# Thermal properties of the medium produced in d+Au and p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV

## using a thermal model

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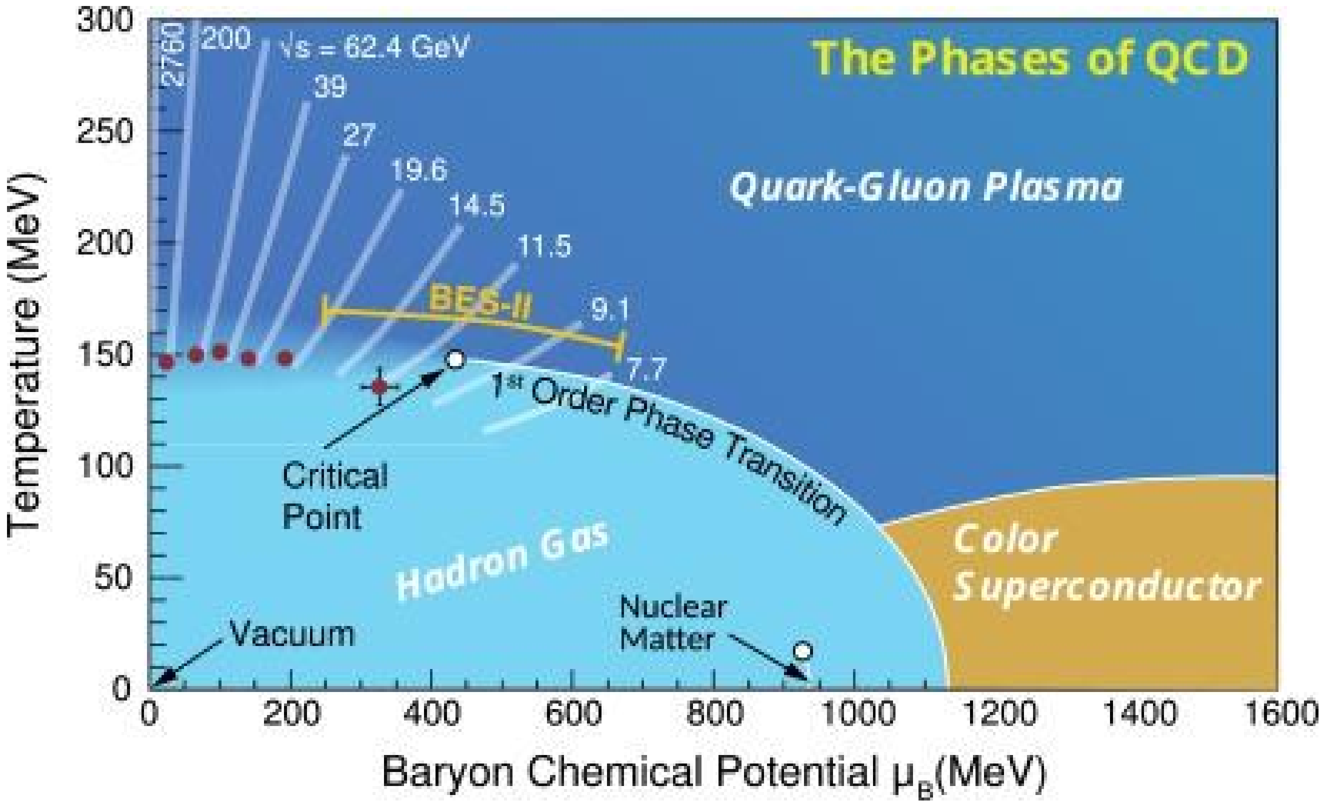
# Motivation



- Investigate nuclear matter produced in heavy-ion collisions via the QCD phase diagram.
- At high T and $\mu_B$, the de-confined quarks and gluons, QGP phase is expected to be present, while at low T and $\mu_B$, the quarks and gluons are confined within hadrons.
- Theoretically, these phases are investigated through lattice QCD, which uses numerical simulations in the non-perturbative QCD regime.
- Experimentally, the exploration is done by varying the center of mass energy ($\sqrt{s_{NN}}$) in heavy-ion collisions.

# Thermal model

- Thermodynamic models are widely and successfully used to describe identified particle yields and ratios produced in hadronic, especially in heavy ion collisions.
- The equilibrium thermodynamic properties of the QCD matter can be determined by T and the three chemical potentials $\mu_Q$, $\mu_B$, and $\mu_S$.
- We use a grand canonical ensemble (GCE) in this thermal model and assume that particles produced from the collision of particles and nuclei (p+p, p+A, A+A) emerge from a thermal source.
- We then calculate the expected particle ratios for various assumed temperatures and chemical potentials.
- Then, the experimental particle ratios are compared with thermal model predictions to assess the degree of agreement by the $\chi^2$/ndf characterizing the fit.
- In the case of minimum $\chi^2$/ndf, the temperature and chemical potentials of the hypothetic thermal particle source are estimated.

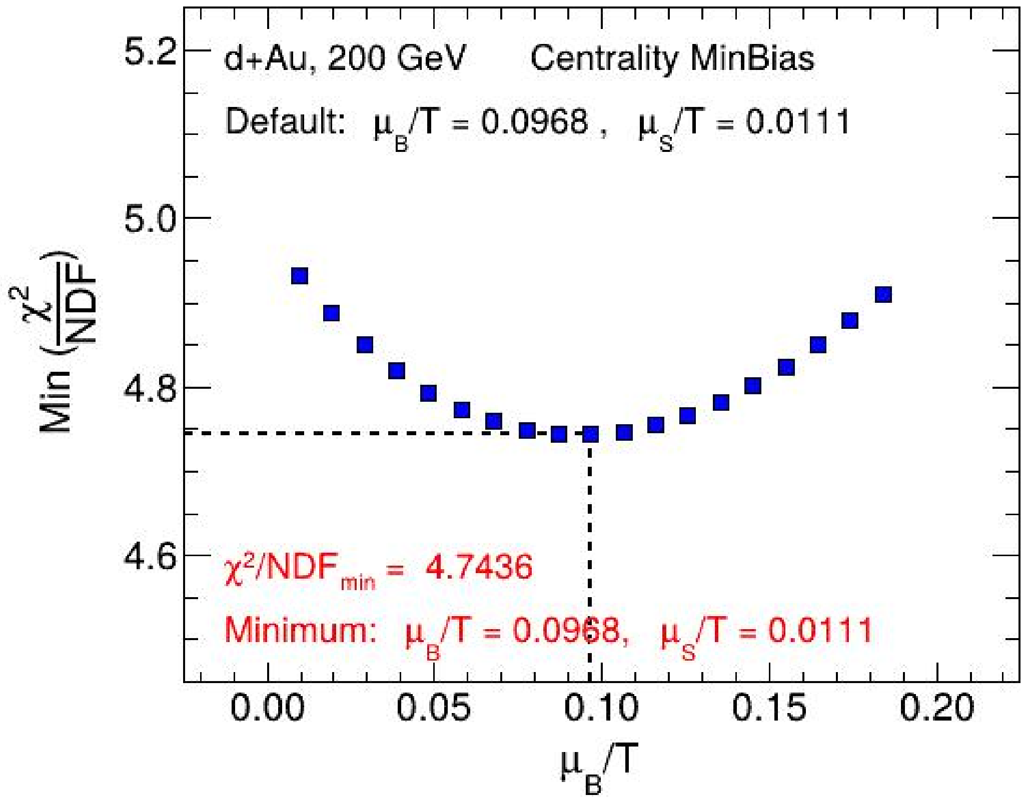
# Input parameters $\mu_B/T$ and $\mu_S/T$

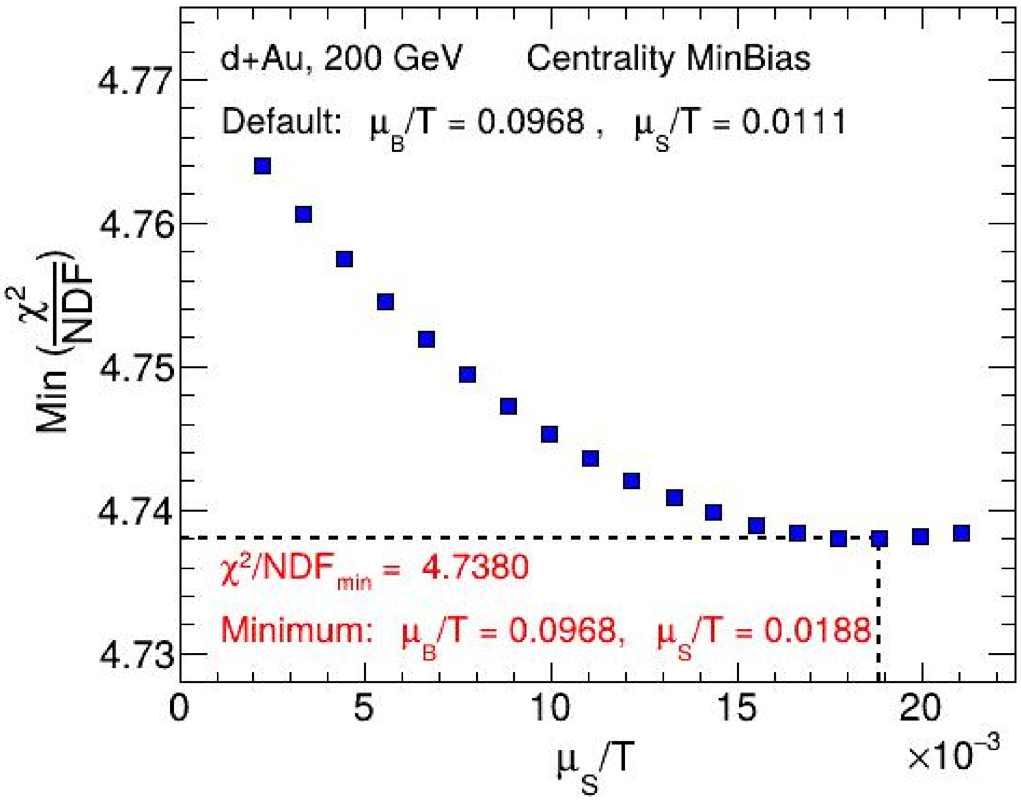
- Initialize with the input parameters:

**Preminiary**

$$\frac{\bar{p}}{p} = e^{\left(\frac{-2\mu_B}{T}\right)} \rightarrow e^{\left(\frac{-2\mu_B}{T}\right)} = 0.824 \rightarrow \frac{\mu_B}{T} = 0.0968$$

$$\frac{K^-}{K^+} = e^{\left(\frac{-2\mu_S}{T}\right)} \rightarrow e^{\left(\frac{-2\mu_S}{T}\right)} = 0.978 \rightarrow \frac{\mu_S}{T} = 0.0111$$



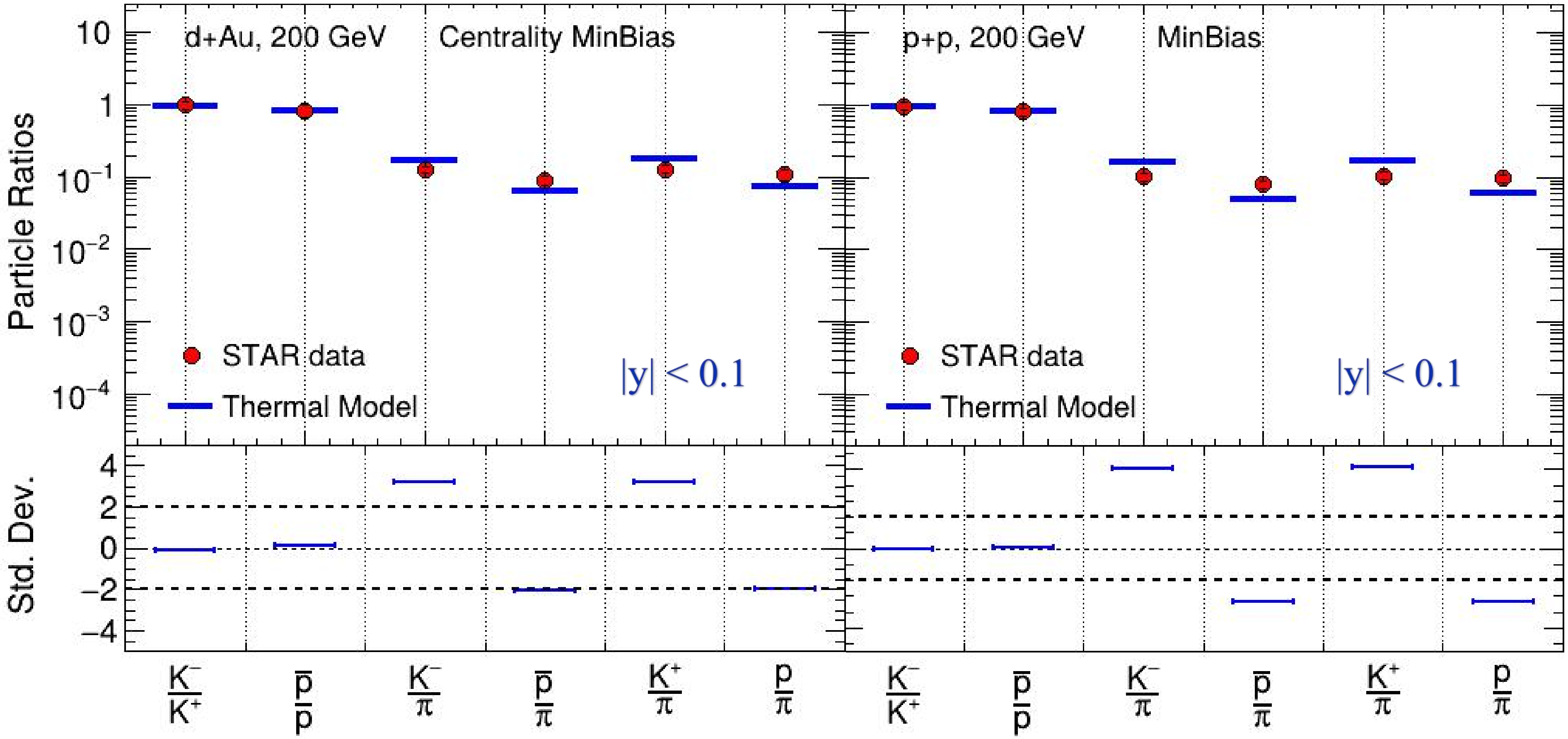


- Varied $\mu_B/T$ and $\mu_S/T$ in steps of ±90% of the initial value, to get minimum of $\chi 2$/NDF.
- $\mu_B/T$ and $\mu_S/T$ at minimum $\chi 2$/NDF is used as the default input parameters for the thermal model.

minimum $\chi 2/NDF = 4.7380 \rightarrow \mu_B/T = 0.0968$ and $\mu_S/T = 0.0188$

# Particle Ratios

**Preminiary**



- The comparison of experimental particle ratios with the thermal model calculation is shown for MinBias d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV.
- Thermal model is successfully predicting the experimental particle ratios within $\pm 5\sigma$ deviation where, Std. dev. ($\sigma$) is represented by:

$$\sigma = \frac{Ratio_{Th.} - Ratio_{Exp}}{\sigma_{Exp}}$$

- B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009)

# Uncertainties on thermal parameters

Statistical uncertainties:

- Statistical uncertainties are obtained as the maximum deviation of the two cases, i.e adding and subtracting the experimental errors from the experimental ratios.

Systematic uncertainties:

- Systematic uncertainties are obtained as the average of deviation of the results from 100% and 0% of weak decay correction.

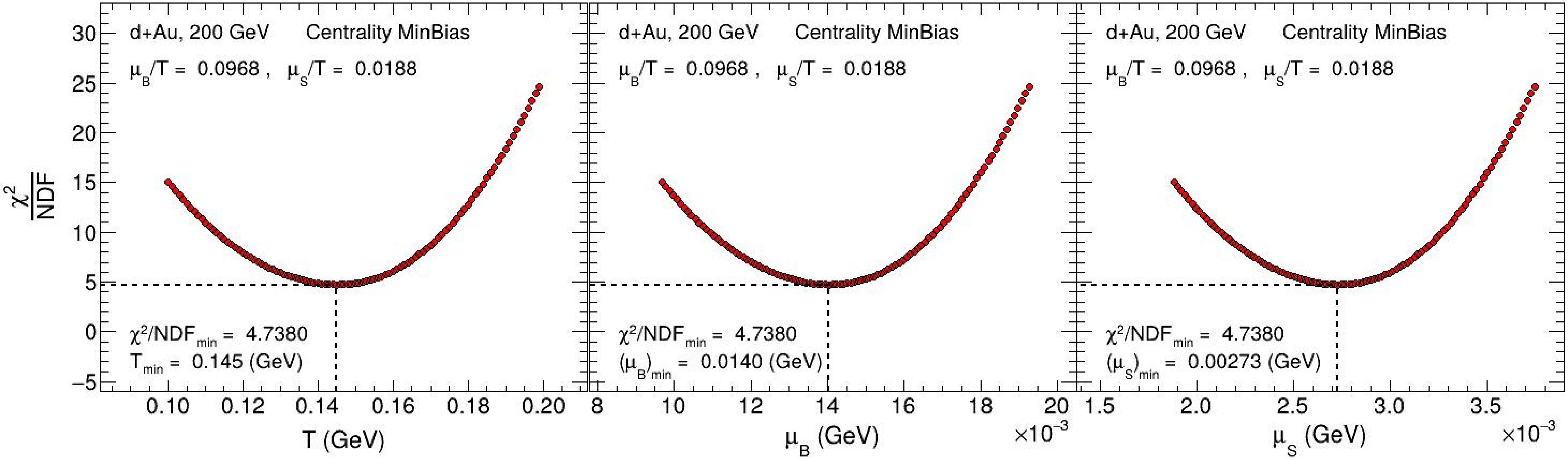
Total uncertainties:

- Total uncertainties on the results are calculated as the square root of quadratic sum of statistical and systematic uncertainties.

# Thermal parameters d+Au $\sqrt{s_{NN}}$ 200 GeV

- Fit results from thermal model is plotted to extract the thermal parameters in MinBias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

**Preminiary**

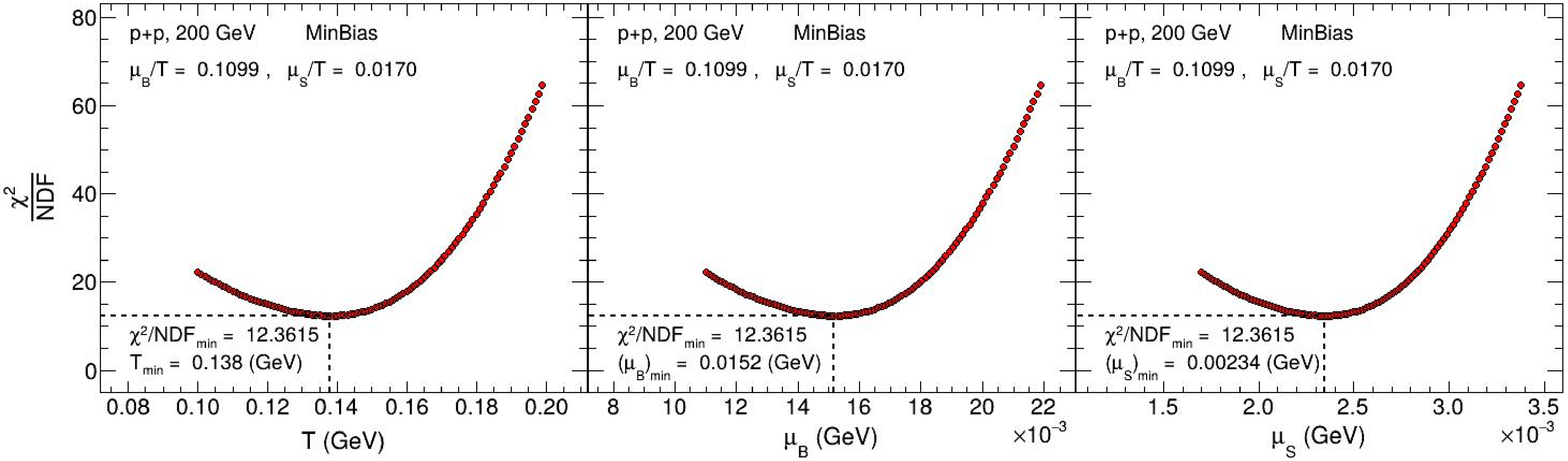


- At the minimum ± of $\chi2/NDF = 4.7380$:
  - $T = 145 \pm 15$ (stat.) ± 12 (sys.) MeV
  - $\mu_B = 14.0 \pm 1.5$ (stat.) ± 1.2 (sys.) MeV
  - $\mu_S = 2.73 \pm 0.28$ (stat.) ±0.22 (sys.) MeV

# Thermal parameters p+p $\sqrt{s_{NN}}$ 200 GeV

- Fit results from thermal model is plotted to extract the thermal parameters in MinBias p+p collisions at $\sqrt{s_{NN}} = 200$ GeV.

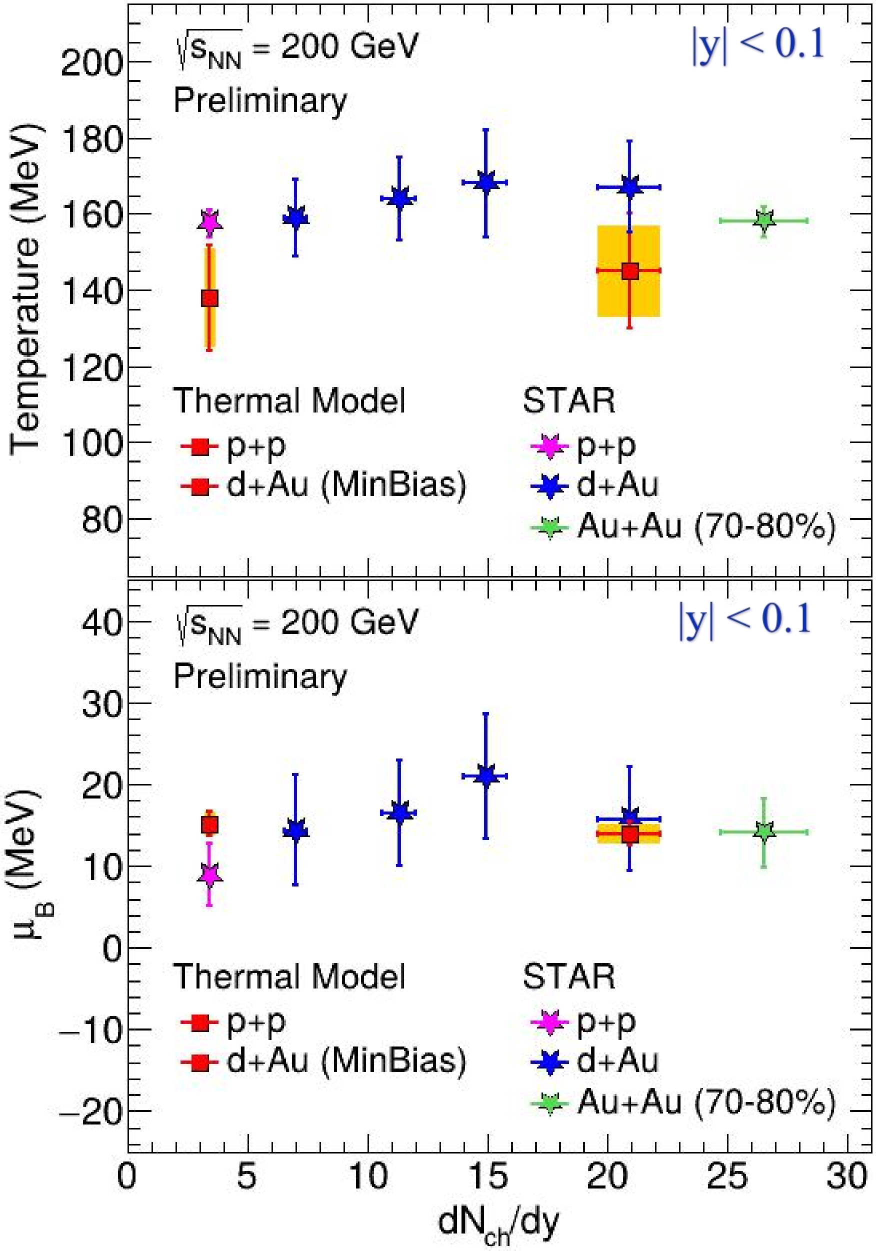
**Preminiary**

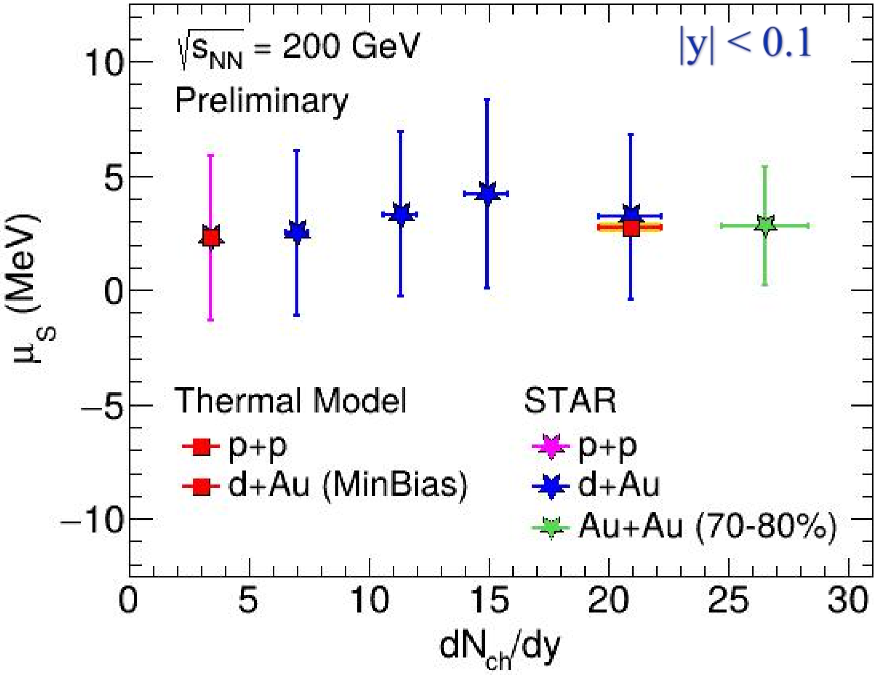


- At the minimum ± of $\chi2/NDF = 12.3615$:
  - $T = 138 \pm 14$ (stat.) ± 13 (sys.) MeV
  - $\mu_B = 15.2 \pm 1.5$ (stat.) ± 1.4 (sys.) MeV
  - $\mu_S = 2.34 \pm 0.24$ (stat.) ±0.21 (sys.) MeV

# Thermal parameters

- Comparison of the temperature (T), baryon chemical potential ($\mu_B$), and strangeness chemical potential ($\mu_S$) obtain from the thermal model with experimental measurements in minimum bias p+p and d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

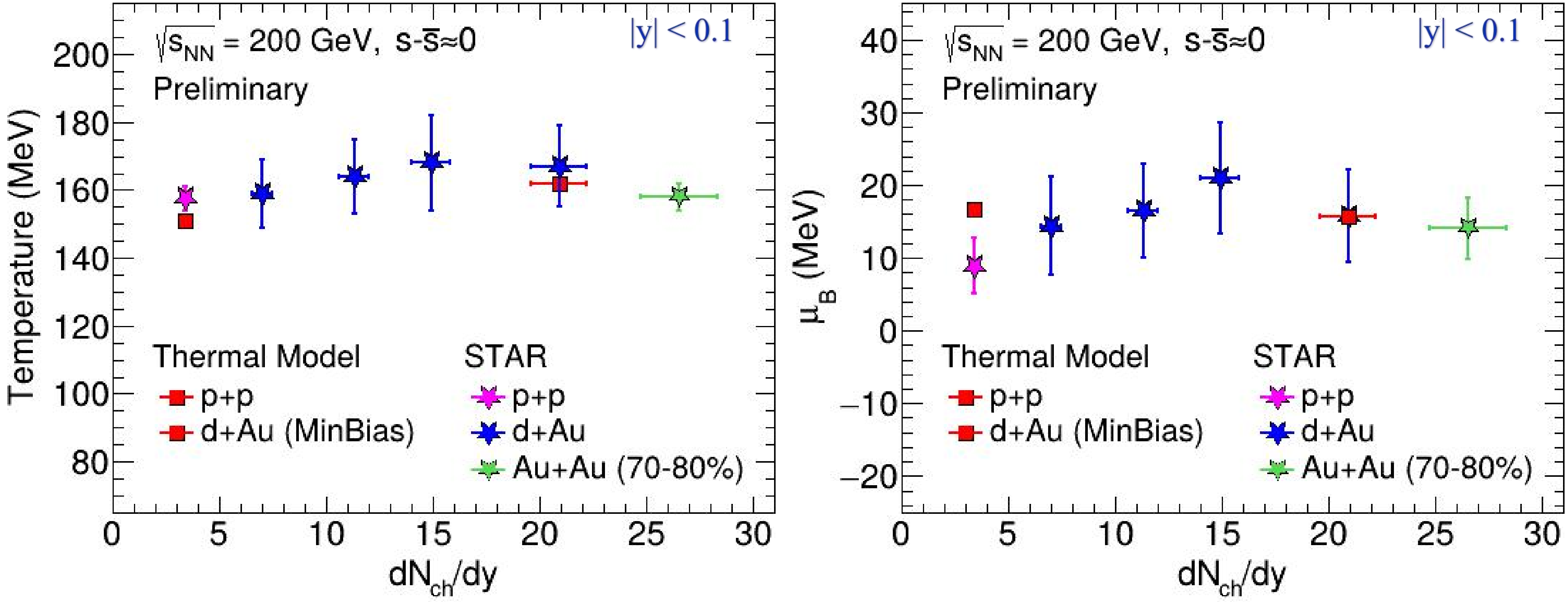




- B. I. Abelev et al. (STAR), Phys. Rev. C 79, 034909 (2009), J. Adams et al. (STAR), Phys. Rev. Lett. 92, 112301 (2004)

# Thermal parameters ($s-\bar{s} \approx 0$)

- With strangeness conservation condition (**$s-\bar{s} \approx 0$**)
- Comparison of the temperature (T) and baryon chemical potential ($\mu_B$) obtain from the thermal model with experimental measurements in minimum bias p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.



- B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009)
- J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 92, 112301 (2004)

# Summary

- Thermal properties temperature (T), chemical potentials ($\mu_B$ and $\mu_S$) are presented for minimum bias d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV using the thermal model.
- Particle ratios from the experimental particle yields are calculated in order to predict thermal properties of the medium produced in d+Au collisions at at $\sqrt{s_{NN}} = 200$ GeV.
- The T, $\mu_B$ and $\mu_S$ are consistent within uncertainties with the results from the thermal model published by the STAR experiment at RHIC.

# Thank you for your attention!

# Backups

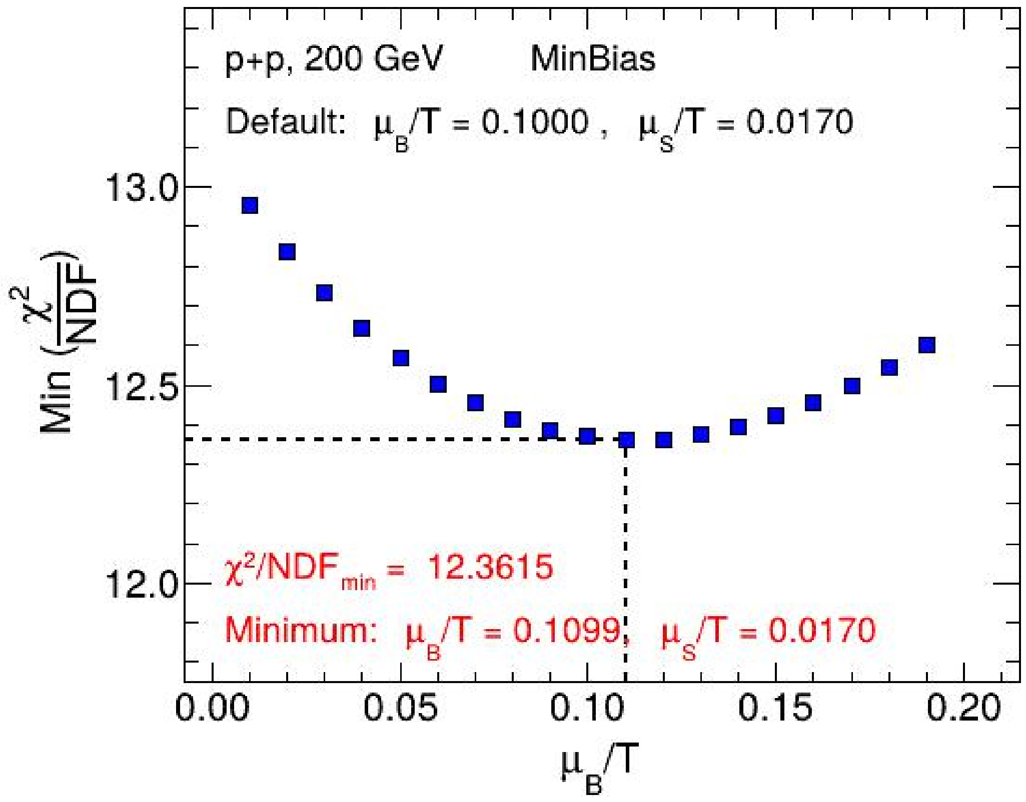
# $\mu_B$/T and $\mu_S$/T (p+p 200 GeV)

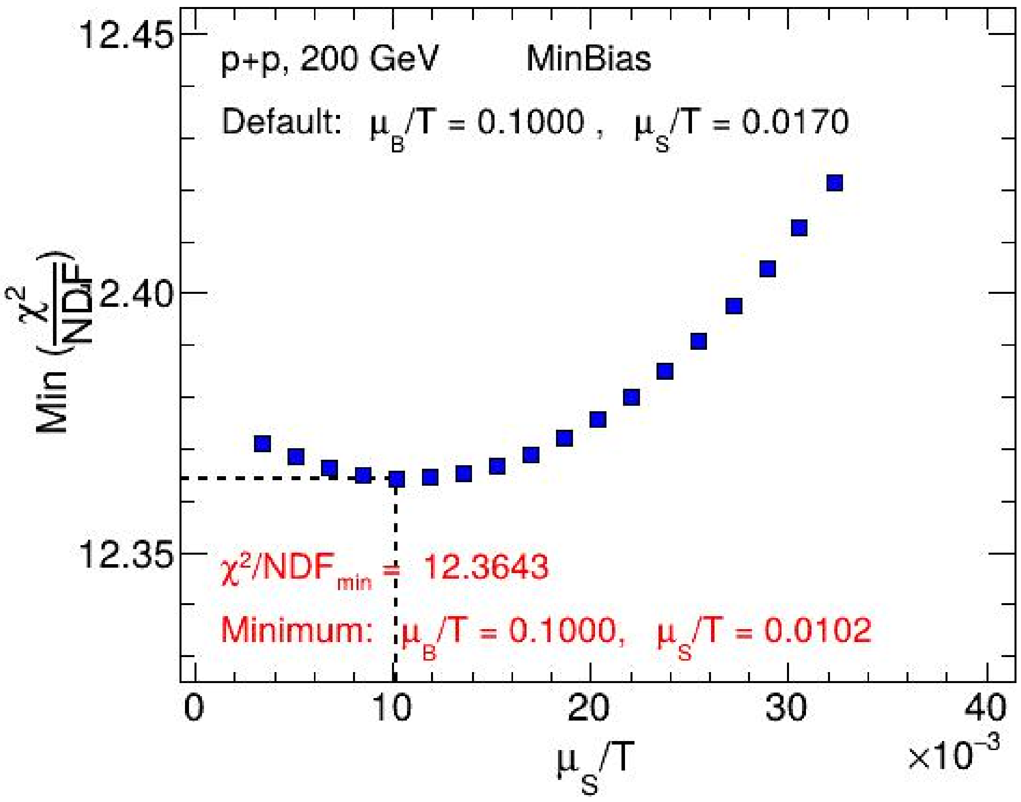
- Initialize with the input parameters:

**Preminiary**

$$\frac{\overline{p}}{p} = e^{\left(\frac{-2\mu_B}{T}\right)} \rightarrow e^{\left(\frac{-2\mu_B}{T}\right)} = 0.833 \rightarrow \frac{\mu_B}{T} = 0.0903$$

$$\frac{K^-}{K^+} = e^{\left(\frac{-2\mu_S}{T}\right)} \rightarrow e^{\left(\frac{-2\mu_S}{T}\right)} = 0.982 \rightarrow \frac{\mu_S}{T} = 0.0091$$





- Varied $\mu_B$/T and $\mu_S$/T in steps of ±90% of the initial value, to get minimum of $\chi$2/NDF.
- $\mu_B$/T and $\mu_S$/T at minimum $\chi$2/NDF is used as the default input parameters for the thermal model.

$$\boxed{\text{minimum } \chi2/\text{NDF} = 12.3615 \rightarrow \mu_B/\text{T} = 0.1099 \text{ and } \mu_S/\text{T} = 0.0170}$$

# Particle Ratios

- Experimental particle ratios and their error are from mid-rapidity ($|y| < 0.1$) in minimum-bias d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV from the STAR experiment at RHIC.

| Particle Ratio | STAR Experiment | | Experimental Error (statistical & systematic) | | Thermal model | |
|---|---|---|---|---|---|---|
| System | **d+Au** | **p+p** | **d+Au** | **p+p** | **d+Au** | **p+p** |
| $\frac{K^-}{K^+}$ | 0.978 | 0.967 | 0.125 | 0.121 | 0.965 | 0.968 |
| $\frac{\bar{p}}{p}$ | 0.824 | 0.812 | 0.155 | 0.101 | 0.838 | 0.814 |
| $\frac{K^-}{\pi^-}$ | 0.126 | 0.101 | 0.014 | 0.012 | 0.171 | 0.161 |
| $\frac{\bar{p}}{\pi^-}$ | 0.089 | 0.079 | 0.013 | 0.009 | 0.062 | 0.049 |
| $\frac{K^+}{\pi^+}$ | 0.129 | 0.105 | 0.015 | 0.012 | 0.177 | 0.167 |
| $\frac{p}{\pi^+}$ | 0.108 | 0.097 | 0.017 | 0.011 | 0.074 | 0.060 |

**Preminiary**

- Particle ratios calculated from this thermal model is also shown.

- B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009)

# Thermal parameters

**Preminiary**

- Comparison of the thermal parameters obtain from the thermal model with experimental measurements at mid-rapidity ($|y| < 0.1$) in minimum bias d+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV.

| Parameters | Experimental Results | | Thermal model | | Thermal model (Strangeness conservation) | |
|---|---|---|---|---|---|---|
| System | **d+Au** | **p+p** | **d+Au** | **p+p** | **d+Au** | **p+p** |
| χ2/NDF | 0.013 | 0.81 | 4.74 | 3.48 | 4.74 | 12.4 |
| T (MeV) | 164±11 | 157.5±3.6 | 145±19 | 138±19 | 162 | 151 |
| $\mu_B$ (MeV) | 16.5±6.5 | 8.9±3.8 | 14.0±1.9 | 15.2±2.1 | 15.7 | 16.6 |
| $\mu_S$ (MeV) | 3.3±3.6 | 2.3±3.6 | 2.48±0.36 | 2.34±0.32 | 3.05 | 2.57 |

- B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009)