Recent results from FOPI -
From the dynamics of HI collisions to the (Anti-)Kaon-nucleon potential

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GSI

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From the dynamcis of HI collisions to the (Anti) Kaon-nucleon potential

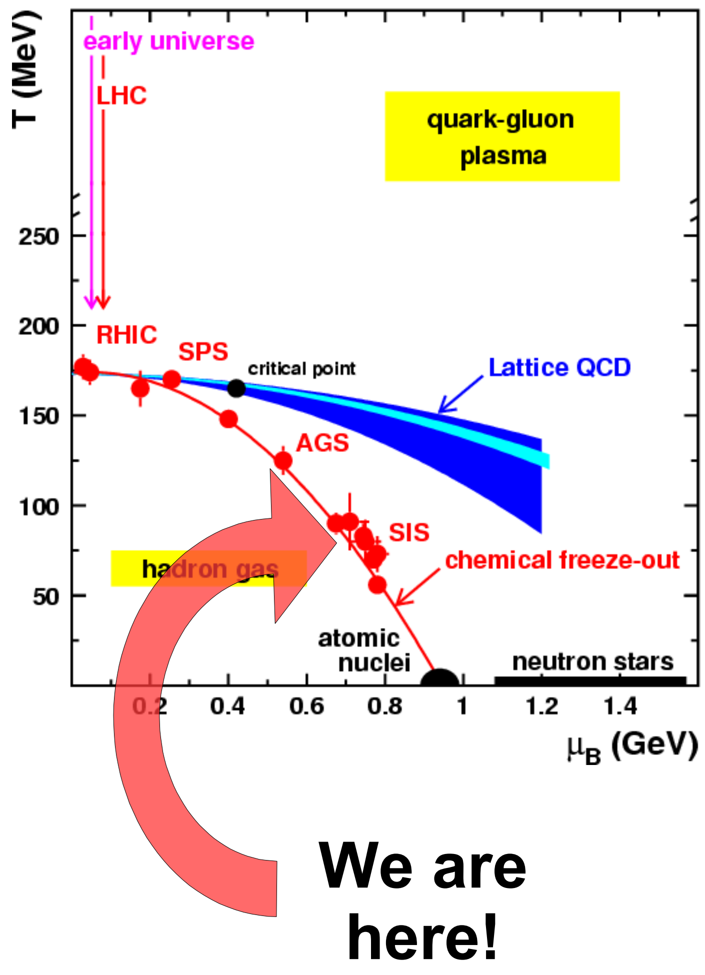
Motivation
- Bulk properties of nuclear matter
- In - medium effects
- K^-N interaction

Dynamics of HI collisions
- Stopping, collective flow

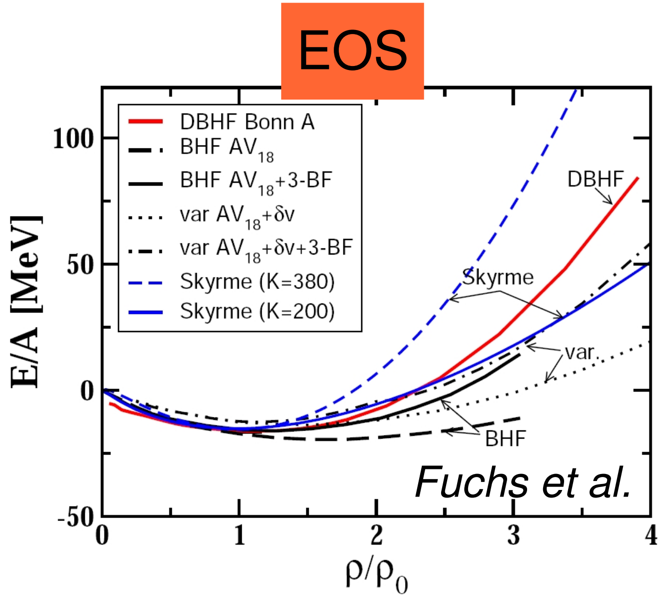
Kaons in Medium
- Inclusive K^0 – production in π A
- Kaon flow

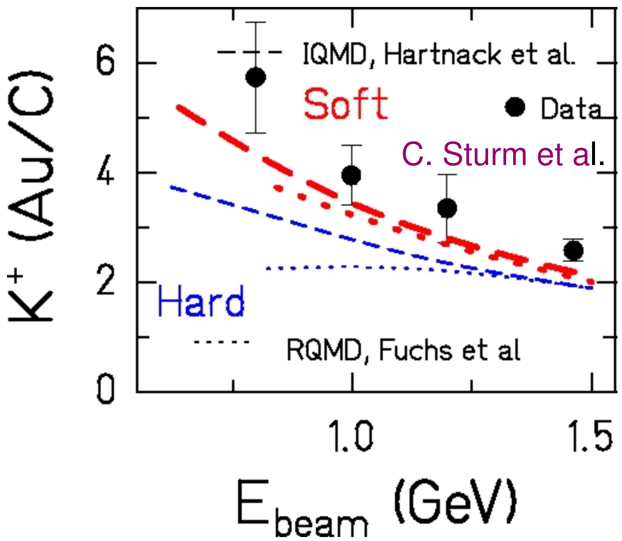
Strange Resonances
- Excited hyperon $\Sigma^*(1385)$
- Mesons $K^*(895)$, ϕ (1020)
- Thermalisation?

Summary/Conclusions



Dynamics of heavy ion collisions at SIS energies 0.1-2AGeV





Characteristics:

- T<100 MeV, 2-3 ρ_0

In medium

- EOS, $\sigma_{NN,medium}$
- Pauli blocking
- Fermi motion
- Δ – lifetime in medium
- Collisional broadening of resonances

Observables:

Collective flow, stopping

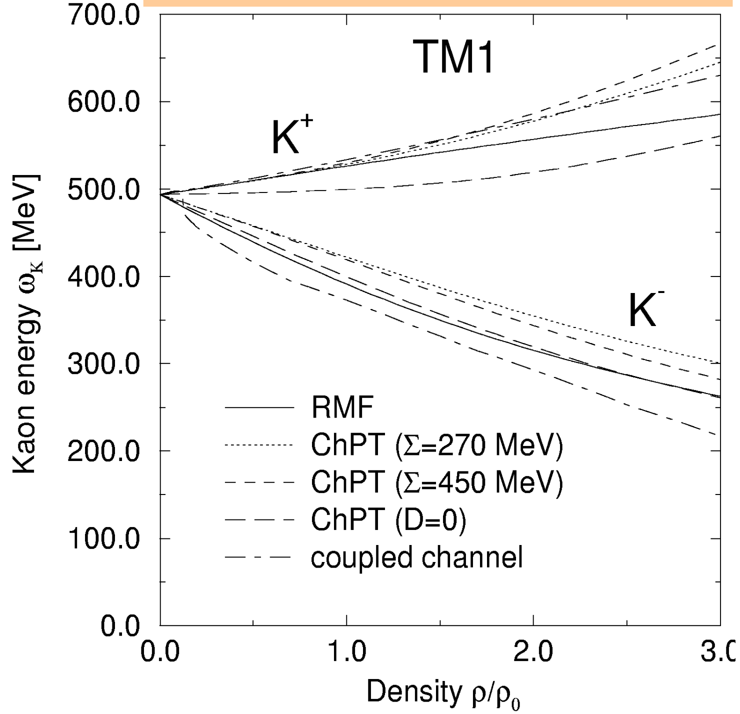
Produced particles and fragment yields

to extract

T and ρ or **NN interaction in medium**

Kaons in dense nuclear medium

in-medium kaon energy



$$\omega_{K^\pm}(p,\rho) = \left(m^{*2}+p^2\right)^{\frac{1}{2}} = U + \left(m_K^2+p^2\right)^{\frac{1}{2}}$$

effective mass **Kaon potential**

Production:

P ~ exp (-m*/T)

→ yields

Propagation:

F=-∇ U

→ K-flow

Bound states:

B= Σm* - Σm

e.g. (ppK-)

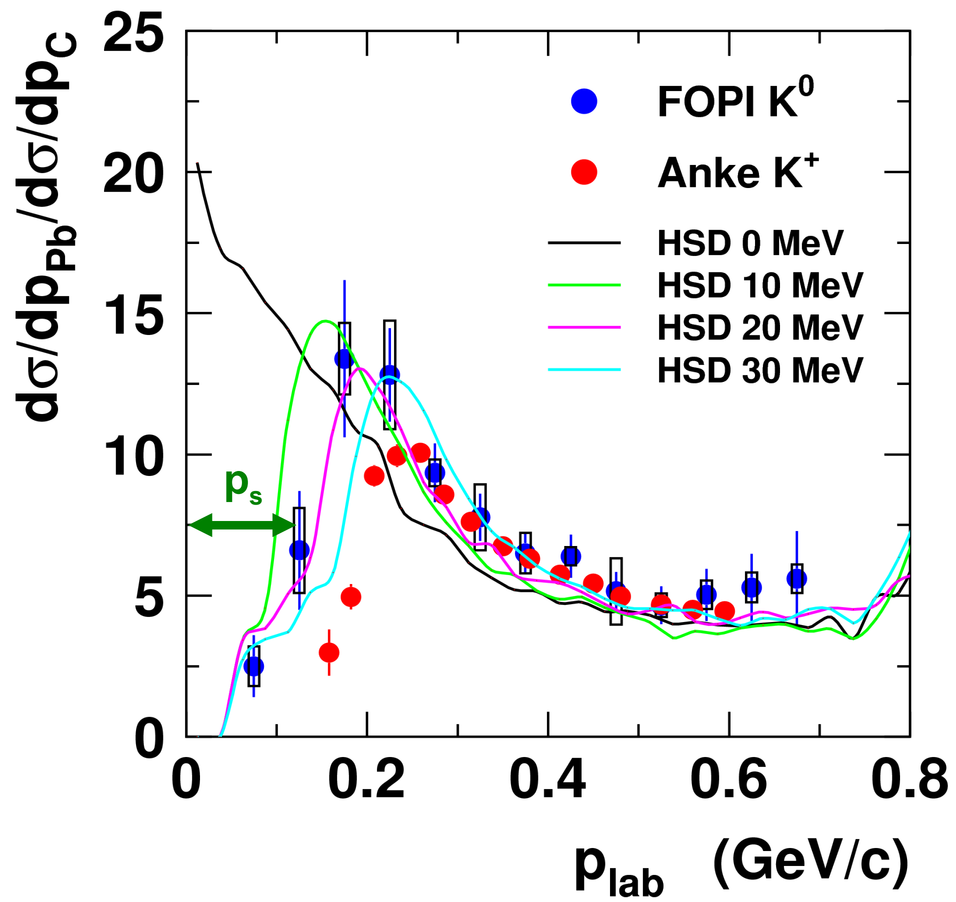
→ Search for Λ+X states

Modified properties of hadrons in dense baryonic matter?

M*(ρ)	**(mass)**
Γ* (ρ)	**(width)**
σ * (ρ)	**(cross section)**

In-medium KN potential

Ratio of momentum distributions:



FOPI data @ SIS
M.L. Benabderramahne et al., *PRL* (2009)
π + 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:
$U(K^0)$ = + 20 MeV

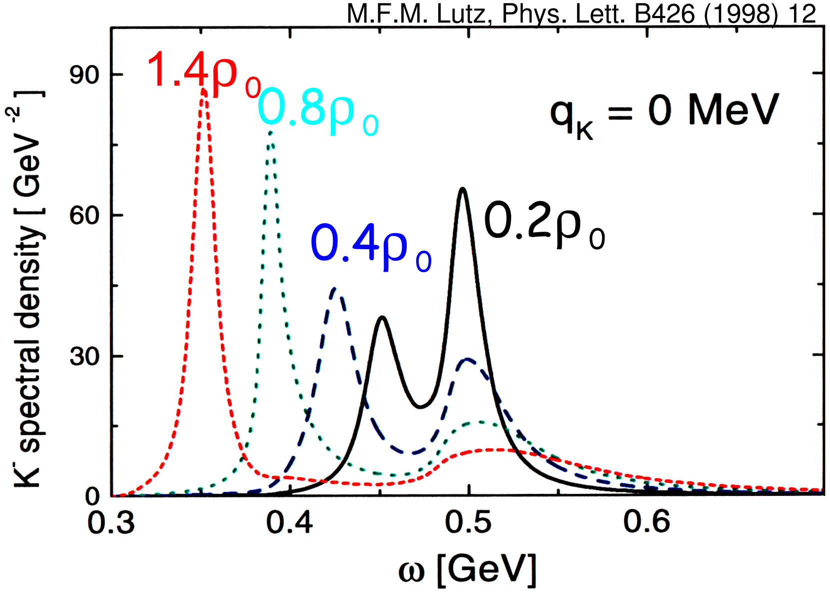
Model independent interpretation:

$$U_K = \frac{p_s^2}{2m_K} = \frac{(140\,\mathrm{MeV})^2}{2\cdot 498\,\mathrm{MeV}} = 20\,\mathrm{MeV}$$

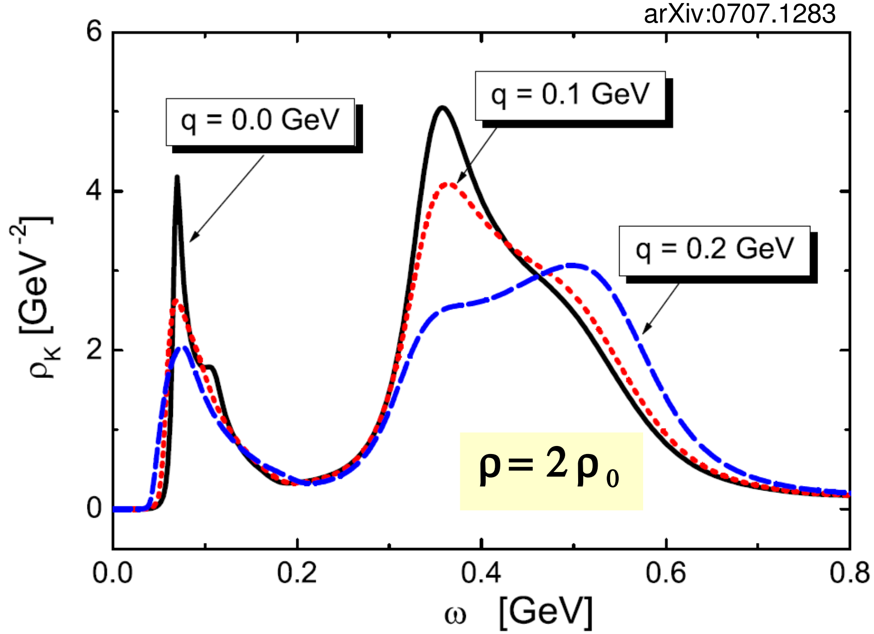
Potential depth: $U(K^0)$ = + 20 (+/- 5) MeV consistent with heavy ion data
Accuracy (only) statistics limited,
Method applicable to determine isospin dependence of KN – potential (e.g. π^- + ^{X}Sn)

Kaons in dense matter
Spectral function of Anti-Kaons

Coupled channel calculation
M.F.M. Lutz, Phys. Lett. B426 (1998) 12



M.F.M. Lutz et al., Nucl.Phys.A808,124 (2008), arXiv:0707.1283



K⁻N interaction

Resonances (Λ(1405)) close to the K⁻N threshold
Non perturbative problem
Chiral SU(3) effective field theories
Coupled channels

Conclusion: K⁻N interaction is attractive but strength unclear

The FOPI detector

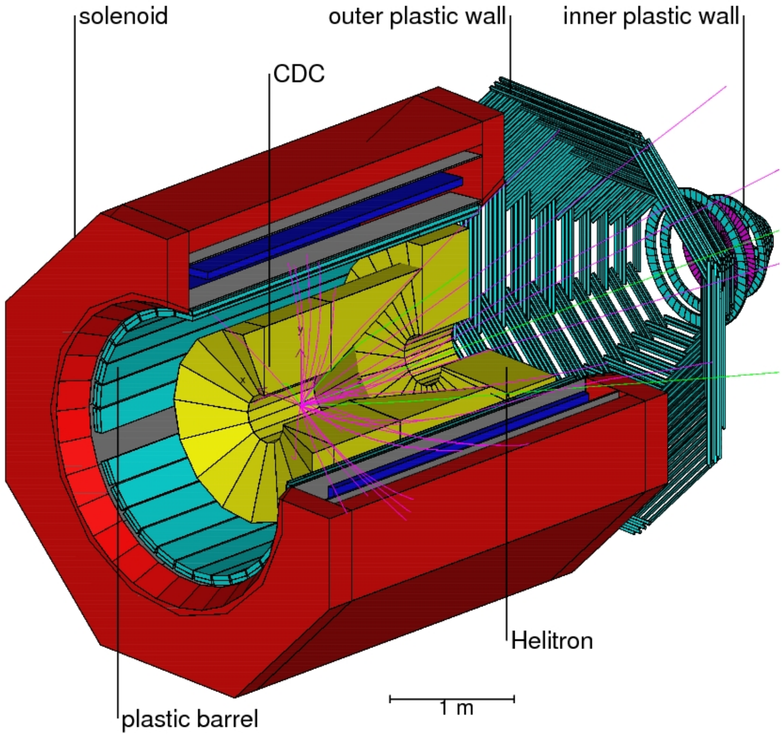
Program:

Dynamics of Heavy Ion Collisions

- **Stopping, collective flow, cluster production**
- **Ca+Ca → Au+Au 0.1-2.0 AGeV**

Strangeness production

- **HI collision (Al+Al, Ni+Ni, Ru+Ru, Ni+Pb)**
- **Pion induced reactions**
- **Proton-proton collisions**



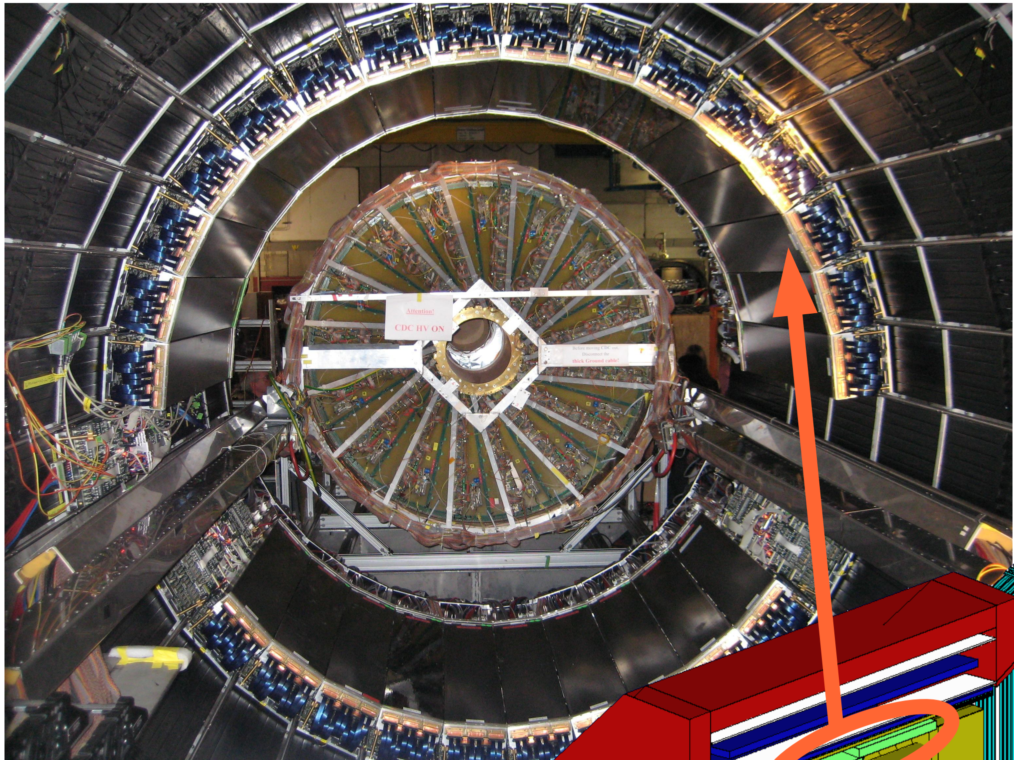
FOPI-Collaboration

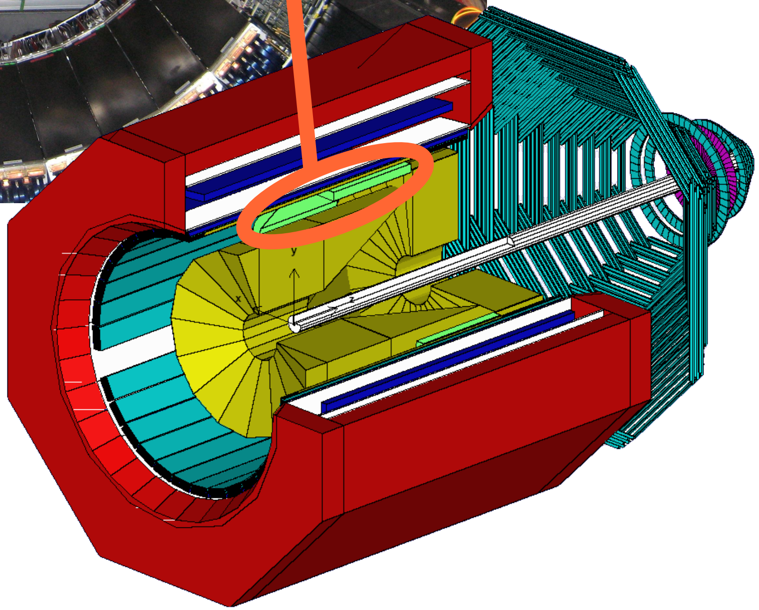
A. Andronic, R. Averbeck, Z. Basrak, N. Bastid, M.L. Benabderramahne, M. Berger, P. Bühler, R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, J. Frühauf, F. Fu, P. Gasik, O. Hartmann, N. Herrmann, K.D. Hildenbrand, B. Hong, T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis, M. Kirejczyk, R. Münzer, P. Koczon, M. Korolija, R. Kotte, A. Lebedev, K.S. Lee, Y. Leifels, P. Loizeau, X. Lopez, M. Marquardt, J. Marton, M. Merschmeyer, M. Petrovici, K. Piasecki, F. Rami, V. Ramillien, A. Reischl, W. Reisdorf, M.S. Ryu, A. Schüttauf, Z. Seres, B. Sikora, K.S. Sim, V. Simion, K. Siwek-Wilczynska, K. Suzuki, Z. Tyminski, J. Weinert, K. Wisniewski, Z. Xiao, H.S. Xu, J.T. Yang, I. Yushmanov, A. Zhilin, Y. Zhang, J. Zmeskal

IPNE Bucharest, Romania
CRIP/KFKI Budapest, Hungary
LPC Clermont-Ferrand, France
GSI Darmstadt, Germany
FZ Rossendorf, Germany
Univ. of Warsaw, Poland
IMP Lanzhou, China
TUM, Munich, Germany
+ P. Kienle (TUM), T.Yamazaki(RIKEN)

ITEP Moscow, Russia
Kurchatov Institute Moscow, Russia
Korea University, Seoul, Korea
IReS Strasbourg, France
Univ. of Heidelberg, Germany
RBI Zagreb, Croatia
SMI Vienna, Austria

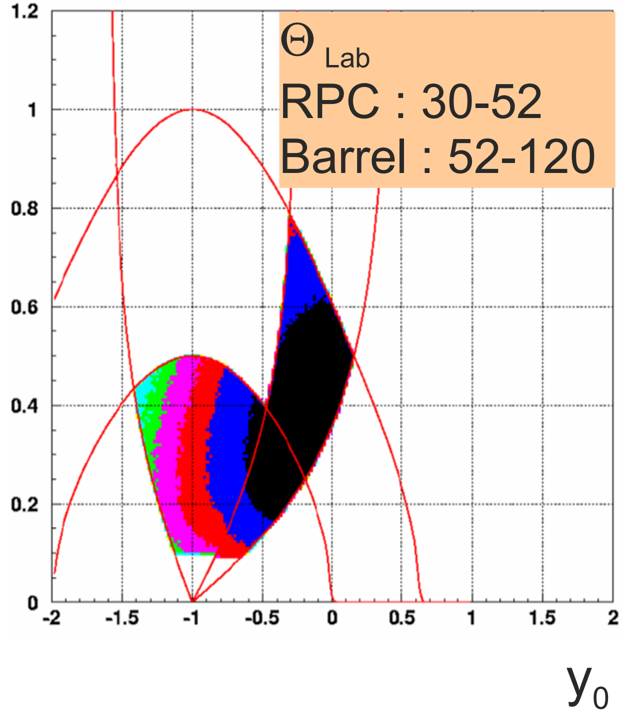
FOPI phase 3 (2008-2010) with improved Kaon PID

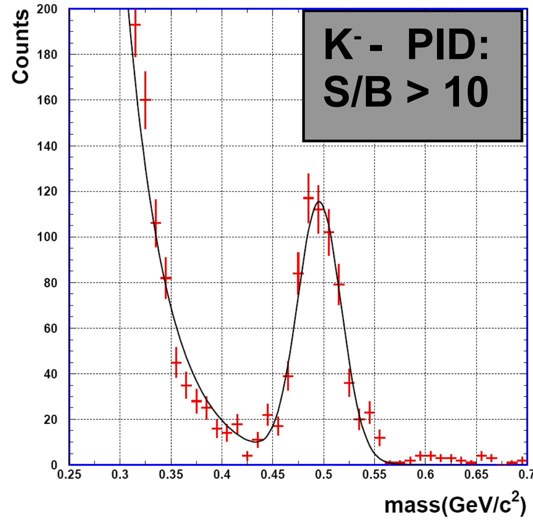




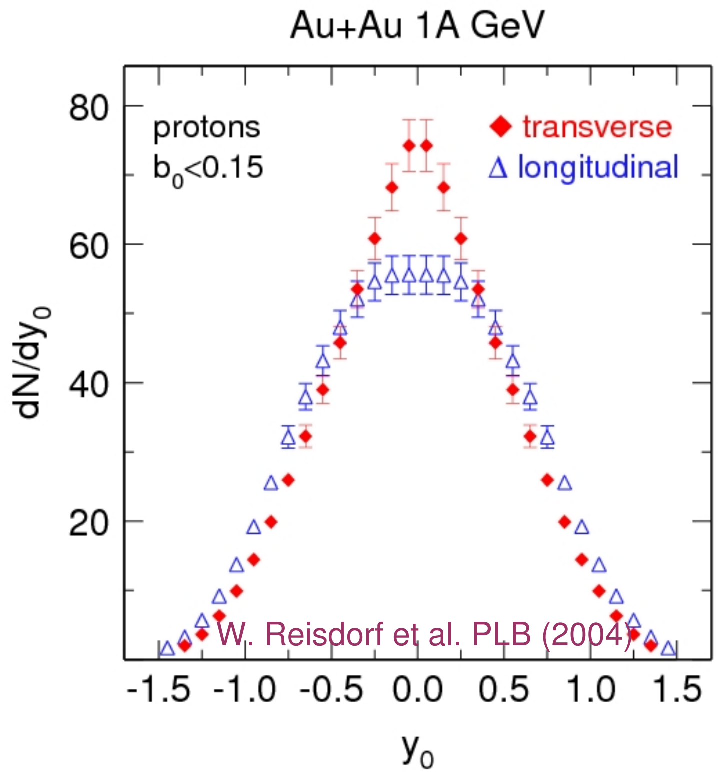
RPC Tof barrel

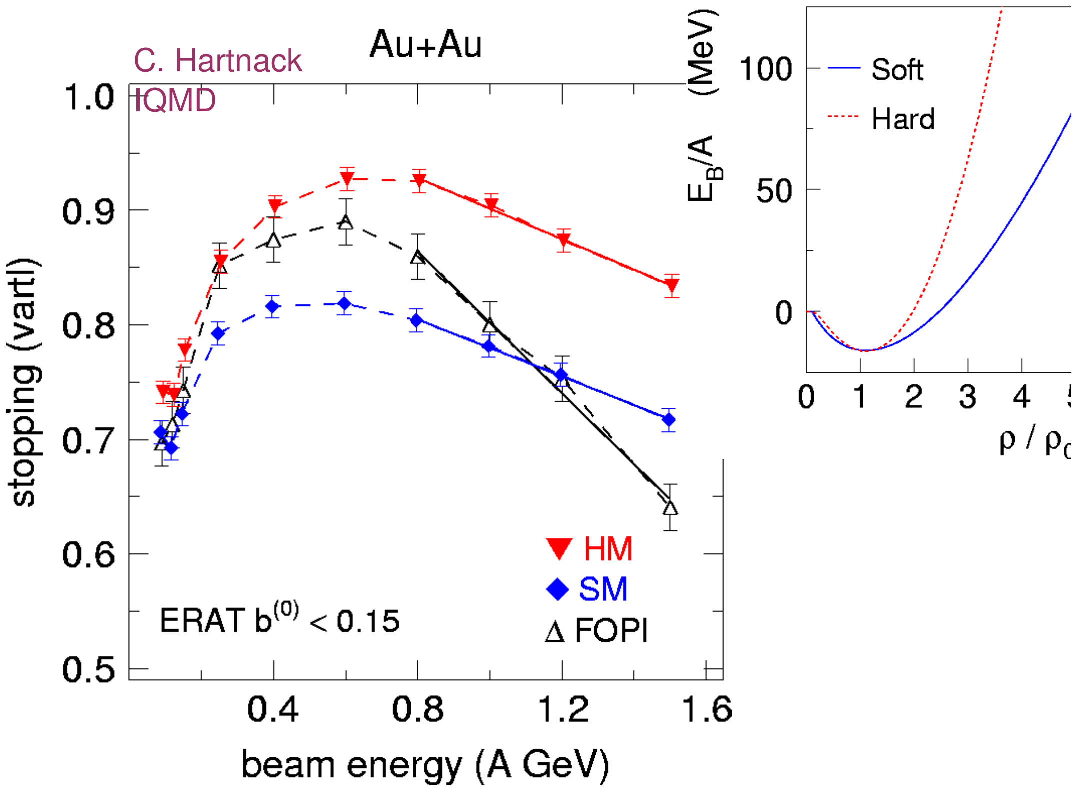
area:	6 m^2
channels:	4500
$\sigma_{tof,sys}$:	~90 ps
$\sigma_{tof,RPC}$:	~65 ps





Dynamics of heavy ion reactions in the SIS energy range



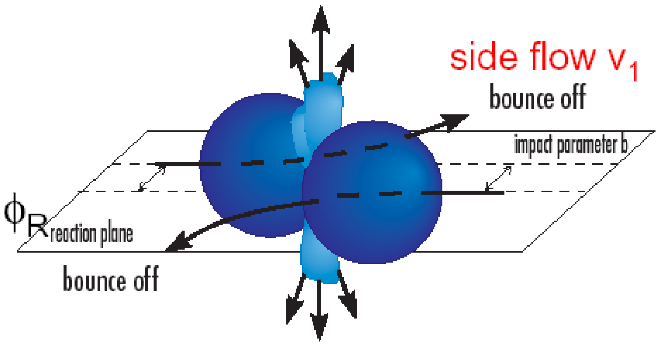


Stopping observable:

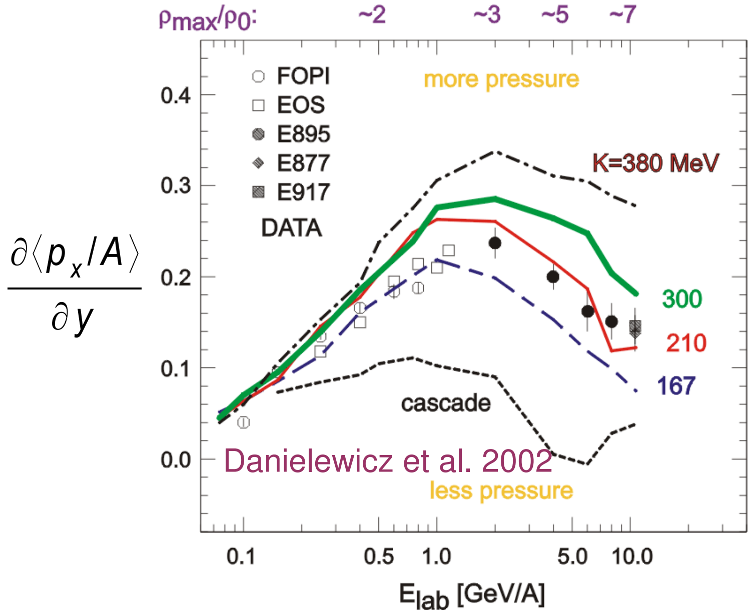
$$\mathrm{vartl} = \frac{\sigma(y_{t0})}{\sigma(y_{l0})}$$

- vartl relates transverse and longitudinal expansion
- Stopping decreases with energy and system size
- vartl is sensitive to EOS AND $\sigma_{NN,med}$
- Other observables constrain $\sigma_{NN,med}$

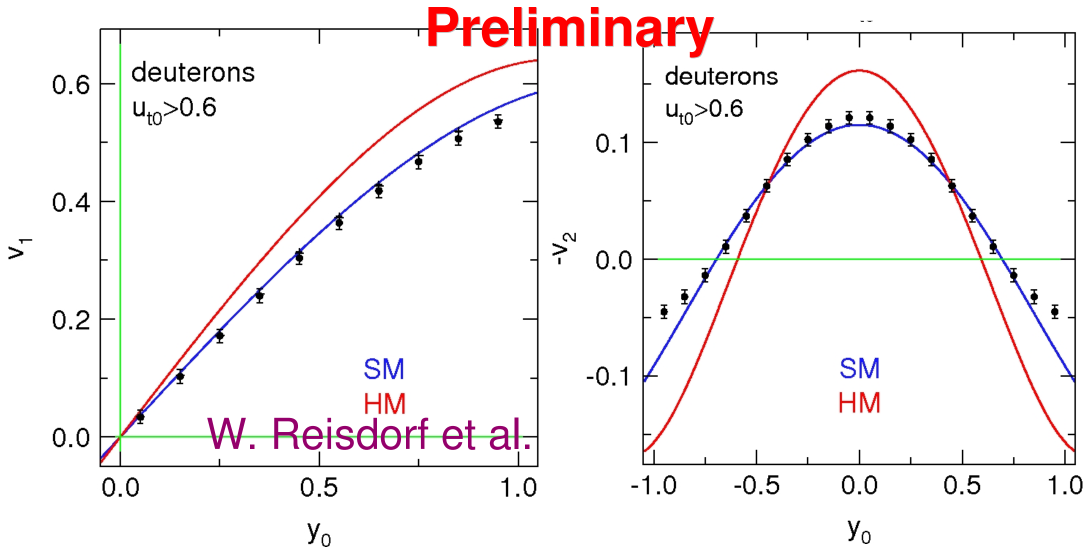
Collective flow



Au + Au



Au + Au 400 AMeV 0.25 < b_0 < 0.45



If the data is correct and the model is correct → soft EOS confirmed

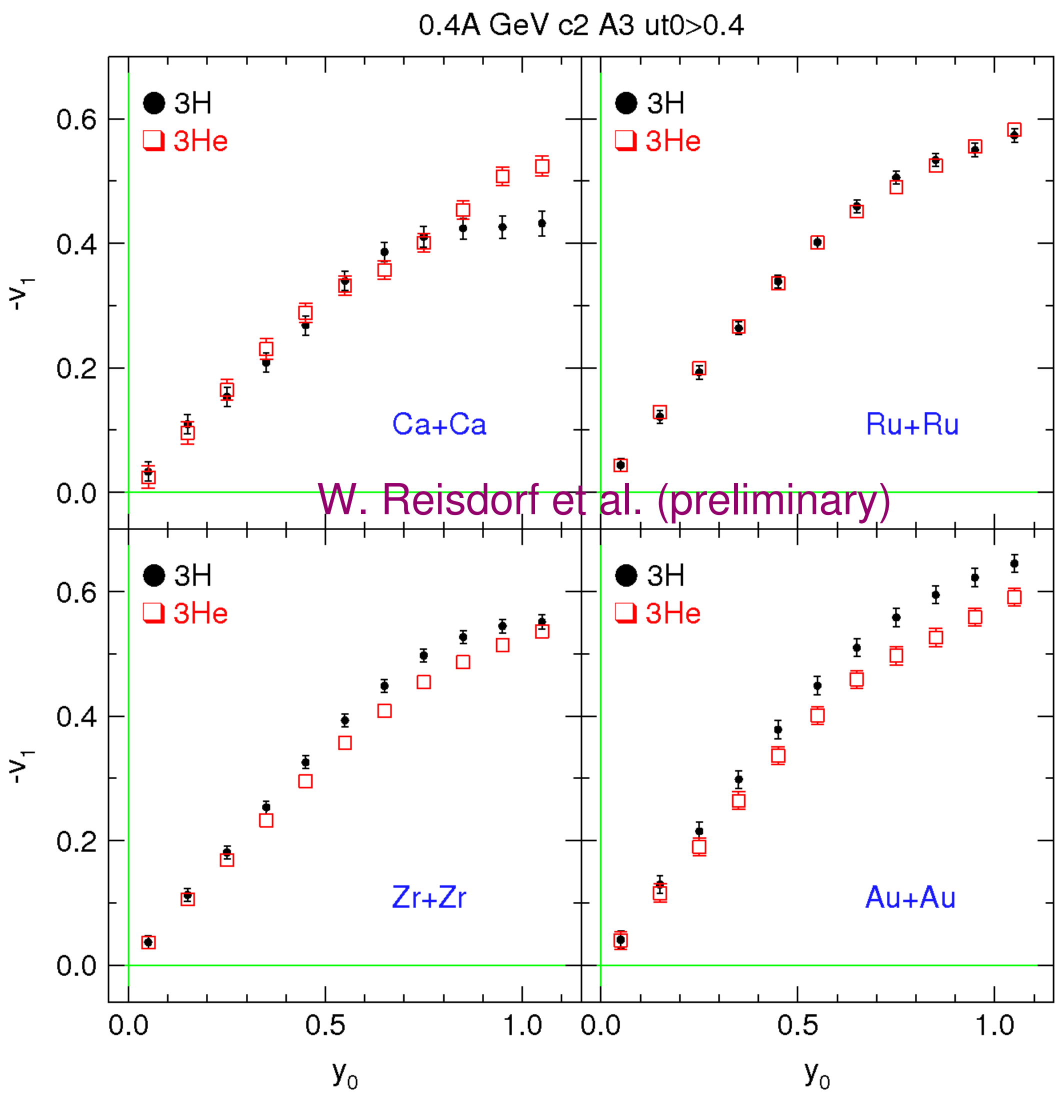
BUT:

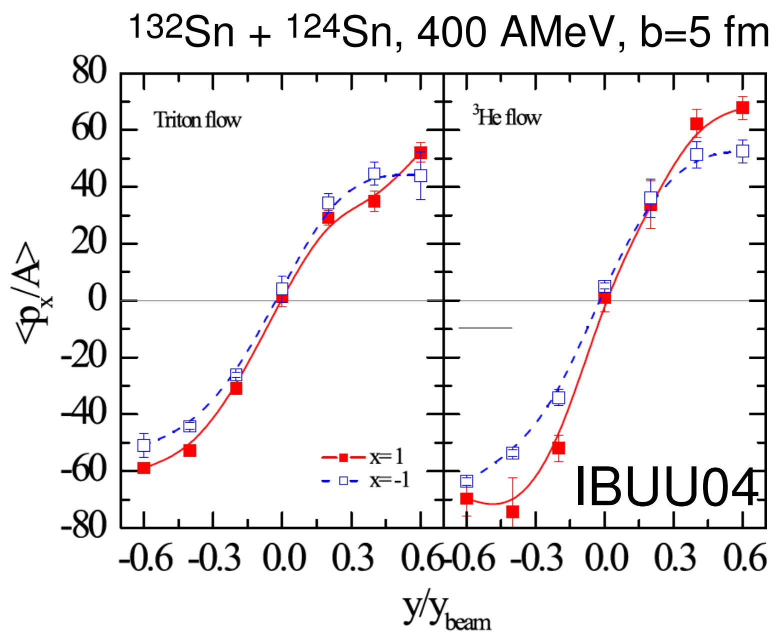
Stopping not described accordingly

Data available for Ca+Ca → Au+Au

5 particles (p, d, **t**, ^{3}**He**, ^{4}He)

t vs 3He flow
Constraining the ASY-EOS at $\rho > \rho_0$?



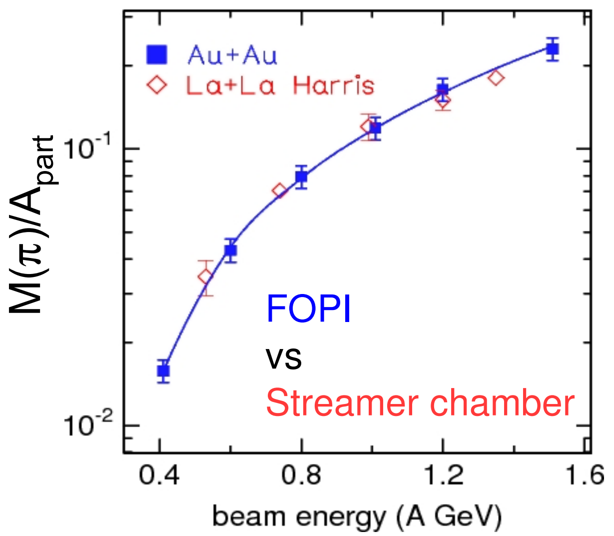


Gao-Chan Yong et al., nucl-the:0906.0939

Larger difference between t and 3He for systems with larger N/Z

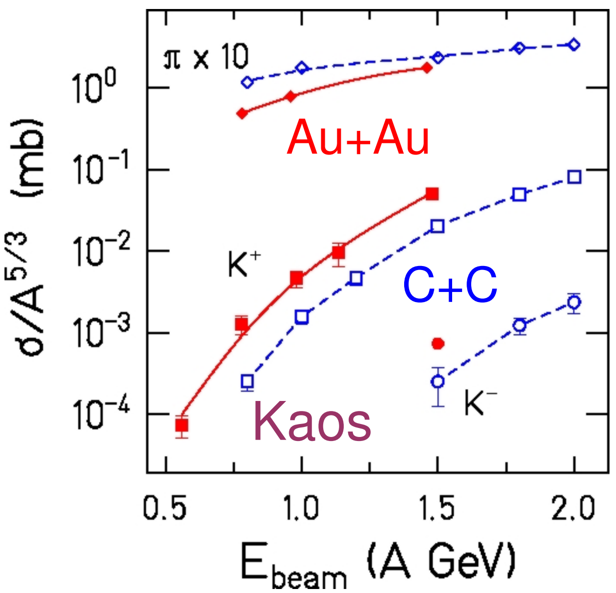
Particle production at SIS energies

Pions and Deltas



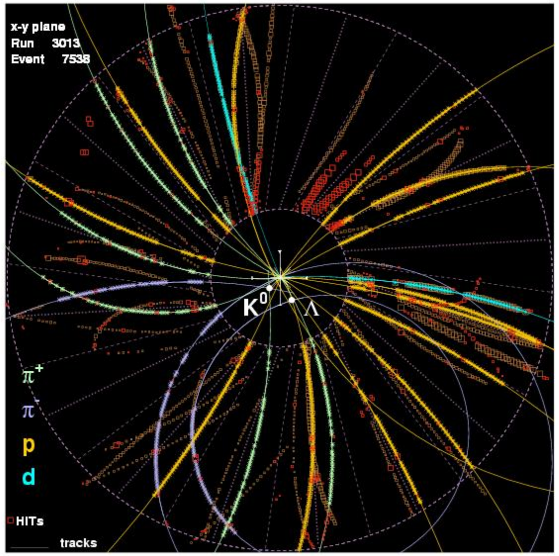
Pions most abundant
20% E_{avail} at highest energies

Kaons



Kaons are produced sub threshold
K^+: πN, ΔN dominant
K^-: YN important

Other baryons and mesons



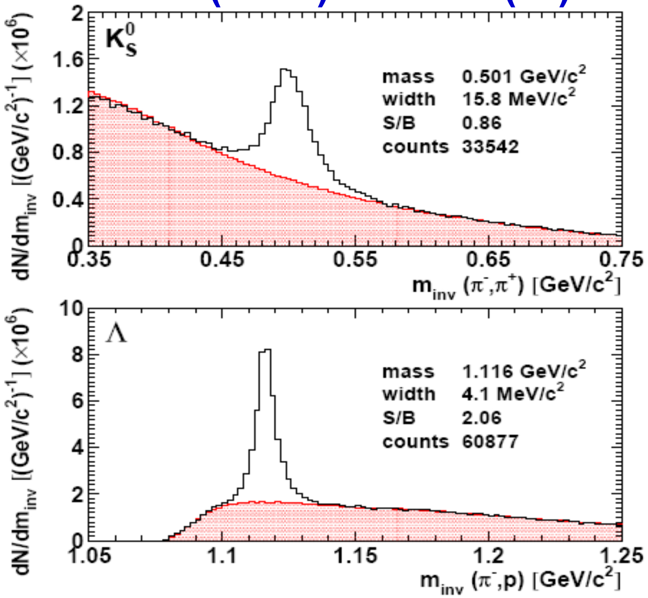
Mesons: K^0, K^{0*}, Φ
Hyperons: Λ, Σ, Σ^*

K^0 and Λ measurements in heavy ion collisions

Reconstruction of secondary vertices

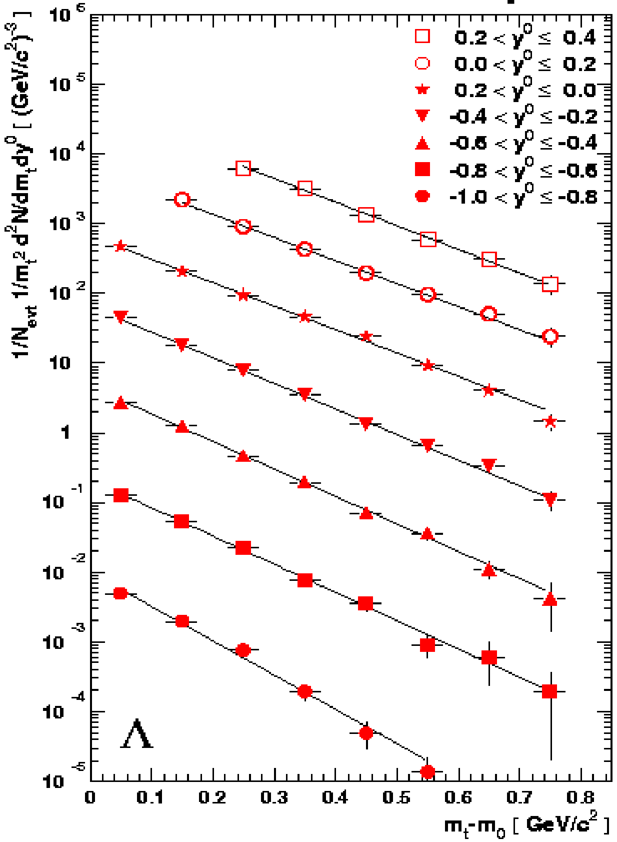
~ 60k (100k) Λ in Ni (Al)

~ 30k (60k) K in Ni (Al)



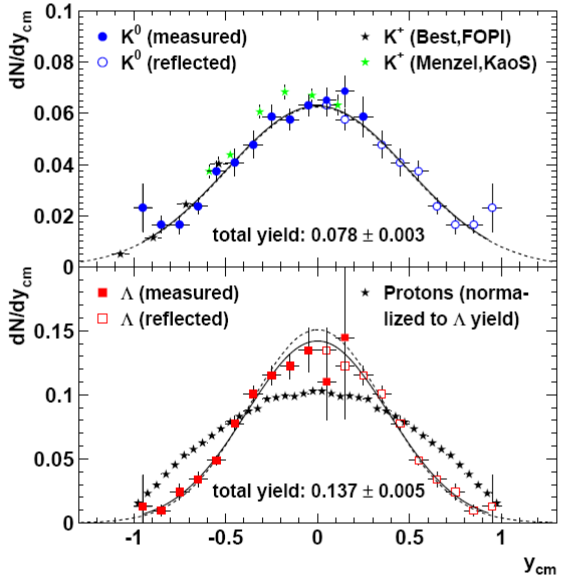
$$P_{det} = P_{prod} \cdot \epsilon \approx 10^{-1} \cdot 10^{-2} = 10^{-3}$$

Transverse mass spectra



M. Merschmeyer et al. (FOPI), PRC 76, 024906 (2007), *nucl-ex/0703036*

Rapidity density distributions



.... T=92 MeV β=0.32

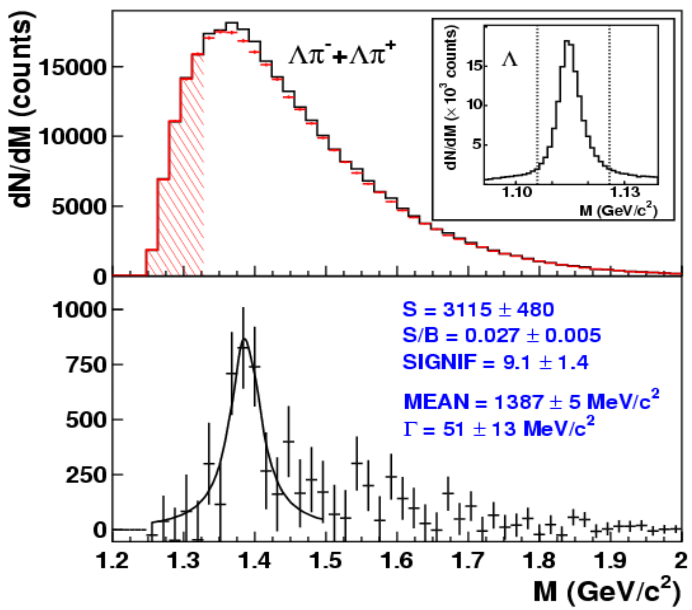
———— T=100 MeV β=0.23

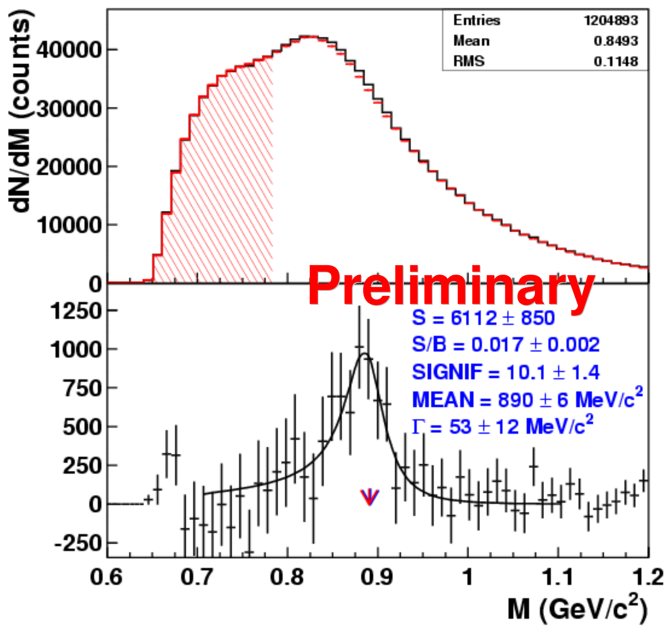
Reconstruction of short lived resonances in Heavy Ion collisions

Σ^*(1385) subthreshold production,
X. Lopez et al. (FOPI), PRC 76, 052203(R) (2007)

$\Sigma^* \rightarrow \Lambda + \pi$ (88 ± 2%)
$\rightarrow p + \pi^- + \pi$
Γ = 39.4 MeV
$c\tau$ = 5 fm
E^{thr}_{NN} = 2.33 GeV

$K^* \rightarrow K + \pi$ (88 ± 2%)
Γ = 50.7 MeV
$c\tau$ = 4 fm
E^{thr}_{NN} = 2.75 GeV





$P_{det} \approx 10^{-5}$

FOPIs reconstruction method and background construction works for wide resonances. Masses and widths consistent with PDG values.

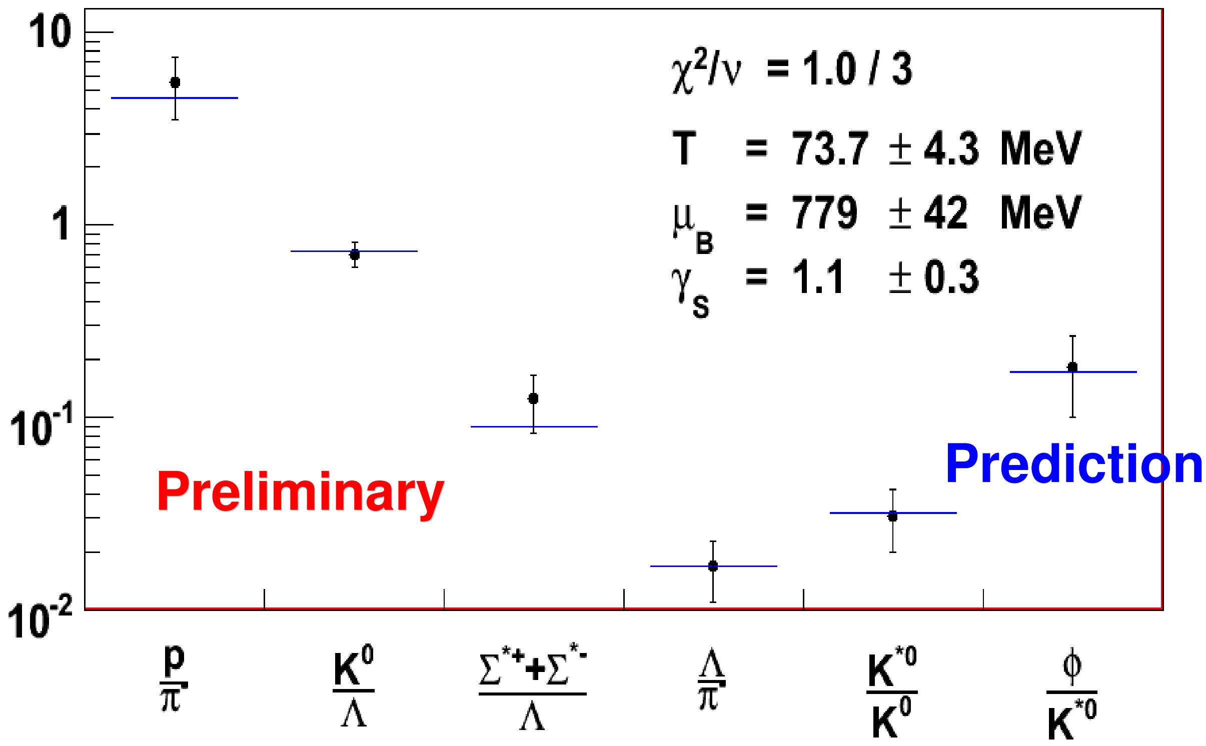
Particle yields at freeze-out

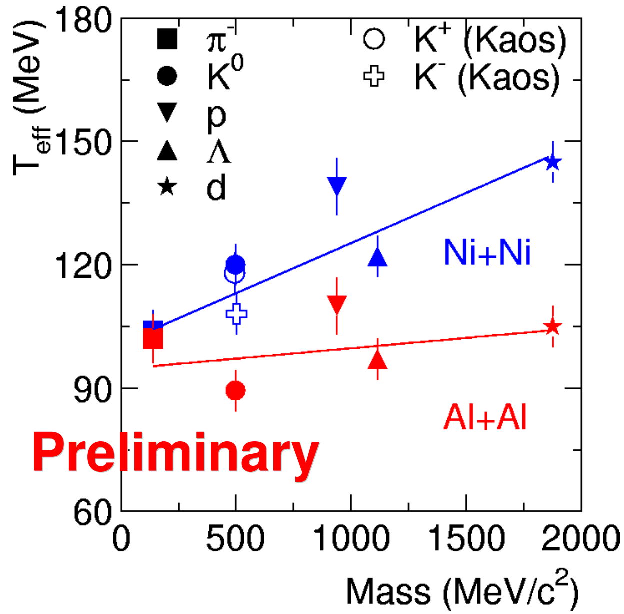
Al+Al 1.9 AGeV

6 independent ratios
with 5 strange particles:
p, π, K^0, K*(892),
(Λ+Σ), Σ*(1382) and Φ

Fit with model Thermus
J. Cleymans et al.
(K. Piasecki)

X. Lopez, M. Merschmeyer, P. Gasik





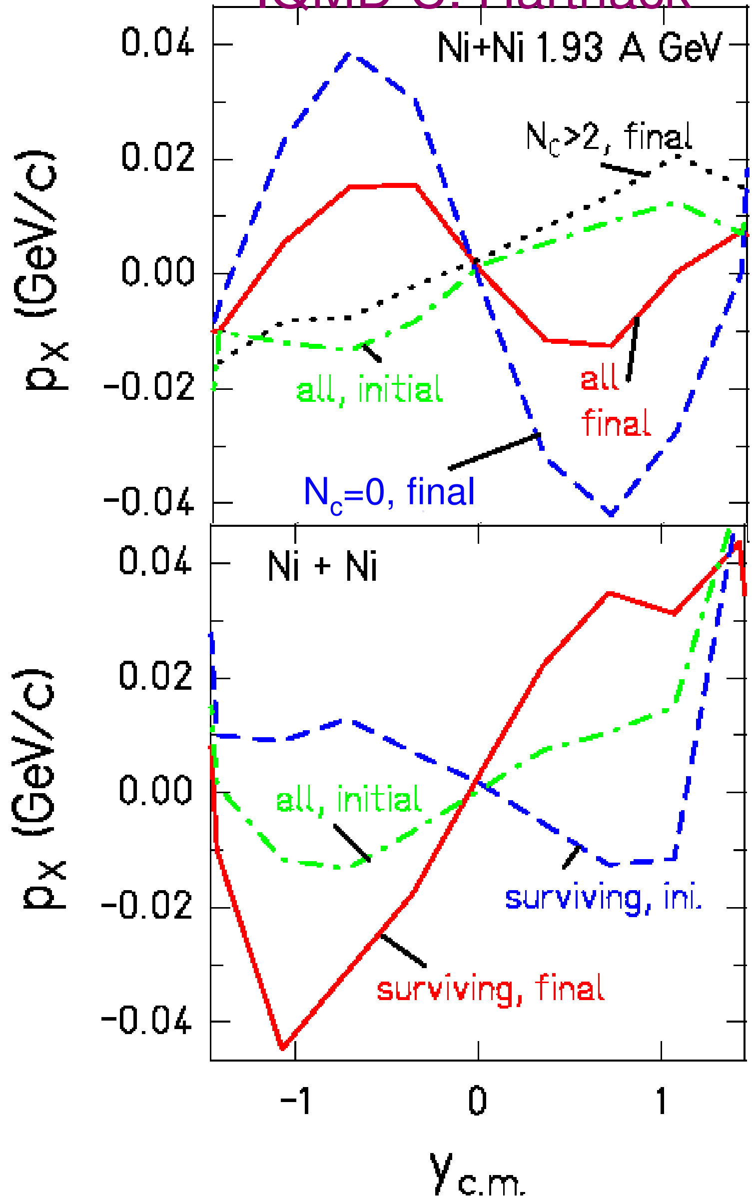
- Rise of inverse slope parameters (T_{eff}) with particle mass → radial flow
- Particles' T_{eff} show deviations from flow scenario
  T_{kin} > 95 MeV > T_{chem} = 75 MeV
- Effective way to parametrize yield ratios

Directed Kaon flow and the in-medium KN potentials

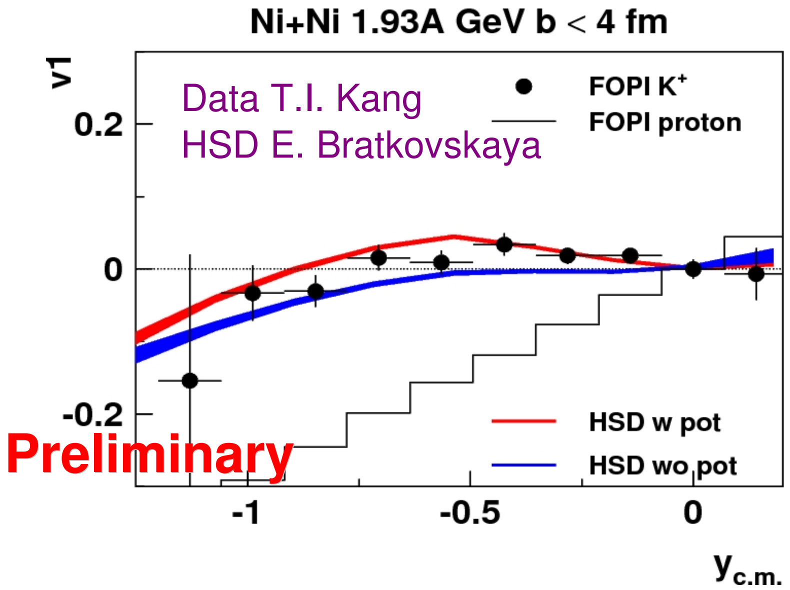
- At production same flow for K^+ and K^-
- K^+ opposite to nucleon flow
  - potential
  - rescattering tends to align to nucleons

- K^- flow similar to nucleon flow
  - absorption
  - strong potential effect

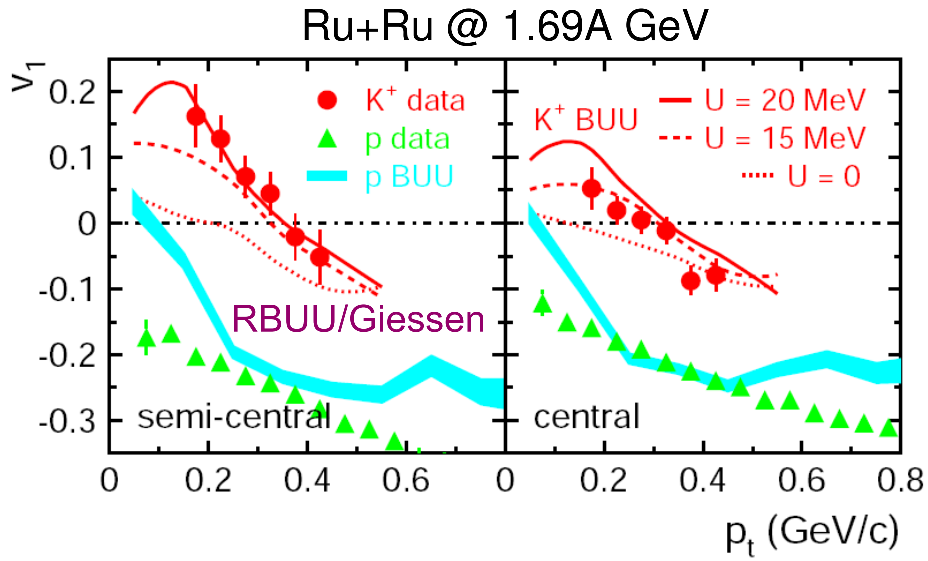
IQMD C. Hartnack



Directed flow of K+ in N+Ni collisions at 1.9 AGeV



P. Crochet et al. (1998)



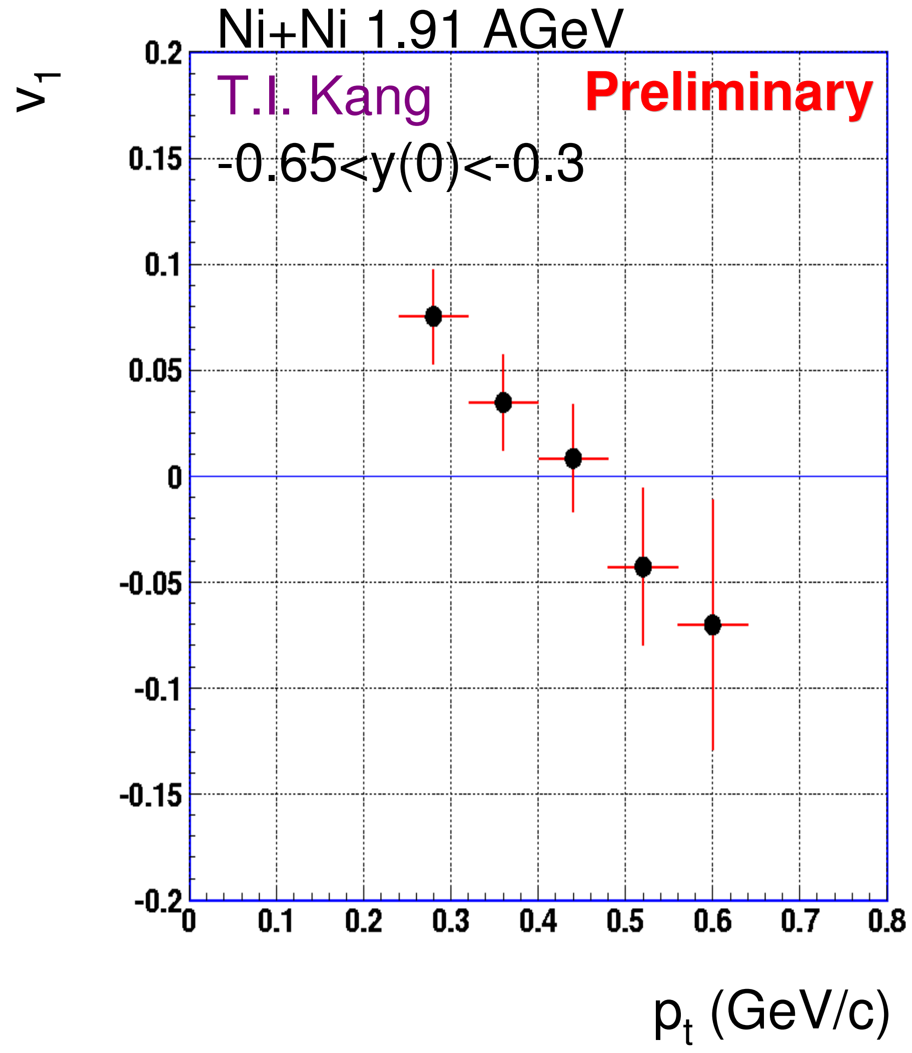
$v_1(y)$

- p_t integrated kaon flow small
- small sensitivity to potentials

$v_1(p_t)$

- strong p_t dependence
- sensitive to KN potential
- U = + 20 MeV
- not described by all models

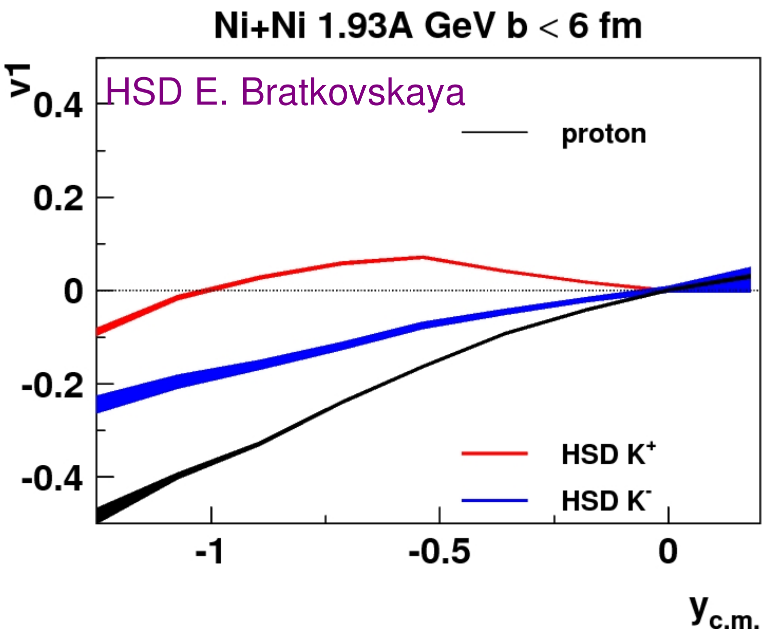
Transverse momentum dependence of directed flow of Kaons

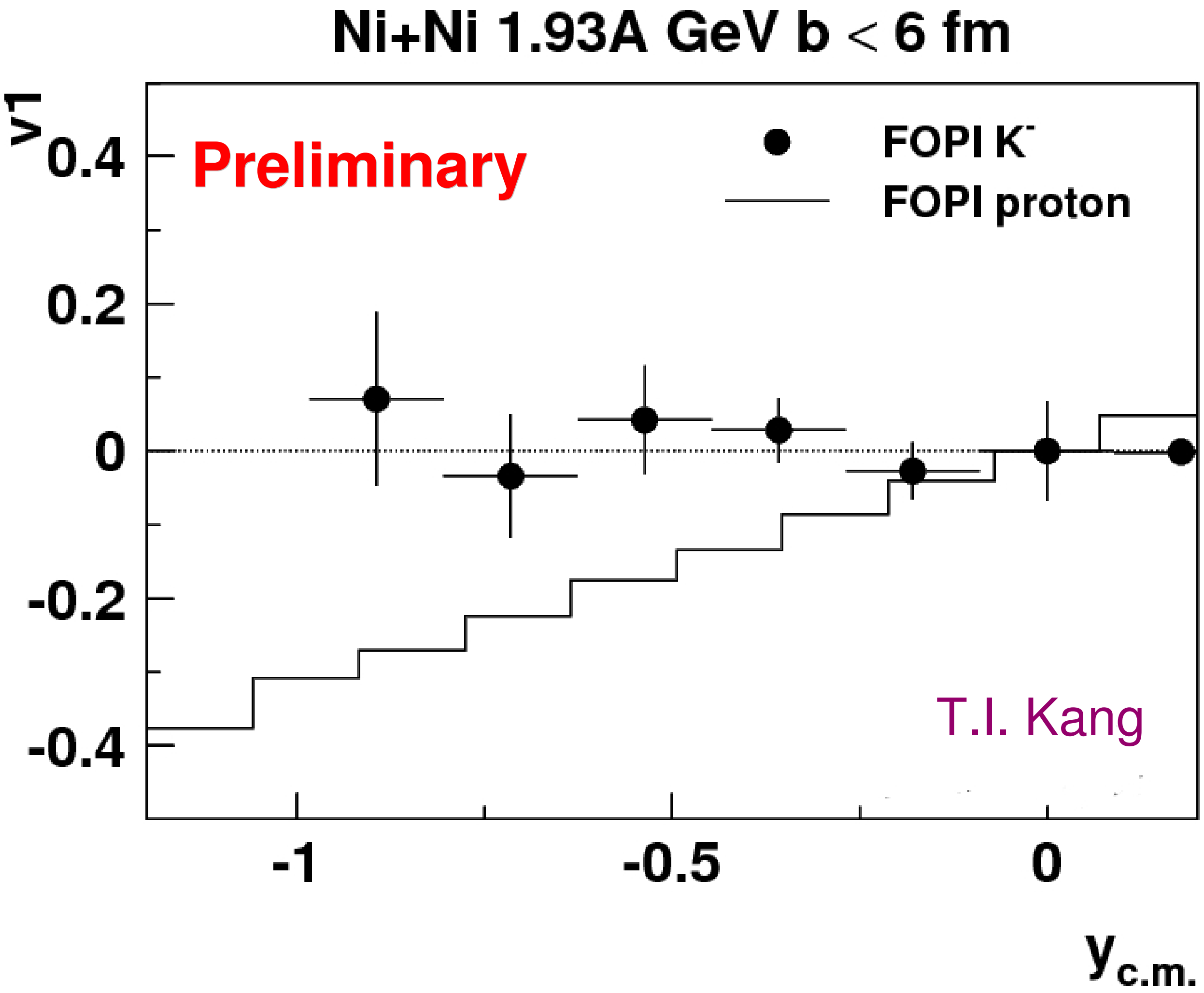


- FOPI remeasured Ni+Ni @ 1.91 AGeV with new TOF barrel
- new data show similar p_t dependence

Directed flow of Anti-Kaons

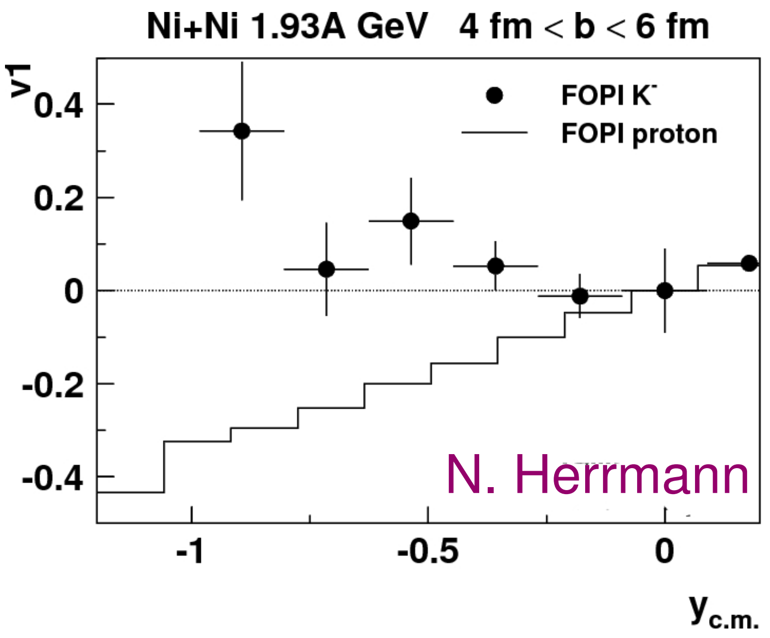
Theoretical predictions:



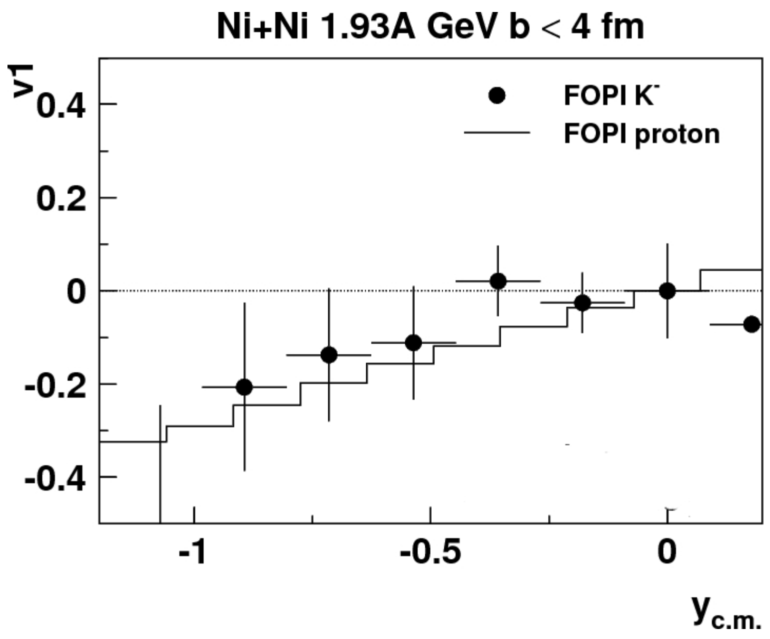


K- directed flow - Centrality dependence?

peripheral



central



Preliminary

Very strong centrality dependence of directed sideflow of K^-?

Conclusions

Properties of baryonic matter and dynamics of heavy ion collisions

learned a lot during recent years

in high precision, high statistics experiments at GSI/SIS18

and

coherent theoretical effort

pars pro toto: Nantes, Giessen, Frankfurt, Munich, Tübingen, MSU, Catania

But there are still unsolved problems:

a consistent description of stopping and directed flow, cluster production

kaon flow, role of short lived strange resonances

Need more data on strangeness

Depth of the K^-N potential important

Deep potential (~ 100MeV) may give rise to exotic states, kaonic clusters (ppK^-)

Current experimental campaign of FOPI aims on the K^-N potential

system size dependence of kaon flow

search for kaonic clusters in pp collisions

Φ production in π induced reactions

Still a lot of interesting physics at SIS18!