Fluctuations in Lambda Multiplicity Distribution in Au+Au collisions at $\sqrt{s_{NN}} = 3.0$ GeV at STAR

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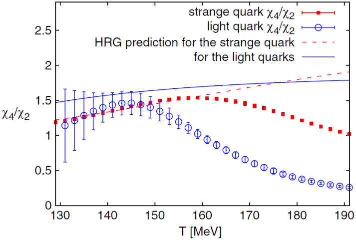
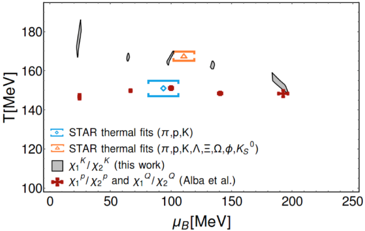
STAR

Motivation: Net-Lambda Fluctuation Analysis



R. Bellwied, et. al. Phys. Rev. Lett, vol. 111, no. 20, p. 202302, 2013.



R. Bellwied, et. al. Phys. Rev. C 99, 034912

- Hadron Resonance Gas (HRG) model and LQCD calculations were compared as a function of T.
- χ_4/χ_2 shows different pseudo-temperature of deconfinement for different quark flavor.

- Susceptibilities from protons and kaons show different freeze-out parameters.

$$\frac{C_2}{C_1} = \frac{\chi^B_{2,\mu}}{\chi^B_{1,\mu}}, \qquad \frac{C_3}{C_2} = \frac{\chi^B_{3,\mu}}{\chi^B_{2,\mu}}, \qquad \frac{C_4}{C_2} = \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}}$$

Chemical freeze-out:

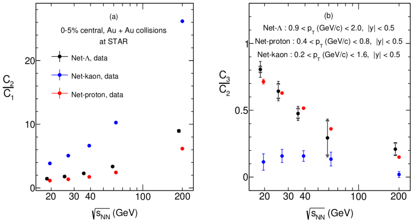
- Relate lambda fluctuations with freeze-out parameters, from light charged particles and strange particles.
- Study freeze-out parameters in the context of quark-mass dependence as a function of $\sqrt{s_{NN}}$.

Motivation: Net-Lambda Fluctuation Analysis

$$C_1 = \langle N \rangle, \quad C_2 = \langle (\delta N)^2 \rangle, \quad C_3 = \langle (\delta N)^3 \rangle, \quad C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2$$

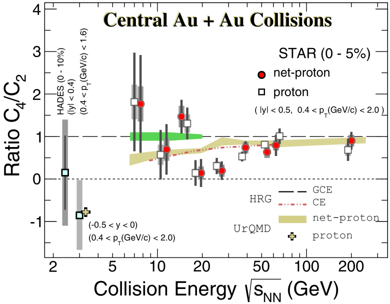
$$C_2 / C_1 = \sigma^2 / M, \qquad C_3 / C_2 = S\sigma, \qquad C_4 / C_2 = \kappa\sigma^2$$

- For the BES-I, net-Lambda fluctuations were calculated.
- Lambda C_2 / C_1 and C_3 / C_2 follow closely the results from protons.
- Higher order cumulants were not calculated due to lack of statistics.



STAR, Phys. Rev. C 102, 024903 (2020)

- Does C_4 / C_2 from lambda also follow closely the results from protons?
- Do we expect to see critical behaviour from lambda particles?

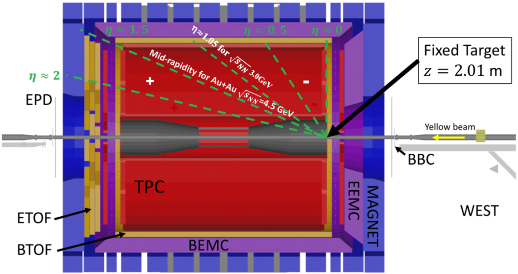


STAR, Phys. Rev. Lett. 128, (2022) 202303

- Continue with the comparison between lambda and proton fluctuations at low $\sqrt{s_{NN}}$.
- Extend Lambda fluctuation analysis to higher orders.

STAR FXT Setup at $\sqrt{s_{NN}} = 3.0$ GeV and Analysis Information

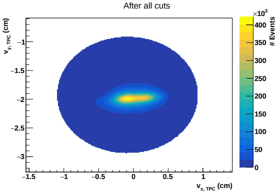
Fixed target experiment



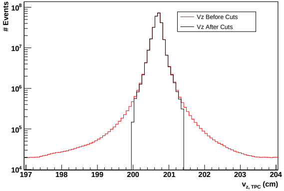
Au+Au collisions $\sqrt{s_{NN}} = 3.0$ GeV (year 2018). At this collisions energy, **mid-rapidity** is at $y = 1.045$

Events: 308M minimum bias recorded, 270M after cuts.

Event selection in vertex position:



Vx-Vy after cuts



Vz distribution, peaked at 200.7cm. Cut ±0.7cm

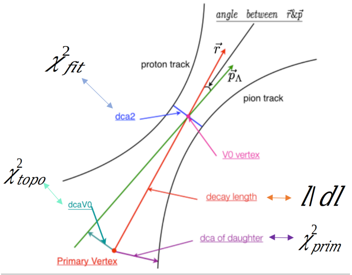
Lambda Particle Reconstruction

Lambda particle reconstruction was done using the Kalman Filter particle package (S. Gorbunov, On-line reconstruction algorithms for the CMB and ALICE experiments, 2013)(I. Kisel (CBM), J. Phys. Conf. Ser. 1070, 012015 (2018)).

$$\Lambda \longrightarrow p + \pi^{-} \qquad\qquad c\tau = 7.86\ \text{cm} \tag{1}$$

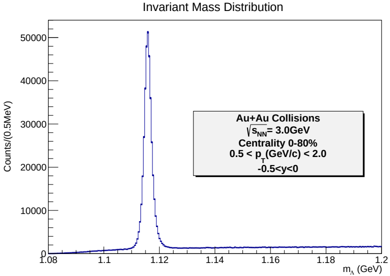
The KF-Package:

- Uses the state vector $\vec{r} = (x, y, z, p_x, p_y, p_z, E, s)$ and the covariance matrix of the particles to calculate the decay vertex, momentum and energy of the mother particle.
- Instead of using DCA and pointing angle θ, it uses the χ^2-criterion, used to estimate the quality of the reconstruction.



Cuts used in KF-Package:

- DCA(PV to Lambda-vertex) $<$ 1.0 cm
- DCA(p to π)$<$ 1.0 cm
- Other cuts were optimized by KF-Package

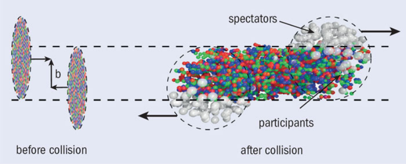


Lambda invariant mass distribution.

Purity in the signal, Purity=0.91 and S/B=49

Centrality Definition

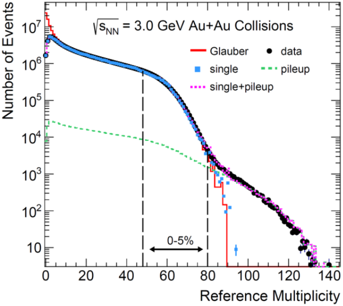
The **reference multiplicity** (FxtMult3) uses the number of charged particles N_{ch} between $\eta : [0, 2]$ excluding protons.



Visualization of a heavy ion collision

% Central	N_{ch} Cut	$\langle N_{part} \rangle$	$\langle b(fm) \rangle$
50-60	4	47 ± 5	10.6 ± 0.3
40-50	6	70 ± 11	9.7 ± 0.4
30-40	10	106 ± 15	8.6 ± 0.4
20-30	16	155 ± 21	7.2 ± 0.5
10-20	26	220 ± 14	5.6 ± 0.5
5-10	38	283 ± 30	3.9 ± 0.5
0-5	48	328 ± 27	2.5 ± 0.6

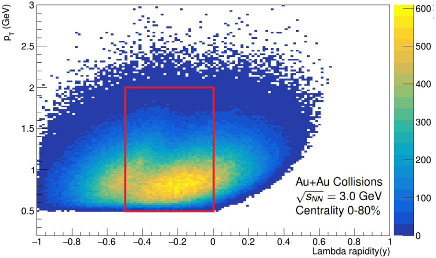
Table of cuts



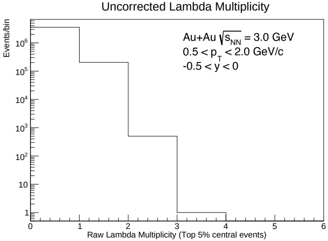
FxtMult3 Distribution including single and pileup events.

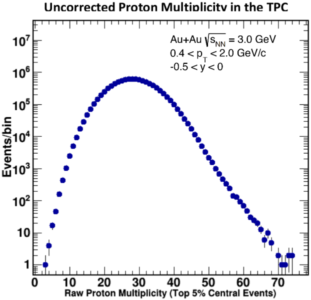
A cut above 80 is used to reduce the contribution of pile up events.

Acceptance and Raw Multiplicity Distribution



Lambda Acceptance





- The **acceptance** used is $0.5 < p_T < 2.0$ GeV/c and $-0.5 < y < 0$.
- **Low multiplicity** of lambda at $\sqrt{s_{NN}} = 3$ GeV.
- While protons show high multiplicity.
- Proton TPC efficiencies are greater than 90%.
- Lambda TPC efficiencies are less than 40% and very p_T dependent.

Corrections Applied to the Raw Cumulants

Centrality Bin Width Correction(J. Phys. G: Nucl. Part. Phys. 40 105104(2013)), accounts for volume fluctuation effects from binning.

$$C_r = \frac{\sum_i n_i C_r^i}{\sum_i n_i}$$

Lambda efficiency correction: Accounts for efficiencies in the TPC. It is based on the ”track-by-track” efficiency correction.
(X. Luo and T. Nonaka, Phys Rev. C. 99, 044917 (2019))
(T. Nonaka et al, Phys. Rev. C. 95.064912 (2017)).

$$\tilde{P}(n) = \sum_N P(N) B_{\varepsilon,N}(n)$$

$$B_{\varepsilon,N}(n) = \frac{N!}{n!(N-n)!} \varepsilon^n (1-\varepsilon)^{N-n}$$

Using the binomial response, a relation between measured and true factorial cumulants is obtained in terms of the efficiency.

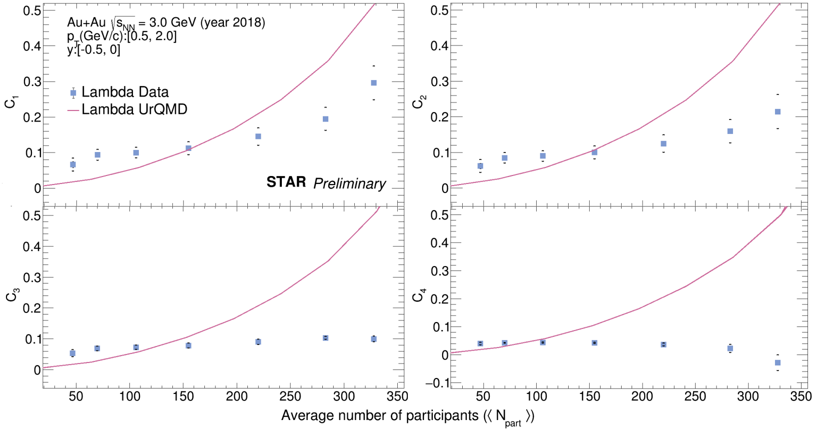
$$\langle n^m \rangle_{fc} = \varepsilon^m \langle N^m \rangle_{fc}$$

Statistical Uncertainties: Statistical uncertainties are calculated using the Bootstrap method. The analysis is randomly sampled and the variance of the sample provides the uncertainty.

Systematic Uncertainties: The sources of systematic uncertainty considered are:

- Purity in the charged daughters PID(nσ)
- Topological cuts from lambda reconstruction.(χ^2 in KF-Package)
- Track quality (NHitsFit)
- Efficiencies

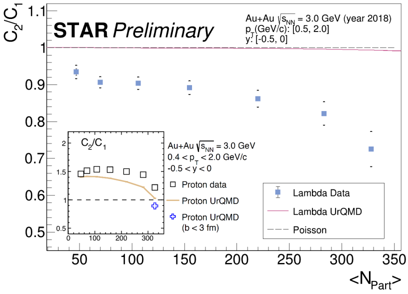
Single Cumulants as a function of $\langle N_{Part} \rangle$

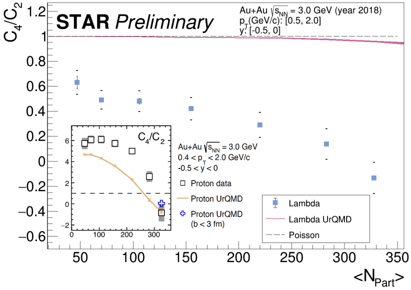


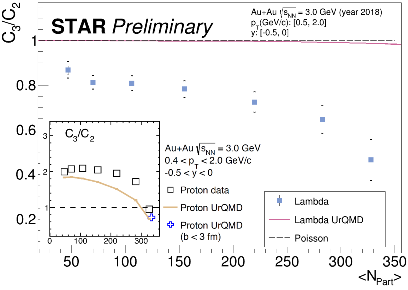
- Single cumulants from UrQMD show **deviations** from data.
- UrQMD seems to have better agreement with data for most peripheral bins.
- UrQMD results show similar trend with data for low order cumulants.

Cumulant Ratios as a function of $\langle N_{Part} \rangle$

Comparison with proton results (STAR, Phys. Rev. Lett. 128, (2022) 202303)(STAR, arXiv : 2209.11940) as a function of $\langle N_{Part} \rangle$



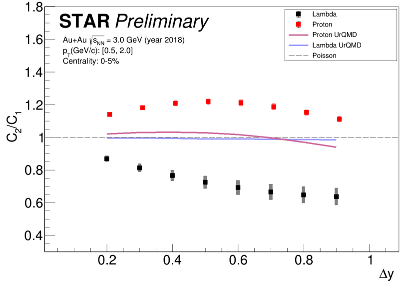


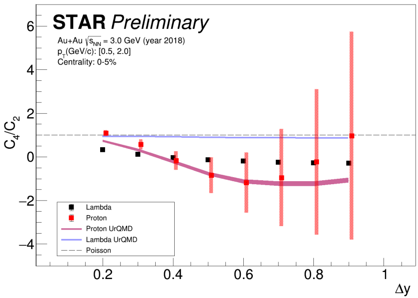


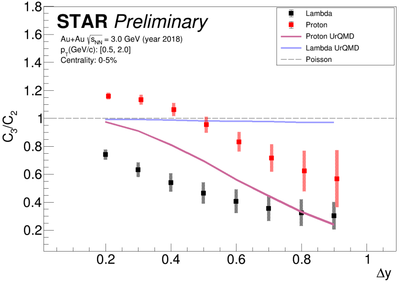
- Lambda cumulant ratios for data and UrQMD approach the **poissonian limit** for most peripheral bins.
- Lambda data approach the poissonian limit from **below**, contrary to proton data.
- UrQMD cumulant ratios show a **weak suppression** with respect the poissonian baseline in the most central bin.
- Lambda data show **suppression** from baseline for most central bins, which is also shown in proton data.

Comparison of Lambda with Proton as a function of Δy

Comparison with proton (STAR, Phys. Rev. Lett. 128, (2022) 202303)(STAR, arXiv : 2209.11940) as a function of rapidity window.



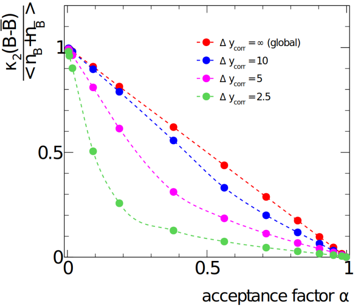




$$\Delta y = 0 - y_{min}, \quad y_{min} = -0.2, \ldots, -0.9$$

- **Poissonian** limit is approached at low coverage.
- Both lambda and proton UrQMD show deviations from data. The trend is similar.
- **Strong decrease** of lambda cumulant ratios from baseline with increasing of Δy, due to baryon and strangeness **conservation laws**.
- Proton results show different trends compared to lambda, likely due to the effects of **baryon stopping** and effects of **nuclear production** (Z. Feckova et al.,Phys. Rev. C 93, 054906(2016)).

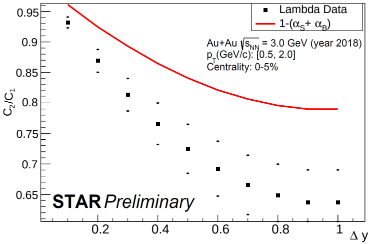
Effects of Number Conservation for Lambda Particle



Normalized k_2 value as a function of accepted fraction of baryons (P. Braun-Munzinger et al., arXiv:1907.03032). Based on ALICE results.

- α is defined as the ratio between baryons inside the acceptance and baryons in full phase space $\alpha = \langle N_B \rangle / \langle N_B^{4\pi} \rangle$.
- This behavior shows the effect of **global baryon conservation** for increasing Δy.
- Rapidity range decreases with decreasing $\sqrt{s_{NN}}$.

- For lambda particles one should consider the effects of both **strangeness** and **baryon** quantum number, so $\alpha = \alpha_S + \alpha_B$.
- The ad-hoc relation is used $C_2 / C_1 = 1 - (\alpha_B + \alpha_S)$. (V.Vovchenko et al., JHEP10(2020)089)(STAR, Phys. Rev. C 102, 024903 (2020))
  Where $\alpha_S = \langle N_\Lambda \rangle / \langle N_S^{4\pi} \rangle$ and $\alpha_B = \langle N_\Lambda \rangle / \langle N_B^{4\pi} \rangle$.

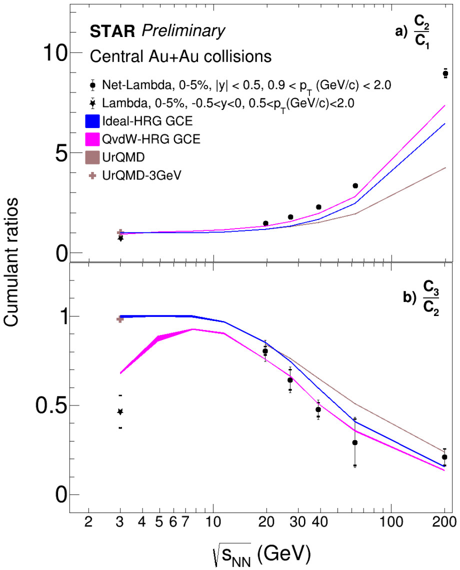


C_2 / C_1 compared with conservation laws prediction.

- Trend of data is captured by the ad-hoc relation.
- α_S plays a more important role for lambda particles at $\sqrt{s_{NN}} = 3.0$ GeV.

Net-Lambda Cumulant Ratios as a function of $\sqrt{s_{NN}}$

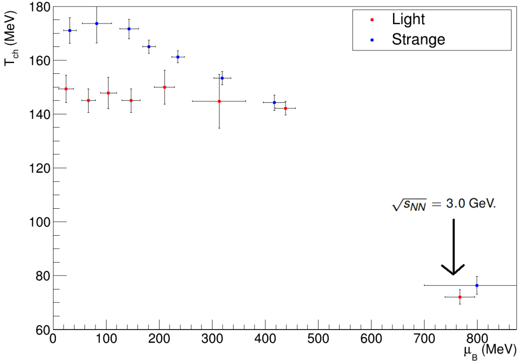
Results from lambda data were compared with the thermal model in both cases, the ideal HRG and QvdW-HRG(includes Quantum Van der Waals interactions)(Thermal-FIST V. Vovchenko, et. al. Comput. Phys. Commun. 224, 295 (2019))(R. V. Poberezhnyuk, et. al. Phys. Rev. C 100, 054904 (2019)).



- $C_3\,/\,C_2$ shows **strong suppression** with respect to the ideal HRG baseline at low $\sqrt{s_{NN}}$ for net-lambda distributions.
- **QvdW-HRG** shows better agreement with data, showing the same trend with data even at low $\sqrt{s_{NN}}$.
- Deviations of the QvdW-HRG from the Ideal-HRG model shows the effect of **hadronic interactions**.
- Hadronic interactions are dominant with decreasing $\sqrt{s_{NN}}$ due to the **high baryon density** at these energies.

Flavor Dependence of Cumulant Ratios

- Freeze-out conditions for **light particles**(π, p, K) and **strange particles**(K, Λ, Ξ, Ω, K_s^0, ϕ) and the corresponding **antiparticles** are calculated using GCE and HRG-QvdW model.
- Freeze-out conditions at $\sqrt{s_{NN}} = 3.0$ GeV are calculated from preliminary results of **light particles**(π, p, K) and **strange particles**(Λ, K, Ξ, ϕ), using SCE and HRG-QvdW model.



Strange and Light GCE fits to STAR data using PDG2016+ hadronic spectrum(P. Alba, et al. PRD. 96 (2017) 034517) and QvdW model (R. V. Poberezhnyuk, et. al. Phys. Rev. C 100, 054904 (2019))

- Different freeze-out conditions **agree** with each other at $\sqrt{s_{NN}} = 3.0$ GeV.
- **No expected differences** in lambda cumulants for different freeze-out conditions at $\sqrt{s_{NN}} = 3.0$ GeV.

Summary

- Lambda cumulants were measured as a function of **centrality** and **rapidity**, which were compared to BES-I results.
- Lambda C_2/C_1 shows a decreasing behaviour with increasing Δy mainly due to **strangeness conservation effects**.
- Lambda high order cumulant ratios show strong suppression with respect to the Poissonian baseline at $\sqrt{s_{NN}} = 3.0$ GeV.
- Lambda and proton cumulant ratios with respect to Δy **show different trends**, mainly due to the effects of baryon stopping and conservation laws.
- The suppression of lambda C_3/C_2 is also observed with the HRG-QvdW model at $\sqrt{s_{NN}} = 3$ GeV, indicating evidence of **hadronic interactions**.
- Obtained freeze-out parameters for different conditions(light and strange) suggest **no flavor hierarchy** at $\sqrt{s_{NN}} = 3$ GeV.

Outlook: Continue with the lambda fluctuation analysis for different FXT energies for better understanding of high baryonic matter.