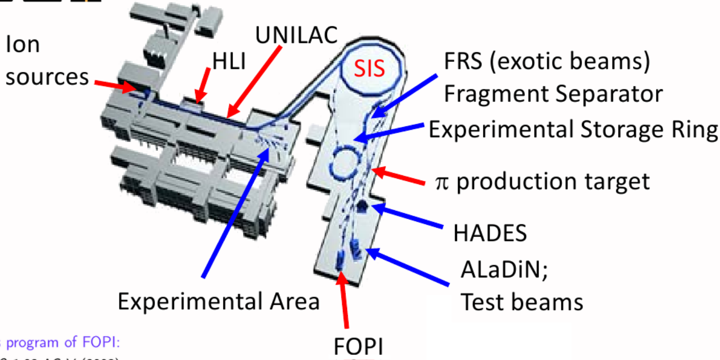
Modification of hadron properties in compressed nuclear matter with FOPI

Victoria Zinyuk for the FOPI collaboration

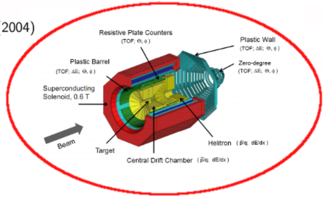
15. January 2015

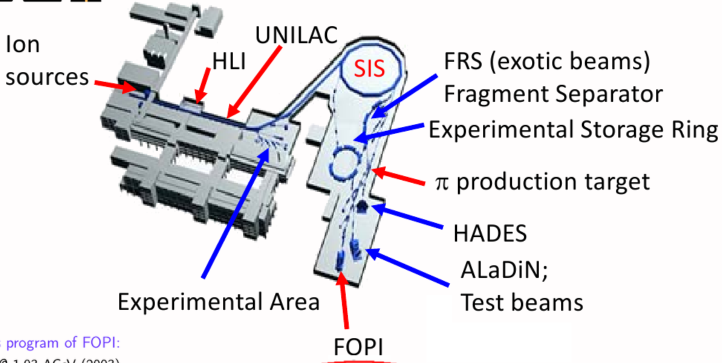
Introduction



Strangeness program of FOPI:

- Ni+Ni @ 1.93 AGeV (2003)
- π^- + C, Al, Cu, Sn, Pb @ 1.15 GeV/c (2004)
- Al+Al @ 1.91 AGeV (2005)
- Ni+Ni @ 1.91 AGeV (2008)
- Ni+Pb @ 1.91 AGeV (2009)
- Ru+Ru @ 1.7 AGeV (2009)
- p+p @ 3 GeV (2009)
- π^- + C, Cu, Pb @ 1.7 GeV/c (2011)





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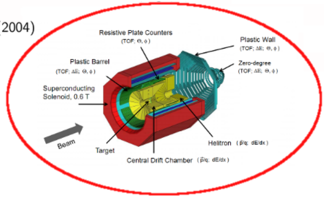


Outline

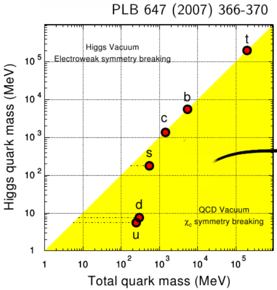
- Motivation: Chiral Symmetry breaking and restoration.
- Results from Heavy Ion Run: Ni+Ni @1.91 AGeV

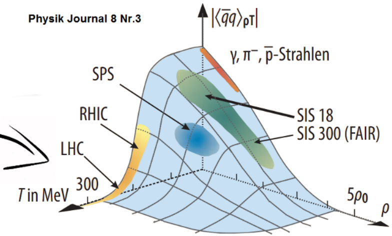
  $\rightarrow$ Flow of charged kaons.

- Results from π^--induced reactions:
  π^-+C, Pb @1.15 GeV/c and @1.7 GeV/c

  $\rightarrow$ 'momentum ratios'.

Chiral Symmetry Breaking





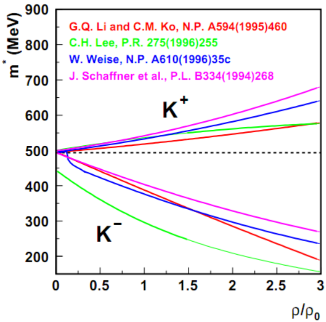
Gel-Mann-Oakes-Renner relation:

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

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

↑ explicit- ↑ spontaneous symmetry breaking

Modified properties of hadrons in dense baryonic matter?



Dispersion relation in the mean-field approximation:

$$\omega^2_{K^\pm}(p,\rho_N) = m_K^2 + p^2 - \frac{\Sigma_{KN}}{f^2}\rho_S \pm \frac{3}{4}\frac{\omega}{f^2}\rho_N$$

$$= (U_{K^\pm}(p,\rho_N) + \sqrt{m_K^2 + p^2})^2$$

Heavy ion collisions at SIS18 energies:

- Compression: ρ=2-3 ρ_0
- Heating: $\sim$ 100 MeV
- Pion-baryon ratio: 1:10
- Strangeness production at threshold $\rightarrow$ in-medium effects

'Trivial' in-medium effects:

- Fermi motion
- Pauli blocking
- Collisional broadening

'Non-trivial' in-medium effects:

- Partial restoration of chiral symmetry
- Meson-baryon coupling/resonances
- Bound states

Expected influence on production and propagation:

- Production cross section
- Phase space distribution
- Effective mass...

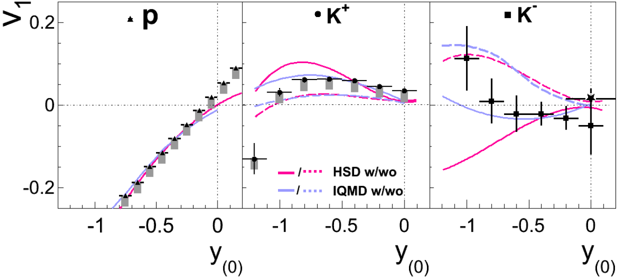
Anisotropies of the azimuthal emission expressed by a Fourier series:

$$\frac{dN}{d\varphi} \propto (1 + 2v_1\ cos(\varphi) + 2v_2\ cos(2\varphi) + ...)$$ φ with respect to RP

Directed Flow: $v_1 = \langle cos\varphi \rangle = \langle p_x/p_t \rangle$

Phys. Rev. C 90, 025210

- ***System:*** Ni+Ni @ 1.93 AGeV
- ***Centrality:*** 60 % σ_{geo}, i.e. $b_{geo} < 7$ fm



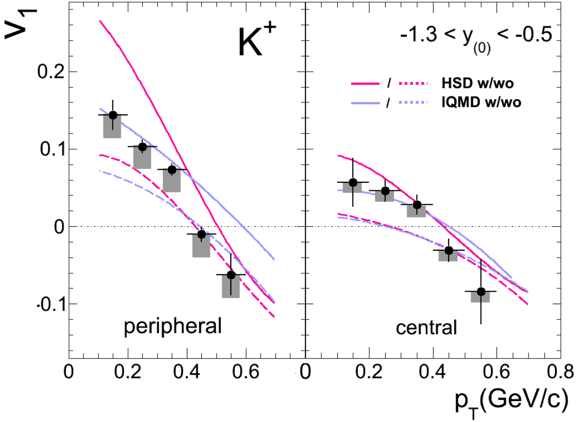
Assumed potentials @ p=0 and ρ_0 (linear density dependence):

HSD & IQMD: U_{K^+N} = **20** ± **5 MeV** U_{K^-N} = **-50** ± **5 MeV**

HSD(E. Bratkovskaya; W. Cassing): Kaons in-medium described by chiral perturbation theory;
Antikaons: chiral perturbation theory with G-Matrix approach;
IQMD (C.Hartnack): Kaons and Antikaons in-medium described by relativistic mean-field model based on chiral SU(3) model;

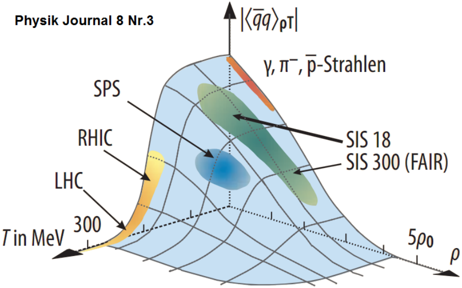
Kaon Flow: p_t dependence

Consider 'hidden' dependencies on p_t and centrality:



Peripheral: 3fm $< b_{geo} <$ 7fm;
Central: $b_{geo} <$ 3fm

Pion Induced Reactions

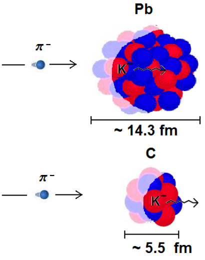


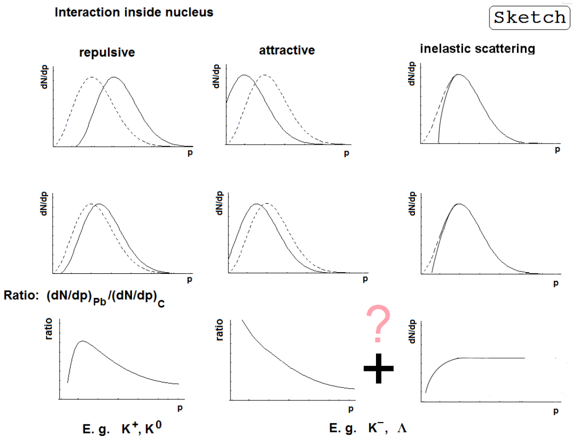
In pion-induced reactions in-medium effects can be studied at normal nuclear matter density:

Predicted reduction of $\langle\bar{q}q\rangle \sim 30$ %

Our observable: 'The Momentum Ratio'

The Momentum Ratio





Mean free path

- π^- @ 1.7 GeV/c: $\lambda \approx 1.5$ fm
- K^- (Λ) @ 0.1 GeV/c:

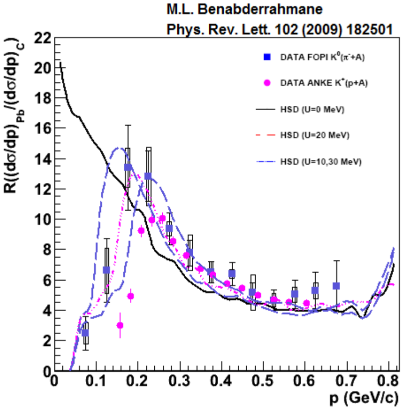
	λ
K^-	0.6 fm
Λ	0.7 fm
K^+ (K^0_S)	**5.35 fm**

Note: For K^- and Λ Strong effects from elastic and inelastic scattering expected!

Measurements of the Momentum Ratio

FOPI: $\pi+A\rightarrow K^0+X$ ***@ 1.15 GeV***
(M. Benabderrahmane PRL 102(2009))
ANKE: p+A $\rightarrow K^{+}+X$ ***@ 2.5 GeV***
(M. Bueschner, EPJ, A22, 301(2004))

- Without potential the ratio at small momenta is not reduced
  $\rightarrow$ (multiple) scattering
- K^+ feel additionally the Coulomb-potential



- K^0_S measurement favors
  U(K^+N @ $\rho=\rho_0$) =20 MeV with and without transport models!

Measurements of Momentum Spectra

Experiment:

$\pi^- + {}^{12}_{6}$C and ${}^{208}_{82}$Pb targets

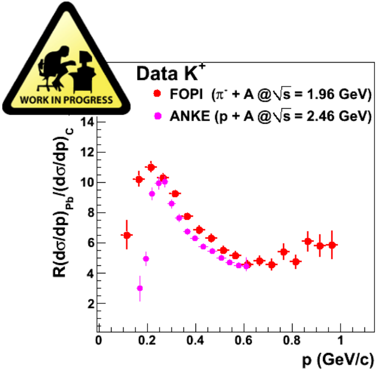
Beam kinetic energy: $E_{kin} = 1.57$ GeV $\Rightarrow \pi^- p$ $\sqrt{s} = 1.96$ GeV,

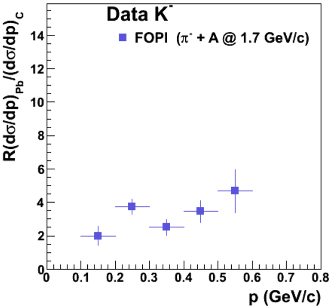
i.e. above the threshold for $\pi^- + p \rightarrow K^+ + K^- + n$

but also $\pi^- + p \rightarrow \phi + n$

Observable:

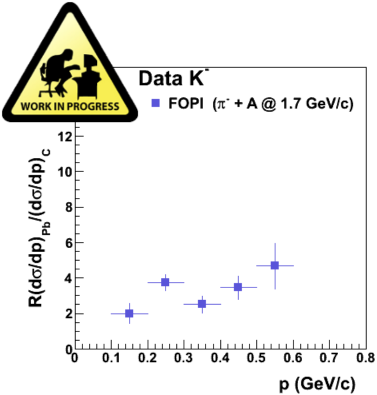
'Momentum Distribution Ratio' : $\Rightarrow$ $\mathbf{(dN/dp)_{Pb}/(dN/dp)_C}$

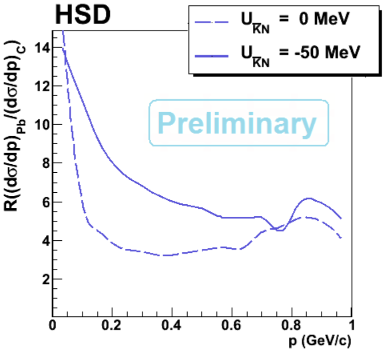




Momentum Ratios of K^-

- Direct measurement of K^- - mesons down to $p_{lab} = 0.1$ GeV/c
  C: $\sim$ 450 K^- candidates , S/B >5 ;
  Pb: $\sim$ 230 K^- candidates , S/B >3;
- Strong absorption & K^- originating from decays:
  Number of primary K^- not clear...





Conclusion & Outlook

- For kaons containing an $\bar{s}$-quark(K^+, K^0) all measurement support the existence of $U(p, \rho)$.
- First measurement of directed (v_1) flow done with FOPI. Results show a much weaker flow signature than anticipated.
- For kaons containing an s-quark (K^-, $\bar{K}^0$) measurement are challenging and transport modeling needs to be refined.
- Simpler system like created in pion induced reaction can help understanding of kaon dynamics in medium.
  $\rightarrow$ Possible impact for transport calculations.
- Analysis supplemented by another strange particles: K^0_S, ϕ, Λ.

Acknowledgment

Sincerely yours, the FOPI Collaboration!

THU Beijing - NIPNE Bucharest - KFKI RMKI Budapest -LPC Clermont-Ferrand - GSI Darmstadt - Helmholtz-Zentrum Dresden-Rossendorf - Universität Heidelberg - IMP Lanzhou - ITEP Moscow -KI Moscow - Technische Universität München - Korea University Seoul - University of Split - IPHC Strasbourg - SMI Vienna - University of Warsaw - RBI Zagreb

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[1]THU Beijing - [2]NIPNE Bucharest - [3]KFKI RMKI Budapest - [4]LPC Clermont-Ferrand - [5]GSI Darmstadt - [6]Helmholtz-Zentrum Dresden-Rossendorf - [7]Universität Heidelberg - [8]IMP Lanzhou - [9]ITEP Moscow - [10]KI Moscow - [11]Technische Universität München - [12]Korea University Seoul - [13]University of Split - [14]IPHC Strasbourg - [15]SMI Vienna - [16]University of Warsaw - [17]RBI Zagreb

Backup

- The KN -potential .... Table
- S325 Kaon PID .... PS + S/B+Yield
- GEM TPC.. TPC | Mu TPC | GEM
- Kaon Flow in S325.. $K^{+/-}$ $v_{1/2}$ vs y_0
  .... K^{+} $v_{1/2}$ vs y_0
  .... K^{-} $v_{1/2}$ vs y_0
- Standard flow analysis method .... Method
- K^{+} flow in central collison, Crochet.. directed flow
- PID with FOPI.. PID
- Reconstructed Kaon Spectra.. Kp, Km -Spectra
- The detector .... Detector
- FOPI Phase III.. FOPI+TPC
- The S339 Experiment.. S339
- Last day of FOPI .... Gabelstapler Klaus

The FOPI Detector: 1991 - 2013

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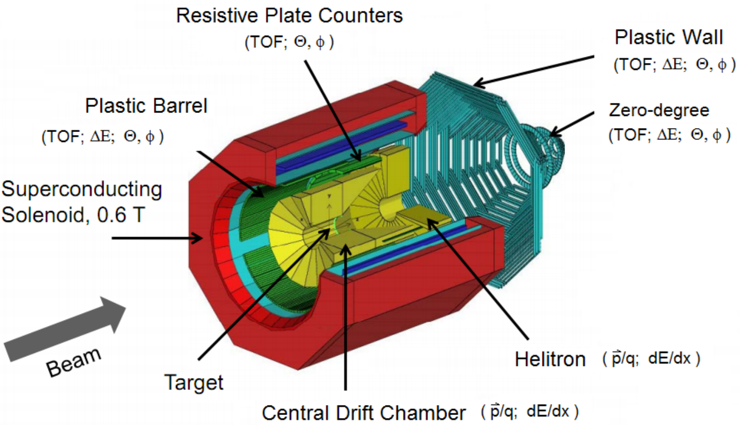
FOPI - Phase II



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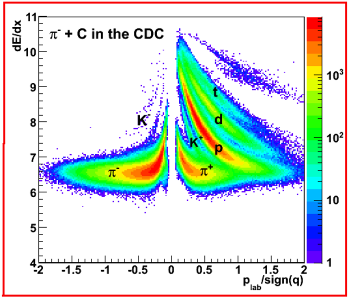
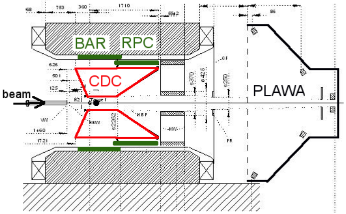
PID with FOPI

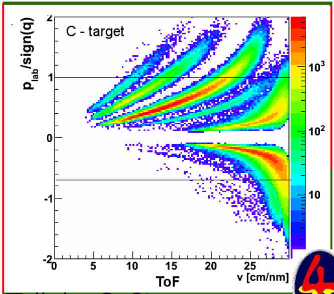




PID of kaons:

- Low p: CDC
  → wide acceptance range
  → Direct measurement of K^- down to $p_{lab} = 0.1$ GeV/c
- High p: CDC + ToF(BAR+MMRPC)
  → high time resolution

($\sigma_{\mathbf{MMRPC}} <$ **88ps**, partially developed in HD)



Ongoing development for the CBM experiment. Talk by C. Simon.

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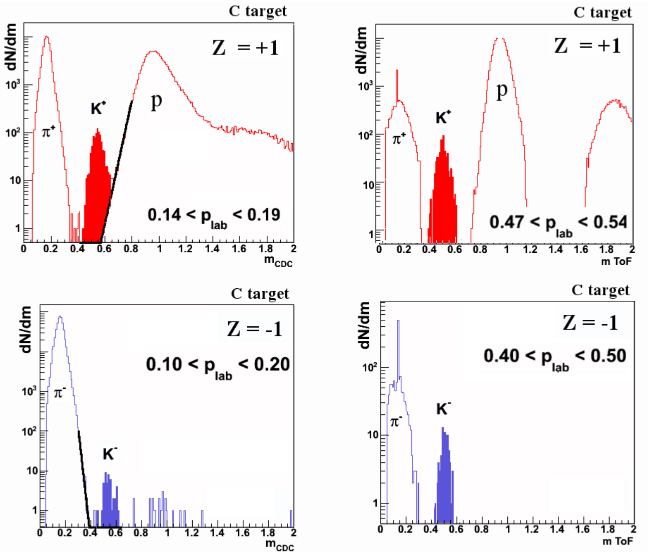
Reconstructed Kaon Spectra

Bin by bin mass reconstruction and background evaluation.



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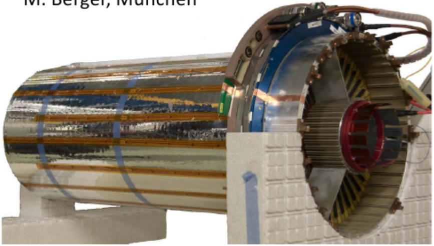
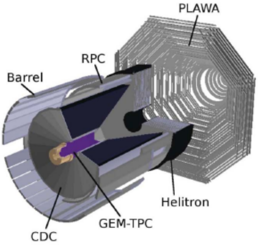
FOPI - Phase III

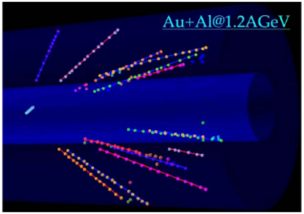
M. Berger, München





GEM TPC upgrade for FOPI

- Vertex resolution: $\sim$ 1 mm in X, Y and Z
- Larger geometrical acceptance for:
  K^0_S and Λ
- Improved resolution of secondary vertices (min factor 10)
- First standalone TPC to be used for physics



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The S339 Experiment

- New experiment was performed in August 2011: $\pi^- + {}^{12}_{6}$**C**, ${}^{63}_{29}$**Cu and** ${}^{208}_{82}$**Pb targets**
- Pion beam intensity: **ca.9000/s**
- Beam time: **290 h**
- Acquired statistics:

Target	events
C	5.47×10^6
Cu	2.56×10^6
Pb	5.58×10^6

- Beam momentum: 1.7 ± 0.03 GeV/c

Beam kinetic energy: $E_{kin} = 1.57$ GeV

$\Rightarrow \pi^- p \quad \sqrt{s} = 2.02$ GeV,

i.e. above the threshold for $\pi^- + p \rightarrow K^+ + K^- + n$

but also $\pi^- + p \rightarrow \phi + n$

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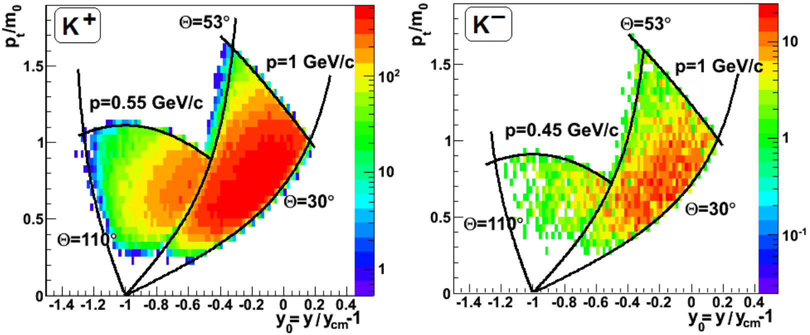
Experimental knowledge about the KN -potential

observable	$U(K^{+}N)$[MeV] @ $\rho = \rho_0$	$U(K^{-}N)$[MeV] @ $\rho = \rho_0$	measured by
charged kaons:			
K^{+} yield (cent)	model-dep.	–	FOPI(1997)
K^{+} sideflow, v_1 (cent)	20 (HSD)	–	FOPI(2000)
$K^{\pm}$ v_1 (per)	20 (IQMD)	- 40 (IQMD)	FOPI(these data)
	0 (HSD)	- 25 (HSD)	FOPI(these data)
K^{-}/K^{+}-ratio	30 (RBUU)	- 70(RBUU)	FOPI(2000)
K^{+}- *ratio heavy/light sys.**	20 (HSD)		ANKE(2004)
neutral kaons:			
K^0_S- $p_t$spectra	40 (IQMD)	–	HADES(2010)
K^0_S- yield	0 (IQMD)	–	FOPI(2004)
K^0_S- inverse slope	20 (IQMD)	–	FOPI(2004)
K^0_S- *ratio heavy/light sys.**	20 (HSD)	–	FOPI(2009)

* *elementary reactions*

→ **Evidence for KN-potential, but no definite conclusion on the strength possible!** Back

Kaon Phase Space



S325+S325e		K^+	K^-
BAR	p_{max}	0.55 GeV/c	0.45 GeV/c
	S/B	∼ 10	∼ 4
	Nr. of Kaons	40966	645
RPC	p_{max}	0.9 GeV/c	0.7 GeV/c
	S/B	∼ 22	∼ 8
	Nr. of Kaons	142027	3150

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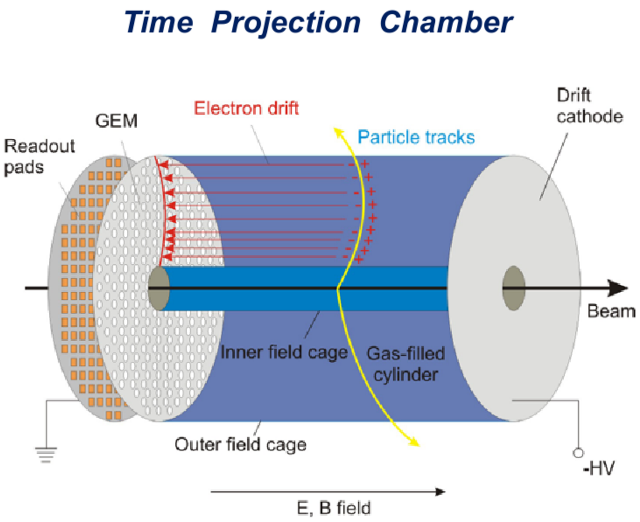
GEM TPC



Time Projection Chamber
Drift cathode
Electron drift
GEM
Particle tracks
Readout pads
Beam
Inner field cage
Gas-filled cylinder
Outer field cage
-HV
E, B field

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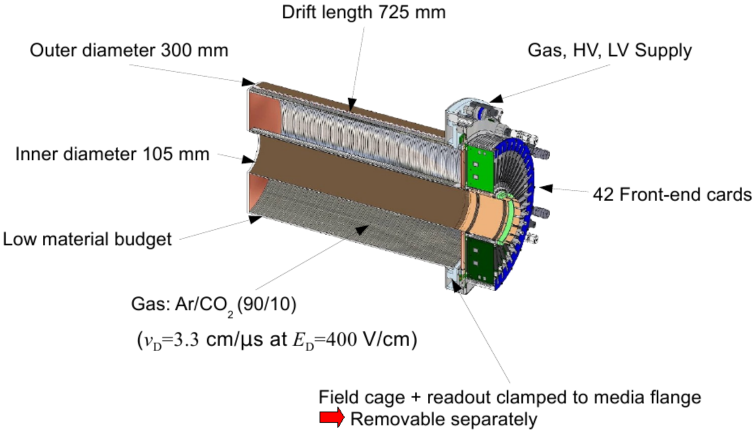
The GEM-TPC



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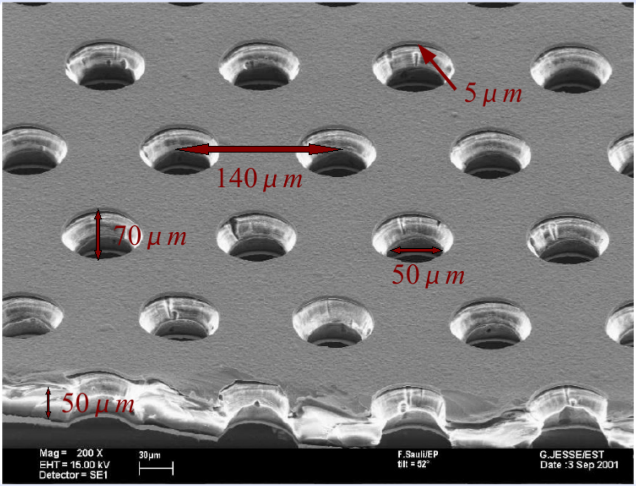
Gas Electron Multiplier



Fabio Sauli, The Gas Electron Multiplier (GEM), Nucl. Instr. and Meth. A 386 (1997) 531-534

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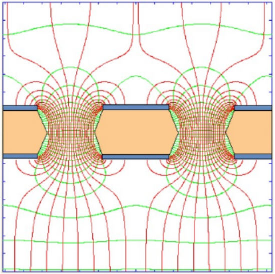
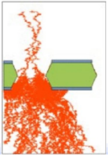
GEM TPC

Gas Electron Multiplier



- ~400V potential difference → 50kV/cm
- Amplification G_{eff} = several 10^3 (with 3 GEMS in a stack)
- Higher extraction field
- Ions are collected on upper side
- Electrons are extracted very effective
- Ion feedback suppressed by $1/G_{eff}$
- Until now no aging visible (GEM's in Compass since 3 years)
- Very uniform spatial resolution (triple GEM's ~ 69.6μm)



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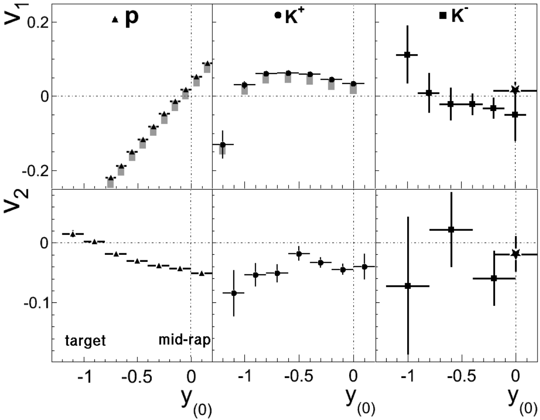
Anisotropies of the azimuthal emission expressed by a Fourier series:

$$\frac{dN}{d\varphi} \propto (1 + 2v_1\ cos(\varphi) + 2v_2\ cos(2\varphi) + \ldots)$$ φ with respect to RP

Directed Flow:
$v_1 = \langle cos\varphi \rangle = \langle p_x/p_t \rangle$

Elliptic Flow:
$v_2 = \langle cos2\varphi \rangle = \langle (p_x^2 - p_y^2)/p_t^2 \rangle$

- ***System:***
  Ni+Ni @ 1.93 AGeV
- ***Centrality:***
  60 % σ_{geo},
  i.e. $b_{geo} < 7$ fm



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K^+ Flow in HSD and IQMD

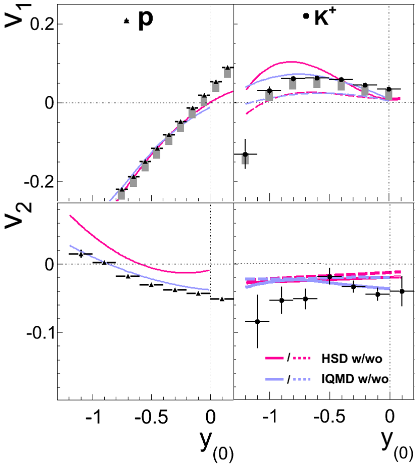
Transport calculations*:

- ***HSD***(*E. Bratkovskaya; W. Cassing*):
  Kaons in-medium described by chiral perturbation theory;

  $U_{K^+N}(\rho_0, p=0) = \mathbf{20\ MeV}$

- ***IQMD*** *(C.Hartnack)*:
  $K^{+/0}$ in-medium described by relativistic mean-field model based on chiral SU(3) model;

  $U_{K^+N}(\rho_0, p=0) = \mathbf{20\ MeV}$



Note: FOPI measurements are compatible with the KaoS results(within errors)

*Transport calculations are filtered for the detector acceptance and centrality selection.

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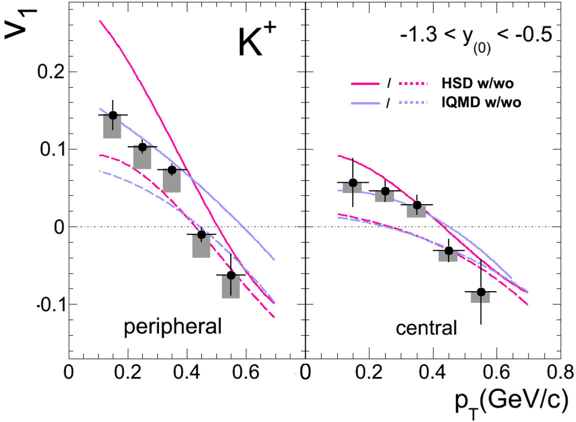
Kaon Flow: p_t dependence

Consider ‘hidden’ dependencies on p_t and centrality:



Peripheral: 3fm $< b_{geo} <$ 7fm;
Central: $b_{geo} <$ 3fm

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K^- Flow in HSD and IQMD

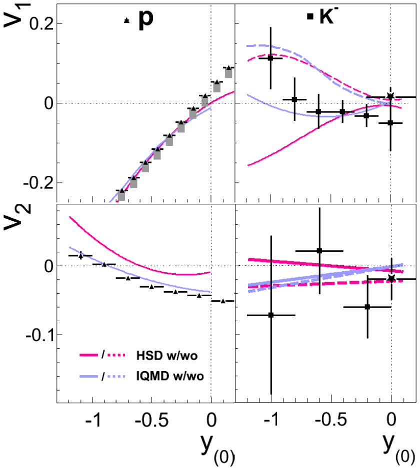
Transport calculations:

- ***HSD**(E. Bratkovskaya; W. Cassing):*
  Antikaons in-medium described by chiral perturbation theory with G-Matrix approach;

  $U_{K^-N}(\rho_0, p = 0) =$ **-50 MeV**

- ***IQMD** (C.Hartnack):*
  Antikaons in-medium described by relativistic mean-field model based on chiral SU(3) model;

  $U_{K^-N}(\rho_0, p = 0) =$ **-45 MeV**



Note: FOPI measurements are compatible with the KaoS measurement (within errors), however no evidence for in-plane emission of K^--mesons.

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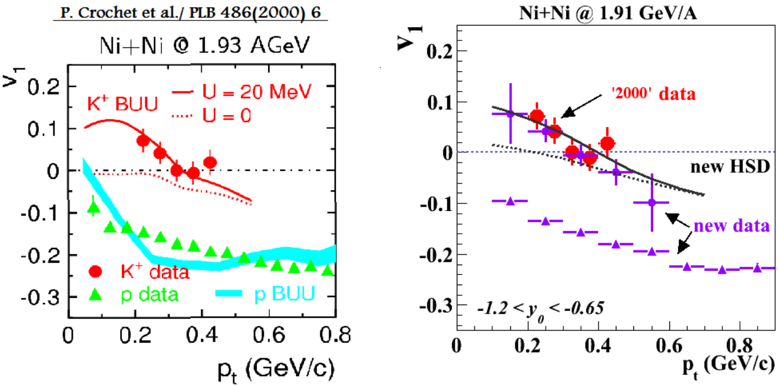

- Conclusion: In central collisions the K^+-flow pattern is described by HSD with 20($\pm$ 5) MeV K^+N-potential

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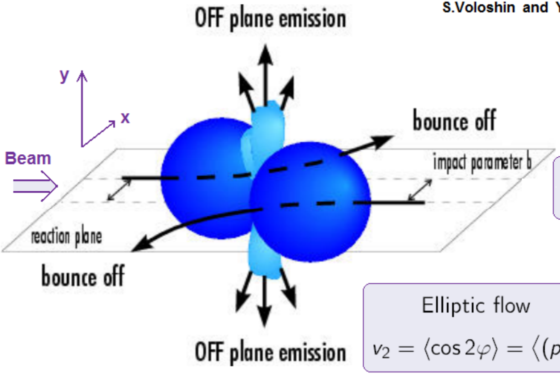
Standard flow analysis method

$$\frac{dN}{d\varphi} \propto (1 + 2v_1 cos(\varphi) + 2v_2 cos(2\varphi) + ...) \quad v_n = \langle \cos n\varphi \rangle \quad n = 1, 2, ...$$

S.Voloshin and Y.Zhang, Z. Phys. C70, 665 (1996)



Directed flow

$v_1 = \langle \cos \varphi \rangle = \langle p_x / p_t \rangle$

Elliptic flow

$v_2 = \langle \cos 2\varphi \rangle = \langle (p_x^2 - p_y^2)/p_t^2 \rangle$

- ***Reaction Plane determination:*** *P. Danielewicz and G. Odyniec, Phys. Lett. 157B, 146 (1985)*
- ***Correction due to the reaction plane: Ollitrault correction*** *J.Y. Ollitrault, Nucl. Phys. A638, 195C (1998)*

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