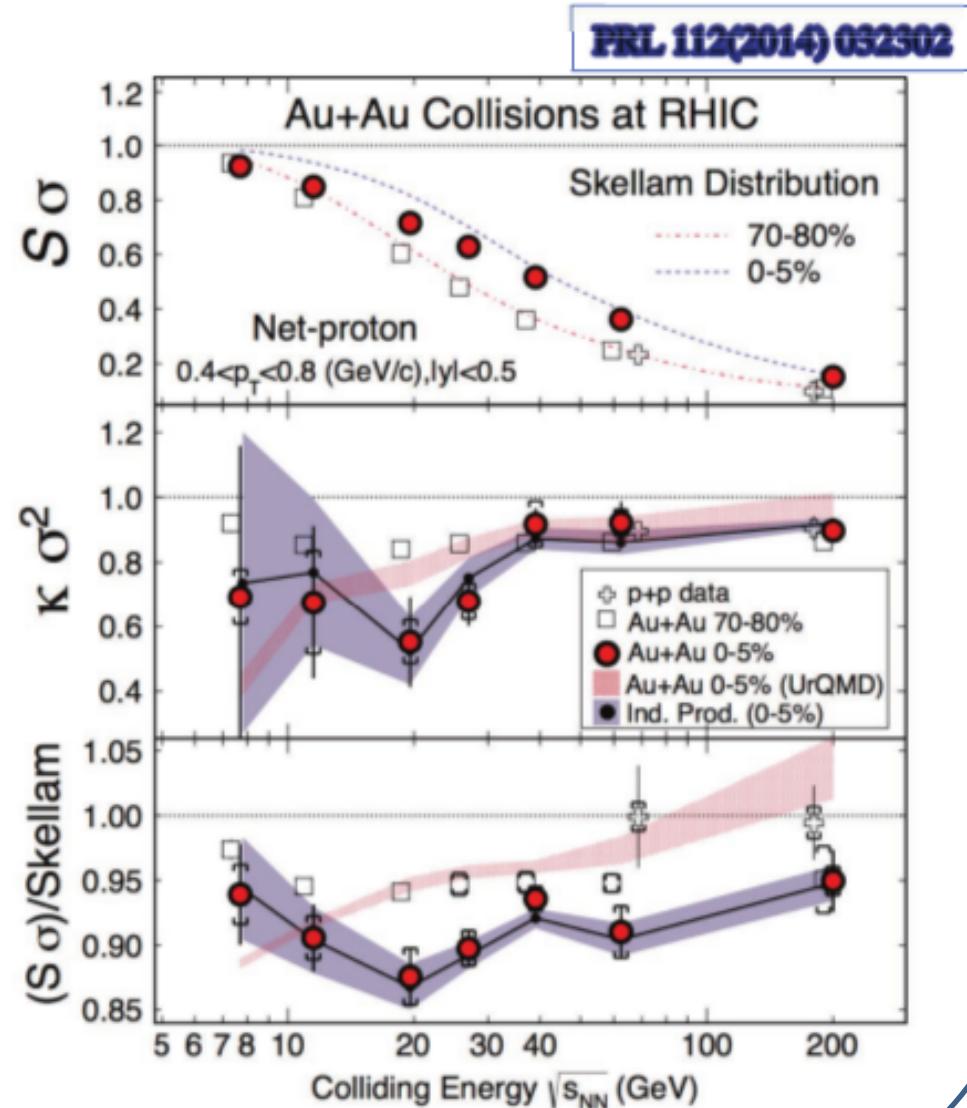
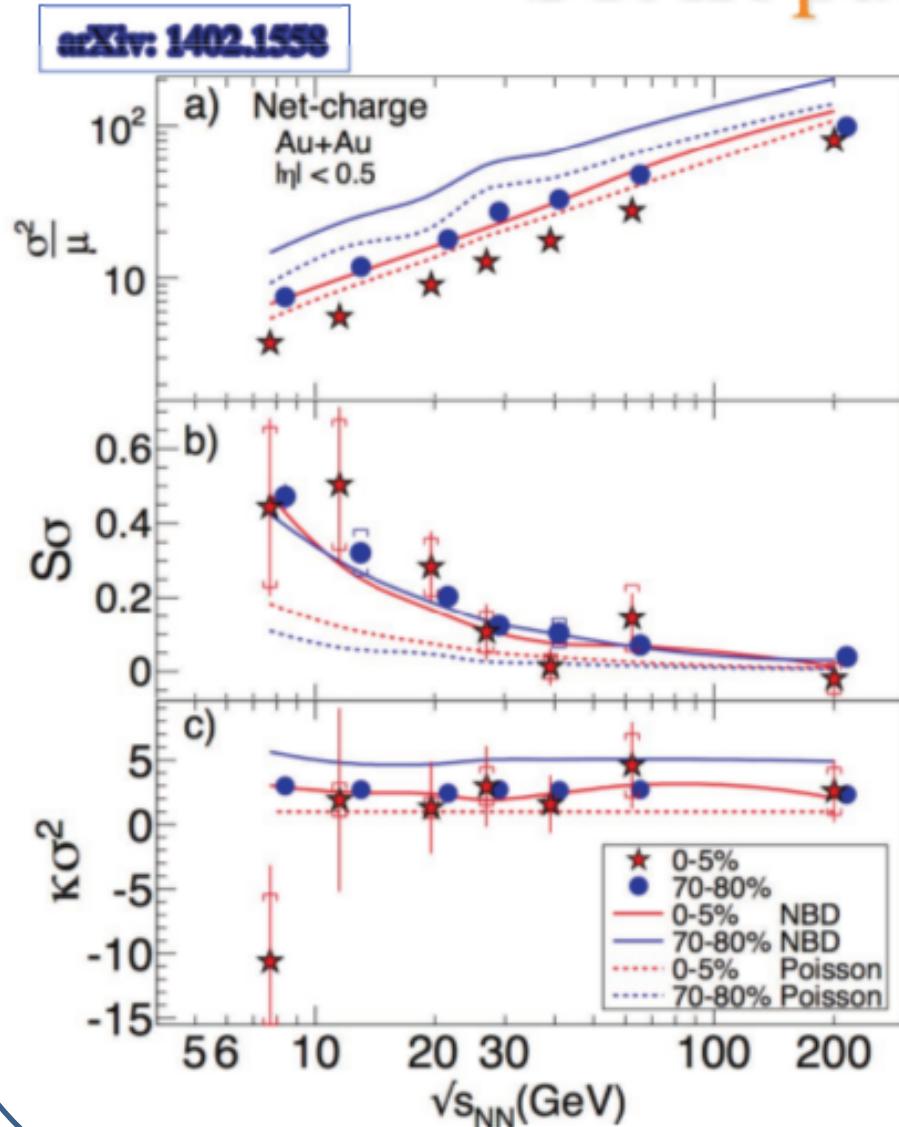
# Backup

# Comparison with other approaches

Feature	UrQMD	HIJING	This model
event-by-event initial state	Glauber-partonic	Glauber	partonic dipole-based
Collectivity	at final state (molecular dynamics)	optional gluon shadowing	string fusion
Dynamics:long, transverse	explicit	Lund strings	String evolution, string fusion
Phase transition	no (can add hydro by hand)	no	yes
Net baryon density	yes (by initial state)	by pdf	valence string model and exclusive pdf
Cascade resonances	yes	as in Lund model	upcoming
Cumulative effect	no	no	yes, full implementation upcoming
Mixed phase	can add by hand	no	yes, predicted by model
Quantum approach	no	no	attempt

# Experimental data – example

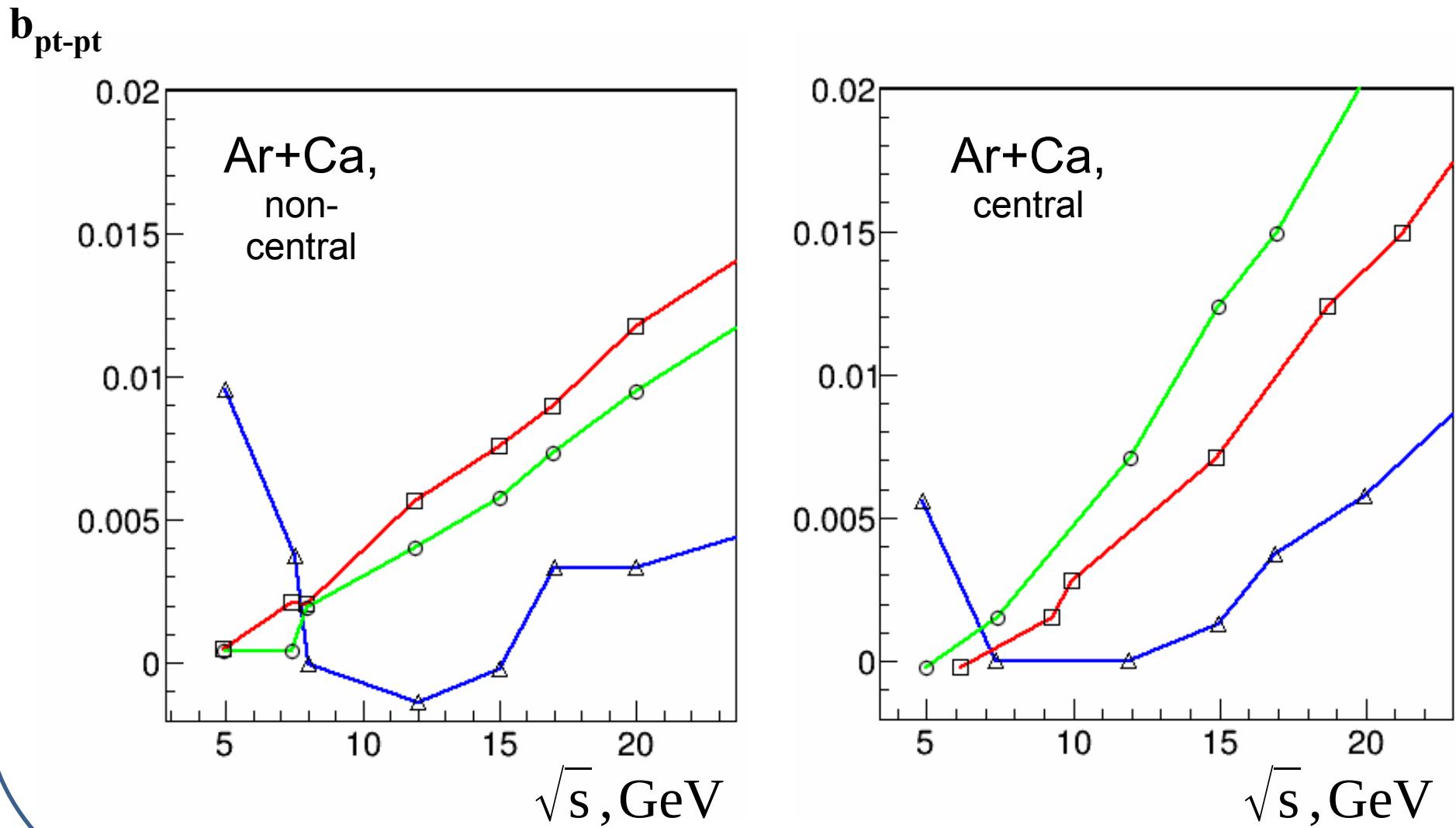
STAR publications 2014



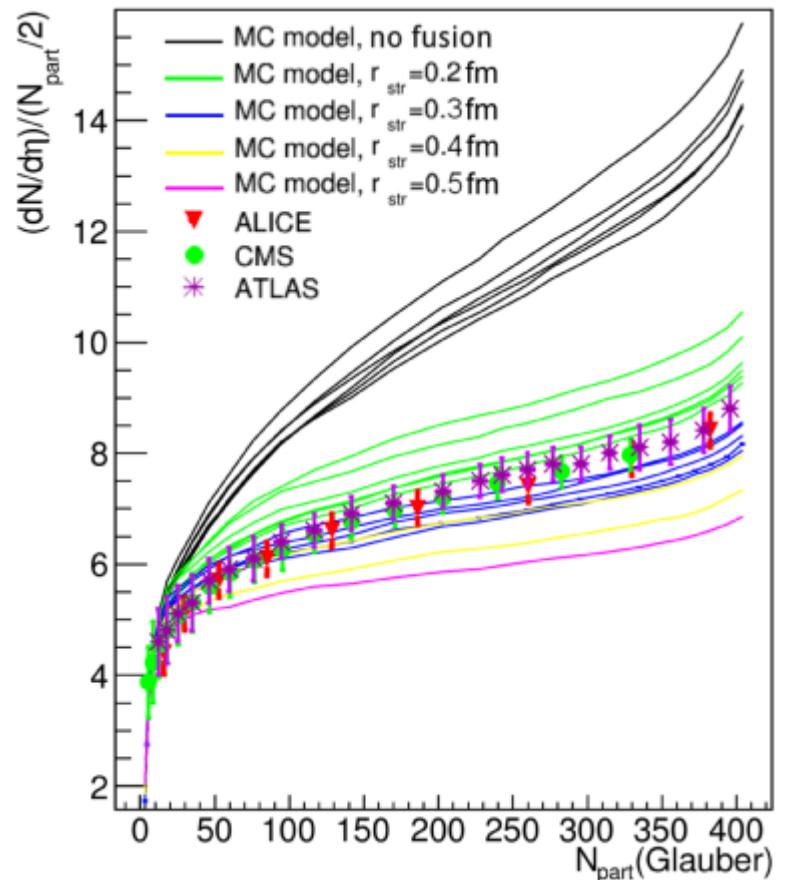
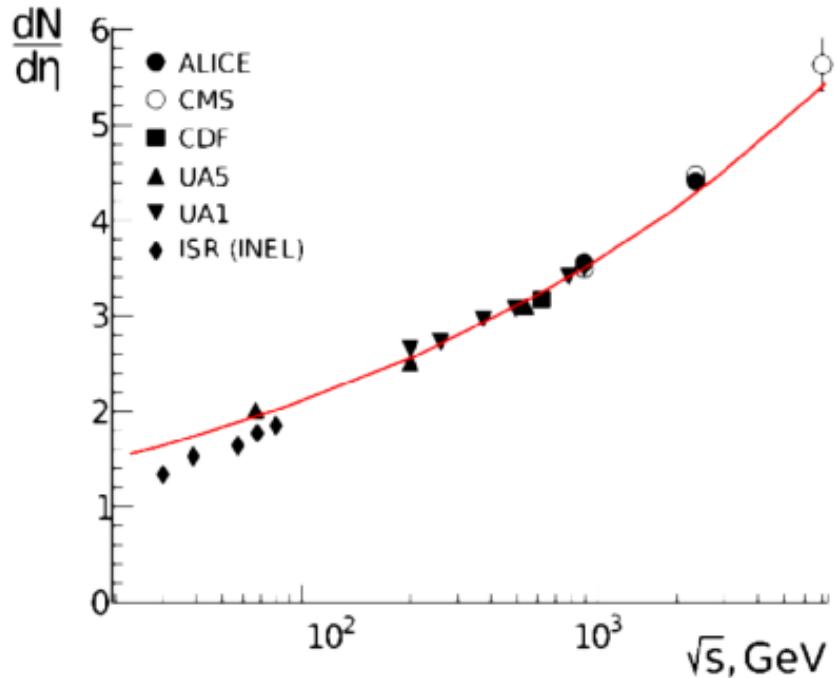
slide from M. J. Tannenbaum, Erice 2014

# Results: pt-pt correlation coefficient

## Ar+Ca more detailed study



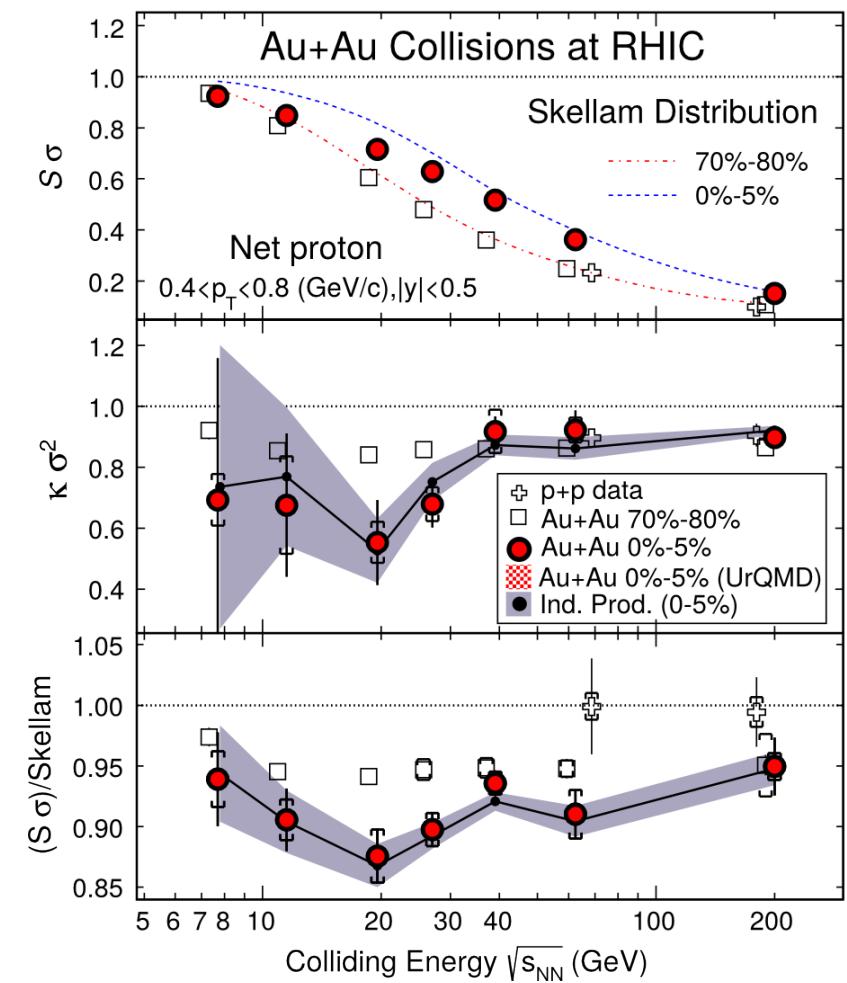
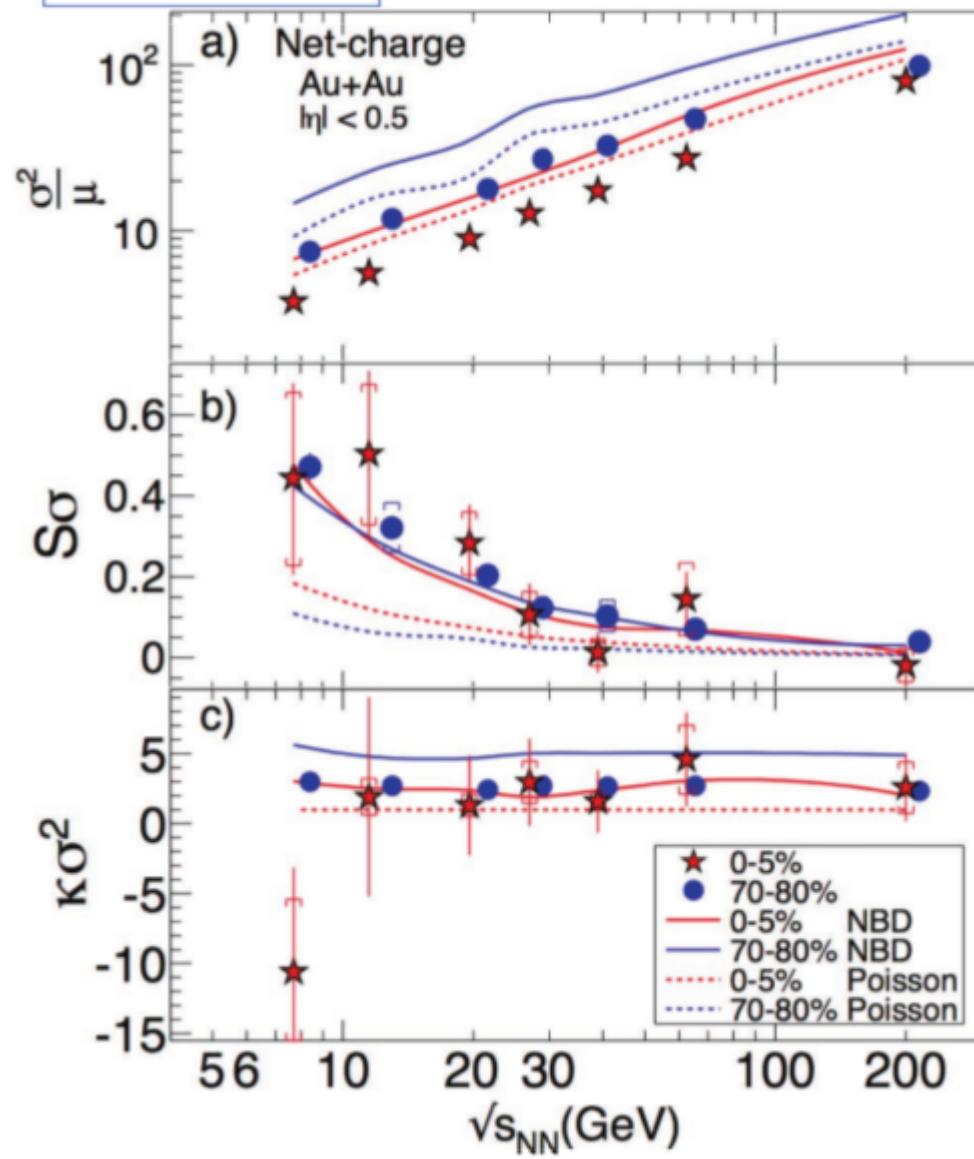
# Parameters fixing: pp and AA



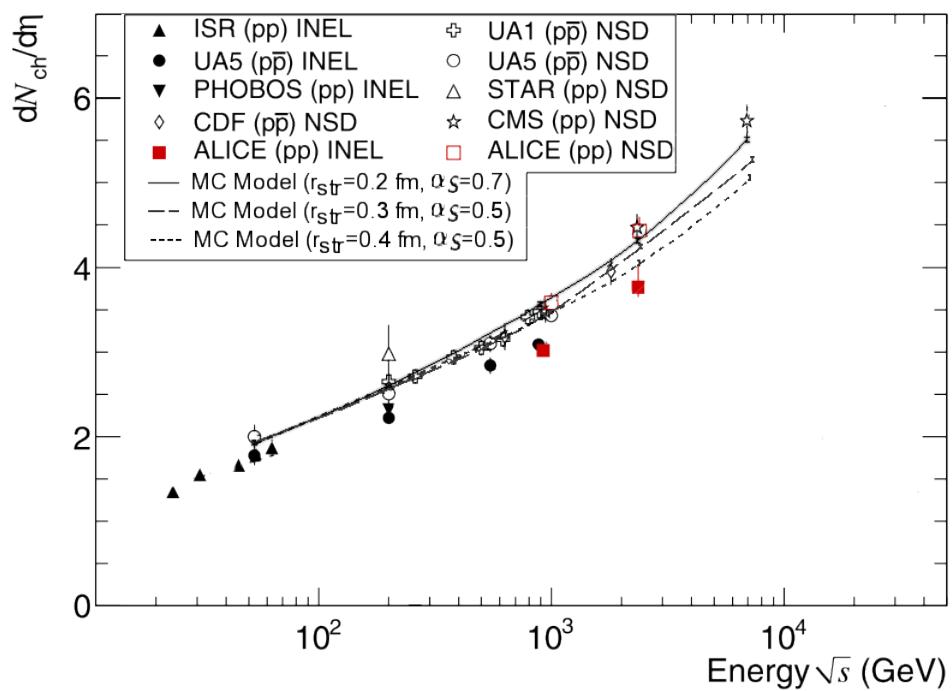
- The model describes
  - total inelastic cross section of pp collisions
  - charged multiplicity pseudorapidity density in pp collisions
  - multiplicity in minimum bias p-Pb collisions at 5.02 TeV
  - centrality dependence of multiplicity in Pb-Pb collisions

V. N. Kovalenko, Phys. Atom. Nucl. 76, 1189 (2013), arXiv:1211.6209 [hep-ph]  
 V. Kovalenko, PoS (QFTHEP 2013) 052 (2013).

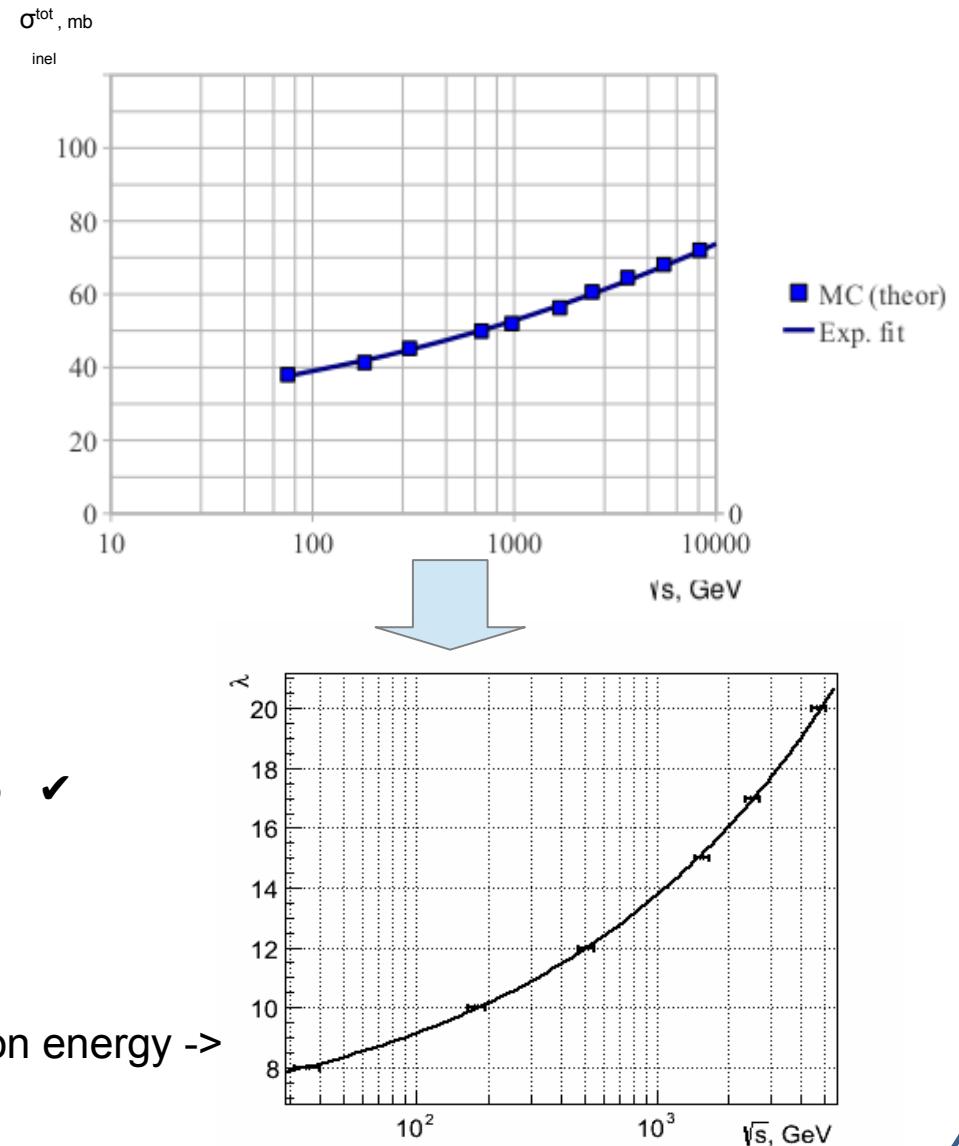
arXiv: 1402.1558



# Parameters fixing



$$r_{str}=0.2, \alpha_s=0.4, \mu_0=1.152, r_0=0.6 \text{ fm}, r_0/r_{max}=0.5 \quad \checkmark$$



Connection of  $\lambda$  with collision energy ->

V. N. Kovalenko, Phys. Atom. Nucl. 76, 1189 (2013), arXiv:1211.6209 [hep-ph]  
 V. Kovalenko, PoS (QFTHEP 2013) 052 (2013).