Imprint of conservation laws in correlated particle production

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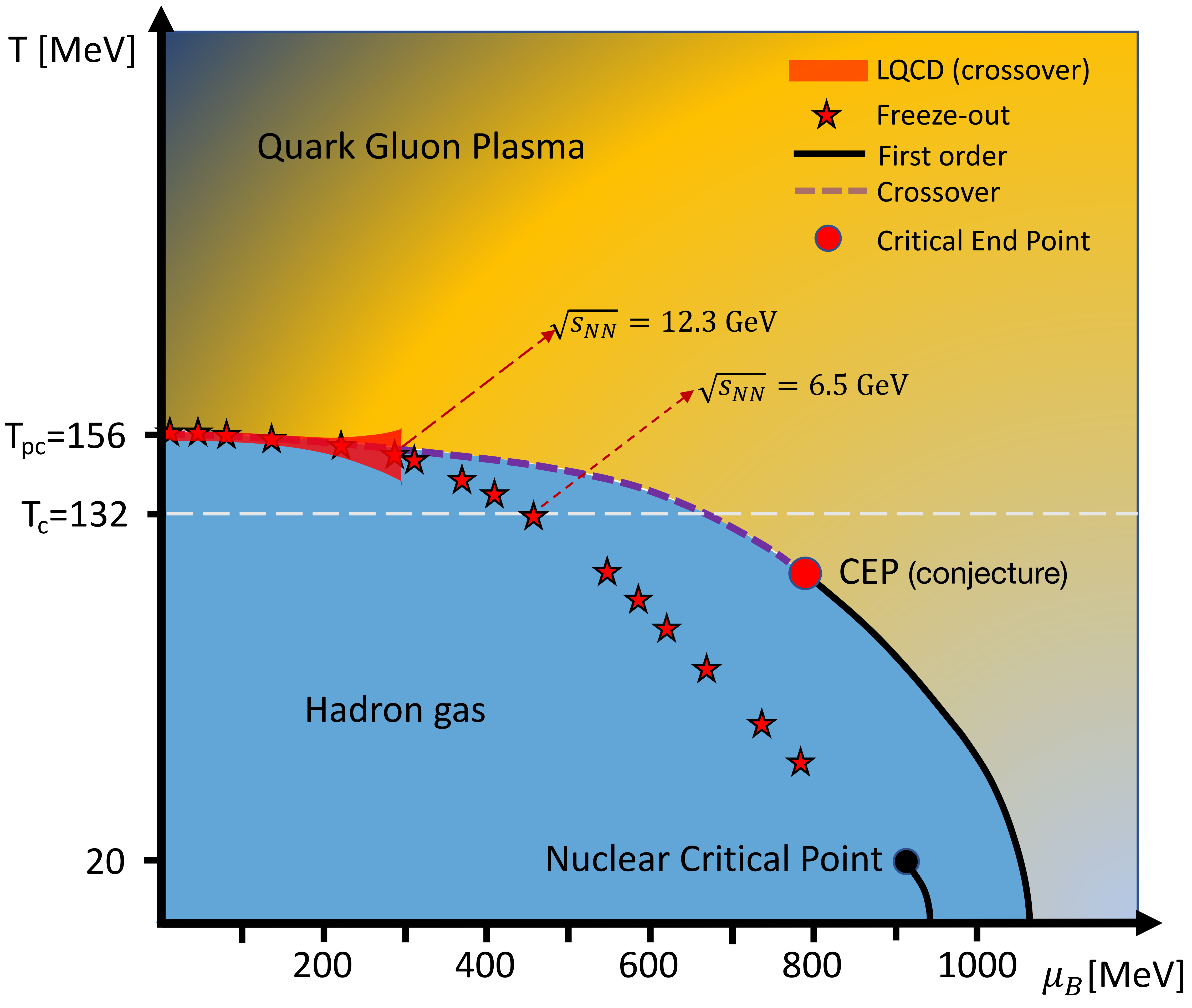
Outline

- Phase diagram and fluctuations
  - Correlations in rapidity space
  - Canonical Ensemble
- Obtained results and comparison to experiments
  - Implications from long range correlations
  - The quest for proton clusters
- Conclusions

Phase diagram and fluctuations



A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature 561, 321–330 (2018)
H. T. Ding et al [HotQCD], arXiv:1903.04801, A. Bazavov et al [HotQCD], arXiv:1812.08235

E-by-E fluctuations are predicted within Grand Canonical Ensemble

direct link to EoS

$$\frac{\kappa_n(N_B - N_{\bar{B}})}{VT^3} = \frac{1}{VT^3}\frac{\partial^n lnZ(V,T,\mu_B)}{\partial\left(\mu_B/T\right)^n} \equiv \hat{\chi}_n^B$$

κ_n - cumulants (measurable in experiment)

$\hat{\chi}_n^B$ - susceptibilities (e.g. from lQCD)

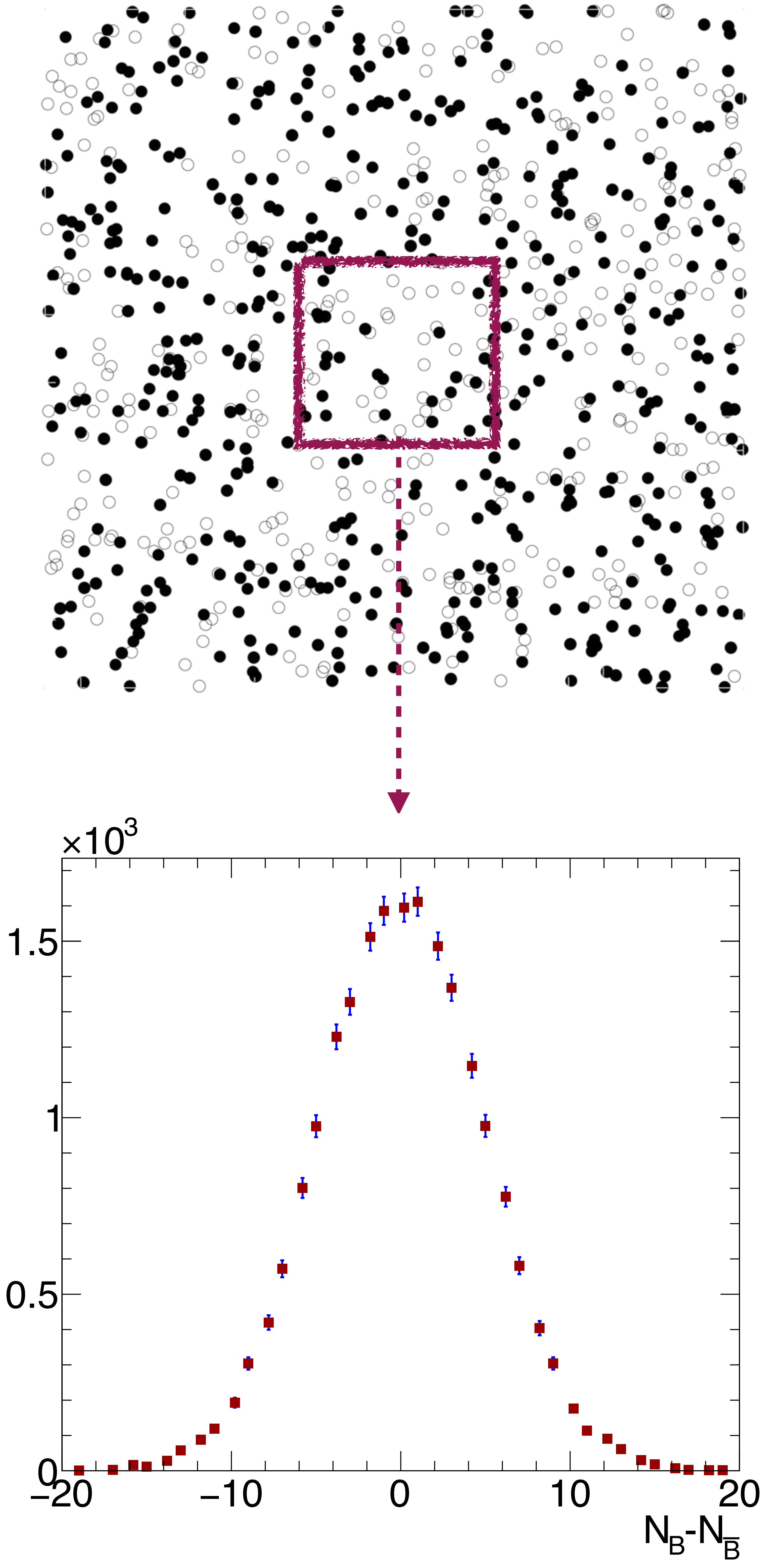
Minimal baseline: GCE + Ideal Gas EoS

$$\kappa_n(N_B - N_{\bar{B}}) = \langle N_B \rangle + (-1)^n \langle N_{\bar{B}} \rangle \equiv k_n(Skellam)$$

P. Braun-Munzinger, AR, J. Stachel, NPA 982 (2019) 307-310

decoding the phase structure of matter with E-by-E fluctuations

Formulation of the problem

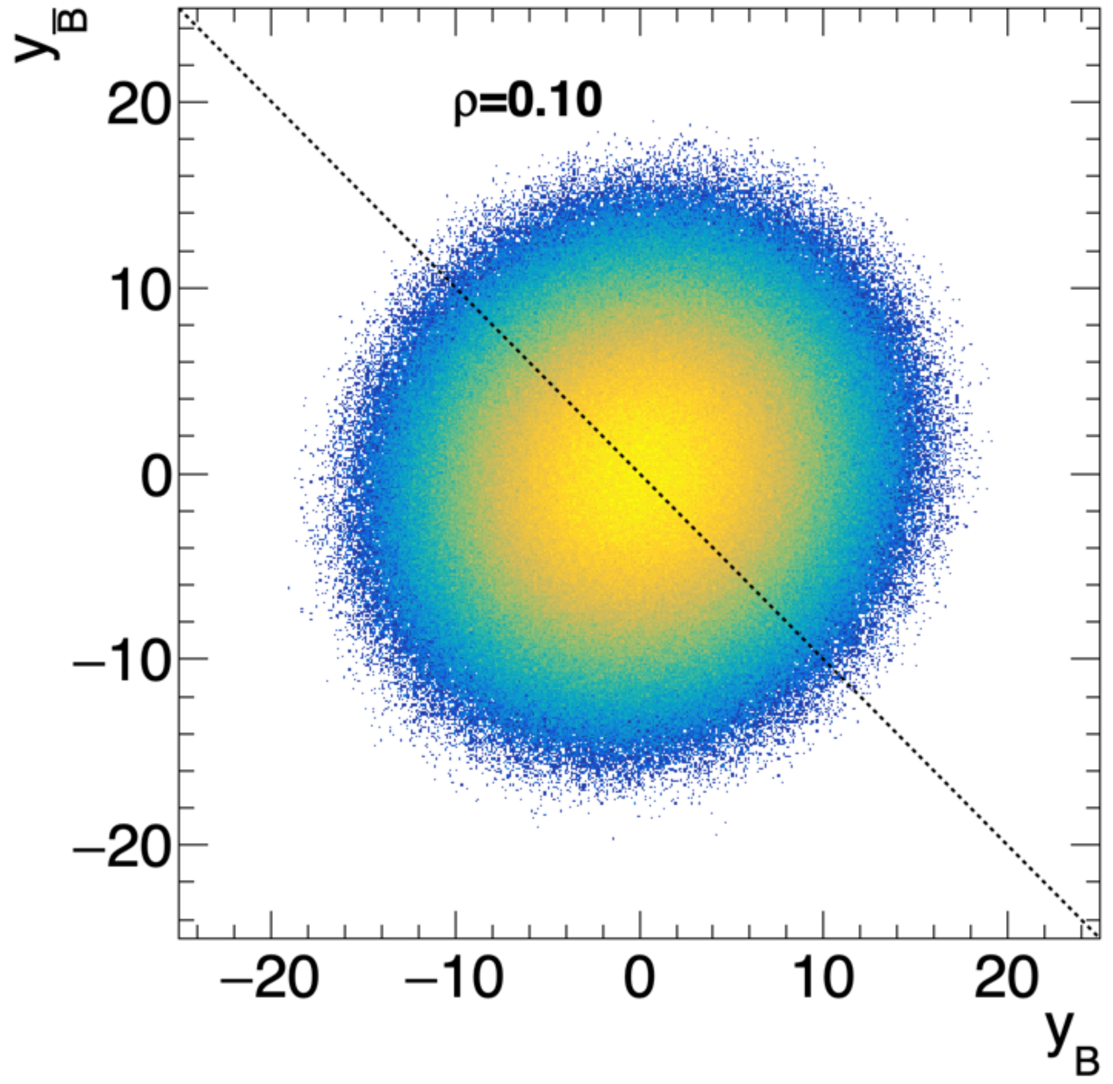


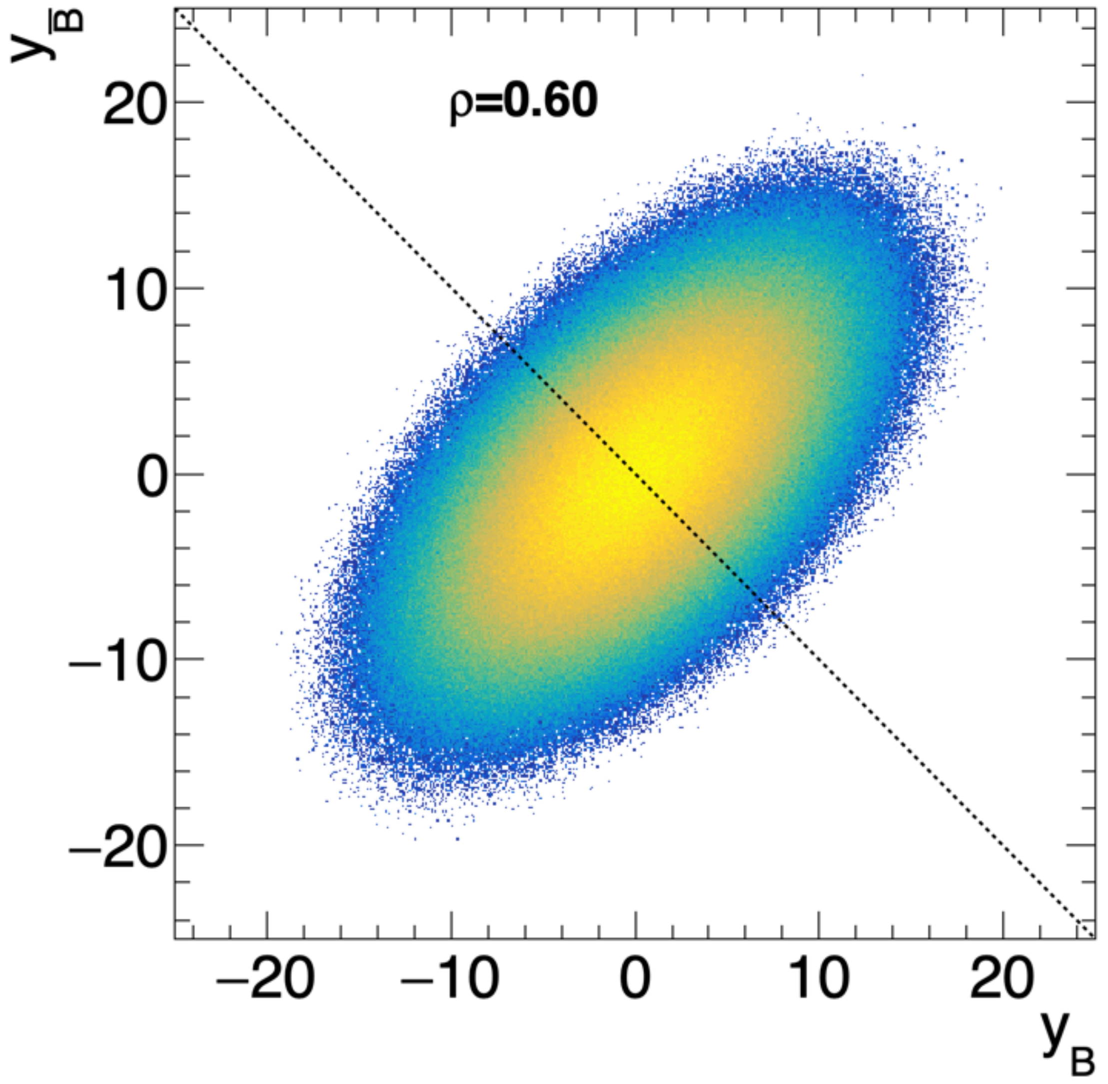
- exploiting **C**anonical **E**nsemble in the full phase space
  - no fluctuations in 4π
  - finite fluctuations inside acceptance

} akin to experiments

P. Braun-Munzinger, B. Friman, K. Redlich, AR., J. Stachel , NPA 1008 (2021) 122141
V. Vovchenko, V. Koch, Ch. Shen, Phys.Rev.C 105 (2022) 1, 014904

novelty in this presentation: <u>correlations in rapidity space</u>





essential for understanding baryon production mechanism

introducing correlations in rapidity space

Cholesky decomposition

André-Louis Cholesky (1875-1918)

$\{x_1, x_2\}$: pairs of random variables; how to introduce correlations between them?

$$\rho = \frac{cov[x_1, x_2]}{\sigma_1 \sigma_2}$$

correlation coefficient

$$cov[x_1, x_2] = \langle x_1 x_2 \rangle - \langle x_1 \rangle \langle x_2 \rangle \qquad \sigma_i^2 = \langle x_i^2 \rangle - \langle x_i \rangle^2$$

Cholesky decomposition: $\Sigma = \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_2\sigma_1 & \sigma_2^2 \end{pmatrix} = \underbrace{\begin{pmatrix} \sigma_1 & 0 \\ \rho\sigma_2 & \sqrt{1-\rho^2}\sigma_2 \end{pmatrix}}_{L} \underbrace{\begin{pmatrix} \sigma_1 & \rho\sigma_2 \\ 0 & \sqrt{1-\rho^2}\sigma_2 \end{pmatrix}}_{L^T}$

covariance matrix

posthumously published: Bulletin Géodésique (in French). 2: 66–67 (1924)

- generate uncorrelated variables from Standard Normal Distribution ($\sigma = 1,\ \mu = 0$)

$\{z_1, z_2\}$ → uncorrelated → $\Sigma_z \equiv \mathbb{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

- get correlated $\{x_1, x_2\}$ pairs

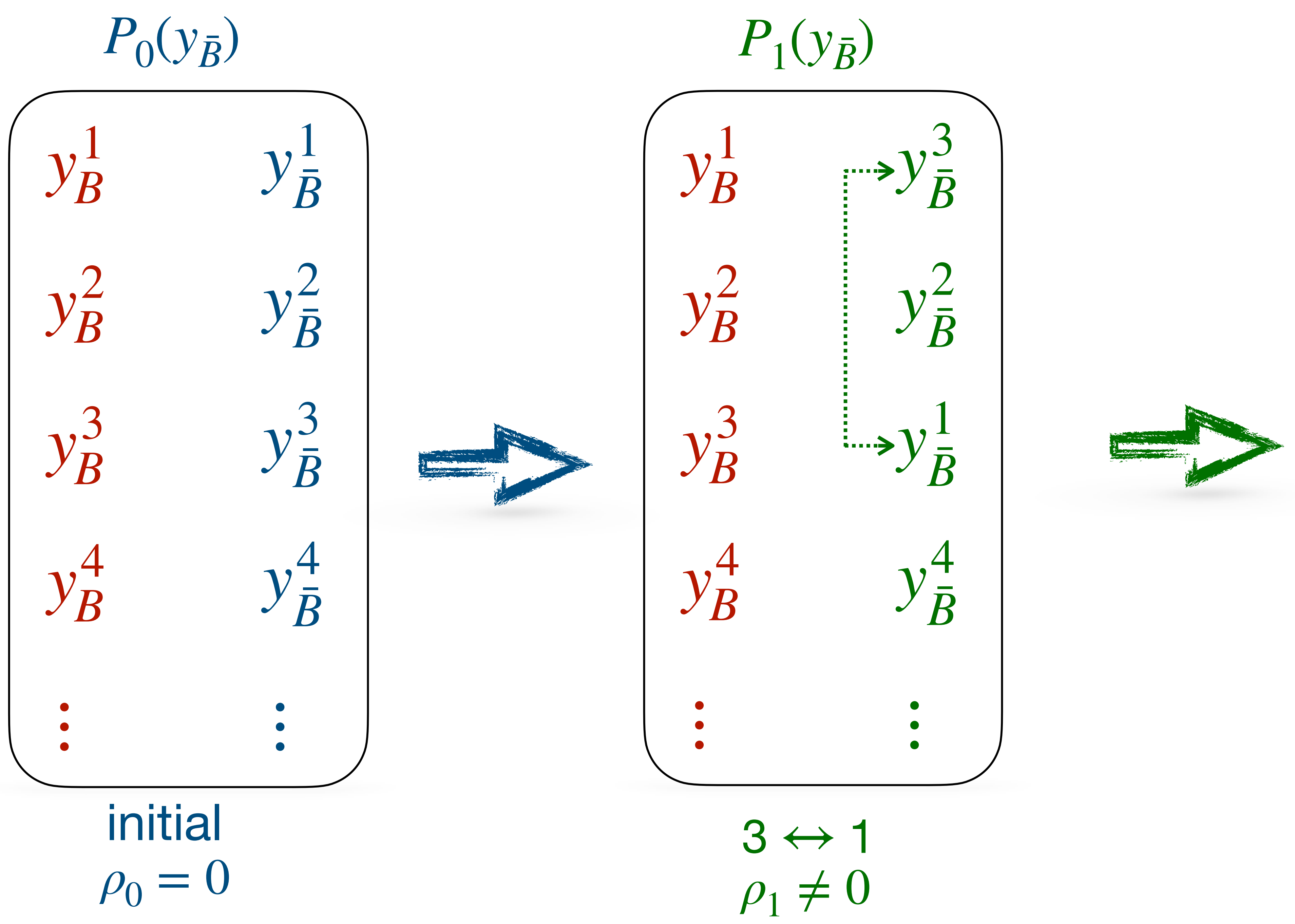
$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} \langle x_1 \rangle \\ \langle x_2 \rangle \end{pmatrix} + L \begin{pmatrix} z_1 \\ z_2 \end{pmatrix}$$

→ correlated → $\Sigma_x = \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_2\sigma_1 & \sigma_2^2 \end{pmatrix}$

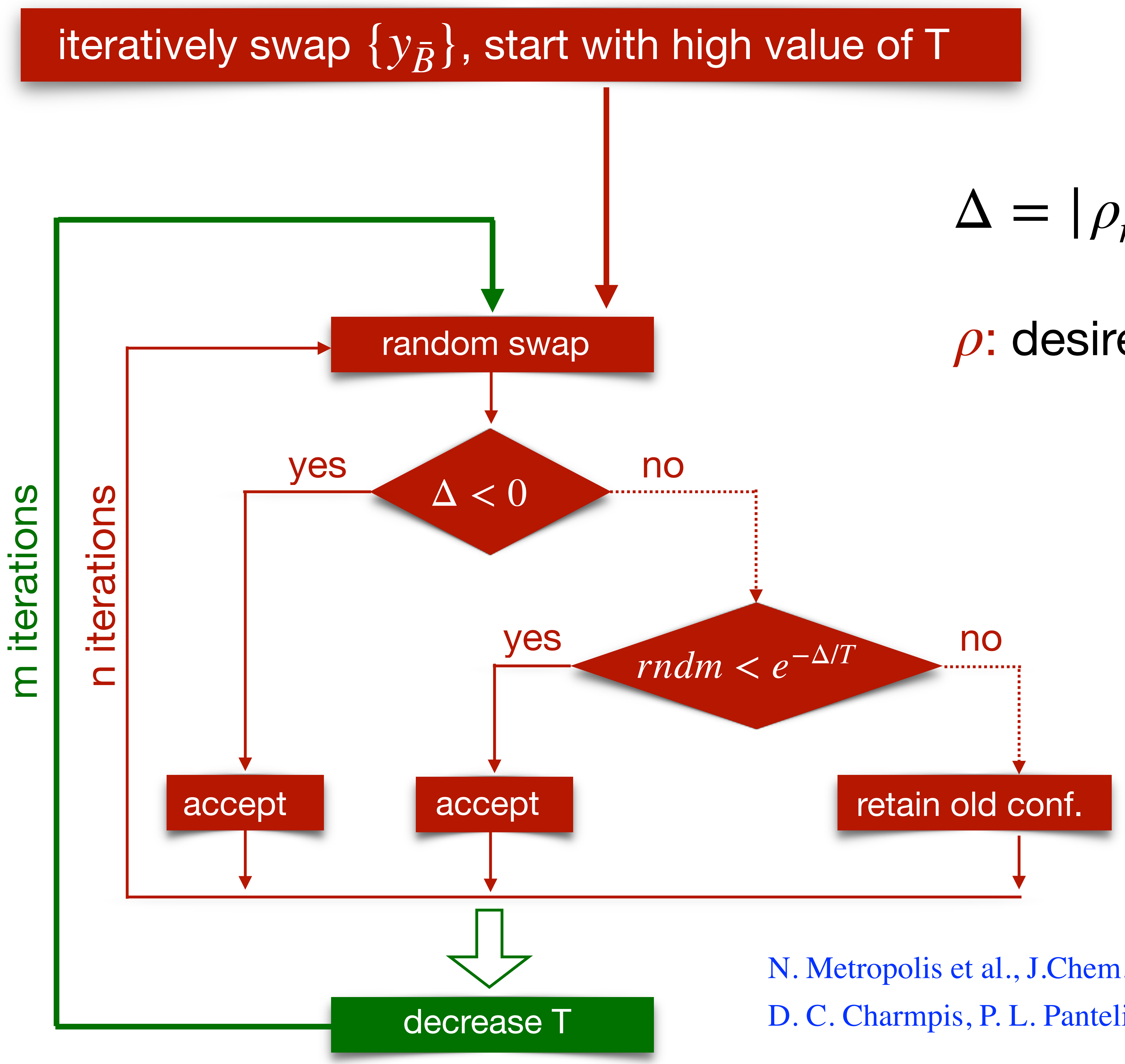
works only for Gaussian distributions

Metropolis algorithm (Simulated annealing)

start with uncorrelated $\{y_B\}$, $\{y_{\bar{B}}\}$



$$\rho_n = \frac{cov[y_B, P_n(y_{\bar{B}})]}{\sigma_{y_B}\sigma_{y_{\bar{B}}}}$$



stop if accepted rate is too small (< 1%)

$$\Delta = |\rho_n - \rho| - |\rho_{n-1} - \rho|$$

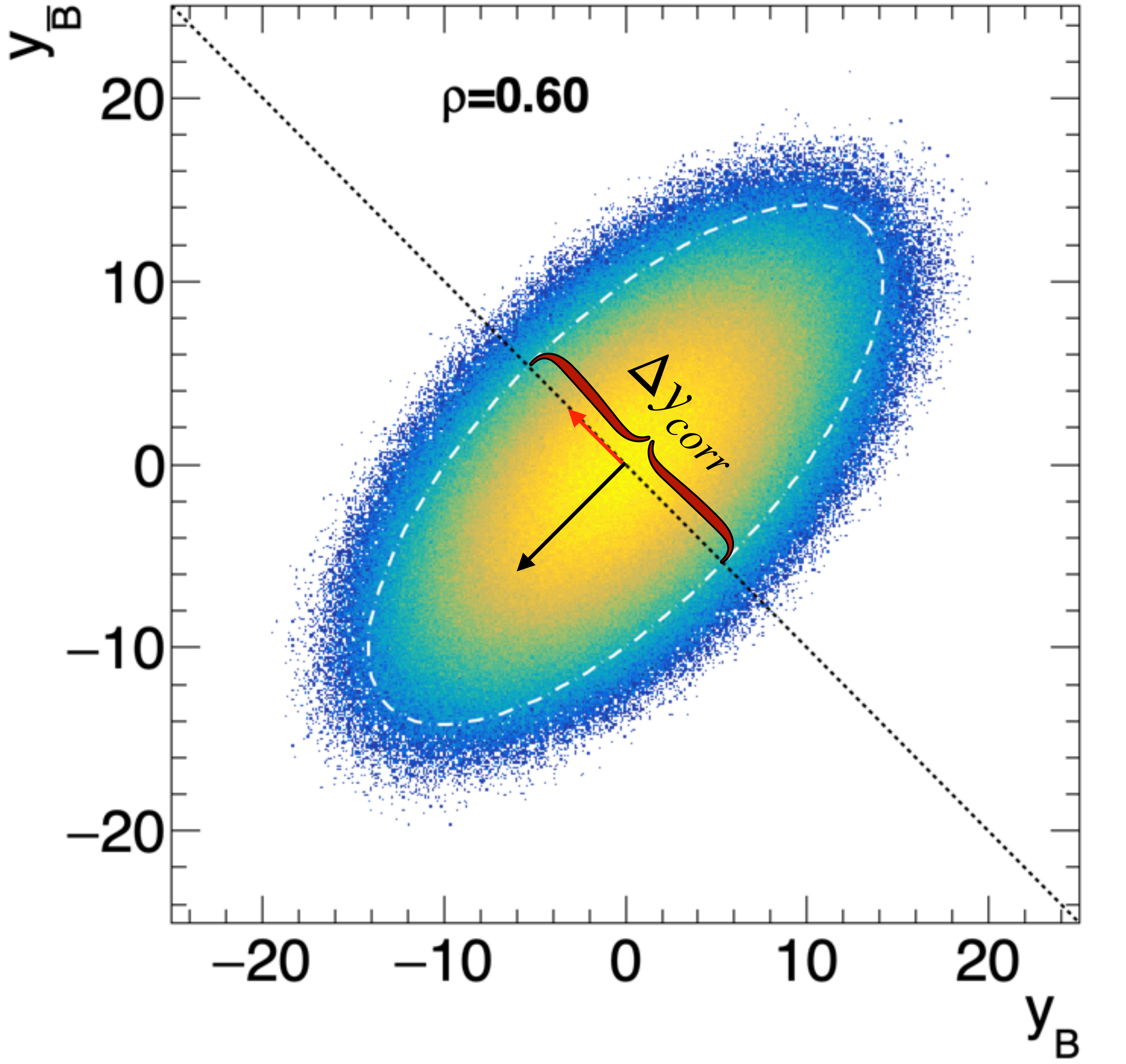
ρ: desired corr. coefficient

N. Metropolis et al., J.Chem.Phys. 21 (1953) 1087-1092

D. C. Charmpis, P. L. Panteli, Comp. Stat. 19 (2004) 283-300

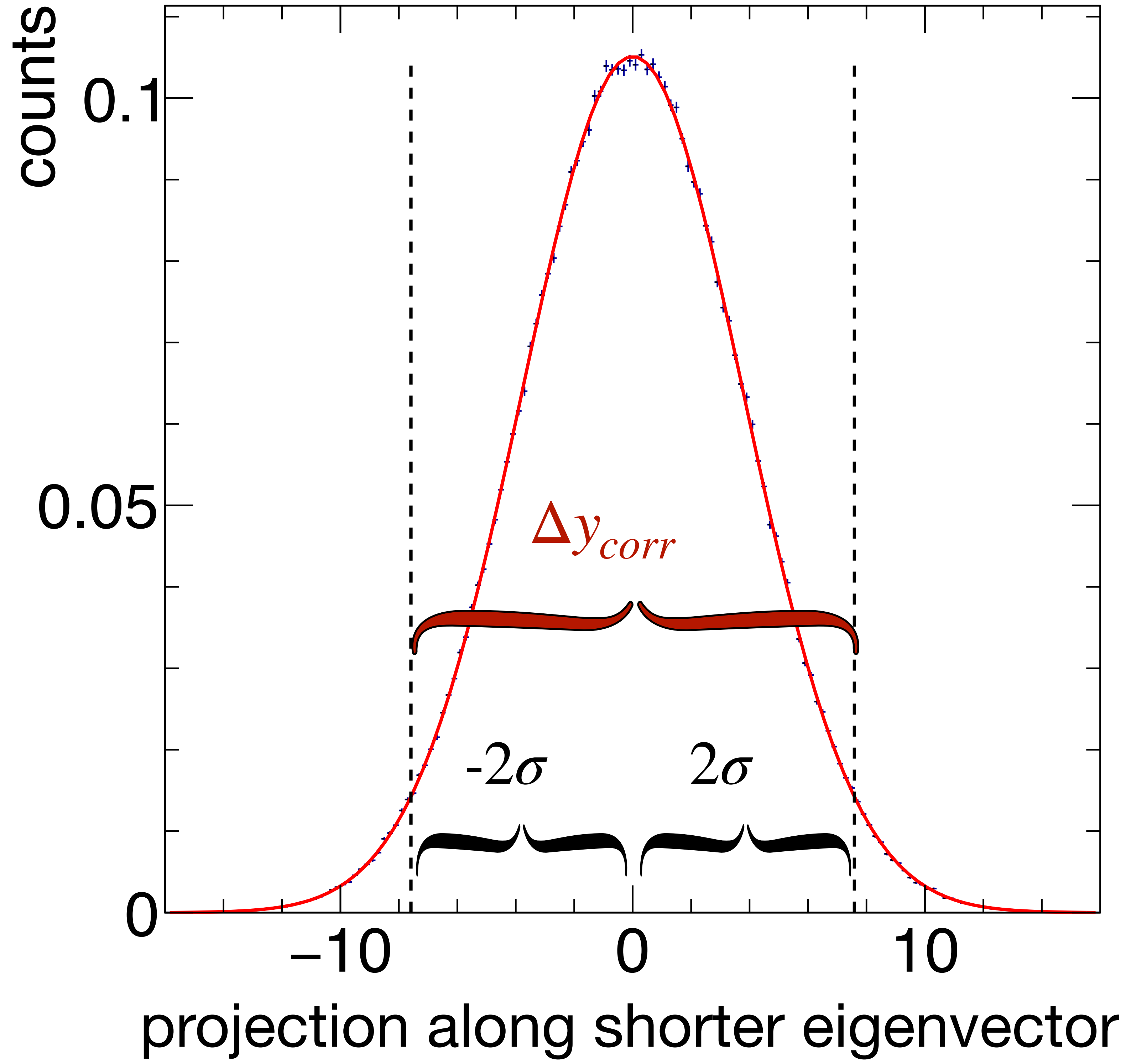
works for arbitrary distributions

Quantifying correlations



ρ - corr. coefficient

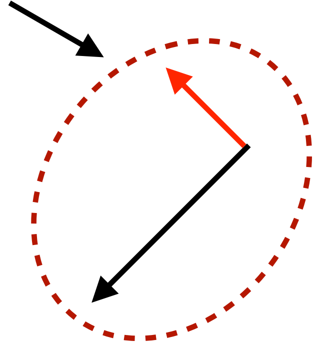
Δy_{corr} - corr. length



eigenequation of covariance matrix: $\begin{pmatrix} \sigma^2_{y_B} & \rho\sigma_{y_B}\sigma_{y_{\bar{B}}} \\ \rho\sigma_{y_{\bar{B}}}\sigma_{y_B} & \sigma^2_{y_{\bar{B}}} \end{pmatrix} \vec{v} = \lambda \vec{v}$

eigenvectors

eigenvalues



correlations are quantified by a pair of numbers: $\rho \leftrightarrow \Delta y_{corr}$

Canonical Ensemble (CE)+correlations

$$Z_B(V,T) = \sum_{N_B=0}^{\infty}\sum_{N_{\bar{B}}=0}^{\infty} \frac{(\lambda_B z_B)^{N_B}}{N_B!}\frac{(\lambda_{\bar{B}} z_{\bar{B}})^{N_{\bar{B}}}}{N_{\bar{B}}!}\delta(N_B - N_{\bar{B}} - B) = \left(\frac{\lambda_B z_B}{\lambda_{\bar{B}} z_{\bar{B}}}\right)^{\frac{B}{2}} I_B(2z\sqrt{\lambda_B \lambda_{\bar{B}}})$$

B net baryon number, conserved in each event

I_B modified Bessel function of the first kind

$z_B, z_{\bar{B}}$ single particle partition functions for baryons, anti baryons

$\lambda_B, \lambda_{\bar{B}}$ auxiliary parameters for calculating cumulants of baryons, anti baryons

P. Braun-Munzinger, B. Friman, K. Redlich, AR., J. Stachel , NPA 1008 (2021) 122141

A. Bzdak, V. Koch, V. Skokov, Phys.Rev.C 87 (2013) 1, 014901

NEW!

baryon number conservation (CE partition function) + **correlations in y space** (Metropolis algorithm) →

$N_B, N_{\bar{B}}, y_B, y_{\bar{B}}$	event 1
$N_B, N_{\bar{B}}, y_B, y_{\bar{B}}$	event 2
...	...
$N_B, N_{\bar{B}}, y_B, y_{\bar{B}}$	event n

Input from experiments

- baryon rapidity distributions
- measured (canonical) $\langle N_B \rangle$, $\langle N_{\bar{B}} \rangle$

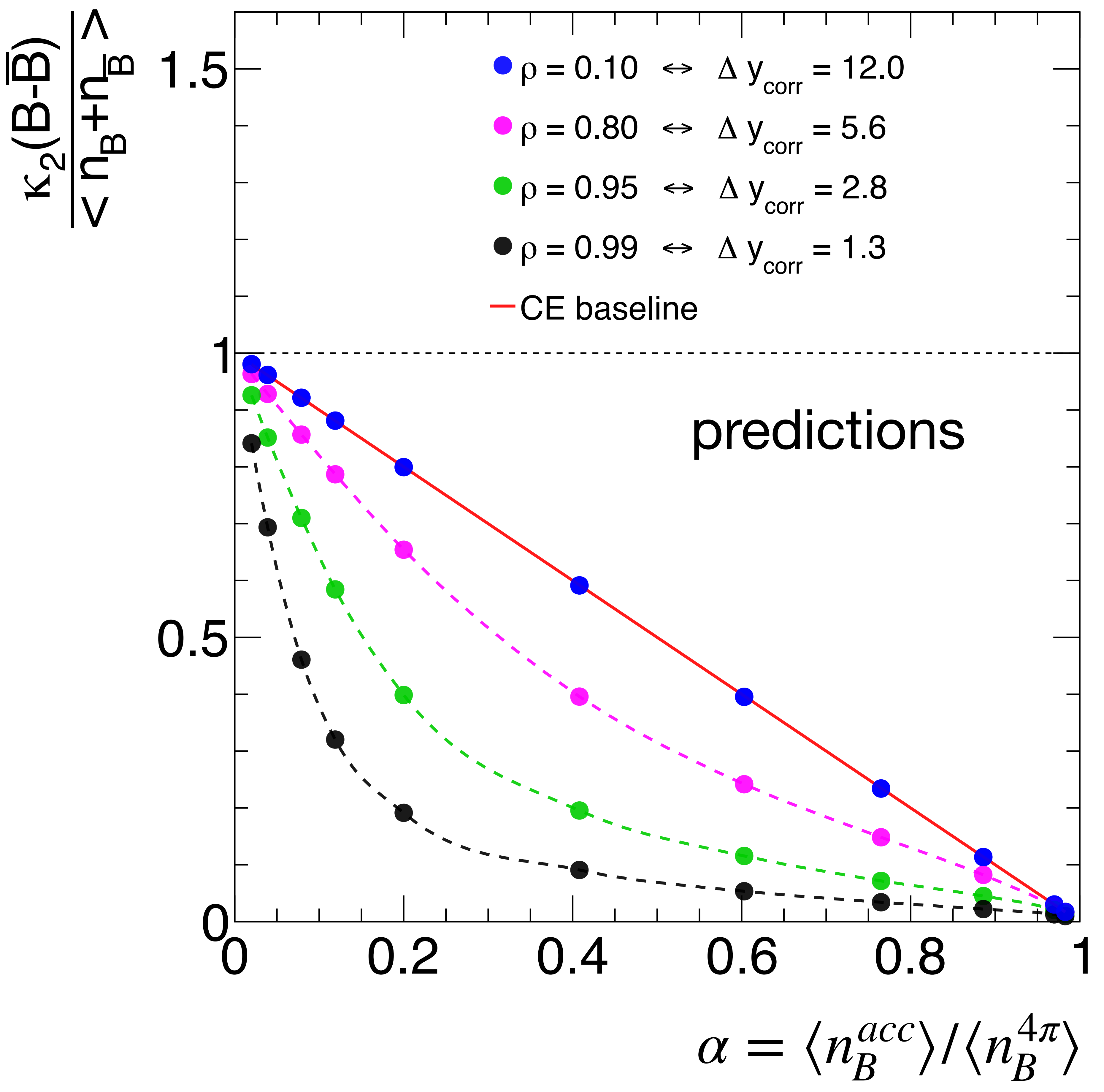
$z = \sqrt{z_B z_{\bar{B}}}$ **is calculated by solving**

$$\langle N_B \rangle = \lambda_B \frac{\partial \ln Z_B}{\partial \lambda_B}\bigg|_{\lambda_B, \lambda_{\bar{B}} = 1} = z\frac{I_{B-1}(2z)}{I_B(2z)}$$

comparison to experimental data

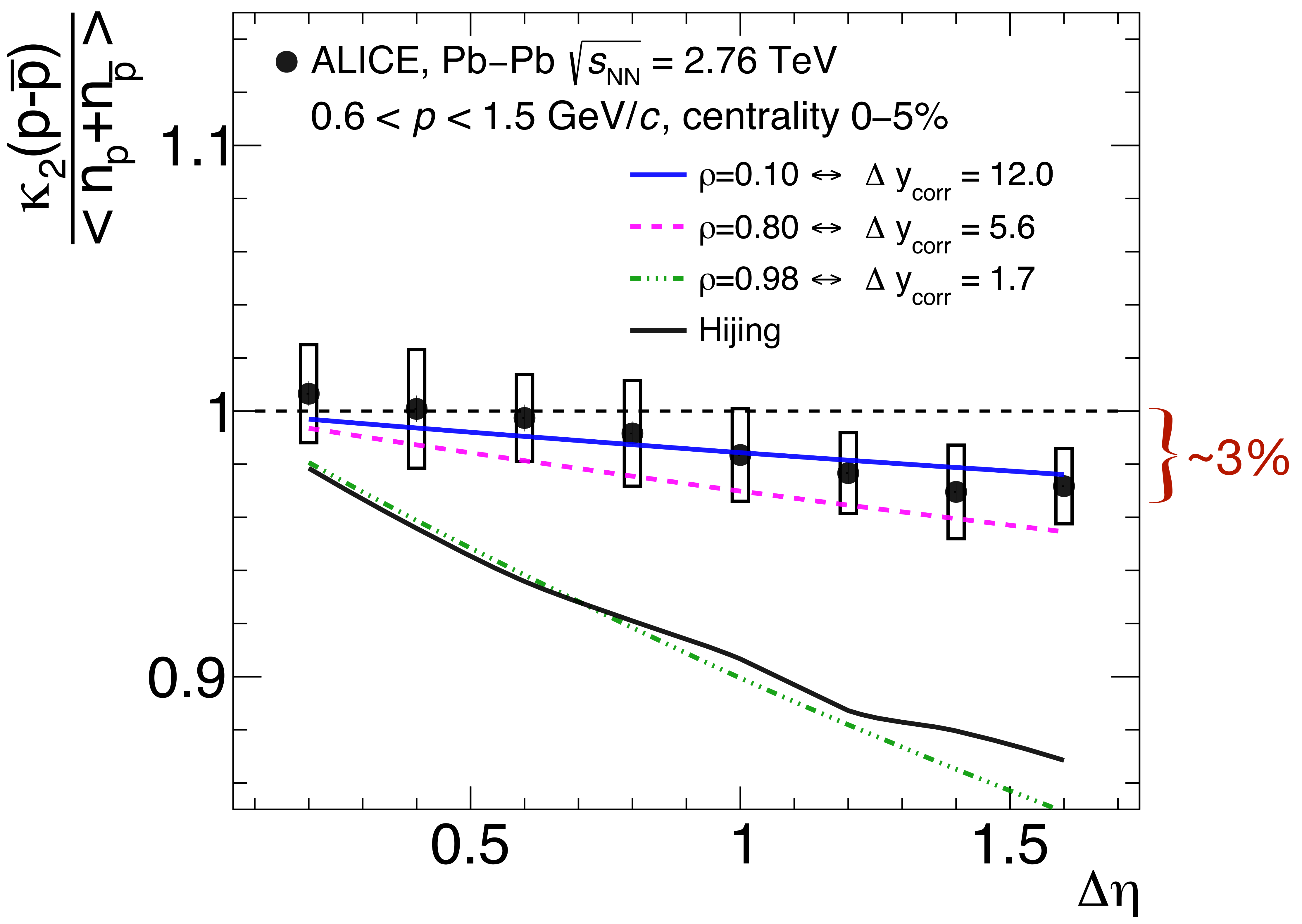
Results at LHC energies

CE baseline: P. Braun-Munzinger, B. Friman, K. Redlich, AR., J. Stachel , NPA 1008 (2021) 122141



comparison to ALICE

AR, NPA 967 (2017) 453-456 **ALICE:** Phys. Lett. B 807 (2020) 135564



P. Braun-Munzinger, AR, J. Stachel, arXiv:1907.03032

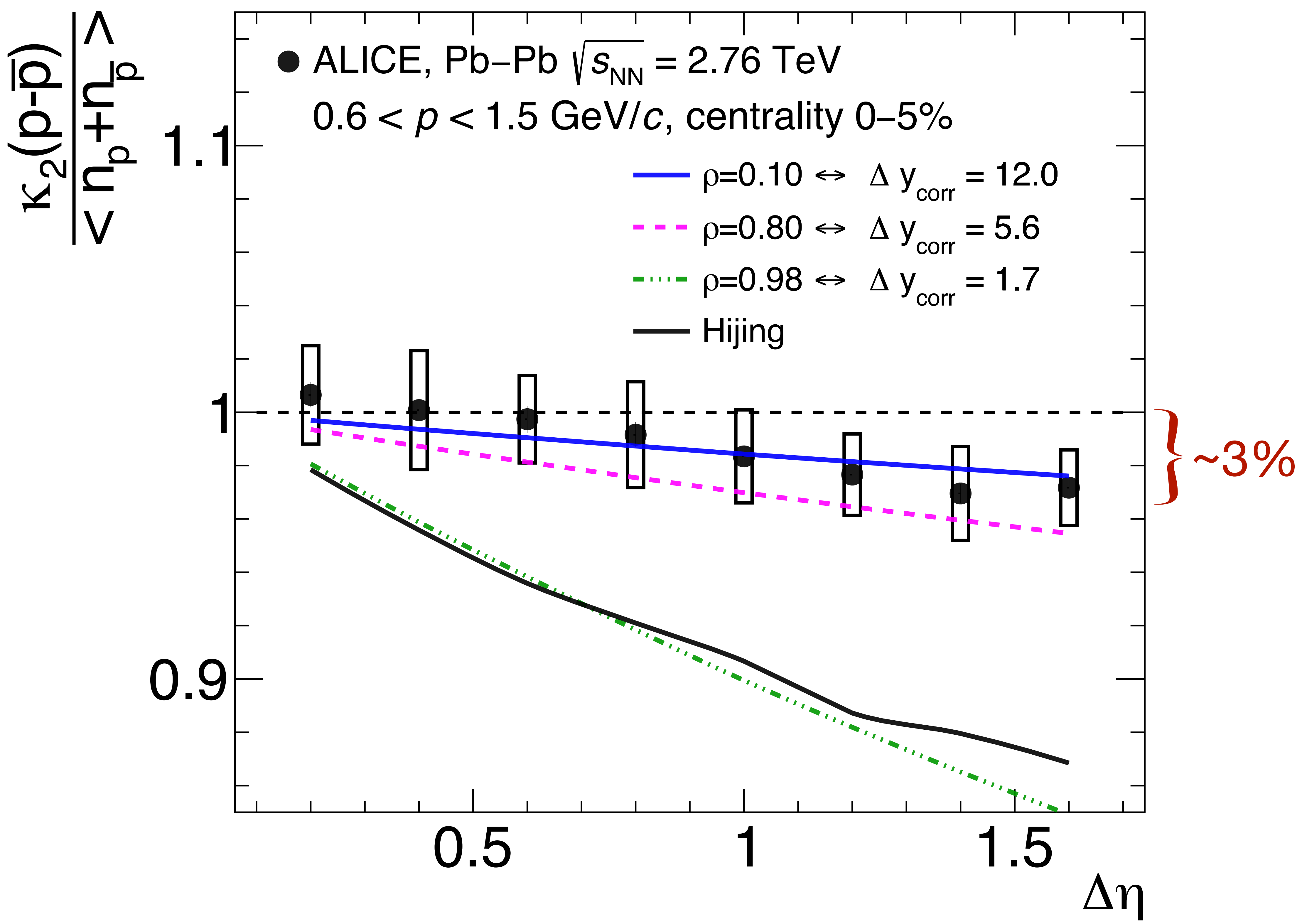
- Alice data: best description with $\rho = 0.1$ (Δy_{corr} = 12) ↔ Global baryon number conservation
- Hjing (Lund String Fragmentation) results are in conflict with the ALICE data

  are consistent with $\rho = 0.98$ (Δy_{corr} = 1.7) ↔ Strong local correlations

Baryon production in string models

comparison to ALICE

AR, NPA 967 (2017) 453-456 **ALICE:** Phys. Lett. B 807 (2020) 135564



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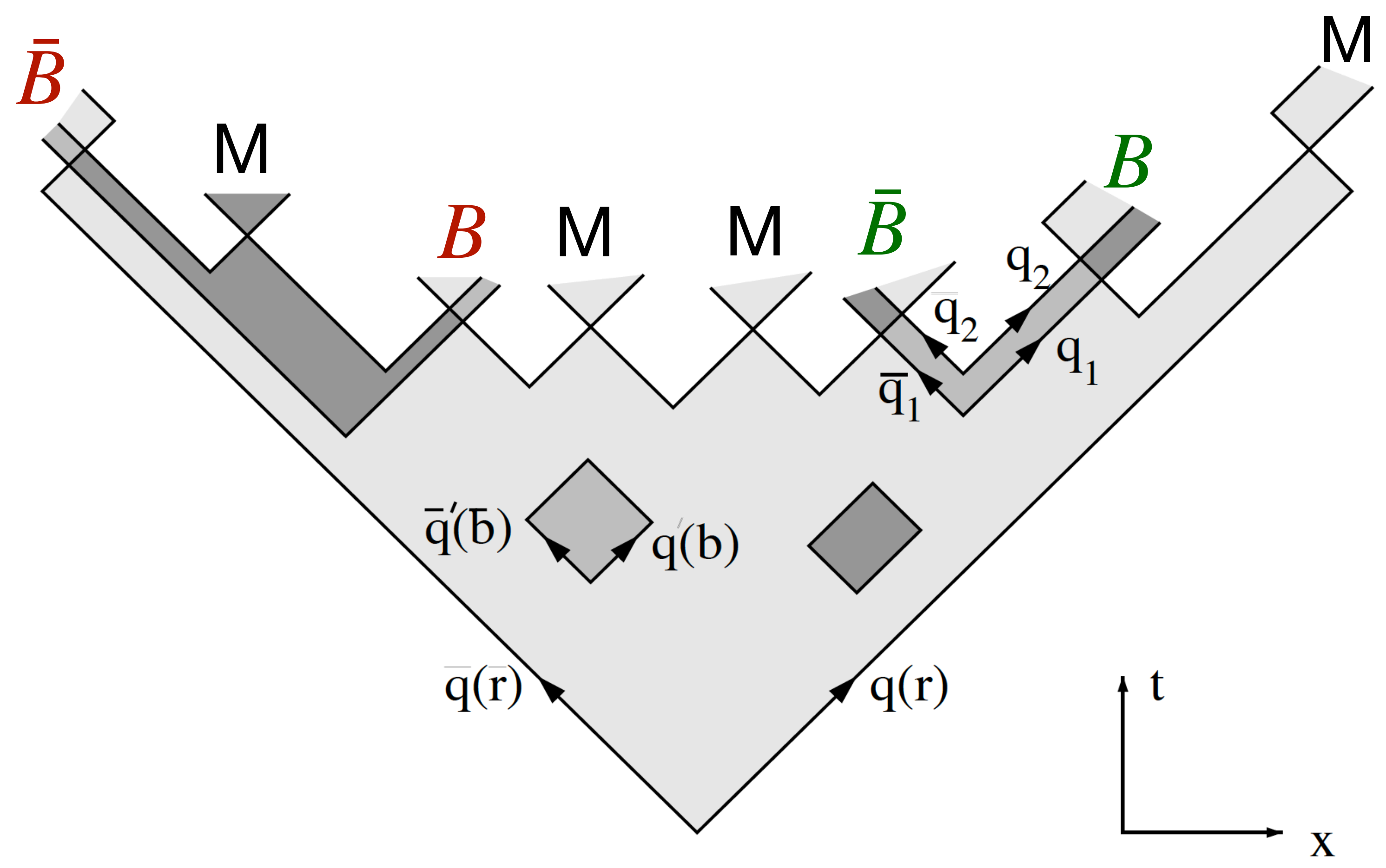
Lund String Fragmentation

baryon production

$q\bar{q}$ pair is replaced by qq-$\bar{q}\bar{q}$ pair



- diquark-antidiquark
- popcorn mechanism

induces short range correlations in rapidity space

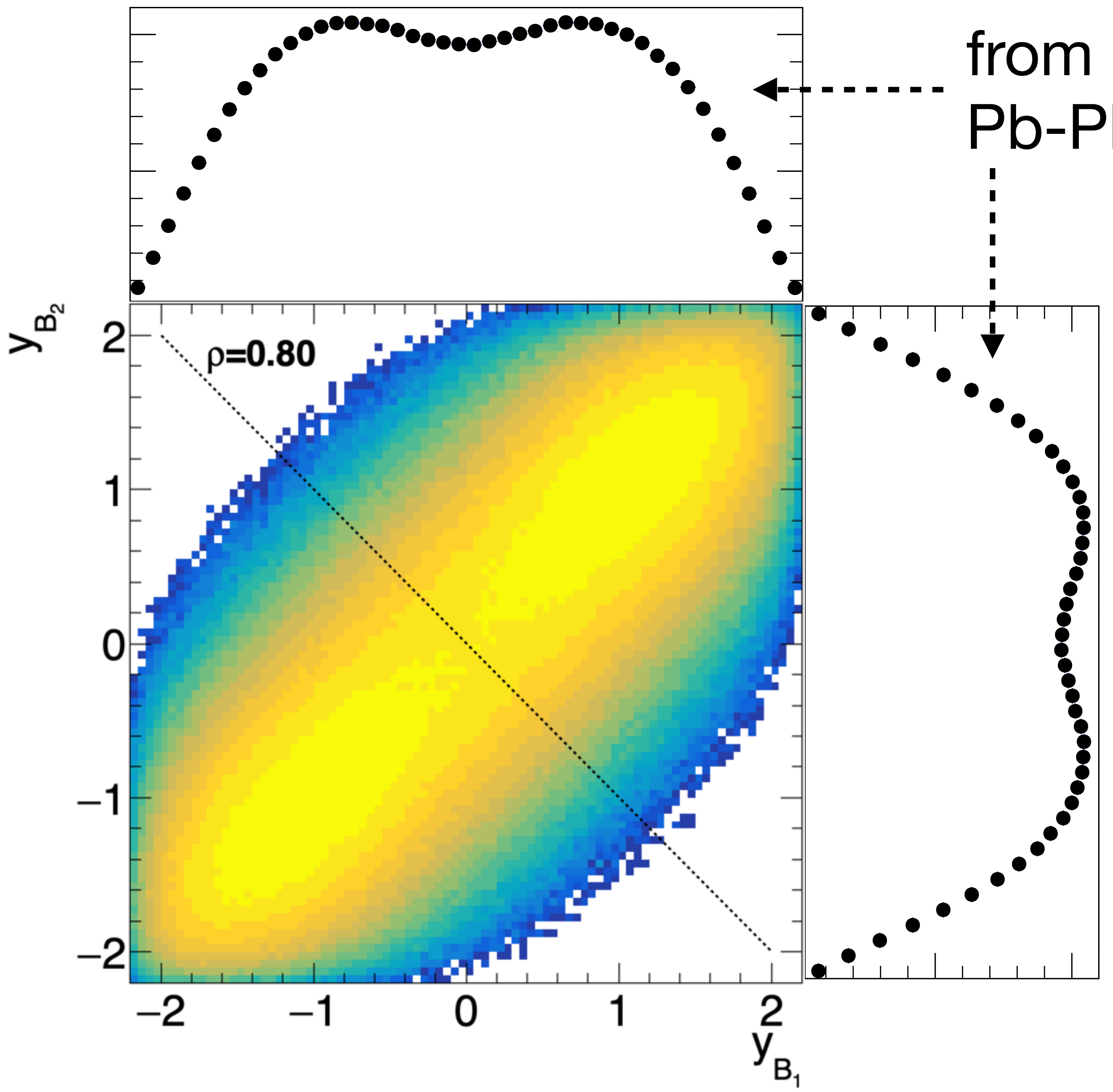
B. Andersson, G. Gustafson, G. Ingelman, T. Sjostrand Phys.Rept. 97 (1983) 31-145

$\kappa_2(p - \bar{p})$ measurements are essential to constrain baryon production mechanisms

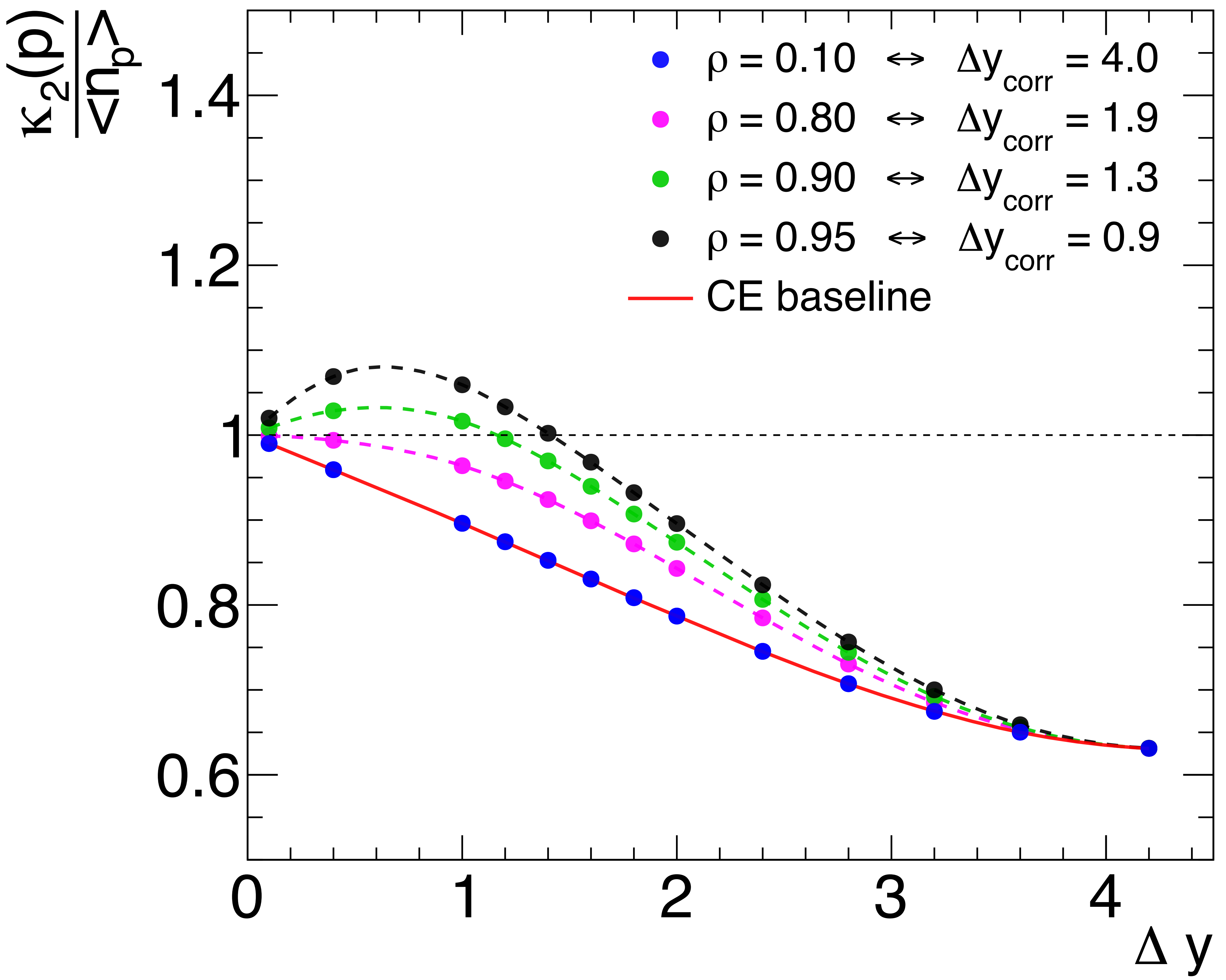
The quest for proton clusters

proton clusters and cumulants A. Bzdak,V. Koch, V. Skokov, Eur.Phys.J.C 77 (2017) 5, 288

correlations between baryons (extra option of the model)



predictions for $\kappa_2(p)/\langle n_p \rangle$ at $\sqrt{s_{NN}}$ = 8.8 GeV



CE baseline: P. Braun-Munzinger, B. Friman, K. Redlich, AR., J. Stachel , NPA 1008 (2021) 122141

- for large values of ρ and small values of Δy it is more probable to treat protons **in pairs**
- this process increases the finally measured proton number fluctuations

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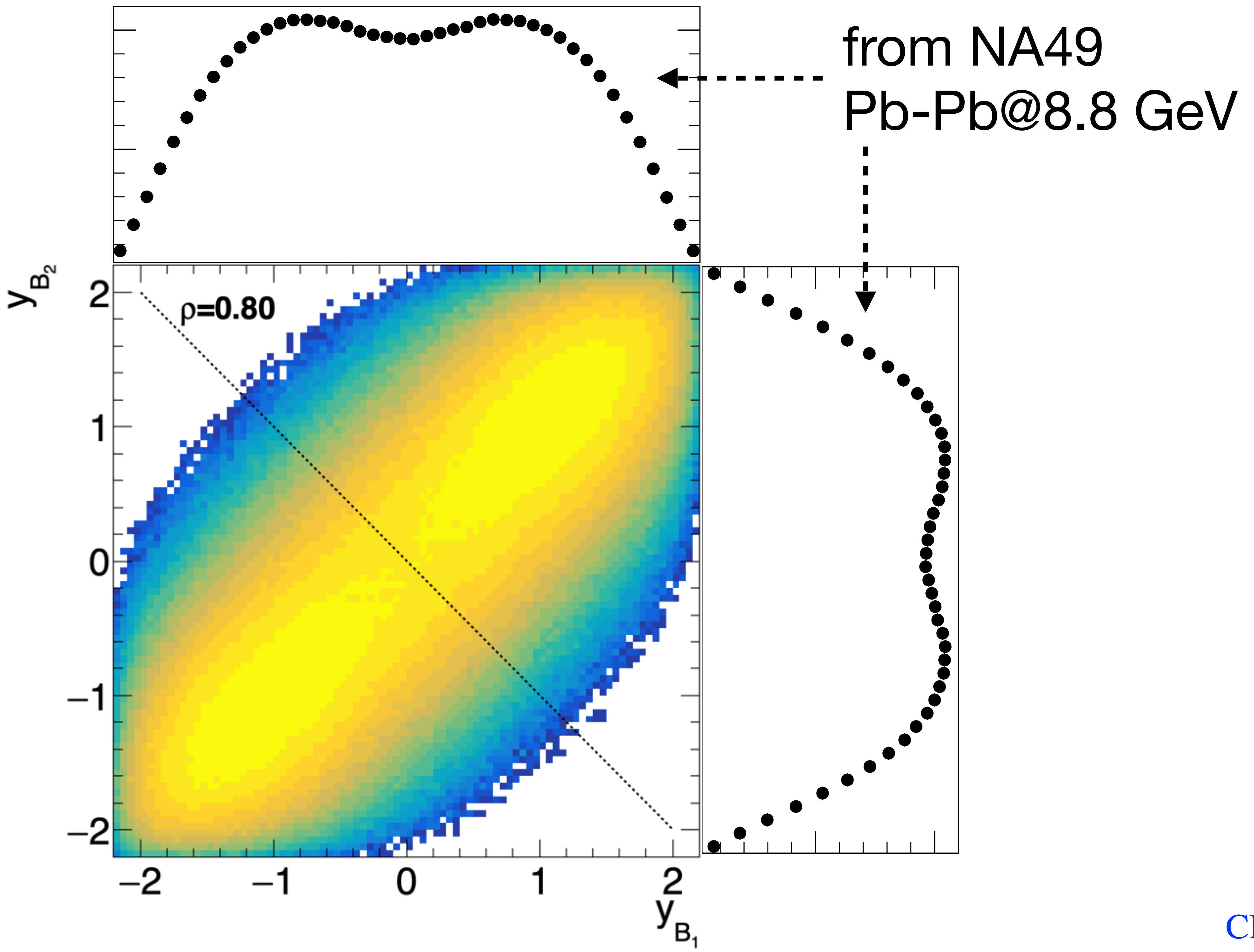

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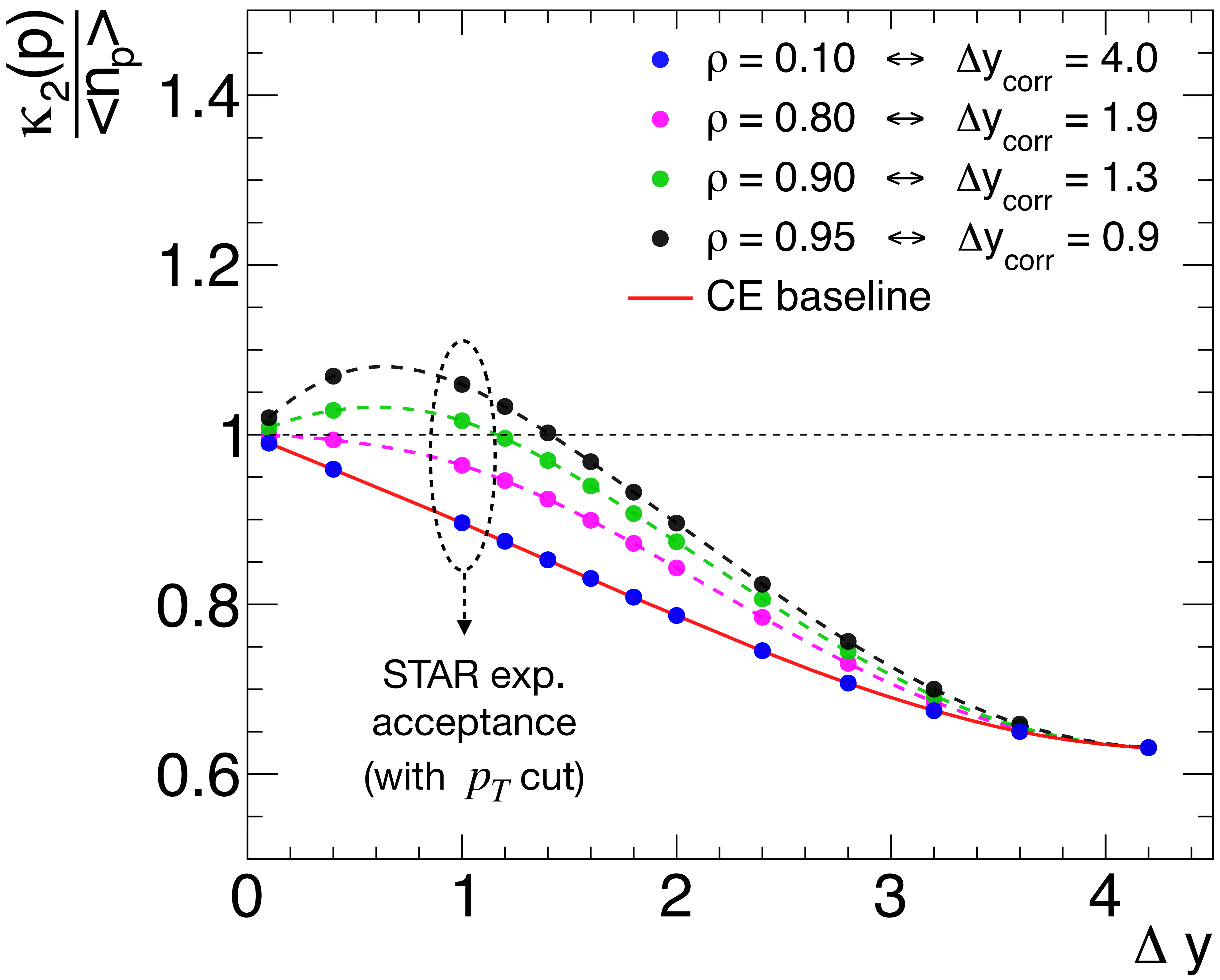

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- for large values of ρ and small values of Δy it is more probable to treat protons **in pairs**
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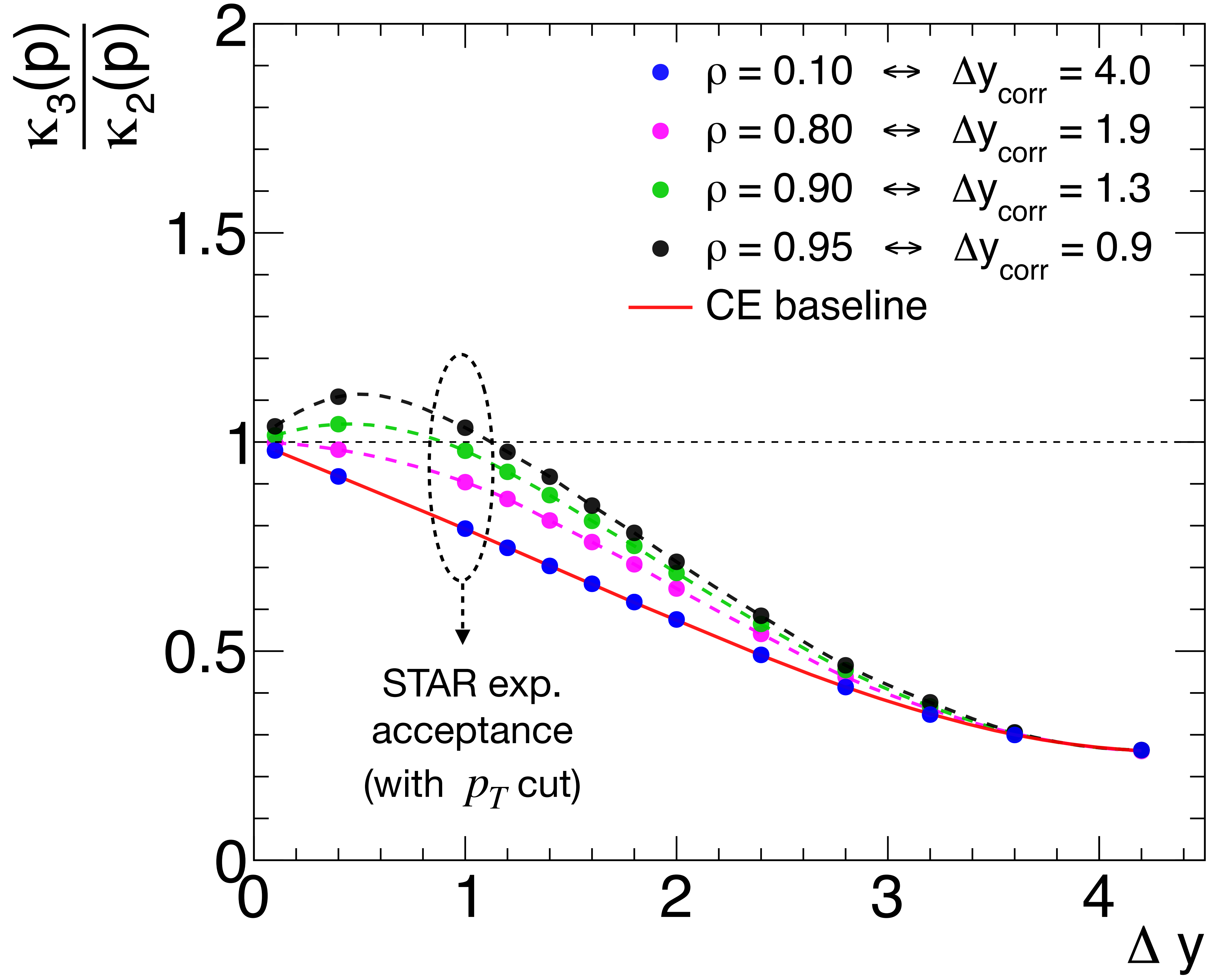
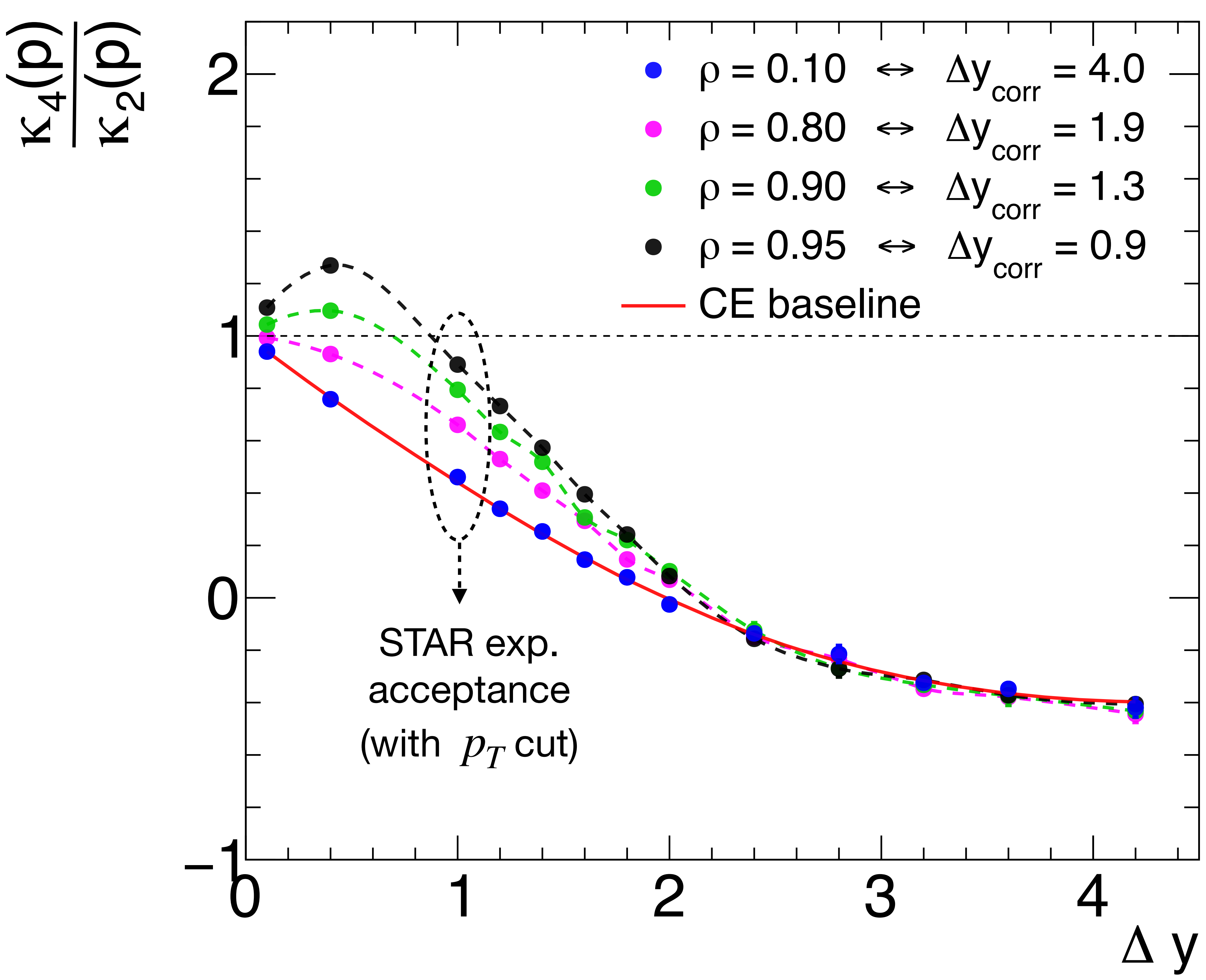
The quest for proton clusters

predictions for $\kappa_3(p)/\kappa_2(p)$
at $\sqrt{s_{NN}}$ = 8.8 GeV



predictions for $\kappa_4(p)/\kappa_2(p)$
at $\sqrt{s_{NN}}$ = 8.8 GeV



CE baseline: P. Braun-Munzinger, B. Friman, K. Redlich, AR., J. Stachel , NPA 1008 (2021) 122141

correlated proton production enhances $\kappa_3(p)/\kappa_2(p)$ and $\kappa_4(p)/\kappa_2(p)$ wrt CE baseline

Comparison to STAR data

STAR: Phys.Rev.Lett. 126 (2021) 9, 092301

CE Baseline: P. Braun-Munzinger, B. Friman, K. Redlich, AR, J. Stachel, NPA 1008 (2021) 122141

- the STAR data is best described with the long range correlations ($\rho = 0.1$) (no clustering)
- the precision of the data however, does not exclude the scenario with $\rho = 0.8$
- at the current precision of the data there is no evidence for critical behaviour!

Conclusions

- Canonical Ensemble + Metropolis algorithm is applied for the first time to account for correlations in rapidity space.
  - The method allows to introduce correlations between $\bar{B}\bar{B}$, $B\bar{B}$ and BB pairs
- The ALICE data exclude short range $B\bar{B}$ correlations
  - The data are best described with the correlation coefficient ρ = 0.1 $\leftrightarrow$ Δy_{corr} = 12
  - This behaviour is at odds with the Lund String Fragmentation model for baryon production
- The STAR data are best described with ρ=0.1 (no evidence for clustering)
  - The current experimental precision, however, does not exclude a scenario with the correlation coefficient ρ = 0.8


THANKS FOR YOUR
ATTENTION