Hadron production in Al+Al collisions at 2A GeV

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FOPI Collaboration

School of Collective Dynamics in High Energy Collisions
The Berkeley School 2010

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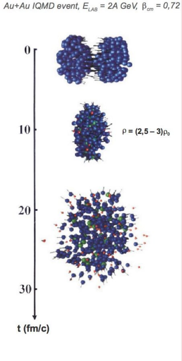
Table of contents

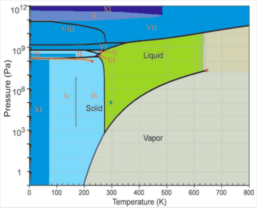
Heavy ion collisions at SIS18 energies (1 - 2A GeV)

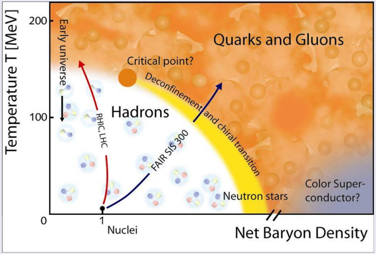
Dynamical picture



- Particle production (π, K, Σ, Λ, ϕ, ...)
- Chemical "freeze - out"
- Kinematic "freeze - out"

Phase diagram





Baryonic matter properties

What do we measure?

- Kinetic energy spectra $\rightarrow T_{kin}$
- Particle yields at chemical "freeze - out" $\rightarrow T_{chem}, \mu_B$
- Position on Phase Diagram

But...

- Can we compare HI collisions at SIS energies with the ultrarelativistic ones? (RHIC, SPS, LHC)
- Do the emitted particles come from the equilibrated source?

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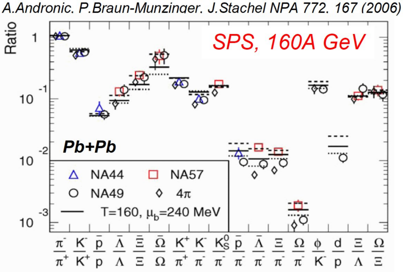

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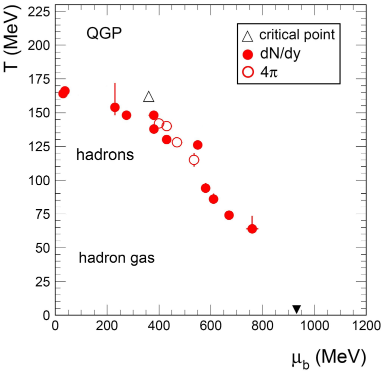

A.Andronic, P.Braun-Munzinger, J.Stachel, NPA 772 (2006) 167

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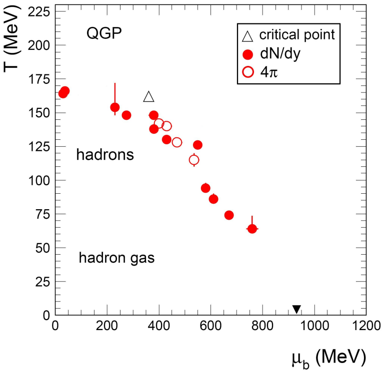

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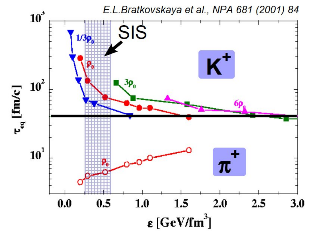
Questions on equilibrium

BUU model

- **B**oltzmann **U**ehling **U**hlenbeck Model
- 'Infinite' hadronic matter, initials: $\epsilon = \epsilon_0$, $\rho_b = \rho_0$, $\rho_S = 0$
- τ_{eq}: typical time of yield stabilization $\tau_{eq} = \frac{2}{3} N_{eq}$



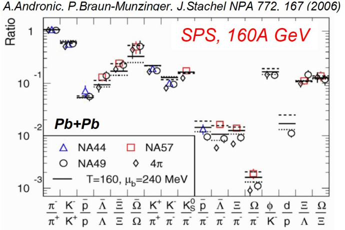
- $\tau_{eq} \gg \tau_{coll}$
- No equilibration of strangeness

Statistical model

- **Assumption:** equilibrium during the chemical "freeze - out"
  Density of species - grand canonical 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:** μ_B, **T**
- **fixed by conservation laws:** μ_s, μ_{I_3}



Extension: $exp(\ldots) \longrightarrow exp(\ldots) \cdot \frac{1}{(\gamma_s)^{n_s}}$

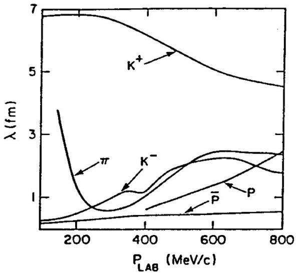
γ_s - "strangeness undersaturation factor"
n_s - number of strange quarks

Strangeness production at SIS

- At the SIS18 energies strangeness is produced near- and sub-threshold:
  - $E^{thr}_{K^+}$ = **1.58 GeV** (NN→NΛK$^+$)
  - $E^{thr}_{K^-}$ = **2.49 GeV** (NN→NNK$^+$K$^-$)
- K$^+$ mesons and hyperons (Y) produced in one- and multi-step processes:
  - $BB \to K^+YB$ (B → p,n,N*,Δ Y → Λ, Σ)
  - $\pi B \to YK^+$
- K$^-$ mesons are produced (as well as absorbed) mainly in strangeness exchange reaction:
  - $\pi Y \leftrightarrow K^-B$

K$^+$ as a probe of nuclear matter

- Relatively long mean free path (λ) of K$^+$ in nuclear matter



C. Dover, G. Walker, Phys. Rep. **89** (1982) 1

Kaons' properties in hot and dense nuclear matter

Mass modification

- KN potential in-medium:
  - repulsive for K^+
  - attractive for K^-
- Theoretical models seldom take into consideration $\phi \rightarrow K^+K^-$ decay
- ϕ decay outside the fireball ($c\tau \approx 50fm$) $\rightarrow$ $K^\pm$ not from high density area
- How many kaons from ϕ?

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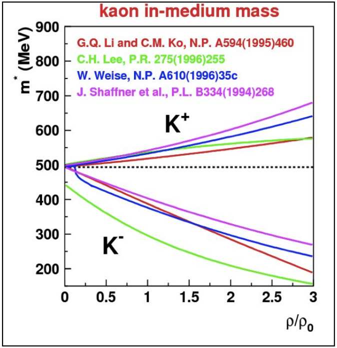

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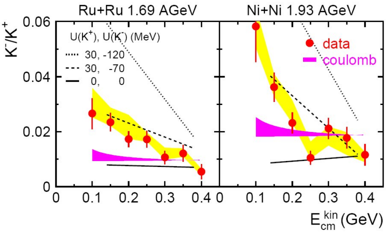

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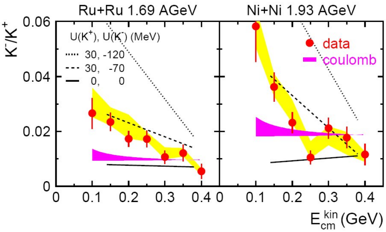

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FOPI @ GSI

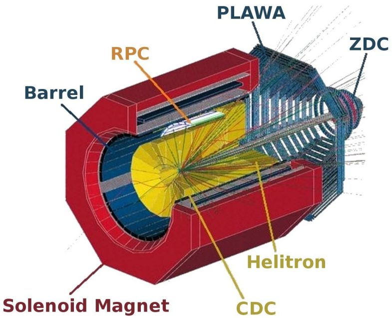
- Almost full 4π coverage
- Magnetic field B = 0.6 T
- 3 types of detectors:
  - Drift Chamber (dE/dx, p_t)
  - Plastic scintilators (ToF)
  - **R**esistive **P**late **C**ounters (ToF)
- Measured particles:

  $p, d, t, {}^3He, \pi^{\pm}, K^{\pm}$

  (direct identification)

  $\Lambda, K^0, K^*, \Sigma^{\pm *}, \phi$

  (invariant mass reconstruction)



Al+Al @ 1.9*A* GeV experiment - 08.2005

- Almost $4 \cdot 10^8$ most central events collected
- Centrality corresponds to 20% of geometrical cross-section

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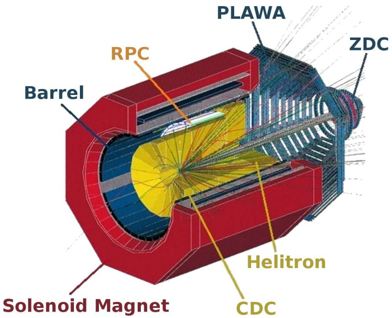

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Particle identification in FOPI

Direct identification

- "**CDC** Mass"
  - dE/dx
  - $\frac{Pt}{q} = \frac{B}{\rho}$
- "**Barrel** Mass"
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  - $M = \frac{P_{cdc}}{\beta\gamma}$
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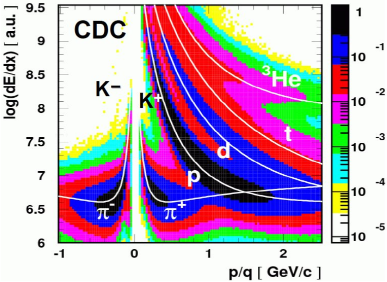

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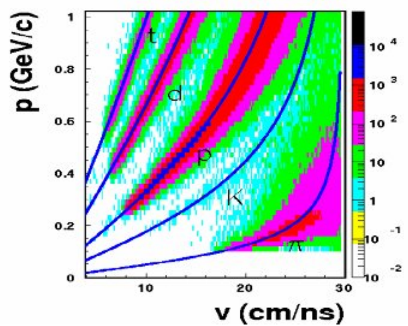

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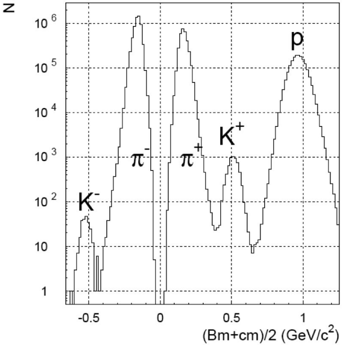

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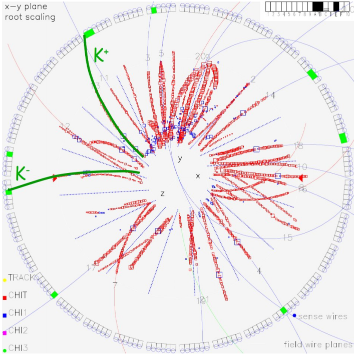

Protons

$p_t(y)$ phase-space

p_t - transverse momentum

y^0 - scaled rapidity

$$y^0 = \frac{y}{y_{cm}} - 1$$

$y^0 = -1$ - target rapidity
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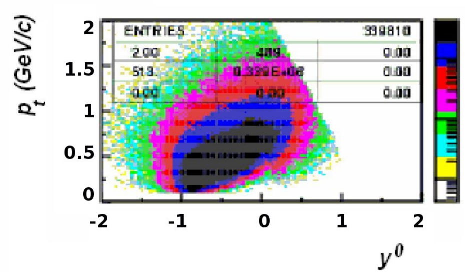
$y^0 = +1$ -projectile rapidity



Transverse mass spectra

$$m_t = \sqrt{m_0^2 + p_t^2}$$

Boltzmann distribution → equilibrium!

$$\frac{d^2N}{dm_t dy} \sim m_t^2 \cdot exp\left(-\frac{m_t cosh(y)}{T}\right)$$

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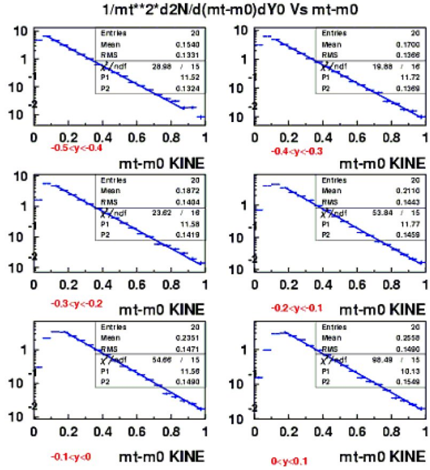

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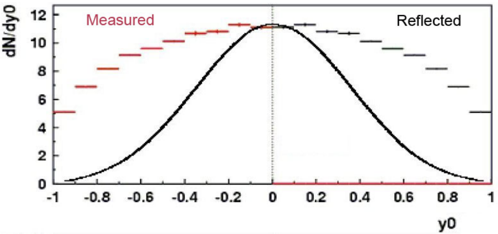

Total yield = **19/event**

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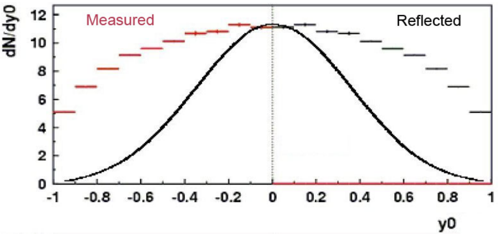

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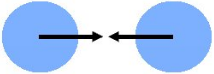
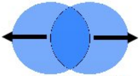
Stopping of baryonic matter

Initial state:



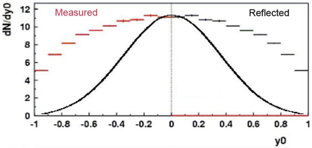
Final state:

stopped



transparent

- Global rapidity distribution is elongated
- Collision memory not reset
- Matter is partially transparent
- Experimental results suggest non-equilibrated barion production (p, d, t, $^{3,4}He$,...)



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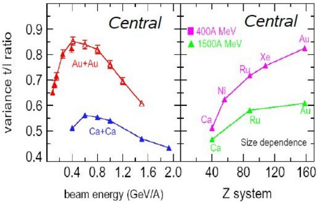

W.Reisdorf et al. (FOPI), PRL 92 (2004) 232301

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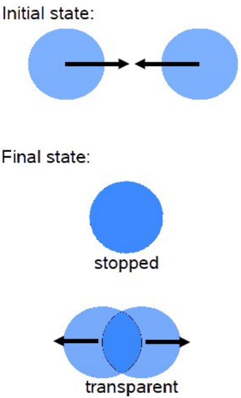

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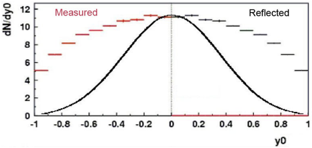

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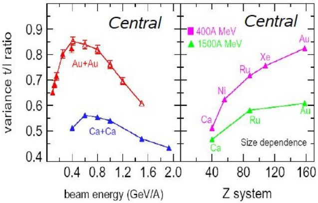

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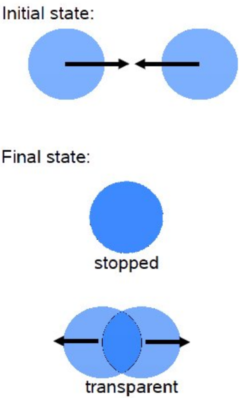

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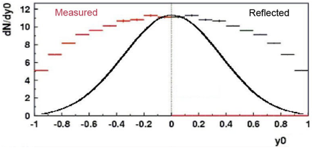

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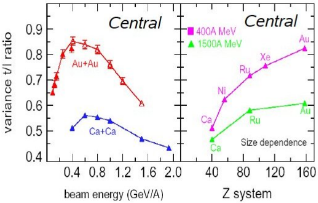

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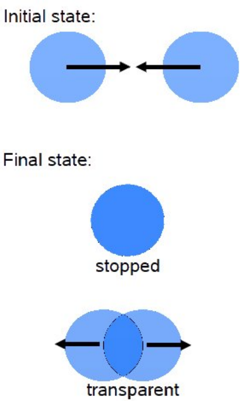

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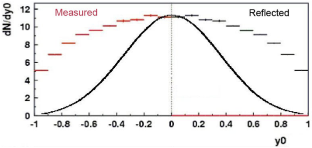

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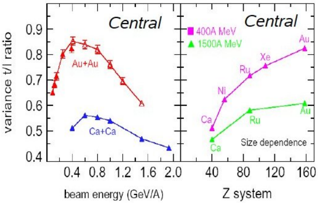

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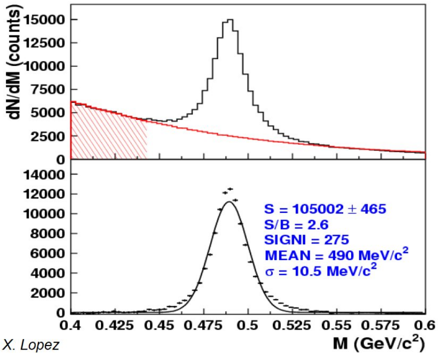
K^0 mesons

Identification

- $K_s^0 \longrightarrow \pi^+\pi^-$ (69%)
- $c\tau = 2.68$ cm
- Decay outside the target
- Invariant mass of $\pi^+\pi^-$ pairs

Transverse mass spectra

- Total yield: $P(K^0) = 0.039 \pm 0.001 \pm 0.004$
- Rapidity distribution →



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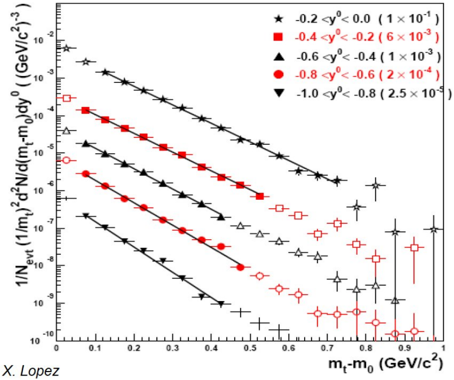
- Total yield: $\mathbf{P}(K^0) = \mathbf{0.039} \pm \mathbf{0.001} \pm \mathbf{0.004}$
- Rapidity distribution → Boltzmann like



X. Lopez

K^0 mesons

Identification

- $K_s^0 \longrightarrow \pi^+\pi^-$ (69%)
- $c\tau = 2.68$ cm
- Decay outside the target
- Invariant mass of $\pi^+\pi^-$ pairs

Transverse mass spectra

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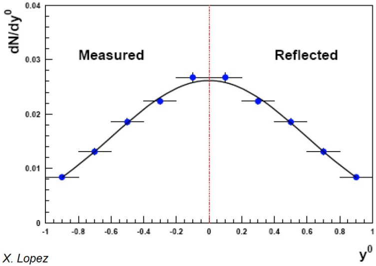

X. Lopez

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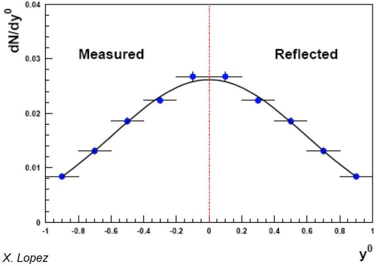
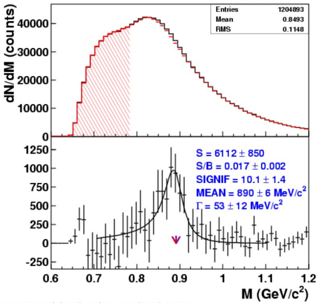
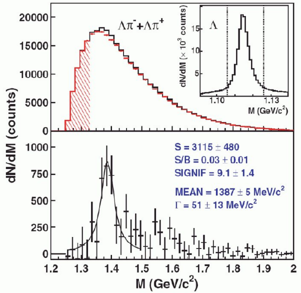


Strange resonances: $K^*(892)$ i $\Sigma^*(1385)$



X. Lopez et al. (FOPI), J. Phys. G 35 (2008) 044020



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

K^*

$K^*(892) \longrightarrow K^+ + \pi^-$ (69%)

$E_{thr} = 2.75$ GeV

$c\tau = 4$ fm

$$\frac{P(K^{0*})}{P(K^0)} = 0.032 \pm 0.003 \pm 0.012$$

Σ^*

$\Sigma^{\pm *}(1385) \longrightarrow \Lambda + \pi^{\pm}$ (88%)

$\searrow p + \pi^-$

$E_{thr} = 2.33$ GeV

$c\tau = 5$ fm

$$\frac{P(\Sigma^{*-} + \Sigma^{*-})}{P(\Lambda + \Sigma^0)} = 0.125 \pm 0.026 \pm 0.033$$

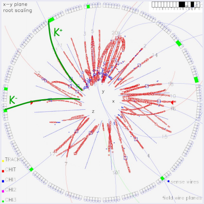
$\phi(1020)$ meson

Main properties

- neutral vector meson
- quark content: $(s\bar{s})$ - *"hidden" strangeness*
- $m_0 = 1.019$ GeV/c^2
- $\tau_\phi \approx 1.55 \cdot 10^{-22}$ s
- $c\tau \approx 50$ *fm*
- $E_{thr} = 2.6$ GeV (only 100 MeV above threshold for K^+K^-)
- main decay channel: $\phi \to K^+K^-$ $(48.9 \pm 0.5$ %)

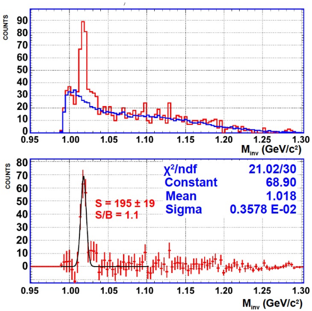
Identification

- ϕ decays in target
- no secondary vertices
- Invariant mass reconstruction of K^+K^- pairs



$\phi(1020)$ reconstruction

K^+K^- invariant mass

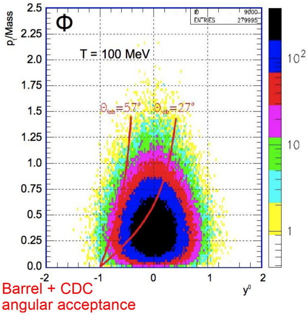


- Background reconstructed using "event-mixing" method

Total yield in 4π:

$$P_\phi = (2.2 \pm 0.5) \cdot 10^{-4}$$

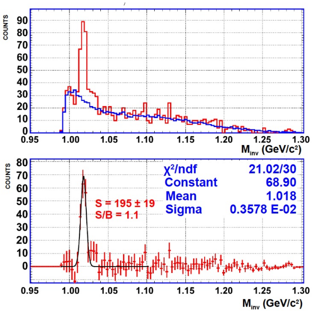
EFFICIENCY



- Detector's efficiency → GEANT
- Al+Al collisions → UrQMD
- ϕ mesons generated thermal, isotropic source (Siemens - Rasmussen formula)
- T_ϕ=70 . . . 130 MeV (errors estimation)
- β_{flow}=0

$\phi(1020)$ reconstruction

K^+K^- invariant mass



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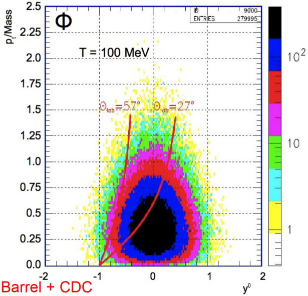

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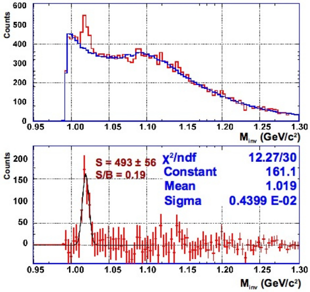
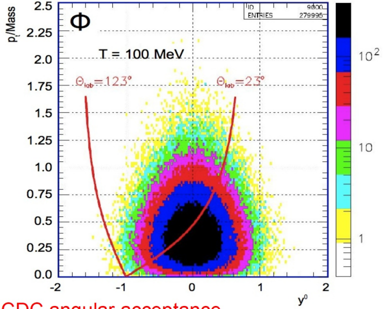
ϕ kinetic energy distribution

- Attempt to enlarge phase-space of reconstructed ϕ mesons
- K^+K^- pairs ONLY from CDC
- $\sim$ 500 ϕ mesons reconstructed
- $P_\phi = (2.7 \pm 0.5) \cdot 10^{-4}$

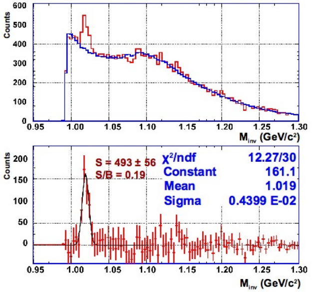


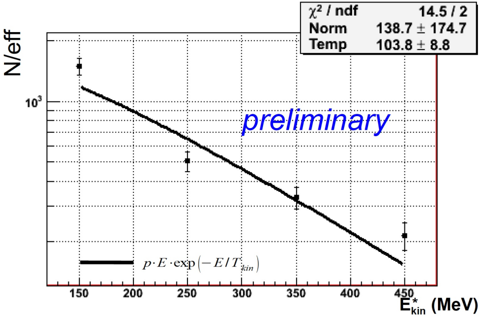


CDC angular acceptance

ϕ kinetic energy distribution

- Attempt to enlarge phase-space of reconstructed ϕ mesons
- K^+K^- pairs ONLY from CDC
- ~ 500 ϕ mesons reconstructed
- $P_\phi = (2.7 \pm 0.5)\cdot 10^{-4}$





How many K^- from ϕ?

K^- yield

K^- yield in Al+Al @ 1.9A GeV was obtained:

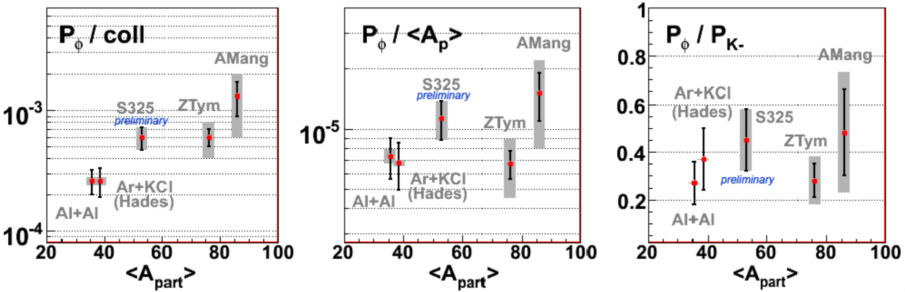
$$P(K^-) = (8.1 \pm 1.7 \pm 0.2) \cdot 10^{-4}\ 1/\text{event}$$

ϕ/K^-

$$\frac{P(\phi)}{P(K^-)} = 0.27 \pm 0.09$$

$B.R._{\phi \to K^+K^-} = 0.49$
$\sim 13\%$ K^- mesons come from $\phi(1020)$ decays.

ϕ systematics



	Experiment	N_ϕ	Comments
Al+Al	Al+Al@1.91*A* GeV (2005)	195±19	P. Gasik for the FOPI coll.
S325	*Ni+Ni@1.91A GeV (2007/08)*	*135±17*	*K. Piasecki for the FOPI coll.*
ZTym	Ni+Ni@1.93*A* GeV (Jan. 2003)	100±17±20	Z. Tyminski for the FOPI coll.
AMan	Ni+Ni@1.93*A* GeV (1995)	23±7±2	A. Mangiarotti et *al*. NPA714(03)89
Hades	Ar+KCl@1.756*A* GeV (HADES@GSI)	168±18	G. Agakishiev et *al*. PRC 80 (2009) 025209

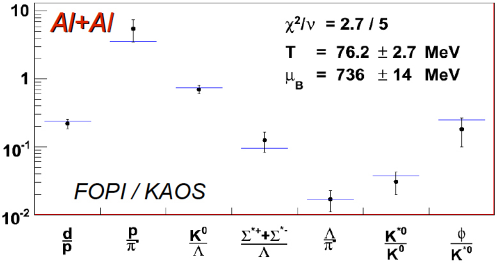
Thermal model

Chemical "freeze-out"

- Thermal fit - THERMUS code
  S.Wheaton,J.Cleymans, hep-ph/0407175
- Grand Canonical ensemble
- For $S \neq 0$ - Canonical ensemble
- 7 independent ratios
- Obtained parameters:

$$T_{chem} = 76 \pm 3 \text{ MeV}$$
$$\mu_b = 736 \pm 14 \text{ MeV}$$

- Fitting quite well

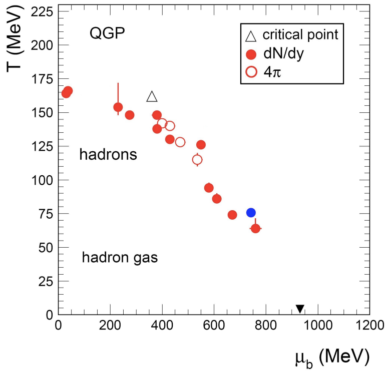


K. Piasecki for the FOPI Coll.

Questions on equilibrium

Phase Diagram

- T(μ_b) at freeze-out fits into systematics - equilibrium?
- Effective way to parametrize yield ratios

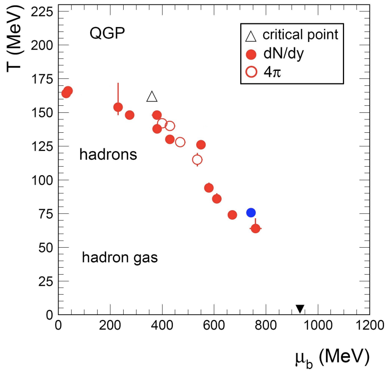


A.Andronic, P.Braun-Munzinger, J.Stachel, NPA 772 (2006) 167

Questions on equilibrium

Phase Diagram

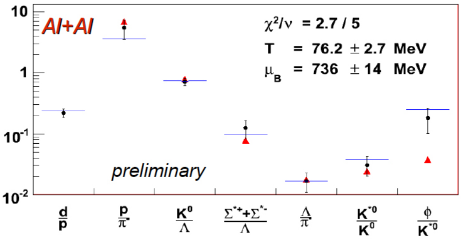
- $T(\mu_b)$ at freeze-out fits into systematics - equilibrium?
- Effective way to parametrize yield ratios



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

UrQMD

- **U**ltrarelativistic **Q**uantum **M**olecular **D**ynamics *M.Bleicher, S.Vogel - Uni Frankfurt*
- UrQMD model fairly good reproduces experimental results
- No thermalisation
- No in-medium effects
- ϕ production mechanism poorly described



K.Piasecki for the FOPI Coll.

Summary

Thermalisation @ 1.9A GeV

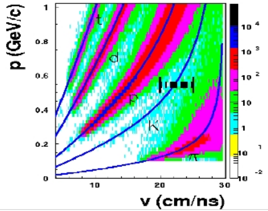
- Production probabilities for different particle species were measured
- Results compared to the Statistical Model calculations. T_{chem}, μ_b obtained.
- SM reproduces measured yields
- **But...**
  - Non-thermal rapidity distributions of p and d
  - Further analysis show "freeze-out" temperatures inversion: $T_{kin} > T_{chem}$
  - UrQMD simulations also reproduce experimental results
- Same situation for Ni+Ni @ 1.93A GeV
- Question on thermalisation still open...

ϕ(1020) @ 1.9A GeV

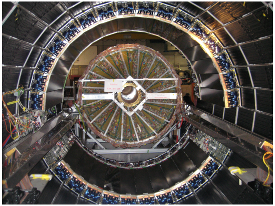
- P_ϕ measured
- New analysis method → factor 2.5 more mesons reconstructed!
- New particle yields ratios measured: ϕ/K^-, ϕ/K^*
- $<A_{part}>$ dependence should be clarified

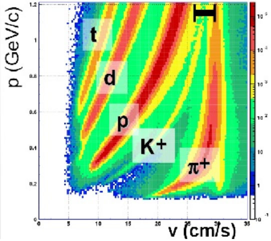
Outlook

- New experimental data:
  - New RPC ToF detectors ($\sigma_{ToF,RPC} < 65$ps)
  - $\sigma_{ToF,SYS} < 90$ps $\rightarrow$ more kaons reconstructed



Plastic Barrel ToF





RPC ToF

- Ni+Ni@1.91A GeV - analysis on-going
- Ni+Pb@1.93A GeV, Ru+Ru@1.65A GeV - wait to be analysed
- Elementary reactions:
  - p+p@3.5A GeV - run in 2009
  - π+p@1.7A GeV - November 2010

FOPI COLLABORATION

A. **Andronic**, R. **Averbeck**, Z. **Basrak**, N. **Bastid**, M.L. **Benabderrahmane**, M. **Berger**, P. **Buhler**, R. **Caplar**, M. **Cargnelli**, M. **Ciobanu**, P. **Crochet**, I. **Deppner**, P. **Dupieux**, M. **Dzelalija**, L. **Fabbietti**, J. **Fruhauf**, 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. **Munzer**, P. **Koczon**, M. **Korolija**, R. **Kotte**, A. **Lebedev**, K.S. **Lee**, Y. **Leifels**, P. **Loizeau**, X. **Lopez**, M. **Marquardt**, J. **Marton**, M. **Merschmeyer**, T. **Matulewicz**, M. **Petrovici**, K. **Piasecki**, F. **Rami**, V. **Ramillien**, A. **Reischl**, W. **Reisdorf**, M.S. **Ryu**, A. **Schuttauf**, Z. **Seres**, B. **Sikora**, K.S. **Sim**, V. **Simion**, K. **Siwek-Wilczynska**, K. **Suzuki**, J. **Weinert**, K. **Wisniewski**, Z. **Xiao**, H.S. **Xu**, J.T. **Yang**, I. **Yushmanov**, A. **Zhilin**, Y. **Zhang**, J. **Zmeskal**

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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)

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