Charm and strangeness production at GSI/FAIR energies

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What we know: Lagrange density of The Standard Model

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$

$$\frac{1}{2} m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$

$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$

$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$

$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$

$$\frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$

$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$

$$\frac{1}{8} g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$

$$gMW^+_\mu W^-_\mu H - \frac{1}{2} g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2} ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2} g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$

$$\phi^+\partial_\mu H)] + \frac{1}{2} g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$

$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$

$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4} g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$

$$\frac{1}{4} g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2} g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2} ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2} g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) + \frac{1}{2} ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$

$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$

$$\frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3} s_w^2 -$$

$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3} s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$

$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$

$$\gamma^5)u^\lambda_j)] +$$

4

$$\frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$

$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$

$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$

$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$

5

$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y -$$

$$\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ -$$

$$\partial_\mu\bar{X}^-X^-) - \frac{1}{2} gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] +$$

$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] +$$

$$igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2} igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

We only need the first two lines... puuh

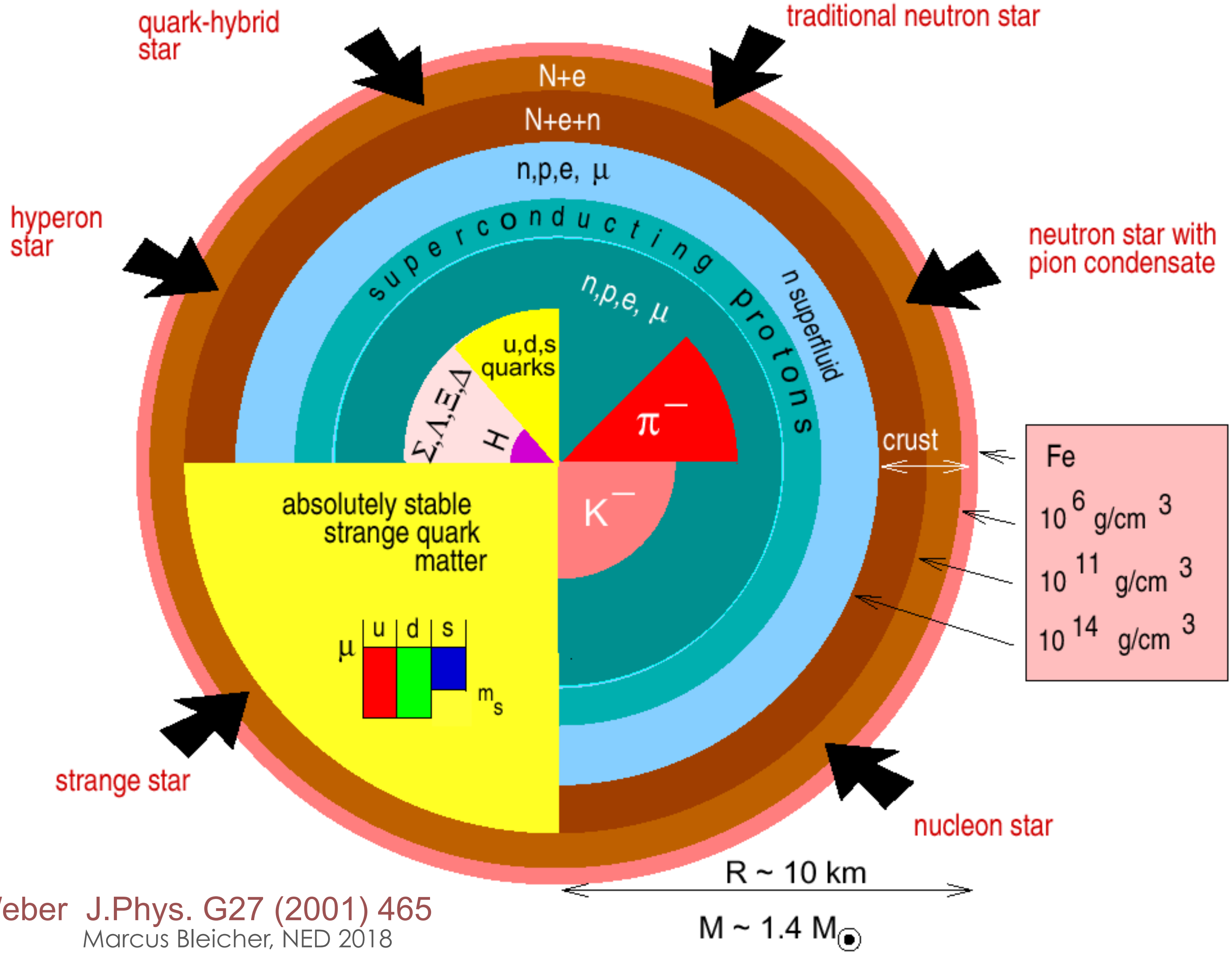
QCD

$$\mathcal{L}_{QCD} = \sum_q \left(\bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu + ig\left(G_\mu^\alpha t_\alpha\right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right) - \frac{1}{4} G_{\mu\nu}^\alpha G_\alpha^{\mu\nu}$$

$$\mathcal{L}_{QED} = \bar{\psi}_e i\gamma^\mu \left[\partial_\mu + ieA_\mu \right] \psi_e - m_e \bar{\psi}_e \psi_e - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

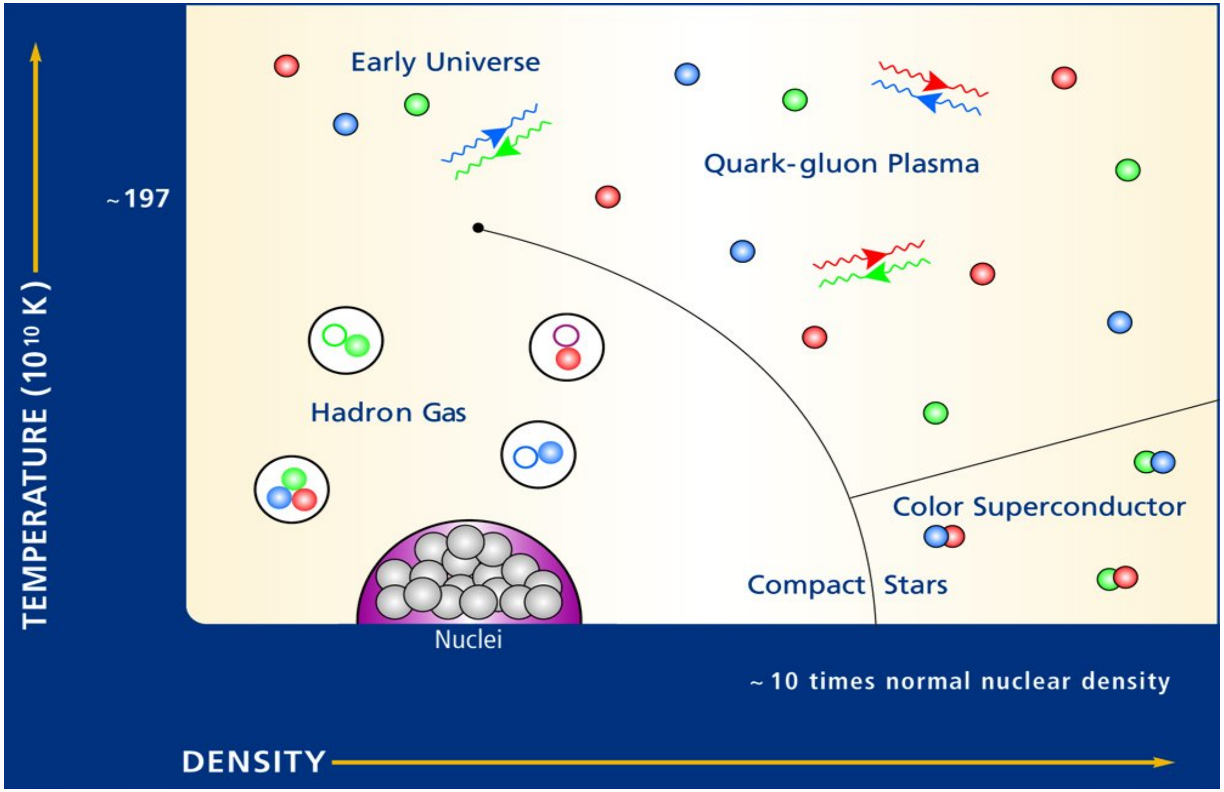
- $G_\alpha^{\mu\nu} = \partial^\mu G_\alpha^\nu - \partial^\nu G_\alpha^\mu - gf^{\alpha\beta\gamma} G_\beta^\mu G_\gamma^\nu$ color fields tensor
- G_α^μ four potential of the gluon fields (α=1,..8)
- t_α 3x3 Gell-Mann matrices; generators of the SU(3) color group
- $f^{\alpha\beta\gamma}$ structure constants of the SU(3) color group
- ψ_i Dirac spinor of the quark field (*i* represents color)
- $g = \sqrt{4\pi\alpha_s}$ $(\hbar = c = 1)$ color charge (strong coupling constant)

Dense matter in nature



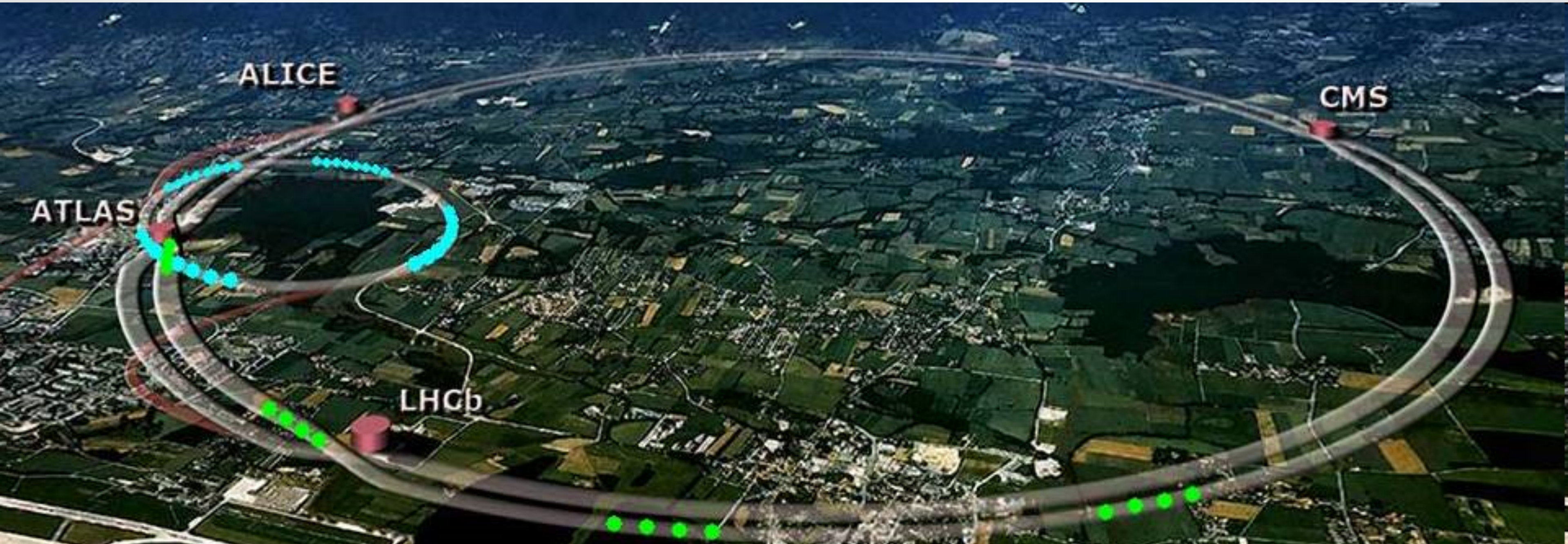
F. Weber J.Phys. G27 (2001) 465

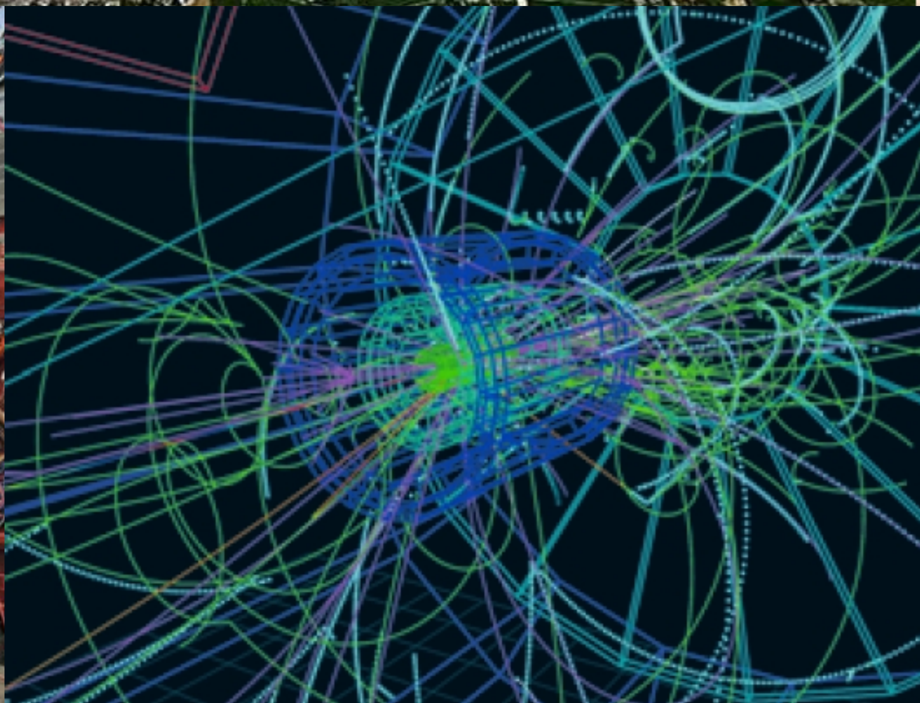
QCD Phase Diagram: Sketch



http://www.ice.csic.es/en/graphics/phase.jpg

In heavy ion collisions heated and compressed nuclear matter is produced under "controlled" conditions

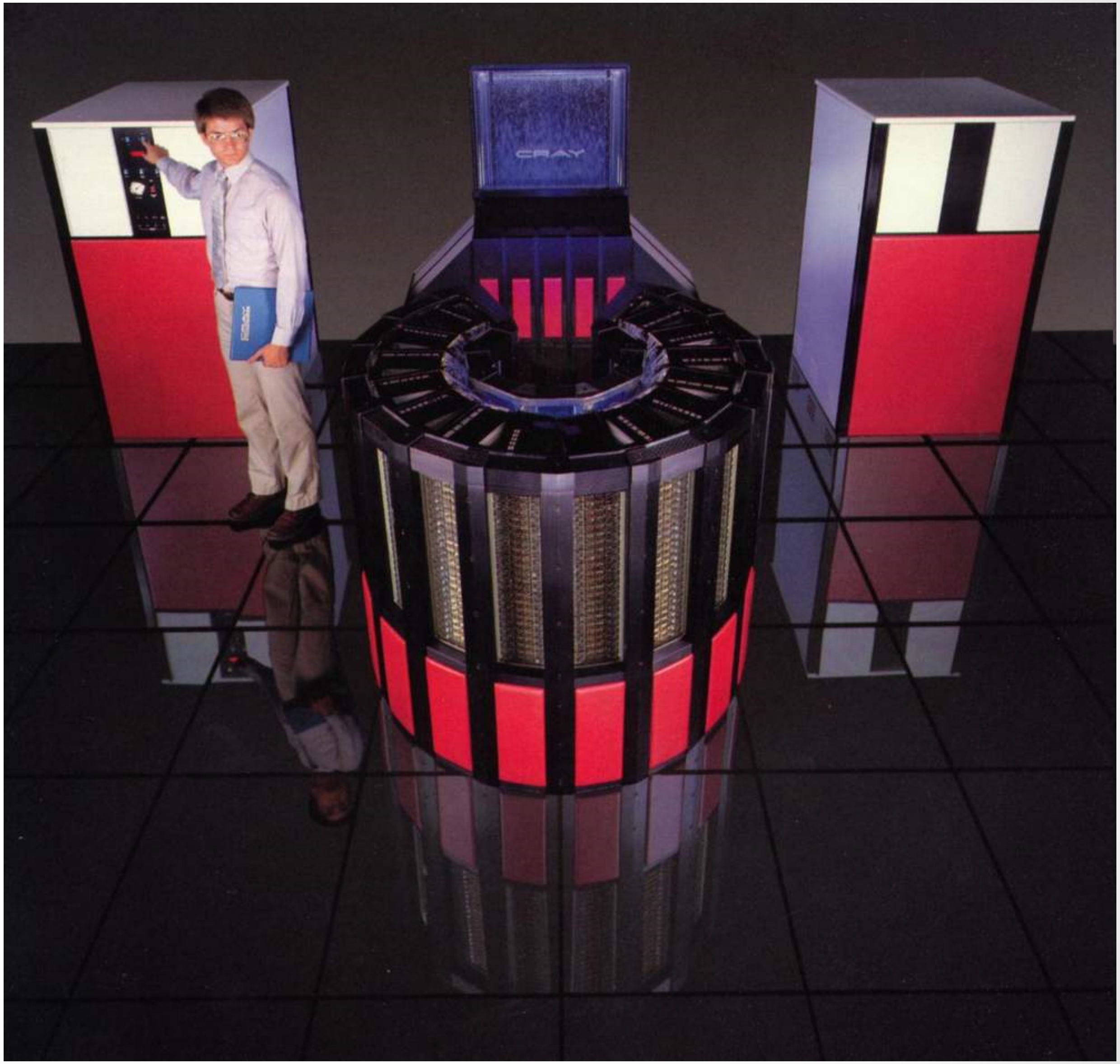

ALICE
CMS
ATLAS
LHCb



FAIR: Facility for Antiproton and Ion Research

Location: GSI, Darmstadt, Germany

Need for Simulations



The tool

- Non-equilibrium transport models
- Hadrons and resonances
- String excitation and fragmentation
- Cross sections are parameterized
  via AQM or calculated by detailed balance
- pQCD hard scattering at high energies

- Generates full space-time dynamics of hadrons and strings

UrQMD: www.urqmd.org

Often used transport/cascade models

- QMD, IQMD, BQMD,…
  (limit particle species, Aichelin, Hartnack,...)
- UrQMD (Frankfurt, Bleicher)
- (P)HSD (Giessen/GSI, Bratkovskaya), GiBUU (Giessen, Mosel)
- SMASH (GSI/FIAS, Petersen)
- Parton cascades (ZPC, MPC, GPC, VNI/B, ….)

NOT transport/cascade models (no d/dt):

- HIJING
- PYTHIA/FRITIOF
- NEXUS, VENUS, EPOS
- DPM

Boltzmann equation

Transport models are solving a (modified and/or complicated) version of the Boltzmann equation.

$$\frac{df_i(x,p)}{dt} = \frac{\partial f}{\partial x}\frac{dx}{dt} + \frac{\partial f}{\partial p}\frac{dp}{dt} = C(f_i, f_j)$$

$$\frac{\partial f_i}{\partial x} v - \frac{\partial f_i}{\partial p}\nabla V = C(f_i, f_j)$$

$$\{p_\mu[\partial_x^\mu - \partial_x^\mu \Sigma_{N*}^\nu(x)\partial_\nu^p + \partial_x^\nu \Sigma_{N*}^\mu(x)\partial_\nu^p] + m_{N*}^* \partial_x^\nu \Sigma_{N*}^S(x)\partial_\nu^p\} \frac{f_{N^*}(\mathbf{x},\mathbf{p},t)}{E_{N^*}^*(p)} = C^{N^*}(x,p). \quad (2.50)$$

Solutions are $f_i(x,p,t)$

Reaction stages

- Initialization of projectile and target (Lorentz contracted Woods-Saxon)
- Generate table with collision/decay sequence from

$$d_{min} = \sqrt{\frac{\sigma_{tot}}{\pi}} \quad , \sigma_{tot} = \sigma_{tot}(\sqrt{s}, |h_1\rangle, |h_2\rangle)$$

- Propagate to next collision
- Perform collision according to cross sections
  - elastic scattering
  - inelastic scattering
    - resonance production
    - soft string formation and fragmentation
    - pQCD hard scattering / fragmentation
- Update particle arrays, update collision table, perform next collisions

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...

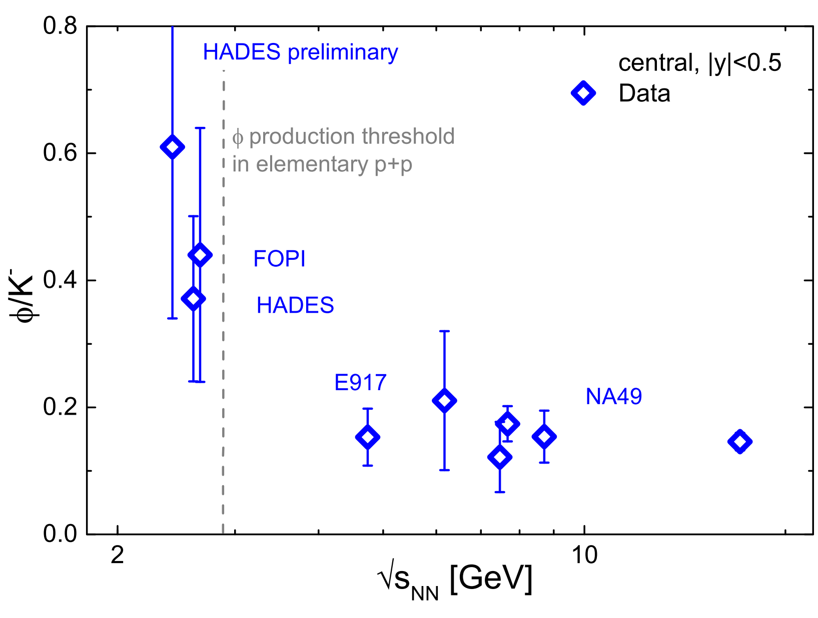
- Explores multi-strange particle production
  i.e. ϕ and Ξ production

  → 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

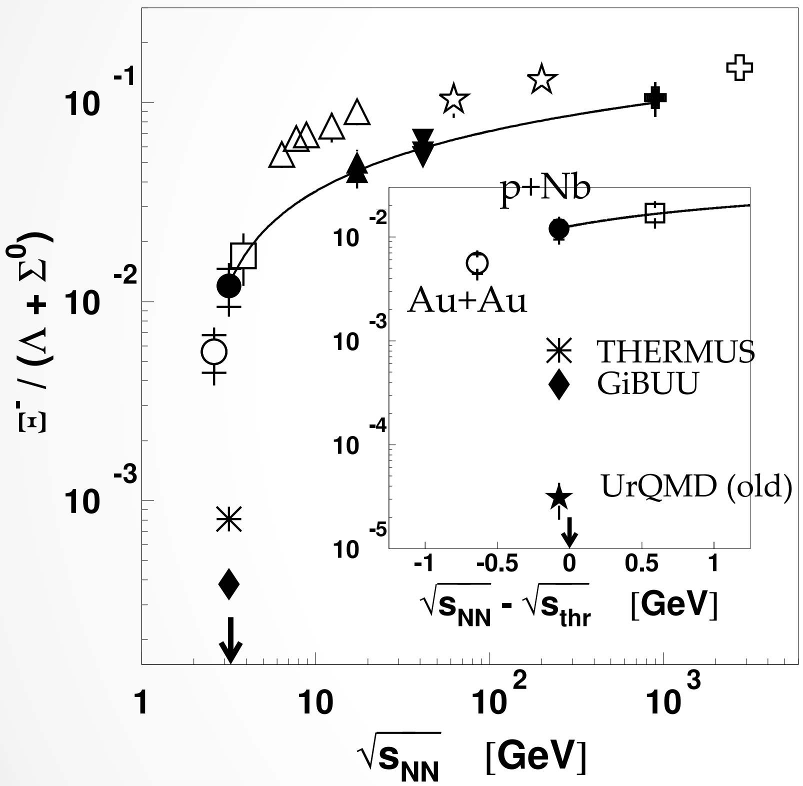


ϕ production

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

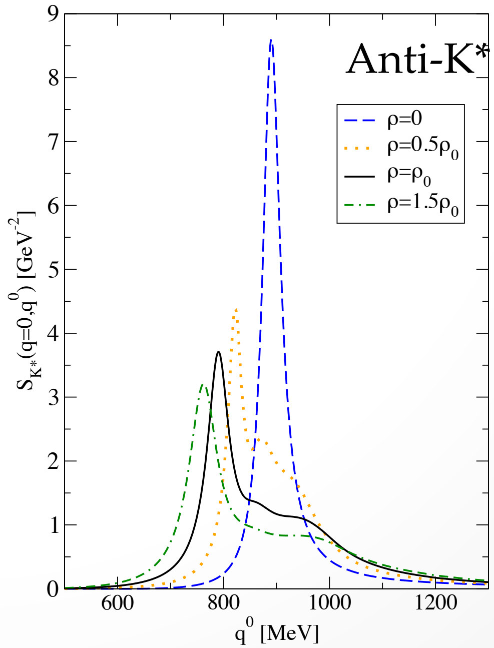
Subthreshold production:Two paradigms

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



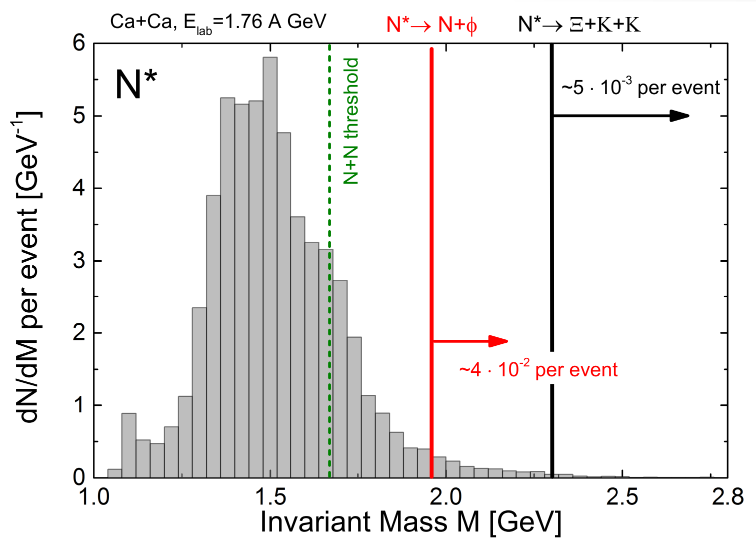
L. Tolos et al., Phys.Rev.C82:045210,2010

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



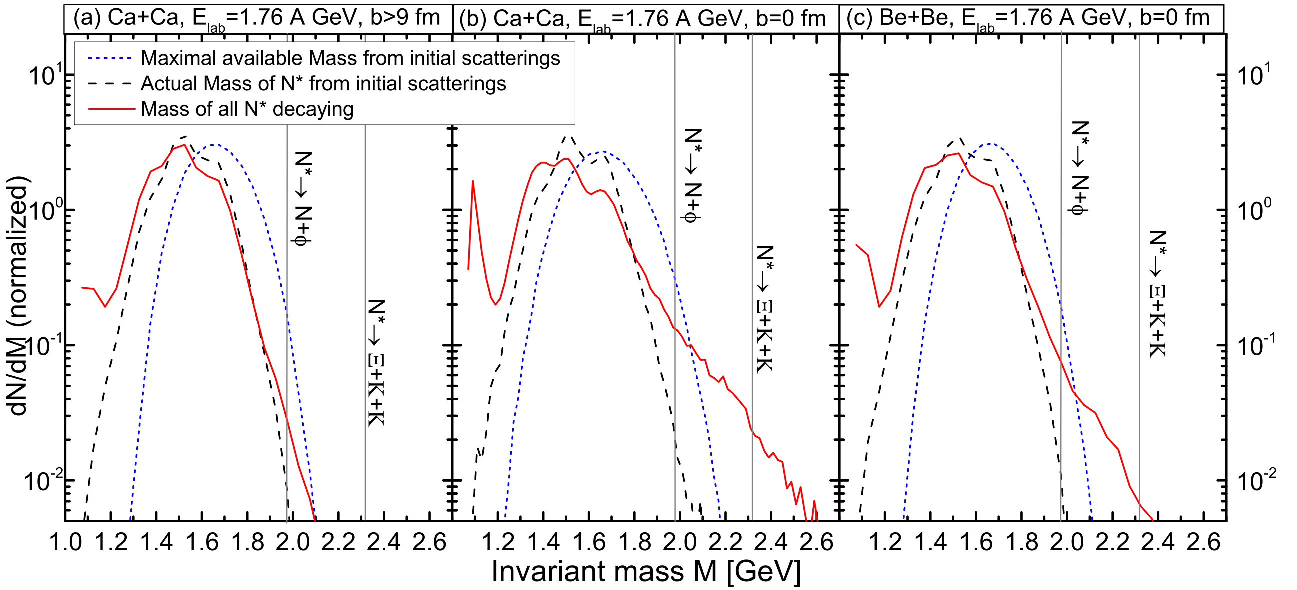
Yes! But for Ξ, only in the tails.

→ Introduce branching ratio for decay into Nϕ

Probabilities

Sub-threshold production baseline

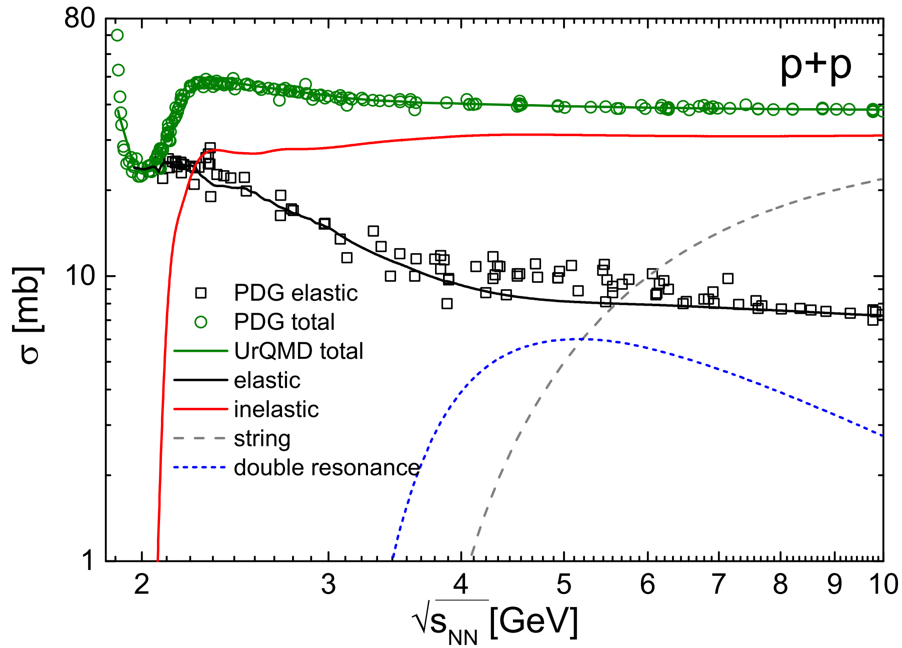
- Fermi momenta lift the collision energy above the threshold.
- Secondary interactions accumulate energy.



Why not introduce these decays for the less known resonances?

New resonances

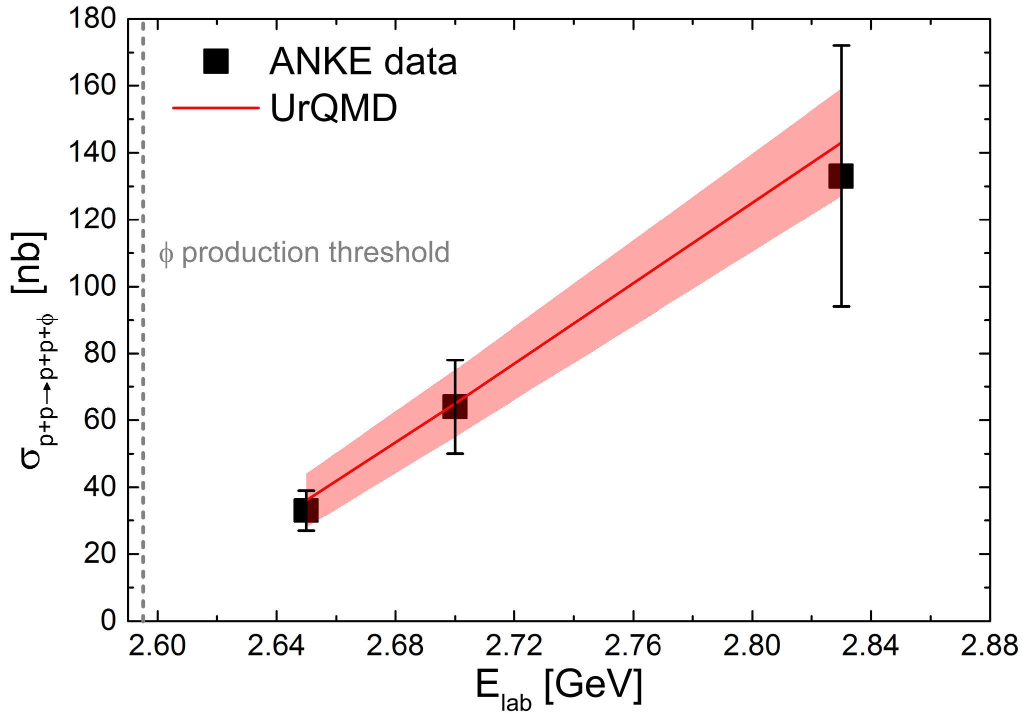
N*(1650)	$\Delta(1232)$
N*(1710)	$\Delta(1600)$
N*(1720)	$\Delta(1620)$
N*(1875)	$\Delta(1700)$
N*(1900)	$\Delta(1900)$
N*(1990)	$\Delta(1905)$
N*(2080)	$\Delta(1910)$
N*(2190)	$\Delta(1920)$
N*(2220)	$\Delta(1930)$
N*(2250)	$\Delta(1950)$
N*(2600)	$\Delta(2440)$
N*(2700)	$\Delta(2750)$
N*(3100)	$\Delta(2950)$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



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

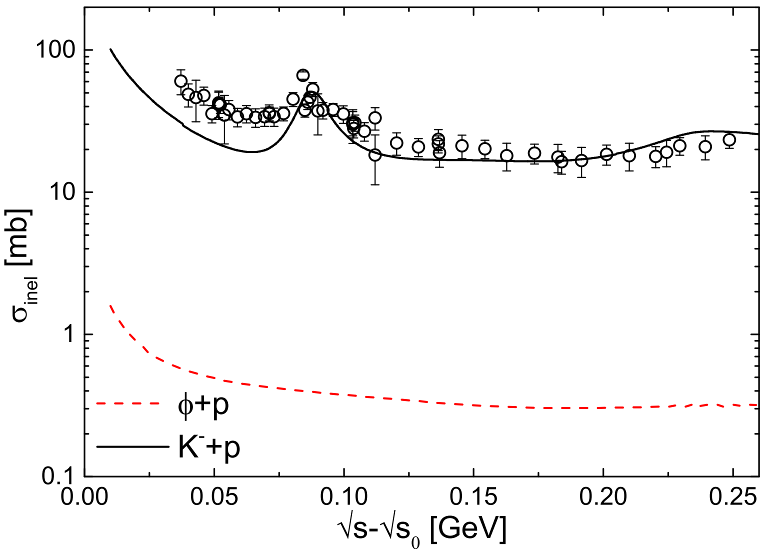
M. Hartmann *et al.*, Phys. Rev. C **85**, 035206 (2012)
T. Ishikawa *et al.*, Phys. Lett. B **608**, 215 (2005)

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.

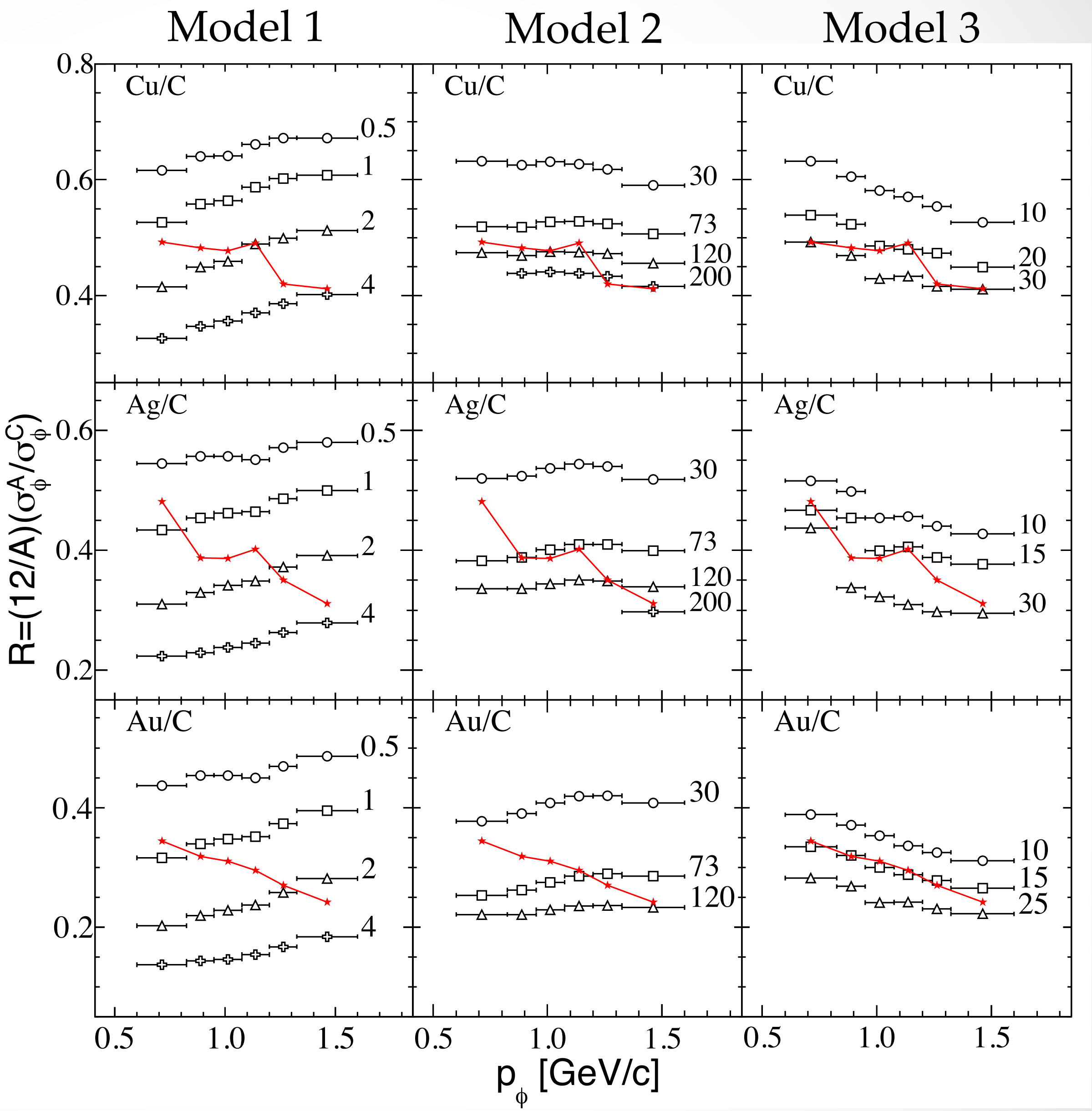


ϕ transparency ratios I

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.

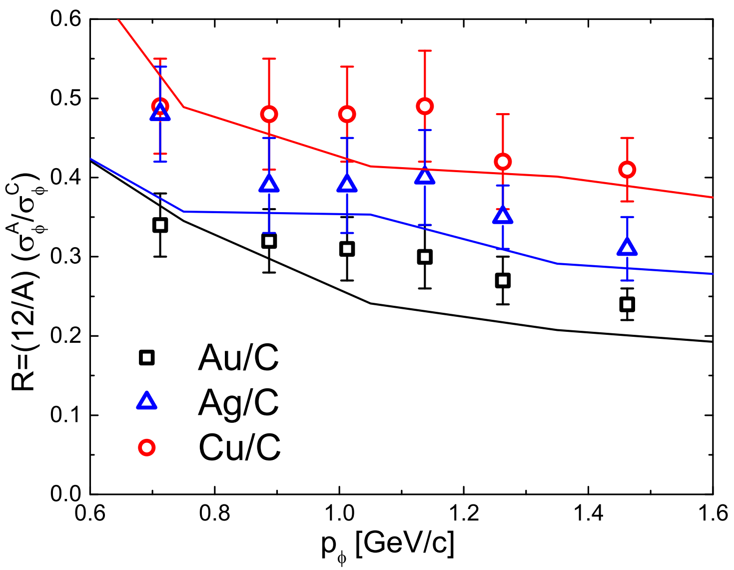


Transparency ratios II

Detailed balance → absorption cross section

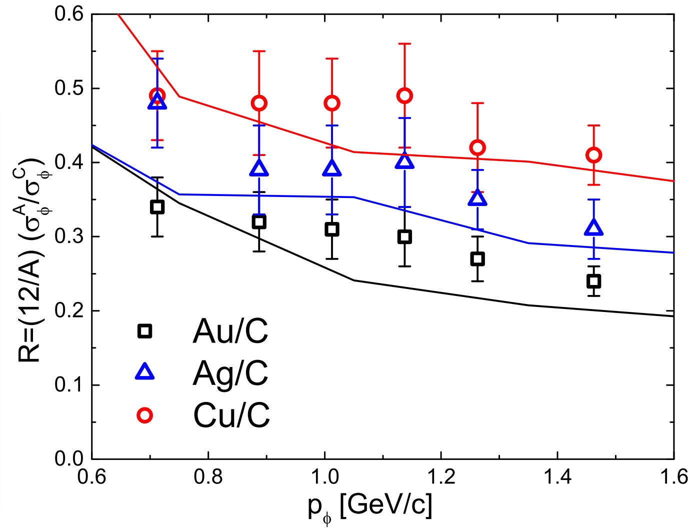
$$\frac{d\sigma_{b\to a}}{d\Omega} = \frac{\langle p_a^2\rangle}{\langle p_b^2\rangle}\frac{(2S_1+1)(2S_2+1)}{(2S_3+1)(2S_4+1)}\sum_{J=J_-}^{J_+}\frac{\langle j_1 m_1 j_2 m_2 || JM\rangle^2}{\langle j_3 m_3 j_4 m_4 || JM\rangle^2}\frac{d\sigma_{a\to b}}{d\Omega}$$

- $\phi + p$ 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!

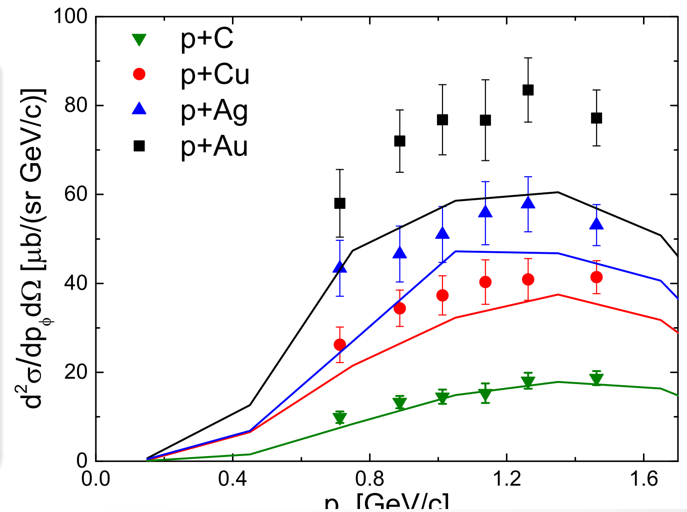


New explanation

- $\phi + p$ 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!

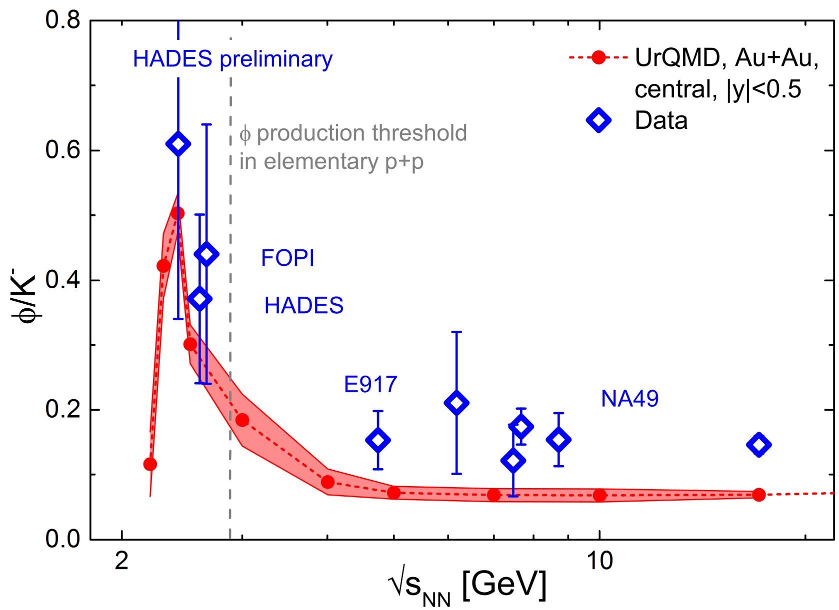


- Not 'absorption' of the ϕ, but of the mother resonance.
- Reactions of the type:
  $N^* + N \rightarrow N'^* + N'^*$
  $N^* + N \rightarrow N'^* + N'^*$
  where the mass of $N'^* < N*$ so no ϕ can be produced.



Extrapolation to AA

When applied to nuclear collisions:

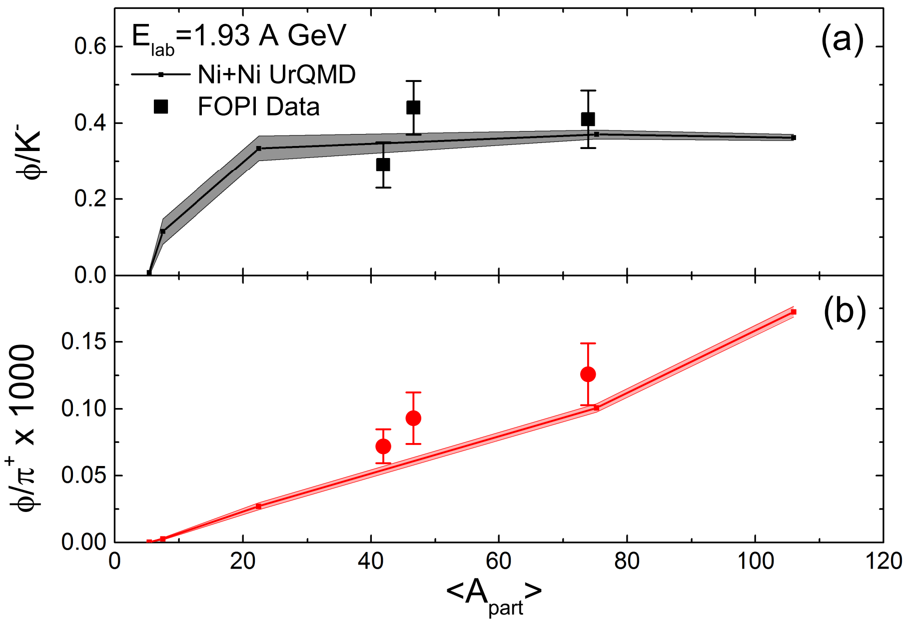


- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV
- High energies: too low due to string production
- HADES preliminary results for 1.23 A GeV, see HADES talks by R. Holzmann and T. Scheib.

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

Centrality

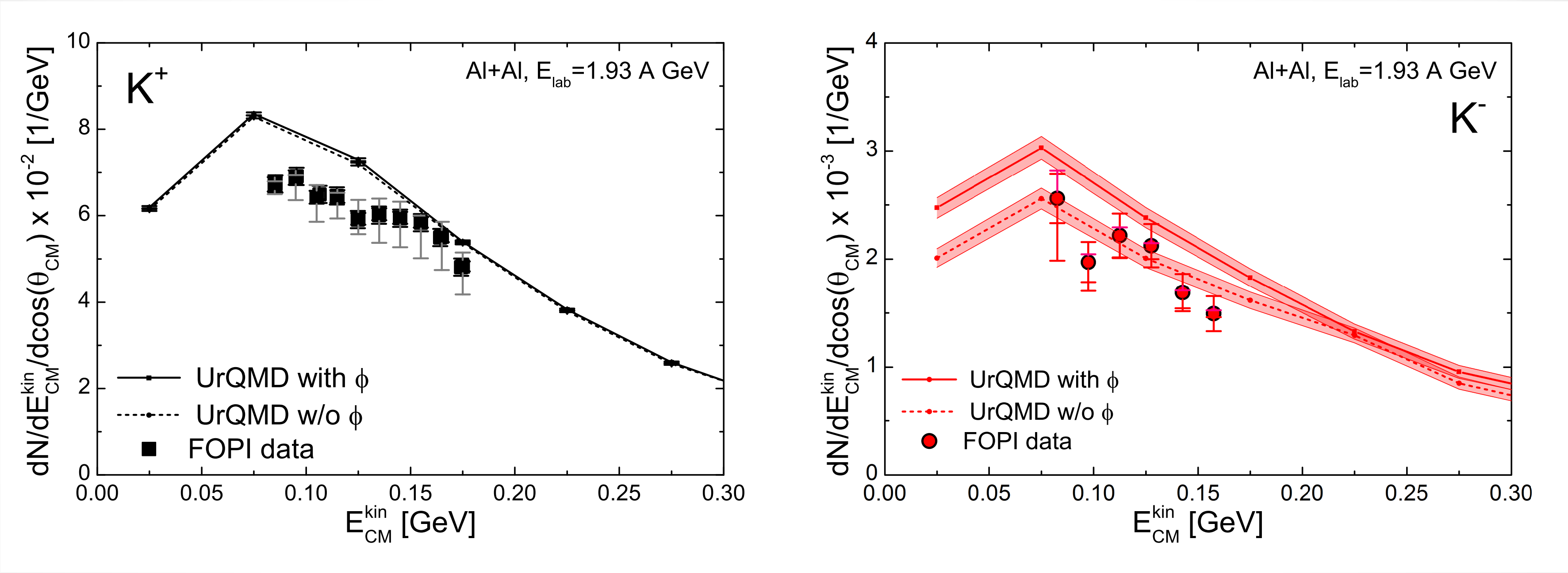
Even centrality dependence works well:



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

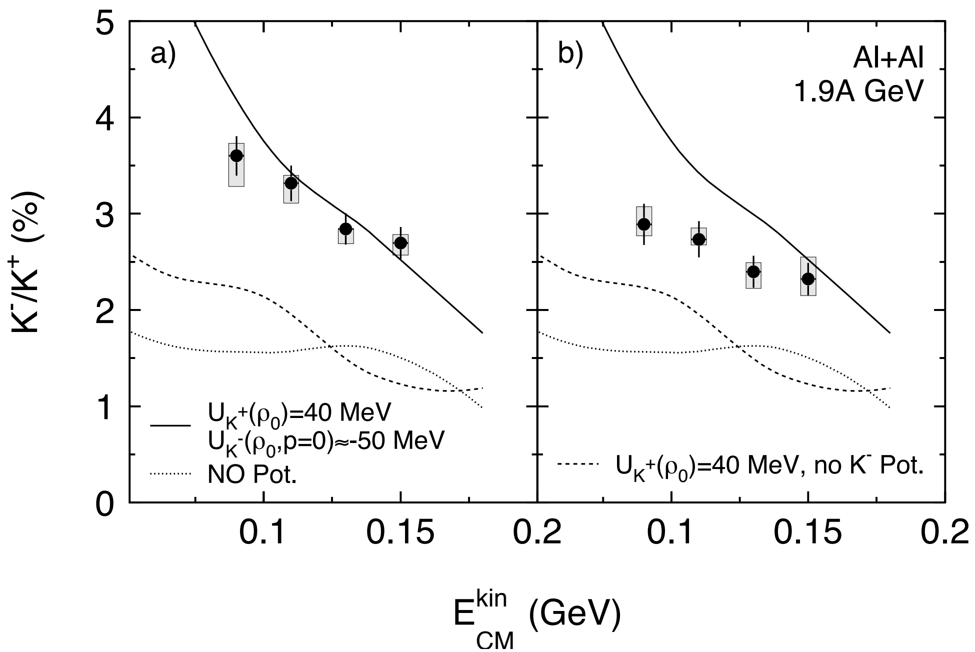
Data from: K. Piasecki et al., arXiv:1602.04378 [nucl-ex].

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].

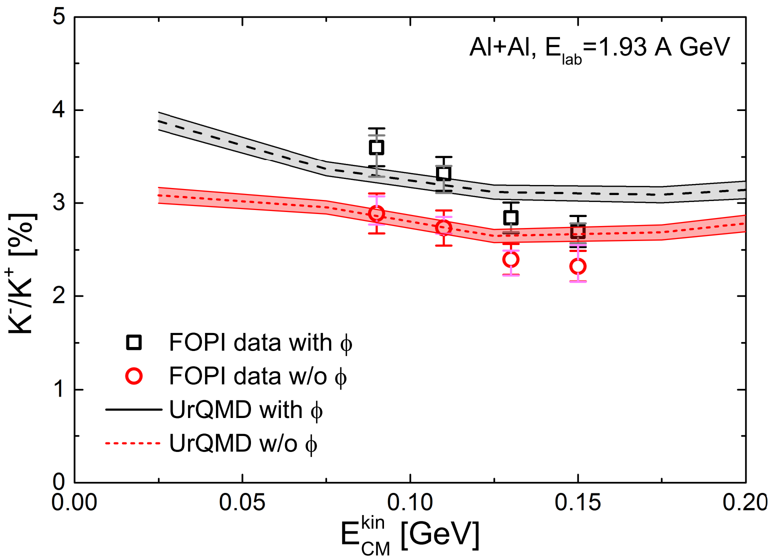
An example

- 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

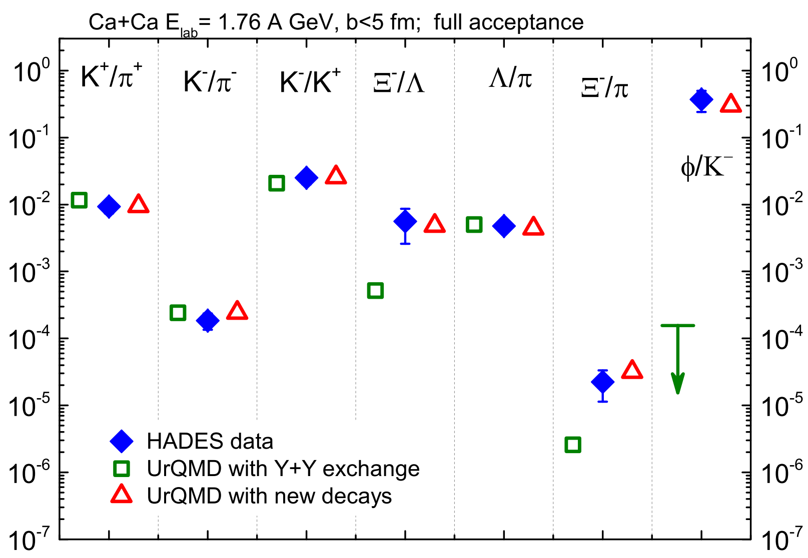
No elementary measurements near threshold.
We use p+Nb at $E_{\rm lab} = 3.5$ GeV data $\rightarrow \Gamma_{N^* \rightarrow \Xi+K+K}/\Gamma_{tot} = 3.0\%$

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].

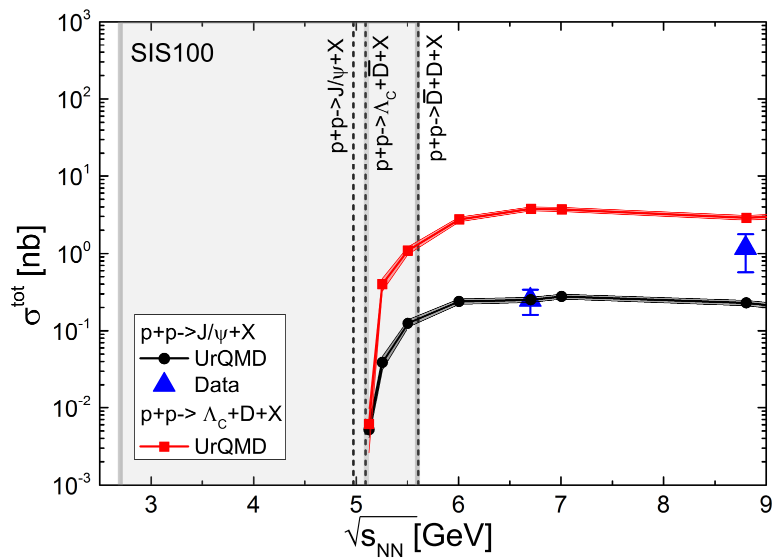
Why is charm interesting?

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

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

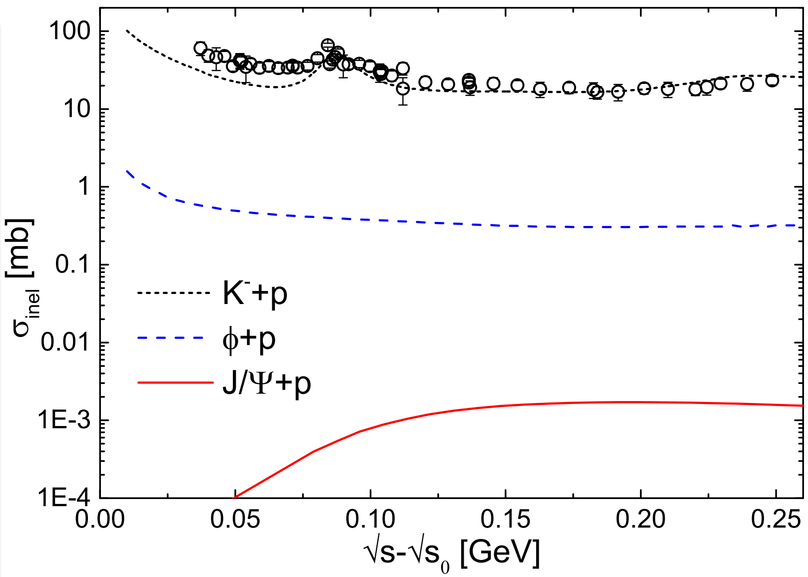
Assumptions

- 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

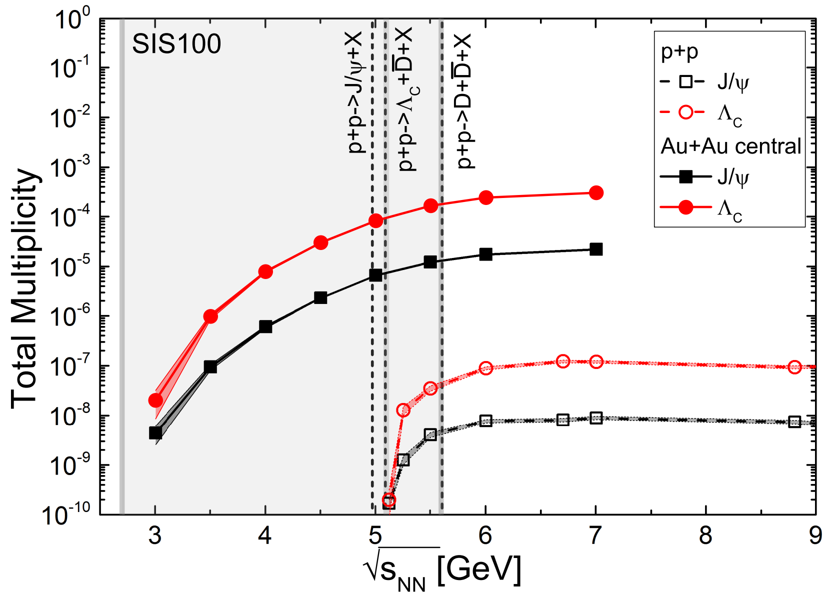
- $J/\Psi + p$ cross section from detailed balance is very small.
- Not 'absorption' of the J/Ψ, but of the mother resonance.
- Reactions of the type:
  $N^* + N \to N'^* + N'^*$
  $N^* + N \to N'^* + N'^*$
  where the mass of $N'^* < N^*$ so no J/Ψ can be produced.



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):



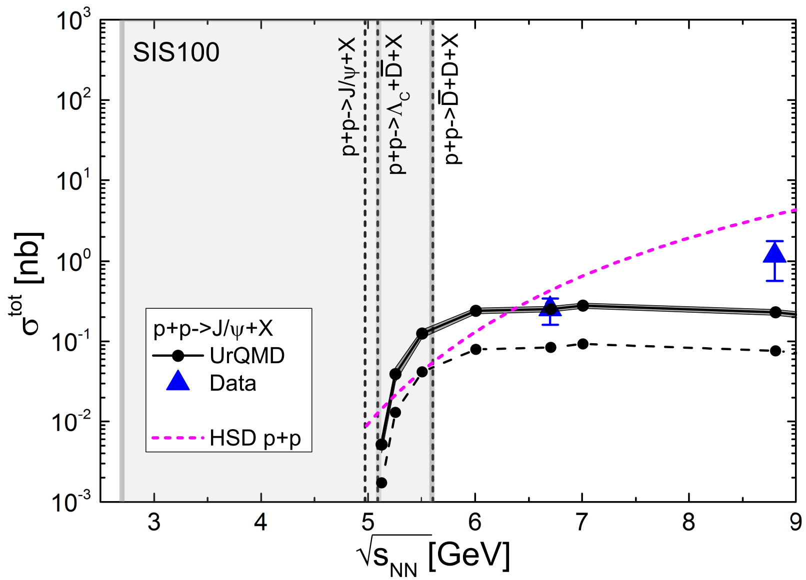
$E_{\text{lab}} = 11$ A GeV

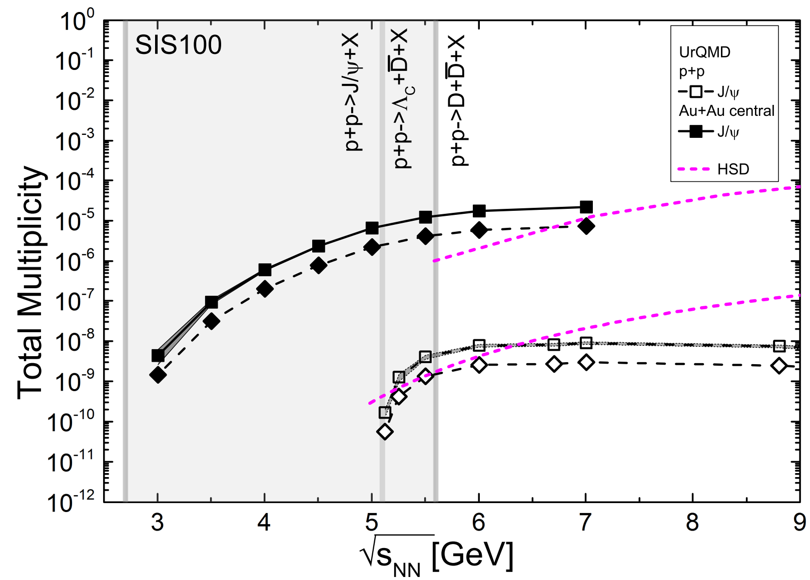
- $1.5 \cdot 10^{-6}$ J/Ψ per event
- $2 \cdot 10^{-5}$ Λ_c per event
- $\approx 3 - 4 \cdot 10^{-5}$ $\overline{D}$ per event

Comparison to others I

Parametrized cross section for J/Ψ

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





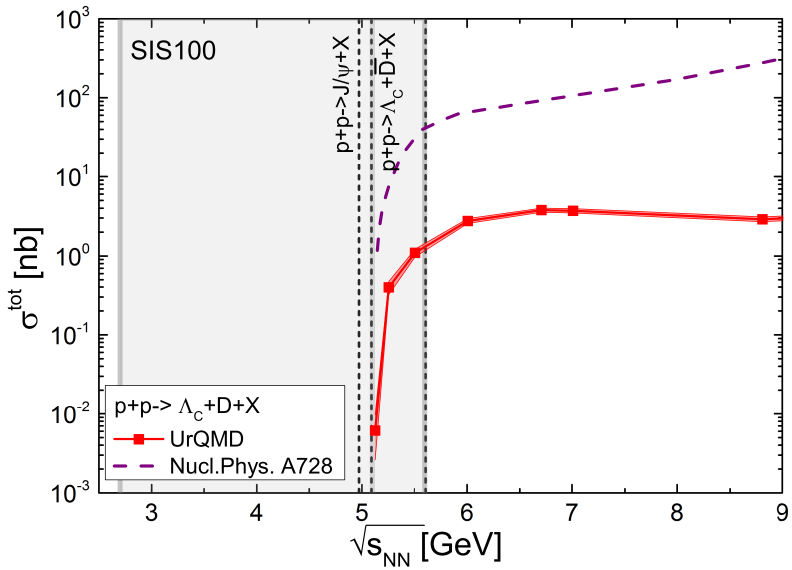
HSD results taken from:

O. Linnyk, E. L. Bratkovskaya and W. 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