Fluctuations of net Lambda distributions measured as a function of collision energy with the STAR detector at RHIC

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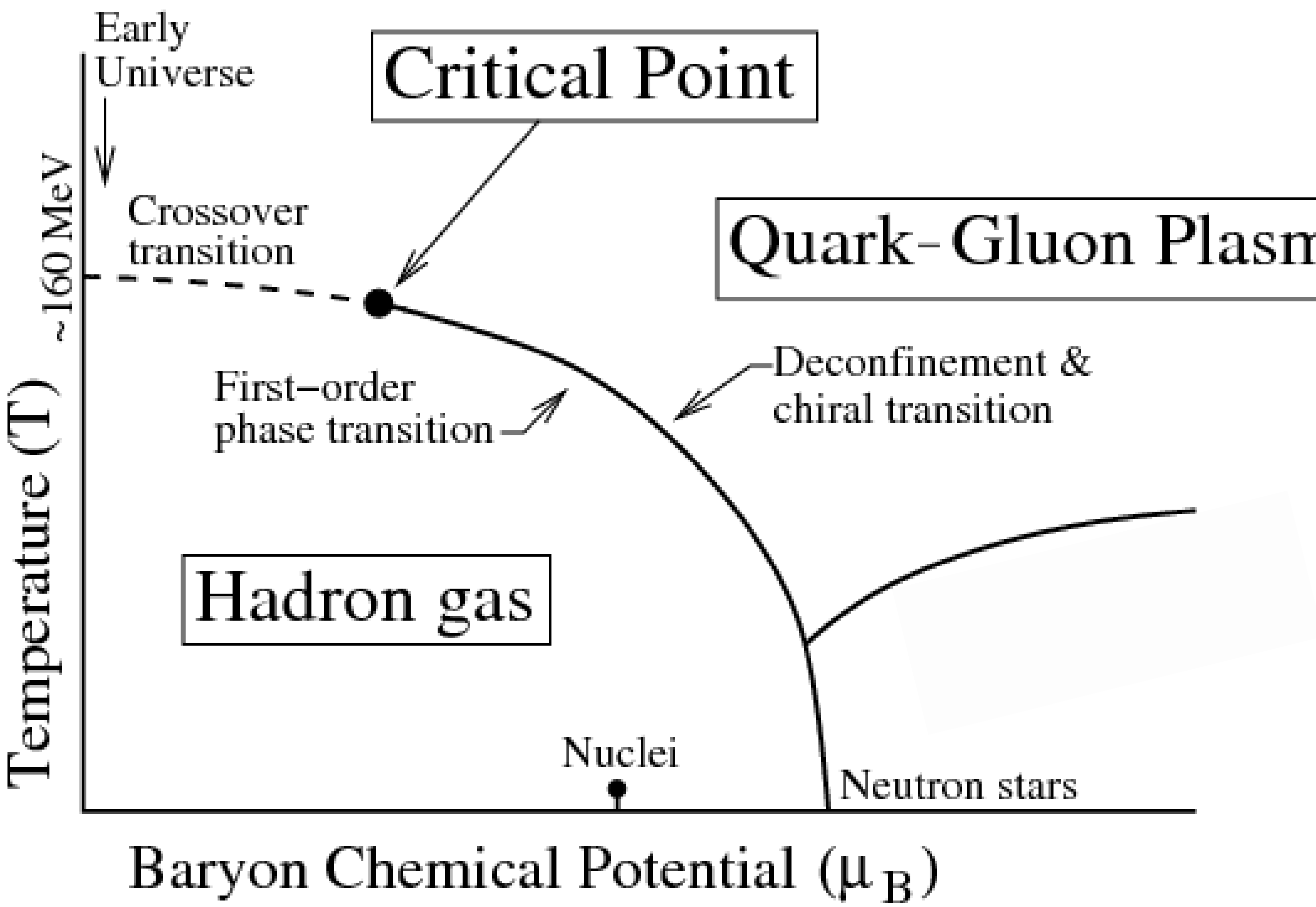
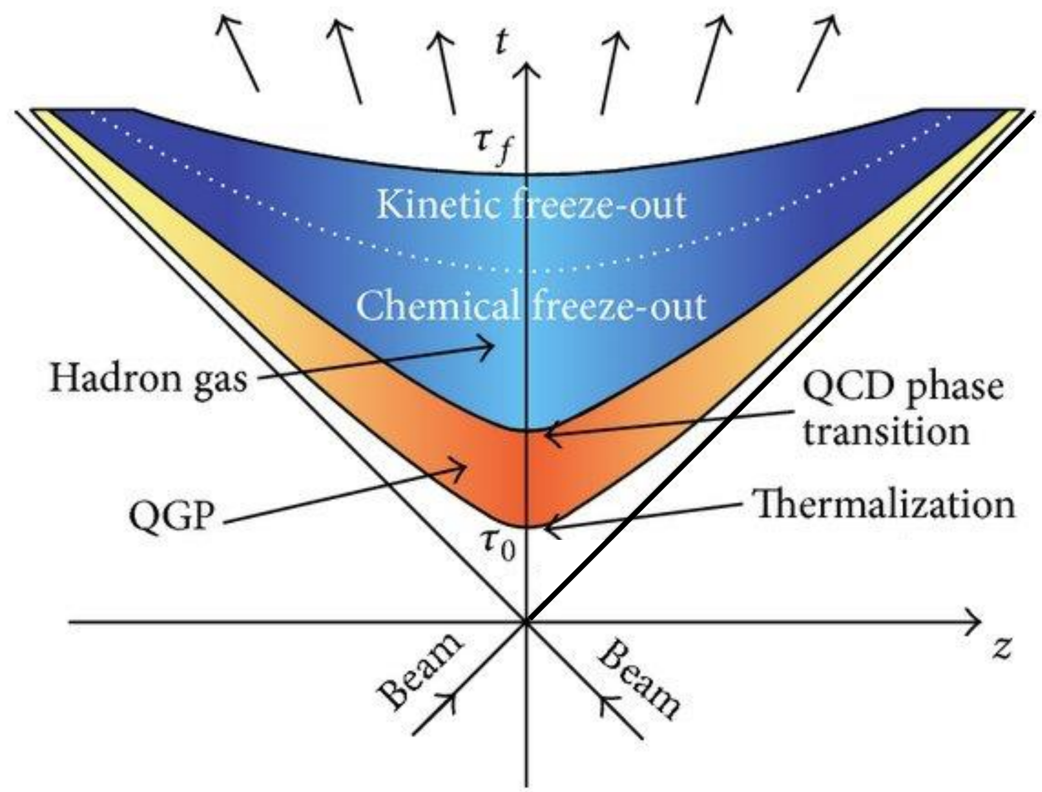
Main motivation(s)

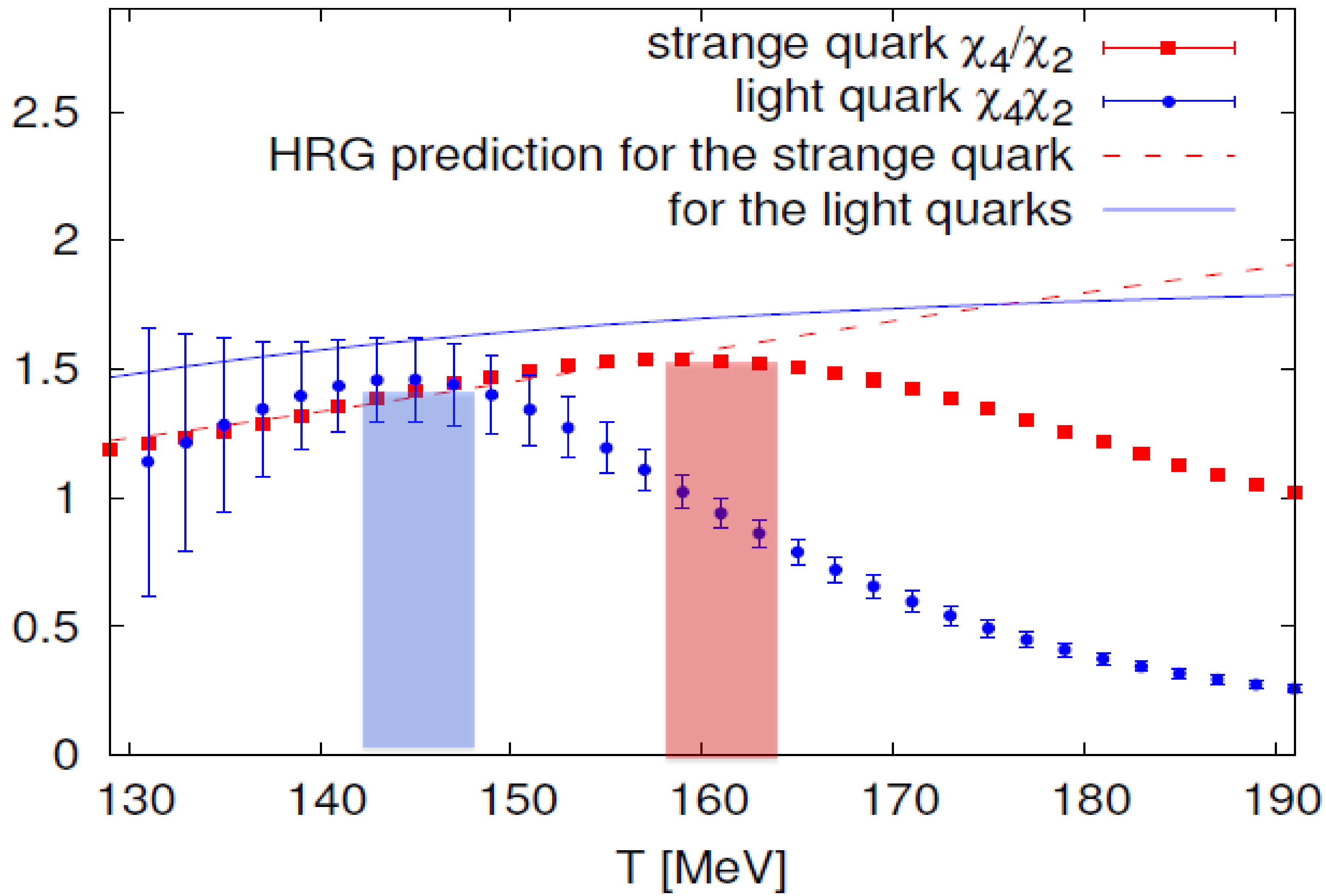




- Mapping the **freeze-out curve** and probing the possible **critical point** through fluctuations of conserved quantum numbers:
  net charge - $\triangle$Q, **net baryons -** $\triangle$B, **net strangeness -** $\triangle$S

- Non monotonic behavior of fluctuations of conserved quantum numbers as a function of collision energy could indicate the presence of a critical point.
- Fluctuations of conserved quantum numbers are related to susceptibilities in lattice QCD: can be used to extract chemical freeze-out parameters: T & μ_B in a model-independent way.

Is there a flavor hierarchy ?



WB Collaboration, PRL 111, 202302 (2013)

- The temperature at which the calculated HRG susceptibility ratio deviates from LQCD calculations indicates different temperatures depending on the quark flavor (strange or light).

Moments of net multiplicity distributions and susceptibilities

- Net charged particles, net protons and net kaons have been used as proxies for net charge, net baryon number and net strangeness, respectively.
- First 4 moments: Mean (M), St.dev. (σ), Skewness (S) & Kurtosis (k).
- Moment ratios/products of net multiplicity distributions relate to appropriate susceptibility ratios.

- Susceptibilities:

$$\chi_{lmn}^{QBS} = \frac{\partial^{l+m+n} p/T^4}{\partial\left(\mu_B/T\right)^l \partial\left(\mu_S/T\right)^m \partial\left(\mu_Q/T\right)^n} \quad \rightarrow \quad \chi_n^{QBS} = \frac{1}{VT^3}\frac{\partial^n(\ln Z)}{\partial\left(\mu_{QBS}/T\right)^n}$$

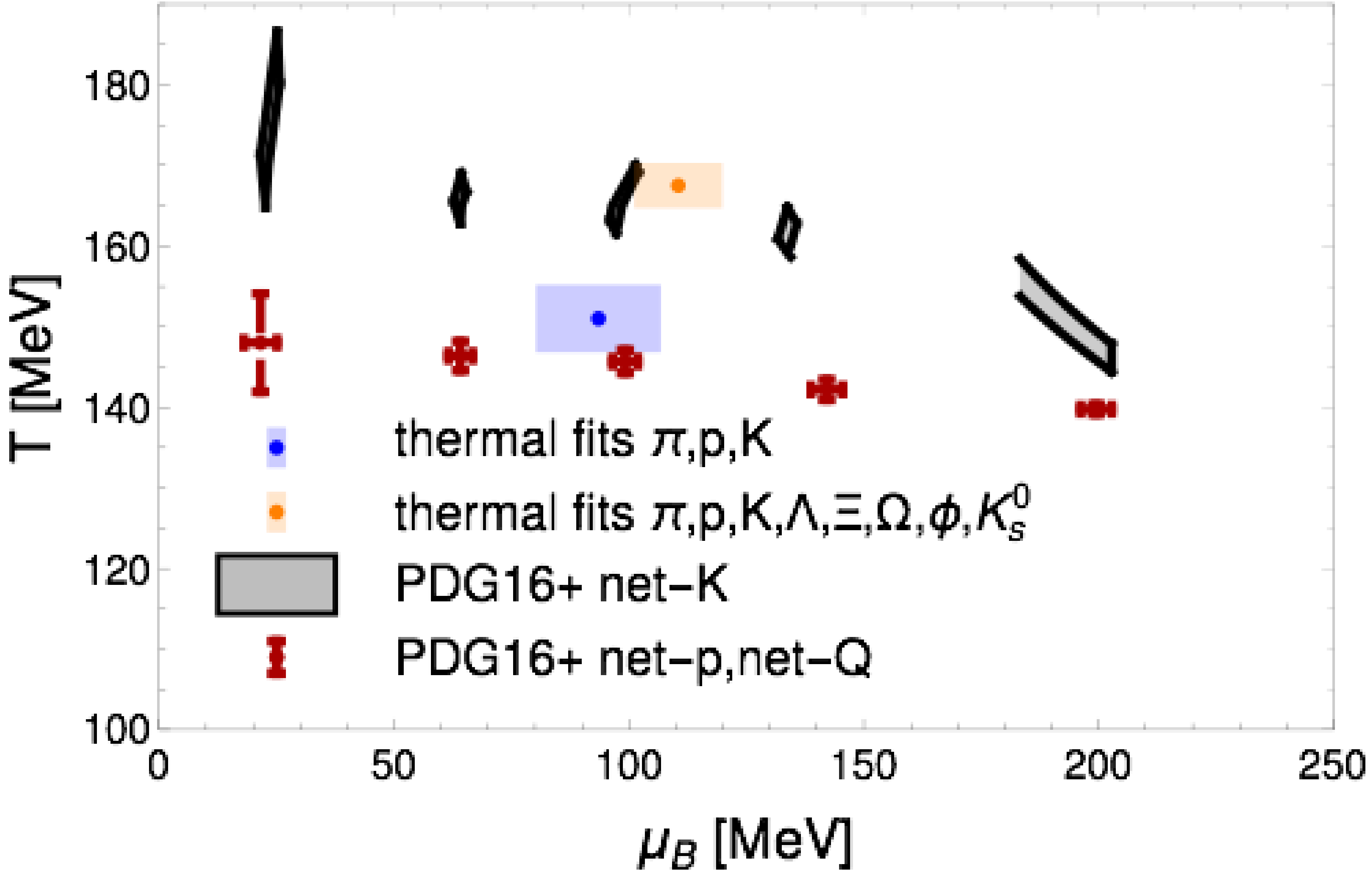
- Relationship of moment products/ratios with susceptibilities:

$$\frac{\sigma_B^2}{M_B} = \frac{\chi_{2,\mu}^B}{\chi_{1,\mu}^B}, \quad S_B\sigma_B = \frac{\chi_{3,\mu}^B}{\chi_{2,\mu}^B}, \quad \kappa_B\sigma_B^2 = \frac{\chi_{4,\mu}^B}{\chi_{2,\mu}^B}$$

- Moments can be experimentally measured and then compared to modeled (HRG, LQCD) susceptibilities in order to extract FO parameters.

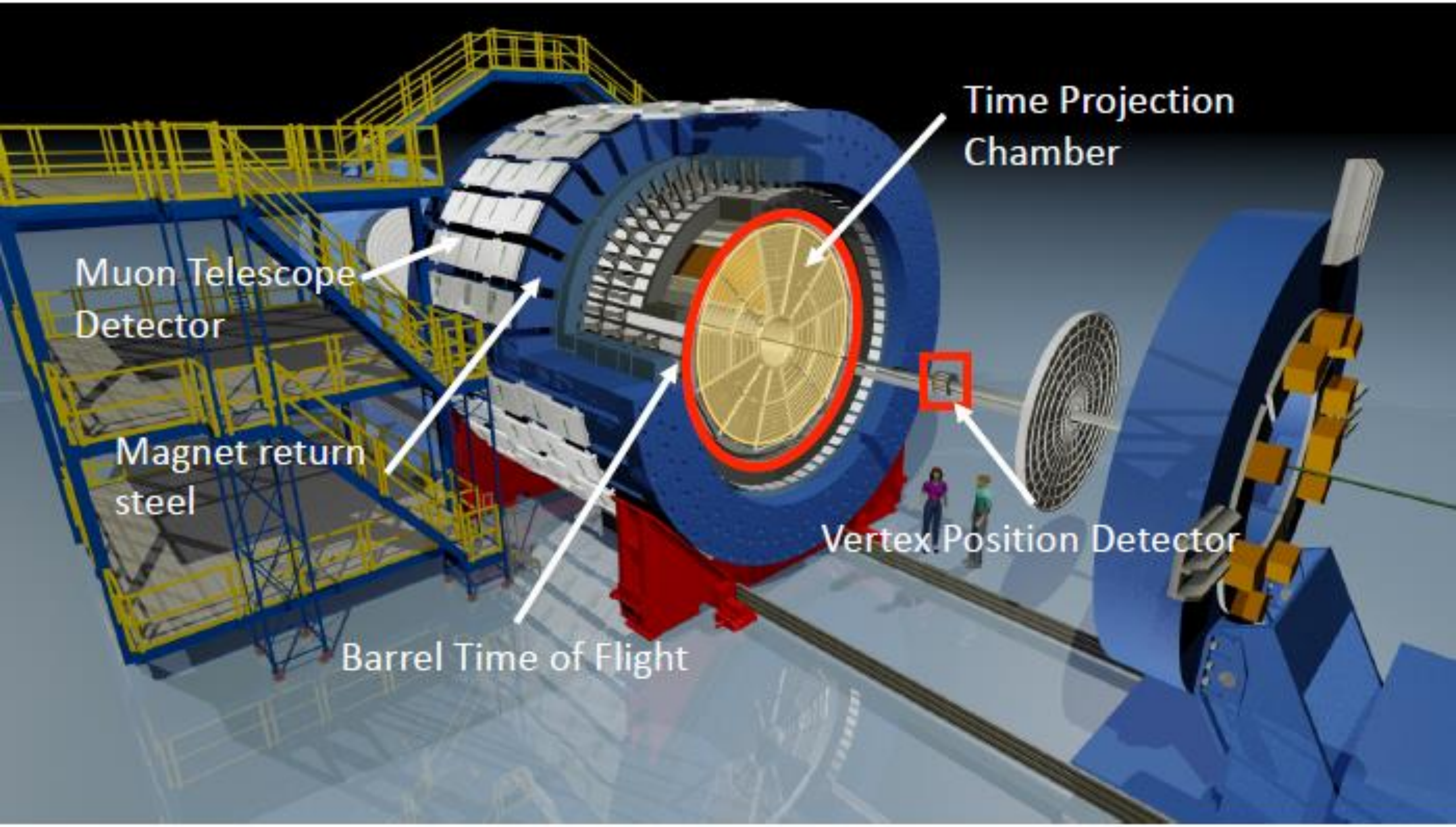
Interpretation of previous STAR results

HRG calculations on the basis of STAR net-proton, net-charge and net-kaon measurements
R. Bellwied et al.,. arXiv.1805.00088



Measure net Lambda fluctuations in order to provide a more complete strangeness proxy together with net kaons and compare with HRG predictions for sequential hadronization.

The Solenoidal Tracker At RHIC (STAR)

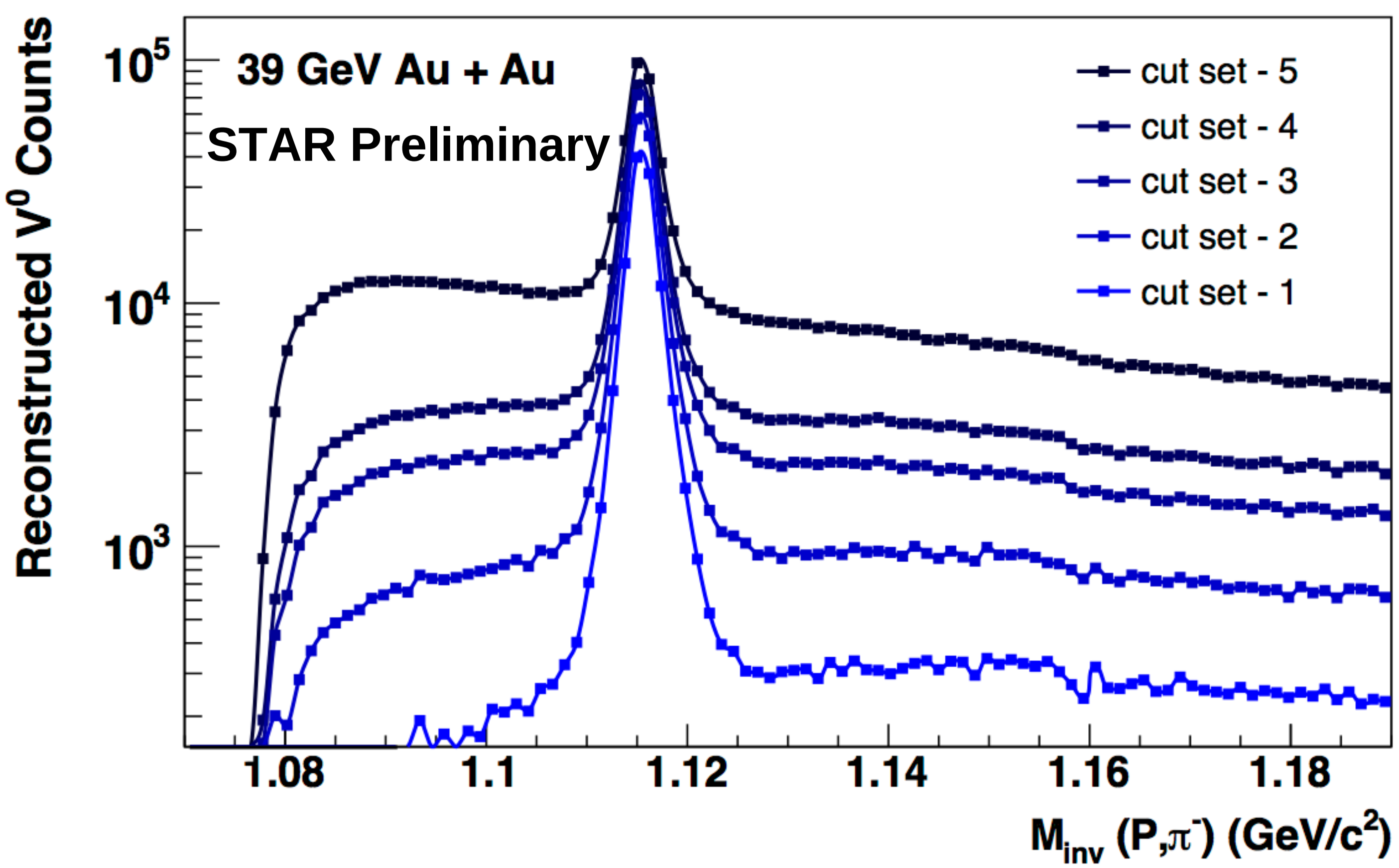


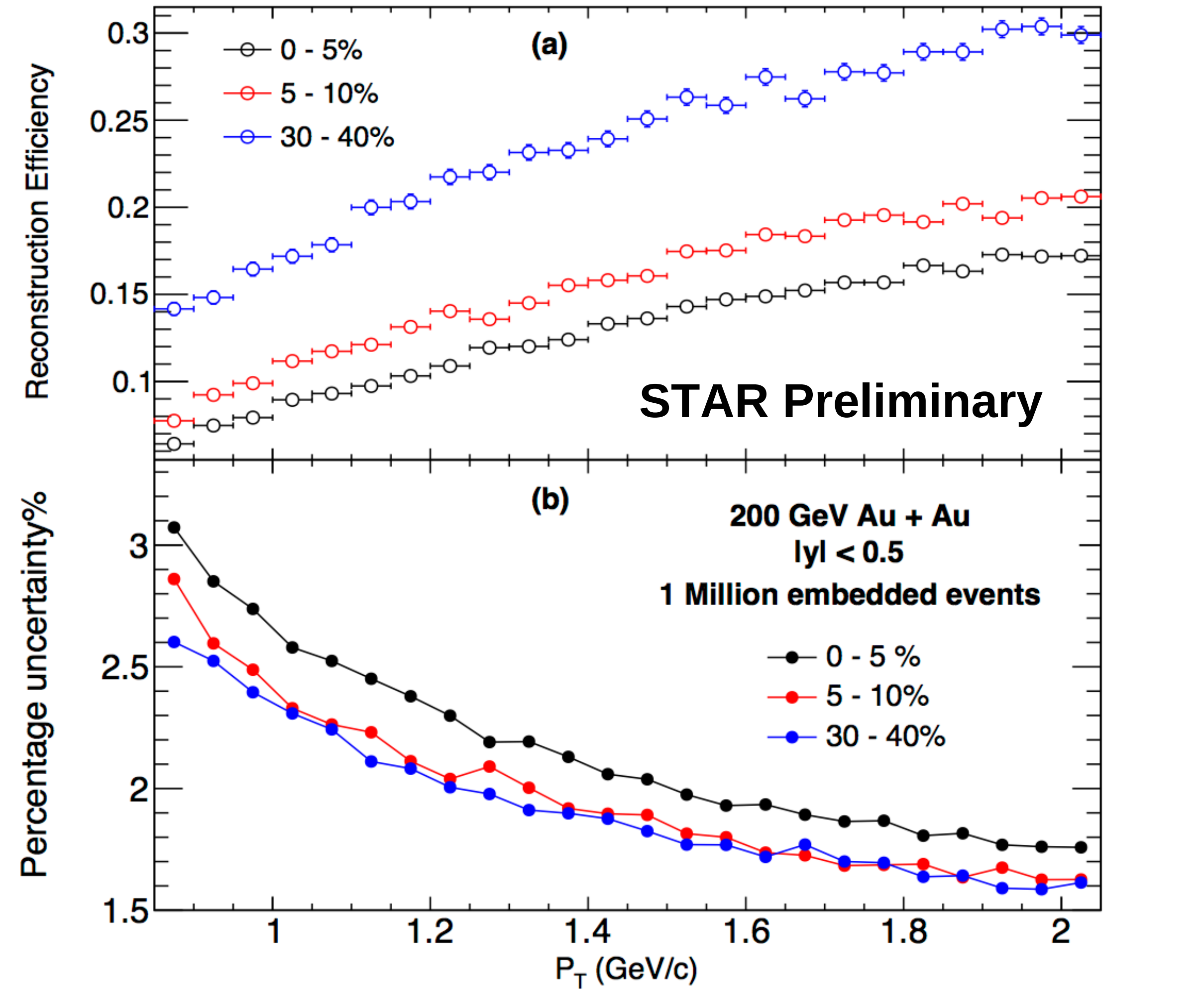
Data sets and statistics

$\sqrt{s_{NN}}$ (GeV)	Statistics (M)	Year	μ_B (MeV)
19.6	~ 34	2011	205
27	~ 71	2011	155
39	~ 114	2010	115
62.4	~ 40	2010	70
200	~ 221	2011	20

Lambda sample optimized for purity & efficiency.

Parameter	cut set - 1	cut set - 2	cut set - 3	cut set - 4	cut set - 5
DCA (V^0 to PV)	< 0.35	< 0.5	< 0.65	< 0.8	< 0.95
DCA (P to PV)	> 0.6	> 0.5	> 0.4	> 0.3	> 0.2
DCA (π to PV)	> 1.75	> 1.5	> 1.25	> 1.0	> 0.75
DCA (P to π)	< 0.5	< 0.6	< 0.7	< 0.8	< 0.9
Background	3196	8608	22908	34184	82161
Signal	108654	160737	196537	213468	253431
S/B	33.00	18.67	8.58	6.24	3.08
Purity	97.14%	94.92%	89.56%	86.20%	75.52%





Corrections applied

- **p_T-dependent efficiency correction** (based on Nonaka et al., PRC95, 064912 (2017)): was applied and compared to p_T-independent correction and the difference was *found to be small in peripheral bins and negligible in central bins for both cumulant ratios (c2/c1, c3/c2)*. p_T-dependence was applied for varying number of p_T-bins.
- **Feed-down correction:** from multi-strange hyperons varies between 15% and 25% depending on collision energy and centrality. Feed-down changes the single cumulants, but *found to be negligible for both cumulant ratios*.
- **Centrality bin width correction** (based on Luo, Xu, arXiv:1701.02105): was applied and *found to be negligible for both cumulant ratios.*

- The data shown in the following are CBW corrected and have a p_T-dependent efficiency correction applied. They are not feed-down corrected.

Statistical uncertainty estimation

- Sub-sampling method was used to estimate the statistical uncertainties.
- Number of samples to be greater than10 in order to be consistent with bootstrapping.
- Both Delta method and sub-sampling gave similar results.

Systematic uncertainty estimation.

Source	Variations	Contribution
DCA of P to π	< 0.6 (default) < 0.5 < 0.55 < 0.65 < 0.70	11.2%
DCA of π to PV & P to PV	> 0.5 & > 1.5 (default) > 0.6 & > 1.7 > 0.55 & > 1.6 > 0.45 & > 1.4 > 0.4 & > 1.3	20.3%
$n\sigma$ (π) & $n\sigma$ (P)	< 2.0 & < 2.0 (default) < 2.5 & < 2.5 < 1.5 & < 1.5	44.9%
Eff (Λ) & Eff ($\overline{\Lambda}$)	ε & ε (default) $\varepsilon \times (1 + 2.25\%)$ & $\varepsilon \times (1 + 2.25\%)$ $\varepsilon \times (1 - 2.25\%)$ & $\varepsilon \times (1 - 2.25\%)$	23.6%

Baselines and model predictions

Baselines

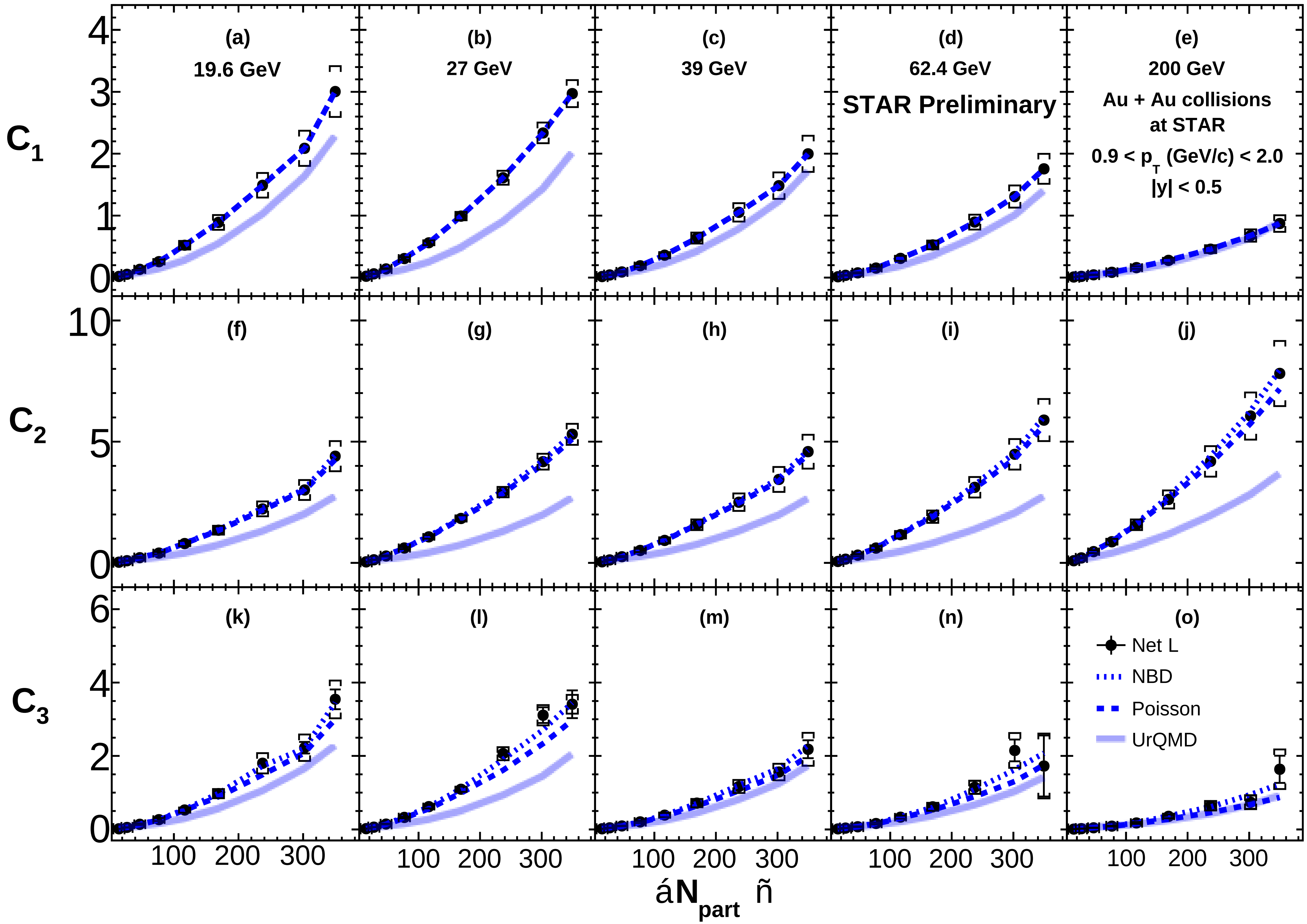
- **Central limit theorem** : Cumulants as a function of number of participant nucleons.
- **Poisson** : Cumulants as a function of mean of individual particle distributions. (if $M = \sigma^2$)
- **Negative binomial distributions** : Cumulants as a function of mean and variance of individual particle distributions.(if $M<\sigma^2$)

Models

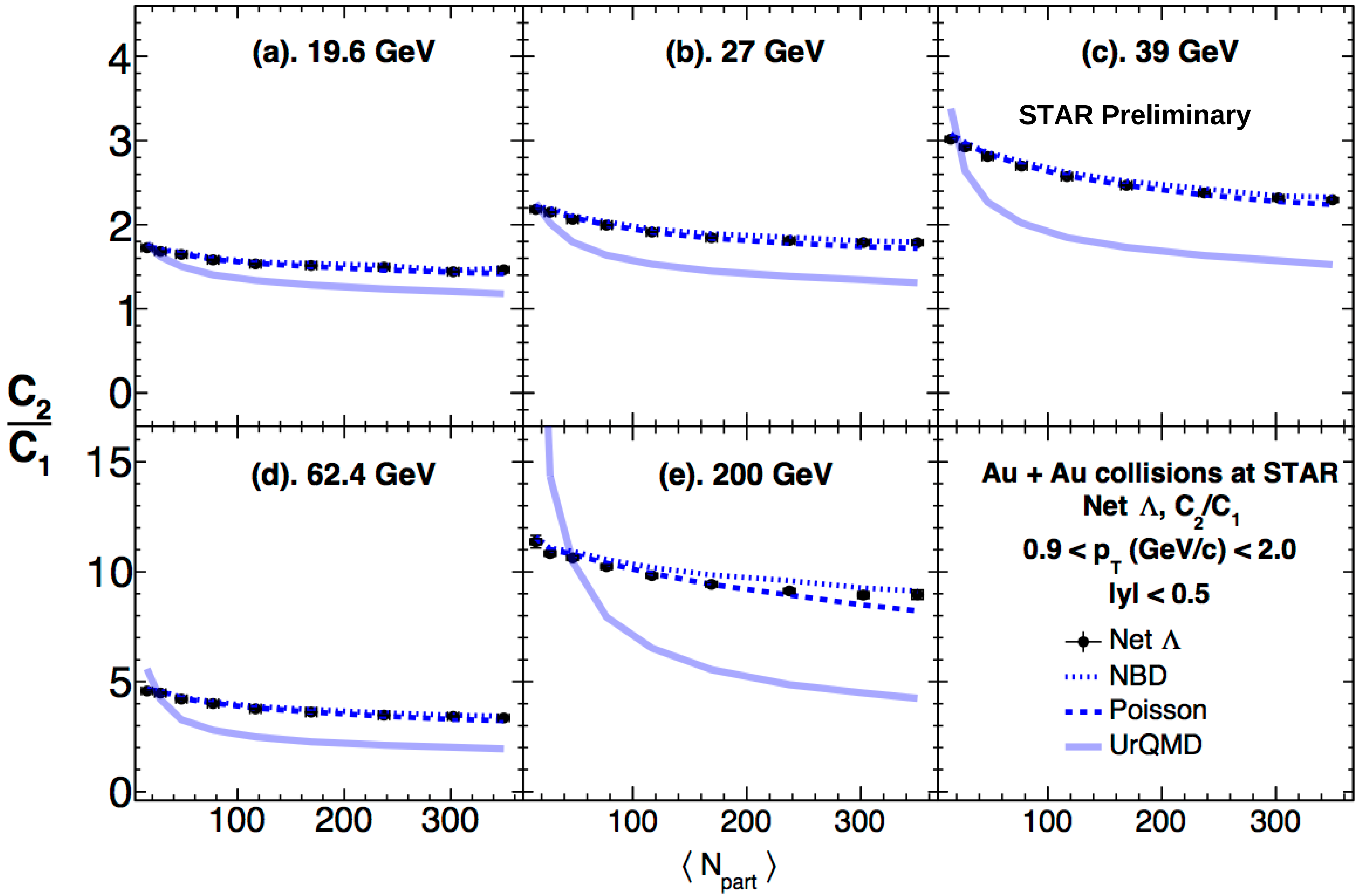
UrQMD : A hadronic transport model used to investigate hadron yields, transverse spectra, strangeness production. No QGP crossover. See https://urqmd.org/

HRG: Statistical model for the low temperature region of QCD phase diagram. Thermodynamic observables can be approximated (even at non-zero chemical potentials). See arXiv.1805.00088

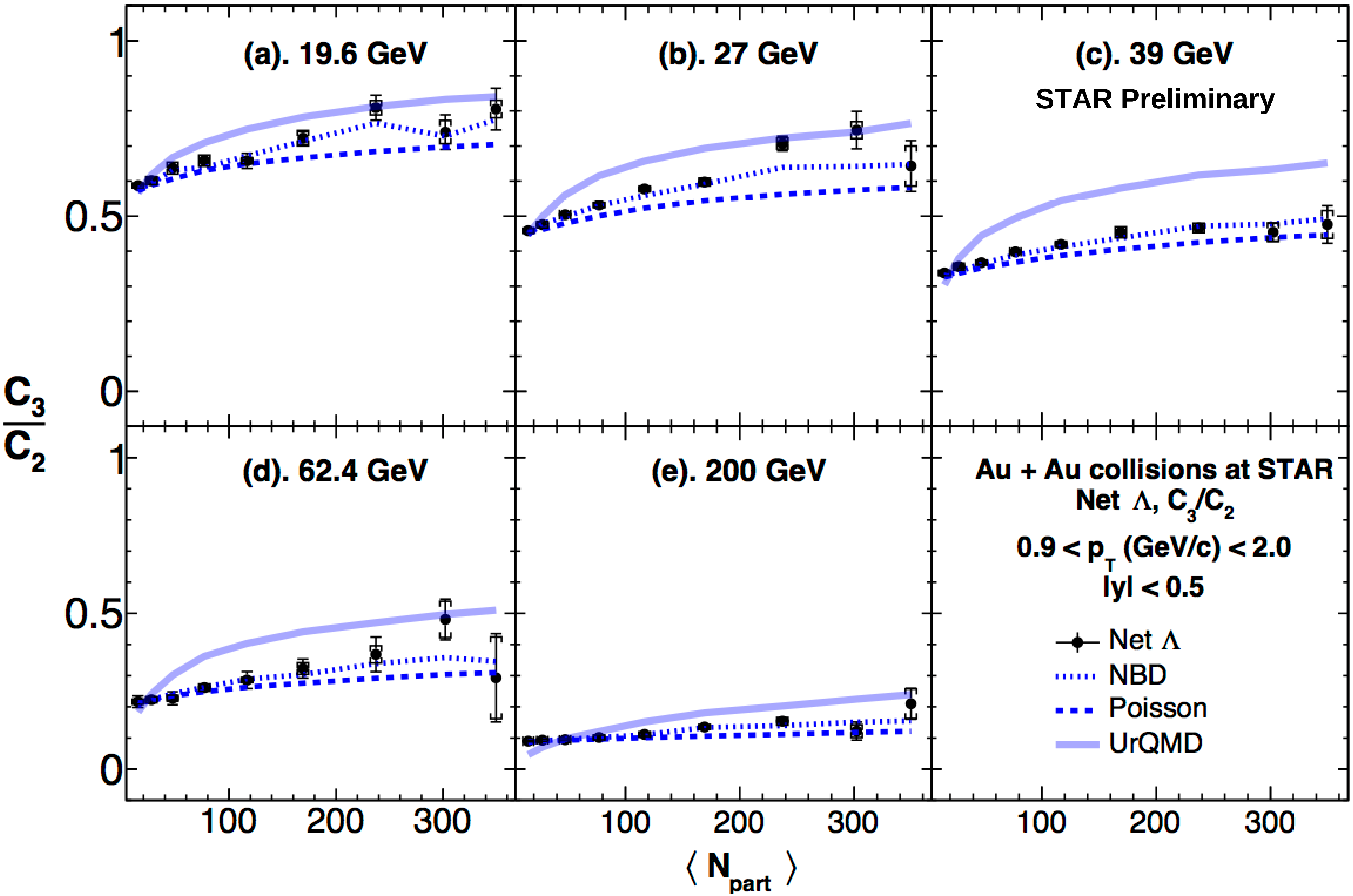
Single cumulants



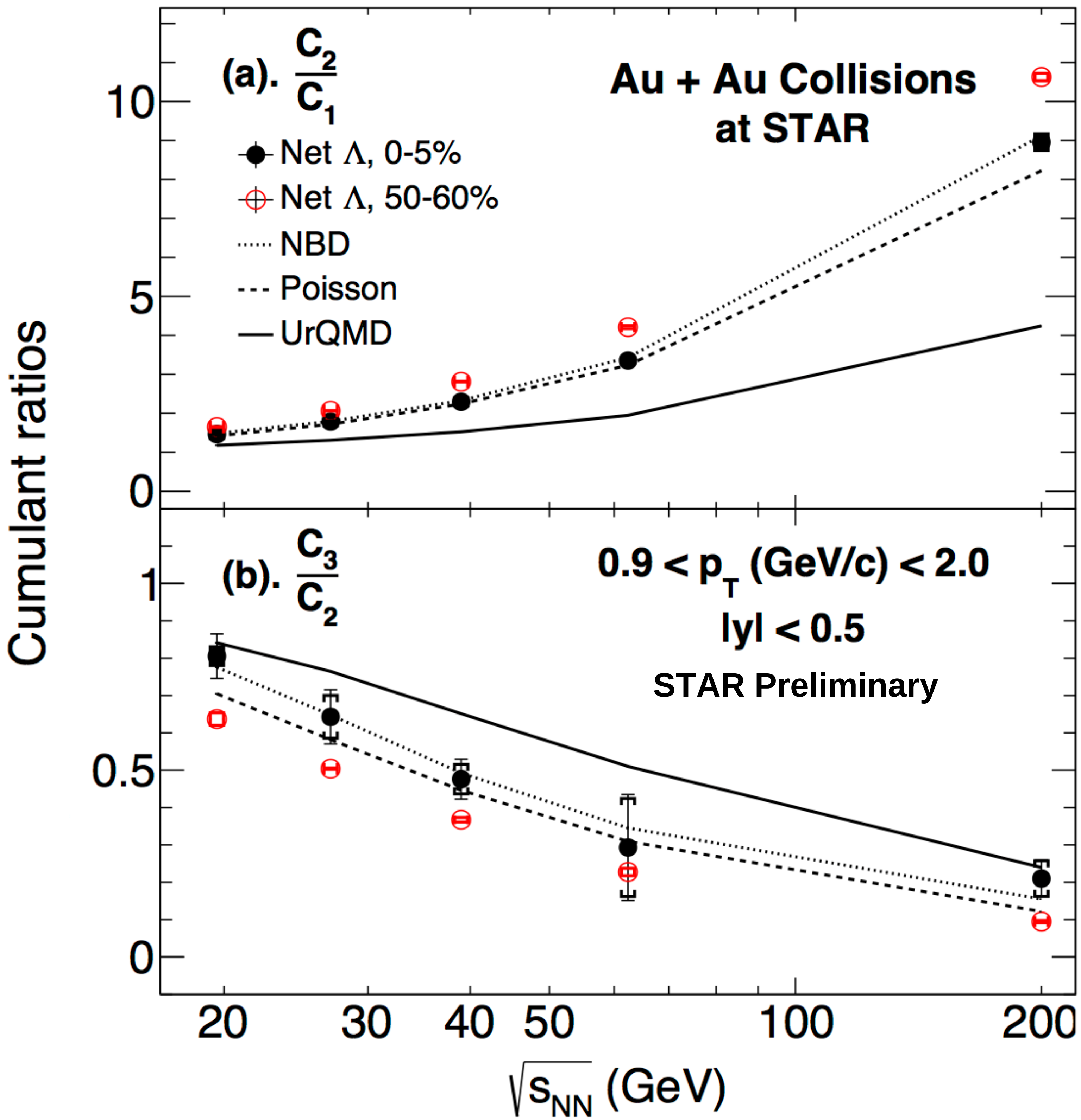
Cumulant ratio, C_2/C_1



Cumulant ratio, C_3/C_2

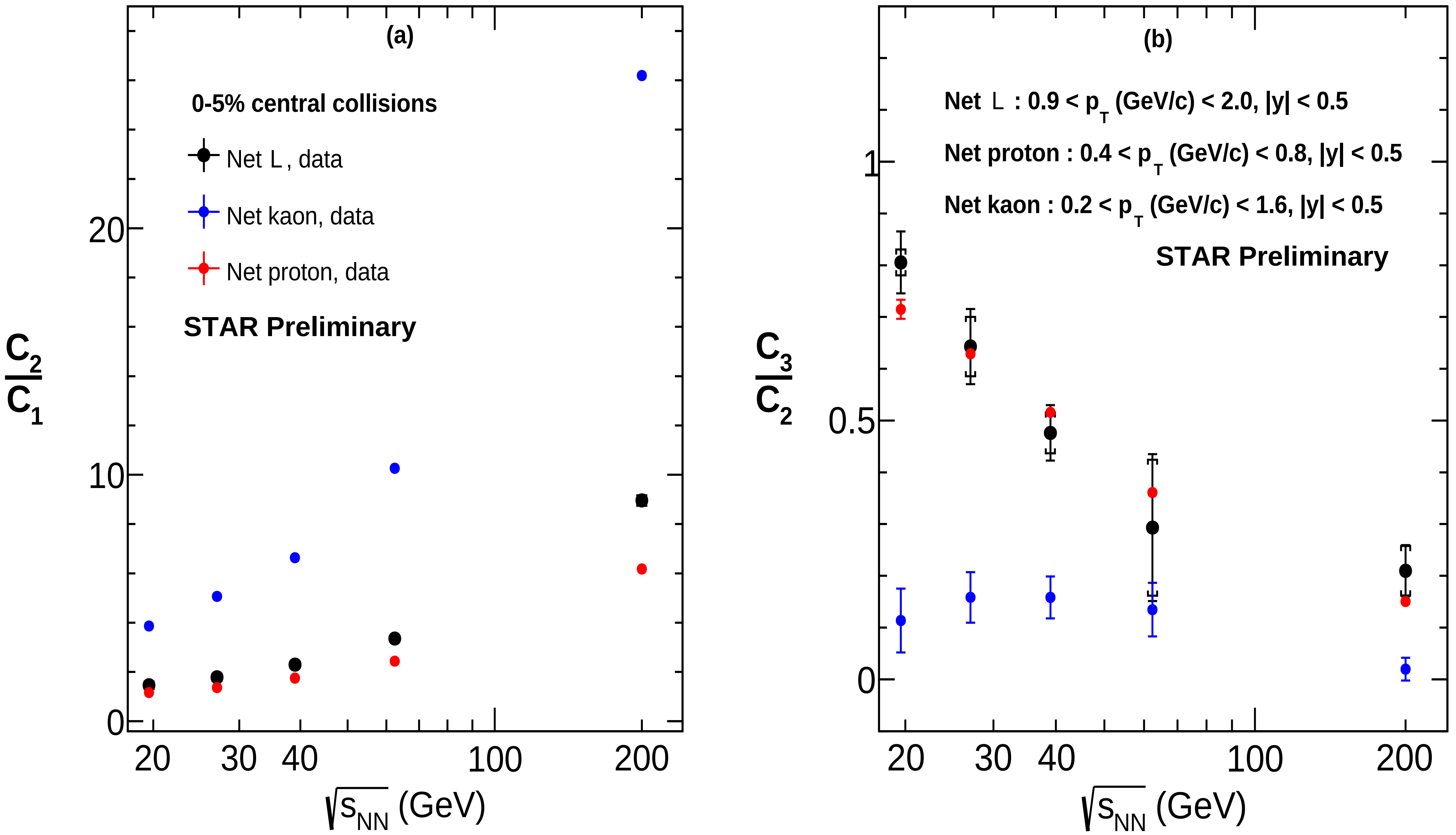


Energy dependence of cumulant ratios



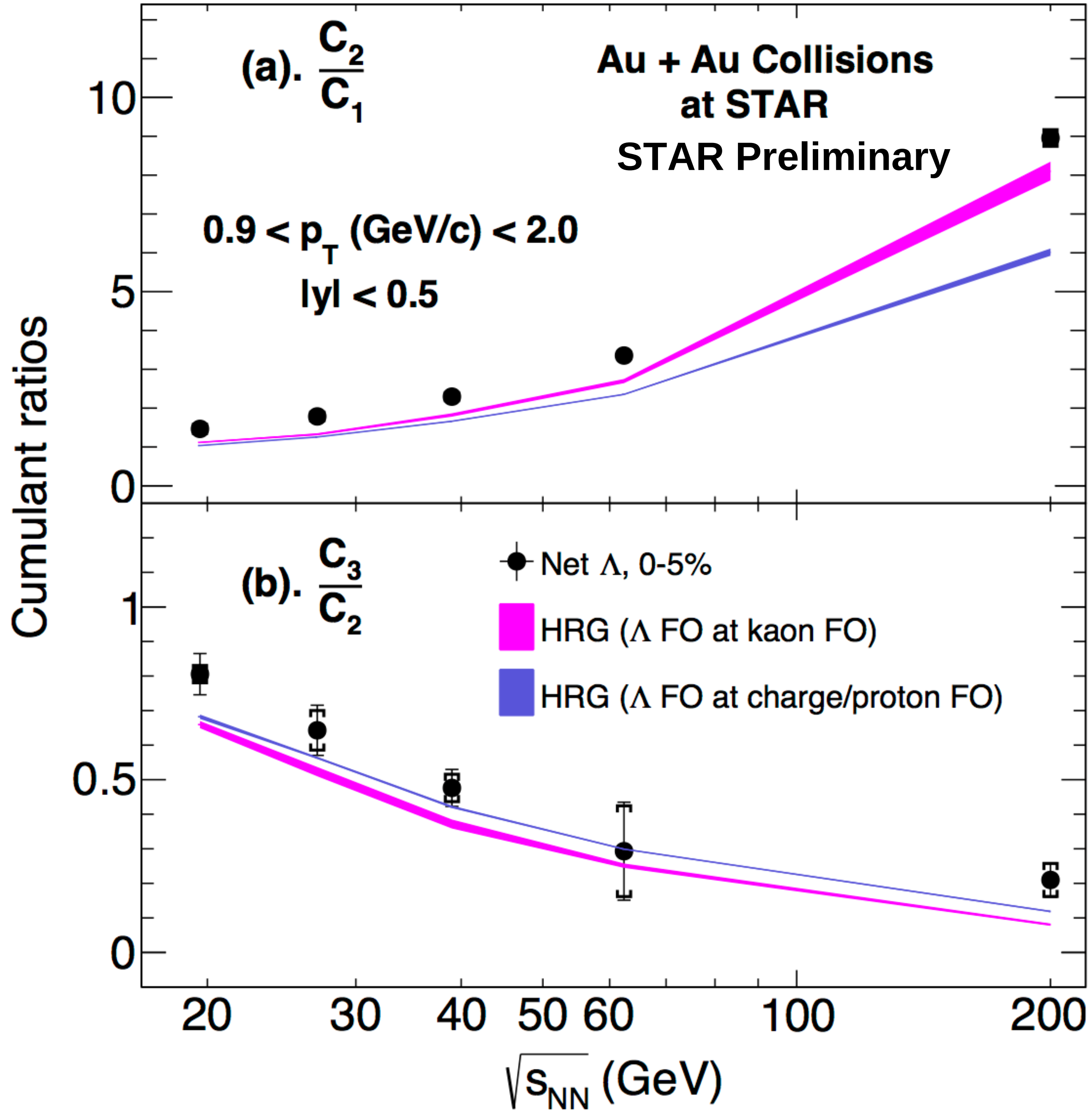
Comparison to STAR net-p and net-k measurements

Net proton, STAR Coll., PRL112, 032302 (2014)
Net kaon, STAR Coll., PLB 785, 551 (2018)



HRG predictions assuming different FO conditions

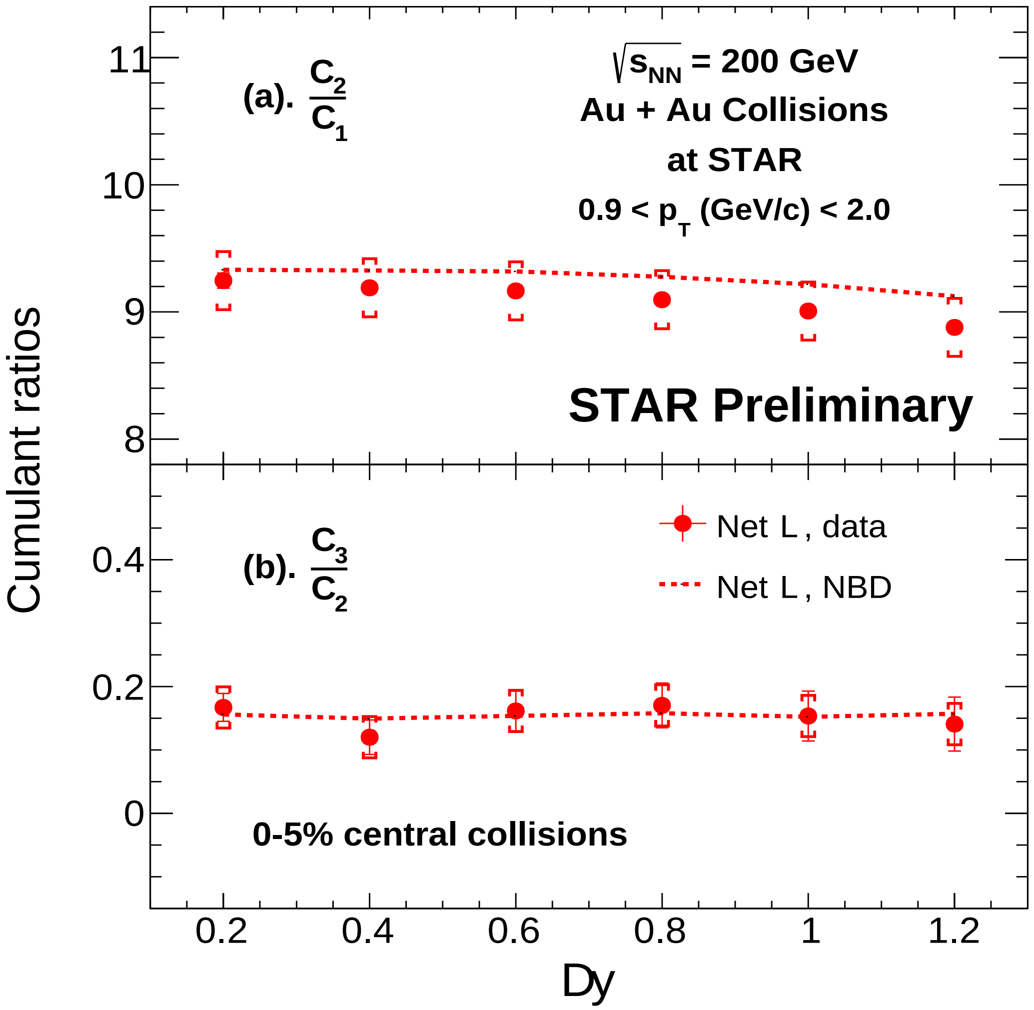
HRG, Bellwied, Noronha-Hostler,Parotto, Vazquez, Ratti, Stafford, arXiv.1805.00088



see talk by
Jamie Stafford
in this session

Higher order ratios are prone to dynamical effects, thus not reliable in the context of FO interpretation (P.. Alba, et. al. , PLB 738 (305) 2014)

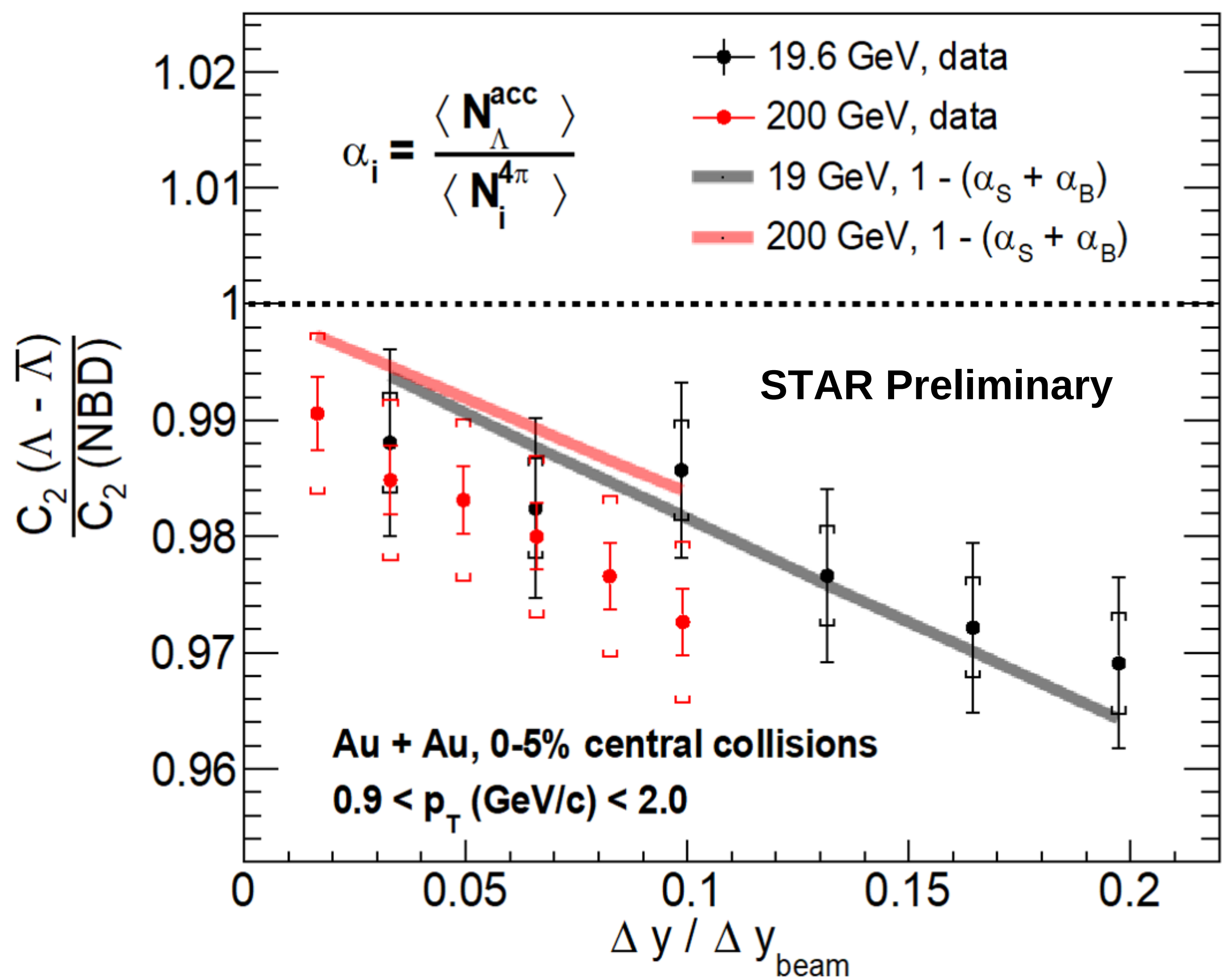
Rapidity dependence



Baryon Number Conservation ?:

Rustamov, PBM, Stachel, NPA 960, 114 (2017)

$$\alpha_{acc} = \frac{\langle N_B^{acc} \rangle}{\langle N_B^{4\pi} \rangle} \qquad \frac{C_2\left(n_B - n_{\overline{B}}\right)}{C_2(Skellam)} = 1 - \alpha_{acc}$$

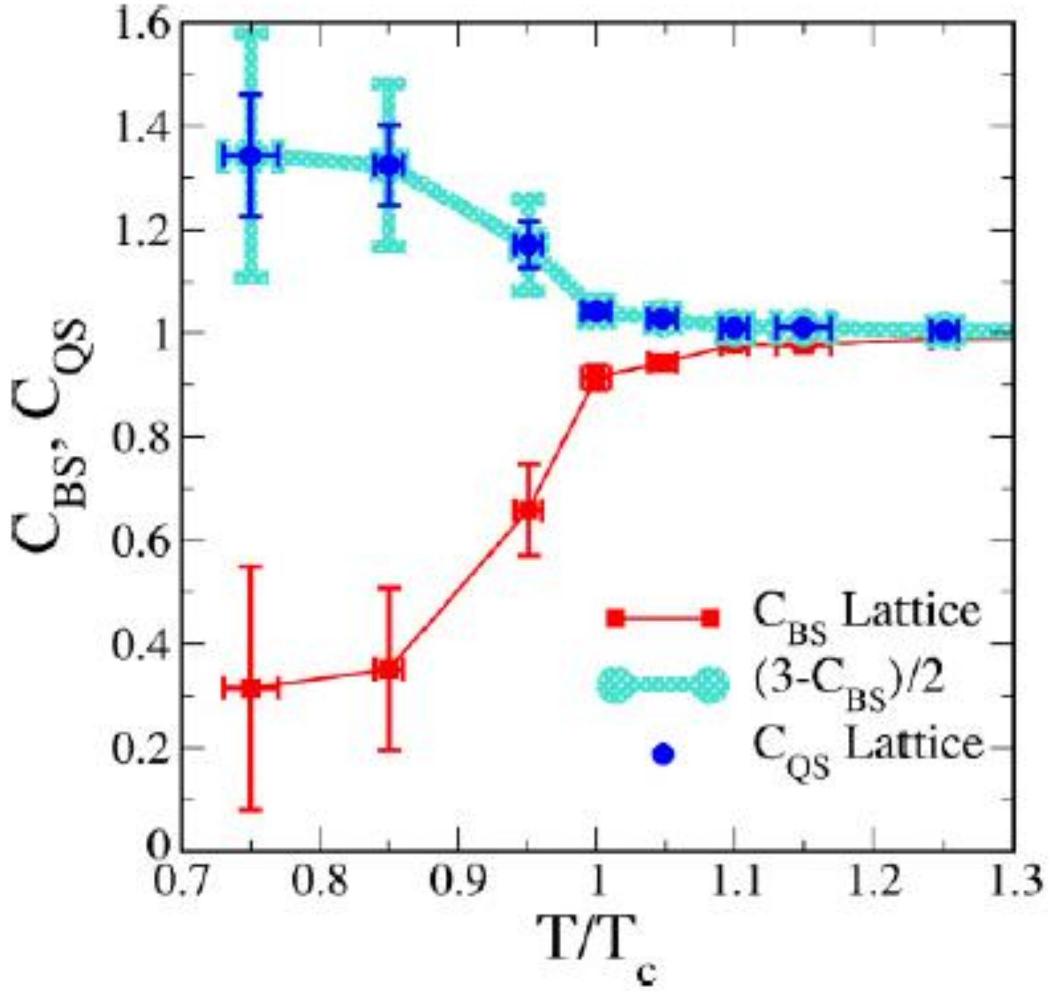


works if B and S conservation are treated additive

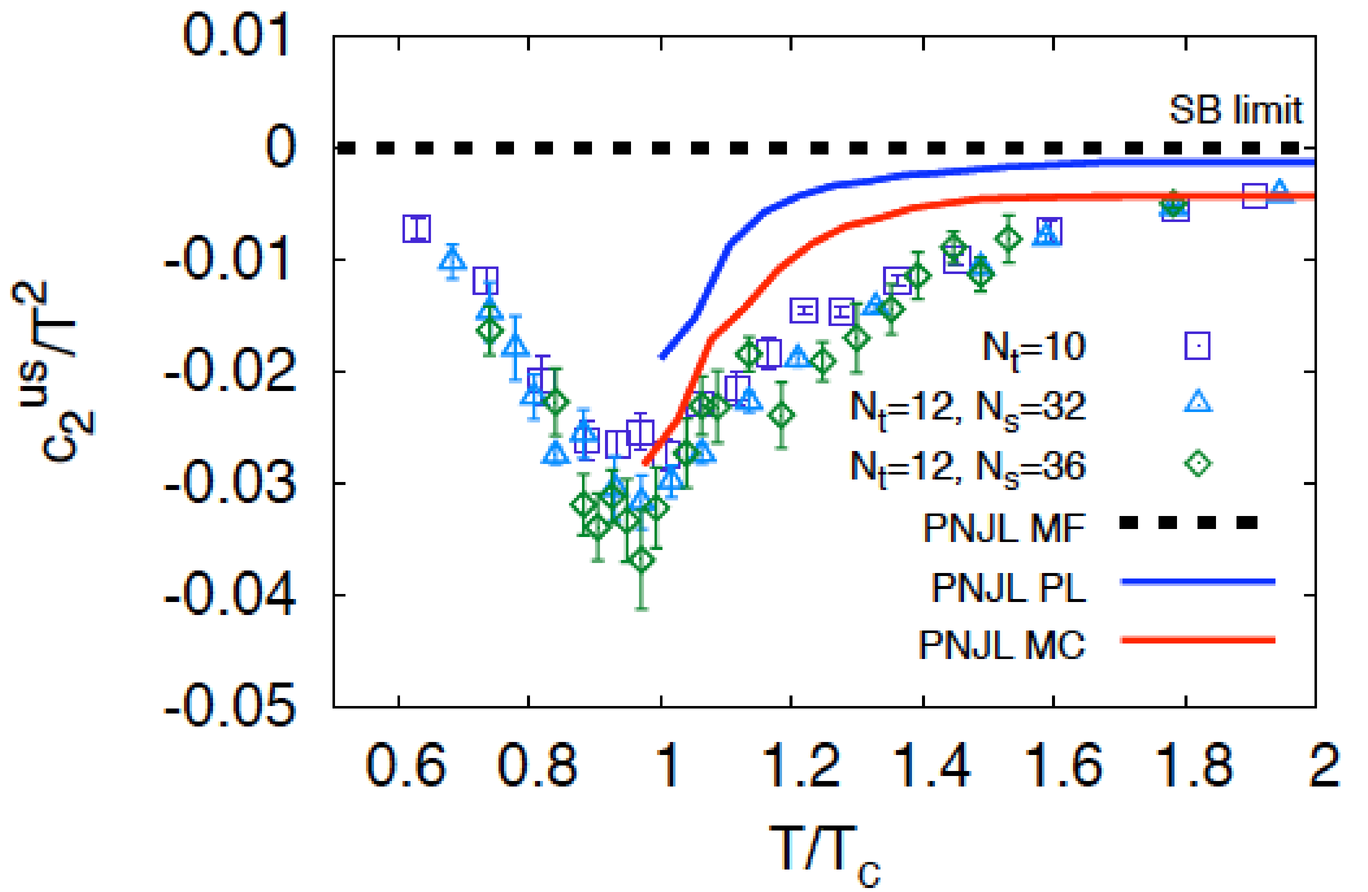
Baryon-Strangeness Correlations

Determined by the ratio of off-diagonal to diagonal cumulants: $\kappa^{1,1}_{B,S}/\kappa^2_S$

The related susceptibility ratio: $C_{B,S} = -3\chi^{1,1}_{B,S}/\chi^2_S$
(-3 is just a normalization factor so that the asymptotic value = +1)



Koch, Majumder, Randrup (2005), Mueller, Majumder (2006)

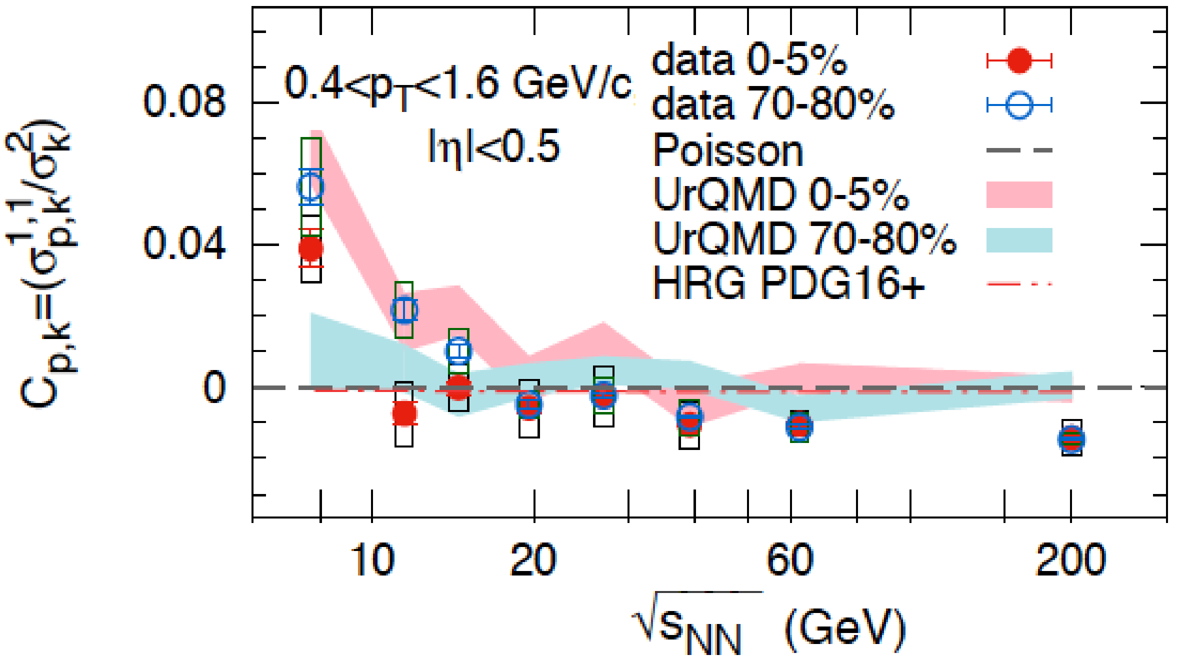


Ratti, Bellwied, Cristoforetti, Barbaro (2011)

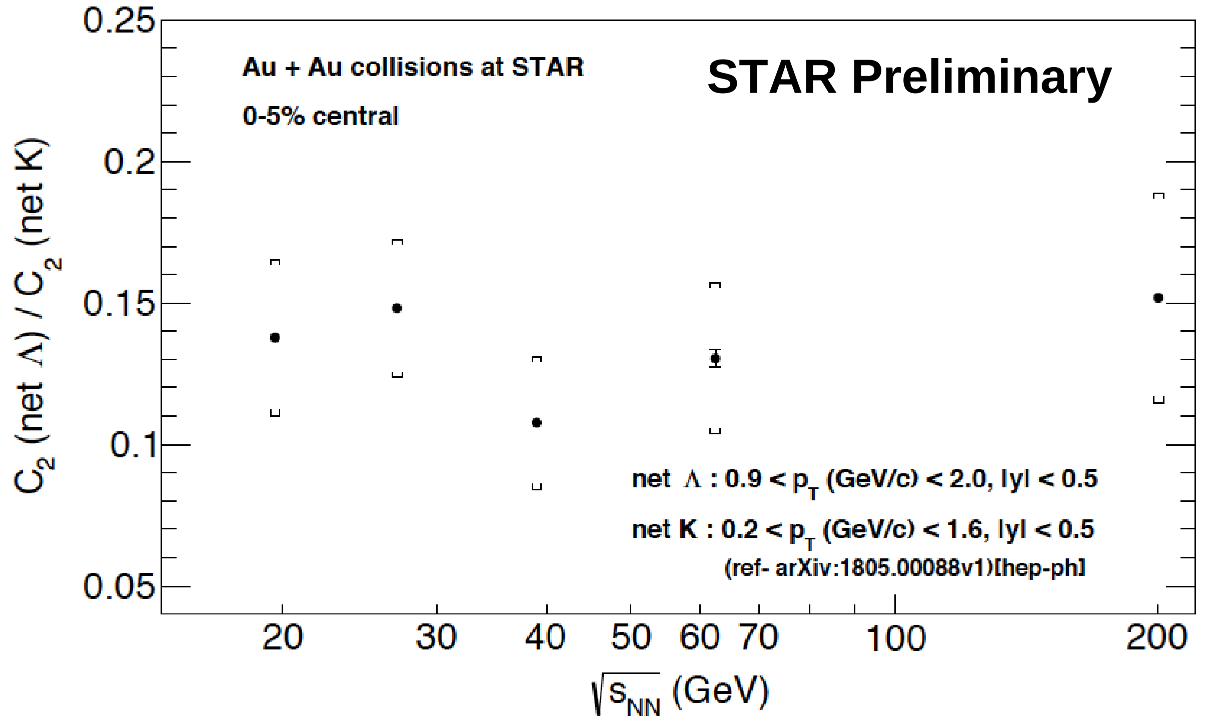
How fast does the BS correlator approach the asymptotic value ?
Is there room for bound states above T_c ?

Contributions to the 2nd-order off-diagonal BS cumulant

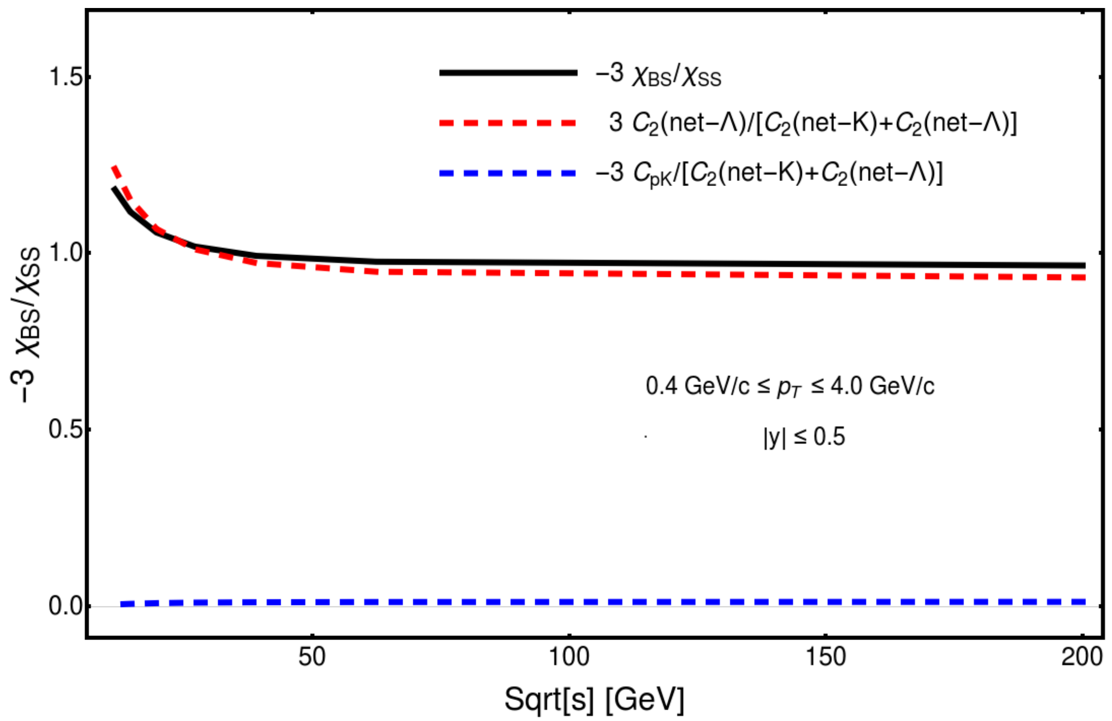
STAR measurements:
pK contribution, arXiv:1903.05370

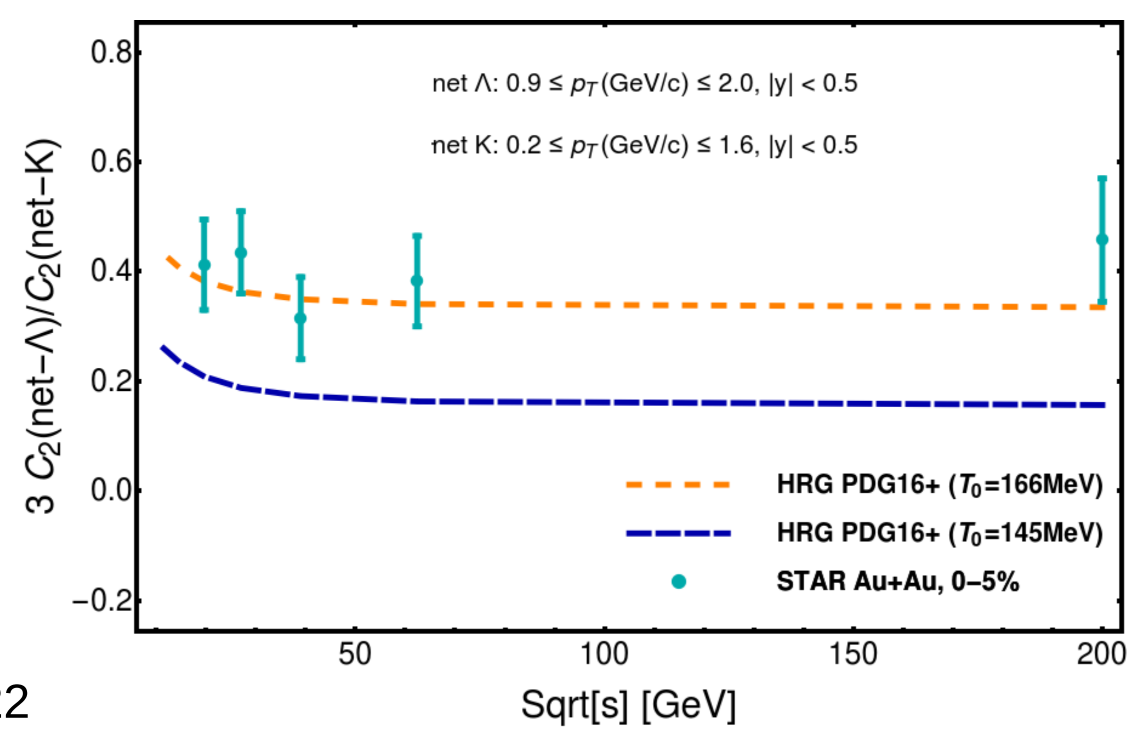


Λ contribution



HRG predictions:
see talk by P. Parotto, this afternoon





Analysis summary

- The first three single cumulants and cumulant ratios of net Lambda distributions were analyzed as a function of collision centrality, energy and rapidity. Statistical and systematic uncertainties were estimated.
- Results were corrected for reconstruction efficiency in a p_T-dependent way. Feed-down and centrality bin width corrections show negligible effects on the cumulant ratios.
- Results can be described by Poisson and NBD expectations.
- There is no non-monotonic behavior of cumulants or cumulant ratios as a function of collision centrality or energy between 19.6 and 200 GeV.
- The variance show significant deviation from UrQMD, which increases as a function of collision centrality and energy.
- The net Lambda fluctuations can be described by the latest HRG model.

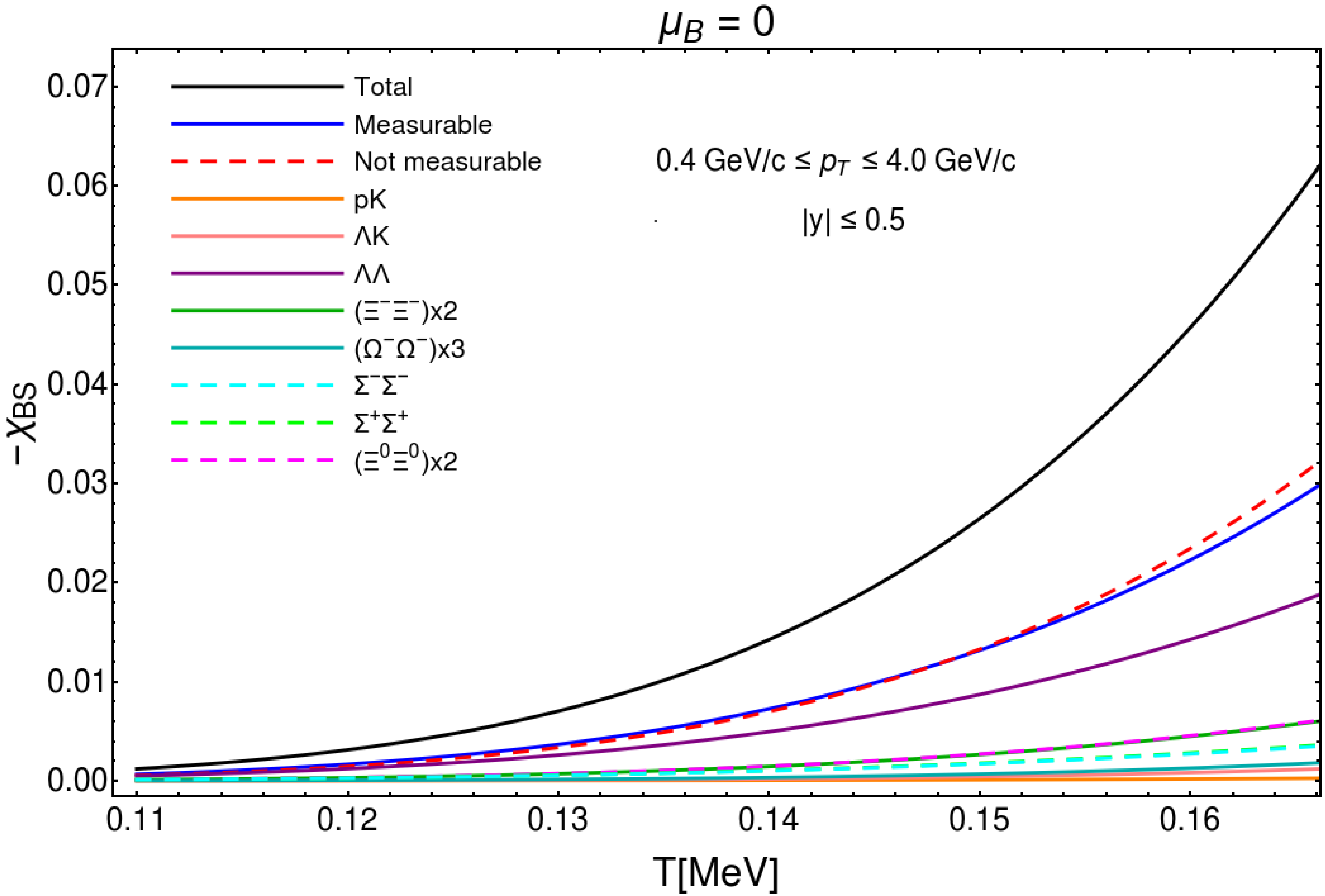
Physics conclusions

- The chemical freeze-out parameters calculated from the net-Lambda c_2/c_1 in a HRG model are consistent with kaon freeze-out conditions and significantly above proton freeze-out conditions.
- The rapidity dependence of the net-Lambda variance shows small deviations from NBD expectations for larger rapidity coverage, which could be attributed to the effect of baryon number and strangeness conservation.
- Lambda fluctuations are the dominant contribution to the non-diagonal BS correlator, and their strength compared to the measured pK correlations in STAR is in agreement with expectations from the HRG model.

Backup

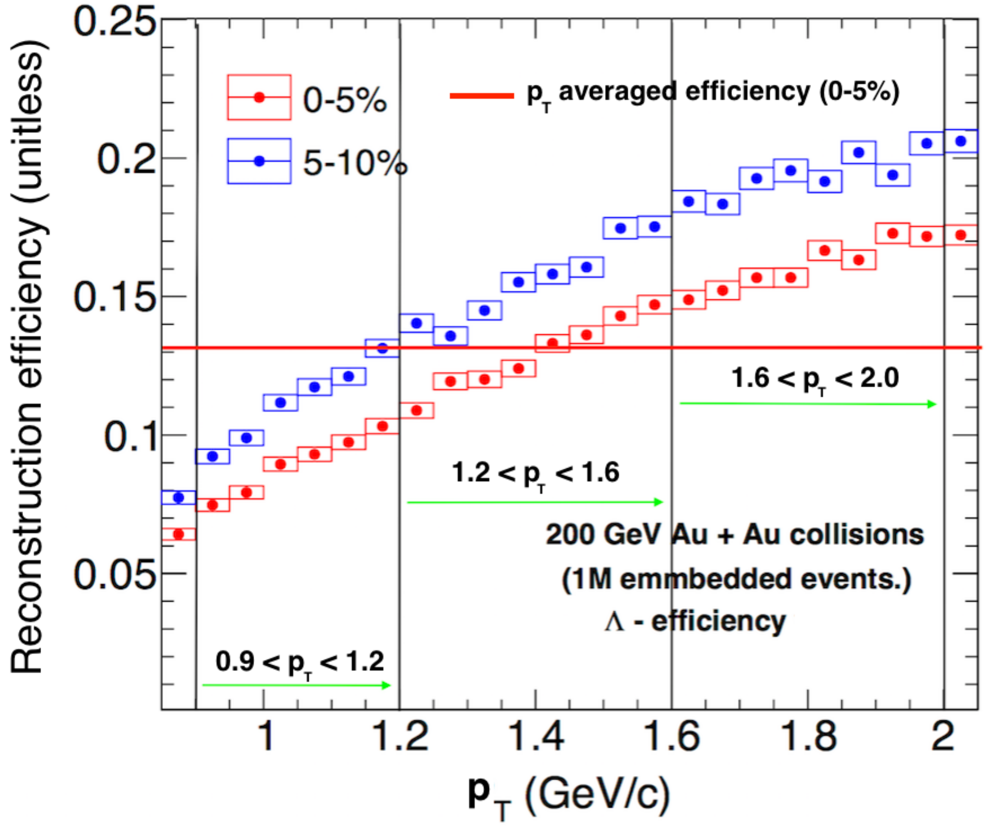
Contributions to the 2nd order off-diagonal BS cumulant

HRG predictions: see talk by P. Parotto, this afternoon



p_T-dependent efficiency correction

Ref : [T. Nonaka, M. Kitazawa, and S. Esumi, Physical Review C, vol. 95, p. 064912, Jun 2017]



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

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

$$P(N) = P(N_1, N_2, \ldots, N_M)$$

$$q_{(r,s)} = q_{(a^r/\varepsilon^s)} = \sum_{i=1}^{M} (a_i^r / \varepsilon_i^s)\, n_i$$

$$\mathbf{M_1} = \langle Q \rangle_c = \langle q_{(1,1)} \rangle_c$$

$$\mathbf{M_2} = \langle Q^2 \rangle_c = \langle q_{(1,1)}^2 \rangle_c + \langle q_{(2,1)} \rangle_c - \langle q_{(2,2)} \rangle_c$$

$$\mathbf{M_3} = \langle Q^3 \rangle_c = \langle q_{(1,1)}^3 \rangle_c + 3\langle q_{(1,1)} q_{(2,1)} \rangle_c - 3\langle q_{(1,1)} q_{(2,2)} \rangle_c + \langle q_{(3,1)} \rangle_c - 3\langle q_{(3,2)} \rangle_c + 2\langle q_{(3,3)} \rangle_c$$

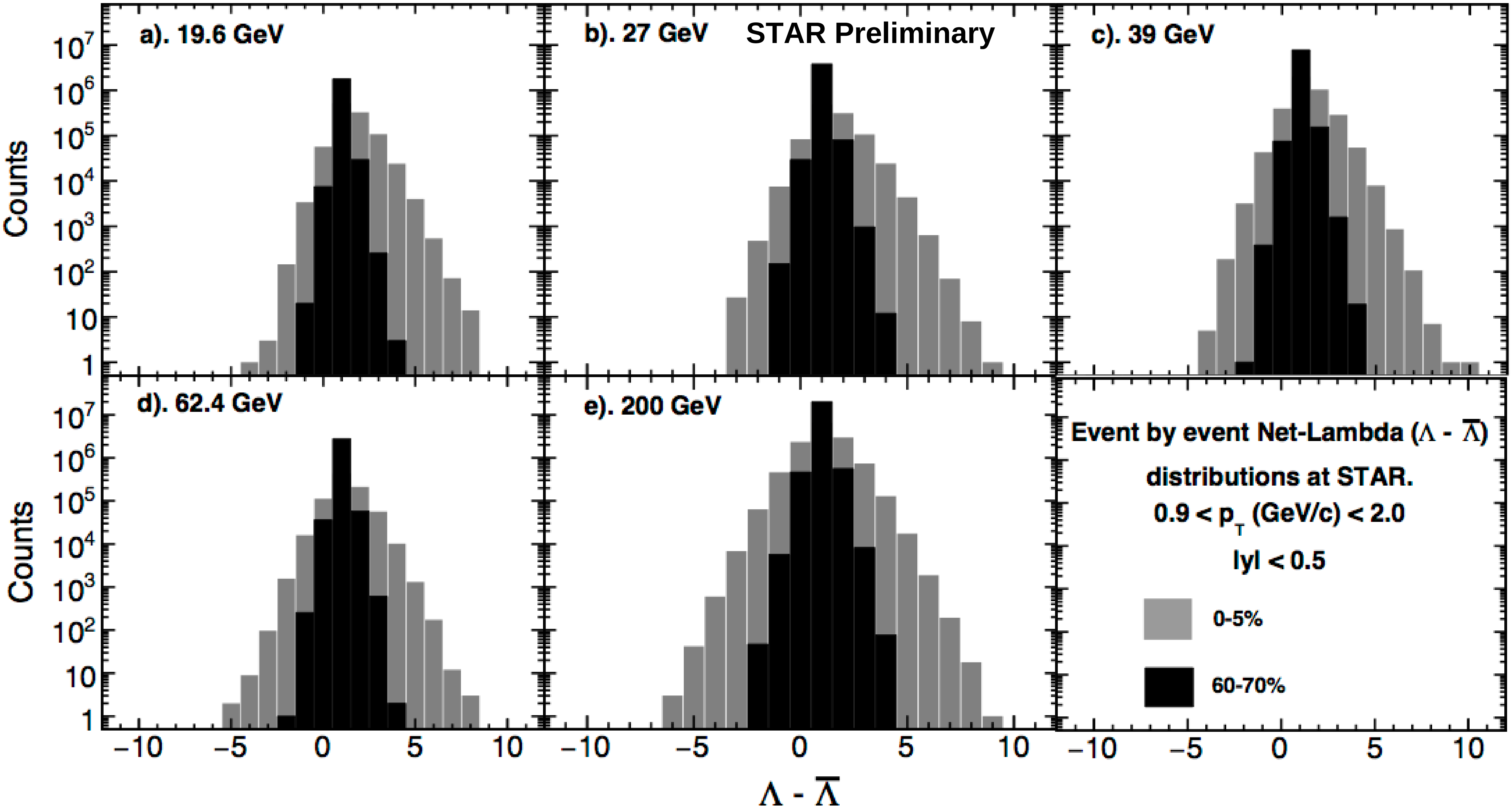
First 3 cumulants :

$$C_1 = \mathbf{M_1}$$

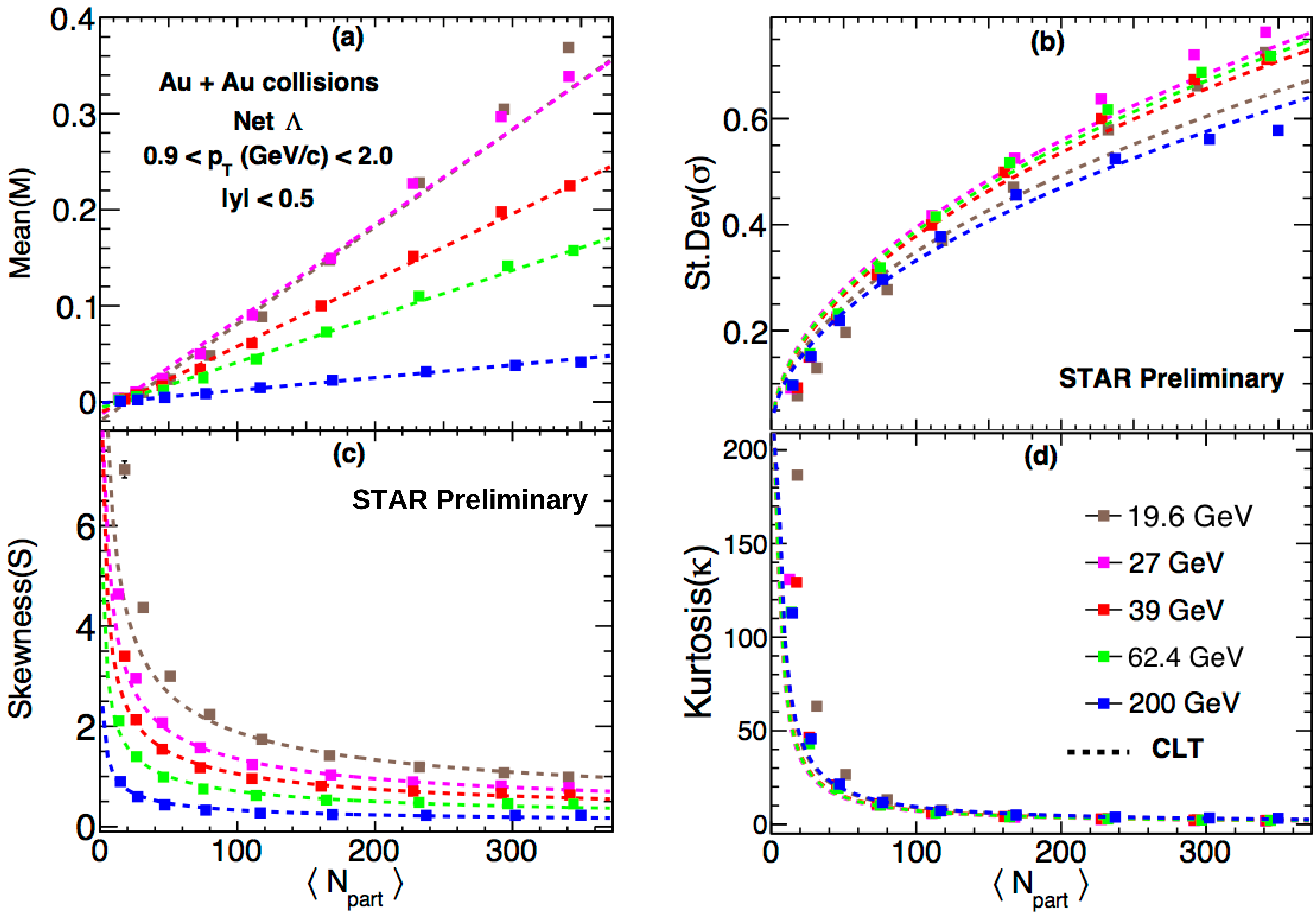
$$C_2 = \mathbf{M_2} - \mathbf{M_1}^2$$

$$C_3 = 2\mathbf{M_2}^3 - 3\mathbf{M_1}.\mathbf{M_2} + \mathbf{M_3}$$

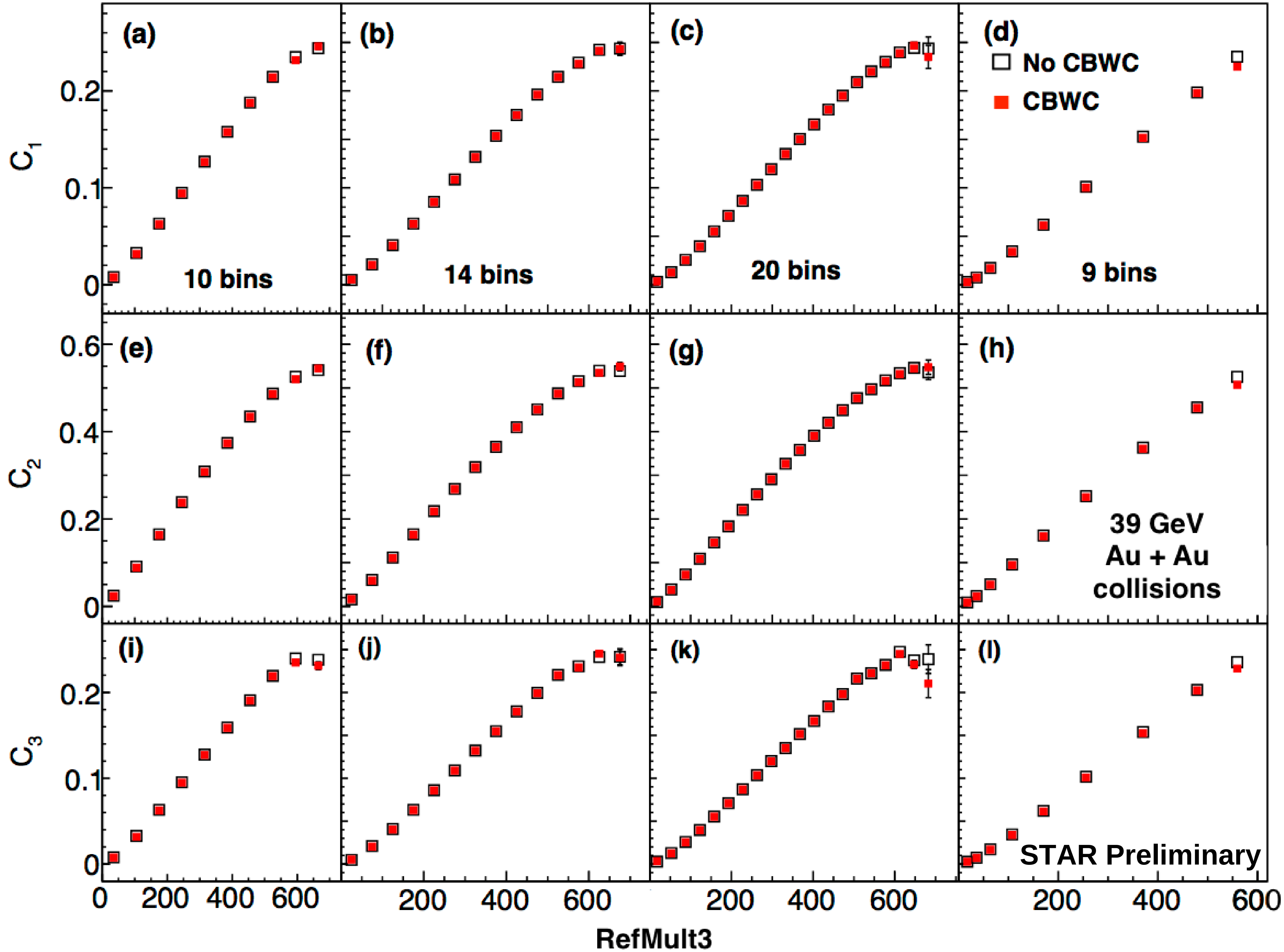
Net Lambda distributions



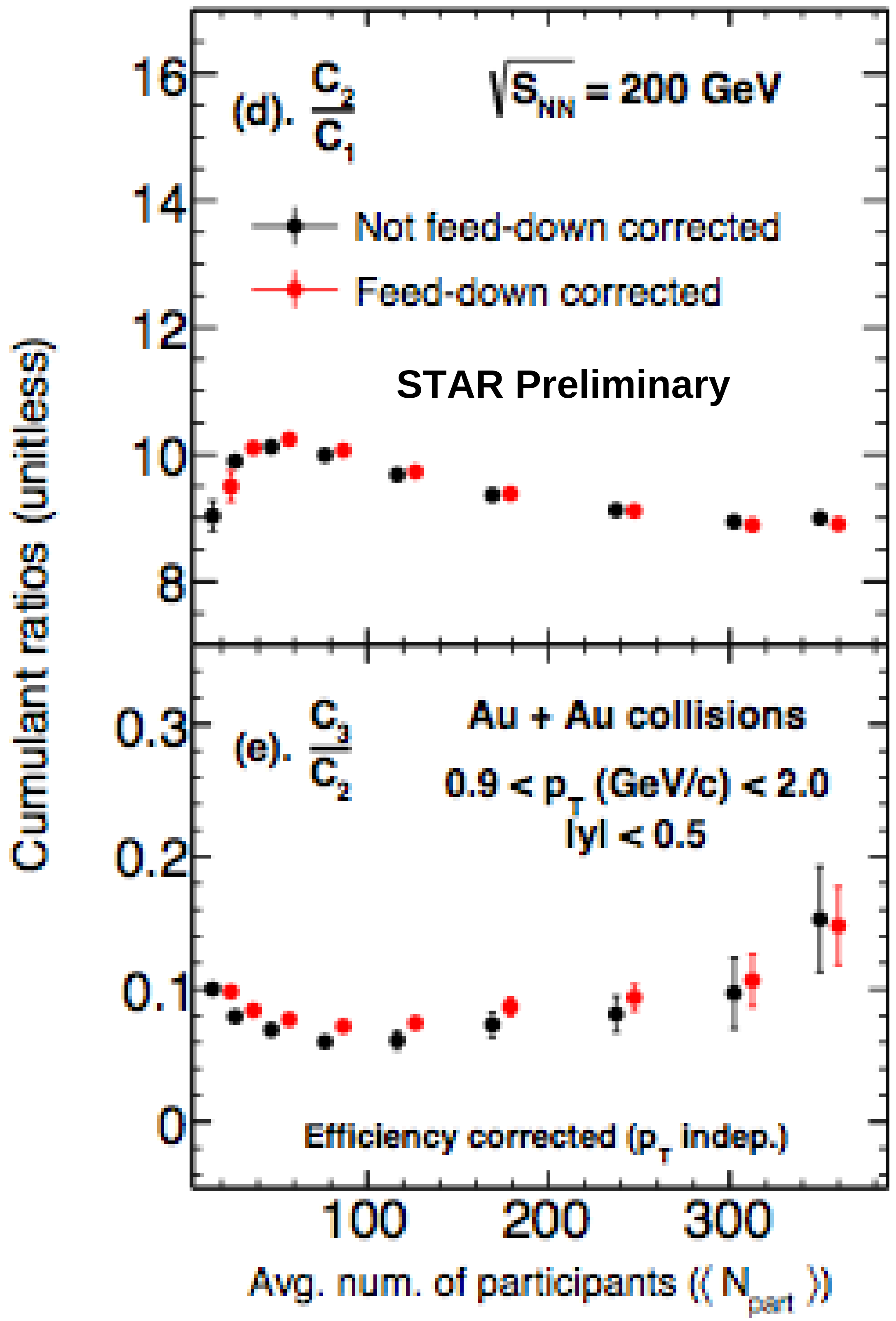
Net Lambda moments - uncorrected



Effect of centrality bin-width correction (CBWC)



Effect of feed-down correction



Track and V0 cuts

Particle	Cut parameter	Cut boundary
Proton	Transverse momentum	$p_T\ (GeV/c) > 0.05$
	Rapidity	$\|y_P\| < 1.0$
	nFitPoints	> 15
	nHitsFit/NFitPoss	> 0.52
	PID	$n\sigma_P < 2.0$
	DCA to PV	> 0.5cm
	DCA to π	< 0.6cm
Pion	Transverse momentum	$p_T\ (GeV/c) > 0.05$
	Rapidity	$\|y\|_\pi < 1.0$
	nFitPoints	> 15
	nHitsFit/NFitPoss	> 0.52
	PID	$n\sigma_\pi < 2.0$
	DCA to PV	> 1.5cm
	DCA to P	< 0.6cm
V^0	Transeverse momentum	$0.9 < p_T\ (GeV/c) < 2.0$
	Rapidity	$\|y\| < 0.5$
	DCA to PV	< 0.5cm
	Decay length	> 3.0cm
	Pointing away from PV	$(\mathbf{r}_{v0} - \mathbf{r}_{pv})\,.\mathbf{p}_{v0} > 0$

Factorial moments

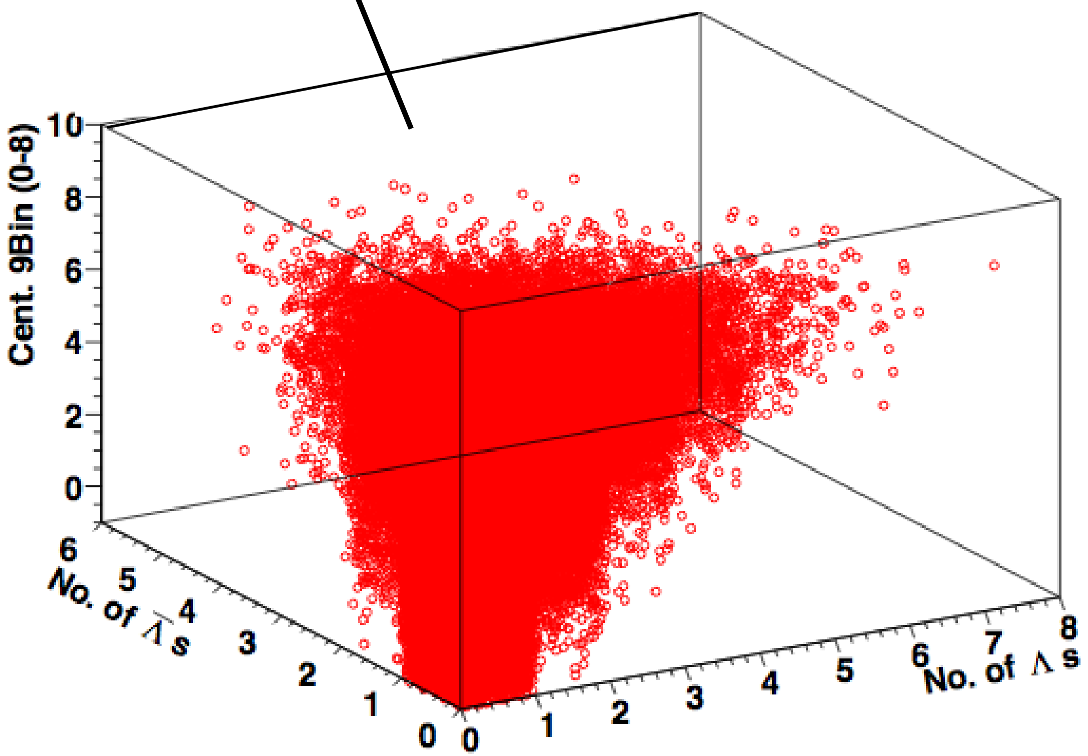
Number of positive/negatively charged particles

Indices of the factorial moment

Upper bound

$$f_{i,k}\left(n_p, n_{\bar{p}}\right) = \left\langle \frac{n_p!}{(n_p - i)!} \frac{n_{\bar{p}}!}{(n_{\bar{p}} - k)!} \right\rangle = \sum_{n_p=i}^{\infty} \sum_{n_{\bar{p}}=k}^{\infty} p\left(n_p, n_{\bar{p}}\right) \frac{n_p!}{(n_p - i)!} \frac{n_{\bar{p}}!}{(n_{\bar{p}} - k)!}$$

$$F_{i,k}\left(N_p, N_{\bar{p}}\right) = \frac{f_{i,k}\left(n_p, n_{\bar{p}}\right)}{\left(\varepsilon_p\right)^i \left(\varepsilon_{\bar{p}}\right)^k}$$



[No. of events in a given cent.]

Cumulants:

$$N = \langle N_p \rangle + \langle N_{\bar{p}} \rangle = \frac{\langle n_p \rangle}{\varepsilon_p} + \frac{\langle n_{\bar{p}} \rangle}{\varepsilon_{\bar{p}}}$$

$$C_1 \equiv K_1 = \langle N_p \rangle - \langle N_{\bar{p}} \rangle$$

$$C_2 \equiv K_2 = N - K_1^2 + F_{02} - 2F_{11} + F_{20}$$

$$C_3 \equiv K_3 = K_1 + 2K_1^3 - F_{03} - 3F_{02} + 3F_{12} + 3F_{20} - 3F_{21} + F_{30}$$
$$-3K_1\left(N + F_{02} - 2F_{11} + F_{20}\right)$$