Cross-correlators of conserved charges

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Strangeness in Quark Matter 2019, Bari, Italia

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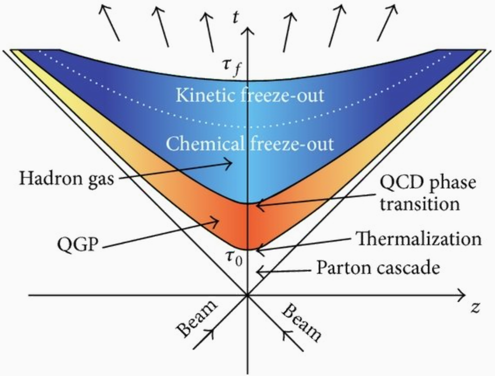
Introduction - Freeze-out

The stages of a heavy-ion collision (HIC)

- **Thermalization**: after a short time the system thermalizes to a QGP (if the energy is sufficient)
- **Hadronization**: when the system reaches T_C, hadrons are formed
- **Chemical freeze-out**: all inelastic collision cease and chemical composition is fixed (abundances, fluctuations)
- **Kinetic freeze-out**: elastic collisions cease and spectra are fixed → free streaming to the detectors



Extraction of freeze-out parameters $(\mathbf{T}, \mu_{\mathbf{B}})$: comparison of experiment and theory

$\Rightarrow$ **Yields, fluctuations**

Fluctuations of conserved charges

Fluctuations are defined as:

$$\chi_{ijk}^{BQS}(T,\mu_B,\mu_Q,\mu_S) = \frac{\partial^{i+j+k} P\left(T,\mu_B,\mu_Q,\mu_S\right)/T^4}{\partial\left(\mu_B/T\right)^i \partial\left(\mu_Q/T\right)^j \partial\left(\mu_S/T\right)^k}$$

and can be related to the moments of net-particle distributions:

mean: $M = \chi_1$ variance: $\sigma^2 = \chi_2$

skewness: $S = \chi_3/\left(\chi_2\right)^{3/2}$ kurtosis: $\kappa = \chi_4/\left(\chi_2\right)^2$

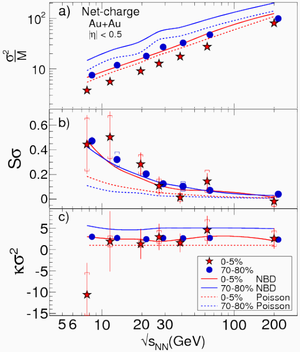
Volume-independent ratios are often used:

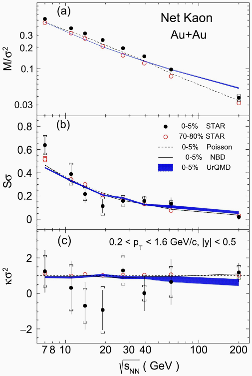
$$M/\sigma^2 = \chi_1/\chi_2 \qquad S\sigma = \chi_3/\chi_2$$

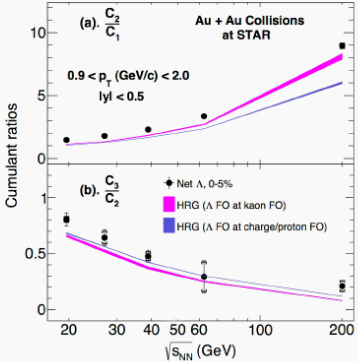
$$S\sigma^3/M = \chi_3/\chi_1 \qquad \kappa\sigma^2 = \chi_4/\chi_2$$

Fluctuations of conserved charges - Experiment

Event-by-event net-particle distributions allow to measure different cumulants (and ratios thereof): **STAR: Phys. Rev. Lett. 113 (2014) 92301; Phys. Lett. B 785 (2018) 551; Preliminary**





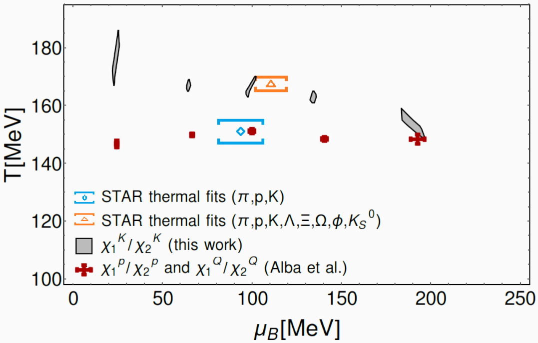


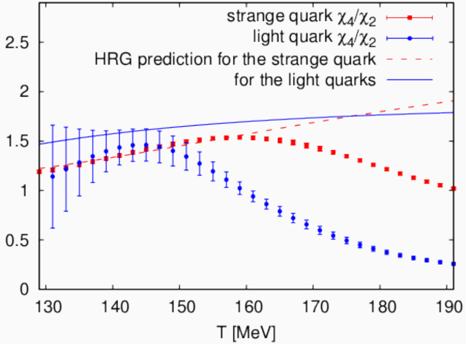
From light particles, the measurements have moved to heavier (strange) species

see talks by J. M. Stafford and R. Bellwied

Fluctuations of conserved charges - Theory

- Fluctuations have been largely utilized to study the freeze-out in HIC
- Comparison with lattice QCD calculations yields information on the relevant degrees of freedom near the QCD transition

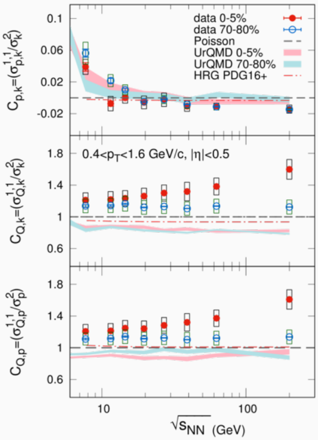




see talks by J. M. Stafford and R. Bellwied

Phys.Rev. C99 (2019) no.3, 034912; Phys.Rev.Lett. 111 (2013) 202302

Cross Correlators



STAR: [nucl-ex] 1903.05370

- New measurements of correlators between different species are becoming available
- The measurable species in HIC are only a handful, but they contain important information about the system thermodynamics
- **In particular:** How much do they tell us about the **correlation between conserved charges**?
- It is important to identify the right observables and proxies

⇒ **Analyze the different contribution to the cross-correlators**

Cross Correlators - Hadron Resonance Gas model

Simple formulation, ideal gas of *all* hadronic resonances. The pressure reads:

$$\frac{P(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_R \frac{(-1)^{B_R+1} d_R}{2\pi^2 T^3} \int_0^\infty dp\, p^2 \log\left[1 + (-1)^{B_R+1} \exp\left(-\sqrt{p^2+m_R^2}/T + \mu_R/T\right)\right]$$

with:

$$\mu_R = \mu_B B_R + \mu_Q Q_R + \mu_S S_R$$

Susceptibilities in the HRG simply read:

$$\chi_{ijk}^{BQS}(T,\mu_B,\mu_Q,\mu_S) = \sum_R B_R\, Q_R\, S_R\, I_{i+j+k}^R(T,\mu_B,\mu_Q,\mu_S)$$

where:

$$I_{i+j+k}^R(T,\mu_B,\mu_Q,\mu_S) = \frac{\partial^{i+j+k} P/T^4}{\partial\left(\mu_R/T\right)^{i+j+k}}$$

Cross Correlators - Hadron Resonance Gas model

In order to compare to experiment:

- Impose **strangeness neutrality**:

$$\langle n_S \rangle = 0 \qquad\qquad \langle n_Q \rangle = 0.4\, \langle n_B \rangle$$

- Include **acceptance cuts** on the kinematics of measured particles:

$$p_T^{\mathrm{m}} \leq p_T \leq p_T^{\mathrm{M}} \qquad\qquad |y| < y^* \quad (\text{or } |\eta| < \eta^*)$$

- Include **resonance decay** feed-down, and consider only hadrons stable under strong interactions:

$$\sum_R B_R\, Q_R\, S_R \longrightarrow \sum_{\mathrm{i}\in\mathrm{stable}} \sum_R P_{R\to i}\, B_i\, Q_i\, S_i$$

  where $P_{R\to i} = \mathrm{BR}_{R\to i}\, n_i^R$ is the average number of particles i produced by a particle R, **after the whole decay cascade**

- I will use the PDG2016+ hadron list from **Phys.Rev. D96 (2017) no.3, 034517**

Cross Correlators - Hadron Resonance Gas model

The species that are stable under strong interactions:

- π^0, π^+, π^-
- $K^+, K^-, K^0, \overline{K}^0$
- $p, \overline{p}, n, \overline{n}$
- $\Lambda, \overline{\Lambda}, \Sigma^+, \overline{\Sigma}^-, \Sigma^-, \overline{\Sigma}^+$
- $\Xi^-, \overline{\Xi}^+, \Xi^0, \overline{\Xi}^0$
- $\Omega^-, \overline{\Omega}^+$

Measurable $\Longrightarrow$

- π^+, π^-
- K^+, K^-
- $p, \overline{p}$
- $\Lambda, \overline{\Lambda}$
- $\Xi^-, \overline{\Xi}^+$
- $\Omega^-, \overline{\Omega}^+$

Define the net-particle number $\widetilde{A} = A - \overline{A}$. Then, we have:

- net-B: $\left(\widetilde{\mathbf{p}} + \widetilde{n} + \widetilde{\mathbf{\Lambda}} + \widetilde{\Sigma}^+ + \widetilde{\Sigma}^- + \widetilde{\mathbf{\Xi}}^- + \widetilde{\Xi}^0 + \widetilde{\mathbf{\Omega}}^-\right)$
- net-Q: $\left(\widetilde{\boldsymbol{\pi}}^+ + \widetilde{\mathbf{K}}^+ + \widetilde{\mathbf{p}} + \widetilde{\Sigma}^+ - \widetilde{\Sigma}^- - \widetilde{\mathbf{\Xi}}^- - \widetilde{\mathbf{\Omega}}^-\right)$
- net-S: $\left(\widetilde{\mathbf{K}}^+ + \widetilde{K}^0 - \widetilde{\mathbf{\Lambda}} - \widetilde{\Sigma}^+ - \widetilde{\Sigma}^- - 2\,\widetilde{\mathbf{\Xi}}^- - 2\,\widetilde{\Xi}^0 - 3\,\widetilde{\mathbf{\Omega}}^-\right)$

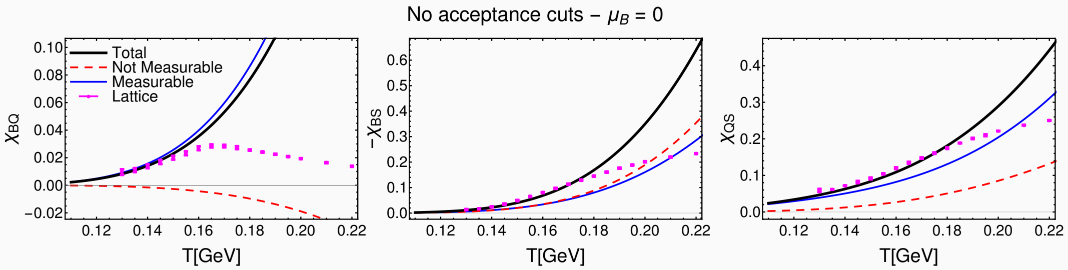
Cross Correlators - Hadron Resonance Gas model

Thanks to this analysis with the HRG model, we will be able to:

- Determine how much of a certain correlator is carried by measurable hadrons
- Identify the leading hadronic channel for each correlator, and **breakdown the different contributions entirely**
- **Identify correct proxies** for conserved charges correlators
- Investigate the role of acceptance cuts on the measurements

Measurable contributions - Cross correlators

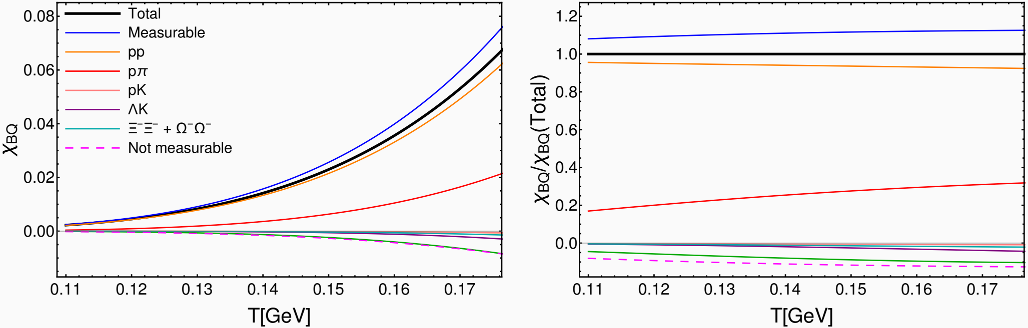
Incuding terms with measurable species only, we estimate the measurable contributions to the different correlators:



- Lattice results are (preliminary) continuum extrapolated
- For the proton- and kaon-dominated χ_{BQ} and χ_{QS}, a large part of the full correlator is carried by measurable particles
- χ_{BS} is less transparent, and requires careful analysis of its contributions

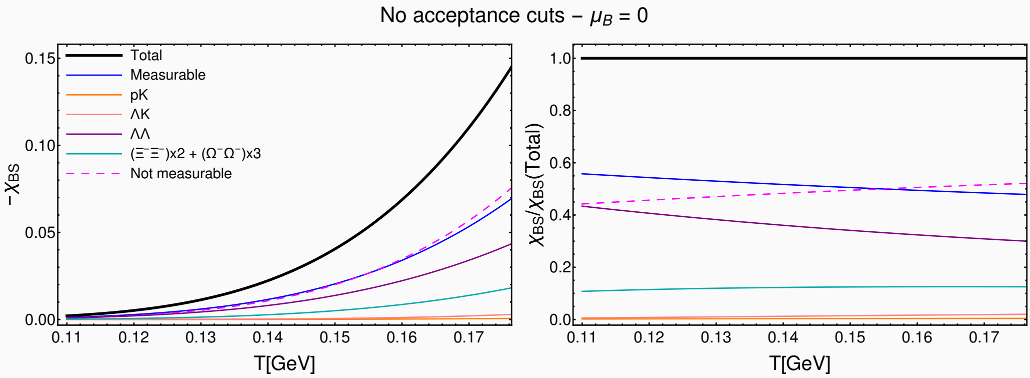
Breakdown of contributions: χ_{BQ}

No acceptance cuts – $\mu_B = 0$



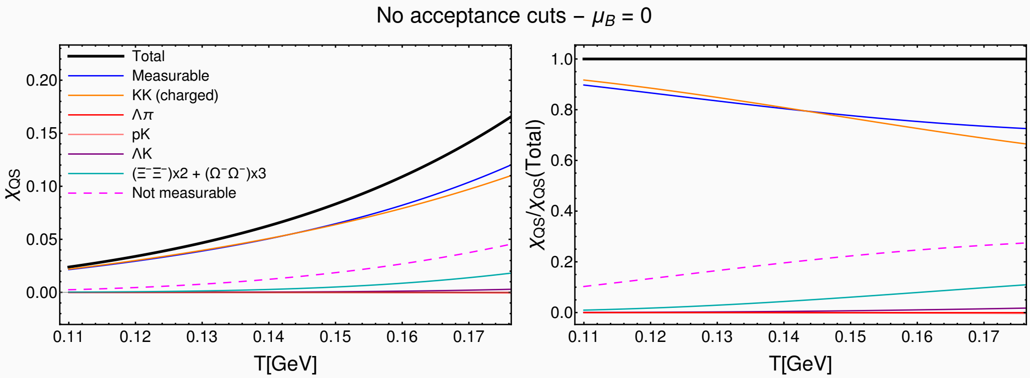
- The variance of net-p distributions dominates the BQ correlator
- The $p\pi$ correlator and multi-strange self-correlatios are the other significant contributions

Breakdown of contributions: χ_{BS}



- The variance of net-Λ distributions dominates the (measurable) BS correlator
- This is a much better proxy for BS than the pK correlator
- Multi-strange species also play a non-negligible role

Breakdown of contributions: χ_{QS}



- The variance of net-K distributions dominates the QS correlator
- No different-species correlator plays a noticeable role

Breakdown of contributions - things to remember

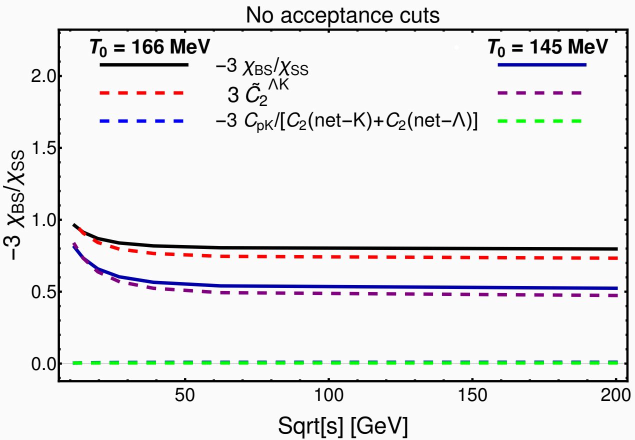
- In general, self-correlations (variances) always play a bigger role than correlations between different species
- The $p\pi$ correlator in χ_{BQ} is the only non-negligible correlator of different species
- Correlations in HRG come only from resonance decay $\rightarrow$ **net-particle variances provide a better opportunity** to study conserved charge correlations with thermal models
- What can we get out of this when comparing to experiment?

Example: χ_{11}^{BS}/χ_2^S, what can be a good proxy?

At different values of the chemical potential and temperature, the ratio:

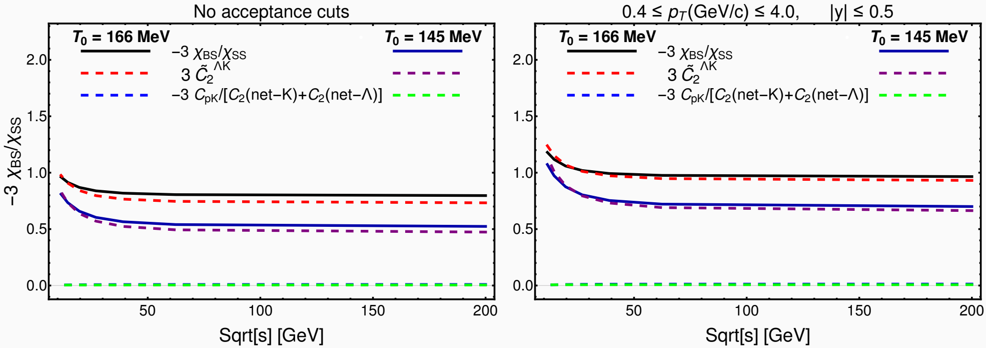
$$\widetilde{C_2}^{\Lambda K} = \frac{C_2\,(\mathrm{net}-\Lambda)}{C_2\,(\mathrm{net}-K) + C_2\,(\mathrm{net}-\Lambda)}$$

remains a very good proxy for the ratio χ_{11}^{BS}/χ_2^S



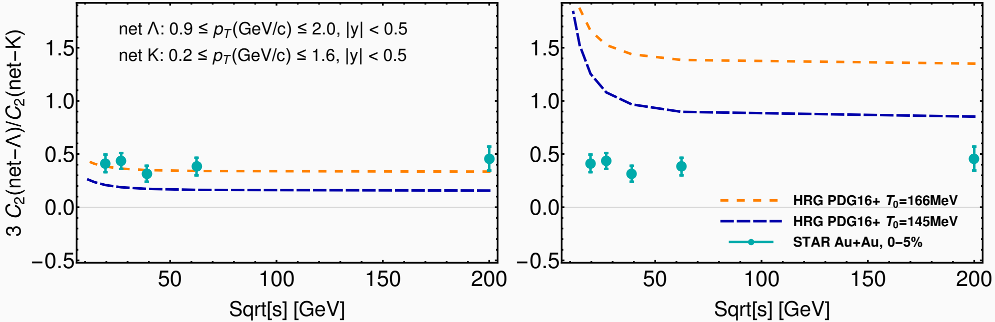
A note on the cuts

- With and without experimental cuts $\widetilde{C_2}^{\Lambda K}$ is still a very good proxy
- If the dependence on cuts is minimal, **comparison to lattice QCD is possible**



A note on the cuts

- The HRG calculations for $C_2\,(\text{net} - \Lambda)\,/C_2\,(\text{net} - K)$ show good agreement with experiment with $T_0 = 166\,\text{MeV}$
- It is essential that the cuts on the different species are included correctly, since the dependence is very strong



Experimental data from: **Phys.Lett. B785 (2018) 551, Nucl.Phys. A982 (2019) 863**

see also talk by R. Bellwied (later today)

Conclusions

- With the HRG model it is possible to separate the contribution from different hadronic channels to the correlators of conserved charges
- Without exception, self-correlations yield the maximum contribution to the correlators
- The HRG model suggets that $\widetilde{C_2}^{\Lambda K}$ is a very good proxy for the ratio $-\chi_{11}^{BS}/\chi_2^S$
- Strong dependence on the acceptance cuts $\rightarrow$ crucial to include the correct cuts in HRG analyis

Conclusions

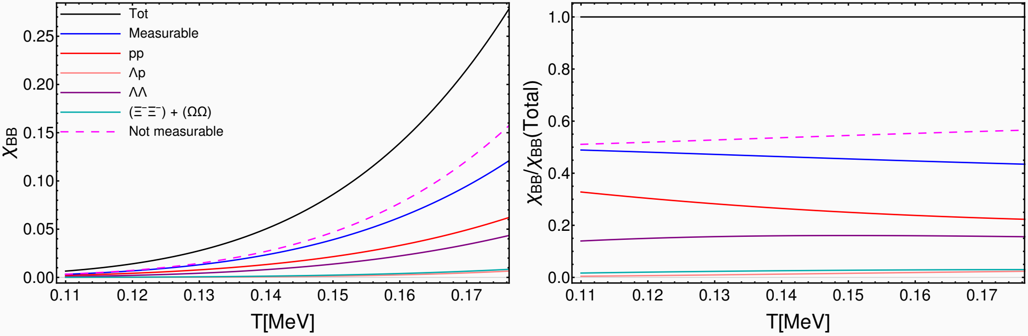
- With the HRG model it is possible to separate the contribution from different hadronic channels to the correlators of conserved charges
- Without exception, self-correlations yield the maximum contribution to the correlators
- The HRG model suggets that $\widetilde{C_2}^{\Lambda K}$ is a very good proxy for the ratio $-\chi_{11}^{BS}/\chi_2^S$
- Strong dependence on the acceptance cuts → crucial to include the correct cuts in HRG analyis

Thank you!

BACKUP

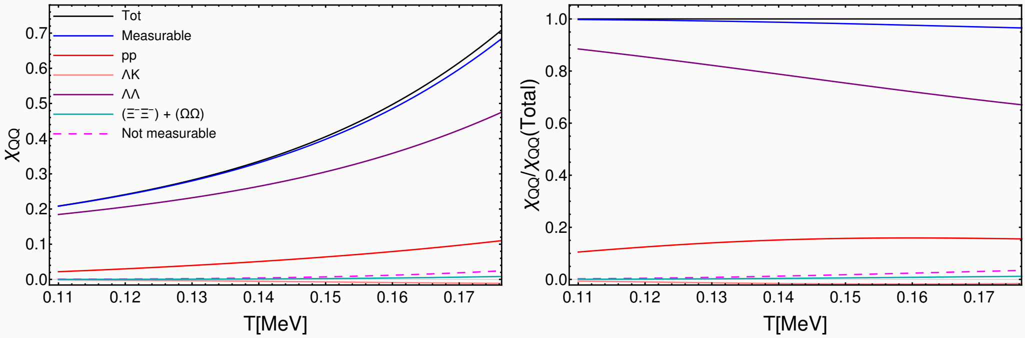
Breakdown of contributions: χ_{BB}

No acceptance cuts – $\mu_B = 0$



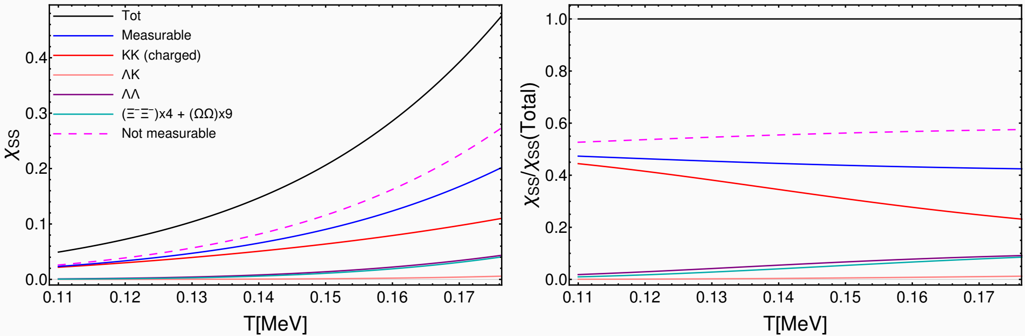
Breakdown of contributions: χ_{QQ}

No acceptance cuts – $\mu_B = 0$



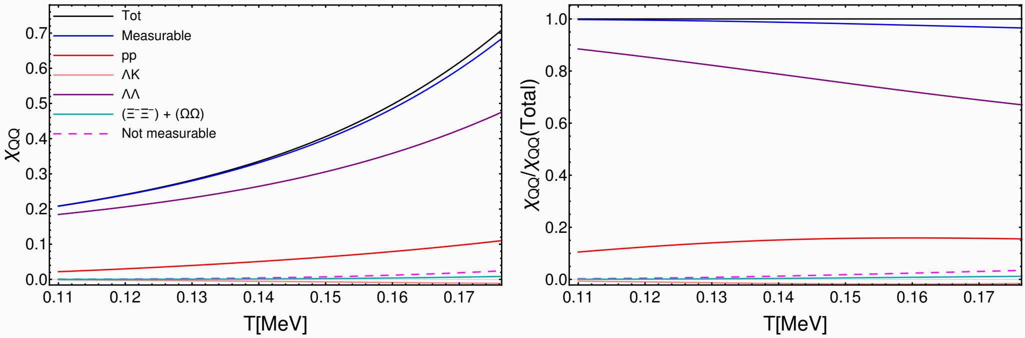
Breakdown of contributions: χ_{SS}

No acceptance cuts – $\mu_B = 0$

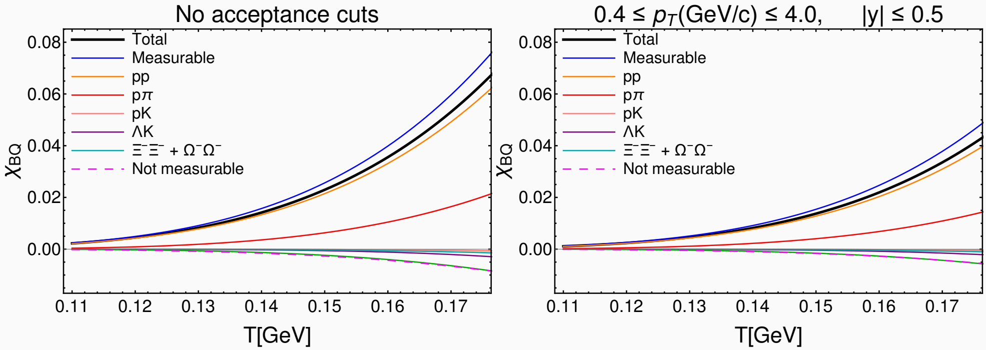


Breakdown of contributions: χ_{QQ}

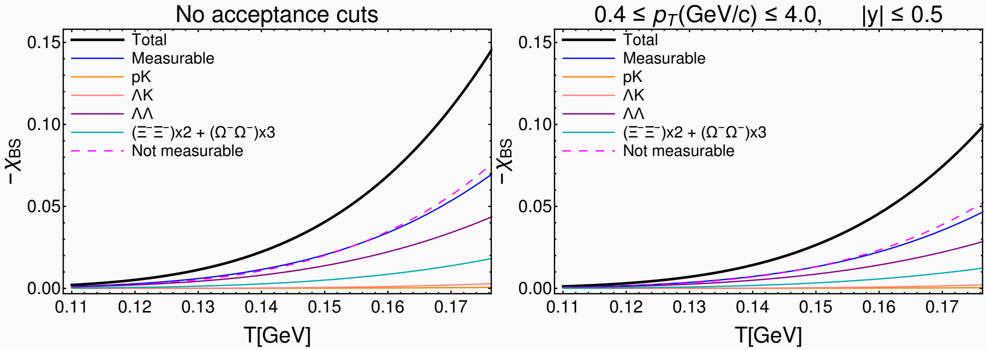
No acceptance cuts – $\mu_B = 0$



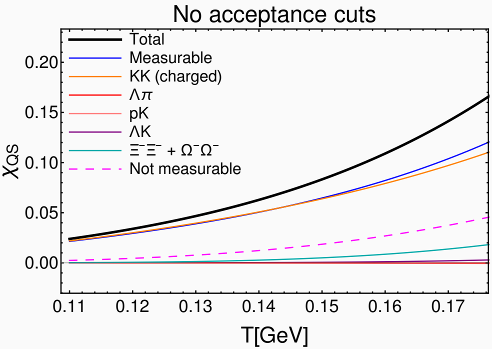
Cuts v No cuts: χ_{BQ}

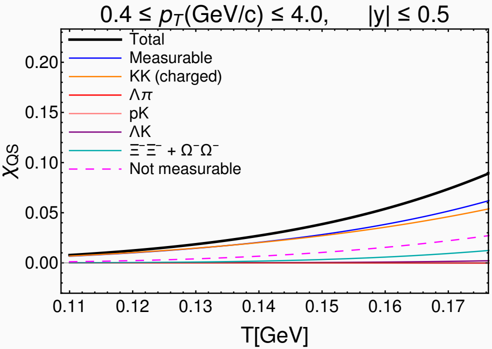


Cuts v No cuts: χ_{BS}

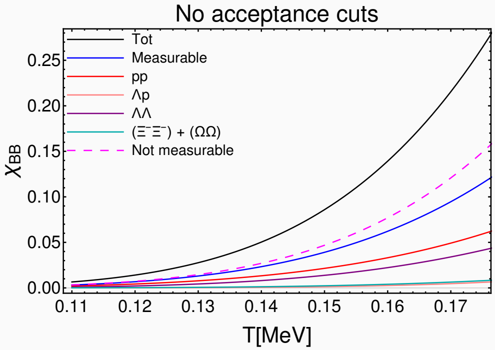


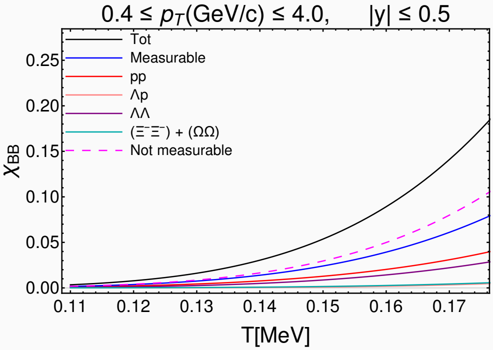
Cuts v No cuts: χ_{QS}



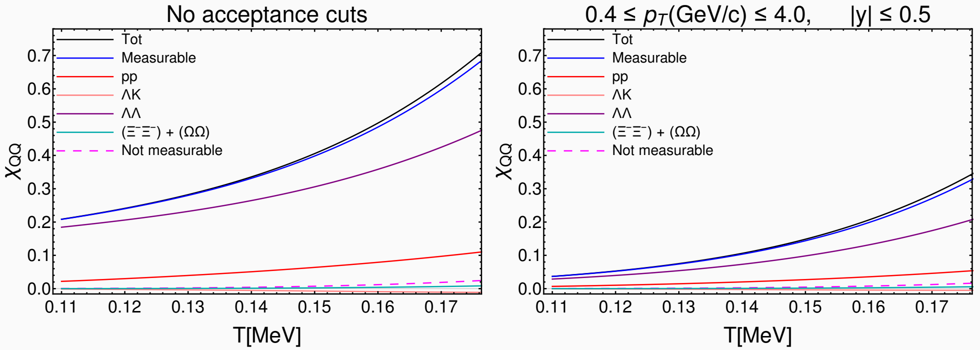


Cuts v No cuts: χ_{BB}





Cuts v No cuts: χ_{QQ}



Cuts v No cuts: χ_{SS}