From Bevalac to RHIC

The First 30 Years of Relativistic Nuclear Collisions Research

R. Stock, University of Frankfurt

- Initial motifs and goals:
  Neutron Star Interior, Nuclear Matter EOS

- From LBL to AGS, SPS, RHIC:
  Collaborations reflect the growth of the field

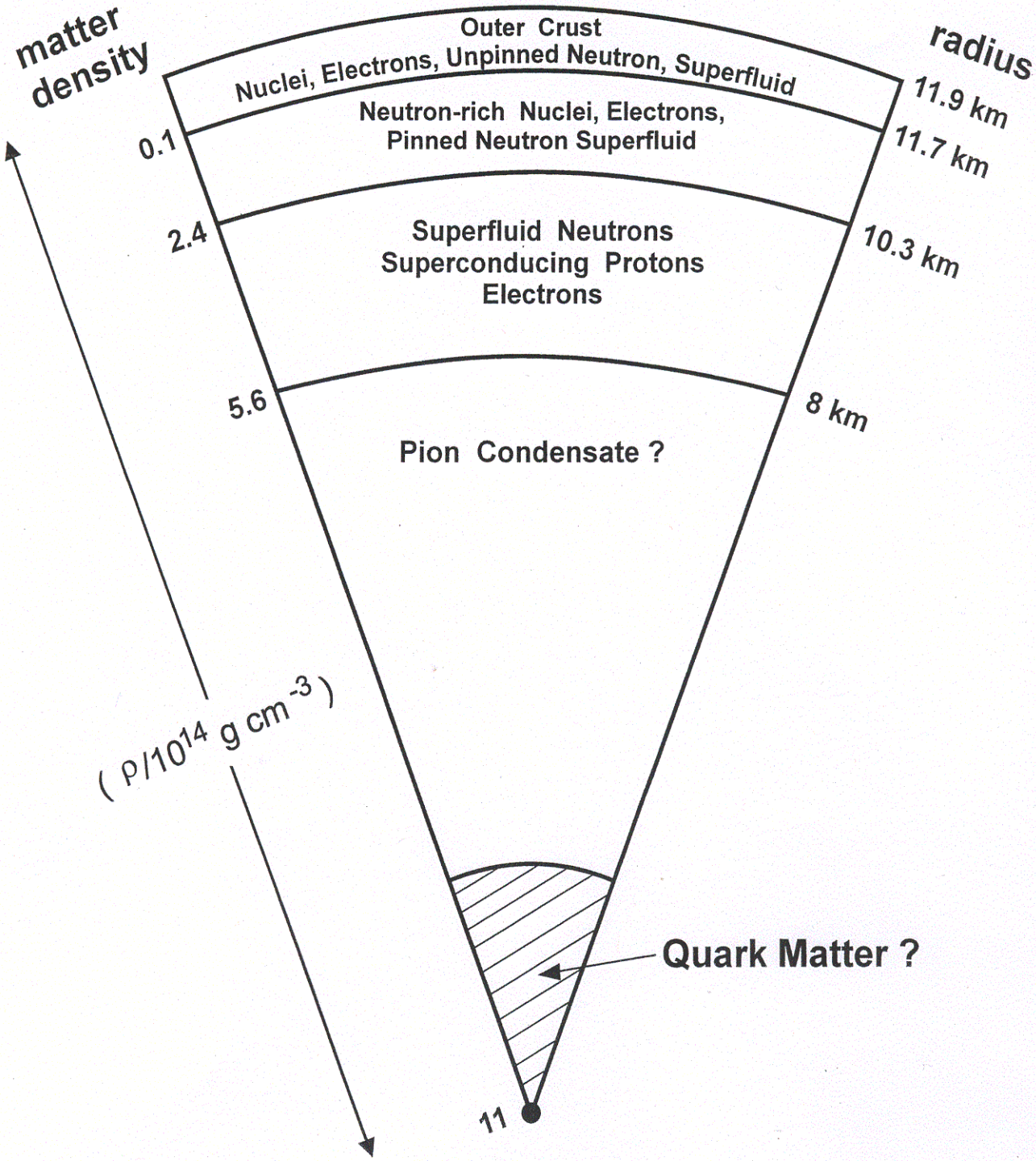
- Observables, onward from Bevalac:
  (some randomly collected examples)
  Collisions centrality
  Rapidity distributions
  Early p, d, π, K data: spectra multiplicity
  Blast wave, radial flow, directed and elliptic flow
  Coalescence
  HBT: Bose-Einstein correlation

- Proposals: CERN SPS 1982, RHIC 1984

- From Bevalac (SIS) to RHIC:
  Hadron multiplicities, Grand Canonical
  Statistical analysis: the QCD phase boundary

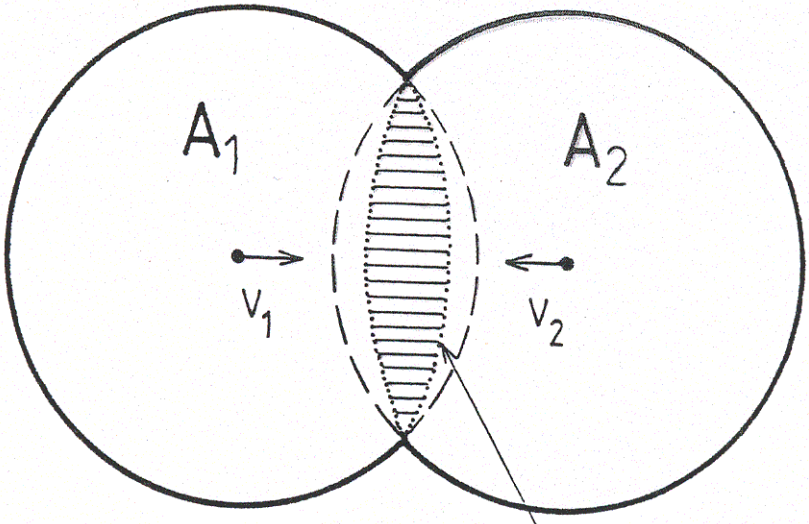
- Outlook: new physics at RHIC

Structure of neutron stars



Shock Compression at Bevalac

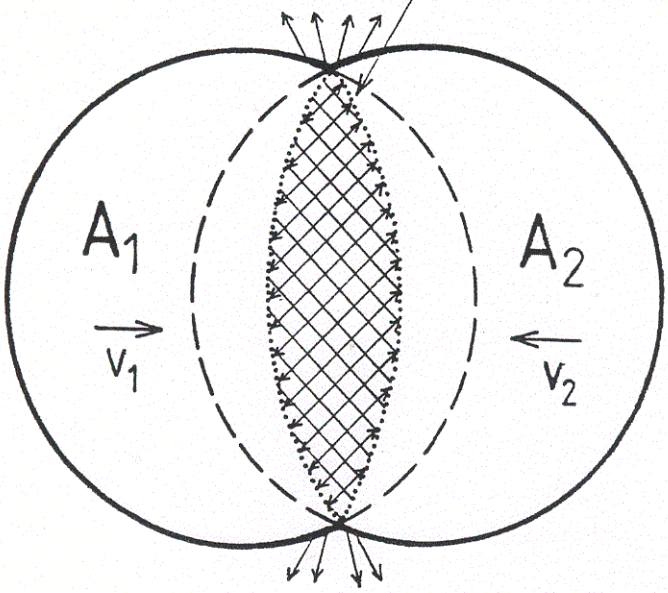
1.



Relative velocity
$\beta \approx 0.8$
$t_1 \approx 10^{-23}$ s

Compression Zone

2.



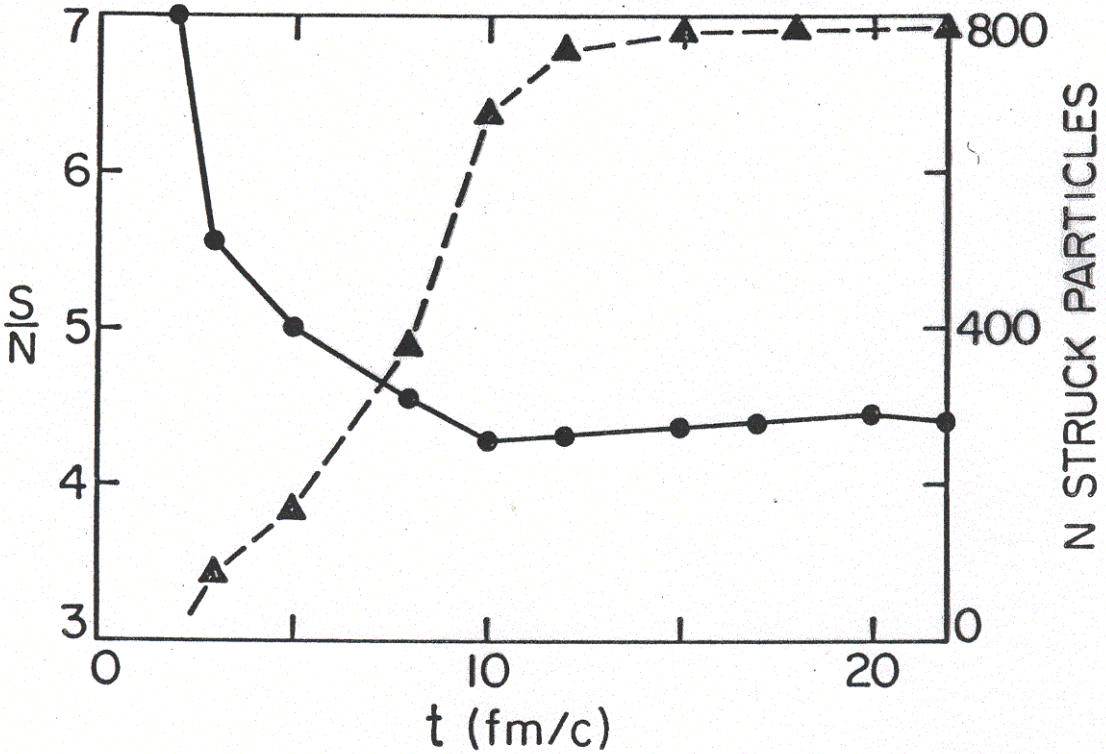
$t_2 > t_1$

$t_2 \approx 2 \times 10^{-23}$ s

Scheid, Mueller, Greiner
Chapline, Teller, Weiss } 1974

Reaction Entropy

G. Bertsch and J. Cugnon, Phys. Rev. C24 (1981) 2514



XBL 817-10510

A + A 182 MeV/A CM

$b = 0.8\ b_{max}$ $b = 0.4\ b_{max}$ $b = 0$

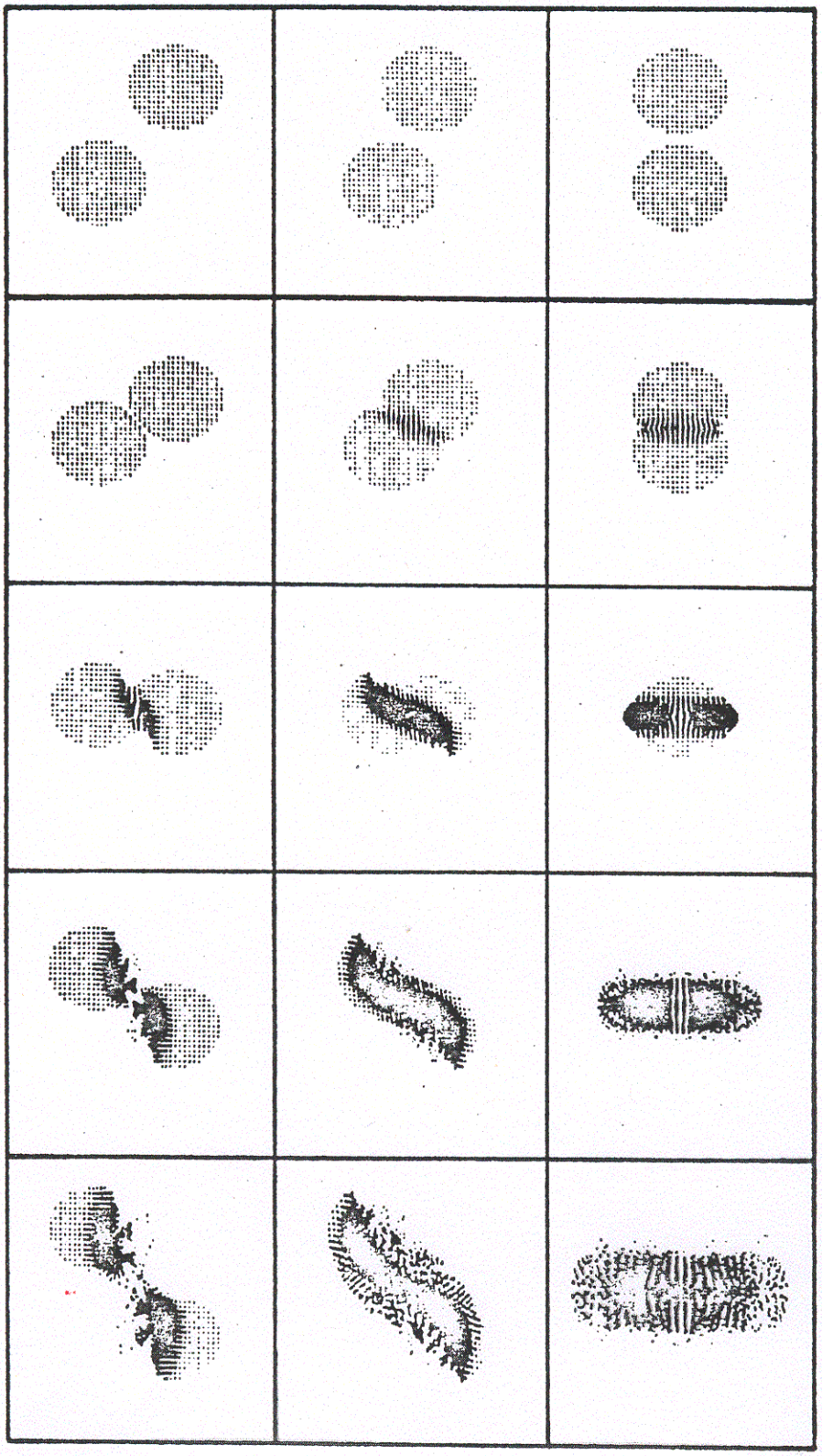


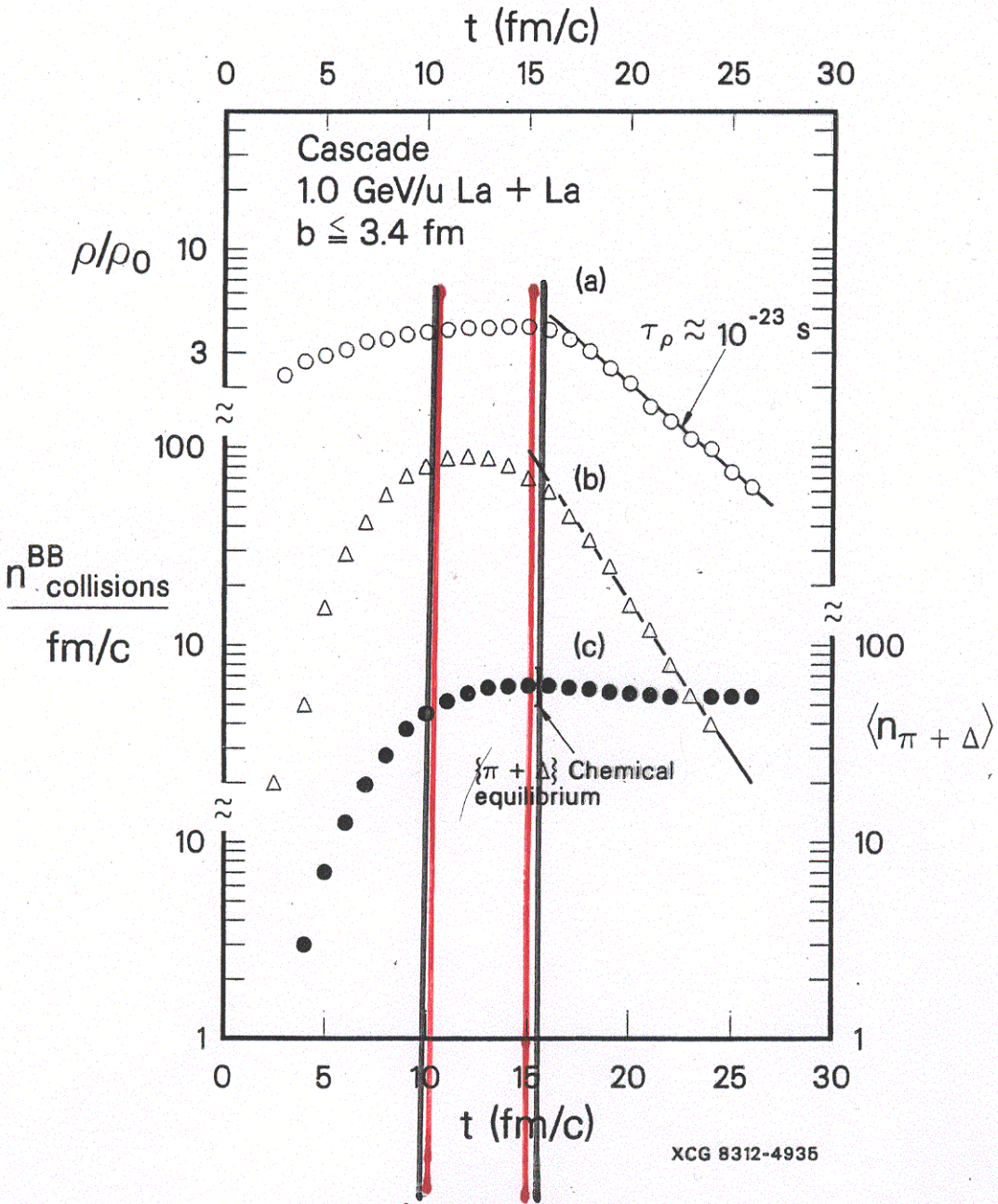
Fig. 19

Hydrodynamics from Los Alamos
(Nix, Strottman)

Meson to Baryon Ratio

J. W. Harris and R. Stock, LBL – 17054, 1984

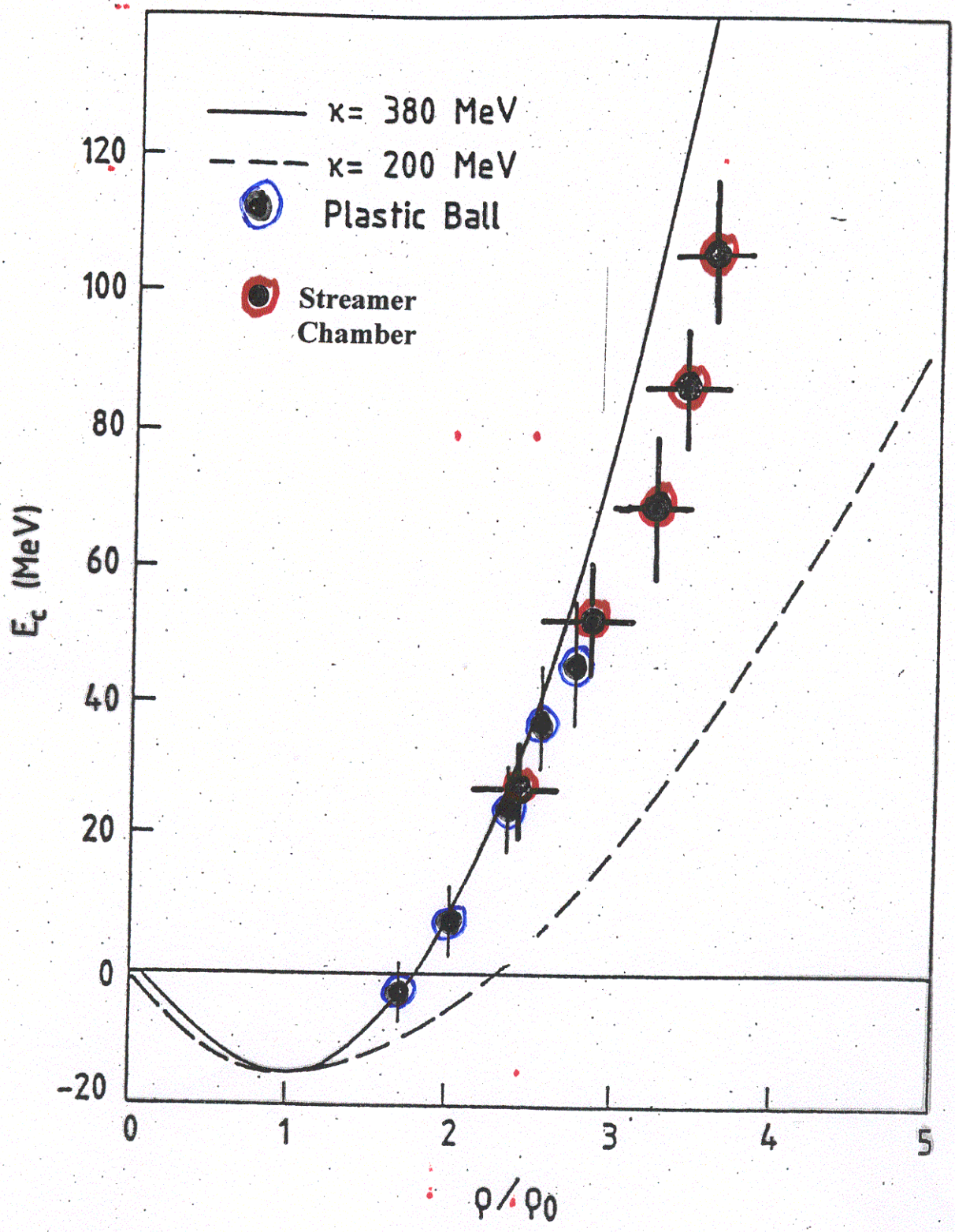
Concept (A. Mekjian) : hadro-chemical "freeze-out"



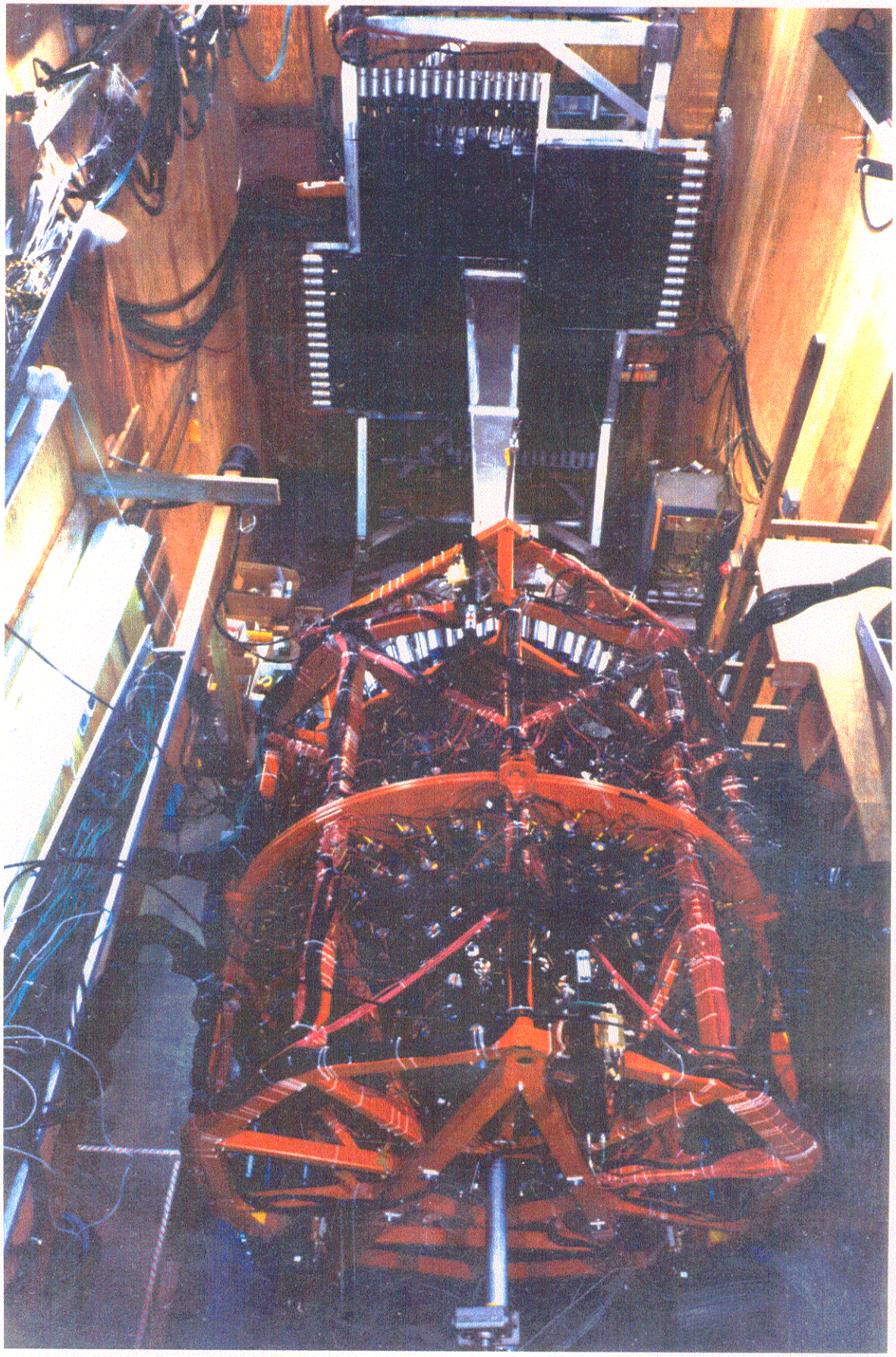
π/M_part established!

NUCLEAR MATTER EOS

Plastic Ball:	K. H. Kampert, LBL 24580, 1988
Streamer Chamber:	J. W. Harris et al., Phys. Lett. 153B (1985) 377
VUU:	J. J. Molitoris et al., Nucl. Phys. A447 (1985) 13



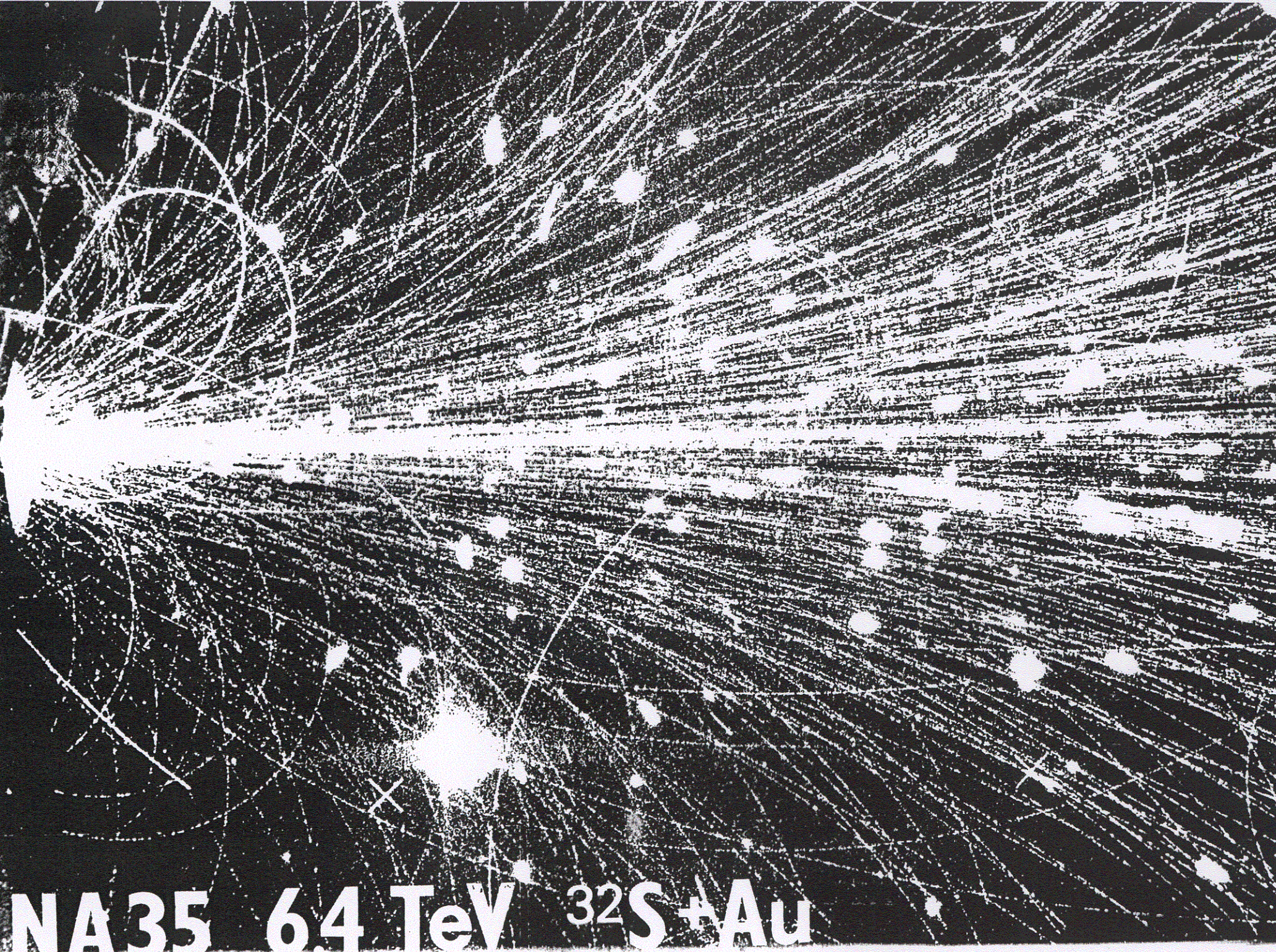
GSI-LBL-Plastic Ball; Gutbrod; Postkanzer; Ritter etal.

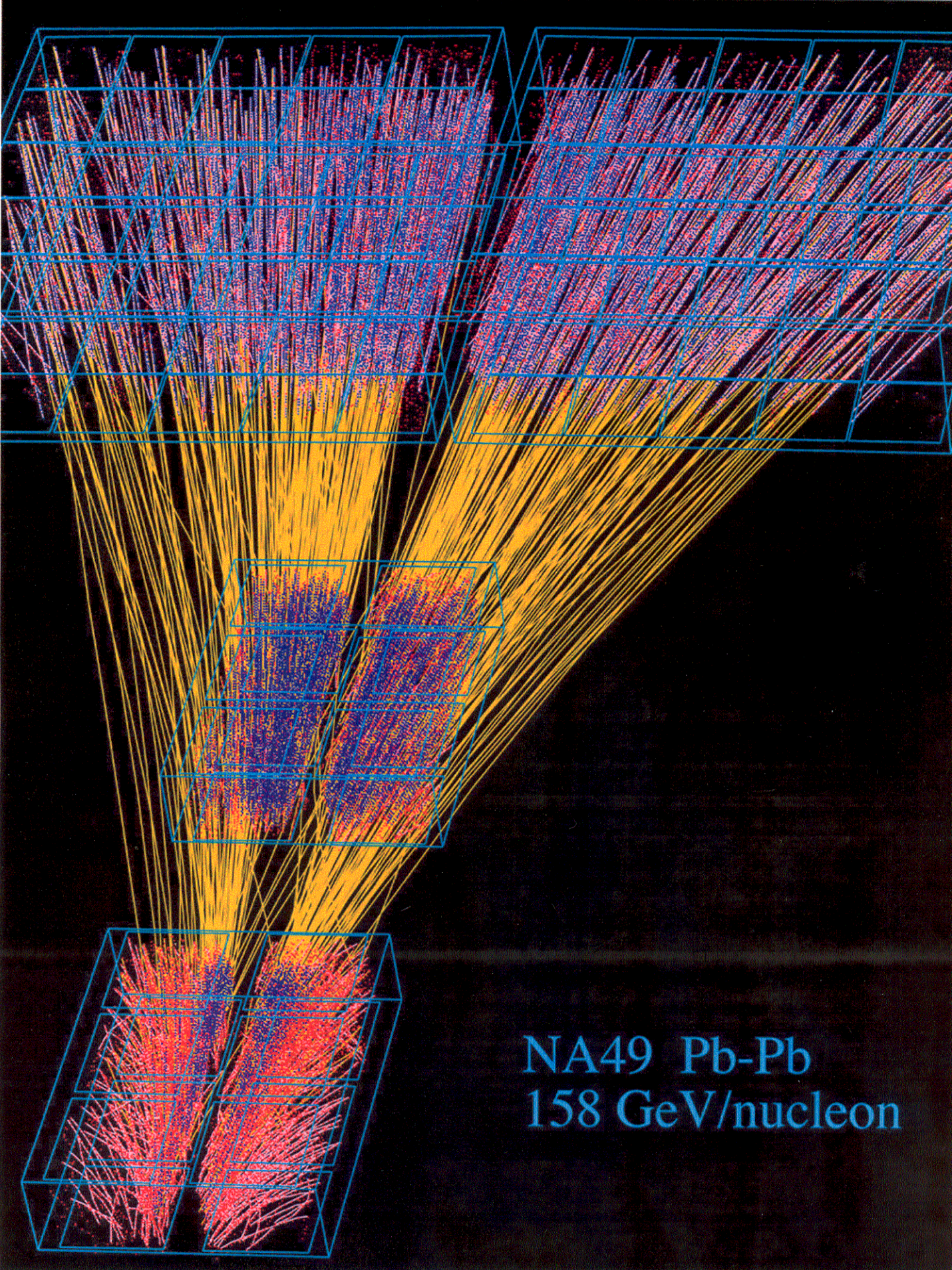


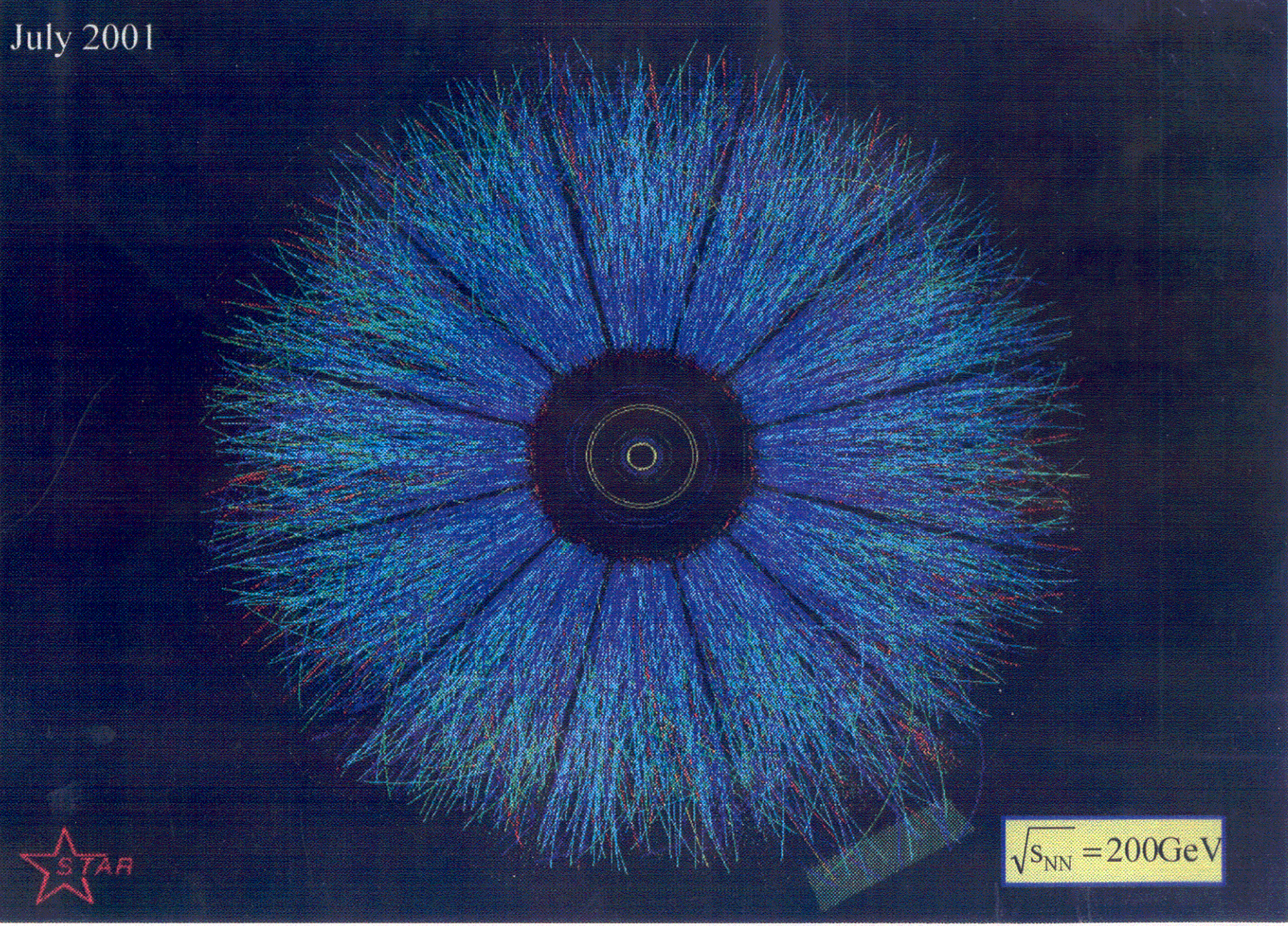
BBC 8/8-8088

The LBL - GSI Streamer Chamber Collaboration

1983 at LBL, California


NA35 6.4 TeV ^{32}S+Au


NA49 Pb-Pb
158 GeV/nucleon



RHIC @ BNL : Au + Au at $\sqrt{s} = 200\,\mathrm{GeV}$

Observables:

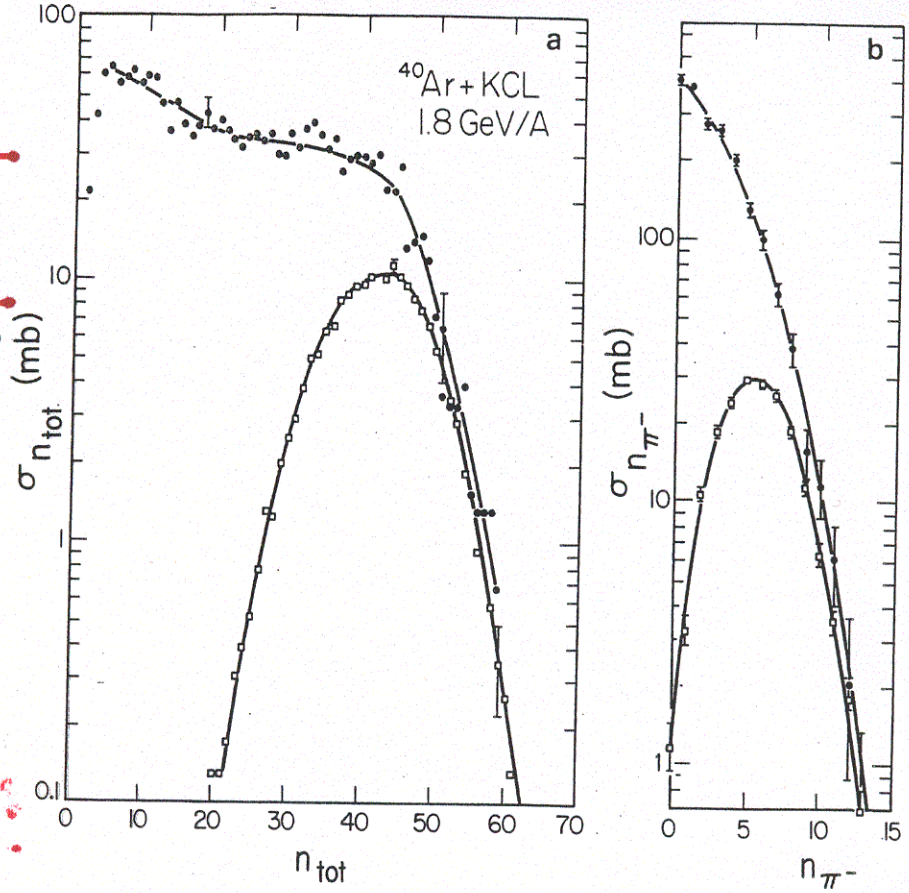
"How David Scott sees it in 1979"

CBB 781-447

CENTRALITY

Sandoval et al.

Streamer Chamber



PHYSICAL REVIEW LETTERS 10 SEPTEMBER

RHIC STAR

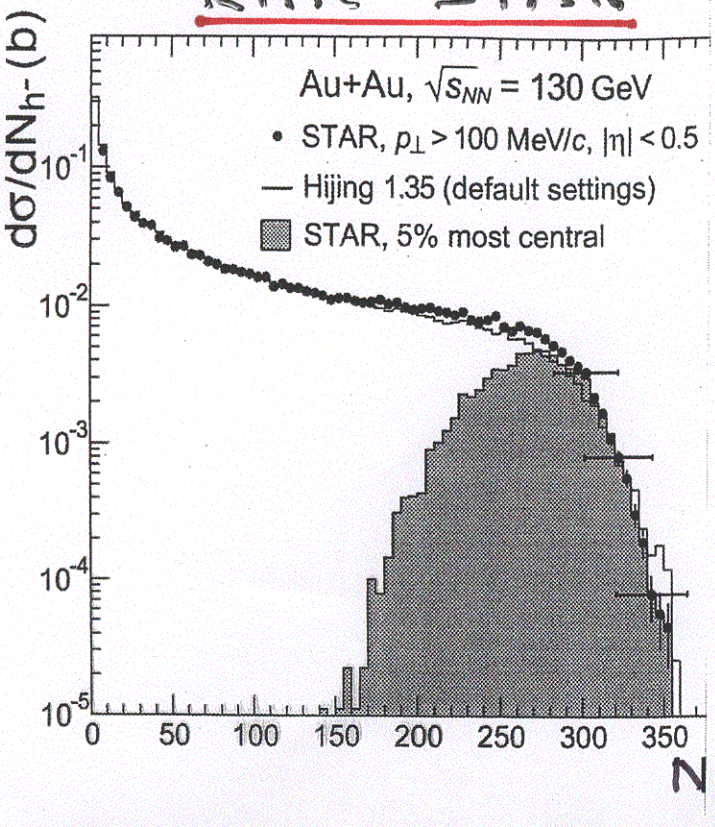
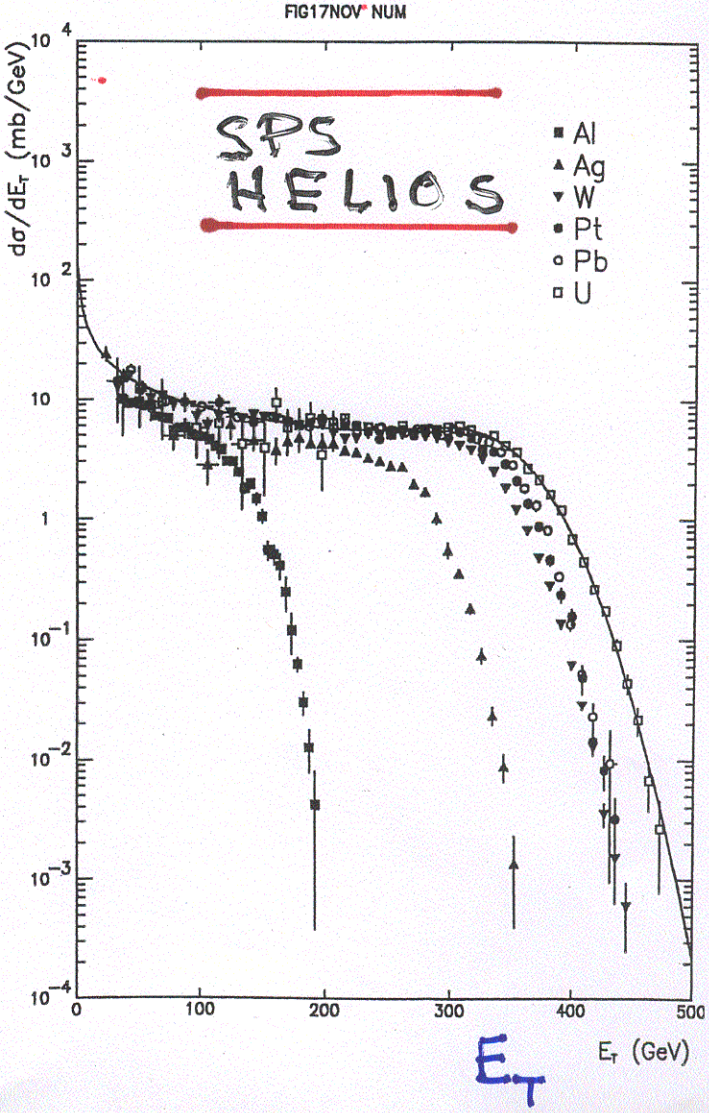


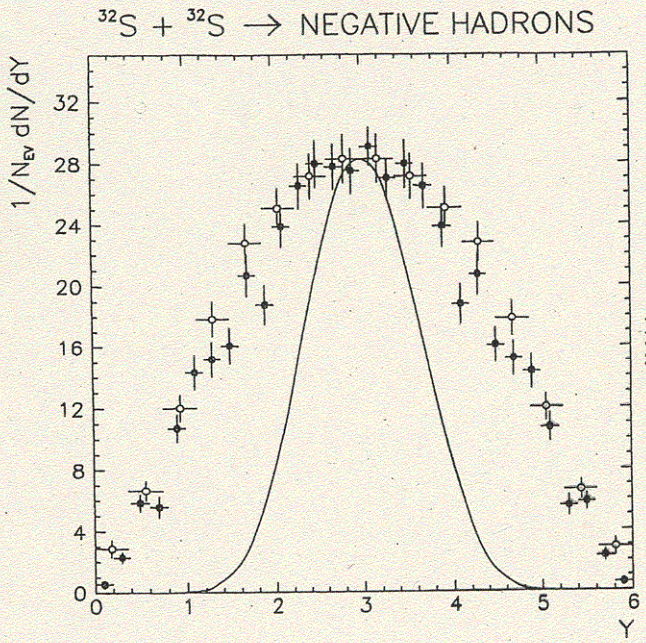
FIG17NOV NUM

SPS HELIOS

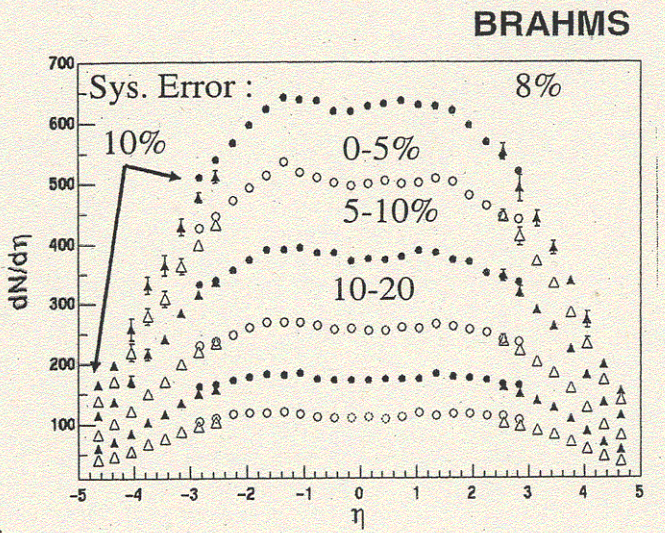


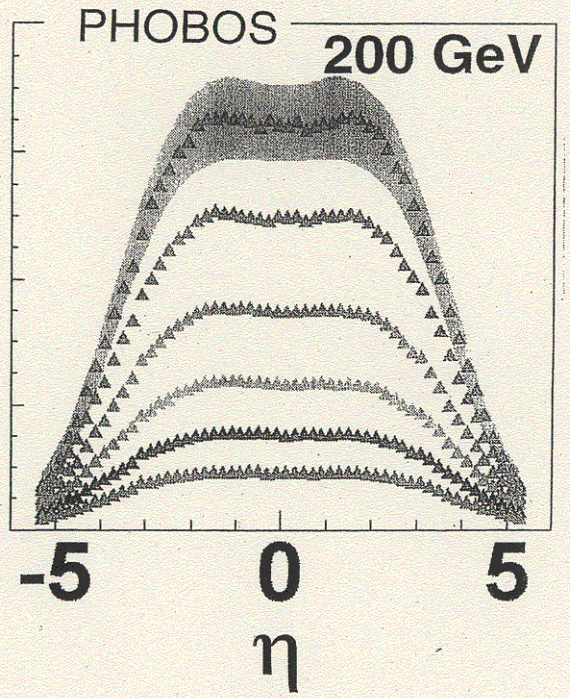
RAPIDITY DISTRIBUTIONS

SPS

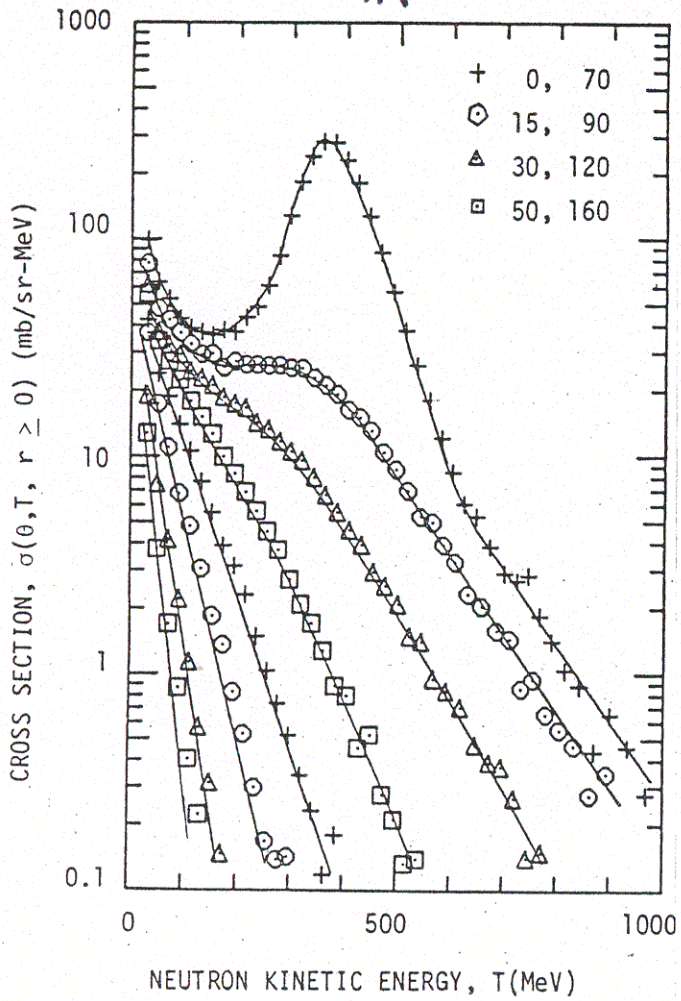


RHIC

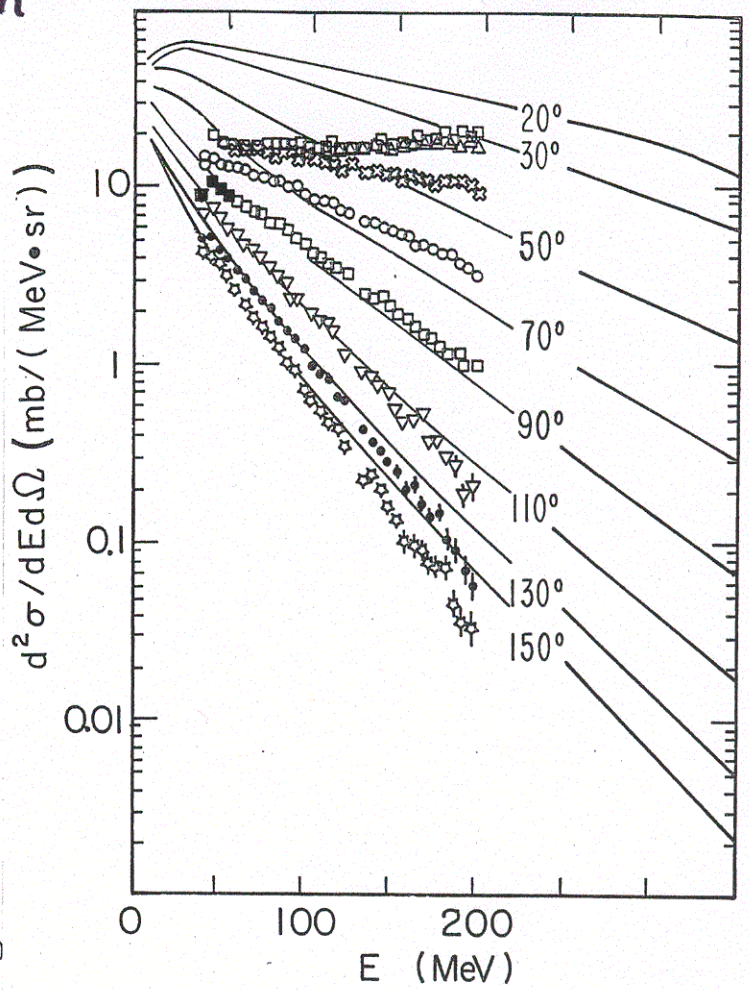




400 MeV/A Ne+Pb → n



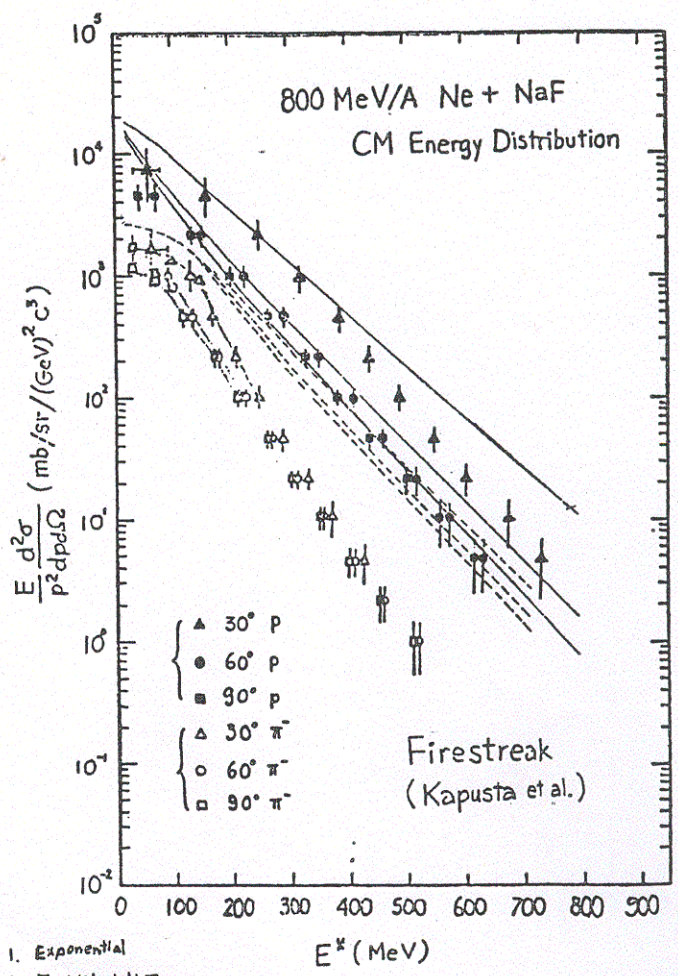
400 MeV/nucl $^{20}Ne + U \rightarrow p$



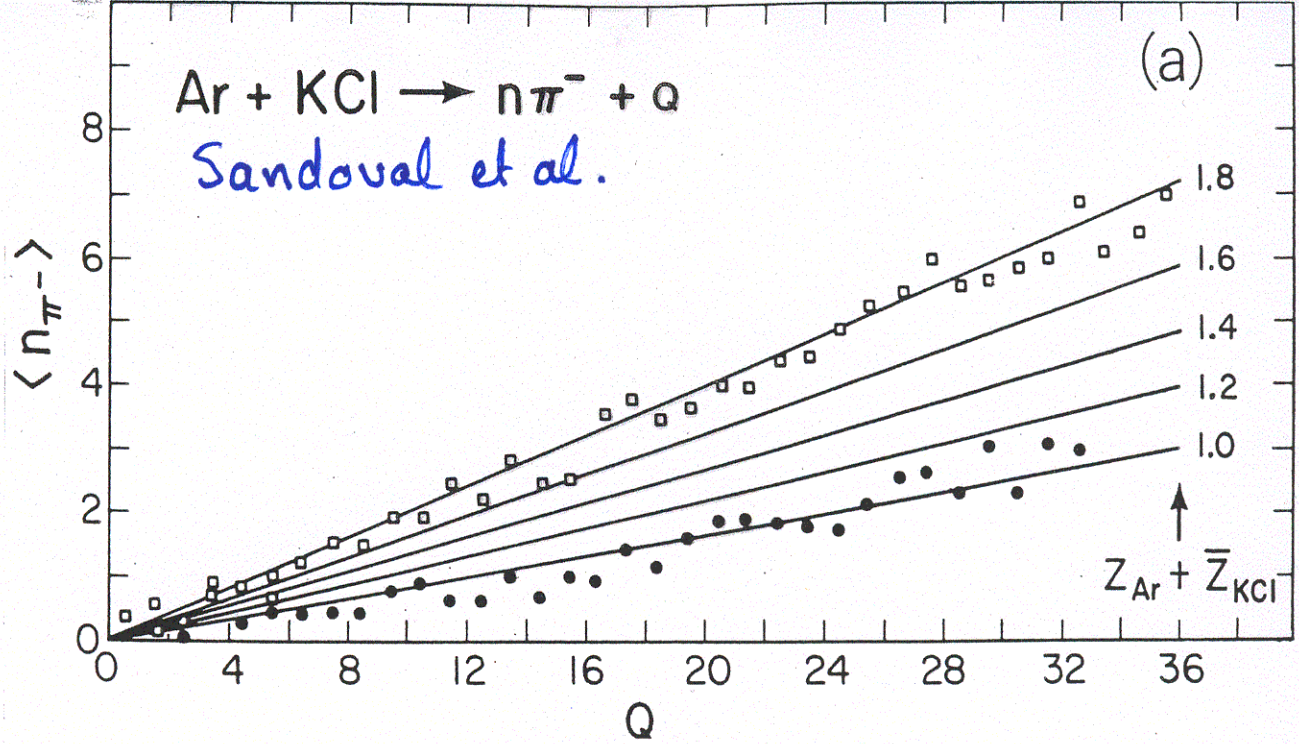
XBL787-1326

Data for the Fireball - Firestreak Model

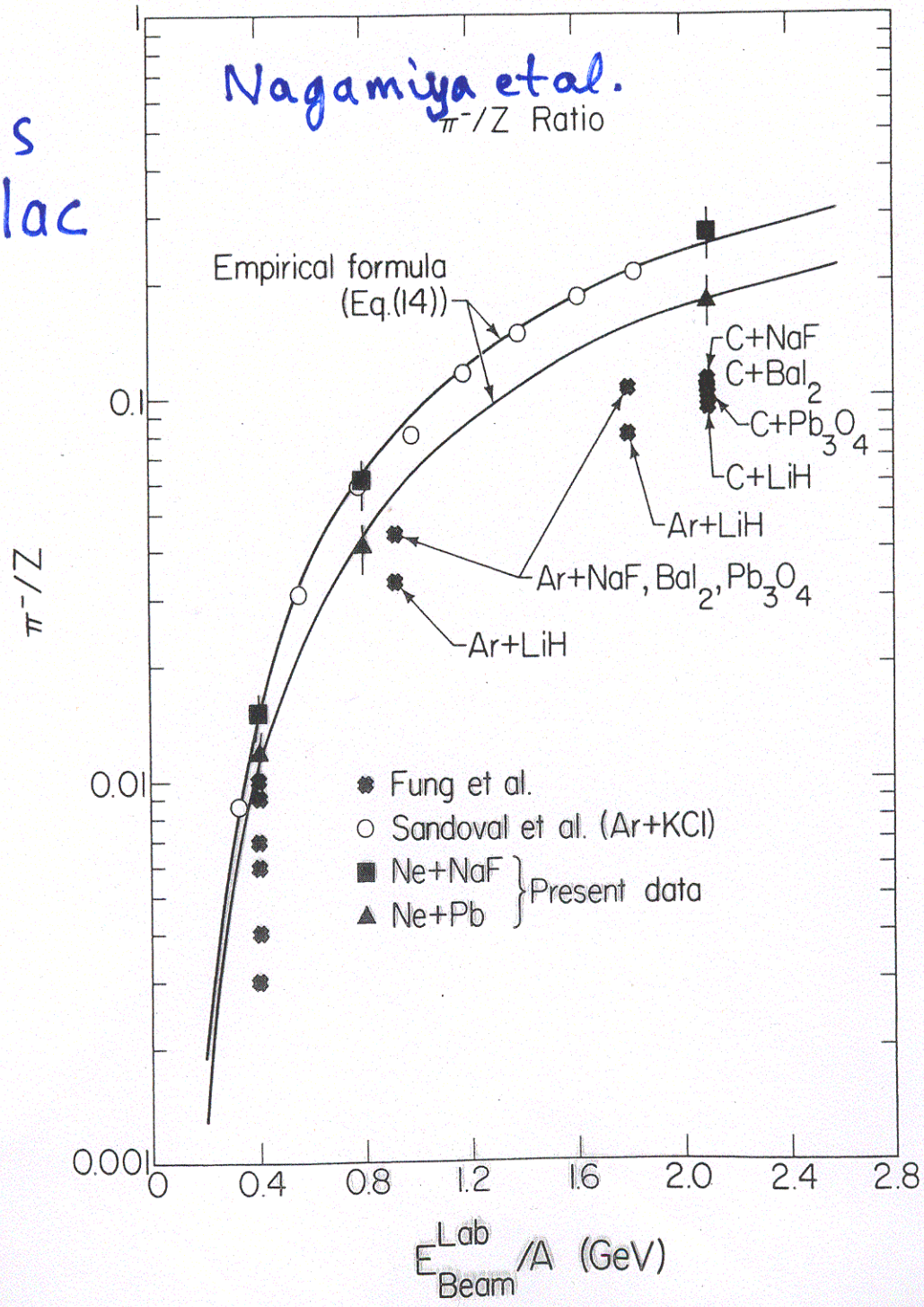
Bevalac → 1979



1. Exponential
2. Too high yield π
3. T(1.5K T(p))

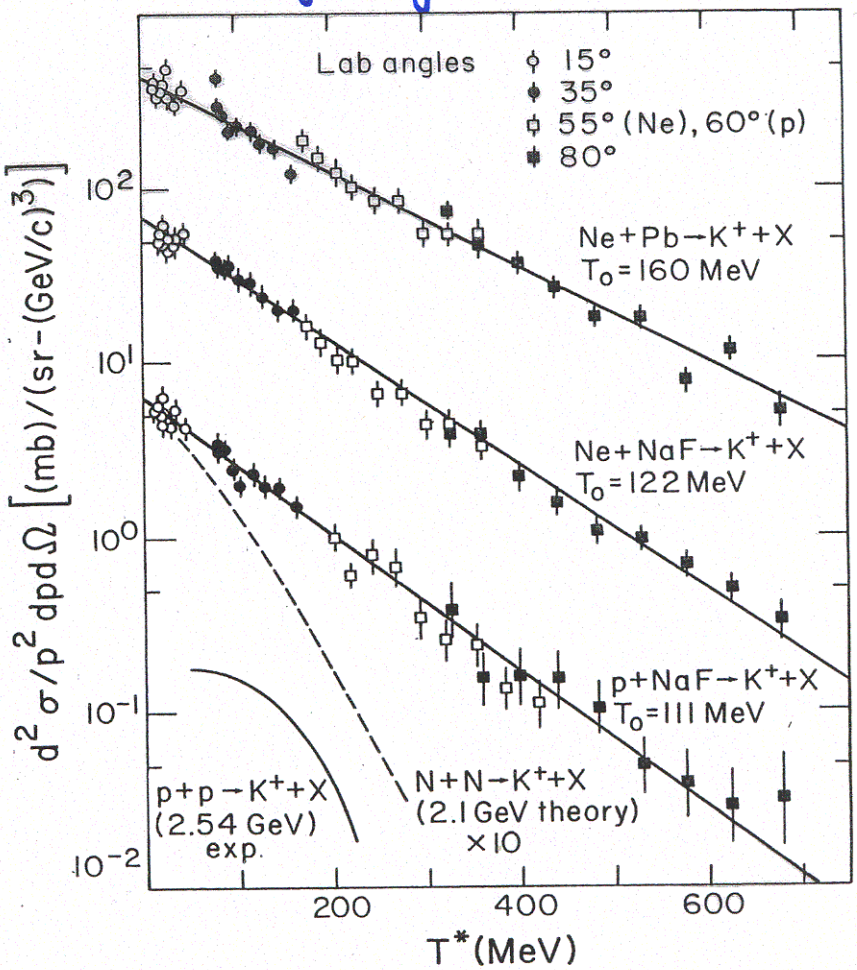


Pions
Bevalac

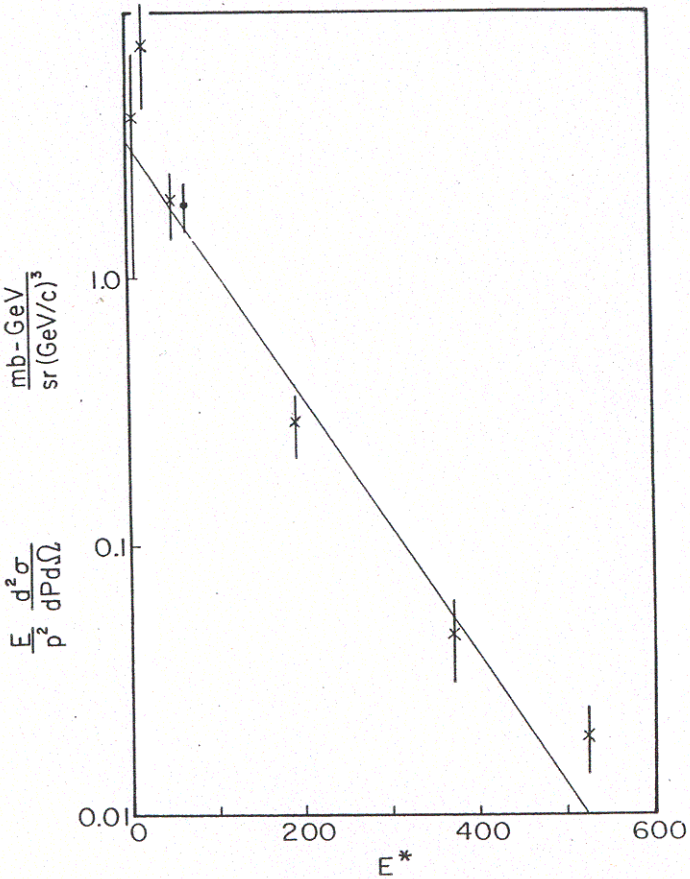


First Kaon Results Bevalac

Nagamiya et al. K^+



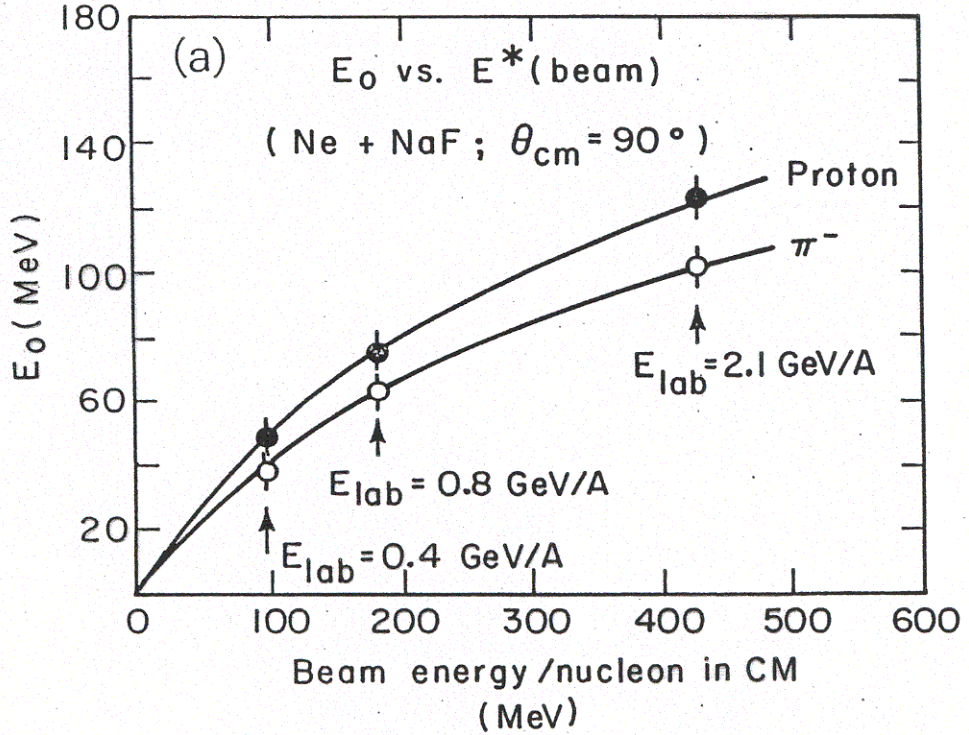
A. Shorr et al. K^-

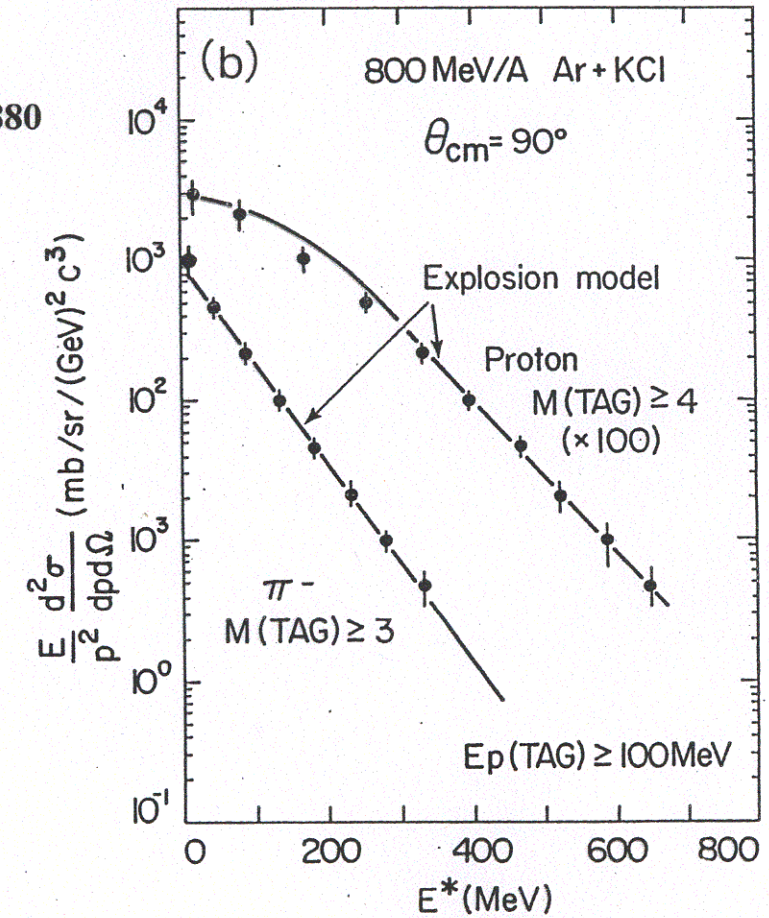


$$\frac{d^3\sigma}{dp^3} = \text{const.}\exp\left(-\frac{\gamma_f E}{T_f}\right)\left[\left(\gamma_f + \frac{T_f}{E}\right)\frac{\sinh\alpha}{\alpha} - \frac{T_f}{E}\cosh\alpha\right]$$

The Blast Wave Model

P. J. Siemens and J. O. Rasmussen, Phys. Rev. Lett. 42 (1979) 880

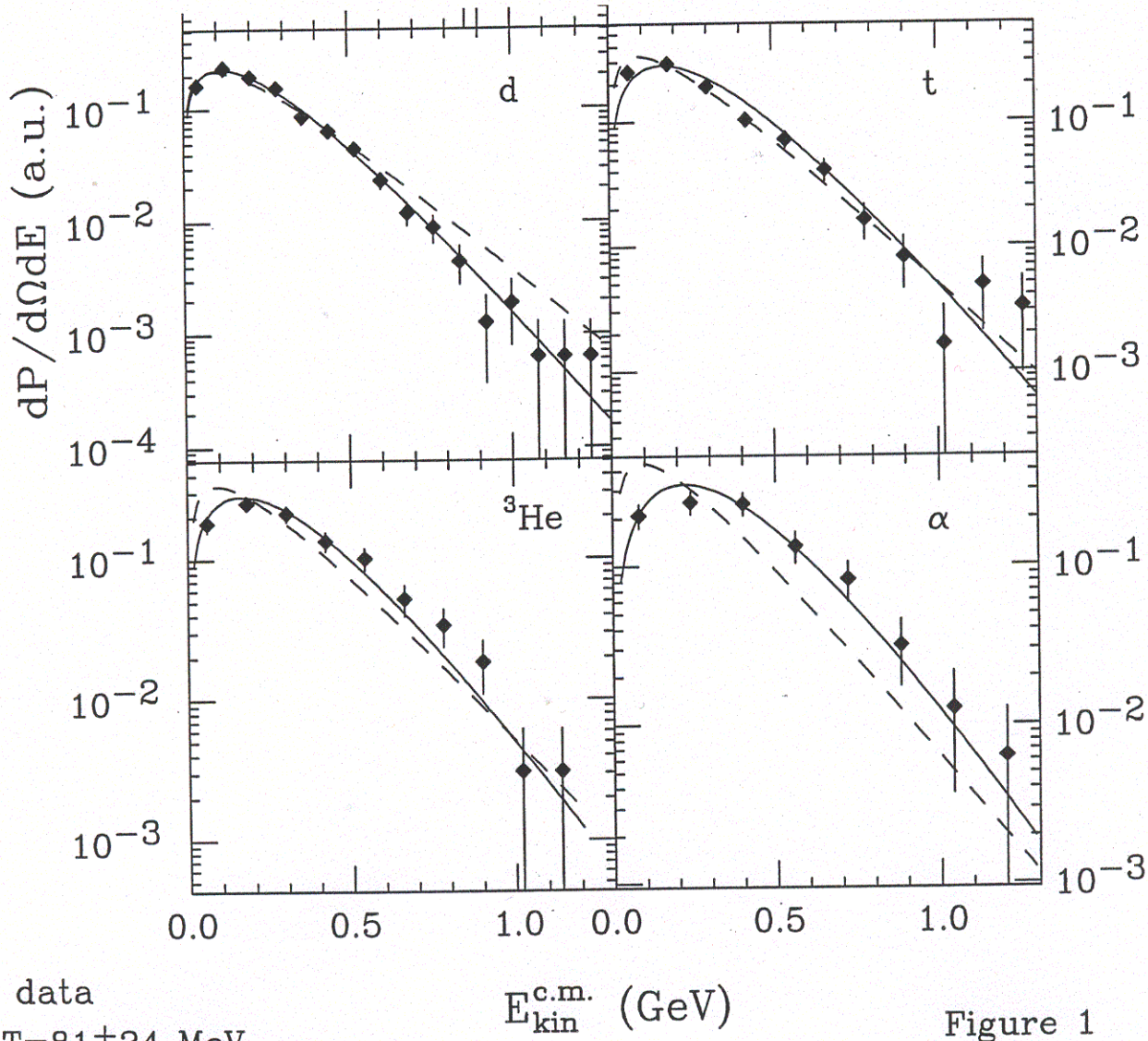




Data Nagamiya et al.

Radial Flow in Au+Au Collisions at E=0.25-1.15 A GeV

The EOS Collaboration
at the Bevalac



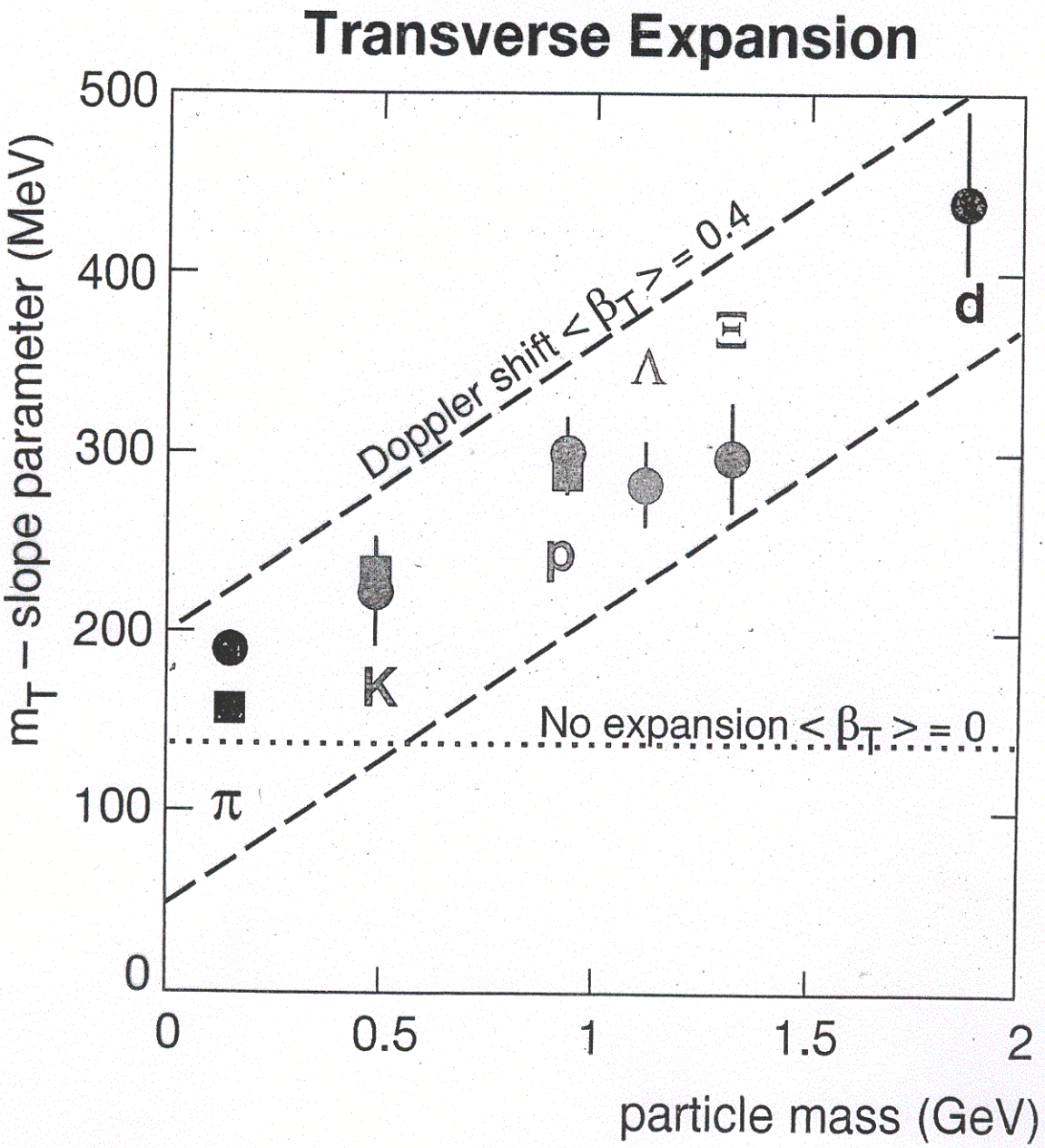
◆ data

—— T=81±24 MeV
β=0.32±0.05
χ^2/ν=1.13

– – T=158±14 MeV
β≡0
χ^2/ν=4.26

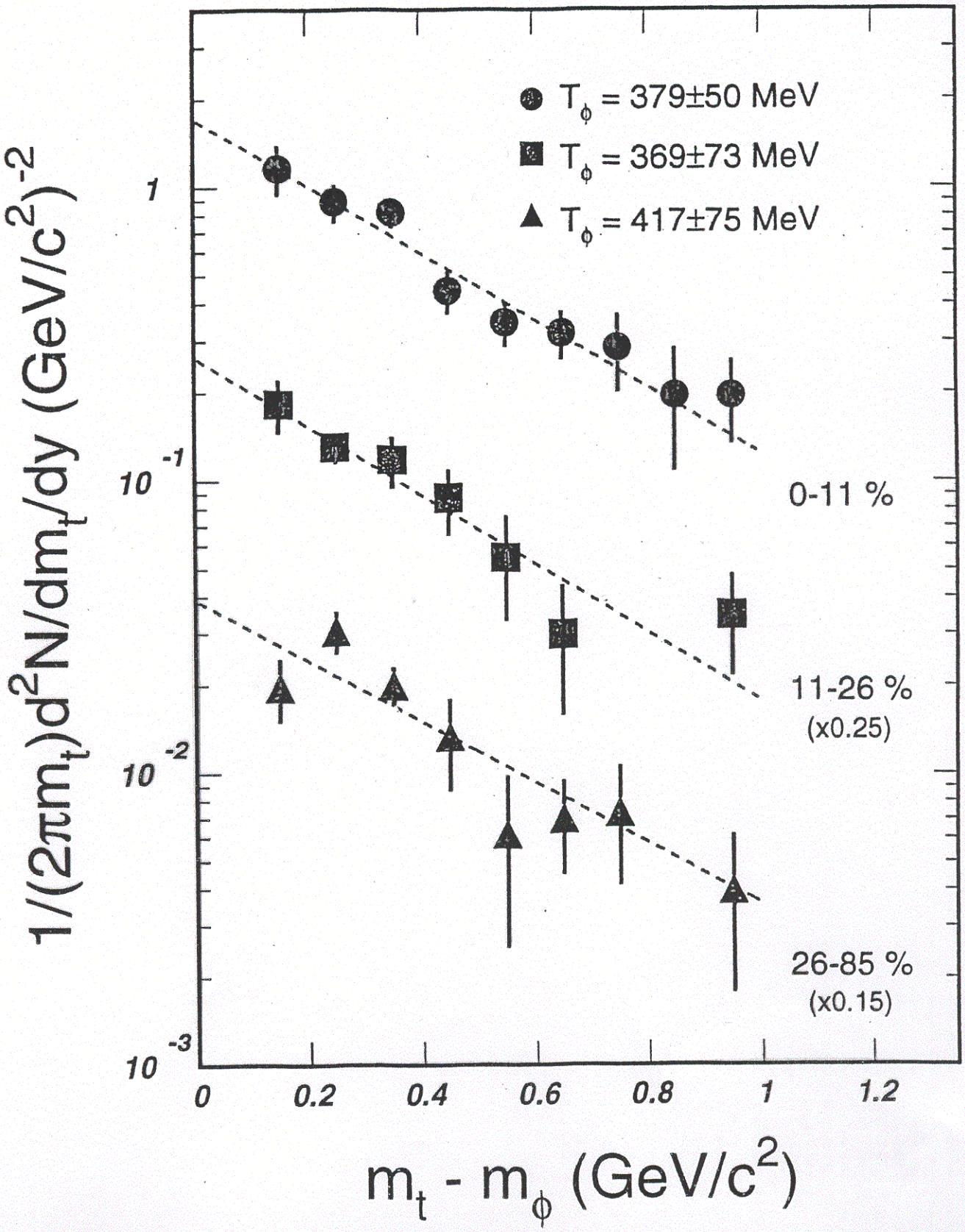
Figure 1

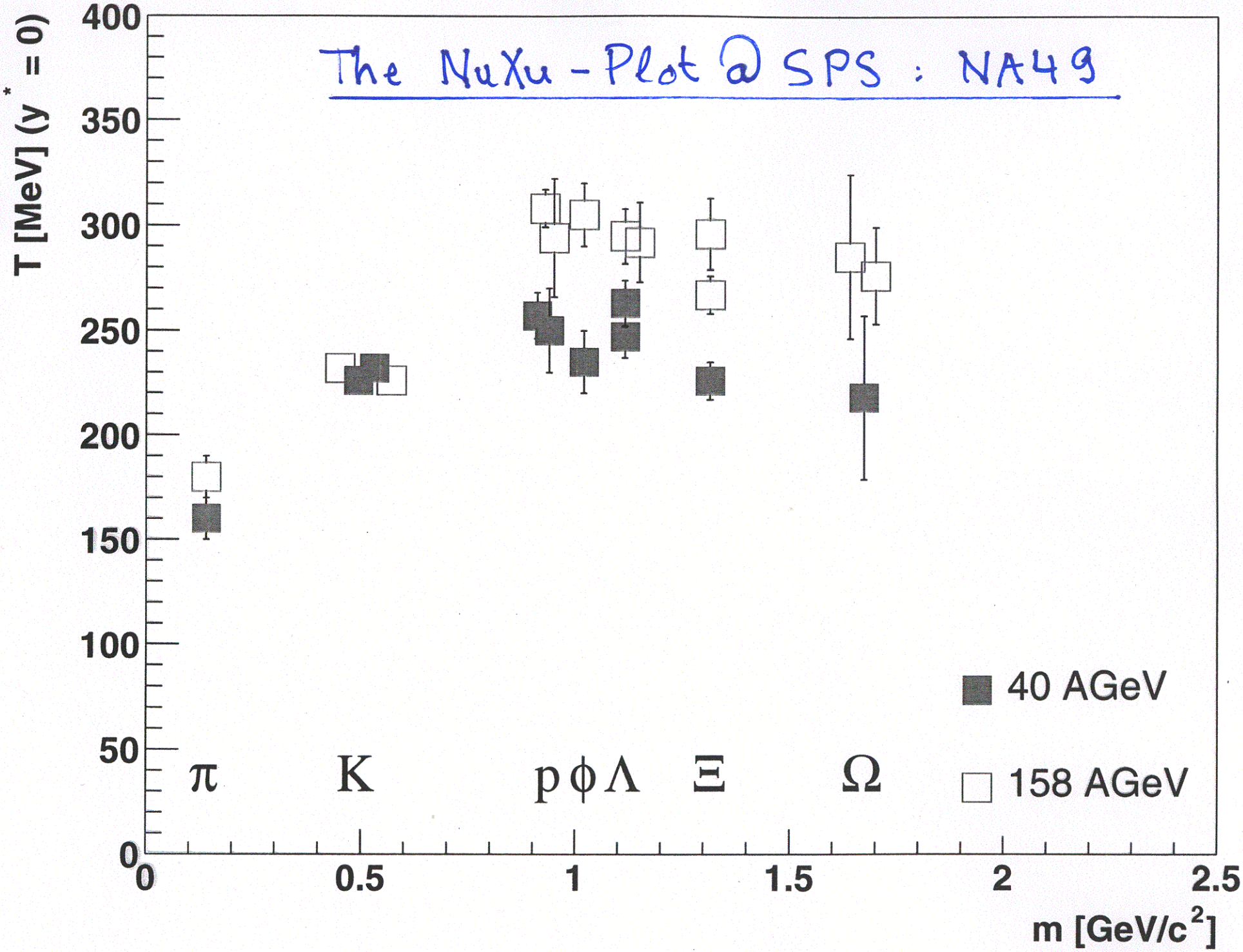
The "Nu Xu – Plot"



The Φ Inverse Slope

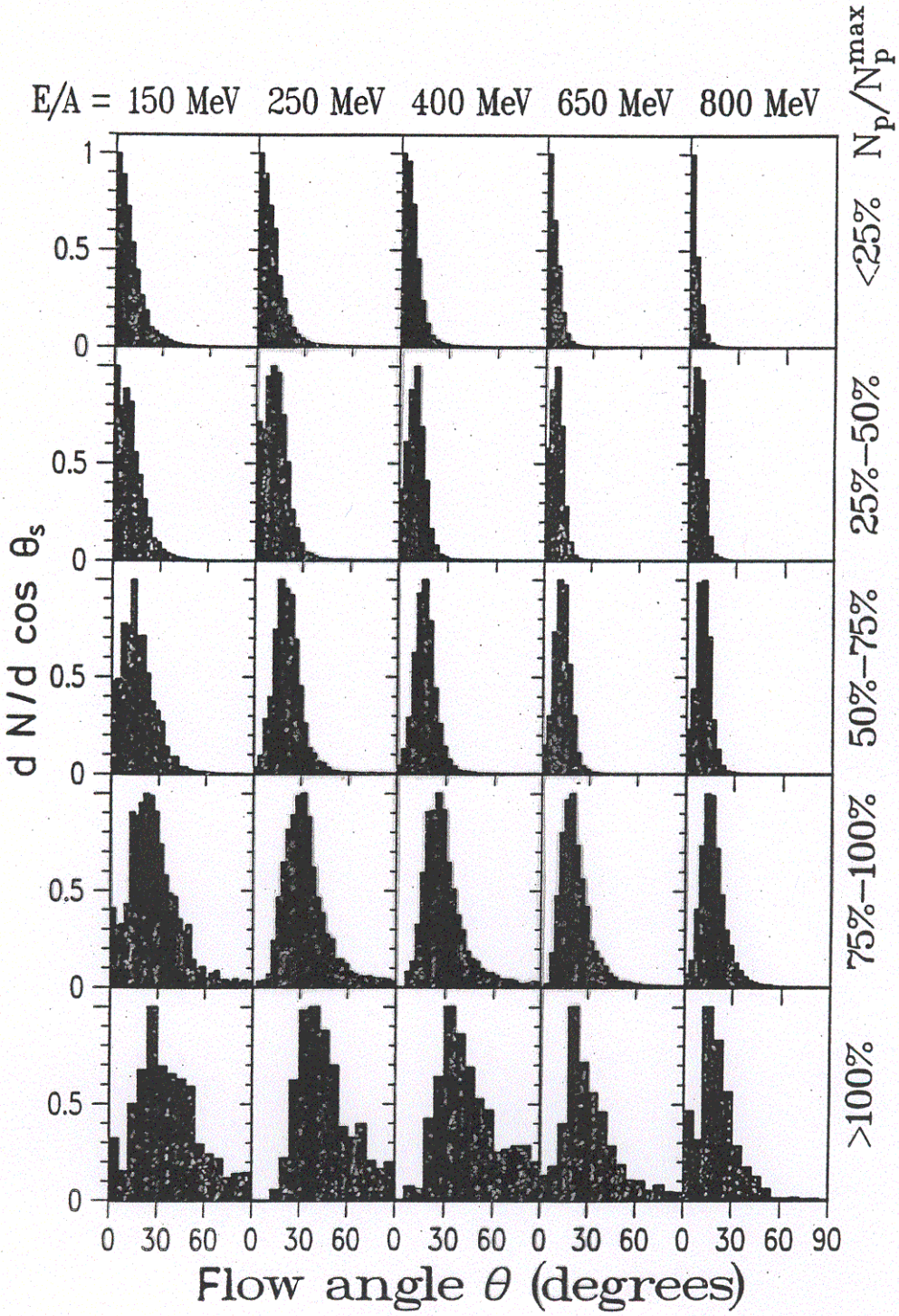
STAR @ 130 GeV




The NuXu-Plot @ SPS : NA49
T [MeV] (y* = 0)
400
350
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
m [GeV/c²]
π
K
p φ Λ
Ξ
Ω
40 AGeV
158 AGeV

Collective Sideward Flow

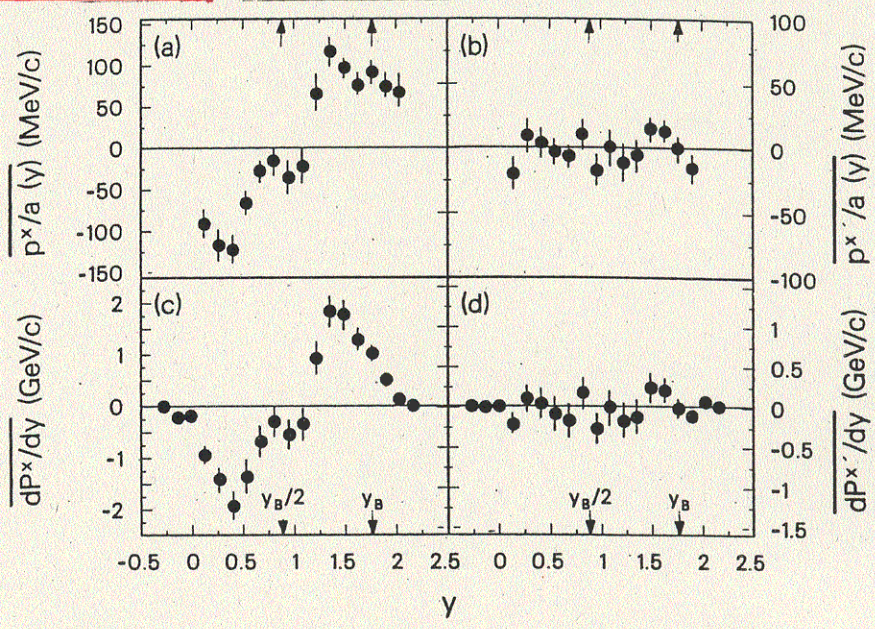
H. A. Gustafsson et al., Phys. Rev. Lett. 52 (1984) 1590



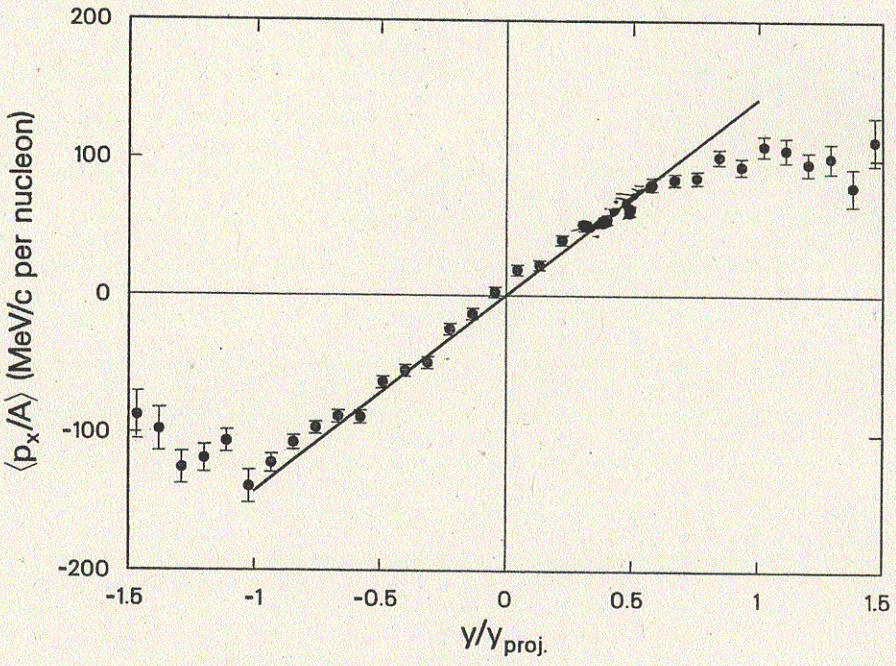
Flow : From Bevalac to AGS

Transverse Momentum Balancing
P. Danielewicz and G. Odyniec, Phys. Lett 157B (1983) 146

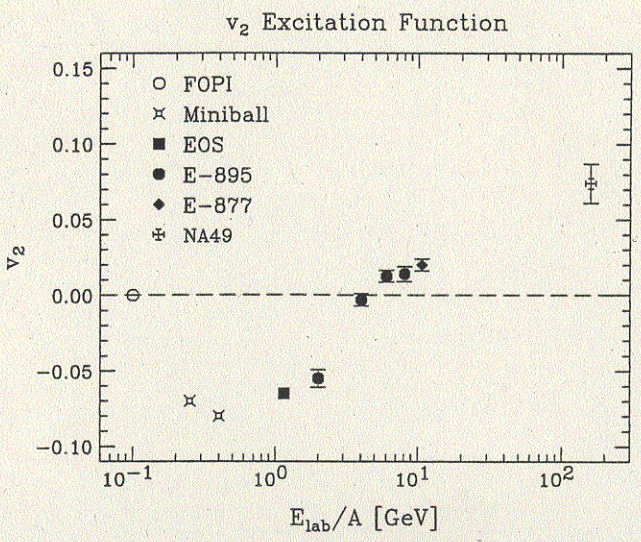
Ar + KCl
Str.Ch.

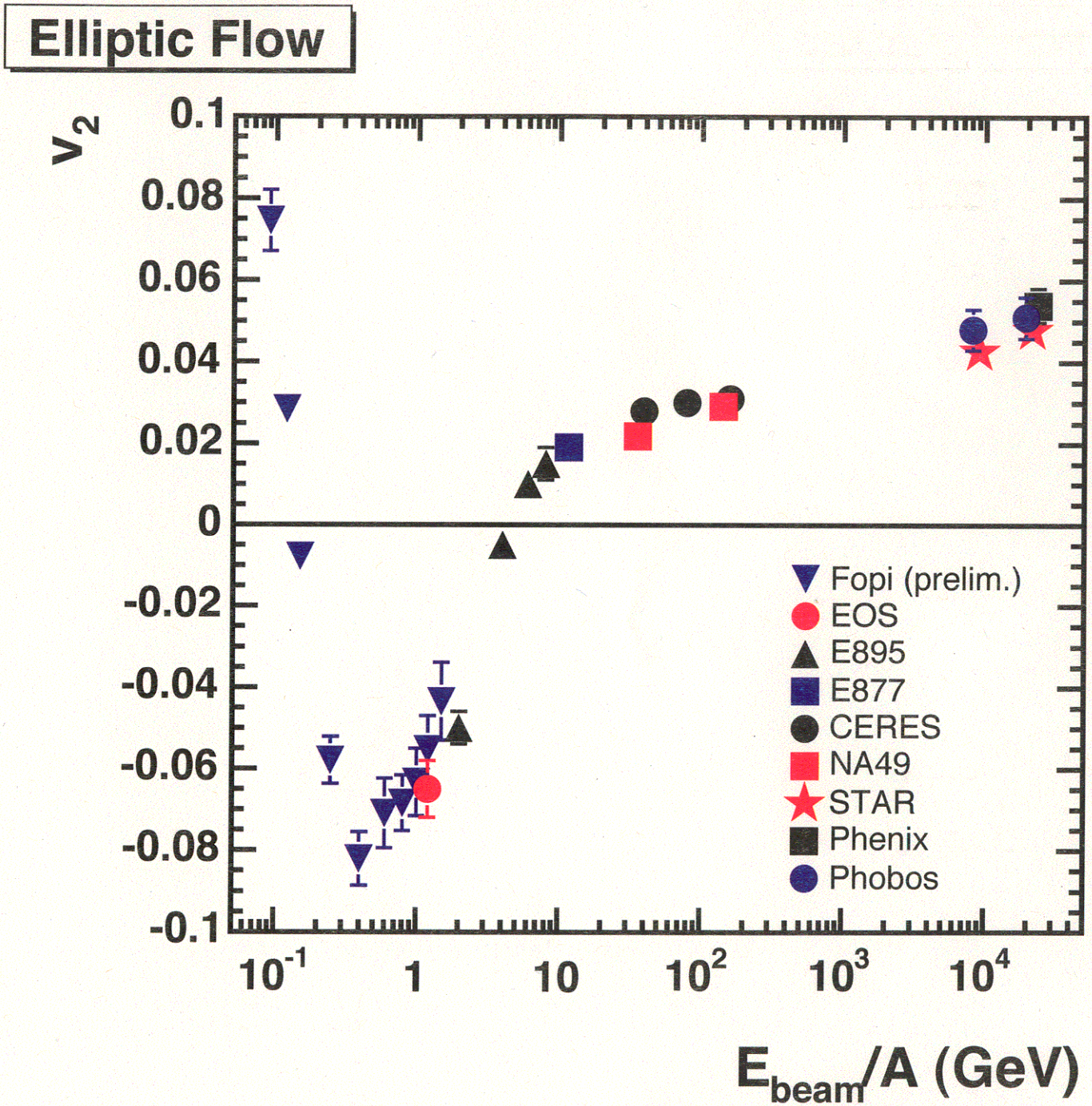


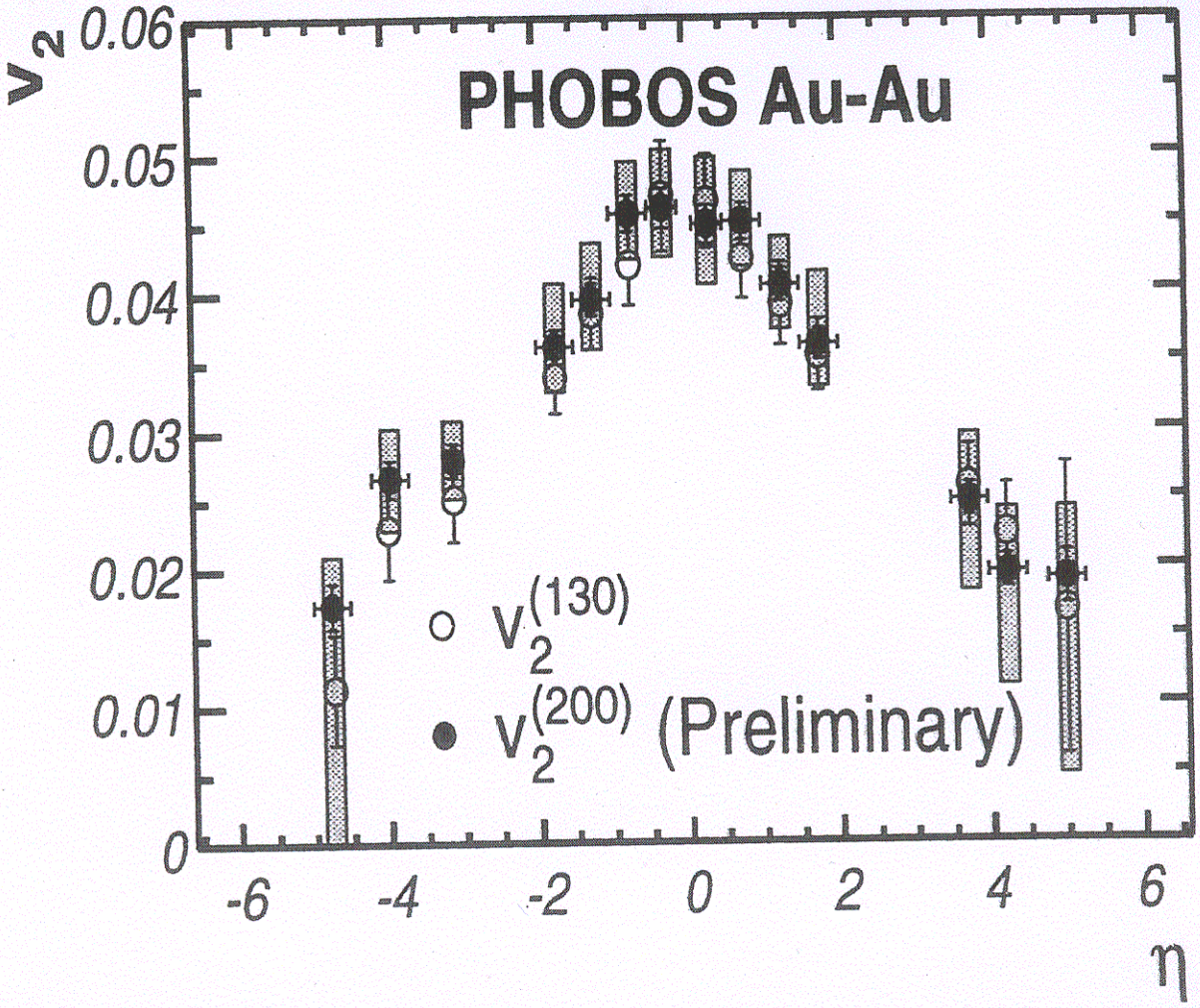
La + La
Pl. Ball

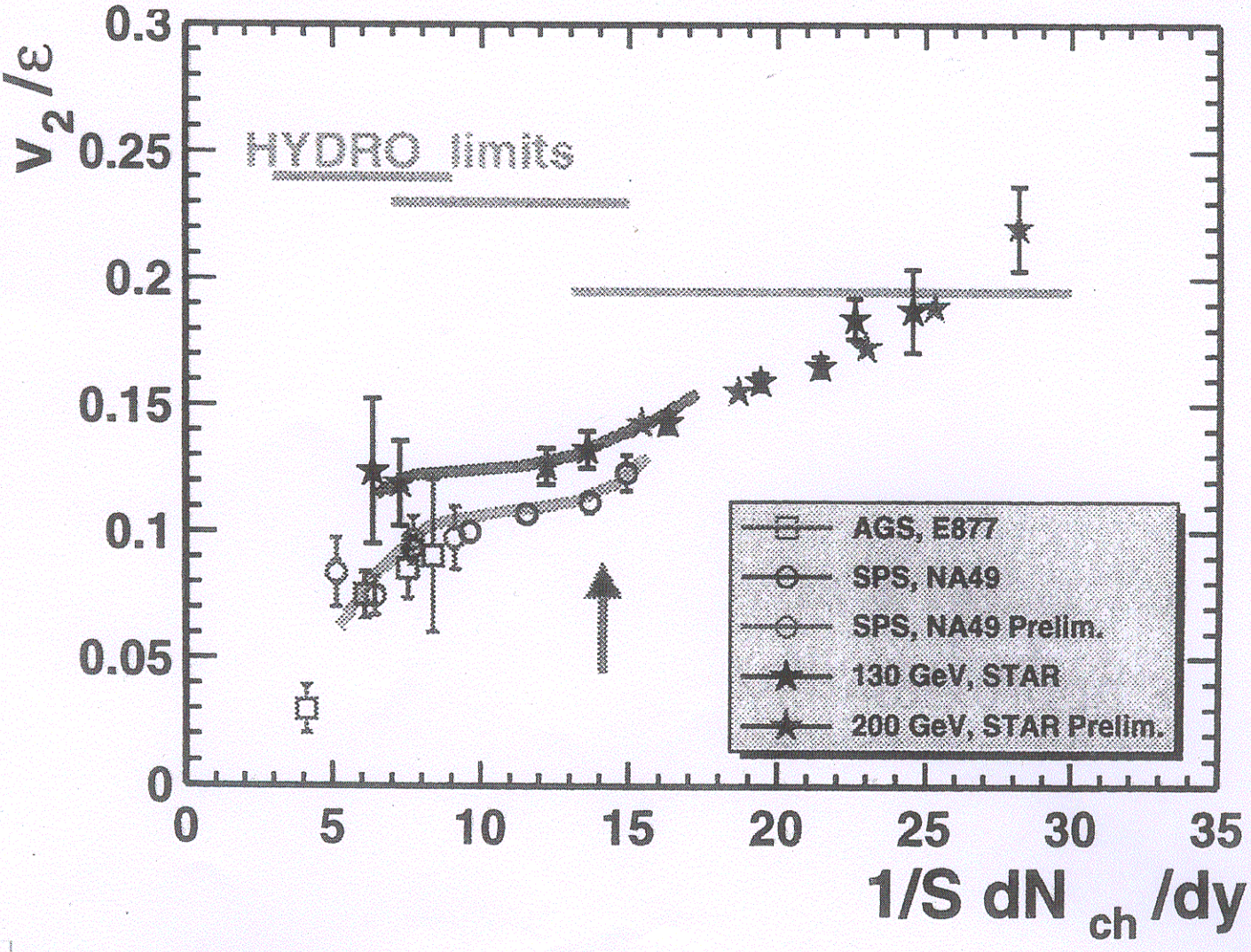


Elliptic
Flow
AGS



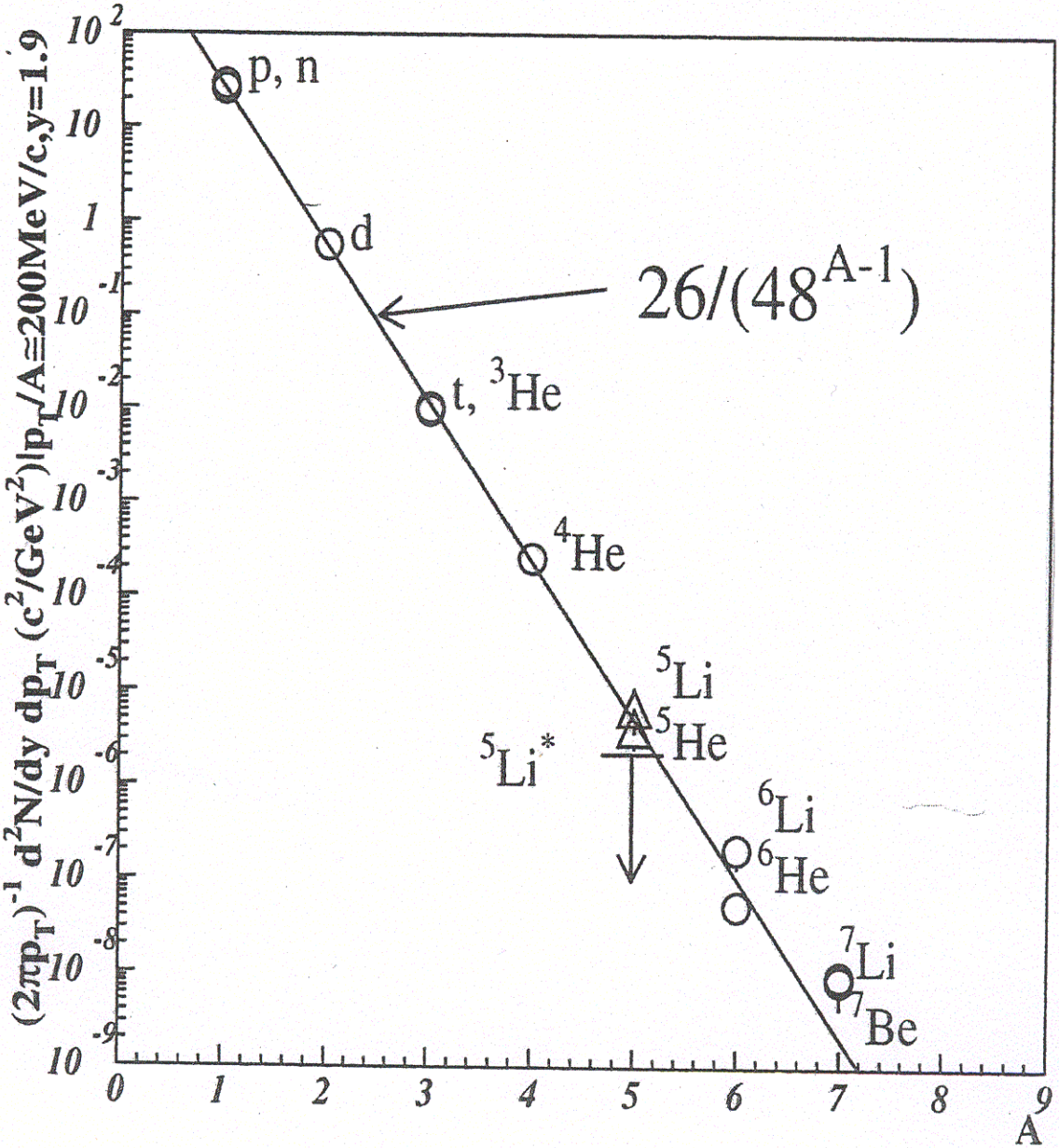

Elliptic Flow
v_2
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
10^{-1}
1
10
10^2
10^3
10^4
E_{beam}/A (GeV)
Fopi (prelim.)
EOS
E895
E877
CERES
NA49
STAR
Phenix
Phobos


PHOBOS Au-Au
v_2
0.06
0.05
0.04
0.03
0.02
0.01
0
-6
-4
-2
0
2
4
6
η
$v_2^{(130)}$
$v_2^{(200)}$
(Preliminary)


v_2/ε
0.3
0.25
0.2
0.15
0.1
0.05
0
HYDRO limits
AGS, E877
SPS, NA49
SPS, NA49 Prelim.
130 GeV, STAR
200 GeV, STAR Prelim.
0
5
10
15
20
25
30
35
$1/S\ dN_{ch}/dy$

Coalescence at the AGS

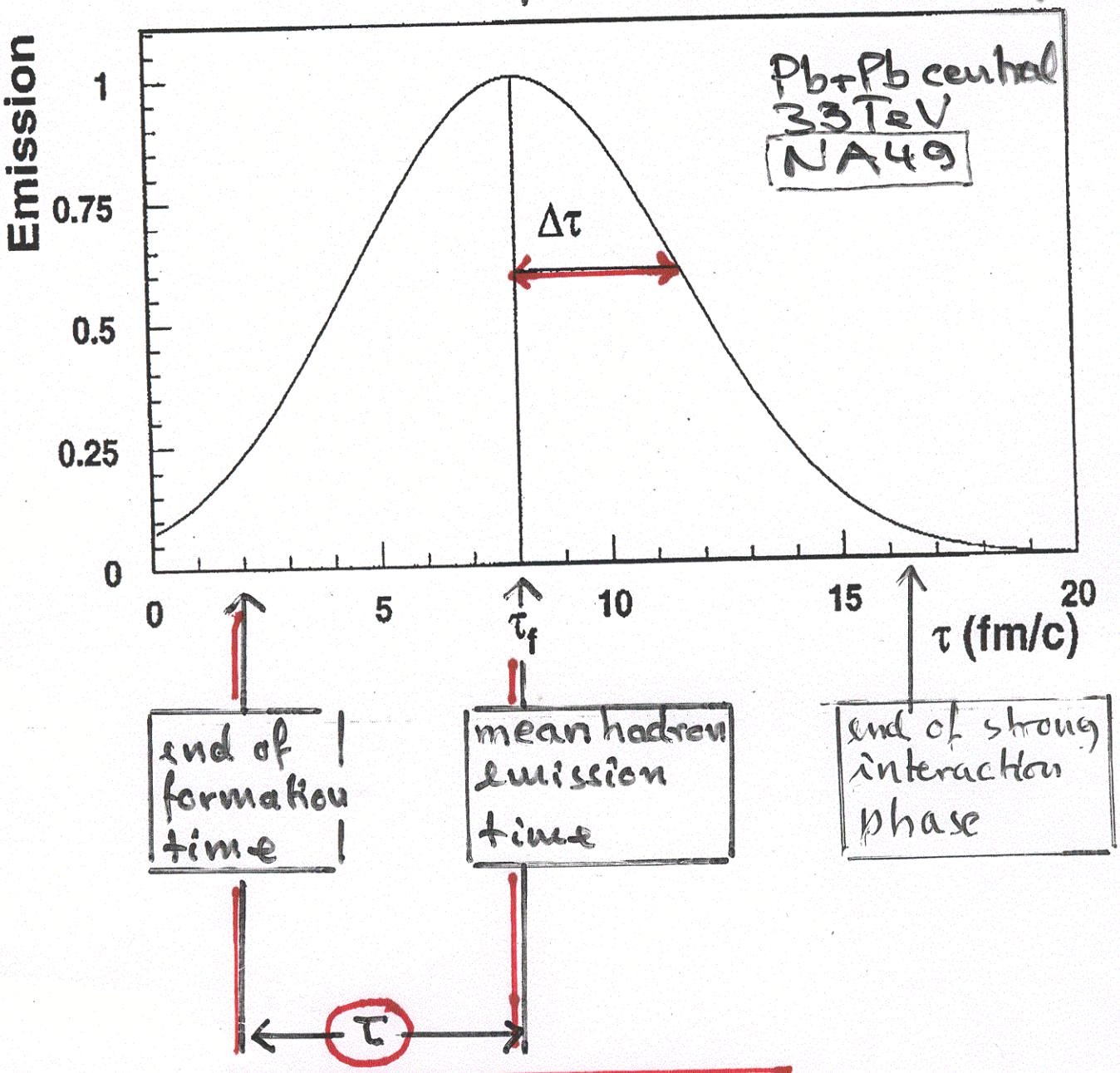
E 864 ; Au + Pb ⟶ light nuclei



HBT: H. Appelshäuser PhD thesis FRA/GSI 97, NA49
Eur. Phys. J. C2 (1998) 661

Do we have sufficient time before "fireball" decomposes?

Hadron emission time profile from Bose-Einstein pion correlation analysis



time gap $\tau \approx 6$ fm/c

Quark-Gluon Matter equilibration time ca. 1.5 fm/c

1982 : The CERN - Proposal

STUDY OF RELATIVISTIC NUCLEUS-NUCLEUS REACTIONS INDUCED BY ^{16}O BEAMS OF 9-13 GEV PER NUCLEON AT THE CERN PS → SPS

Proposal submitted to the CERN PSCC by the

GSI[1]-LBL[2]-Heidelberg[3]-Marburg[4]-Warsaw[5]-Collaboration

February 1982

N. Angert[1], H. Bialkowska[5], R. Bock[1], H.H. Gutbrod[1], J. Harris[1], M.R. Maier[4], A.M. Poskanzer[2], F. Pühlhofer[4], H.G. Pugh[2], R.E. Renfordt[3], H.G. Ritter[1], A. Sandoval[1], L.S. Schroeder[2], E. Skrzypczak[5], R. Stock[1], H. Ströbele[1], R.Szwed[5], A. Warwick[1], F. Weik[1], H. Wiemann[1], K.L. Wolf[2]

ABSTRACT

We propose to study the target fragmentation modes and $\pi^{\pm}$, K^0, Λ, $\bar{p}$ and $\bar{\Lambda}$ production in collisions of ^{16}O with target nuclei ranging from ^{40}Ca to ^{206}Pb. The acceleration of ^{16}O in the PS will be facilitated by a high charge state ion source installed by us at the Linac I. Experimental equipment will be the Plastic Ball spectrometer, currently employed by us at the Bevalac, LBL Berkeley, and the streamer chamber of the MPI-München group, presently used at the SPS inside a CERN Vertex magnet. The experiments require the acceleration of 10^7 oxygen ions per PS cycle and two splits in the East Hall external beam system delivering about 10^5 ions/s to the streamer chamber and the main part of the intensity to the Plastic Ball. A beam of hadrons (preferably protons) of similarly low intensity, in the 10 to 26 GeV energy range, is needed for setup purposes and in order to study the scaling with projectile mass. The anticipated date of data taking is spring 1984, with an initial request of 250 hours of devoted PS running time.

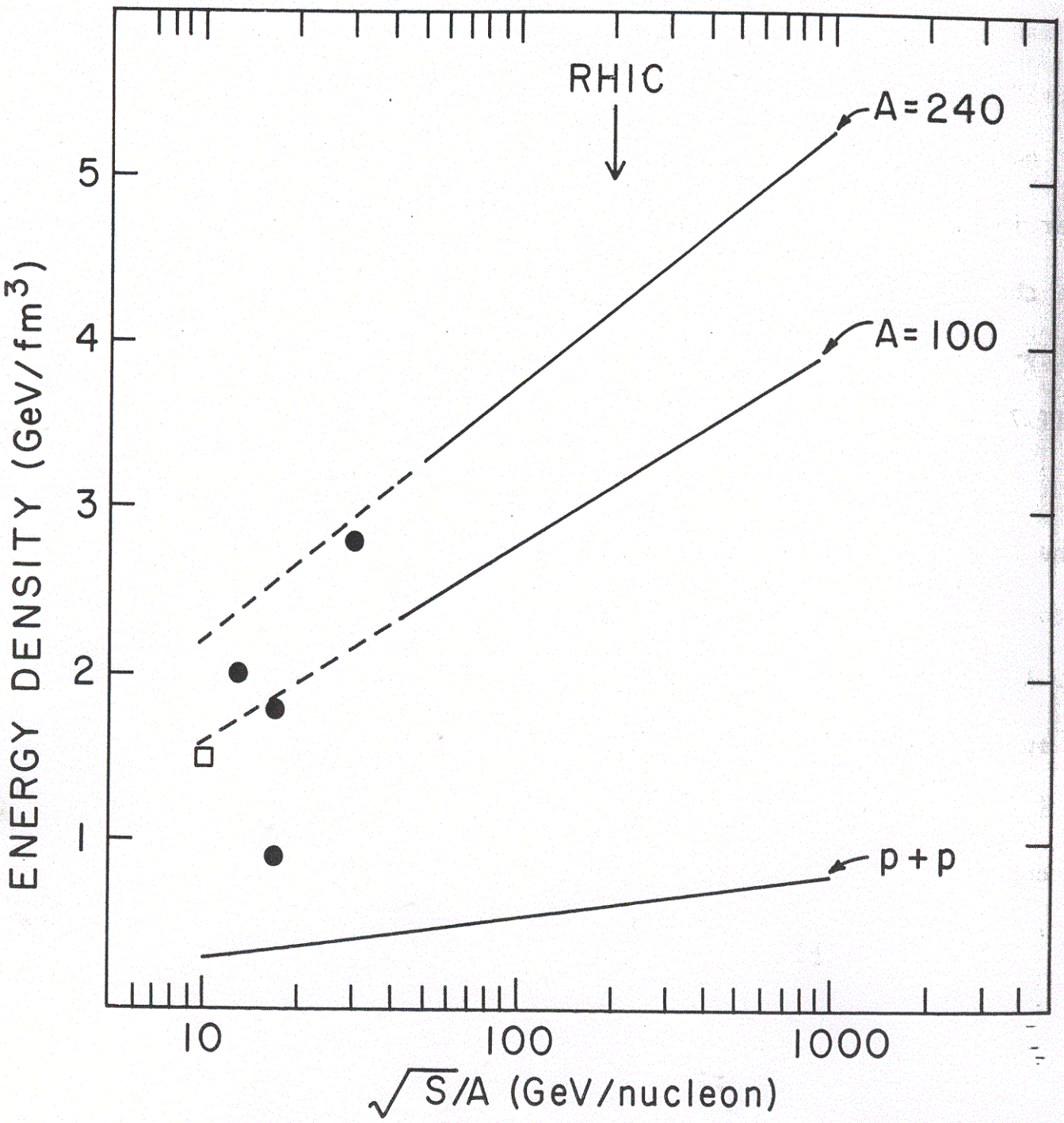
BNL 51801

RHIC and Quark Matter

BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

1984

RHIC Proposal 1984



. II.9 Predicted energy density in the central region as a function of lision energy, for various masses of colliding nuclei. The dat points are from cosmic ray events. The colliding nuclei were S Ag (round points) and Ar + Pb (square point).

2.N

Nuclear Physics A312 (1978) 491–523; © *North-Holland Publishing Co., Amsterdam*

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STATISTICAL THERMODYNAMICS OF RELATIVISTIC HEAVY ION COLLISIONS

ARAM Z. MEKJIAN

Rutgers University, Dept. of Physics, New Brunswick, NJ 08904

Received 23 February 1978

Abstract: Statistical thermodynamics is used to investigate properties of the collision of two heavy ions at high energies. Composite particle formation and multiparticle production are considered. The basis of the description is a heated system of nucleons and produced particles which expands from some initial state to some break-up state where interactions cease. In this expansion dynamical processes occur which form and fragment nuclei, and produce and absorb particles. Interactions persist until the mean free paths describing the various processes become comparable to the size of the system. Thereafter, the system is non-interacting and the multiplicity of the various species present at the break-up stage is assumed to reflect a frozen-in equilibrium. Using the Van't Hoff reaction box, the phase space distribution of composite particles is shown to be quasiclassical. Pion multiplicities are also considered and the importance of the expansion stage on this multiplicity is stressed. For an isentropic expansion, the multiplicity of produced pions is shown to be greatly reduced. The predictions of the model may be useful in establishing the role of viscosity in collisions of heavy ions.

1. Introduction – Statistical thermodynamics and high multiplicity events

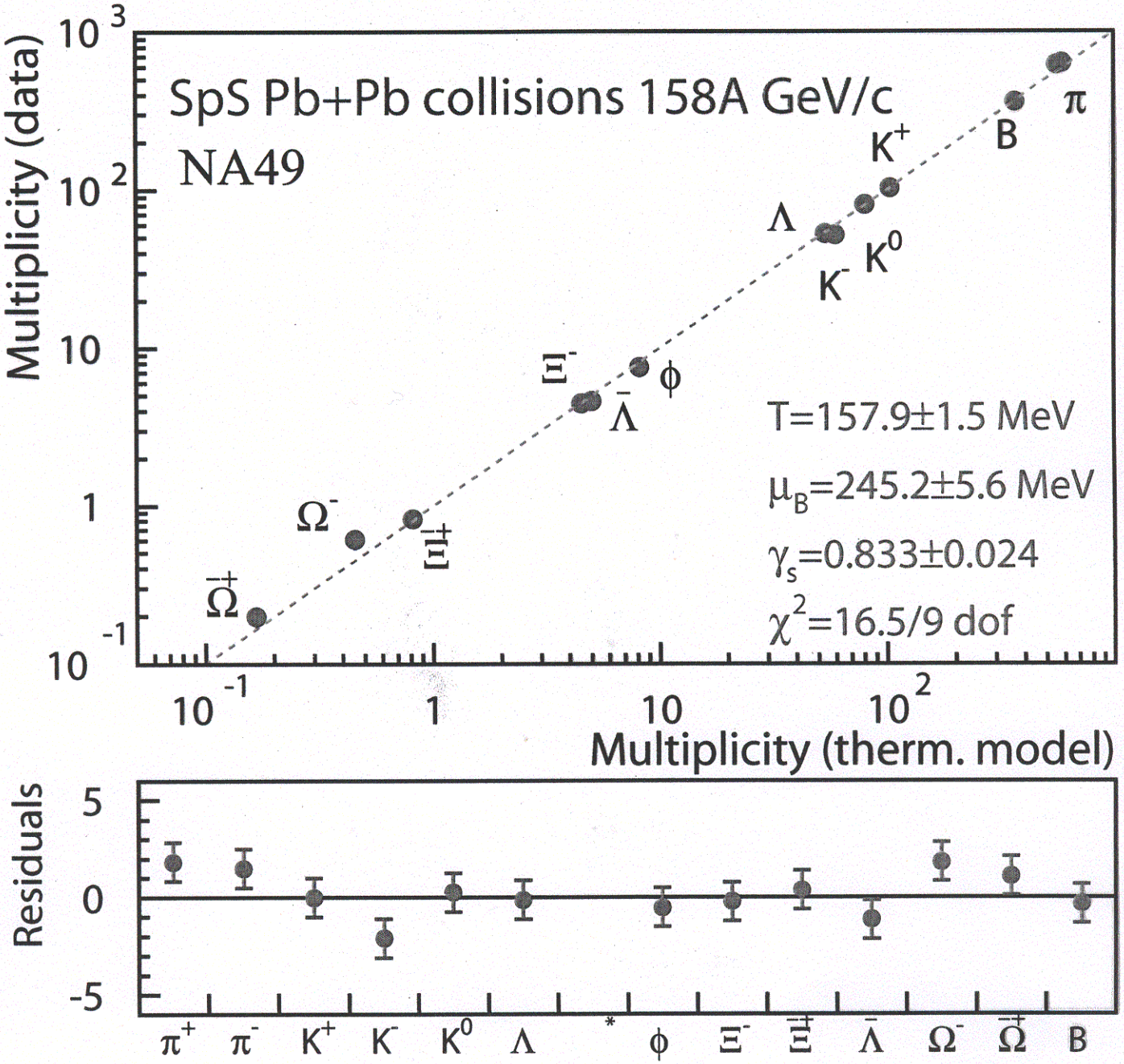
In the collision of two high energy particles, high multiplicity events are observed which reflect the production of a large number of particles. A method for describing such multi-pronged events was initiated by Fermi [1]) who proposed the use of statistical concepts in understanding the multiple formation of particles. His theory was based on the idea that in the collision of two very high energy particles, the inelastic energy of the collision is released in a small interaction region in which the particles are created. Then, owing to the strong interactions that exist between these particles, the distribution of this energy and the number of particles created may be governed by statistical laws rather than by any specific theory of the detailed dynamics of the process. In this theory, the particles that are produced then escape the volume without any further interaction so that the observed distribution reflects a "frozen" state of thermodynamic equilibrium.

Similarly, in the collision of two heavy nuclei at relativistic energies, events are observed in streamer chamber experiments which are quite violent or explosive [2–4]) in which multiplicities of up to ten times those observed in particle collisions are

† Work supported by the National Foundation Grant NSF FY 77-00478.

Grand Canonical statistical hadronization

Becattini, Braun-Munzinger, Claymans, Öschler, Tounsi, Redlich, Stachel, Stock et al.



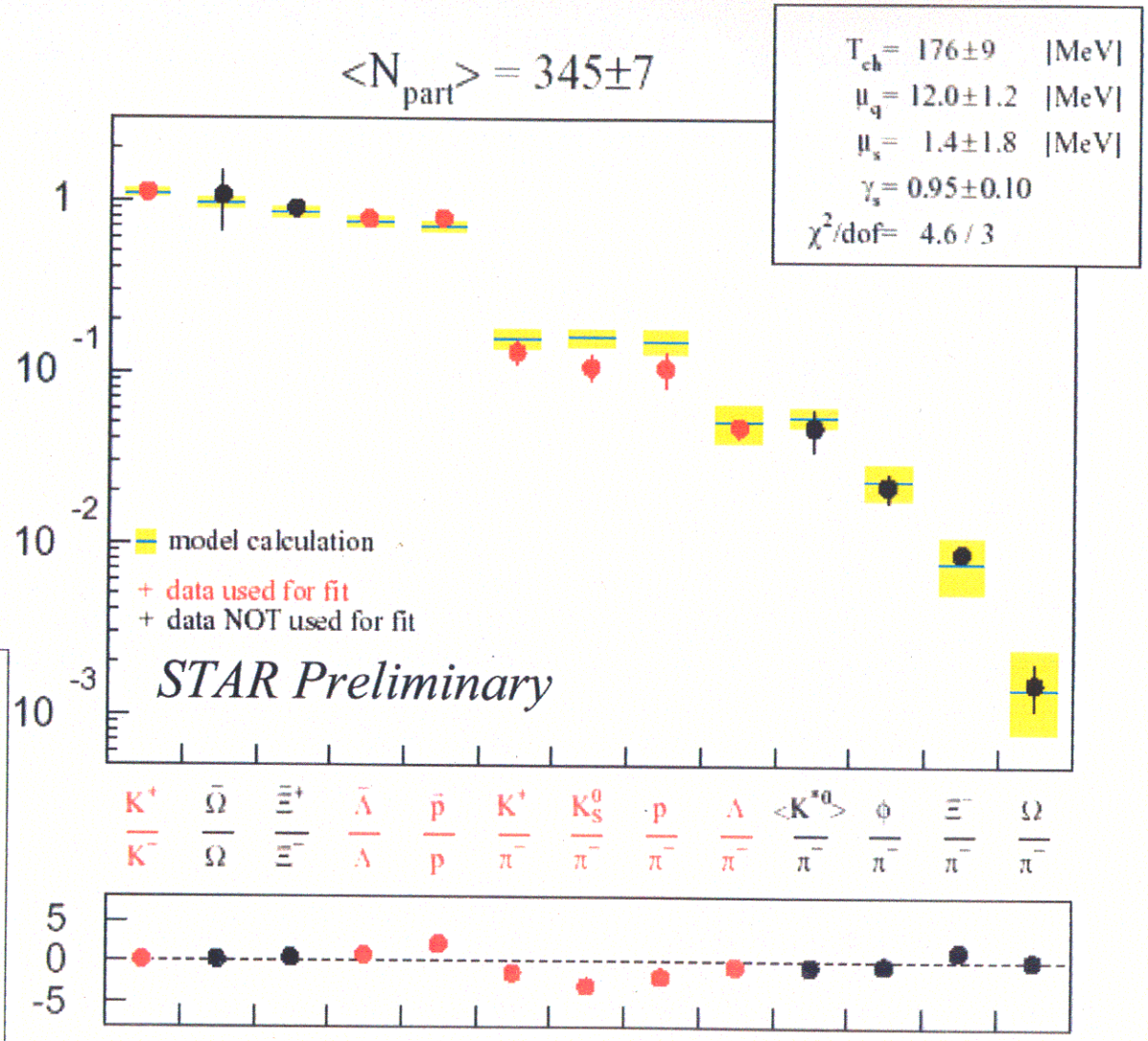
The Becattini – Plot

Grand Canonical Analysis : The Braun-Munzinger, Stachel Plot

Ratios, experiment vs. a model

Central
130 GeV Au+Au
Preliminary Data

Agreement between model and data is very good!



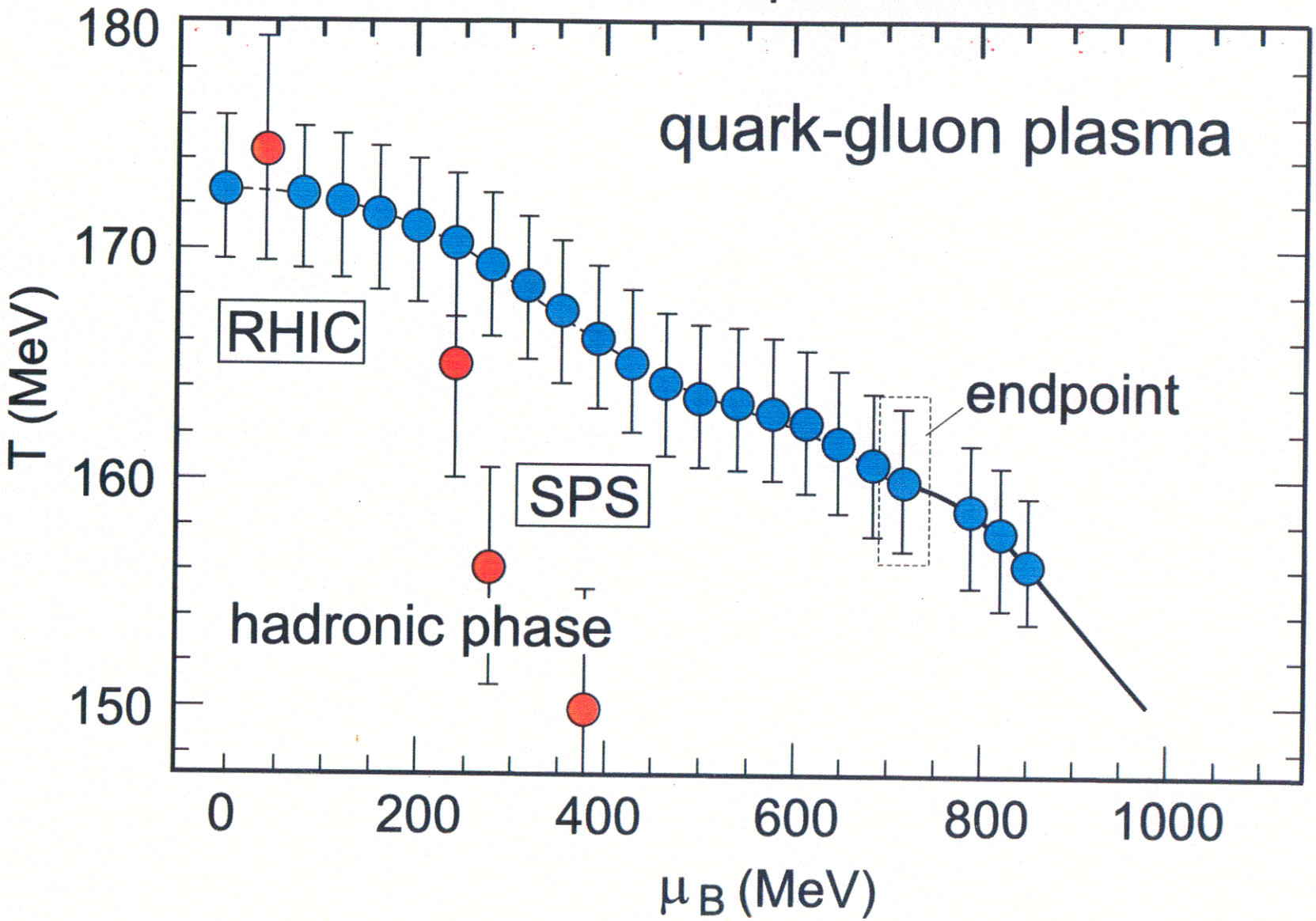
Thermal fits to mid-rapidity spectra have caveats regarding non-4π measurements (local vs. global equilibrium, boost-invariance).

M. Kaneta and N. Xu, J. Phys. G**27** (2001) 589

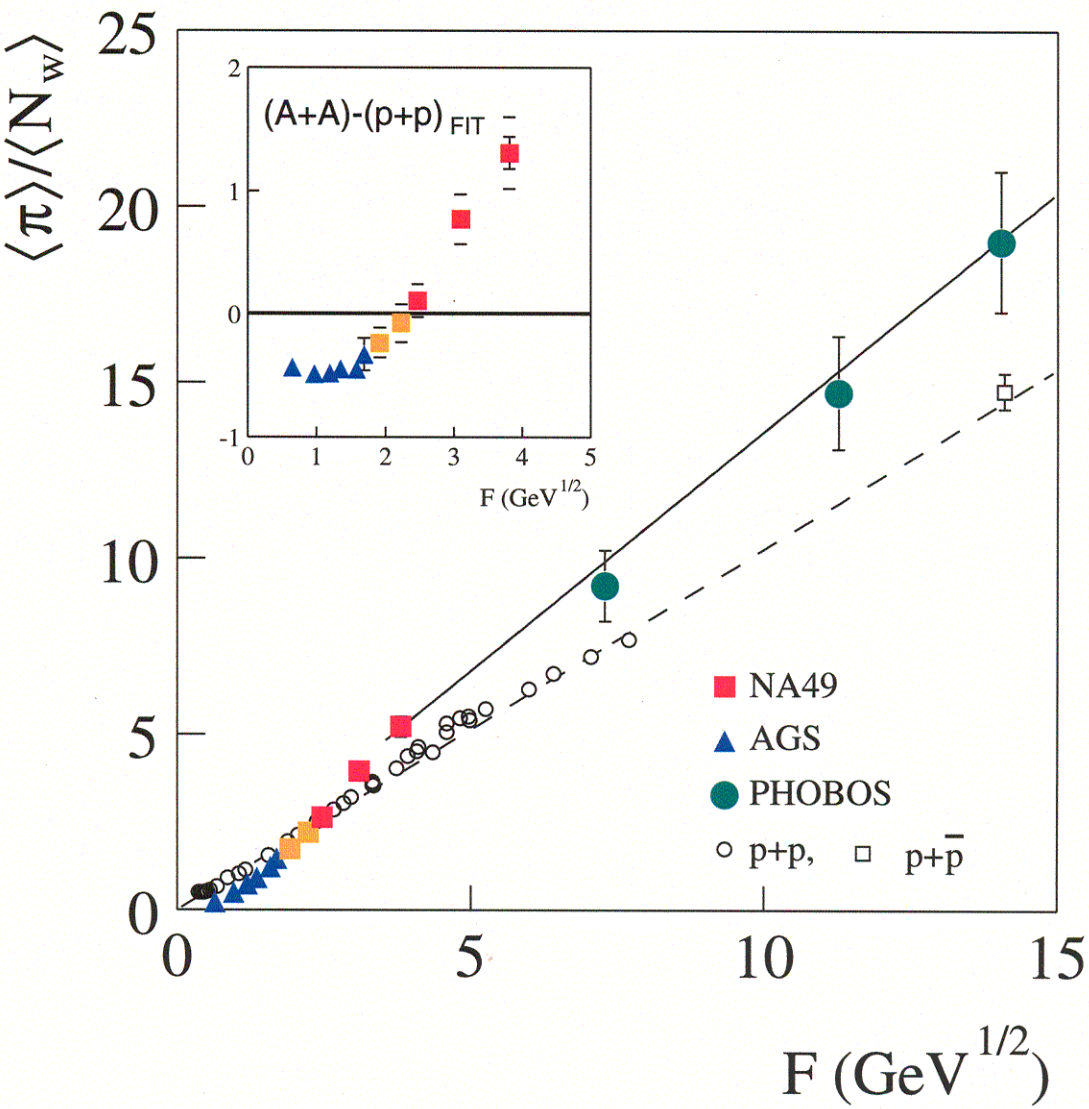
STAR QM Poster: M. Kaneta

Grand Canonical Analysis vs. the QCD Phase Boundary

Fodor and Katz, hep-lat 01-06002

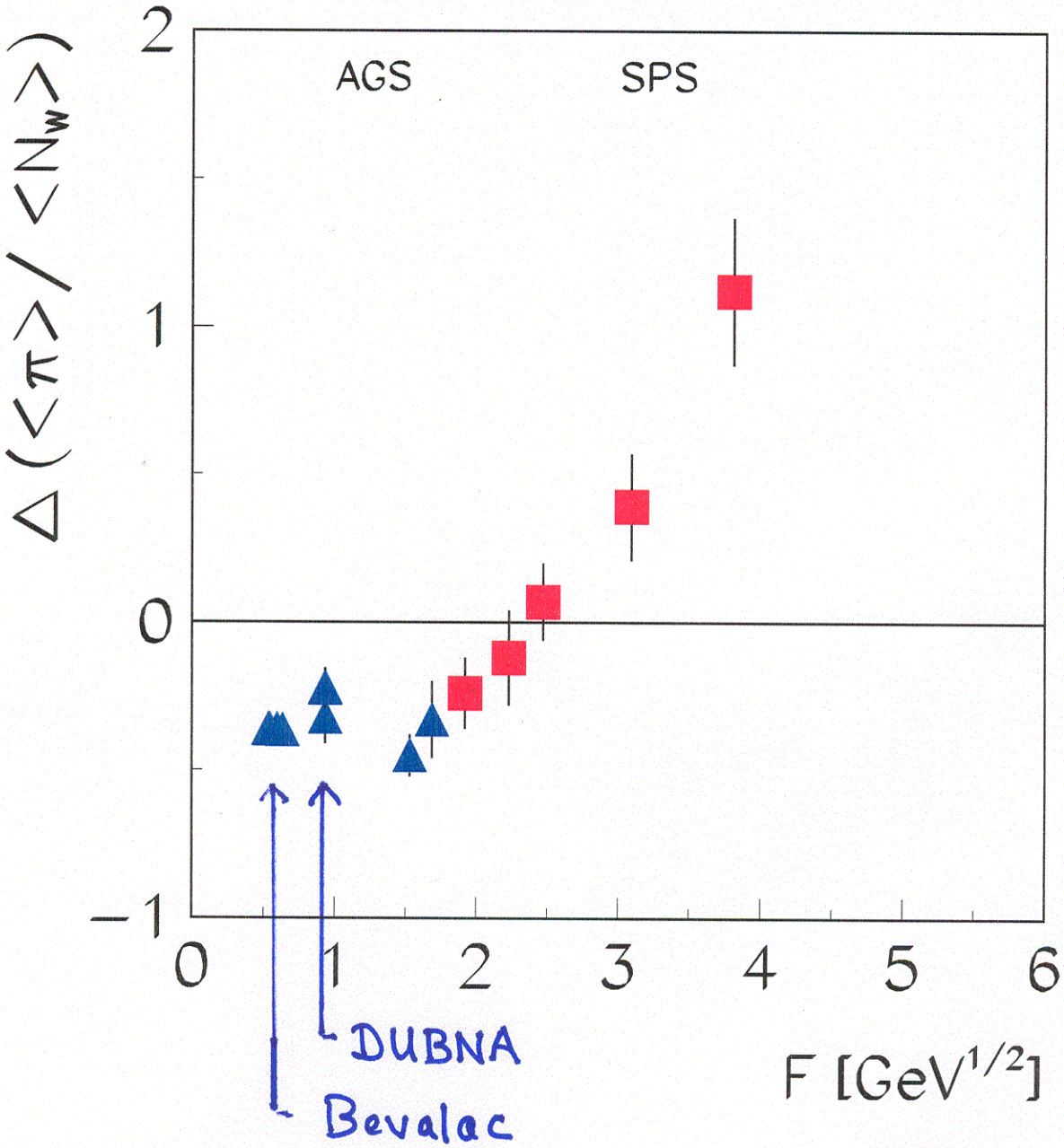


Pion Production, Bevalac to RHIC

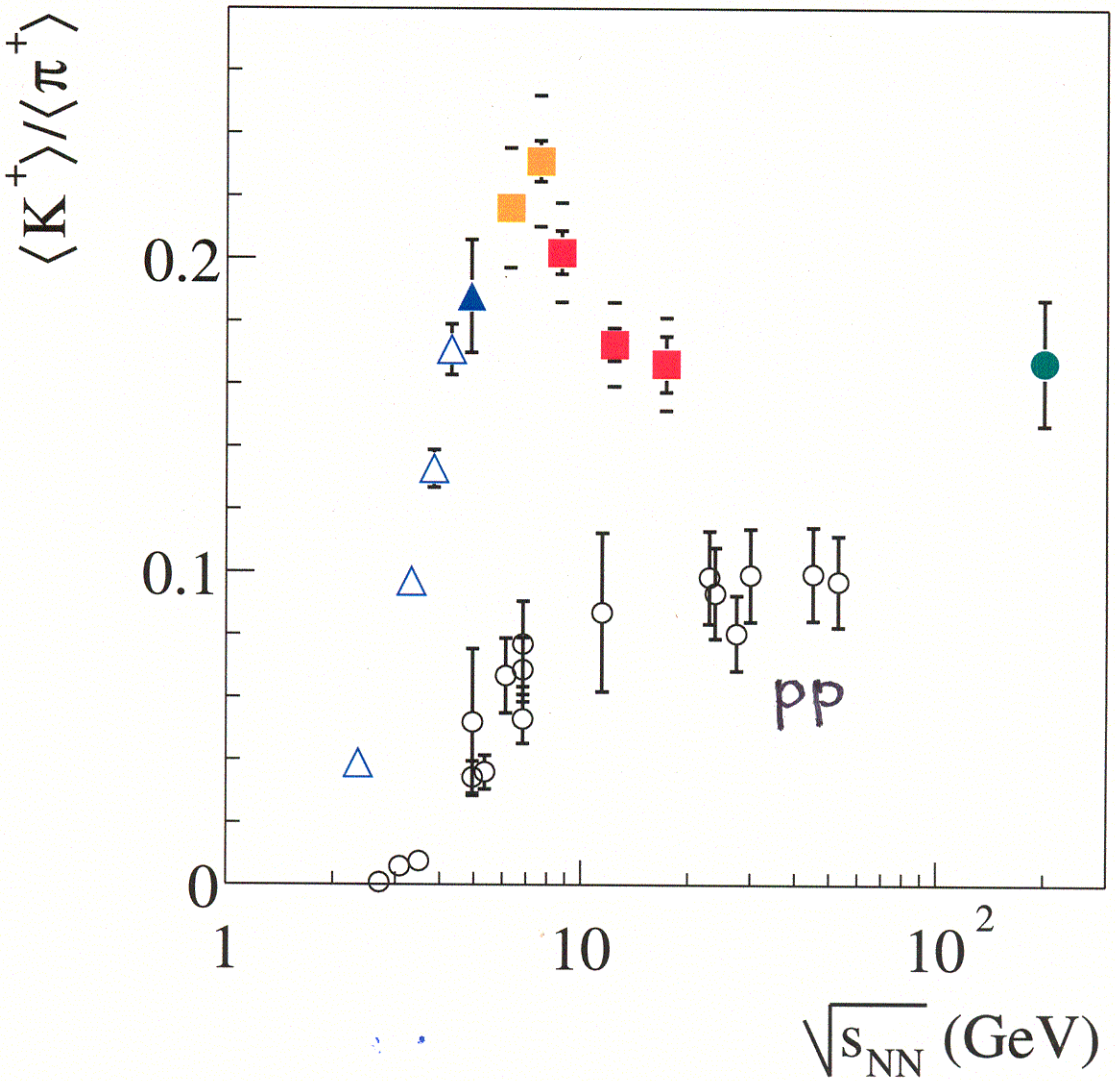


Pion Production : "AA - pp"

The Gazdzicki - Plot

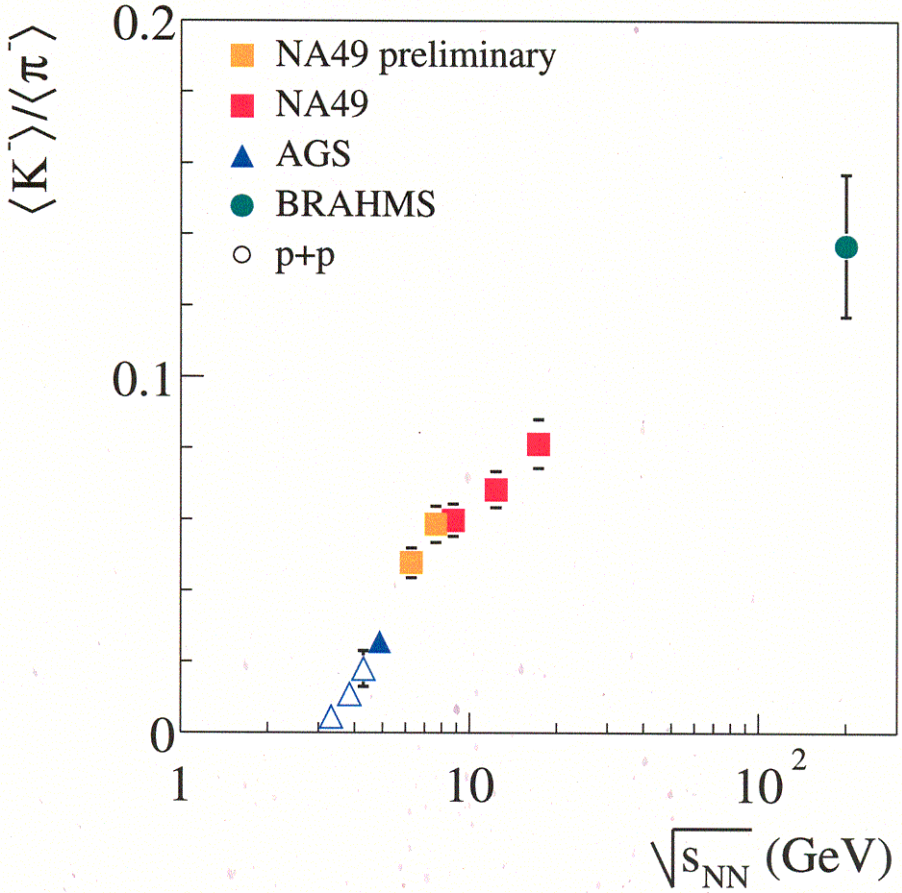


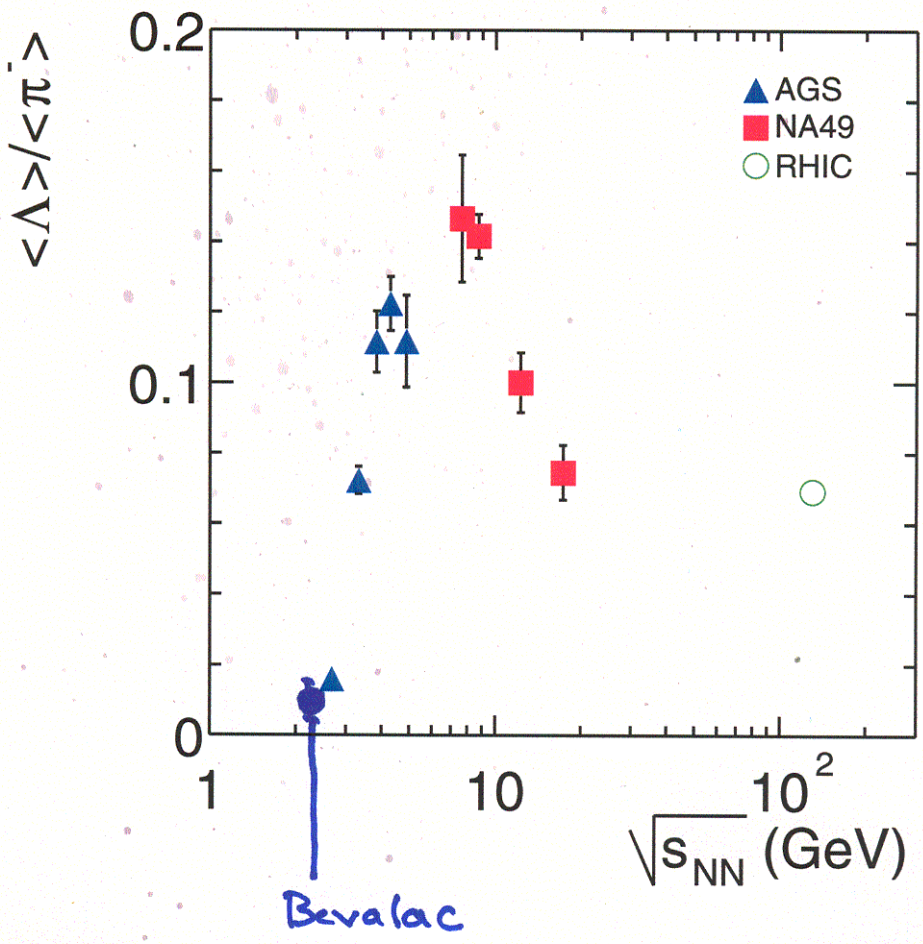
The $\langle K^+ \rangle / \langle \pi^+ \rangle$ Ratio from Bevalac to RHIC



4π - Data

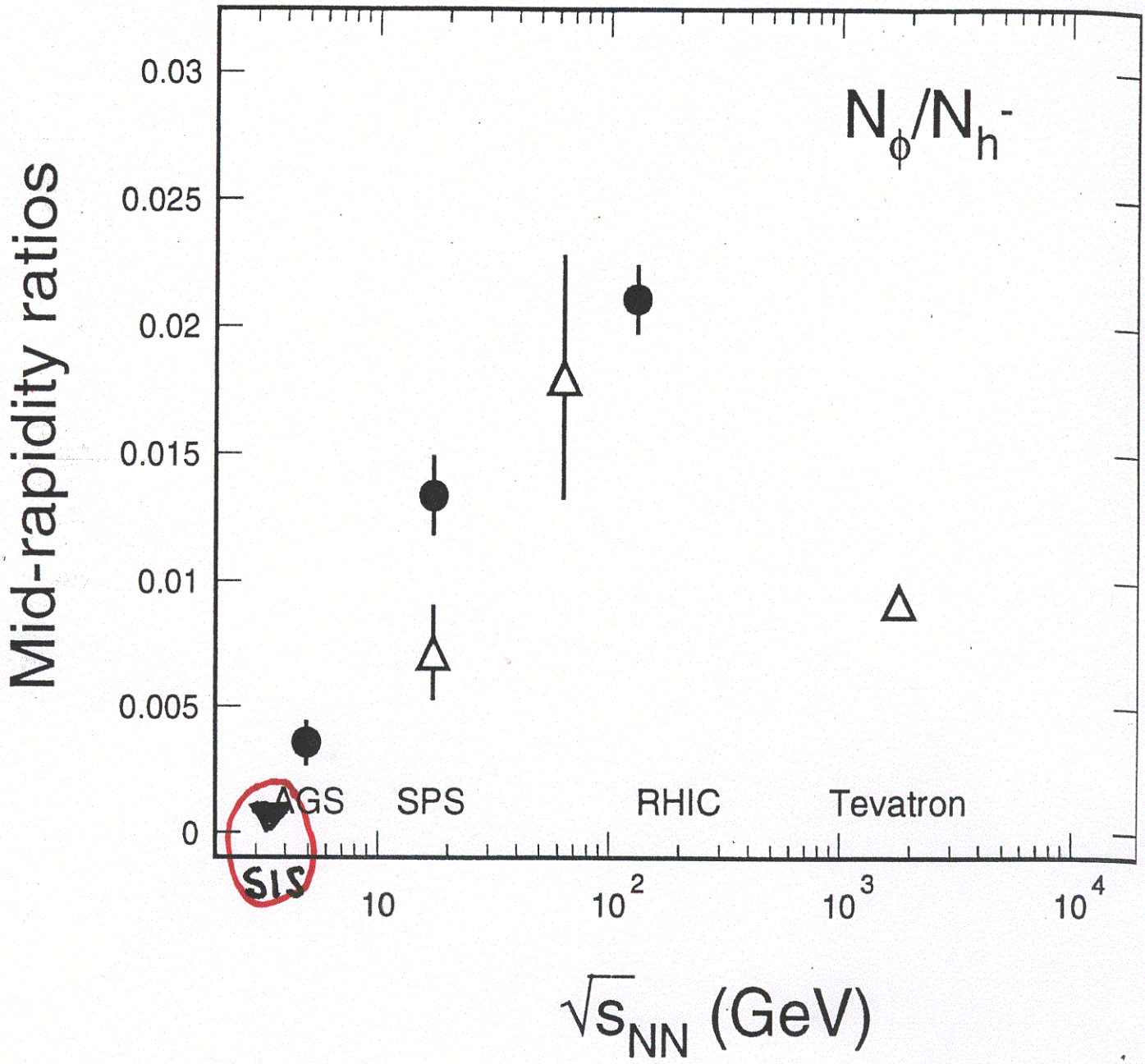
K^- and Λ Production: from Bev. to RHIC



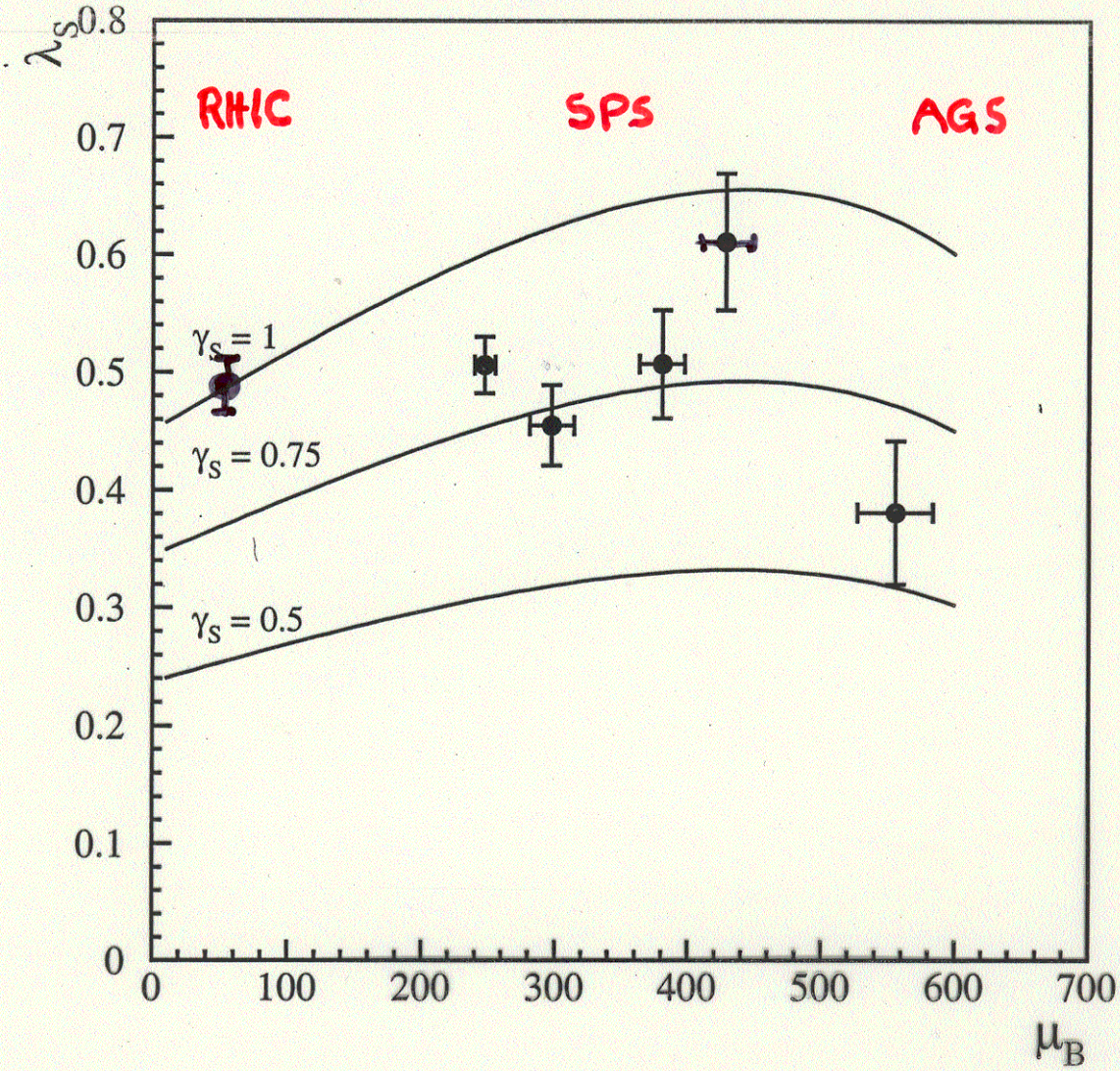


$\phi \equiv [s\bar{s}]$ Production

From SIS to RHIC



The "Wroblewski-Factor" in central A+A

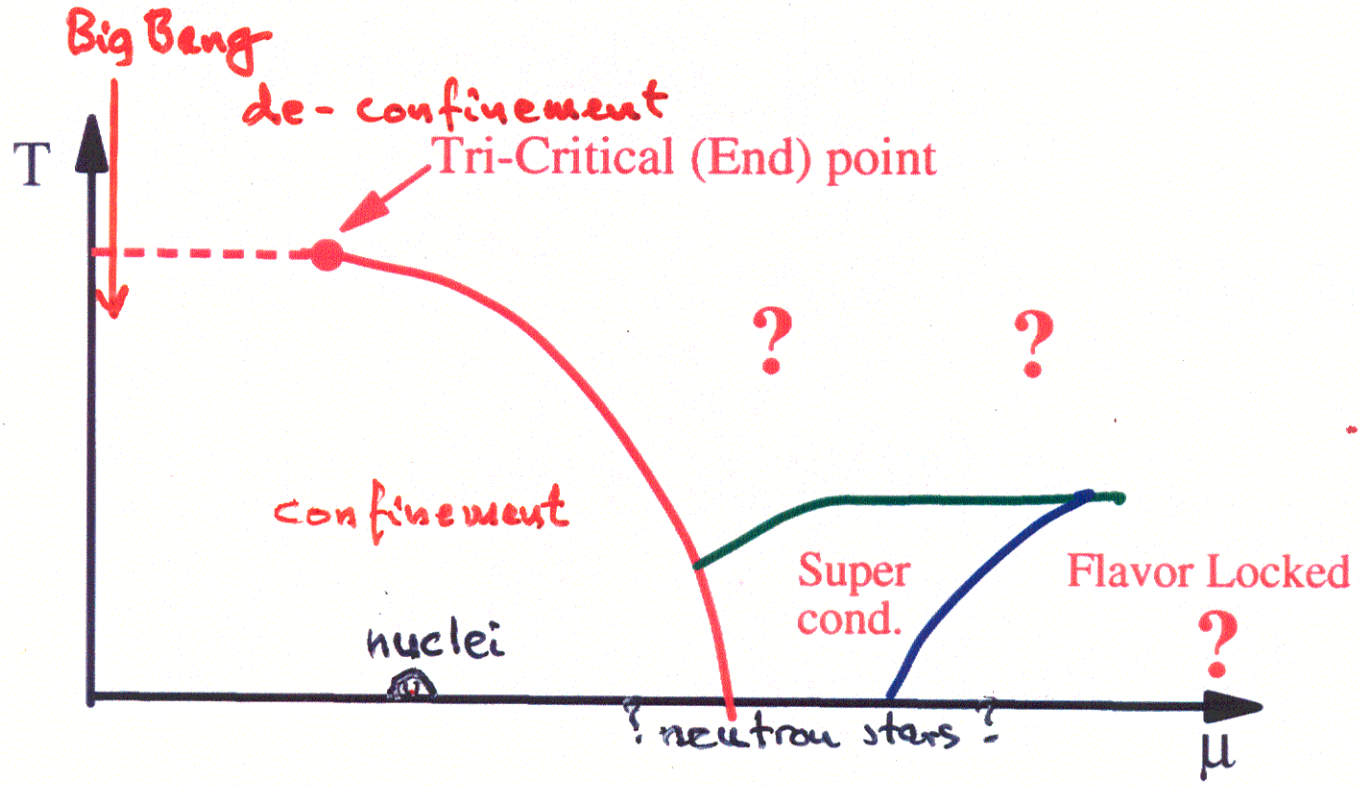


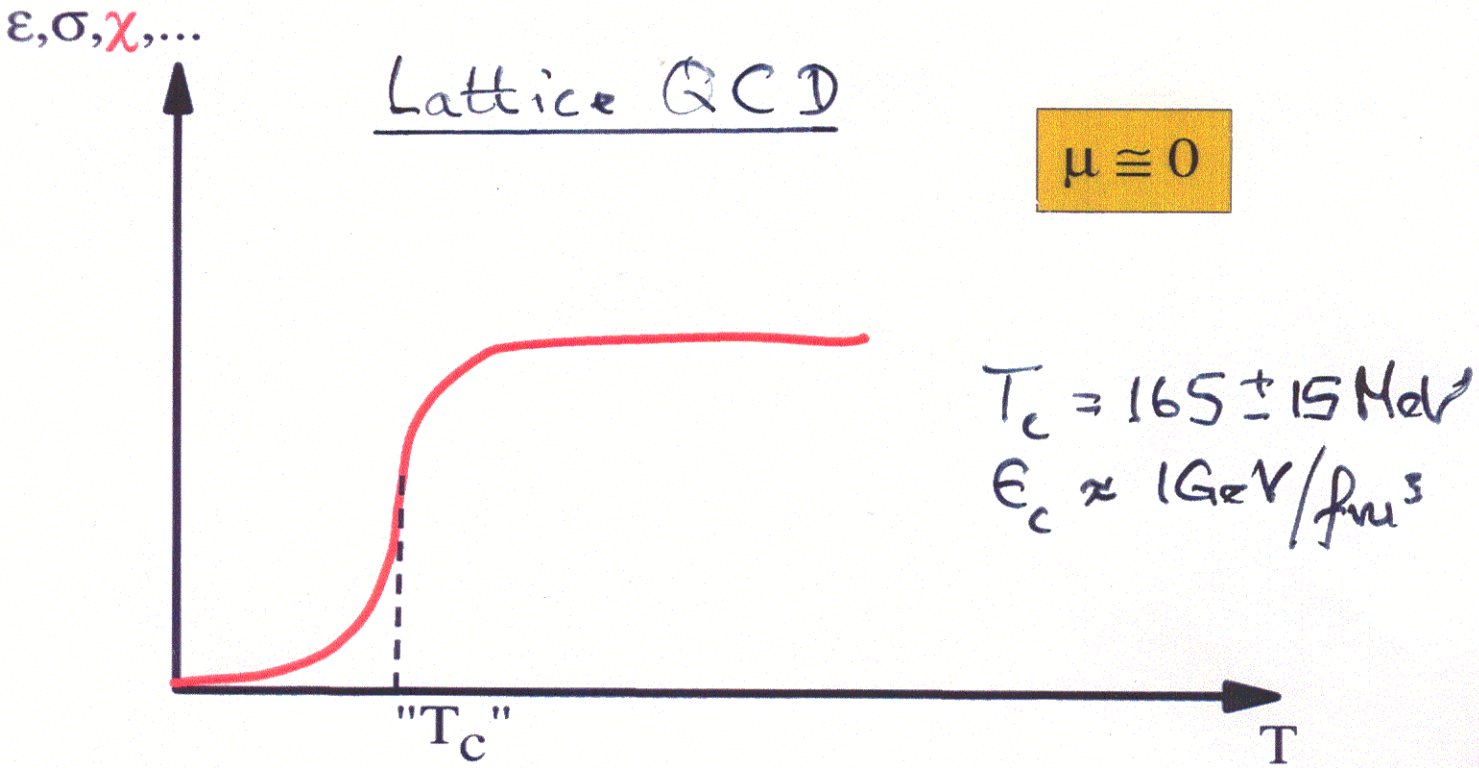
$$\lambda_s = \frac{2(s+\bar{s})}{u+\bar{u}+d+\bar{d}}$$ from quark counting at hadron freeze-out

from
Grand Canonical Gibbs Ensemble

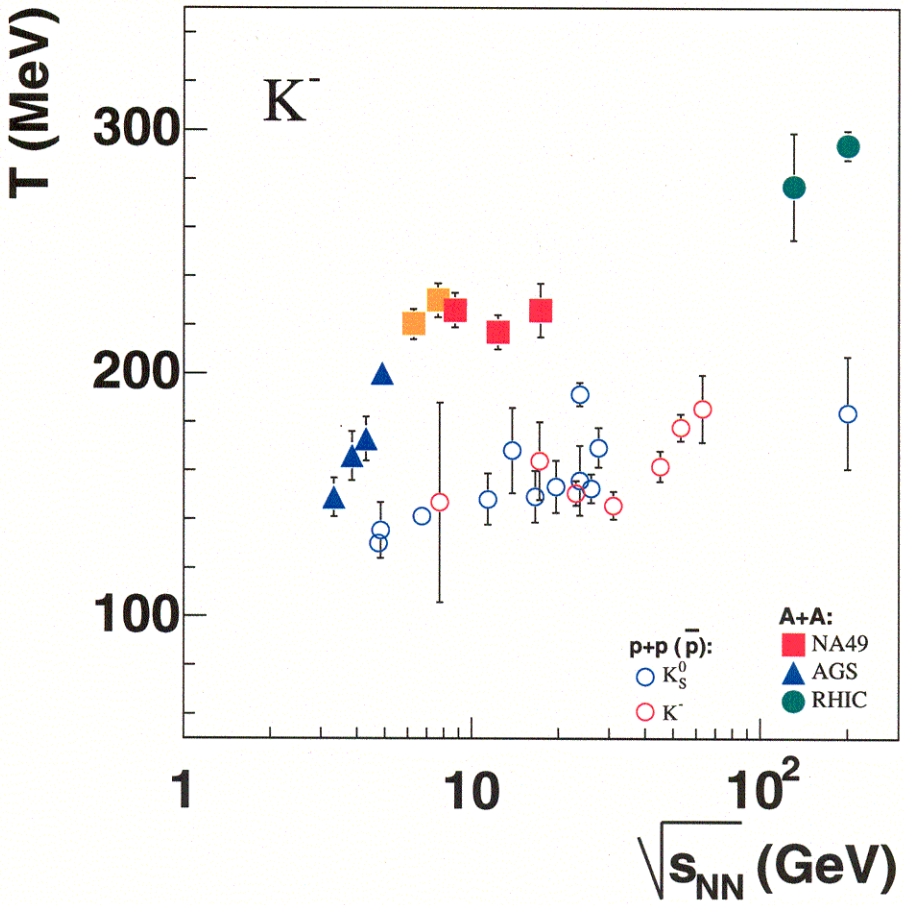
Beccattini, Braun-Munzinger, Cleymans, Redlich, Tounsi, Stachel et al.

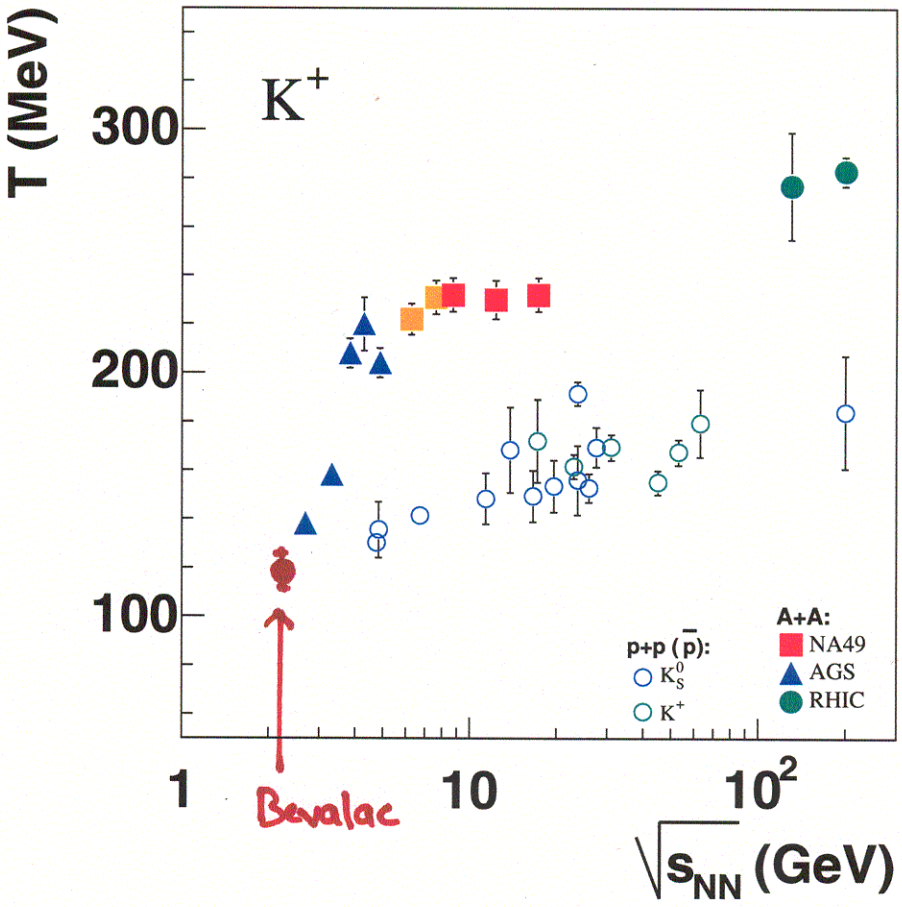
The QCD Phase-Diagram





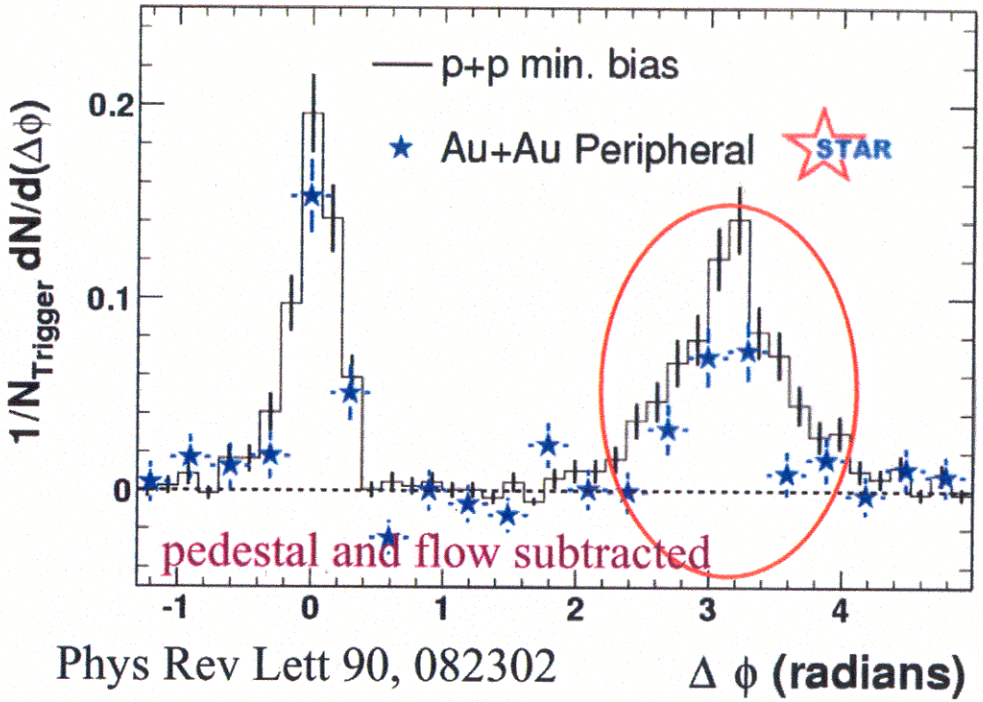
The Kaon Inverse Slope : from Bevalac to RHIC





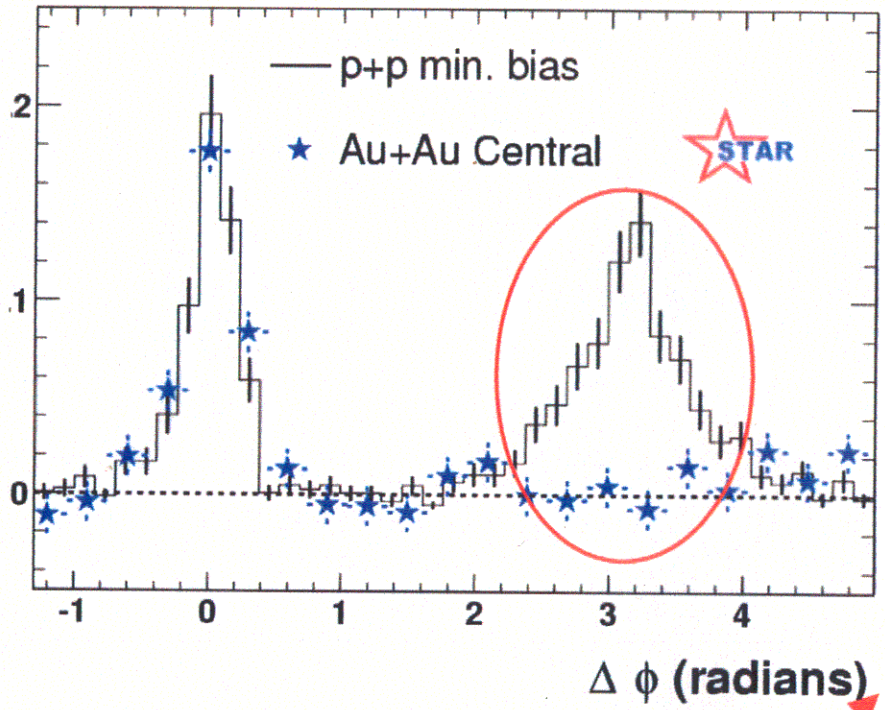
Azimuthal distributions in Au+Au

Au+Au peripheral



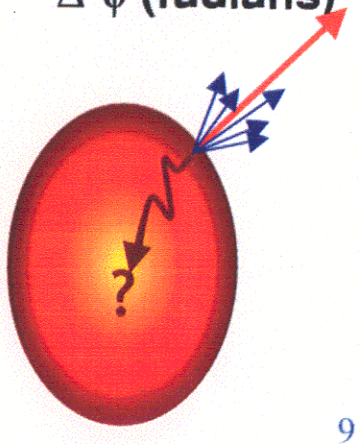
Phys Rev Lett 90, 082302

Au+Au central



Near-side: peripheral and central Au+Au similar to p+p

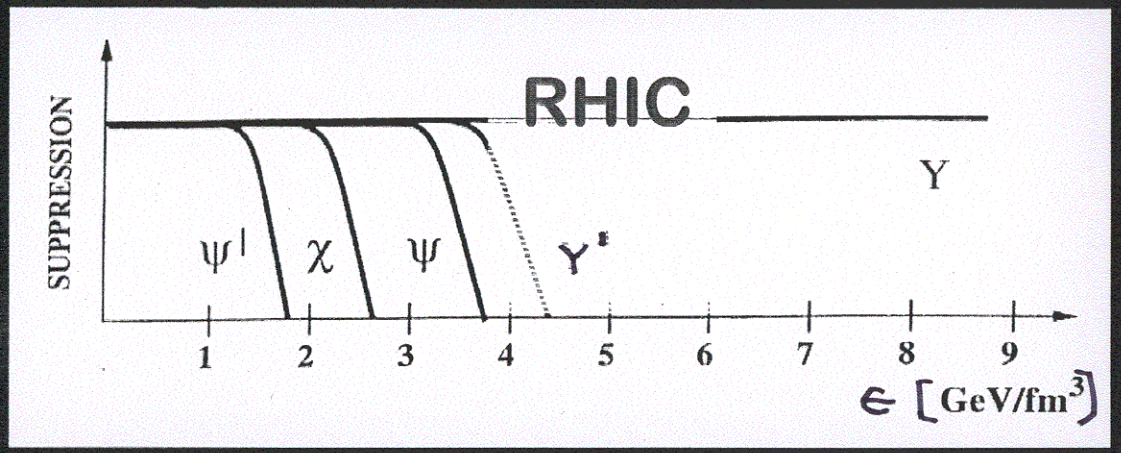
Strong suppression of back-to-back correlations in central Au+Au



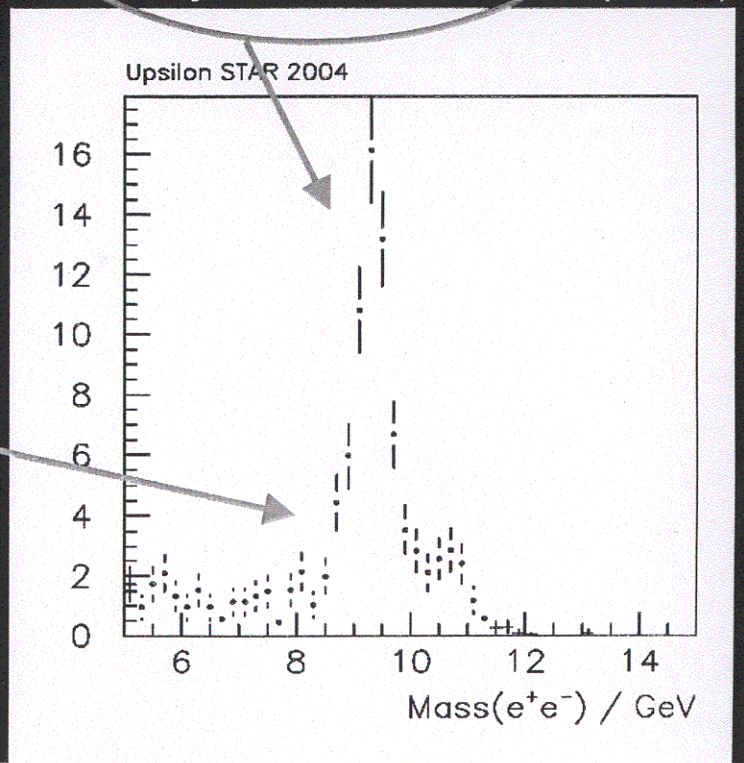
Opening a Window in STAR on Onium

First look in STAR at the onium states (J/ψ, Upsilon, and excited states) to measure the thermodynamics of deconfinement through varying dissociation temperatures

To deeply probe the plasma through studies of (Debye) screening length $\lambda \sim 1/gT$



Study vs. p_T
Study vs. centrality
Study in lighter systems
Study vs a control (the Υ)



- Upsilon rate ~ 10^{-3} J/Ψ

Yield in 10 weeks of AuAu running at 32 μb^{-1} /week will be a start

To fully utilize this probe requires high luminosity RHIC running

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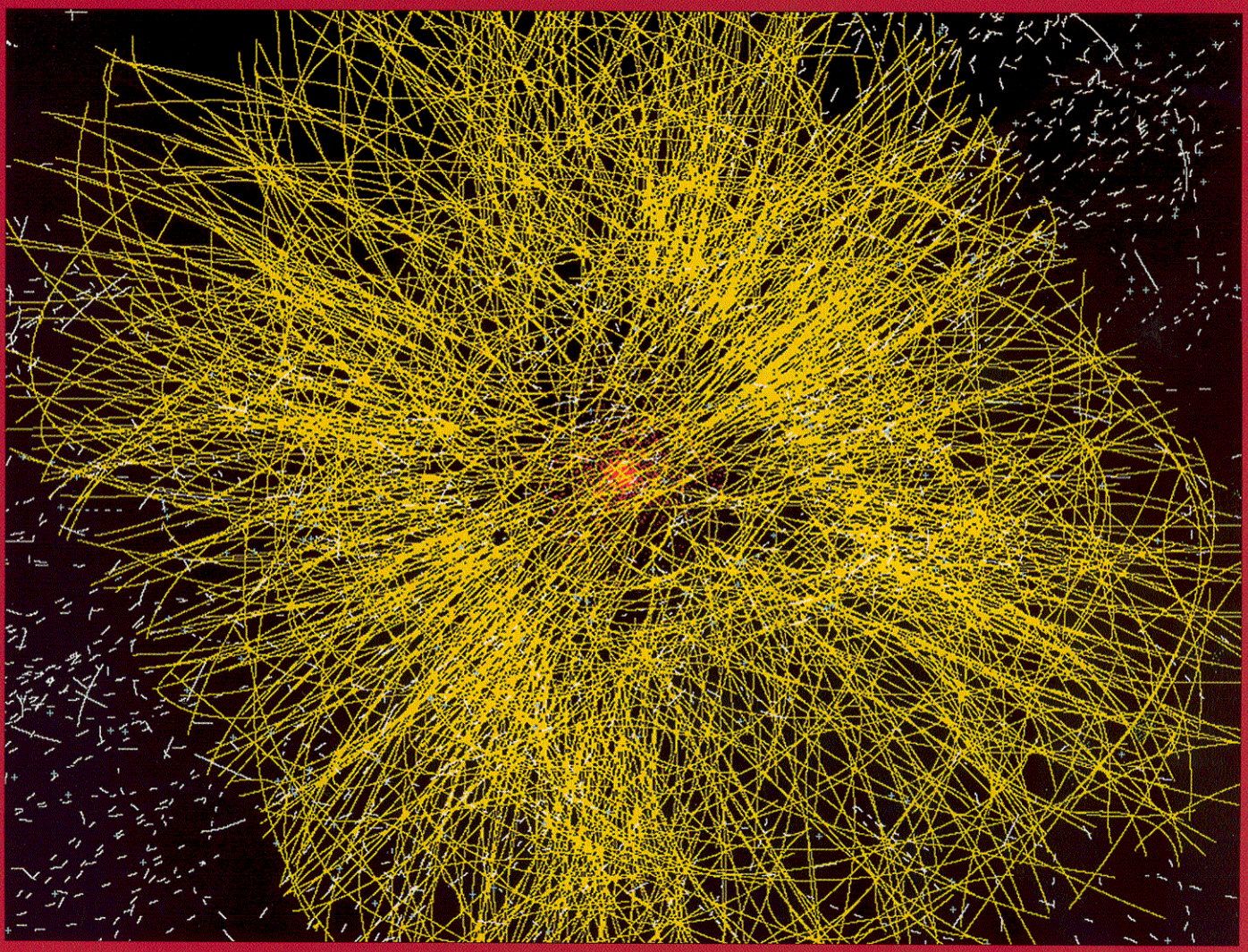
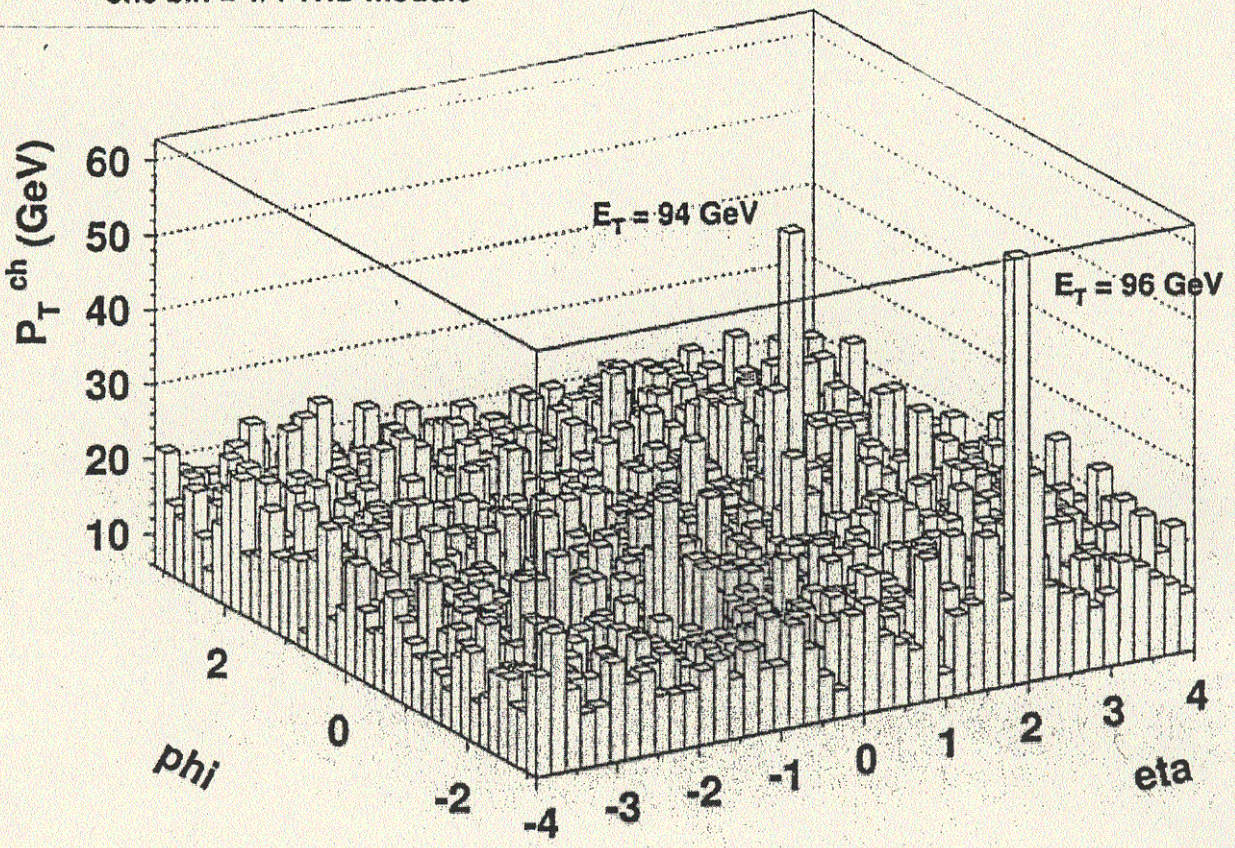
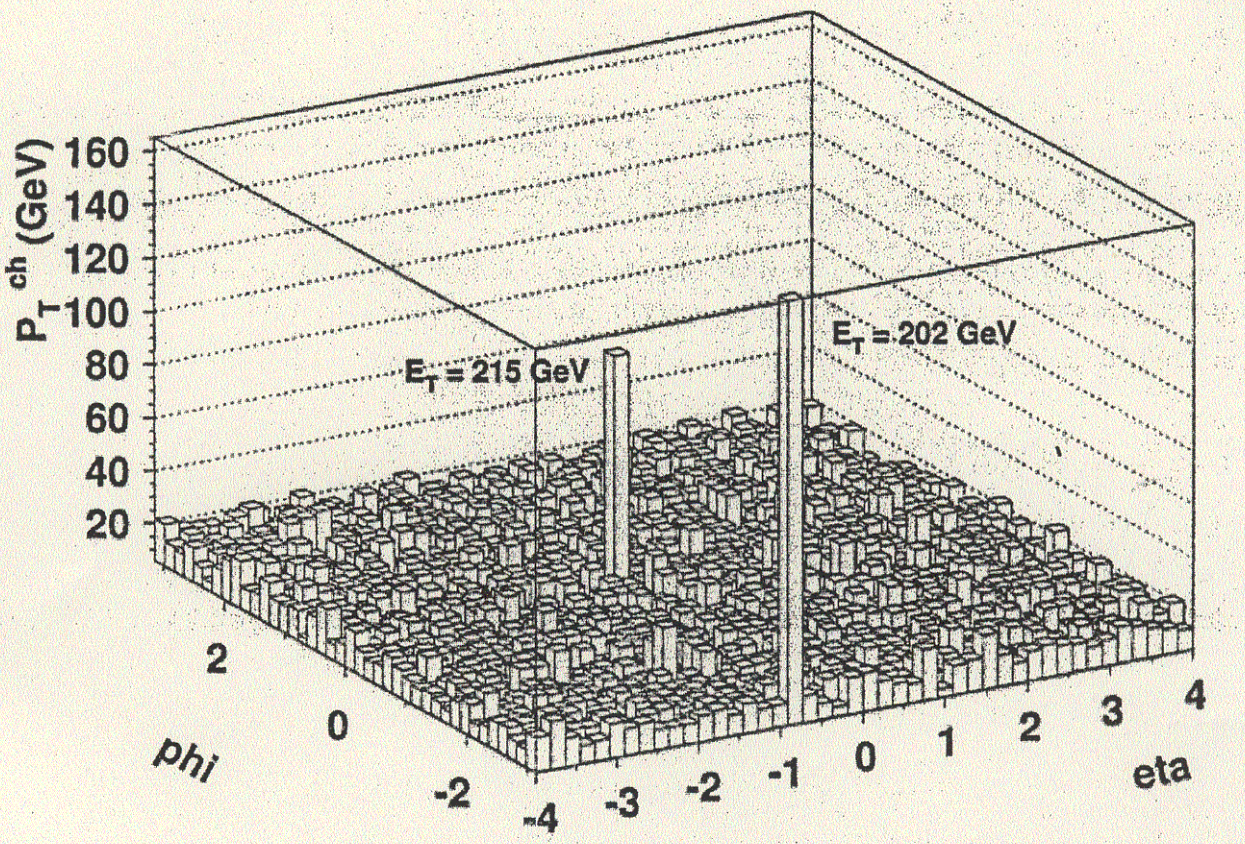
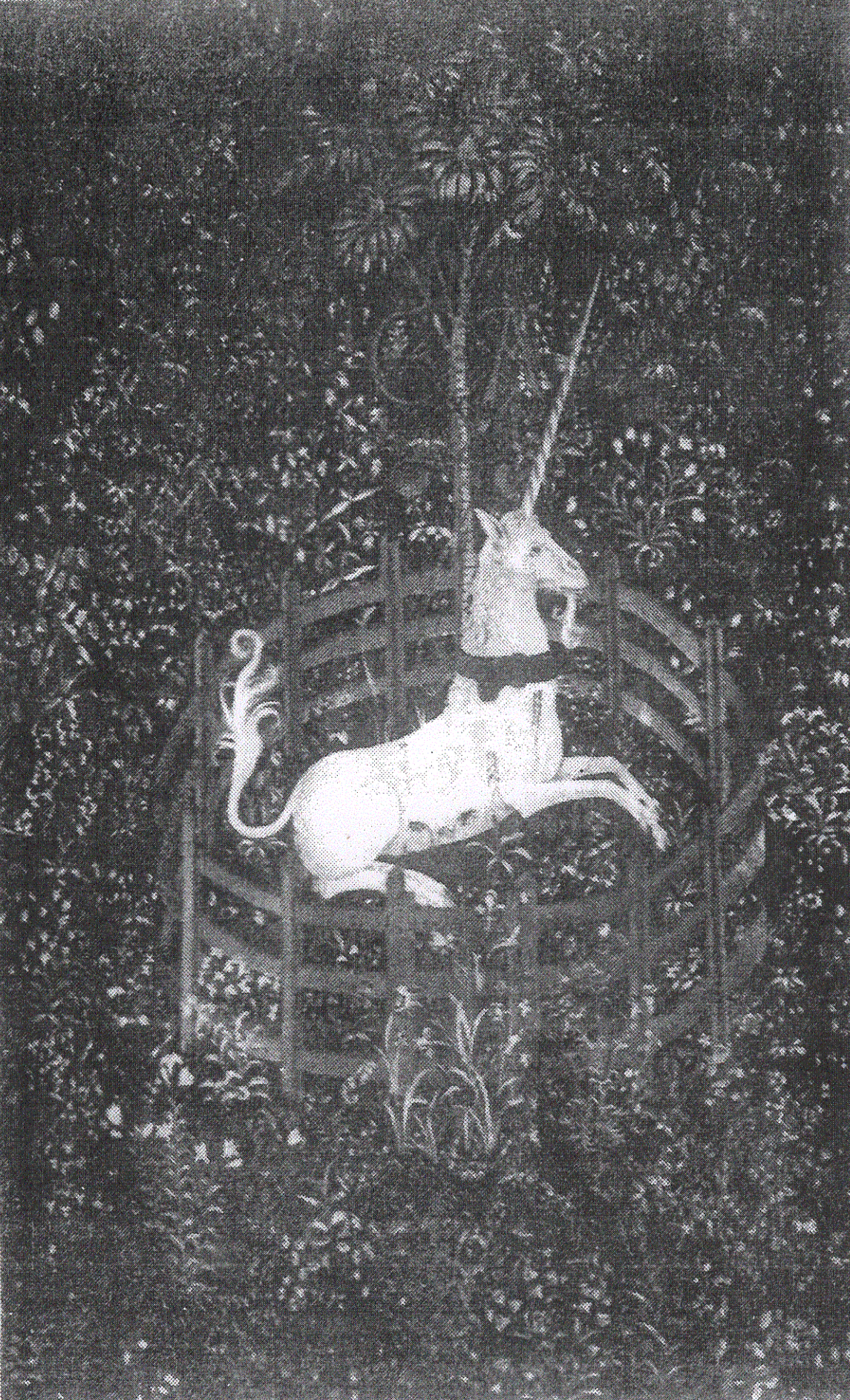


Net closes in on quark–gluon plasma

Jet Physics at the LHC

D. Miskowiec

Pythia jets sticking out of shaker background

one bin = 1/4 TRD module