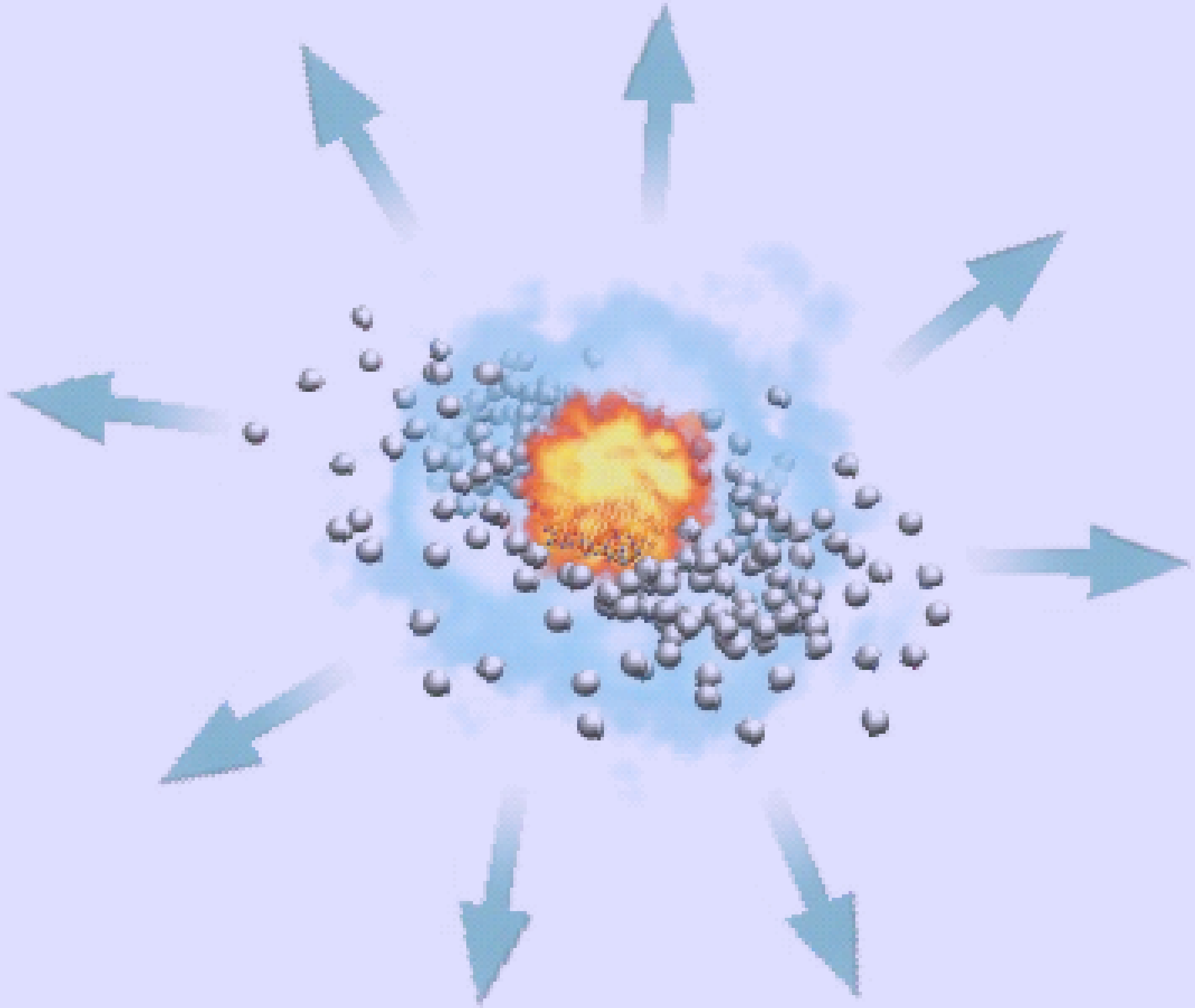
Dense Baryonic Matter (Part II)

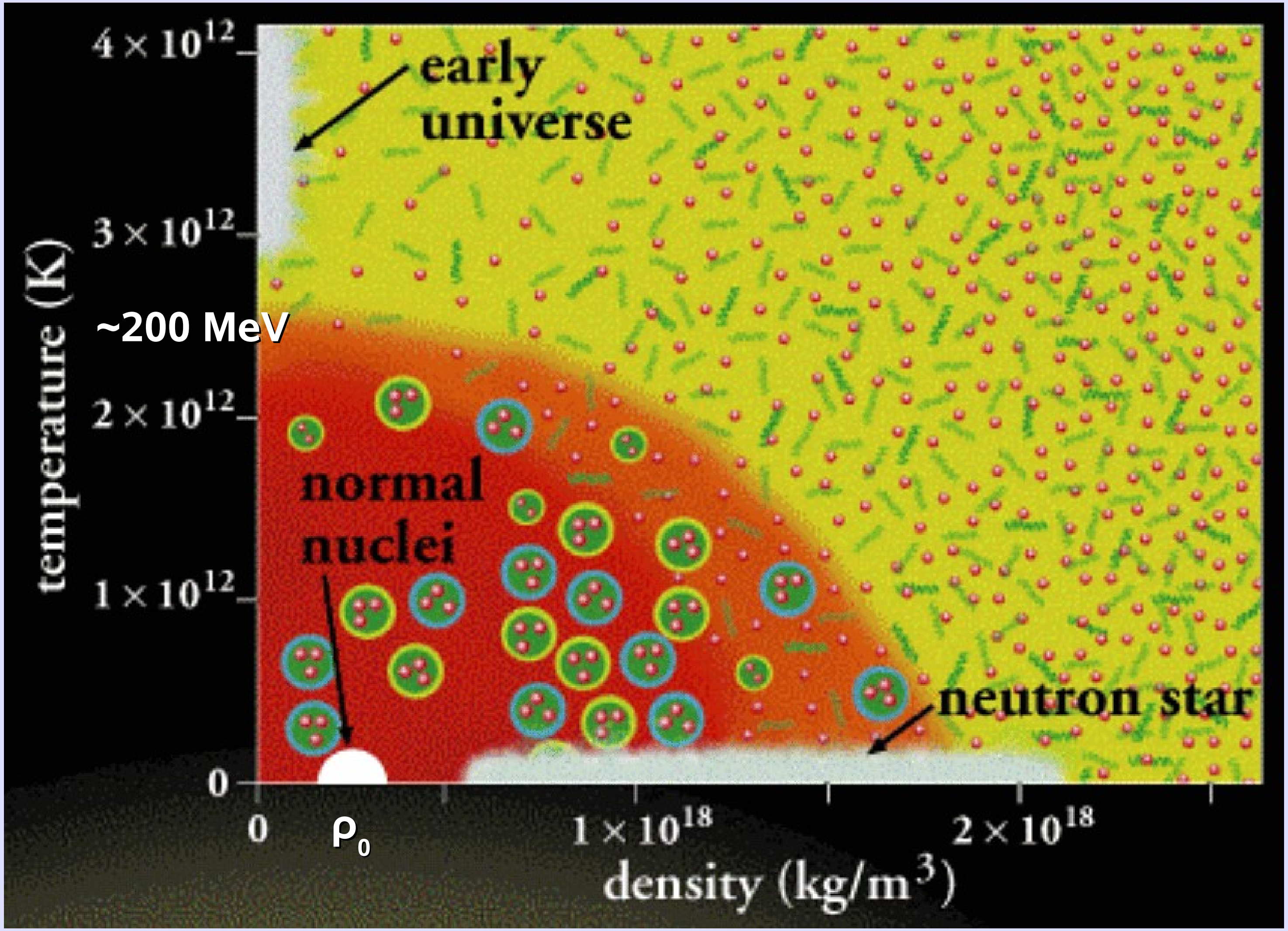
Today:

- Introduction (Retrospect)
- GSI: SIS-18
  - Experiments
  - Results
- Outlook



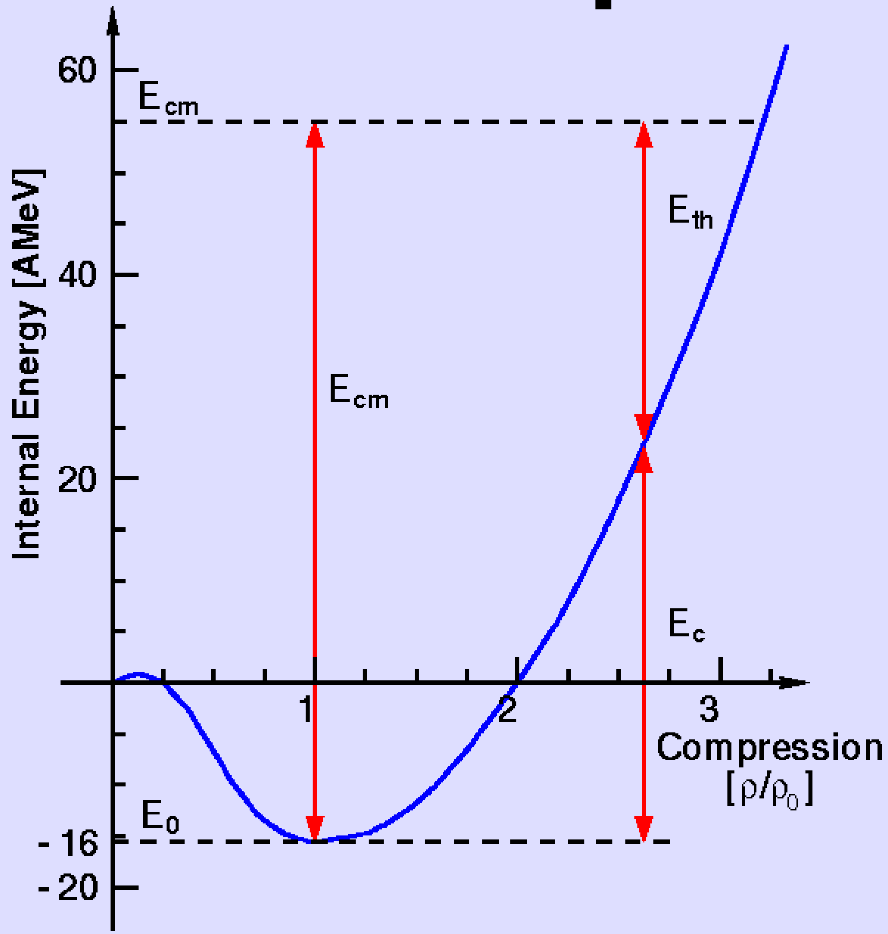
Phase Diagram of Nuclear Matter

- normal nucl. matter: liquid (droplet model)
- heating and compression
  - hadron gas
  - quark-gluon plasma
- high ρ, low T
  - CSC, CFL



(ABC's of Nuclear Science, LBL)

The Equation of State (EOS)



saturation density of nuclear matter
$\rho_0 = 0.17\ \mathrm{fm}^{-3} = 0.16\ \mathrm{GeV/fm}^3$

- example: internal energy

$$E(\rho, T) = E_{th}(\rho, T) + E_c(\rho, T=0) + E_0$$

- (in)compressibility

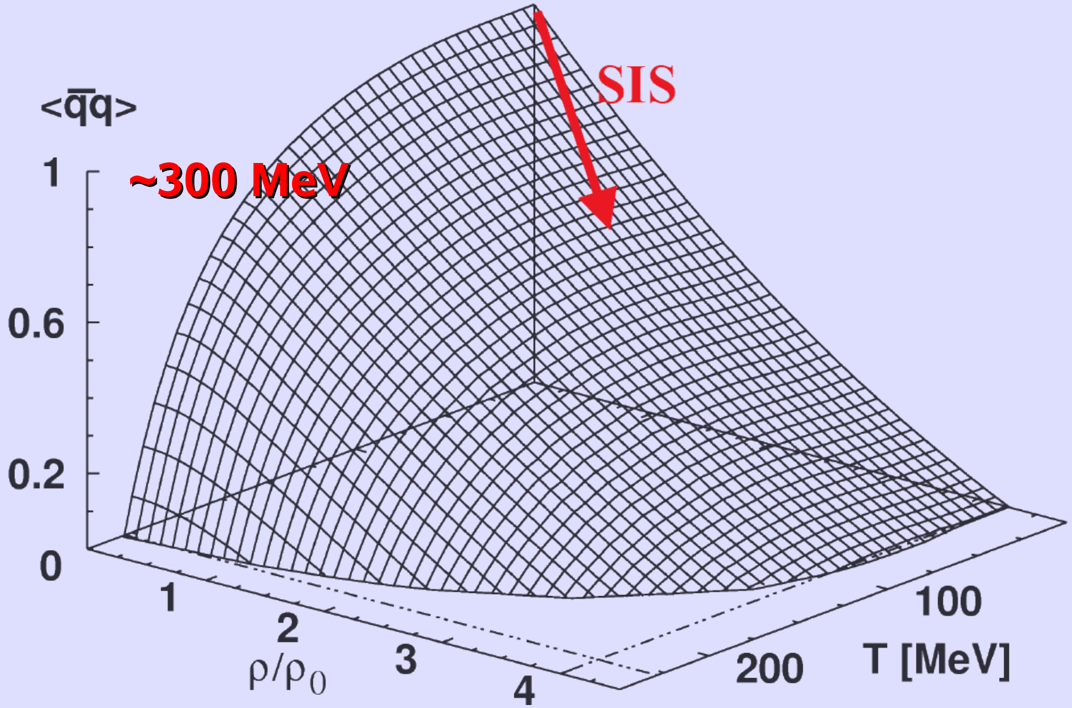
$$K_\infty = 9\rho_0^2 \left[\frac{d^2 E_c}{d\rho^2} \right]_{\rho=\rho_0}$$

  - soft EOS: K ≈ 200 MeV
  - stiff EOS: K ≈ 400 MeV

→ astrophysical consequence: neutron star mass limit

The Quark Condensate

- QCD vacuum not empty at all: strong condensation of $q\bar{q}$ pairs
- effective QCD theories predict decrease of $\langle\bar{q}q\rangle$ with increasing ***T*** and ***ρ***
- GOR relations predict change of particle properties:



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

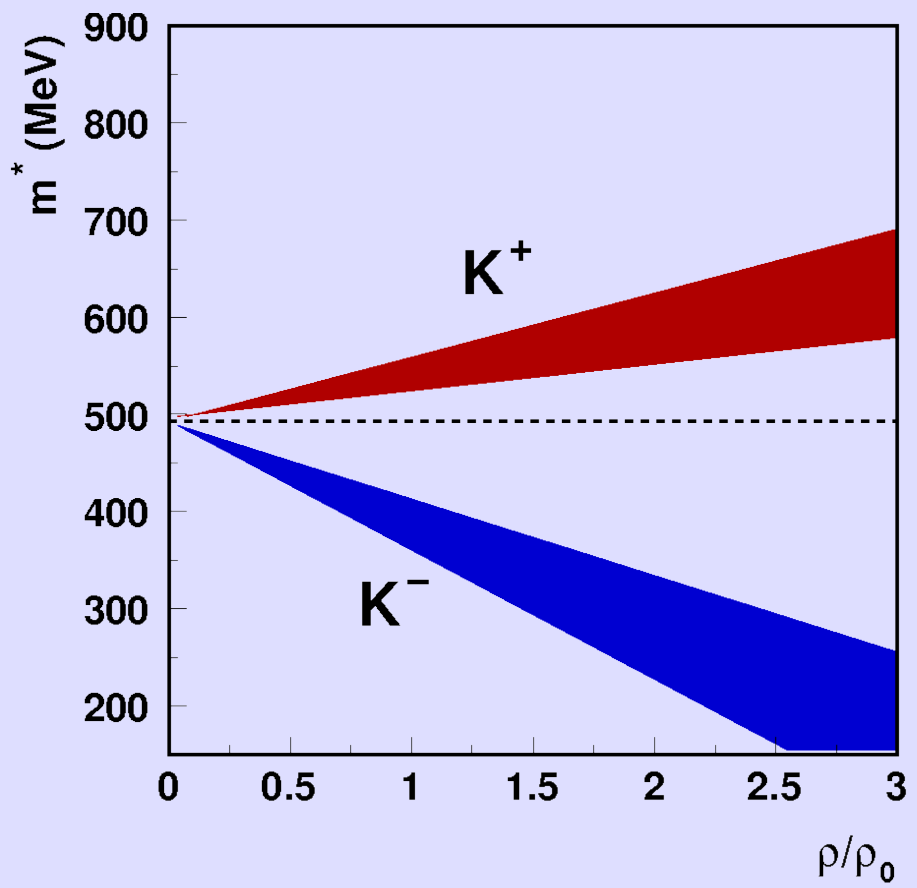
$$m_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u + m_d)\langle\bar{u}u + \bar{d}d\rangle + O(m_u^2)$$

$$m_K^2 f_K^2 = -\frac{1}{2}(m_q + m_s)\langle\bar{q}q + \bar{s}s\rangle + O(m_s^2)$$

M. Gell-Mann, R. J. Oakes and B. Renner, Phys. Rev. 175 (1968) 2195

Consequence: In-Medium Effects

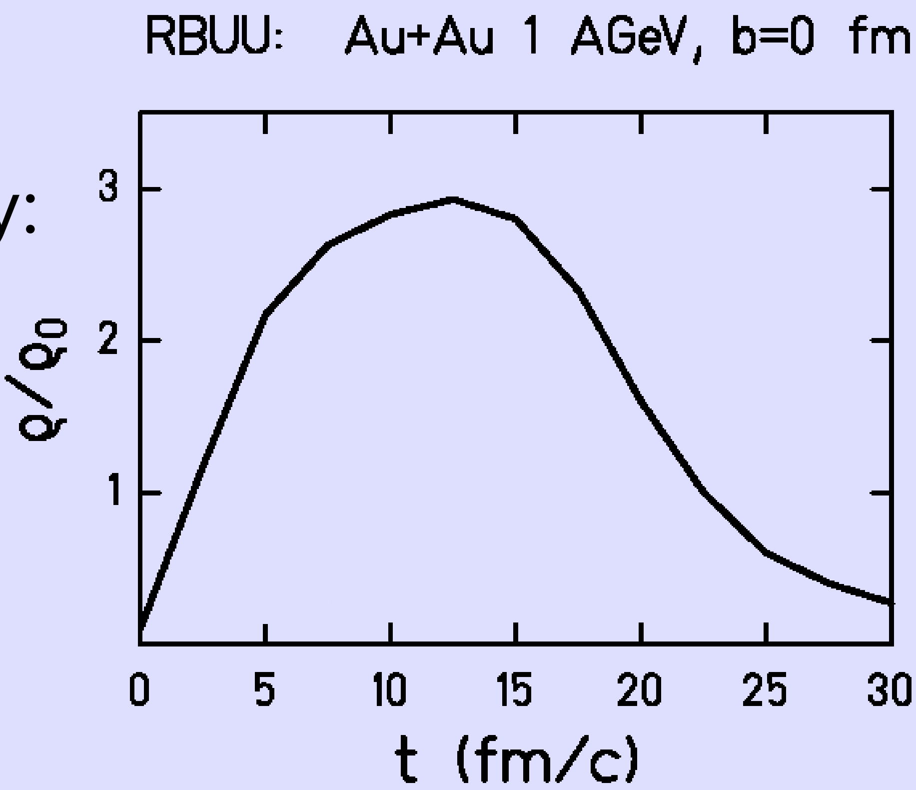
- quark condensate reduced in hot & dense nuclear matter, particle properties may change
- observables: produced particles
  - masses, widths (ρ,ω,...)
    - short lifetime (~ 10^{-23} s)
    - decay in collision zone
    - leptonic decay channels
  - yields, spectra (K^+,K^-...)
    - long lifetime (10^{-8} – 10^{-10} s)
    - mostly decay outside coll. zone



Heavy-Ion Collisions (II)

- Facilities: **SIS**, AGS, SPS, RHIC, LHC
  E ~ 100 AMeV – 2.7 ATeV

- situation at 2 AGeV beam energy:
  - velocity: $\beta \approx 0.9$
  - time scale:
    $$t \approx 5 - 10\ fm/c \approx 2 \cdot 10^{-23}\ s$$
  - density: $\rho \approx 2 - 3 \cdot \rho_0$

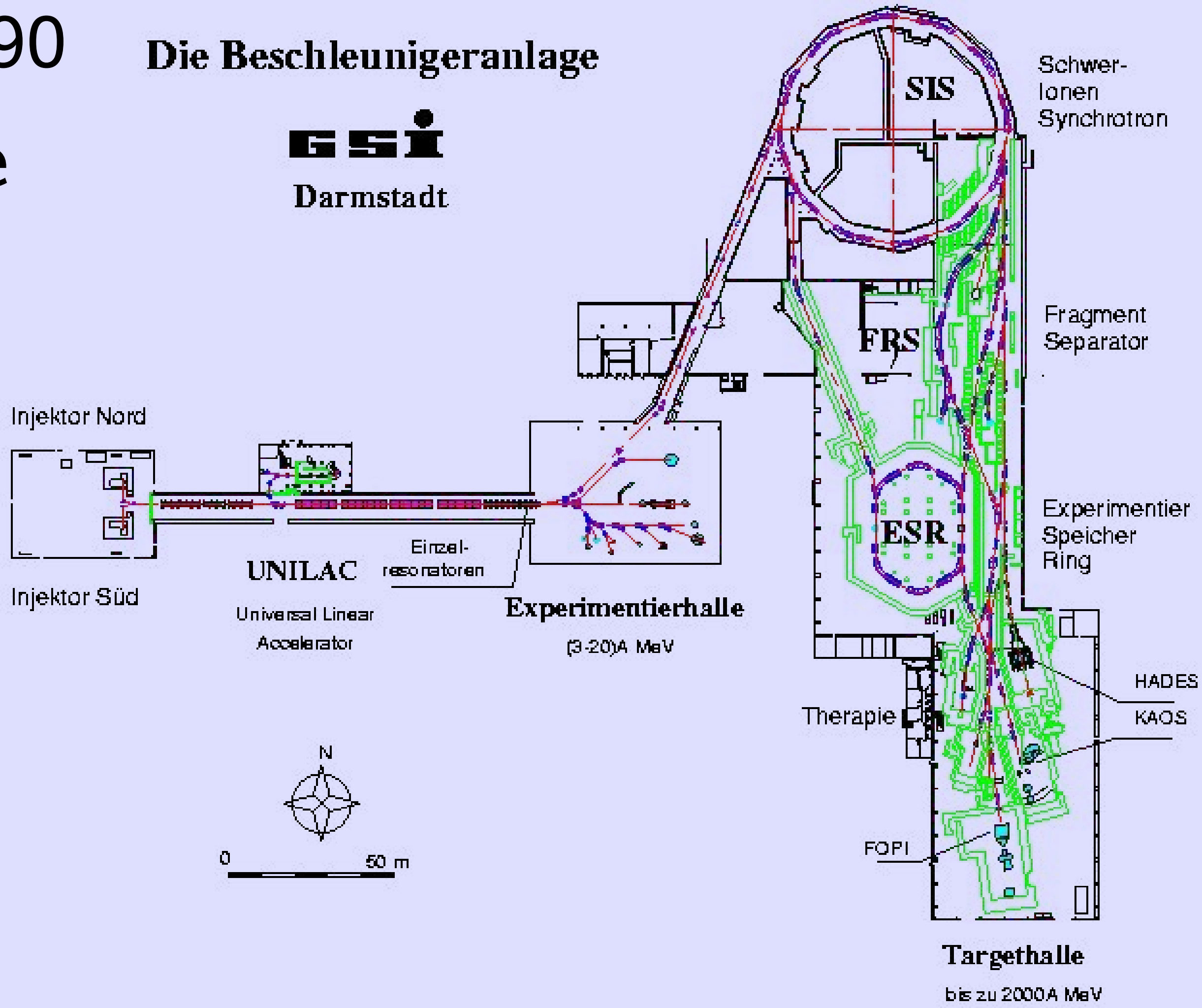


X.S. Fang et al., NPA 575 (1994) 766

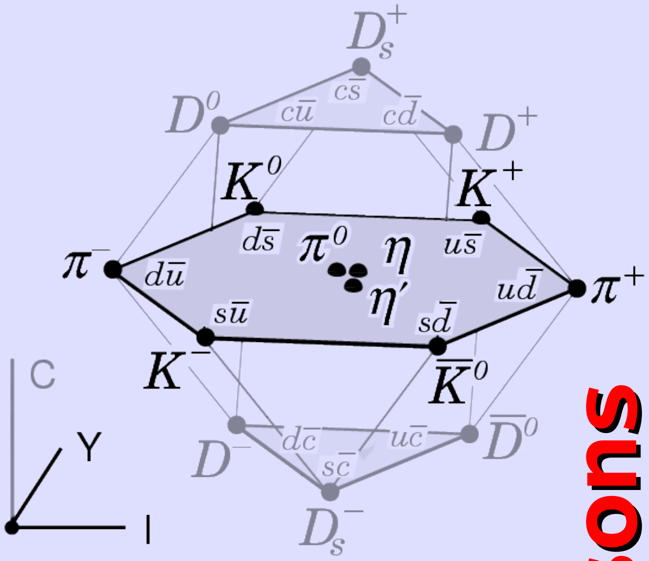
GSI: SIS-18

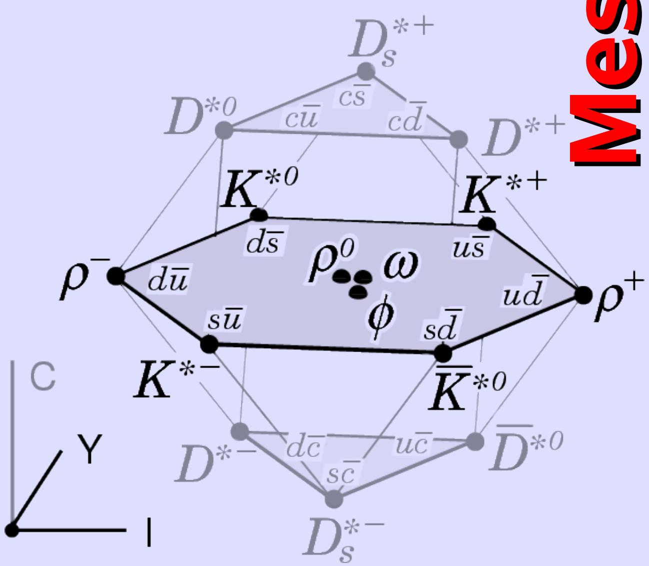
The Present: SIS-18

- SIS available since 1990
- particle energies range between 50 – 2000 AMeV
- beam intensities (at highest energies): ~ 10^6/s (on target)
- spill length ~ 10s



Accessible Particles (SIS-18)



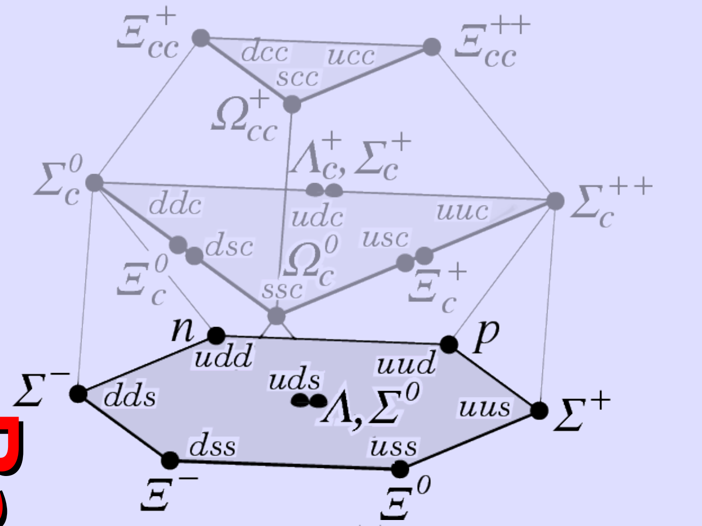


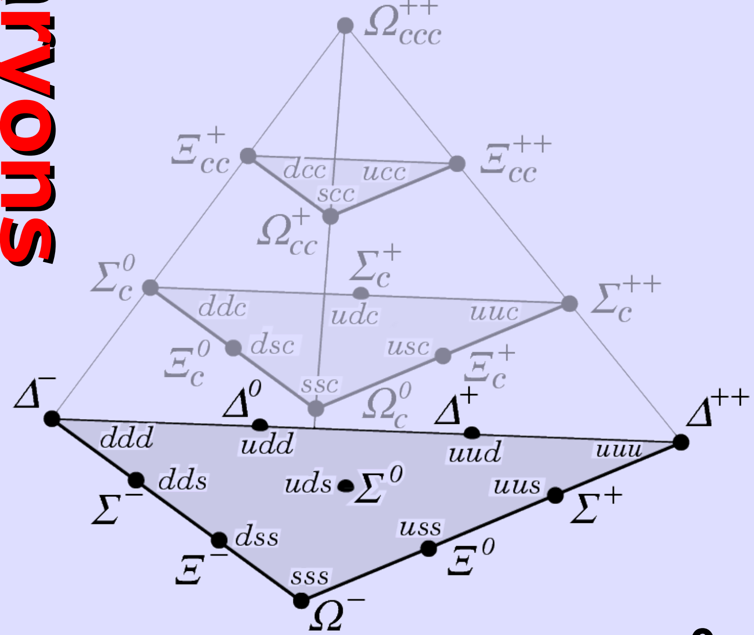
Mesons

- new degree of freedom: *strangeness*

- detection:
  - direct observation (K^-, K^+)
  - reconstruction from charged decay products (Λ, ϕ, resonances)

Baryons





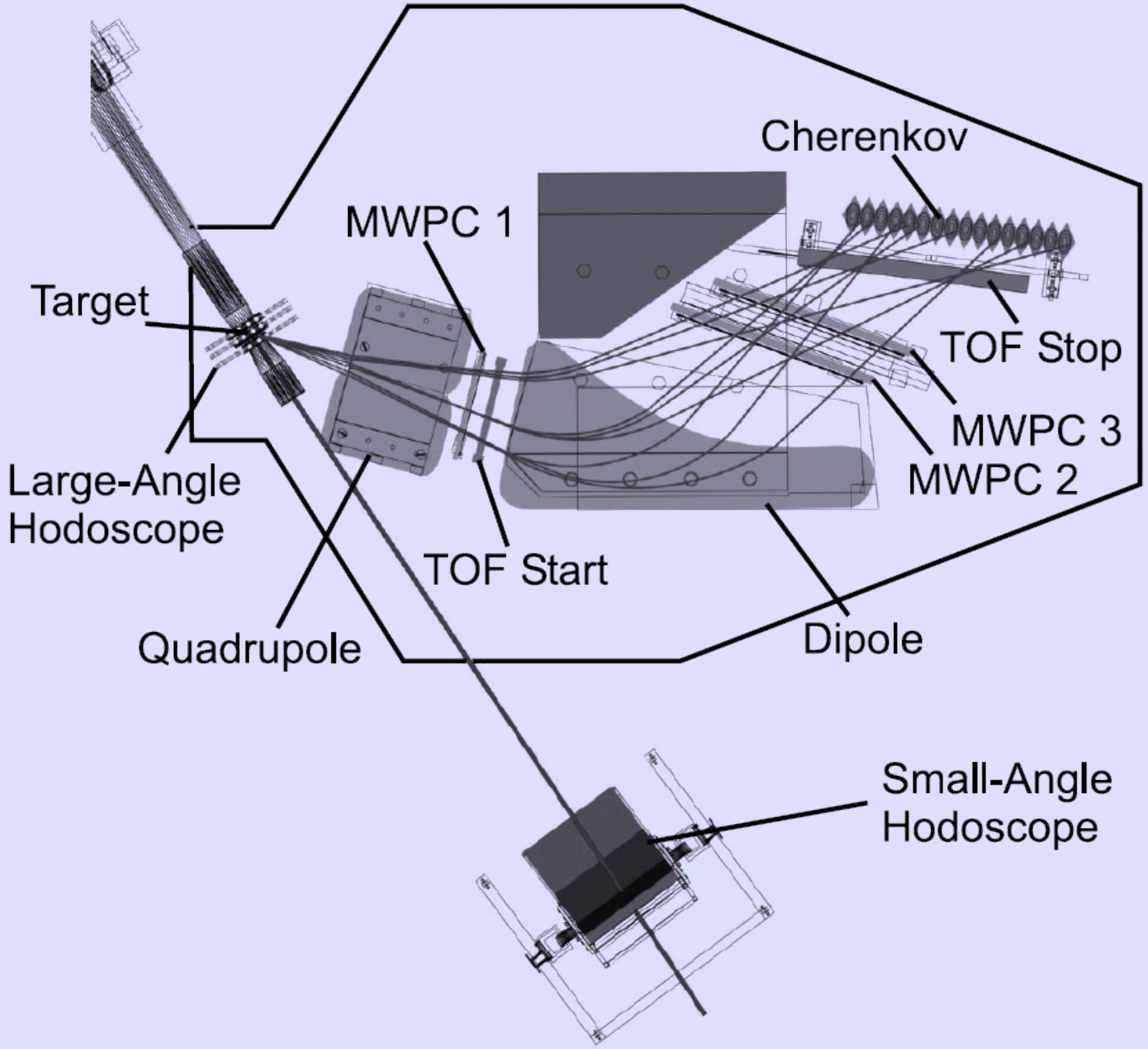
Production Thresholds

- beam energies at SIS-18
  - 1 – 2 AGeV
- typical particle production thresholds for free N+N collisions (in QCD vacuum):
  - 1.6 – 2.5 GeV
- additional effects in HIC:
  - multi-step processes
    - π+N, Δ+N, ... collisions
  - strangeness exchange
    - e.g. $\pi + \Lambda \leftrightarrow N + K^-$

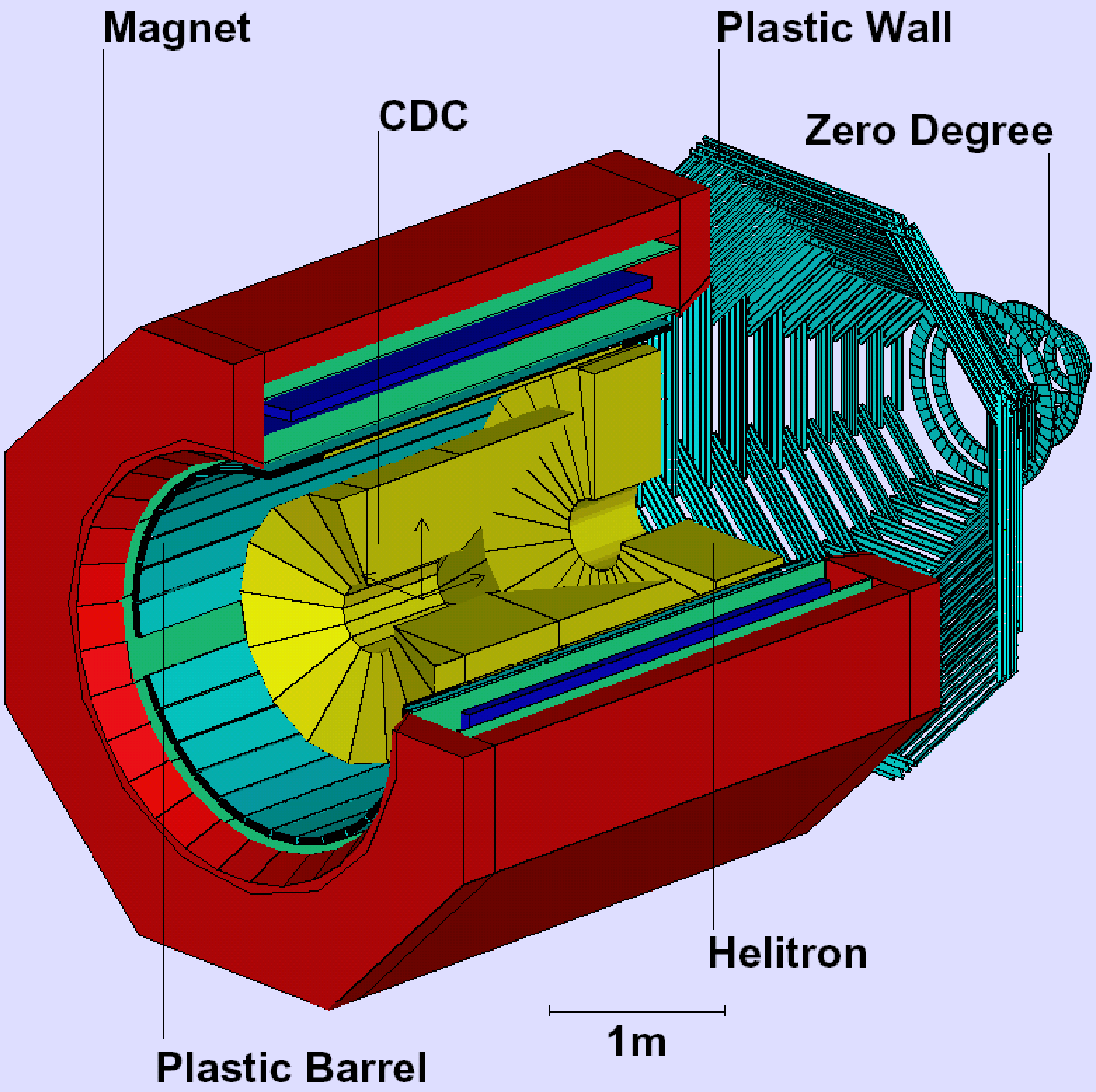
Process			E_{thr} [GeV]
N N	$\rightarrow$	$N K^+ \Lambda^0$	1,58
		$N K^+ \Sigma$	1,80
		$N N K^+ K^-$	2,50
		$N \Xi^- K^+ K^+$	3,74

The KaoS Experiment

- spectrometer optimized for Kaon detection
- compact size: flight path from 5.0 – 6.6 m
  → minimize Kaon loss due to decay ($c\tau$ = 3.7 m)
- PID via
  - TOF
  - Cherenkov Det.
- experiment finished...

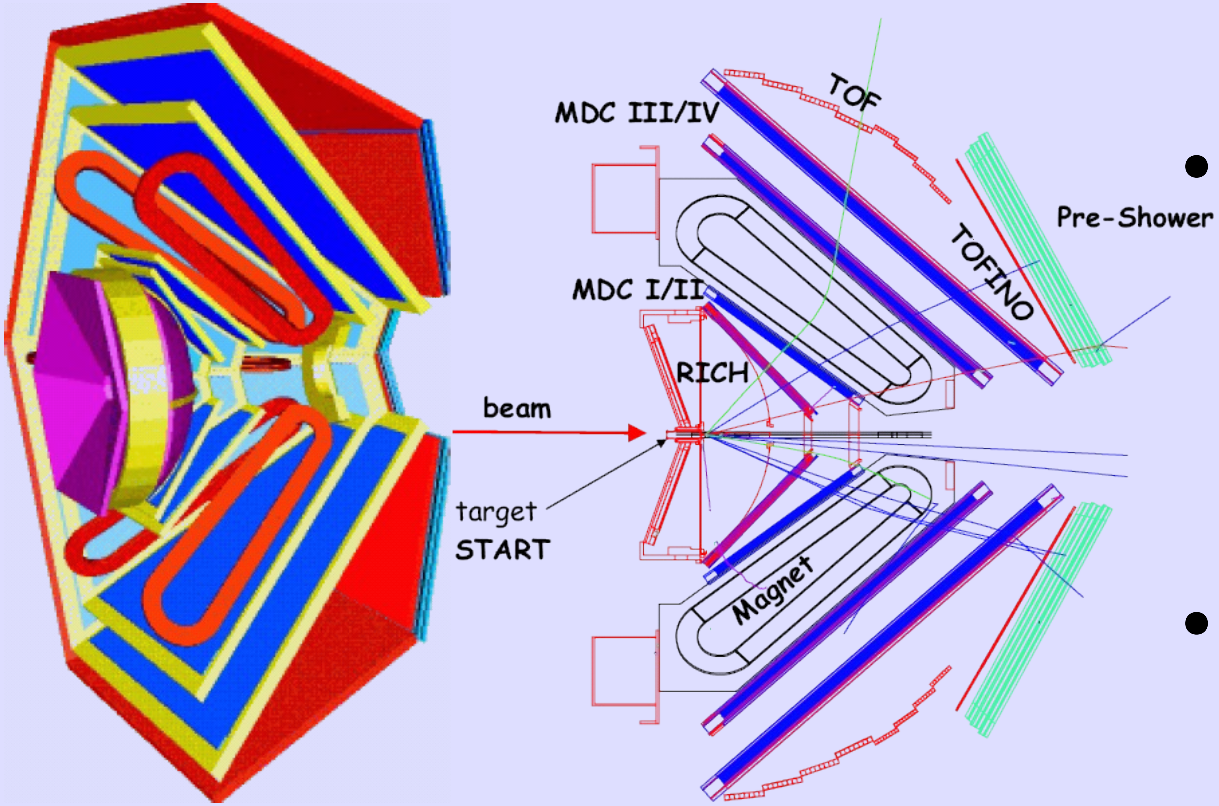


The FOPI Experiment



- multi-purpose detector
  - 4π geom. acceptance
  - drift chambers & scintillators
- strange particle detection
  - Plastic Barrel ($K^{\pm}$), directly measured via TOF
  - Central Drift Chamber (K^0,Λ,...) via invariant mass reconstr.

The HADES Experiment

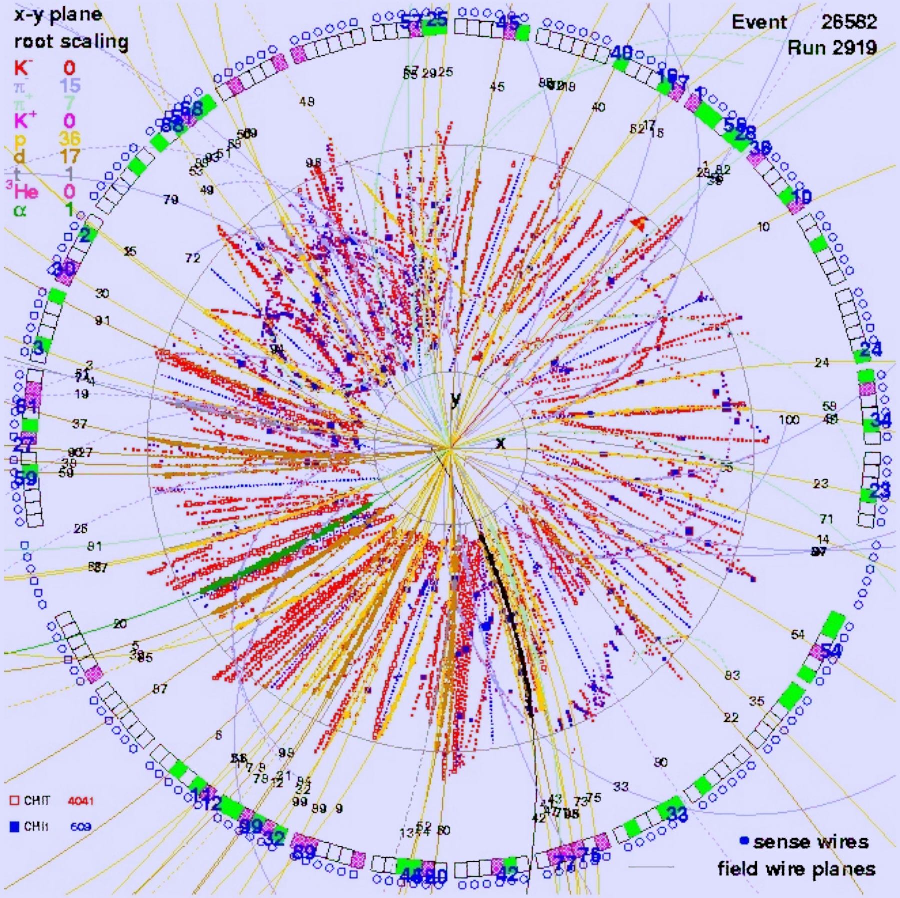


P. Salabura et al., NPA 749 (2005) 150c

- **H**igh **A**cceptance **D**i-**E**lectron **S**pectrometer
- study vector meson properties in π+A, p+A and A+A reactions via e^+e^- pairs from ρ, ω and ϕ decays (in the fireball !)
- presented first results on K^0 production; vector meson measurements under way

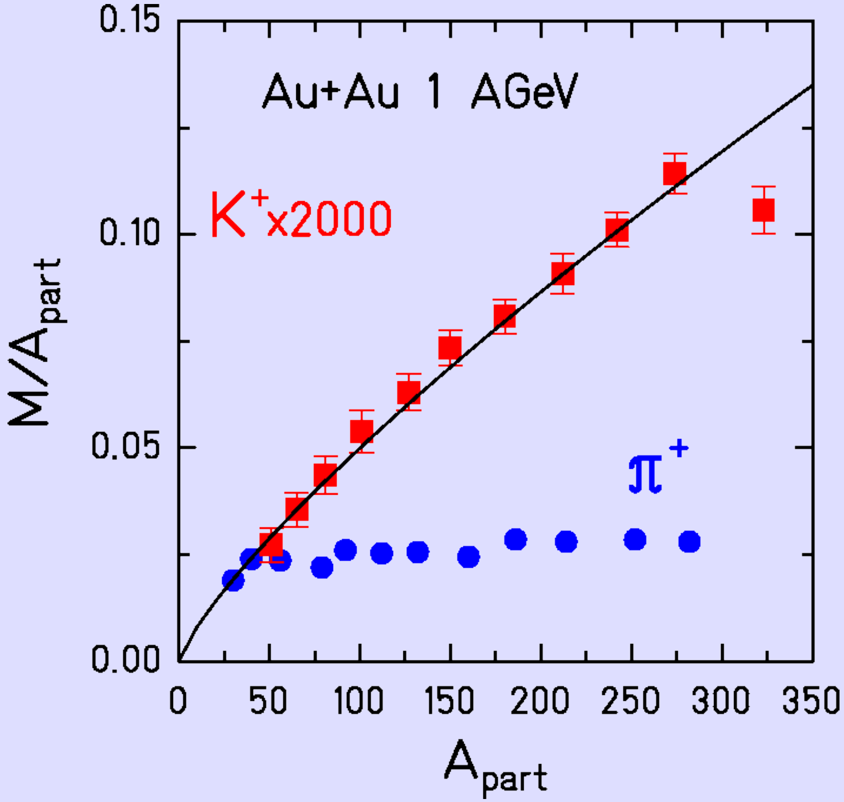
Search for Strange Particles

- At SIS: strange particle production close to / below threshold
  - high sensitivity
  - low yields
    (P(K±)/Event ~ 10^{-2} - 10^{-4})

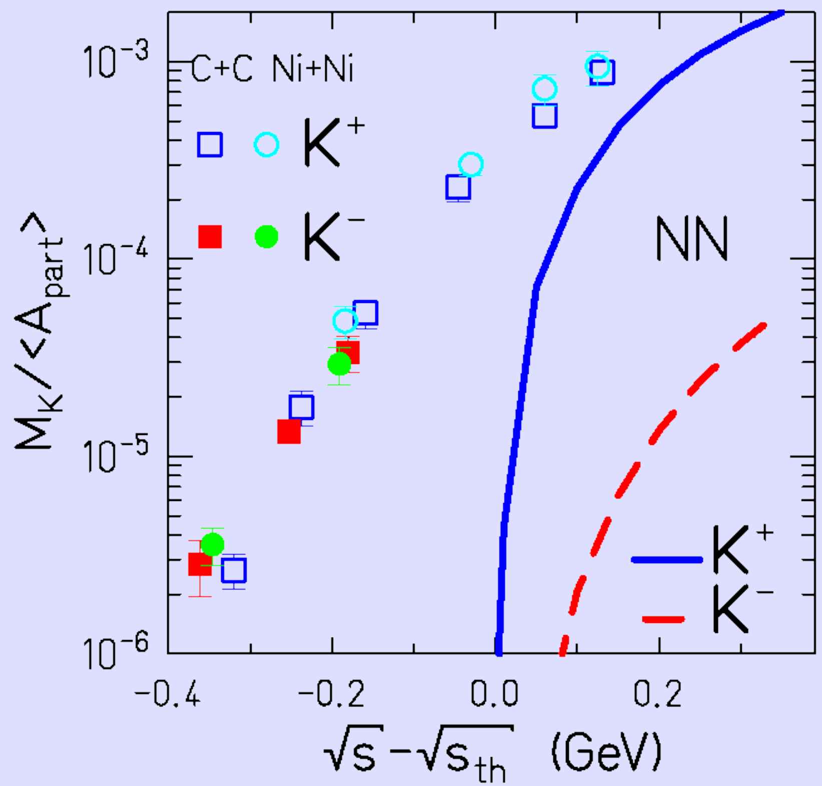


- find / reconstruct particles from background of few tens up to ~200 tracks

Kaon Production



M. Mang, PhD Thesis, IKF, Univ. Frankfurt, (1997)



F. Laue et al., PRL 82 (1999) 1640

- K^+ multiplicity rises strongly with A_{part} → multi-step proc.
- same behaviour of K^+ & K^-
- produced below threshold

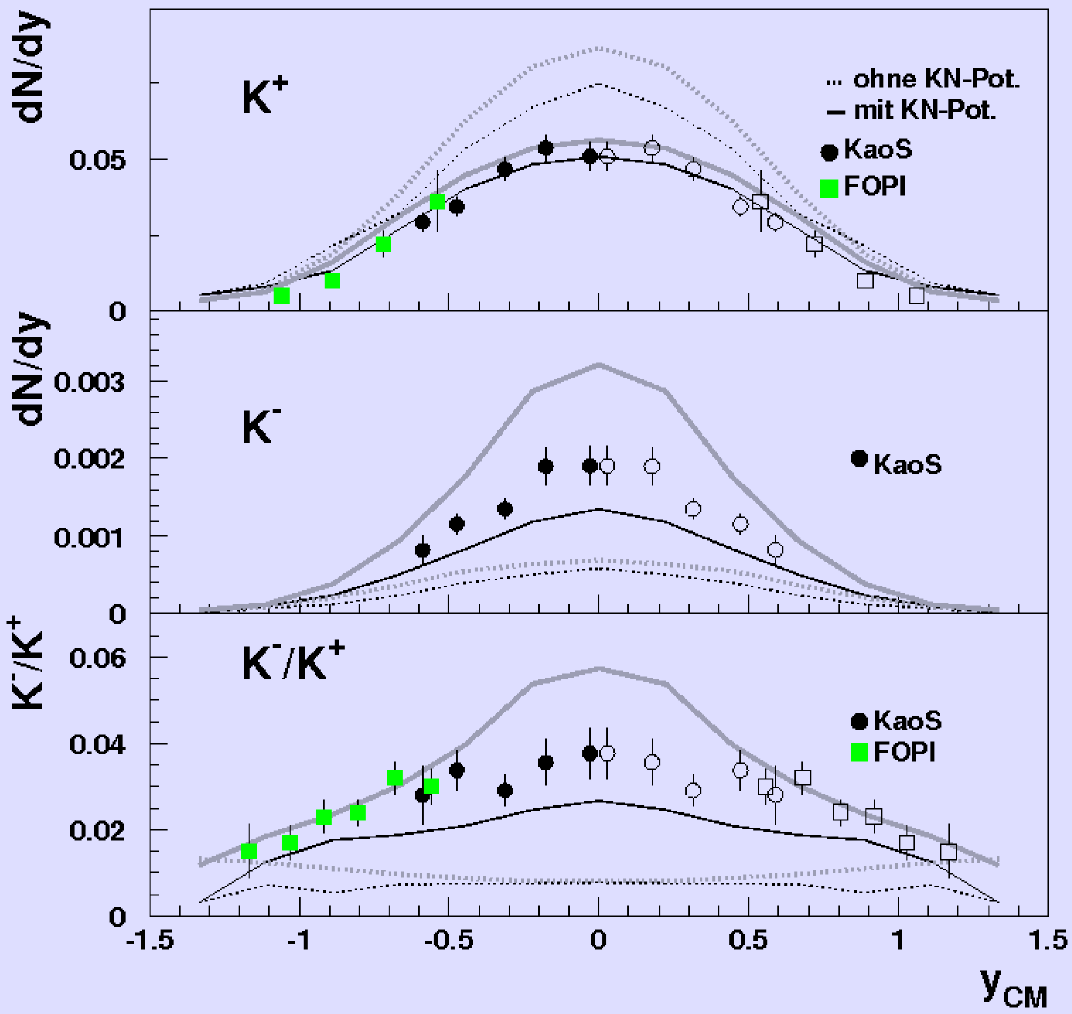
Kaon Rapidity Distributions

$$y_{CM} = y_{lab} - \frac{y_{beam}}{2}$$

(symm. system)

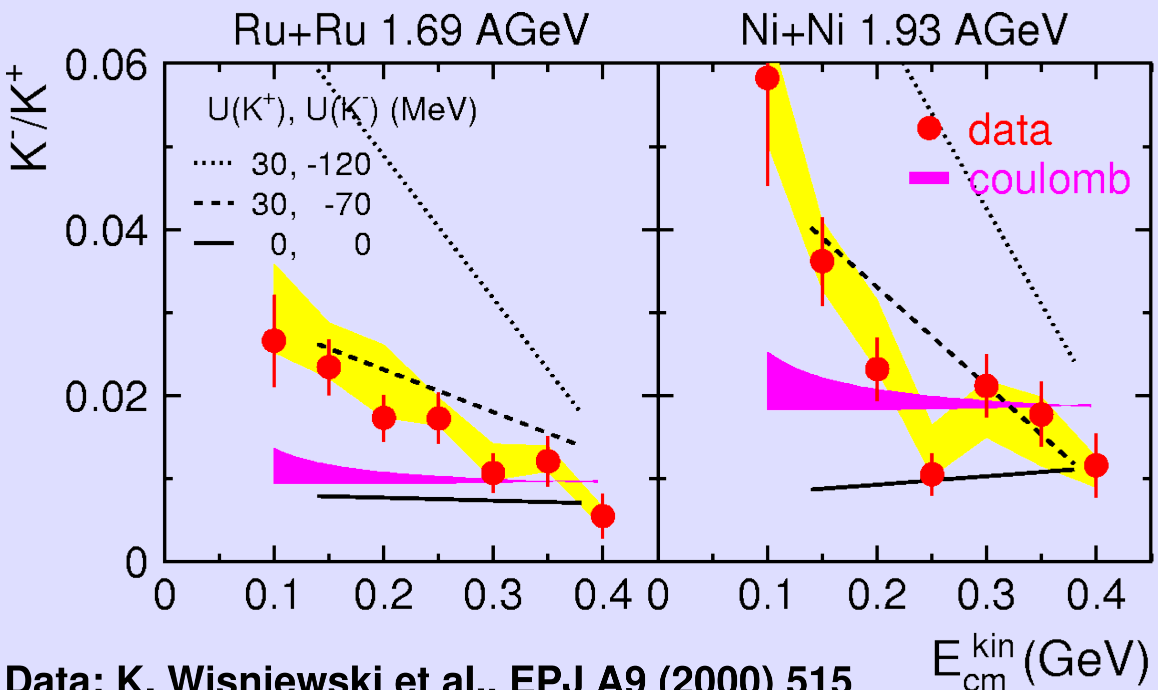
- compare transport model calc. to FOPI / KaoS data
- repulsive & attractive kaon-nucleon potentials needed
- problem: reproduce more than one observable at the same time

Ni+Ni, 1.93 AGeV

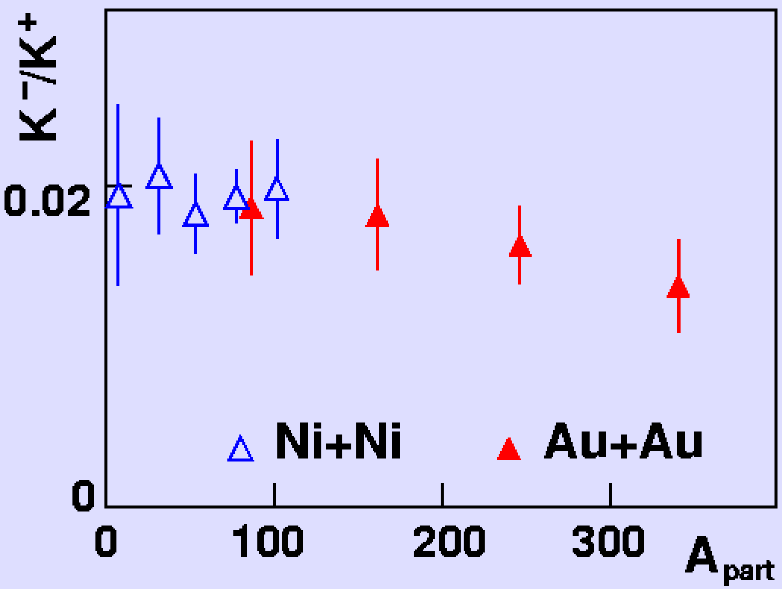


P. Senger, Acta Phys. Pol. B 31 (2000) 2313

K^-/K^+ Ratios



Data: K. Wisniewski et al., EPJ A9 (2000) 515
RBUU: W.Cassing, E.L.Bratkovskaya, Phys.Rept.308 (1999) 65



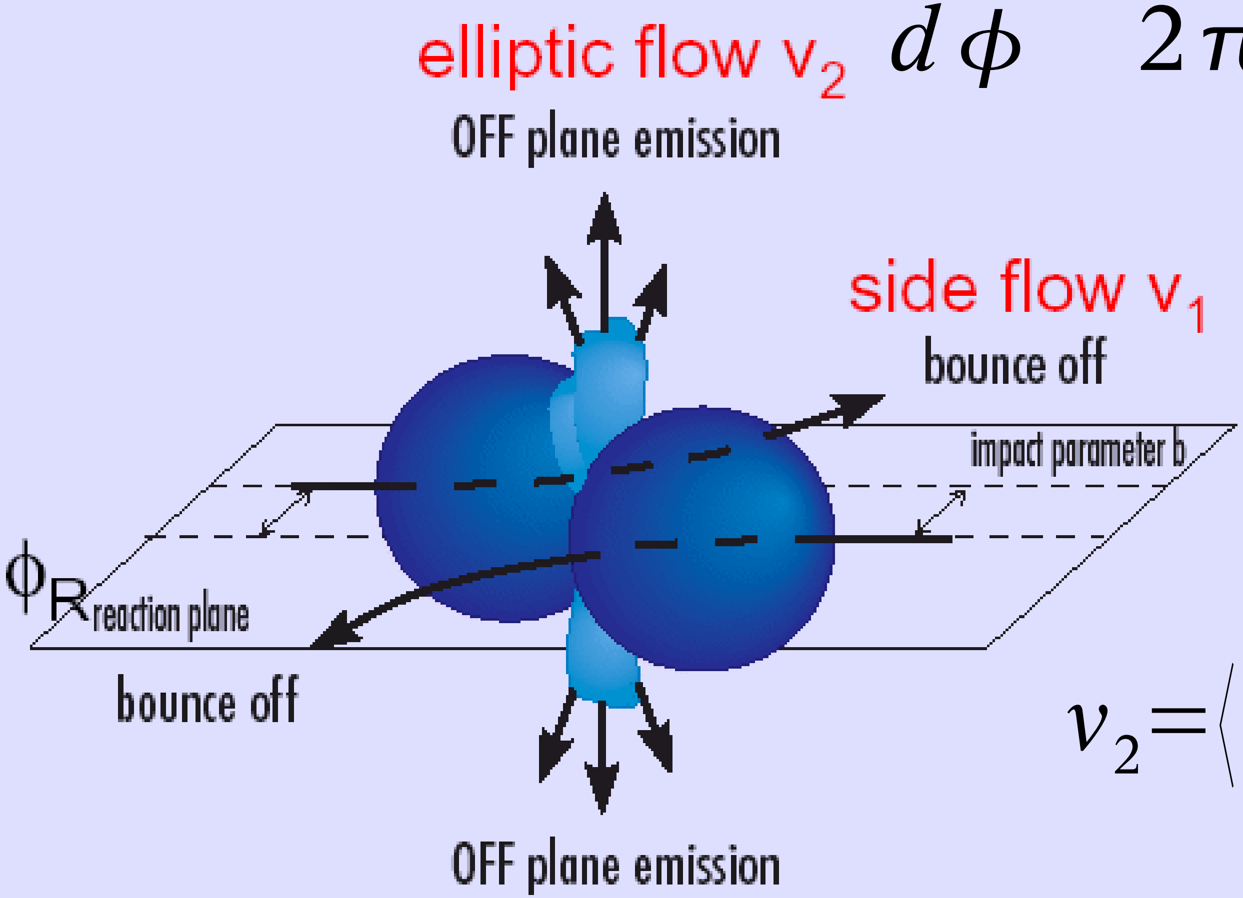
A. Förster et al., PRL 91 (2003) 152301

- probe both particles in the same environment
- IME needed to explain observations

- ratio nearly constant with centrality
- kaon yields linked due to strangeness exchange?

Flow in Nuclear Collisions

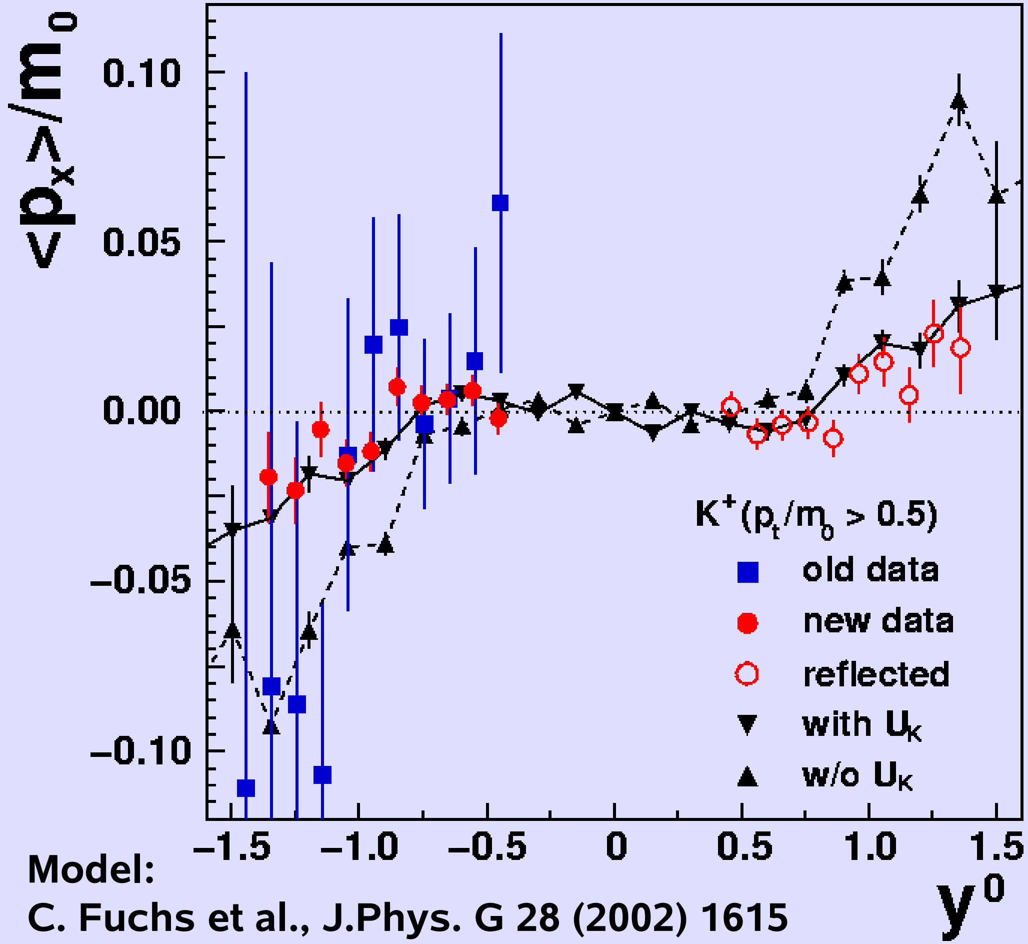
$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2 v_n \cos(n\phi)\right)$$



$$v_1 = \langle \cos(\phi_{em}) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$

$$v_2 = \langle \cos(2\phi_{em}) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

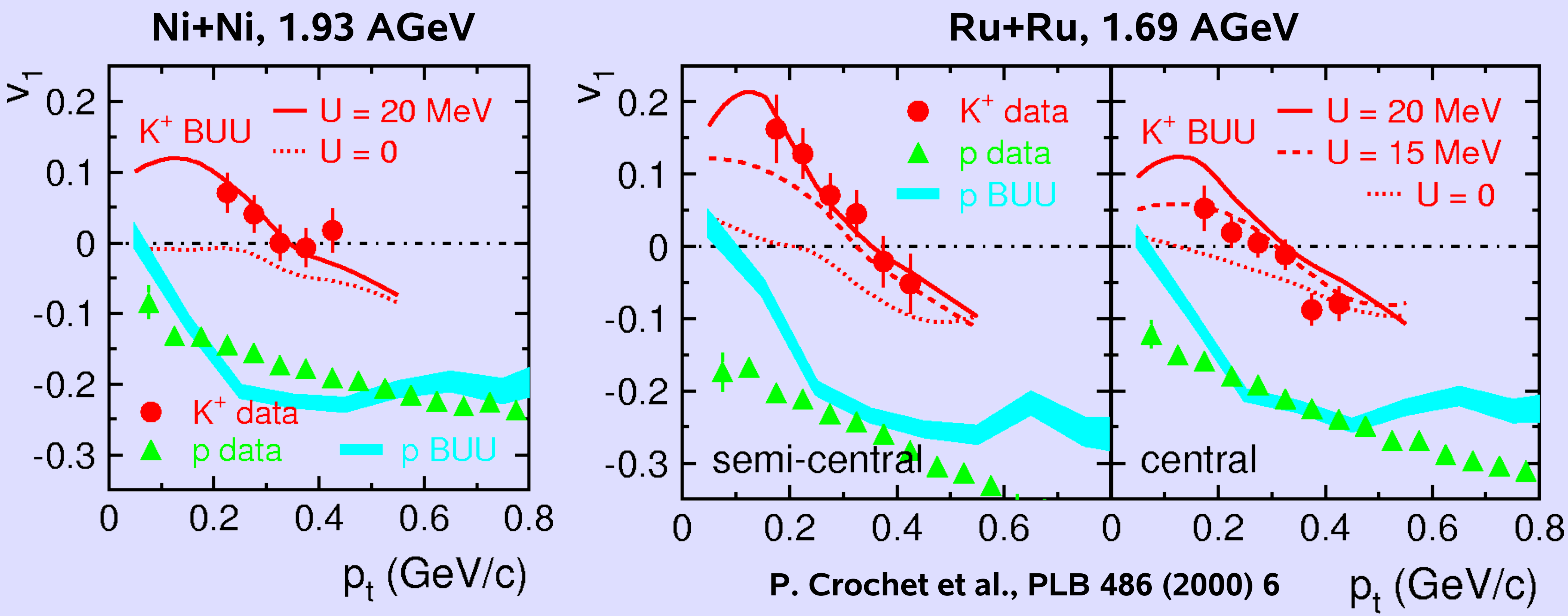
K^+ Sideflow



Model:
C. Fuchs et al., J.Phys. G 28 (2002) 1615
Data:
J. Ritman et al.,Z.Phys. A325 (1995) 355
N. Herrmann et al., Prog.Part.Nucl.Phys. 42 (1999) 187

- study emission of K+
- no (integral) K^+ flow seen between target & projectile rapidities
- compatible with QMD calc. using in-medium K-N pot.
- Future: measure K^- flow using improved TOF information (RPC Barrel)

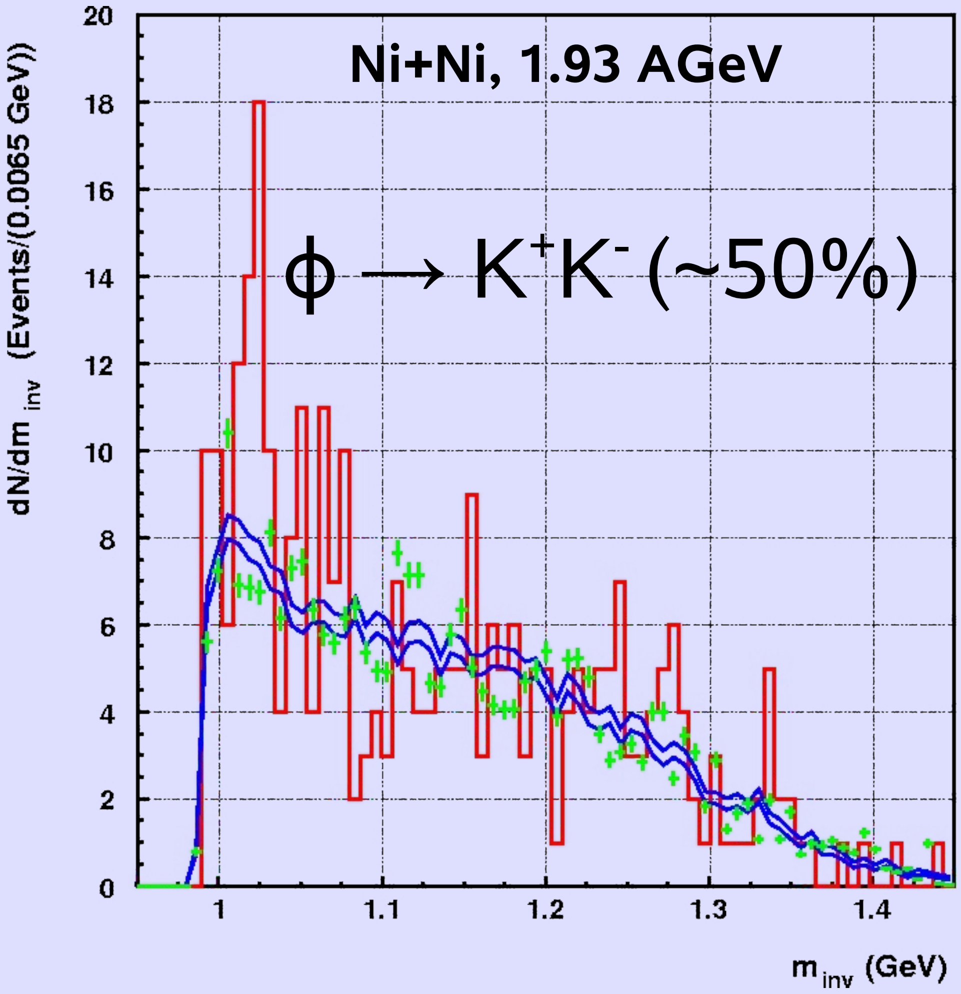
K^+ Differential Sideflow



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

- K^+ anti-flowing for low p_t (w.r.t. protons)
- different flow patterns
- model comparison favors repulsive in-medium potential (~20 MeV)

ϕ Meson Production

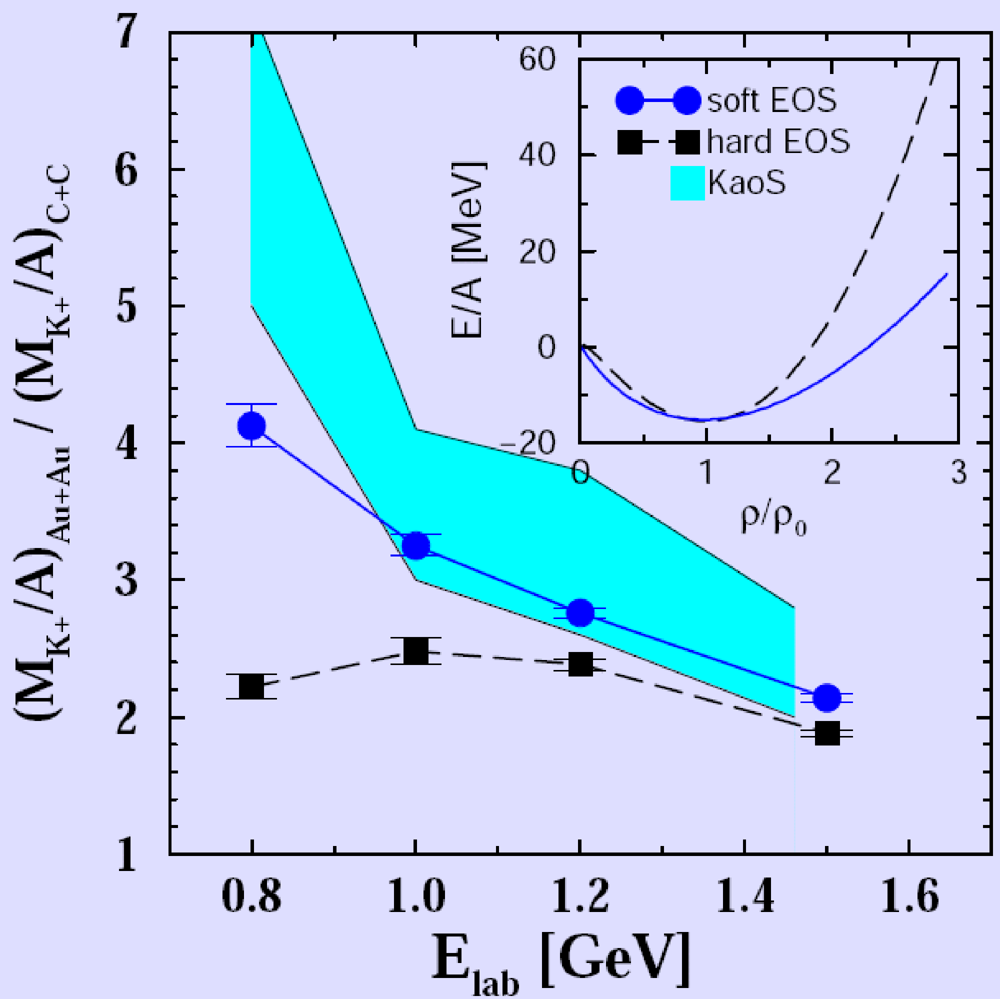


A. Mangiarotti et al., NPA 714 (2003) 89

- K^- is a rare probe; production mechanism understood?
  - IME
  - feeding via ϕ decays or Λ
- ϕ/K^- ratio:
  - R(130 MeV) = (0.44±0.15±0.21)
  - R(70 MeV) = (1.80±0.60±0.85)
- at least 20% of K^- originate from decay of a ϕ meson

EOS from K^+

- investigate EOS via K^+ production (sensitive to incompressibility κ)
- use Au+Au to C+C ratio
  - cancel experimental effects
  - avoid influence of cross sections in model calc.
- comparison to theory:
  - soft EOS: κ = 200 MeV
  - hard EOS: κ = 380 MeV
- soft EOS favored



C. Fuchs et al., Phys.Rev.Lett. 86 (2001) 1974

What have we learned already ?

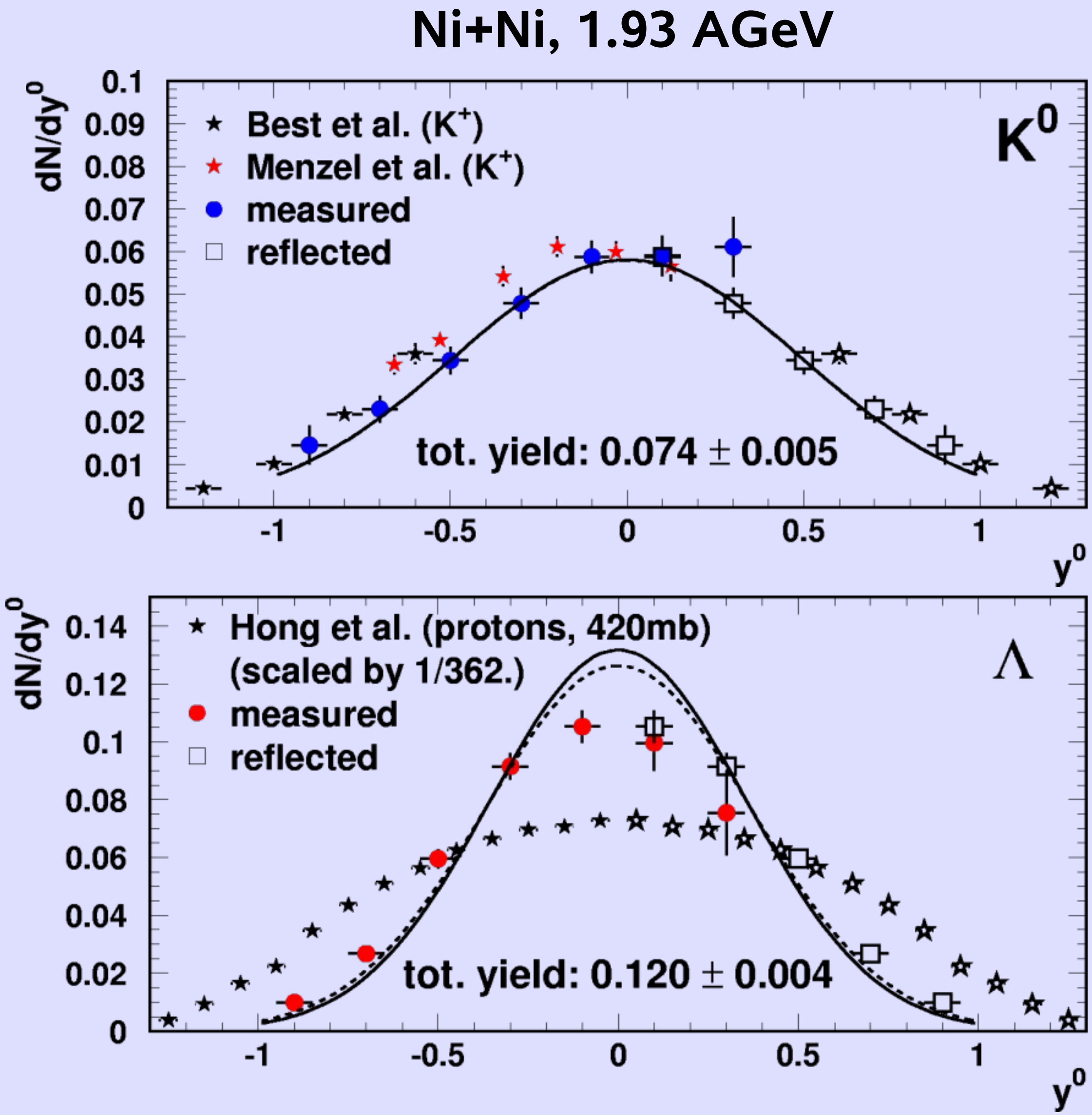
- particle production
  - multi-step processes
  - models need IM-potentials
  - strangeness exchange
- particle flow
  - supports need of IM-pot.
  - direct observation of K+ proton anti-correlation
- rare probes
  - origin of K^- ?

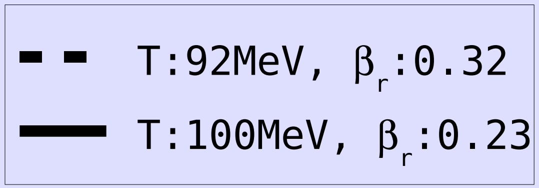
- systematic studies
  - EOS → soft (?)

→ need higher statistics
  - access to new probes
  - more quantitative studies
  - provide further model constraints

K^0 & Λ Particle Yields

- dN/dy^0 distributions of K^+ and K^0 agree
- different reaction dynamics for Λ and protons
- comparison to distributions from an expanding (β) thermal (T) source
  - K^0 distribution reproduced
  - Λ closer to thermal distribution than protons





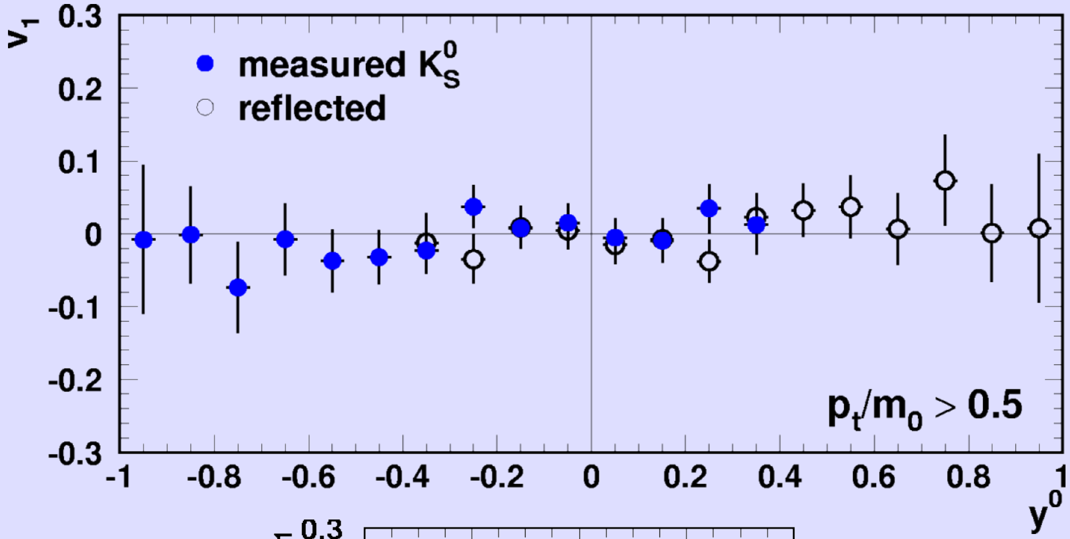
K^0 Sideflow

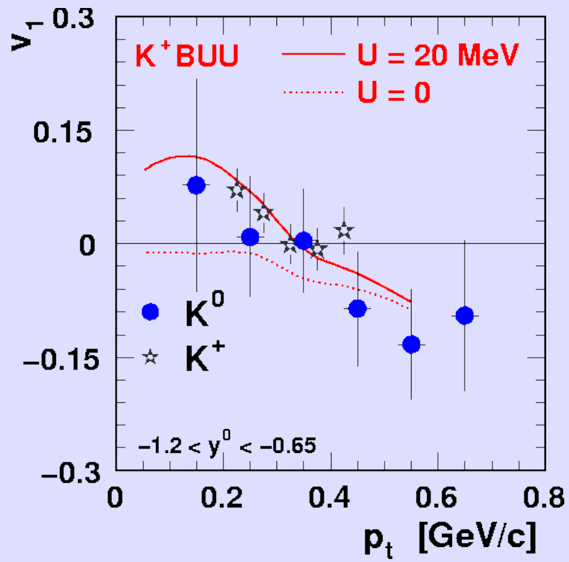
- K^0 flow is compatible with K^+ results from previous experiment

$\Rightarrow$ negligible influence of Coulomb effects

- evidence for IME found in K^+ sideflow also supported by K^0 results

Ni+Ni, 1.93 AGeV



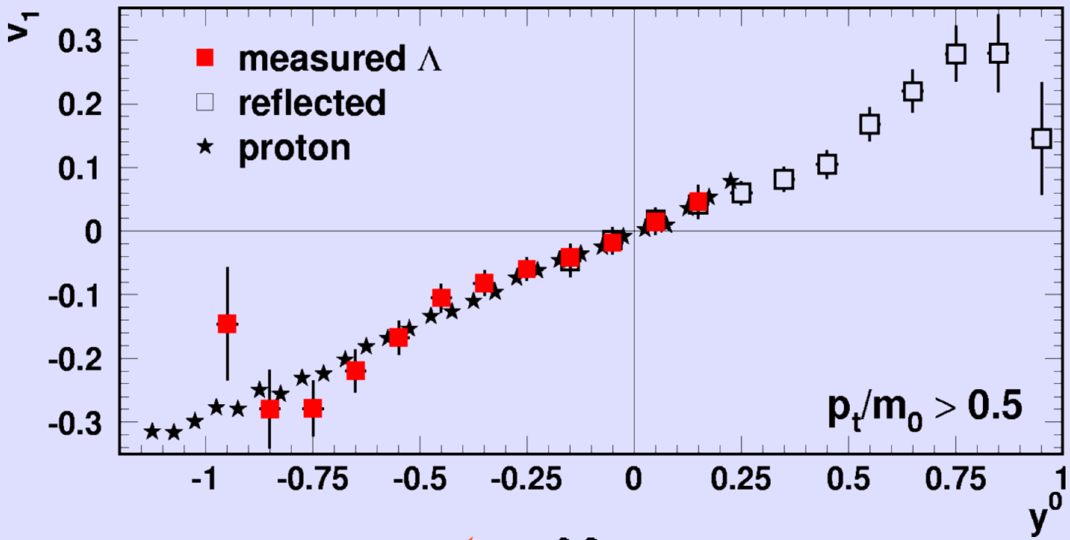


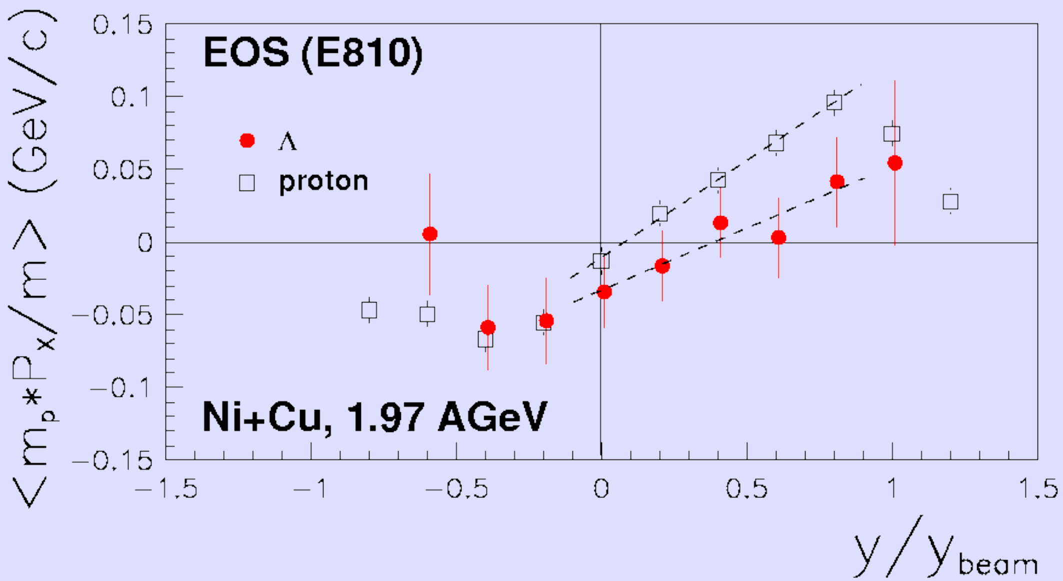
Λ Sideflow

- both, Λ and proton integral and differential sideflow agree

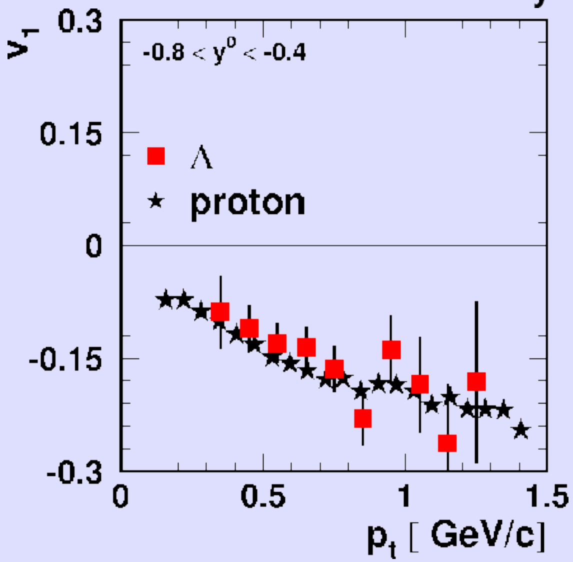
⇒ how strong is the in-medium Λ-N potential $U_{\Lambda N}$?

Ni+Ni, 1.93 AGeV





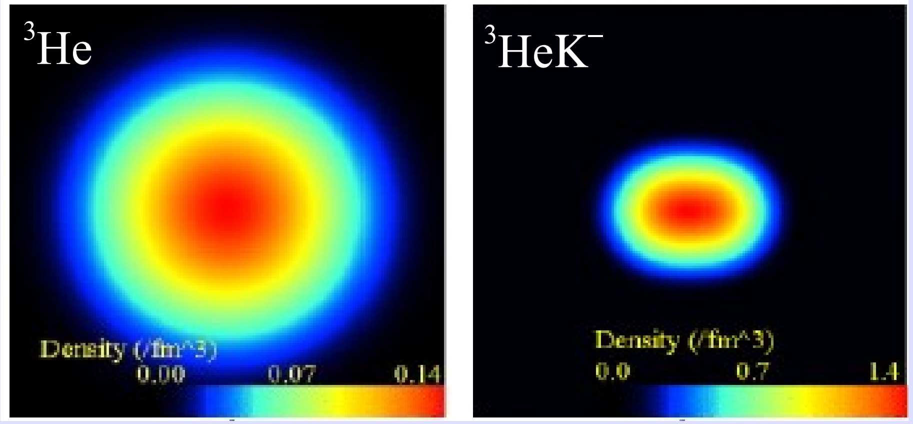
$$U_{\Lambda N} = \frac{2}{3} U_{NN}$$



What have we learned from SIS-18 ?

- got some answers
  - K^0 and K^+ have same flow behavior
  - K^+ flow pattern not caused by Coulomb repulsion
  - Λ and proton have same flow behavior
- raised new questions
  - origin of the K^- ?
  - baryon dynamics ?
- pending / to come
  - K^- measurements (flow)
  - more on strange Baryons

Are there even stranger things ?



Y. Akaishi and T.Yamazaki, Phys.Rev. C65 (2002) 044005

T.Yamazaki and Y. Akaishi, Phys.Lett. B535 (2002) 70

- theoretical calculations predict series of strongly bound states; result of a strongly attractive K^- potential
- narrow states (Γ ~ 20 MeV)
- hypothetical decay channels into Λ+ X

$ppK^- \rightarrow \Lambda + p + 263$ MeV
$ppnK^- \rightarrow \Lambda + d + 208$ MeV
$pppK^- \rightarrow \Lambda + p + p + 219$ MeV
$ppnnK^- \rightarrow \Lambda + t + 217$ MeV
$pppnK^- \rightarrow \Lambda + {}^3He + 219$ MeV