# TRANSPORT MODELS AND STRANGENESS PRODUCTION

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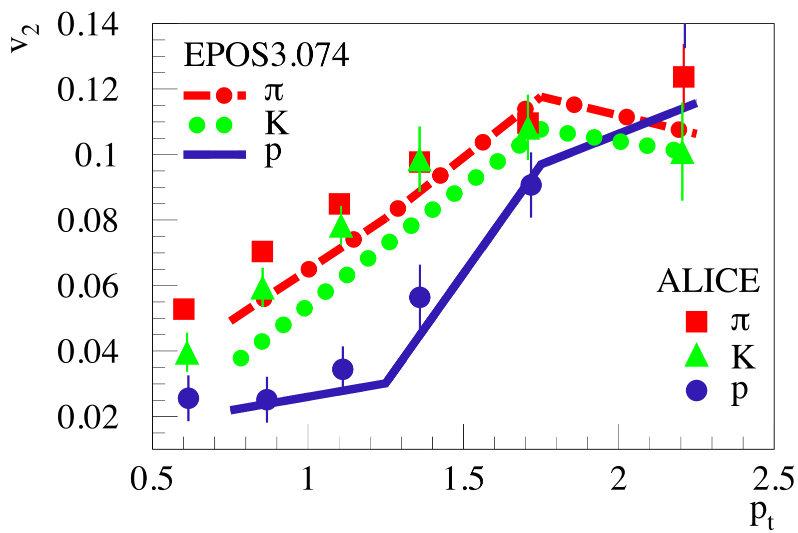
# Recent developments

- EPOS: Elliptic flow in p+Pb at LHC

## Elliptic flow in p+Pb

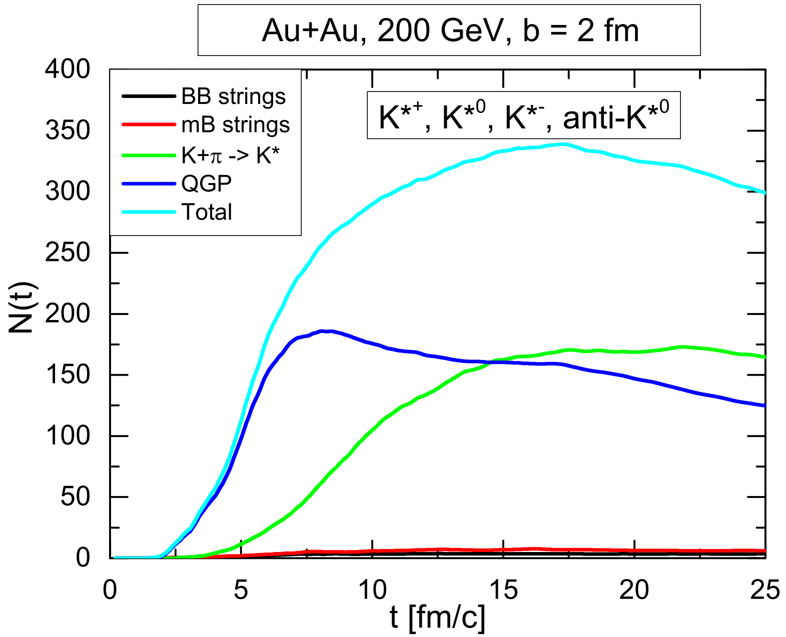



Werner, Bleicher, Pierog, Karpenko, Phys.Rev.Lett. 112 (2014) 23, 232301

# Recent developments

- EPOS: Elliptic flow in p+Pb at LHC
- pHSD: Resonances from the QGP at RHIC

## Resonances from the QGP

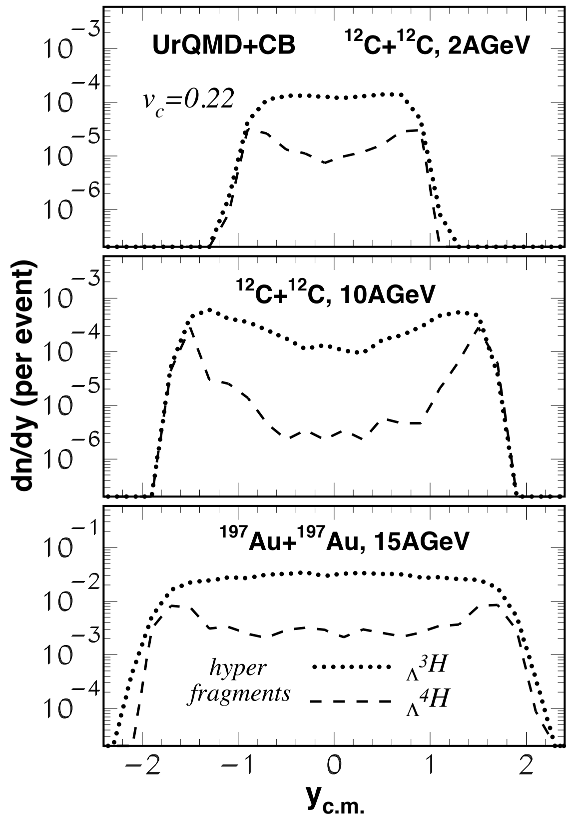



Illner, Cabrera, Bratkovskaya, EPJ Web Conf. 97 (2015) 00016

# Recent developments

- EPOS: Elliptic flow in p+Pb at LHC
- pHSD: Resonances from the QGP at RHIC
- UrQMD: Hypermatter

## Hypermatter production

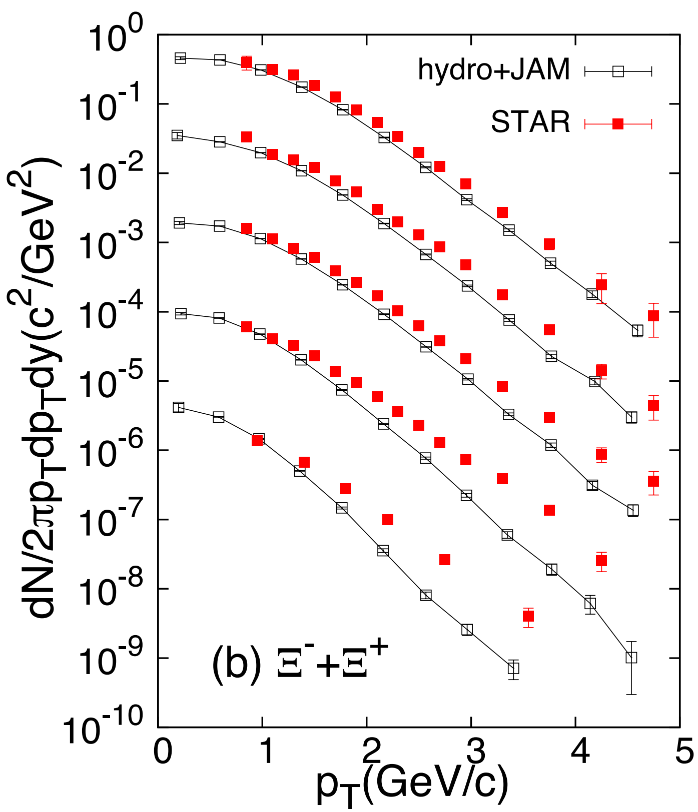



Botvina, Bratkovskaya, Steinheimer, Bleicher, Pochodzalla, Phys.Lett. B742 (2015) 7-14

# Recent developments

- EPOS: Elliptic flow in p+Pb at LHC
- pHSD: Resonances from the QGP at RHIC
- UrQMD: Hypermatter
- Hydro+JAM: Strangeness production at RHIC
- → Hybrid models

## Multi-strange particles at RHIC




Takeuchi, Murase, Hirano, Huovinen, Nara, arXiv:1505.05961

# Multi-strange hadrons

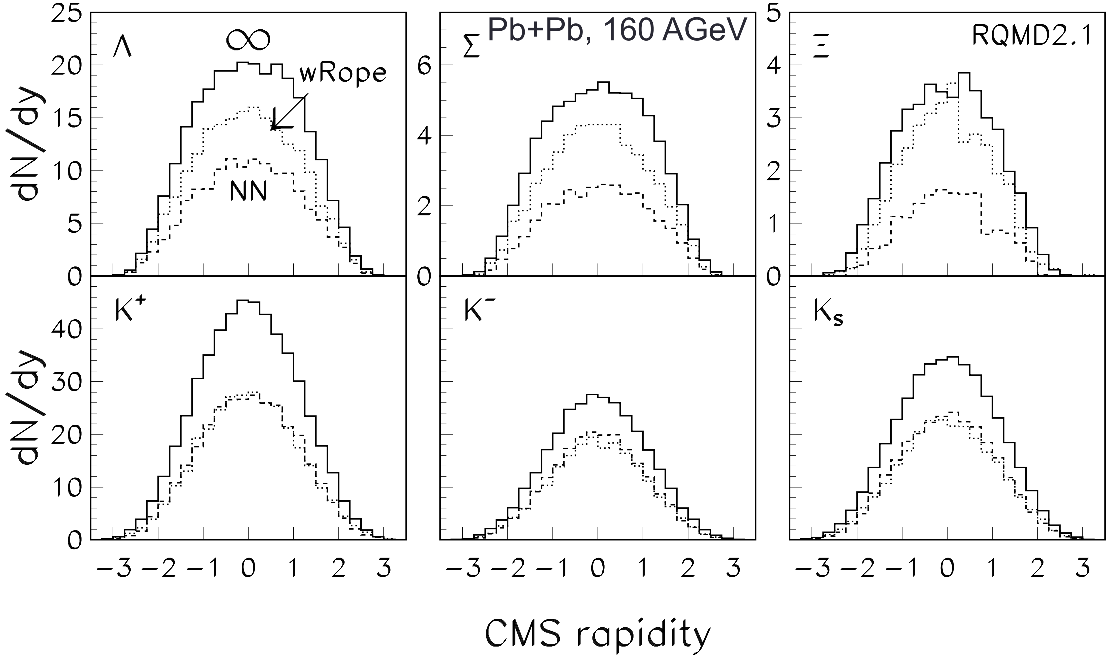
## Pro's

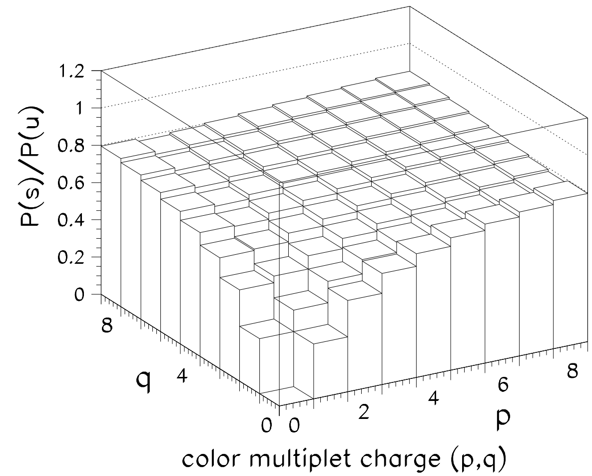
- Infer matter properties/ potentials/equilibration times
- Provides hints for novel processes (ropes?)
- Explore subthreshold multi-step processes
- Explore canonical effects

## Con's

- Experimentally not well explored
- Difficult to measure (di-leptons, multi-particle correlation)
- Theoretically not well understood

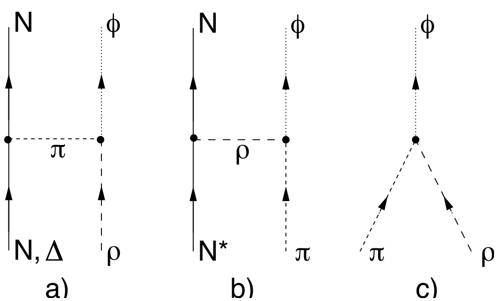
J.Randrup and C.M.Ko, Nucl. Phys. A 343, 519 (1980),
P.Koch, B.Müller and J.Rafelski, Phys. Rept. 142, 167 (1986),
W.Cassing, E.L.Bratkovskaya, U.Mosel, S.Teis and A.Sibirtsev, Nucl. Phys. A 614 , 415 (1997),
S.Bass, M. Belkacem, M.Bleicher, et al, Phys. Rev. Lett. 81 (1998) 4092,
C.Hartnack, H.Oeschler, Y.Leifels, E.L.Bratkovskaya and J.Aichelin, Phys. Rept. 510, 119(2012)
…. and many more



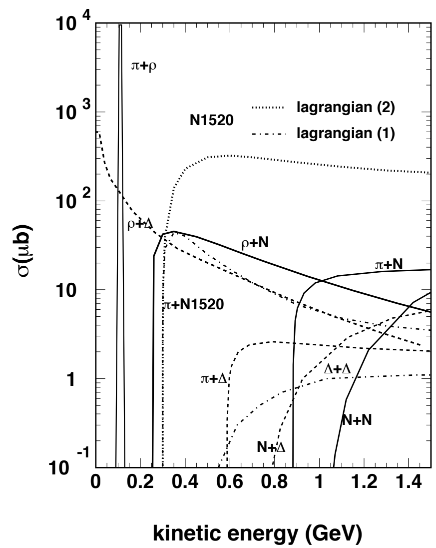




H. Sorge, Phys.Rev. C52 (1995) 3291-3314

# Multi-strange particle production: „Old“ problem in transport simulations




Catalytic phi production, Kolomeitsev, Tomasik, J.Phys. G36 (2009) 095104

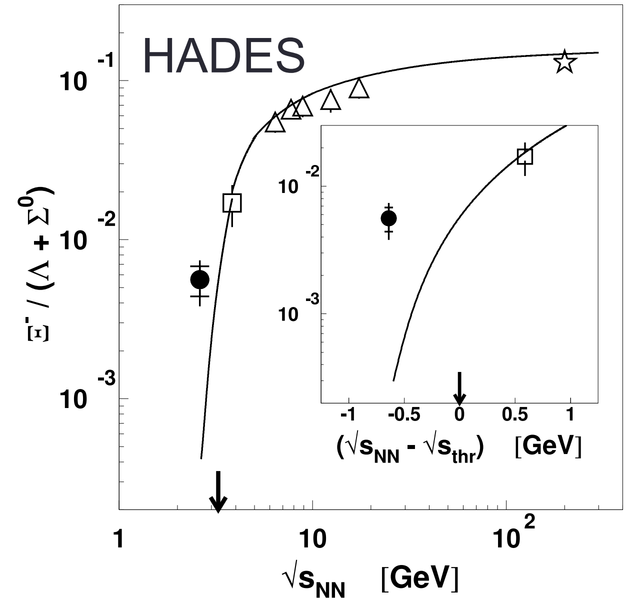



| yields from | Ni + Ni (1.93 GeV) | Ru + Ru (1.69 GeV) |
|---|---|---|
| B + B | $3.5 \cdot 10^{-4}$ | $3.1 \cdot 10^{-4}$ |
| $\pi$ + B | $2.9 \cdot 10^{-4}$ | $3.2 \cdot 10^{-4}$ |
| $\rho$ + B | $8.9 \cdot 10^{-4}$ | $11.8 \cdot 10^{-4}$ |
| $\pi + \rho$ | $1.6 \cdot 10^{-4}$ | $1.5 \cdot 10^{-4}$ |
| $\pi$ + N(1520) | $0.5 \cdot 10^{-4}$ | $0.6 \cdot 10^{-4}$ |
| total yield | $1.7 \cdot 10^{-3}$ | $2.0 \cdot 10^{-3}$ |
| experiment [1] | $(8.7 \pm 3.6) \cdot 10^{-3}$ | $(6.4 \pm 2.5) \cdot 10^{-3}$ |

H. Barz, M. Zetenyi, G. Wolf, B. Kämpfer, Nucl.Phys. A705 (2002) 223
Data: FOPI

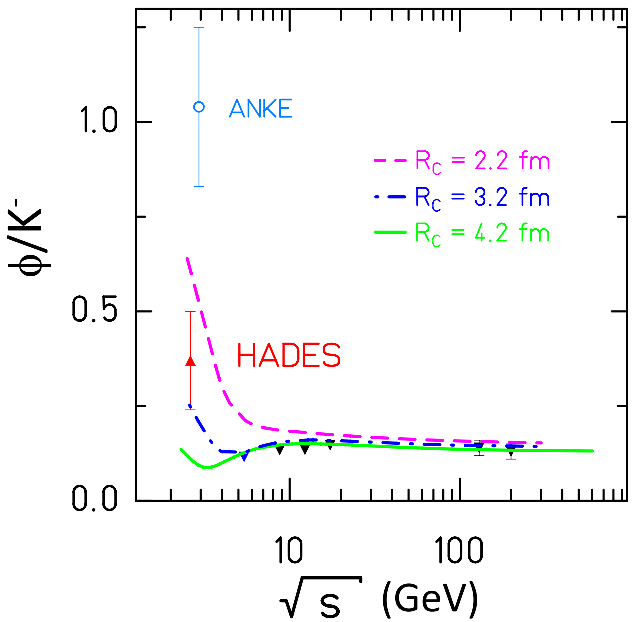
# Motivation

- HADES reported unusually high yield of Ξ-baryons (Ξ/Λ=5.6 $10^{-3}$)




HADES, Phys.Rev.Lett. 103 (2009) 132301

- HADES reported unusually large contribution from φ to $K^-$ yield (18%)



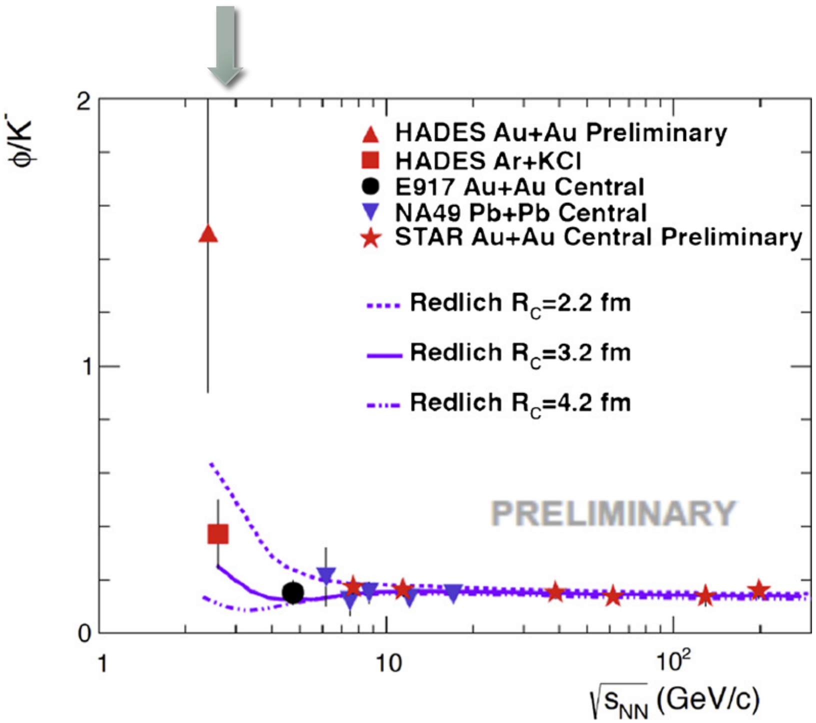

HADES, Phys.Rev. C80 (2009) 025209

# Recent HADES measurements near and below threshold

## $\phi$ production

- Threshold for $p+p \rightarrow p+p+\phi \approx 2.895$ GeV
- Measured in Ar+KCl and Au+Au

## HADES data on $\phi$ production



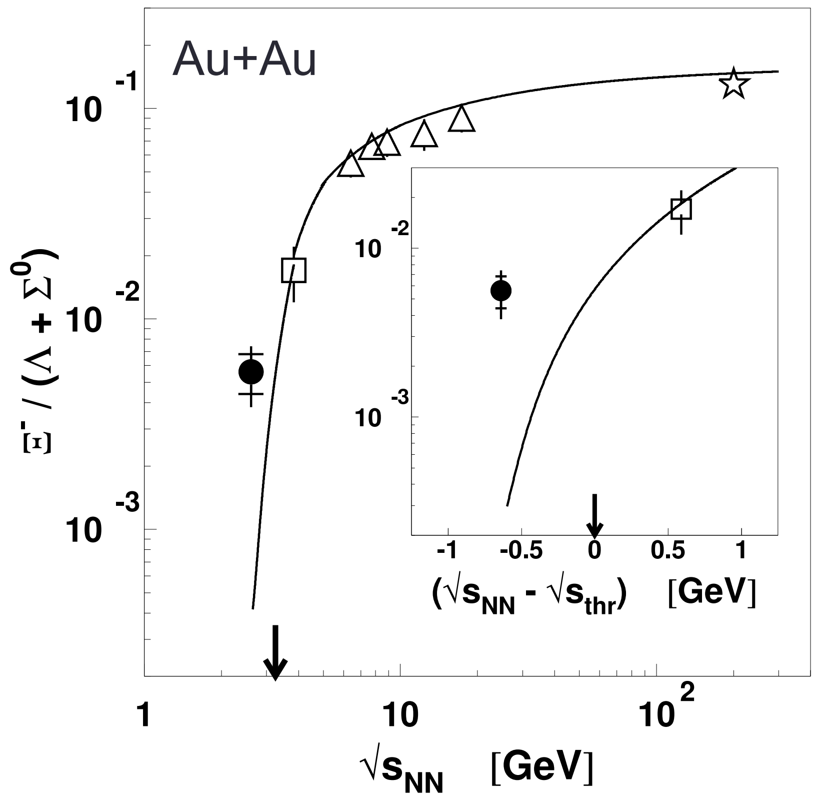

M. Lorenz [HADES Collaboration], Nucl. Phys. A 931, 785 (2014).

# Recent HADES measurements near and below threshold

## Ξ production

- Threshold for p+p→p+p+φ ≈ 2.895 GeV
- Measured in Ar+KCl and Au+Au
- Threshold for p+p→N+Ξ+K+K≈3.24GeV
- Measured in p+Nb and Au+Au

## HADES data on Ξ production



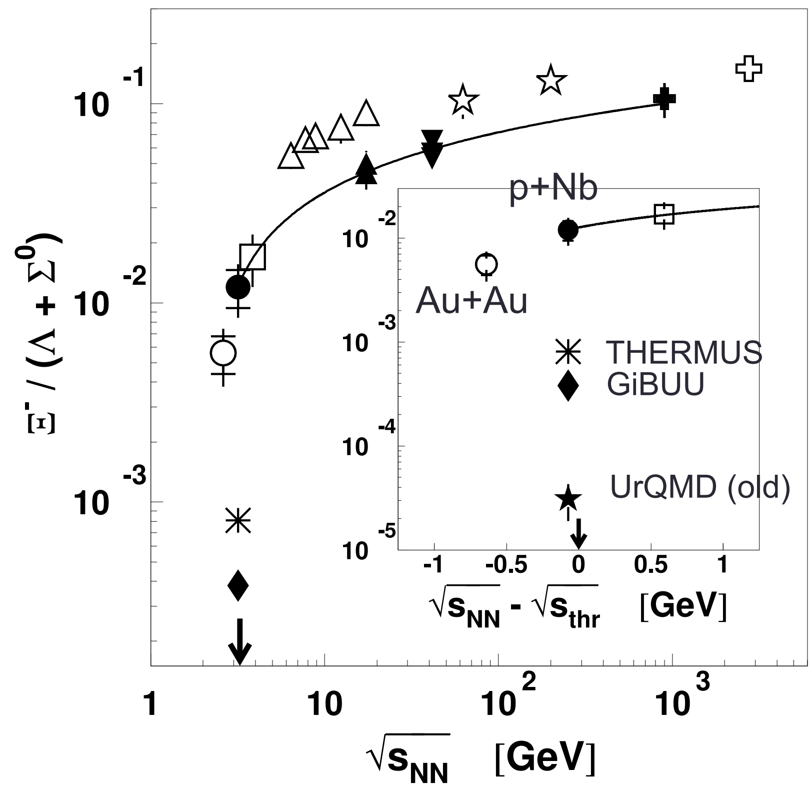

G.Agakishiev et al. [HADES Collaboration], Phys. Rev. Lett. 103, 132301 (2009)

# Recent HADES measurements near and below threshold

## Ξ, ϕ production

- Threshold for p+p→p+p+ϕ ≈ 2.895 GeV
- Measured in Ar+KCl and Au+Au
- Threshold for p+p→N+Ξ+K+K≈3.24GeV
- Measured in p+Nb and Au+Au
- Both particles are not well described by models

## HADES data on Ξ production




G.Agakishiev et al. [HADES Collaboration], arXiv:1501.03894

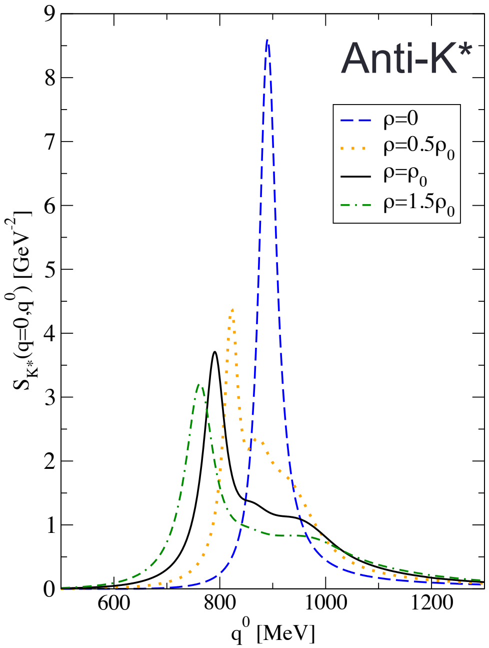
# Subthreshold production:Two paradigms

## 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

# Strangeness production in UrQMD

## Particle production goes via

- Resonance excitation:
  N+N → X
  N+M → X
  M+M → X

## Relevant channels at HADES

NN → $N\Delta_{1232}$

NN → $NN^*$

NN → $N\Delta^*$

NN → $\Delta_{1232}\Delta_{1232}$

NN → $N^*\Delta_{1232}$

NN → $\Delta^*\Delta_{1232}$

NN → $R^*R^*$

# Strangeness production in UrQMD

## Particle production goes via

- Resonance excitation:
  N+N → X
  N+M → X
  M+M → X
- Annihilation:
  B+anti-B → X

## Relevant channels at HADES

Not relevant at this energy

# Strangeness production in UrQMD

Particle production goes via

- Resonance excitation:
  N+N → X
  N+M → X
  M+M → X
- Annihilation:
  B+anti-B → X
- String excitation
  N+N → X ($s^{1/2}$>3.5 GeV)
  N+M → X ($s^{1/2}$>2.2 GeV)
  M+M → X ($s^{1/2}$>2.2 GeV)

Relevant channels at HADES

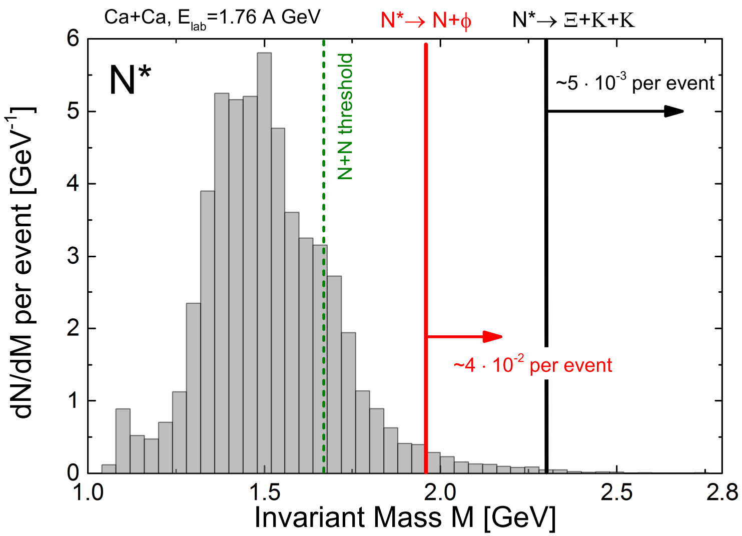
Could be relevant

# 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 $\phi$ and $\Xi$ production?

## Resonance mass distribution




Yes! But for $\Xi$, only in the tails.

→ Introduce branching ratio for decay into N$\phi$

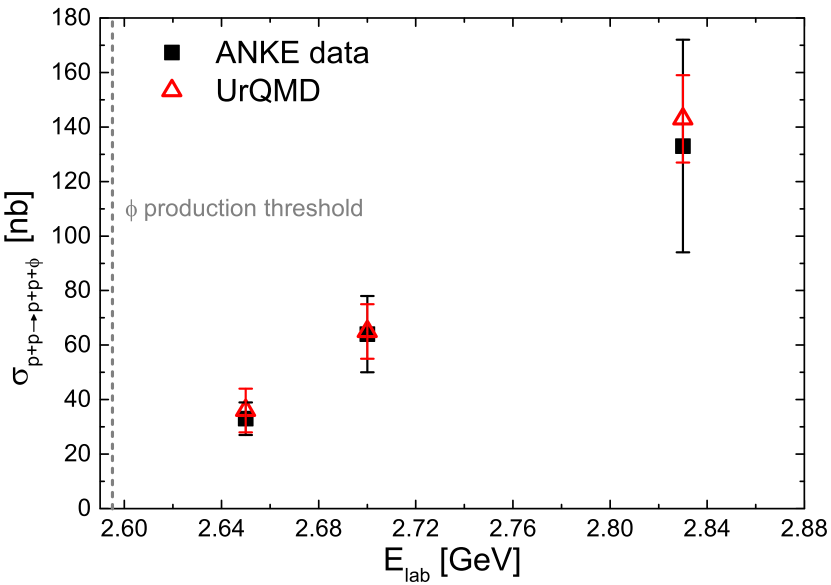
# Introduce a branching ratio to $\phi$ for heavy N* states

In UrQMD these are the states:
N* (1990), N*(2080), N*(2190), N*(2220), N*(2250)

Assumption: Branching ratio to $\phi$ is equal for all resonances (typical branching ratio into $\omega$ is 5-20%)

# Fixing the branching ratio

- $\phi$ production yields from ANKE can be consistently described with $\Gamma^{N^*\rightarrow N\phi}/\Gamma^{total}$ = 0.2%
- Branching ratio is consistent with extracted OZI suppression ($\omega/\phi$)




Y. Maeda et al. [ANKE Collaboration], Phys. Rev. C 77, 015204 (2008)

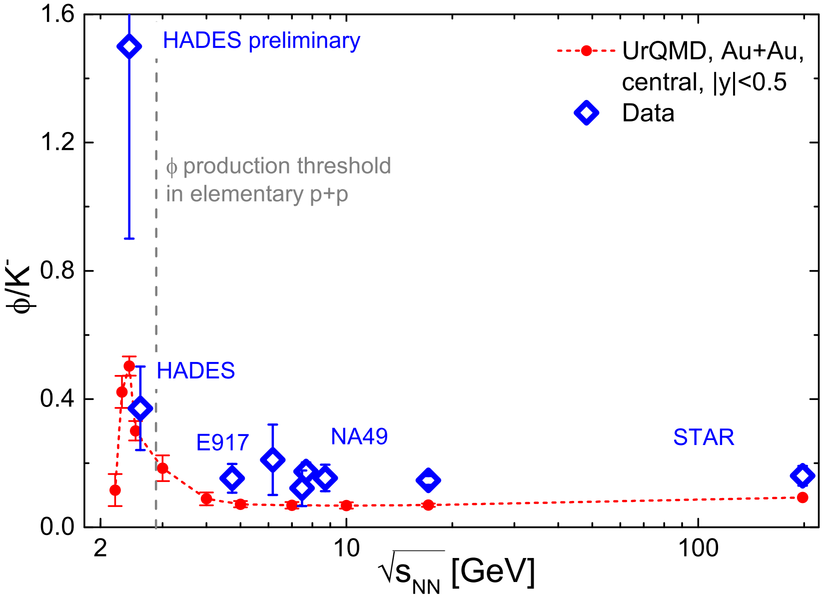
A. Sibirtsev, J. Haidenbauer and U. G. Meissner, Eur. Phys. J. A 27, 263 (2006)

# ϕ production in nuclear collisions

## Conclusions for ϕ

- Qualitative behaviour nicely reproduced
- Peak predicted at $E_{lab}$=1.25 AGeV
- Underestimation at higher energies, due to string fragmentation
- Preliminary HADES data is still higher…

## When applied to nuclear collisions



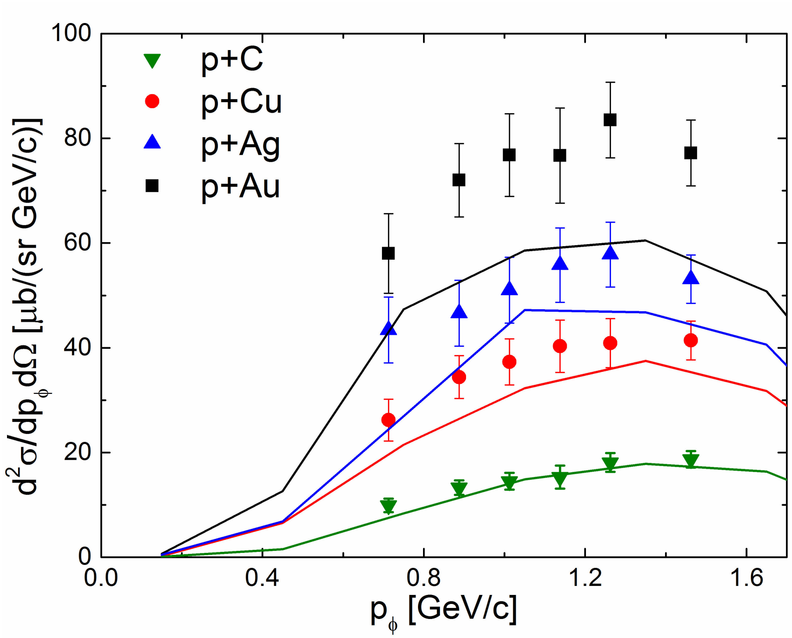

J. Steinheimer, M. Bleicher, arXiv:1503.07305

# $\phi$ production in p+A at COSY

## Model performance

- The cross section for smaller targets is better reproduced.
- Very good description of the shape of the momentum dependent cross section
- Slightly too much absorption in nuclear matter, without any in-medium modification of the phi.

## UrQMD vs ANKE data: Differential cross section




Beam energy is 2.83 GeV, results are in ANKE acceptance

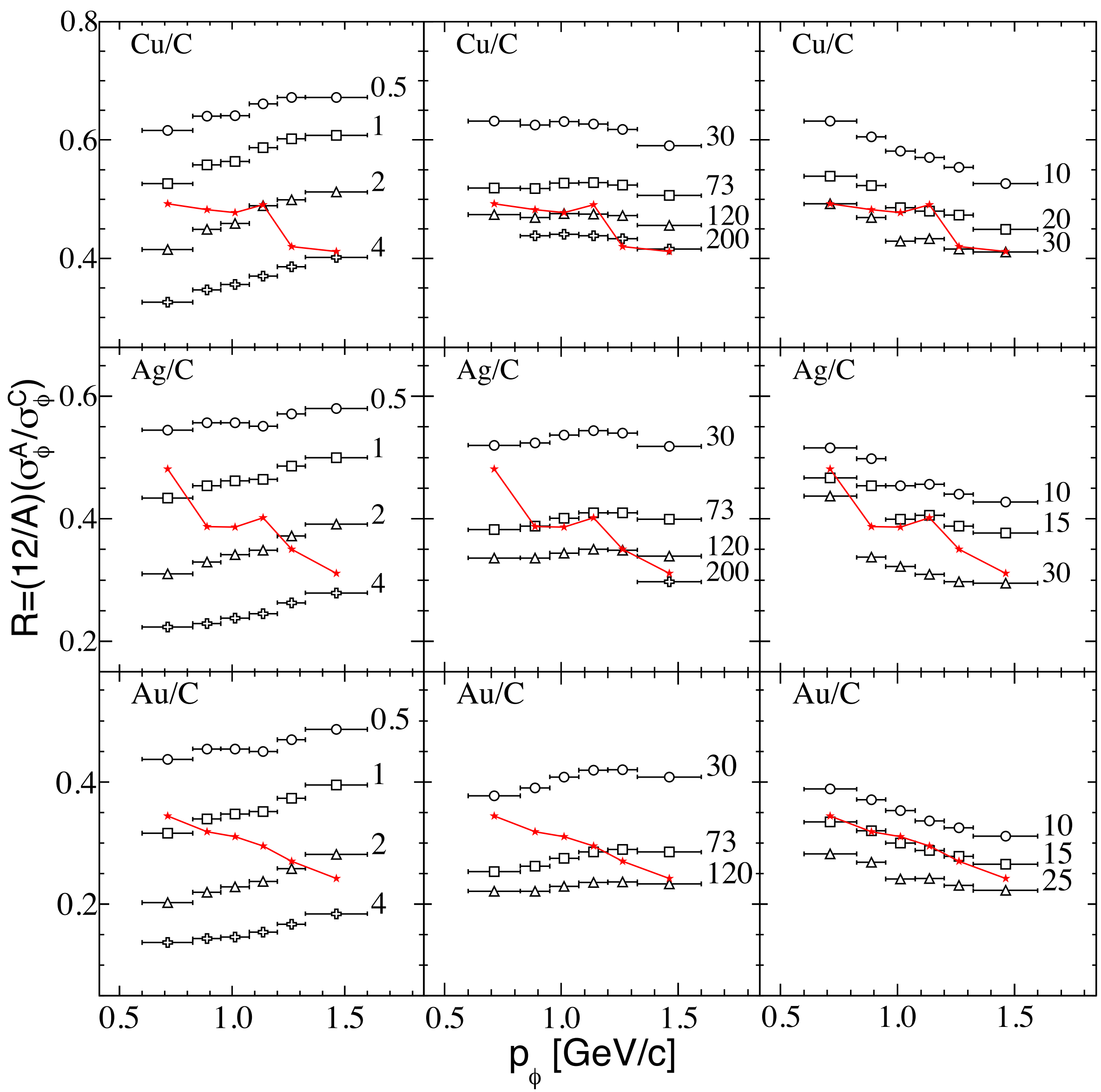
M. Hartmann et al., Phys. Rev. C 85, 035206 (2012)

# ϕ transparency ratios

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.



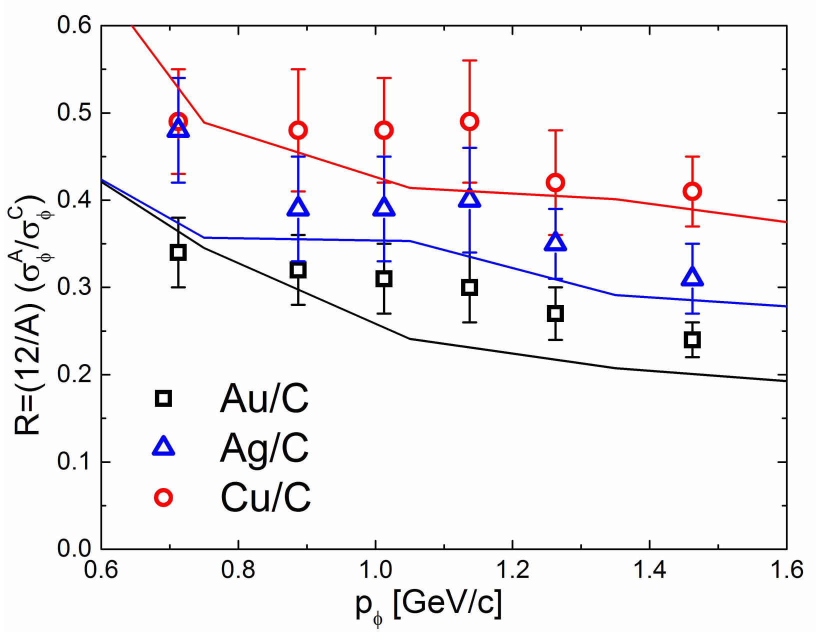

M. Hartmann et al., Phys. Rev. C 85, 035206 (2012)

# ϕ production in p+A at COSY: Transparency ratios

## Model performance

- Slightly too much absorption in nuclear matter, without any in-medium modification of the ϕ.
- Not 'absorption' of the ϕ, but of the mother resonance
- Reactions of the type
  N*+N→N'*+N'*
  N*+N→N'*+N
  where the mass of N'* is smaller than of N* so that no ϕ can be produced.

## UrQMD vs ANKE data: Transparency ratios




Beam energy is 2.83 GeV, results are in ANKE acceptance

M. Hartmann et al., Phys. Rev. C 85, 035206 (2012)

# Subthreshold Ξ production

- Can we employ the same idea to describe the Ξ data at HADES?

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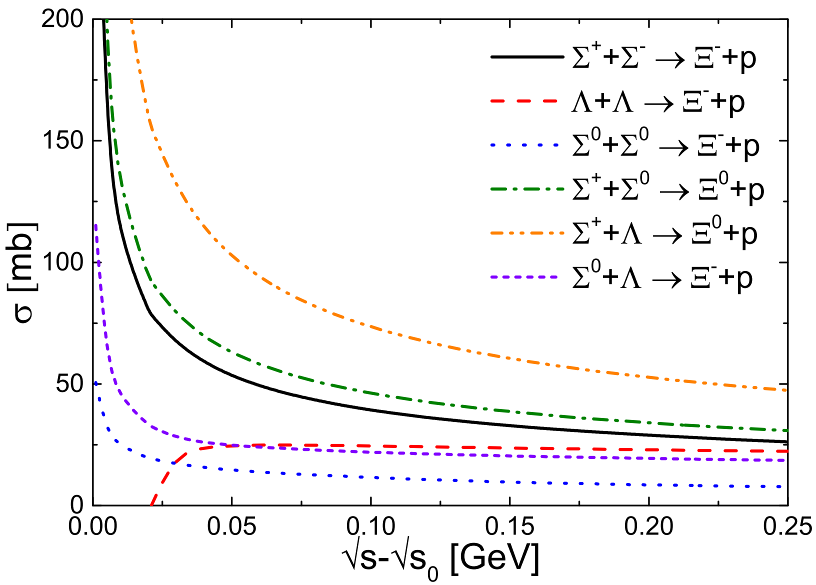
- First fix the 'standard' channels for X production → Hyperon-hyperon reactions
- Then use p+Nb data to fix branching ratio for N*→Ξ+K+K

# Hyperon-hyperon interactions

## Cross sections




$$\sigma_{\Lambda\Lambda\to\Xi^- p} = \sigma_{\Lambda\Lambda\to\Xi^0 n} = \frac{1}{2}\sigma_{\Lambda\Lambda\to\Xi N} = \frac{37.15}{2}\frac{p_N}{p_\Lambda}(\sqrt{s}-\sqrt{s_0})^{-0.16}\mathrm{mb}$$

$$\sigma_{\Lambda\Sigma^+\to\Xi^0 p} = \sigma_{\Lambda\Sigma^-\to\Xi^- n} = 24.3781(\sqrt{s}-\sqrt{s_0})^{-0.479}\mathrm{mb}$$

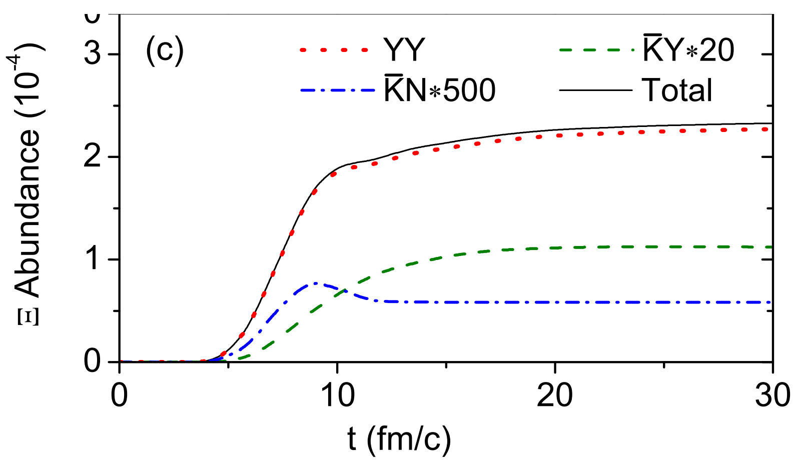
$$\sigma_{\Lambda\Sigma^0\to\Xi^- p} = \sigma_{\Lambda\Sigma^0\to\Xi^0 n} = \begin{cases} 6.475(\sqrt{s}-\sqrt{s_0})^{-0.4167}\mathrm{mb} & \text{for } (\sqrt{s}-\sqrt{s_0}) < 0.03336\mathrm{GeV} \\ 14.5054(\sqrt{s}-\sqrt{s_0})^{-0.1795}\mathrm{mb} & \text{for } (\sqrt{s}-\sqrt{s_0}) > 0.03336\mathrm{GeV} \end{cases}$$

$$\sigma_{\Sigma^0\Sigma^0\to\Xi^- p} = \sigma_{\Lambda\Sigma^0\to\Xi^0 n} = \begin{cases} 5.625(\sqrt{s}-\sqrt{s_0})^{-0.318}\mathrm{mb} & \text{for } (\sqrt{s}-\sqrt{s_0}) < 0.09047\mathrm{GeV} \\ 4.174(\sqrt{s}-\sqrt{s_0})^{-0.4421}\mathrm{mb} & \text{for } (\sqrt{s}-\sqrt{s_0}) > 0.09047\mathrm{GeV} \end{cases}$$

$$\sigma_{\Sigma^+\Sigma^0\to\Xi^0 p} = \sigma_{\Sigma^0\Sigma^-\to\Xi^- n} = 4\sigma_{\Sigma^0\Sigma^0\to\Xi^- p}$$

$$\sigma_{\Sigma^+\Sigma^-\to\Xi^- p} = \sigma_{\Sigma^+\Sigma^-\to\Xi^0 n} = 14.194(\sqrt{s}-\sqrt{s_0})^{-0.442}\mathrm{mb}$$

## Strong contribution to Χ yield

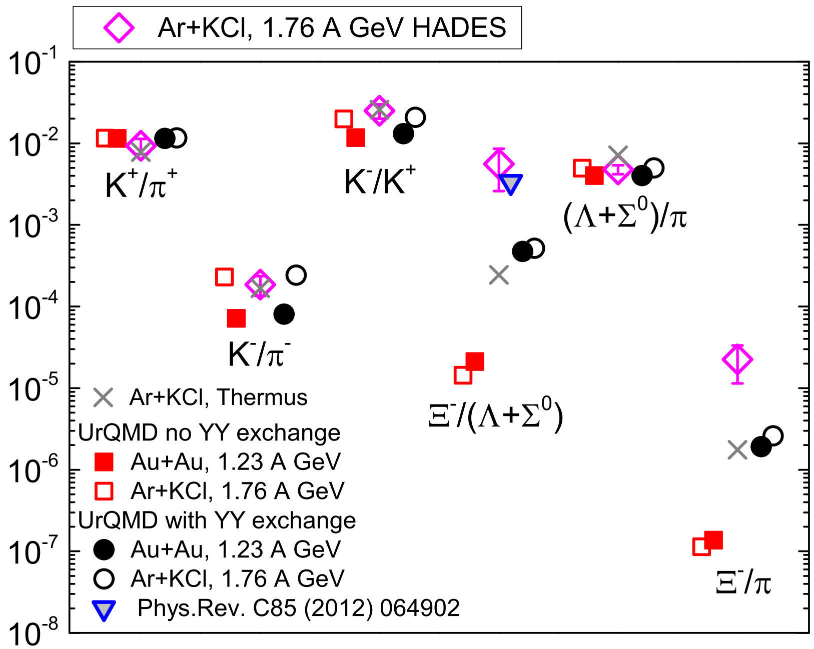



Results from Li and Ko

C.H. Li, C.M. Ko, Nucl.Phys. A712 (2002) 110-130
F. Li, L.W. Chen, C.M. Ko, S.H. Lee,
Phys.Rev. C85 (2012) 064902

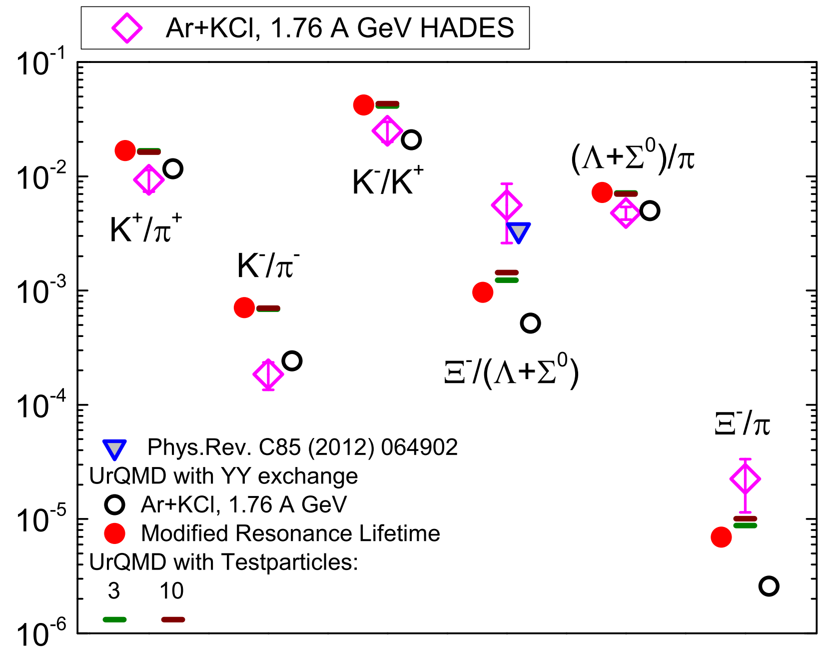
# UrQMD results

## Effect of YY→Ξ+N channel




Nearly a factor 100 improvement for Ξ/Λ and Ξ/π, but not good enough!

## Tests




Results differ from Li and Ko, due to test-particles and delayed Λ production due to resonance life times

Gräf, Steinheimer, Li, Bleicher, Phys.Rev. C90 (2014) 064909

# Fixing the N*→Ξ+K+K branching ratio

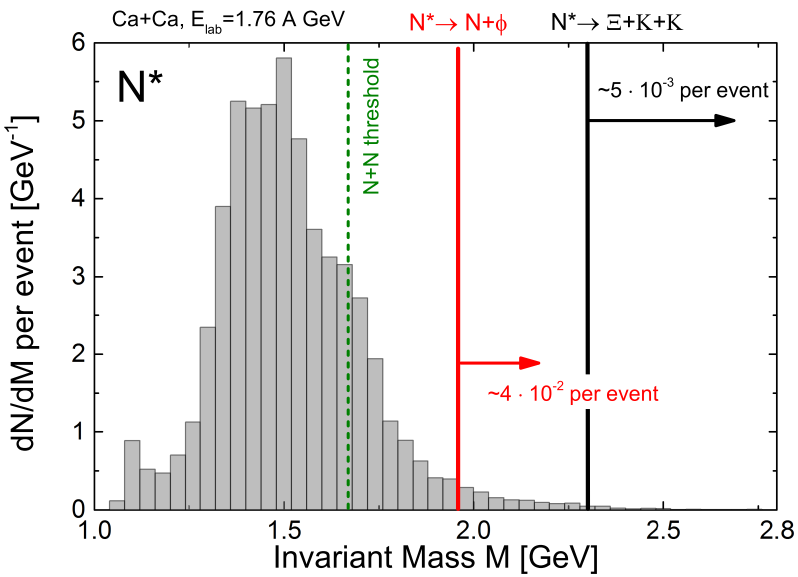
## Use HADES p+Nb data at 3.5 GeV

- Branching ratio needed in the tails of the heavy resonances!
- Ξ production in p+Nb can be consistently described with an integrated branching ratio $\Gamma^{N^* \to \Xi KK}/\Gamma^{total} < 1\%$

(i.e 10% where kinematically allowed)

## Comparison to the HADES yields

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

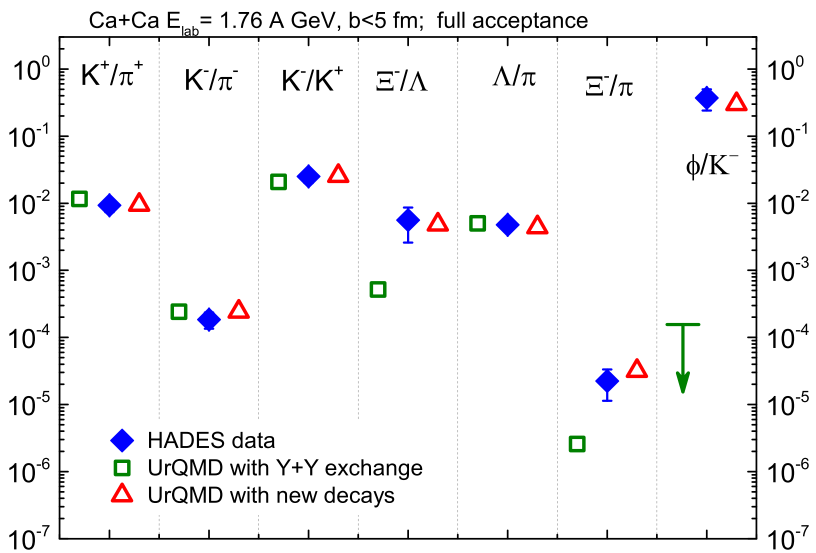


# Ξ production below threshold

## Conclusions

- Ξ yield nicely reproduced in Ar+KCl
- Results consistent with p+Nb data
- Non-thermal mass tails allow for a non-thermal Ξ production
- All other strange particles are also in line with data

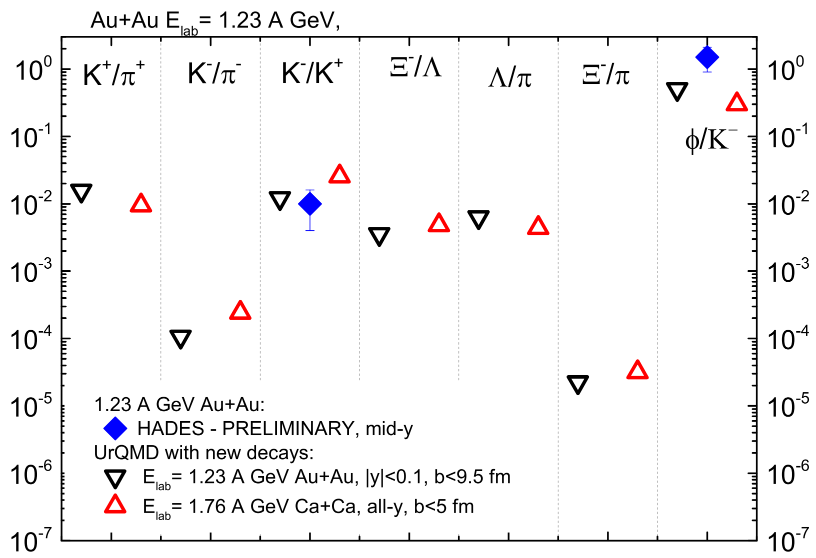
## Data vs. model



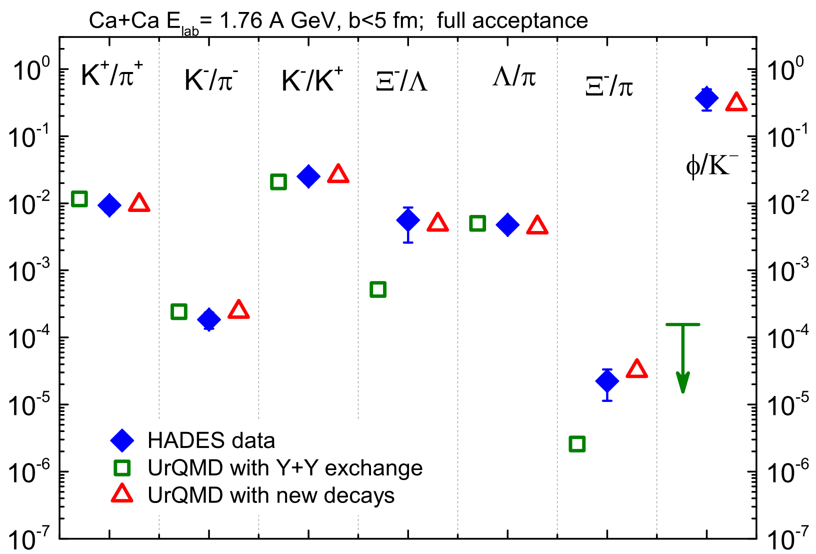

Steinheimer, Bleicher, arXiv:1503.07305

# Predictions for Au+Au

## Au+Au at 1.23 AGeV




## Ar+KCl at 1.76 AGeV




Not much change in the $\Xi/\Lambda$ ratio
Data suggests even higher $\phi$/K ratio!

Steinheimer, Bleicher, arXiv:1503.07305

# Summary

- We introduced a new mechanism for $\phi$ and $\Xi$ production (resonance decay)
- This allows to describe the $\phi$ and $\Xi$ production in elementary and nuclear collisions
- The used branching ratios are small and consistent with OZI