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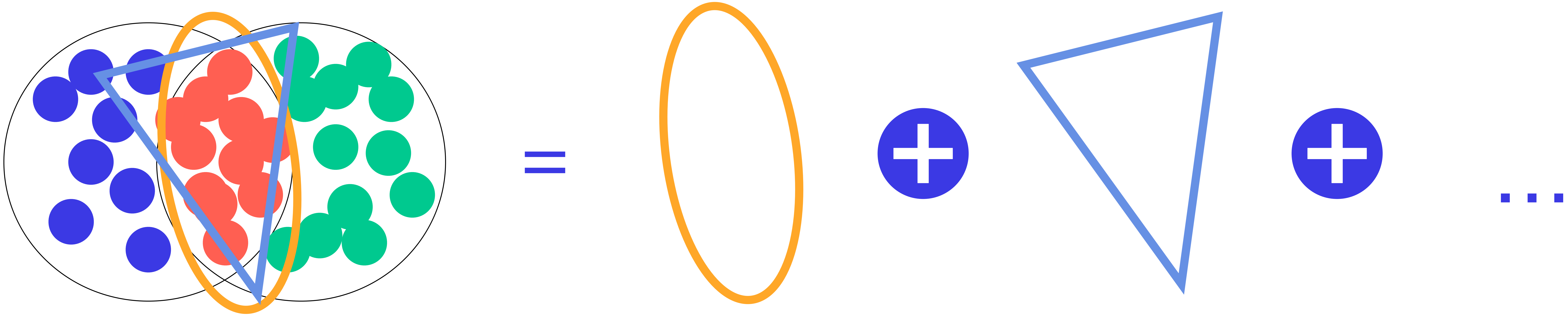
Azimuthal flow as a probe of color string fusion in p+p collision

EVGENY ANDRONOV, DARIA PROKHOROVA, SAINT PETERSBURG STATE UNIVERSITY, 21/09/2023

INTRODUCTION

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

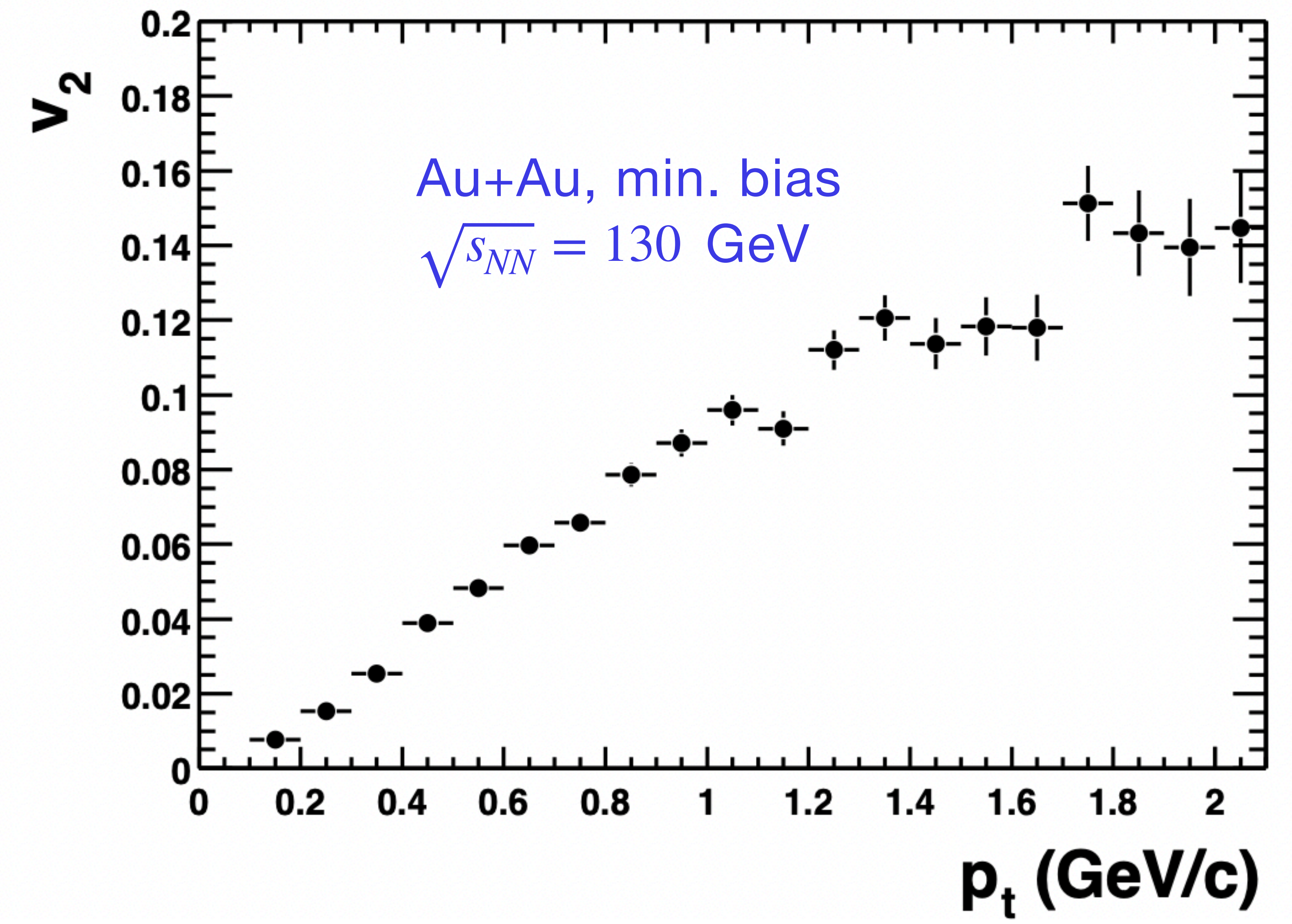
This decomposition affects momentum space anisotropy of the produced particles

Azimuthal flow

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

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

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



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

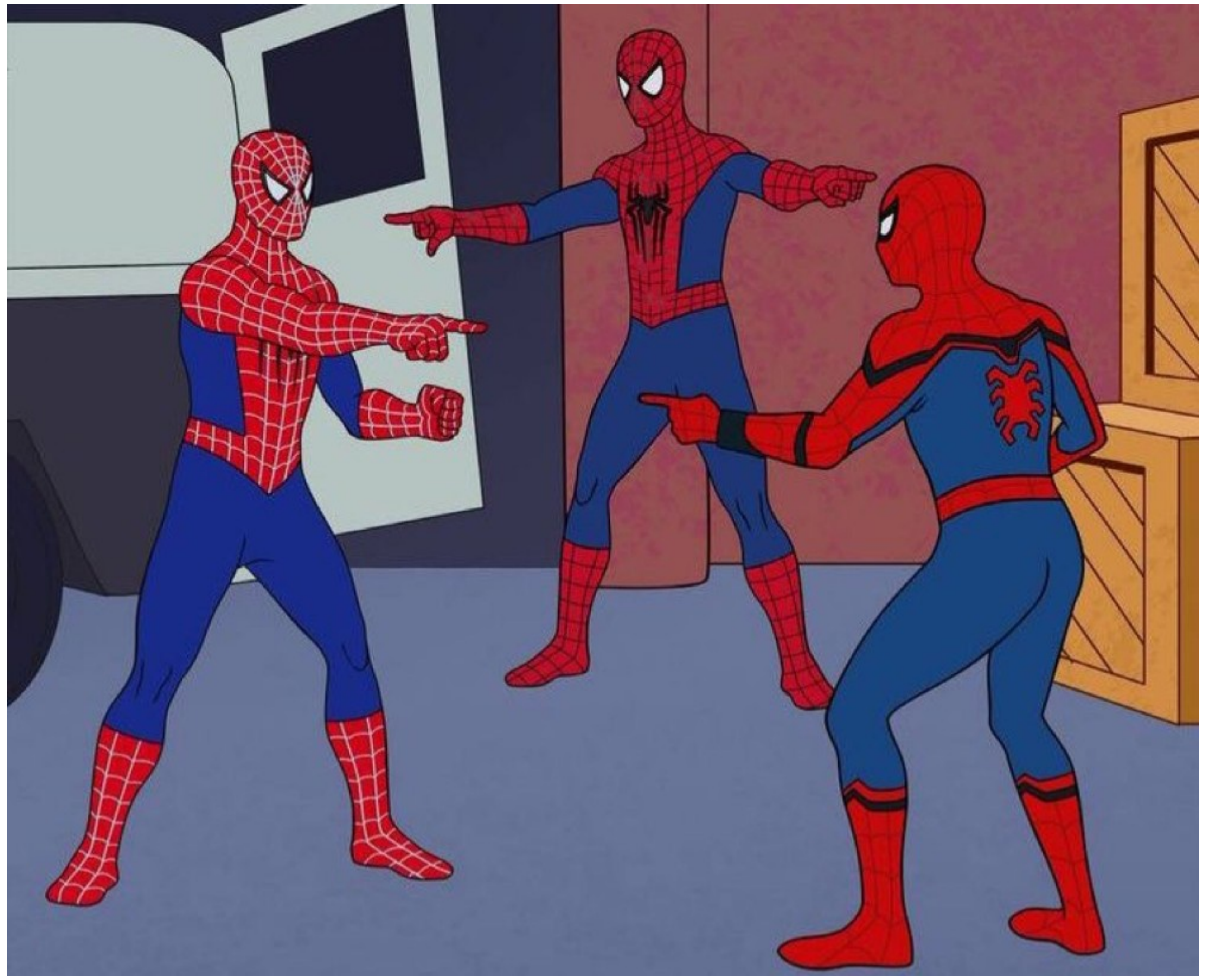
Experimental results on flow in heavy ion collisions perfectly explained as a collective effect due to viscous relativistic hydro evolution of QGP (different pressure gradients in different directions)

Azimuthal flow - methods

There are multiple ways to extract information on anisotropy:

Event plane determination (non applicable for low-multiplicty events (low resolution))

Two-particle correlations (one has to apply additional cut $|\Delta\eta| > \eta_{gap}$ to suppress non-flow)



Q-cumulant analysis (i.e. multi-particle correlations) - allows to further suppress non-flow

Azimuthal flow - cumulants

Average correlation in an event

Averaging over all events

$$\langle 2\rangle = \langle e^{in(\phi_1 - \phi_2)}\rangle$$

$$\langle\langle 2\rangle\rangle = \langle\langle e^{in(\phi_1 - \phi_2)}\rangle\rangle = \frac{\sum_{events} w_{2,i}\langle 2\rangle_i}{\sum_{events} w_i}$$

$$\langle 4\rangle = \langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)}\rangle$$

$$\langle\langle 4\rangle\rangle = \langle\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)}\rangle\rangle = \frac{\sum_{events} w_{2,i}\langle 4\rangle_i}{\sum_{events} w_i}$$

Cumulant expansion of multi-particle correlations allow to express harmonics through cumulants

$$c_n\{2\} = \langle\langle 2\rangle\rangle$$

$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2$$

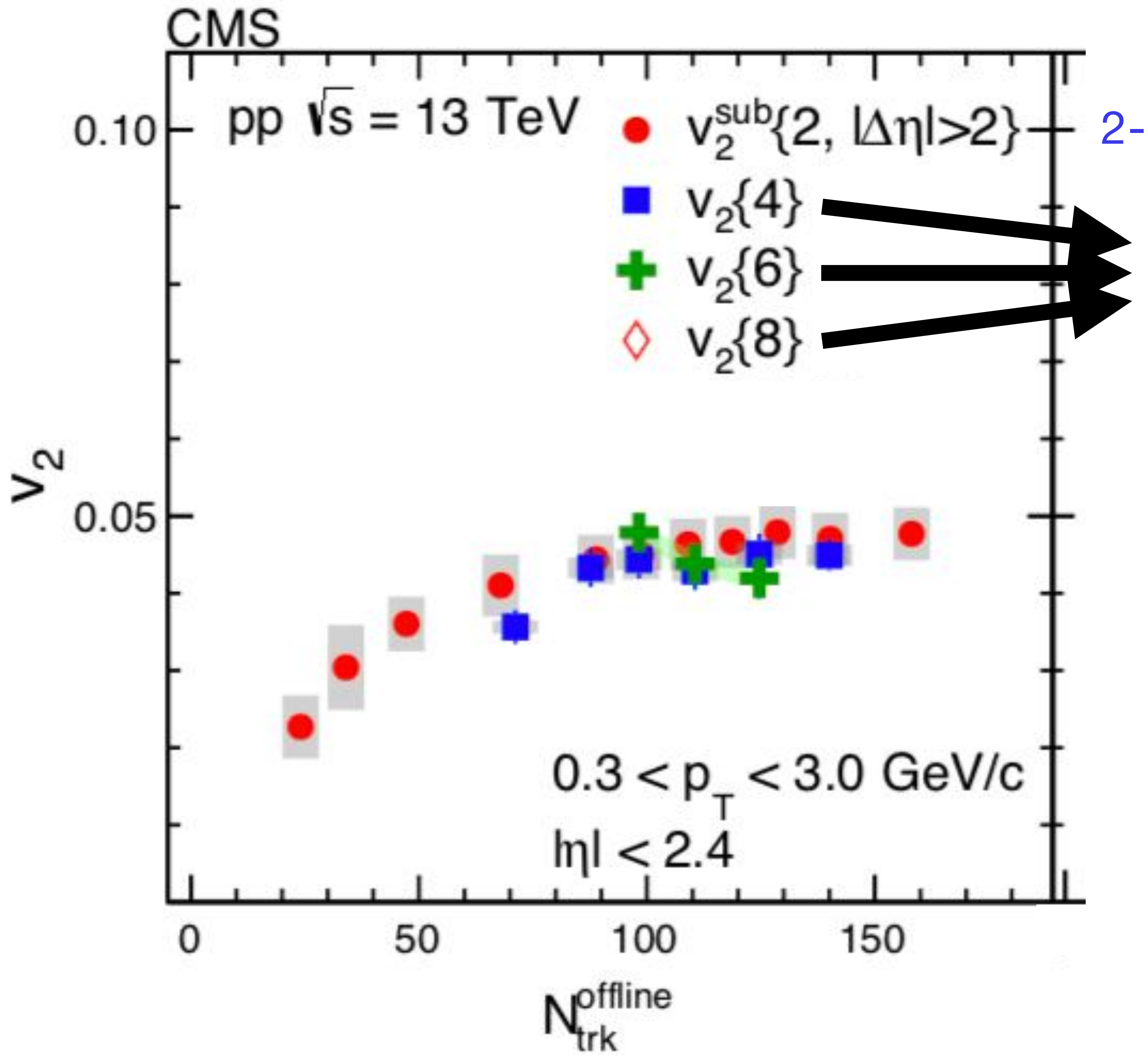
$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

N. Borghini, P.M. Dinh, J.Y. Ollitrault, *Phys.Rev.C* 64 (2001) 054901
A. Bilandzic, R. Snellings, S. Voloshin, **Phys. Rev. C 83, 044913 (2011).**

Azimuthal flow as seen in p+p collisions

Recent results from LHC collaborations suggest that flow is also built up in p+p collisions



2-particle correlations

{n}-order cumulants

CMS Coll., Phys. Lett. B 765, 193 (2017)

Key observations from CMS:

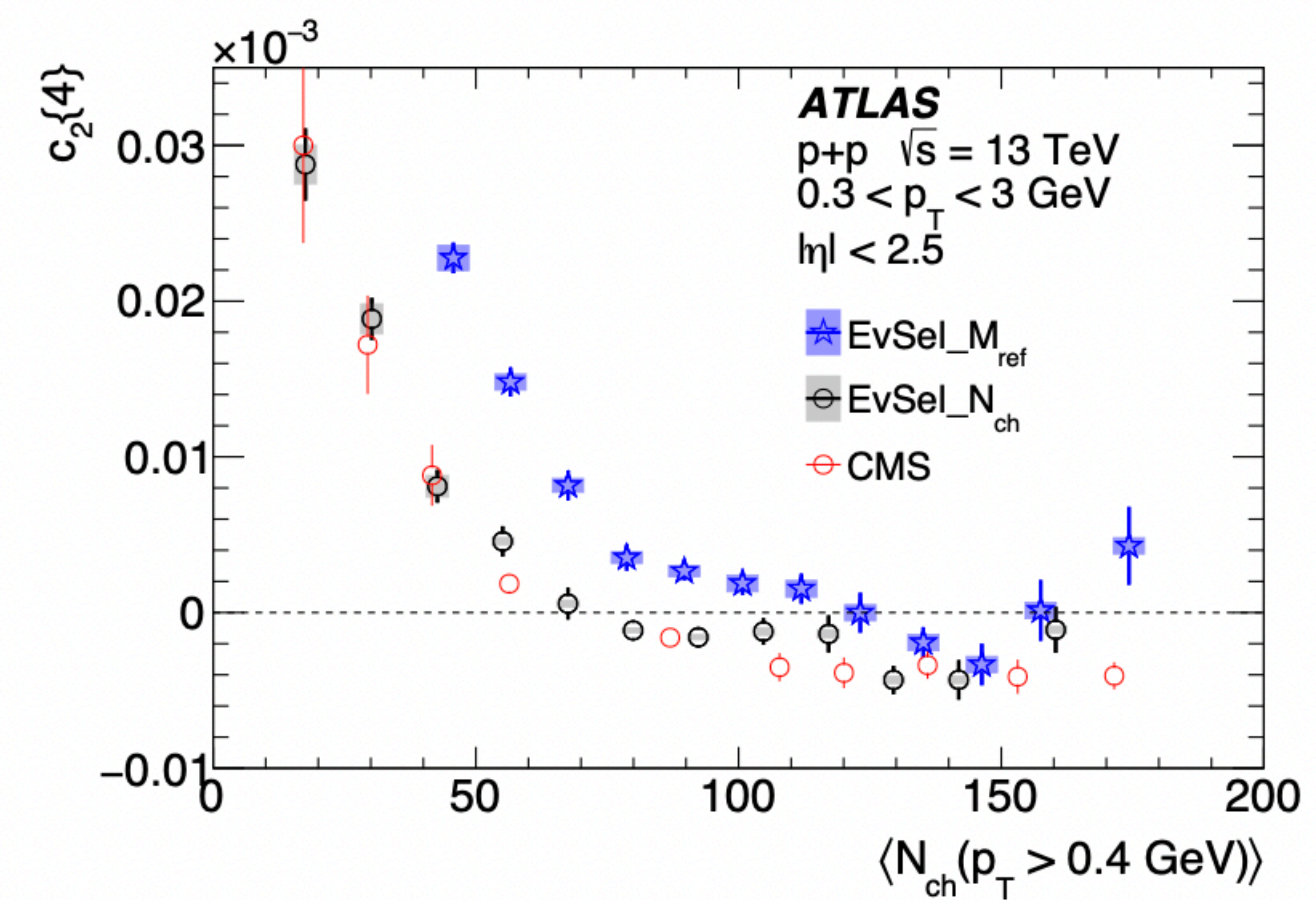
1) increase of v2 for more «central» events
2) almost no difference between 2PC and cumulants results ($v_2\{2\} > v2\{n\}$ for A+A collisions)

comparable within uncertainties. These observations provide strong evidence supporting the interpretation of a collective origin for the observed long-range correlations in high-multiplicity pp collisions.

Azimuthal flow as seen in p+p collisions

Further analysis by ATLAS indicated that it is a subtle matter

$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$



ATLAS Coll., *Eur.Phys.J.C* 77, 428 (2017)

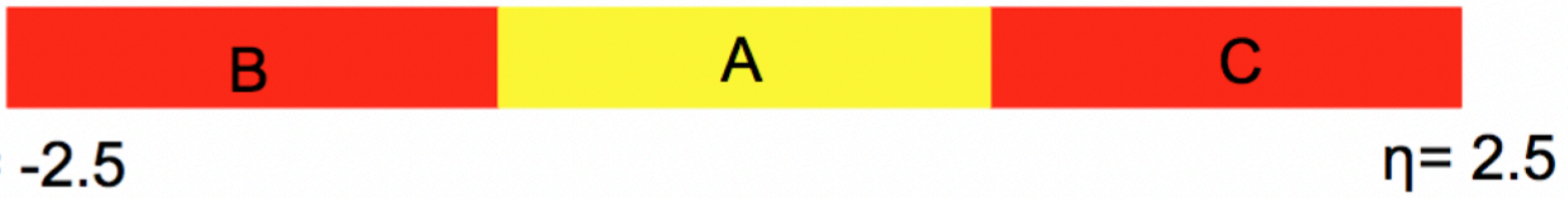
Key observations from ATLAS:

1) $c_2\{4\} > 0$ for $\sqrt{s} = 5.02$ TeV (not shown here) and mostly for $\sqrt{s} = 13$ TeV
2) results for p+Pb and Pb+Pb are more consistent with CMS (not shown here)

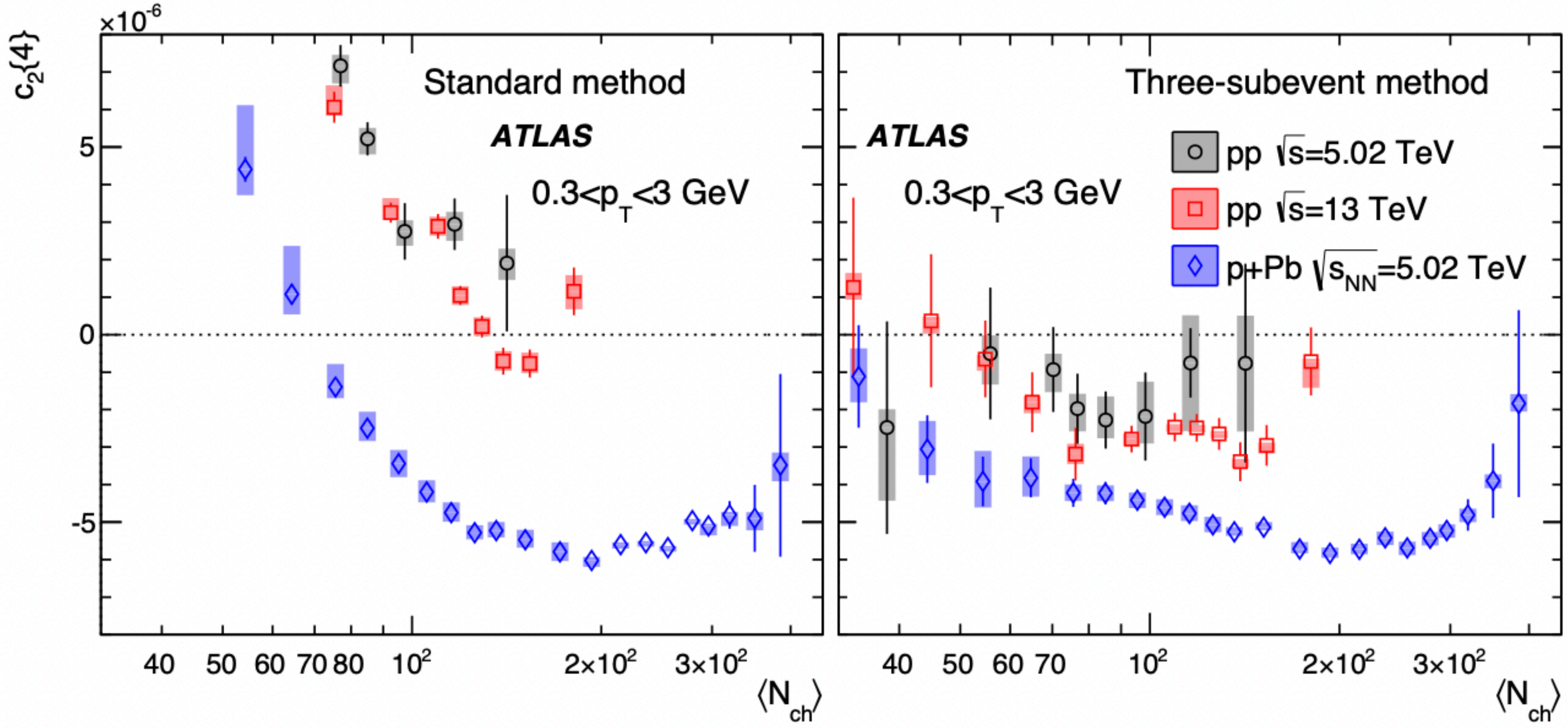
Azimuthal flow as seen in p+p collisions

Further suppression of non-flow was achieved by ATLAS using subevent method

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$



J. Jia, M. Zhou, A. Trzupek, *Phys.Rev.C* 96, 034906 (2017)



ATLAS Coll., *Phys.Rev.C* 97, 024904 (2018)

$$c_n^{A,A|B,C}\{4\} = \langle\langle 4\rangle\rangle_{A,A|B,C} - 2\cdot\langle\langle 2\rangle\rangle_{A|B}\cdot\langle\langle 2\rangle\rangle_{A|C}$$

2 particles from subevent A,

1 - from B,

1 - from C

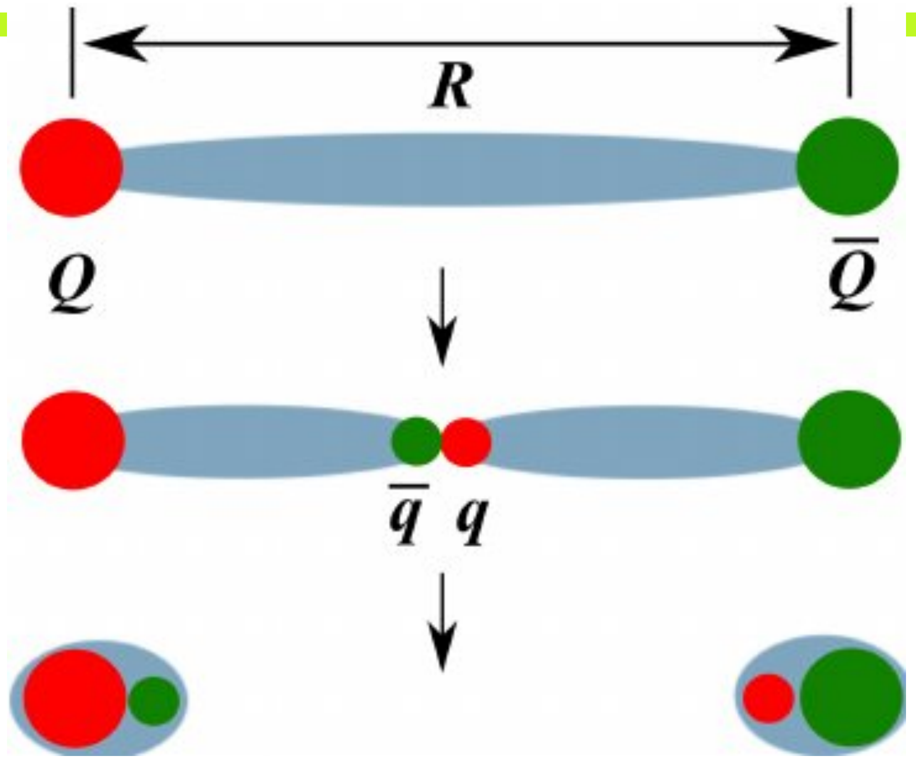
1 - from A

1 - from B

1 - from A

1 - from C

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

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

$z = \dfrac{2w\gamma s^{\Delta}}{R^2 + \alpha' \ln s}$, 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

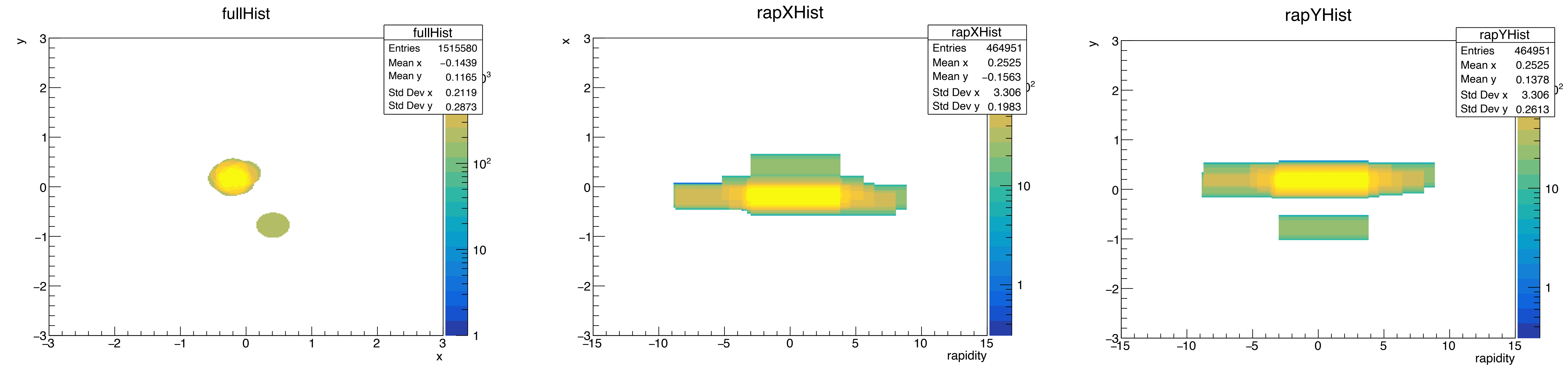
T.Kalaydzhyan, E.Shuryak, Phys.Rev. C 90, 014901 (2014)

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

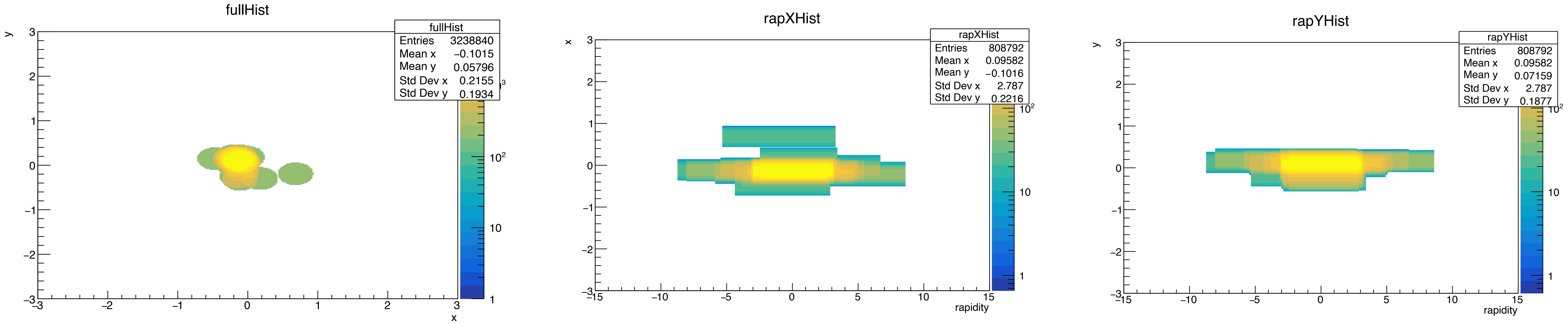
based on:
D. Prokhorova, E. Andronov, G. Feofilov, Physics 5, 636 (2023)
E. Andronov, D. Prokhorova, A. Belousov, TMF 216, 417 (2023)

Examples of string configurations

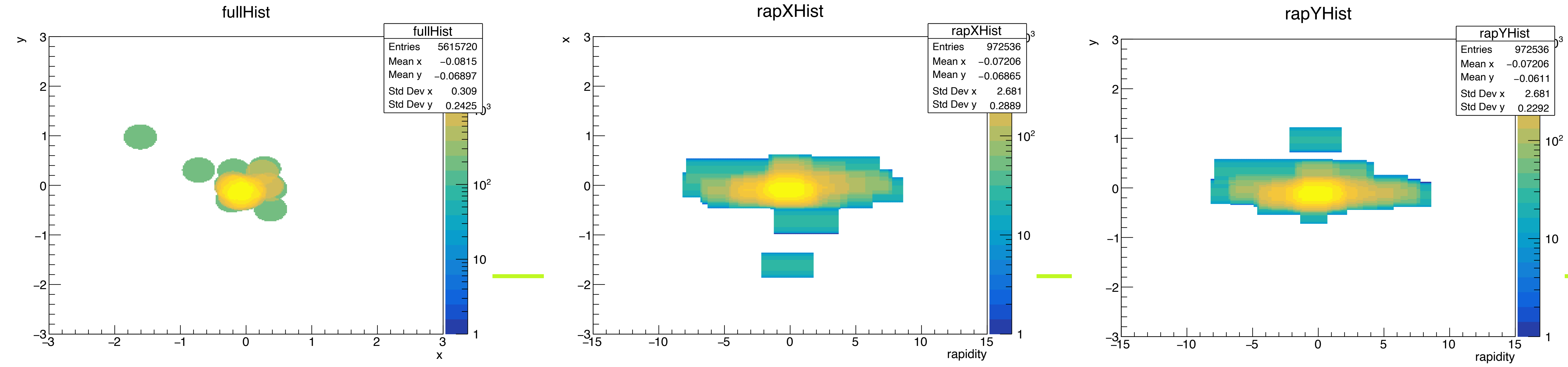
14 STRINGS



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

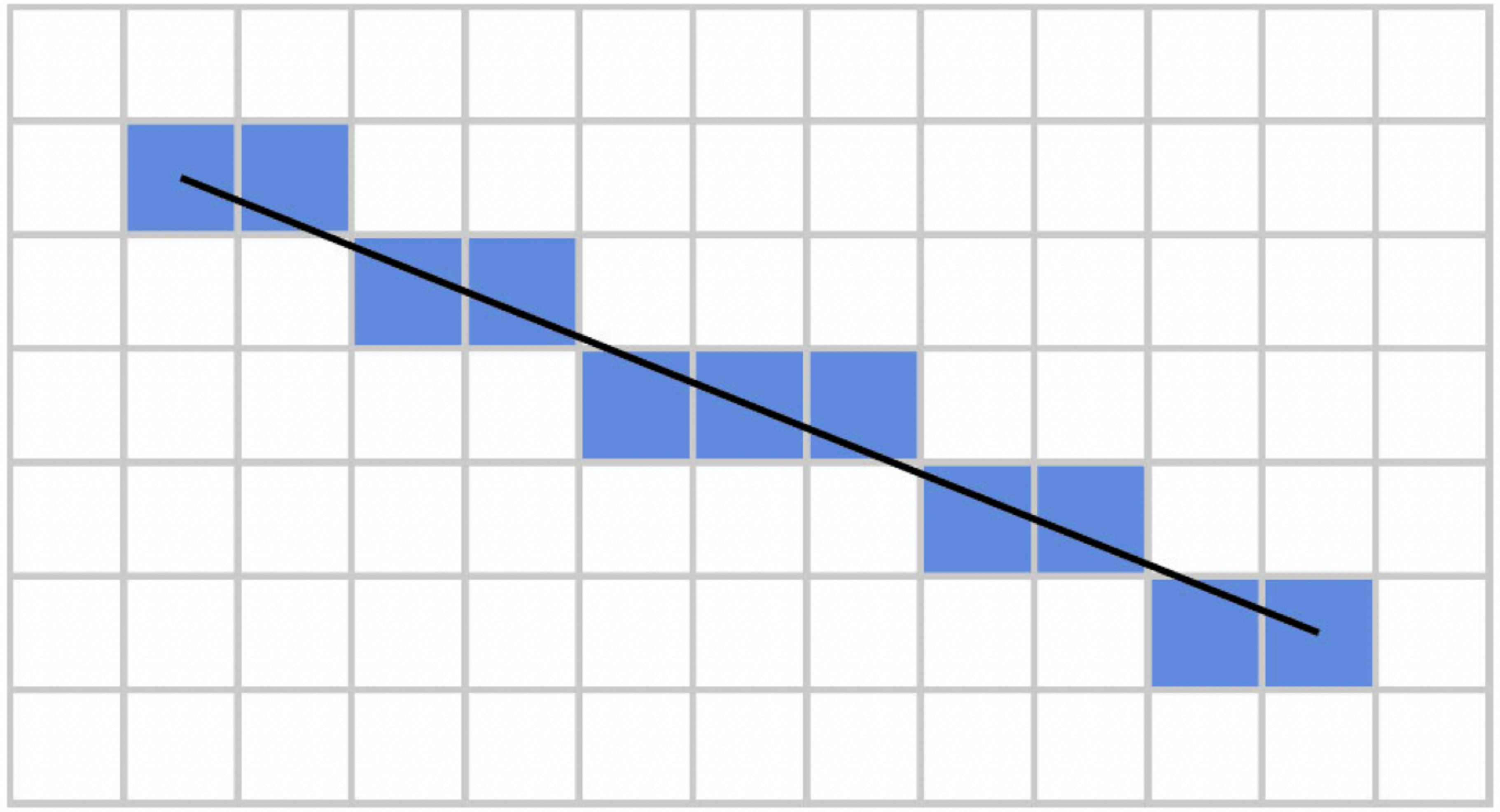
1) mean multiplicity from 3d bin: $\langle N_{bin} \rangle = \mu_0 \cdot \epsilon \cdot \sqrt{k} \cdot \frac{S_{bin}}{S_0}$, multiplicity from the Poisson distribution $P_{Pois}\left(\langle N_{bin} \rangle\right)$
2) For each particle we sample transverse momentum according to $f(p_T) = \frac{\pi p_T}{2\langle p_T \rangle_{bin}^2} \exp\left(-\frac{\pi p_T^2}{4\langle p_T \rangle_{bin}^2}\right)$, 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: $\frac{dp(x)}{dx} = -0.12e^2\left(eEp(x)\right)^{2/3}$
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



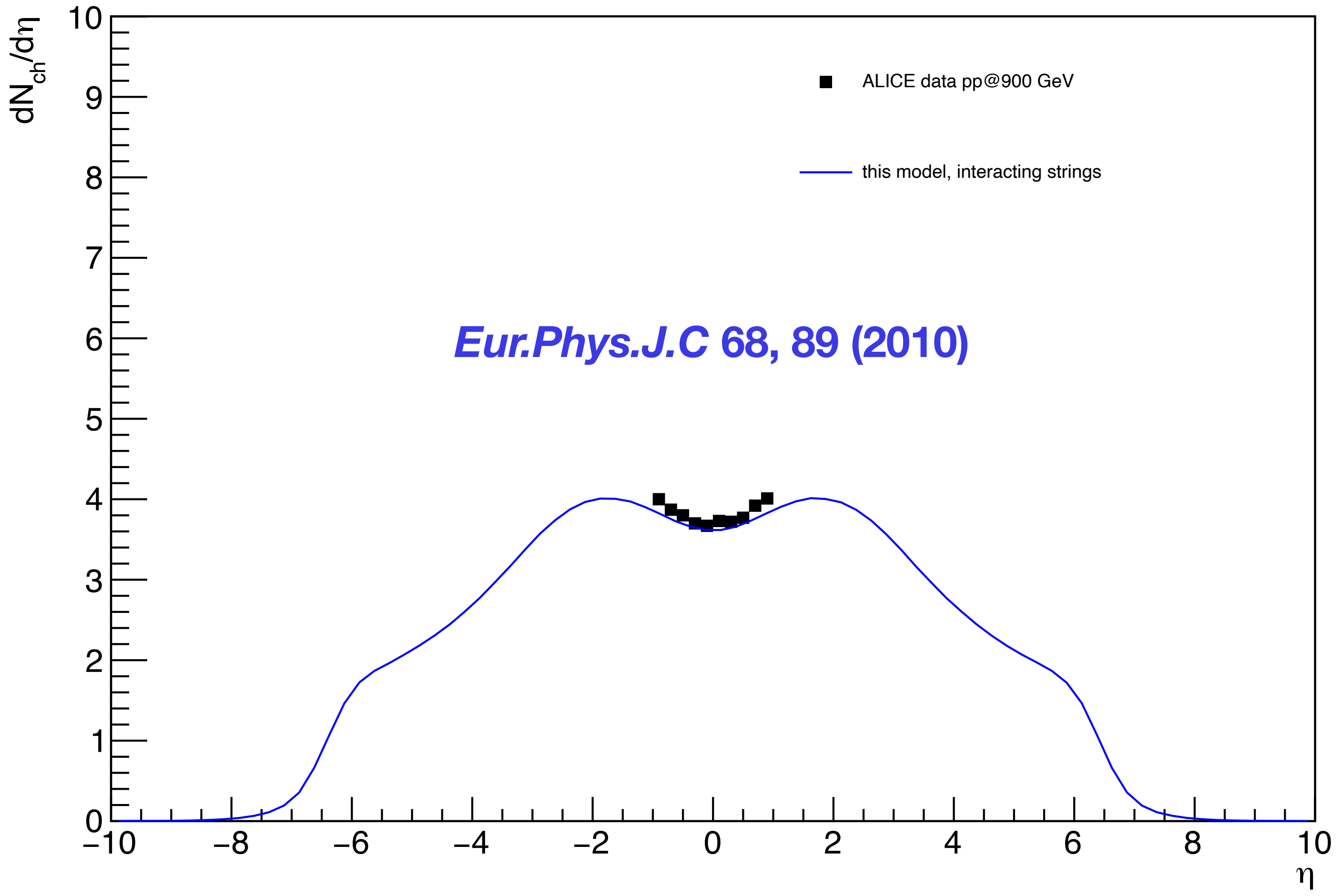
V. Kovalenko, EPJ Web Conf 137, 07012 (2017)
J. E. Bresneham, IBM Syst. J. 4, 25 (1965)

MODEL TUNING

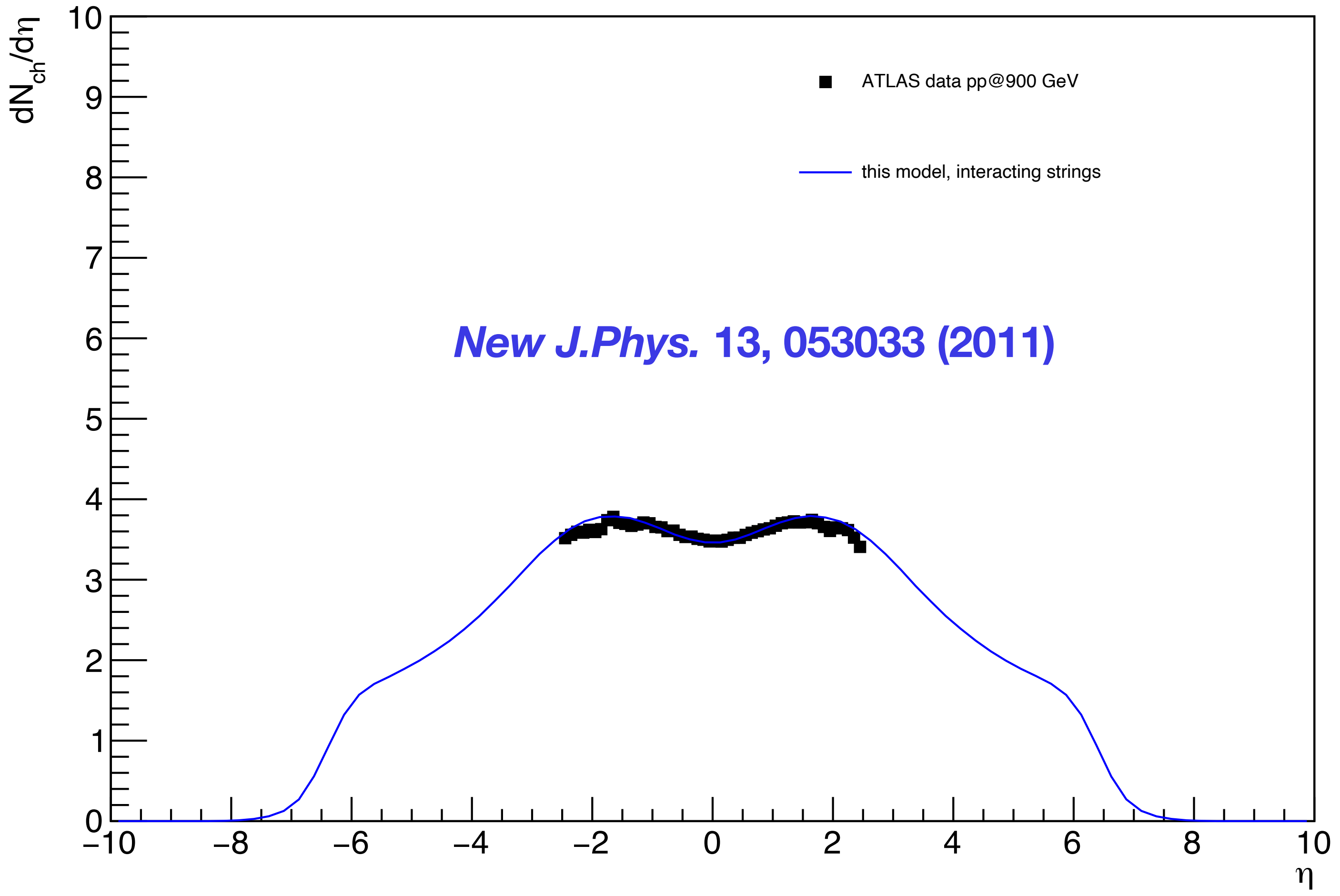
900 GeV

NEW!

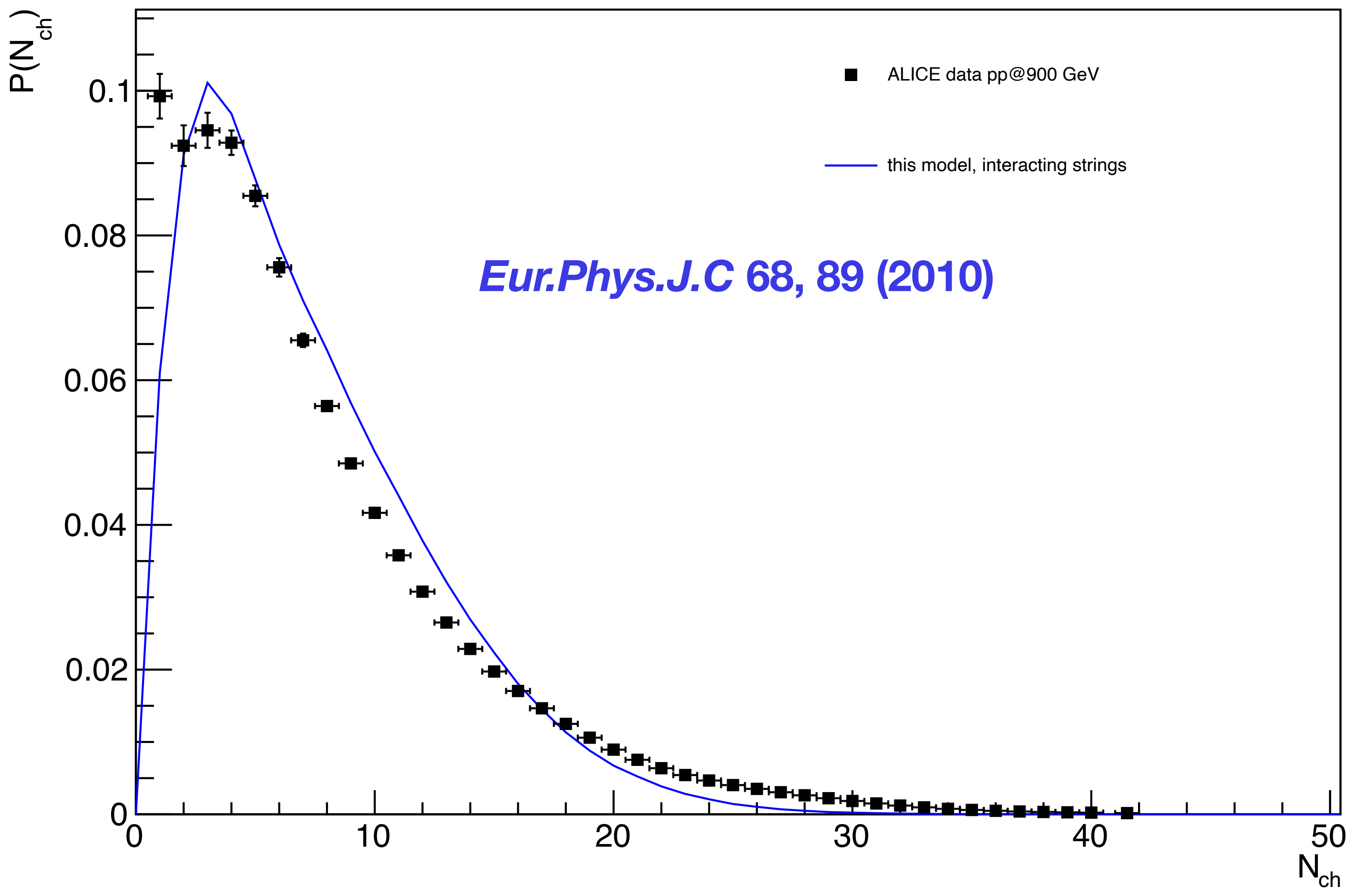
ALICE, INEL>0



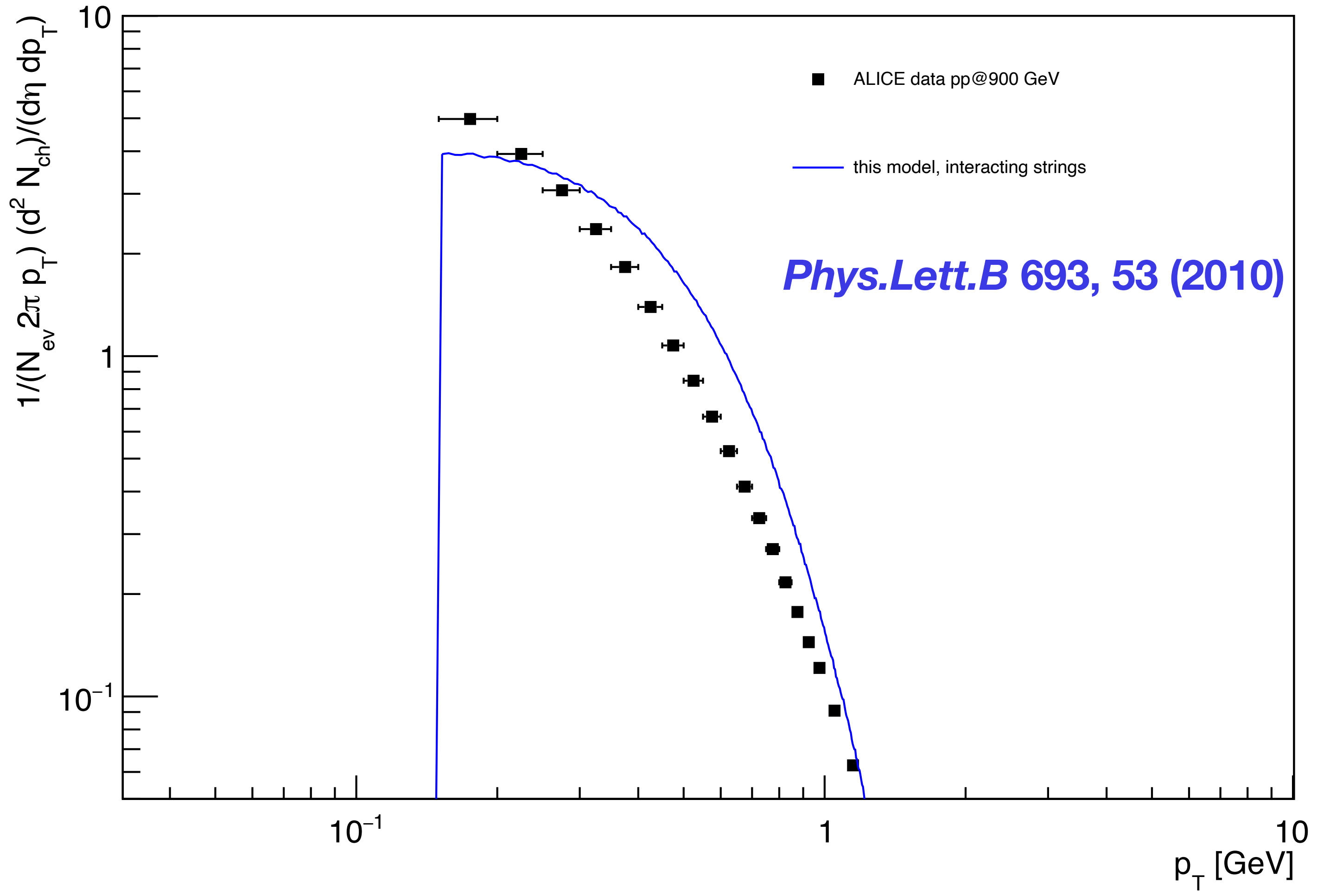
ATLAS, Nch>1, pT>0.1 GeV/c



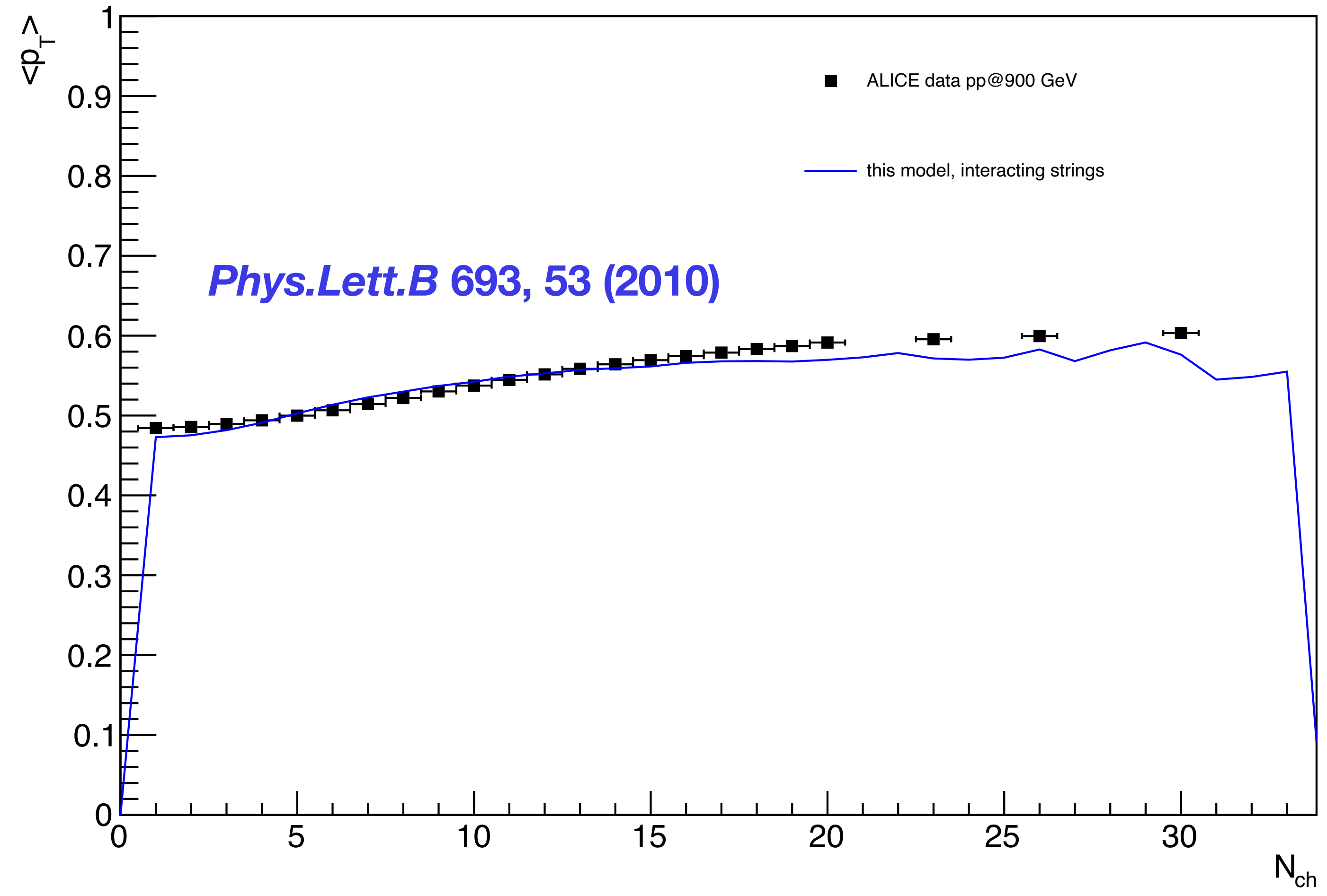
ALICE, $|\eta| < 1.0$, INEL, Nch>0



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



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



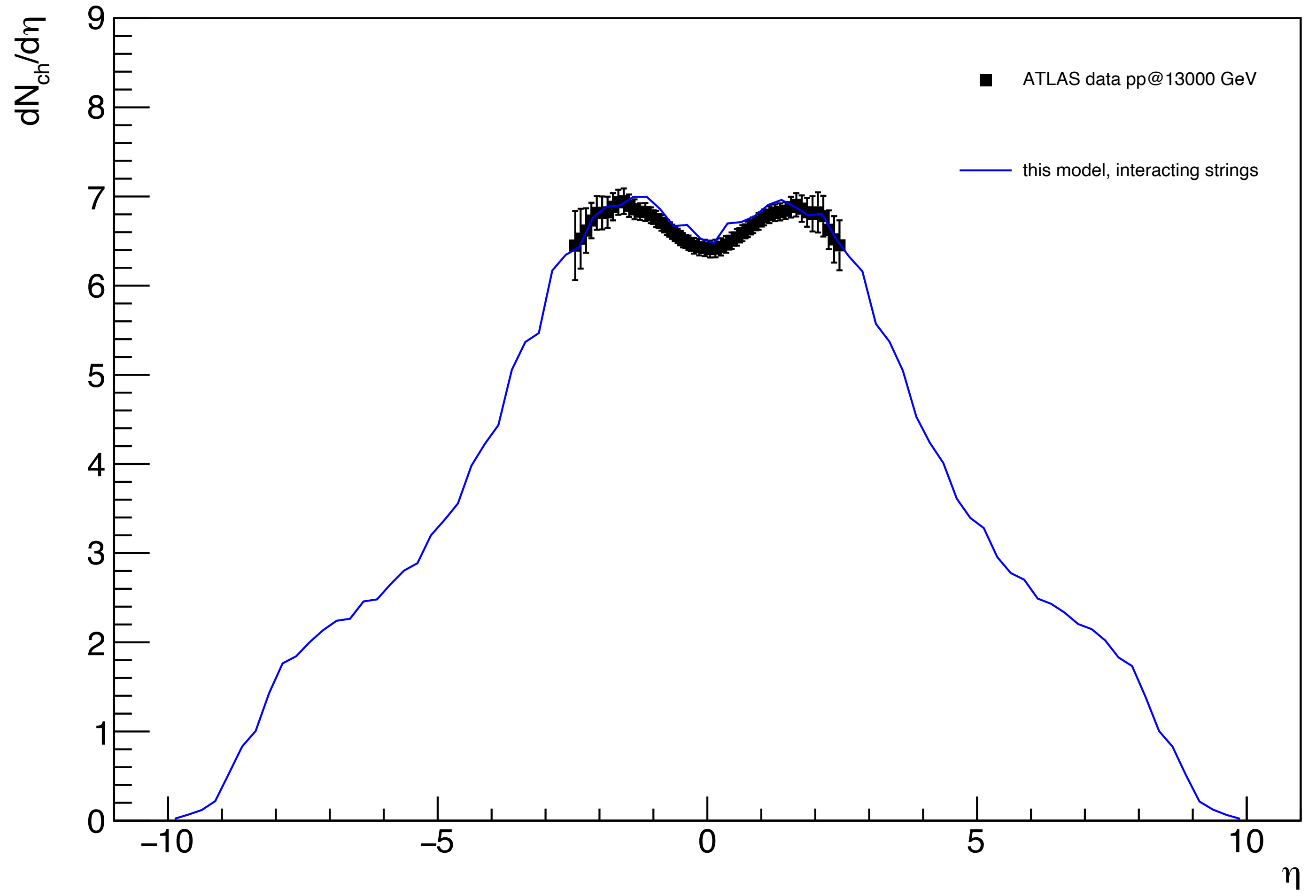
13000 GeV

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

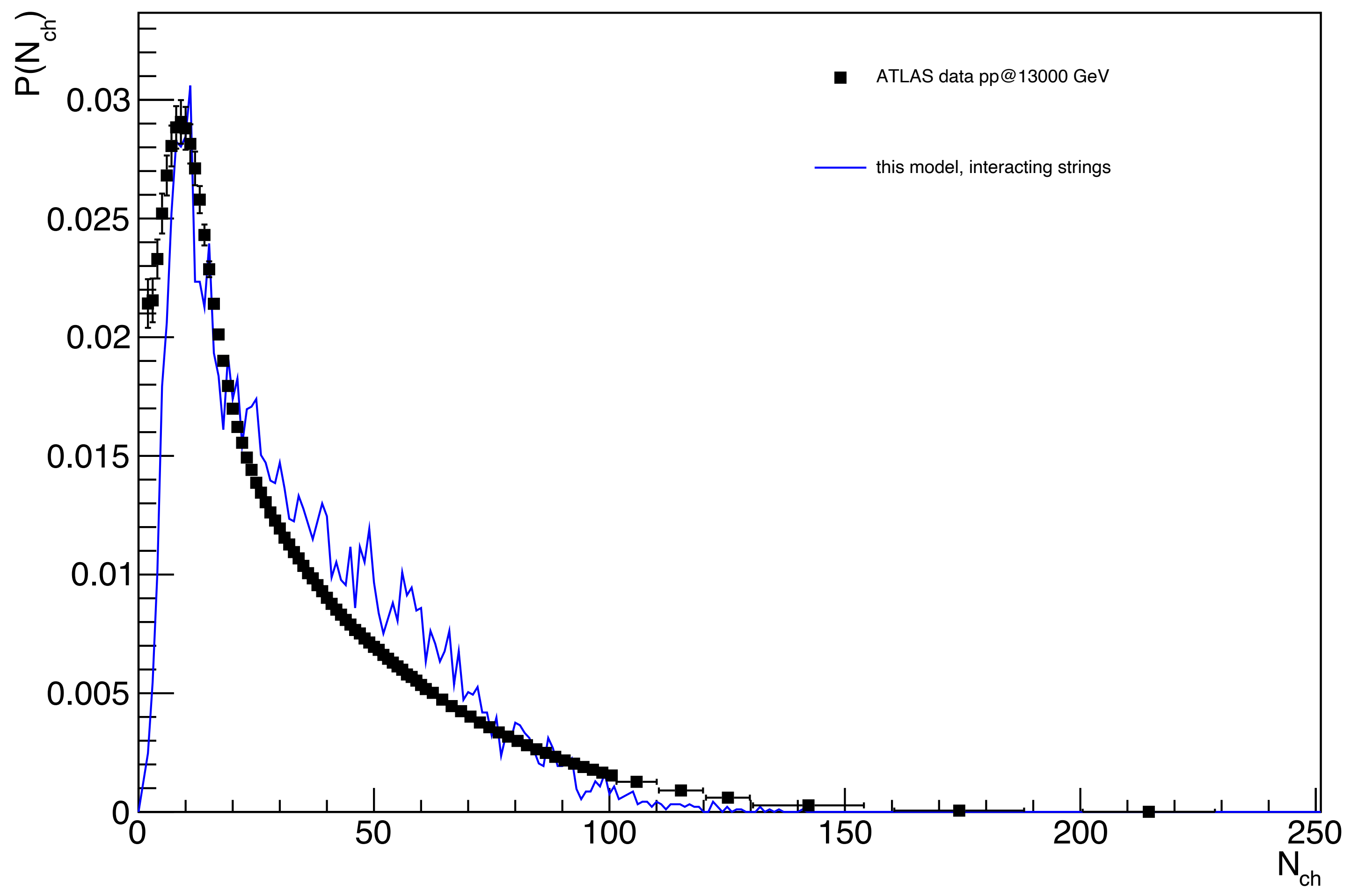
***Eur.Phys.J.C* 76, 502 (2016)**

NEW!

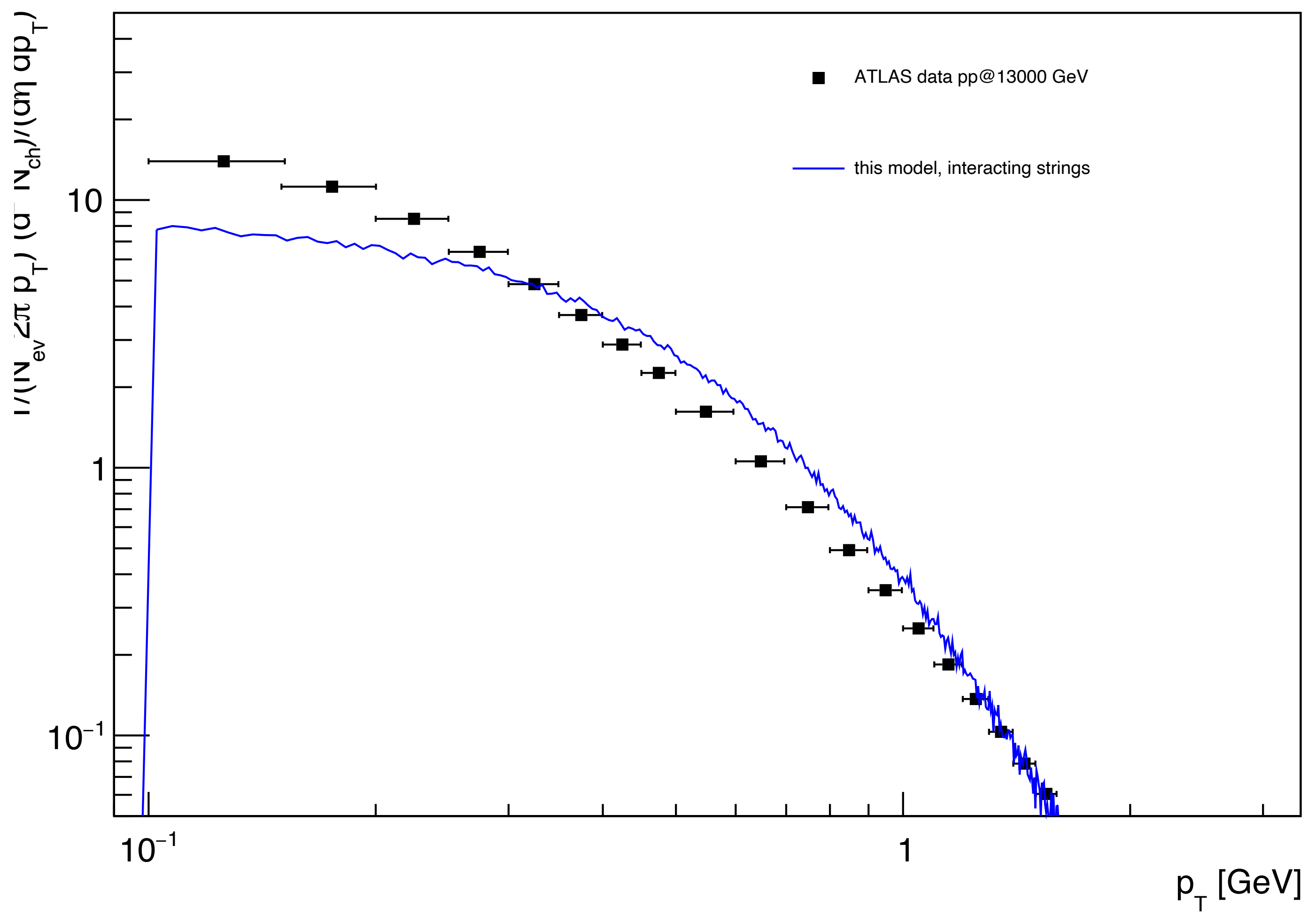
pseudorapidity



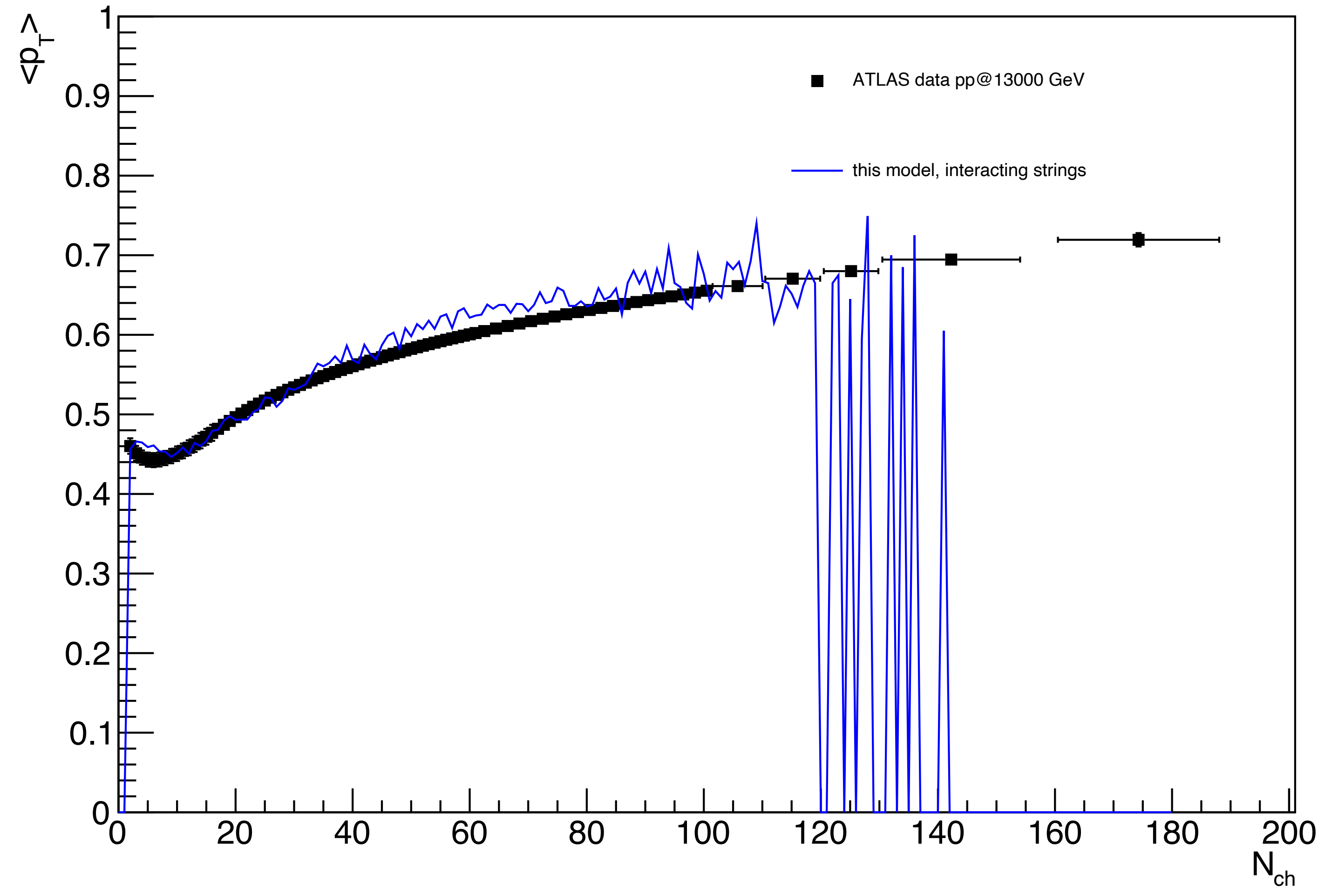
multiplicity



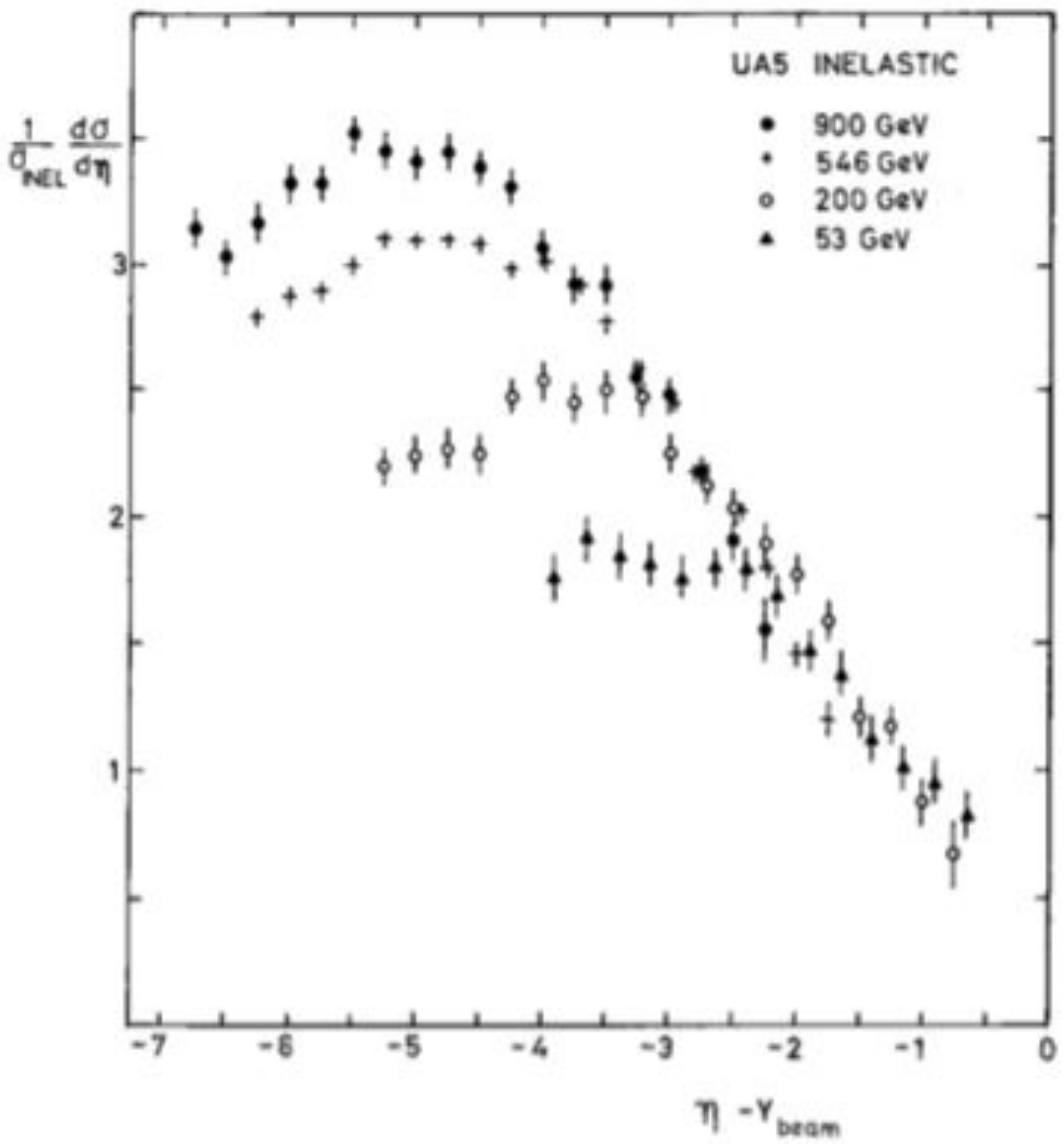
pT spectra



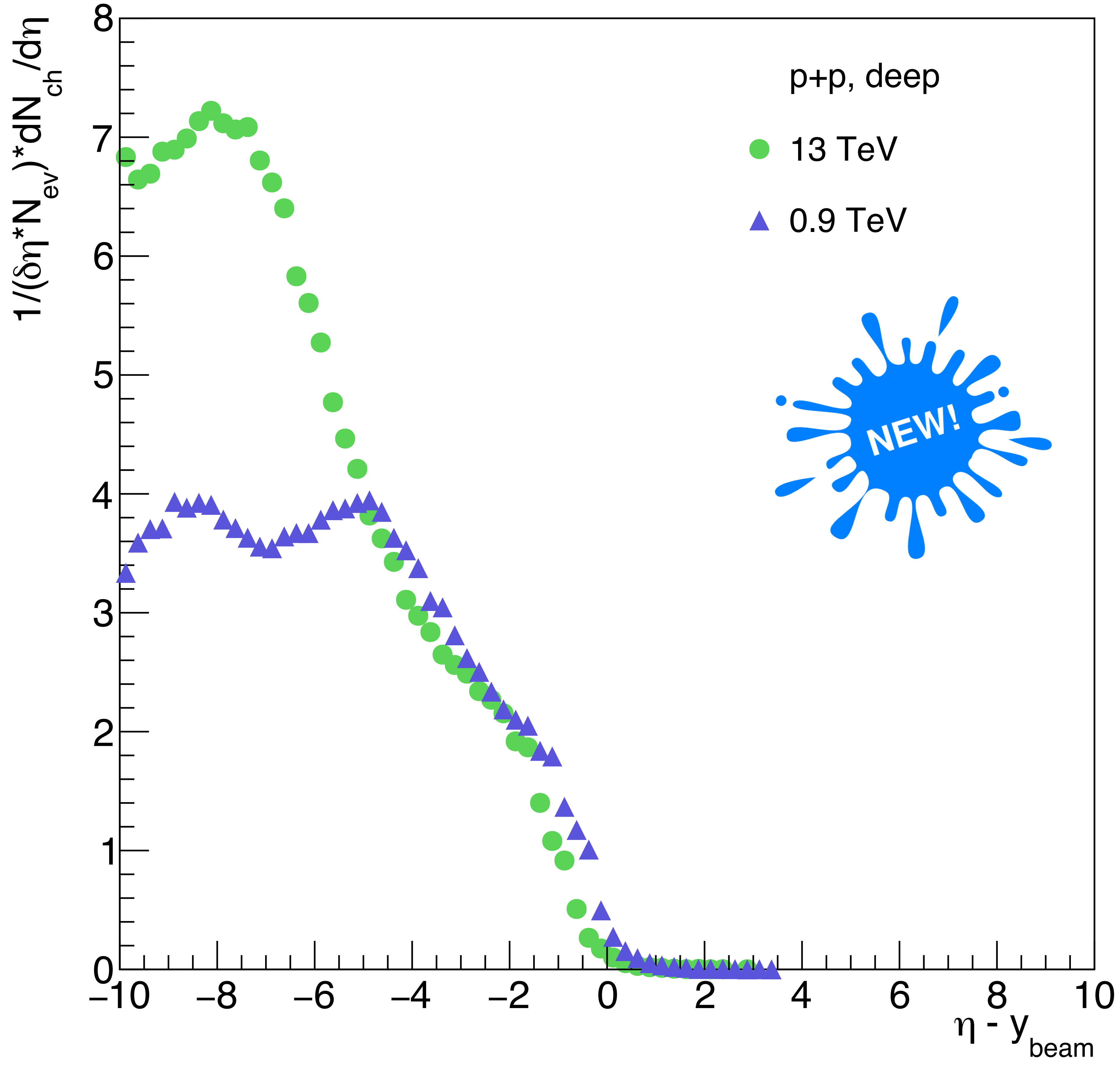
pT-N correlation



Scaling of pseudorapidity spectra



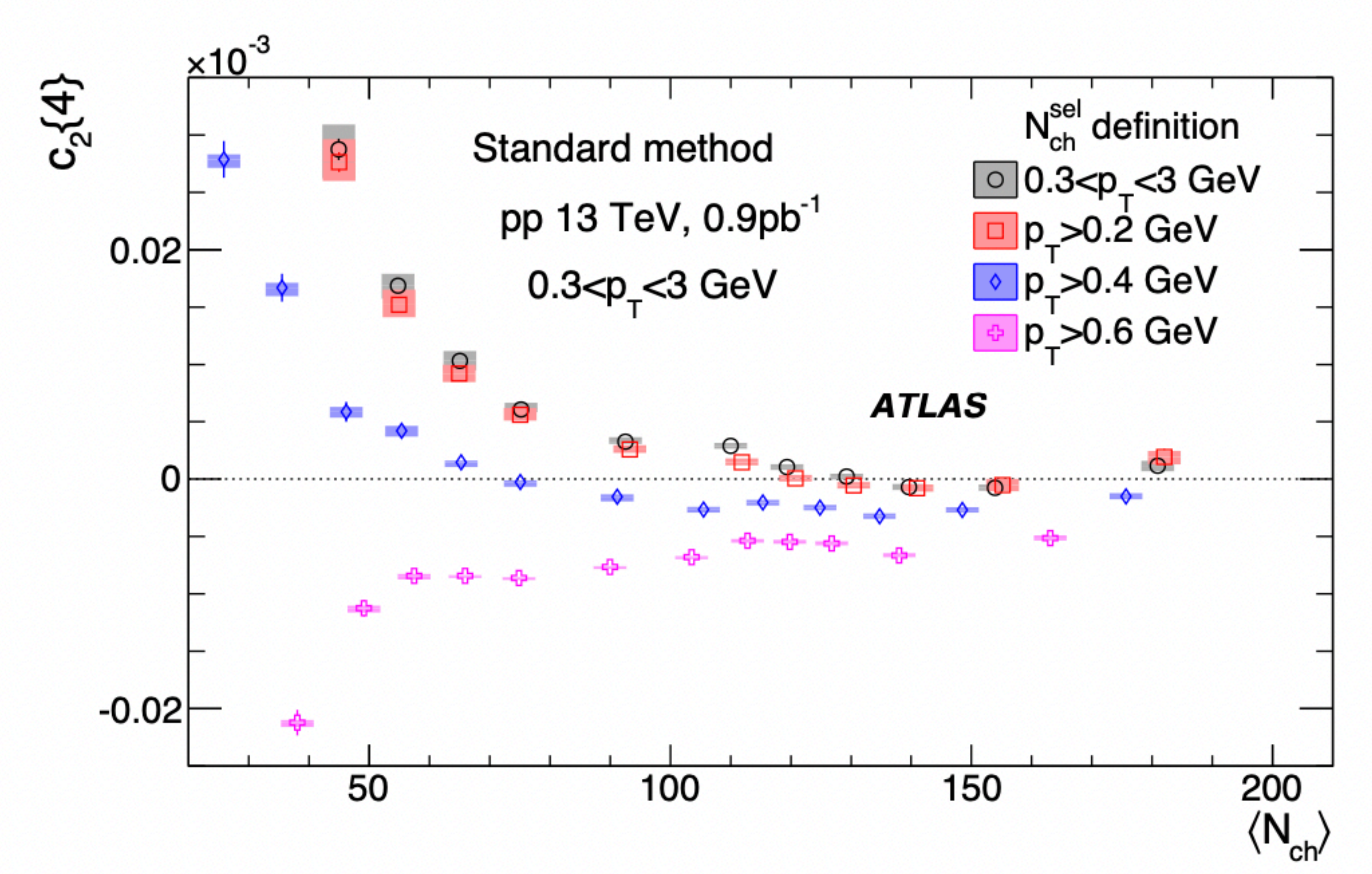
UA5 Coll., Z. Phys. C 33, 1 (1986)



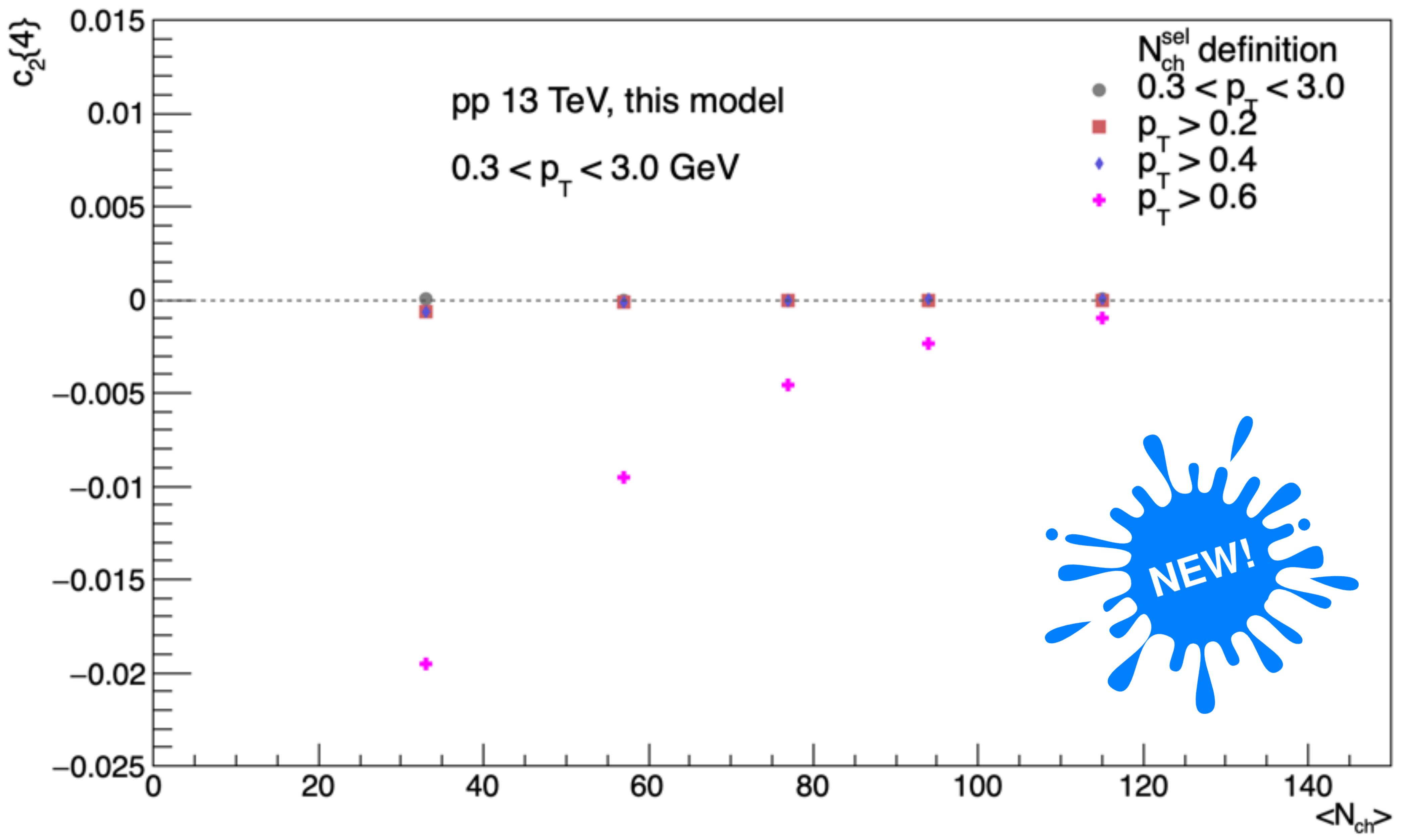
FLOW. RESULTS.

p+p@$\sqrt{s} = 13$ TeV - cumulants

ATLAS Coll., *Phys.Rev.C* 97, 024904 (2018)



STRING MODEL



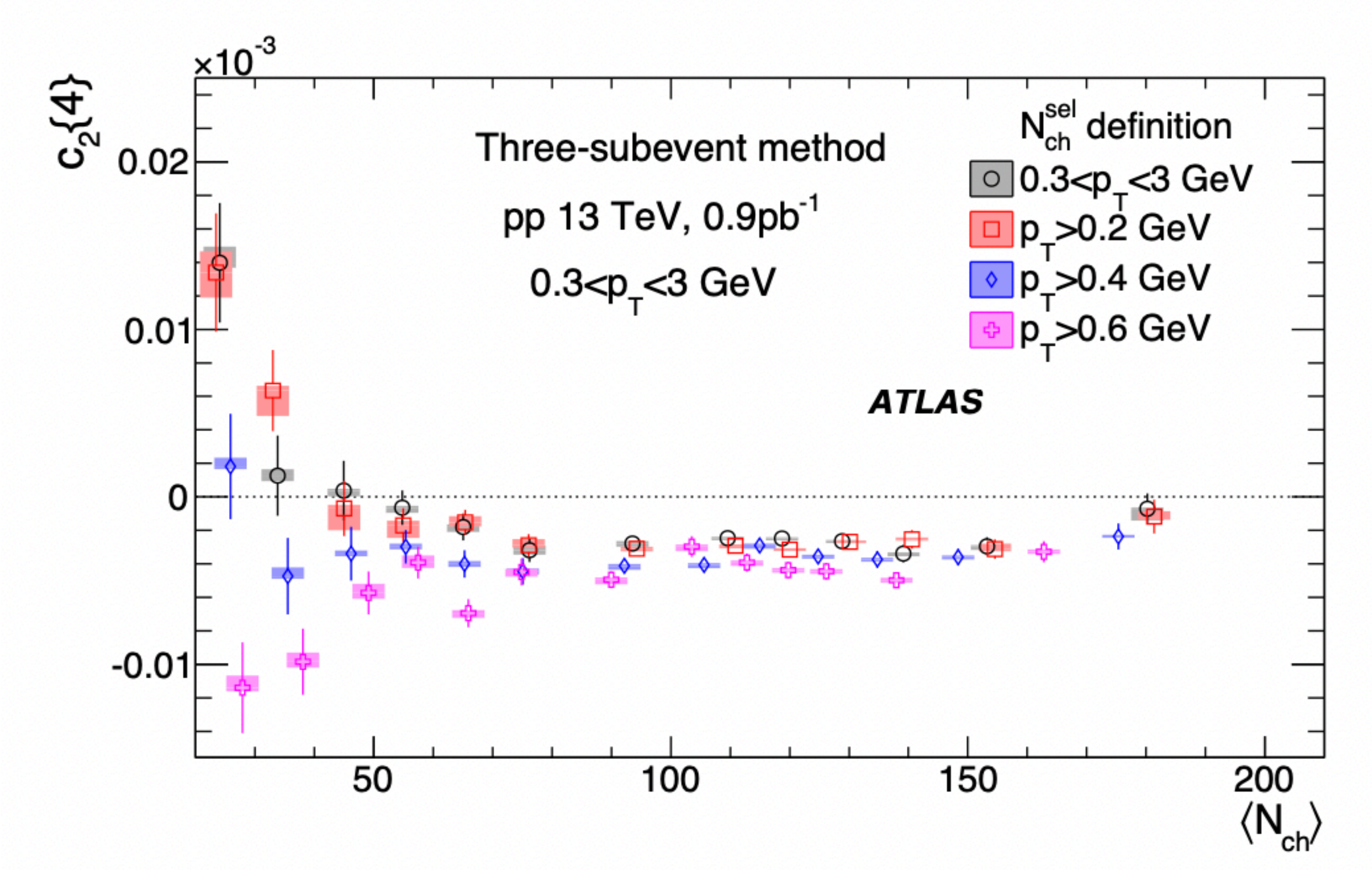
1) Cumulant $c_2\{4\}$ shows strong dependence on event classification

2) Similar effect is obtained in the model

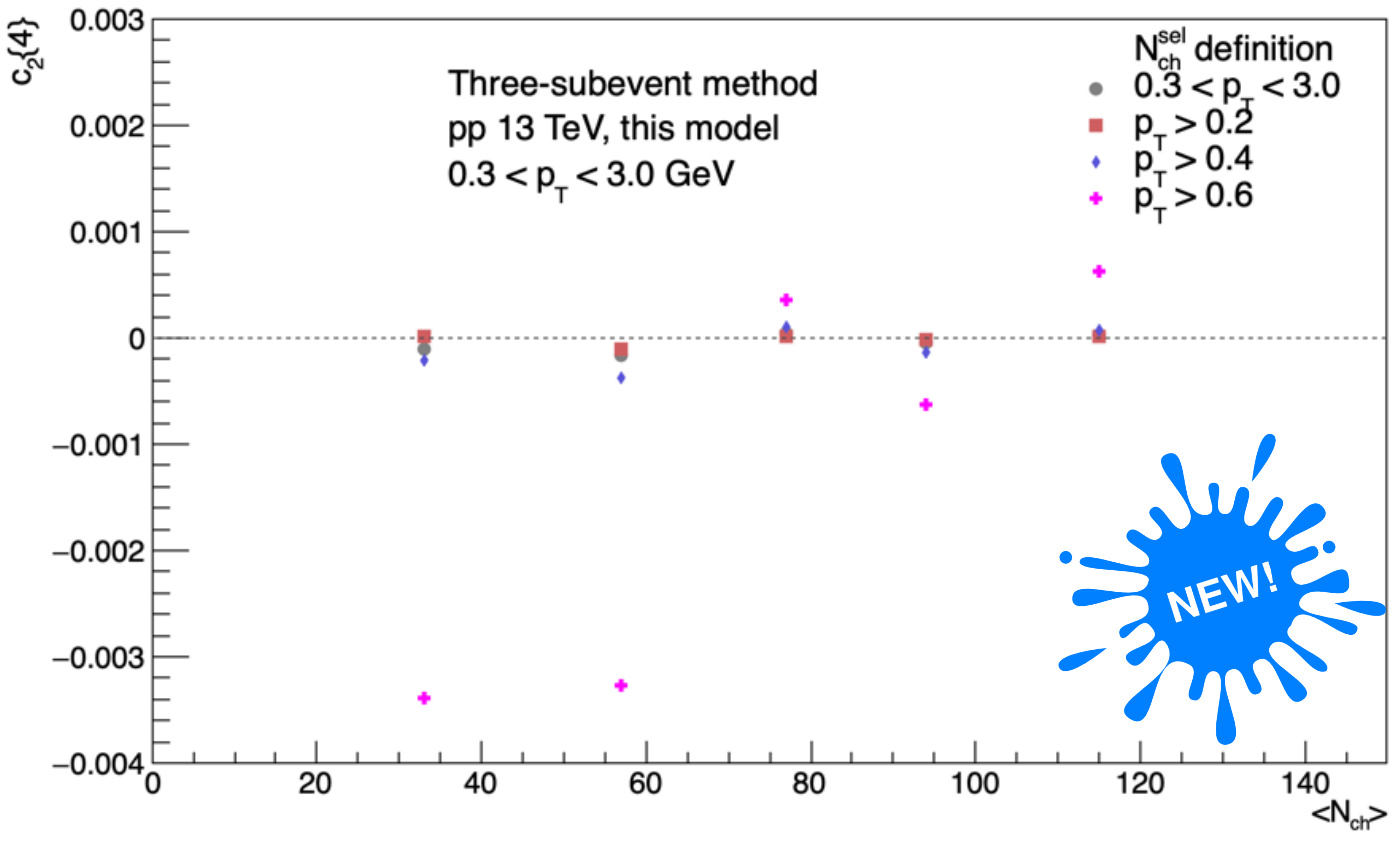
3) No positive values of $c_2\{4\}$ in the model

p+p@$\sqrt{s} = 13$ TeV - cumulants

ATLAS Coll., *Phys.Rev.C* 97, 024904 (2018)



STRING MODEL



1) Application of sub-event method result in a more consistent behaviour of $c_2\{4\}$ for different event classification

2) Still results for classification based on $p_T > 0.6$ GeV/c is lower than others

3) $c_2\{4\}$ for $p_T > 0.6$ GeV/c is closer to 0 in comparison to the standard method

4) Similar effect is seen in the model

Conclusions

- Collectivity in small systems (e.g. non-negligible anisotropic flow) was a great surprise
- Quenching introduced in the Colour string model allows to mimic v2 as seen by LHC experiments:
  - Negative values of $c_2\{4\}$
  - Dependence on event classification
  - Difference in results for the standard and sub-event methods
- Detailed description of the transverse and longitudinal string dynamics gives perspective to predict rapidity decorrelation, v2-mean pT correlations, symmetric cumulants etc.

This work was supported by Saint Petersburg State University, project ID: 94031112

Thank you for your attention!

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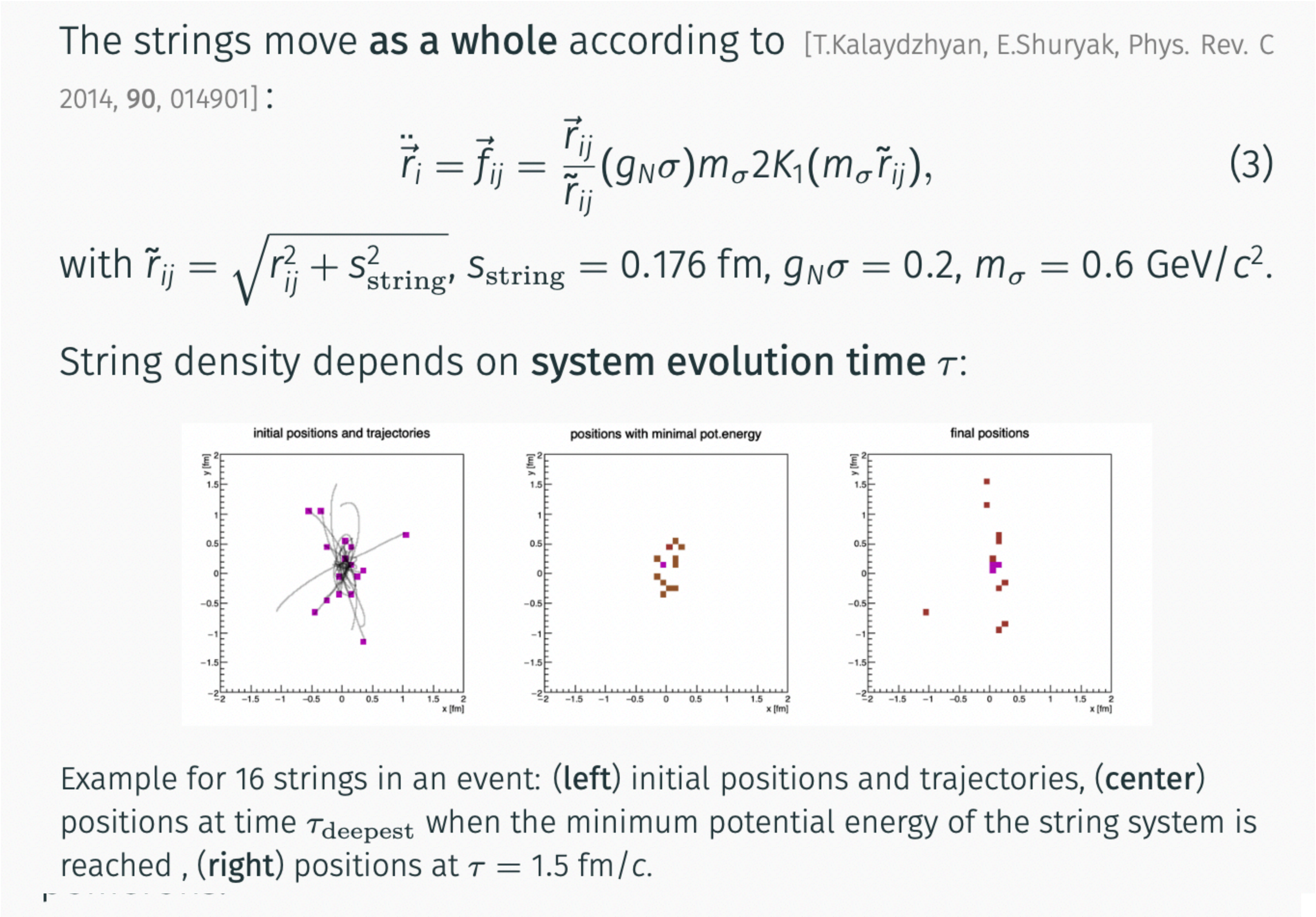
EXTRA

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]:

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

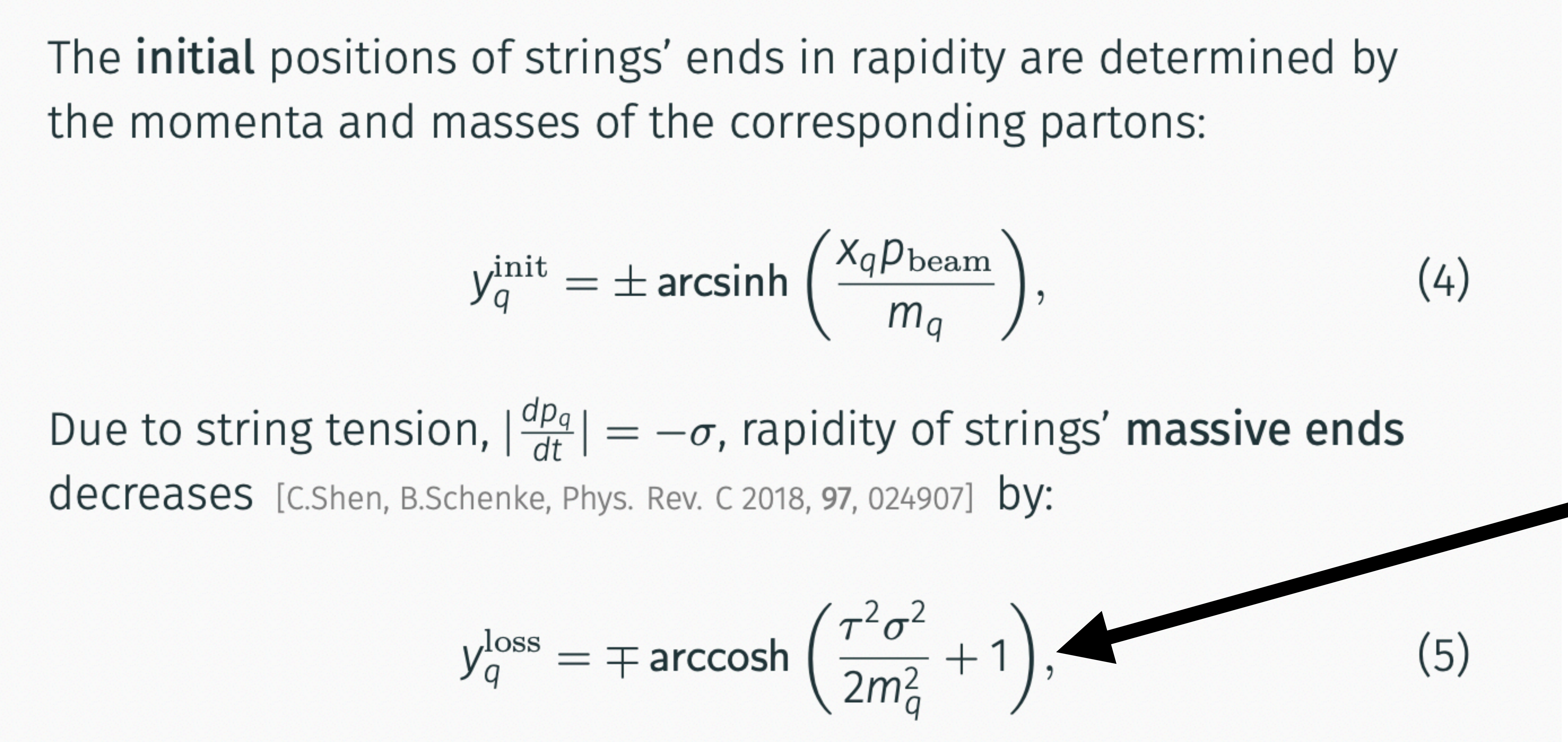
with $\tilde{r}_{ij} = \sqrt{r_{ij}^2 + s_{\mathrm{string}}^2}$, $s_{\mathrm{string}} = 0.176$ fm, $g_N\sigma = 0.2$, $m_\sigma = 0.6\ \mathrm{GeV}/c^2$.

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 $\tau = 1.5\ \mathrm{fm}/c$.

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:

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

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:

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

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):

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