Sub-threshold strangeness and charm production (in UrQMD)

Marcus Bleicher and Jan Steinheimer

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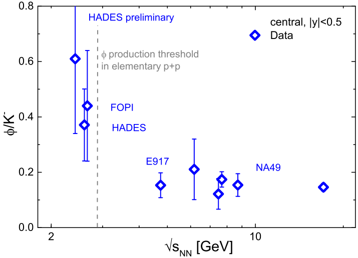
Motivation

Recent measurements on near and below threshold production.



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)

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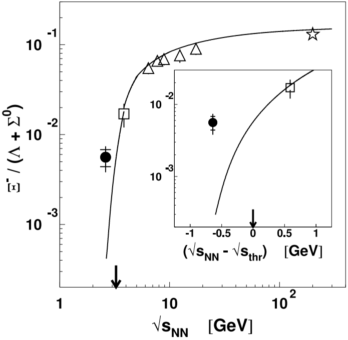

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Ξ production

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

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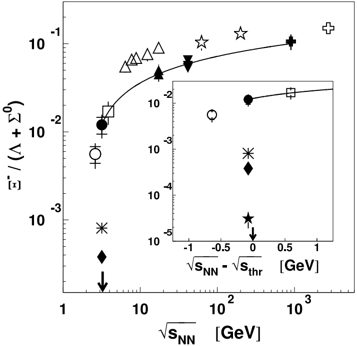

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Ξ^{-} yield, measured in Ar+KCl much larger than thermal model.
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Both particles are not well described in microscopic transport models and thermal fits are also not convincing.

G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. Lett. **103**, 132301 (2009)

The notorious $\phi + N$ cross section

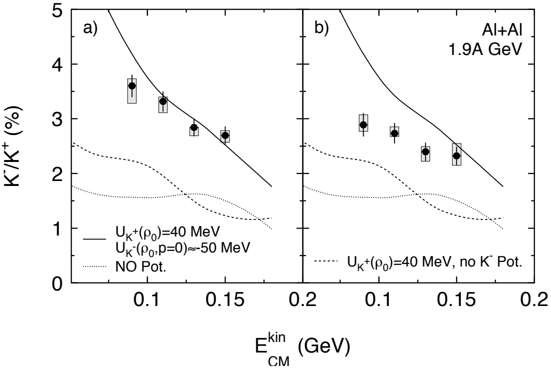
Does the ϕ have a small hadronic cross section?

- 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)

The Kaon-Nuclear potential



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

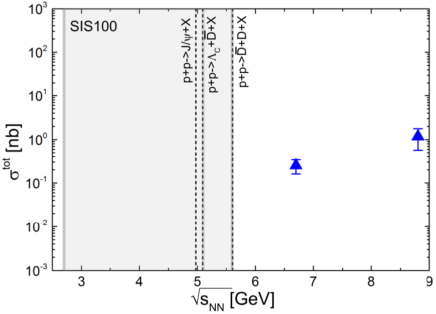
An example

- 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.

Why is a sub threshold charm prediction 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!



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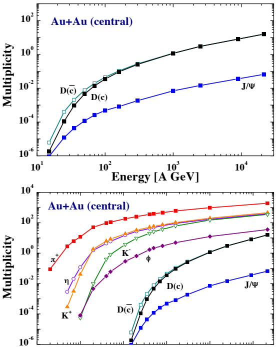


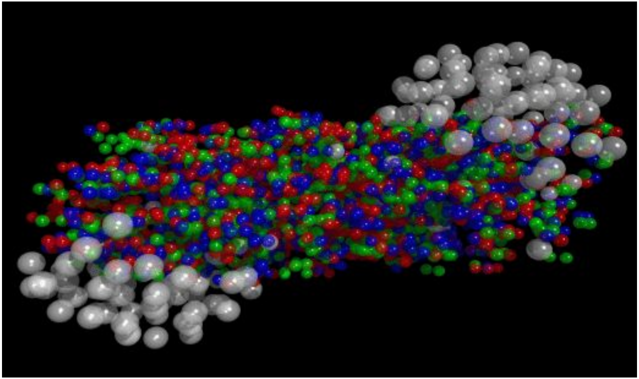
HSD study: Based on parametrized cross section.

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

Get a baseline

UrQMD

- We will use it in cascade mode.
- No long range interactions like potentials.



Strangeness Production in UrQMD

UrQMD is a microscopic transport model

- Only $2 \leftrightarrow 2$, $2 \leftrightarrow 1$, $2 \rightarrow N$ and $1 \rightarrow N$ interactions allowed.
- Resonance decays according to PDG values $+$ guesstimates.
- Detailed balance. (Violated in string excitations, annihilations and some dacays)

Strangeness Production in UrQMD

Strange particle production goes ONLY via

Resonance excitation:

- N+N→ X
- N+M→ X
- M+M→ X

Relevant channels:

1. $NN \rightarrow N\Delta_{1232}$
2. $NN \rightarrow NN^*$
3. $NN \rightarrow N\Delta^*$
4. $NN \rightarrow \Delta_{1232}\Delta_{1232}$
5. $NN \rightarrow \Delta_{1232}N^*$
6. $NN \rightarrow \Delta_{1232}\Delta^*$
7. $NN \rightarrow R^*R^*$

Strangeness Production in UrQMD

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- N+N→ X
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- M+M→ X

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

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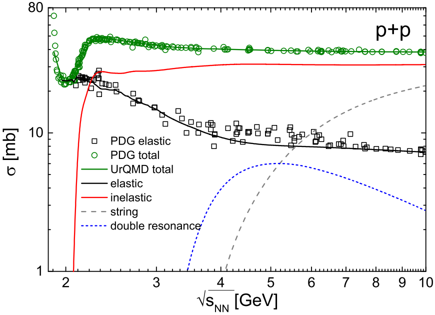
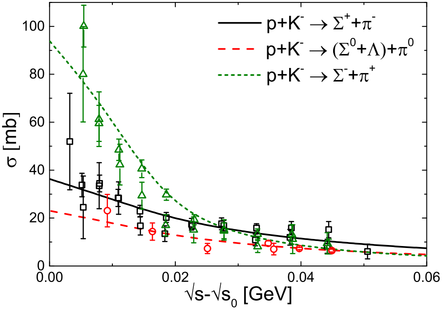


N+N Cross section

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

Strangeness exchange reactions

In addition Strange hadrons may be created in strangeness exchange reactions.

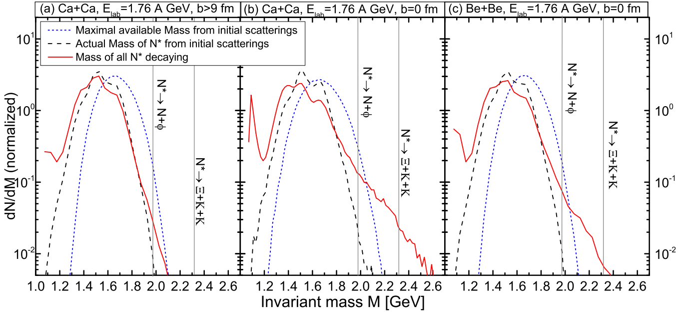


First the ϕ

On the probability of sub threshold production

Sub-threshold production baseline

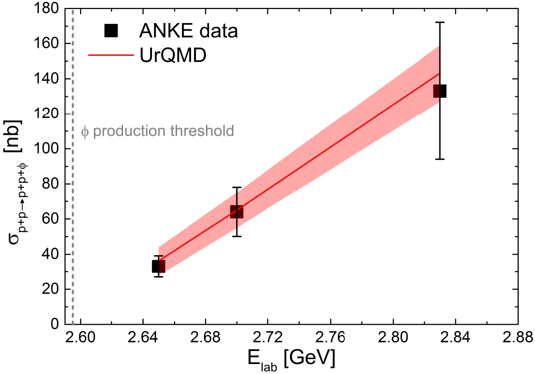
- Fermi momenta lift the collision energy above the threshold.
- Secondary interactions accumulate energy.



Why not introduce these decays for the less known resonances?

Fixing the $N^* \to \phi + N$ decay with p+p data

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!

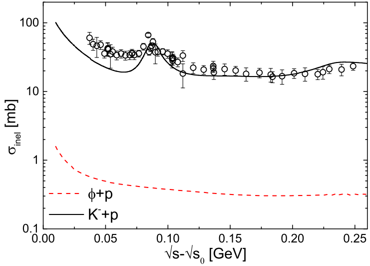
Y. Maeda *et al.* [ANKE Collaboration], Phys. Rev. C **77**, 015204 (2008) [arXiv:0710.1755 [nucl-ex]].

ϕ suppression in nuclear medium

Detailed balance → 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.



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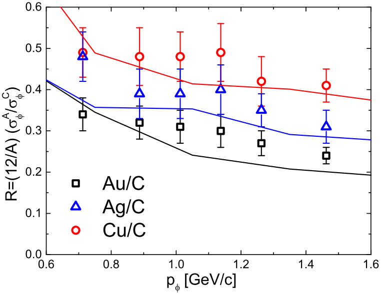
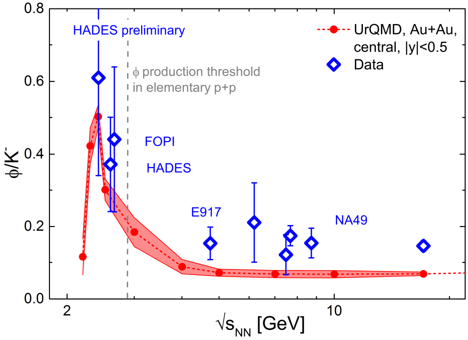
- $\phi + p$ cross section from detailed balance is very small.
- Still the transparency ratio is well reproduced. Remember: this is what lead to the 20 mb cross section from ANKE.
- Cross section from transparency ratio is model dependent!



ϕ production in nuclear collisions below the p+p threshold

When applied to nuclear collisions:



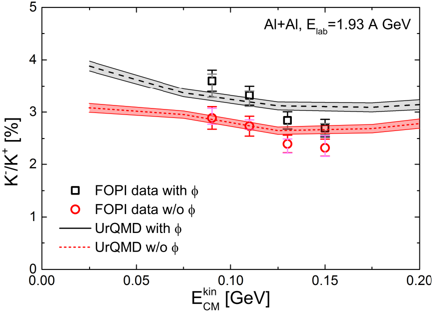
- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV
- High energies: too low due to string production
- HADES preliminary results for 1.23 A GeV, see HADES talks by R. Holzmann and T. Scheib.

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

About the Kaon 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 the Ξ

How to fix the $N^* \to \Xi^- + K + K$ decay?

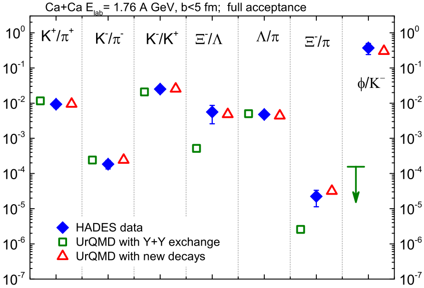
No elementary measurements near threshold.
We use p+Nb at $E_{\text{lab}} = 3.5$ GeV data → $\Gamma_{N^* \to \Xi + K + K}/\Gamma_{tot} = 3.0\%$

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 $E_{\text{lab}} = 3.5$ GeV, compared with recent HADES results

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

Ξ^- production in nuclear collisions below the p+p threshold



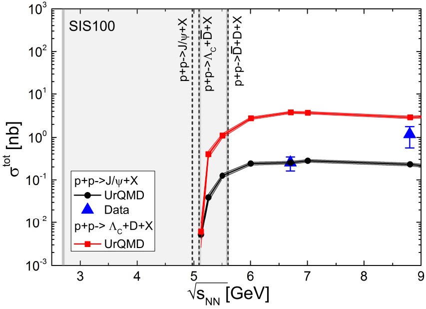
- Ξ^- yield in Ar+KCl collisions is nicely reproduced
- Consistent with the p+Nb data.
- Indication for Ξ production from non-thermal 'tails' of particle production.
- All other strange particle ratios are also in line with experiment

Can we make predictions about sub-threshold charm production?

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

Fixing the $N^* \to J/\Psi + N$ decay with p+p data

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 suppression in nuclear medium

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:
  $N^* + N \rightarrow N'^* + N'^*$
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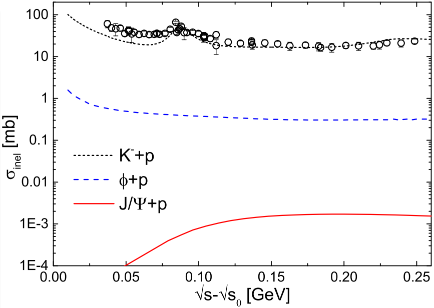
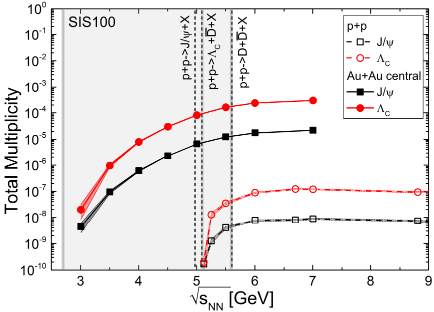


Comparable to: D. Kharzeev and H. Satz, Phys. Lett. B **334**, 155 (1994).

J/Ψ and open charm production in nuclear collisions below the p+p threshold

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



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

- $3 \cdot 10^{-7}$ J/Ψ per event
- $4 \cdot 10^{-6}$ Λ_c per event
- $\approx 6 - 8 \cdot 10^{-6}$ $\overline{D}$ per event

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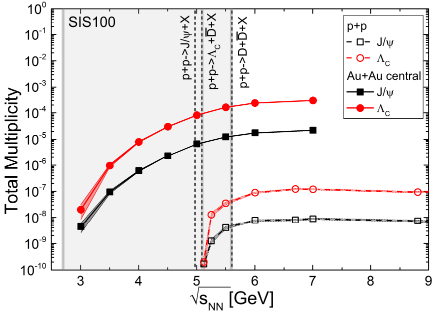

$E_{\text{lab}} = 11$ A GeV

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

Fermi's Golden Rule, heavy resonances and equilibration

If resonance excitation and decay are governed mainly by phase space, 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, arXiv:1603.02051 [nucl-th] accepted by PRC.

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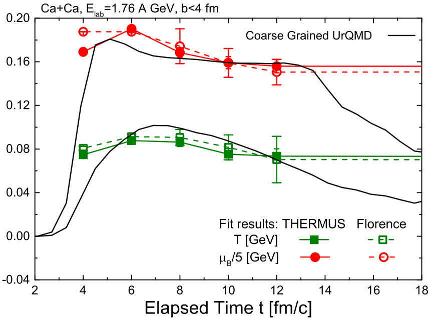
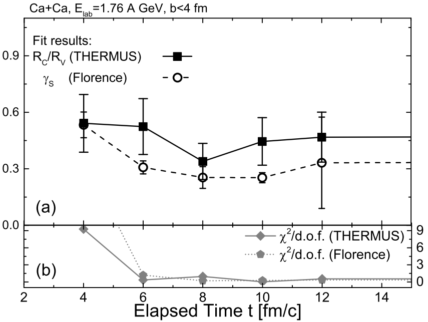




- Fit quality is good even after 2 fm/c.
- Extracted values of T and μ_B consistent with coarse rained approach which assumes instant local equilibration.

J. Steinheimer, M. Lorenz, F. Becattini, R. Stock and M. Bleicher, arXiv:1603.02051 [nucl-th] accepted by PRC.

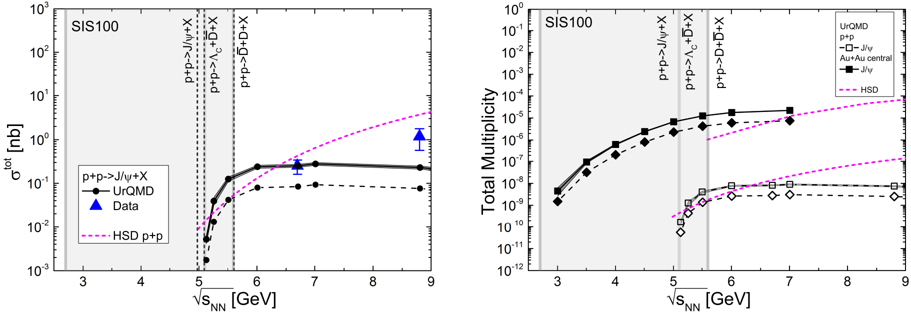
Summary

- We introduced a new mechanism of ϕ and Ξ production in elementary and nuclear collisions, through the decay of heavy resonances.
- We can nicely describe the ϕ and Ξ^- production in elementary and nuclear collisions near and below the ϕ production threshold from elementary input.
- We made predictions for sub threshold J/Ψ, Λ_c and $\overline{D}$ production in sub threshold collisions at the SIS100, observing a realistic chance of J/Ψ and open charm measurements.

Comparisons to HSD

Parametrized cross section for J/Ψ

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

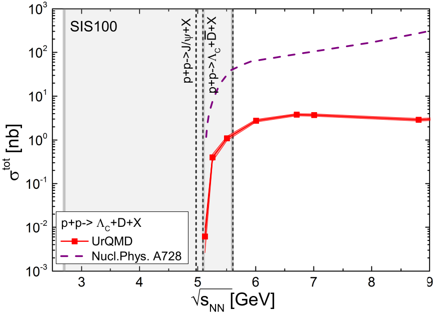


HSD results taken from:

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

Comparisons to hadronic Lagrangian

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



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

The extracted cross sections depend on model assumptions

SPring-8

Used a Glauber model for the absorption.

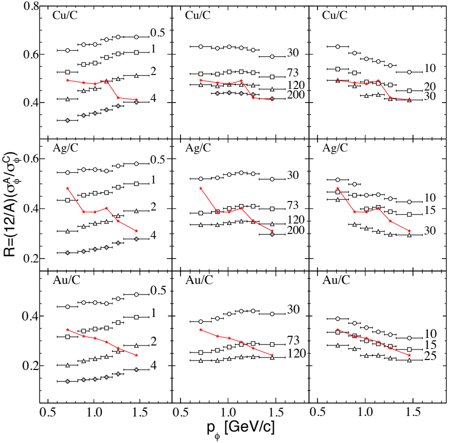
The extracted cross sections depend on model assumptions

SPring-8

Used a Glauber model for the absorption.

ANKE

- 1: The eikonal approximation of the Valencia group.
- 2: Paryev developed the spectral function approach for ϕ production in both the primary proton- nucleon and secondary pion nucleon channels.
- BUU transport calculation of the Rossendorf group. Accounts for baryon baryon and meson baryon ϕ production processes.



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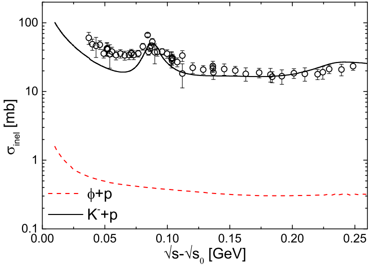
- $\phi + p$ cross section from detailed balance is very small.



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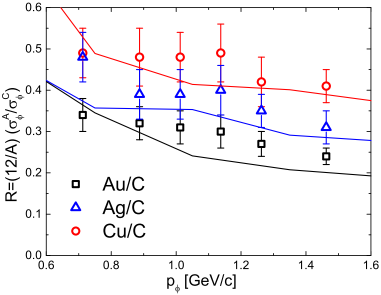

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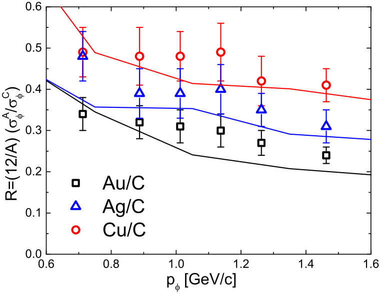

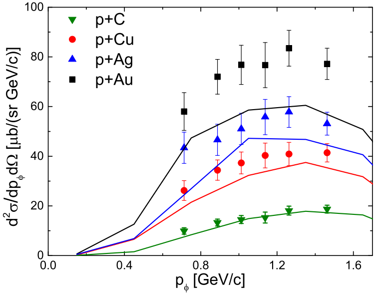

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- Reactions of the type:
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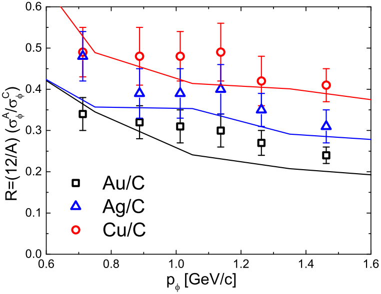
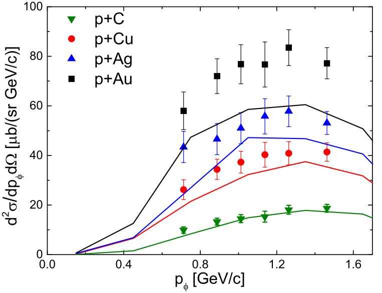
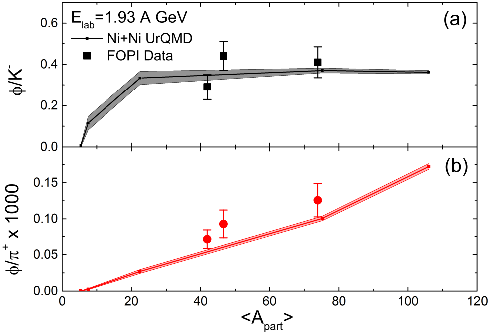




ϕ production in nuclear collisions below the p+p threshold

Even centrality dependence works well:



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

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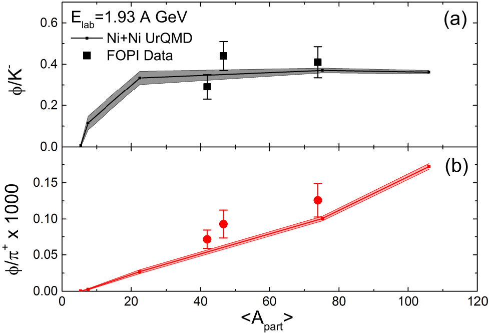
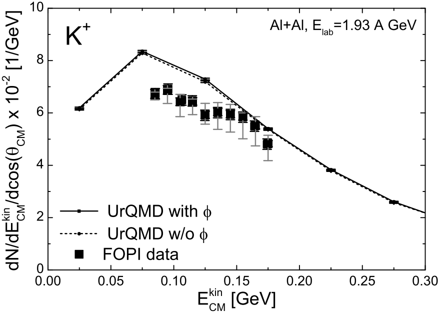
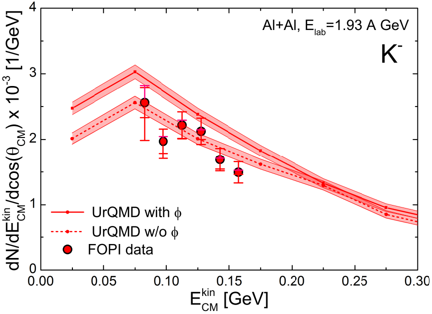


- Centrality dependence nicely reproduced.
- Good indicator for multi step production.

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

Backup


K$^+$
Al+Al, E$_{lab}$=1.93 A GeV
UrQMD with ϕ
UrQMD w/o ϕ
FOPI data
dN/dE$^{kin}_{CM}$/dcos(θ$_{CM}$) x 10^{-2} [1/GeV]
E$^{kin}_{CM}$ [GeV]
0
2
4
6
8
10
0.00
0.05
0.10
0.15
0.20
0.25
0.30


Al+Al, E$_{lab}$=1.93 A GeV
K$^-$
UrQMD with ϕ
UrQMD w/o ϕ
FOPI data
dN/dE$^{kin}_{CM}$/dcos(θ$_{CM}$) x 10^{-3} [1/GeV]
E$^{kin}_{CM}$ [GeV]
0
1
2
3
4
0.00
0.05
0.10
0.15
0.20
0.25
0.30

Strangeness Production in UrQMD

Strange particle production goes ONLY via

Resonance excitation:

- N+N→ X
- N+M→ X
- M+M→ X

Relevant channels:

1. $NN \rightarrow N\Delta_{1232}$
2. $NN \rightarrow NN^*$
3. $NN \rightarrow N\Delta^*$
4. $NN \rightarrow \Delta_{1232}\Delta_{1232}$
5. $NN \rightarrow \Delta_{1232}N^*$
6. $NN \rightarrow \Delta_{1232}\Delta^*$
7. $NN \rightarrow R^*R^*$

Strangeness Production in UrQMD

Strange particle production goes ONLY via

Resonance excitation:

- N+N→ X
- N+M→ X
- M+M→ X

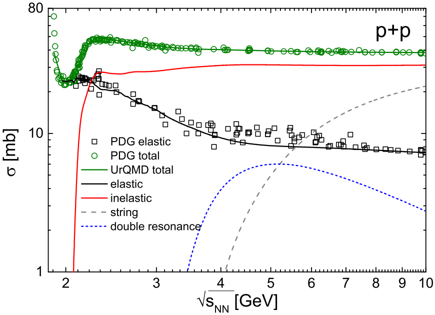
N*(1650)	$\Delta(1232)$
N*(1710)	$\Delta(1600)$
N*(1720)	$\Delta(1620)$
N*(1875)	$\Delta(1700)$
N*(1900)	$\Delta(1900)$
N*(1990)	$\Delta(1905)$
N*(2080)	$\Delta(1910)$
N*(2190)	$\Delta(1920)$
N*(2220)	$\Delta(1930)$
N*(2250)	$\Delta(1950)$
N*(2600)	$\Delta(2440)$
N*(2700)	$\Delta(2750)$
N*(3100)	$\Delta(2950)$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

Strangeness Production in UrQMD

Strange particle production goes ONLY via

Resonance excitation:

- N+N→ X
- N+M→ X
- M+M→ X



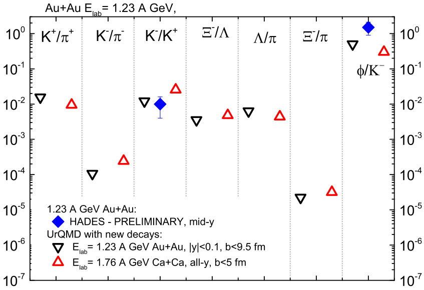
N+N Cross section

$$\sigma_{1,2\rightarrow3,4}(\sqrt{s}) \propto (2S_3+1)(2S_4+1)\frac{\langle p_{3,4}\rangle}{\langle p_{1,2}\rangle}\left|M(m3,m4)\right|^2$$

with

$$\left|M(m3,m4)\right|^2 = \frac{A}{(m_4-m_3)^2(m_4+m_3)^2}$$

Predictions for Au+Au at $E_{\mathrm{lab}} = 1.23$ A GeV



Ξ^-/Λ does not decrease much.