Naresuan University

Azimuthal Emission of K^+ in Ni+Ni collisions at energy 1.91 A GeV

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HADRON NUCLEAR PHYSICS 2015
July 7- 11, 2015 @Krabi, Thailand

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- Kaon production in transport model
- Probing in-medium kaon potential
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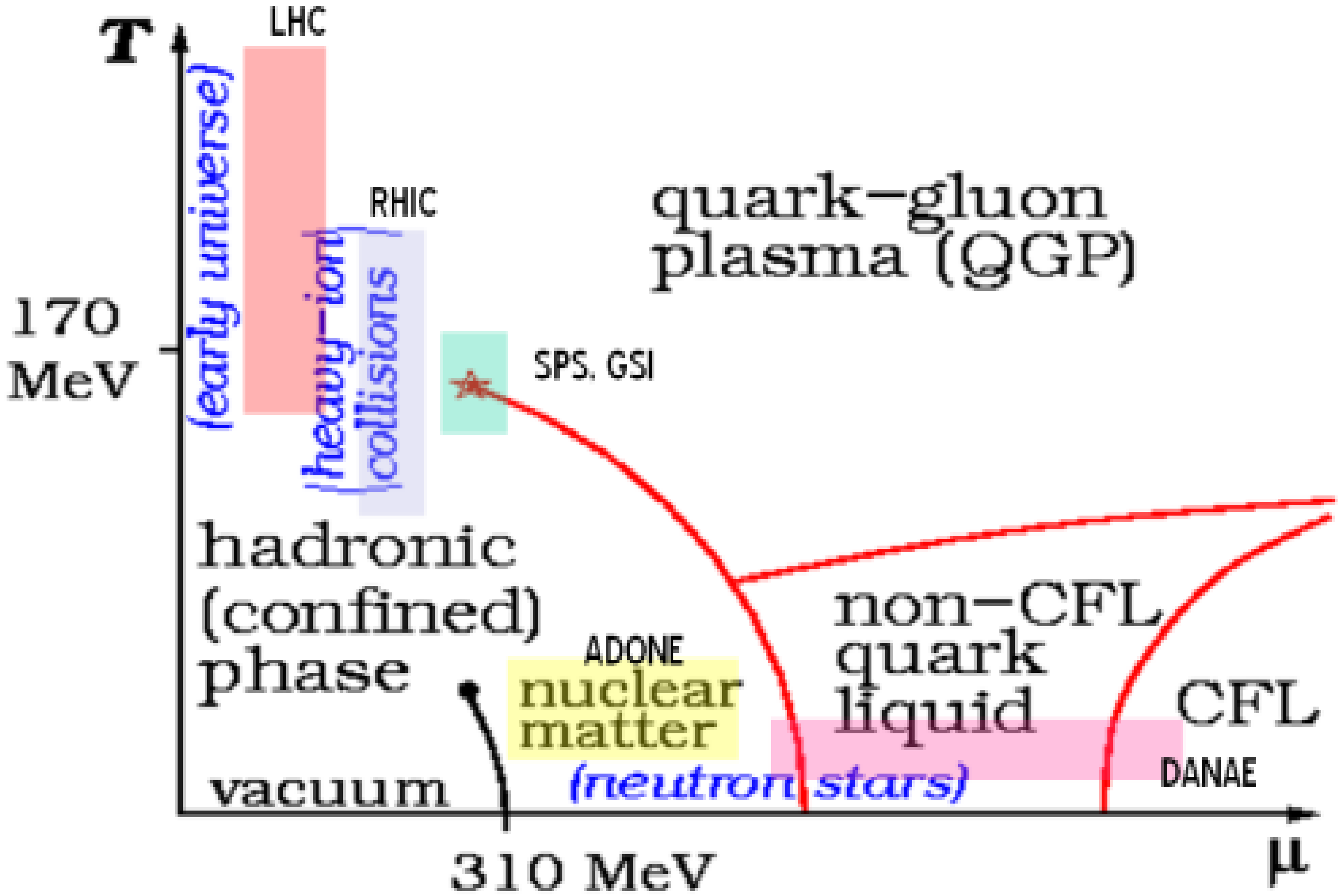

T
LHC
(early universe)
RHIC
(heavy-ion collisions)
quark–gluon plasma (QGP)
170 MeV
SPS, GSI
hadronic (confined) phase
non–CFL quark liquid
ADONE
nuclear matter
CFL
DANAE
vacuum
(neutron stars)
310 MeV
μ

Introduction

- Kaons in dense hadronic matter are important for, a possible restoration of chiral symmetry in dense hadronic matter.
- KaOS and FOPI search for the kaon in-medium properties in HIC.
- We apply covariant kaon dynamics to study azimuthal emission of K^+

Kaons in dense matter

- Chiral SU(3) Lagrangian

The chiral $SU(3)_L \times SU(3)_R$ Lagrangian used by Kaplan and Nelson

$$\begin{aligned}
\mathcal{L} &= \frac{1}{4} f^2 \mathrm{Tr}\partial^\mu \Sigma \partial_\mu \Sigma^+ + \frac{1}{2} f^2 \Lambda [\mathrm{Tr} M_q (\Sigma - 1) + \mathrm{h.c.}] + \mathrm{Tr}\bar{B}(i\gamma^\mu \partial_\mu - m_B) B \\
&+ i\mathrm{Tr}\bar{B}\gamma^\mu [V_\mu, B] + D\mathrm{Tr}\bar{B}\gamma^\mu \gamma^5 \{A_\mu, B\} + F\mathrm{Tr}\bar{B}\gamma^\mu \gamma^5 [A_\mu, B] \\
&+ a_1 \mathrm{Tr}\bar{B}(\xi M_q \xi + \mathrm{h.c.}) B + a_2 \mathrm{Tr}\bar{B} B (\xi M_q \xi + \mathrm{h.c.}) \\
&+ a_3 [\mathrm{Tr} M_q \Sigma + \mathrm{h.c.}] \mathrm{Tr}\bar{B} B. \qquad (1)
\end{aligned}$$

[PLB 175 (86) 57, NPLB 192 (87) 193]

The degrees of freedom in this eq 1. are the

baryon octet B

$$B = \begin{pmatrix} \frac{\Lambda}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\ \Sigma^- & \Sigma^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix} \quad (2)$$

the pseudoscalar meson octet ϕ

$$\phi = \begin{pmatrix} \frac{\eta_s}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_s}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \overline{K^0} & -\frac{2\eta_s}{\sqrt{6}} \end{pmatrix} \quad (3)$$

The chiral pseudoscalar meson field are

$$\Sigma = \exp(2i\phi / f_\pi)$$
$$\xi = \sqrt{\Sigma} = \exp(i\phi / f_\pi) \qquad (4)$$

$f_\pi \approx 93$ MeV.

The current quark mass matrix is given by

$$M_q = \begin{pmatrix} m_q & 0 & 0 \\ 0 & m_q & 0 \\ 0 & 0 & m_s \end{pmatrix} \qquad (5)$$

where $m_u \approx m_d \equiv m_q \approx 5.5$ MeV.

The mesonic vector V_μ and axial vector A_μ

$$V_\mu = \frac{1}{2}\left(\xi^+ \partial_\mu \xi + \xi \partial_\mu \xi^+\right) \qquad (6)$$
$$A_\mu = \frac{i}{2}\left(\xi^+ \partial_\mu \xi - \xi \partial_\mu \xi^+\right)$$

- Effective chiral Lagrangian

By expending the pseudoscalar meson field Σ up to $1/f_\pi^2$, and only keeping the kaon field K and explicitly only nucleon and kaon degrees of freedom, the Lagrangian (1) is reduced to the effectve chiral kaon-nucleon Lagrangian

$$L = \bar{N}\left(i\gamma^\mu \partial_\mu - m_N\right)N + \partial^\mu \bar{K}\partial_\mu K - \left(m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\bar{N}N\right)\bar{K}K - \frac{3i}{8f_\pi^2}\bar{N}\gamma^\mu N\bar{K}\overleftrightarrow{\partial}_\mu K \qquad (7)$$

where the kaon field and the nucleon field are

$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \quad \bar{K} = \begin{pmatrix} K^- & \bar{K}^0 \end{pmatrix}, \quad N = \begin{pmatrix} p \\ n \end{pmatrix} \quad \bar{N} = \begin{pmatrix} \bar{p} & \bar{n} \end{pmatrix}$$

The kaon mass m_K can be related to the vacuum quark condensates

$$m_K^2 = \frac{1}{2}(m_u + m_s)\langle \bar{u}u + \bar{s}s \rangle \qquad (8)$$

The kaon-nucleon sigma term is

$$\Sigma_{KN} = \frac{1}{2}(m_u + m_s)\langle N | \bar{u}u + s\bar{s} | N \rangle \qquad (9)$$

Kaon-nucleon scattering yields values for the isospin averaged sigma term of about

$$\Sigma_{KN} \approx 400 \text{ MeV}$$

- Mean field dynamics

By applying the mean-field approximation, the field equations for the $K^{\pm}$

$$\left[\partial_\mu\partial^\mu \pm \frac{3i}{4f_\pi^2} j_\mu \partial^\mu + \left(m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho_s\right)\right]\phi_{K^\pm}(x) = 0 \quad . \qquad (10)$$

ρ_s is the baryon scalar density,
j_μ is the baryon four-vector current
f_π^2 is the in-medium pion decay constant.

the kaonic vector potential

$$V_\mu = \frac{3}{8f_\pi^2} j_\mu \qquad (11)$$

Eq. (10) can be rewritten in the form

$$\left[(\partial_\mu \pm iV_\mu)^2 + m_K^{*2}\right]\phi_{K^\pm}(x) = 0 \quad . \qquad (12)$$

$$m_K^* = \sqrt{m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho_s + V_\mu V^\mu} \quad (13)$$

Introducing effective momenta ($k_\mu^* = (E^*, K^*)$) as

$$k_\mu^* = k_\mu \mp V_\mu \quad (14)$$

the Klein-Gordon Eqs. (10) and (12) reads in momentum space

$$\left[k^{*2} - m_K^{*2}\right] \phi_K(k) = 0 \quad . \quad (15)$$

Through the in-medium dispersion relation

$$0 = k_\mu^{*2} - m_K^{*2} = k_\mu^2 - m_K^2 - 2m_K U_{opt} \quad . \quad (16)$$

one gets the kaon optical potential

$$U_{opt}(\rho, \mathbf{k}) = -\Sigma_S \pm \frac{k_\mu V^\mu}{m_K} + \frac{\Sigma_S^2 - V_\mu^2}{2m_K} = \pm \frac{k_\mu V^\mu}{m_K} - \frac{\Sigma_{KN}}{f_\pi^2 2m_K}\rho_s \quad (17)$$

The total scalar kaon self-energy is

$$\Sigma_S = m_K - m_K^* \approx \frac{1}{2m_K}\left(\frac{\Sigma_{KN}}{f_\pi^2}\rho_s - V_\mu^2\right) \qquad (18)$$

From Eq. (15) the dispersion relation follows

$$E(k) = k_0 = \sqrt{k^{*2} + m_K^{*2}} \pm V_0 \qquad (19)$$

In nuclear matter at rest where the space-like components of the vector potential vanish, i.e. V=0

and K* = K, Eq. (19) reduces to

$$E(k) = k_0 = \sqrt{k^2 + m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho_s + V_0^2} \pm V_0 \qquad (20)$$

The covariant equations of motion for kaons can be derived from Eq. (15). They are analogous to the corresponding relativistic equations for baryons and read

$$\frac{dq^\mu}{d\tau} = \frac{k^{*\mu}}{m_K^*} = u^\mu \quad (23)$$

$$\frac{dk^{*\mu}}{d\tau} = \frac{k^*_\nu}{m_K^*} F^{\mu\nu} + \partial^\mu m_K^* \ . \quad (24)$$

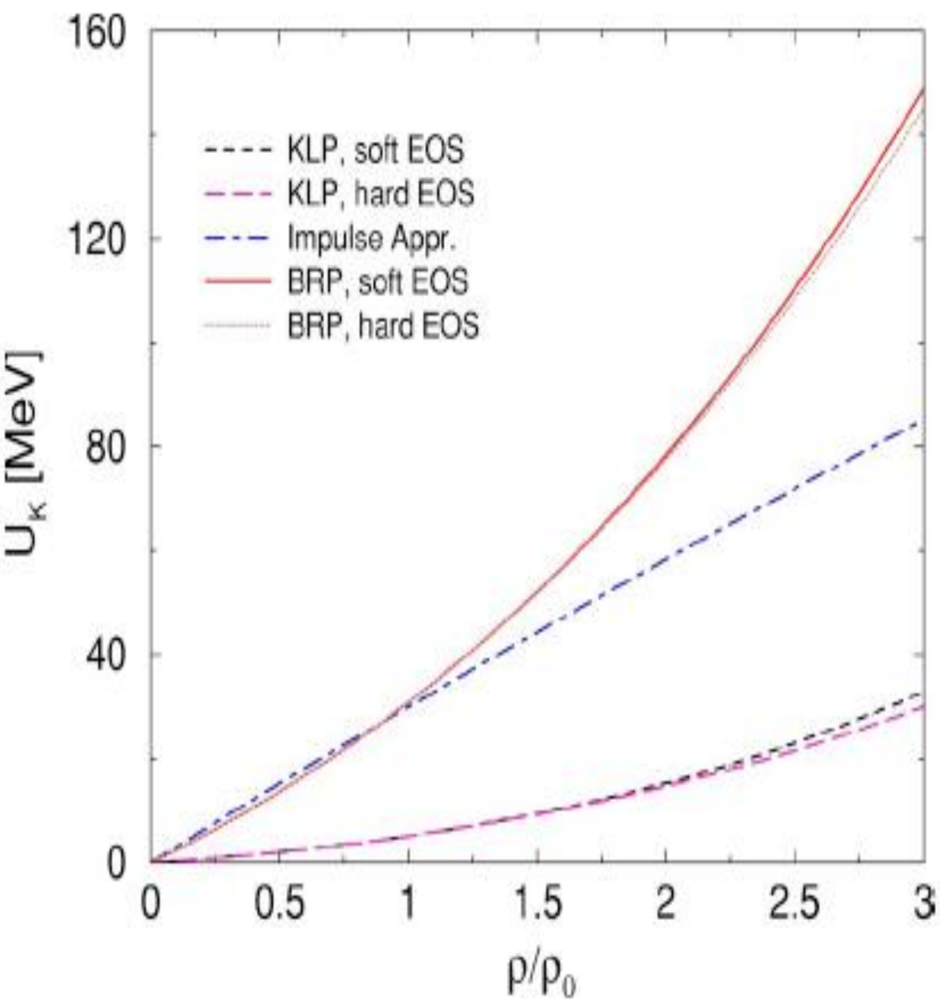
Here $q^\mu = (t, \mathbf{q})$ are the coordinates in Minkowski space

$F^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu$ is the field strength tensor for K^+.

The structure of Eq. (24) may become more transparent considering only the spatial components

$$\frac{d\mathbf{k}^*}{dt} = -\frac{m_K^*}{E^*}\frac{\partial m_K^*}{\partial \mathbf{q}} \mp \frac{\partial V^0}{\partial \mathbf{q}} \pm \frac{\mathbf{k}^*}{E^*} \times \left(\frac{\partial}{\partial \mathbf{q}} \times \mathbf{V}\right)$$

the kaon optical potential



$$U(\rho,\mathbf{k}) = \omega(\rho,\mathbf{k}) - \omega_0(\mathbf{k})$$

$$= \sqrt{\mathbf{k}^2 + m_K^2 - \frac{\Sigma_{KN}}{f_\pi^{*2}}\rho_s + V_0^2} \pm V_0$$

$$- \sqrt{\mathbf{k}^2 + m_K^2}$$

BR potential $U_K(\rho_0) \approx 30 \quad MeV$

$$\Sigma_{KN} = 450 \quad MeV$$

$$f_\pi^{*2} = 0.6 f_\pi^2 \quad ; \quad f_\pi^{*2} = f_\pi^2$$

KL potential $U_K(\rho_0) \approx 5 \quad MeV$

$$\Sigma_{KN} = 350 \quad MeV$$

$$f_\pi^{*2} = f_\pi^2$$

Density dependence of the in-medium kaon potential at zero momentum. IA: the impulse approximation

[NPA 567 (1994) 937],

Kaon production in transport model

Kaon; m_0= 0.454 GeV

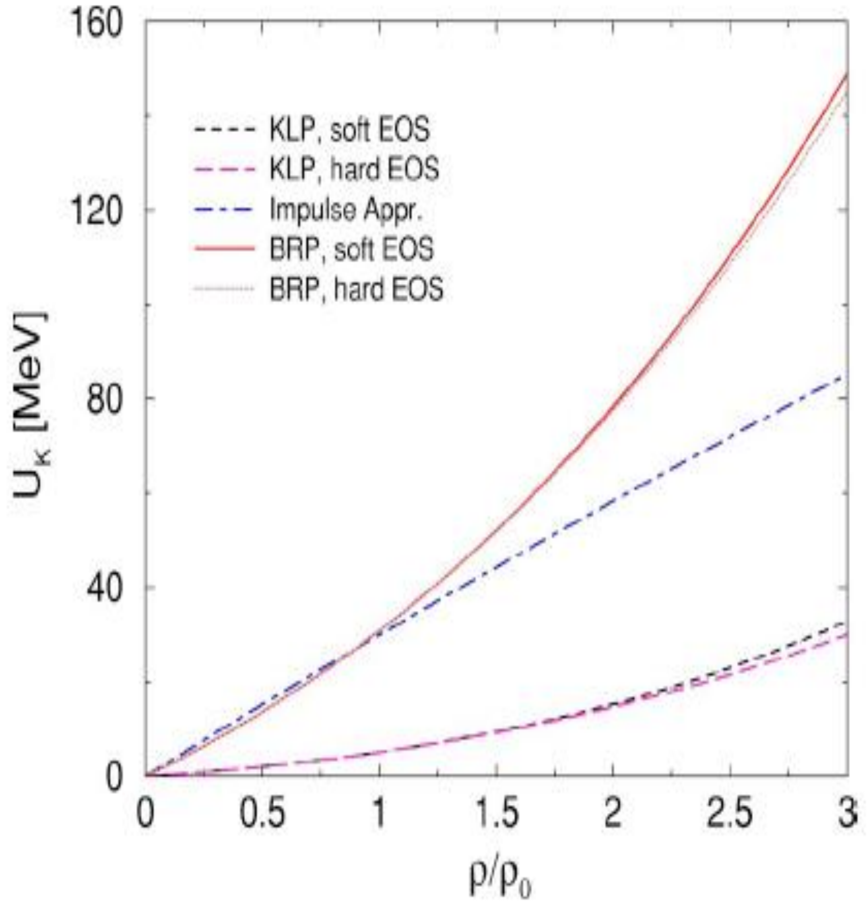
$$K^+(u\bar{s}):\quad NN \to N\Lambda K^+ \qquad E_{thr} = 1.58\ \ GeV$$

$$\pi N \to \Lambda K^+$$

$$K^-(\bar{u}s):\quad NN \to NNK^+K^- \qquad E_{thr} = 2.5\ \ GeV$$

Subthreshold Kaon production (E_{Lab}< E_{thr}):

K^+ Long Mean free path ~7 fm at ρ_0



$$U(\rho,\mathbf{k}) = \omega(\rho,\mathbf{k}) - \omega_0(\mathbf{k})$$
$$= \sqrt{\mathbf{k}^2 + m_K^2 - \frac{\Sigma_{KN}}{f_\pi^{*2}}\rho_s + V_0^2 \pm V_0}$$
$$- \sqrt{\mathbf{k}^2 + m_K^2}$$

BR potential $U_K(\rho_0) \simeq 30 \quad MeV$

$$\Sigma_{KN} = 450 \quad MeV$$
$$f_\pi^{*2} = 0.6 f_\pi^2 \quad ; \quad f_\pi^{*2} = f_\pi^2$$

KL potential $U_K(\rho_0) \simeq 5 \quad MeV$

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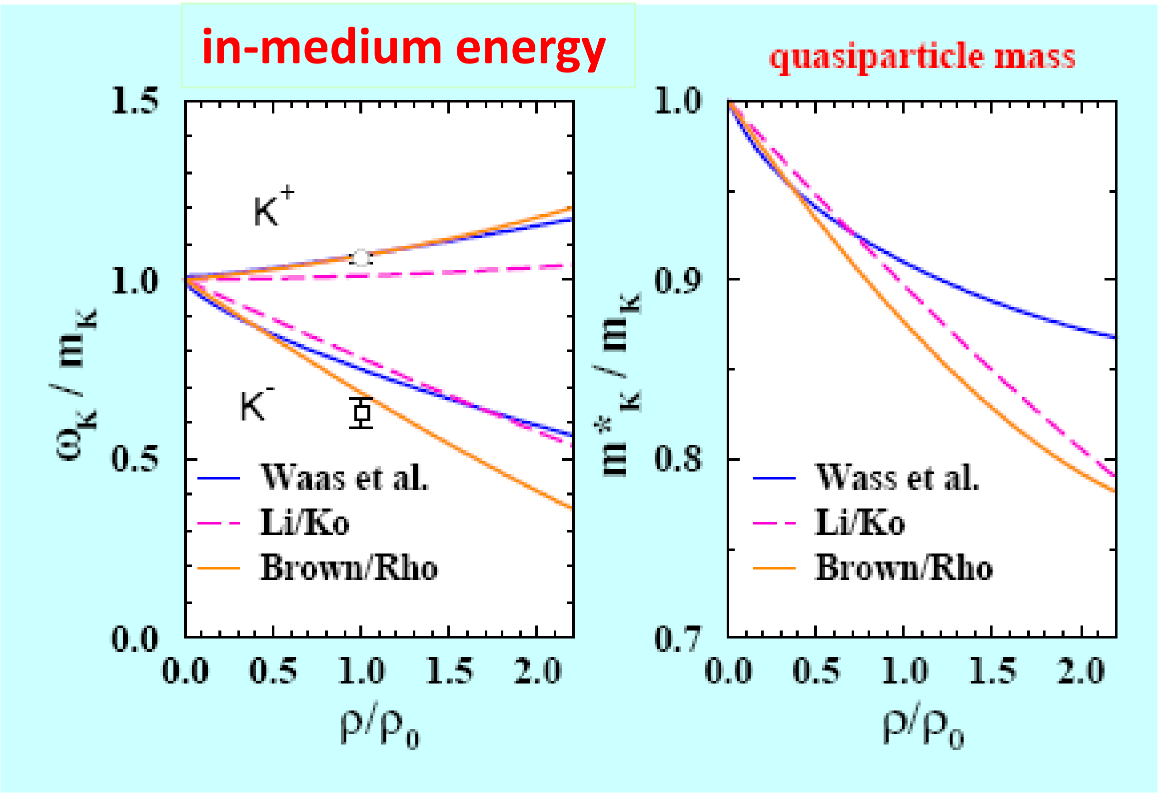
Density dependence of the in-medium kaon potential at zero momentum. IA: the impulse approximation

[NPA 567 (1994) 937],

• Kaons change their properties in dense matter



$$\left[\left(\partial_\mu \pm iV_\mu\right)^2 + m_K^{*2}\right]\phi_{K^\pm} = 0$$

$$m_K^* = \sqrt{m_K^2 - \frac{\sum_{KN}}{f_\pi^2}\rho_s + V_\nu V^\mu}$$

$$\left[k^{*2} - m_K^{*2}\right]\phi_{K^\pm} = 0$$

Dispersion relation

$$\omega = \sqrt{k^{*2} + m_K^{*2}} \pm V_0$$

Quantum Molecular Dynamics

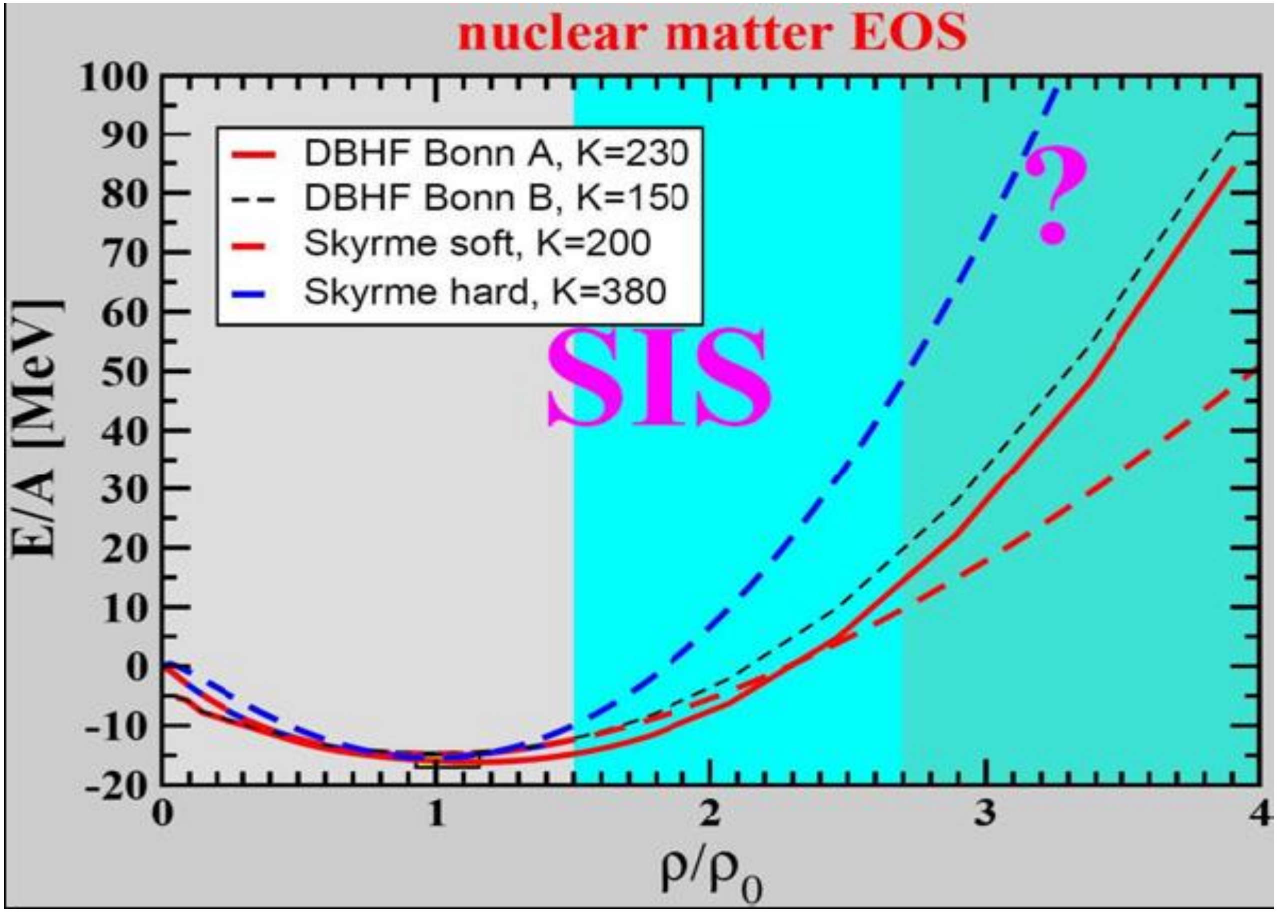
The nuclear Hamiltonian

$$H = \sum_i \sqrt{\mathbf{p}_{io}^2 + m_i^2} + \frac{1}{2}\sum_{i \neq j}\left(U_{ij}^{str} + U_{ij}^{cou}\right)$$

The strength of the nuclear compression is repeated normally in terms of the incompressibility constant K

$$K = 9\rho \left.\frac{\partial P}{\partial \rho}\right|_{S=const}$$

A soft EOS of state is represented by a value of K = 200 MeV
A hard EOS of state is represented by a value of K = 380 MeV.



$E(\rho)$, ρ_0 from ^{208}Pb

finite nuclei: $\rho/\rho_0 \leq 1$

heavy ions: $\rho/\rho_0 \leq 3$–?

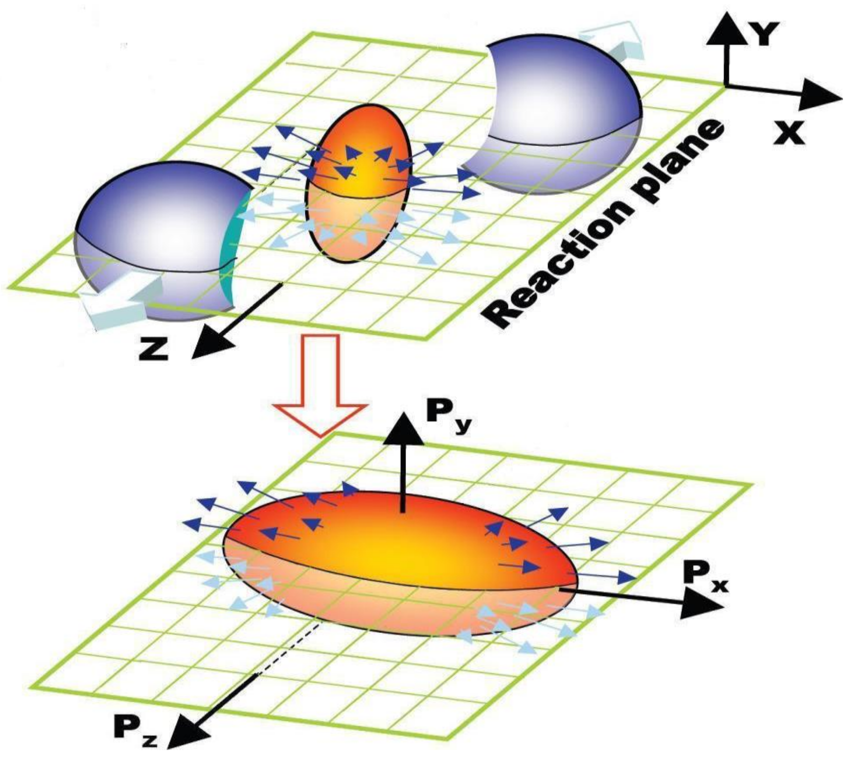
neutron stars: $\rho/\rho_0 \leq 10$

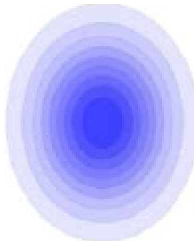
- [Fuchs C 2006 *Prog. Part. Nucl. Phys.* 56 1]

Direct Flow

The azimuthal distribution $$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \Sigma 2v_n \cos\left(n\left(\phi - \psi_R\right)\right)\right)$$

$$v_1 = \langle \cos\phi \rangle = \left\langle \frac{p_x}{p_t} \right\rangle \qquad p_t = \sqrt{p_x^2 + p_y^2}$$



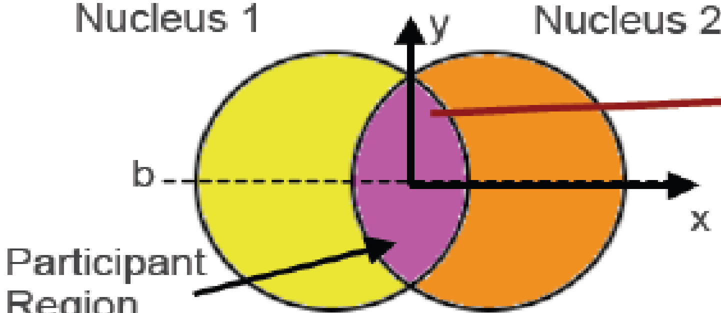


n = 2

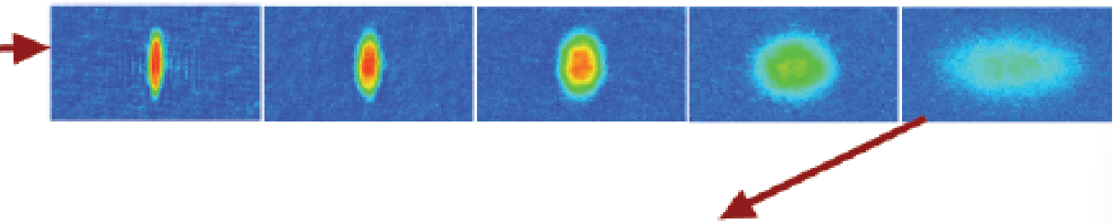
Elliptic Flow

B. Alver ,talk at Renmontres lons Lourds (2010)

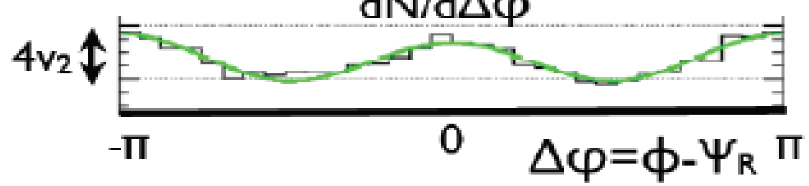
Initial anisotropy



Pressure driven expansion



Final anisotropy



The azimuthal distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

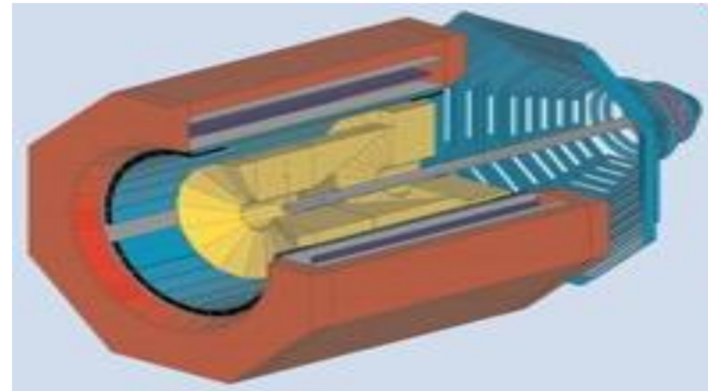
$$v_2 = \left\langle \cos\left(2(\phi - \underline{\psi_R})\right)\right\rangle \propto \varepsilon$$

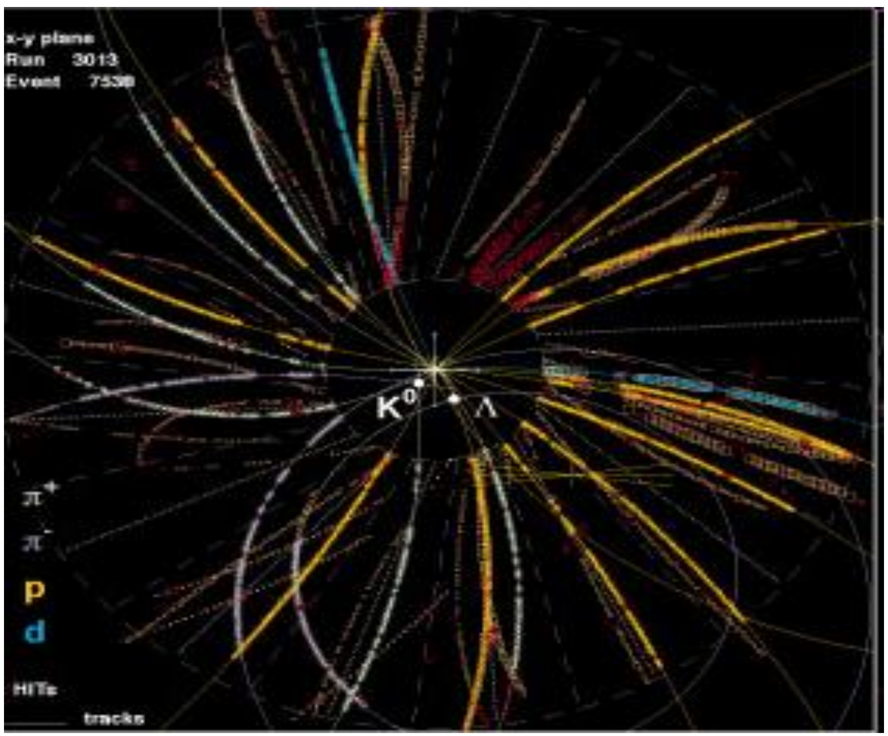
Elliptic flow is quantified by the second Fourier coefficient (v_2) of the observed particle distribution

- ❖**Off plane : $v_2 < 0$**
- ❖**In – plane : $v_2 > 0$**

FOPI Experimentes

The FOPI detector has documented the investigation of the collisions. As suggested by the name - FOPI stands for 4pi a synonym for the entire solid angle- this detector detects, identifies, and determines the momentum of all charged particles emitted in a heavy-ion reaction.

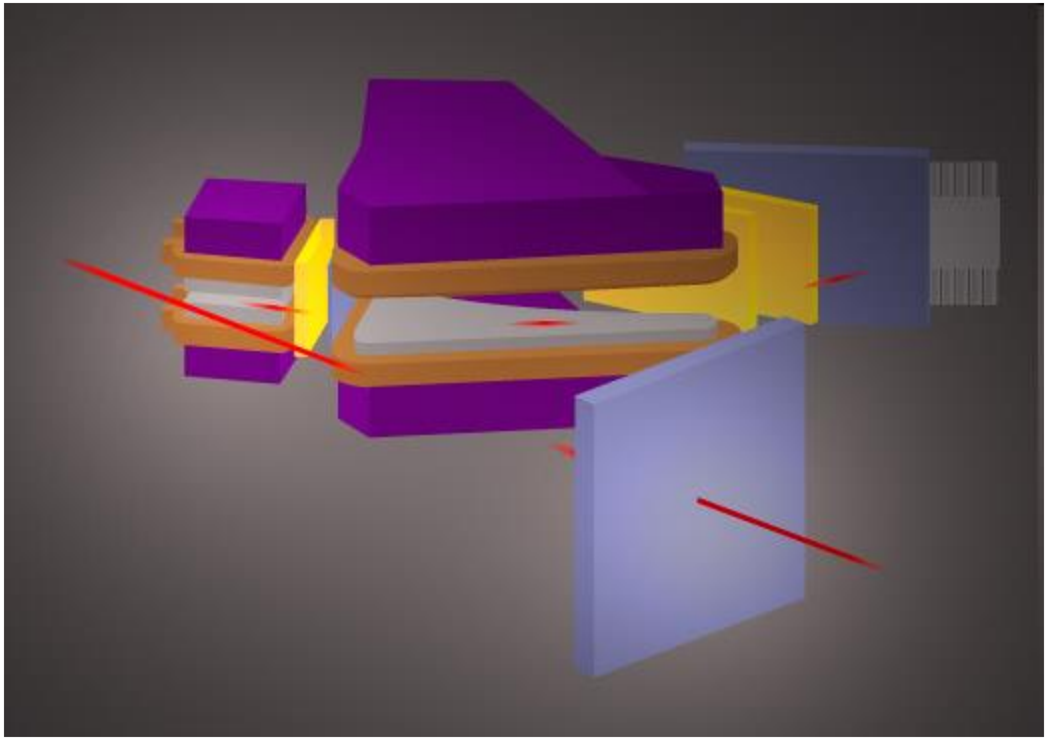


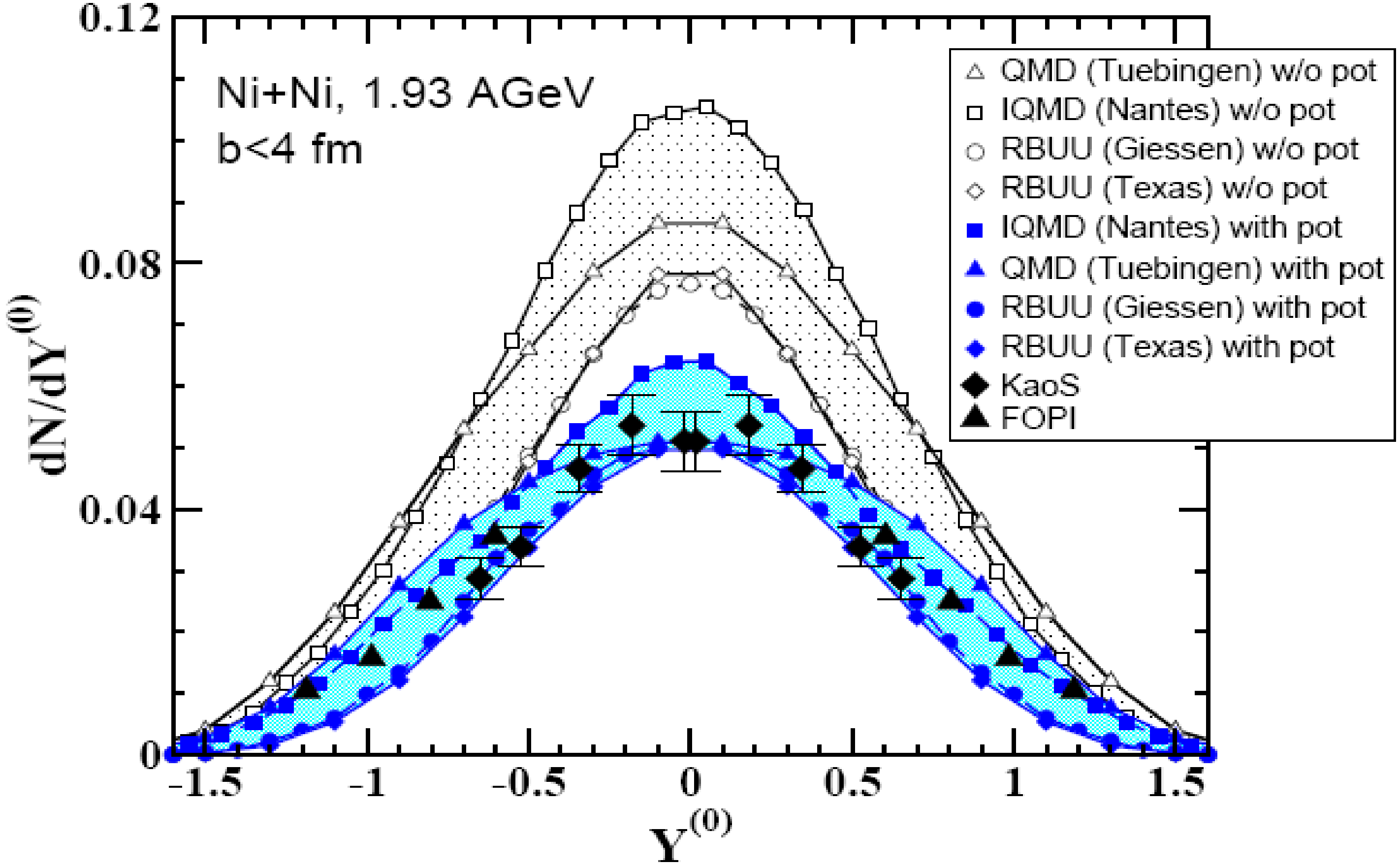


: Ni + Ni collision at E= 1.93 A GeV leave tracks in the central drift chamber. The individual signals in the detector are form the track Unambiguous identification of the particle is possible from the curvature of the track and additional information from other sections of the FOPI detector. In the example shown, two strange particles (K^0 and Λ) arise simultaneously and decay after a short flight.

KaoS Experiments

The aim of the KaoS experiment is to study nuclear matter under extreme conditions and the properties of strange mesons in a dense medium. In particular the identification of strange mesons - which are produced very rarely at SIS energies - is an experimental challenge.



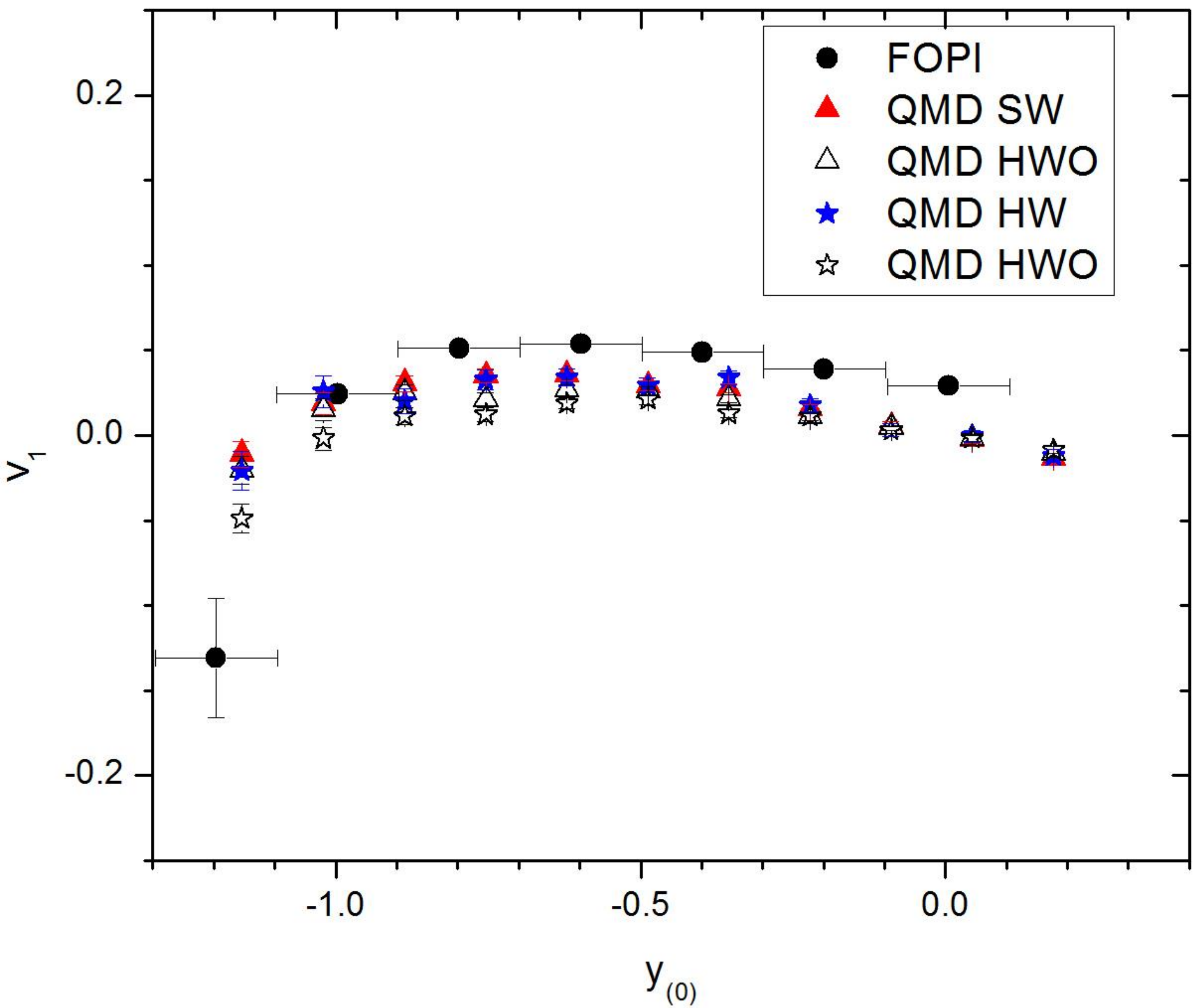


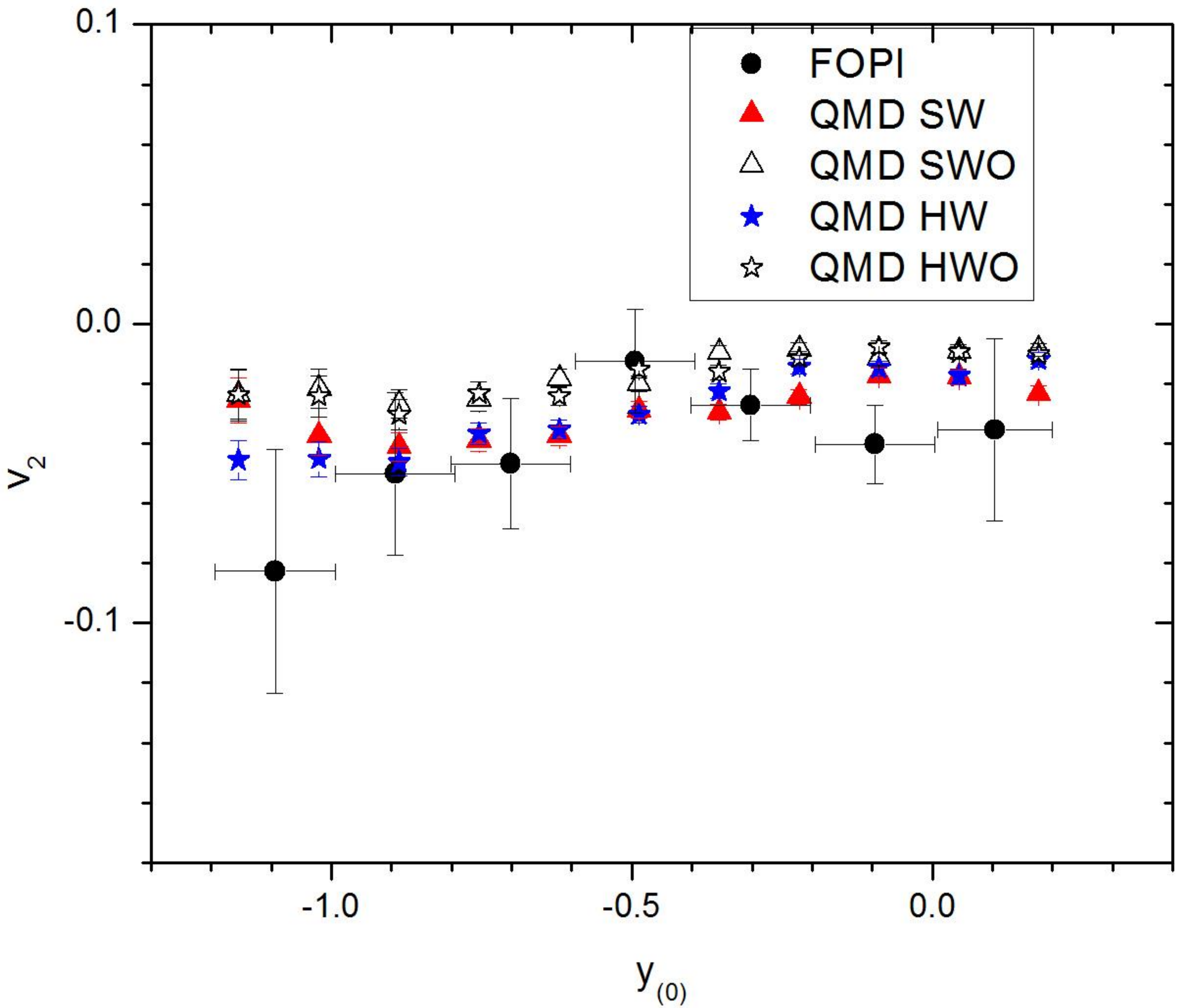
K^+ rapidity distributions in Ni + Ni reactions at 1.93 AGeV. Data are from FOPI [NPA625 (97) 307] and KaoS [PLB 495 (2000) 26].

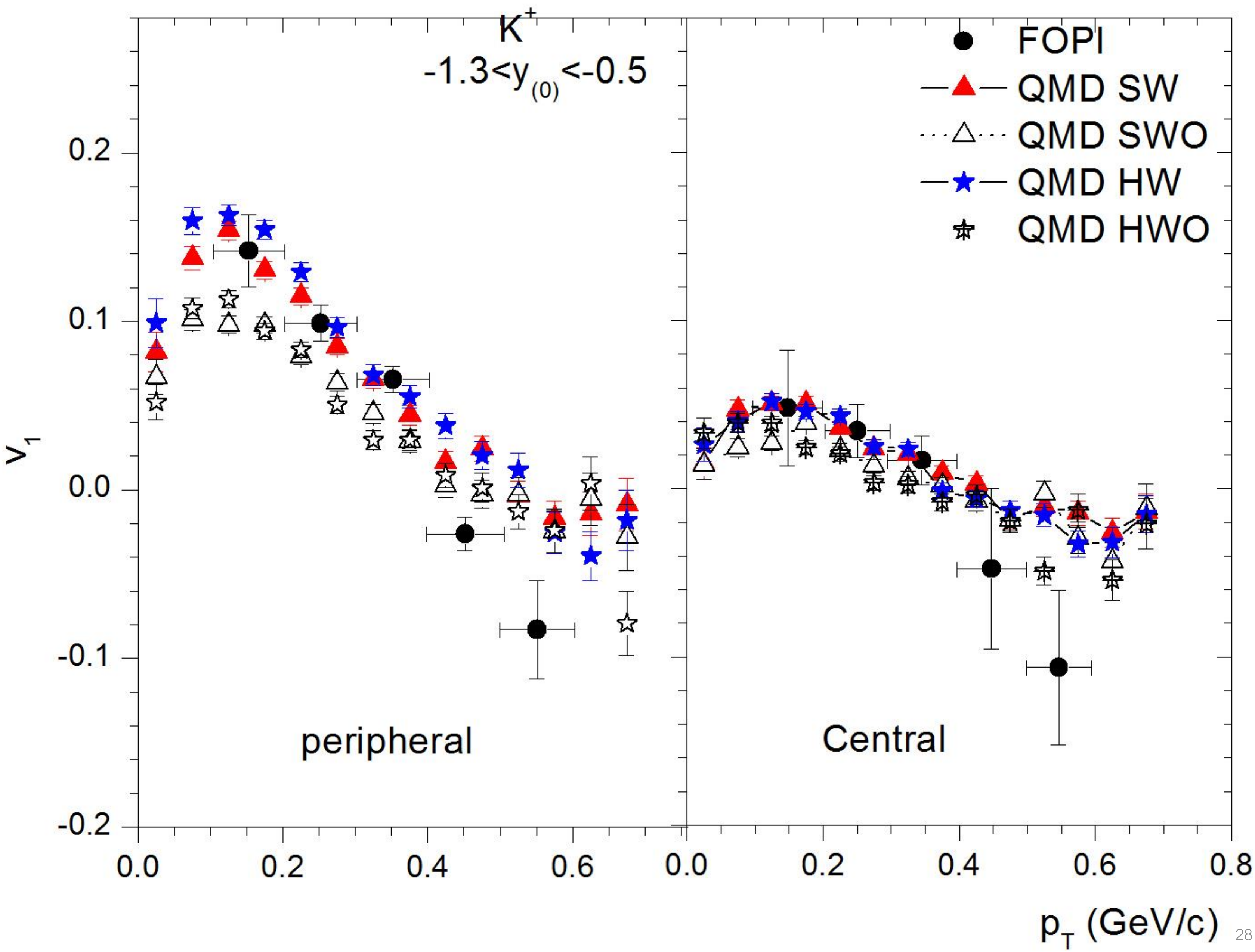
PHYSICAL REVIEW C **90**, 025210 (2014)

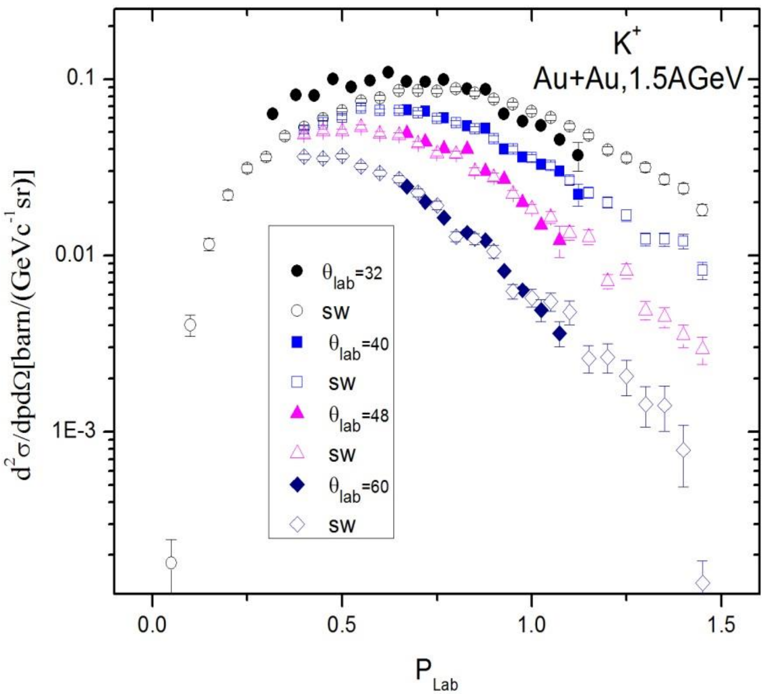
Azimuthal emission patterns of K^+ and of K^- mesons in Ni + Ni collisions near the strangeness production threshold

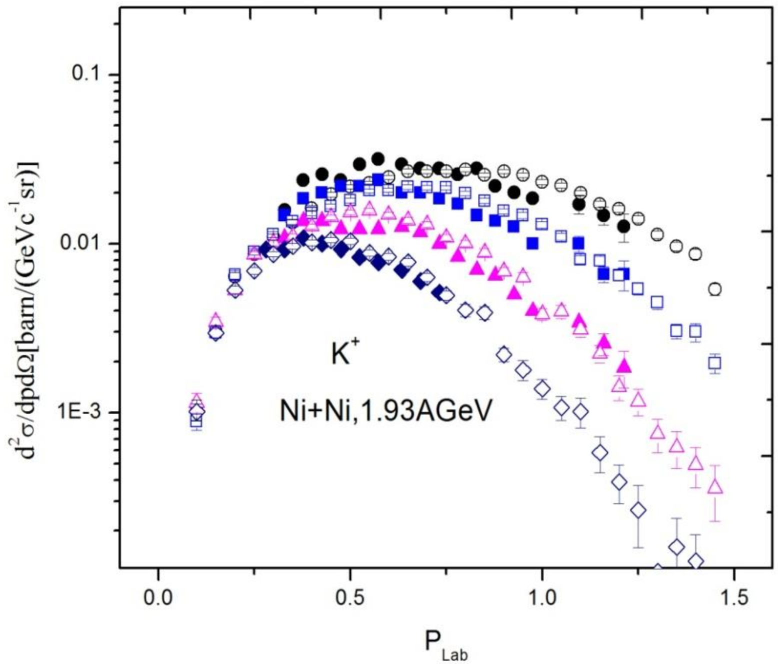
V. Zinyuk,[1,*] T. I. Kang,[2,3,†] Y. Leifels,[2] N. Herrmann,[1] B. Hong,[3] R. Averbeck,[2] A. Andronic,[2] V. Barret,[4] Z. Basrak,[5] N. Bastid,[4] M. L. Benabderrahmane,[1] M. Berger,[6,7] P. Buehler,[8] M. Cargnelli,[8] R. Čaplar,[5] I. Carevic,[9] P. Crochet,[4] I. Deppner,[1] P. Dupieux,[4] M. Dželalija,[9] L. Fabbietti,[6,7] Z. Fodor,[10] P. Gasik,[11] I. Gašparić,[5] Y. Grishkin,[12] O. N. Hartmann,[2] K. D. Hildenbrand,[2] J. Kecskemeti,[10] Y. J. Kim,[2] M. Kirejczyk,[11] M. Kiš,[2,5] P. Koczon,[2] R. Kotte,[13] A. Lebedev,[12] A. Le Fèvre,[2] J. L. Liu,[1,14] X. Lopez,[4] V. Manko,[15] J. Marton,[8] T. Matulewicz,[11] R. Münzer,[6,7] M. Petrovici,[16] K. Piasecki,[11] F. Rami,[17] A. Reischl,[1] W. Reisdorf,[2] M. S. Ryu,[3] P. Schmidt,[8] A. Schüttauf,[2] Z. Seres,[10] B. Sikora,[11] K. S. Sim,[3] V. Simion,[16] K. Siwek-Wilczyńska,[11] V. Smolyankin,[12] K. Suzuki,[8] Z. Tyminski,[11] P. Wagner,[17] E. Widmann,[8] K. Wiśniewski,[1,11] Z. G. Xiao,[18] I. Yushmanov,[15] Y. Zhang,[1,19] A. Zhilin,[12] and J. Zmeskal[8]
(FOPI Collaboration)

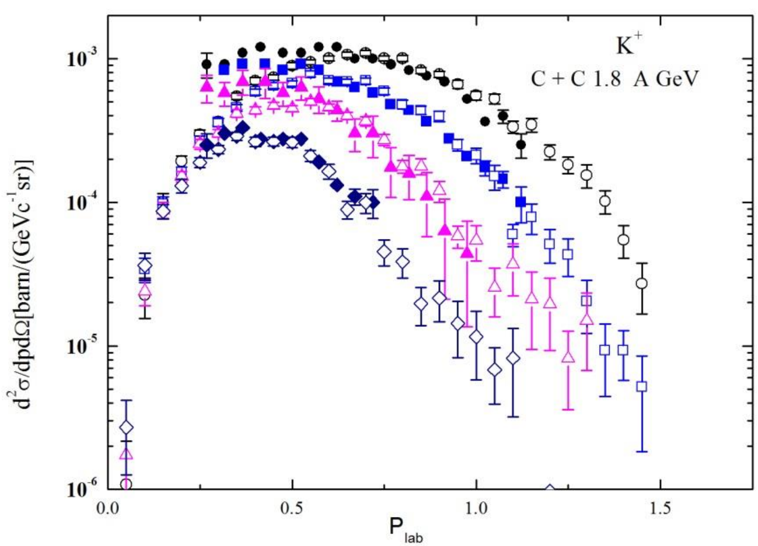

FOPI
QMD SW
QMD HWO
QMD HW
QMD HWO
0.2
0.0
-0.2
v1
-1.0
-0.5
0.0
y(0)


FOPI
QMD SW
QMD SWO
QMD HW
QMD HWO
0.1
0.0
-0.1
v_2
-1.0
-0.5
0.0
$y_{(0)}$


K+
-1.3<y(0)<-0.5
FOPI
QMD SW
QMD SWO
QMD HW
QMD HWO
v1
0.2
0.1
0.0
-0.1
-0.2
peripheral
Central
0.0
0.2
0.4
0.6
0.0
0.2
0.4
0.6
0.8
pT (GeV/c)


K+
Au+Au,1.5AGeV
θlab=32
SW
θlab=40
SW
θlab=48
SW
θlab=60
SW
d²σ/dpdΩ[barn/(GeVc⁻¹sr)]
PLab


K+
Ni+Ni,1.93AGeV
d²σ/dpdΩ[barn/(GeVc⁻¹sr)]
PLab


K+
C + C 1.8 A GeV
d²σ/dpdΩ[barn/(GeVc⁻¹sr)]
Plab

Summary

The influence of the chiral mean field on kaon production in heavy ion collisions at SIS energy is investigated within covariant kaon dynamics.

Azimuthal emission patterns of K^+ the compressed and heated nuclear medium and favor the existence of a kaon-nucleon in-medium potential.

The cross section of K^+ is higher in heavy collision systems than in light systems.

Kob Kun ka/krub for your attention