Charm and strangeness production at GSI/FAIR energies

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FAIR: Facility for Antiproton and Ion Research

Location: GSI, Darmstadt, Germany

What is sub-threshold particle production?

And why is it interesting for us?

Production of hadrons below threshold

- In elementary reactions, e.g. pp, it is not possible to produce a particle with mass m_{new}, if $m_P+m_P+m_{new}>E_{CM,pp}$ (energy conservation)
- However, in p+A and A+A reaction this is possible
- The question is, what mechanism allows for the production and are they realized

Mechanisms

- Generally three different mechanisms are available:

  1) Fermi motion
  (more energy available than we thought)

  2) mass reduction/potentials
  (lowers the threshold for production)

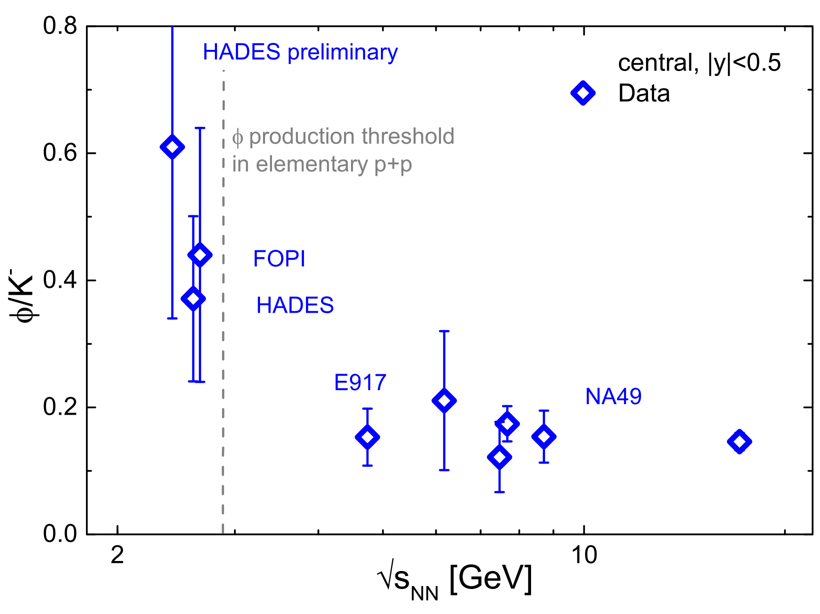
  3) multi-step/multi-particle processes
  (collect energy to reach the threshold)

This talk...

- Explores multi-strange particle production
  i.e. ϕ and Ξ production
  → solves a long standing puzzle at GSI energies

- Explores charm production
  i.e. J/Ψ, Lc and D-mesons
  → new road for a charm program at FAIR

Motivation: ϕ

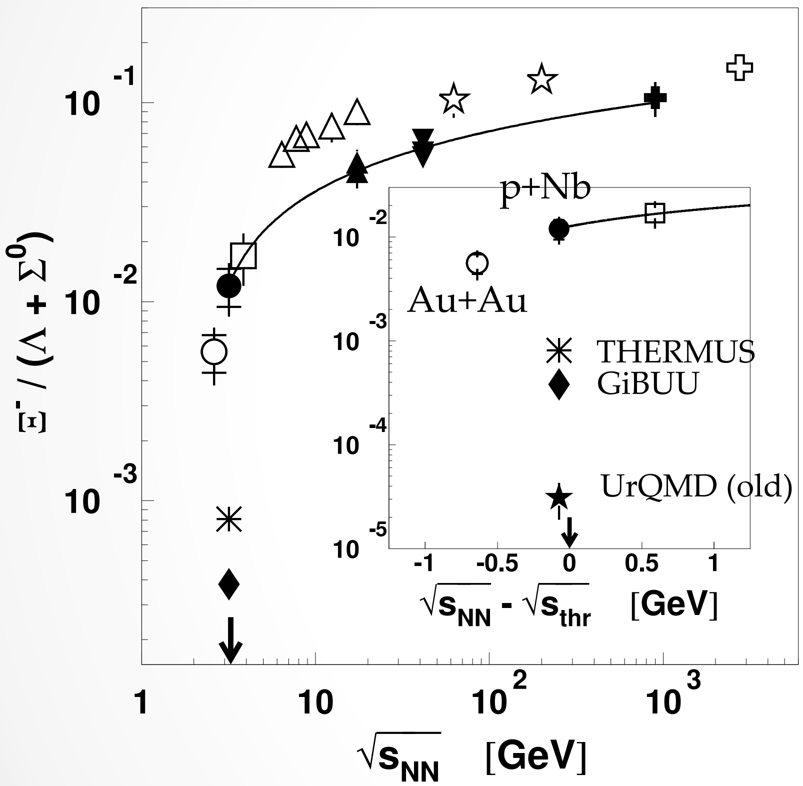


ϕ production

HADES and FOPI reported unexpected large ϕ contribution to the K^- yield.

G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **80**, 025209 (2009)

Motivation: Ξ



G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **80**, 025209 (2009)

ϕ production

HADES and FOPI reported unexpected large ϕ contribution to the K^- yield.

Ξ production

Ξ^- yield, measured in Ar+KCl much larger than thermal model.
Confirmed in p+Nb $\rightarrow$ No Y+Y exchange!!

Both particles are not well described in microscopic transport models and thermal fits are also not convincing.

Threshold for p+p→p+p+ϕ ≈ 2.895 GeV
Threshold for p+p→N+Ξ+K+K ≈ 3.24 GeV

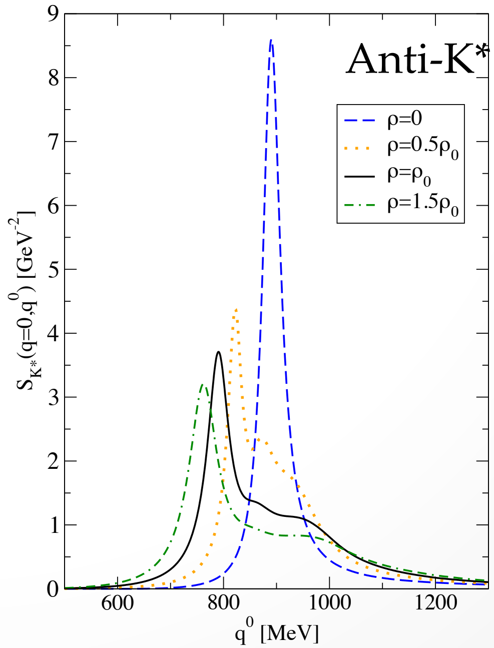
Subthreshold production:Two paradigms

Multi-step processes

- Increase the available energy above threshold by creation of heavy resonances
- NN→NN*, N*N*→NN**,
  a) N**N**→ string→X
  b) N**→Nϕ
  c) N**→ΞKK

In-medium modifications

- Decrease the needed energy by in-medium modifications



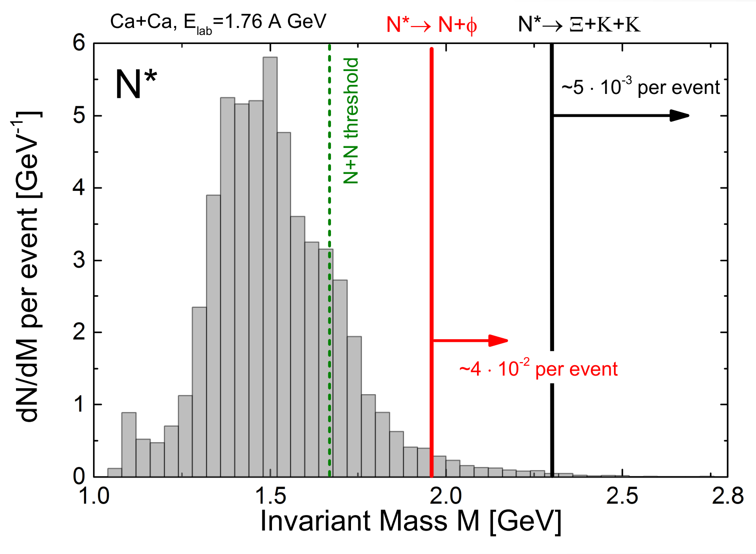
L. Tolos et al., Phys.Rev.C82:045210,2010

Subthreshold particle production

How does it work?

- Fermi momenta can lift the collision energy above threshold
- Secondary interactions accumulate energy
- Ar+KCl at E_{lab}=1.76 AGeV
  Is there enough energy for ϕ and Ξ production?

Resonance mass distribution



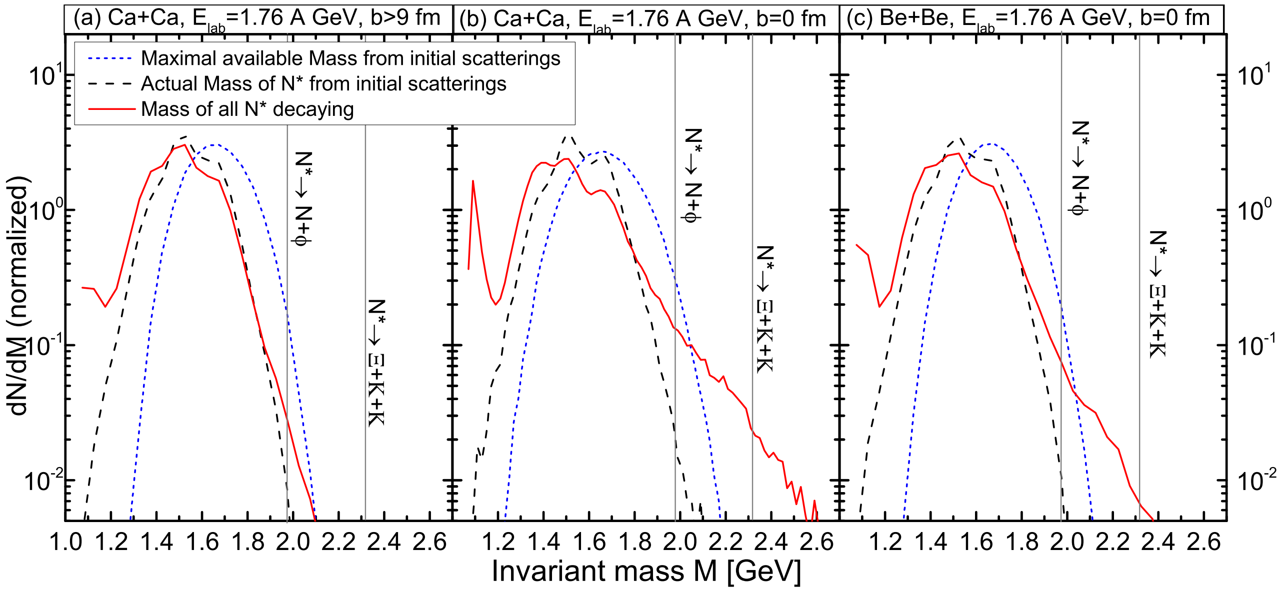
Yes! But for Ξ, only in the tails.

→ Introduce branching ratio for decay into Nϕ

Probabilities

Sub-threshold production baseline

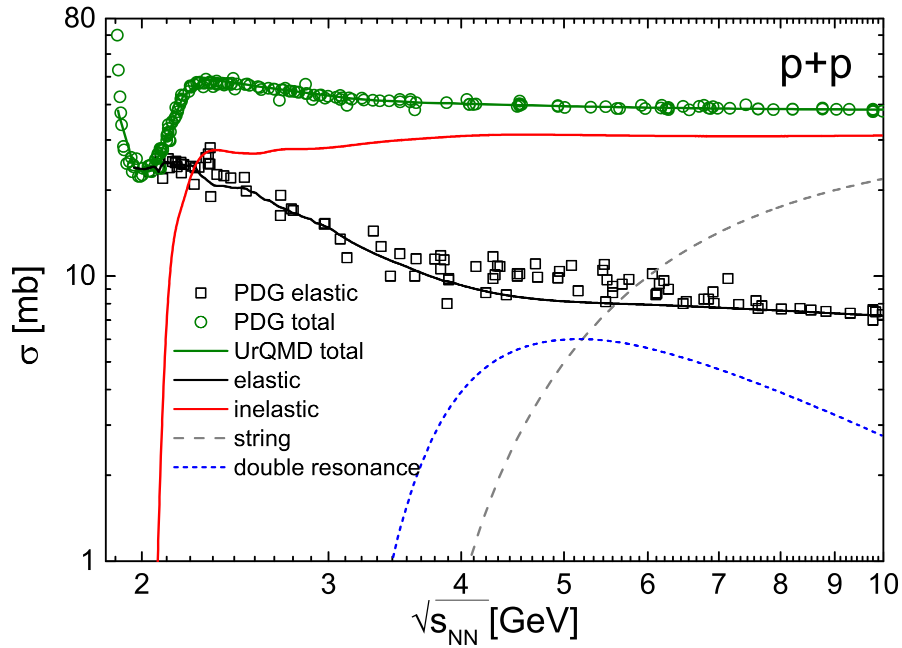
- Fermi momenta lift the collision energy above the threshold.
- Secondary interactions accumulate energy.



Why not introduce these decays for the less known resonances?

New resonances

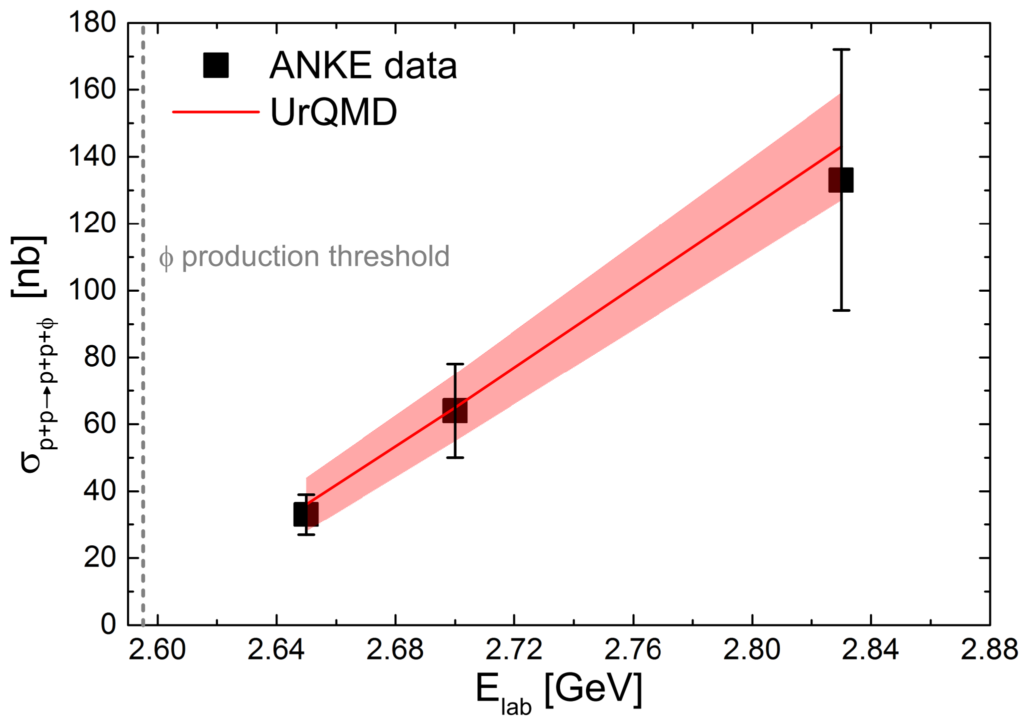
N*(1650)	Δ(1232)
N*(1710)	Δ(1600)
N*(1720)	Δ(1620)
N*(1875)	Δ(1700)
N*(1900)	Δ(1900)
N*(1990)	Δ(1905)
N*(2080)	Δ(1910)
N*(2190)	Δ(1920)
N*(2220)	Δ(1930)
N*(2250)	Δ(1950)
N*(2600)	Δ(2440)
N*(2700)	Δ(2750)
N*(3100)	Δ(2950)
N*(3500)	Δ(3300)
N*(3800)	Δ(3500)
N*(4200)	Δ(4200)



Important: New resonances replace the strings, no additional pp cross section is introduced

Fixing the branching ratio

We use ANKE data on the ϕ production cross section to fix the $N^* \to N + \phi$ branching fraction.



Only 1 parameter

$\Gamma_{N^*\to N\phi}/\Gamma_{tot} = 0.2\%$

1 parameter fits all 3 points!

Y. Maeda *et al.* [ANKE Collaboration], Phys. Rev. C **77**, 015204 (2008) [arXiv:0710.1755 [nucl-ex]].

The ϕ+N cross section

Does the ϕ have a small hadronic cross section?

- The idea that the ϕ has a small hadronic cross section is not new.
  A. Shor, Phys. Rev. Lett. **54**, 1122 (1985).
- The ϕ would be an important probe of hadronization.
- COSY and LEPS experiments have found large nuclear absorption cross sections

ANKE	SPring-8
14-21 mb	35 mb

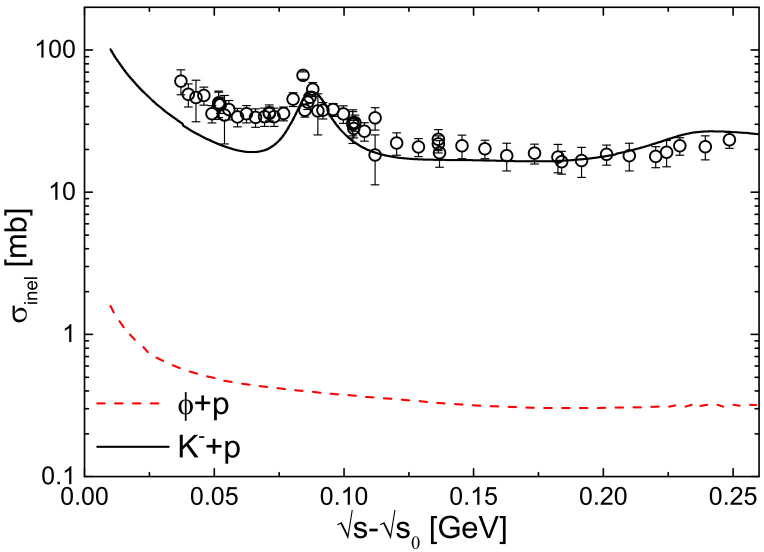
M. Hartmann *et al.*, Phys. Rev. C **85**, 035206 (2012)
T. Ishikawa *et al.*, Phys. Lett. B **608**, 215 (2005)

Cross sections

Detailed balance $\rightarrow$ absorption cross section

$$\frac{d\sigma_{b\to a}}{d\Omega} = \frac{\langle p_a^2\rangle}{\langle p_b^2\rangle}\frac{(2S_1+1)(2S_2+1)}{(2S_3+1)(2S_4+1)}\sum_{J=J_-}^{J_+}\frac{\langle j_1 m_1 j_2 m_2 || JM\rangle^2}{\langle j_3 m_3 j_4 m_4 || JM\rangle^2}\frac{d\sigma_{a\to b}}{d\Omega}$$

- $\phi + p$ cross section from detailed balance is very small.

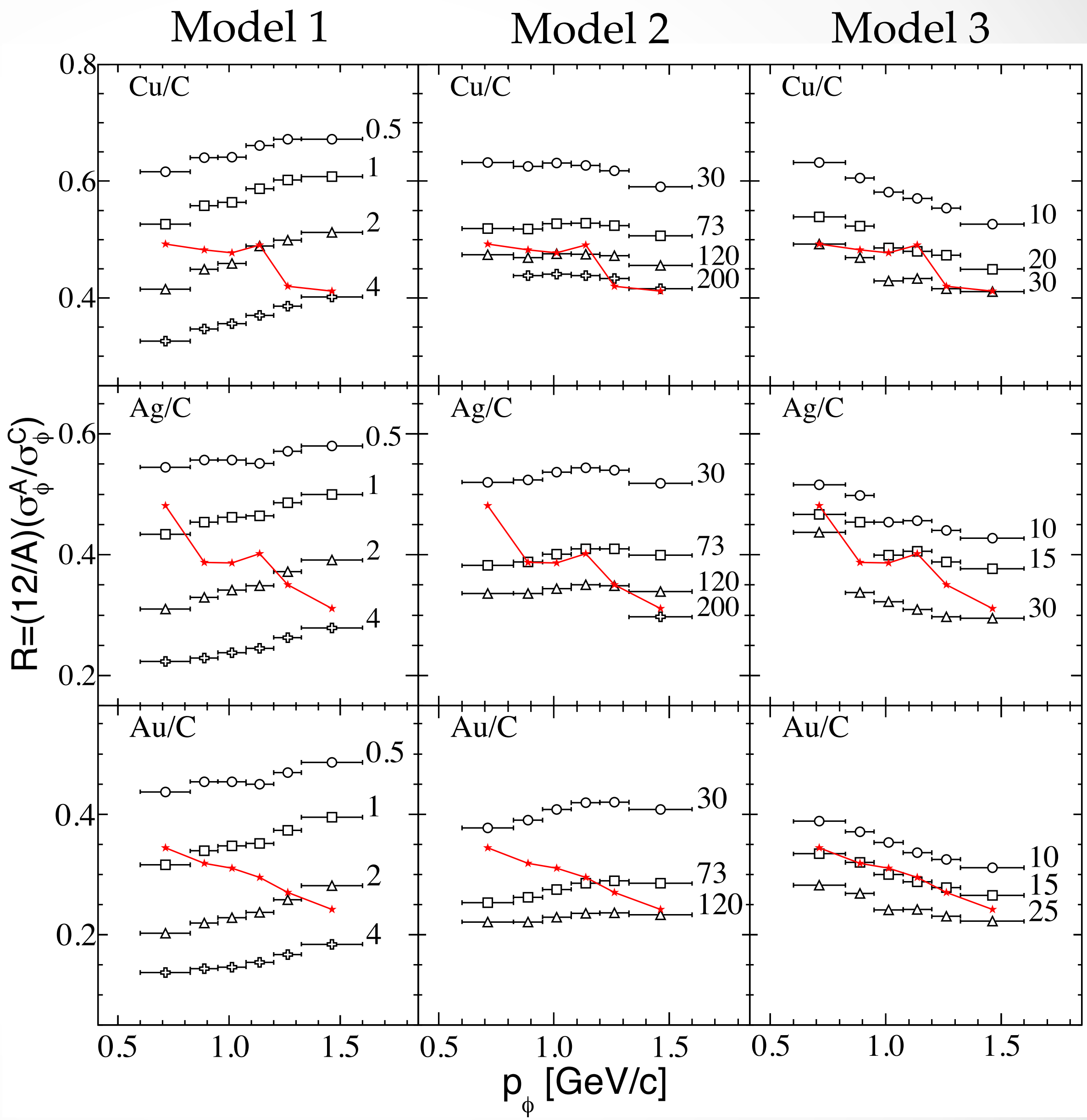


ϕ transparency ratios I

Model 1: The eikonal approximation of the Valencia group.

Model 2: Paryev developed the spectral function approach for ϕ production in both the primary proton- nucleon and secondary pion- nucleon channels.

Model 3: BUU transport calculation of the Rossendorf group. Accounts for baryon-baryon and meson-baryon ϕ production processes.

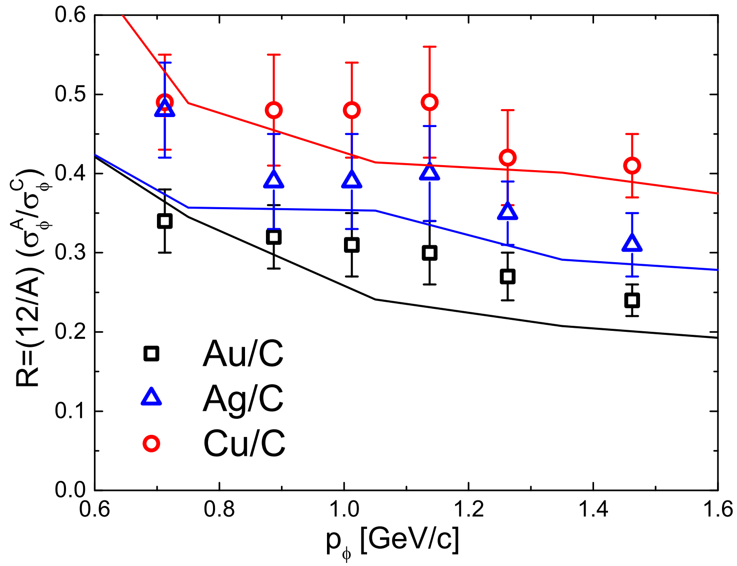


Transparency ratios II

Detailed balance $\to$ absorption cross section

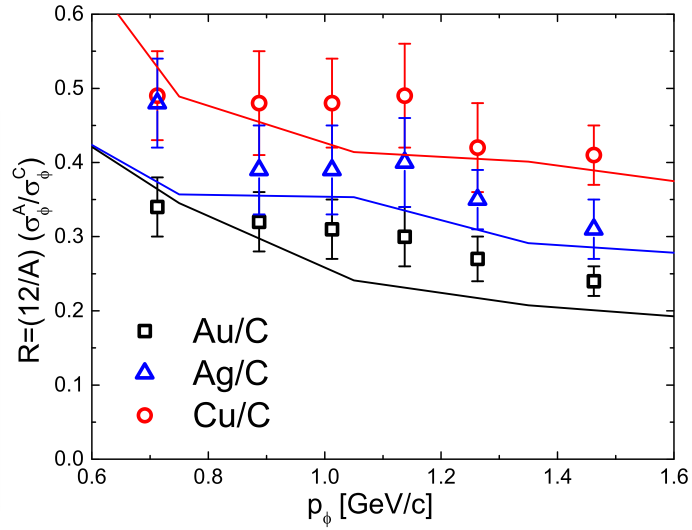
$$\frac{d\sigma_{b\to a}}{d\Omega} = \frac{\langle p_a^2\rangle}{\langle p_b^2\rangle}\frac{(2S_1+1)(2S_2+1)}{(2S_3+1)(2S_4+1)}\sum_{J=J_-}^{J_+}\frac{\langle j_1 m_1 j_2 m_2||JM\rangle^2}{\langle j_3 m_3 j_4 m_4||JM\rangle^2}\frac{d\sigma_{a\to b}}{d\Omega}$$

- $\phi + p$ cross section from detailed balance is very small.
- Still the transparency ratio is well reproduced. Remember: this is what lead to the 20 mb cross section from ANKE.
- Cross section from transparency ratio is model dependent!

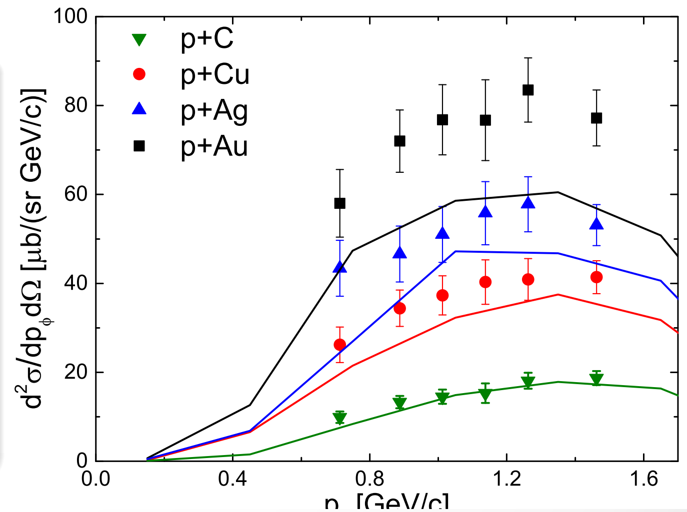


New explanation

- $\phi + p$ cross section from detailed balance is very small.
- Still the transparency ratio is well reproduced. Remember: this is what lead to the 20 mb cross section from ANKE.
- Cross section from trabsparency ratio is model dependent!

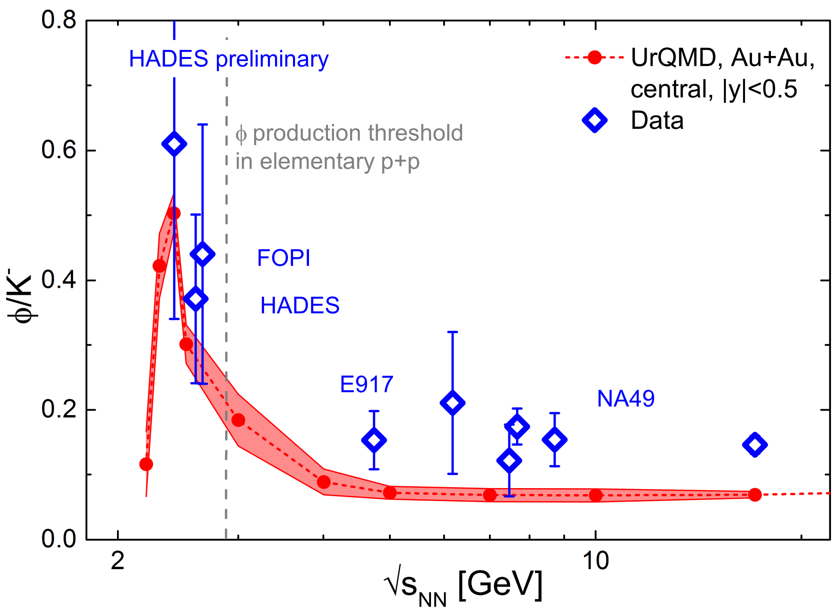


- Not 'absorption' of the ϕ, but of the mother resonance.
- Reactions of the type:
  $N^* + N \rightarrow N'^* + N'^*$
  $N^* + N \rightarrow N'^* + N'^*$
  where the mass of $N'^* < N*$ so no ϕ can be produced.



Extrapolation to AA

When applied to nuclear collisions:

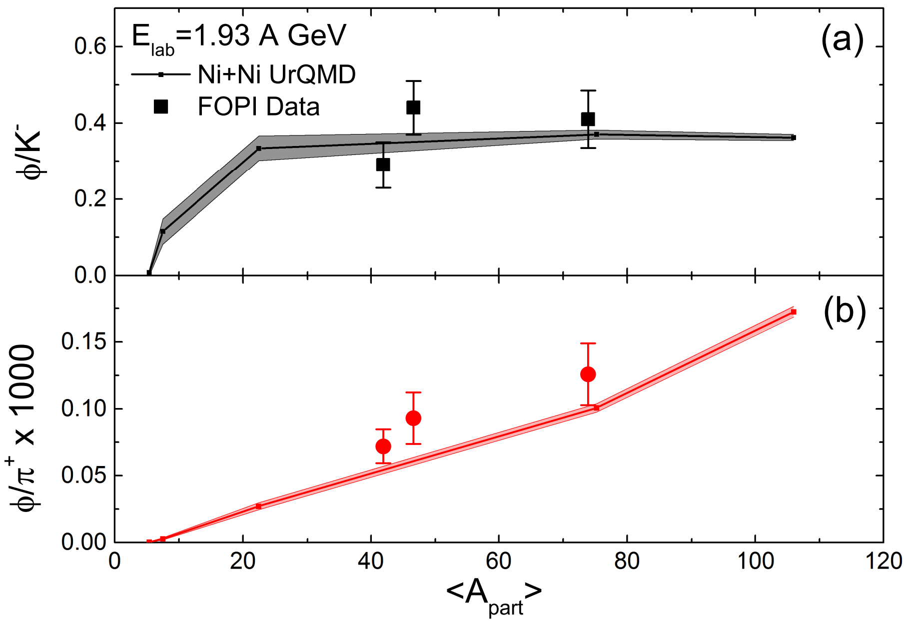


- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV
- High energies: too low due to string production
- HADES preliminary results for 1.23 A GeV, see HADES talks by R. Holzmann and T. Scheib.

Even centrality dependence is very well reproduced: Signal for multi step processes.

Centrality

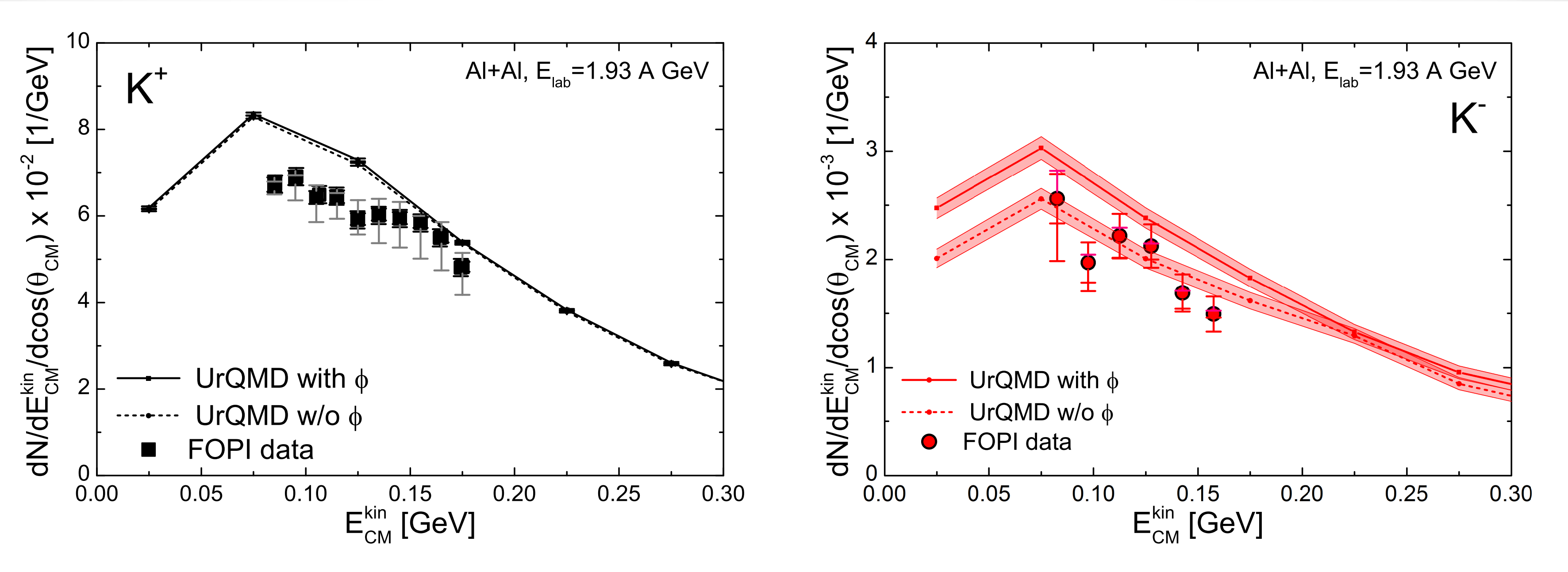
Even centrality dependence works well:



- Centrality dependence nicely reproduced.
- Good indicator for multi step production.

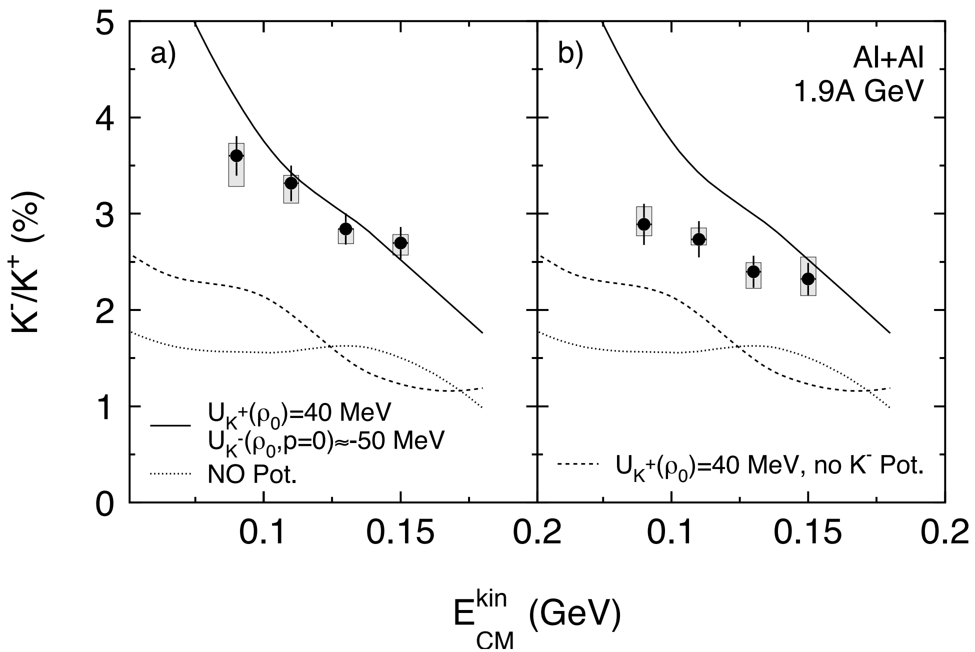
Data from: K. Piasecki et al., arXiv:1602.04378 [nucl-ex].

Plain Kaon yields



Good description of the Kaon data

Comparison to other model studies



P. Gasik *et al.* [FOPI Collaboration], arXiv:1512.06988 [nucl-ex].

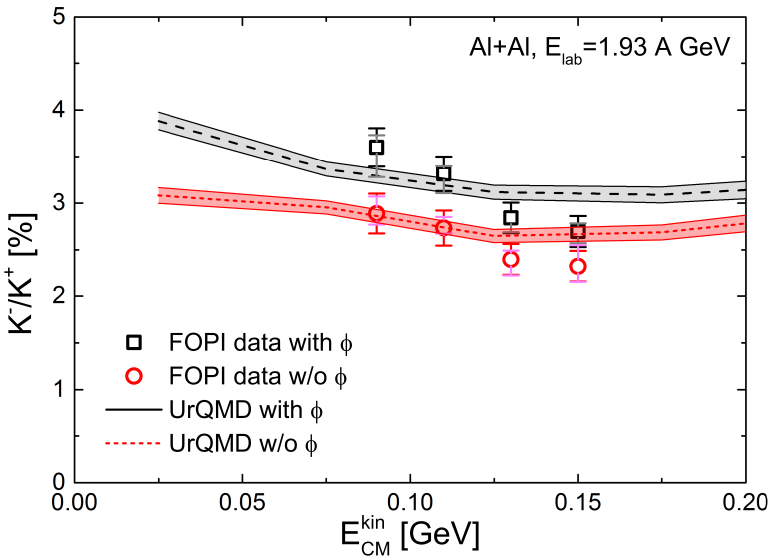
An example

- The K^-/K^+ ratio is used to determine the Kaon nuclear potentials.
- Quantitative result relies on the baseline of non-potential case.
- ϕ contribution to the K^- found to be important.

A word on the K potential

Kaon Potentials

- To constrain the Kaon potentials from kaon spectra one needs to understand the baseline
- For example the ϕ contribution to the K^-.
- But also the general shape of the spectra may depend on the model.



UrQMD results

- K^-/K^+ ratio as function of Kaon energy.
- With and without the ϕ the ratio is much closer to the data already as in a comparable study with K^- potential.
- Can we make robust quantitative statements?

Now for the Ξ

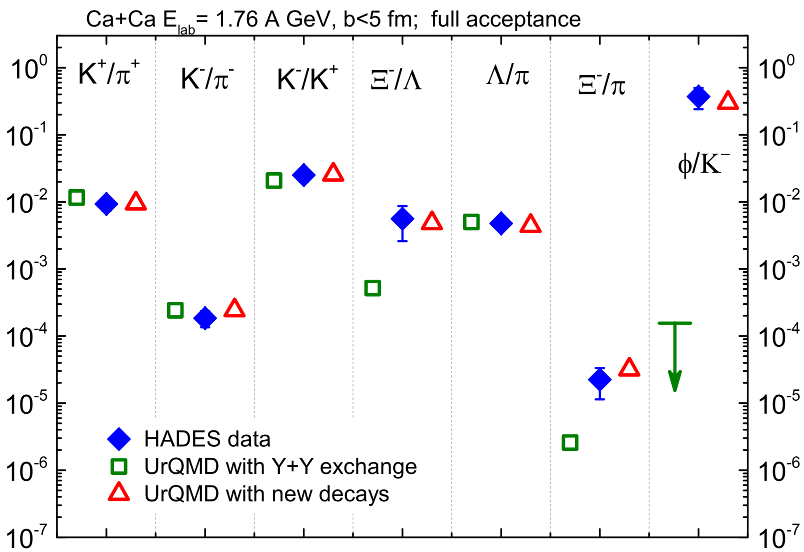
No elementary measurements near threshold.
We use p+Nb at $E_{\rm lab} = 3.5$ GeV data $\rightarrow \Gamma_{N^* \rightarrow \Xi+K+K}/\Gamma_{tot} = 3.0\%$

HADES data	
$\langle \Xi^- \rangle$	Ξ^-/Λ
$(2.0 \pm 0.3 \pm 0.4) \times 10^{-4}$	$(1.2 \pm 0.3 \pm 0.4) \times 10^{-2}$
UrQMD	
$\langle \Xi^- \rangle$	Ξ^-/Λ
$(1.44 \pm 0.05) \times 10^{-4}$	$(0.71 \pm 0.03) \times 10^{-2}$

Table: Ξ^- production yield and Ξ^-/Λ ratio for minimum bias $p + Nb$ collision at a beam energy of $E_{\rm lab} = 3.5$ GeV, compared with recent HADES results

G. Agakishiev *et al.*, Phys.Rev.Lett. 114 (2015) no.21, 212301.

Comparison to data for Ξ



- 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

Can we also use this for charm?

Bold..., but possible...

J. Steinheimer, A. Botvina and M. Bleicher, arXiv:1605.03439 [nucl-th].

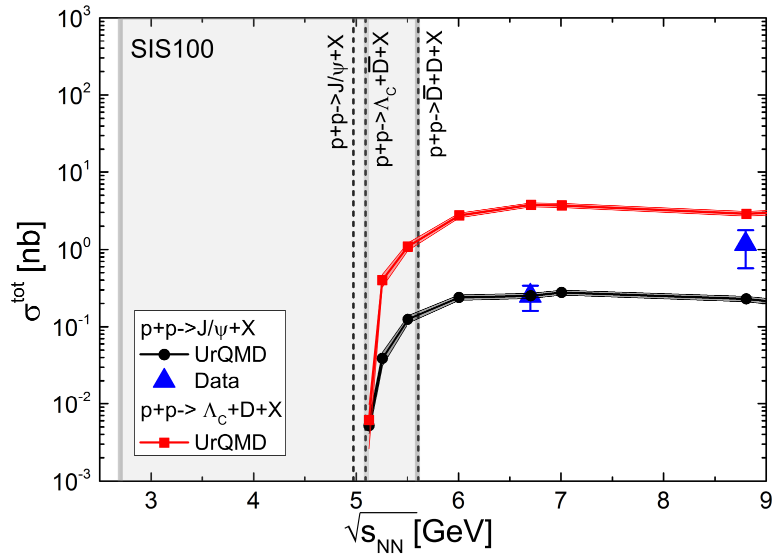
Why is charm interesting?

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...but that was SIS300!

Fixing the branching ratio

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



Only 1 parameter

$$\Gamma_{N^* \rightarrow NJ\Psi}/\Gamma_{tot} = 2.5 \cdot 10^{-5}$$

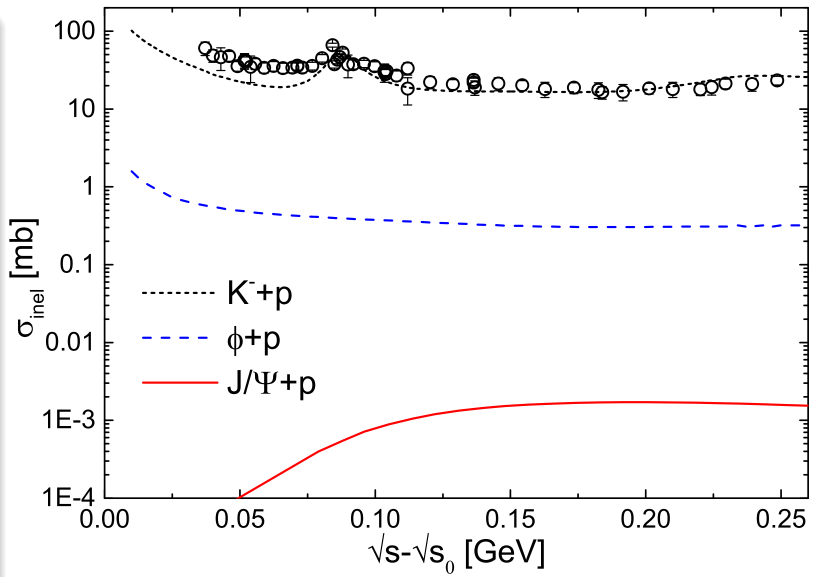
Assumptions

- We assume the associated production of $N^* \rightarrow \Lambda_c + \overline{D}$ to be a factor 15 larger at that beam energy and to contribute about the half of the total charm production.
- We neglect $D + \overline{D}$ pair production as it has a significantly higher threshold
- We neglect string production
- All the contributions should even increase the expected yield.

J/Ψ cross section

Detailed balance → absorption cross section

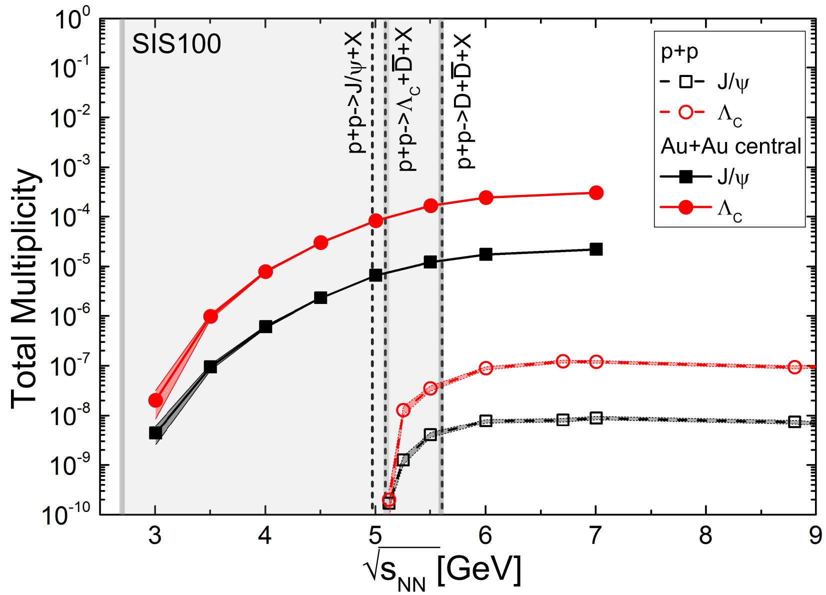
- $J/\Psi + p$ cross section from detailed balance is very small.
- Not 'absorption' of the J/Ψ, but of the mother resonance.
- Reactions of the type:
  $N^* + N \rightarrow N'^* + N'^*$
  $N^* + N \rightarrow N'^* + N'^*$
  where the mass of $N'^* < N^*$ so no J/Ψ can be produced.



Comparable to: D. Kharzeev and H. Satz, Phys. Lett. B **334**, 155 (1994).

Predictions for SIS-100

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



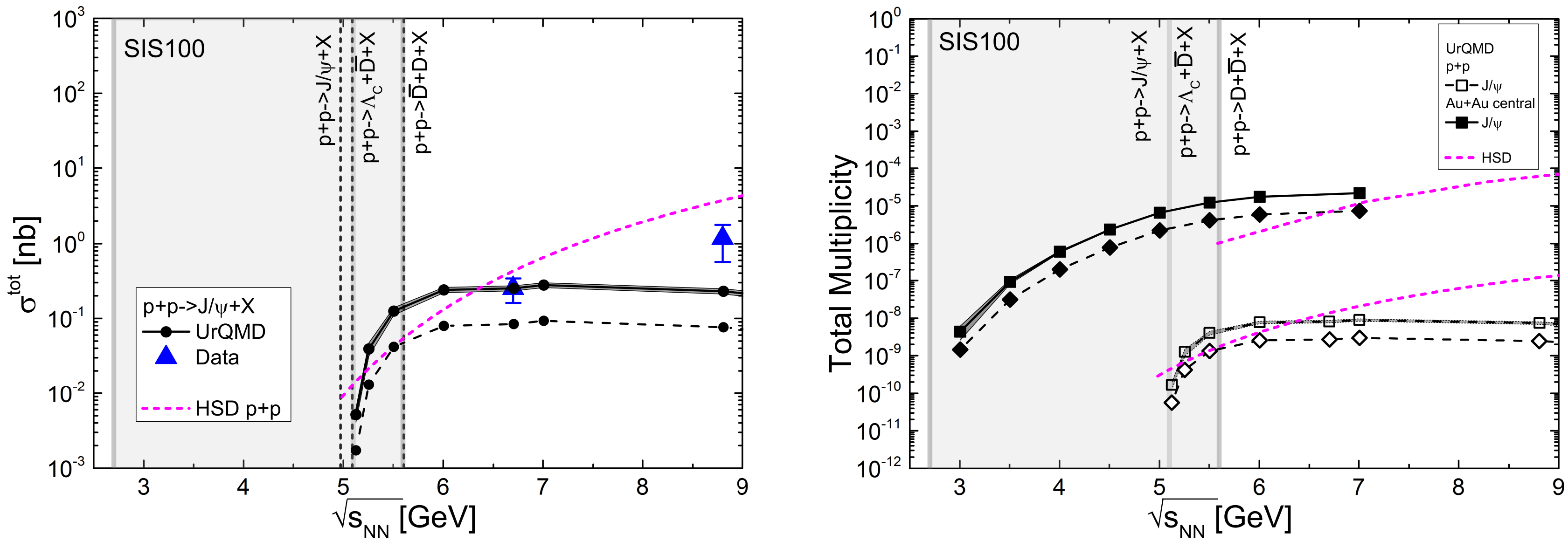
$E_{\text{lab}} = 11$ A GeV

- $1.5 \cdot 10^{-6}$ J/Ψ per event
- $2 \cdot 10^{-5}$ Λ_c per event
- $\approx 3 - 4 \cdot 10^{-5}$ $\overline{D}$ per event

Comparison to others I

Parametrized cross section for J/Ψ

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



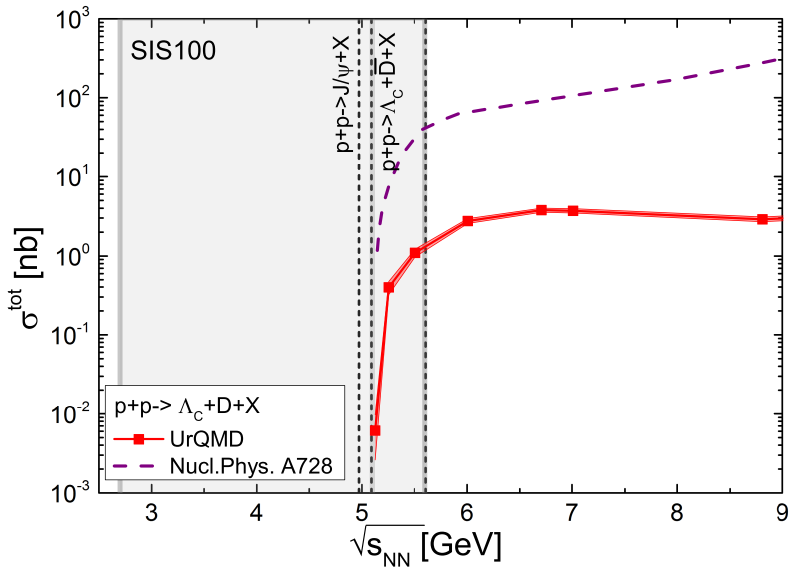
HSD results taken from:

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

Comparison to others II

Cross section for $p + p \rightarrow p + \overline{D}^0 + \Lambda_c$

Hadronic Lagrangian



Taken from:

W. Liu, C. M. Ko and S. H. Lee, Nucl. Phys. A **728**, 457 (2003)

Summary

- A new mechanism for the production of Ξ and ϕ is introduced and validated in elementary collisions
- This new branching ratio of high mass resonances is fitted to available data and extrapolated to AA
- It allows for the first time to describe the sub-threshold multi-strange particle production
- If this mechanism is also be applicable to charm production it may open a new road for charm studies at FAIR-SIS 100