Global dynamics and strangeness production in HI collisions @ 1-2A GeV with FOPI

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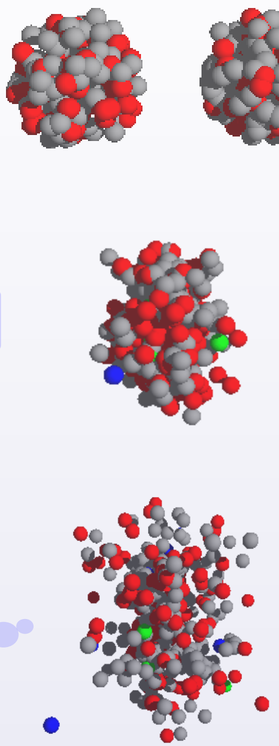
- Global dynamics of HI collisions:
  - *Stopping, Flow, Yield ratios, Phase diagram*
- Strangeness production
  - *In-medium modifications of* $K^{+,-,0}$
  - *"Other" sources of* K^{-} *:* $\Sigma(1385)$, ϕ
  - *Neutral strangeness*

Heavy Ion Collisions around E_{beam} = 1-2A GeV

Dynamical picture



$\rho_B \rightarrow 2..3\ \rho_0$

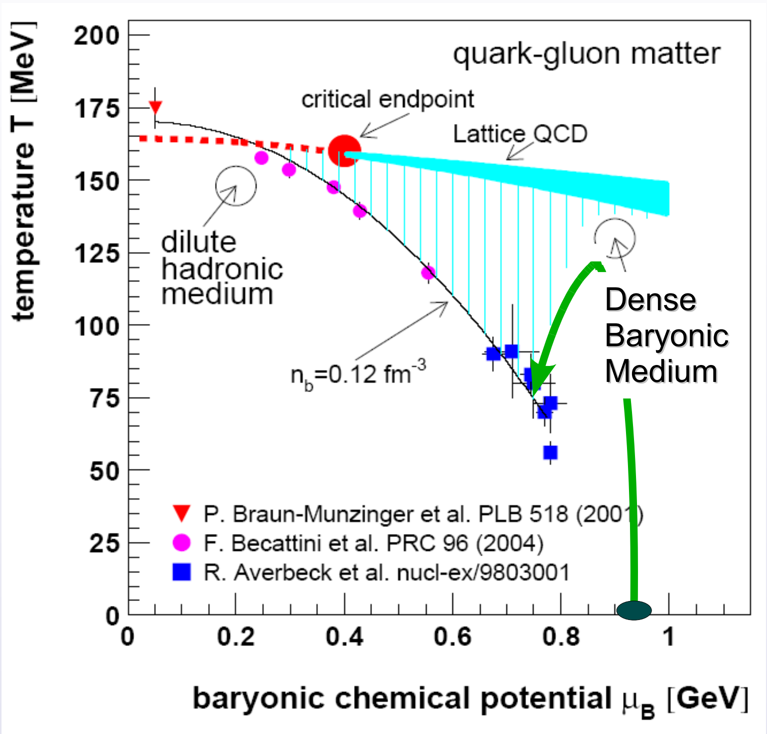
$\pi^{\pm}\ K^{\pm 0}\ \phi$

$\Lambda\ \Sigma^0$

$\Delta\ K^*\ \Sigma^{*\pm}$

$\tau \sim$ 20-30 fm/c

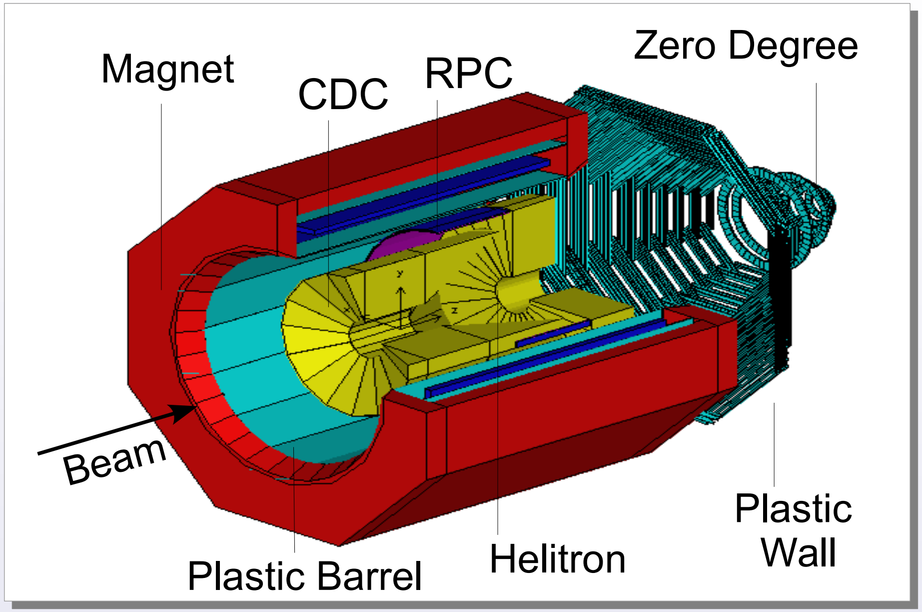
Phase diagram



- $T_{Freeze\ Out}$ = 50..90 MeV

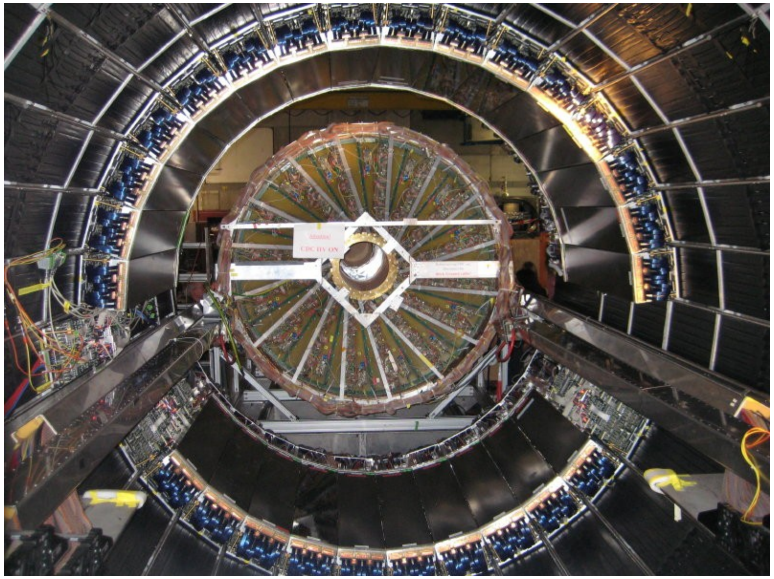
- *Equilibration at freeze-out ?*
- *Dynamical picture vs 2-dim phase diagram?*

FOPI experimental setup

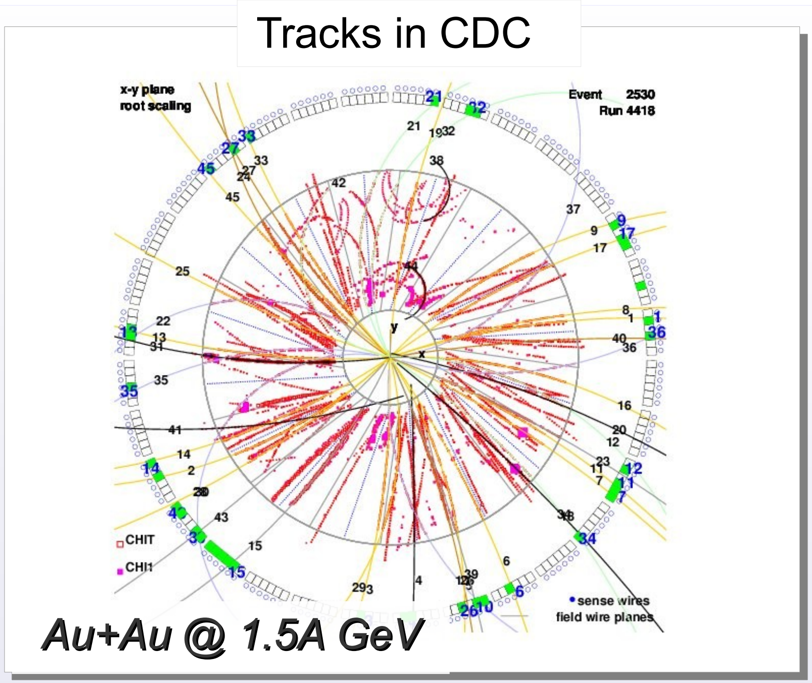


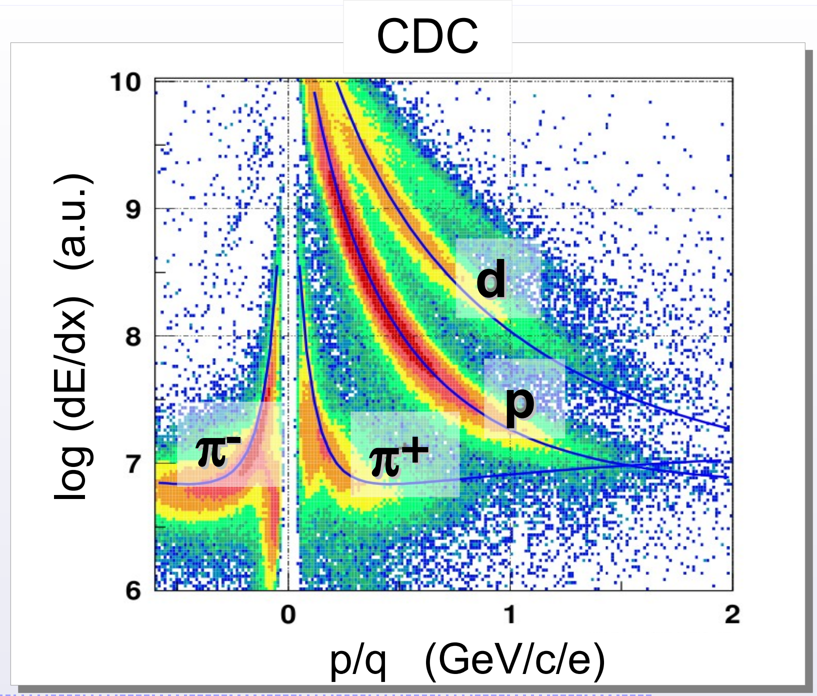
- Nearly 4π coverage
- Drift chambers: CDC, Helitron
  ToF : Plastic Barrel, RPC
  Forward: Plastic Wall, Zero Degree

NIPNE Bucharest, Romania
ITEP Moscow, Russia
CRIP/KFKI Budapest, Hungary
LPC Clermont-Ferrand, France
Korea University, Seoul, Korea
IMP Lanzhou, China
Kurchatov Institute Moscow, Russia
ITEP Moscow, Russia
TUM, Munich, Germany
SMI Vienna, Austria
GSI Darmstadt, Germany
IReS Strasbourg, France
FZ Rossendorf, Germany
Univ. of Heidelberg, Germany
Univ. of Warsaw, Poland
RBI Zagreb, Croatia

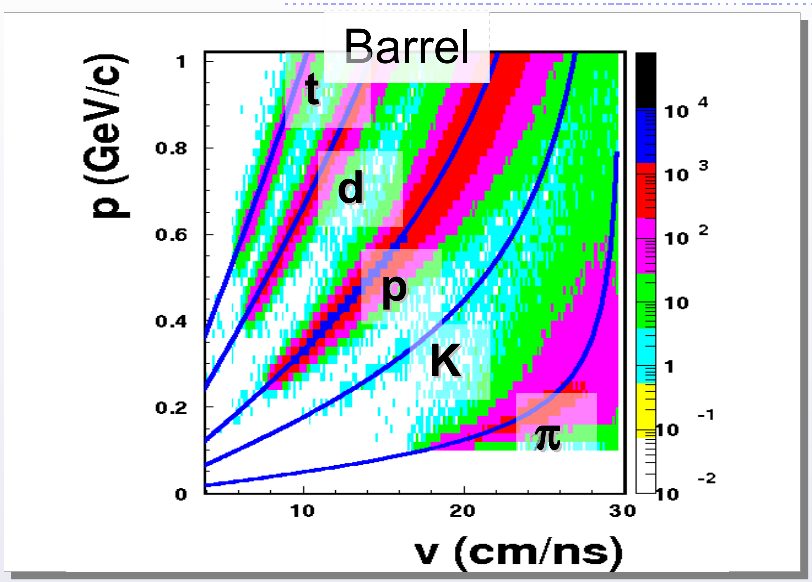


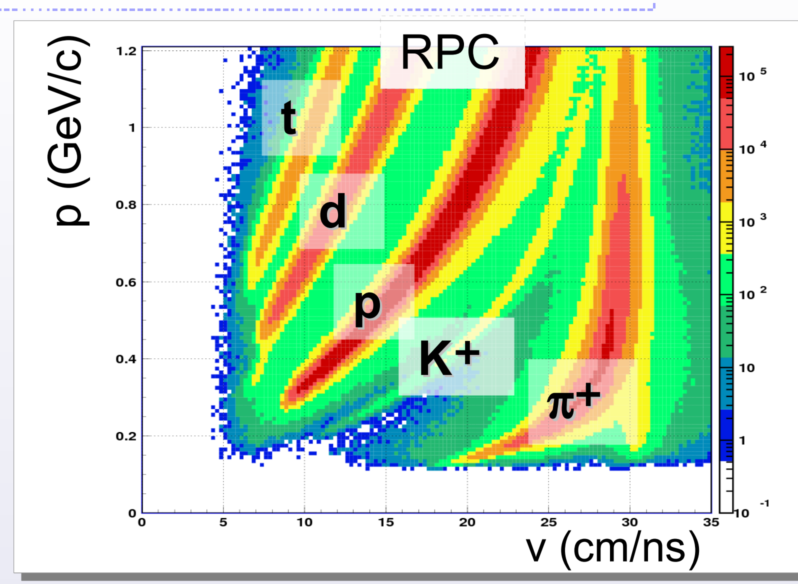
Identificaton of charged particles





Direct identification of $\pi^{\pm}$, $K^{\pm}$, p, d, t, $^{3,4}He$



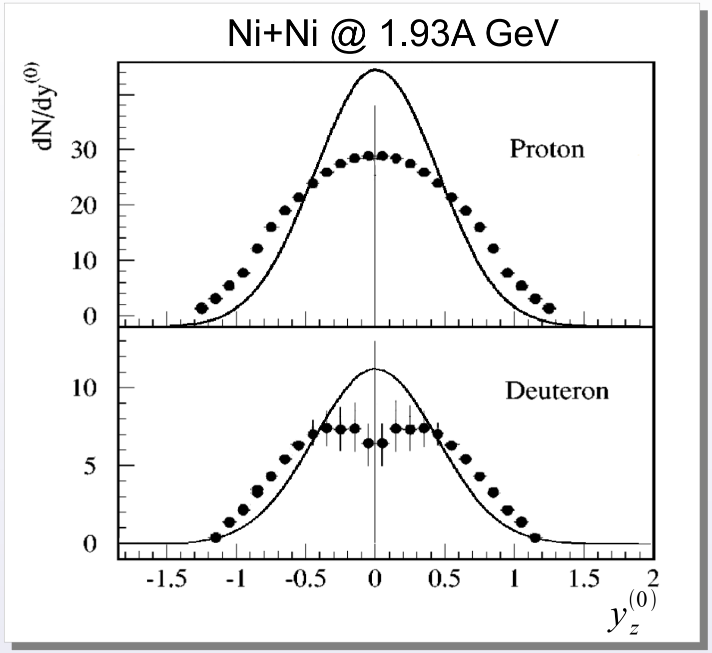


1. Global dynamics

- *Nuclear stopping vs transparency*
- *Directed flow of charged barions*
- *Elliptic flow of charged barions*

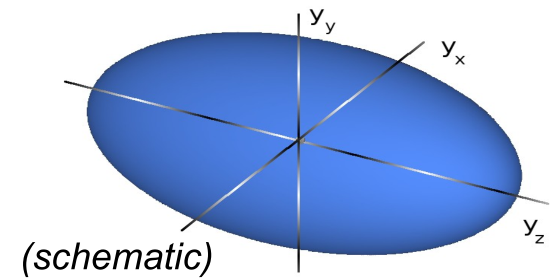
Rapidity distributions

- protons, deuterons



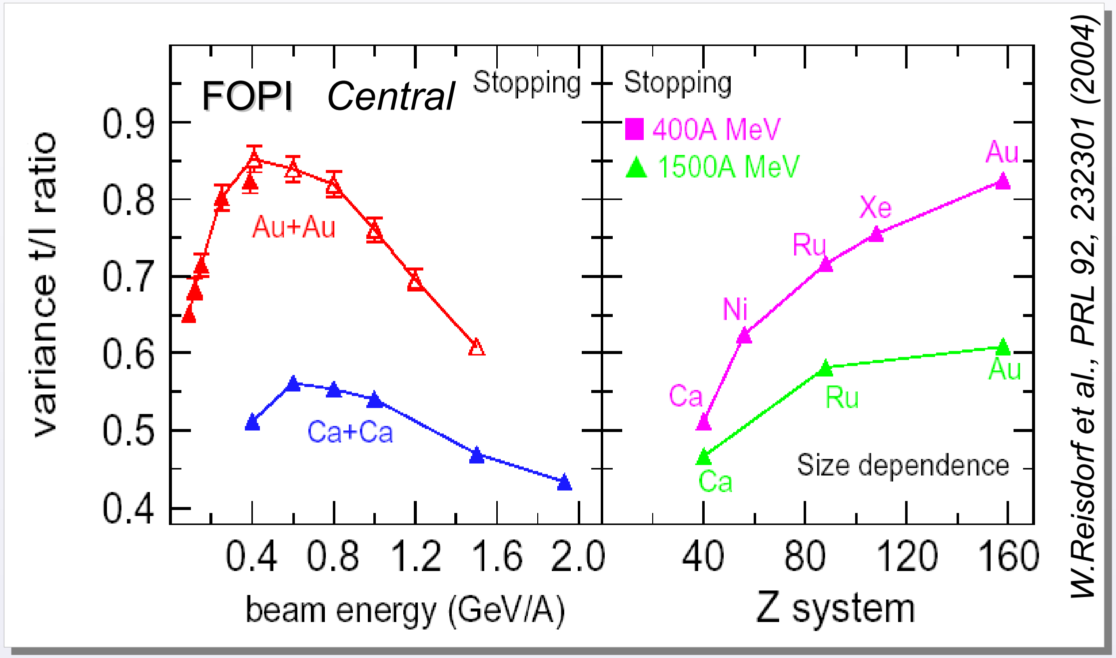
B.Hong et al (FOPI), PRC 57, 244 (1998)

- All charged baryons: p,d,t,^{3,4}He,Li,...



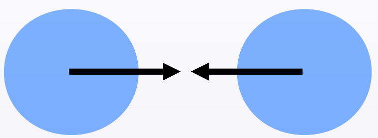
Variance t/l ratio:

$$vartl = \frac{\sigma^2(y_t)}{\sigma^2(y_z)}$$

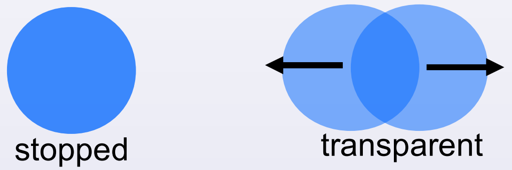


W.Reisdorf et al., PRL 92, 232301 (2004)

Initial state: ***Transparency***



Final state:



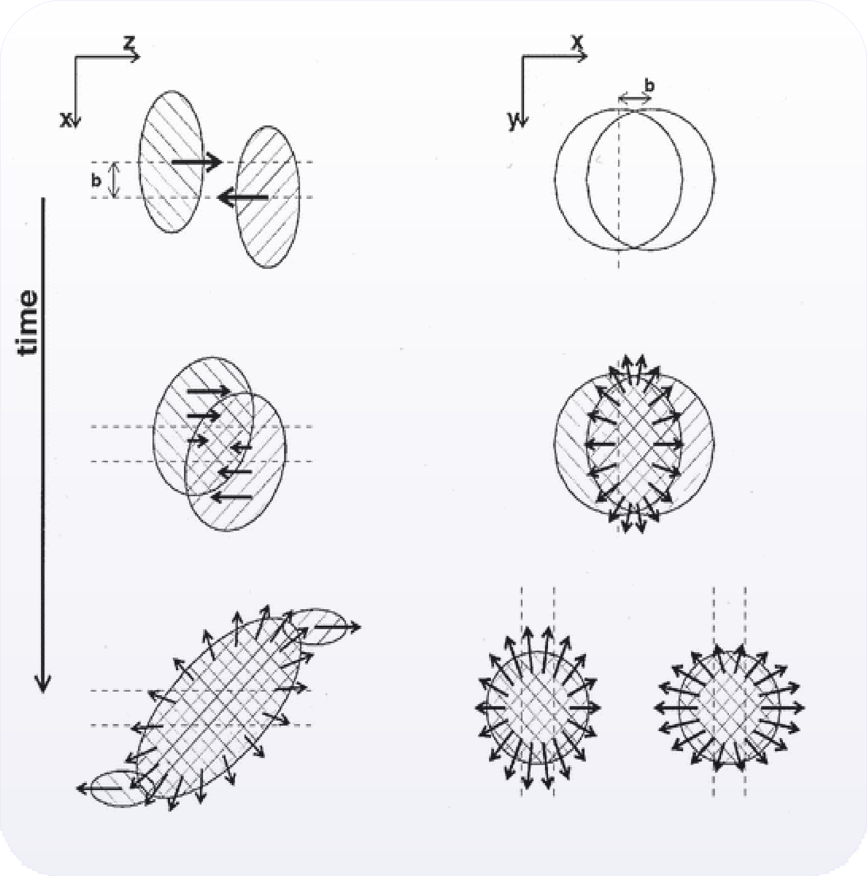
Partial transparency

- ***Reasons:***

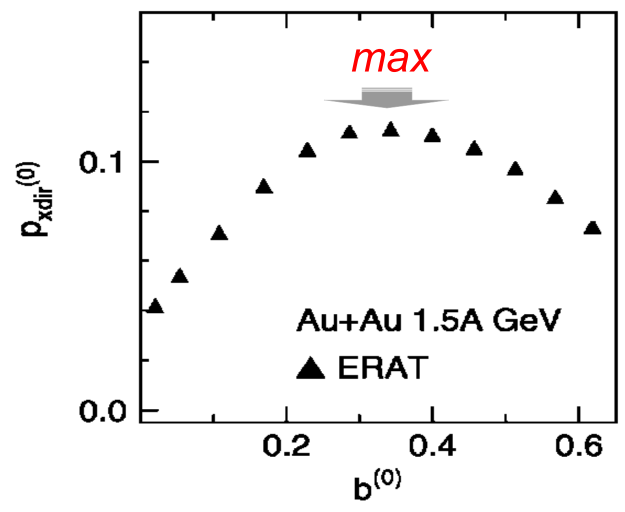
Low T_{beam} → Pauli exclusion

High T_{beam} → in-medium σ (?)

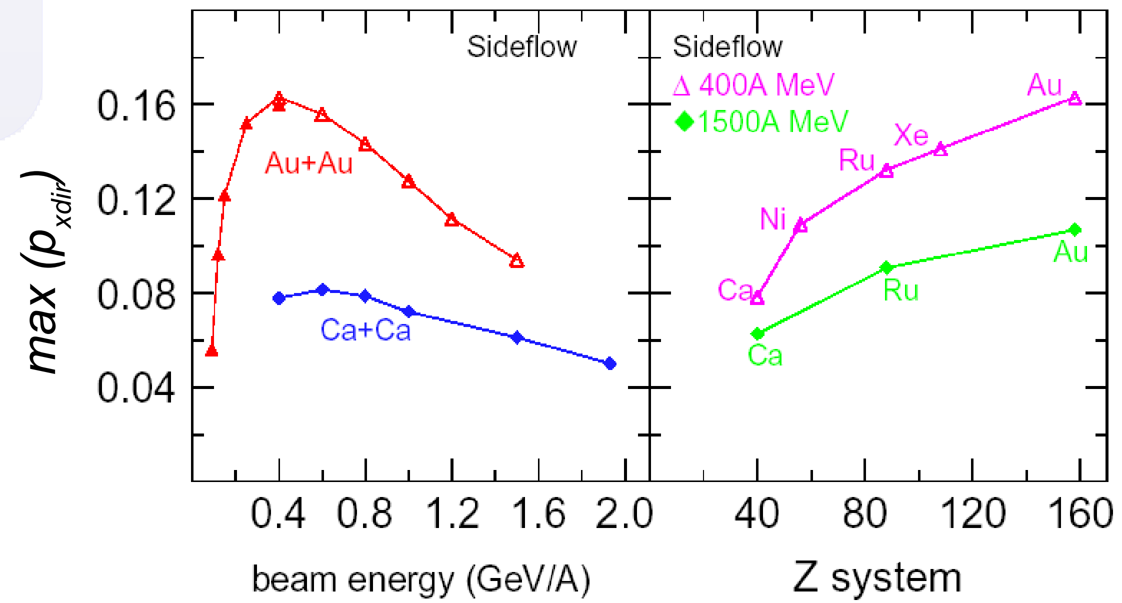
Side flow



$$p^{(0)}_{xdir} = \sum sgn(y) Z v_x \cdot \frac{1}{v_{beam}} \cdot \frac{1}{\Sigma Z}$$

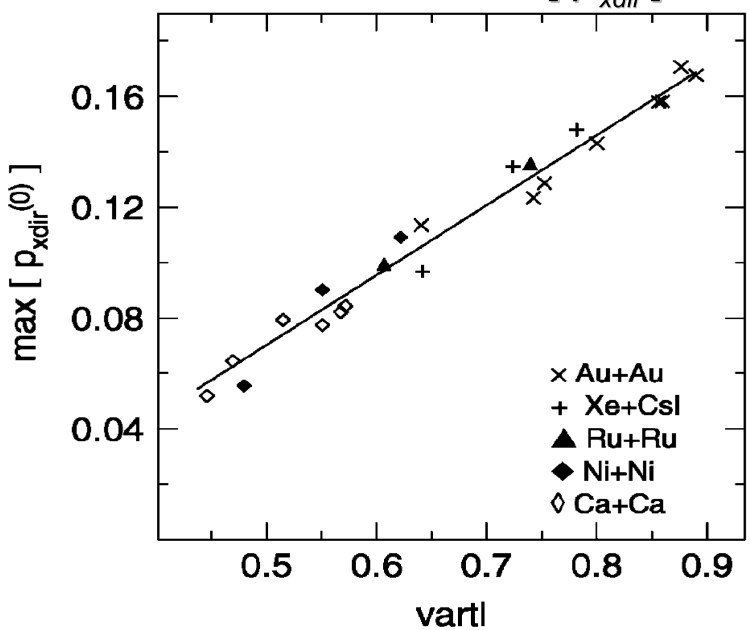


- Pattern identical as *vartl !*



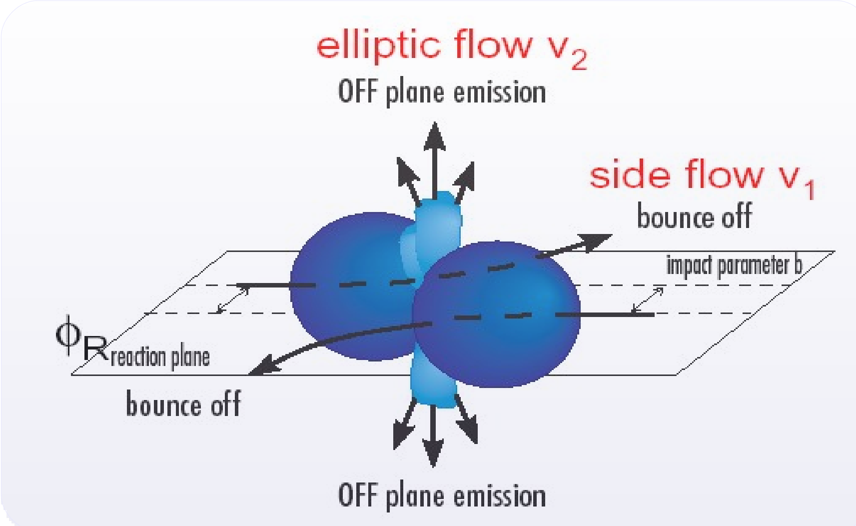
Elliptic flow

- Correlation between *vartl* and *max[p_{xdir}]*

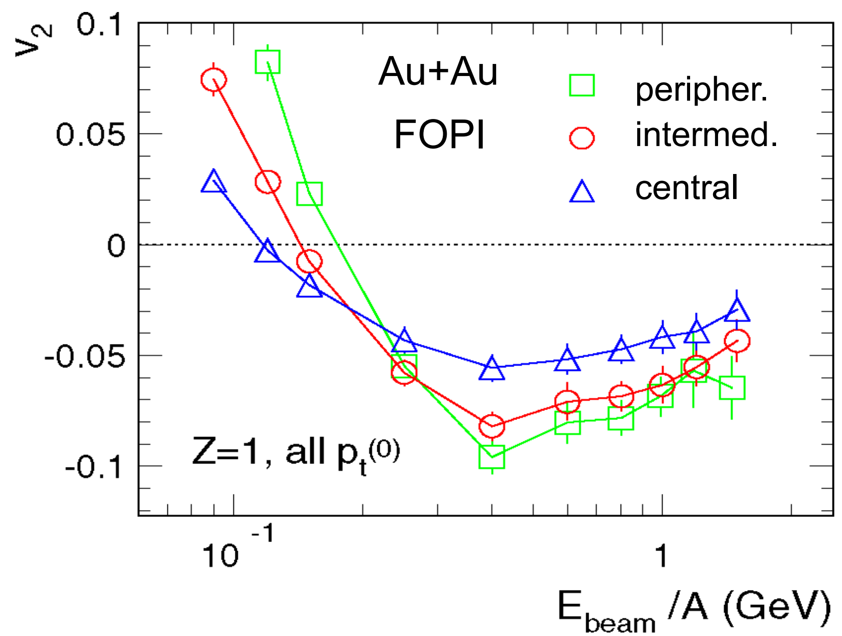


- more stopping (*vartl*)
  → more pressure
  → more side flow (p_{xdir})
  → more shadowing in-plane
  → more out-of-plane emission (v_2)

- more transparency (*vartl*)
  → less pressure
  → less side flow (p_{xdir})
  → less shadowing in-plane
  → less out-of-plane emission (v_2)



$$\frac{dN}{d\phi} \sim 1 + 2v_1 \cos\phi + 2v_2 \cos(2\phi) + \ldots$$



A.Andronic et al., Phys.Lett B 612, 173 (2005)

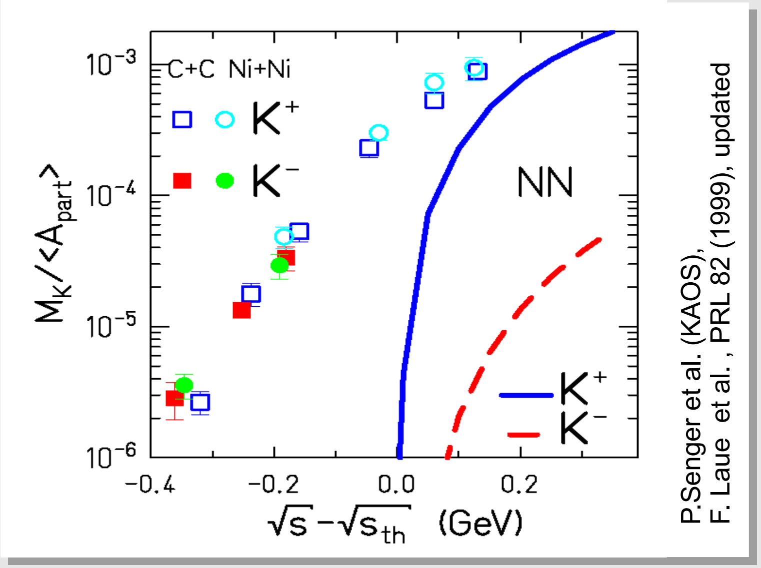
2. Strangeness in medium

- *KN interaction (potential)*
  - *Directed flow*
  - *K momenta of π+A and p+A*
  - *K^-/K^+ as function of Kinetic Energy and Rapidity*

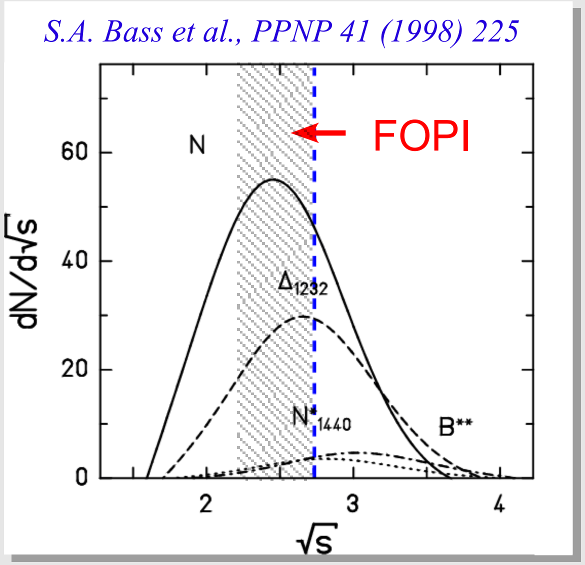
- *Other K^- sources*
  - *$\Sigma^{\pm *}$ (1385) , ϕ*

Sub- and Nearthreshold Production of Kaons

- **Production thresholds:** $NN \rightarrow N\mathbf{K}^{+}\Lambda$ E_{lab} = 1.6 GeV
  $NN \rightarrow K^{+}\mathbf{K}^{-}NN$ E_{lab} = 2.5 GeV



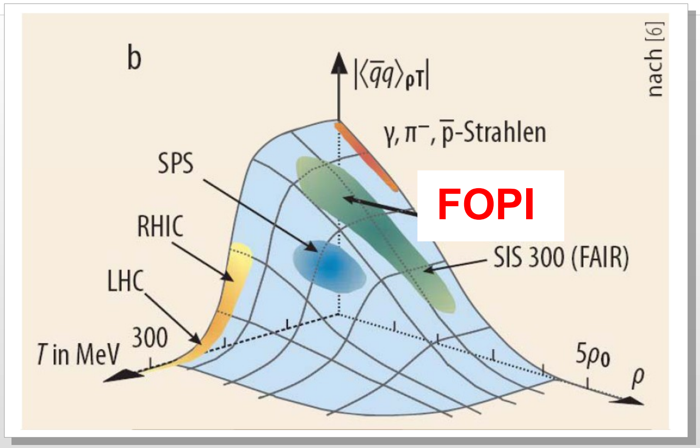
- At SIS energies, resonance production (Δ, N*) reaches maximum



Production processes (dominant)

- **K^{+0}** and **Y** via **multi-step** processes $N + N \rightarrow \Delta + N \rightarrow K^{+,0} + Y + B$
- **K^{-}** production more complex :
  - via **strangeness exchange** reactions : $\pi + Y \leftrightarrow K^{-} + B$
  - coupled to resonances e.g. Σ(1385), Λ(1405) and Λ(1520)
  - $K^{-}N$ potential attractive

Probing partial restoration of chiral symmetry



W. Weise, Prog.Theor.Phys.Suppl. 149, 1 (2003)

Gell-Mann Oakes Renner – relation:

$$m_K^{*2} f_K^{*2} = -\frac{m_u + m_s}{2}\langle \bar{u}u + \bar{s}s\rangle + \Theta\left(m_s^2\right)$$

Decay constant

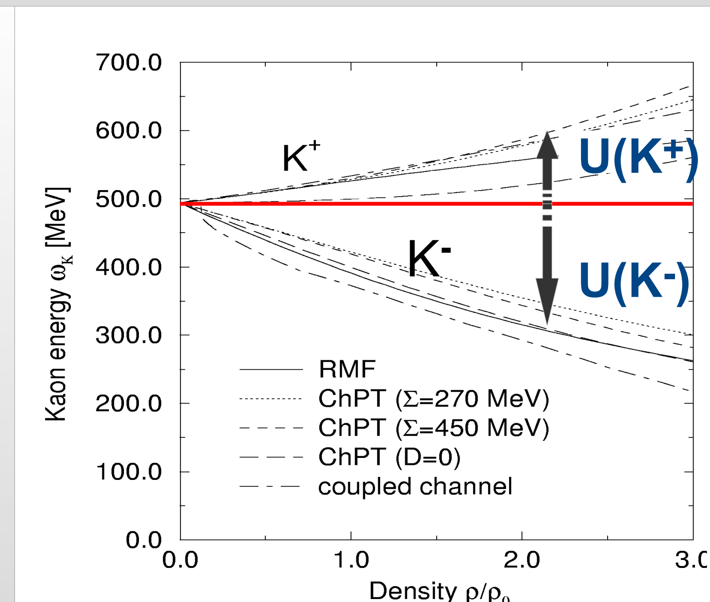
Mass

- *Energy of Kaon in medium:*

$$\omega_K = \sqrt{p_K^2 + \left(m + U_S\right)^2} + U_V$$

For p = 0, $\omega_K = m + V_{Total}(\rho)$

- $\vec{F} = -\vec{\nabla} U \Rightarrow$ K⁻ attracted, K⁺ repelled

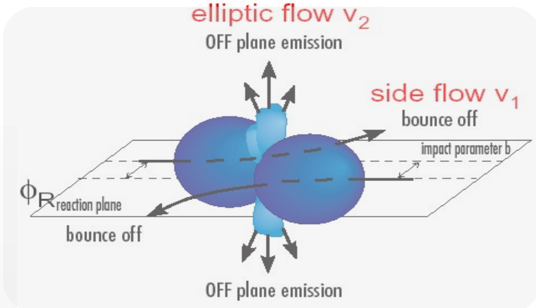


J. Schaffner-Bielich *et al.* NPA 625(1997) 325

- Ways to probe U(K) :
  - Sideward Flow of kaons
  - K⁻/K⁺ vs kinetic energy
  - Decay constants
  - Kaonic clusters

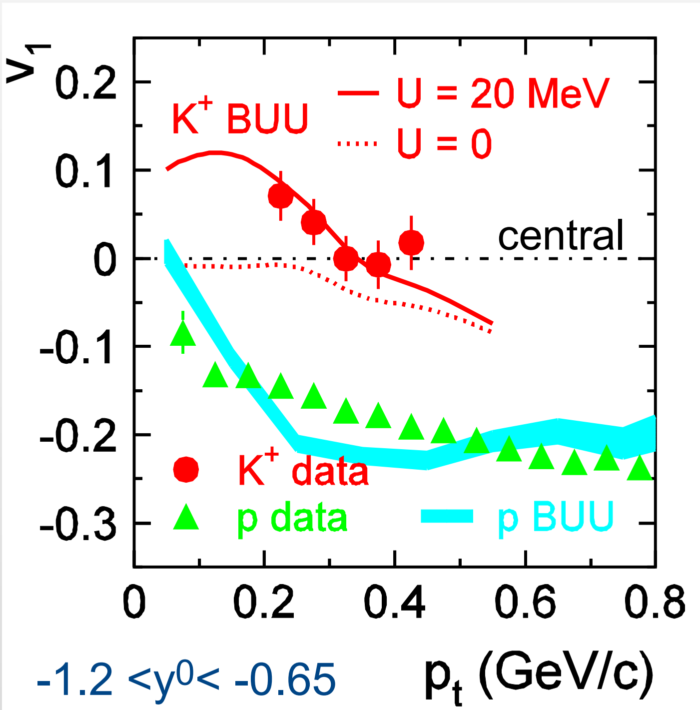
In-medium KN potential: K^+ Flow

$$\frac{dN}{d\phi} \sim 1 + 2v_1\cos\phi + 2v_2\cos(2\phi) + \dots$$

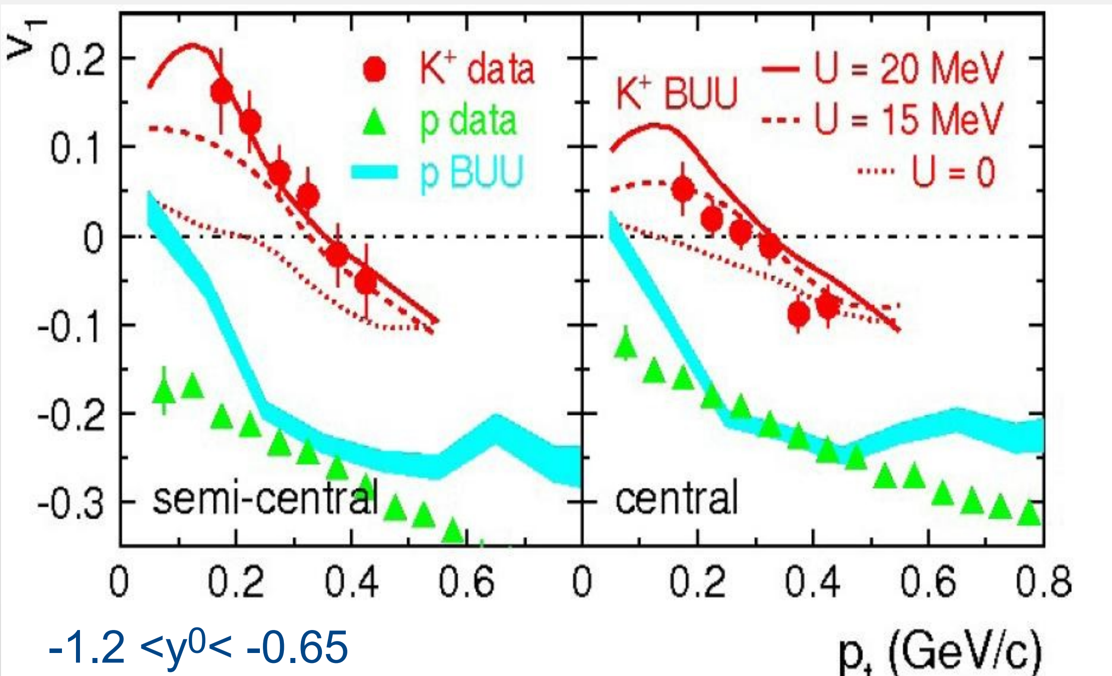


P. Crochet et al. (FOPI), PLB 486, 6 (2000)

Ni+Ni @ 1.93A GeV

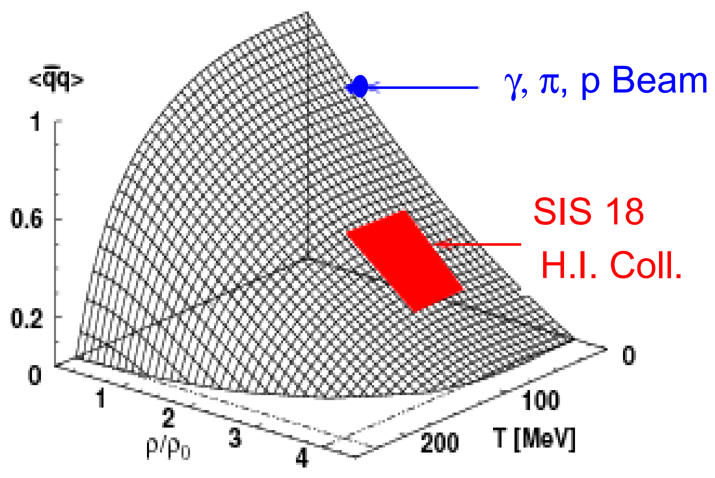


Ru+Ru @ 1.69A GeV



→ K^+ flow compared to RBUU, favours weak repulsive $U(K^+N) \sim +20$ MeV

In-medium KN potential at $\rho < \rho_0$



W. Weise, Prog.Theor.Phys.Suppl. 149, 1 (2003)

π^- *(p=1.15 GeV/c)* + A $\rightarrow$ K^0 + … *FOPI*

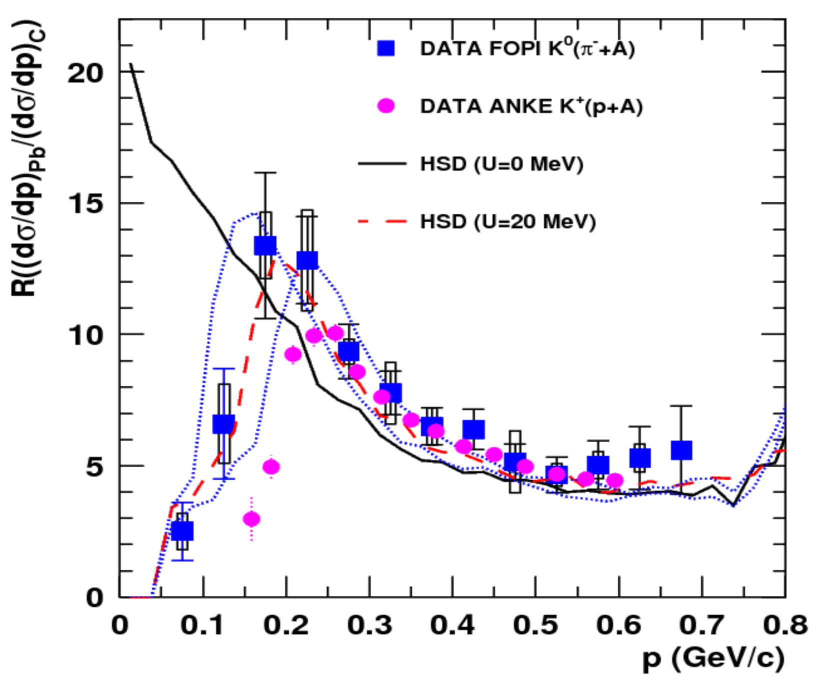
p (p=2.25 GeV/c) + A $\rightarrow$ K^+ + … *ANKE*

CBUU

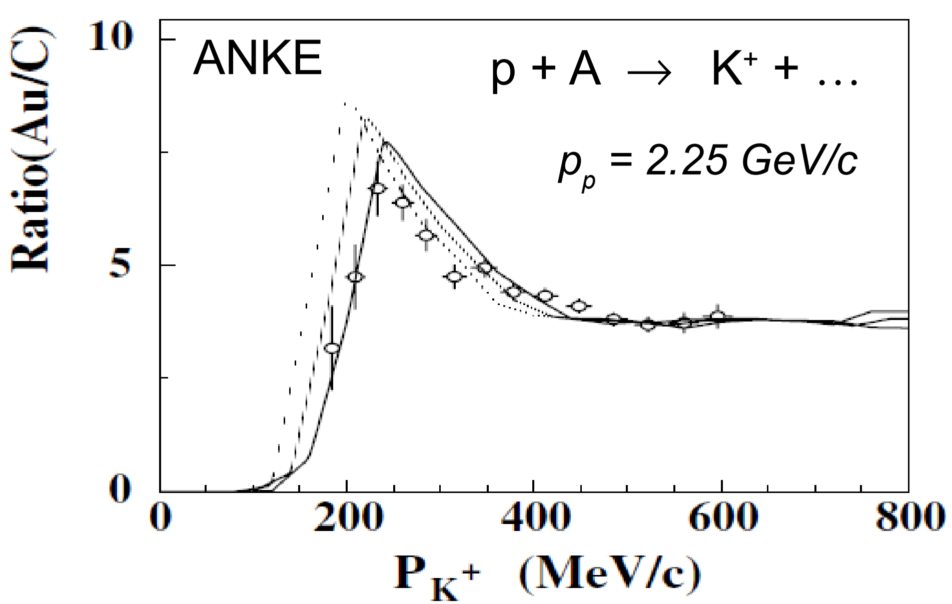
V_{KN} = 0 MeV

V_{KN} = 10 MeV

V_{KN} = 20 MeV

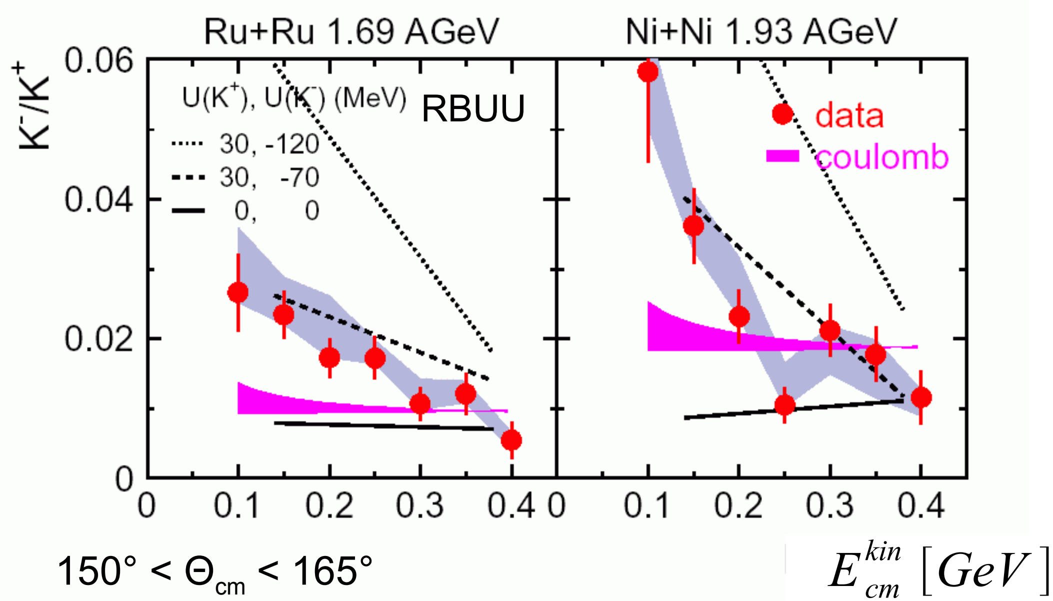


M.L. Benabderrahmane et al., PRL 102, 182501 (2009)



Z. Rudy et al., EPJA 23, 379 (2005)

In-medium KN potential: K^-/K^+ yield

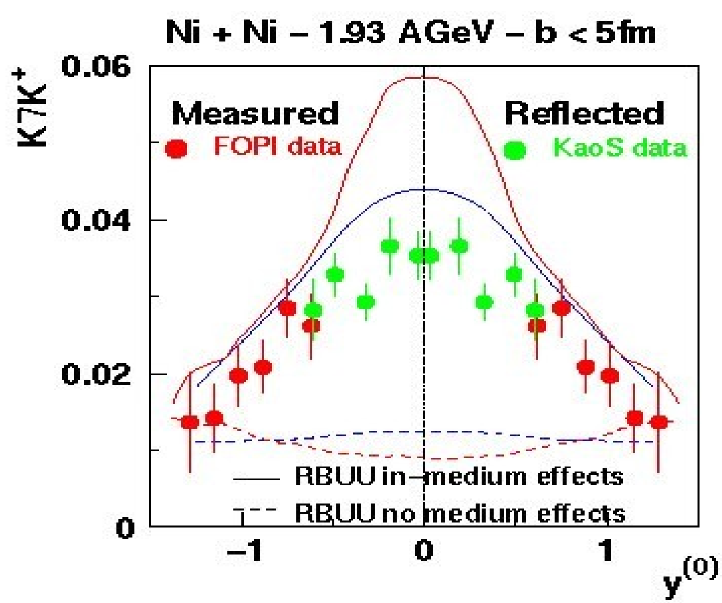


E_{cm}^{kin} $[GeV]$

K. Wiśniewski *et al.* (FOPI), EPJ A9, 515(2000)

Data – vs – RBUU

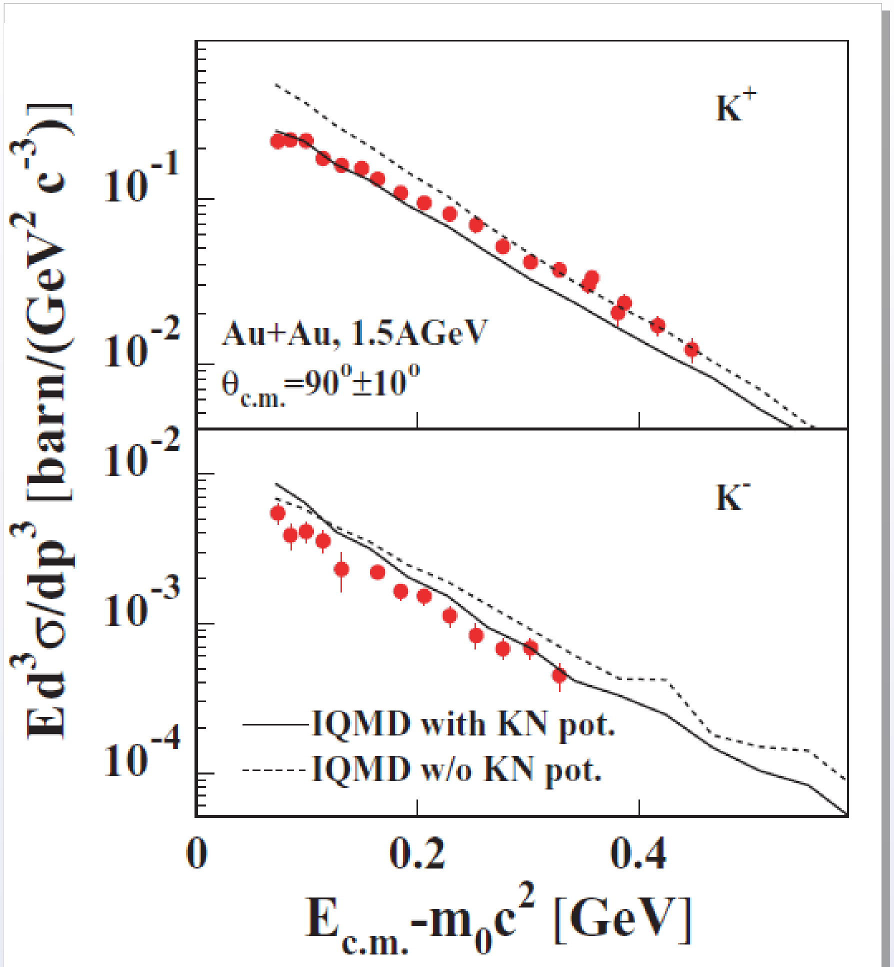
- $U = 0 \rightarrow K^-/K^+$ flat
- Strong effect at low E_{kin}

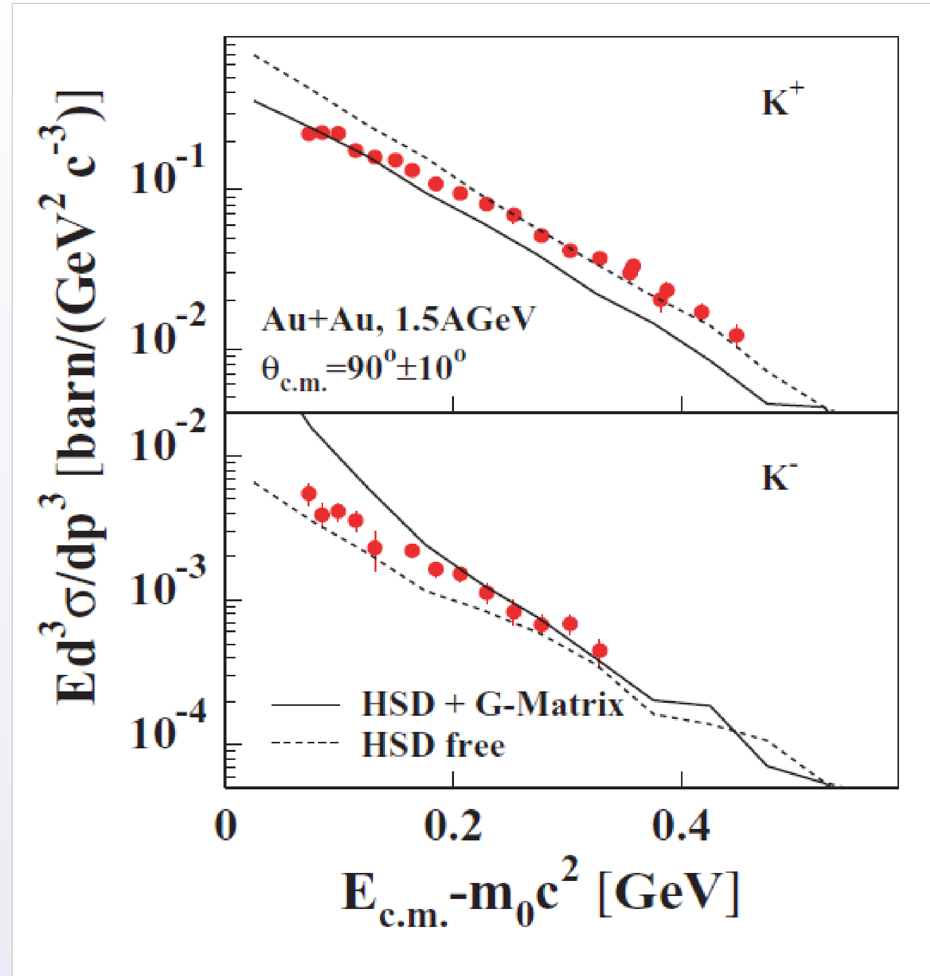


Data – vs – RBUU

- Clear preference for $U_{KN} > 0$ option
- Red/Blue = Soft/Hard EOS option
- Still description not ideal

K^- and K^+ data from KaoS





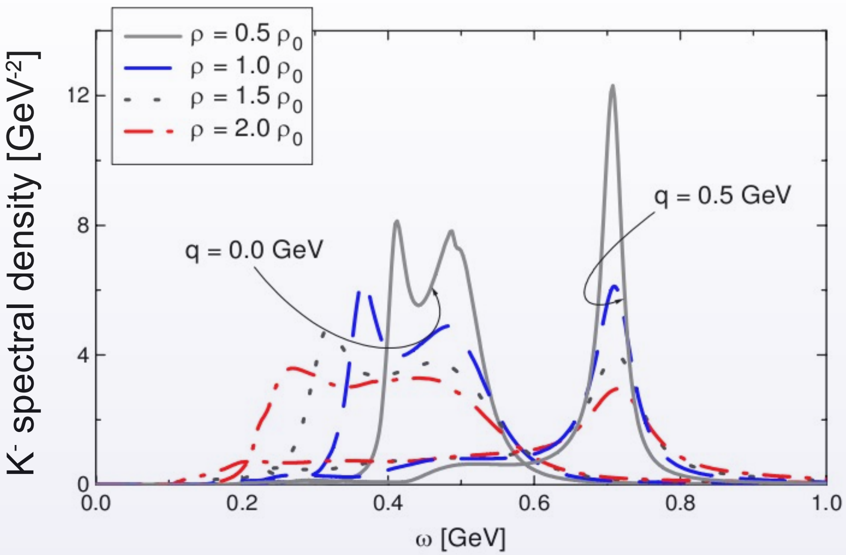
Our understanding too simplistic ?

- K^- production via resonances
- Some K^- from ϕ (outside medium)

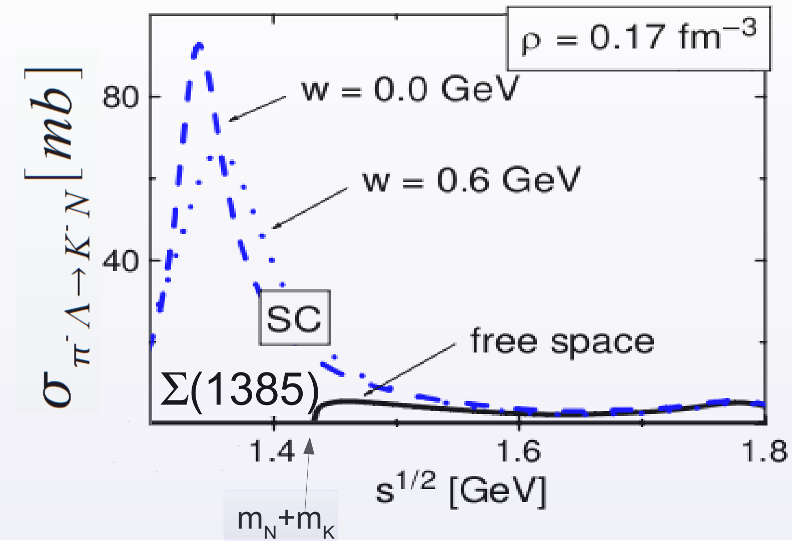
K$^-$ production in medium

Chiral perturbation theory (χPT) M.F.M. Lutz, PPNP 53, 125 (2004)

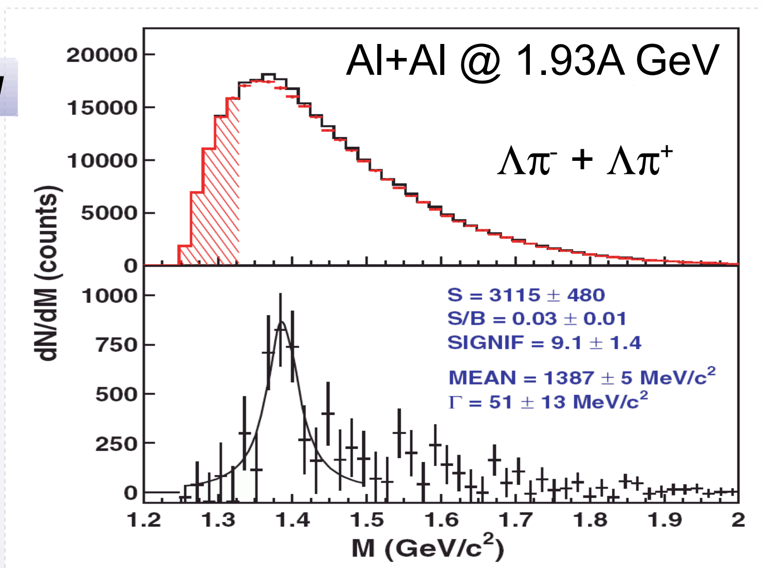
- *Antikaon spectral function in dense matter*



- *Strange resonances in K$^-$ production*



FOPI



$\Sigma^{\pm *}$ **(1385)** $\rightarrow$ **Λ +** $\pi^{\pm}$ (88 ± 2%)

↳ **p +** π^-

E_{th} = 2.33 GeV *(subthreshold)*

Γ = 39.4 MeV, cτ = 5 fm *(short lived)*

$$\frac{P(\Sigma^{*-}+\Sigma^{*+})}{P(\Lambda+\Sigma^0)}=0.125\pm0.026\pm0.033$$

X. Lopez et al. (FOPI), PRC 76, 052203(R) (2007)

ϕ meson $(s\bar{s})$

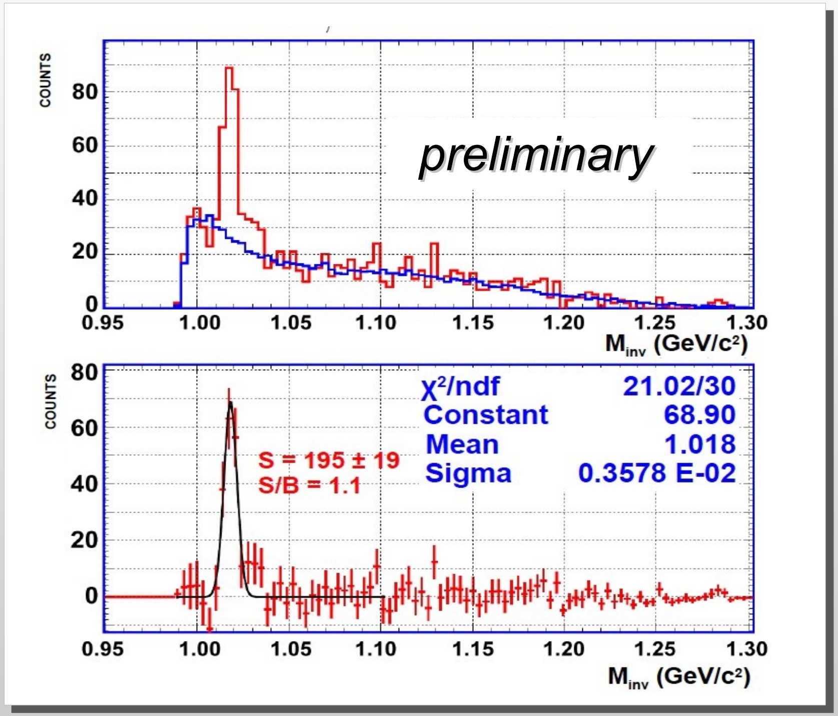
- $\phi\ (s\bar{s}) \rightarrow K^+K^-$ *(BR = 49%)*

  m = 1019 MeV

  $c\tau$ = 50 fm *(decays mostly outside collision zone)*

  E_{th} = 2.6 GeV *(subthreshold)*

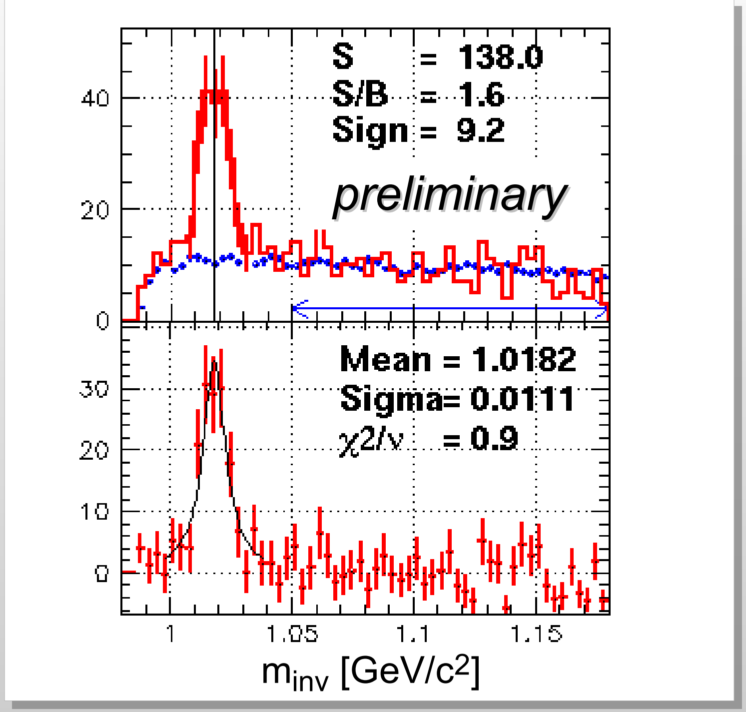
- **Al+Al @ 1.93A GeV** *(P. Gasik)*



- P_ϕ */ collision = (2.2±0.5±0.2) · 10^{-4}*

$$\frac{P(\phi)}{P(K^-)} = 0.27 \pm 0.10$$

- **Ni+Ni @ 1.93A GeV** (KP)



- P_ϕ */ collision = (6 ± 1 ± 2) · 10^{-4}*

$$\frac{P(\phi)}{P(K^-)} = 0.44 \pm 0.13$$

3. The Final Concerto

- *Strange neutral particles: K^0 and Λ^0*
- *"Kinematical temperature"*
- *"Statistical temperature"*
- *Phase Diagram*

K^0 and Λ at 1.9A GeV

- K^0 and Λ (from secondary vertices)

$K^0 \rightarrow \pi^+ + \pi^-$ (69%)

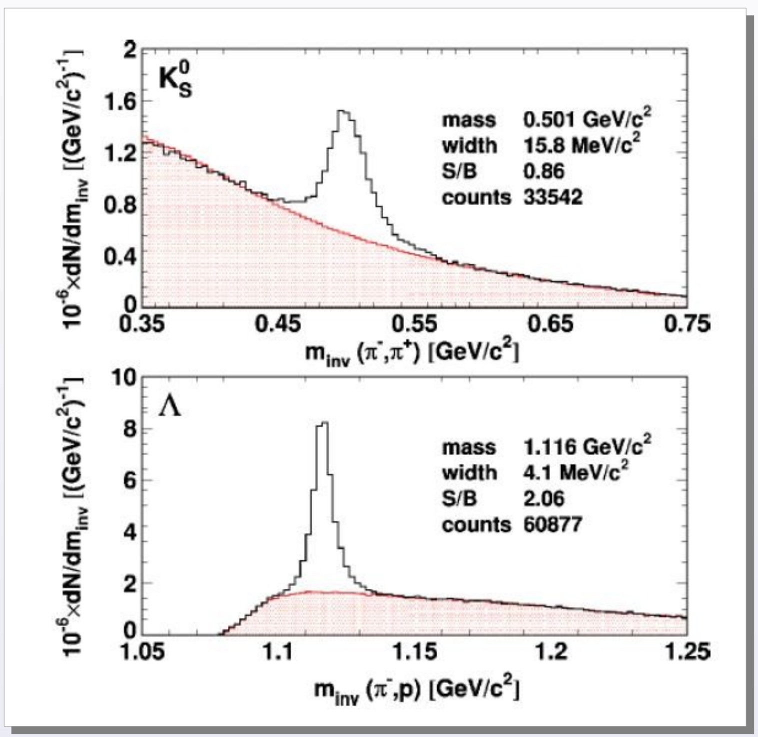
$\Lambda \rightarrow \pi^- + p$ (64%)

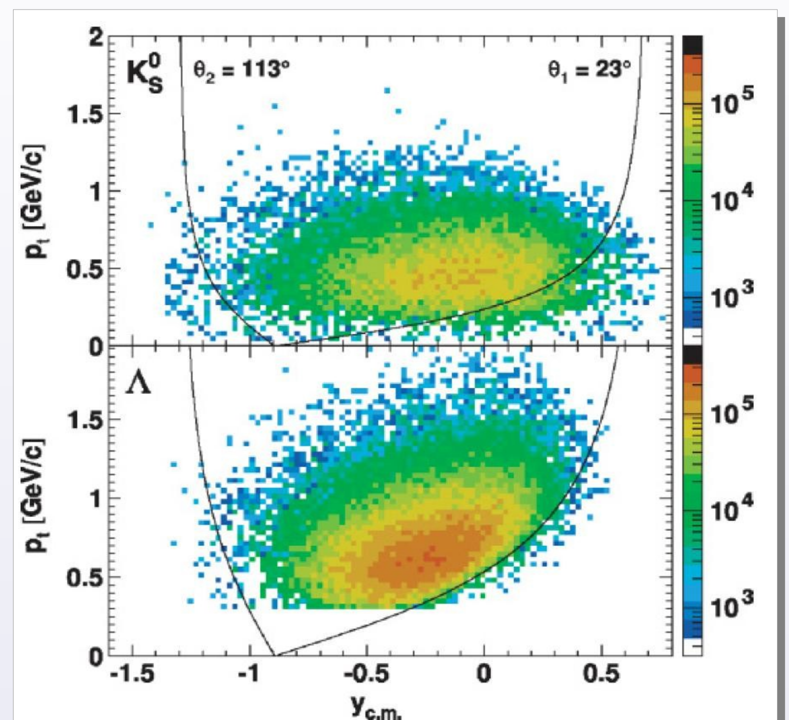
	K^0 $(d\bar{s})$	Λ (uds)
Ni+Ni	30 k	60 k
Al+Al	60 k	100 k

- Identification of K^0 and Λ

- Phase space: occupancy vs acceptance

Ni+Ni @ 1.93A MeV

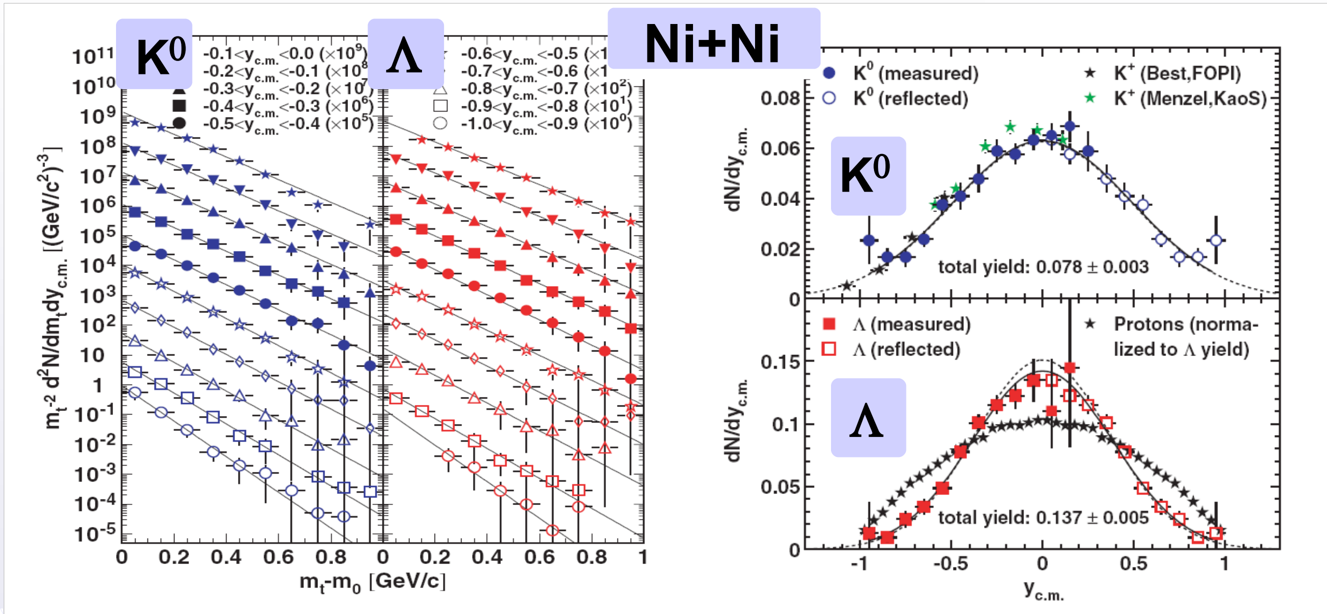




M. Merschmeyer, X. Lopez et al. (FOPI), PRC 76, 024906 (2007)

M. Merschmeyer, X. Lopez et al. (FOPI), PRC 76, 024906 (2007)

K^0 and Λ: phase space analysis

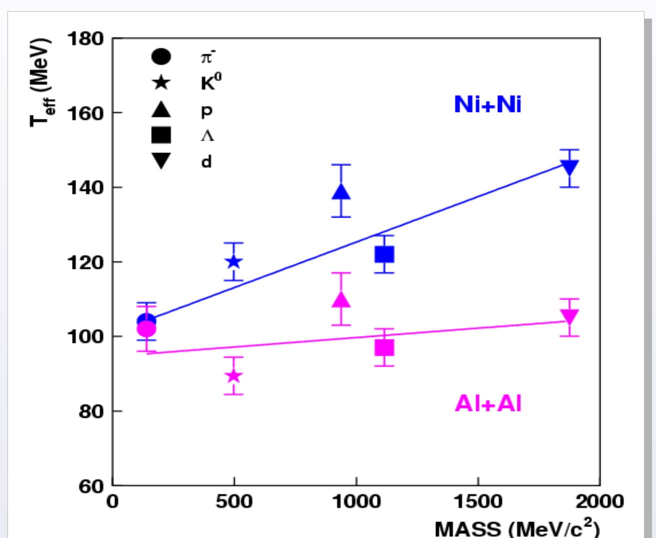


E_{beam} = 1.93A GeV

- Λ and K^0 obeying Boltzmann distributions
- Λ and proton: emission patterns different ($p \rightarrow$ transparency)

Temperature of colliding system

$$T_{eff} = T + \frac{2}{3} \cdot \frac{m_0 \langle \beta_{rad} \rangle^2}{2}$$



- Ni+Ni: radial flow
  Al+Al: almost no expansion
- Same kinetical freeze-out T in Al+Al and Ni+Ni (**T ~ 90..100 MeV**)

Statistical model: particle yields

- *Assumption*: equilibrium @ chemical freeze-out

Density of species i (in grandcanonical ensemble) **:**

$$n_i(\mu,T) = \frac{N_i}{V} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{\exp\left(\frac{E_i-\mu_B B_i-\mu_S S_i-\mu_{I_3} I_{3i}}{T}\right)\pm 1}$$

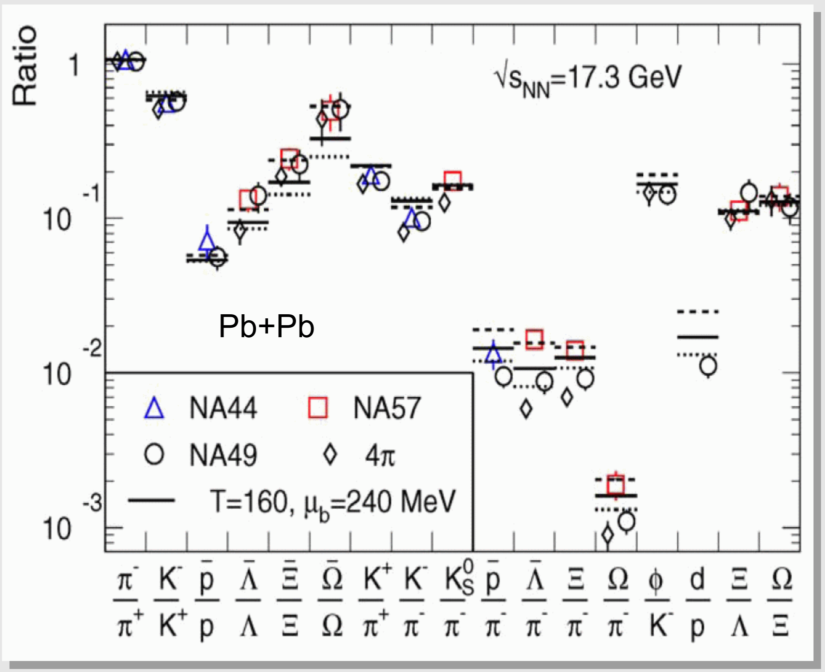
Free parameters: chemical potential μ_B, temperature T

For particle *ratios* : V cancels out

Fixed by conservation laws: μ_S, μ_{I3}

Yield ratios @ SPS

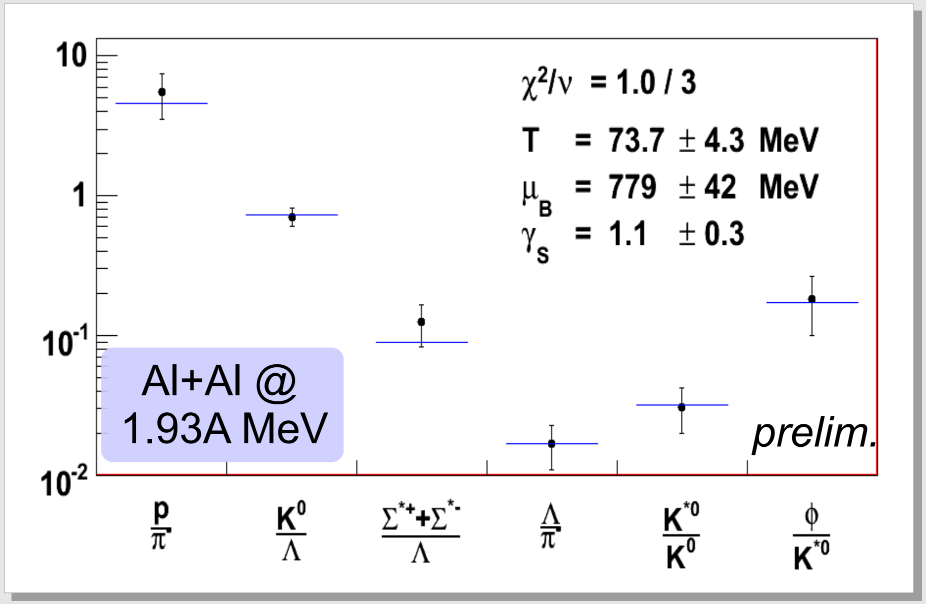
A.Andronic, P.Braun-Munzinger, J.Stachel NPA 772 (2006) 167



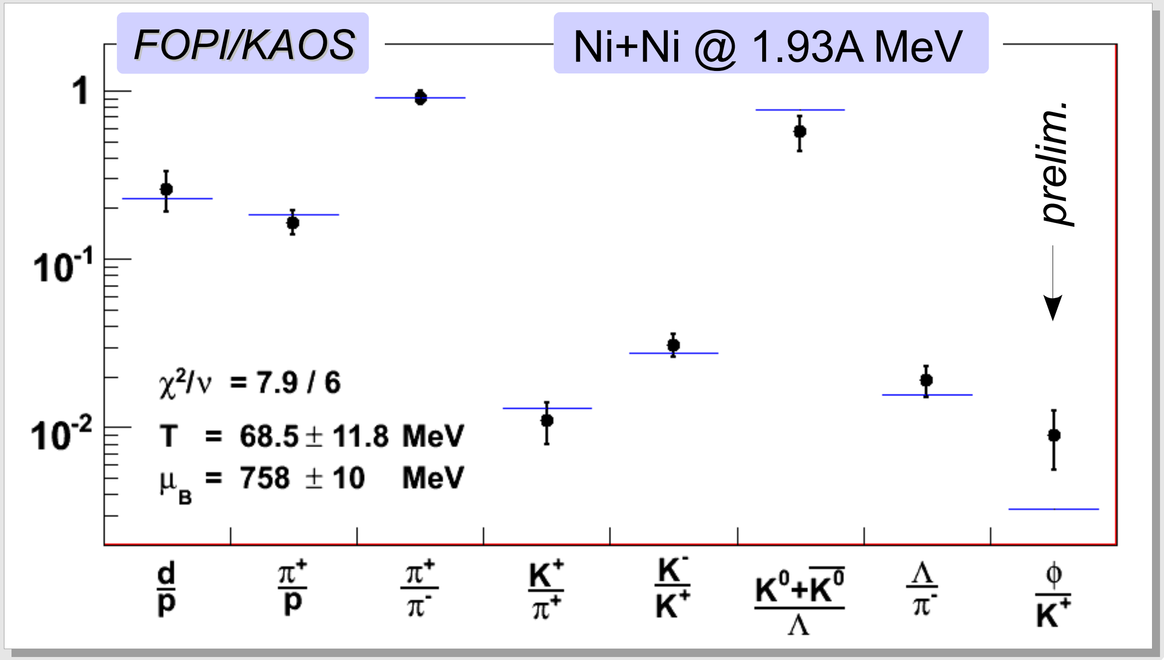
→ *looks promising*

Particle yields at freeze-out

- **Al+Al**
  - 6 independent ratios with 5 strange particles :
    p, π⁻, K^0, Λ, ϕ, K^{*0}(892) and $\Sigma^{*\pm}$(1385)



- **Ni+Ni**
  - 8 independent ratios with 4 strange particles
    p,d, π±, K±, K^0, ϕ, Λ



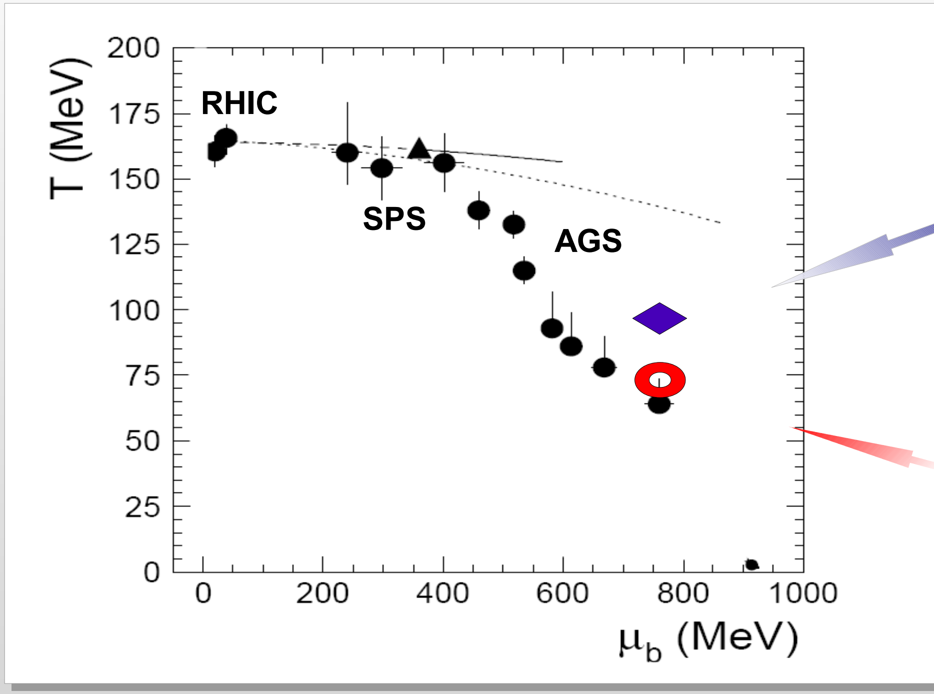
Statistical Model

(calc.: **THERMUS** code
S.Wheaton, J.Cleymans hep-ph/0407175)

- Grand Canonical ensemble;
  For S≠0, Canonical ensemble
- T ~ 70 MeV, μ_B = 770 MeV
- For Al+Al, $\gamma_s \approx 1$
- Model fitting well

Freeze-out on phase diagram

P.Braun-Munzinger, J. Wambach, Rev. Mod. Phys 81, 1031 (2009)



T ~ 90..100 MeV

from m_T spectra
(kinematic freeze-out)

T ~ 70 MeV

from Statistical Model
(chemical freeze out)

Assumming those models, we obtain

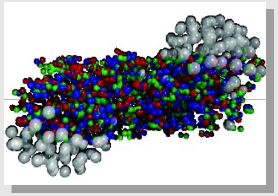
$T_{kin} > T_{chem}$

...

Is the equilibrium assumption wrong?

Need for more systematics

Particle yields and UrQMD



UrQMD

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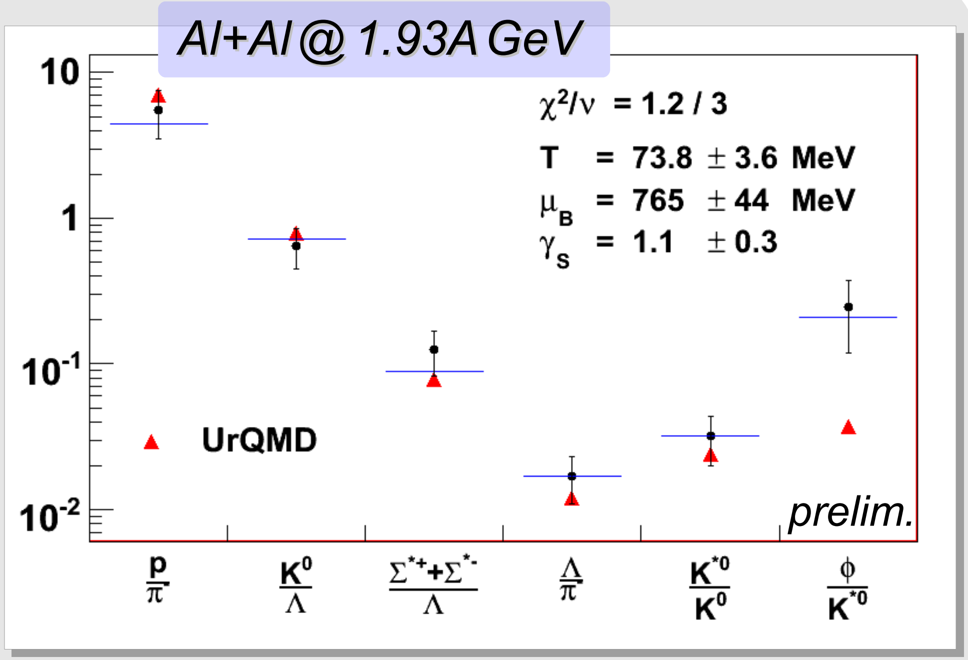
- No equilibration assumed
- Cascade model – no mean field
  – no in-medium effects
- $\Sigma^{*\pm}$ and K* reconstructable in experiment:
  Excluded decay products undergoing inelastic rescattering with medium



- UrQMD in agreement with data and Statistical Model

Either: *More precise data needed*

Or: *Integrated yields are not a good signature to study thermalisation issues*

Summary and conclusion

- General dynamics of the collision at 1-2A GeV:

  stopping $\rightarrow$ pressure $\rightarrow$ side flow $\rightarrow$ shadowing $\rightarrow$ out-of-plane preference

  vartl max $[p_{xdir}]$ v_2

- In-medium modification of strangeness

  $\rightarrow$ Flow of K^+ $\rightarrow$ $V_{KN} \approx +20$ MeV
  $\rightarrow$ p_{Kaon} (Pb) / p_{Kaon} (C) $\rightarrow$ $V_{KN} \approx +20$ MeV
  $\rightarrow$ K^+/K^- (E_{kin}) $\rightarrow$ $V_{KN} \approx +30$ MeV, $V_{\bar{K}N} \approx -70$ MeV (quantitative)
  $\rightarrow$ K^+ and K^- separately $\rightarrow$ with in-medium better, but inconclusive

- Other kaon sources [$\Sigma^*(1385)$, ϕ] may bias model calculations of in-medium effects

- Phase space analysis of particles $\rightarrow$ "kinematical temperatures" T_{kine}
- Yield ratio compared to thermal model $\rightarrow$ "thermal temperatures" T_{ther}

- Unexpected inversion $T_{kine} > T_{ther}$ $\rightarrow$ thermal assumption wrong?

Thank you