New developments in heavy ion theory:

Subthreshold charm and strangeness production at GSI/FAIR energies

Marcus Bleicher and Jan Steinheimer
Frankfurt Institute for Advanced Studies
Institut für Theoretische Physik
Goethe Universität - Frankfurt

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…

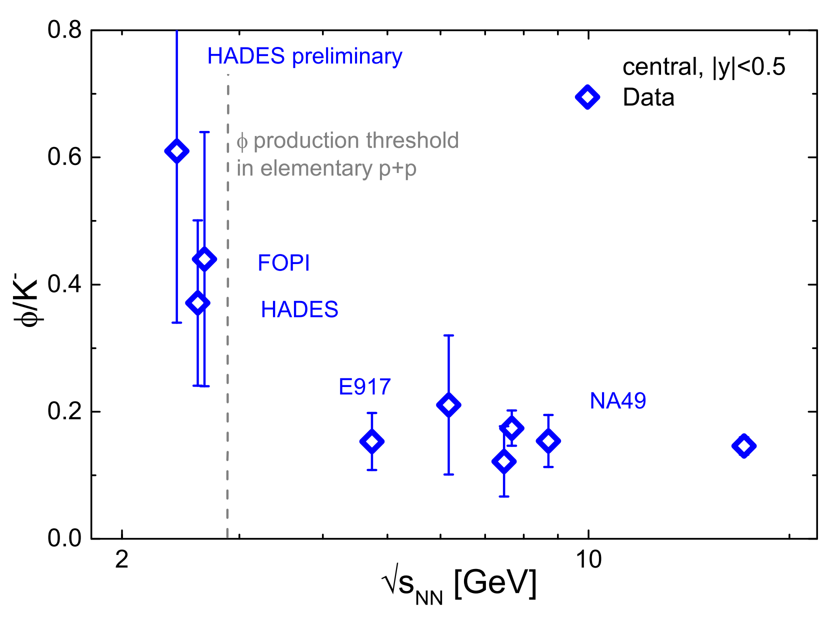
- Explores multi-strange particle production
  i.e. ϕ and Ξ production

  → 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

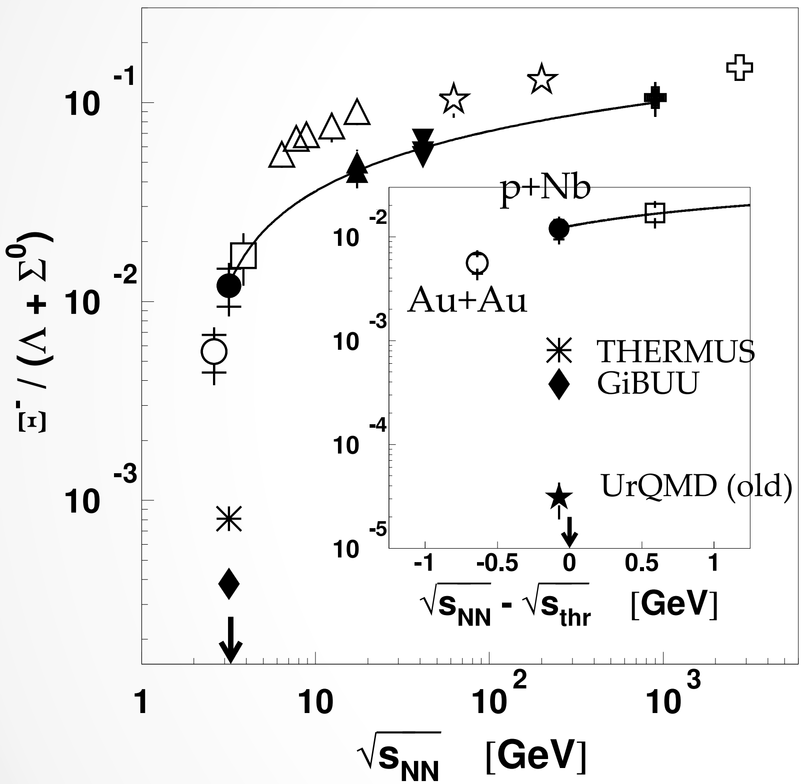


ϕ production

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!!

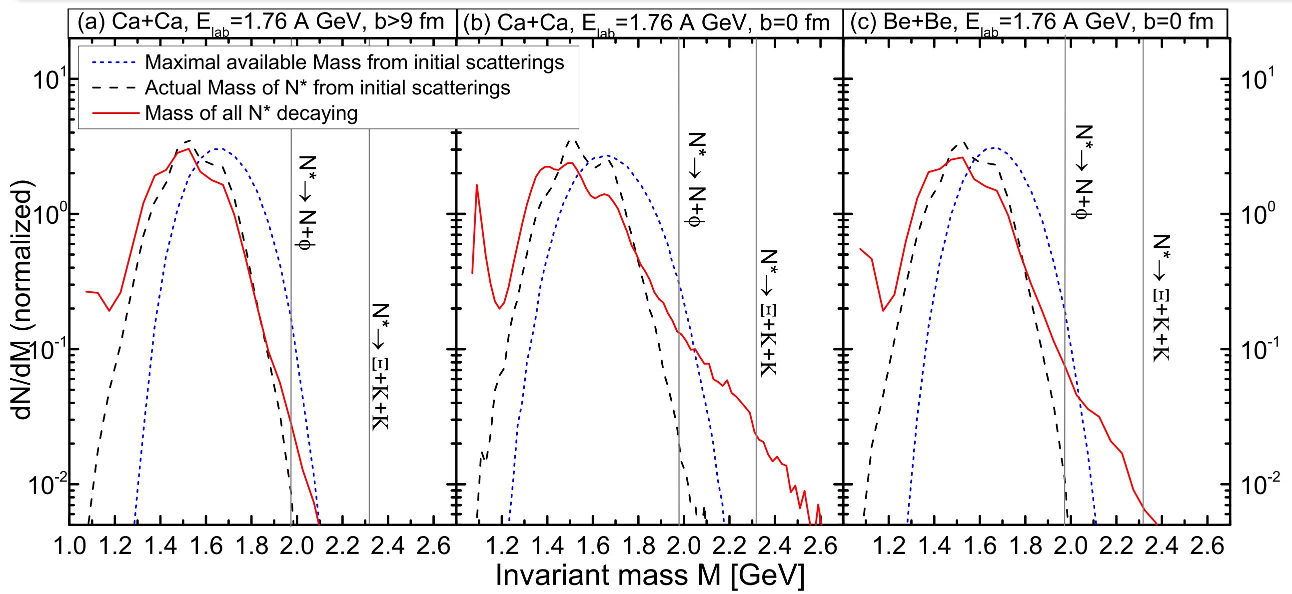
Both particles are not well described in microscopic transport models and thermal fits are also not convincing.

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

Probabilities

Sub-threshold production baseline

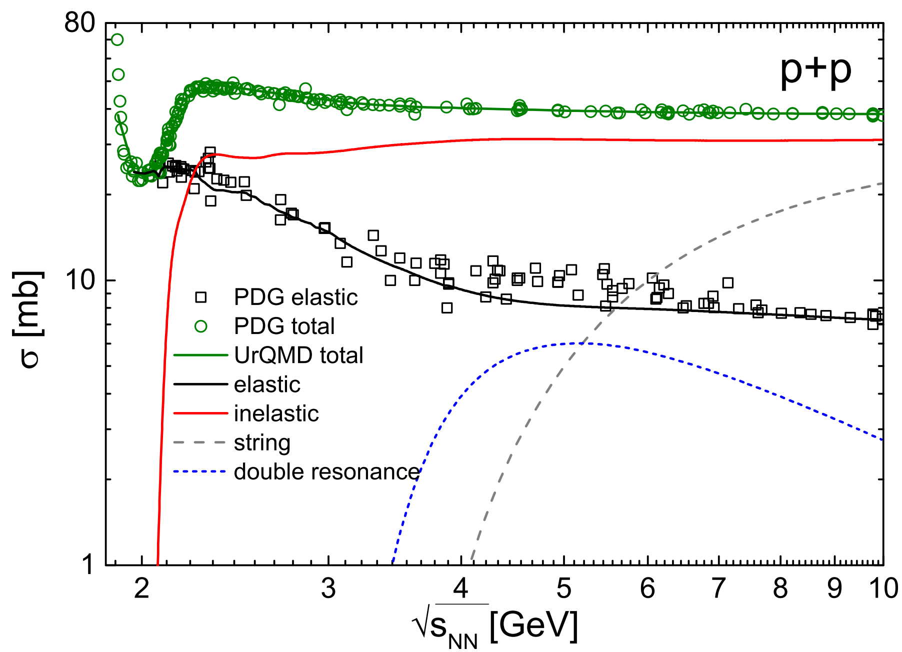
- Fermi momenta lift the collision energy above the threshold.
- Secondary interactions accumulate energy.



Why not introduce these decays for the less known resonances?

New resonances

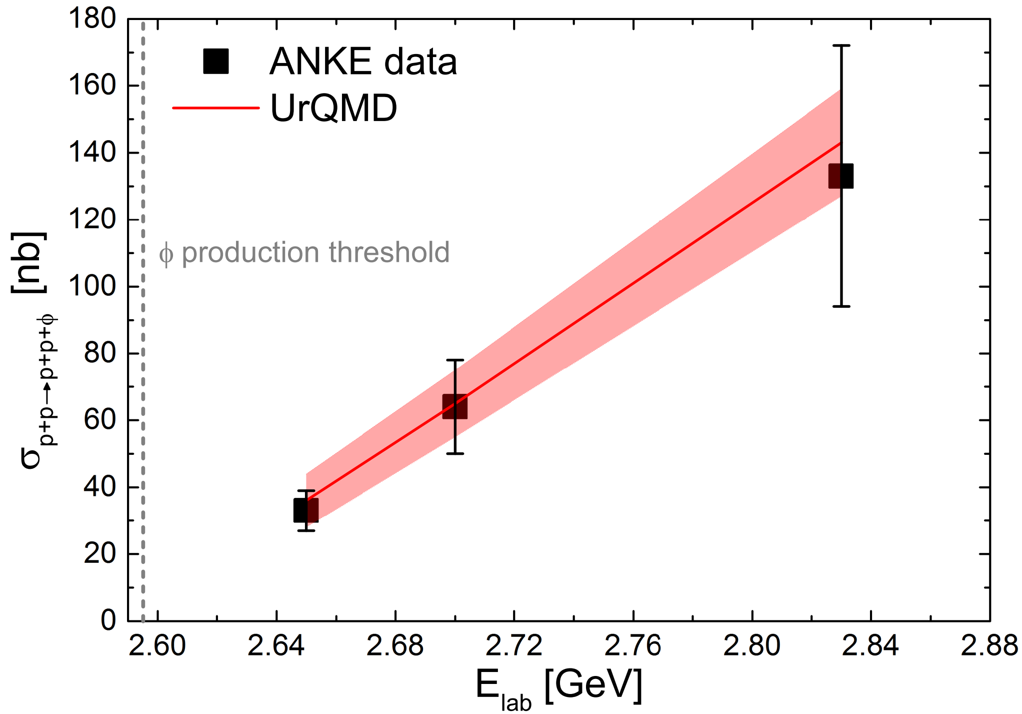
N*(1650)	Δ(1232)
N*(1710)	Δ(1600)
N*(1720)	Δ(1620)
N*(1875)	Δ(1700)
N*(1900)	Δ(1900)
N*(1990)	Δ(1905)
N*(2080)	Δ(1910)
N*(2190)	Δ(1920)
N*(2220)	Δ(1930)
N*(2250)	Δ(1950)
N*(2600)	Δ(2440)
N*(2700)	Δ(2750)
N*(3100)	Δ(2950)
N*(3500)	Δ(3300)
N*(3800)	Δ(3500)
N*(4200)	Δ(4200)



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!

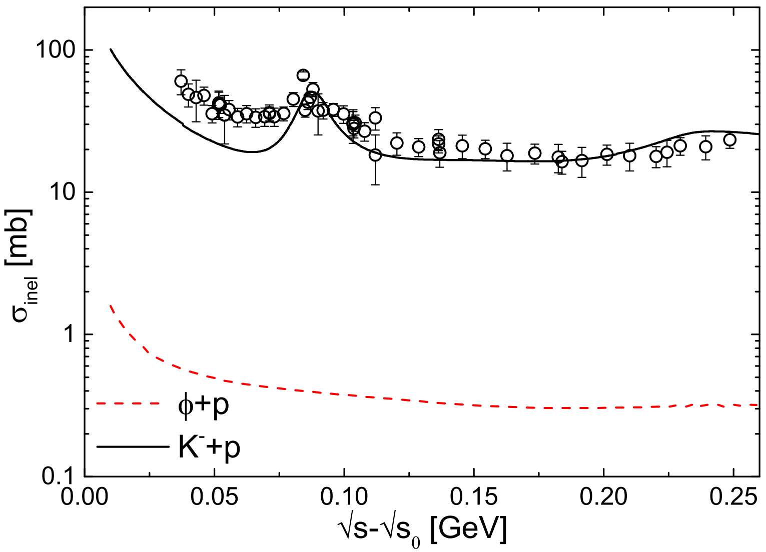
Y. Maeda *et al.* [ANKE Collaboration], Phys. Rev. C **77**, 015204 (2008) [arXiv:0710.1755 [nucl-ex]].

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.

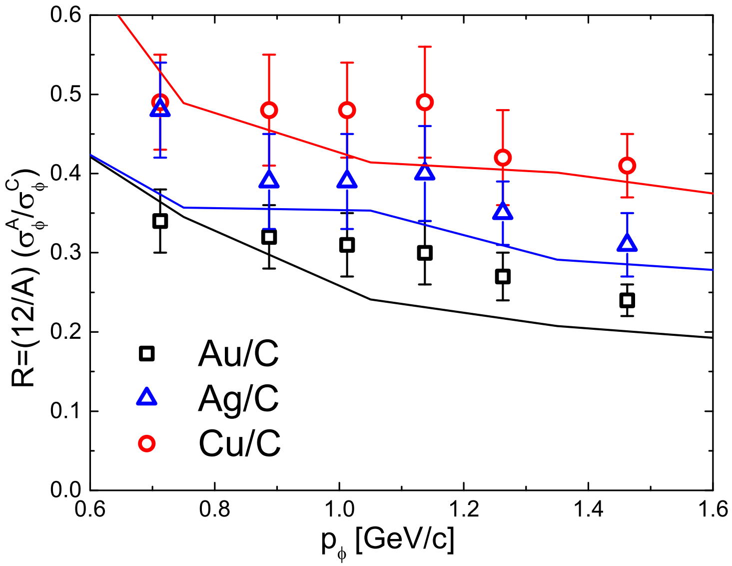


Transparency ratios

Detailed balance $\rightarrow$ absorption cross section

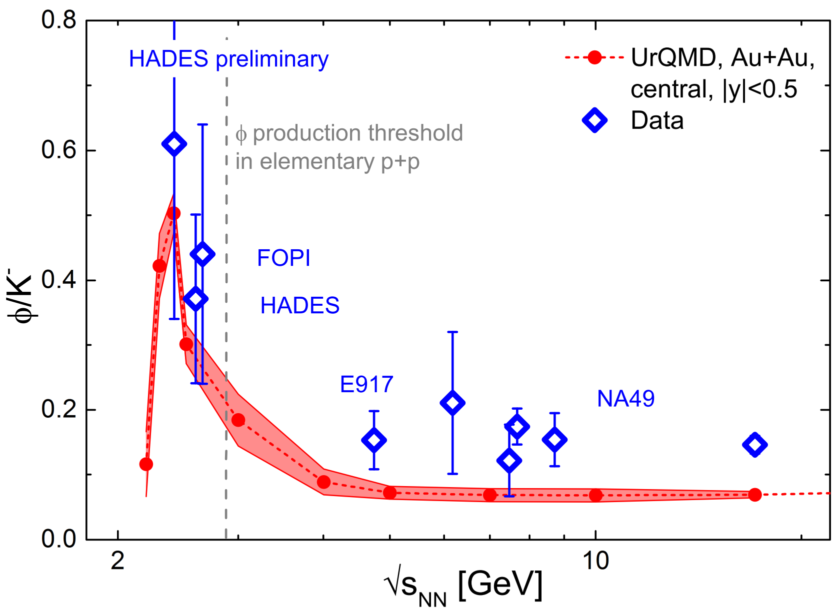
$$\frac{d\sigma_{b\to a}}{d\Omega} = \frac{\langle p_a^2\rangle}{\langle p_b^2\rangle}\frac{(2S_1+1)(2S_2+1)}{(2S_3+1)(2S_4+1)}\sum_{J=J_-}^{J_+}\frac{\langle j_1 m_1 j_2 m_2 | |JM\rangle^2}{\langle j_3 m_3 j_4 m_4 | |JM\rangle^2}\frac{d\sigma_{a\to b}}{d\Omega}$$

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



Extrapolation to AA

When applied to nuclear collisions:

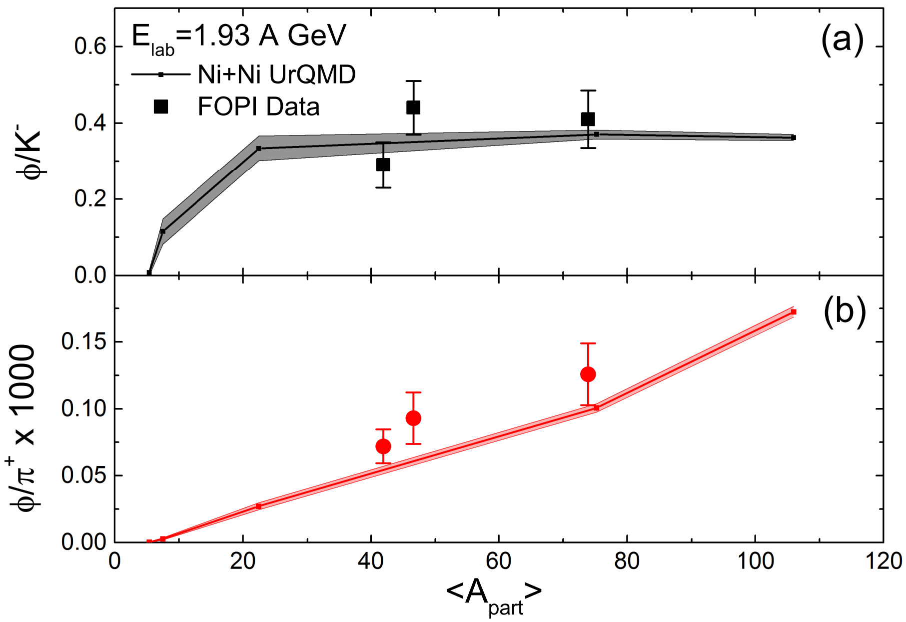


- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV
- High energies: too low due to string production
- HADES preliminary results for 1.23 A GeV, see HADES talks by R. Holzmann and T. Scheib.

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

Centrality

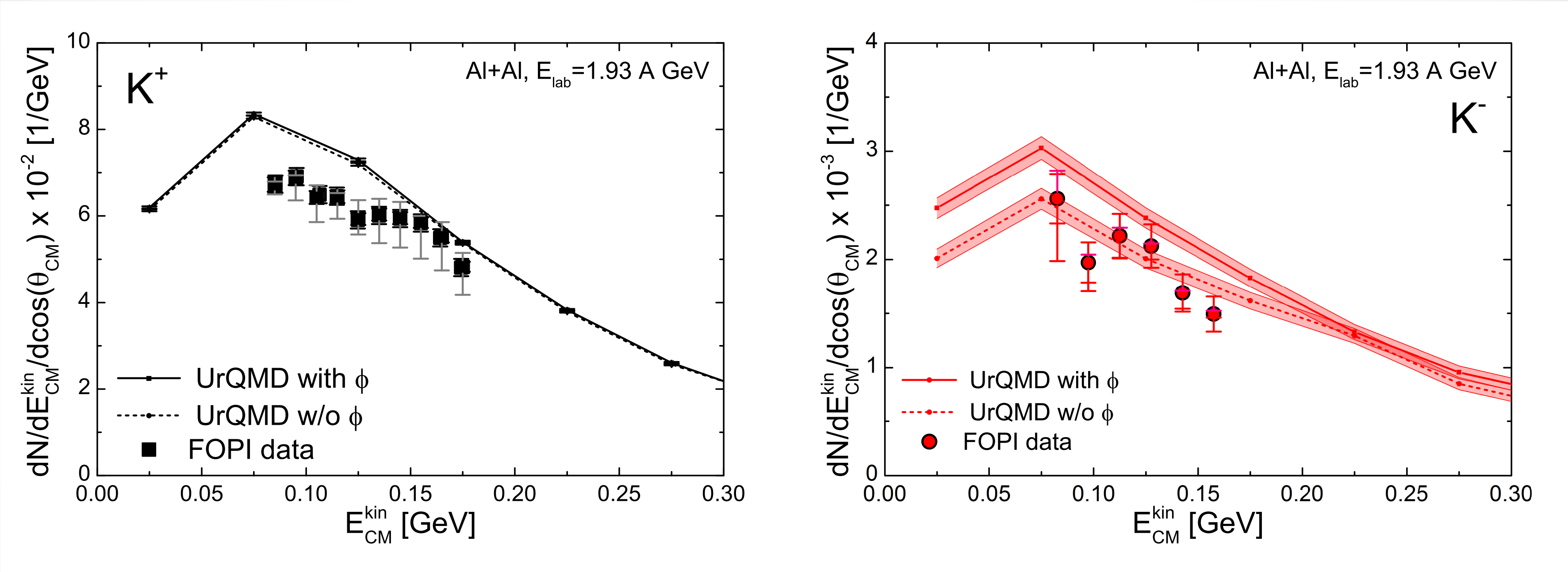
Even centrality dependence works well:



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

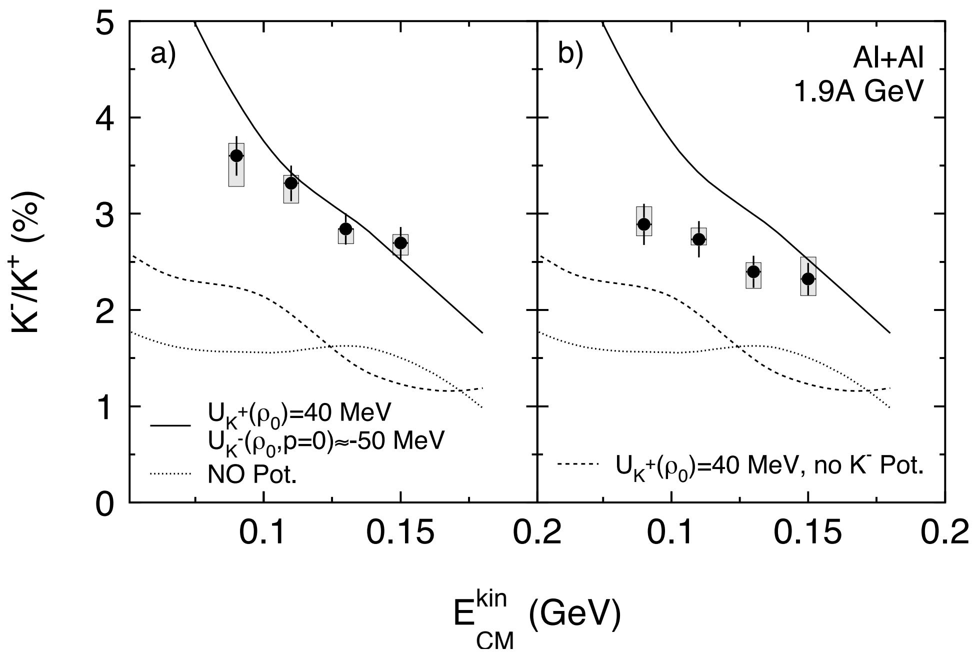
Data from: K. Piasecki et al., arXiv:1602.04378 [nucl-ex].

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].

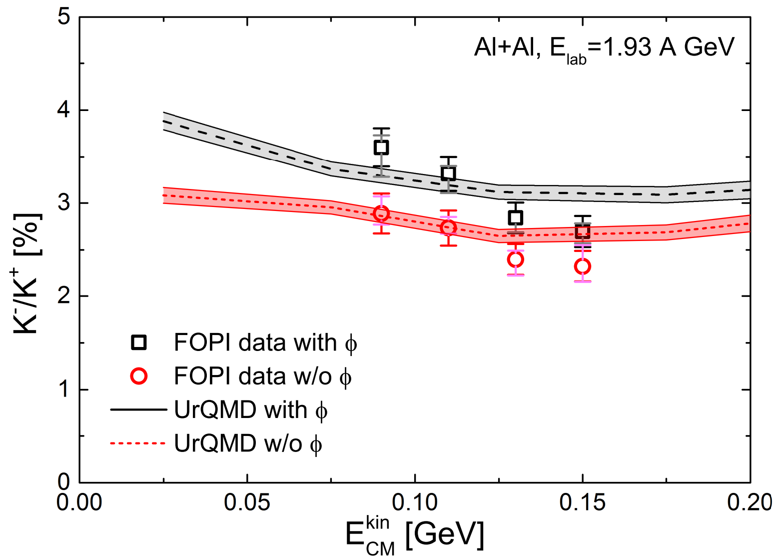
An example

- 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

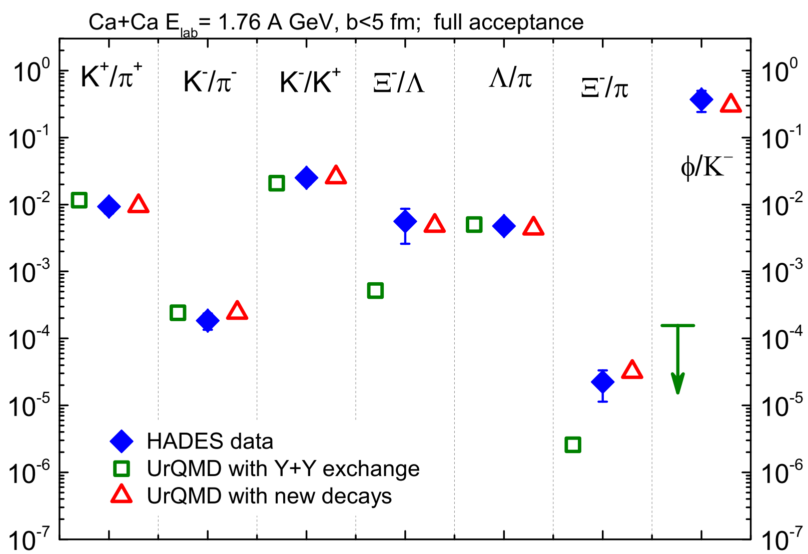
No elementary measurements near threshold.
We use p+Nb at $E_{\rm lab} = 3.5$ GeV data $\rightarrow \Gamma_{N^* \rightarrow \Xi+K+K}/\Gamma_{tot} = 3.0\%$

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

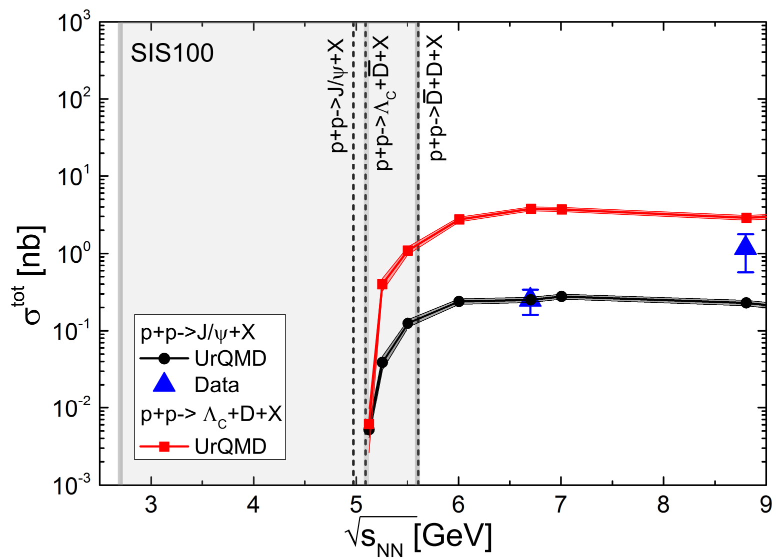
Can we also use this for charm?

Bold..., but possible...

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

Fixing the branching ratio

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

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

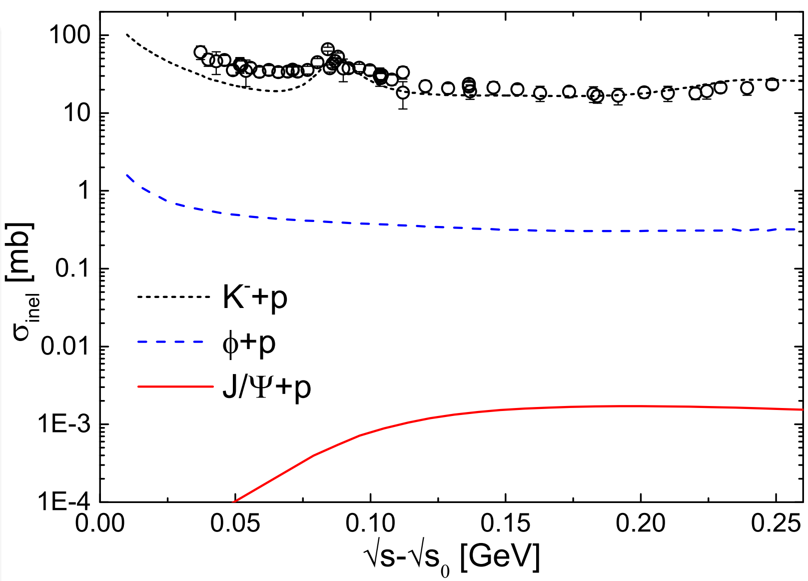
Assumptions

- We assume the associated production of $N^* \to \Lambda_c + \overline{D}$ 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

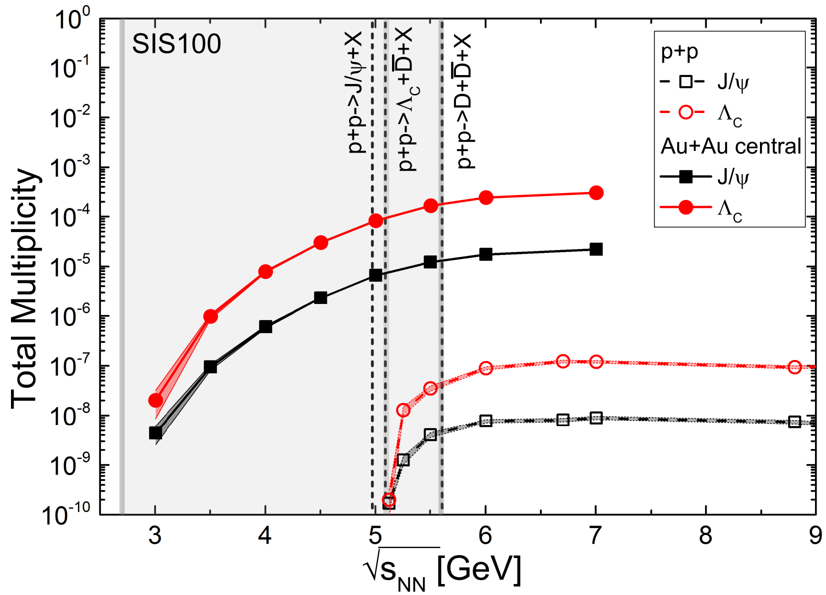
- $J/\Psi + p$ cross section from detailed balance is very small.
- Not 'absorption' of the J/Ψ, but of the mother resonance.
- Reactions of the type:
  $N^* + N \rightarrow N'^* + N'^*$
  $N^* + N \rightarrow N'^* + N'^*$
  where the mass of $N'^* < N^*$ so no J/Ψ can be produced.



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):



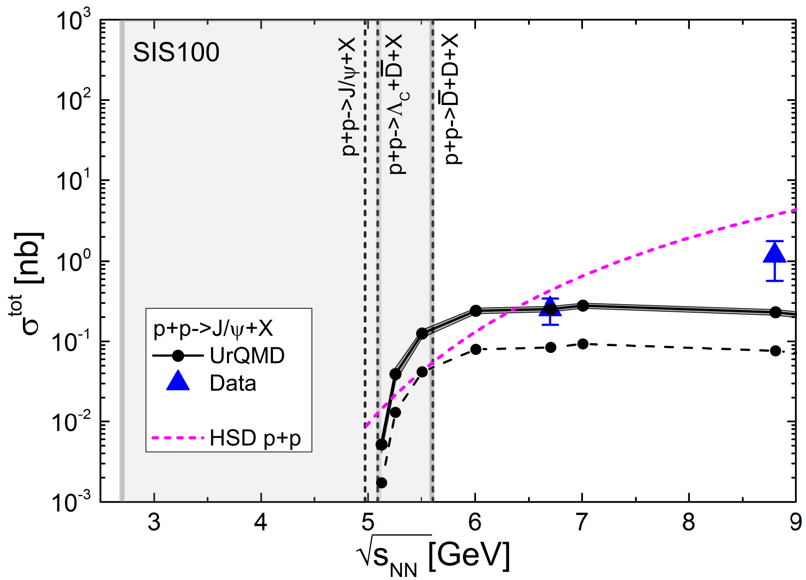
$E_{\rm lab} = 11$ A GeV

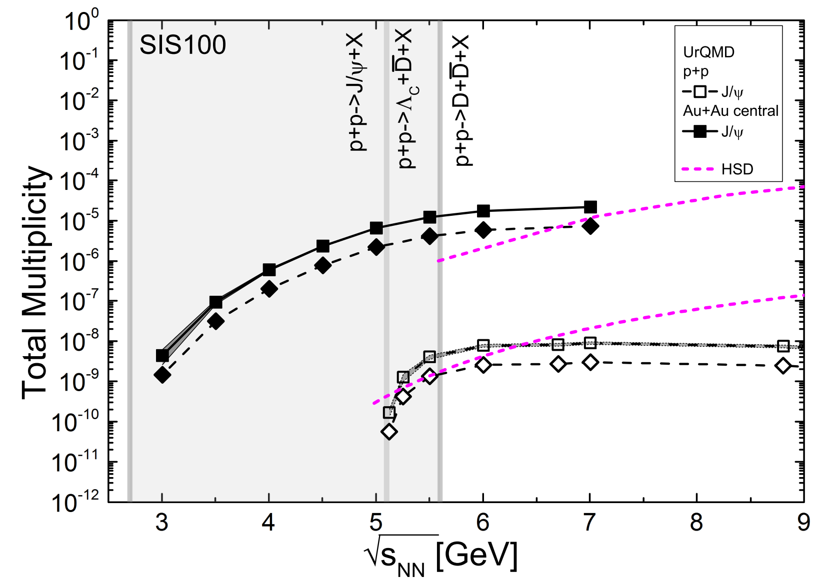
- $1.5 \cdot 10^{-6}$ J/Ψ per event
- $2 \cdot 10^{-5}$ Λ_c per event
- $\approx 3 - 4 \cdot 10^{-5}$ $\overline{D}$ per event

Comparison to others I

Parametrized cross section for J/Ψ

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





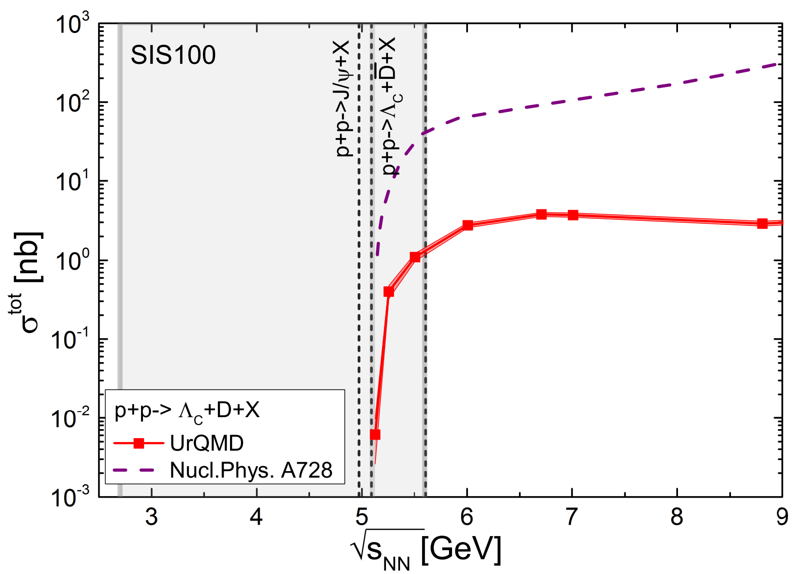
HSD results taken from:

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

Comparison to others II

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

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