Evgeny Andronov

Probing collectivity in string models via machine learning

ICPPA, MOSCOW, 24 OCTOBER 2024

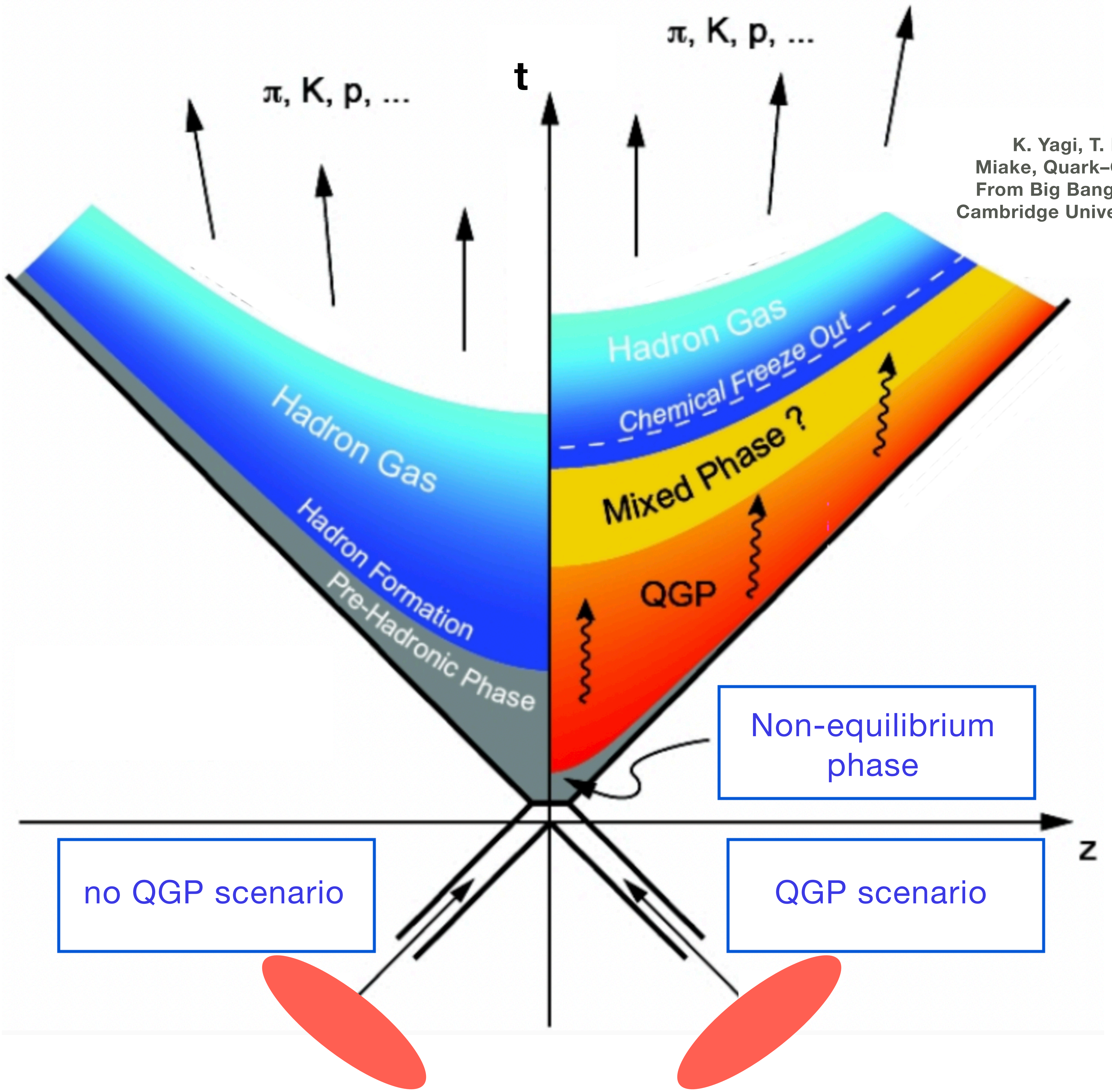
p+p and A+A collisions

Predicted and observed QGP «signals» for A+A:

- azimuthal anisotropy (flow)
- enhanced strange particles yields
- jet quenching

Now, in 2024 we know that some of these effects are present in *p+p* interactions:

- QGP in p+p?
- other source of collectivity?



K. Yagi, T. Hatsuda, Y. Miake, Quark-Gluon Plasma - From Big Bang to Little Bang, Cambridge University Press, 2005

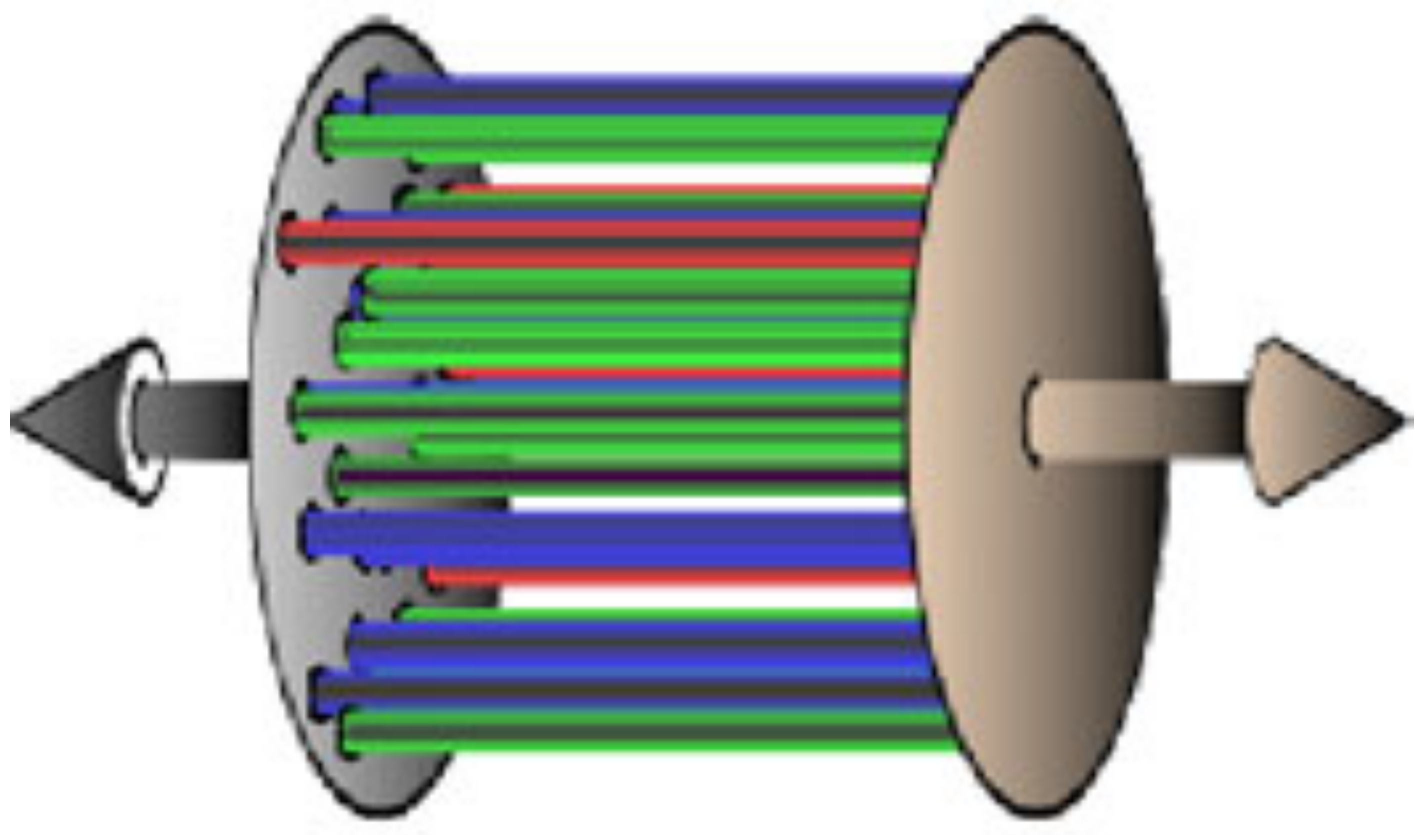
Color string models

Two-stage process:

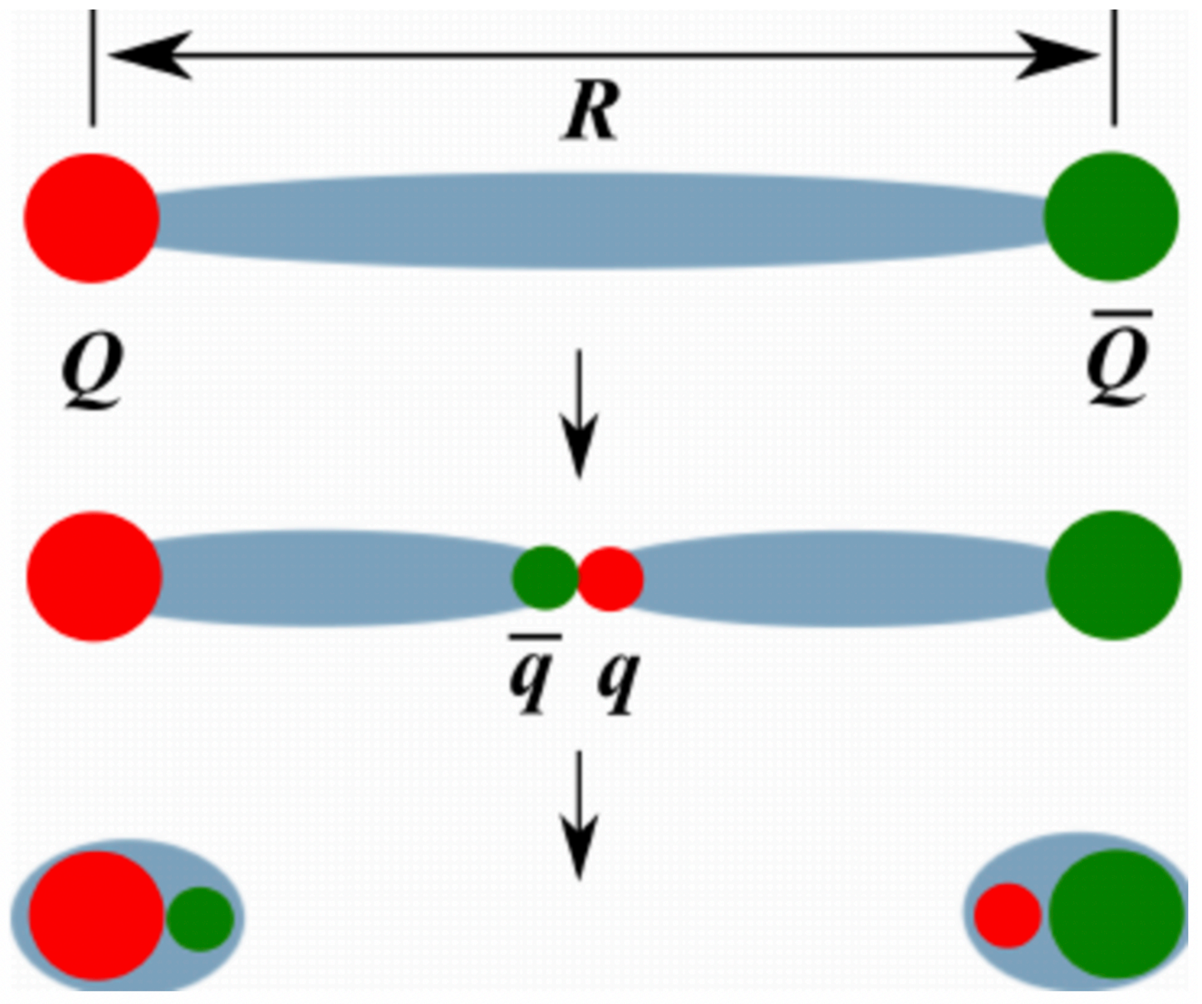
- partons' colour charges form tubes of colour field
- tubes are hadronized via Schwinger mechanism (tunnelling)

but!

- string may interact before hadronization
  [M.A. Braun, C. Pajares, Phys.Lett.B 287, 154 (1992)]
- how can we distinguish between different scenarios of string-string interactions?



F. Gelis et al., Ann.Rev.Nucl.Part.Phys. 60, 463 (2010)

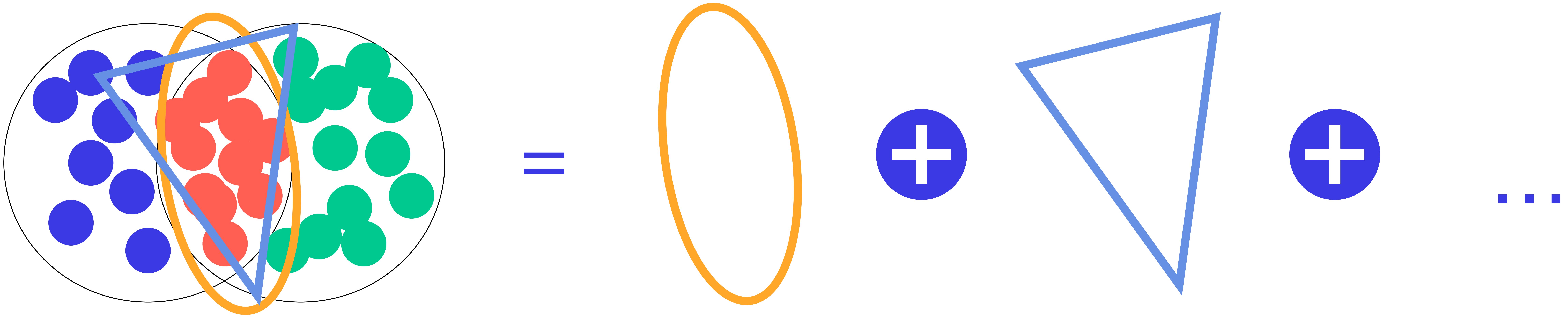


M.N. Chernodub, Mod.Phys.Lett.A 29, 1450162 (2014)

Goal of this work:

- consider multiple versions of string-string interaction leading to the same azimuthal anisotropy
- train neural nets on event-by-event observables to distinguish between models

Initial state as a source of anisotropy



Typical picture of a heavy ion collision - spatial anisotropy of particle emitting sources can be decomposed into harmonics

This decomposition affects momentum space anisotropy of the produced particles

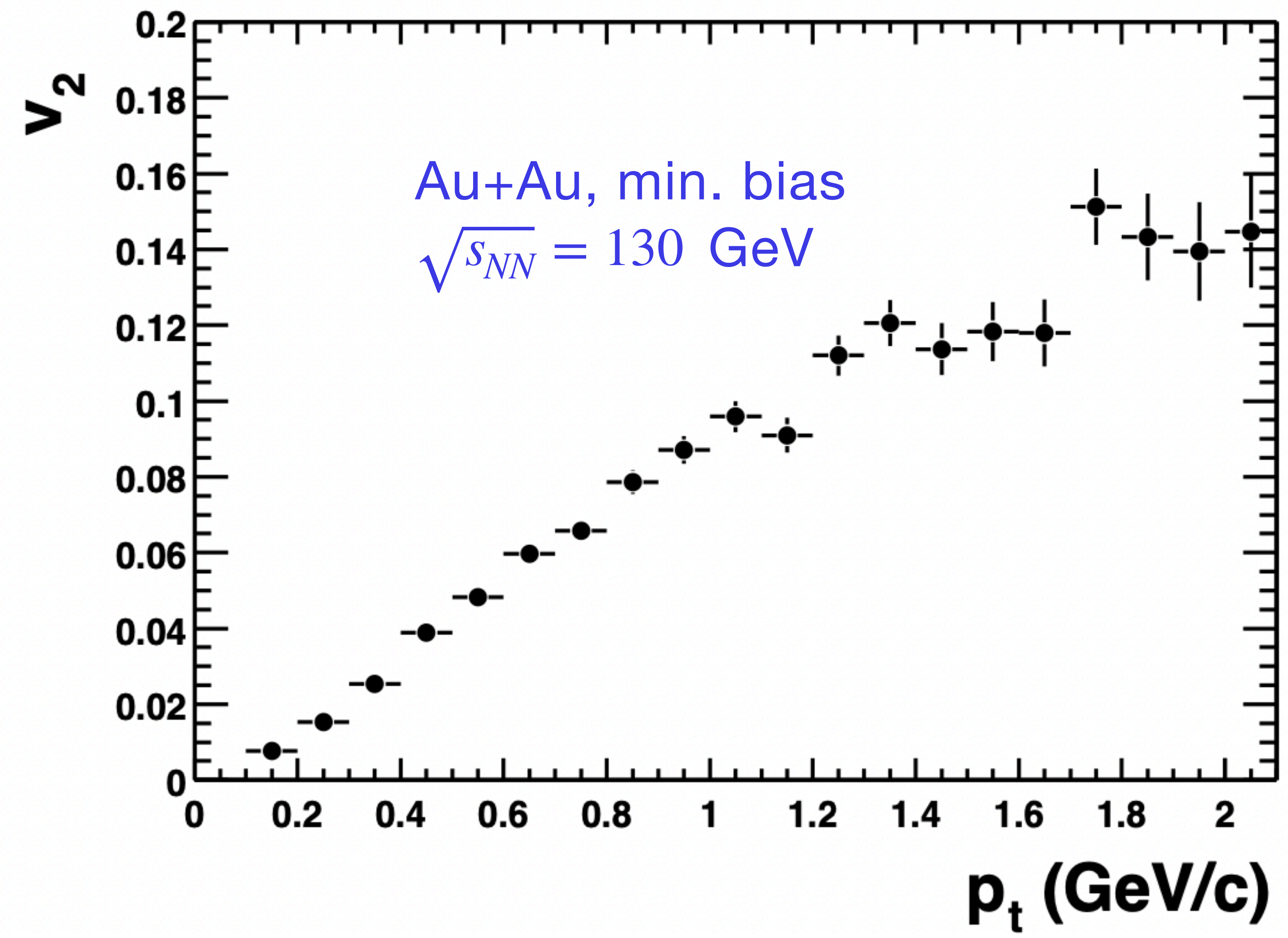
Azimuthal flow

Momentum space anisotropy is quantified by the anisotropic flow - coefficients of the Fourier series expansion of azimuthal angle spectrum:

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy} \cdot \left(1 + 2\sum_{n=1}^{\infty} v_n cos\left[n\left(\phi - \Psi_{RP}\right)\right]\right)$$

$$v_n = \langle cos\left[n\left(\phi - \Psi_n\right)\right]\rangle$$

Experimental results on flow in heavy ion collisions perfectly explained as a collective effect due to viscous relativistic hydro evolution of QGP (different pressure gradients in different directions)



STAR Coll., Phys. Rev. Lett. 86, 402 (2001)

Interacting colour strings

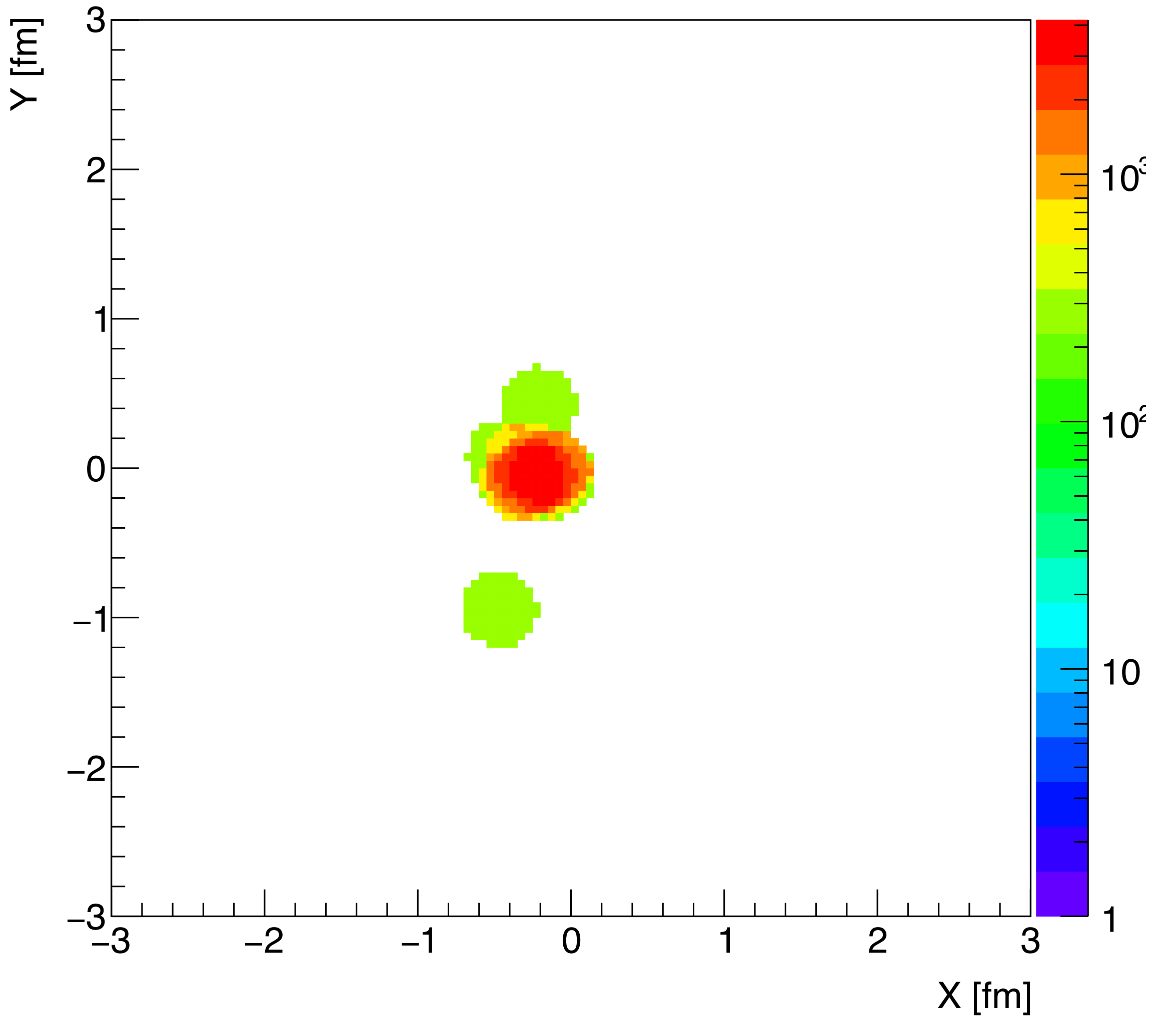
D. Prokhorova, E. Andronov, Phys.Part.Nucl. 54(3), 412 (2023).

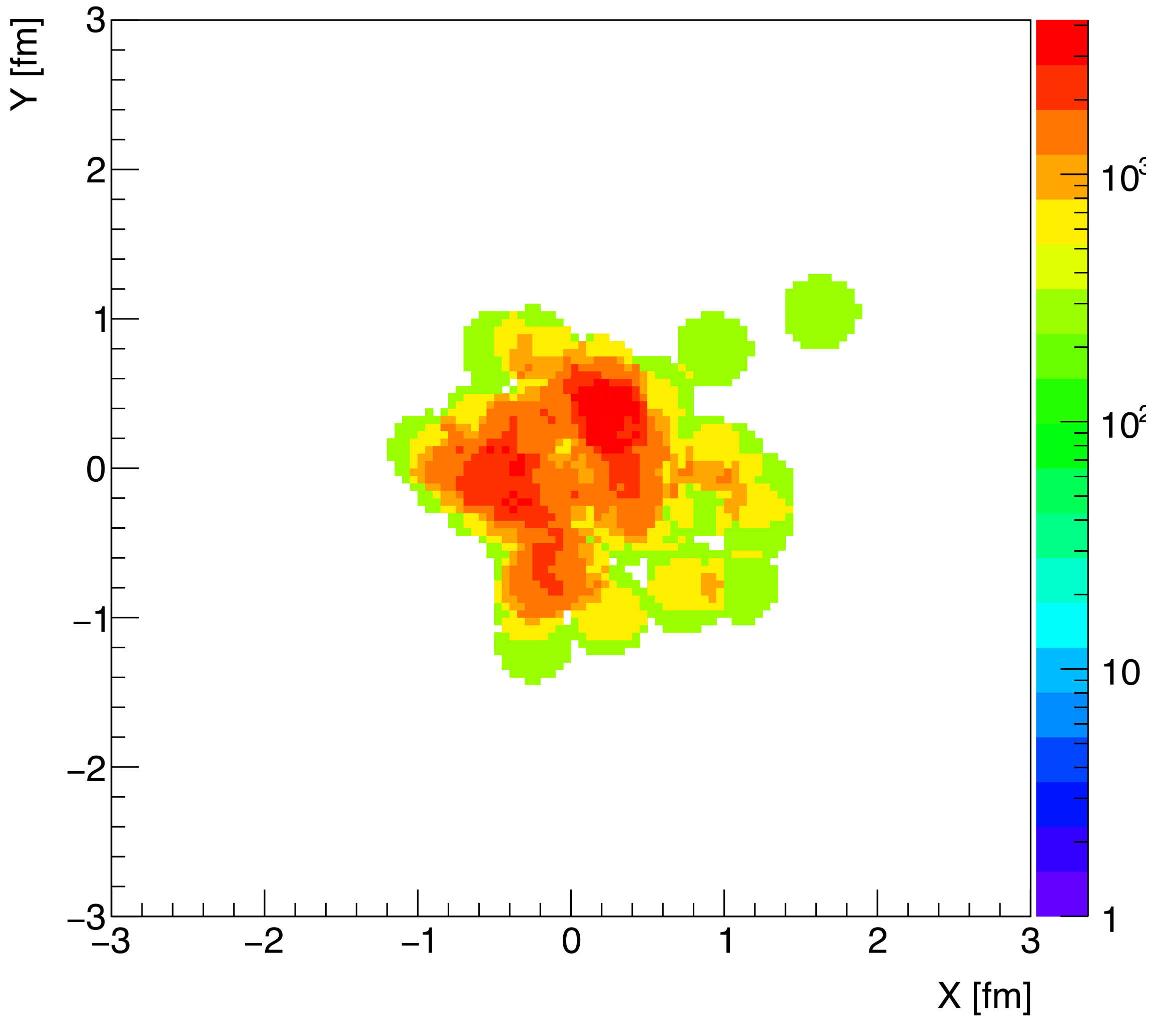
D. Prokhorova, E. Andronov, G. Feofilov, Physics 5(2), 636 (2023).

E.V. Andronov, D.S. Prokhorova, A.A. Belousov, Theor.Math.Phys. 216(3), 1265 (2023).

D.S. Prokhorova, E.V. Andronov, Phys.Part.Nucl.Lett. 20(6), 1496 (2023).

D. Prokhorova, E. Andronov, Physics 6(1), 264 (2024).





Model:

- interacting strings of finite length in rapidity
- number of strings from Glauber+multipomeron exchange model

Applicability:

- p+p and A+A collisions in 10-13000 GeV range

How to transform position space anisotropy to momentum space:

- momentum loss in fused string medium [M.A.Braun,C.Pajares, Eur.Phys.J.C 71, 1558 (2011)]
- string shoving [V.A. Abramovsky, O.V. Kanchely, JETP Lett. 31, 566 (1980); I. Altsybeev, G. Feofilov, EPJ Web Conf 125, 04011 (2016)]

Momentum loss in string medium

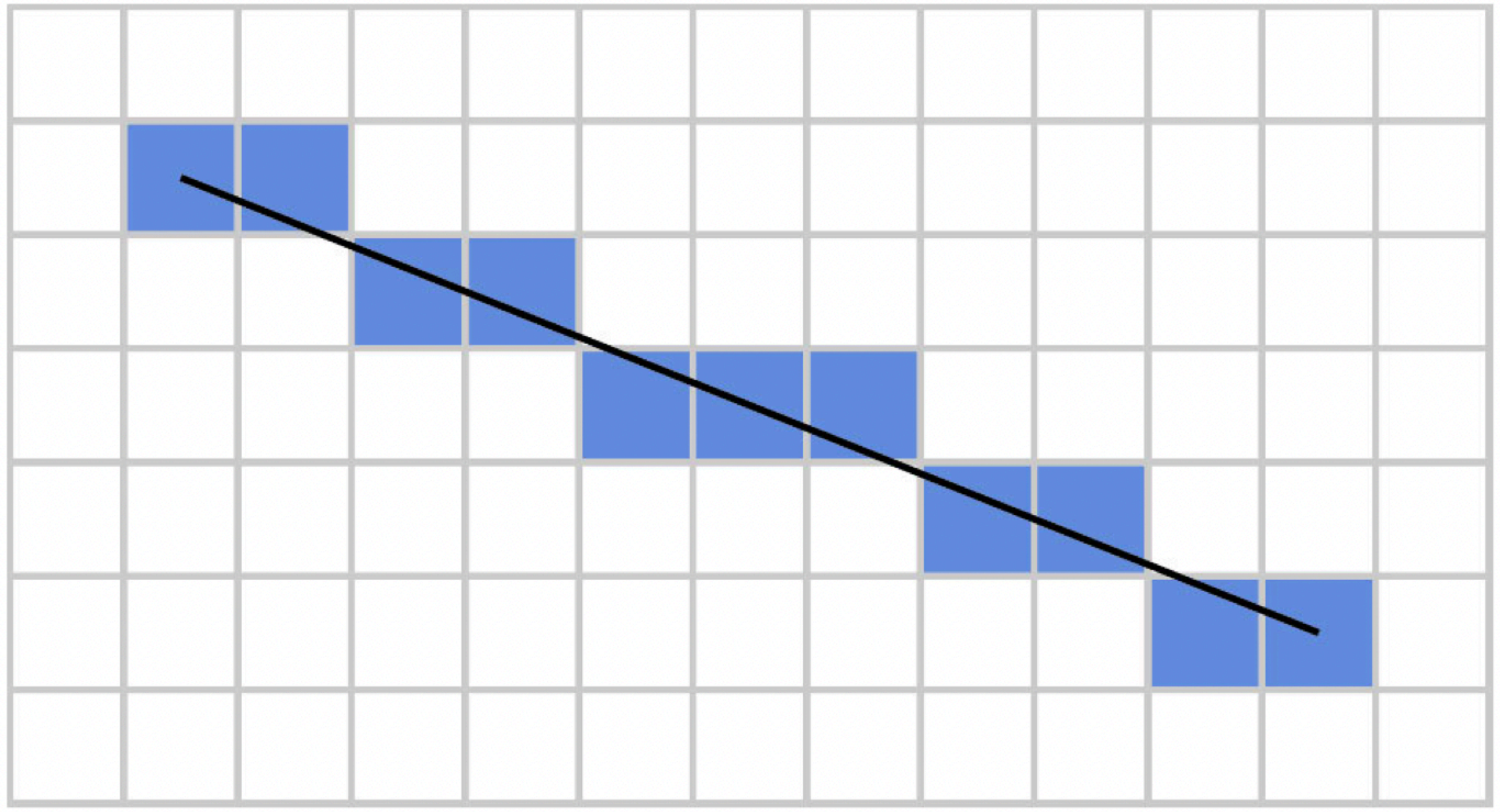
M.A.Braun,C.Pajares, Eur.Phys.J.C 71, 1558 (2011)
A.I.Nikishov, V.I.Ritus, Sov. Phys. Uspekhi, 13 (1970) 303

1) QED with external EM field suggests the loss of energy: $\frac{dp(x)}{dx} = -0.12e^2\left(eEp(x)\right)^{2/3}$

2) By analogy for gluon field $p_{initial} = p_{final}\left(1 + \kappa p^{-1/3}\sigma^{2/3}l\right)^3$, where σ is a string tension (depends on fusion) and κ is a quenching parameter that needs to be tuned

3) One need to find a path of particle through the strings and at each step decrement its transverse momentum -> anisotropy

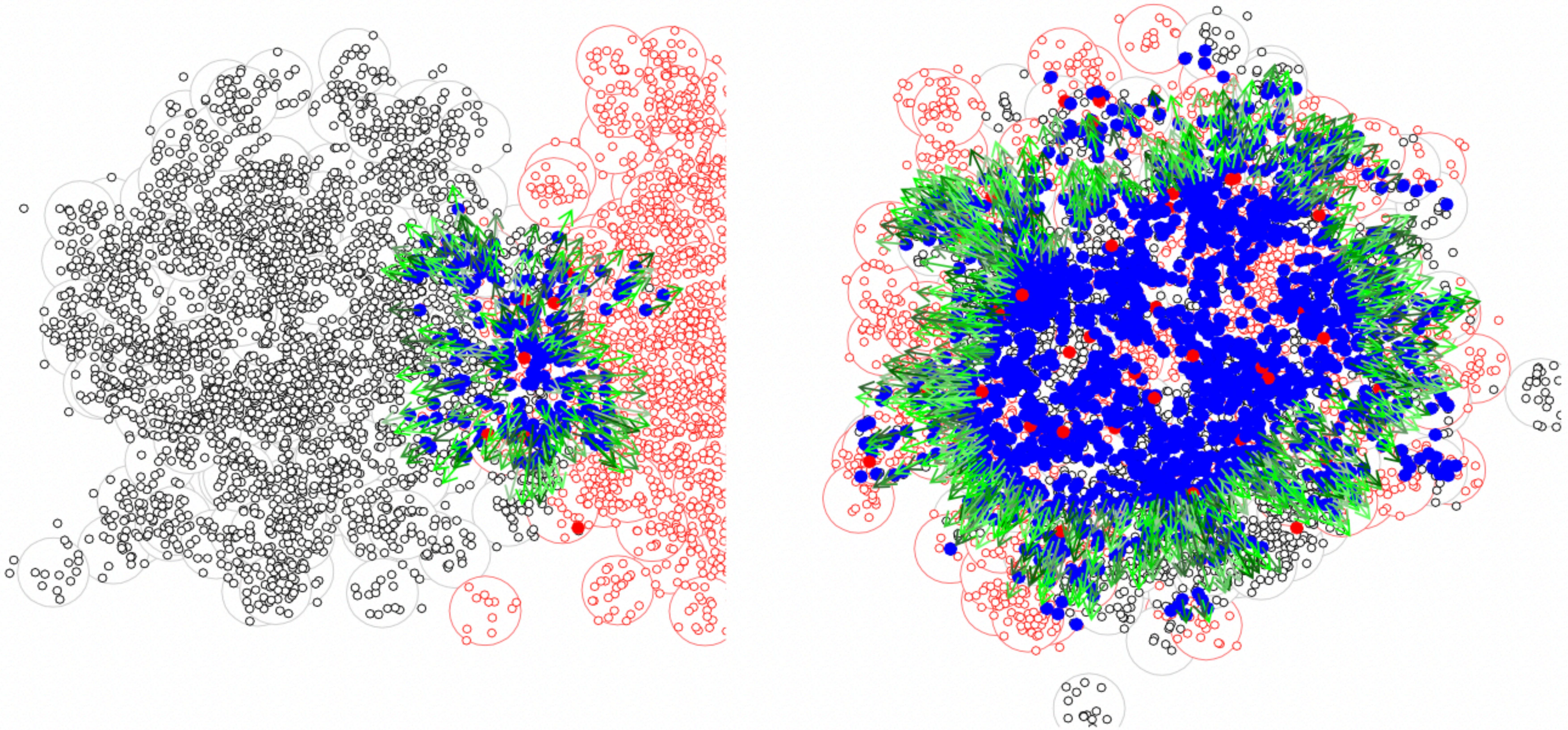
4) Trajectory in bins is found using Bresenham algorithm



V. Kovalenko, EPJ Web Conf 137, 07012 (2017)
J. E. Bresneham, IBM Syst. J. 4, 25 (1965)

String shoving

I. Altsybeev, AIP Conf. Proc. 1701, 100002 (2016)



Partially overlapped strings gain oppositely directed transverse momenta:

$p_{Tstring} = l\sqrt{\left(\lambda + \lambda_1 S/S_{string}\right)^2 - \lambda^2}$, where λ - string energy density, λ_1 - energy excess due to overlap, l - string length

Data set

Reaction:

- Au+Au at $\sqrt{s_{NN}} = 200$ GeV
- centrality class: 30-70% by impact parameter

Event-by-event features:

- pT-phi 6*48 2d histogram ($0 < p_T < 1$ GeV/c) [L.-G.Pang et al., Nature Commun. 9 (2018) 1, 210]
- events were grouped into 5 classes by number of strings
- 5000 events for training and 1000 for testing for each label

2 possible labels (+5 labels for string number):

- momentum loss in fused string medium [M.A.Braun,C.Pajares, Eur.Phys.J.C 71, 1558 (2011)]
- string shoving [V.A. Abramovsky, O.V. Kanchely, JETP Lett. 31, 566 (1980); I. Altsybeev, G. Feofilov, EPJ Web Conf 125, 04011 (2016)]

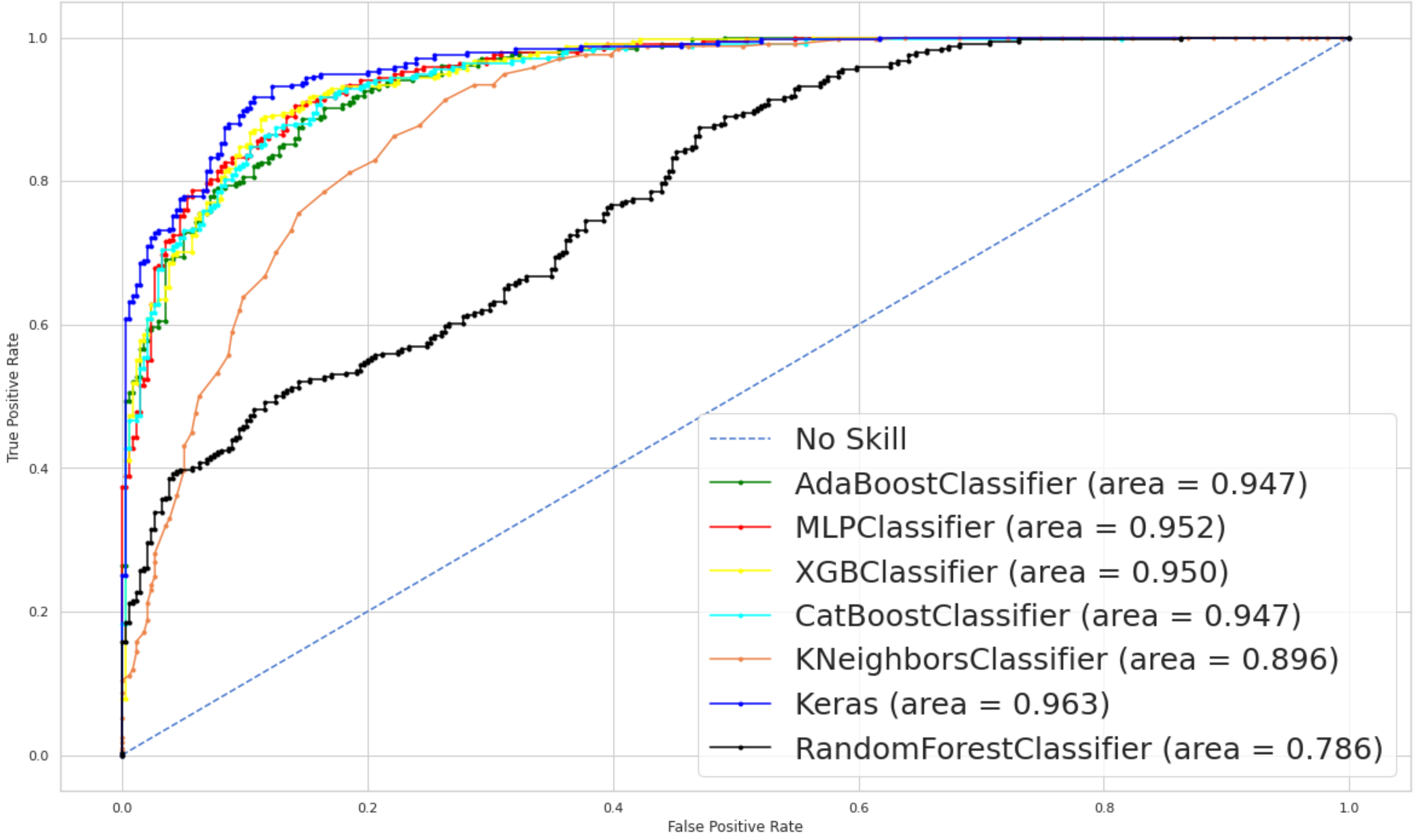
Binary classification

Algorithms:

- methods from scikit-learn
- decision tree ensemble (XGBoost, CatBoost)
- convolution neural net

Metrics:

Classifier	accuracy	precision	recall	F1	ROC AUC
AdaBoostClassifier	0.859	0.857	0.862	0.860	0.947
GaussianNB	0.582	0.654	0.350	0.860	0.704
DecisionTreeClassifier	0.596	0.594	0.605	0.599	0.598
MLPClassifier	0.876	0.866	0.889	0.877	0.952
XGBClassifier	0.883	0.879	0.889	0.884	0.950
CatBoostClassifier	0.871	0.867	0.877	0.872	0.947
KNeighborsClassifier	0.807	0.731	0.970	0.834	0.896
RandomForestClassifier	0.674	0.736	0.542	0.624	0.786



Methods:

- all the parameters were optimized using GridSearch etc.

Best results are achieved for convolution neural net

Multi-class classification

Algorithms:

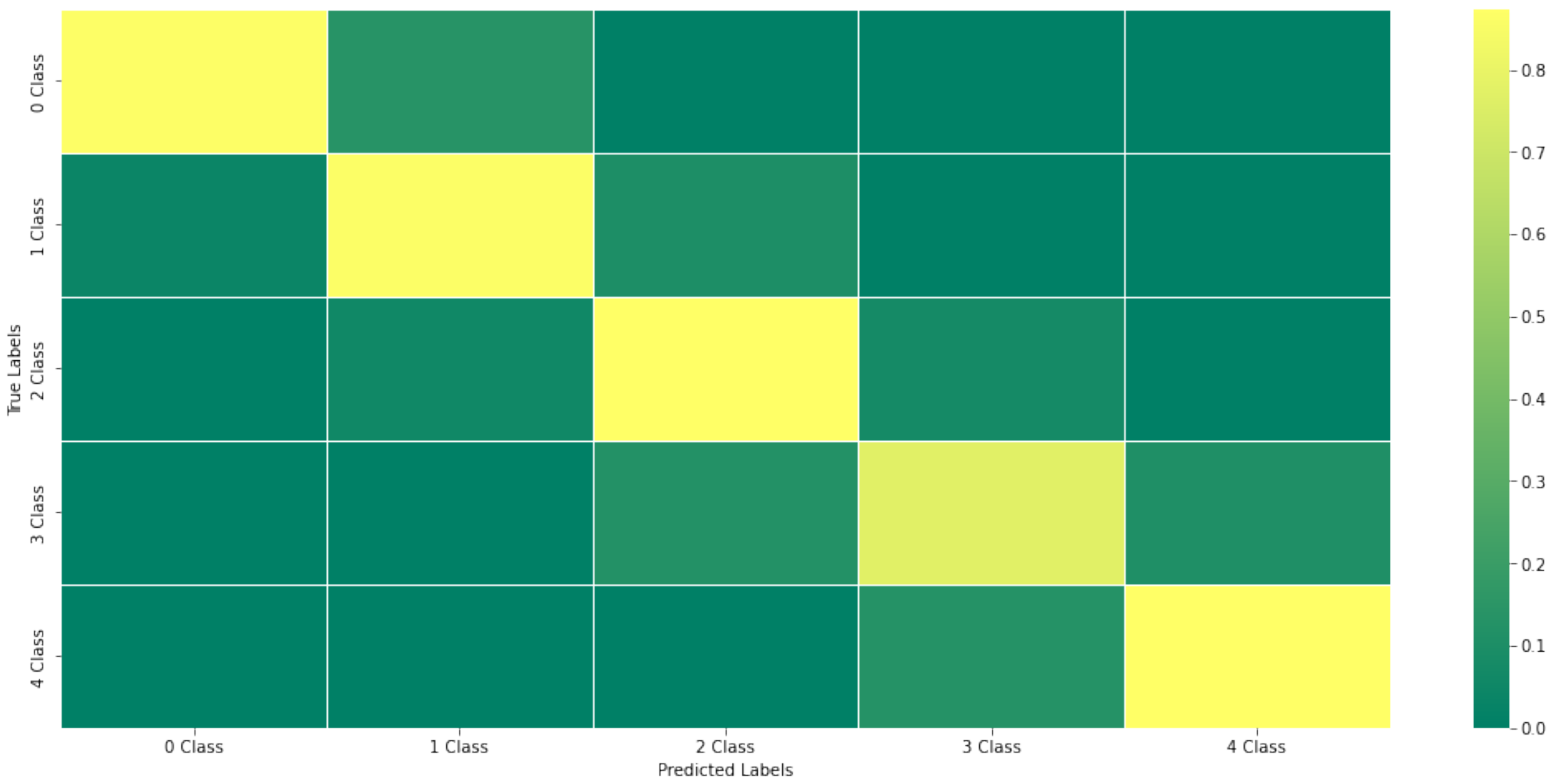
- additional branch was attached to the convolution neural net
- branch's parameters were optimized

Results:

- areas under ROC for each individual class are ~0.9 for all classes
- confusion matrix is of diagonal form

Summary:

- presenting e-by-e 2d spectra as data for computer vision problem allows us to distinguish between different versions of string model and to extract info on initial conditions



Thank you for your attention!

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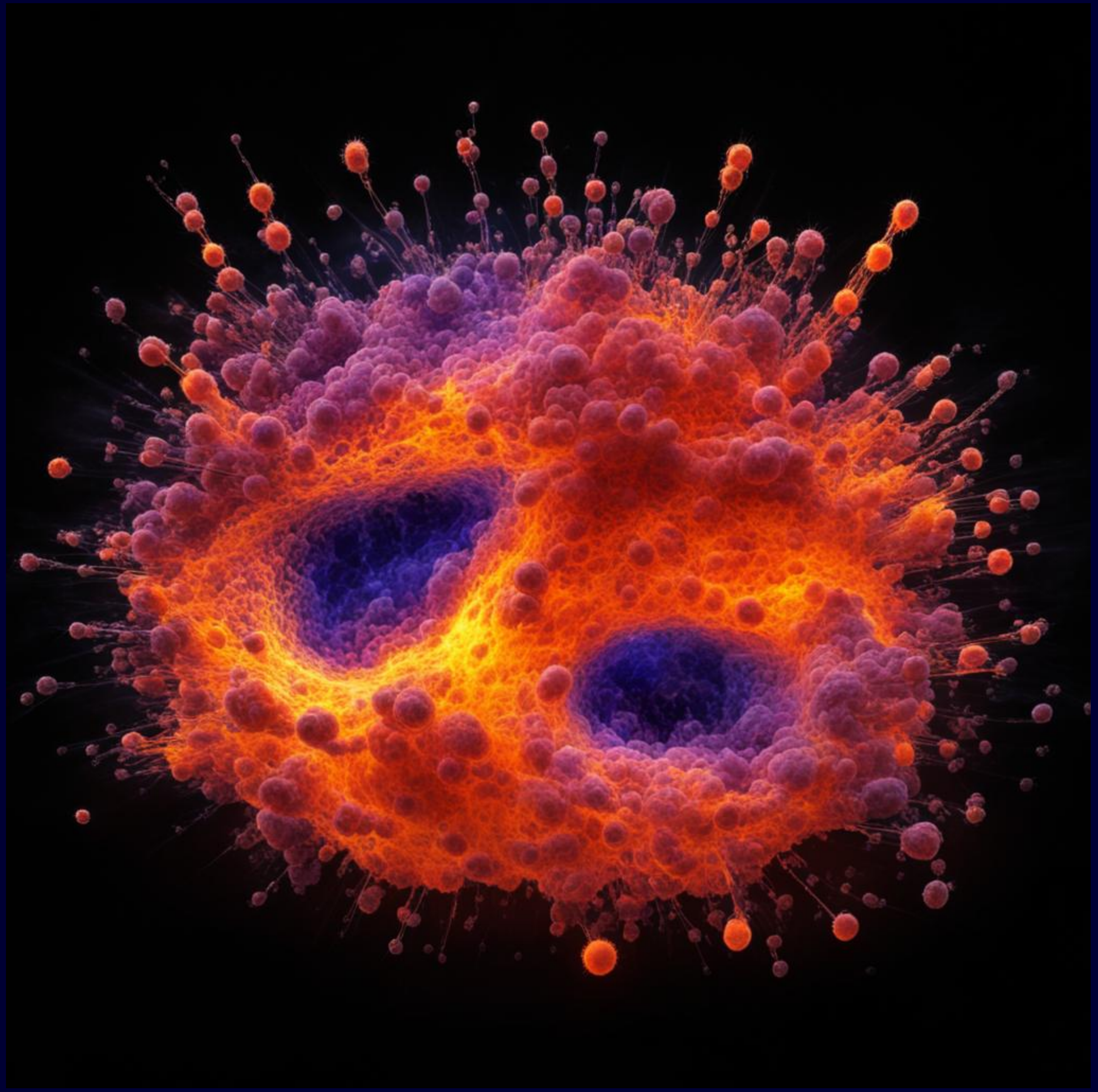
https://rscf.ru/en/project/23-72-01061/

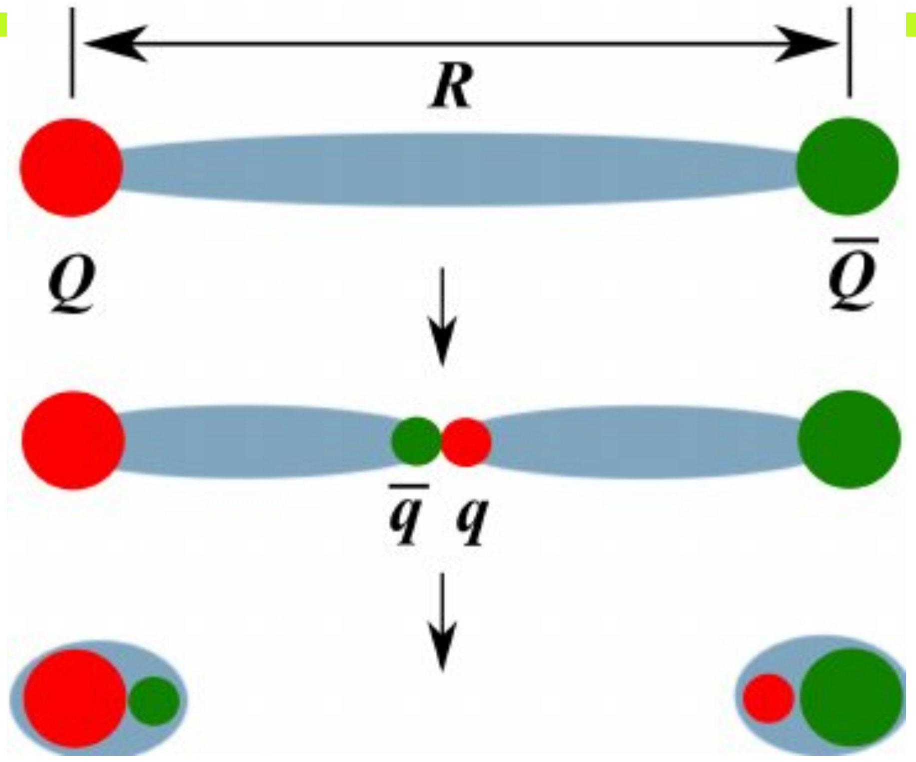
e.v.andronov@spbu.ru



Kandinsky bot: «Quark-gluon plasma»

EXTRA

Color string models



M.N. Chernodub *Mod.Phys.Lett.A* 29, 1450162 (2014)

- PYTHIA/FRITIOF/QGSM/PHSD/EPOS are among the most successful MC event generators that are able to describe p+p and A+A data (Color strings as particle emitting sources)
- With an increase of the collision energy multi-string configurations start to play a bigger role, ideas: rope formation, string fusion, string repulsion/shoving - useful for description of strangeness enhancement, correlations etc.

V.A. Abramovsky, O.V. Kanchely, JETP Lett. 31, 566 (1980)
T.S. Biro, H.B. Nielsen, J. Knoll, Nucl.Phys.B 245, 449 (1984)
M.A. Braun, C. Pajares, Phys.Lett.B 287, 154 (1992)
I. Altsybeev, AIP Conf. Proc. 1701, 100002 (2016)
I. Altsybeev, G. Feofilov, EPJ Web Conf 125, 04011 (2016)
C. Bierlich, G. Gustafson, L. Lonnblad, Phys.Lett.B 779, 58 (2018)

- Anisotropy in string model can be produced due to the quenching of partons/hadrons momenta due to the presence of the gluon field of the stretched strings (NB: field changes due to interaction of strings) [**M.A.Braun,C.Pajares, Eur.Phys.J.C 71, 1558 (2011)**] - description of elliptic and triangular flow in A+A collisions

Parameters

I. Altsybeev, AIP Conf. Proc. 1701, 100002 (2016)

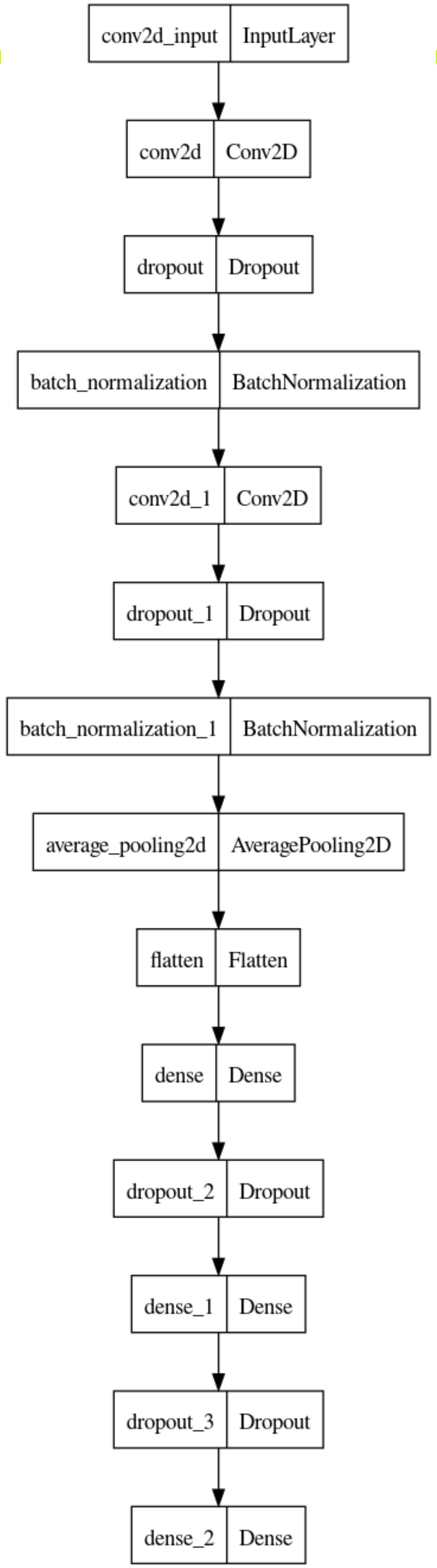
Partially overlapped strings gain oppositely directed transverse momenta:

$p_{Tstring} = l\sqrt{\left(\lambda + \lambda_1 S/S_{string}\right)^2 - \lambda^2}$, where λ - string energy density, λ_1 - energy excess due to overlap, l - string length

$\lambda = 1$

$\lambda_1 = 0.0001$

```
clf_ada = AdaBoostClassifier(n_estimators=500, learning_rate=1.0)
clf_gaus = GaussianNB()
clf_decTree = DecisionTreeClassifier(max_depth=25)
clf_mlp = MLPClassifier(solver='lbfgs', activation='tanh', learning_rate='constant', alpha=0.05, hidden_layer_sizes=(100,2))
clf_xg = XGBClassifier(learning_rate=0.02, objective='binary:logistic', silent=True, nthread=1, subsample = 0.8, n_estimators = 1500,
min_child_weight = 10, max_depth = 4, gamma = 1.5, colsample_bytree = 0.6)
clf_cat = CatBoostClassifier(depth=4, iterations=1000, learning_rate=0.1)
clf_kneigh = KNeighborsClassifier(100)
clf_forest = RandomForestClassifier(max_depth=8, n_estimators=500, max_features=1)
```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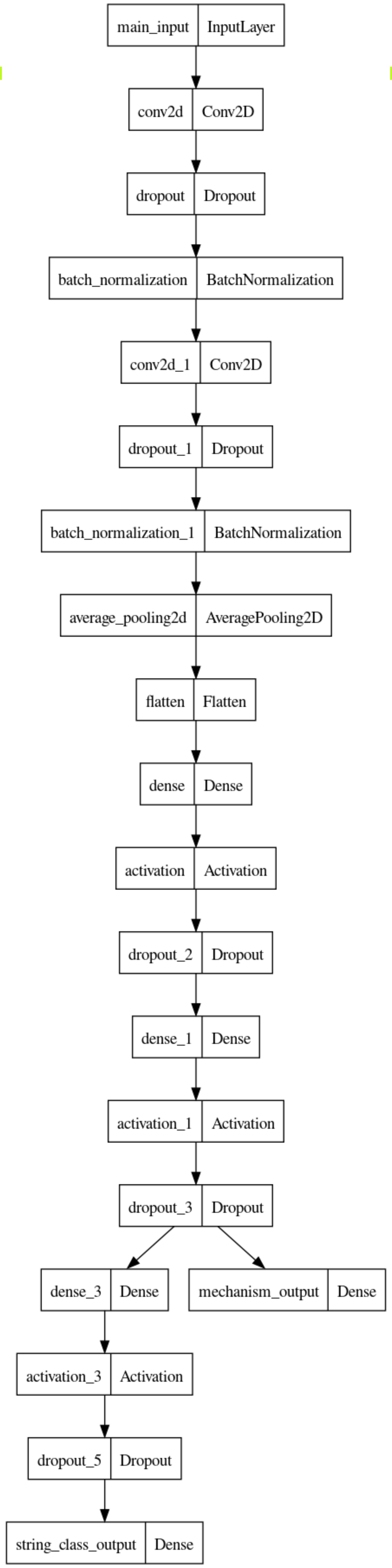
conv2d | Conv2D
dropout | Dropout
batch_normalization | BatchNormalization
conv2d_1 | Conv2D
dropout_1 | Dropout
batch_normalization_1 | BatchNormalization
average_pooling2d | AveragePooling2D
flatten | Flatten
dense | Dense
dropout_2 | Dropout
dense_1 | Dense
dropout_3 | Dropout
dense_2 | Dense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conv2d | Conv2D
dropout | Dropout
batch_normalization | BatchNormalization
conv2d_1 | Conv2D
dropout_1 | Dropout
batch_normalization_1 | BatchNormalization
average_pooling2d | AveragePooling2D
flatten | Flatten
dense | Dense
activation | Activation
dropout_2 | Dropout
dense_1 | Dense
activation_1 | Activation
dropout_3 | Dropout
dense_3 | Dense
mechanism_output | Dense
activation_3 | Activation
dropout_5 | Dropout
string_class_output | Dense

Building blocks of the model

INITIALIZATION

1) Preparation of protons with different numbers of partons (x from PDF, valence and sea quarks and diquarks, $\sum_i x_i = 1, \sum_i E_i = E_{proton}$)

2) Combine protons with the same number of partons in pairs, stretch strings between partons, define initial rapidities of the string endpoints

3) Sample from the prepared pairs of protons according to the distribution on number of pomeron exchanges: $P\left(n_{\text{pom}}\right) = C(z)\frac{1}{zn_{\text{pom}}}\left(1 - \exp(-z)\sum_{l=0}^{n_{\text{pom}}-1}\frac{z^l}{l!}\right)$, where

$z = \frac{2w\gamma s^{\Delta}}{R^2 + \alpha' \ln s}$, w=1.5, $\Delta = \alpha(0) - 1 = 0.2$, $\gamma = 1.035$ GeV^{-2}, $R^2 = 3.3$ GeV^{-2}, $\alpha^{'} = 0.05$ GeV^{-2}

based on:
D. Prokhorova, E. Andronov, G. Feofilov, Physics 5, 636 (2023)
E. Andronov, D. Prokhorova, A. Belousov, TMF 216, 417 (2023)

Building blocks of the model

LONGITUDINAL DYNAMICS

C.Shen, B.Schenke, Phys.Rev. C 97, 024907 (2018)

1) Due to string tension, $|\frac{dp_q}{dt}| = -\sigma$, rapidity of strings'endpoints changes:

$$y_q^{loss} = \mp \text{arccosh}\left(\frac{\tau^2\sigma^2}{2m_q^2} + 1\right)$$

TRANSVERSE DYNAMICS

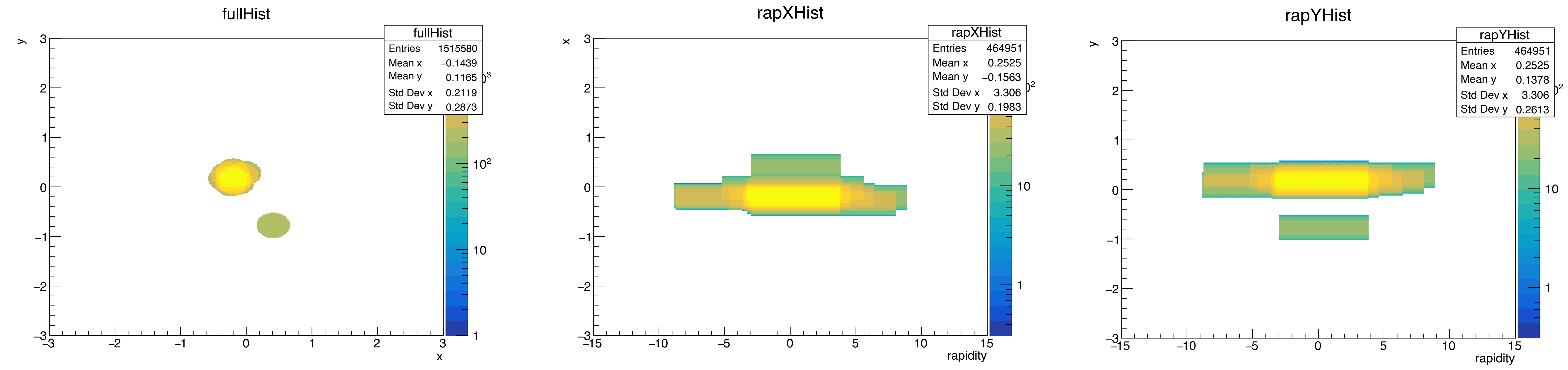
T.Kalaydzhyan, E.Shuryak, Phys.Rev. C 90, 014901 (2014)

1) Attractive interaction of strings (due to the sigma meson exchange) leads to their movement in the transverse plane according to $\ddot{\vec{r}}_i = \vec{f}_{ij} \propto \frac{\vec{r}_{ij}}{\tilde{r}_{ij}} K_1(m_\sigma \tilde{r}_{ij})$, where r_{ij} is a distance between i-th and j-th strings, $\tilde{r}_{ij} = \sqrt{r_{ij}^2 + s_{\text{string}}^2}$ is a regularised distance, $s_{\text{string}} = 0.176$ fm and K_1 is a modified Bessel function of the II type

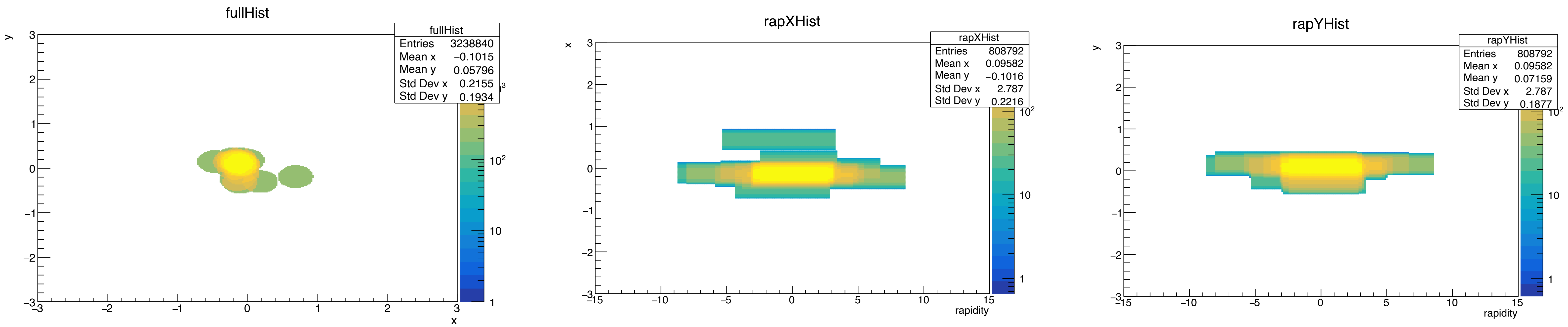
based on:
D. Prokhorova, E. Andronov, G. Feofilov, Physics 5, 636 (2023)
E. Andronov, D. Prokhorova, A. Belousov, TMF 216, 417 (2023)

Examples of string configurations

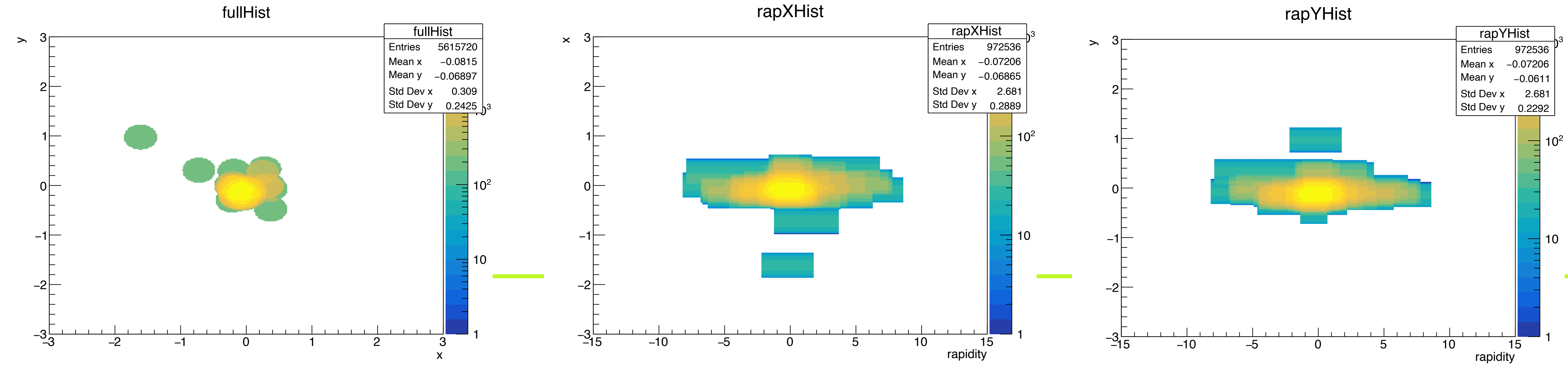
14 STRINGS



30 STRINGS



52 STRINGS



Building blocks of the model

STRING FUSION

M.A. Braun, C. Pajares, Phys.Lett.B 287, 154 (1992)

1) Rapidity space is split into slices and transverse plane is split into bins - we have 3d bins with different number of strings

2) Mean multiplicity from a string piece of length ϵ in rapidity - $\mu_0 \cdot \epsilon$

3) When color fields overlap due to their random orientation $\mu_0 \cdot \epsilon$ is enhanced non linearly: $\mu_0 \cdot \epsilon \cdot \sqrt{k} \cdot \frac{S_{bin}}{S_0}$, where k - number of strings in 3d bin, S_0 - area of a string, S_{bin} - area of 2d bin

4) Mean transverse momentum from an independent string - p_0

5) Mean transverse momentum from a 3d bin - $p_0 \cdot k^{\beta}$, where $\beta = 1.16[1 - (\ln\sqrt{s} - 2.52)^{-0.19}]$

V.Kovalenko et al,, Universe 8, 246 (2022)

Building blocks of the model

PARTICLE PRODUCTION

1) mean multiplicity from 3d bin: $\langle N_{bin} \rangle = \mu_0 \cdot \epsilon \cdot \sqrt{k} \cdot \frac{S_{bin}}{S_0}$, multiplicity from the Poisson distribution $P_{Pois}\left(\langle N_{bin} \rangle\right)$

2) For each particle we sample transverse momentum according to

$$f(p_T) = \frac{\pi p_T}{2\langle p_T \rangle_{bin}^2} \exp\left(-\frac{\pi p_T^2}{4\langle p_T \rangle_{bin}^2}\right), \text{ with } \langle p_T \rangle_{bin} = p_0 \cdot k^{\beta}$$

3) Particle species are sampled according to $\propto \exp\left(-\frac{\pi m_i^2}{4\langle p_T \rangle_{bin}^2}\right)$, where i corresponds to pions, kaons, protons, rho-mesons

Building blocks of the model

QUENCHING

M.A.Braun,C.Pajares, Eur.Phys.J.C 71, 1558 (2011)
A.I.Nikishov, V.I.Ritus, Sov. Phys. Uspekhi, 13 (1970) 303

1) QED with external EM field suggests the loss of energy: $\frac{dp(x)}{dx} = -0.12e^2\left(eEp(x)\right)^{2/3}$

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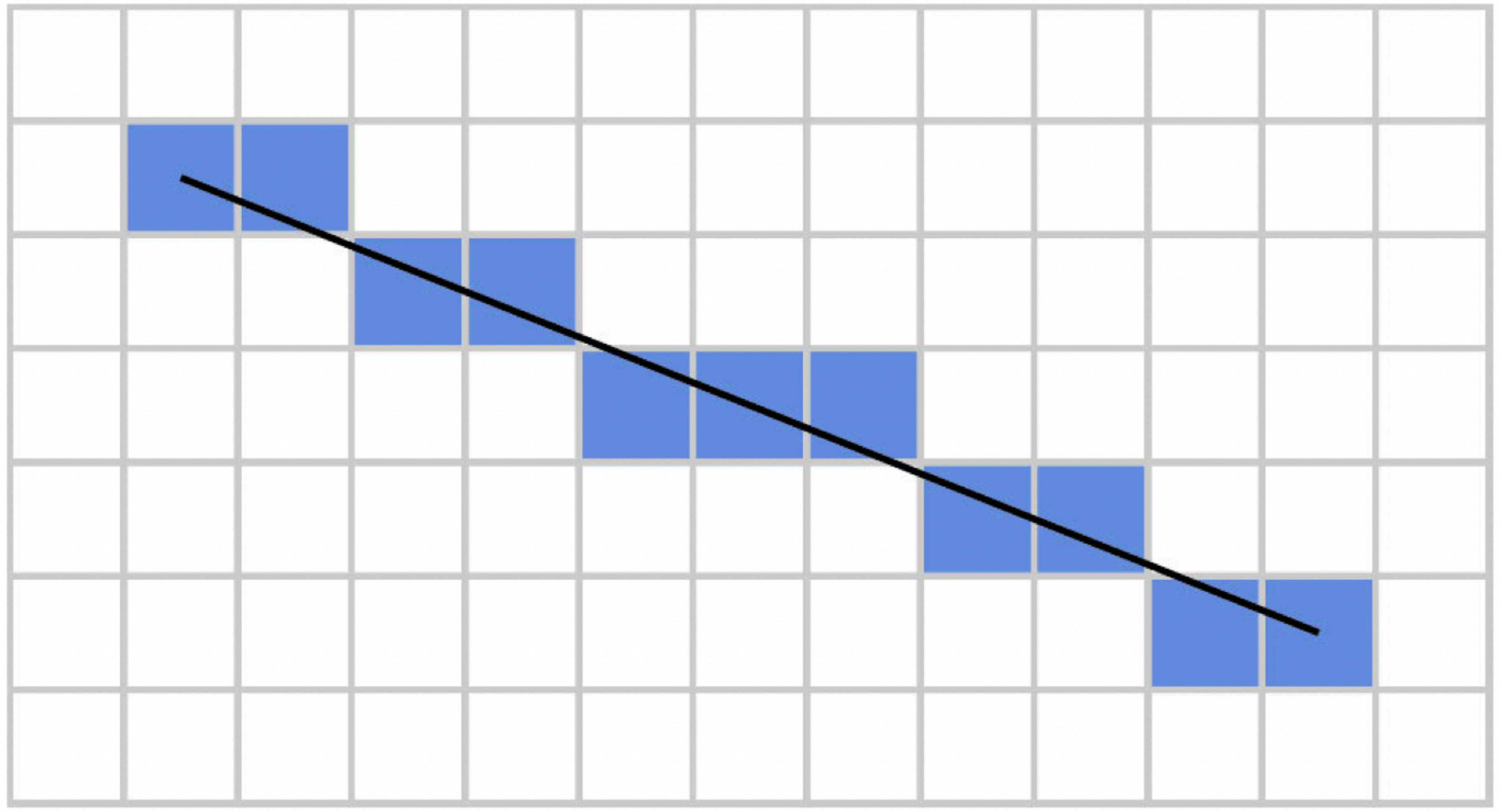
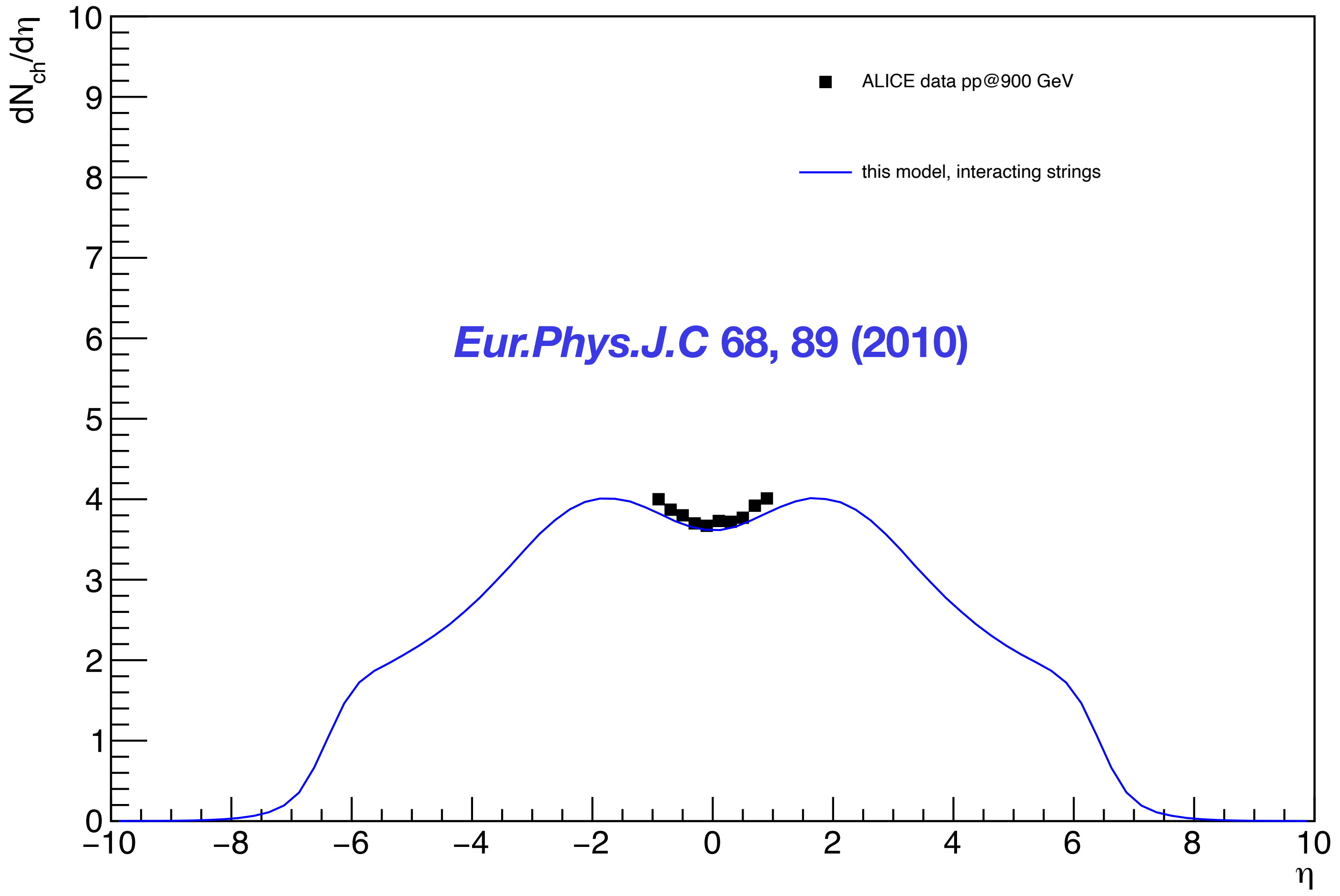


V. Kovalenko, EPJ Web Conf 137, 07012 (2017)
J. E. Bresneham, IBM Syst. J. 4, 25 (1965)

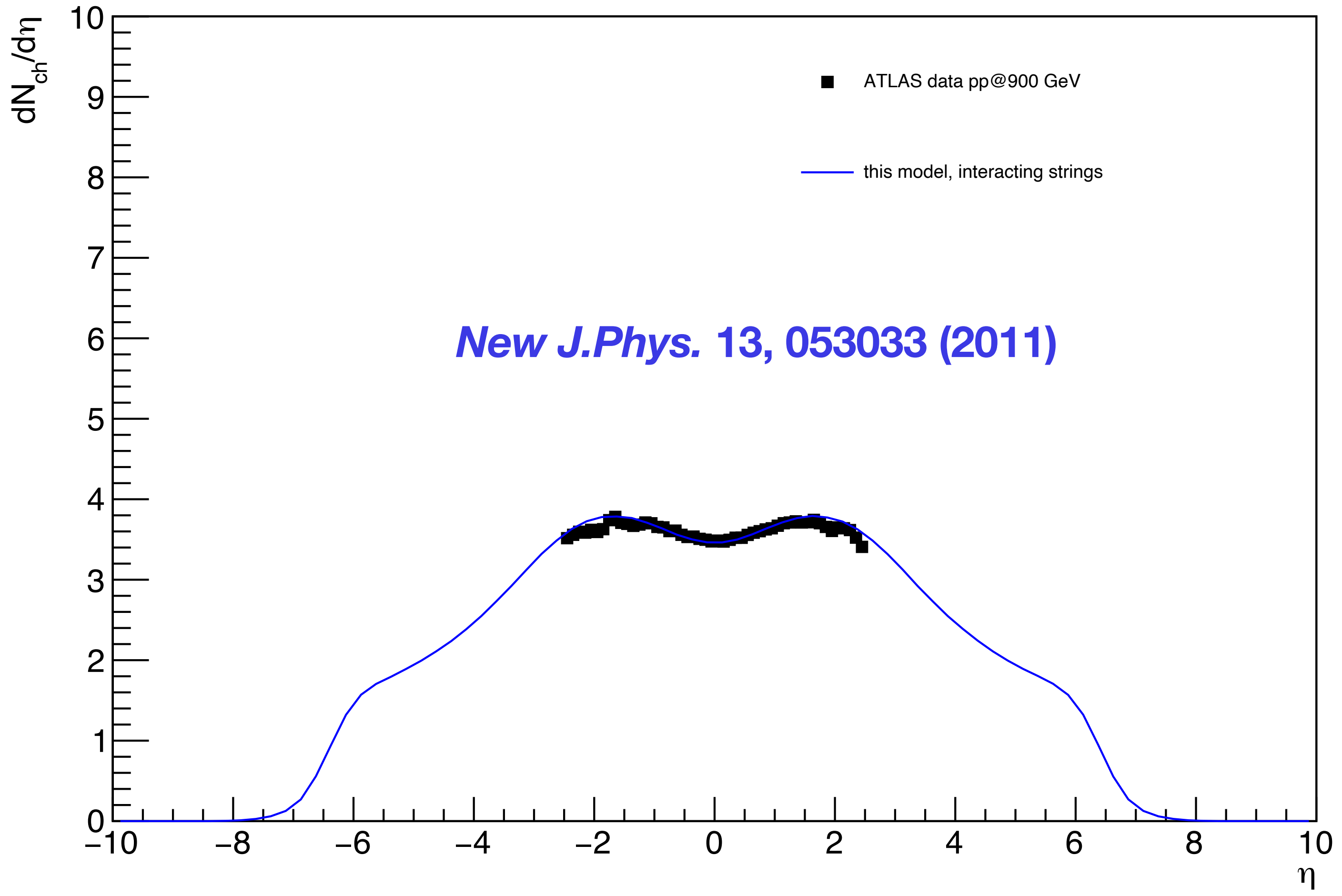
MODEL TUNING

900 GeV

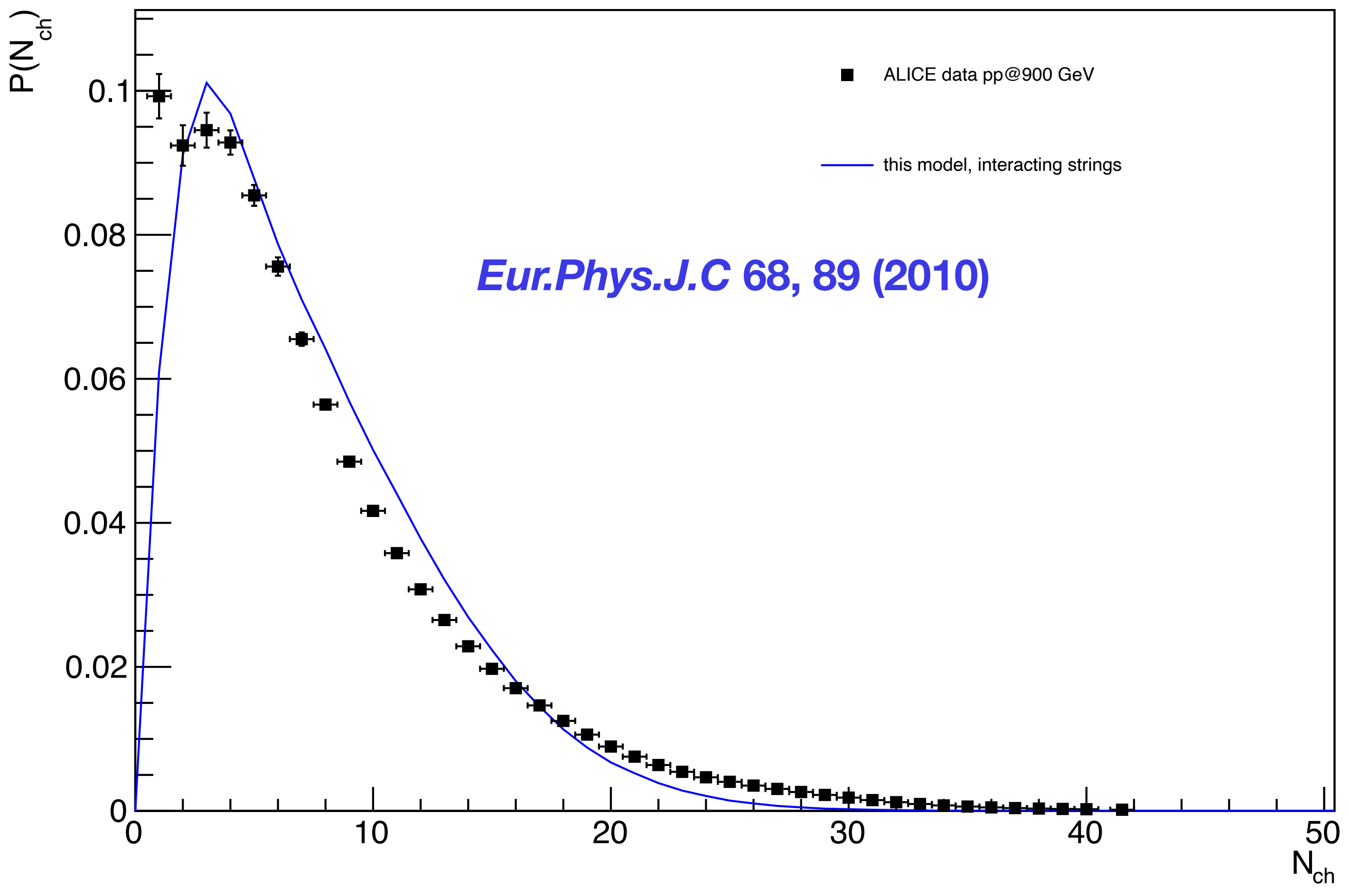
ALICE, INEL>0



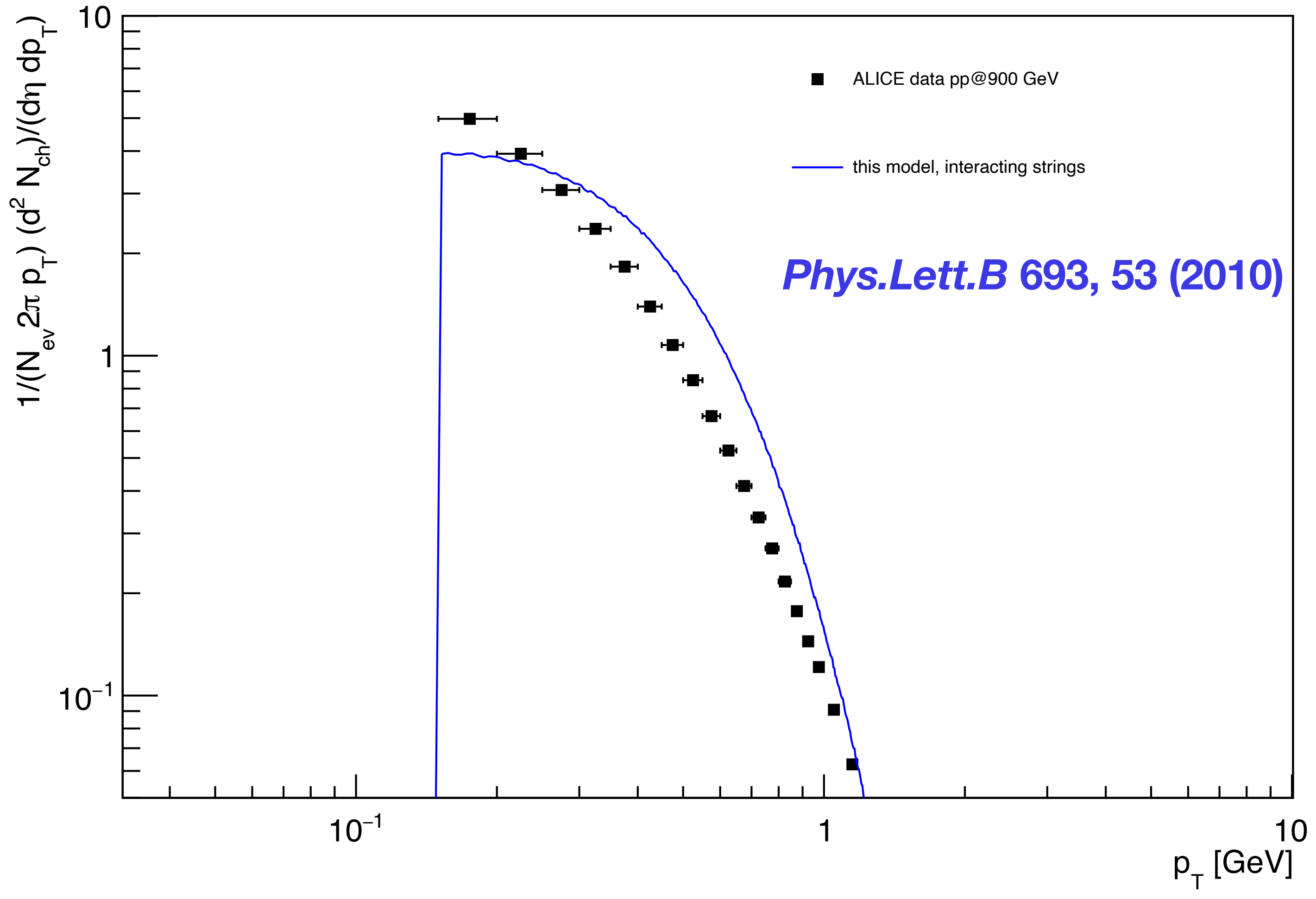
ATLAS, Nch>1, pT>0.1 GeV/c



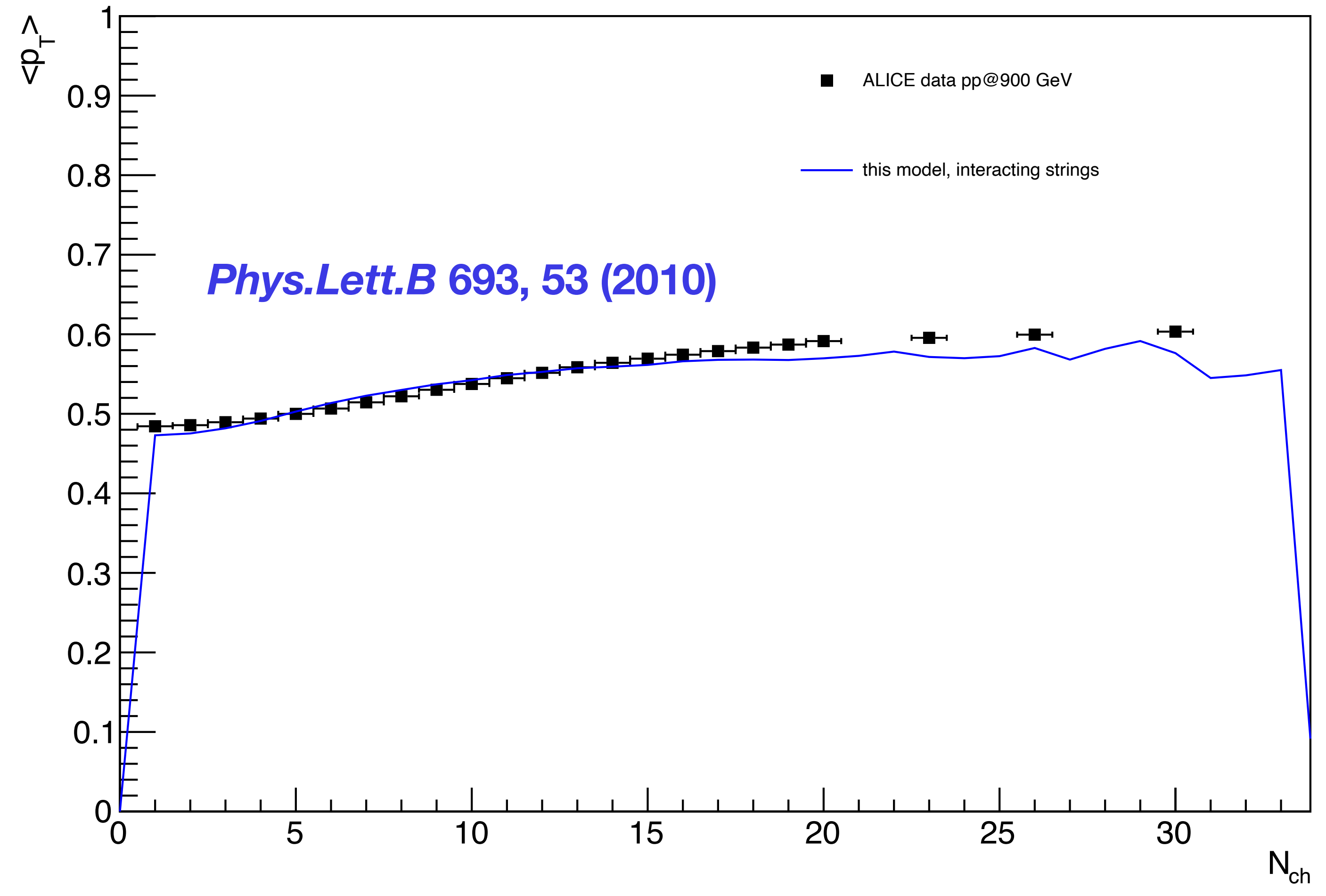
ALICE, $|\eta| < 1.0$, INEL, Nch>0



ALICE, pT spectra, $|\eta| < 0.8$



ALICE, pT-N correlation, pT>0.15 GeV/c, $|\eta| < 0.8$

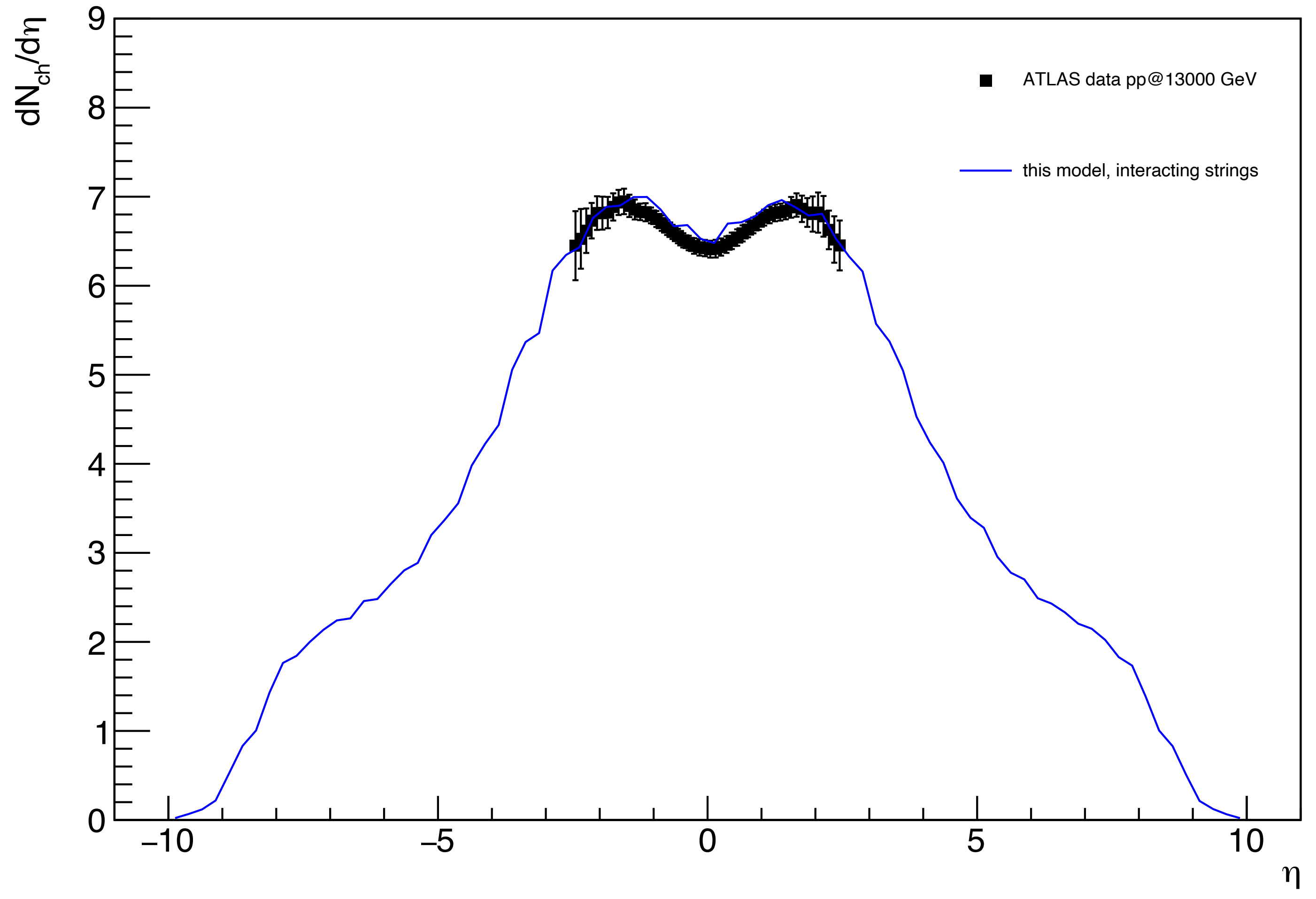


13000 GeV

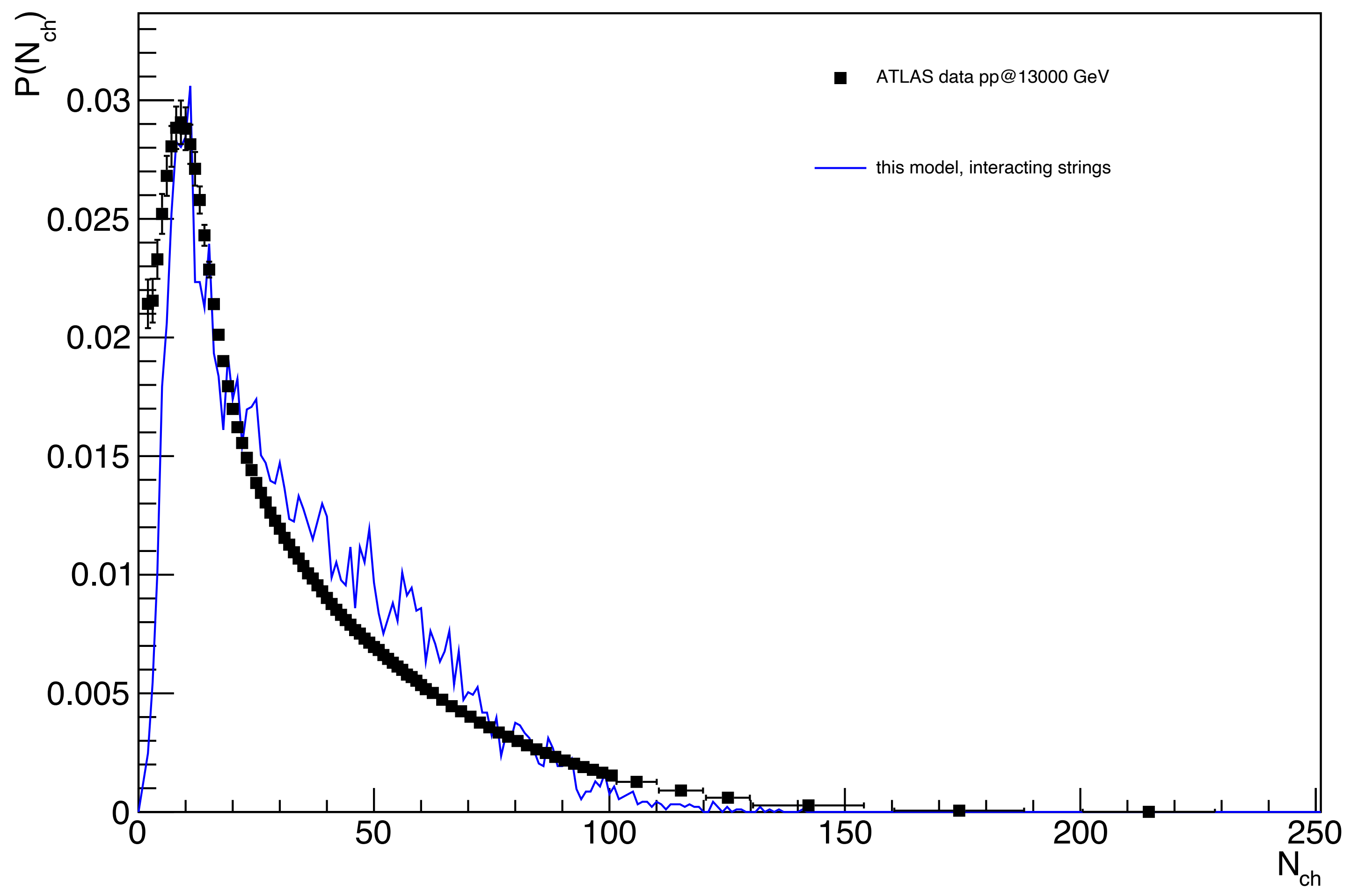
ATLAS, Nch>1, pT>0.1 GeV/c, $|\eta| < 2.5$

***Eur.Phys.J.C* 76, 502 (2016)**

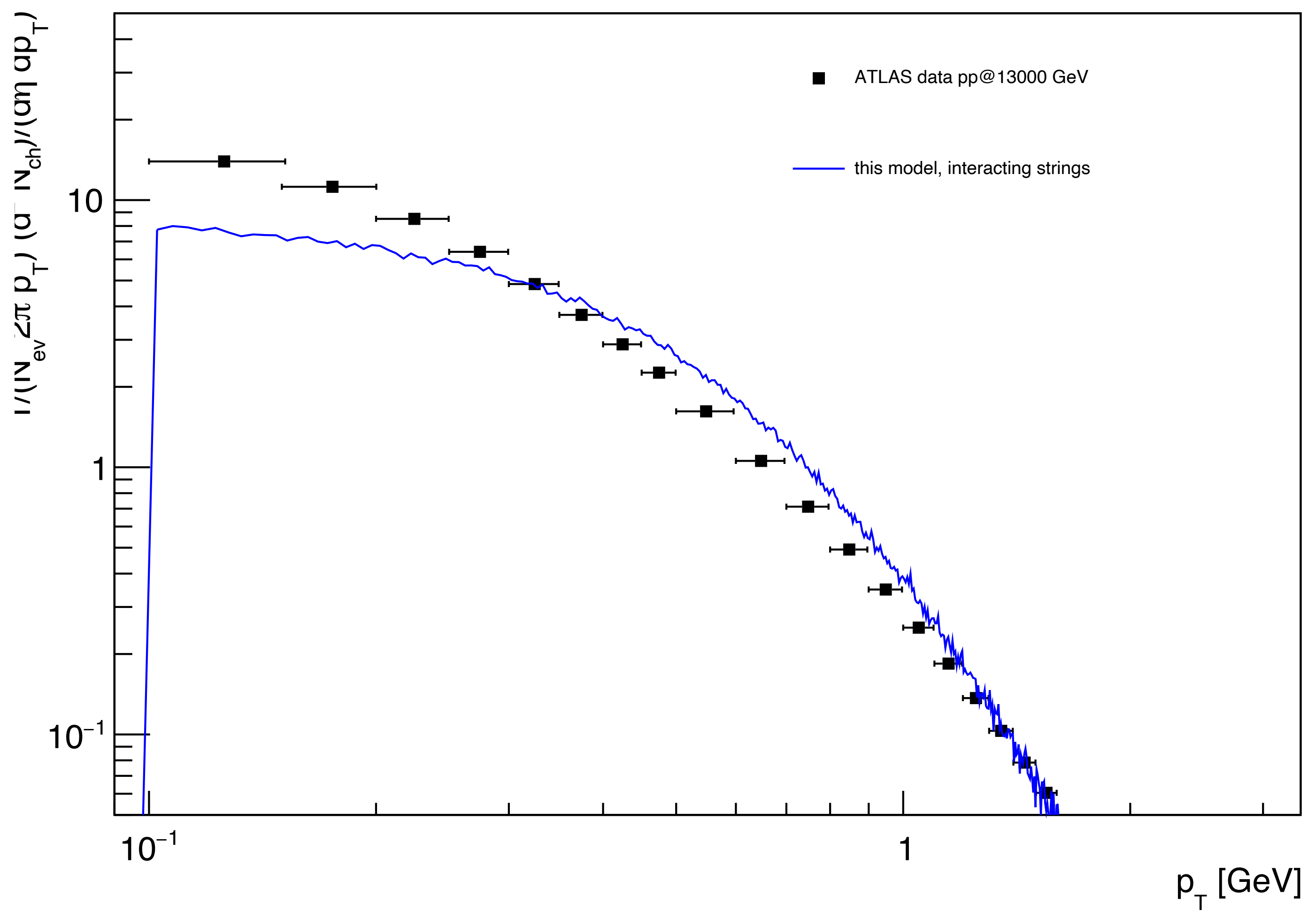
pseudorapidity



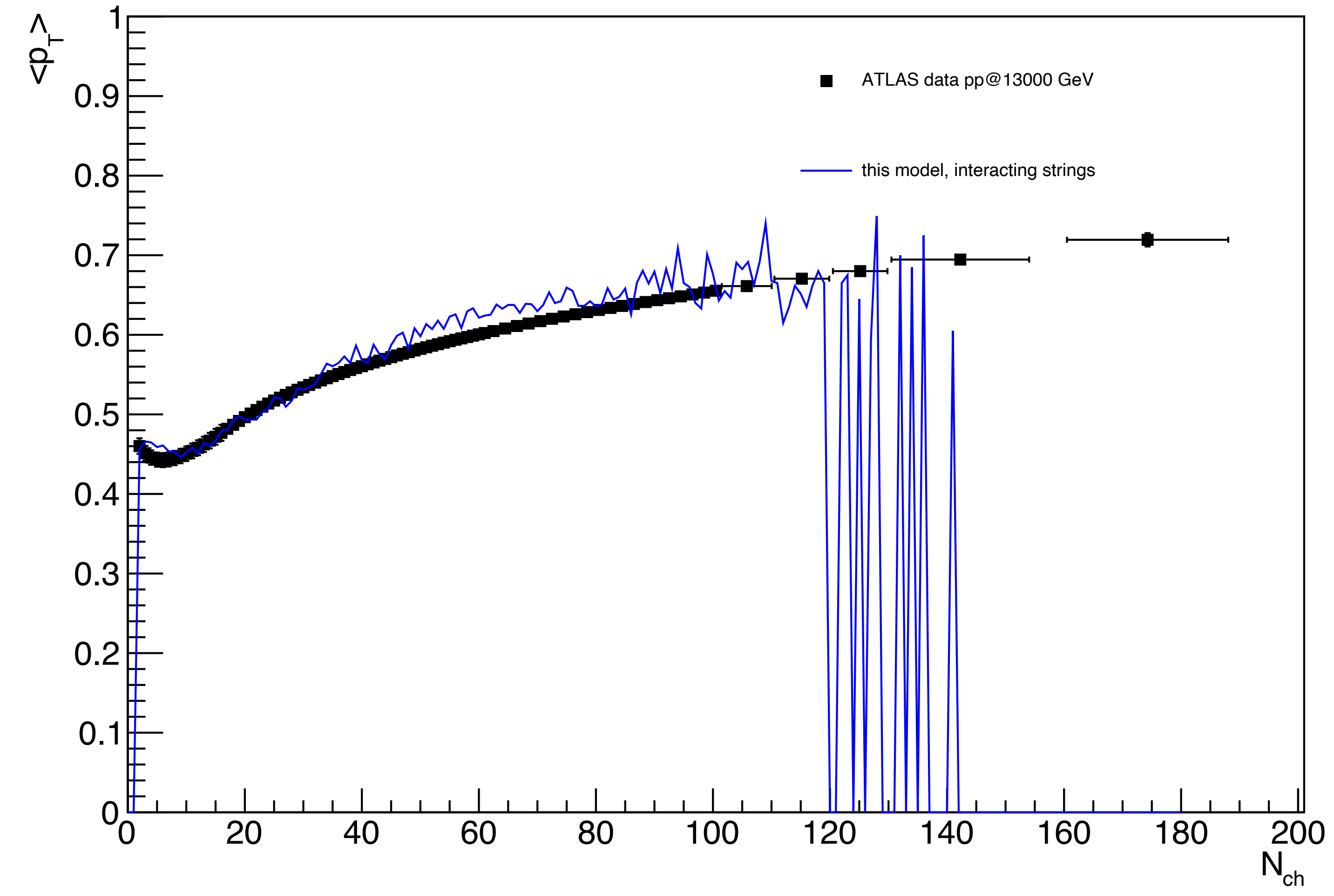
multiplicity



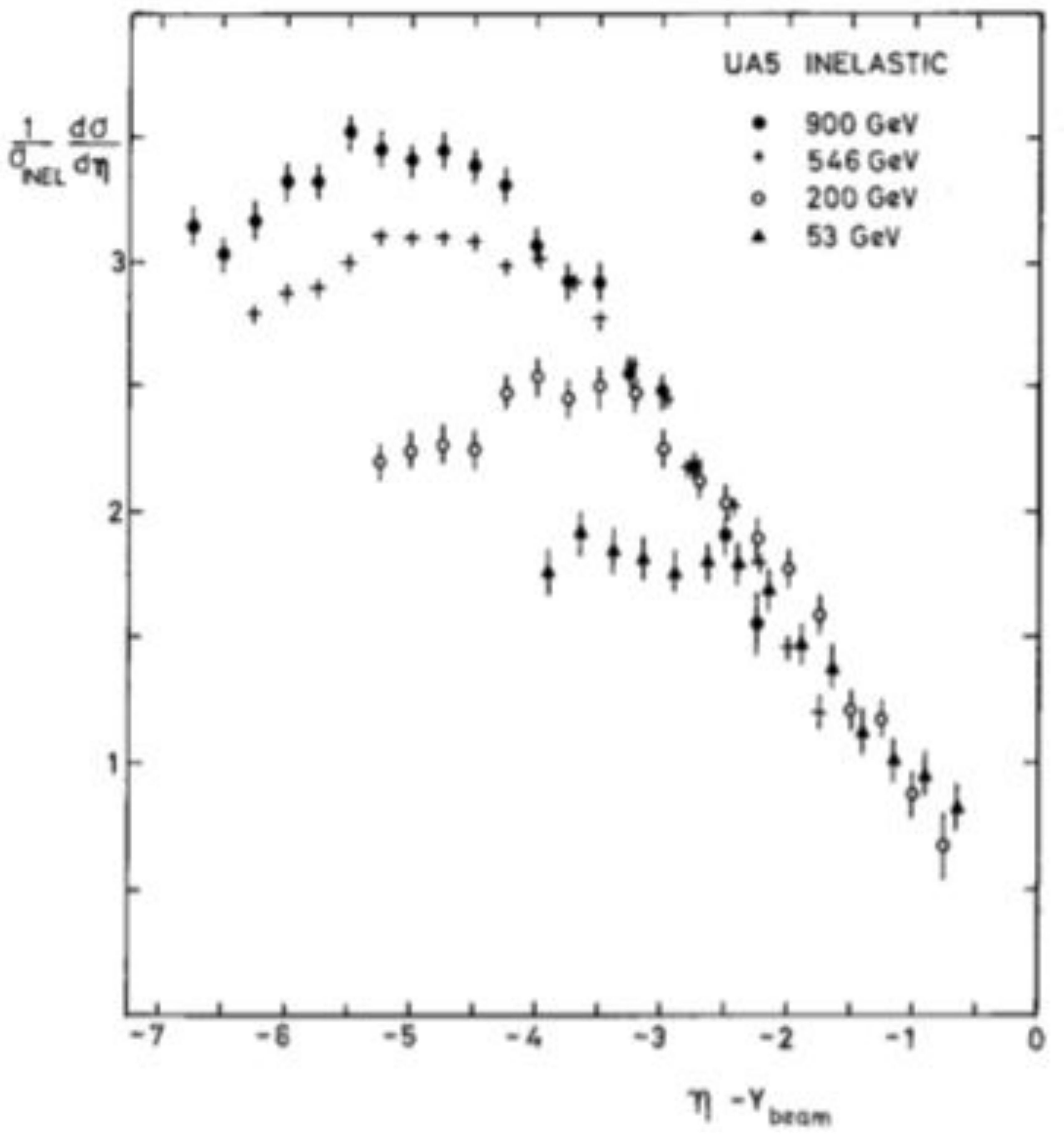
pT spectra

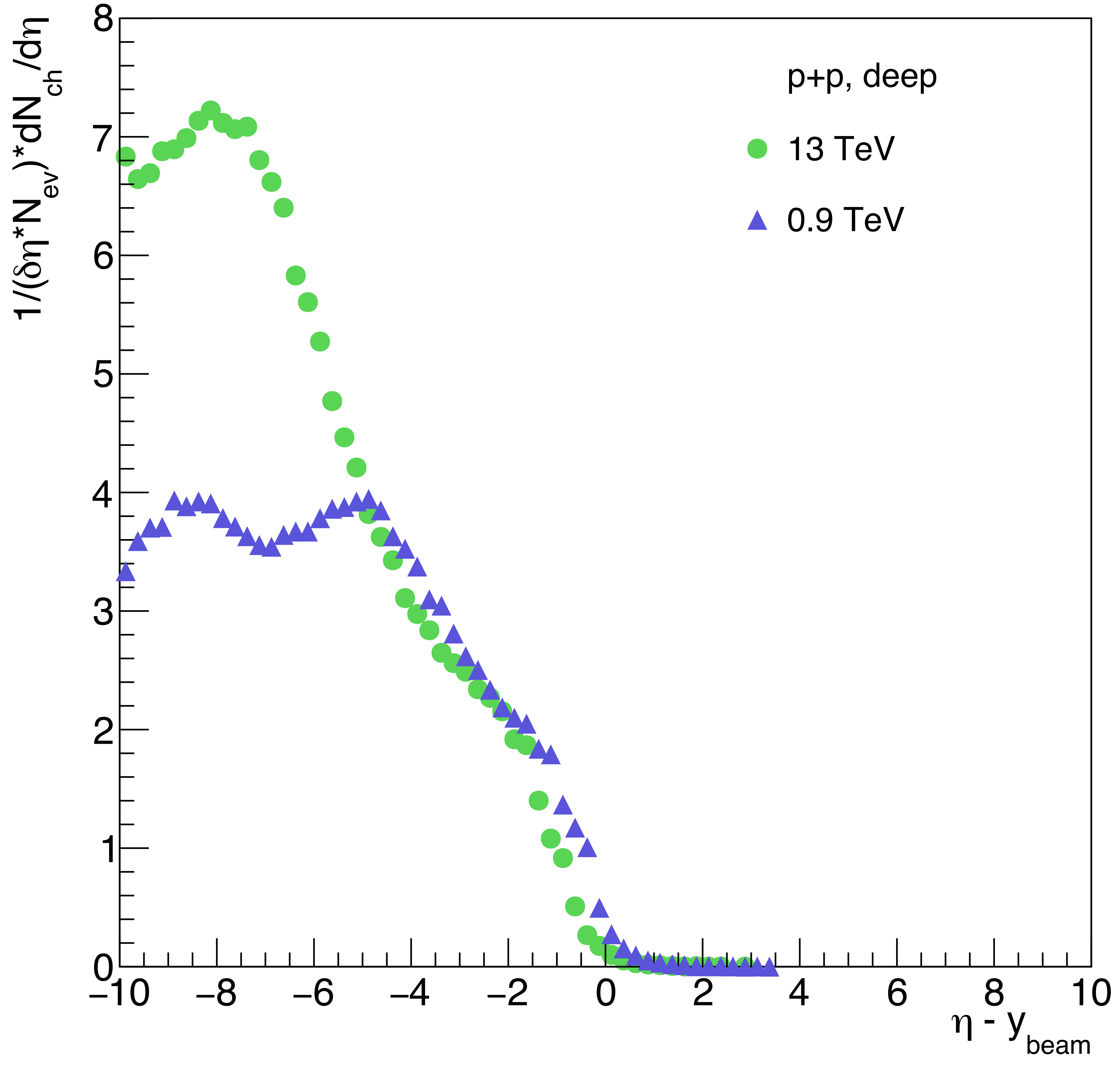


pT-N correlation



Scaling of pseudorapidity spectra





UA5 Coll., Z. Phys. C 33, 1 (1986)

String model with transverse dynamics

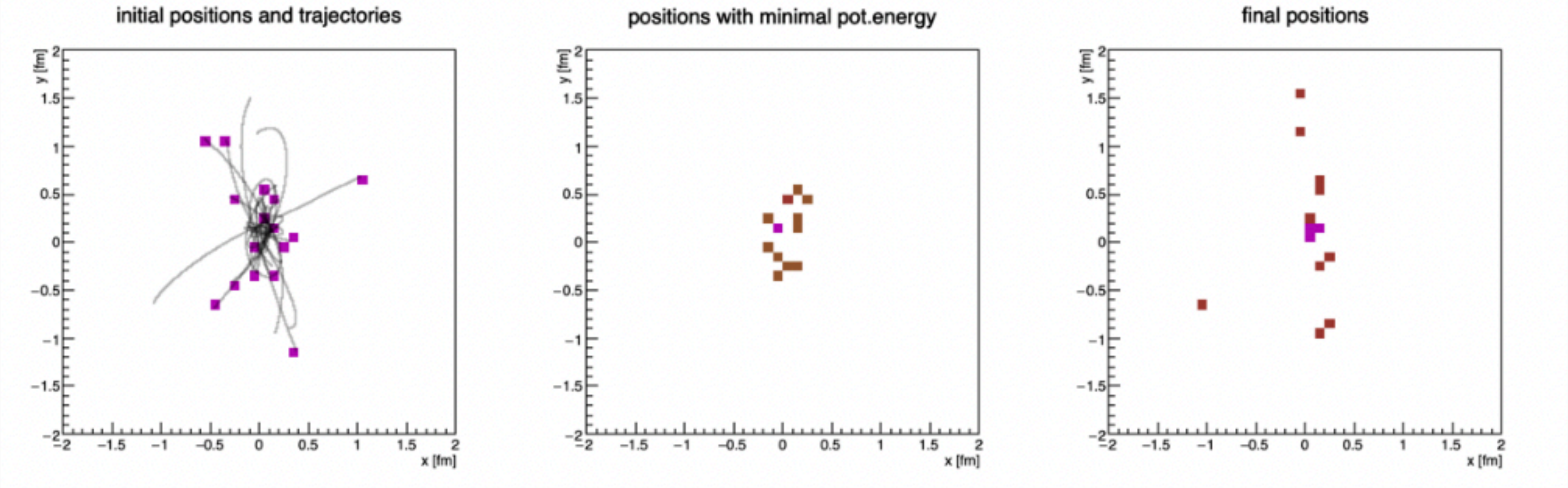
based on:
D. Prokhorova, E. Andronov, G. Feofilov, Physics 5, 636 (2023)
E. Andronov, D. Prokhorova, A. Belousov, TMF 216, 417 (2023)

The strings move **as a whole** according to [T.Kalaydzhyan, E.Shuryak, Phys. Rev. C 2014, **90**, 014901]:

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\tilde{r}_{ij}}(g_N\sigma)m_\sigma 2K_1(m_\sigma\tilde{r}_{ij}), \qquad (3)$$

with $\tilde{r}_{ij} = \sqrt{r_{ij}^2 + s_{\text{string}}^2}$, $s_{\text{string}} = 0.176$ fm, $g_N\sigma = 0.2$, $m_\sigma = 0.6$ GeV$/c^2$.

String density depends on **system evolution time** τ:



Example for 16 strings in an event: (**left**) initial positions and trajectories, (**center**) positions at time τ_{deepest} when the minimum potential energy of the string system is reached , (**right**) positions at $\tau = 1.5$ fm$/c$.

String model with longitudinal dynamics

based on:
D. Prokhorova, E. Andronov, G. Feofilov, Physics 5, 636 (2023)
E. Andronov, D. Prokhorova, A. Belousov, TMF 216, 417 (2023)

The **initial** positions of strings' ends in rapidity are determined by the momenta and masses of the corresponding partons:

$$y_q^{\text{init}} = \pm \,\text{arcsinh}\left(\frac{x_q p_{\text{beam}}}{m_q}\right), \qquad (4)$$

Due to string tension, $|\frac{dp_q}{dt}| = -\sigma$, rapidity of strings' **massive ends** decreases [C.Shen, B.Schenke, Phys. Rev. C 2018, **97**, 024907] by:

$$y_q^{\text{loss}} = \mp \,\text{arccosh}\left(\frac{\tau^2\sigma^2}{2m_q^2} + 1\right), \qquad (5)$$

This is valid up to the turning point of a parton at the string end

After the turning point rapidity start to change in the different direction until parton reaches another turning point etc.

Considered partons -

valence u and d quarks

sea u, d, s, c quarks and antiquarks

ud, dd diquarks

Conditions on string formation:

1) sum of charges of parton endpoints is integer

2) sufficient energy for creation of at least to hadrons (based on quark content):

$$E_{str} = \sqrt{m_{part1}^2 + p_{part1}^2} + \sqrt{m_{part2}^2 + p_{part2}^2} > M_{daughter1} + M_{daughter2}$$