Final state hadronic interactions

Jan Steinheimer

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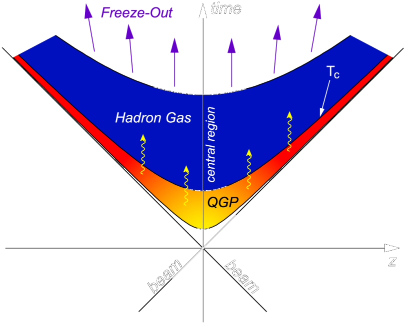
FIAS Frankfurt Institute for Advanced Studies

The Space-time evolution of an Ultra-relativistic Heavy Ion Collision

A rough Picture - likely inaccurate

- Pre-Equilibrium Phase
- Near Equilibrium / Fluid Phase
- Freeze Out Phase - Dynamic Decoupling



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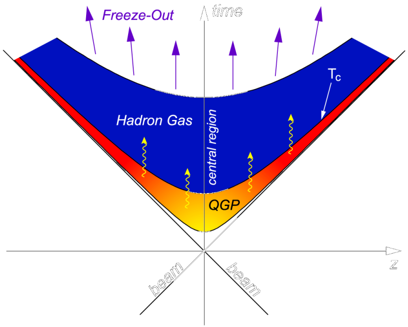
This talk

What happens during the hadronic freeze-out?



What to expect from hadronic rescattering

Elastic and pseudo-elastic rescattering

- CHANGES: spectra
- CHANGES: correlations and fluctuations

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Inelastic rescattering

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The idea of a hadronic phase was/is motivated by:

- Particle spectra have a temperature much smaller than the "chemical" Temperature.
- Resonance yields are not consistent with thermal fits
- NOT mainly to introduce effects of annihilation! Though it is an interesting effect and probably will take up most of the discussion.

How to deal with it?

Option 1

- Ignore

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- Extend fluid dynamical description
- Implement non-equilibrium EoS.

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Option 3

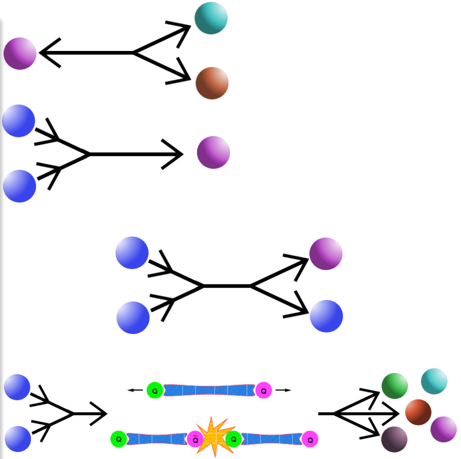
- Describe the hadronic phase with a microscopic model.
- Dynamical freeze-out $\rightarrow$ fall out of equilibrium.

The UrQMD model

Use UrQMD for the hadronic phase. Of course the result will depend on the model ingredients. We just include, and constrain it, as much as we can.

What is UrQMD

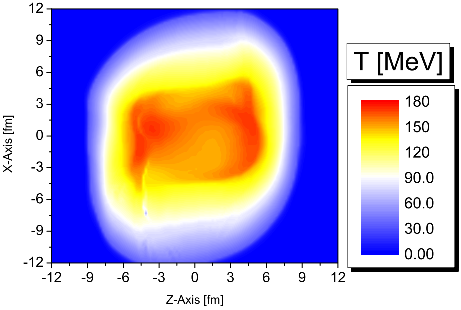
- Microscopic model based on geometric interpretation of cross sections.
- $2 \rightarrow n$ particle scattering according to measured cross sections
- Resonance decays plus string excitations at $\sqrt{s} > 3$ GeV.
- Newest version: Strangeness exchange $\overline{K} + N \leftrightarrow \pi + Y$ and $Y + Y \leftrightarrow \Xi + N$



The UrQMD model- hybrid

Employ fluid dynamical simulation until a 'hadronization' Temperature is reached. Then produced hadrons are propagated in a transport approach based on hadron-hadron crossections.

- Hadronization at a fixed temperature, e.g. 162 MeV
- Cooper Frye Prescription $E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$
  Cornelius hypersurface finder!



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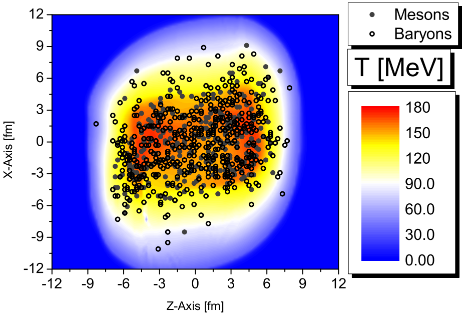
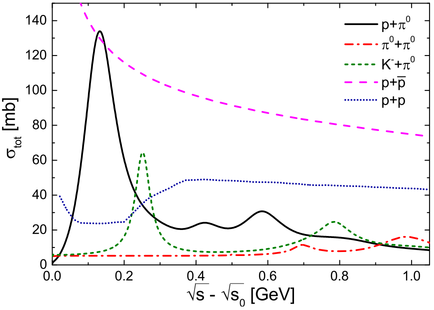


Hadrons are produced and then can rescatter according to measured crossections until they dynamically decouple.

Implemented cross sections

Example of total cross sections in UrQMD

- Largest cross section is annihilation



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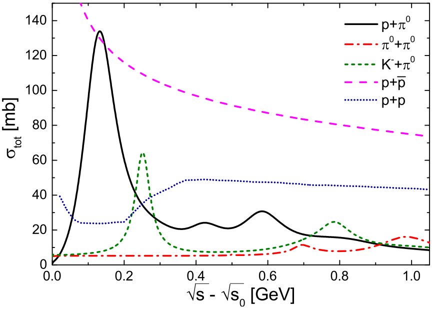
- Largest cross section is annihilation
- Second is resonance excitation



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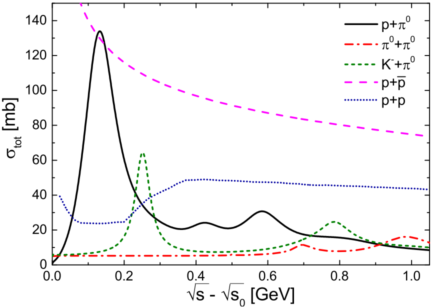
- Microscopic transport is important.



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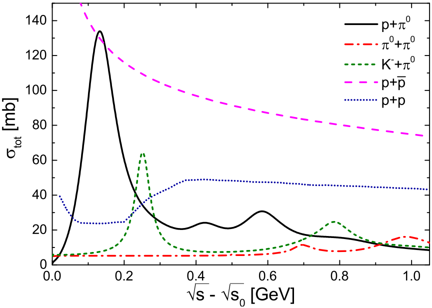

I will discuss the hadronic re-scattering mainly for most central Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ and 2700 GeV.

Examples of applications

- VISHNU + UrQMD
- MUSIC + UrQMD
- EPOS + UrQMD
- Now also JAM+hydro, Nara et. al.

Bayesian analysis of

Multiplicities, spectra, flow, HBT:
J. Auvinen, J. E. Bernhard, S. A. Bass and I. Karpenko, Phys. Rev. C **97**, no. 4, 044905 (2018)

Useful for deuteron production

Deuteron coalescence in UrQMD

1. During the evolution of the system, we follow the protons and neutrons until their individual space-time points of last interaction.
2. For each p-n pair the momentum and position of proton and neutron is boosted to the 2-particle restframe of this p-n pair.
3. The particle that has decoupled earlier is then propagated to the later time of the other particle.

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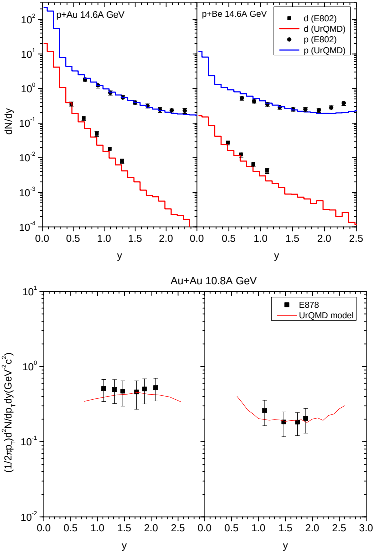
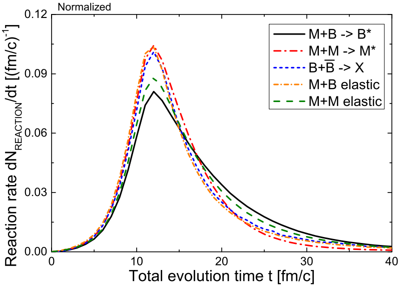
S. Sombun, K. Tomuang, A. Limphirat, P. Hillmann, C. Herold, J. Steinheimer, Y. Yan and M. Bleicher, arXiv:1805.11509 [nucl-th].



A general view on reaction rates at RHIC



Reaction rates $|y| < 0.5$

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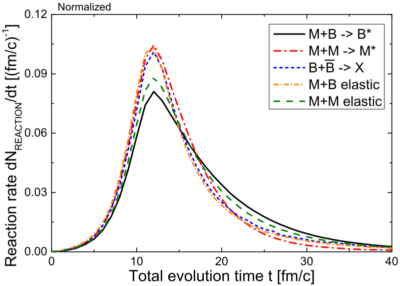

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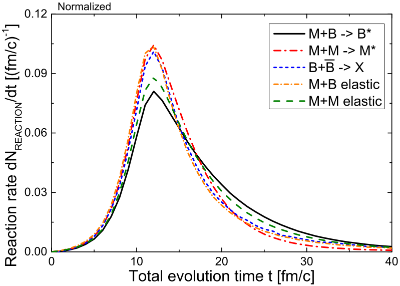

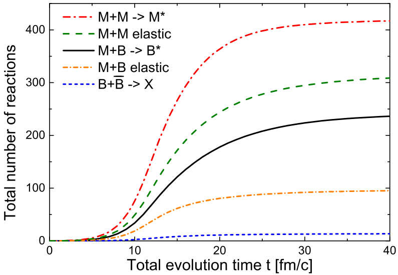

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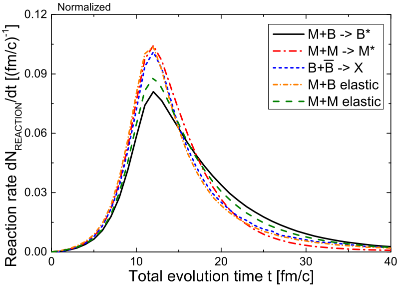

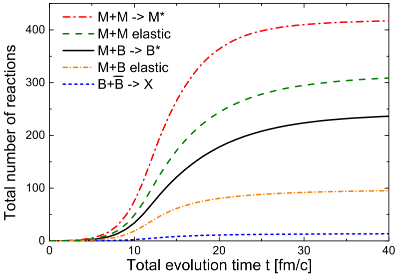

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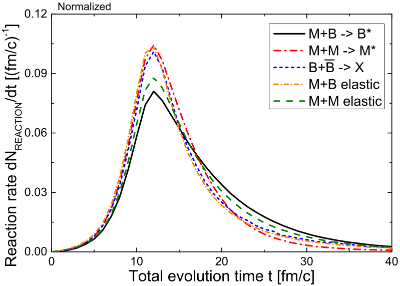

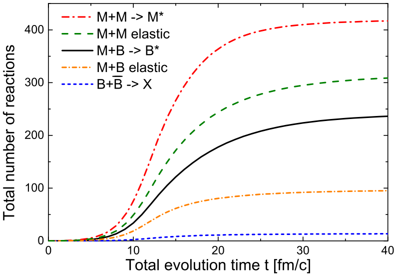

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- Few annihilations.
- (Pseudo-)elastic dominate.

Resonances as probes

If most reactions are resonance excitations:

Use them as probes of the hadronic phase.

J. Auvinen, K. Redlich and S. A. Bass, J. Phys. Conf. Ser. **779, no. 1, 012045 (2017)**

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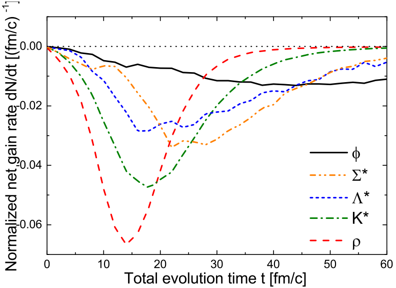
How do we count a resonance in UrQMD?

Define a measurable resonance in UrQMD:

- **Has decayed in the correct final state**
- **Decay products have not rescattered**
- **Might miss contributions from resonances where the decay product has scattered with small momentum change.**

Reaction rates for resonances - a closer look



Gain rates

Number of created - number of decayed resonances

- Always negative
- Clear lifetime ordering - except the Σ^*

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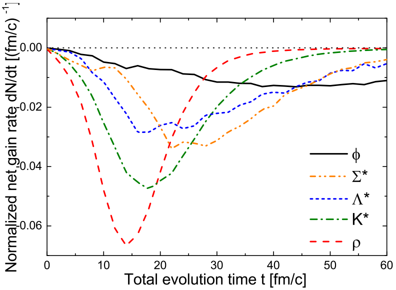

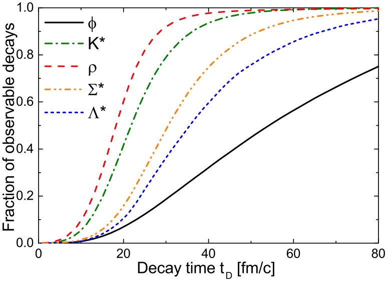

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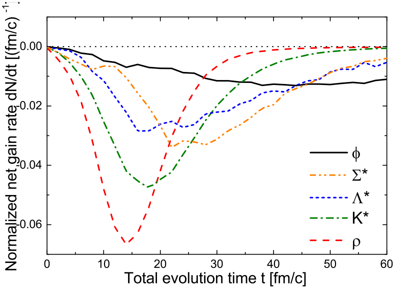

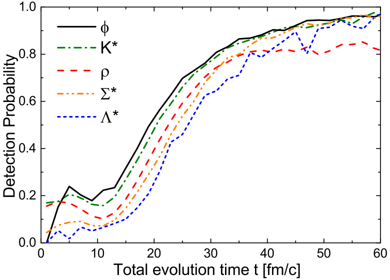

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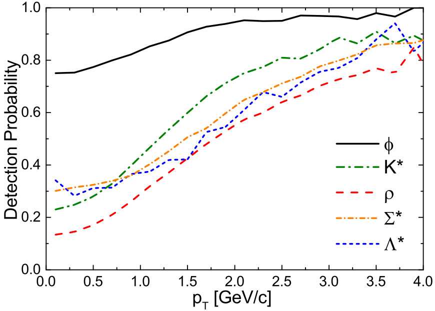
Detection probabilty

- Shows expected time dependence.
- ϕ is best detectable.

Reaction rates for resonances - a closer look



Detection probability and decay time give the expected picture.

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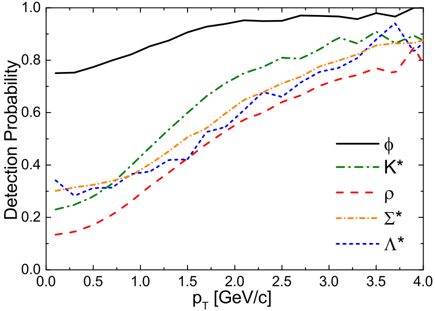

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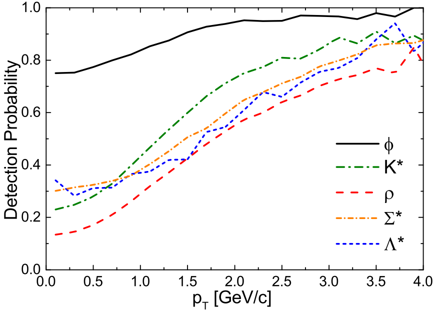
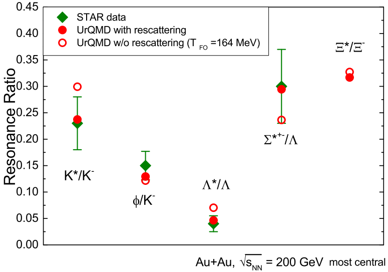


Detection probability and decay time give the expected picture.

- ϕ is best messenger from the early times (e.g. spectra, flow)
- BUT: ϕ properties are from later time decay (e.g. spectral function)

Comparison with STAR data

- Resonance to stable ratios from STAR are well reproduced
- K^* and Λ^* are especially sensitive.



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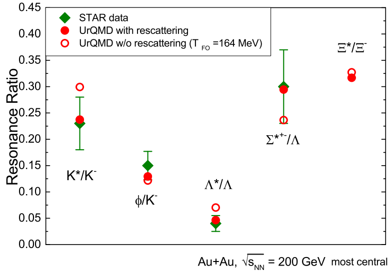

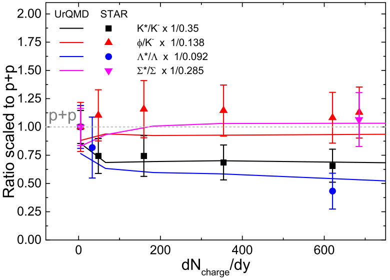

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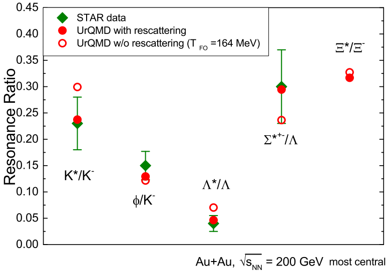
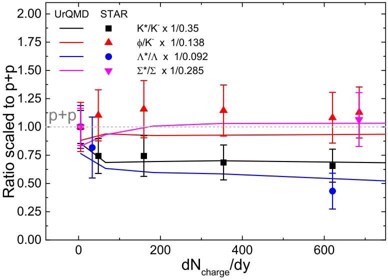
- Σ^* shows signs of significant regeneration $\rightarrow$ systematics cannot be reproduced by simple shift in T_{FO}

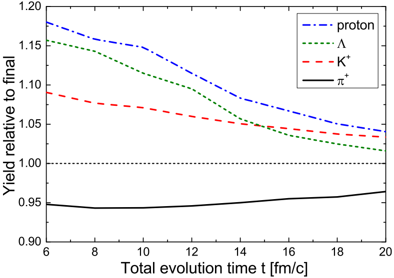




Stable particles

Also stable particle yields are affected

- Baryon yield is decreased due to annihilation
- Pion yield is increased



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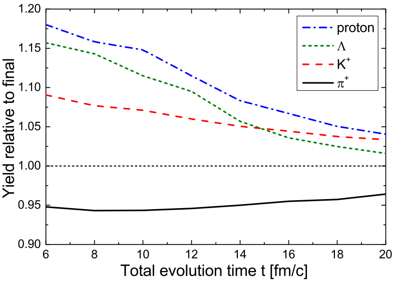

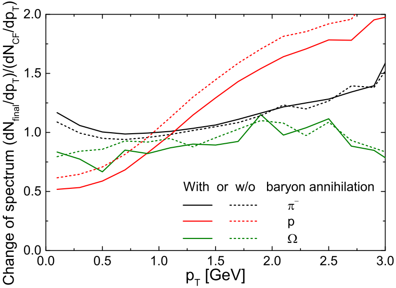

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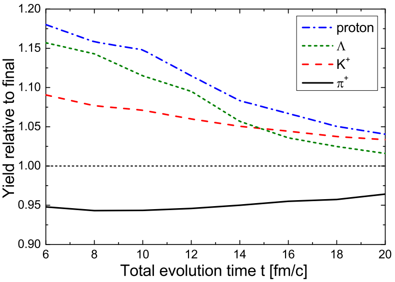

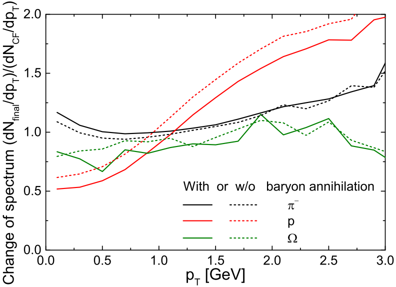

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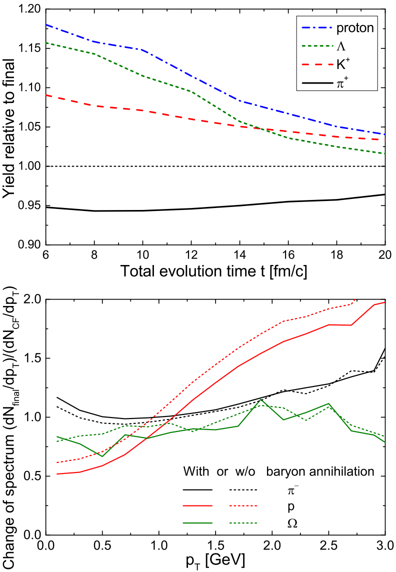

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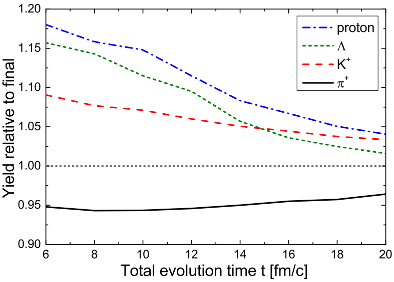
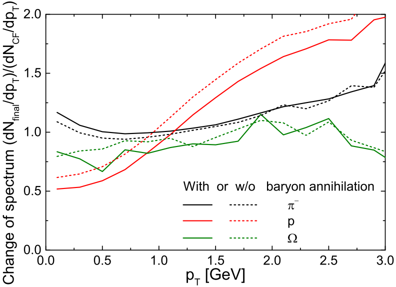
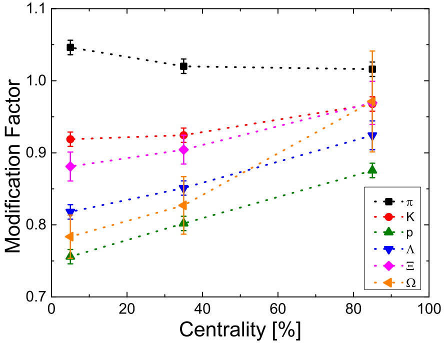
- Pion spectrum is increased at low AND high p_T!





Collisions at the LHC: Similar results to RHIC

Modification factor $= \frac{\text{Final hadron yield}}{\text{Hadron yield at particlization}}$



Centrality dependence of Modification factor

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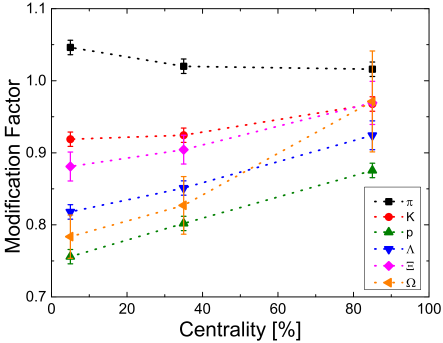

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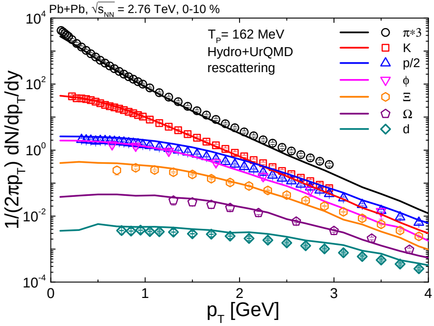

Final state interactions in most central collisions do a good job.

System size dependence of deuteron Production

Deuteron results

- Using the hadronic final state one can also calculate deuteron properties.

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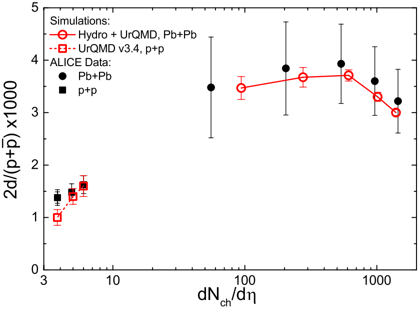
- Using the hadronic final state one can also calculate deuteron properties.
- System size dependence well reproduced.
- Indicates: Once proton properties are understood: Deuteron is well described.



What about the annihilation issue

An important issue

Detailed balance.

Mainly violated by:

- Multi particle decays

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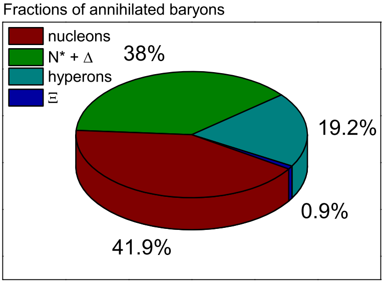
- May be more complicated than thought - Most annihilated baryons are not ground state nucleons!



Taking into account the pair creation - Understanding model results

Results of PHSD model study

- PHSD $\neq$ Hydro+UrQMD. A direct comparison can be confusing.

E. Seifert and W. Cassing, Phys. Rev. C **97**, no. 4, 044907 (2018)

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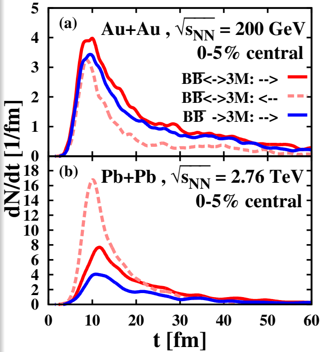

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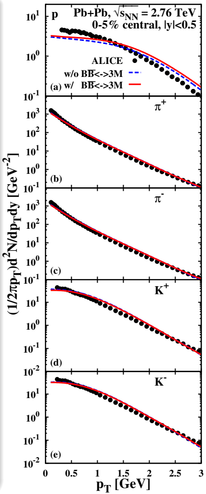

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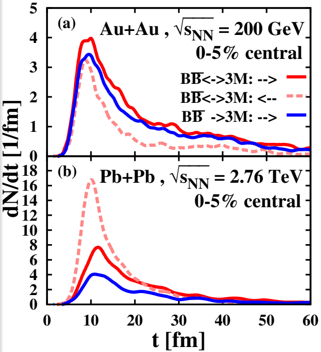

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- However, this is a result of an under saturation of protons at hadronisation.
- At RHIC energies this is not so severe and therefore the back reaction much less.
- Confirms: The duration of the hadronic phase 10 fm/c.
- Confirms: If one starts from equilibrium yields the hadronic phase would reduce the baryon number.
- Although effect can be up to 50$\%$ smaller.

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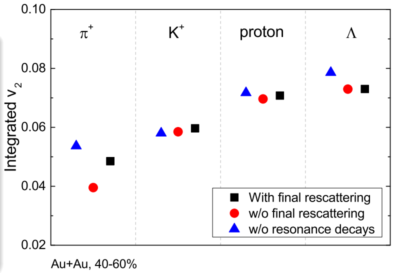
- Unknown hadronic interactions make the problem even worse.
- Lifetime of the hadronic phase < 10 fm/c (UrQMD and PHSD).
- More detailed studies with different models would be important to quantify the problem.

Effects on v_2

Investigate effect on v_2

- Already resonance decays change v_2.



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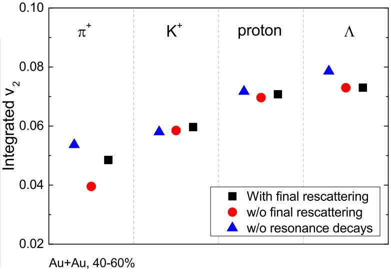

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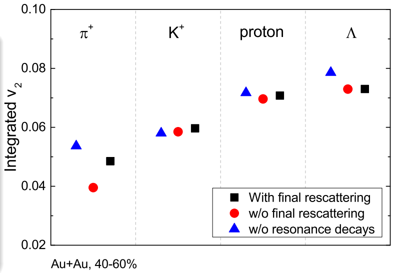

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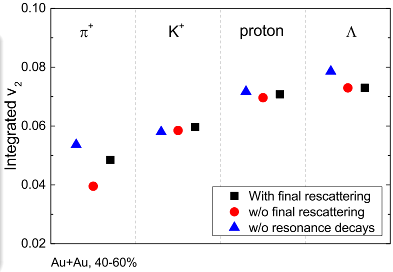
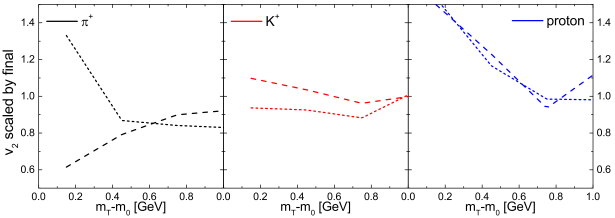


Change in p_T dependent v_2, before (short dashed lines) and including resonance decays (long dashed lines)



Effects on particle fluctuations I

Even more than changing particle yields the interactions will change correlations and fluctuations.

How well are fluctuations remembered?

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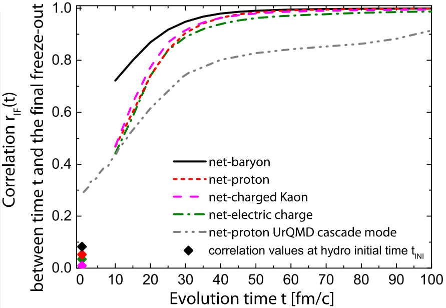

Different charges in STAR experimental acceptance.

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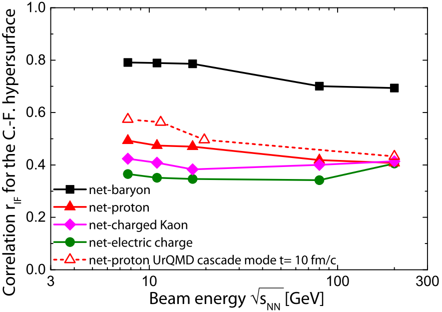

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Effects on particle fluctuations II

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