Sub Threshold Charm and the properties of dense QCD matter

Jan Steinheimer

With: Marcus Bleicher, Anton Motornenko, Thorben Finke ….

Thanks to the organizers for inviting me

Questions for this talk:

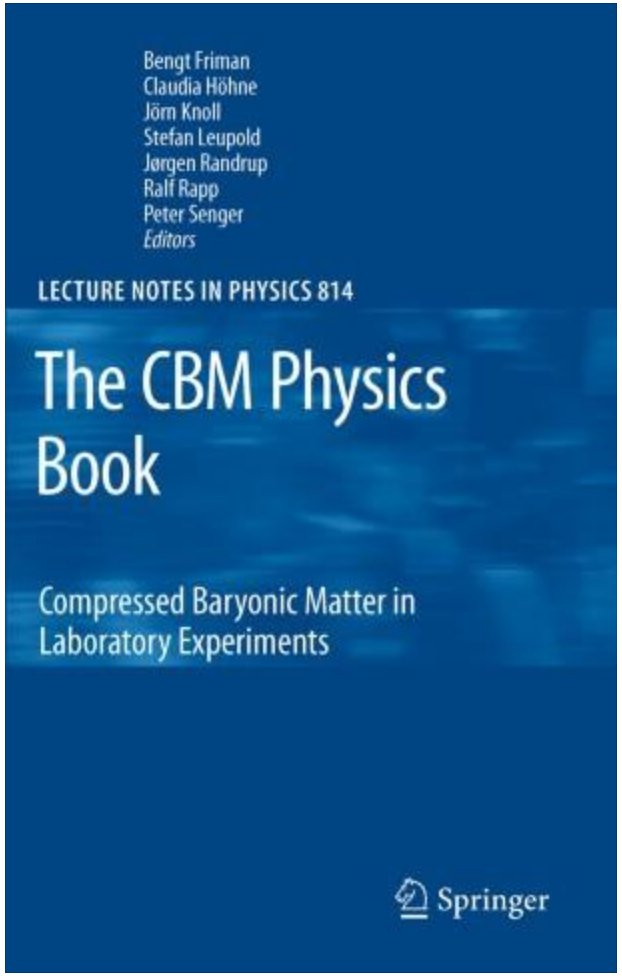
- How to combine the study of charm quarks production (one topic of workshop)
- With Baryon stopping (another topic)
- And the QCD/nuclear matter equation of state?
- And the goal of CBM@FAIR anyway.

→ Charm Sub-threshold

The CBM problem

- CBM claims reaction rates up to 10 MHz.
- Even if we assume much less… 1 Million events per second is a lot
- Most observables will have very low statistical error within hours of operation.
- Good argument to look for exotic object.
- What else to do with all that event-rate?

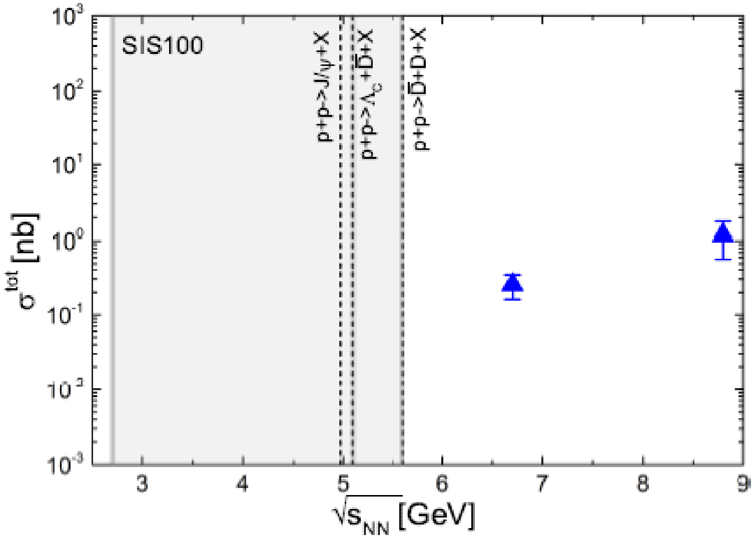
There are some interesting questions for low beam energy charm physics



Charm at high baryon densities

- Study properties of charmed hadrons in dense nuclear matter.
- Study hadronic charm rescattering.
- Study charm in cold nuclear matter.
- Big part of CBM program. ~ 90 pages in CBM physics book.
- But that was SIS300 $\rightarrow$ predictions only down to threshold.

Few data available above threshold.



Process	Energy [GeV]
$N+N \rightarrow N+N+J/\psi$	4.973
$N+N \rightarrow N+\Lambda_c+\overline{D}$	5.096
$N+N \rightarrow N+N+D+\overline{D}$	5.611

Table: Threshold center-of-mass energies, as implemented in UrQMD, for different charm production processes. N refers to any ground state nucleon.

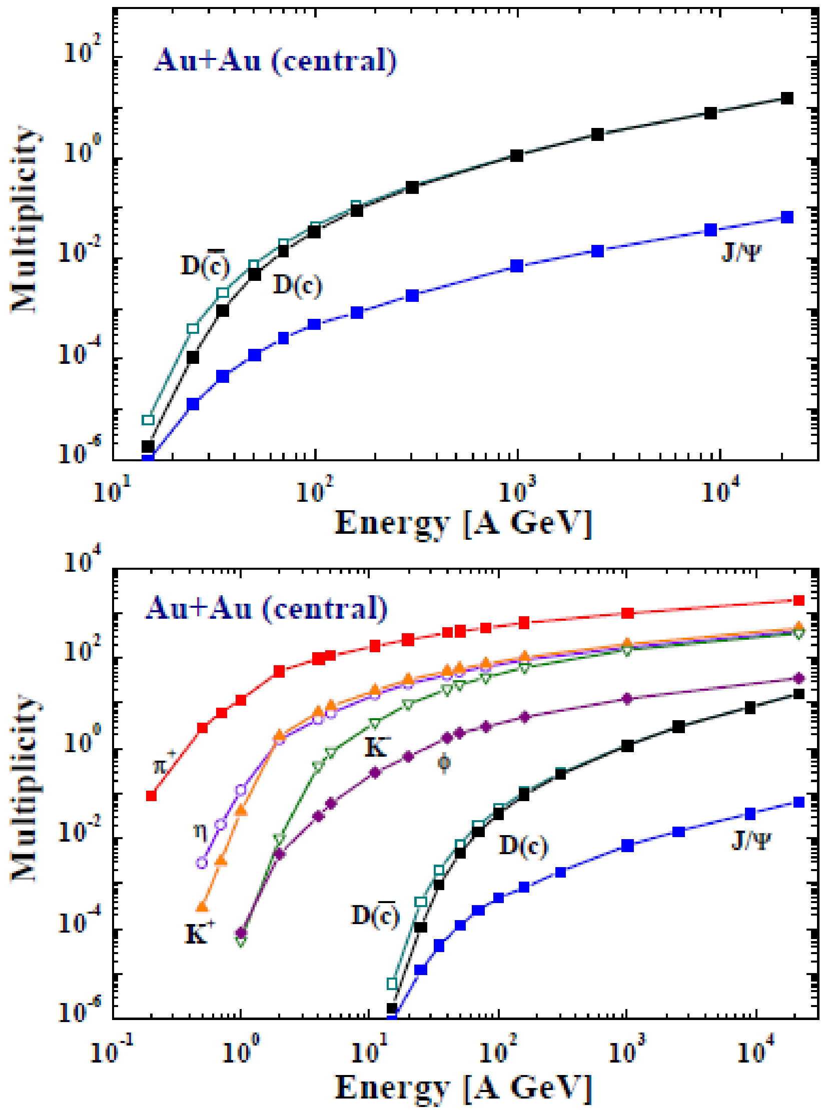
Charm at high baryon densities

- But that was SIS300 → predictions only down to threshold.

HSD study: Based on parametrized cross section.

W. Cassing, E. L. Bratkovskaya and A. Sibirtsev, Nucl. Phys. A **691**, 753 (2001)

Not a single prediction below threshold



How does particle production work at SIS18/100?

- I do not consider „thermal production“ as a valid microscopic mechanism.

The old receipe

- Strangeness is cooked.
- Idea most of particle production toward equilibration may go through secondary M+B reactions.
- Long equilibration times for hadronic matter $\rightarrow$ signal for quark matter.
- Can this picture be uphold in light of new measurements?

P. Koch, B. Muller and J. Rafelski, Phys. Rept. **142**, 167 (1986).

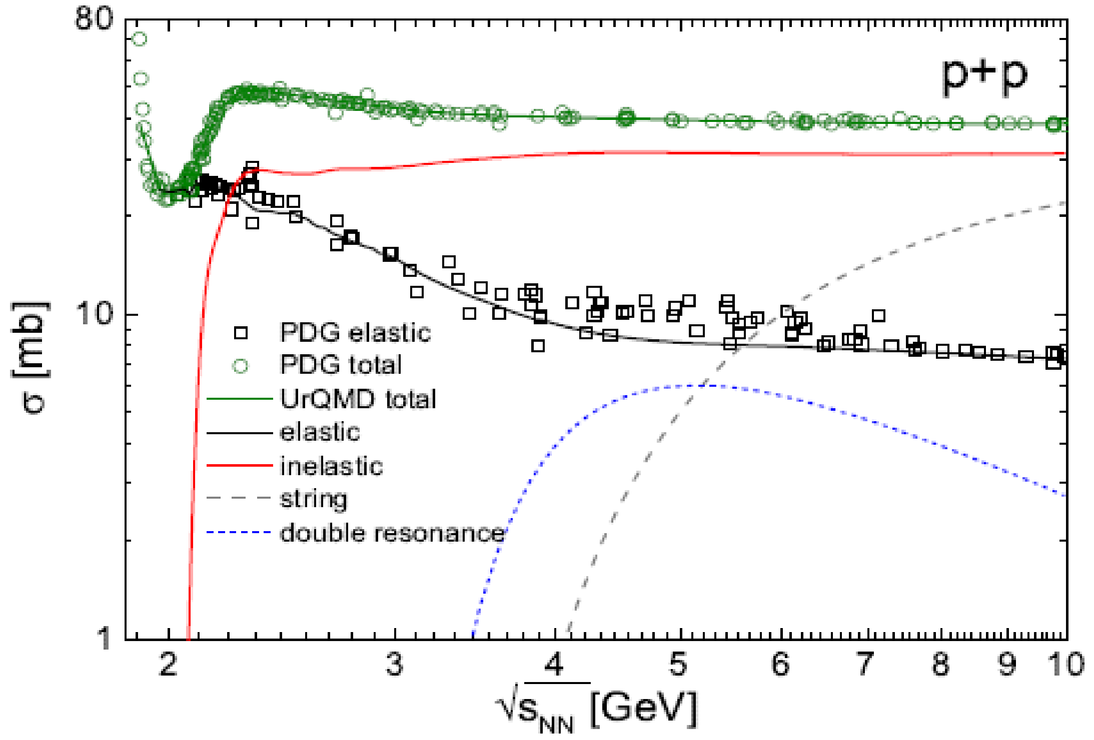
Microscopic models

Hadron production goes Mainly via

Resonance excitation:

- $N+N \to X$
- $N+M \to X$
- $M+M \to X$

Keep in mind this is a convenient way to ensure detailed balance.



N+N Cross section

Fixed to data where available. Otherwise fixed Matrix element + phase space.

If resonance excitation and decay are governed mainly by the available energy and momentum for B+B, does that help in equilibration of hadron yields?

Run UrQMD for SIS18 energies and fit FINAL particle yields at different time steps:

J. Steinheimer, M. Lorenz, F. Becattini, R. Stock and M. Bleicher, Phys. Rev. C 93, no. 6, 064908 (2016).

A. Motornenko, J. Steinheimer, V. Vovchenko, R. Stock and H. Stoecker, [arXiv:2104.06036 [hep-ph]].

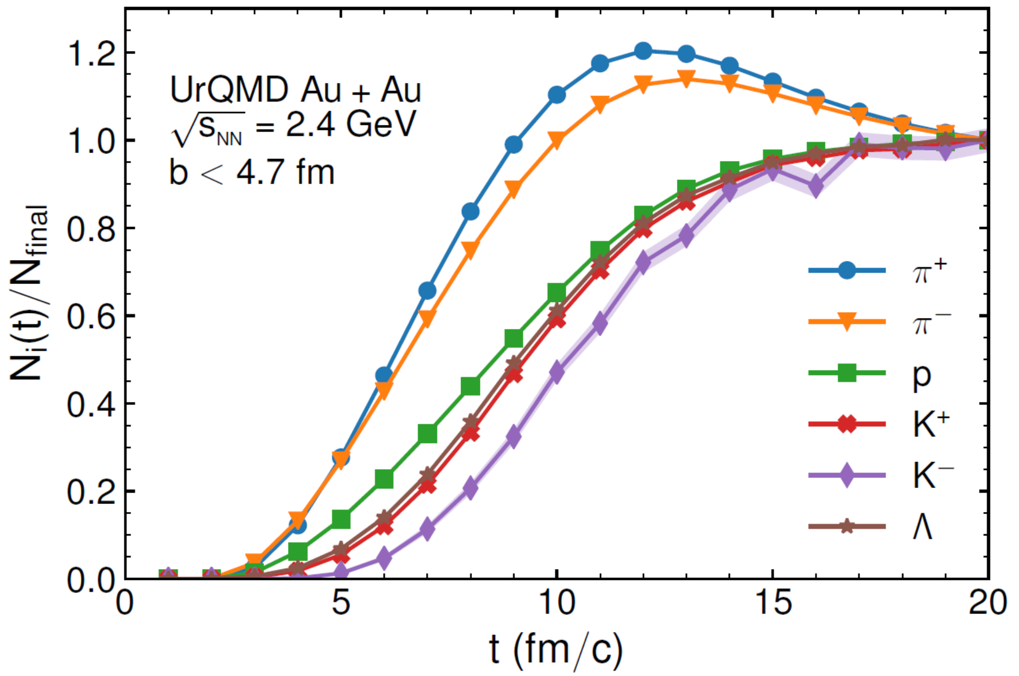
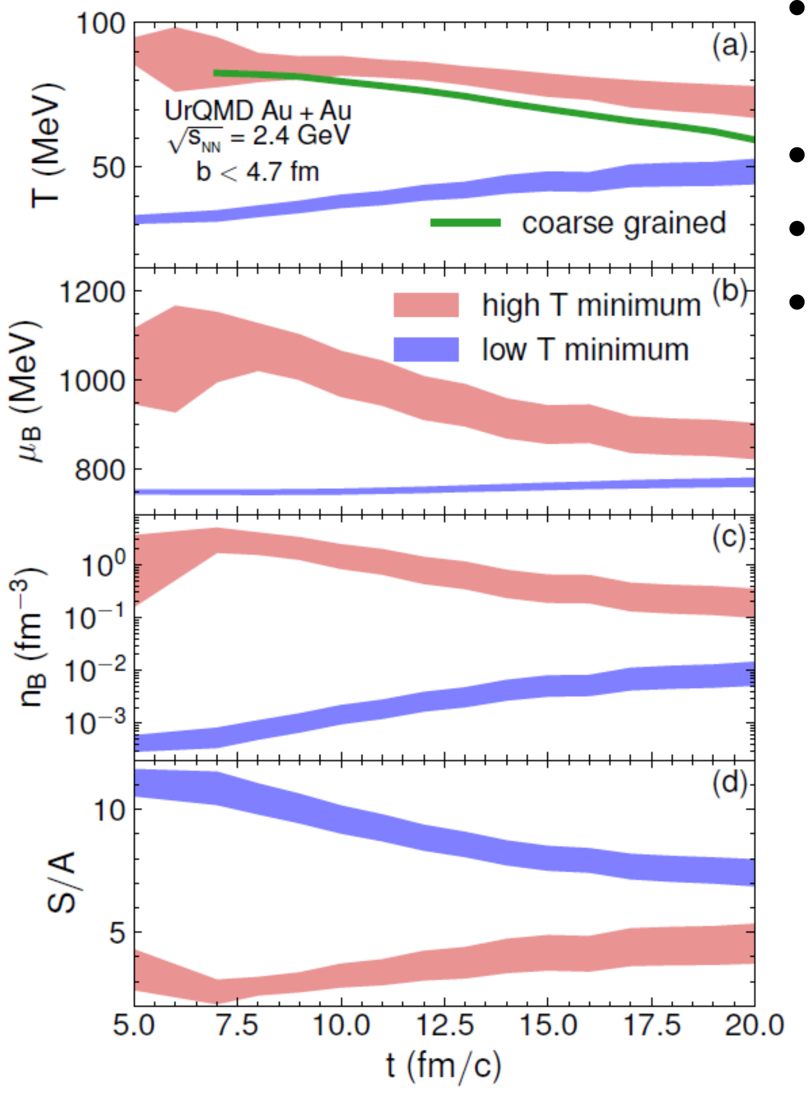


Figure from Anton Motornenko

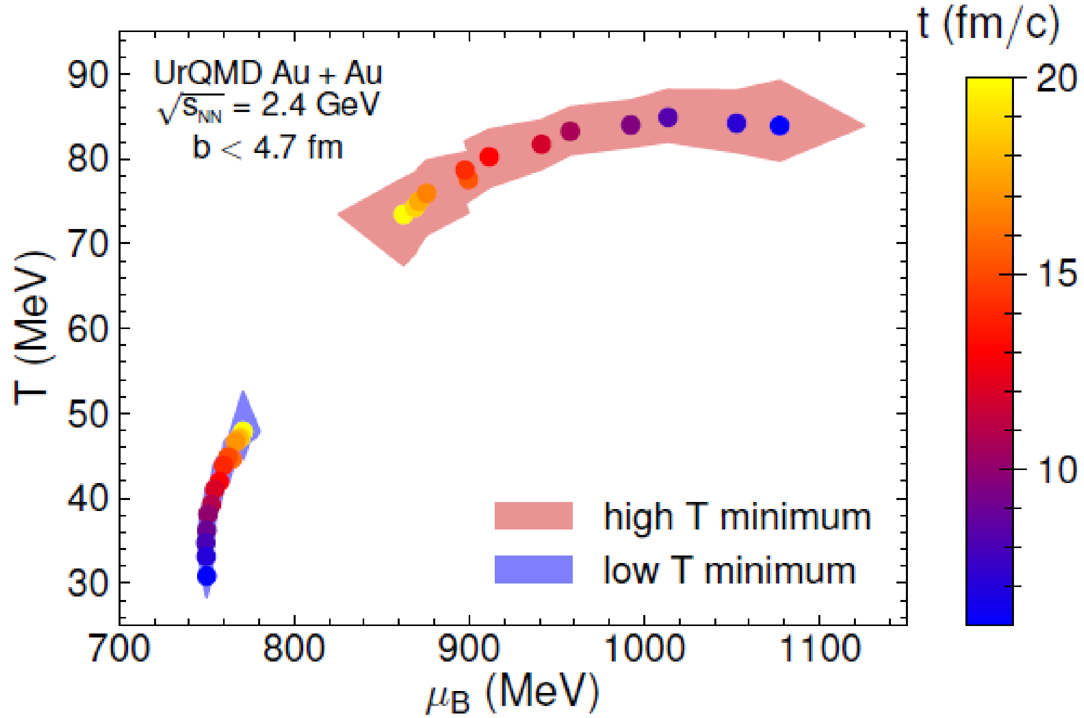
- Light hadron production is fast and then tries to saturate
- Strange hadrons are produced mainly in ‘high’ energy collisions and just remain.

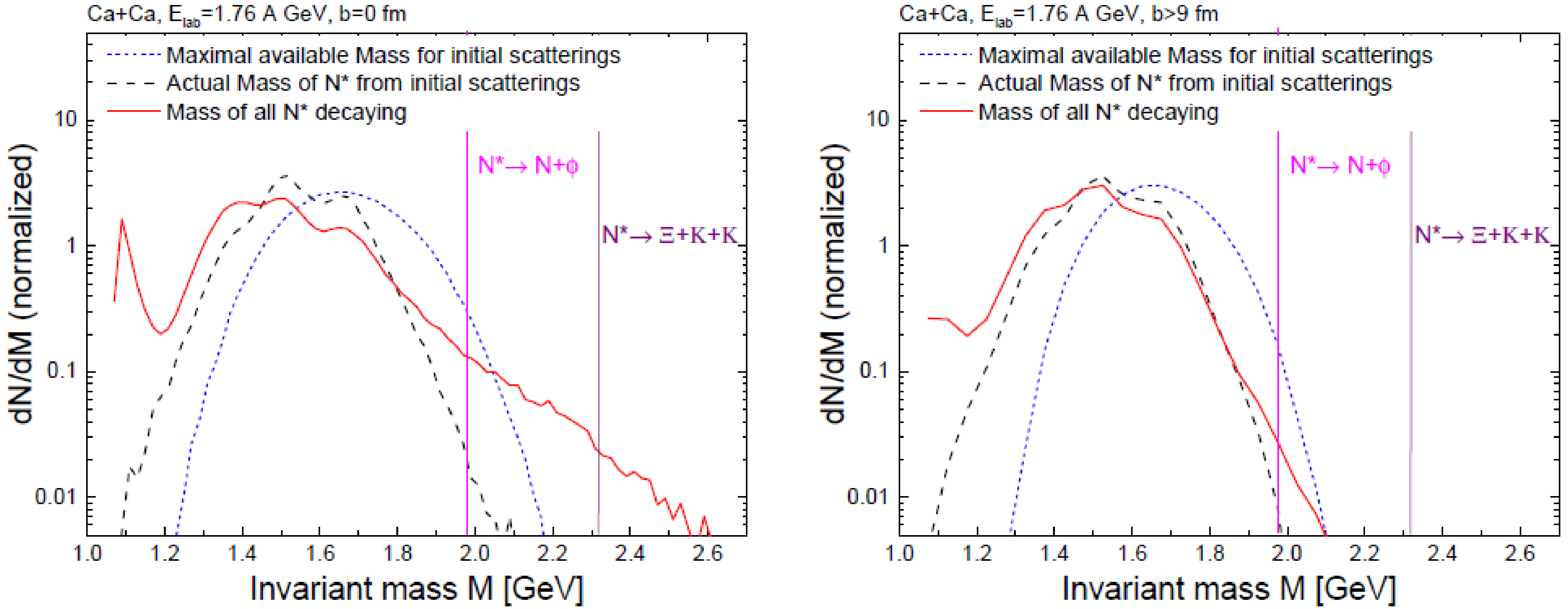
- Can we do a time dependent thermal fit?
- Does it look thermal?

Thermal fit to UrQMD at SIS18



- Thermal fit works but gets two degenerate minima. (As in the data!)
- Fit quality is very good even early on: Apparent equilibrium
- Pseudo-trajectories can be extracted
- The rapid excitation and decay of very heavy (baryonic-)states mimics equilibration and is the main process of particle production.



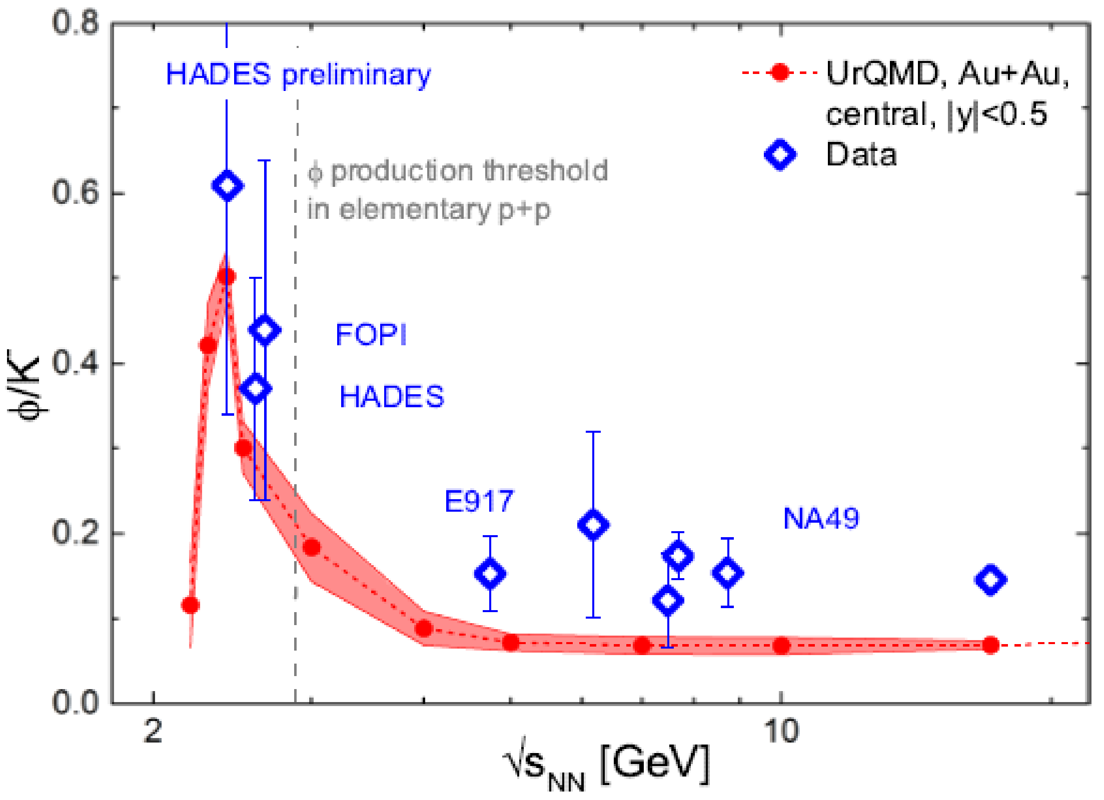


So how can we accumulate enough energy to go above the threshold

- Let us compare the available energy per collision $\sqrt{s} - m_N$, for two different centralities.
- Central system more rescatterings, peripheral system less rescatterings
- Already less then two rescatterings create a tail of high mass states with enough energy.

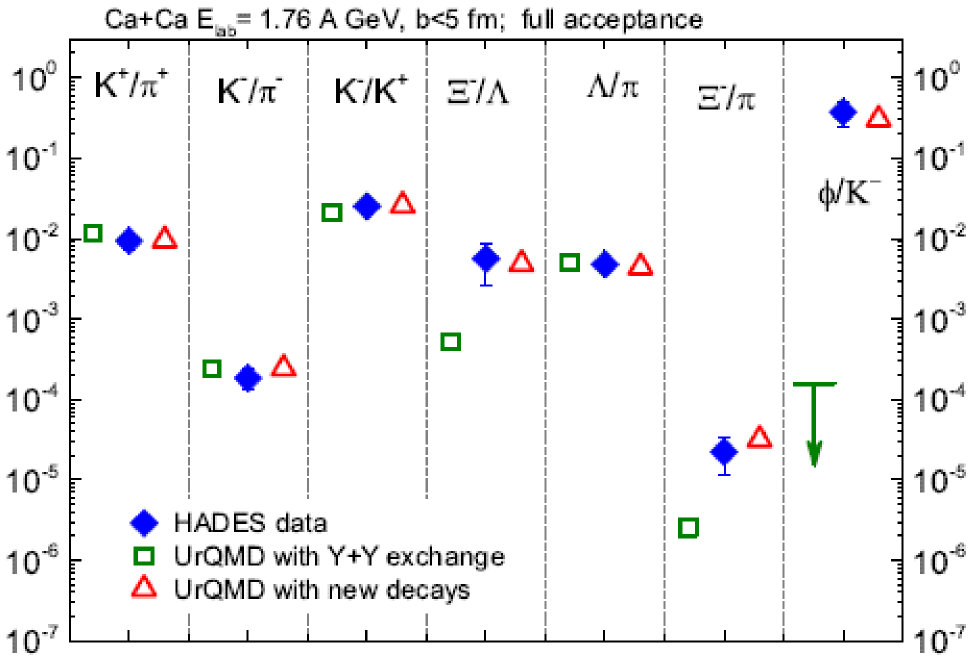
Works for strange hadrons....

- Sub threshold phi production well described.



- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV
- High energies: too low due to string production
- HADES results for 1.23 A GeV.

- Same for Xi. But here there is less data and no elementary cross section available.



- Ξ^- yield in Ar+KCl collisions is nicely reproduced
- Consistent with the p+Nb data.
- Indication for Ξ production from non-thermal 'tails' of particle production.
- All other strange particle ratios are also in line with experiment

What are the consequences?

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Subthreshold Kaon Production as a Probe of the Nuclear Equation of State

J. Aichelin and Che Ming Ko[a]
Joint Institute for Heavy Ion Research, Holifield Heavy Ion Research Facility, Oak Ridge, Tennessee 37831
(Received 11 June 1985; revised manuscript received 23 September 1985)

The production of kaons at subthreshold energies from heavy-ion collisions is sensitive to the nuclear equation of state. In the Boltzmann-Uehling-Uhlenbeck model, the number of produced kaons from central collisions between heavy nuclei at incident energies around 700 MeV/nucleon can vary by a factor of ~ 3, depending on the equation of state.

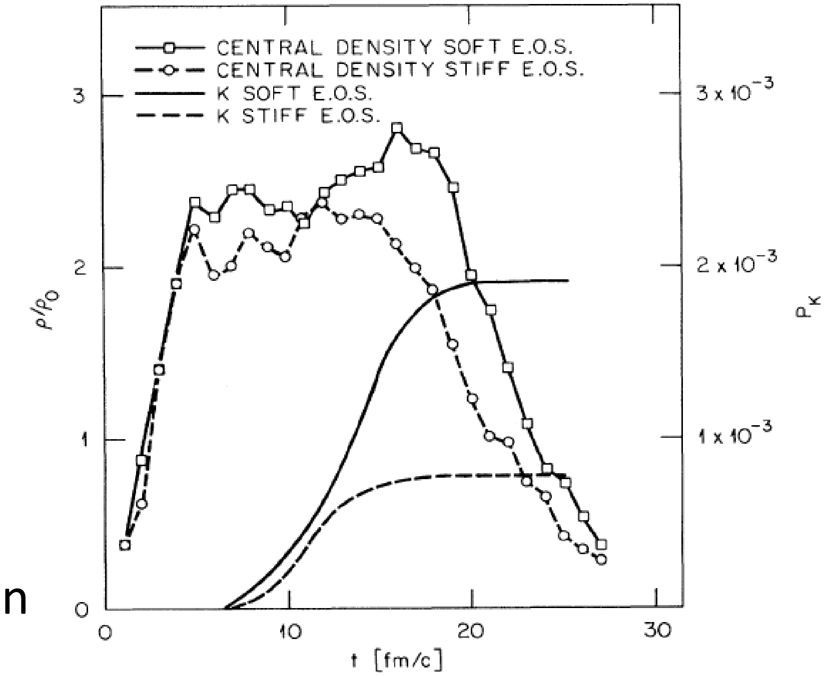


FIG. 1. Central density ρ/ρ_0 and total kaon-production probability P_K as functions of the collision time for reactions between Nb nuclei at an incident energy 700A MeV and at an impact parameter $b = 0.5$ fm.

In a nutshell:

- Softer EoS leads to higher compression leads to more secondary interaction
- Thus the larger probability to produce particles sub-threshold

Potentials in UrQMD

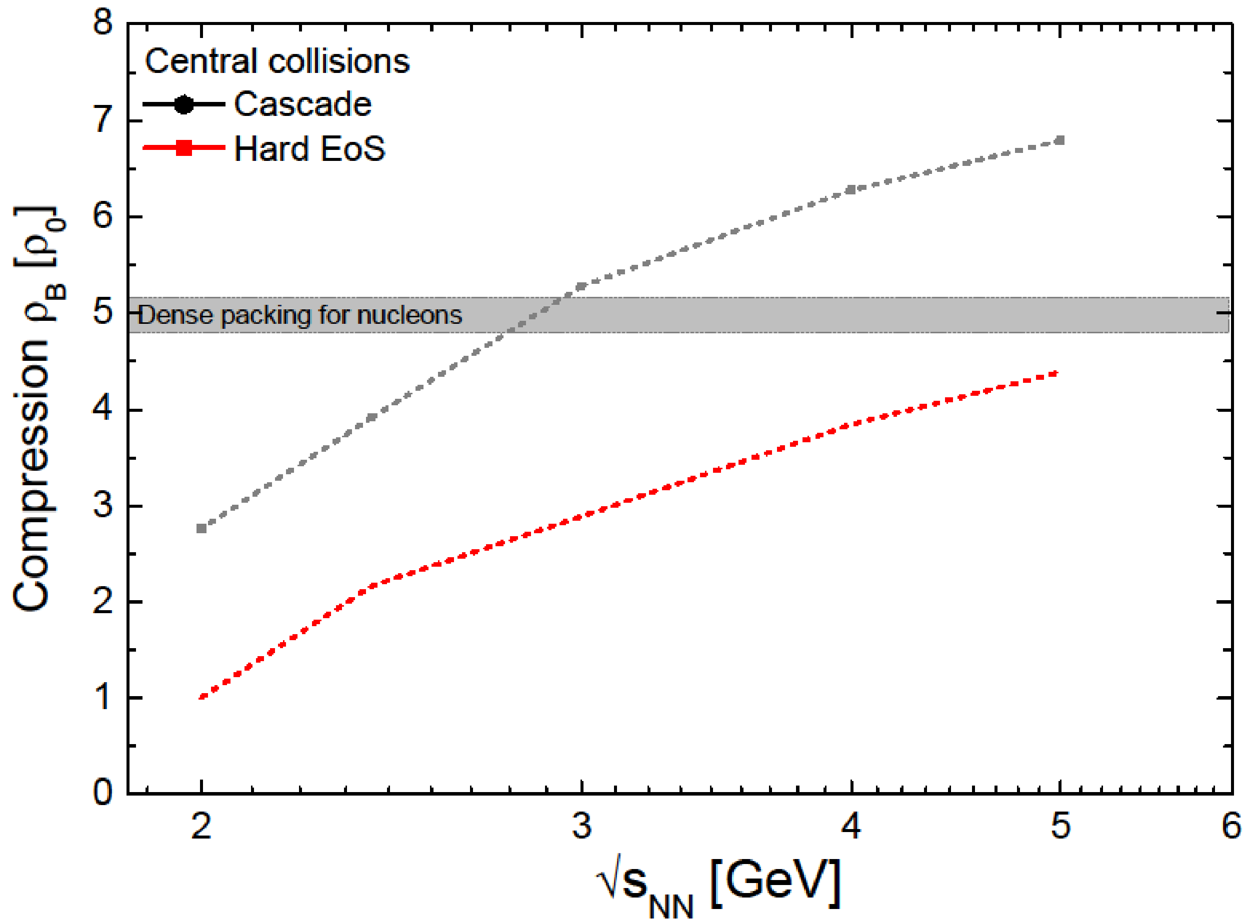
- UrQMD employs a QMD approach with a Skyrme-type mean field potential.
- The force that acts on a nucleon is calculated from the local interaction density which enters the two terms of the Skyrme potential.

$$V_j^{\mathrm{Sk2}} = t_1 \varrho_j^{\mathrm{int}}(\boldsymbol{r}_j) \qquad V_j^{\mathrm{Sk3}} \approx t_2 3^{-\frac{3}{2}} (\varrho_j^{\mathrm{int}})^2 \rightarrow t_\gamma (\gamma+1)^{-\frac{3}{2}} (\varrho_j^{\mathrm{int}})^\gamma$$

- The parameters are partly fixed by demanding stable nuclear matter around saturation density.
- This leaves one free parameter which the controls the „stiffness" of the EoS
- Note, this approach is rather rudimentary as it does not allow for any realistic high density EoS.
- Right now: only proof of concept.

Densities reached at SIS100

- The densities reached in the SIS100 energy range depend strongly on the EoS.
- This will strongly influence whether we see deconfinement or not.
- Here: What is the effect on charm?



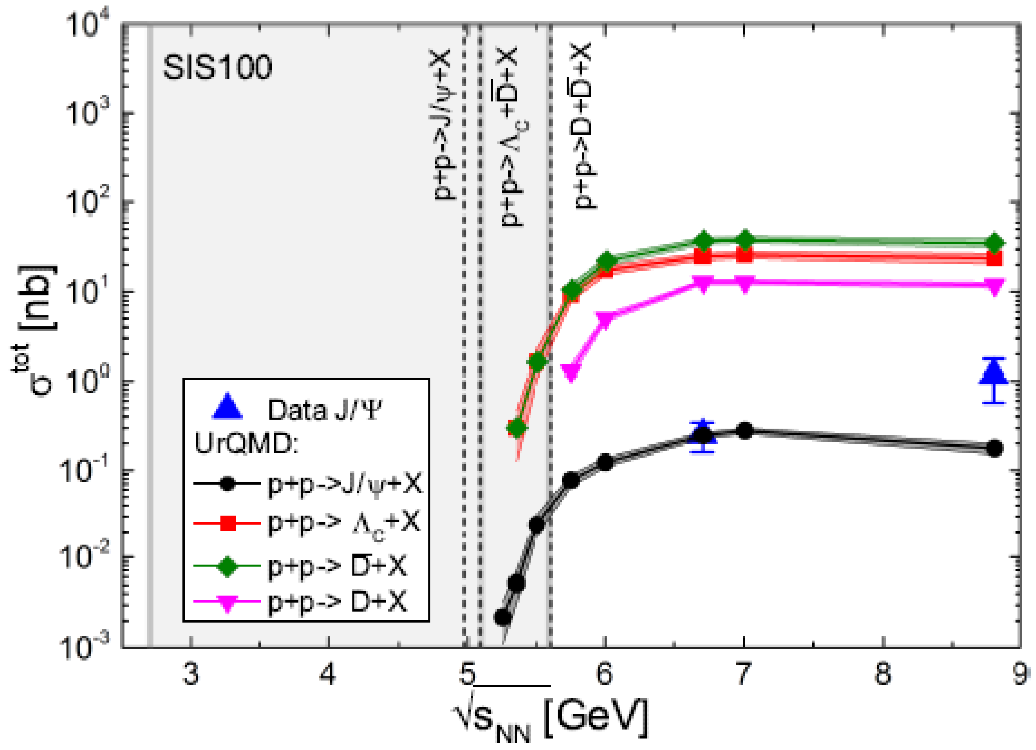
Can we make predictions about sub-threshold charm production?

J. Steinheimer, A. Botvina and M. Bleicher, Phys. Rev. C **95**, no. 1, 014911 (2017)

- Charm needs some very high mass states
- Basically on the transition to a string
- However, convenient for associated production

N*(1650)	Δ(1232)
N*(1710)	Δ(1600)
N*(1720)	Δ(1620)
N*(1875)	Δ(1700)
N*(1900)	Δ(1900)
N*(1990)	Δ(1905)
N*(2080)	Δ(1910)
N*(2190)	Δ(1920)
N*(2220)	Δ(1930)
N*(2250)	Δ(1950)
N*(2600)	Δ(2440)
N*(2700)	Δ(2750)
N*(3100)	Δ(2950)
N*(3500)	Δ(3300)
N*(3800)	Δ(3500)
N*(4200)	Δ(4200)

We use data from p+p at $\sqrt{s} = 6.7$ GeV to fix the $N^* \to N + J/\Psi$ branching fraction.



Only 1 parameter

$$\Gamma_{N^* \to N J\Psi} / \Gamma_{tot} = 5 \cdot 10^{-5}$$

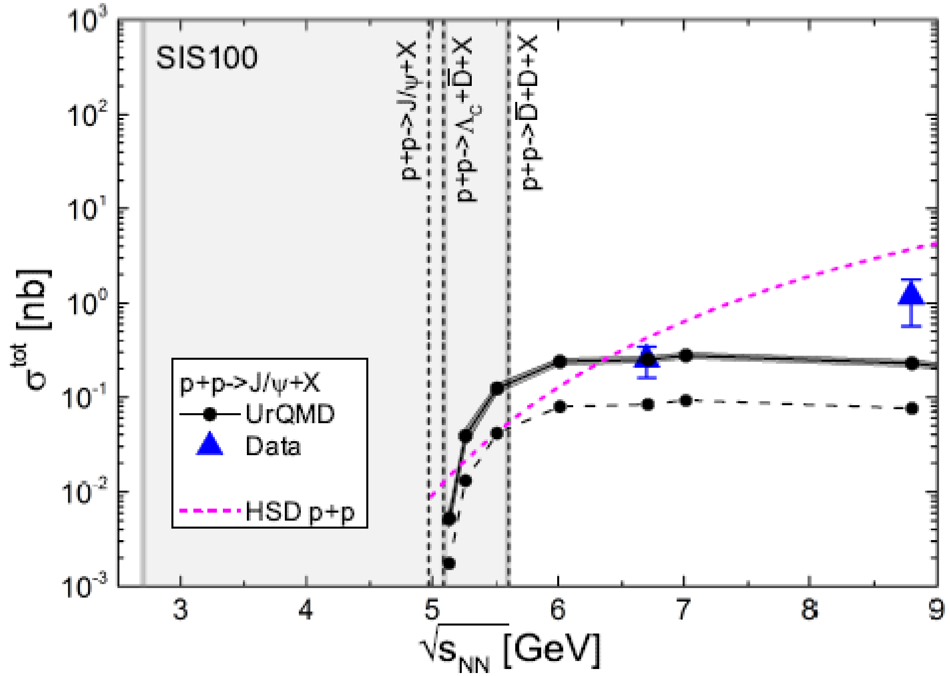
Assumptions

- We assume the associated production of $N^* \to \Lambda_c + \overline{D}$ to be a factor 20 larger at that beam energy and to contribute about the half of the total charm production.
- $D + \overline{D}$ pair production is also allowed with $\Gamma_{N^* \to N + D + \overline{D}} / \Gamma_{tot} = 2 \cdot 10^{-3}$
- No string production

Comparisons to HSD

Parametrized cross section for J/Ψ

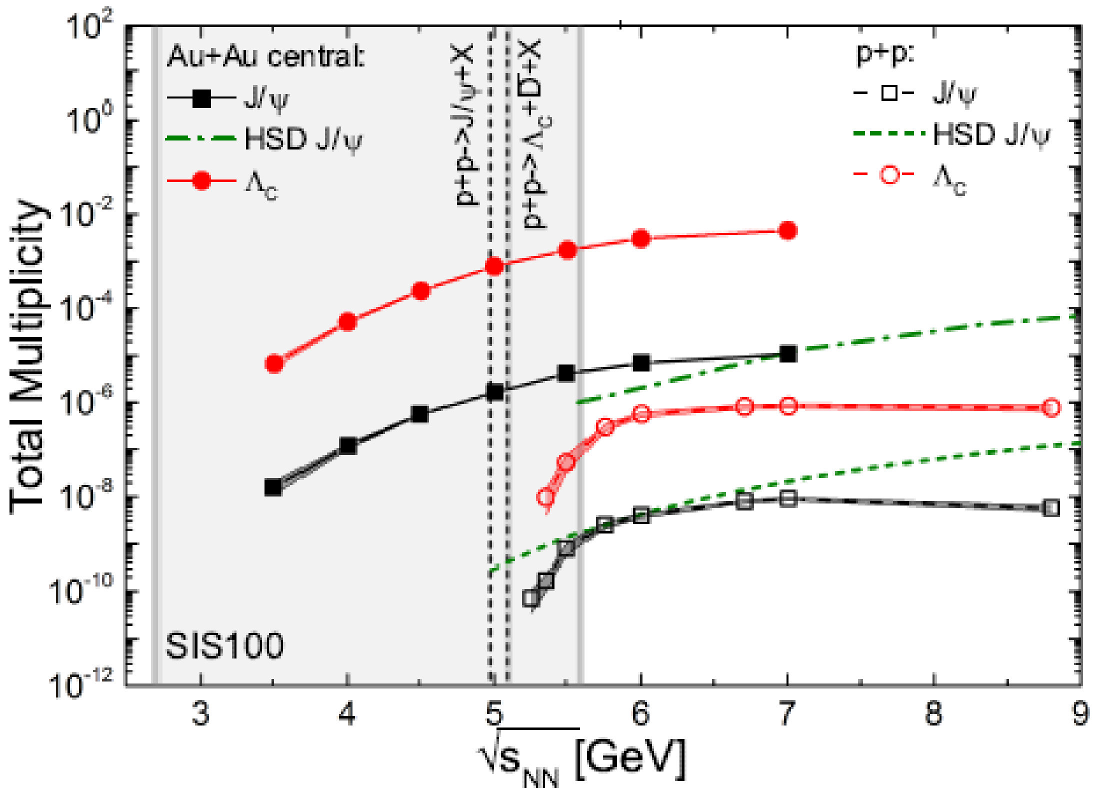
$$\sigma_i^{NN}(s) = f_i a \left(1 - \frac{m_i}{\sqrt{s}}\right)^{\alpha} \left(\frac{\sqrt{s}}{m_i}\right)^{\beta} \theta(\sqrt{s} - \sqrt{s_{0i}})$$



HSD results taken from:

O. Linnyk, E. L. Bratkovskaya and W. Cassing, Int. J. Mod. Phys. E **17**, 1367 (2008)

When applied to central nuclear collisions (min. bias: divide by 5):



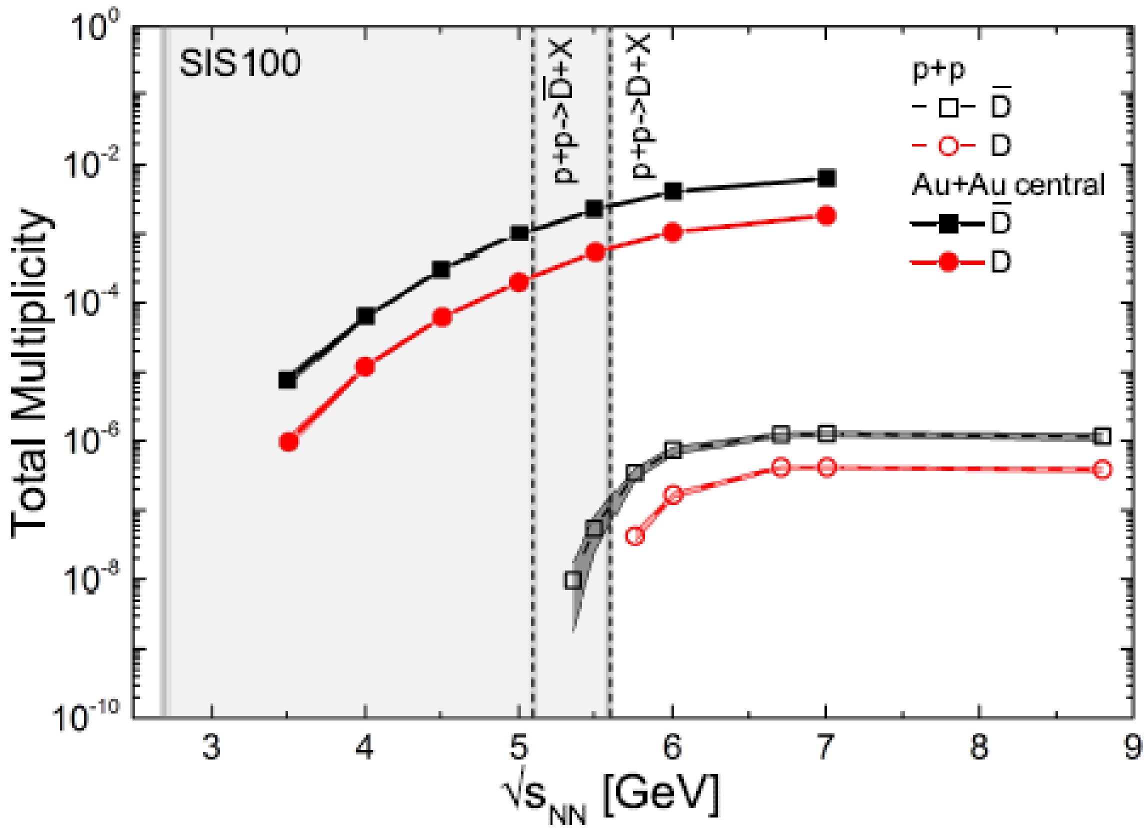
$E_{\text{lab}} = 6$ A GeV

- $1 \cdot 10^{-7}$ J/Ψ per event.
- $5 \cdot 10^{-5}$ Λ_c per event.

$E_{\text{lab}} = 11$ A GeV

- yield is about one order of magnitude larger

When applied to central nuclear collisions (min. bias: divide by 5):



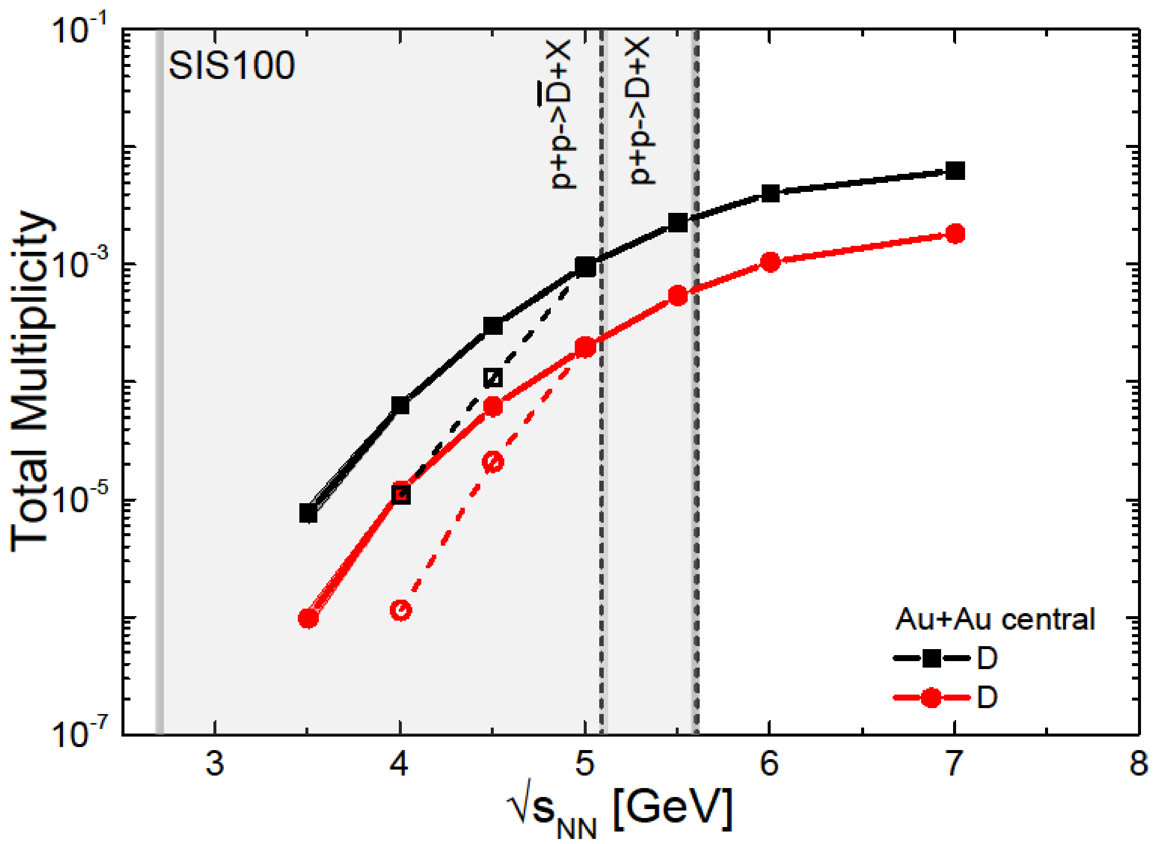
$E_{\mathrm{lab}} = 6$ A GeV

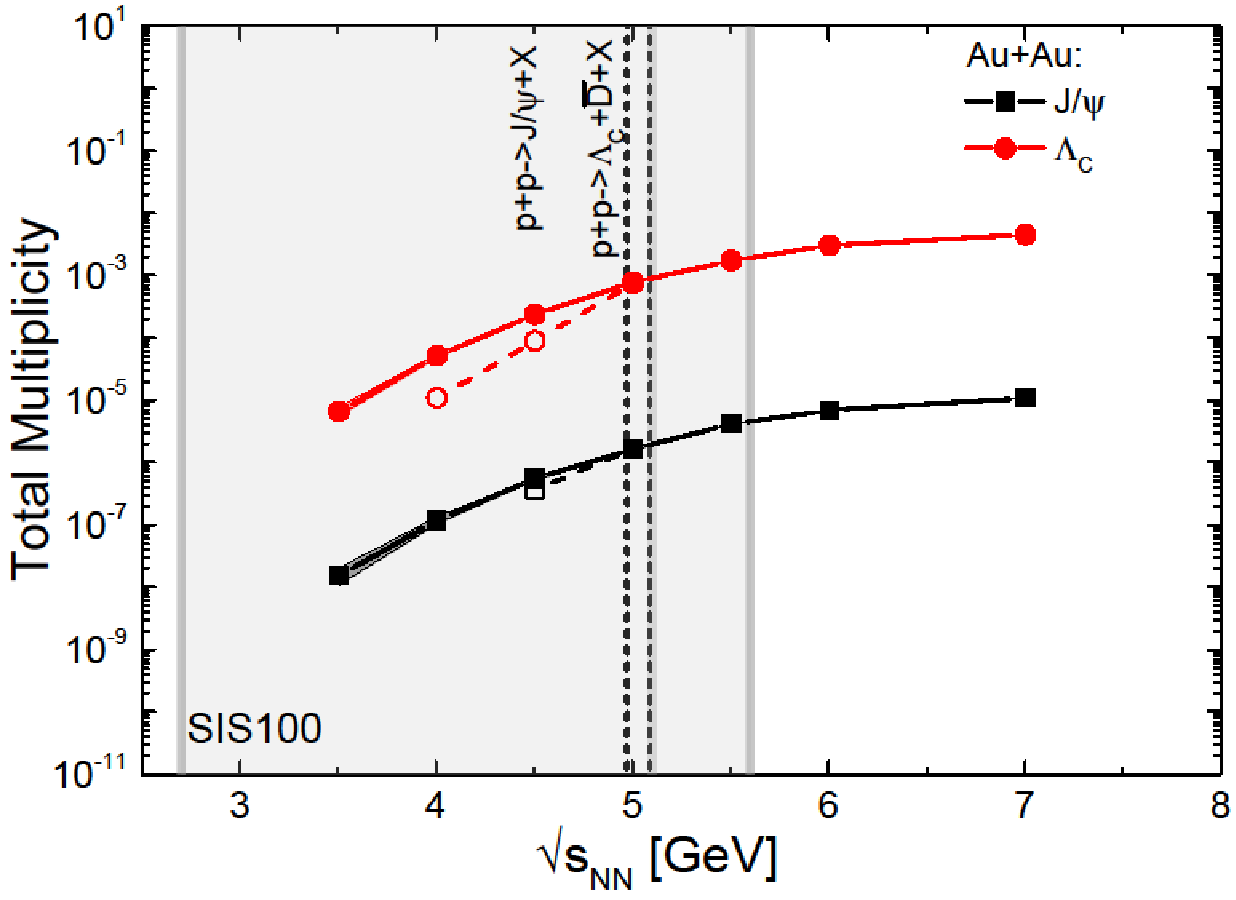
- $6 \cdot 10^{-5}$ $\overline{D}$ per event.
- $1 \cdot 10^{-5}$ D per event.

$E_{\mathrm{lab}} = 11$ A GeV

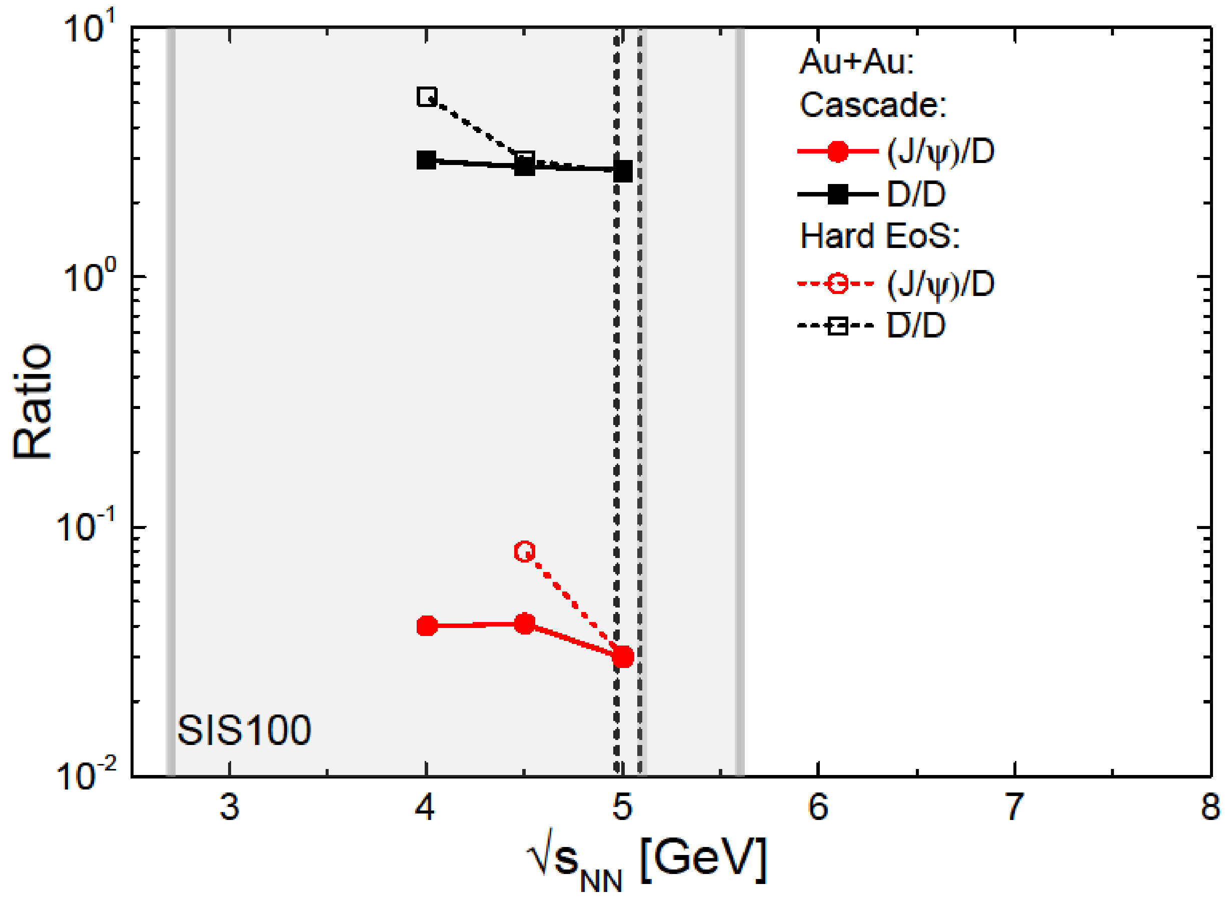
- Yield is about one order of magnitude larger

What happens if we introduce nuclear potentials?





Charmed ratios



Charm production depends on the EoS

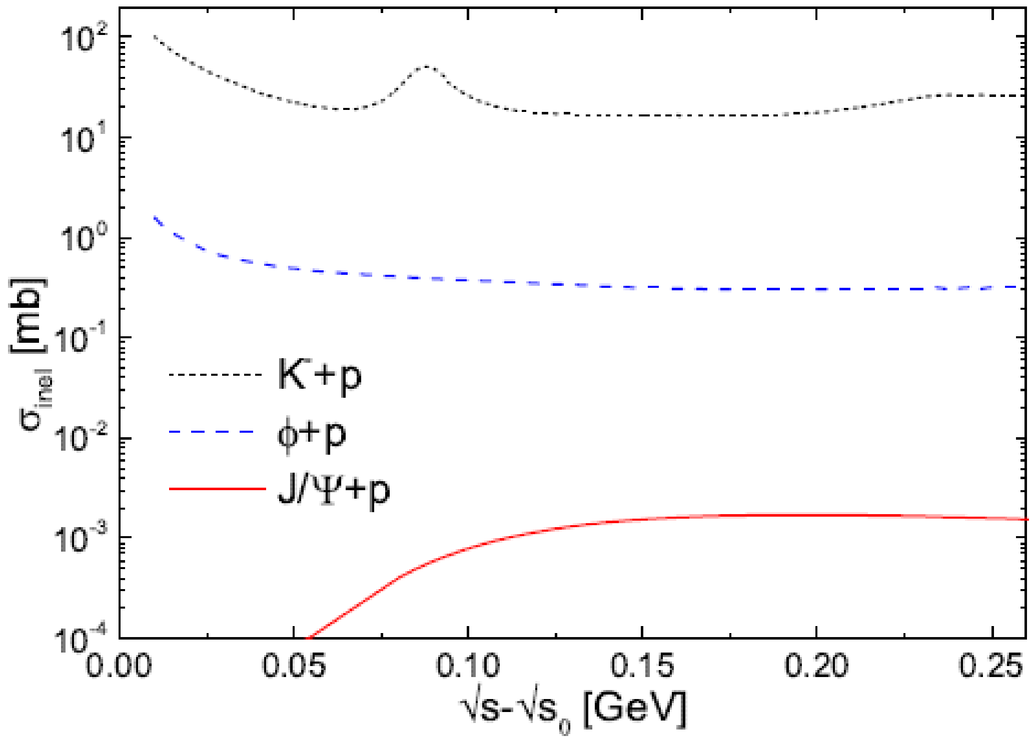
- As for strangeness production the probability to produce charm sub-threshold depends on the maximal compression and thus on the EoS.
- This time the density is larger, so we can probe higher densities.
- On the other hand effects of deconfinement and chiral symmetry restauration have not been considered.
- That makes the whole situation more complicated/interesting
- If charm stays a relevant part of CBM physics, significant work ahead.

Suppression of J/Psi in nuclear medium.

- In p+A collisions we can study the absorption of J/Psi in nuclear matter.
- First we need some understanding of how that absorption can appear and what the cross section may be.

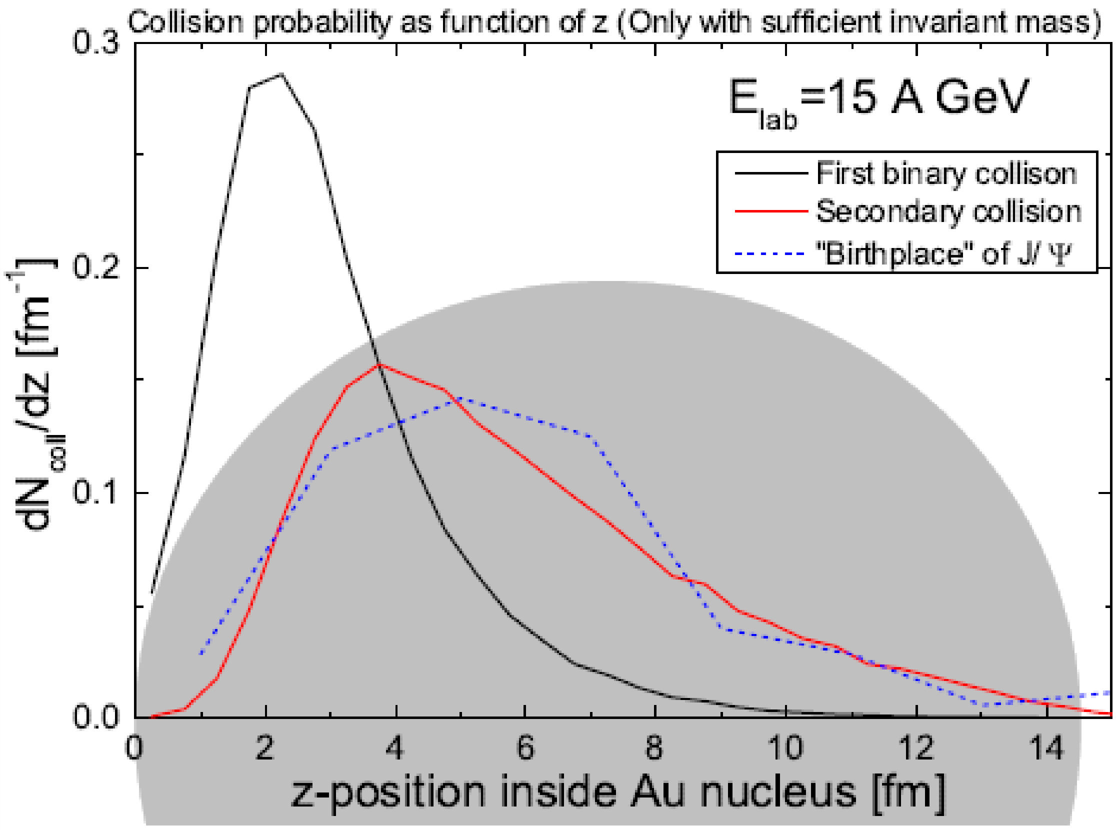
Detailed balance → absorption cross section

- $J/\Psi + p$ cross section from detailed balance is very small.



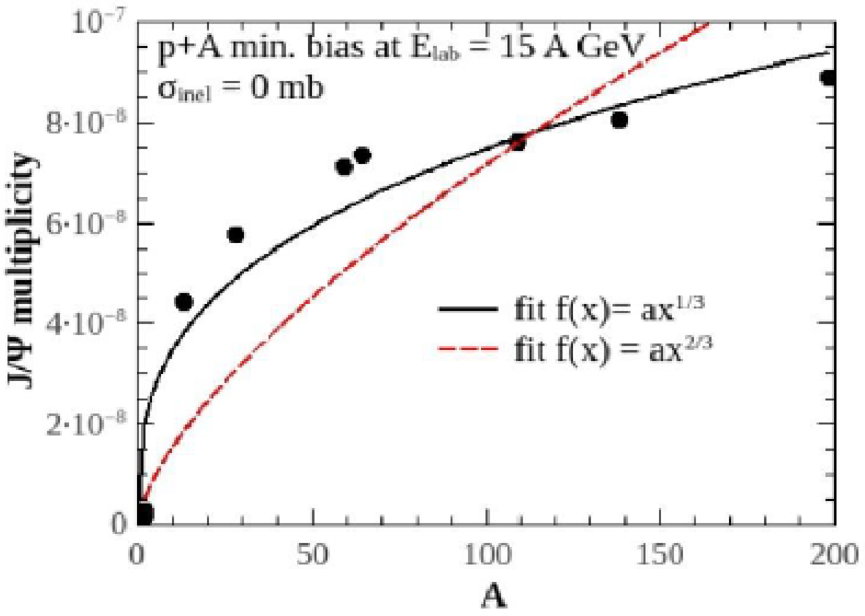
Birthplace of the J/Ψ

- The J/Ψ is 'born' after the heavy state decays inside the nucleus.
- Not 'absorption' of the J/Ψ, but of the mother resonance.
- Reactions of the type:
  $N^* + N \rightarrow N'^* + N'^*$
  $N^* + N \rightarrow N'^* + N'^*$
  where the mass of $N'^* < N^*$ so no J/Ψ can be produced.



The p+A case: nuclear absorption

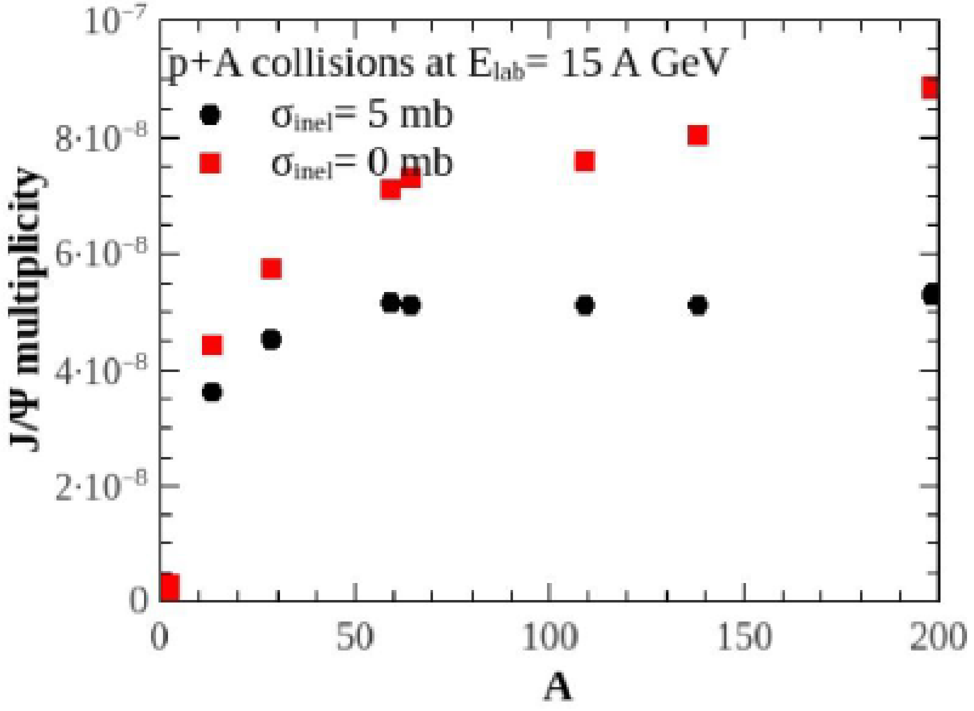
- Close to threshold the J/Ψ production is proportional to $A^{1/3}$.



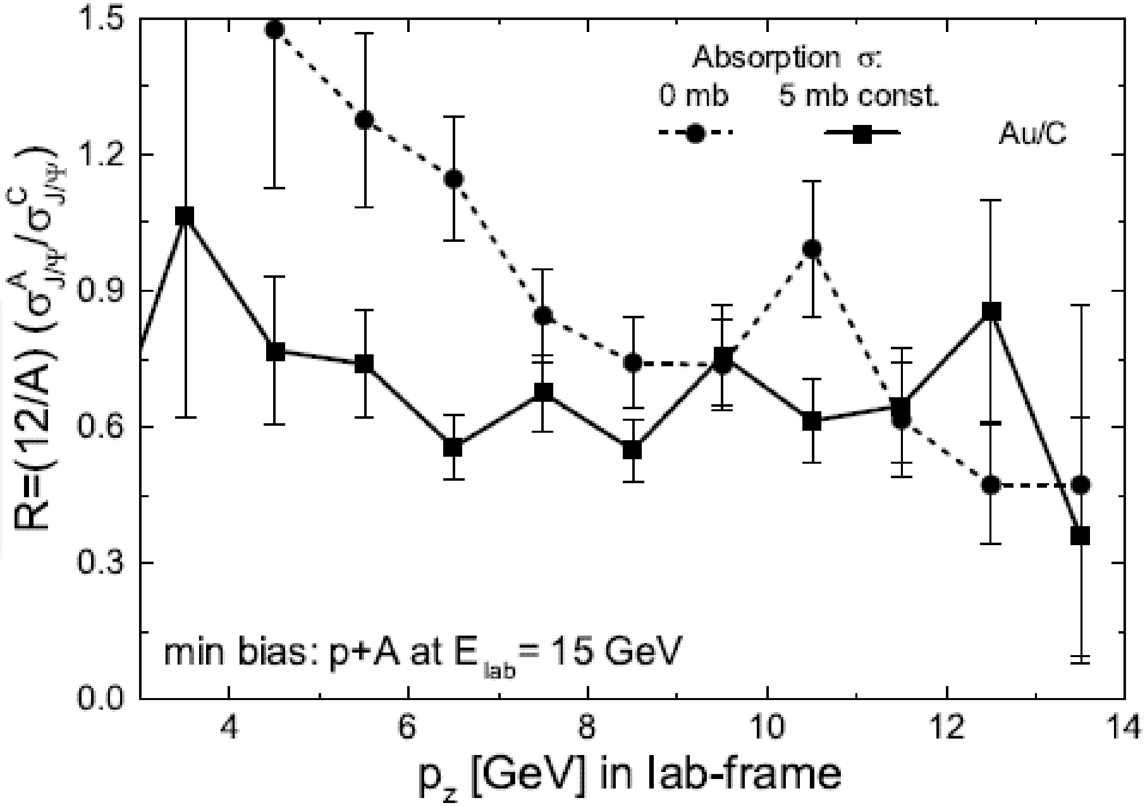
- Bachelor thesis of Thorben Finke, 2017

The p+A case: nuclear absorption

- Close to threshold the J/Ψ production is proportional to $A^{1/3}$.
- Clear effect of a constant absorption cross section: saturation of yield for large nuclei.

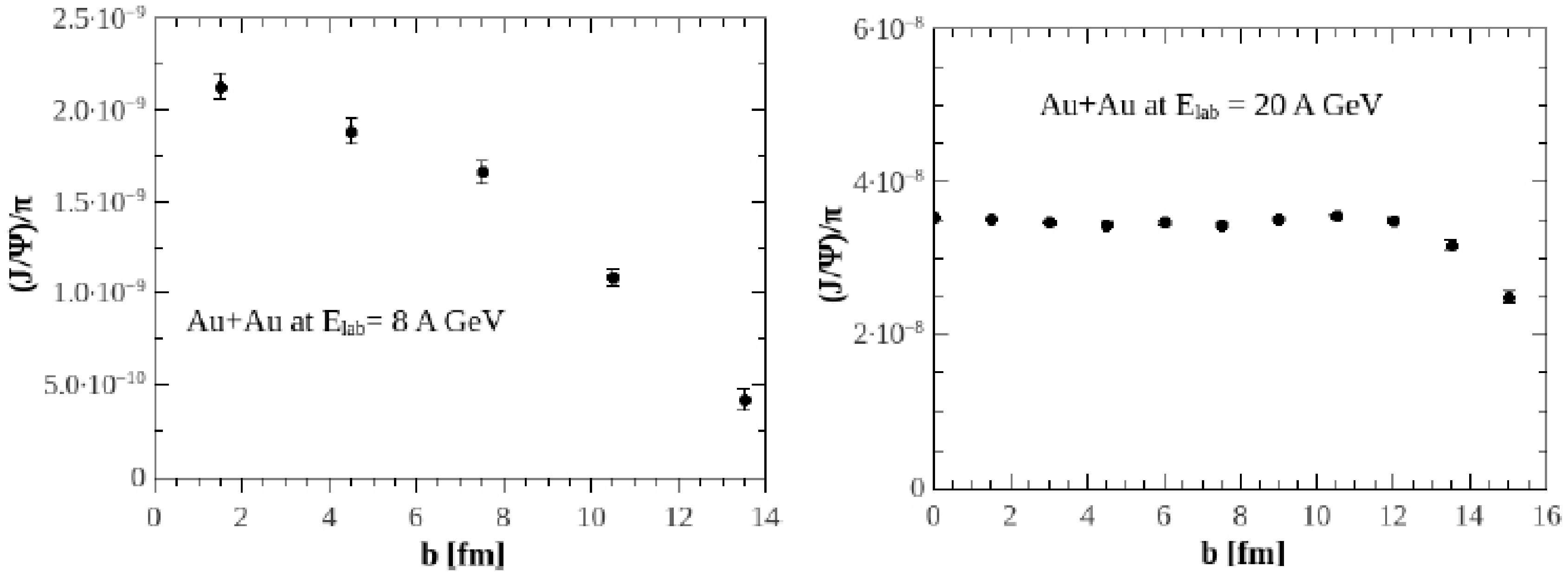


- The absorption cross section then can be measured by comparing different system sizes.



Centrality dependence as indicator for production process

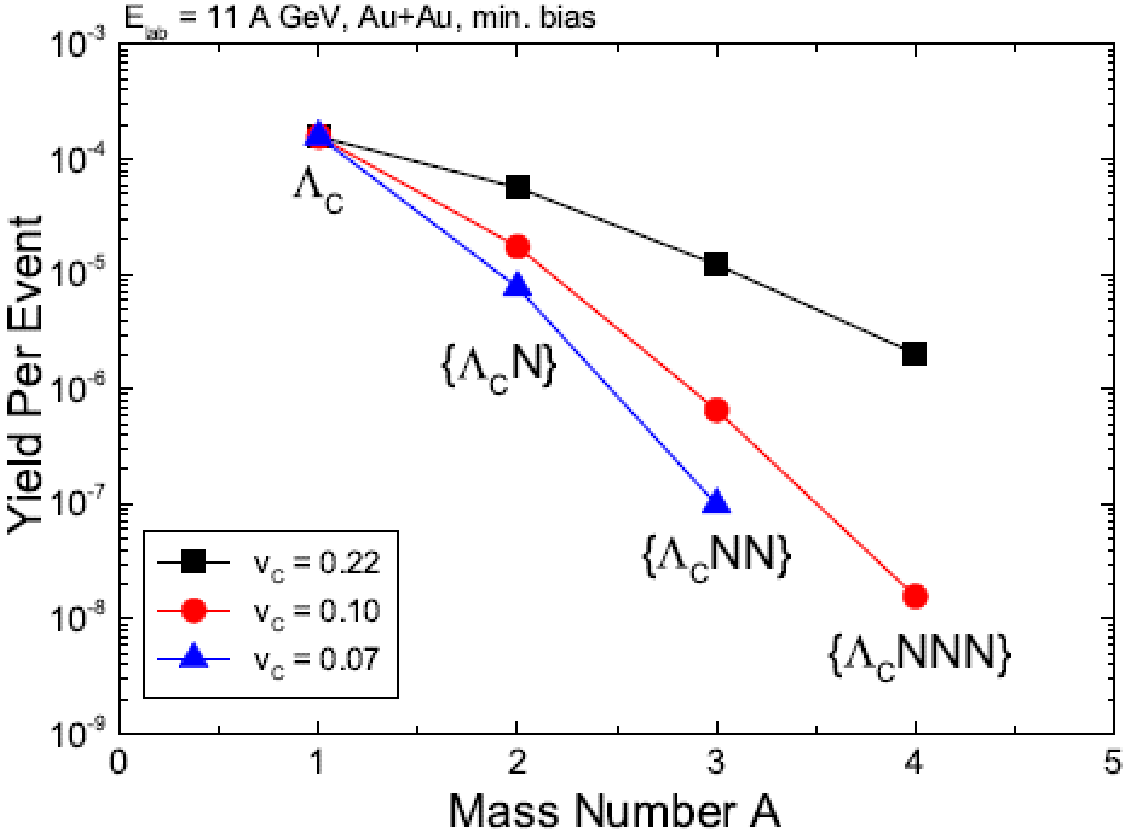
- Below threshold J/Ψ per pion yield keep sincreasing due to secondary interactions.
- Above the threshold we observe almost no centrality dependence, consistent with a Glauber model.
- Direct production dominates.



Charmed nuclei

- Nuclei with one or more bound Λ_c are called charmed (super-)nuclei.
- Very useful to understand charmed nuclear interactions.
- Studies at J-PARC discussed.

Our prediction from coalescence:



Summary

- Charm physics at CBM and SIS100 still has some potential
- Even probing the dense EoS may be possible
- Nuclear absorption can be large, even if the actual cross section of a formed J/Psi is small.
- Prospects of discovering the first charmed nucleus?

- Enjoy the afternoon!