Thermal properties of the medium created in heavy-ion collisions

For Au-Au collisions at $\sqrt{s_{NN}}$= 19.6, 27 and 39 GeV

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10th International Conference on New Frontiers in Physics (ICNFP 2021)
23 August - 2 September 2021
Kolymbari, Crete, Greece

Thermal models for particle production

Hadronic reactions involving copious production of secondary particles have been associated with an underlying thermodynamic behaviour since the earliest observations in cosmic rays e.g. [1]

Thermodynamic models are widely and successfully used to describe identified particle yields and particle ratios produced in hadronic and especially heavy ion collisions e.g. [2].

We use the grand canonical ensemble; we assume that particles produced out of collision of particles and/or nuclei (p+p, p+A, A+A) at colliders are emerging from a thermal source and we calculate the expected particle ratios, for various assumed Temperatures and chemical potentials. We compare the experimental data to these predictions to assess the degree of agreement of this hypothesis with experimental data. If the agreement is good, (as evidenced by the Chi-Squared/DOF characterizing the fit) this comparison is used to estimate the temperature and chemical potentials of the hypothetic thermal particle source.

References:

1. Y. Fujimoto and S. Hayakawa, in Encylopedia of physics, vol. 46, no. 2) 4, 044904
2. F. Becattini et al, Phys.Rev.C 64 (2001) 024901 • e-Print: hep-ph/0002267 [hep-ph]

- *S. Kabana, The European Physical Journal C, Volume 21, Issue 3, pp. 545-555 (2001)*
- *S. Kabana, P. Minkowski, New J.Phys. 3 (2001) 4*
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*
- *J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton Phys. Rev. C 73, 034905 (2006)*
- *G. Torrieri, J. Rafelski, New J.Phys. 3 (2001) 12 • e-Print: hep-ph/0012102 [hep-ph]*
- O.V. Vityuk et al, Eur.Phys.J.A 57 (2021) 2, 74 • e-Print: 2007.07376 [hep-ph]
- *K.A. Bugaev et al, Eur.Phys.J.A 56 (2020) 11, 293 • e-Print: 2005.01555 [nucl-th]*
- *S. Chatterjee et al, Advances in High Energy Physics, vol. 2015, Article ID 349013, 20 pages, 2015.*

Particle Ratios for Au-Au collisions at 19.6 GeV

Preliminary

Particles	Exp. Ratio	Error in Ratio	Th. Ratio
$\frac{K^-}{K^+}$	0.635	0.089	0.656
$\frac{\overline{p}}{p}$	0.123	0.022	0.124
$\frac{\overline{\Lambda}}{\Lambda}$	0.148	0.010	0.157
$\frac{\overline{\Xi}^+}{\Xi^-}$	0.260	0.025	0.250
$\frac{K^-}{\pi^-}$	0.113	0.017	0.142
$\frac{\overline{p}}{\pi^-}$	0.025	0.004	0.027
$\frac{\overline{\Lambda}}{\pi^-}$	0.076	0.009	0.073
$\frac{\overline{\Xi}^+}{\pi^-}$	0.0025	0.0003	0.0025

- Exp. Ratios and Error in Ratio correspond to the ratios calculated and the error in the them respectively, from the STAR results
- Th. Ratios corresponds to the ratios from this Thermal Model and are compared to the STAR results for 19.6 GeV

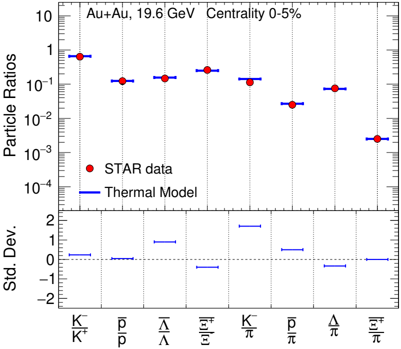
References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Particle Ratios for Au-Au collisions at 19.6 GeV

Preliminary

- The comparison of experimental particle ratios and ratios from the thermal model is plotted from Au-Au collision at 19.6 GeV for 0-5% centrality



- Thermal model is successfully predicting the experimental particle ratios within $\pm 2\sigma$ deviation where, σ is represented by:

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

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

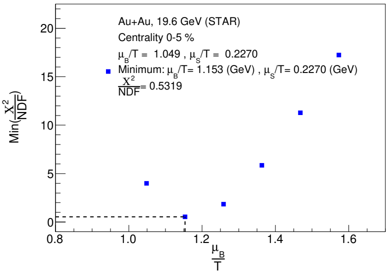
Variation of Input parameters ($\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$)

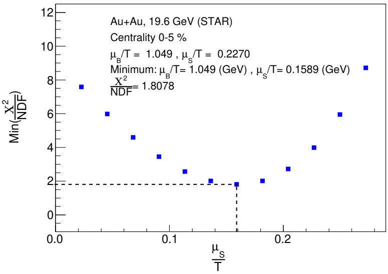
Preliminary

$$\frac{\overline{p}}{p} = \exp\left(\frac{-2\mu_B}{T}\right) \text{ and } \frac{K^-}{K^+} = \exp\left(\frac{-2\mu_S}{T}\right)$$

$\frac{ap}{p} = 0.123$, $\ln\frac{ap}{p} = -2.0971$, $\frac{\mu_B}{T} = -\frac{\ln\frac{ap}{p}}{2} = 1.049$

$\frac{K-}{K+} = 0.635$, $\ln\frac{K-}{K+} = -0.454$, $\frac{\mu_S}{T} = -\frac{\ln\frac{K-}{K+}}{2} = 0.2270$



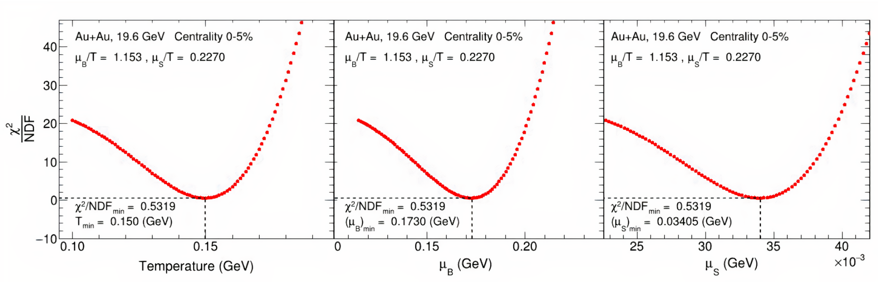


- $\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$ are varied in steps upto $\pm$ 90% of the initial value, as a function of $\frac{\chi^2}{NDF}$. A minimum $\frac{\chi^2}{NDF}$ is found for the variation
- $\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$ corresponding to the minimum $\frac{\chi^2}{NDF}$ is chosen as the input parameter

Thermal parameters for Au-Au collisions at 19.6 GeV

Preliminary

- Fit results from thermal model is plotted to extract the thermal parameters at Au-Au collisions at 19.6 GeV for 0-5% centrality



- At the minimum of $\frac{\chi^2}{NDF}$, i.e. $\frac{\chi^2}{NDF} = 0.5319$, we get $T = 0.150 \pm 0.006\, GeV, \mu_B = 0.1730 \pm 0.007\, GeV, \mu_S = 0.03405 \pm 0.0013\, GeV$

Thermal parameters for Au-Au collisions at 19.6 GeV

Preliminary

- Table for the results from Au-Au at 19.6 GeV for 0-5% centrality
  - π and Λ are corrected for weak decays
    - p, K and Ξ are inclusive

	STAR results	Thermal Model	Thermal Model (Strangeness Conservation)
χ^2/NDF	1.3	0.5319	2.929
T (GeV)	0.1539 $\pm$0.0052	0.150 $\pm$0.006	0.159 $\pm$0.0108
μ_B (GeV)	0.1879 $\pm$0.0086	0.173 $\pm$0.007	0.18333 $\pm$0.0125
μ_S (GeV)	0.0432 $\pm$0.0038	0.03405 $\pm$0.0013	0.036093 $\pm$0.0024

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Error on Thermal Parameters

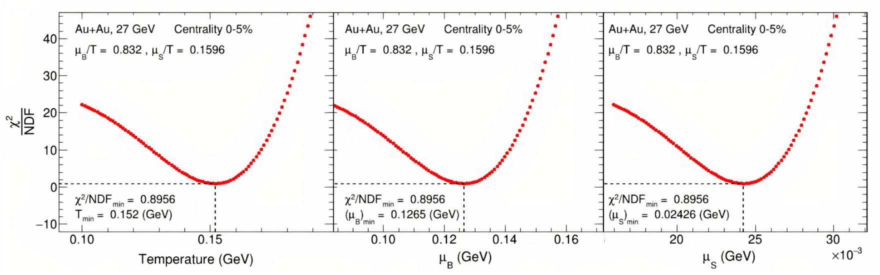
Preliminary

- Default Case
  - Systematic error is taken to be the average of deviation of the results from 100% and 0% of weak decay correction
  - Statistical error is taken to be the maximum deviation of the two cases, i.e. by adding and subtracting the experimental errors from the experimental ratios
  - Total error on the results is calculated as the square root of quadratic sum of Statistical and Systematic Errors
- Strangeness Conservation Case
  - The error is taken for the strangeness conservation case to be the deviation from the default case
  - The total error is the square root of the quadratic sum of the error in the default case and the strangeness conservation case

Thermal parameters for Au-Au collisions at 27 GeV

Preliminary

- Fit results from thermal model is plotted to extract the thermal parameters from Au-Au collisions at 27 GeV for 0-5% centrality



- At the minimum of $\frac{\chi^2}{NDF}$, i.e. $\frac{\chi^2}{NDF} = 0.856$, we get $T = 0.152 \pm 0.0058\ GeV, \mu_B = 0.1265 \pm 0.0049\ GeV, \mu_S = 0.02426 \pm 0.00088\ GeV$

Thermal parameters for Au-Au collisions at 27 GeV

Preliminary

- Table for the results from Au-Au at 27 GeV for 0-5% centrality
- π and Λ are corrected for weak decays
- p, K and Ξ are inclusive

	STAR results	Thermal Model	Thermal Model (Strangeness Conservation)
χ^2/NDF	1.3	0.8956	2.17
T (GeV)	0.155 $\pm$0.0051	0.152 $\pm$0.0058	0.159 $\pm$0.009
μ_B (GeV)	0.144 $\pm$0.0072	0.1265 $\pm$0.0049	0.13229 $\pm$0.0076
μ_S (GeV)	0.0335 $\pm$0.0036	0.02426 $\pm$0.00088	0.025376 $\pm$0.0014

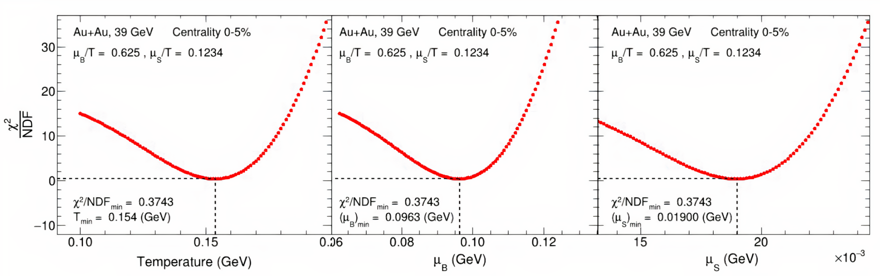
References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Thermal parameters for Au-Au collisions at 39 GeV

Preliminary

- Fit results from thermal model is plotted to extract the thermal parameters from Au-Au collisions at 39 GeV for 0-5% centrality



- At the minimum of $\frac{\chi^2}{NDF}$, i.e. $\frac{\chi^2}{NDF} = 0.3743$, we get $T = 0.154 \pm 0.0072\, GeV, \mu_B = 0.0963 \pm 0.0045\, GeV, \mu_S = 0.0190 \pm 0.0008\, GeV$

Thermal parameters for Au-Au collisions at 39 GeV

Preliminary

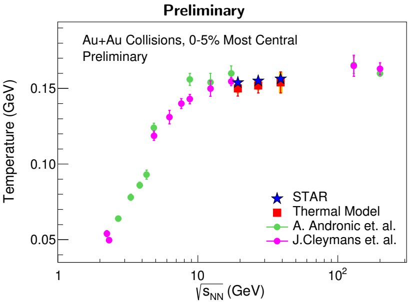
- Table for the results from Au-Au at 39 GeV for 0-5% centrality
- π and Λ are corrected for weak decays
- p, K and Ξ are inclusive

	STAR results	Thermal Model	Thermal Model (Strangeness Conservation)
χ^2/NDF	0.9	0.3743	0.7488
T (GeV)	0.1564 $\pm$0.0054	0.154 $\pm$0.0072	0.162 $\pm$0.0086
μ_B (GeV)	0.1032 $\pm$0.0074	0.0963 $\pm$0.0045	0.10125 $\pm$0.0067
μ_S (GeV)	0.0245 $\pm$0.0038	0.019 $\pm$0.0008	0.019991 $\pm$0.0013

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Energy dependence of freezeout Temperature

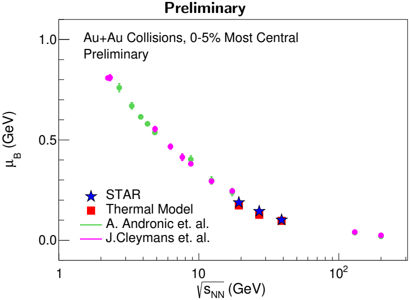


- Temperature as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The results from A. Andronic and J.Cleymans are shown by the green and magenta marker, respectively
- The chemical freezeout temperature increases with the beam energy
- The results of this Thermal model agrees with the results from the other model (STAR Thermus) at the same energy, within errors.
- All the models are showing consistently the same behaviour

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*
- *J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton Phys. Rev. C 73, 034905 (2006)*

Energy dependence of Baryon chemical potential

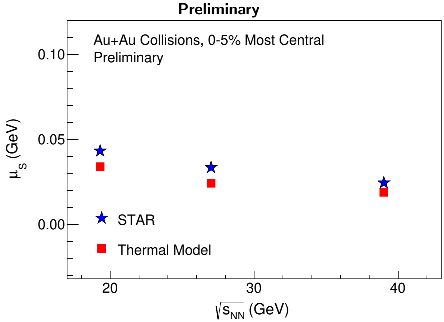


- Baryon chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The results from A. Andronic and J.Cleymans are shown by the green and magenta marker, respectively
- The Baryon chemical potential decreases with increasing the beam energy
- The results of this Thermal model agrees with the results from the other model (STAR Thermus) at the same energy, within errors.
- All the models are showing consistently the same behaviour

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*
- *J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton Phys. Rev. C 73, 034905 (2006)*

Energy dependence of Strangeness chemical potential



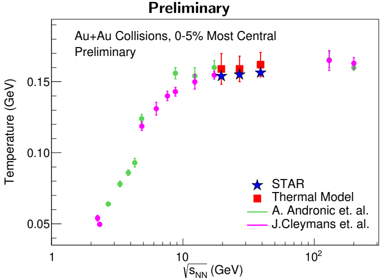
- Strangeness chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The Strangeness chemical potential decreases with increasing the beam energy
- The results of this Thermal model deviates from the other model (STAR Thermus)
- All the models are showing consistently the same behaviour

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Energy dependence of freezeout Temperature

With the condition of Strangeness Conservation ($s - \bar{s} = 0$)



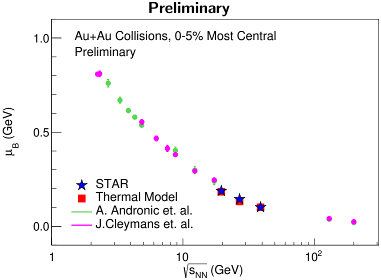
- Temperature as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The results from A. Andronic and J.Cleymans are shown by the green and magenta marker, respectively
- The freezeout temperature increases with the beam energy
- The results of this Thermal model agrees with the results from the other model (STAR Thermus) at the same energy, within errors.
- All the models are showing consistently the same behaviour

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*

Energy dependence of Baryon chemical potential

With the condition of Strangeness Conservation ($s - \bar{s} = 0$)



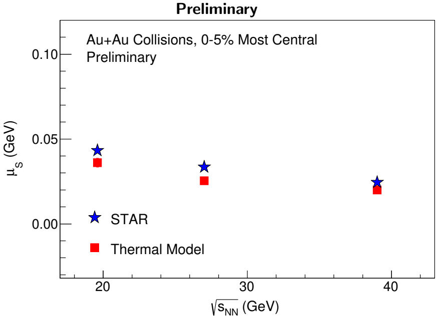
- Baryon chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The results from A. Andronic and J.Cleymans are shown by the green and magenta marker, respectively
- The Baryon chemical potential decreases with the increase in beam energy
- The results of this Thermal model agrees with the results from the other model (STAR Thermus) at the same energy, within errors.
- All the models are showing consistently the same behaviour

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904
- *A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772, 167-199 (2006)*
- *J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton Phys. Rev. C 73, 034905 (2006)*

Energy dependence of Strangeness chemical potential

With the condition of Strangeness Conservation ($s - \bar{s} = 0$)



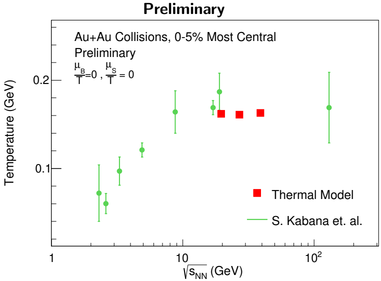
- Strangeness chemical potential as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results form the STAR experiment are shown in blue stars and those from this Thermal model by red squares
- The Strangeness chemical potential decreases with increasing the beam energy
- The results of this Thermal model deviates from the other model (STAR Thermus)
- All the models are showing consistently the same behaviour

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Energy dependence of Zero potential Temperature

With the condition of Strangeness Conservation ($s - \bar{s} = 0$)



- Temperature for zero potential as a function of beam energy is plotted for 19.6, 27 and 39 GeV
- The results from this Thermal model by red squares
- The results from S. Kabana are shown by the green marker
- The zero potential freezeout temperature saturates with the beam energy
- The results of this Thermal model agrees with the previously published results with different data
- Both the models (preliminary and previously published) are showing consistently the same behaviour

References:

- *S. Kabana, The European Physical Journal C, Volume 21, Issue 3, pp. 545-555 (2001)*
- *S. Kabana, P. Minkowski, New J.Phys. 3 (2001) 4*

Summary

Preliminary

- We have shown Thermal model parameters (T, μ_B and μ_S) for different Beam energies from 19.6, 27 and 39 GeV
- The model successfully describes the value of different particle ratios within 2σ and χ^2/NDF by the order of 1-2
- Chemical freezeout temperature increases as we increase the Beam energy
- Baryon chemical potential decreases as we increase the Beam energy
- The results of thermal parameters and their energy dependence is consistent with the STAR results within uncertainties
- The results are comparable with other thermal model calculations from A. Andronic, J.Cleymans and S. Kabana.

Thank You

Backup

Preliminary

Au-Au Collisions at 19.6 GeV for 0-5% Centrality
Variation of $\frac{\mu_B}{T}$ and $\frac{\mu_S}{T}$

$$\frac{ap}{p} = 0.123,\ \ln\frac{ap}{p} = -2.0971,\ \frac{\mu_B}{T} = -\frac{\ln\frac{ap}{p}}{2} = 1.049$$

$$\frac{K-}{K+} = 0.635,\ \ln\frac{K-}{K+} = -0.454,\ \frac{\mu_S}{T} = -\frac{\ln\frac{K-}{K+}}{2} = 0.2270$$

Case	$\frac{\mu_B}{T}$	$\frac{\mu_S}{T}$	% change	Case	$\frac{\mu_B}{T}$	$\frac{\mu_S}{T}$
0	1.049	0.227	0			
1	0.105	0.227	-90	19	1.049	0.0227
2	0.210	0.227	-80	20	1.049	0.0454
3	0.315	0.227	-70	21	1.049	0.0681
4	0.419	0.227	-60	22	1.049	0.0908
5	0.524	0.227	-50	23	1.049	0.1135
6	0.629	0.227	-40	24	1.049	0.1362
7	0.734	0.227	-30	25	1.049	0.1589
8	0.839	0.227	-20	26	1.049	0.1816
9	0.944	0.227	-10	27	1.049	0.2043
10	1.153	0.227	10	28	1.049	0.2497
11	1.258	0.227	20	29	1.049	0.2724
12	1.363	0.227	30	30	1.049	0.2950
13	1.468	0.227	40	31	1.049	0.3177
14	1.573	0.227	50	32	1.049	0.3404
15	1.678	0.227	60	33	1.049	0.3631
16	1.783	0.227	70	34	1.049	0.3858
17	1.887	0.227	80	35	1.049	0.4085
18	1.992	0.227	90	36	1.049	0.4312

Backup

Preliminary

Particle Ratios for Au-Au collisions at 27 GeV

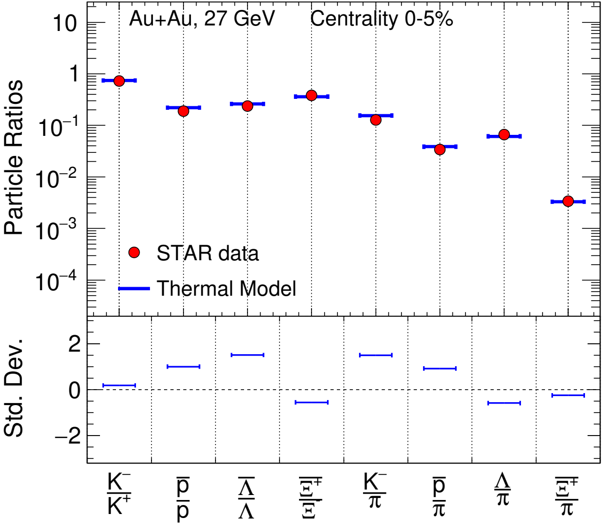
Particles	Exp. Ratio	Error in Ratio	Th. Ratio
$\frac{K^-}{K^+}$	0.727	0.092	0.744
$\frac{\overline{p}}{p}$	0.189	0.032	0.221
$\frac{\Lambda}{\lambda}$	0.236	0.0159	0.260
$\frac{\overline{\Xi}^+}{\overline{\Xi}^-}$	0.381	0.036	0.361
$\frac{K^-}{\pi^-}$	0.128	0.018	0.155
$\frac{\overline{p}}{\pi^-}$	0.034	0.005	0.0386
$\frac{\Lambda}{\pi^-}$	0.066	0.008	0.0613
$\frac{\overline{\Xi}^+}{\pi^-}$	0.0034	0.0004	0.0033

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Preliminary

Particle Ratios for Au-Au collisions at 27 GeV



Backup

Preliminary

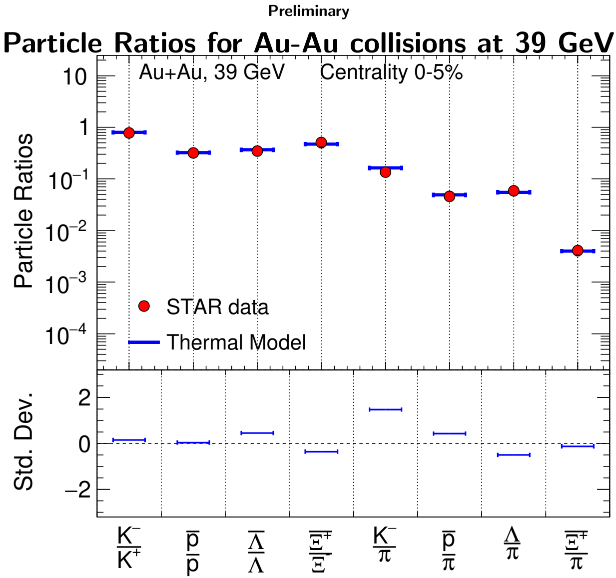
Particle Ratios for Au-Au collisions at 39 GeV

Particles	Exp. Ratio	Error in Ratio	Th. Ratio
$\frac{K^-}{K^+}$	0.781	0.101	0.796
$\frac{\overline{p}}{p}$	0.321	0.052	0.323
$\frac{\overline{\Lambda}}{\lambda}$	0.347	0.042	0.366
$\frac{\overline{\Xi}^+}{\Xi^-}$	0.506	0.095	0.472
$\frac{K^-}{\pi^-}$	0.135	0.019	0.163
$\frac{\overline{p}}{\pi^-}$	0.046	0.007	0.049
$\frac{\overline{\Lambda}}{\pi^-}$	0.059	0.008	0.055
$\frac{\overline{\Xi}^+}{\pi^-}$	0.0041	0.0008	0.0040

References:

- L. Adamczyk et. al. (STAR Collaboration) Phys.Rev.C 96 (2017) 4, 044904

Backup



Preliminary
Particle Ratios for Au-Au collisions at 39 GeV
Au+Au, 39 GeV
Centrality 0-5%
Particle Ratios
STAR data
Thermal Model
Std. Dev.