

Evgeny Andronov



Two-particle rapidity correlations in strongly intensive quantities within string model

ISHEPP-2025, 15 SEPTEMBER 2025, DUBNA

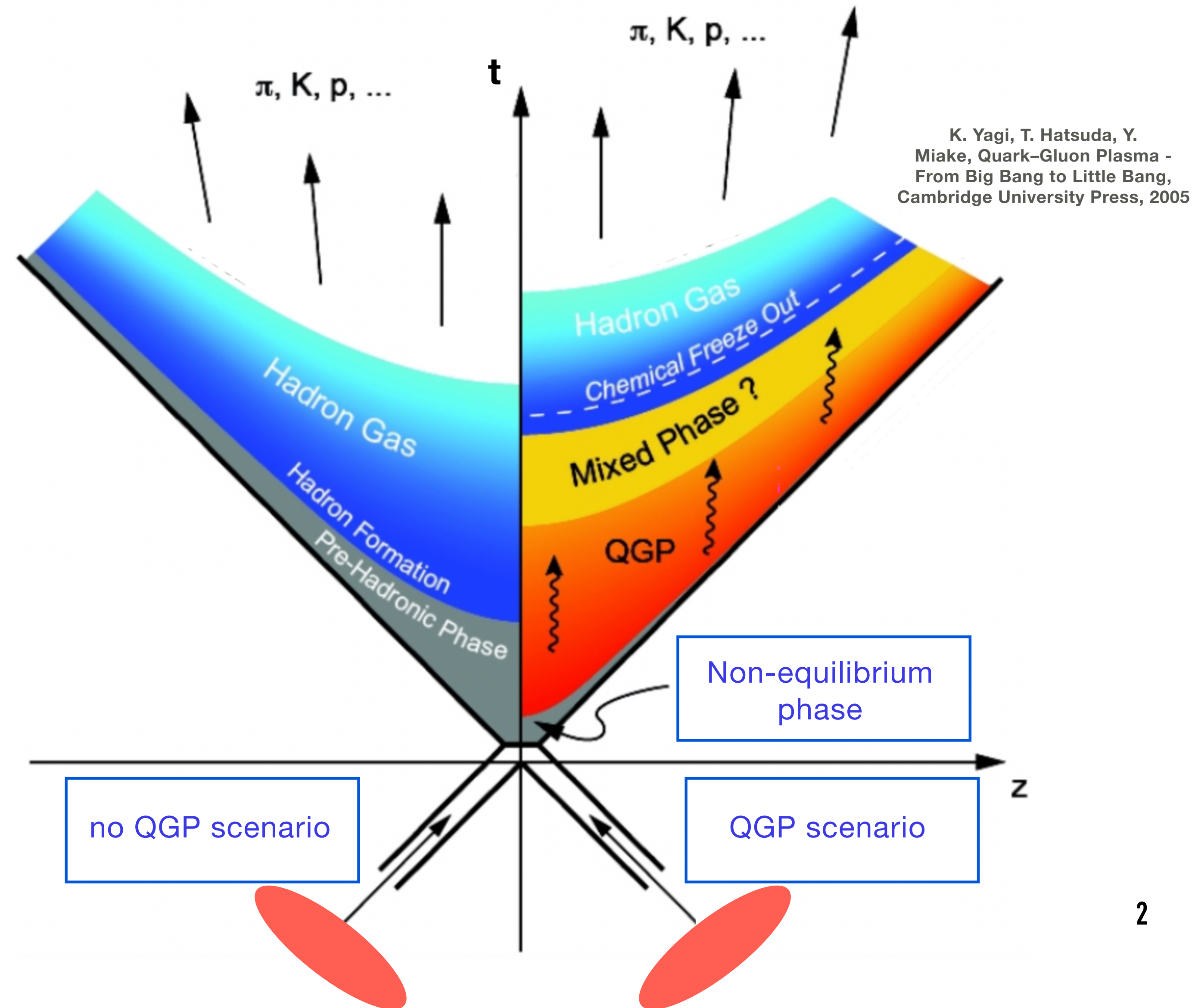
p+p and A+A collisions

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

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

Now, in 2025 we know that some of these effects are present in *p+p* interactions:

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



Color string models

Two-stage process:

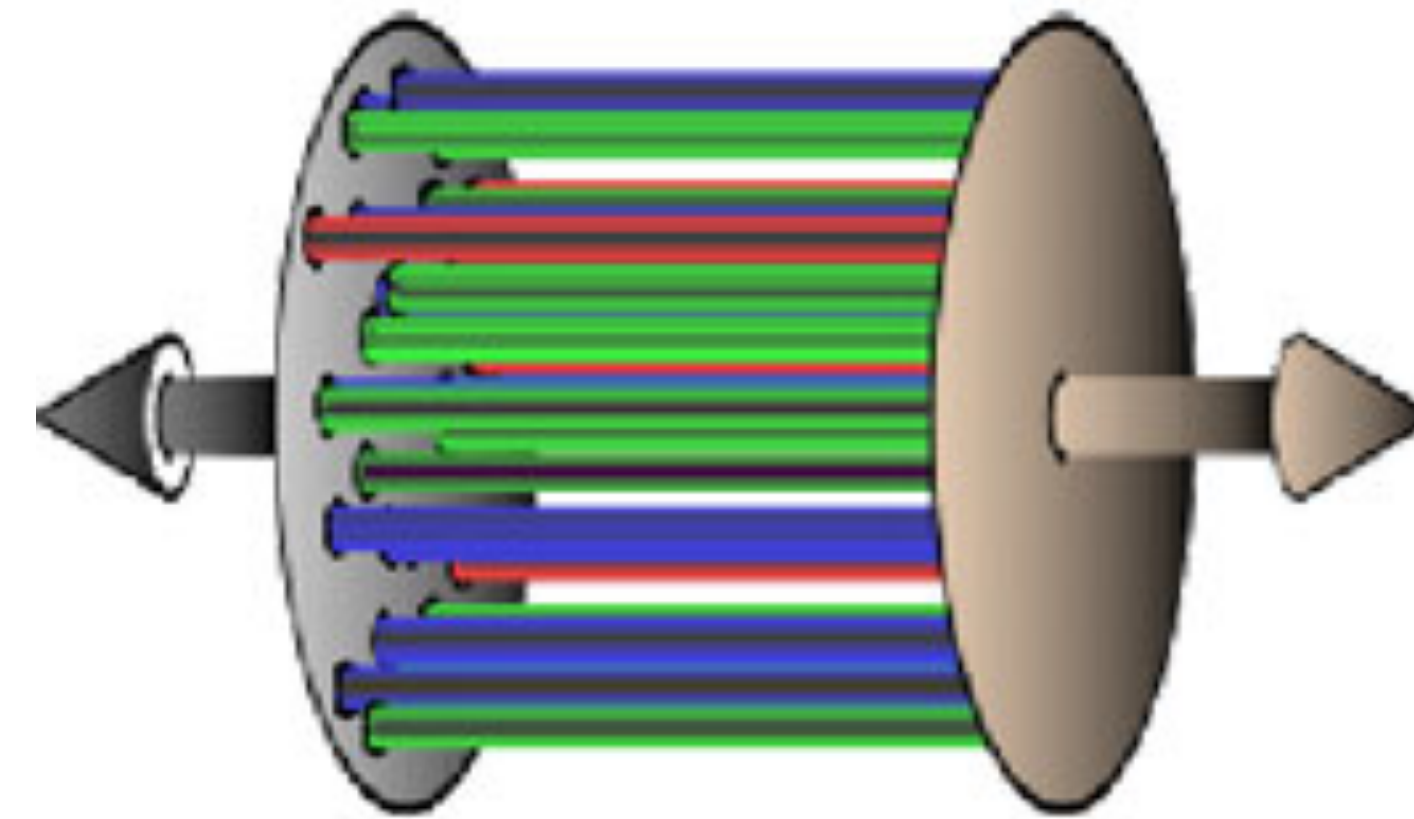
- partons' colour charges form tubes of colour field
- tubes are hadronized via Schwinger mechanism (tunnelling)

but!

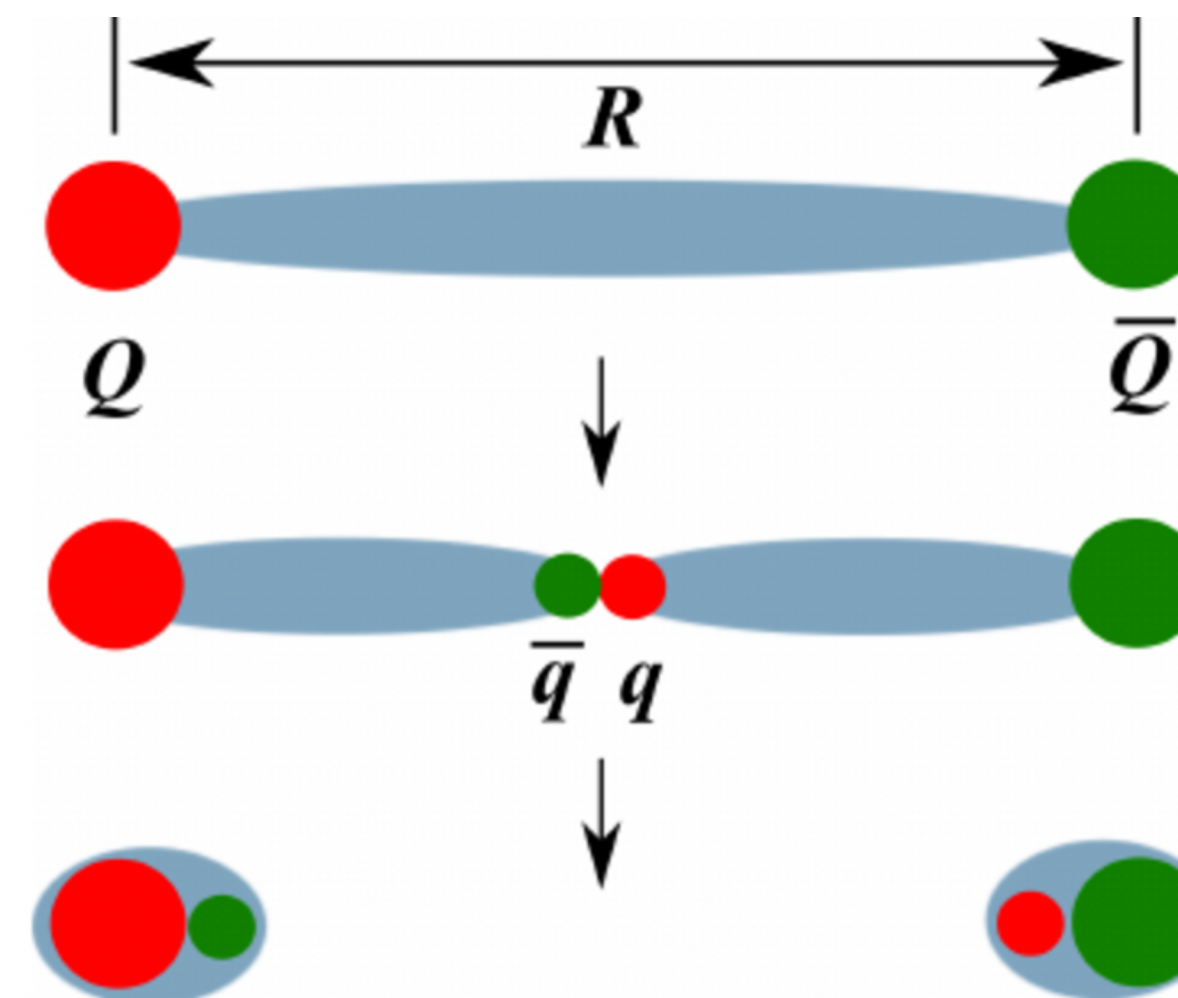
- string may interact before hadronization
[M.A. Braun, C. Pajares, Phys.Lett.B 287, 154 (1992)]
- how can we distinguish between different scenarios of string-string interactions?

Goal:

- find observables that are sensitive to details of string fragmentation



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



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

Strongly intensive quantities

Extensive quantities:

- proportional to the system's volume
- e.g. mean multiplicity $\langle N \rangle$

Intensive quantities:

- independent of the expectation value of the system's volume
- e.g. event-mean transverse momentum $\langle \overline{p_T} \rangle$

Strongly intensive quantities: M.I. Gorenstein, M. Gazdzicki Phys.Rev.C 84, 014904 (2011)

- independent of the expectation value of the system's volume and of the volume fluctuations

• e.g. $\Sigma[A, B] = \frac{1}{C_\Sigma} (\omega[B]\langle A \rangle + \omega[A]\langle B \rangle - 2cov(A, B))$

$\langle N_F \rangle$ - mean A, $\omega[A] = \frac{\langle A^2 \rangle - \langle A \rangle^2}{\langle A \rangle}$ - scaled variance

Rapidity correlations

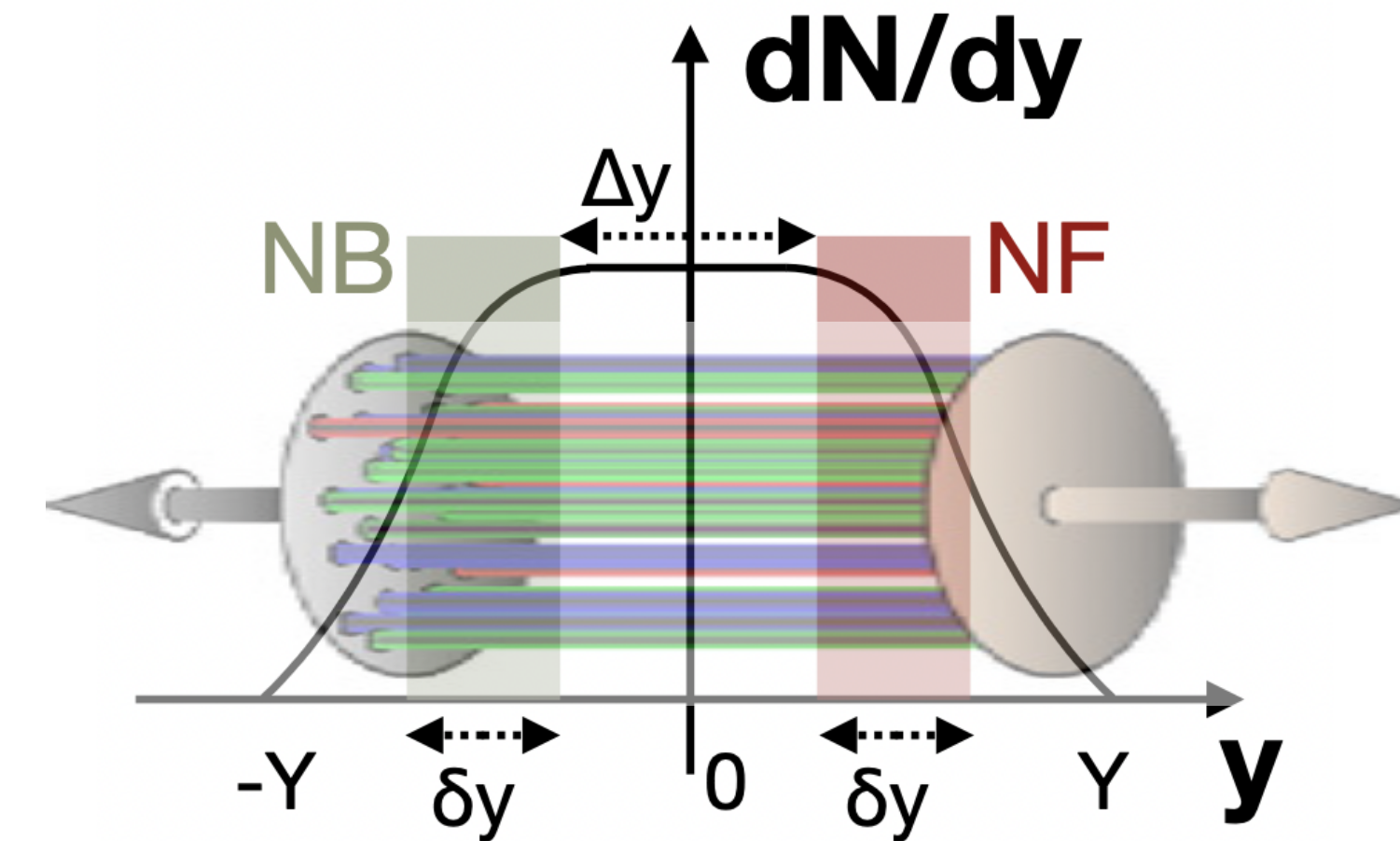
E.V. Andronov, Theor. Math. Phys. 185(1), 1383 (2015)

Strings - source of correlated particle production

- **Q:** how can one quantify degree of collectivity_
- **A:** joint particle number fluctuations in separated rapidity intervals
- Let us construct SIQ for multiplicities in two windows

$$\Sigma[N_F, N_B] = \frac{\omega[N_B] \cdot \langle N_F \rangle + \omega[N_F] \cdot \langle N_B \rangle - 2 \cdot \text{cov}(N_F, N_B)}{\langle N_B + N_F \rangle}$$

$$\langle N_F \rangle - \text{mean NF}, \omega[N_F] = \frac{\langle N_F^2 \rangle - \langle N_F \rangle^2}{\langle N_F \rangle} - \text{scaled variance}$$



In case of symmetric windows we have

$$\Sigma[N_F, N_B] = \omega[N_B] - \frac{\text{cov}(N_F, N_B)}{\langle N_B \rangle}$$

Independent strings

E. Andronov, V. Vechernin, Eur.Phys.J.A 55(1), 14 (2019).

V. Vechernin, **E. Andronov**, Universe 5(1), 15 (2019).

E. Andronov, V. Vechernin, Phys.Part.Nucl. 51(3), 337 (2020).

Model:

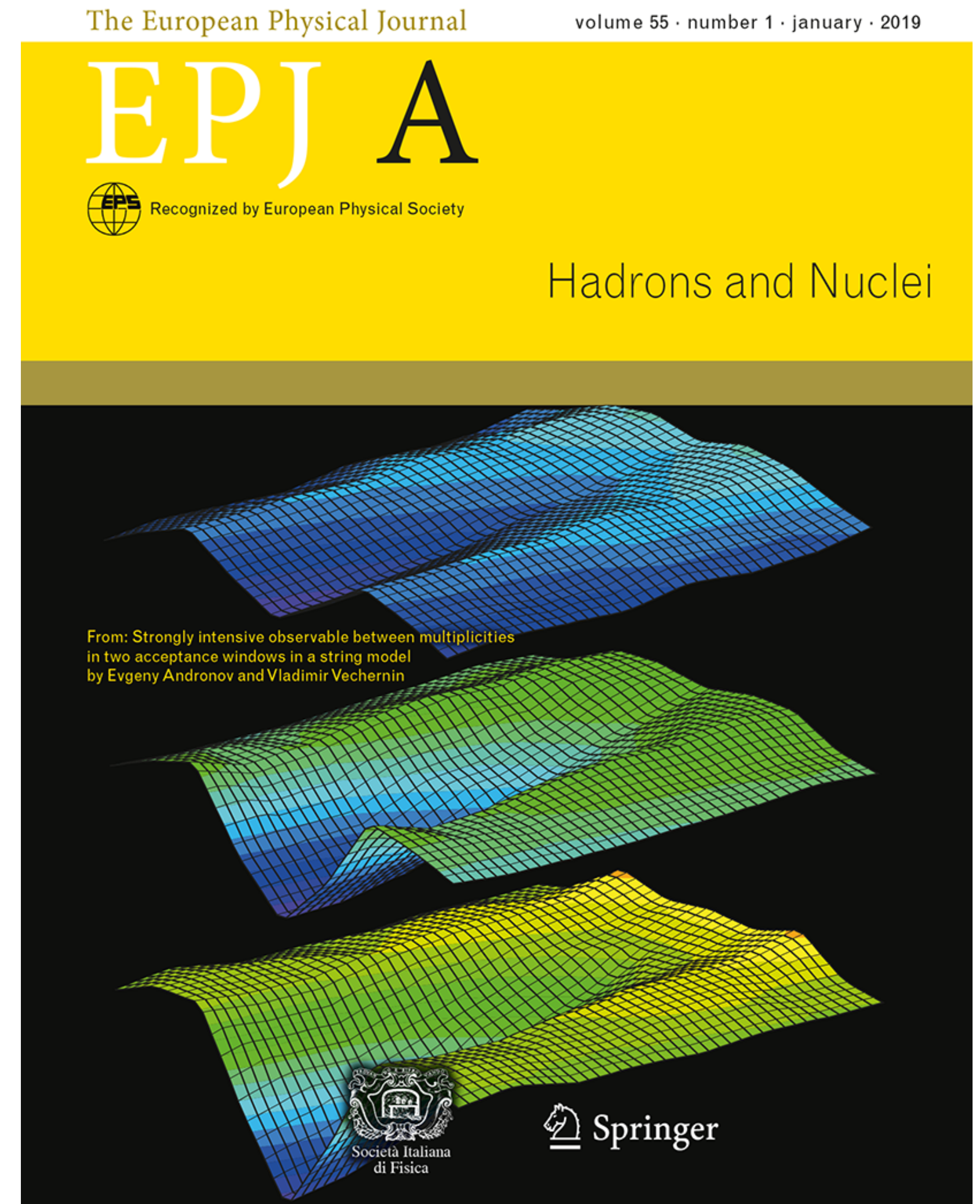
- Infinitely long non-interacting strings

Datasets:

- p+p interactions at 900, 2760 and 7000 GeV

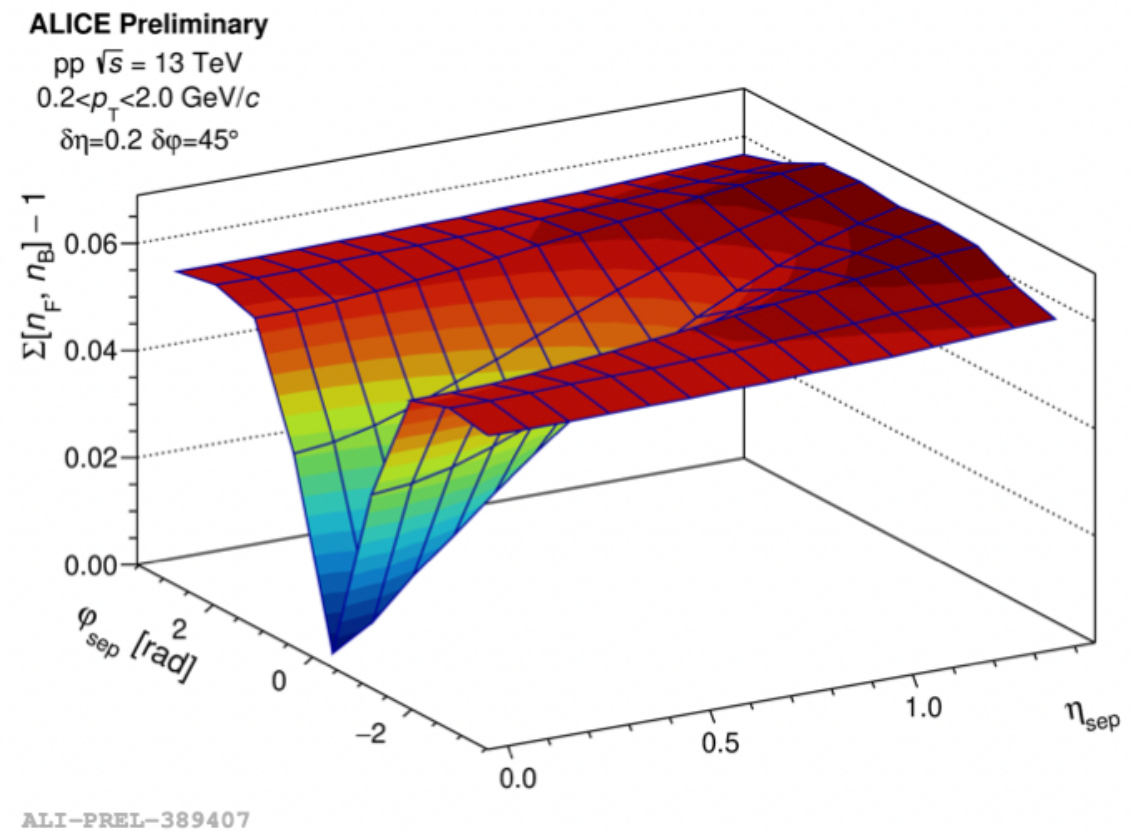
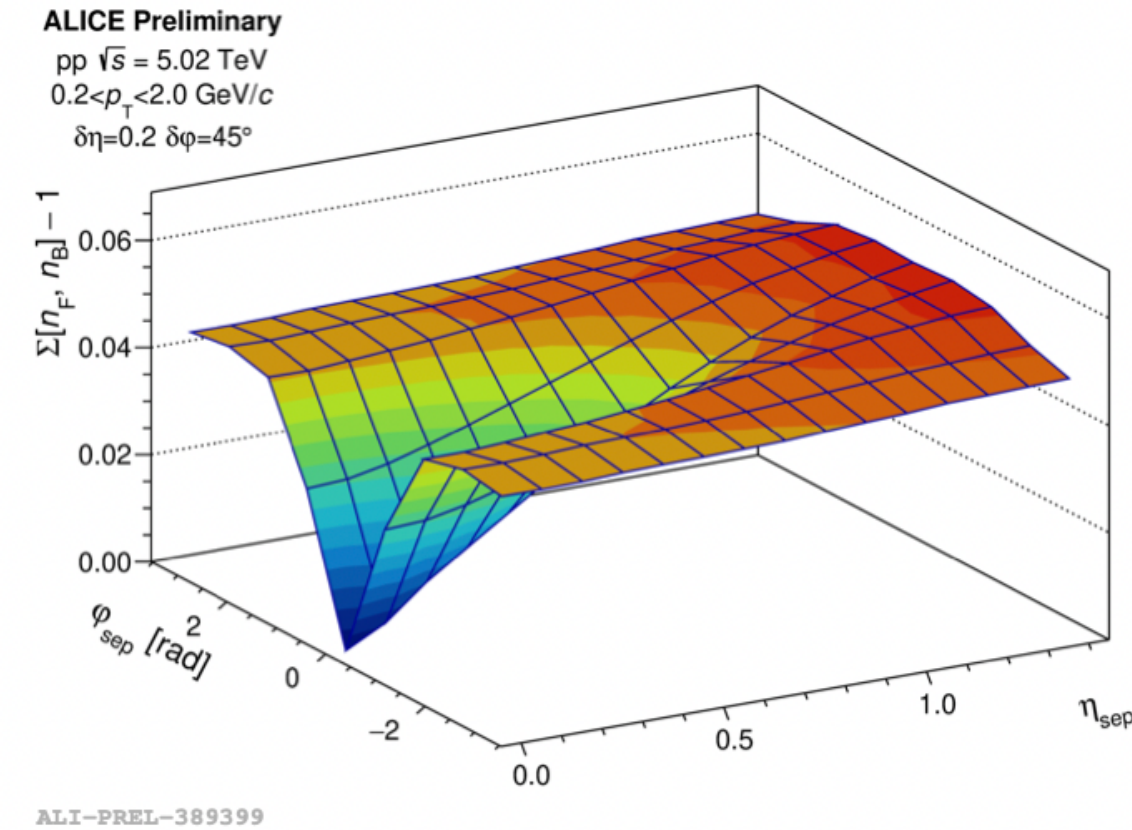
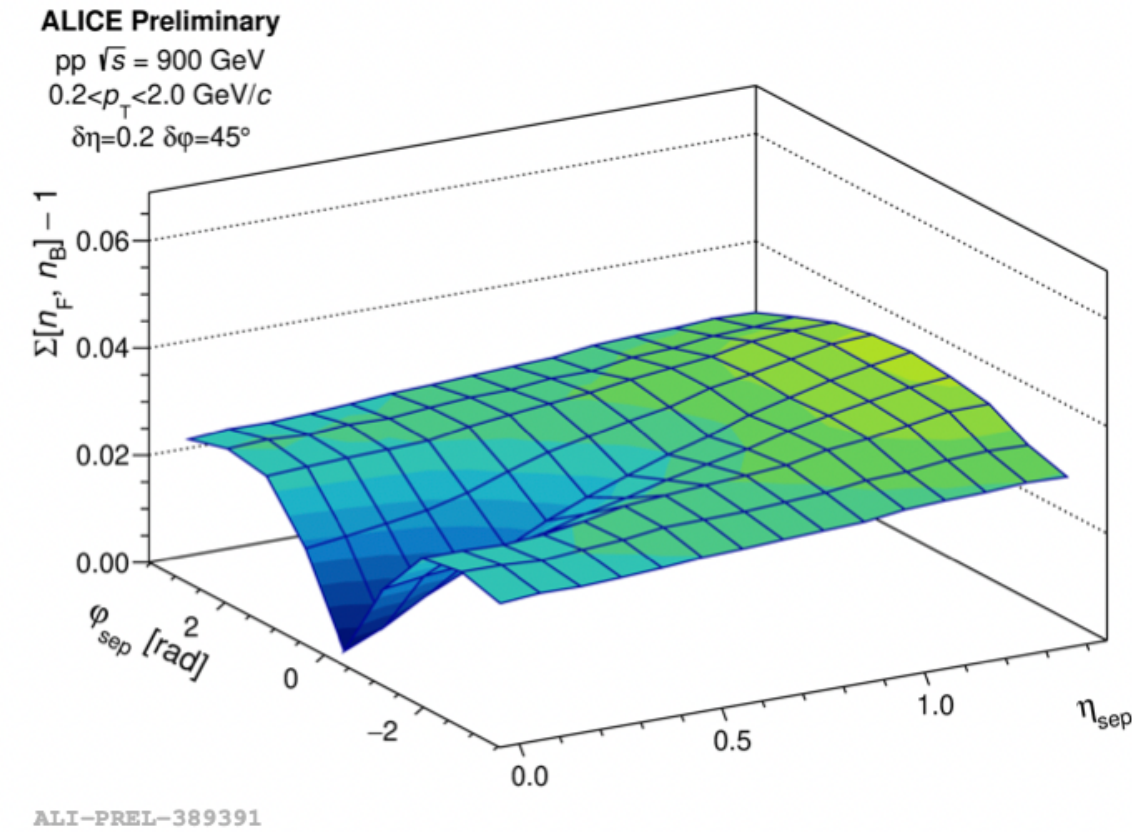
Results:

- rapidity and azimuthal dependence of $\Sigma \rightarrow$ string fragmentation function



ALICE experiment in two years:

ALICE, PoS CPD2021
(2022) 027



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Recognized by European Physical Society

Hadrons and Nuclei

From: Strongly intensive observable between multiplicities in two acceptance windows in a string model by Evgeny Andronov and Vladimir Vechernin

Società Italiana di Fisica

Springer

Rapidity correlations

$\Sigma[N_F, N_B]$ behaviour is (mostly) driven by two-particle correlation structure from a single string

In this report we adopt idea (originally used for baryon number correlations) to model (and quantify) rapidity correlations from by exploiting the Simulated Annealing method [P. Braun-Munzinger et al., *JHEP* 08 (2024) 113]

Start with string decaying to N uncorrelated particles

set 1	y1(1)	y2(1)	y3(1)	...	yN(1)
set 2	y1(2)	y2(2)	y3(2)	...	yN(2)
set 3	y1(3)	y2(3)	y3(3)	...	yN(3)
set 4	y1(4)	y2(4)	y3(4)	...	yN(4)
...					

$$C_2(\Delta y) = 1$$

randomly swap
y2(i) with **y2(j)**



set 1	y1(1)	y2(1)	y3(1)	...	yN(1)
...	...	...	...	...	...
set i	y1(i)	y2(j)	y3(i)	...	yN(i)
...	...	...	...	...	...
set j	y1(j)	y2(i)	y3(j)	...	yN(j)

$$C_2(\Delta y) \neq 1$$

Rapidity correlations

The swap is accepted if the cost function $D = |\sigma_{swap} - \sigma| - |\sigma_{noswap} - \sigma| < 0$

(σ - desired std deviation of $C_2(\Delta y)$)

If $D > 0$ the swap acceptance probability is $p = e^{-D/T}$

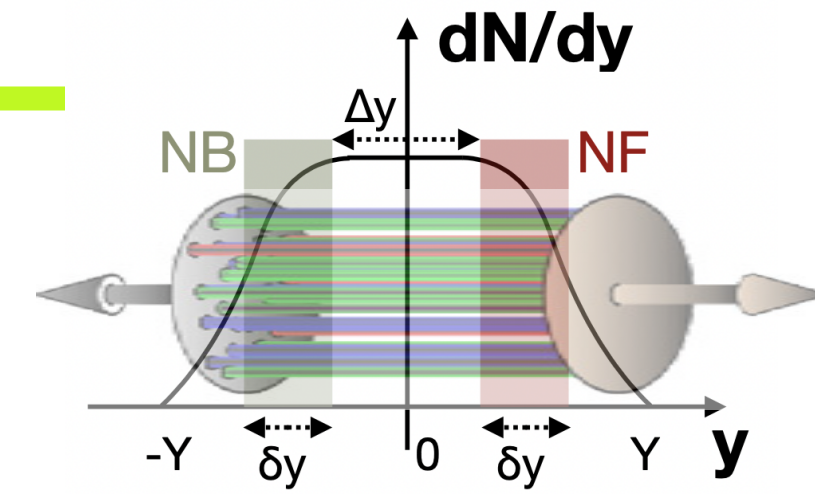
We do N_{in} swaps within each column

Once the loop is finished we reduce parameter T

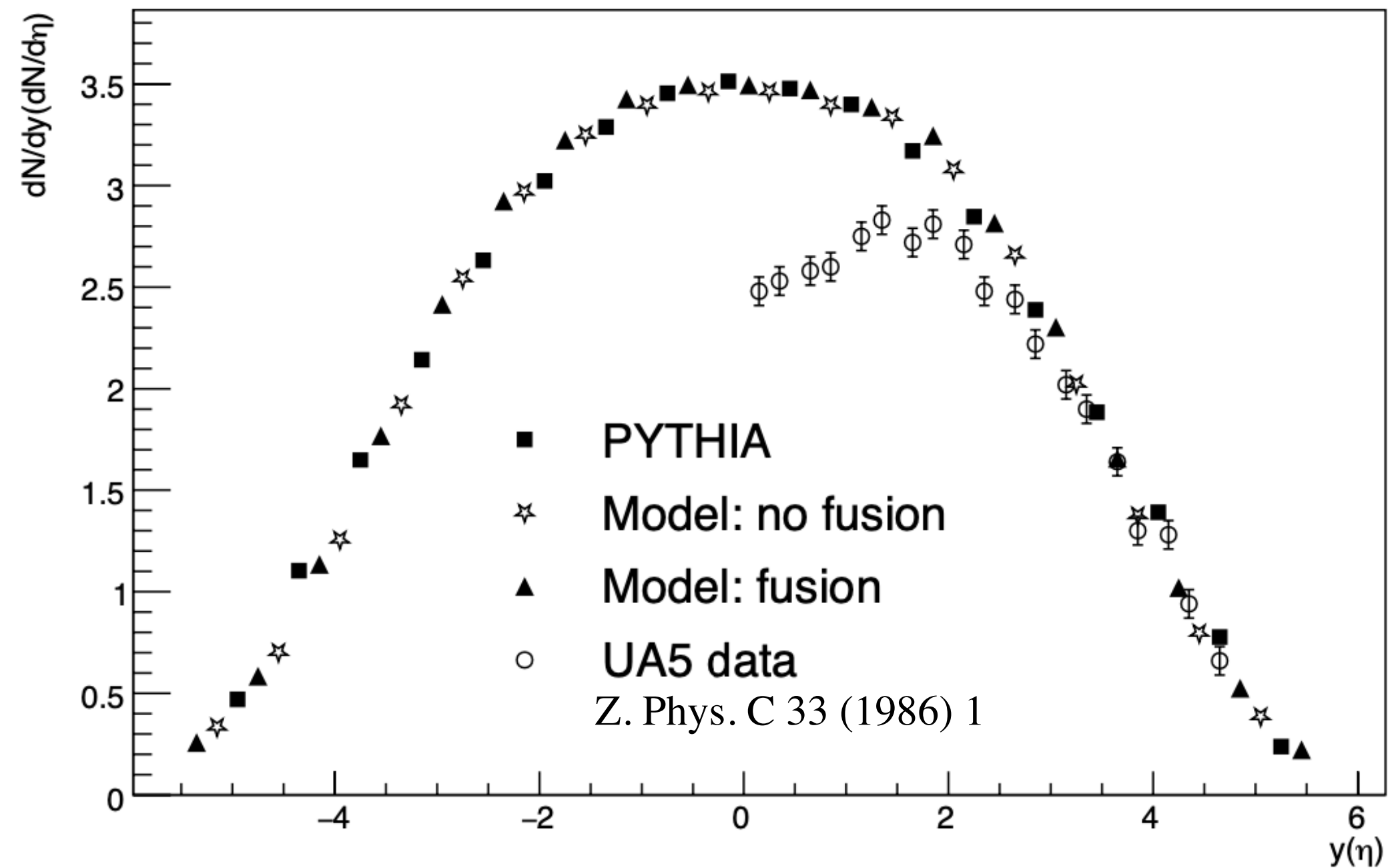
The loop is repeated N_{out} times (one can stop earlier if the number of accepted swaps is reduced to 1%)

Result: sets of correlated values of particle rapidities for different multiplicities N

Results: p+p at 200 GeV

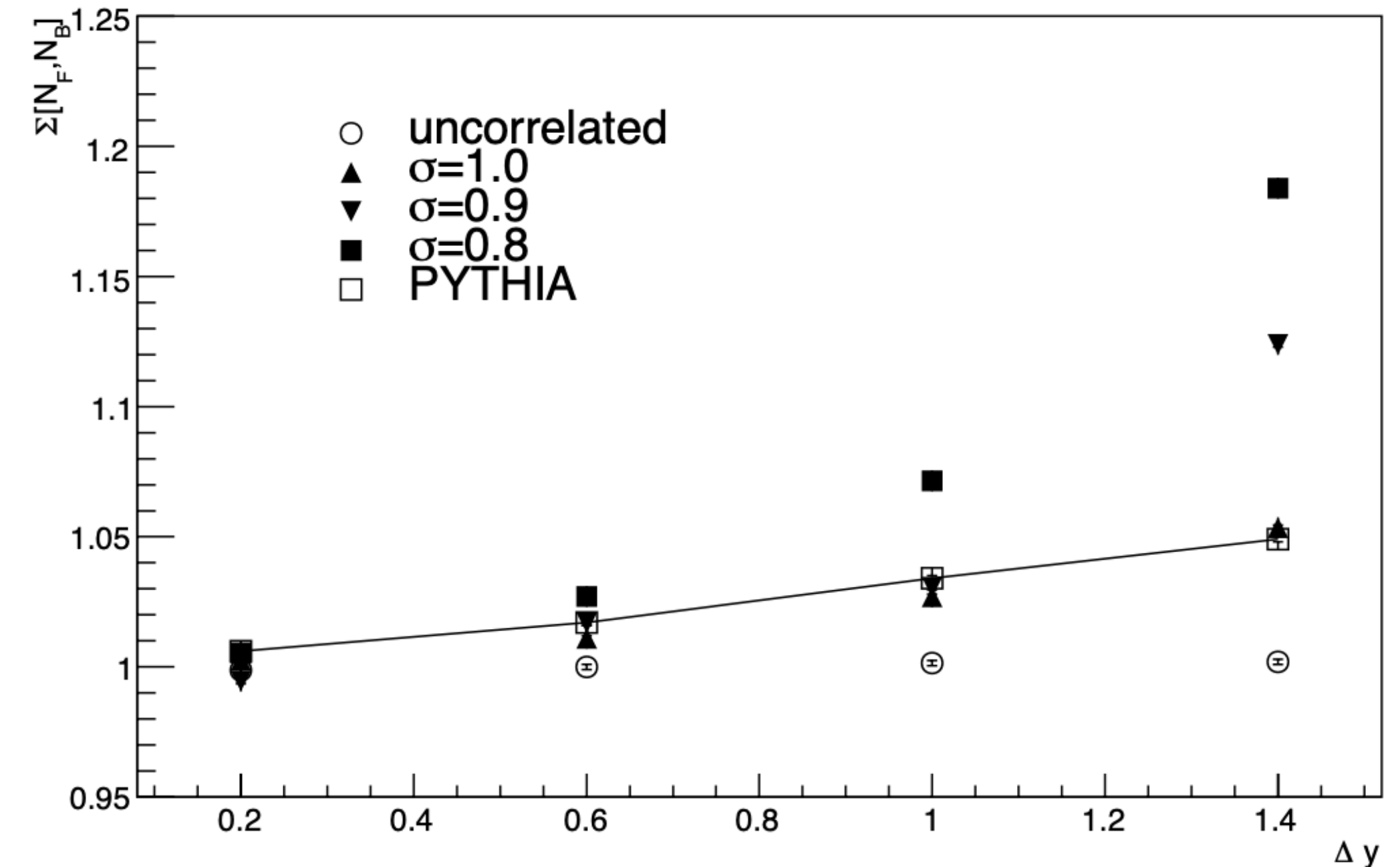


p-p, $\sqrt{s}=200\text{GeV}$



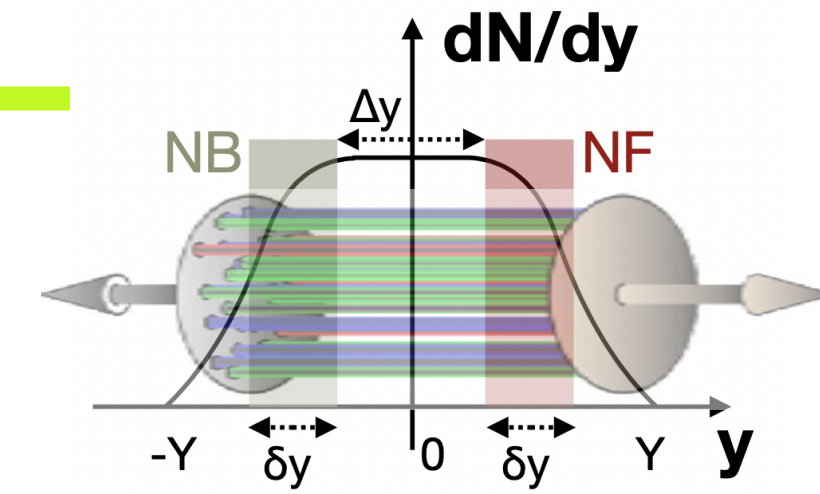
string parameters were fitted in order to reproduce rapidity spectrum

p-p, $\sqrt{s}=200\text{ GeV}$, No fusion, $\delta y=0.2$

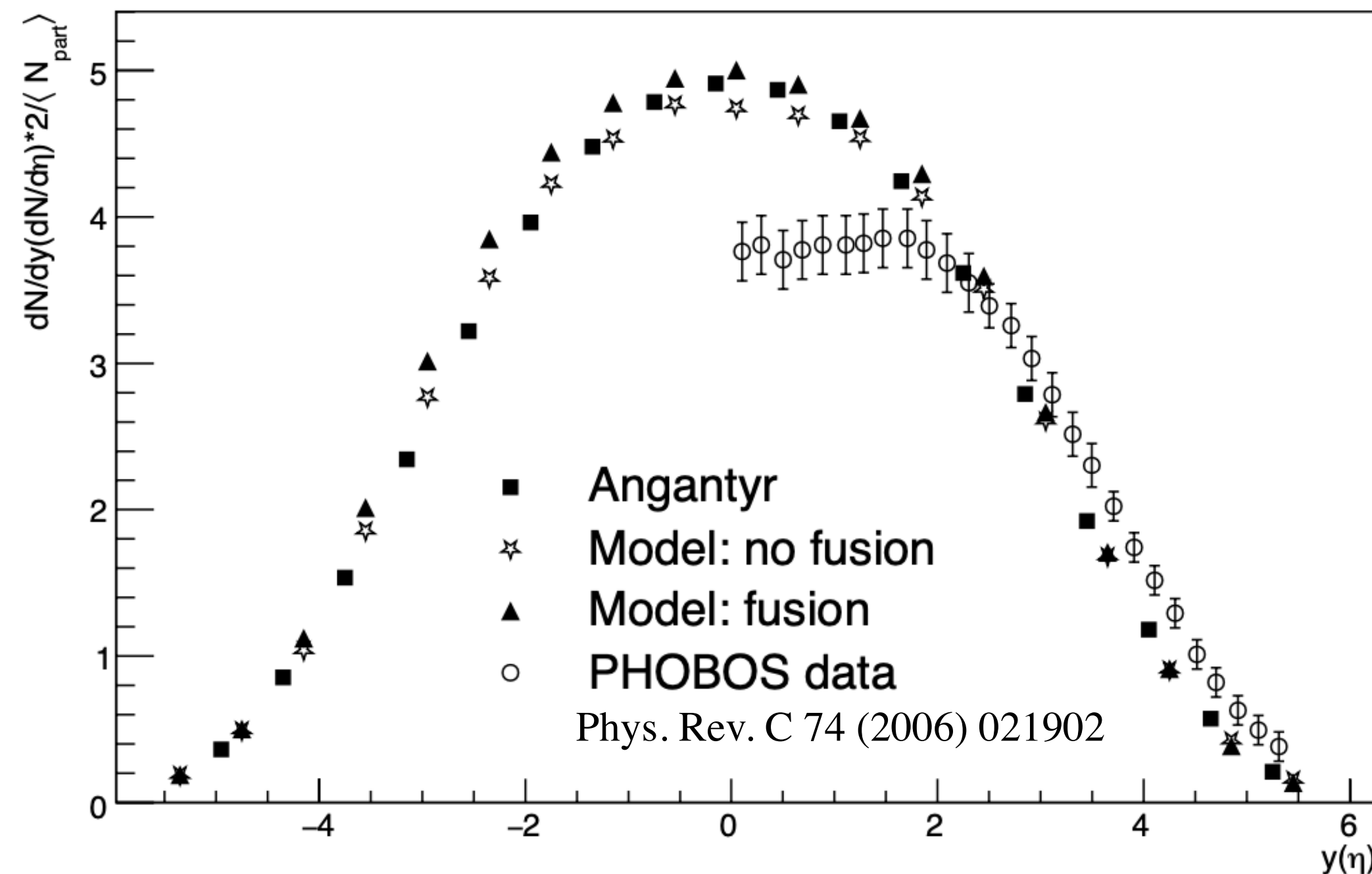


no data on fluctuations available
we compare with PYTHIA

Results: Au+Au at 200 GeV



Au-Au, $\sqrt{s_{NN}}=200\text{GeV}, 0-3\%$



string parameters were fitted in order to reproduce rapidity spectrum

PHOBOS measured rapidity correlations using

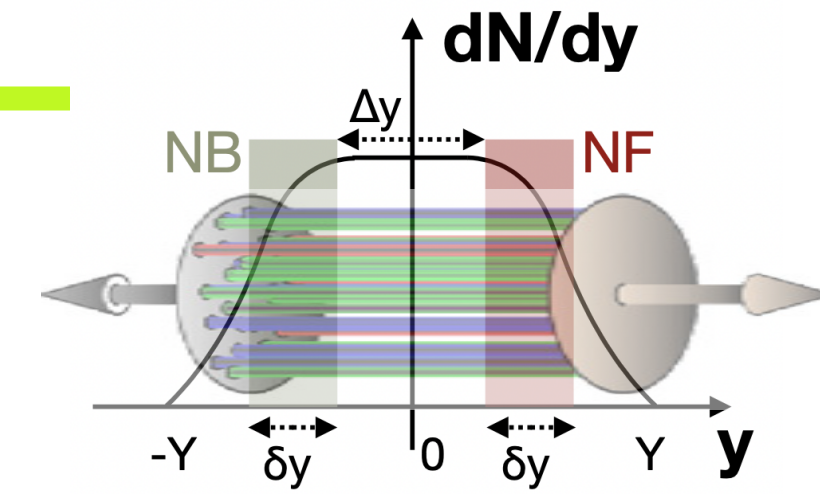
$$\sigma_C^2 = \left\langle \frac{(N_F - N_B)^2}{N_F + N_B} \right\rangle - \left\langle \frac{N_F - N_B}{\sqrt{N_F + N_B}} \right\rangle^2$$

It was shown that

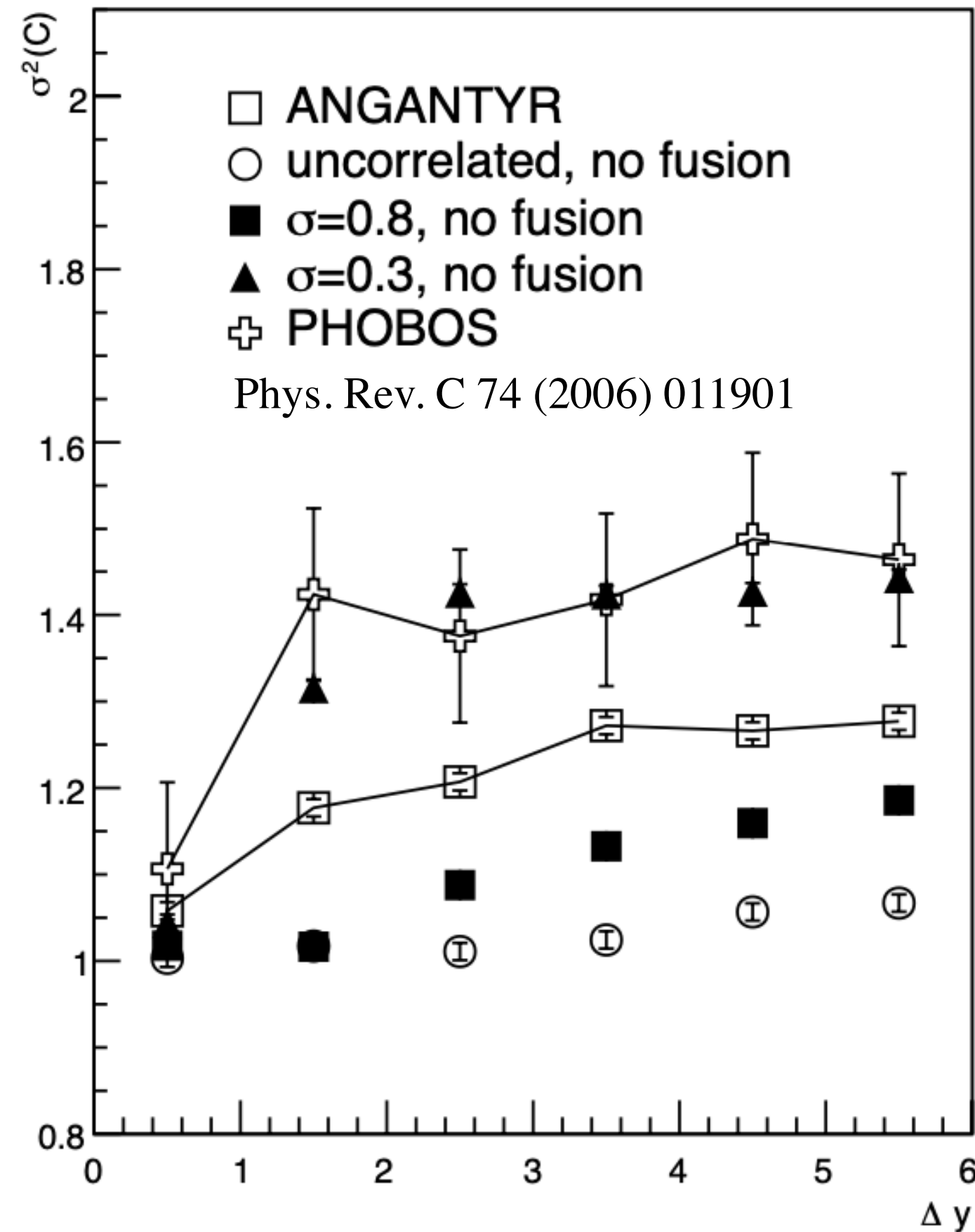
$$\sigma_C^2 \approx \Sigma[N_F, N_B]$$

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

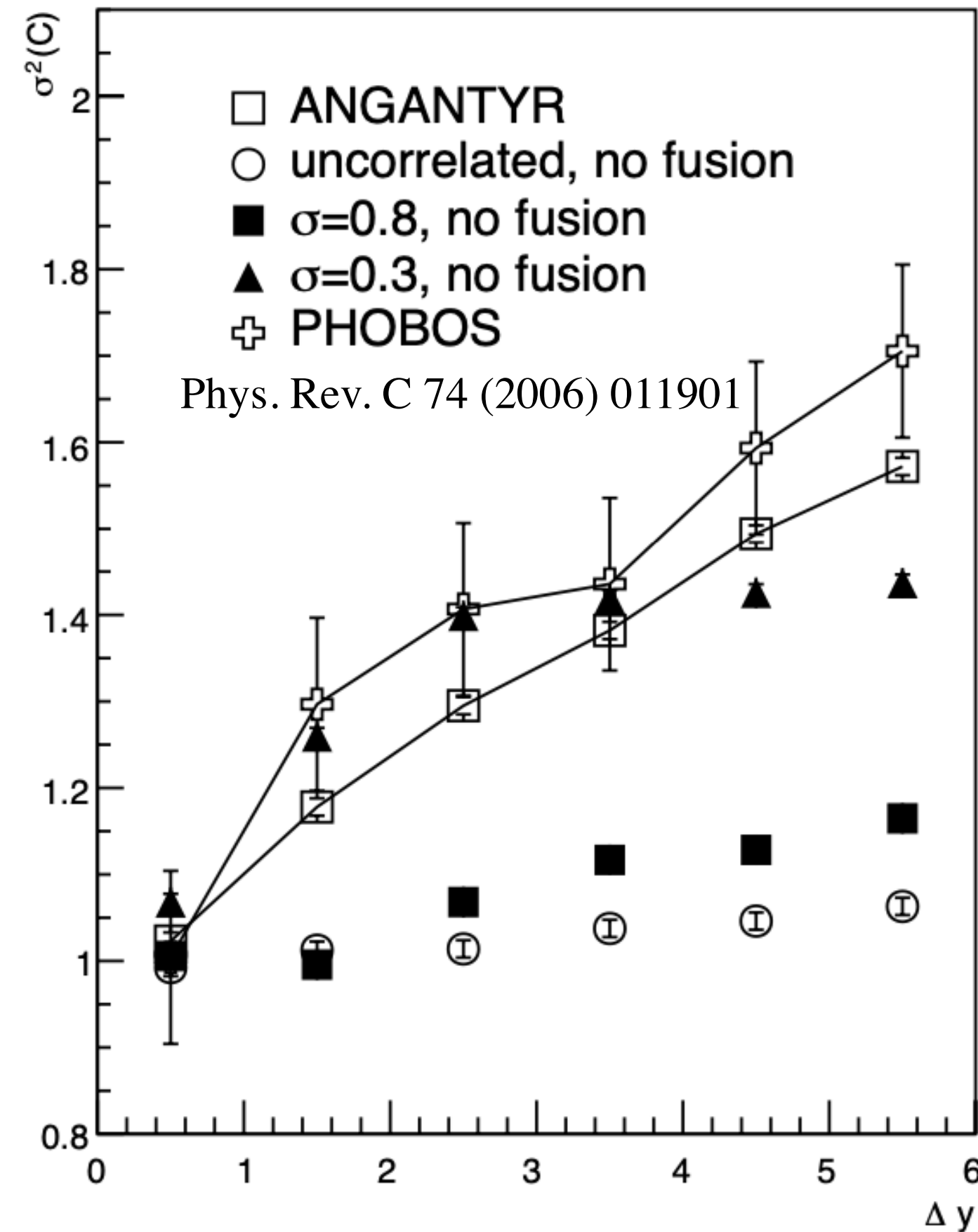
Results: Au+Au at 200 GeV



Au-Au, $\sqrt{s_{NN}}=200$ GeV, 0-20%, $\delta y=0.5$



Au-Au, $\sqrt{s_{NN}}=200$ GeV, 40-60%, $\delta y=0.5$



No fusion (independent strings)
scenario reproduces data with
 $\sigma = 0.3$

Higher-order SIQs

From W. Broniowski, A. Olszewski, Phys. Rev. C 95, 064910 (2017):

P - cumulants of final observables, Q - cumulants in number of sources, R - cumulants from a single source

$$\langle N_F^3 \rangle - 3\langle N_F^2 \rangle \langle N_F \rangle + 2\langle N_F \rangle^3 = P_{03} = Q_3 \cdot R_{01}^3 + 3Q_2 R_{01} R_{02} + Q_1 R_{03}$$

$$\langle N_F^2 N_B \rangle - 2\langle N_F N_B \rangle \langle N_F \rangle - \langle N_F^2 \rangle \langle N_B \rangle + 2\langle N_F \rangle^2 \langle N_B \rangle = P_{12} = Q_3 \cdot R_{01}^2 R_{10} + Q_2 (2R_{01} R_{11} + R_{02} R_{10}) + Q_1 R_{12}$$

$$\langle N_B^2 N_F \rangle - 2\langle N_F N_B \rangle \langle N_B \rangle - \langle N_B^2 \rangle \langle N_F \rangle + 2\langle N_B \rangle^2 \langle N_F \rangle = P_{21} = Q_3 \cdot R_{10}^2 R_{01} + Q_2 (2R_{10} R_{11} + R_{20} R_{01}) + Q_1 R_{21}$$

$$\langle N_B^3 \rangle - 3\langle N_B^2 \rangle \langle N_B \rangle + 2\langle N_B \rangle^3 = P_{30} = Q_3 \cdot R_{10}^3 + 3Q_2 R_{10} R_{20} + Q_1 R_{30}$$

One can define:

$$\Gamma[N_F, N_B] = \frac{P_{01} P_{30}}{P_{10}^2} - 3 \frac{P_{21}}{P_{10}} + 3 \frac{P_{12}}{P_{01}} - \frac{P_{10} P_{03}}{P_{01}^2} = \frac{R_{01} R_{30}}{R_{10}^2} - 3 \frac{R_{21}}{R_{10}} + 3 \frac{R_{12}}{R_{01}} - \frac{R_{10} R_{03}}{R_{01}^2}$$

$\Gamma[N_F, N_B] = 0$ for symmetric windows

Higher-order SIQs

For small (->Poissonian distribution in a windows) far-separated (->not correlated) windows:

$$R_{01} = \overline{\mu_F} = \delta y_F \cdot \mu_0 \quad R_{10} = \overline{\mu_B} = \delta y_B \cdot \mu_0$$

$$R_{12} = \overline{\mu_F^2 \mu_B} - 2\overline{\mu_F \mu_B} \cdot \overline{\mu_F} - \overline{\mu_F^2} \cdot \overline{\mu_B} + 2\overline{\mu_F}^2 \cdot \overline{\mu_B} \approx \overline{\mu_F} \cdot \overline{\mu_B} = \delta y_F \cdot \delta y_B \cdot \overline{\mu_0}^2 = R_{21}$$

$$R_{03} = \overline{\mu_F^3} - 3\overline{\mu_F^2} \cdot \overline{\mu_F} + 2\overline{\mu_F}^3 \approx \overline{\mu_F} = \delta y_F \cdot \mu_0$$

$$R_{30} = \overline{\mu_B^3} - 3\overline{\mu_B^2} \cdot \overline{\mu_B} + 2\overline{\mu_B}^3 \approx \overline{\mu_B} = \delta y_B \cdot \mu_0$$

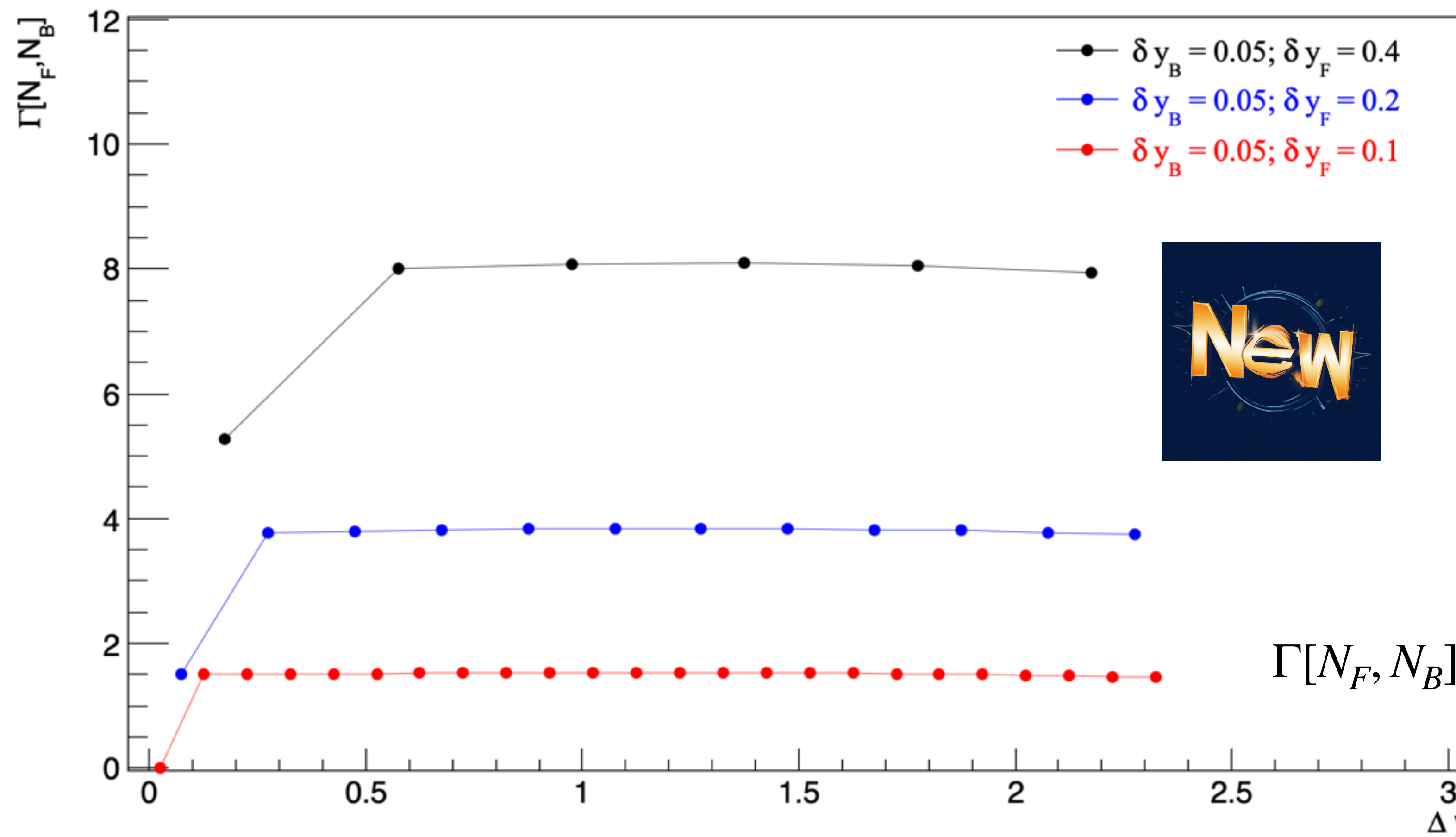
$$\Gamma[N_F, N_B] = \frac{R_{01}R_{30}}{R_{10}^2} - 3\frac{R_{21}}{R_{10}} + 3\frac{R_{12}}{R_{01}} - \frac{R_{10}R_{03}}{R_{01}^2} \approx \frac{\overline{\mu_F} \cdot \overline{\mu_B}}{\overline{\mu_B}^2} - 3\frac{\overline{\mu_F} \cdot \overline{\mu_B}}{\overline{\mu_B}} + 3\frac{\overline{\mu_F} \cdot \overline{\mu_B}}{\overline{\mu_F}} - \frac{\overline{\mu_B} \cdot \overline{\mu_F}}{\overline{\mu_F}^2}$$

$$\text{Finally, } \Gamma[N_F, N_B] = 3 \cdot \mu_0 \cdot (\delta y_B - \delta y_F) + \frac{\delta y_F^2 - \delta y_B^2}{\delta y_B \delta y_F}$$

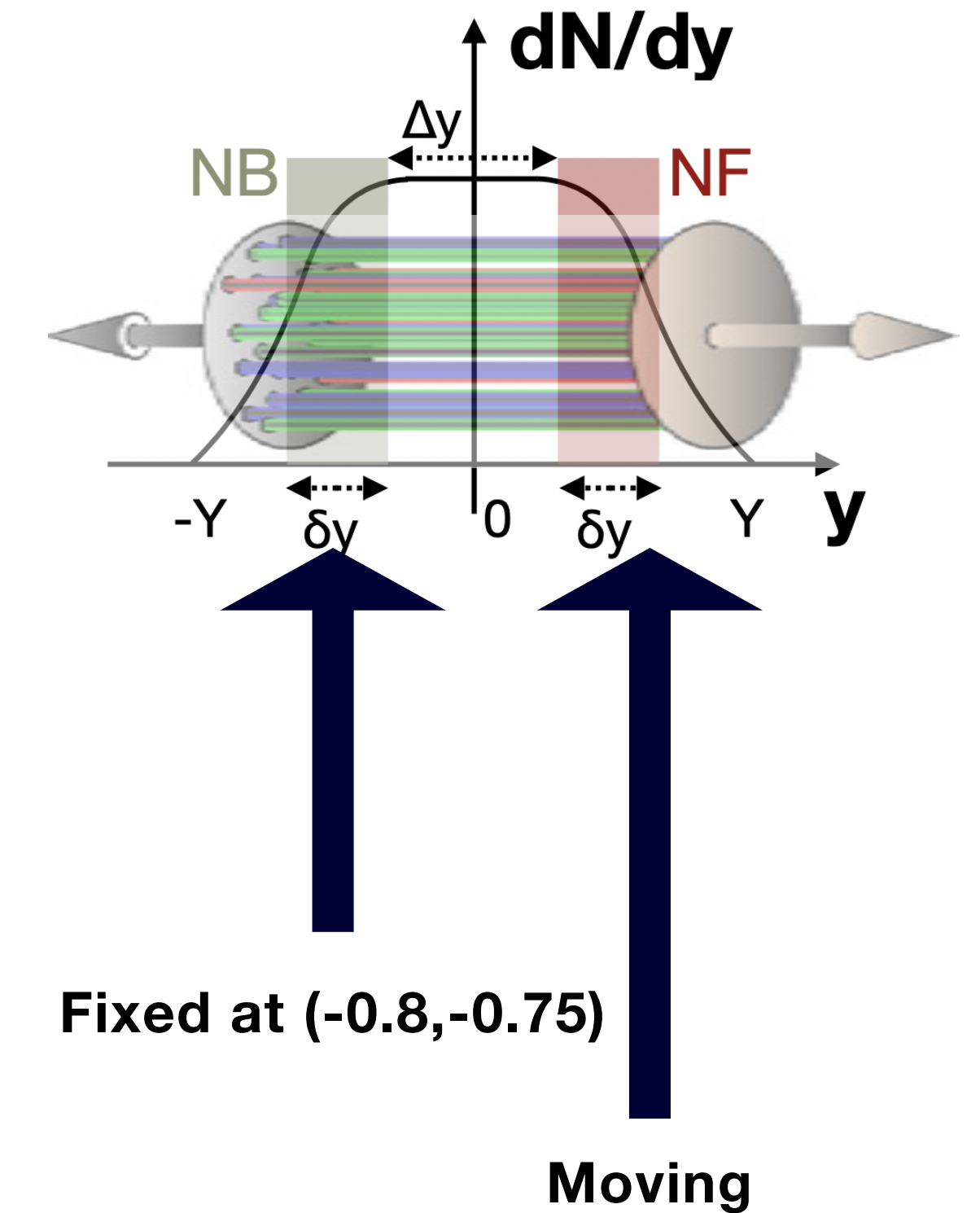


Higher-order SIQs

PYTHIA8.3, NSD p+p @ $\sqrt{s} = 900\text{GeV}$, $0.3 < p_T < 1.5\text{GeV}/c$



$$\Gamma[N_F, N_B] = 3 \cdot \mu_0 \cdot (\delta y_B - \delta y_F) + \frac{\delta y_F^2 - \delta y_B^2}{\delta y_B \delta y_F}$$



Summary

Second-order strongly intensive quantities:

- can probe correlation length from a string

Third-order strongly intensive quantities:

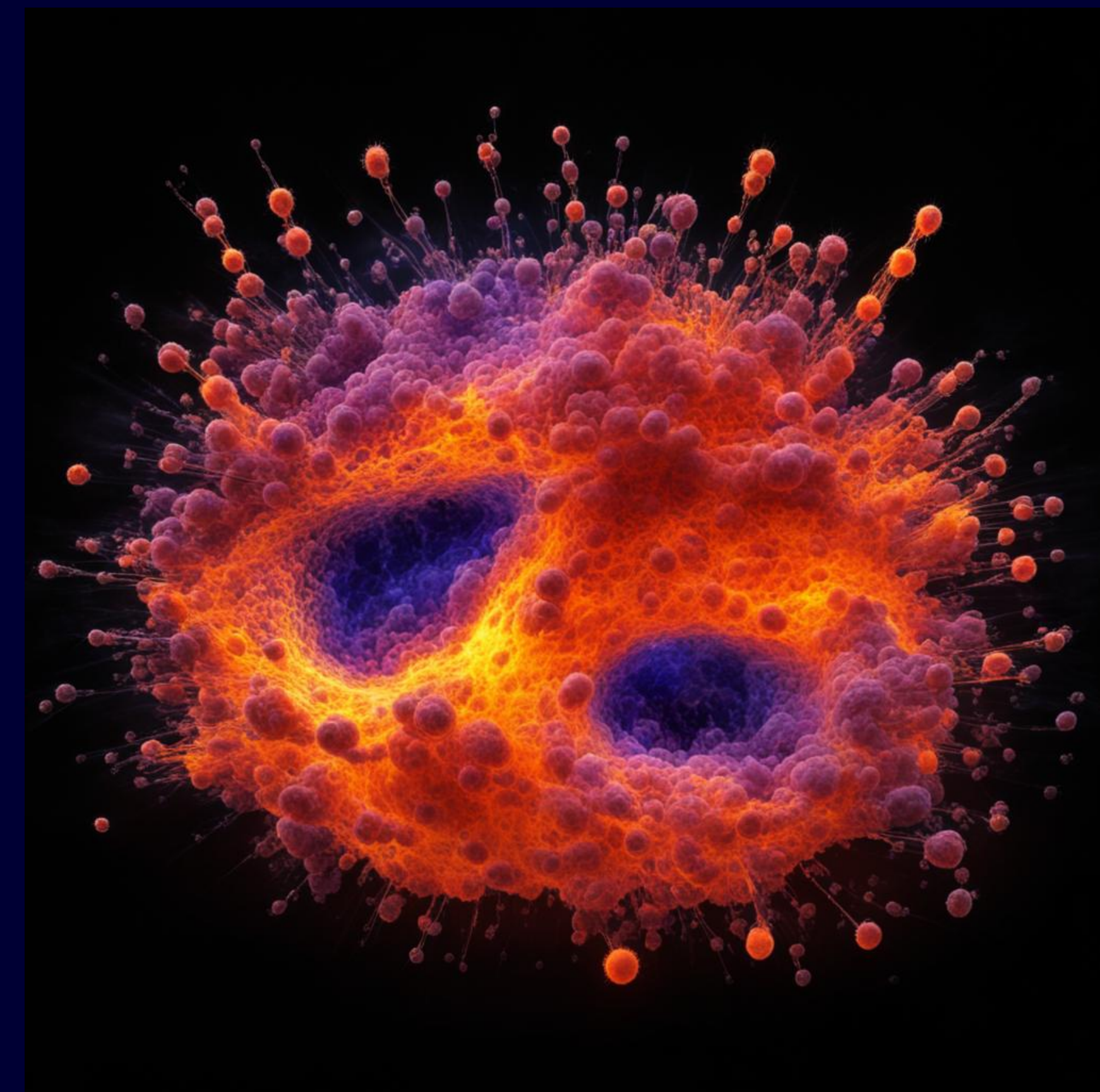
- new observable $\Gamma[N_F, N_B]$ was analyzed in simplified string model and within PYTHIA
- at large separations $\Gamma[N_F, N_B]$ reaches its plateau values

Thank you for your attention!

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Kandinsky bot: «Quark-gluon plasma»

EXTRA

Independent strings

For independent strings:

$$\Sigma[N_F, N_B] = \frac{\omega[N_B] \cdot \langle N_F \rangle + \omega[N_F] \cdot \langle N_B \rangle - 2 \cdot \text{cov}(N_F, N_B)}{\langle N_B + N_F \rangle} = \Sigma[\mu_F, \mu_B]$$

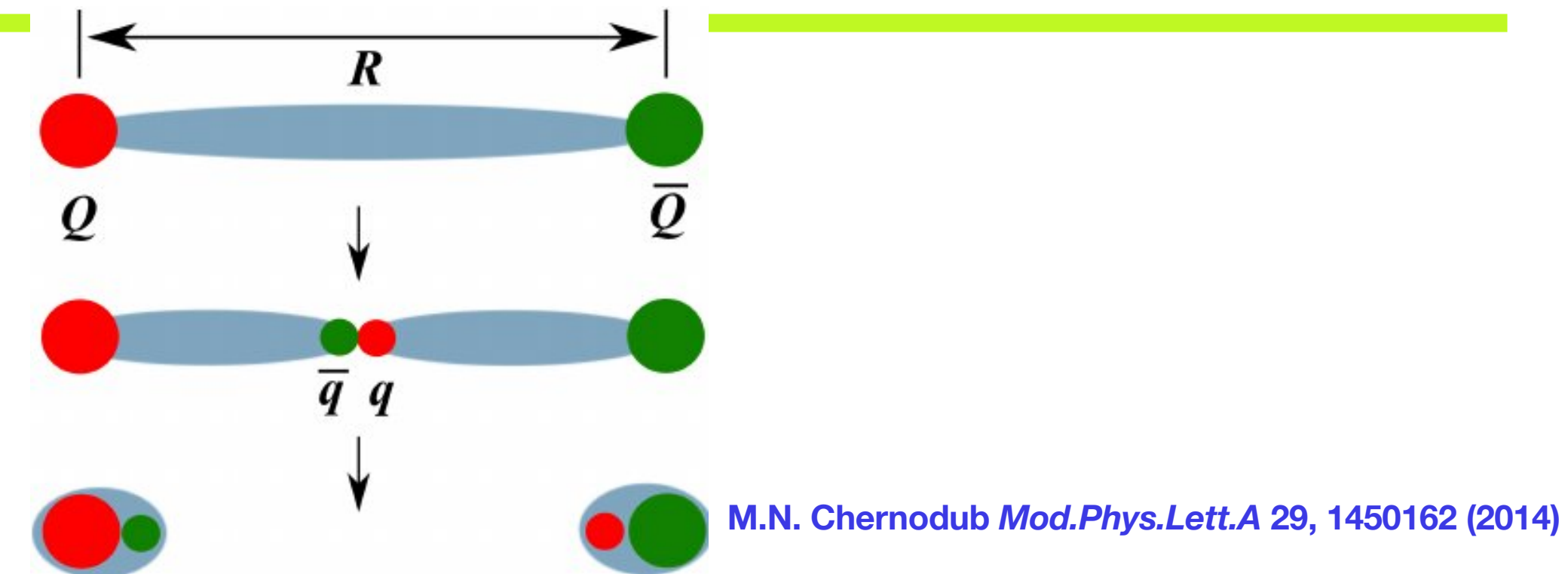
$$\Delta[N_F, N_B] = \frac{\omega[N_B] \cdot \langle N_F \rangle - \omega[N_F] \cdot \langle N_B \rangle}{\langle N_F - N_B \rangle} = \Delta[\mu_F, \mu_B]$$

For small (->Poissonian distribution in a windows) far-separated (->not correlated) windows:

$$\Sigma[N_F, N_B] \approx 1$$

$$\Delta[N_F, N_B] \approx 1$$

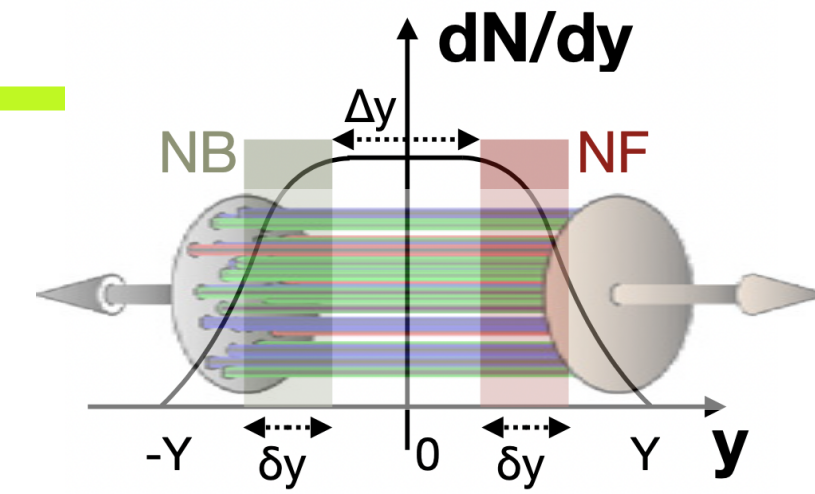
Color string models



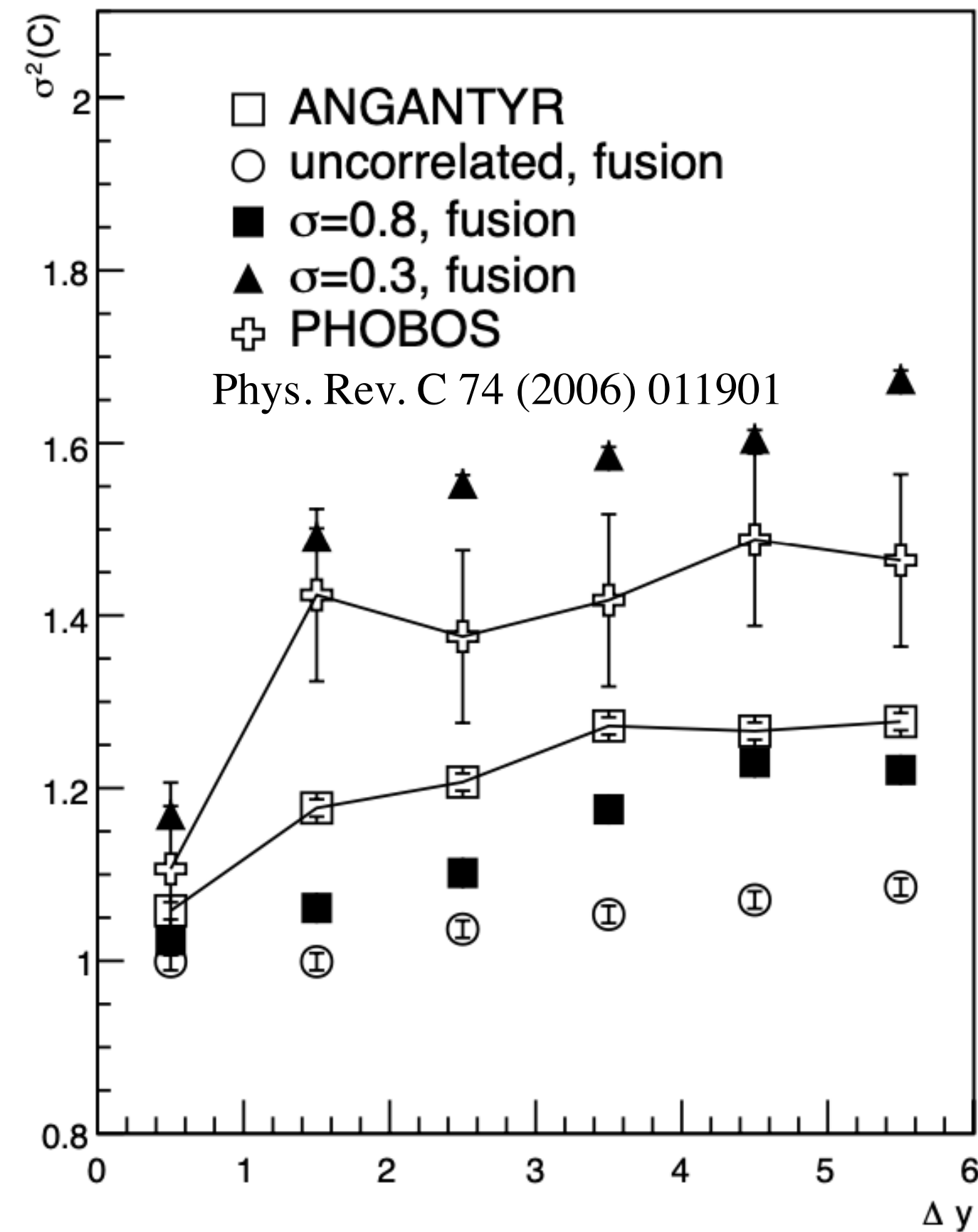
- PYTHIA/FRITIOF/QGSM/PHSD/EPOS are among the most successful MC event generators that are able to describe p+p and A+A data (Color strings as particle emitting sources)
- With an increase of the collision energy multi-string configurations start to play a bigger role, ideas: rope formation, string fusion,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

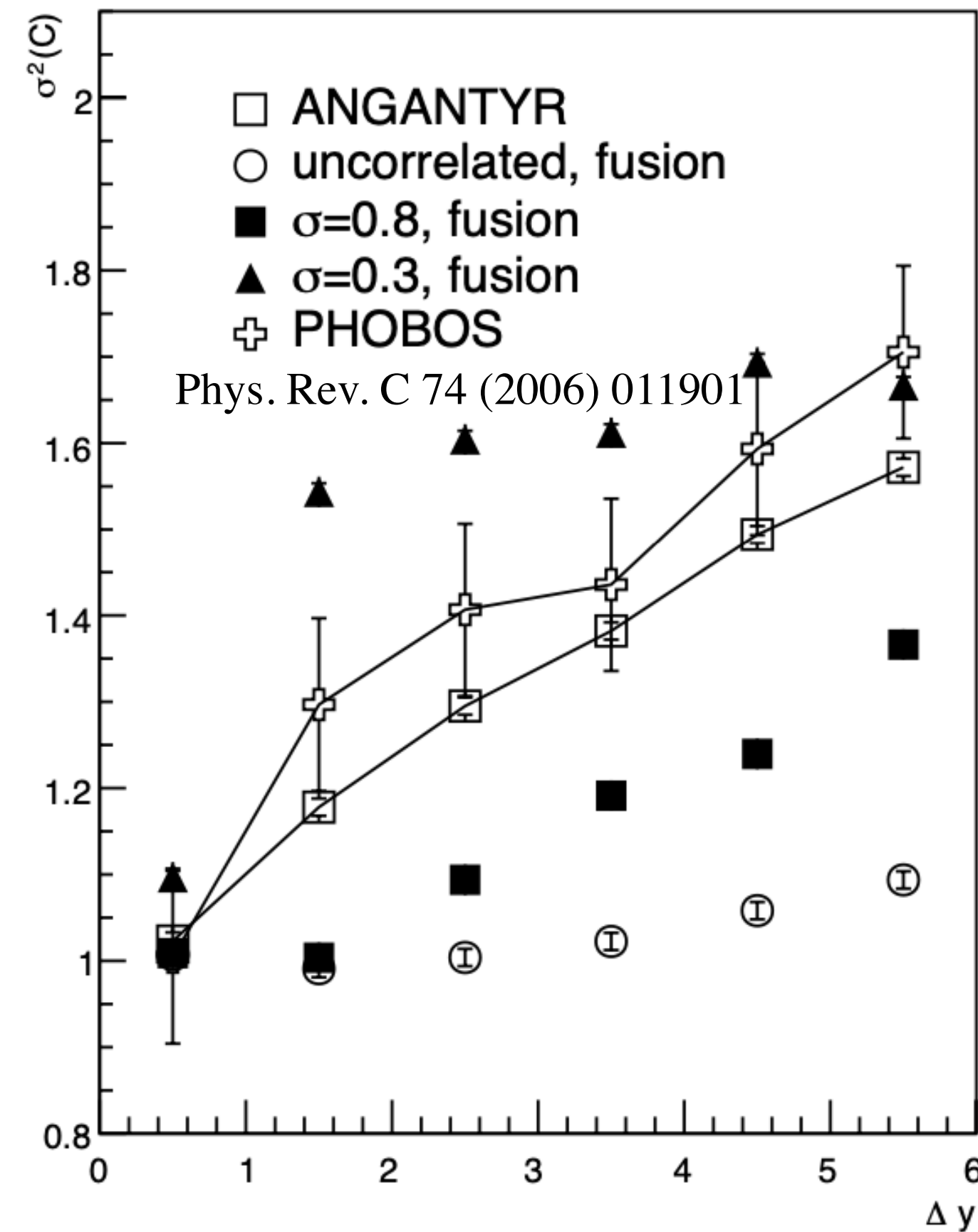
Results: Au+Au at 200 GeV



Au-Au, $\sqrt{s_{NN}}=200$ GeV, 0-20%, $\delta y=0.5$



Au-Au, $\sqrt{s_{NN}}=200$ GeV, 40-60%, $\delta y=0.5$



Fusion modifies SIQ behaviour