Strange hadron production at SIS energies (in UrQMD)

Jan Steinheimer

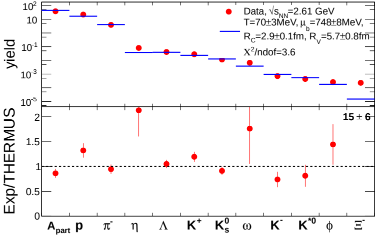
FIAS Frankfurt Institute for Advanced Studies

How we know what we know

- Most of what we "know" in HIC comes from comparisons of models with data.
- These models are based on certain assumptions.

How we know what we know

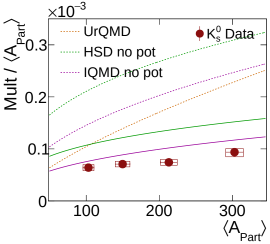
- Most of what we "know" in HIC comes from comparisons of models with data.
- These models are based on certain assumptions.
- Assume we accept the basic assumptions of using transport models:

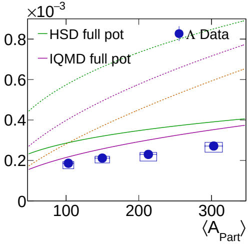


G. Agakishiev *et al.* [HADES Collaboration], Eur. Phys. J. A **52**, no. 6, 178 (2016)

How we know what we know

- Most of what we "know" in HIC comes from comparisons of models with data.
- These models are based on certain assumptions.
- Assume we accept the basic assumptions of using transport models:
- Example I: The particle yields can be described by a thermal fit → The system must reach chemial equilibrium.

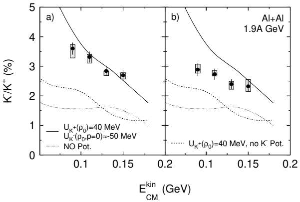




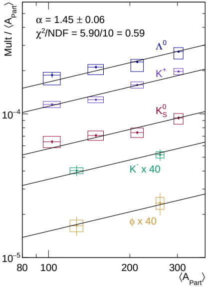
How we know what we know

- Most of what we "know" in HIC comes from comparisons of models with data.
- These models are based on certain assumptions.
- Assume we accept the basic assumptions of using transport models:
- Example I: The particle yields can be described by a thermal fit $\rightarrow$ The system must reach chemial equilibrium.
- Example II: Transport simulations with "All" potentials best describe Kaon yields $\rightarrow$ their values for the Koan potential must be right

J. Adamczewski-Musch *et al.* [HADES Collaboration], arXiv:1812.07304 [nucl-ex].



P. Gasik *et al.* [FOPI Collaboration], arXiv:1512.06988 [nucl-ex]. J. Adamczewski-Musch *et al.* [HADES Collaboration], arXiv:1812.07304 [nucl-ex].



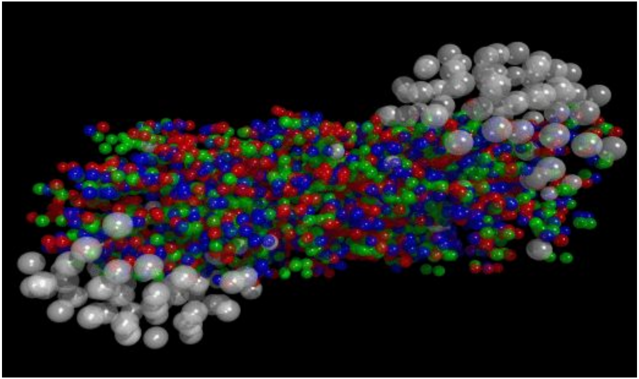
How we know what we know

- Most of what we "know" in HIC comes from comparisons of models with data.
- These models are based on certain assumptions.
- Assume we accept the basic assumptions of using transport models:
- Example I: The particle yields can be described by a thermal fit $\rightarrow$ The system must reach chemial equilibrium.
- Example II: Transport simulations with "All" potentials best describe Kaon yields $\rightarrow$ their values for the Koan potential must be right
- Example III: K^+ and K^- production seems correlated $\rightarrow$ Strangeness exchange is the main source of K^-

UrQMD

UrQMD is a microscopic transport model

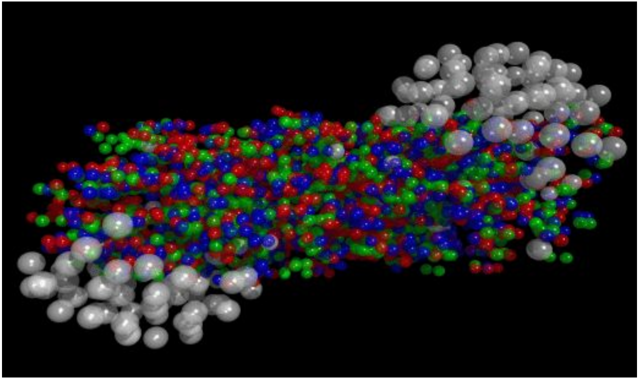
- We will use it in cascade mode.



UrQMD

UrQMD is a microscopic transport model

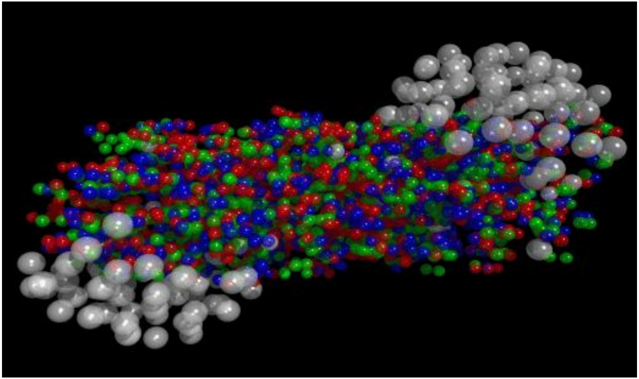
- We will use it in cascade mode.
- Particles follow a straight line until they scatter.



UrQMD

UrQMD is a microscopic transport model

- We will use it in cascade mode.
- Particles follow a straight line until they scatter.
- No long range interactions like potentials.



Nuclear Potentials in UrQMD

- Long range interaction between electric charges described by Coulomb potential.
- Yukawa potential for two particle interaction.
- The stiffness of the EoS is detrermined by the density dependent Skyrme potential:

$$V_{Sk} = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0} \right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0} \right)^{\gamma}$$

where the parameters are fixed to describe collective flow of protons at low beam energies.

Nuclear Potentials in UrQMD

- Long range interaction between electric charges described by Coulomb potential.
- Yukawa potential for two particle interaction.
- The stiffness of the EoS is detrermined by the density dependent Skyrme potential:

$$V_{Sk} = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0} \right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0} \right)^{\gamma}$$

where the parameters are fixed to describe collective flow of protons at low beam energies.

- NO momentum dependent potentials.
- NO hyperon potentials.
- NO isospin dependent potentials.
- NO kaon 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.

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.

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$\rightarrow$ X
- N+M$\rightarrow$ X
- M+M$\rightarrow$ 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

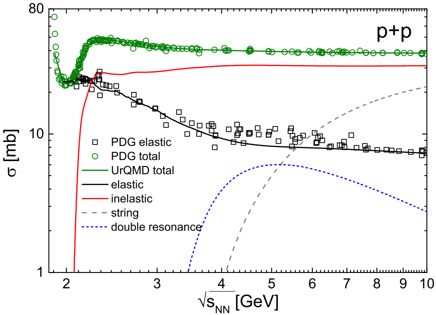
N*(1650)	Δ(1232)
N*(1710)	Δ(1600)
N*(1720)	Δ(1620)
N*(1875)	Δ(1700)
N*(1900)	Δ(1900)
N*(1990)	Δ(1905)
N*(2080)	Δ(1910)
N*(2190)	Δ(1920)
N*(2220)	Δ(1930)
N*(2250)	Δ(1950)
N*(2600)	Δ(2440)
N*(2700)	Δ(2750)
N*(3100)	Δ(2950)
N*(3500)	Δ(3300)
N*(3800)	Δ(3500)
N*(4200)	Δ(4200)

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

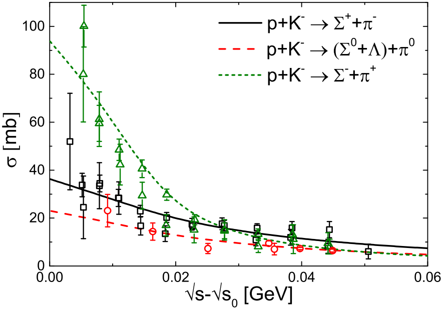
$$\sigma_{1,2\to3,4}(\sqrt{s}) \propto (2S_3+1)(2S_4+1)\frac{\langle p_{3,4}\rangle}{\langle p_{1,2}\rangle}\,|M(m3,m4)|^2$$

with

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

Strangeness exchange reactions

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



Channels for K^- production

In addition to the strangeness exchange K^- can be produced by

- As Kaon+anti-Kaon pair in a string. (not relevant at is beam energy!)

Channels for K^- production

In addition to the strangeness exchange K^- can be produced by

- As Kaon+anti-Kaon pair in a string. (not relevant at is beam energy!)
- From a Y^* decay: $Y^* \rightarrow B + K^-$ Need to produce heavy hyperon first!

Channels for K^- production

In addition to the strangeness exchange K^- can be produced by

- As Kaon+anti-Kaon pair in a string. (not relevant at is beam energy!)
- From a Y* decay: $Y^* \to B + K^-$ Need to produce heavy hyperon first!
- From a N* decay: $N^* \to B + M \to B + K^- + K^+$
- Where M could be a ϕ or other meson (e.g. a_0, f_0).

equilibrium in an non-equilibrium Model

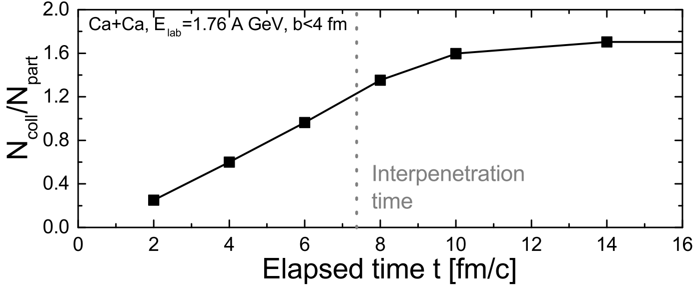
- At SIS18 energies the dominant process for resonance creation is B+B$\rightarrow$B+B.

equilibrium in an non-equilibrium Model

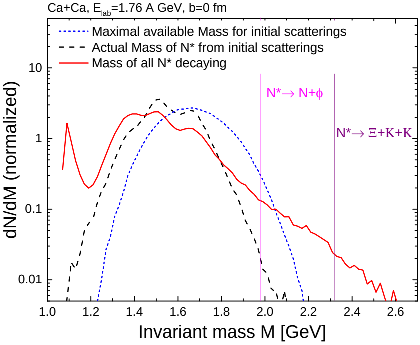
- At SIS18 energies the dominant process for resonance creation is B+B→B+B.
- As a test case we will study the Ar+KCl at $E_{lab} = 1.76$ A GeV.

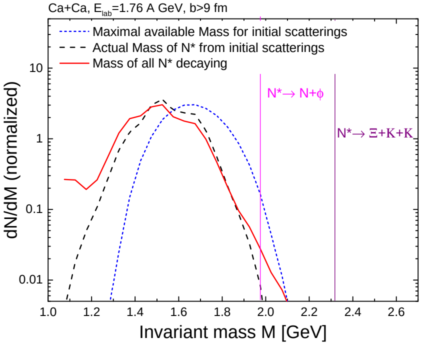
equilibrium in an non-equilibrium Model

- At SIS18 energies the dominant process for resonance creation is B+B→B+B.
- As a test case we will study the Ar+KCl at $E_{lab} = 1.76$ A GeV.
- Shown is the average number of total scatterings per participant as function of time. It is < 2!!



Equilibrium in an non-equilibrium Model?

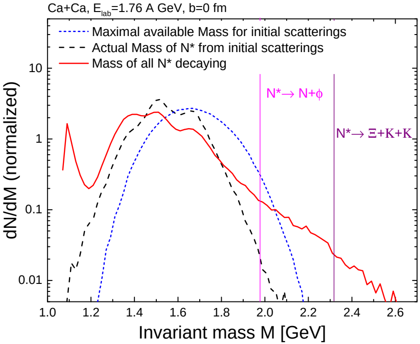




So how can we accumulate enough energy to go above the threshold

- Let us compare the available energy per collision $\sqrt{s} - m_N$, for two different centralities.
- Central system more rescatterings, peripheral system less rescatterings

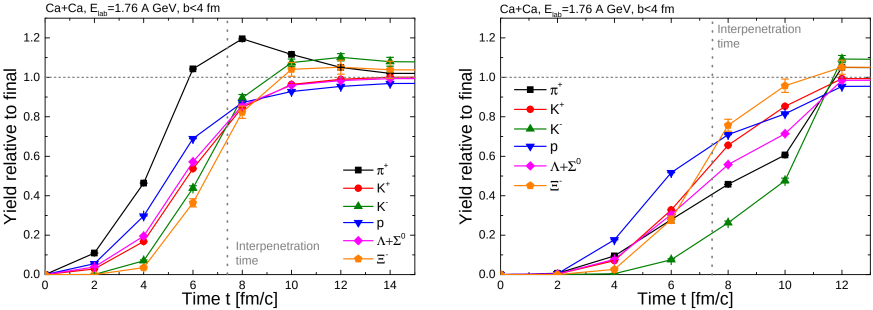
Equilibrium in an non-equilibrium Model?



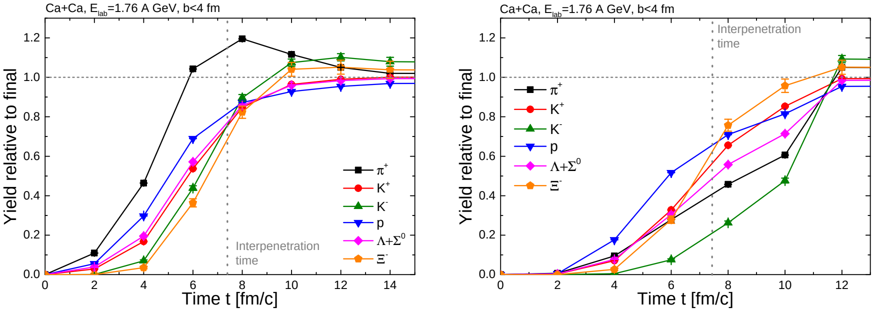
So how can we accumulate enough energy to go above the threshold

- 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.

Looking at the time dependence of particle multiplicity we can learn something about the production mechanisms.



Looking at the time dependence of particle multiplicity we can learn something about the production mechanisms.



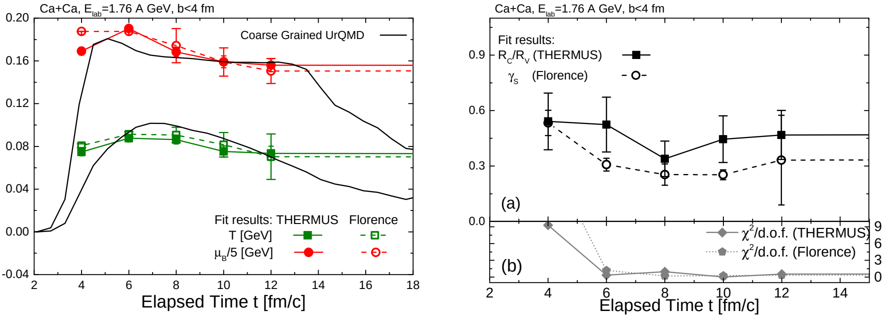
- K^- is delayed due to resonance production and gets reduced at late time due to exchange reactions.
- Pions mostly 'hidden' in resonances

Check for equilibrium the 'standard' way

- Take the time depended hadron multiplicities after decays and fit them with a thermal model

Check for equilibrium the 'standard' way

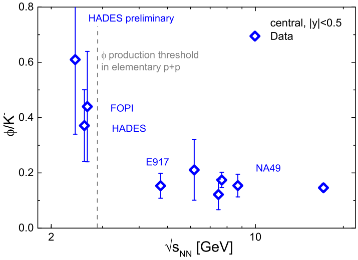
- Take the time depended hadron multiplicities after decays and fit them with a thermal model
- We can extract T, μ_B, γ_s or R_{CS} and $\chi^2/d.o.f.$



Result: The fit works well and the extracted thermal parameters correspond to the values obtained from a coarse-grained study assuming local equilibrium.

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

Recent measurements on near and below threshold production.



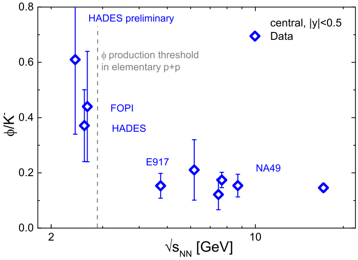
ϕ production

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

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

Motivation

Recent measurements on near and below threshold production.



ϕ production

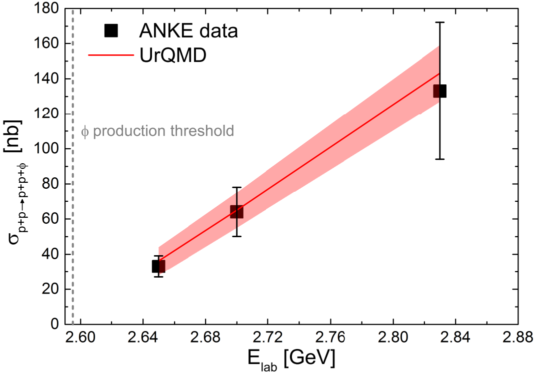
HADES and FOPI reported unexpected large ϕ contribution to the K^- yield.

UrQMD does not have a channel for ϕ production at low beam energies.
Doesn't man that is does not exist
$\rightarrow$ Use resonances.

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

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

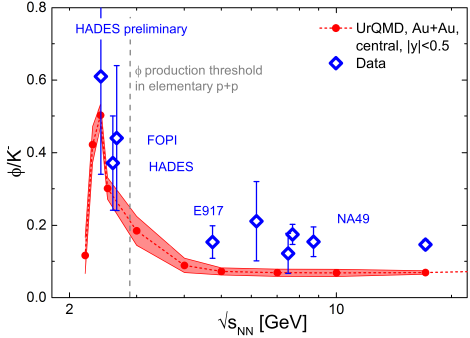
$\Gamma_{N^* \to N\phi}/\Gamma_{tot} = 0.2\%$

1 parameter fits all 3 points!

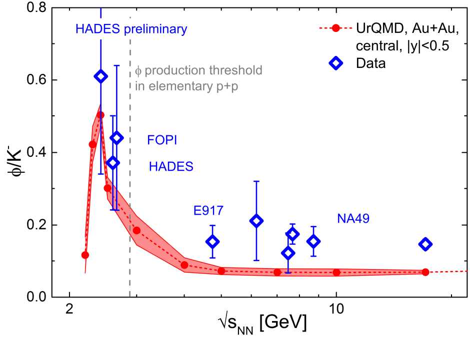
Y. Maeda *et al.* [ANKE Collaboration], Phys. Rev. C **77**, 015204 (2008) [arXiv:0710.1755 [nucl-ex]].

ϕ production in nuclear collisions below the p+p threshold

When applied to nuclear collisions:



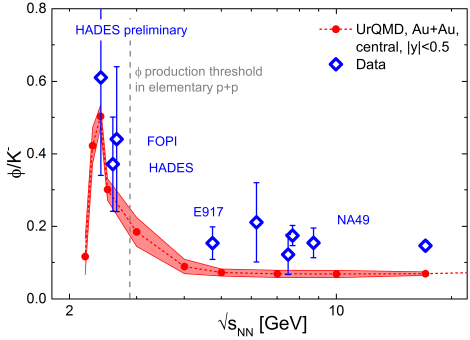
When applied to nuclear collisions:



- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV

ϕ production in nuclear collisions below the p+p threshold

When applied to nuclear collisions:



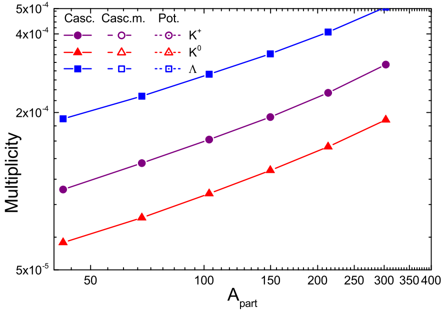
- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV
- High energies: too low due to string production
- HADES results for 1.23 A GeV.

Note

As we will see later K$^-$ production in UrQMD is to large. ϕ/K^- still within the errors.

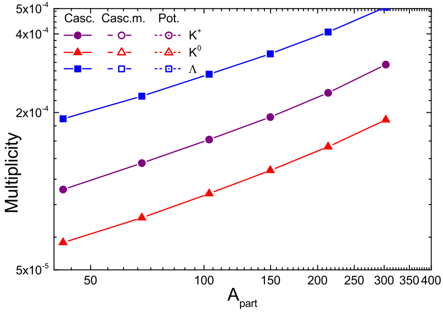
Centrality dependence

Using UrQMD we can calculate the centrality dependence of strange particle yields at $E_{lab} = 1.23$ A GeV.



Centrality dependence

Using UrQMD we can calculate the centrality dependence of strange particle yields at $E_{lab} = 1.23$ A GeV.

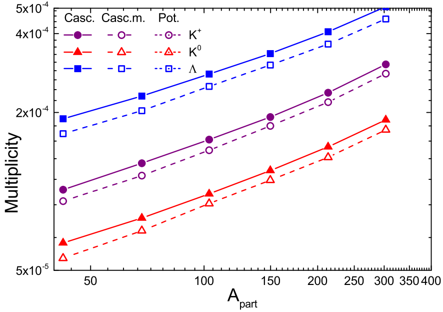


- Fitting the increase with A_{part} as $N_H \propto A_{part}^{\alpha}$: $\alpha = 1.55$

HADES: $\alpha \approx 1.45$

Centrality dependence

Using UrQMD we can calculate the centrality dependence of strange particle yields at $E_{lab} = 1.23$ A GeV.

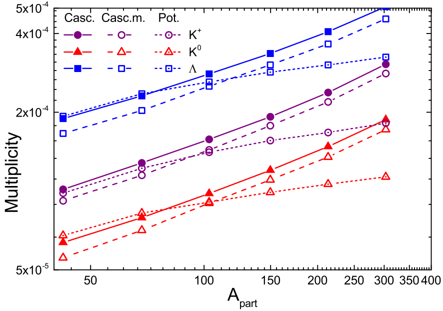


- Fitting the increase with A_{part} as $N_H \propto A_{part}^{\alpha}$:
  $\alpha = 1.55$
- When changing the branching ratios, α remains the same

HADES: $\alpha \approx 1.45$

Centrality dependence

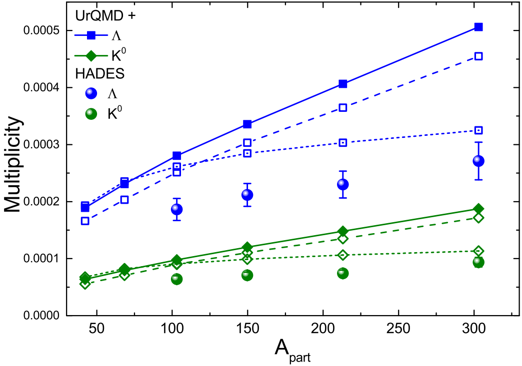
Using UrQMD we can calculate the centrality dependence of strange particle yields at $E_{lab} = 1.23$ A GeV.



- Fitting the increase with A_{part} as $N_H \propto A_{part}^{\alpha}$: $\alpha = 1.55$
- When changing the branching ratios, α remains the same
- Including (nuclear) potentials changes the A_{part} dependence, $\alpha \approx 1.25$.

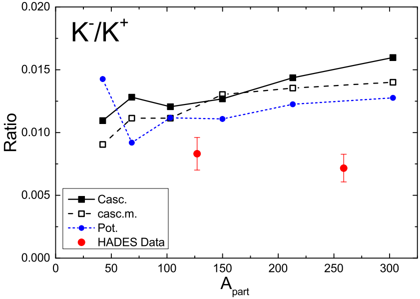
HADES: $\alpha \approx 1.45$

Direct Comparison with data



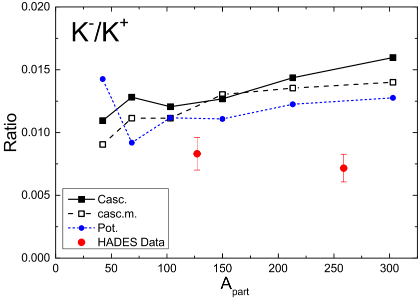
- The standard cascade version overestimates strangeness production.
- The potential version works better, still peripheral are overestimated
- For $A_{part} \approx 50$ the potentials are not important
  $\rightarrow$ this is where to gauge the parameters!

The K^-

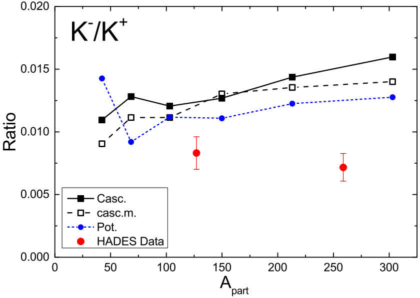


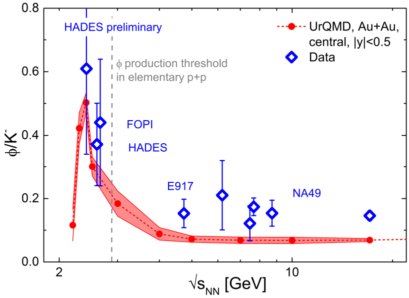
- The K^- to K^+ ratio is about 50% to large.
- Can be changed by decreasing the K^- production.

The K^-



- The K^- to K^+ ratio is about 50% to large.
- Can be changed by decreasing the K^- production.
- What about the ϕ to K^- then?





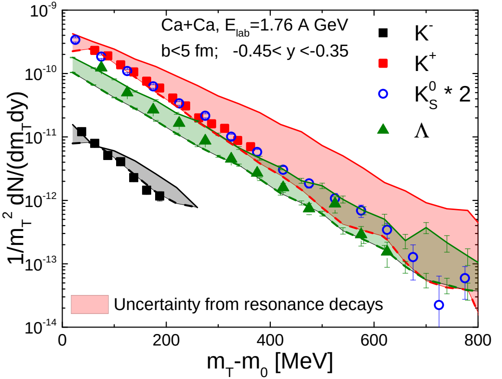
- The K$^-$ to K$^+$ ratio is about 50% to large.
- Can be changed by decreasing the K$^-$ production.
- What about the ϕ to K$^-$ then?
- The data can accommodate a 50% increase of ϕ to K$^-$!

Spectra shapes from resonances

Ratio [%]	$\Gamma_{\Lambda K}/\Gamma_{tot}$		$\Gamma_{\Sigma K}/\Gamma_{tot}$	
Resonance	I	II	I	II
N*(1650)	7	7	2	2
N*(1710)	10	10	3	3
N*(1720)	10	10	2	2
N*(1900)	2	2	0	0
N*(1990)	3	3	0	0
N*(2080)	12	0	0	0
N*(2190)	12	0	0	0
N*(2220)	12	0	0	0
N*(2250)	12	0	0	0
$\Delta(1920)$	0	0	3	3
$\Delta(1930)$	0	0	15	0
$\Delta(1950)$	0	0	12	0

Ratio [%]	$\Gamma_{\Lambda K}/\Gamma_{tot}$		$\Gamma_{\Sigma K}/\Gamma_{tot}$	
Resonance	I	II	I	II
N*(1650)	7	7	2	2
N*(1710)	10	10	3	3
N*(1720)	10	10	2	2
N*(1900)	2	2	0	0
N*(1990)	3	3	0	0
N*(2080)	12	0	0	0
N*(2190)	12	0	0	0
N*(2220)	12	0	0	0
N*(2250)	12	0	0	0
$\Delta(1920)$	0	0	3	3
$\Delta(1930)$	0	0	15	0
$\Delta(1950)$	0	0	12	0

Unknown resonance branching ratios also accommodate for Kaon spectra.



$\rightarrow \pi + N$ reactions are good testing ground for single meson channels.

Summary

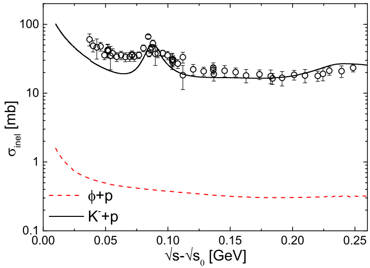
- Strangeness production at the SIS energy regime is still not fully understood.
- A pseudo chemically equilibrated system can be created from resonance decays alone.
- To understand the effects of potential interaction a more systematic study of centrality dependence is necessary.
- PDG hadron properties have large uncertainties - A more general approach to branching ratios should be useful.

ϕ suppression in nuclear medium

Detailed balance $\rightarrow$ absorption cross section

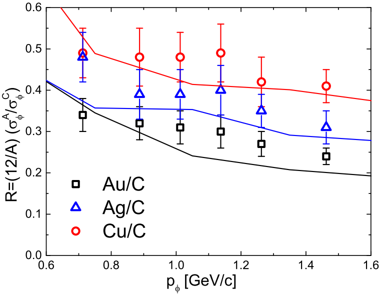
$$\frac{d\sigma_{b\to a}}{d\Omega} = \frac{\langle p_a^2\rangle}{\langle p_b^2\rangle}\frac{(2S_1+1)(2S_2+1)}{(2S_3+1)(2S_4+1)}\sum_{J=J_-}^{J_+}\frac{\langle j_1 m_1 j_2 m_2 || JM\rangle^2}{\langle j_3 m_3 j_4 m_4 || JM\rangle^2}\frac{d\sigma_{a\to b}}{d\Omega}$$

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

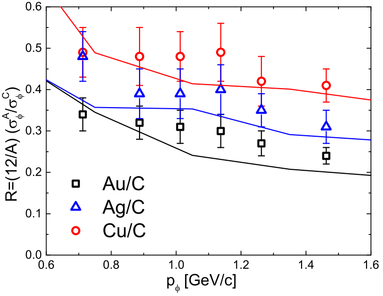


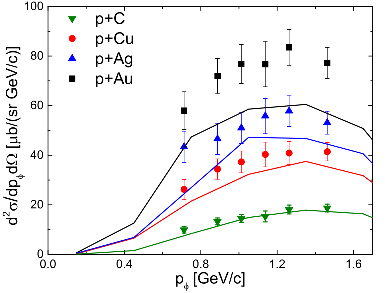
ϕ suppression in nuclear medium

- $\phi + p$ 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.



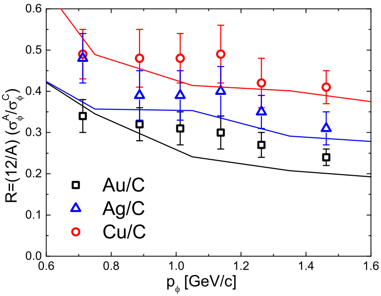
- $\phi + p$ cross section from detailed balance is very small.
- Still the transparency ratio is well reproduced. Remember: this is what lead to the 20 mb cross section from ANKE.
- Even the shape of the spectra looks good.



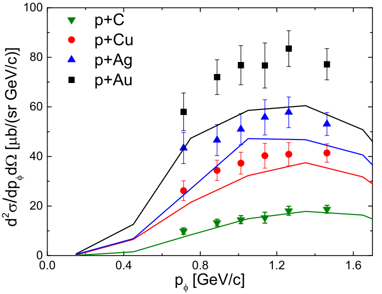


ϕ suppression in nuclear medium

- $\phi + p$ 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.
- Even the shape of the spectra looks good.

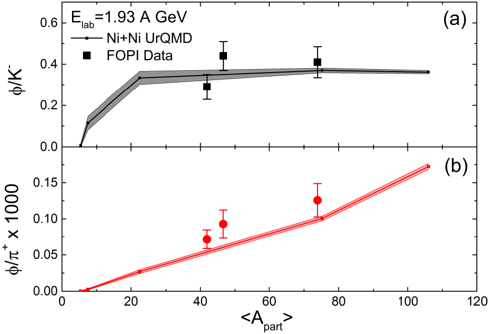


- Not 'absorption' of the ϕ, but of the mother resonance.
- Reactions of the type:
  $N^* + N \rightarrow N'^* + N'^*$
  $N^* + N \rightarrow N'^* + N'^*$
  where the mass of $N'^* < N*$ so no ϕ can be produced.



ϕ production in nuclear collisions below the p+p threshold

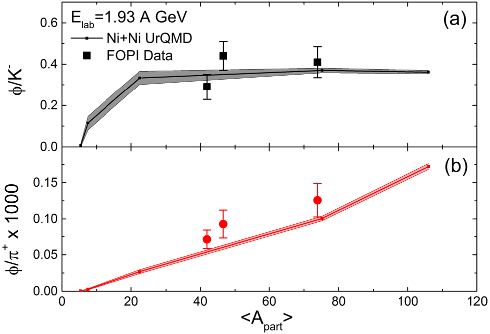
Even centrality dependence works well:



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

ϕ production in nuclear collisions below the p+p threshold

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].

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^-.

About the Kaon potential

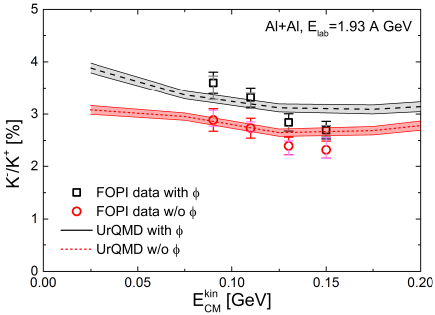
Kaon Potentials

- 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.

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.



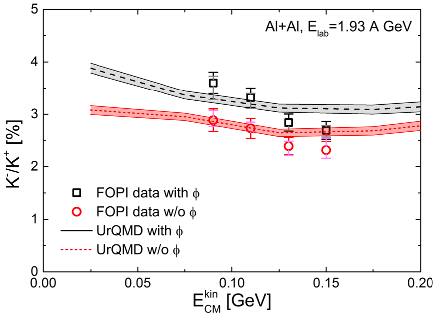
UrQMD results

- 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.

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?