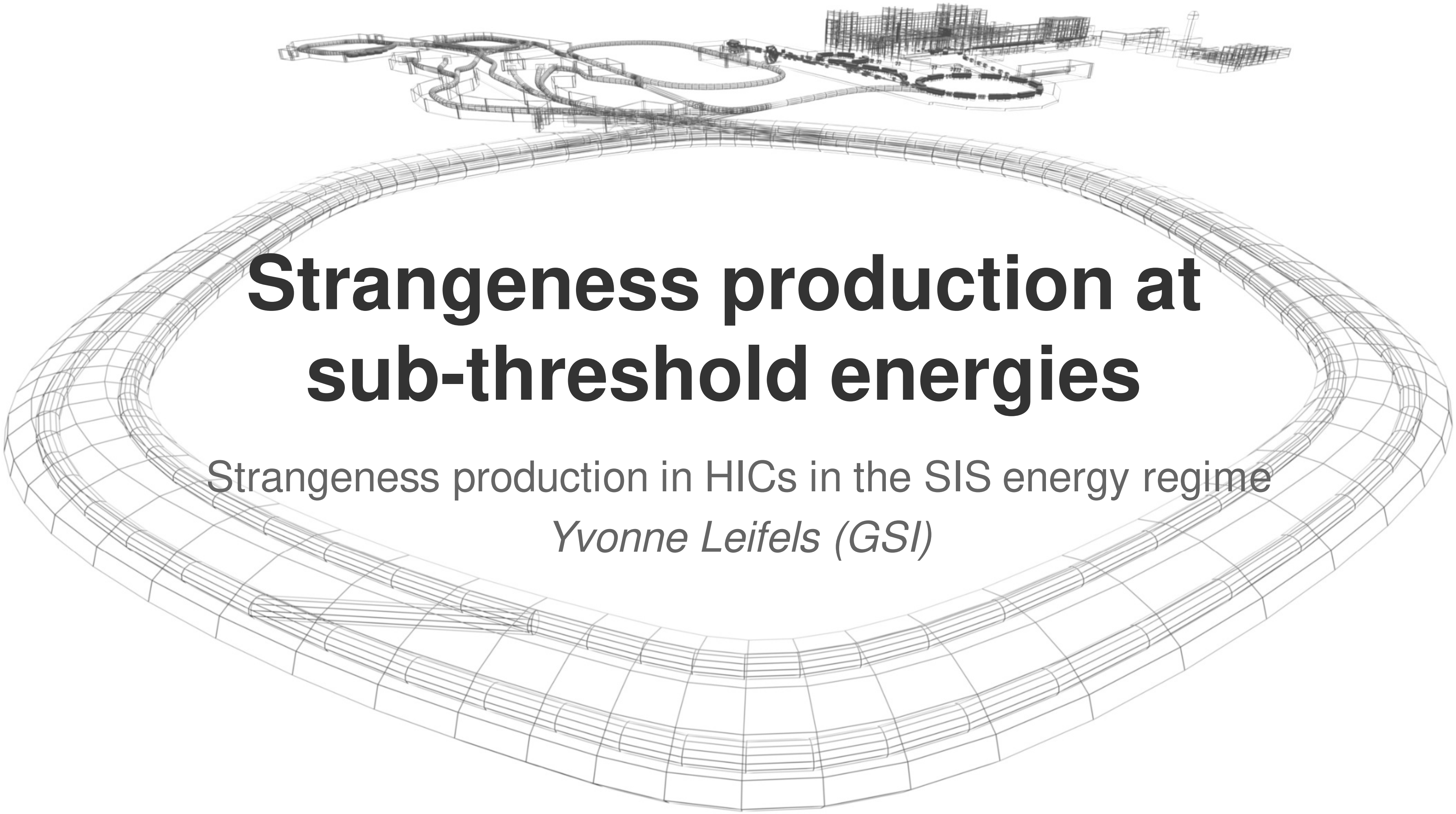


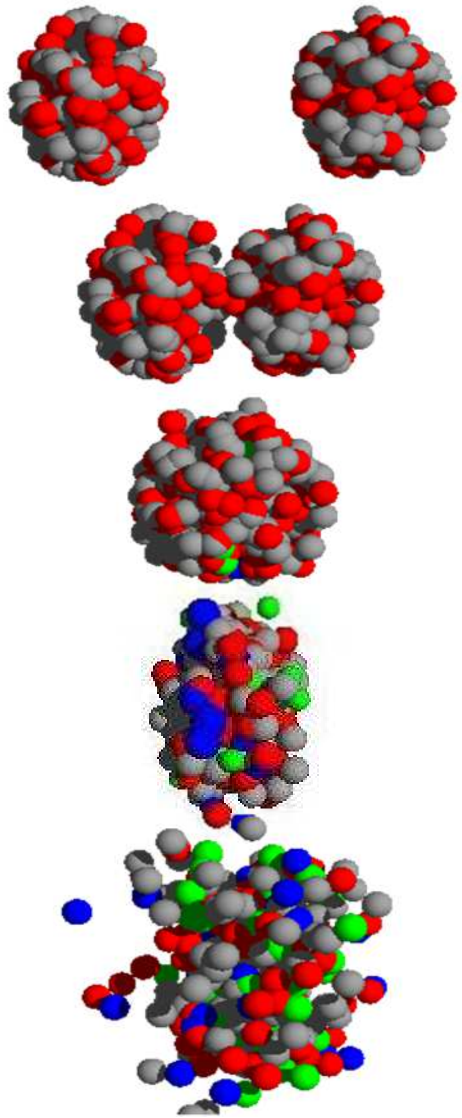
Strangeness production at sub-threshold energies

Strangeness production in HICs in the SIS energy regime

Yvonne Leifels (GSI)

Outline

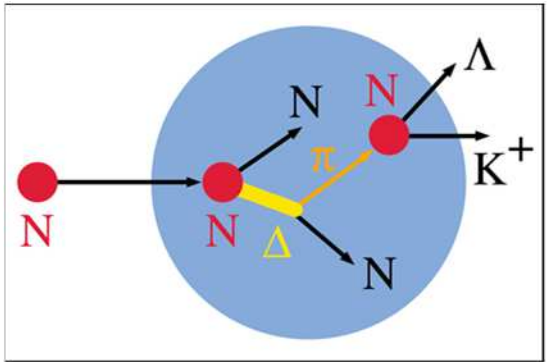
- Introduction
- Strangeness production
  - yields
  - spectra
- Hyperons
  - bound states with strangeness
- Summary and Conclusion



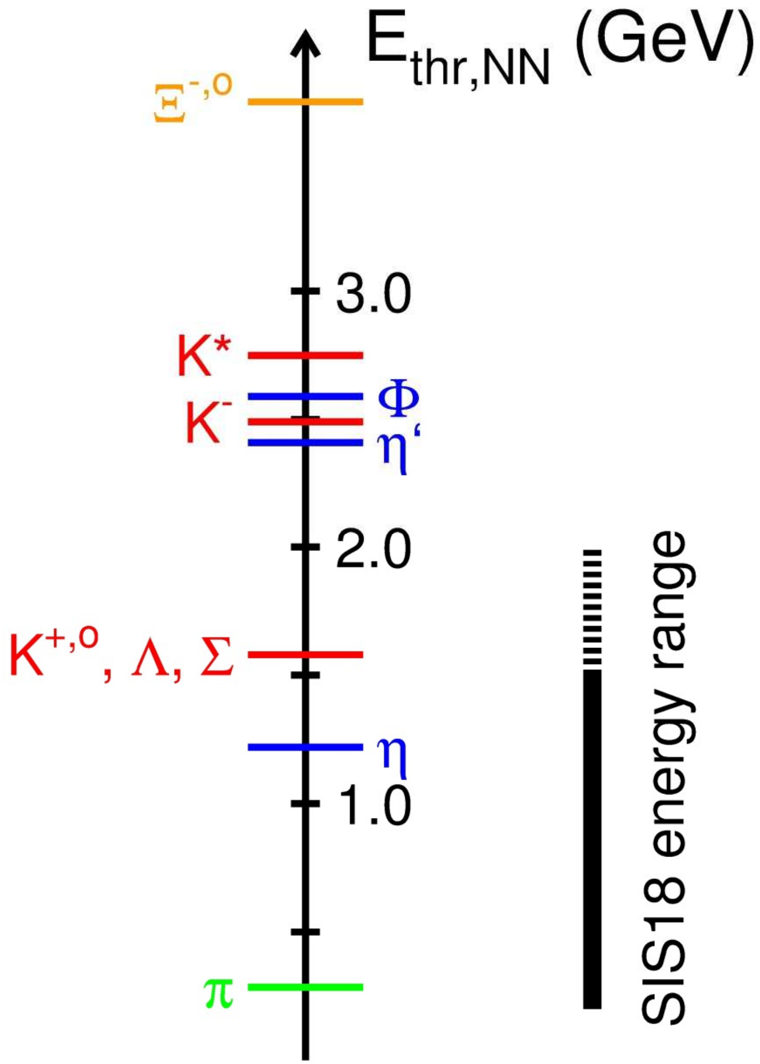
KAOS collaboration
FOPI collaboration in particular Chris Piasecki
HADES collaboration
HYPHI collaboration
J. Aichelin, E. Bratkovskaya,
C. Hartnack, A. LeFevre

Introduction

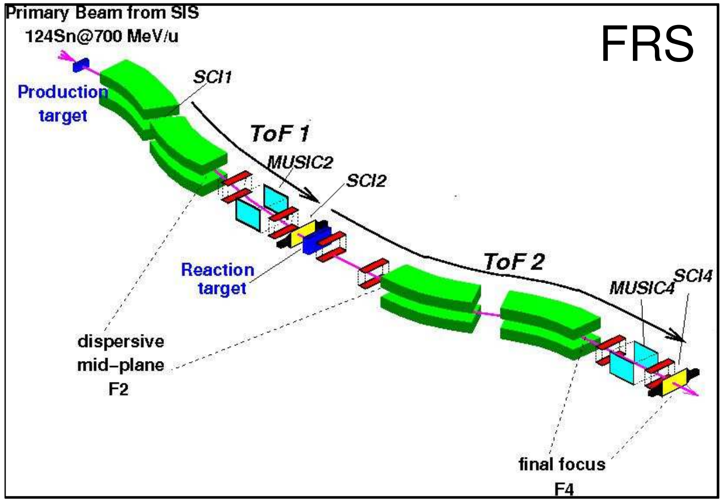
Strangeness production in heavy-ion collisions at energies below or close to the threshold in NN system

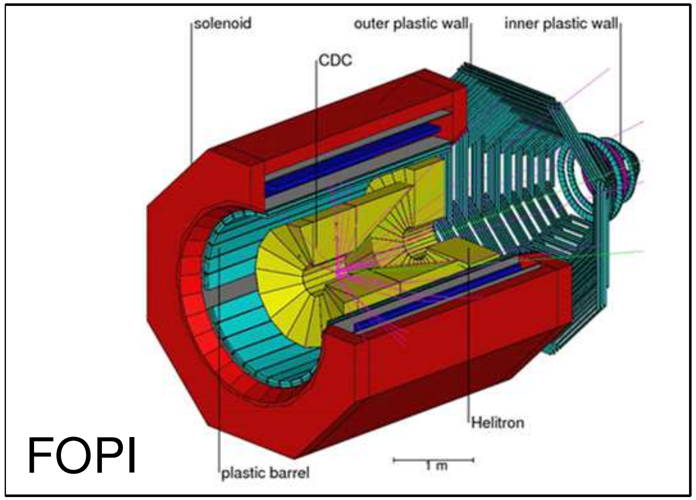


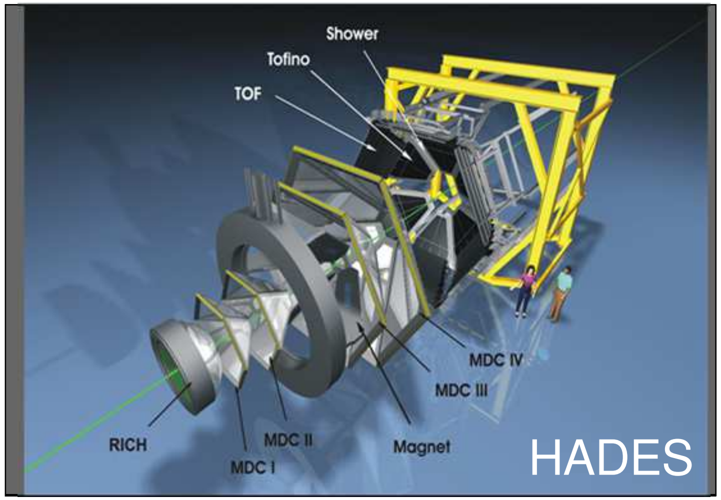
- Fermi momenta may contribute energy
- multistep processes can cumulate the energy needed
- intermediate resonances used as an energy reservoir
- production at high densities due to short life time of resonances



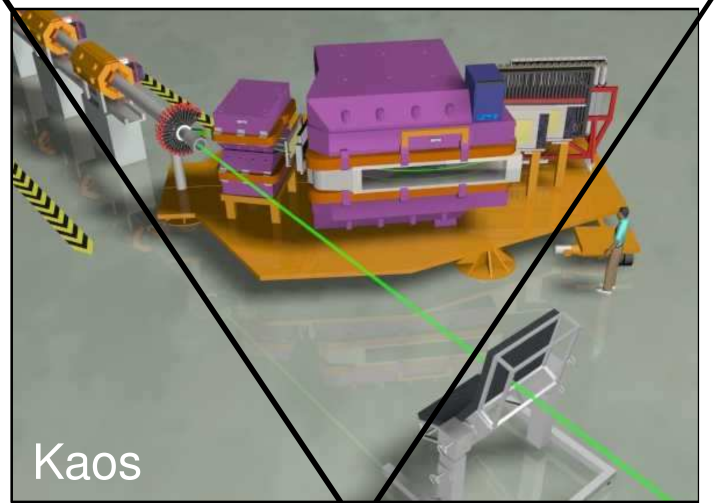
Introduction
Experiments at GSI

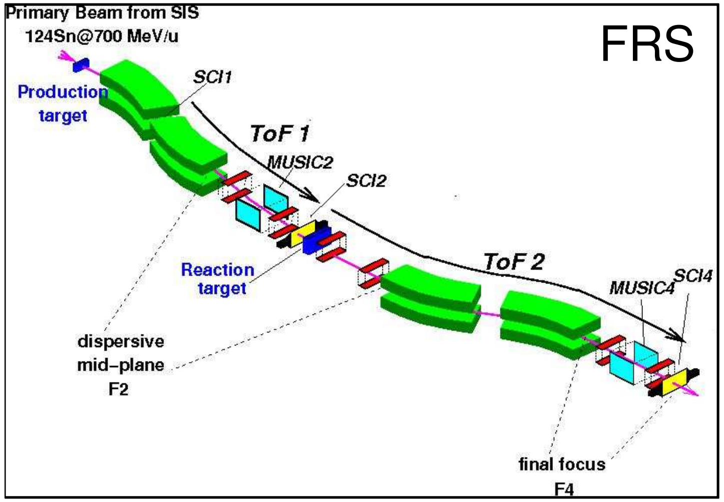


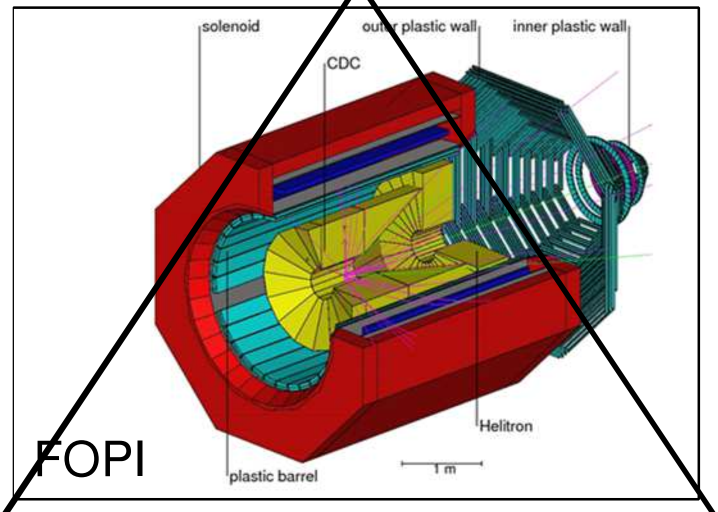


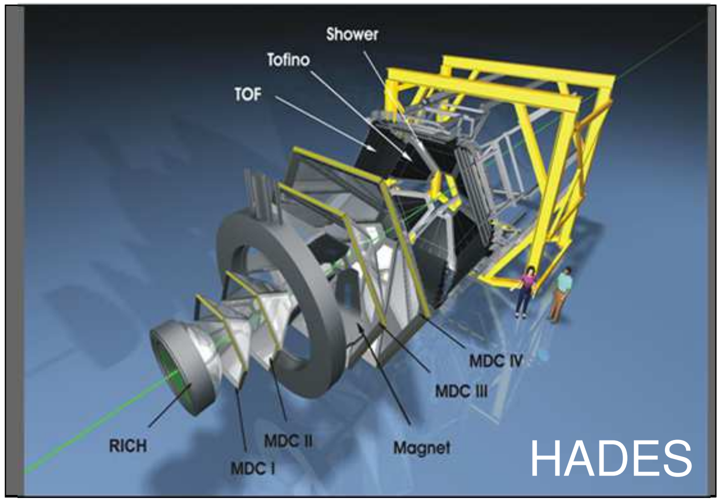


Experiments at GSI

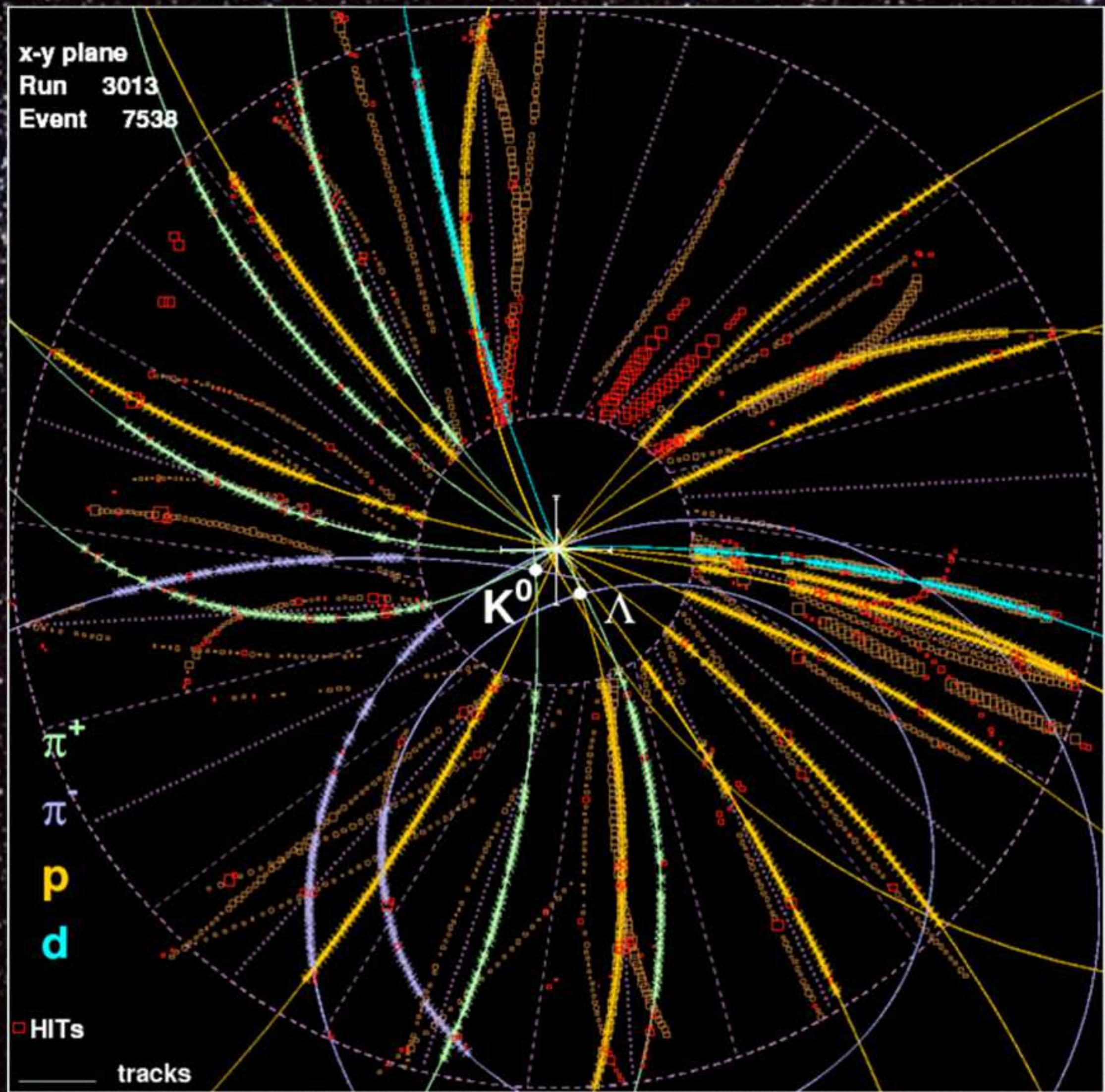








Ni+Ni 1.93 AGeV

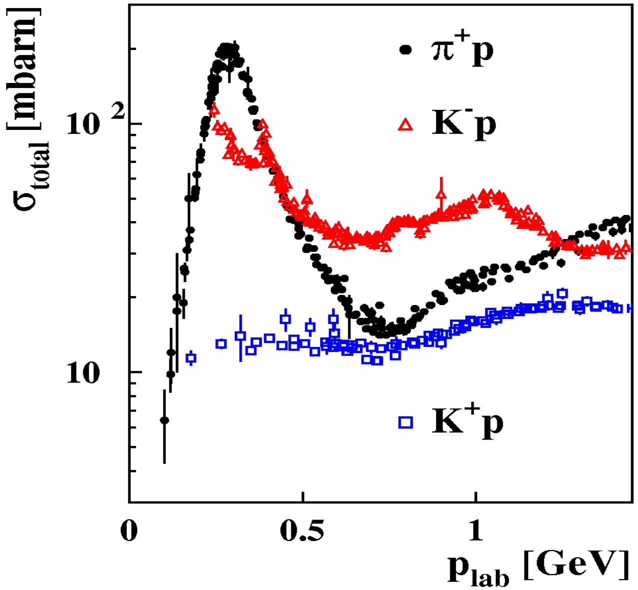


Introduction

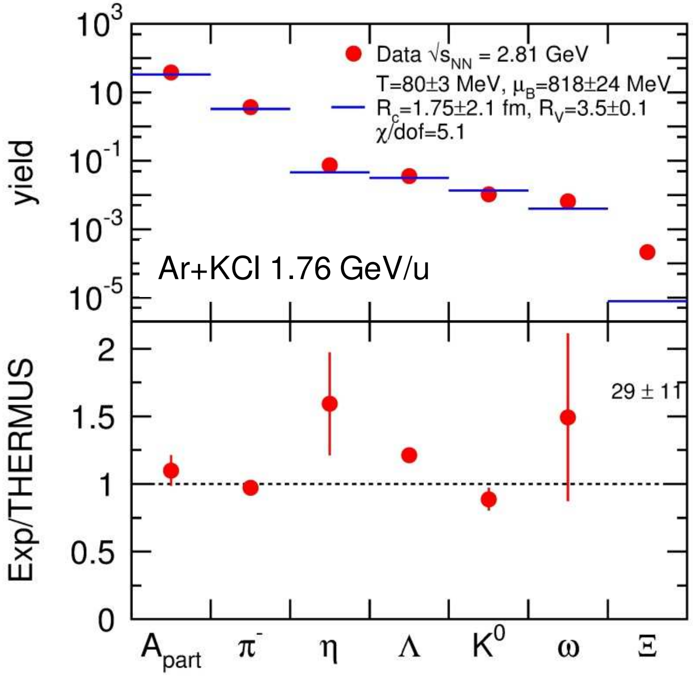
Production of strange particles in heavy-ion collisions at energies close to threshold energies:

- access to bulk properties to nuclear matter
- reaction dynamics
- interaction of particles in dense matter
  - relevant production processes
- in-medium properties
- exotic states
  - hyper-nuclei
  - K^-, η‘ bound states

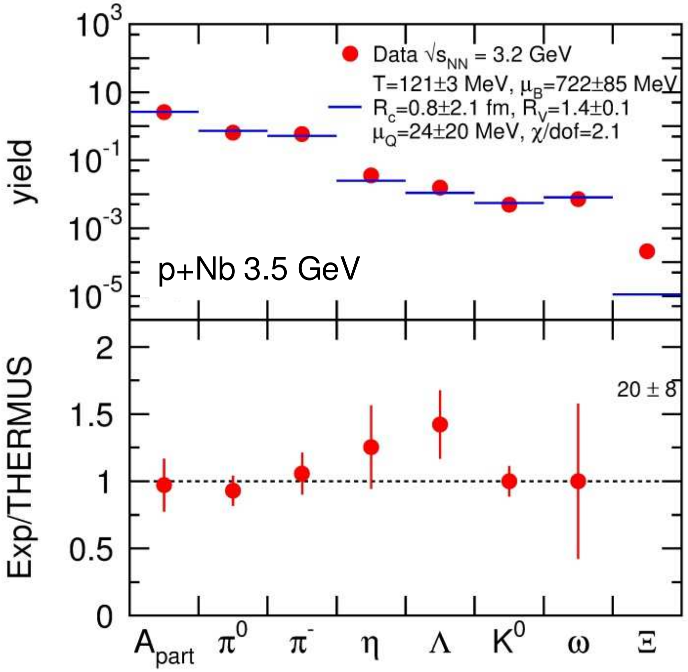
- K^+ only weakly interacting
- K^- strongly absorbed (like pions)
  - Strangeness Exchange
    $\pi + \Lambda \leftrightarrow K^- + N$

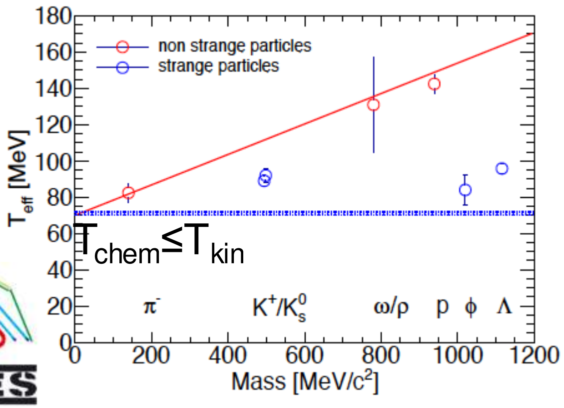


Strangeness production within thermal models



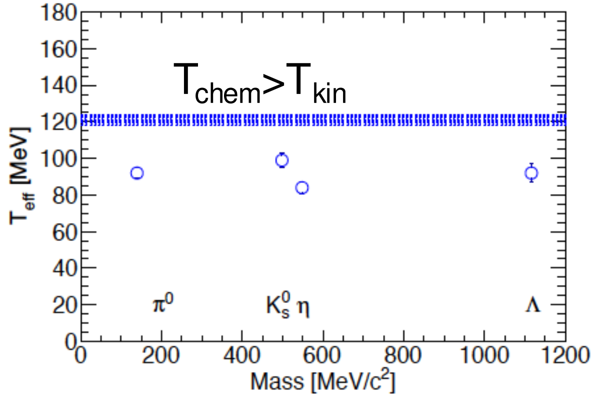
HADES arXiv: 1512.07070v1.





Predictions of thermal model THERMUS:

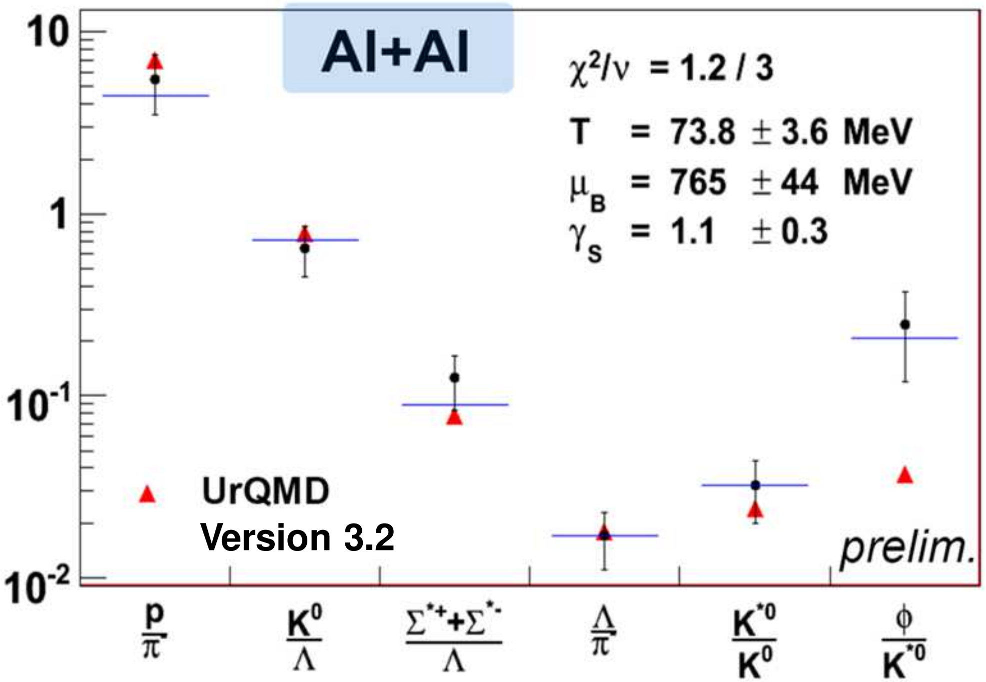
Thermus V2.3
Wheaton & Cleymans
Comp. Phys. Comm. 180 (2009)



M. Lorenz SQM 2015

And in Al+Al....

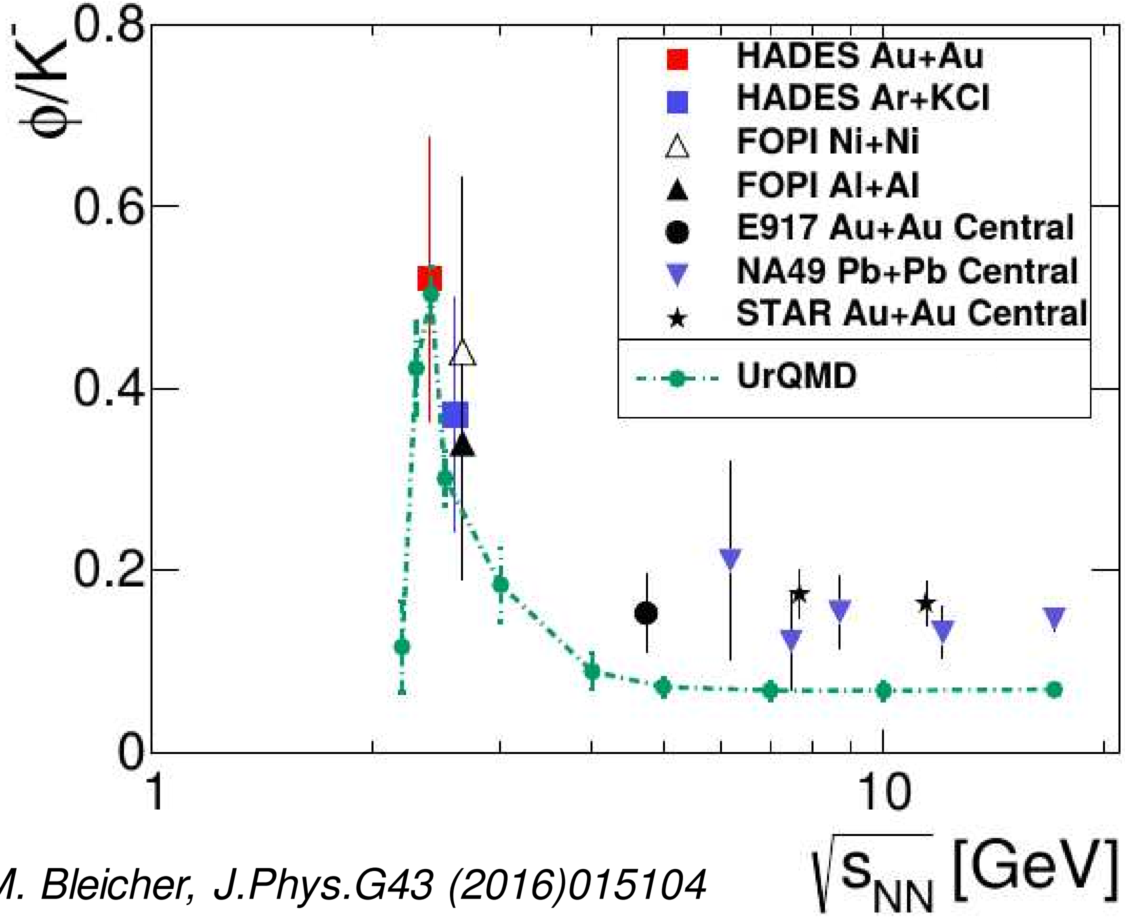
FOPI data for Al+Al at 1.91 AGeV
Statistical model analysis with
THERMUS code (K. Piasecki)



- Particle yields are described by Thermal models with reasonable parameters consistent over the complete energy range upto LHC. But at SIS energies:
  - Al+Al collisions are most probably not equilibrated
  - Phase space distributions are generally elongated beyond 400AMeV even in Au+Au
  - Systems are not completely mixed
  - No equilibration within microscopic models
  - Microscopic models account for particles ratios

Phi/K-

URQMD microscopic model predictions, including decay of heavy resonances

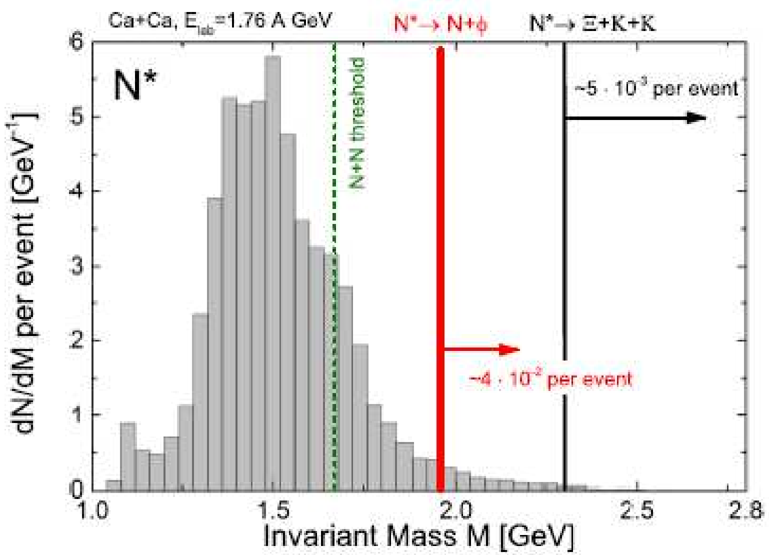


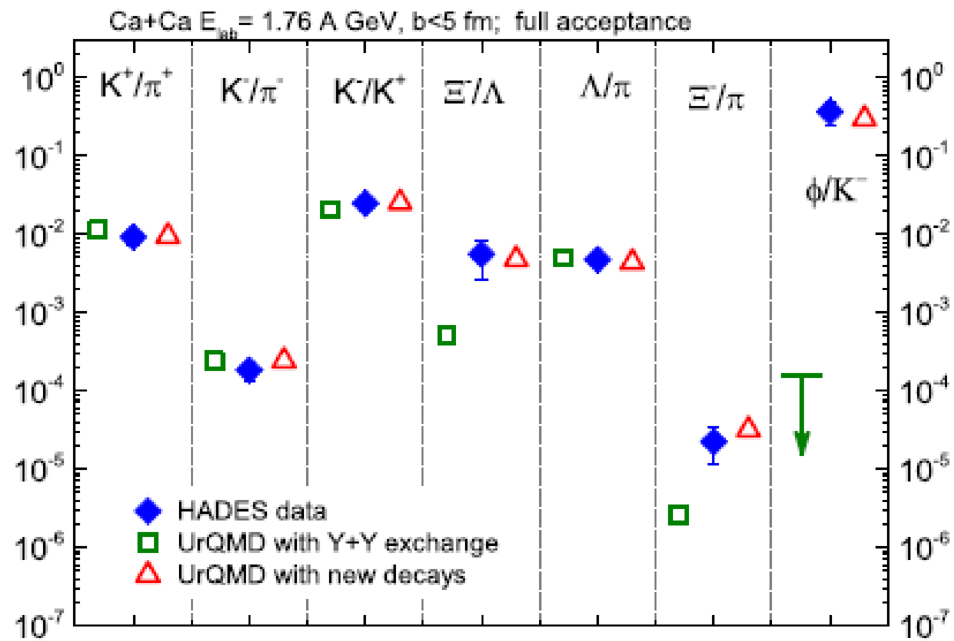
J. Steinheimer, M. Bleicher, J.Phys.G43 (2016)015104

Xsi- production

Introducing branching ratios to Φ, Ξ for heavy resonances:
constrained by elementary reactions (e.g. p+Nb or p+p data)

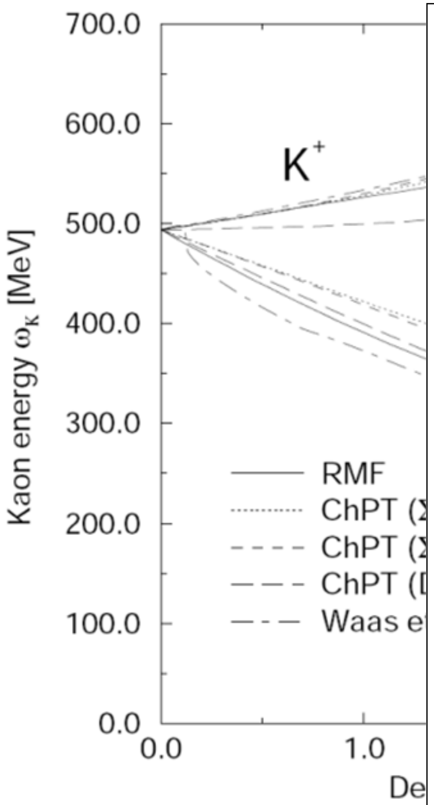
- small and consistent with OZI rule
- branching ratios needed in the tails of the resonances





J. Steinheimer, M. Bleicher, J. Phys. G43 (2016)015104

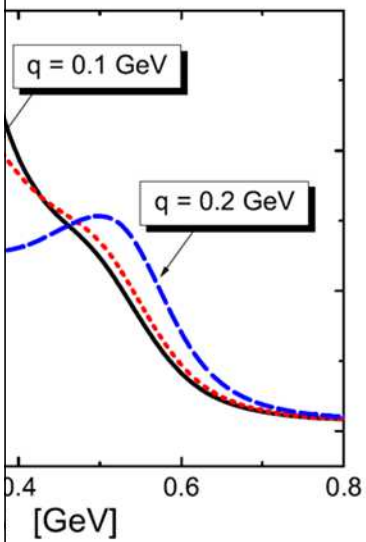
In medium properties strange mesons



HSD (V1.5, BUU – Bratkovskaya)
IQMD (KQMD – Hartnack)

→ BUU / QMD code
→ EOS (soft, κ = 200-230 MeV)
→ Kaon production perturbatively
→ equal cross sections (production/re-scattering)
→ "equal" KN potential
→ Treatment of anti-kaons
→ IQMD quasi particles
→ HSD G-Matrix formalism $U(\rho=\rho_0, p=0) = -50$ MeV

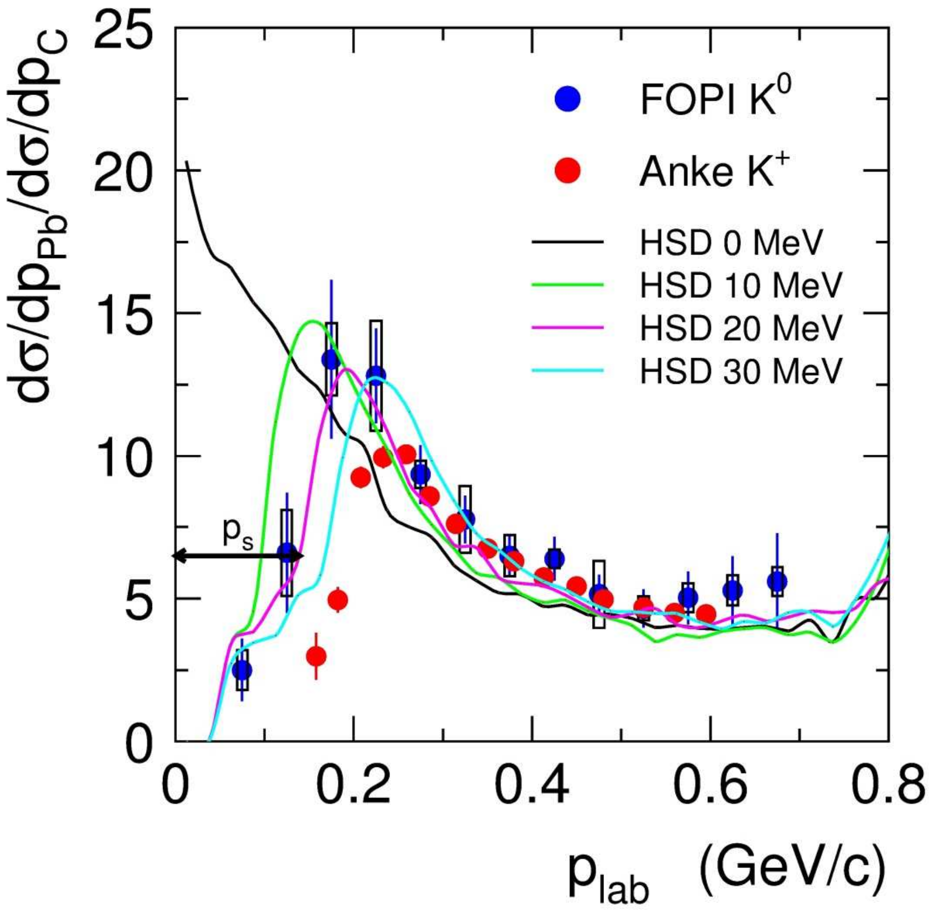
→ C. Hartnack et al. Phys. Rep. 510, 119 (2012)



K⁺N – interaction re
ground state densiti

nances
ffective field theory with
nels
nel G-Matrix approach
attractive at finite
ensities, but strength
(depth of potential) unclear at high
densities

In medium KN-Potential in pion induced reactions



FOPI data @ SIS

M.L. Benabderramahne et al., *PRL* (2009)

$\pi + A \rightarrow K^0 + X$ at 1.15 GeV/c

Anke data @ COSY

M. Büscher et al., *EPJ*, A22, 301 (2004)

$p + A \rightarrow K^+ + X$ at 2.5 GeV

Model interpretation with HSD:

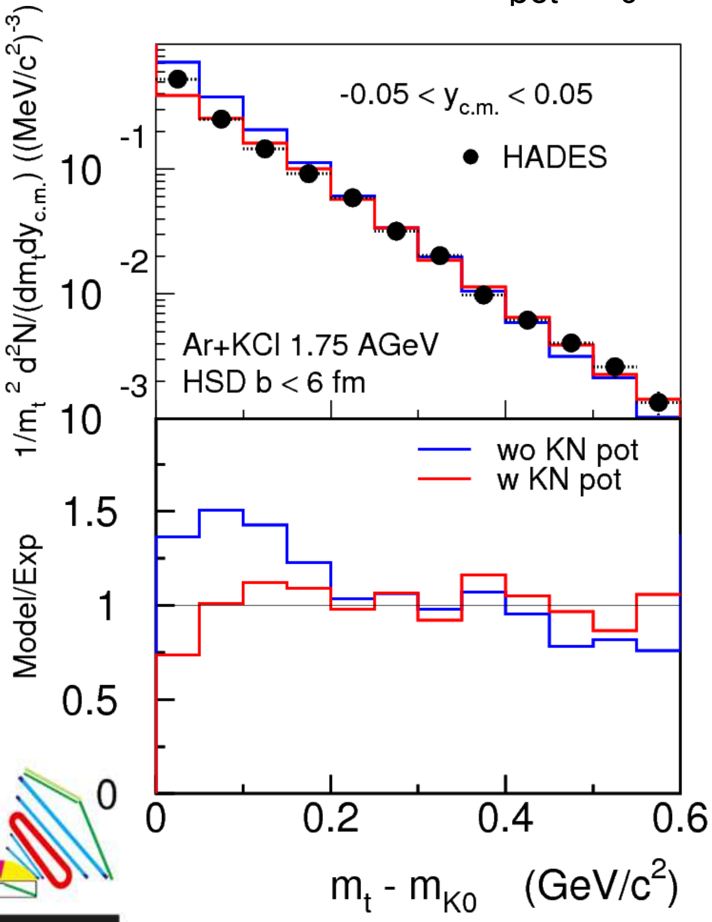
$U_{KN}(\rho_0) = + 20 +/- 10$ MeV

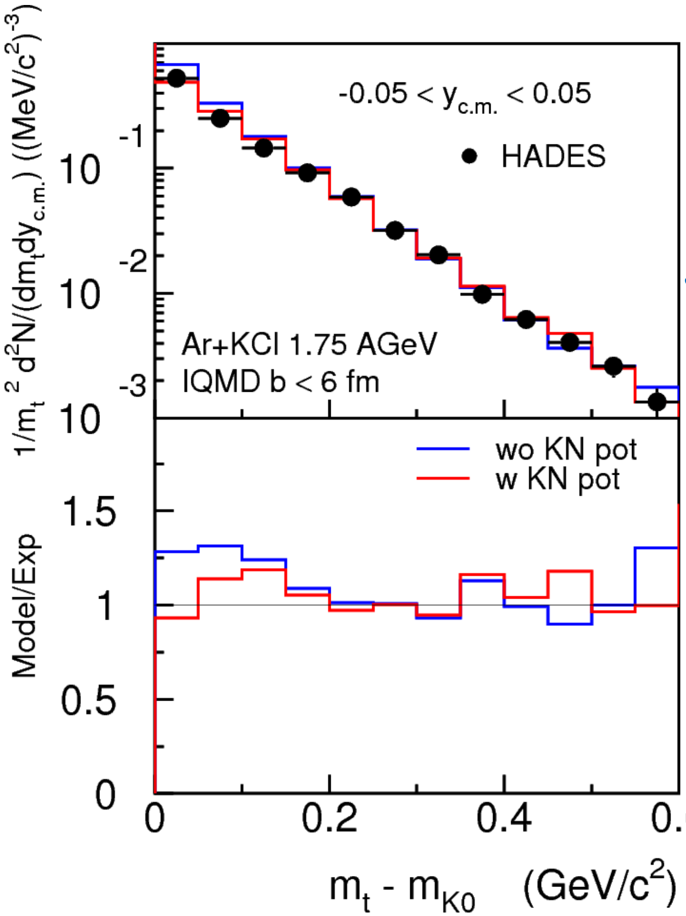
Result only limited by statistics

→ more systematic studies

In-medium KN Potential in heavy ion collisions

KN U_{pot} (ρ_0) = +40 MeV both IQMD and HSD





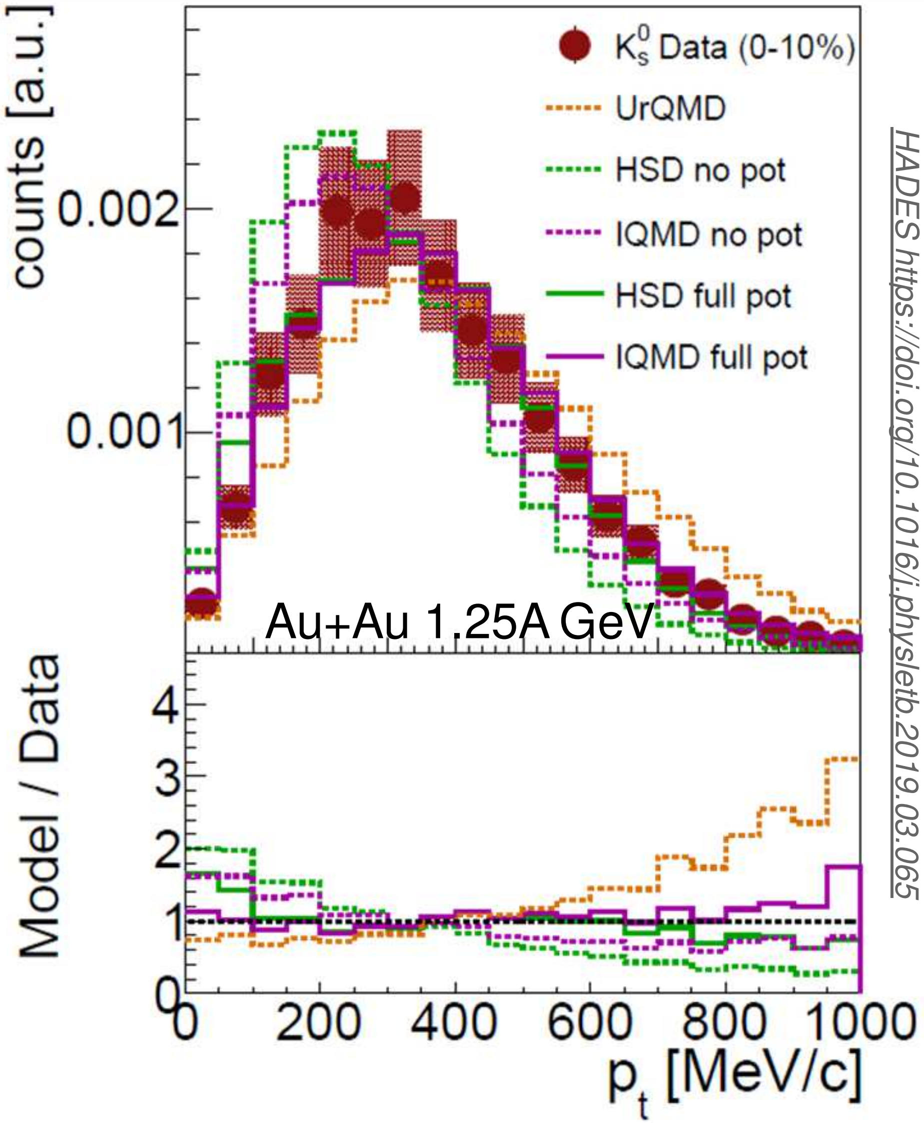
HADES, Phys. Rev. C82:044907, 2010

HADES

In-medium KN-potential from low momenta

KN $U_{pot}(\rho_0) = +40$ MeV
both for IQMD and HSD

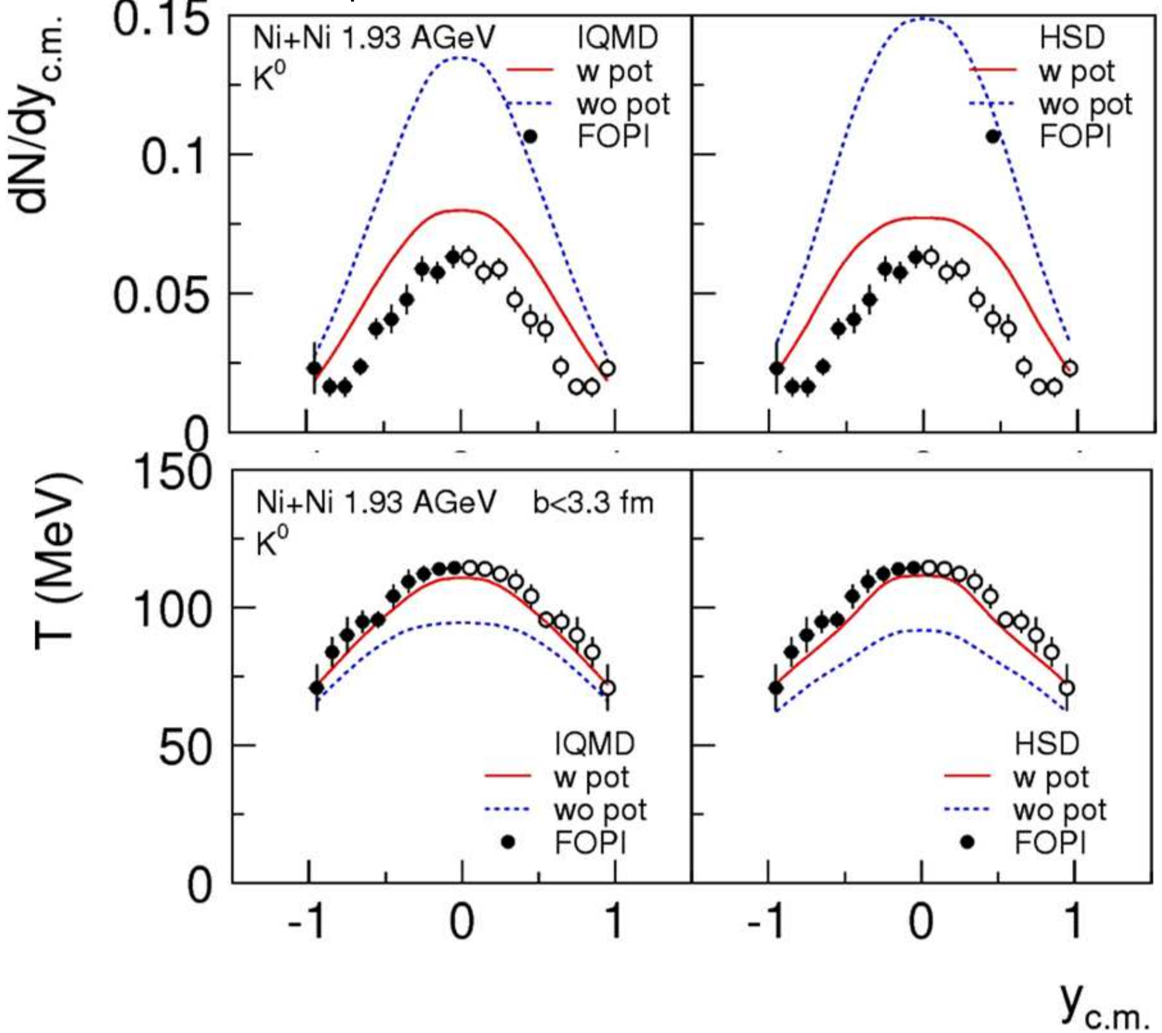
UrQMD no potential



HADES https://doi.org/10.1016/j.physletb.2019.03.065

In-medium KN potential
K^0 in Ni+Ni at 1.9A GeV

KN U_{pot} = +40 MeV both IQMD and HSD

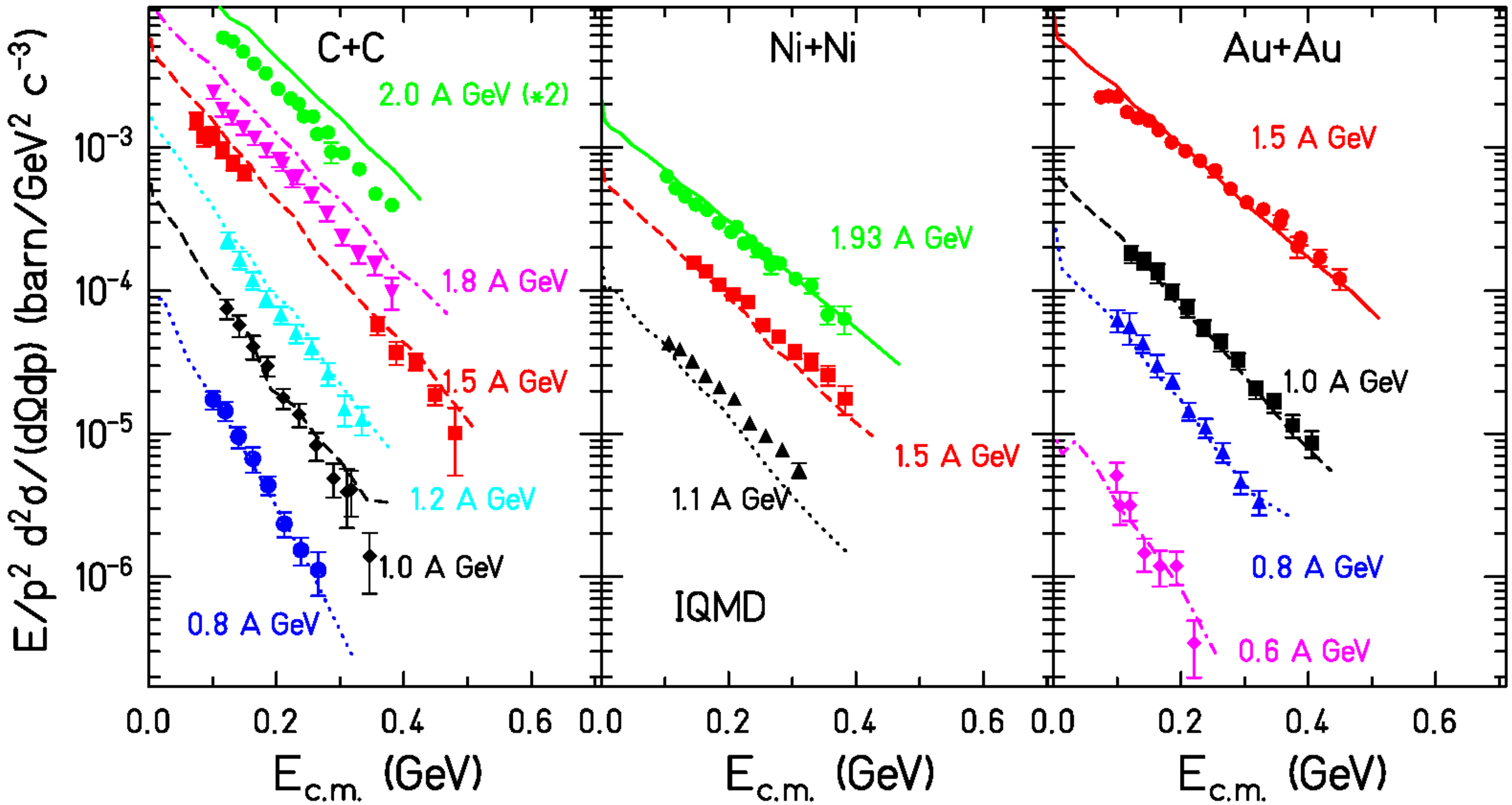


X. Lopez
M. Merschmeyer

Most of experimental data reasonably well described by HSD and IQMD

In-medium KN potential
Heavy ion collisions C+C to Au+Au

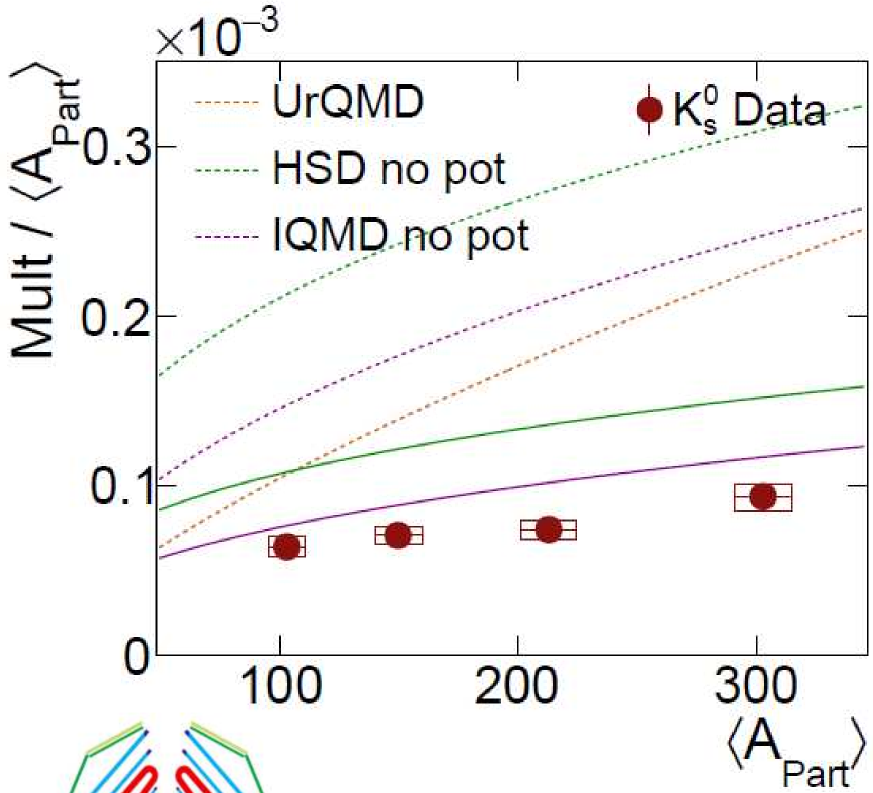
KaoS K^+ data (inclusive, approx. mid-rapidity)

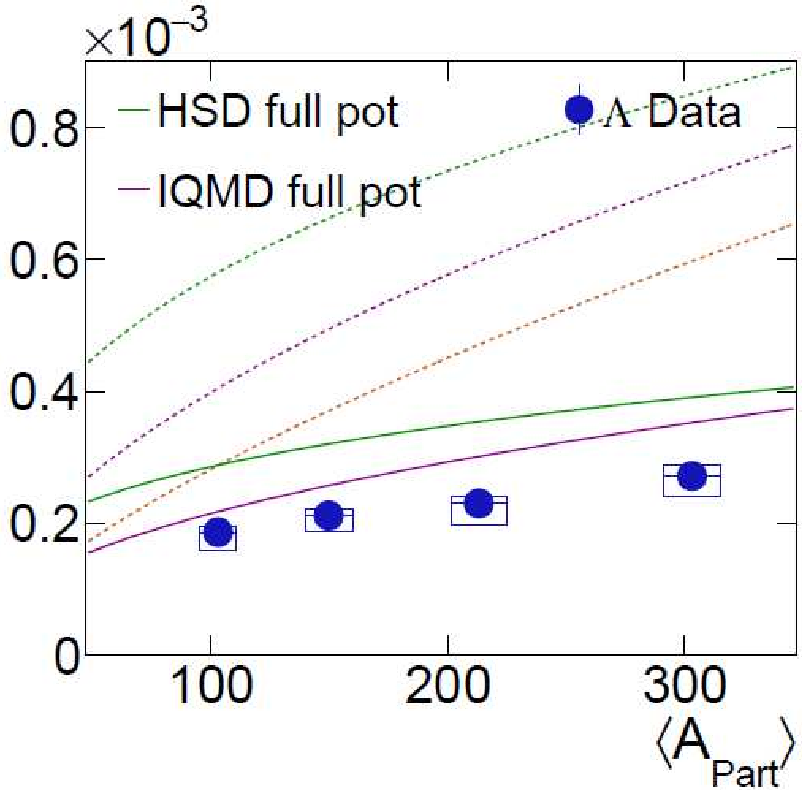


→ repulsive KN potentia U_{pot} (ρ_0) = +20...40 MeV

In-medium KN potential
HADES data on Au+Au

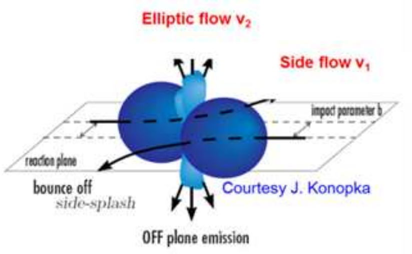
- Au+Au 1.23 GeV/u



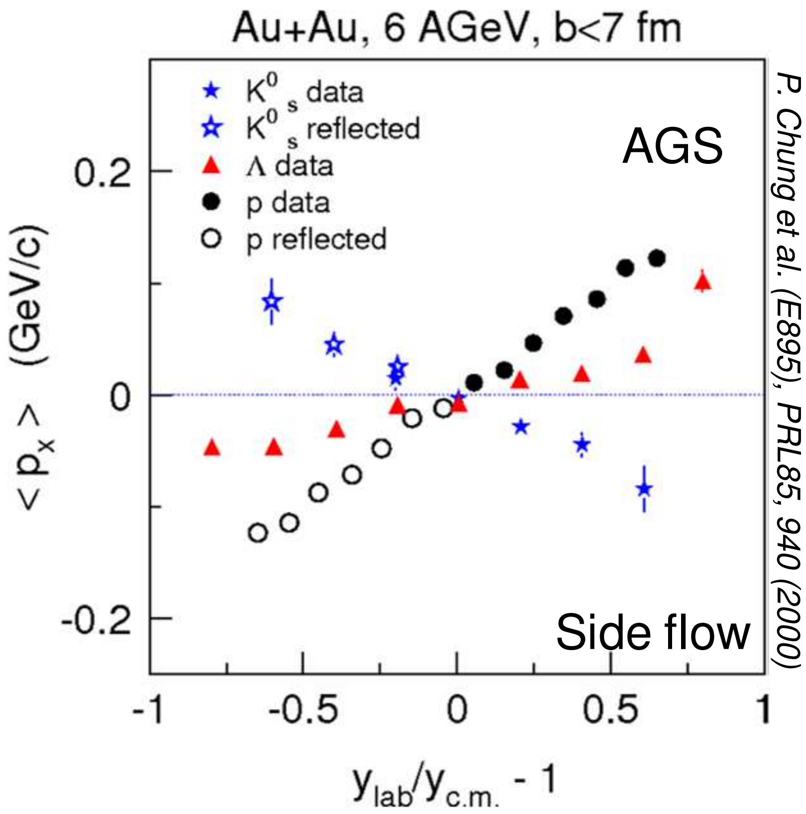


HADES https://doi.org/10.1016/j.physletb.2019.03.065

In-medium potential at AGS Energies
Side flow v_1



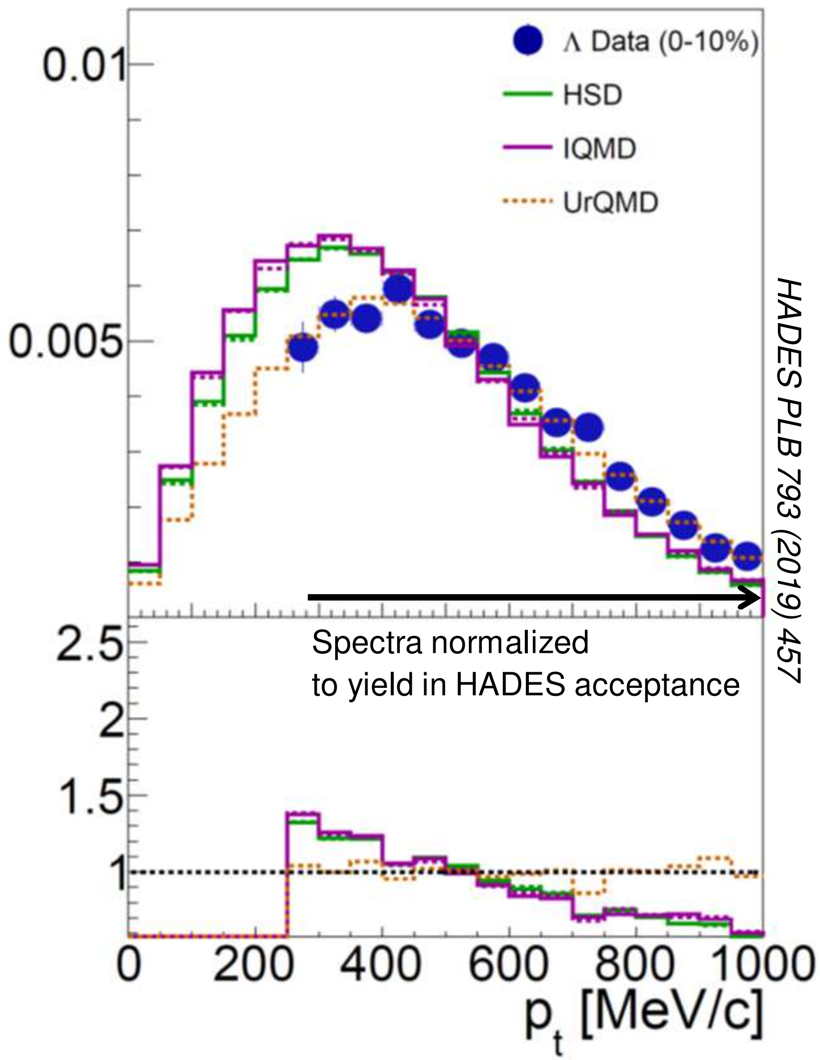
$$\frac{dN}{d\Phi} \sim 1 + 2v_1\cos\Phi + 2v_2\cos^2\Phi$$
$$\Phi = \varphi - \Phi_{Reac}$$



Data: P. Chung et al. (E895), PRL85, 940 (2000)

- very strong kaon antiflow signal,
  - as big as proton flow (opposite sign!)
- comparisons to microscopic transport models → repulsive KN potential
- lambda flow signal consistent with attractive potential ~ 2/3 V_{NN}

Hyperon production in Au+Au 1.23 GeV/u



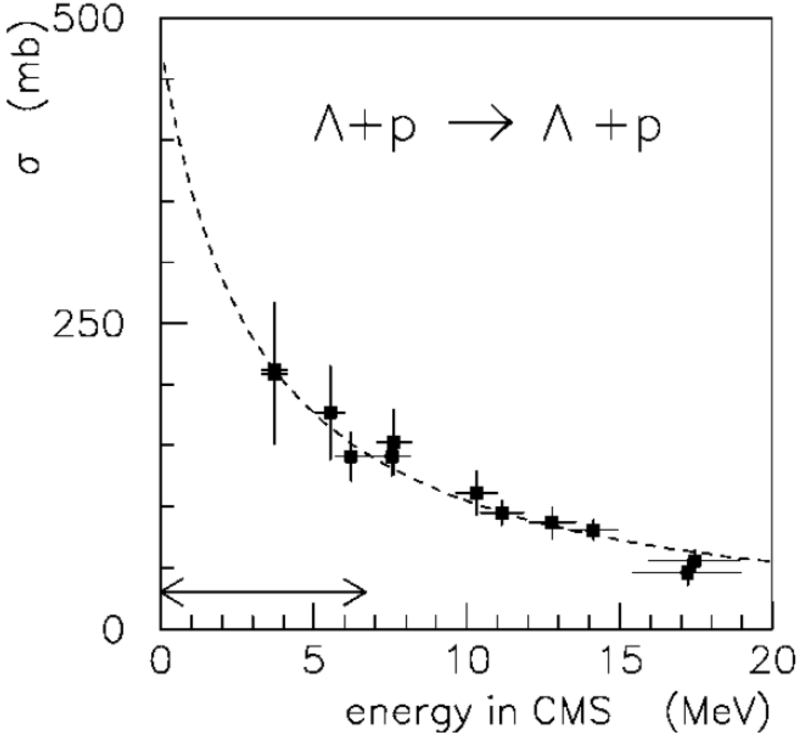
UrQMD describes shape of spectra best

- production process (via resonances)

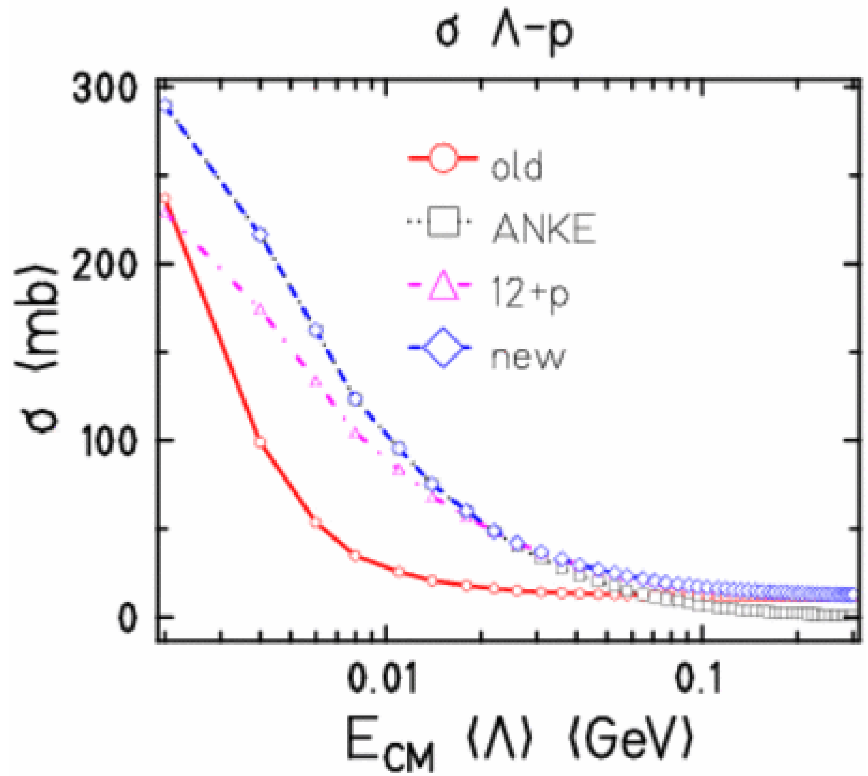
IQMD

- two and tree-body production mechanisms (NN, ΔN, πN)
- ΛN potential ~2/3 V_{NN}
- parametrization for ΛN rescattering fitted to experimental data

Constraints to Λ+p scattering at low energies



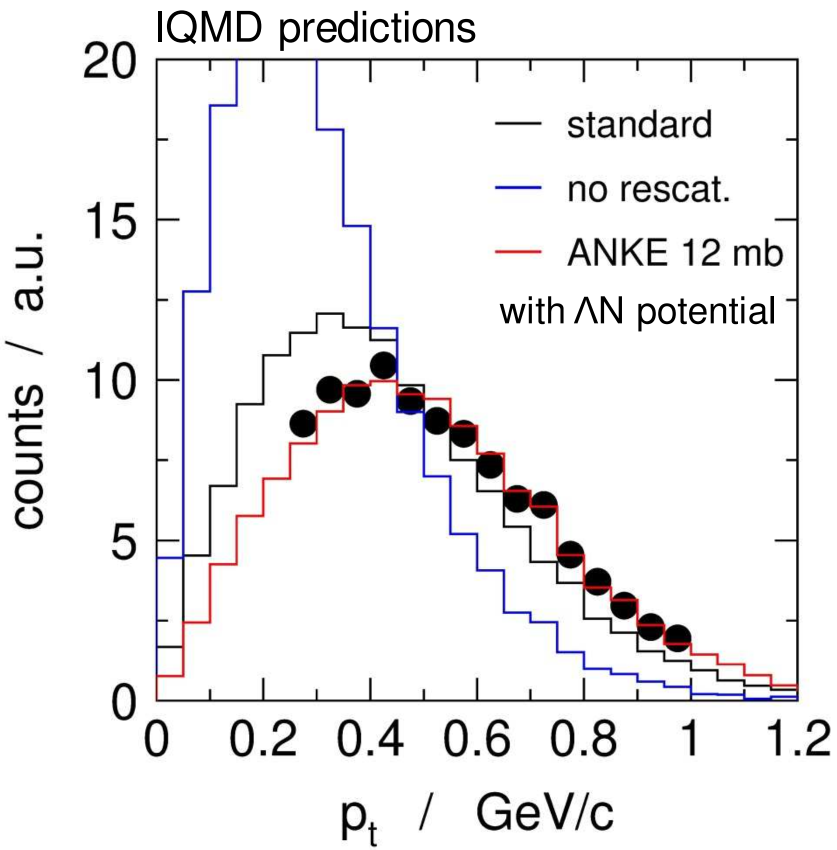
J.T.Balewski et al. Eur. Phys.J A 2, 99 (1998)

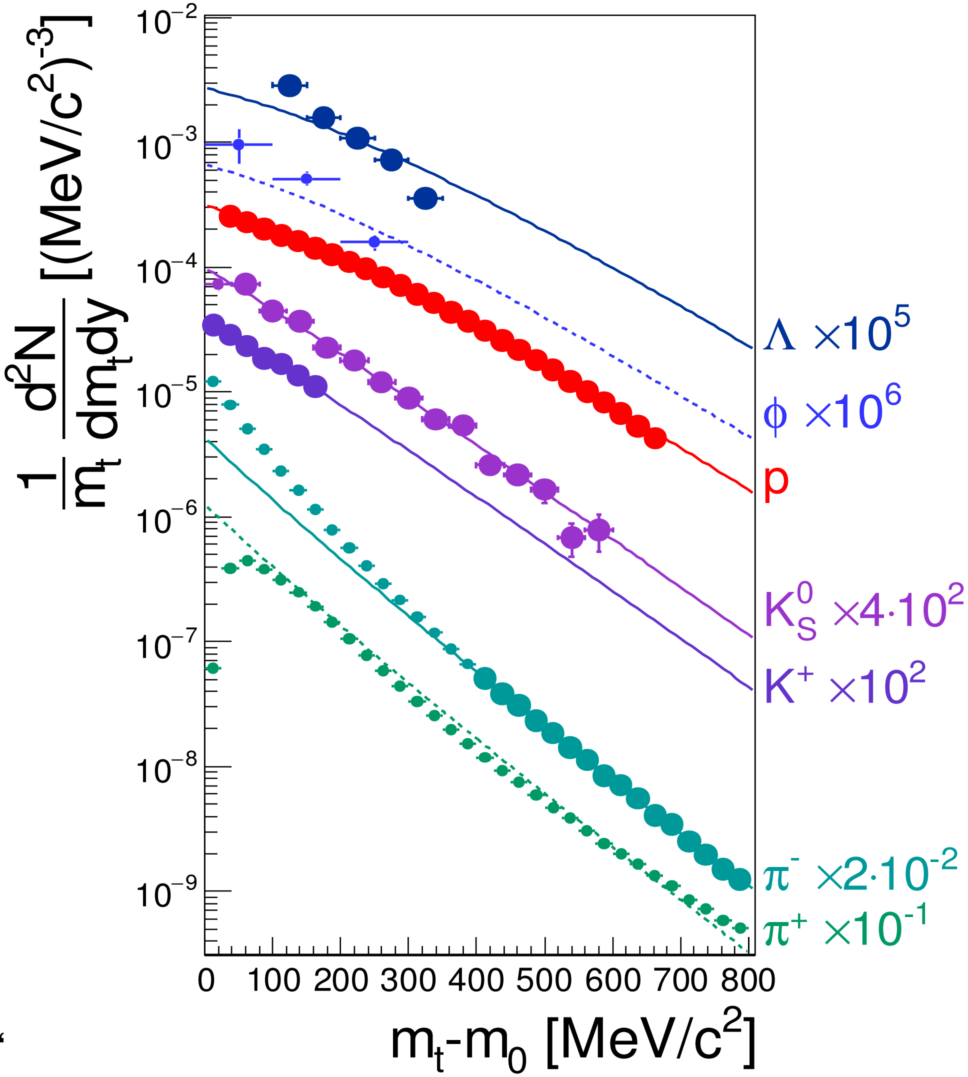


ANKE data constrains cross sections upto 25 MeV*

- "new" uses the parametrization suggested by the ANKE measurement with a constant high energy cross section of 12 mb

Hyperon production in Au+Au@1.23GeV/u



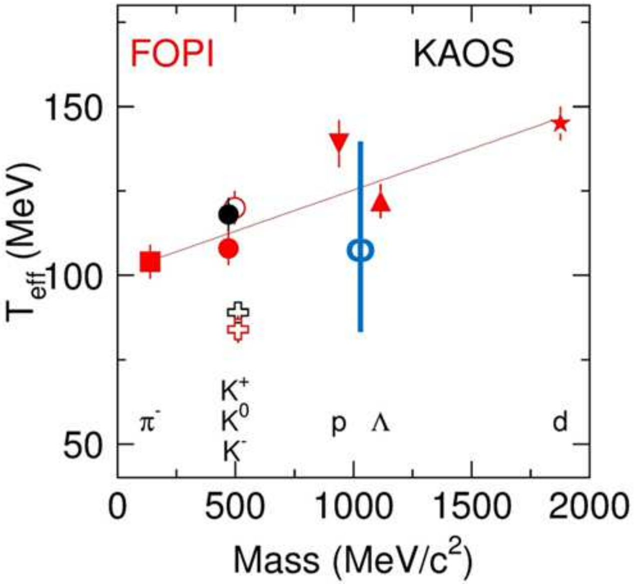


- low momentum spectrum can be described by employing higher Λp scattering cross section
- scattering leads to higher „temperature"

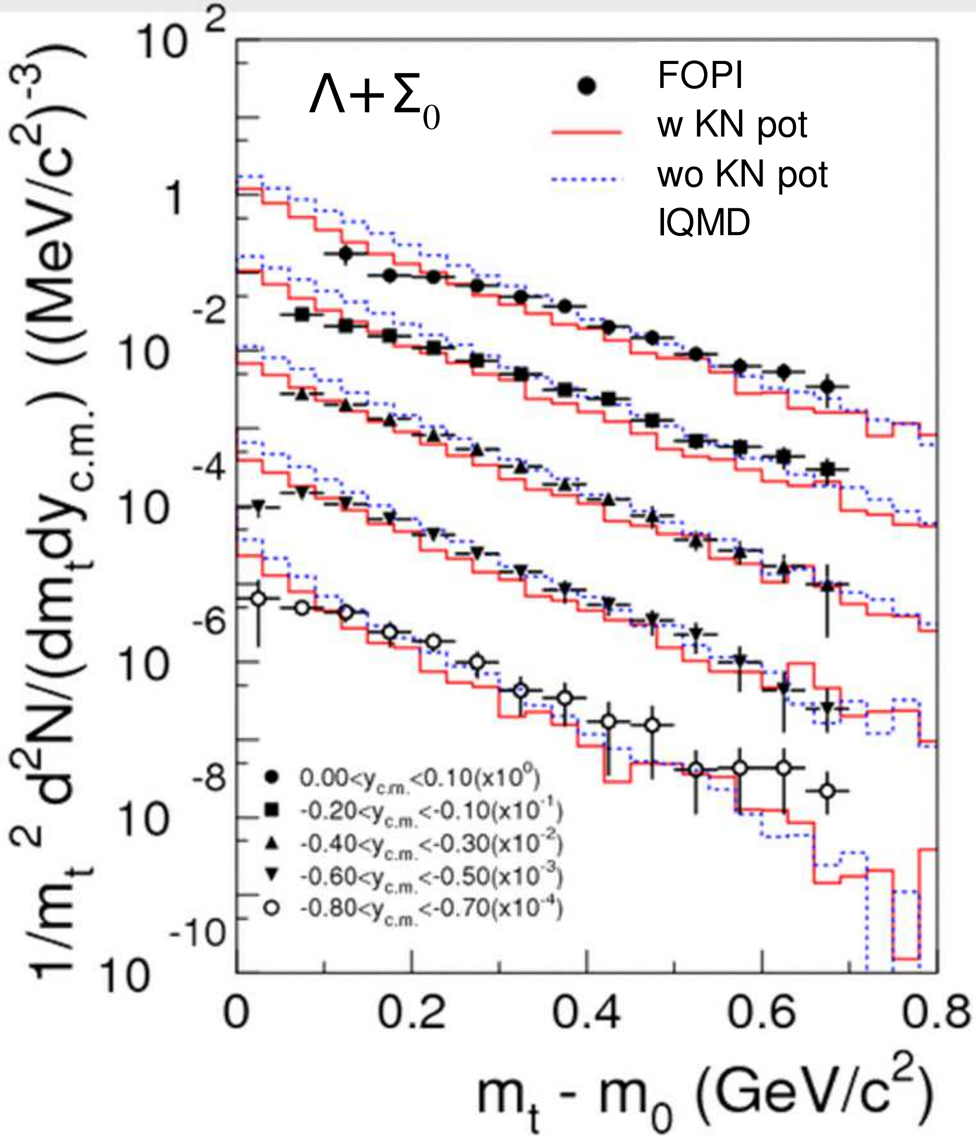
Hyperon production in Ni+Ni 1.93 GeV/u

IQMD calculations with attractive $V_{\Lambda N}$ potential

- inconclusive
- experimental spectra less steep than model prediction
  - higher inverse slope parameter
- Note: experimental inverse slope parameter of Λ substantially lower than that of protons

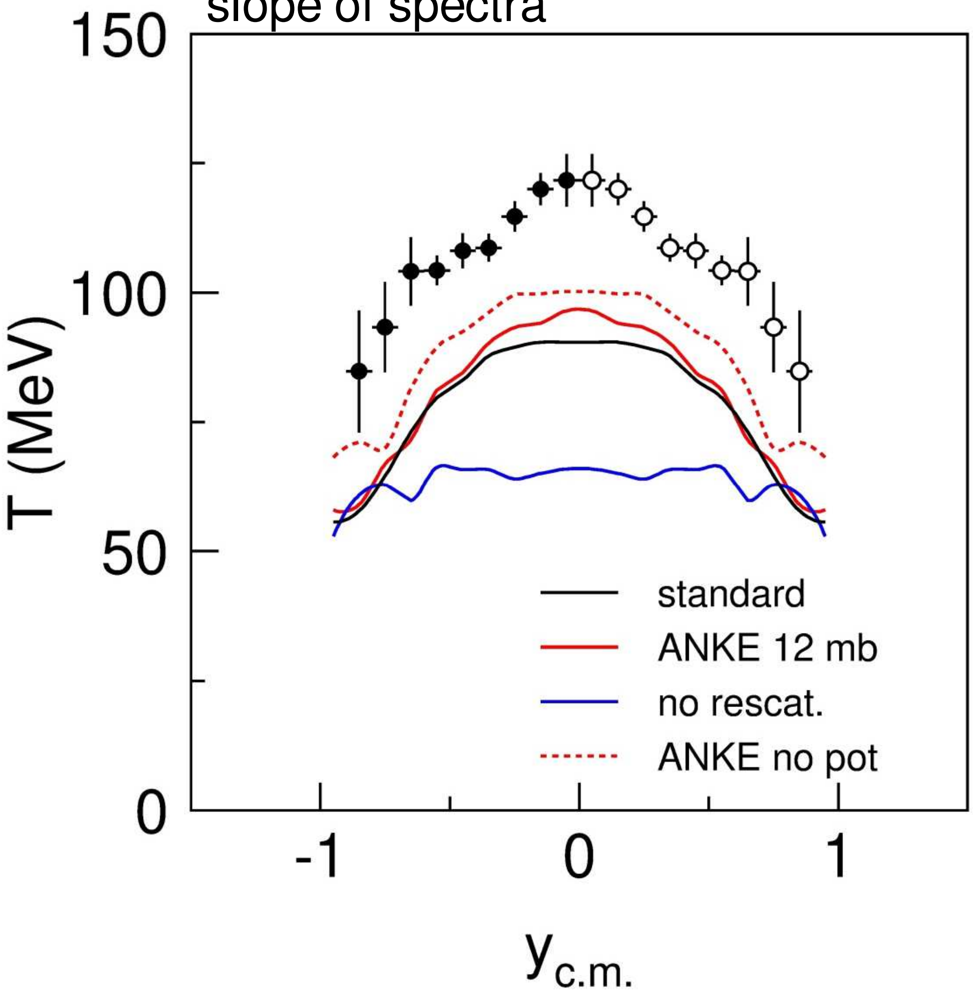


A. Förster KaoS, PRC 75, 024906 (2007)
K. Piasecki FOPI, PRC 91, 054904 (2015)
X. Lopez FOPI, PRC 81, 061902 (2010)



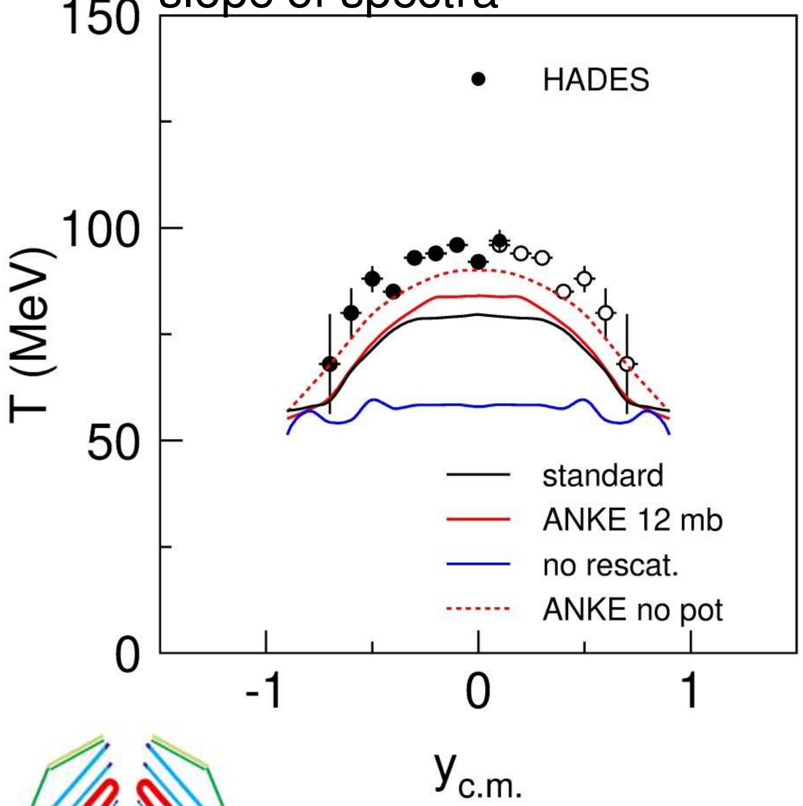
Hyperon production
in Ni+Ni at 1.93 GeV/u

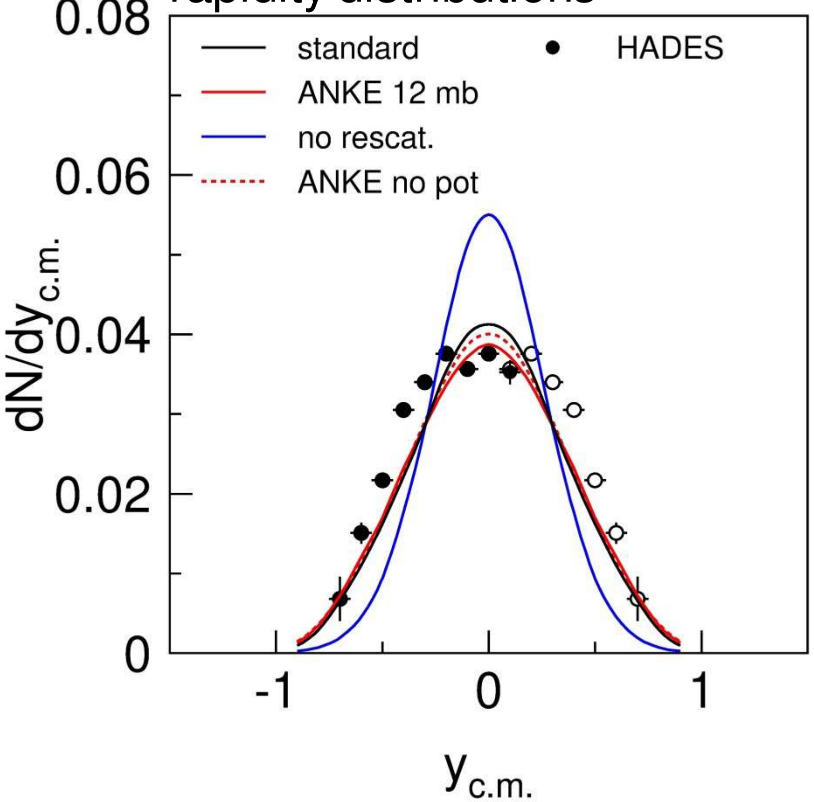
IQMD predictions
slope of spectra



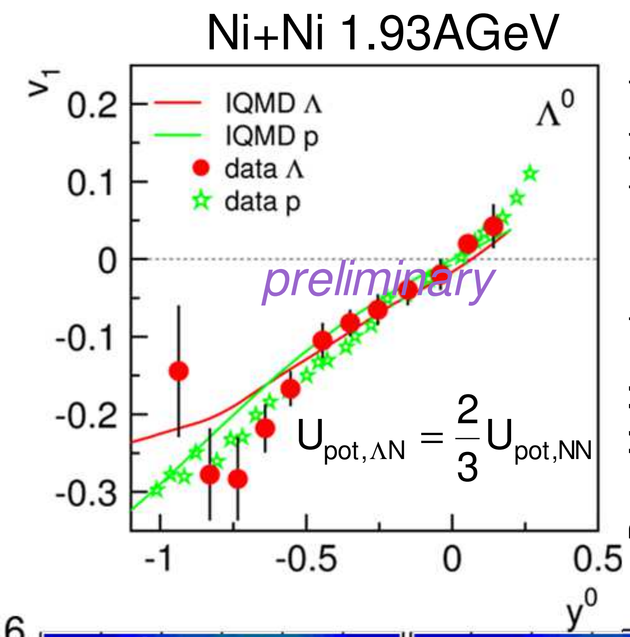
- Hyperons rather „cool“ after production
- gain energy by rescattering
- attractive ΛN potential counteracting and reducing the average kinetic energy
- not enough collisions to reach the measured inverse slope parameters

Hyperon production in Ar+KCl 1.76 GeV/u

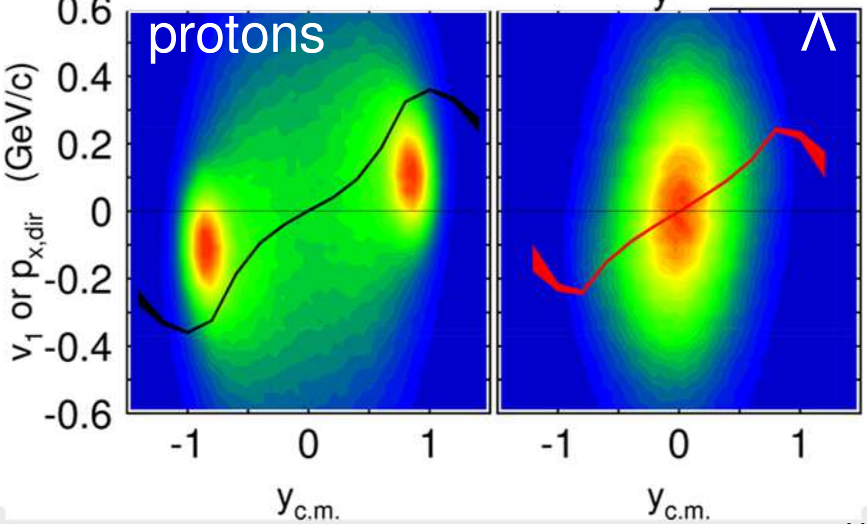




In-medium potential Hyperons



Data: M. Merschmeyer phd thesis
IQMD: C. Hartnack



Lambda directed flow

- data consistent with
- re-scattering cross section
- can be constrained by
  - flow
  - spectra, rapidity distributions

Production of hypernuclei

Λs preferentially emitted at mid-rapidity but hyper-nuclei production might take place:

- more easily in the presence of spectator matter → crucial to get Λs in the region of the spectator matter
- by “coalescence” at mid-rapidity

FRIGA

Fragment Recognition In General Applications

- Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm) + overal cluster binding energy minimization
- so far applied with various transport models: BQMD, IQMD, pHSD.
- describes spectator fragmentation
- prediction of (light and heavy) (hyper)isotope yields and full phase space distribution.

Germanic mythological goddess Frigg/Friga, spinning the clouds

A. LeFevre, J. Aichelin, E. Bratkovskaya, C. Hartnack, V. Kireyeu, Y. Leifels

FRIGA in short

Transport : **IQMD** *(C. Hartnack et al., Eur. Phys. J. A 1 (1998) 151)*

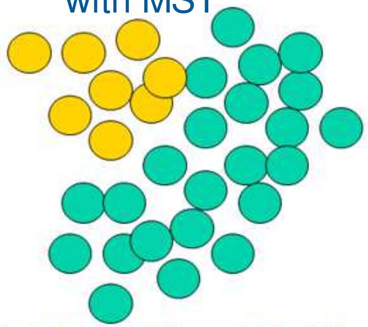
+ Clustering algorithm: **FRIGA** *(A. Le Fèvre et al, 2016 J. Phys.: Conf. Ser. 668 012021)*

- simulated annealing with Minimum Spanning Tree coalescence as 1st step + overall cluster binding energy minimization

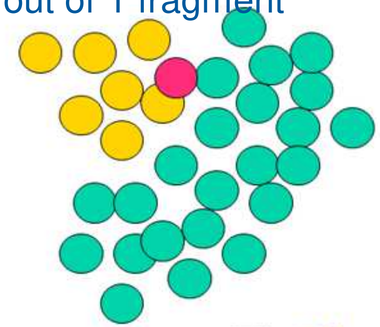
$$E_{bind} = E_{kin} + E_{Coul} + E_{m.f.} + E^{surf.}_{Yuk.} + E^{pot}_{asy} + E_{struct}$$

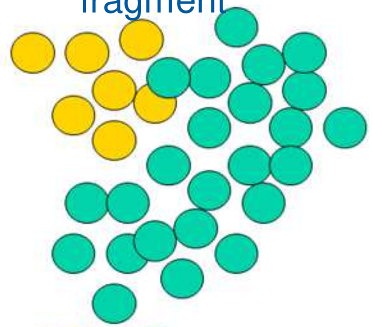
- veto of unstable isotopes
- ^3He+n; secondary decay of excited primary clusters (GEMINI);

1. Preselect fragments with MST
2. Take randomly 1 nucleon out of 1 fragment
3. Place it randomly in another fragment



$E=E^1_{kin}+E^2_{kin}+V^1+V^2$





$E'=E^{1'}_{kin}+E^{2'}_{kin}+V^{1'}+V^{2'}$

If E' < E take the new configuration

If E' > E take the old with a probability depending on E'-E

Repeat this procedure very many times... (Metropolis procedure)

It leads automatically to **the most bound configuration**.

Reconstruction of hyper nuclei

Soft EOS
with m.d.i.
no Kaon pot.

FRIGA ingredients:

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei). We consider the strange quark as inert as a first approach ⇒ $U(N\Lambda) = 2/3 \cdot U(NN)$

② Surface effect correction: Yukawa term.

And optionally:

③ Symmetry energy E_{asy}

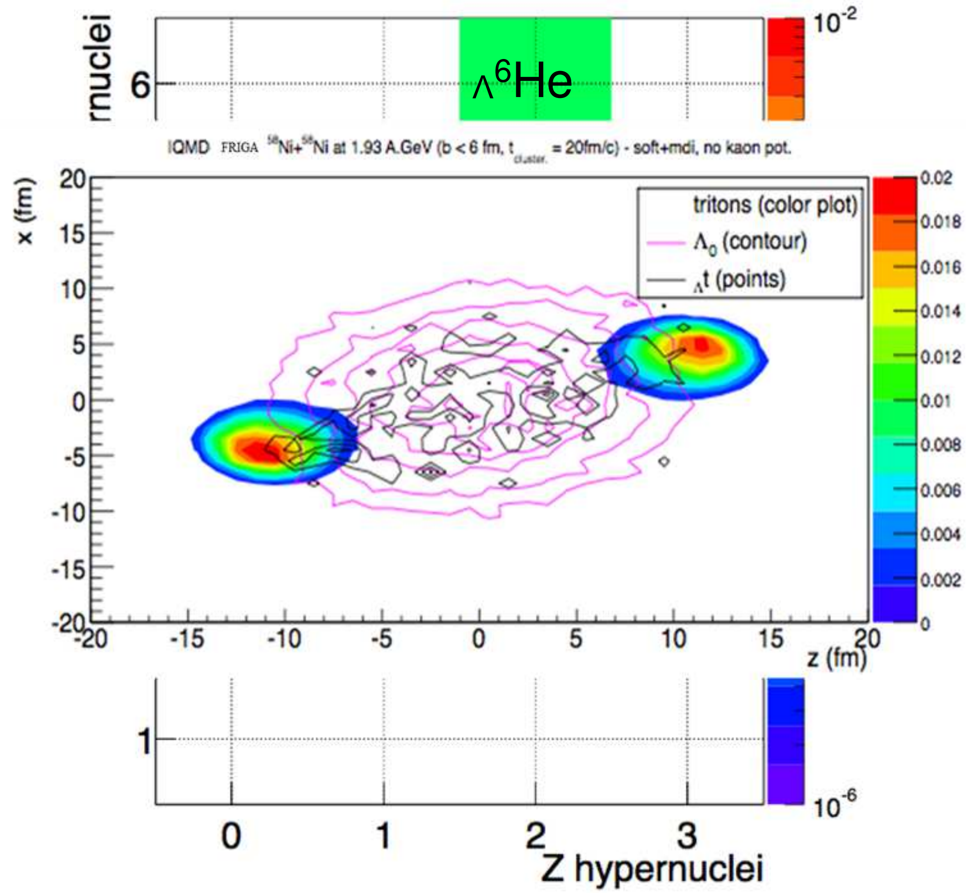
④ ~~Extra « structure » energy (N,Z,ρ) = $B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$~~

⑤ ~~^3He+n recombination.~~

⑥ ~~Secondary decay: GEMINI.~~

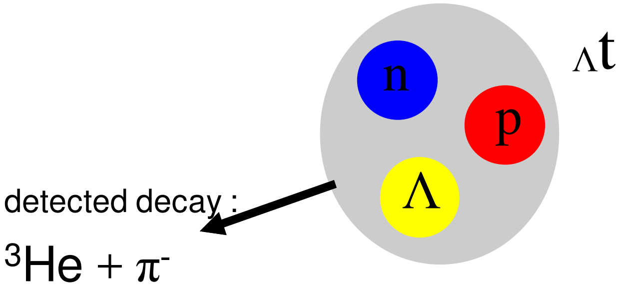
⑦ Rejection of « non-existing » isotopes and hyper-clusters.

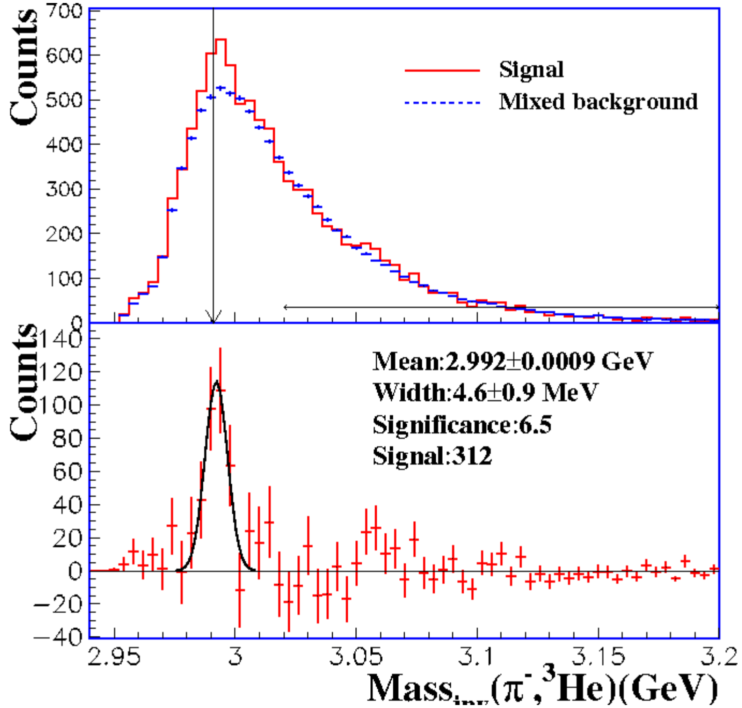
IQMD+FRIGA 1.9GeV/u Ni+Ni

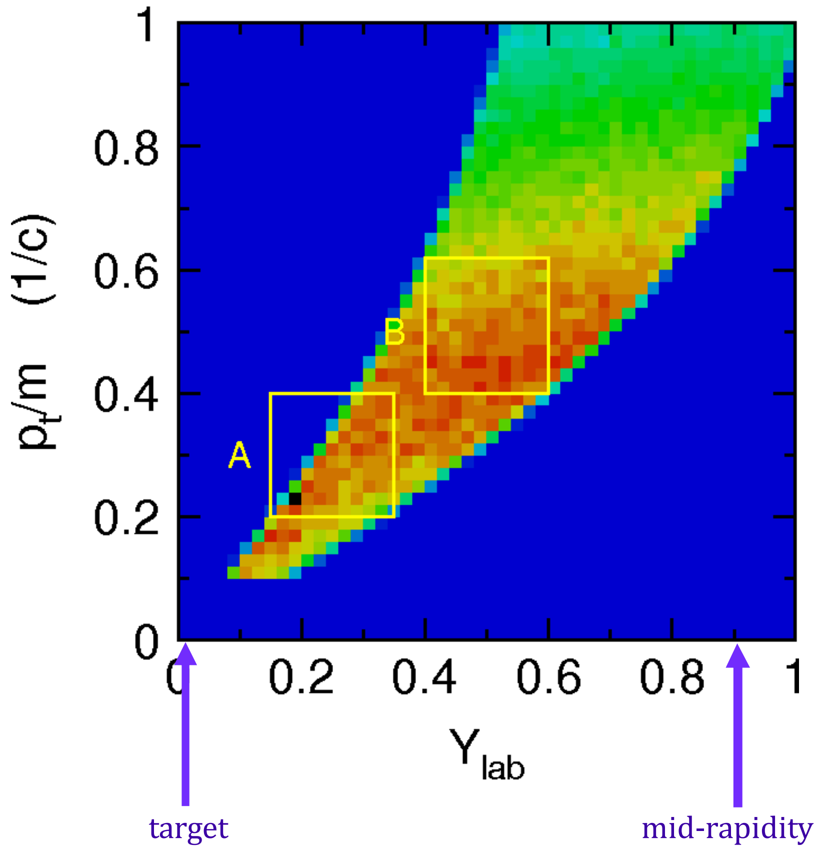


Hyper nuclei production in Ni+Ni collisions 1.91 Gev/u

FOPI

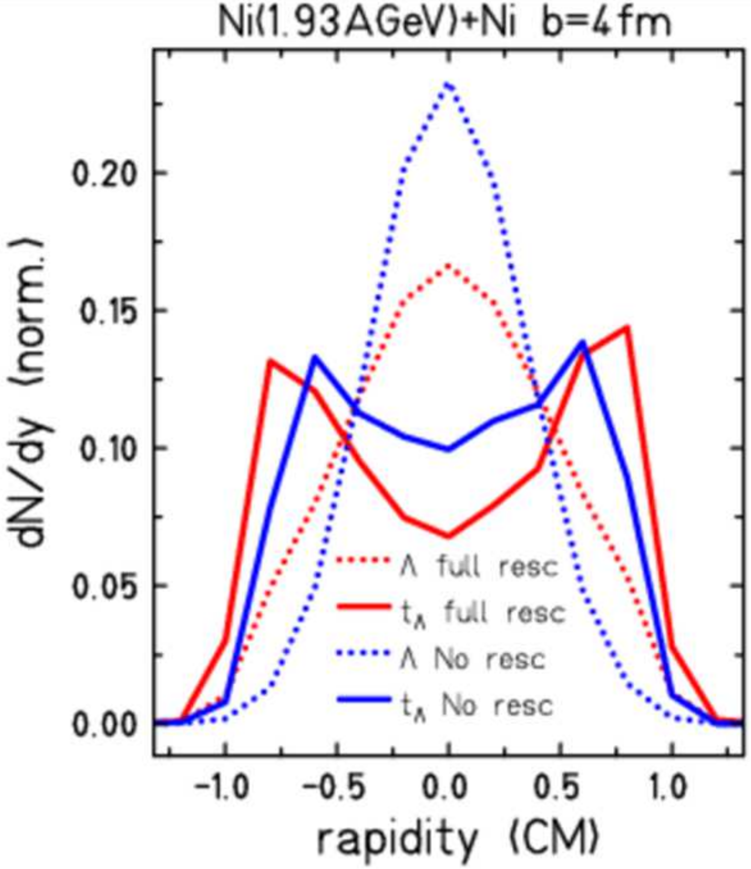


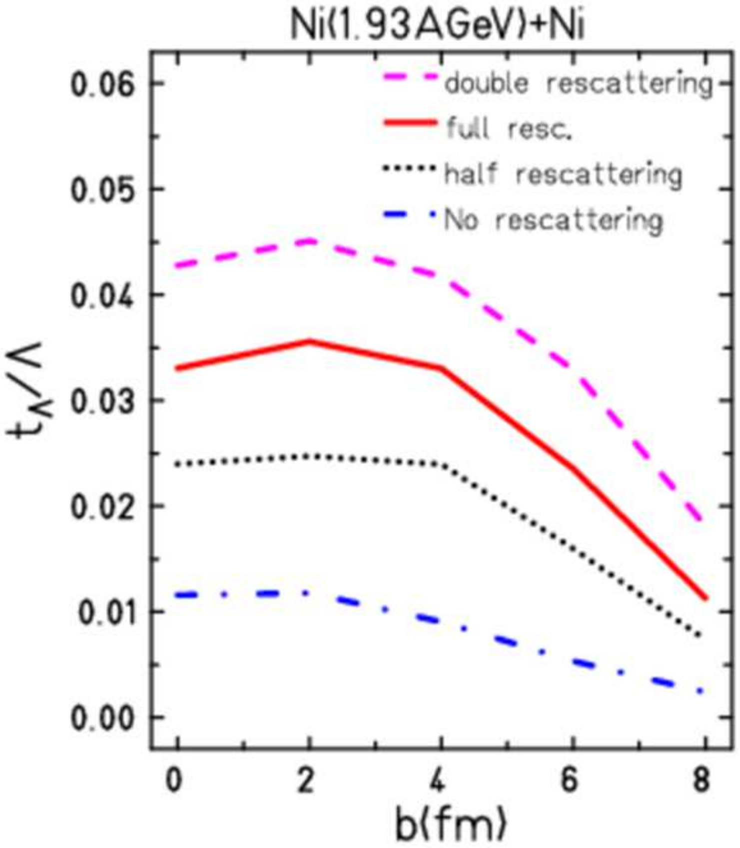




Y. Zhang
phd thesis Heidelberg

Influence of Lambda re-scattering on hyper nuclei yield

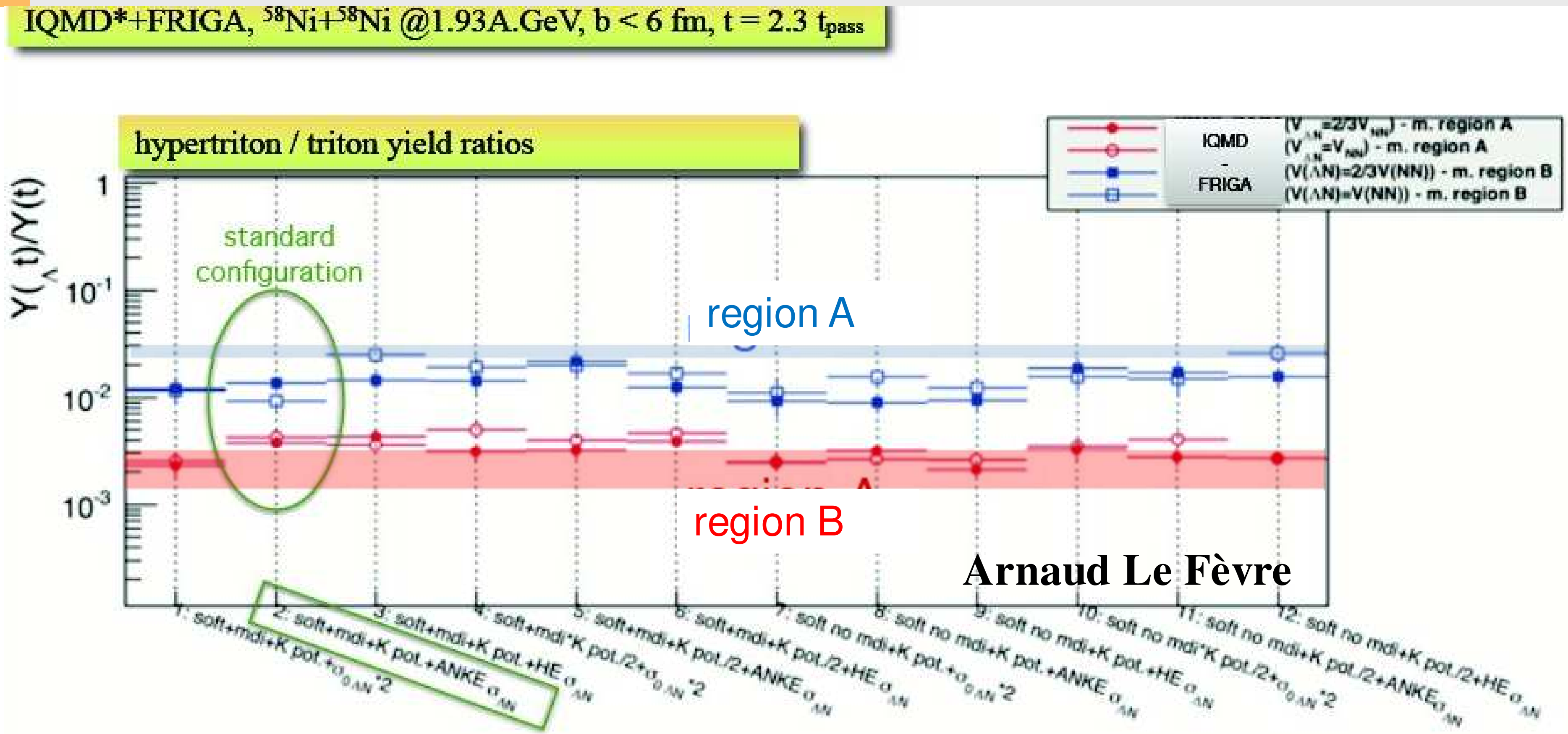




IQMD calculations C. Hartnack

- rescattering changes rapidity distribution of hyperons
- and consequently the overlapp region between hyperons and spectator nucleons
- huge influence on yields on hyper nuclei

Results on $_{\Lambda}$t/t ratio in Ni+Ni collisions 1.91 GeV/u



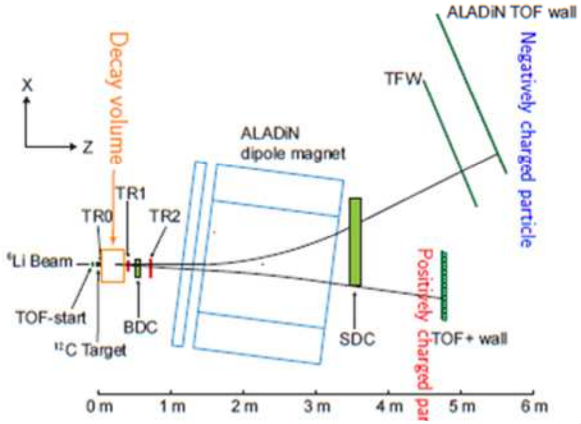
FOPI result preliminary

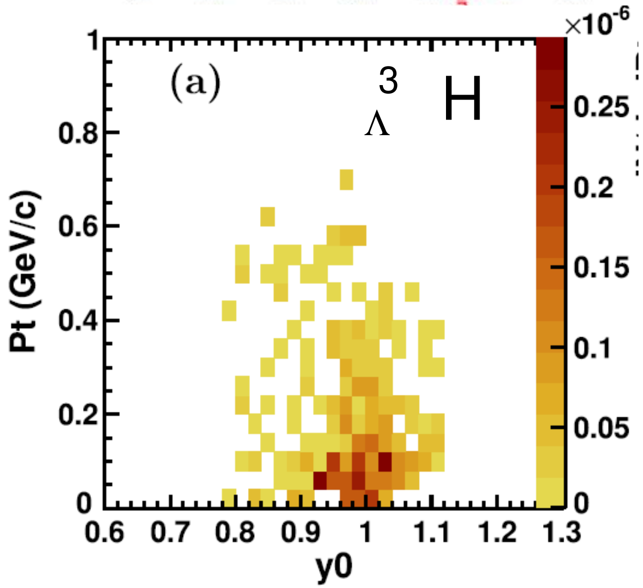
IQMD/FRIGA : d production in coll. (Remler ...)

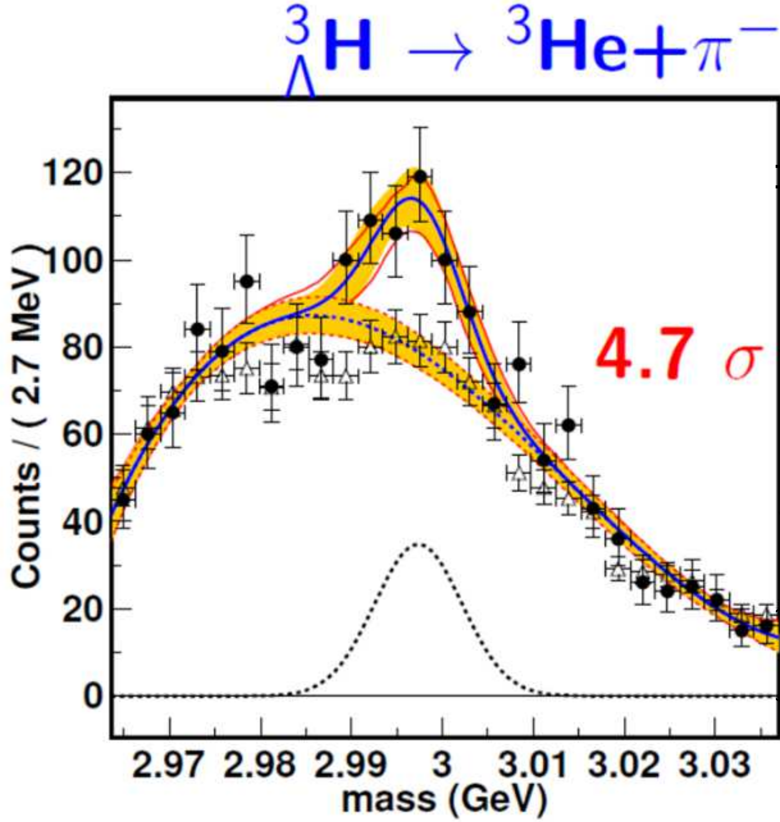
Y. Zhang + A. LeFevre

Hyper nuclei production in the spectator region

HYPHI Experiment at GSI: Li+C 2A GeV



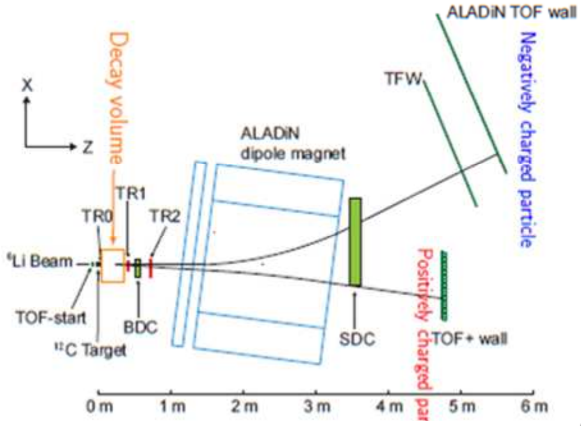


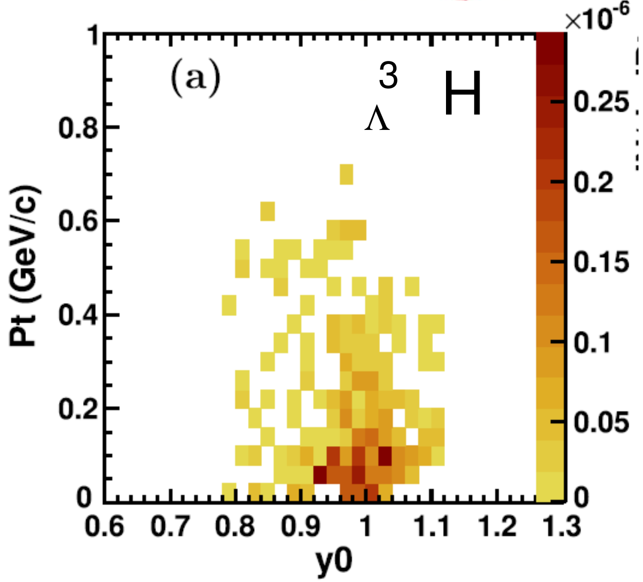


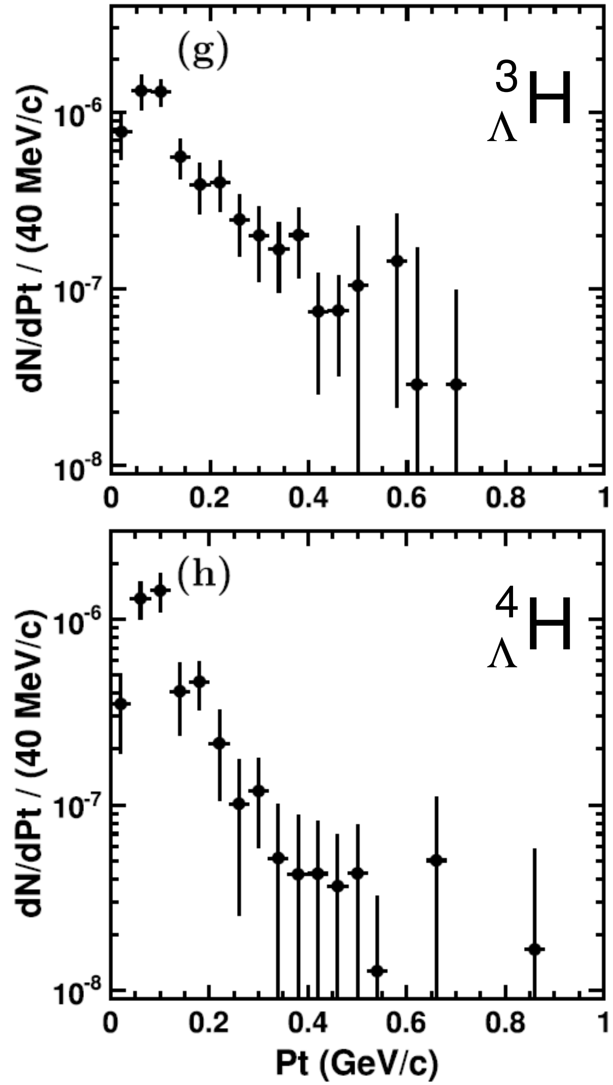
C. Rappold et al., PLB 247, 129 (2015)

Hyper nuclei production in the spectator region

HYPHI Experiment at GSI: Li+C 2A GeV

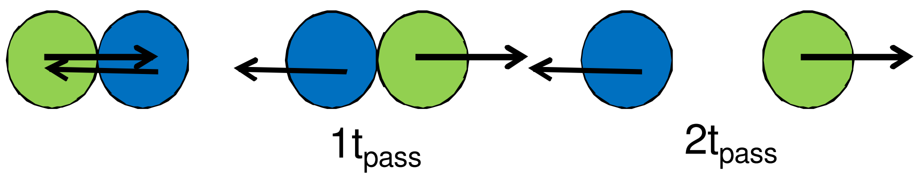






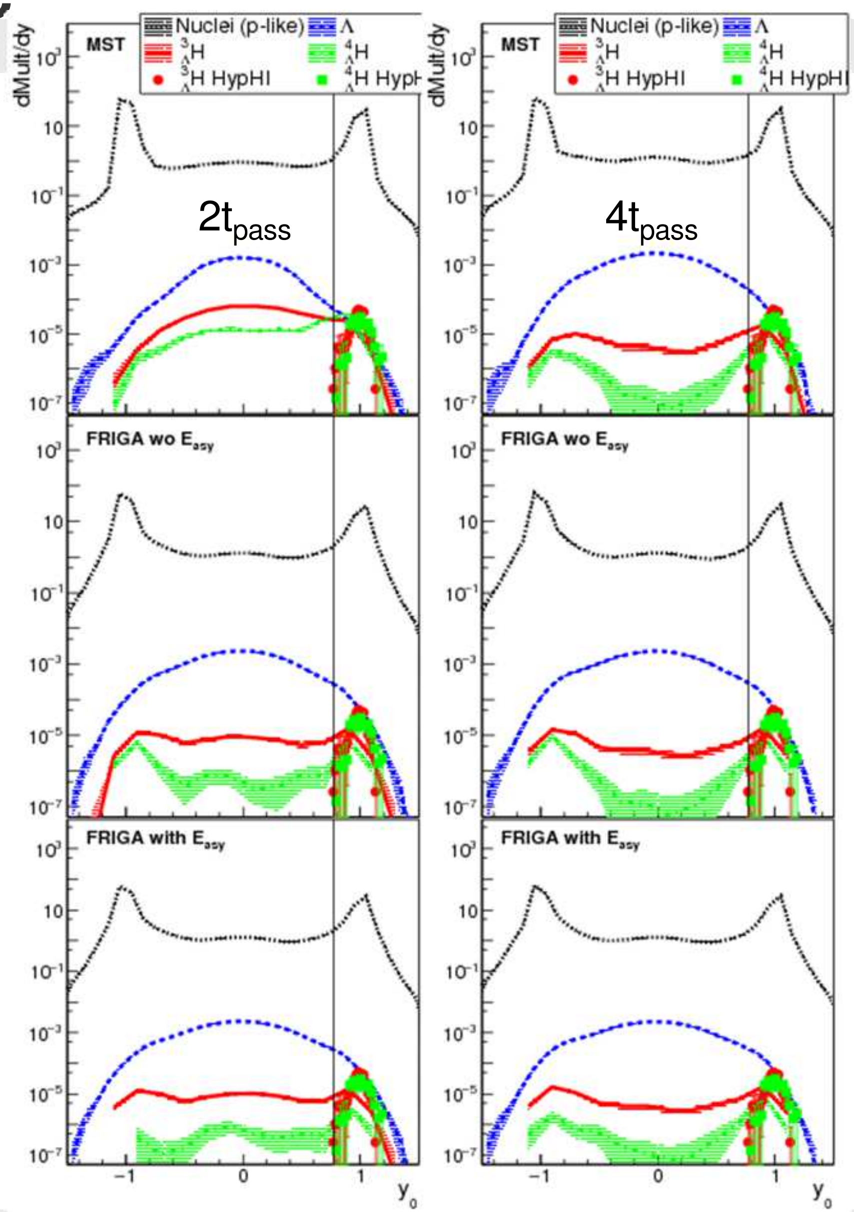
C. Rappold et al., PLB 247, 129 (2015)

FRIGA predictions for hyper nuclei production in Li+C



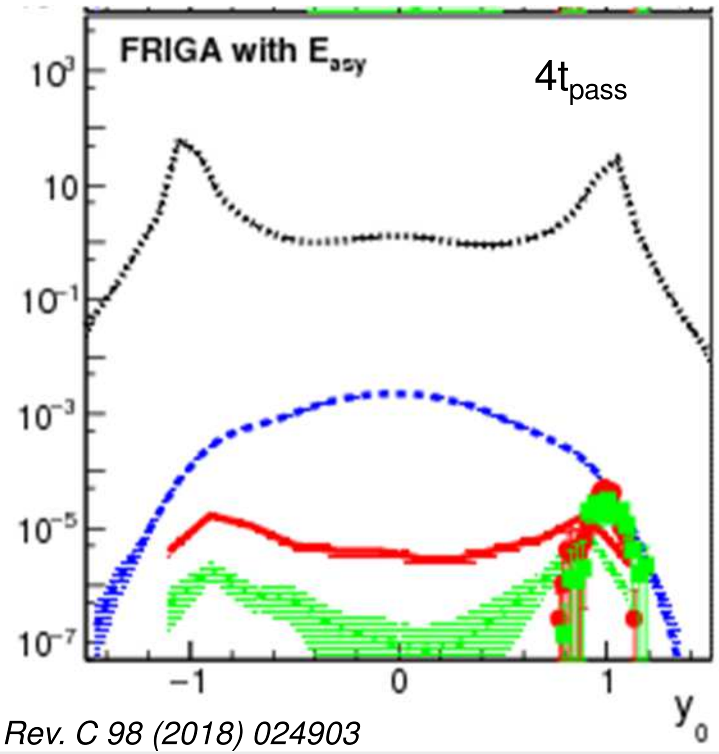
IQMD+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2 – 4\ t_{pass}$)

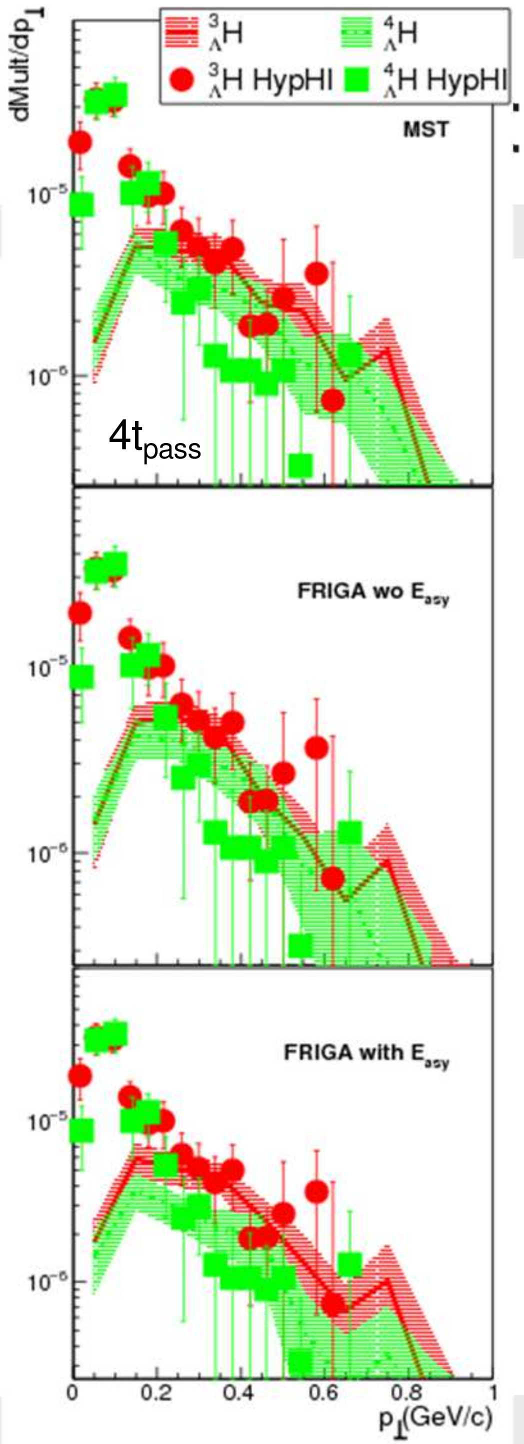
- formation of heavy hyper- nuclei predominantly in the spectator region
- crucially ingredient is the ΛN re-scattering cross section
- cluster multiplicity in the mid-rapidity region depends on the clusterization time
- in contrast to spectator region (relatively stable)



FRIGA predictions for hyper nuclei production in Li+C

- experimental data slightly under predicted
- high pt part of spectra reproduced :
- hyperons gain large y by rescattering, but rescattering enhances also pT
- low pt stem from decay of heavier hyper nuclei ?*





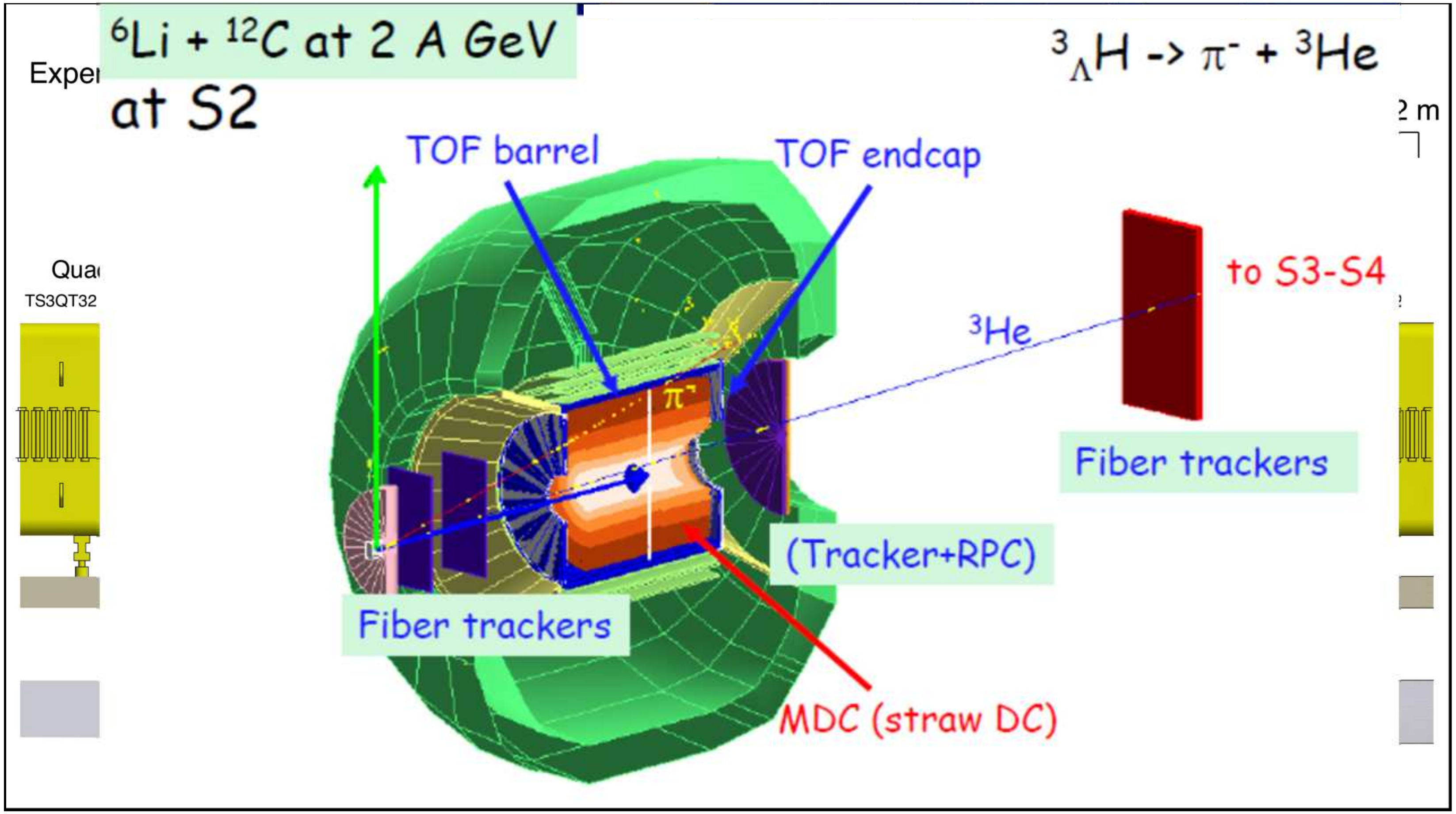
*Y.L. Sun, Phys. Rev. C 98 (2018) 024903

Summary

- Strangeness production close to threshold
  - high intensity beams and high quality data and rare probes
  - sensitive probe
    - bulk properties and reaction dynamics
    - in – medium potentials
      - production, re-scattering, absorption must be under control
      - **repulsive K^+N potential ($U(\rho_0)$= 20 – 40 MeV)**
  - microscopic transport models crucial
  - access to lambda interactions in matter
  - more data is needed
    - flow data in heavier systems
    - elementary productions cross sections
- Study of hyper nuclei production in heavy ion collisions
  - reaction dynamics
  - hot versus cold clusterization

Outlook (short term)

- Hyper nuclei production at FRS with WASA




FAIR