TRIESTE / ICTP
17-22 Sept. '90

L. RAMELLO

RELATIVISTIC HEAVY-ION SCATTERING EXPERIMENTS

I. Physics interest

II. Beams & experiments

III. Results on global features E_T, N_{CH}

IV. Results on $p_\perp$, particle ratios flow, equilibration

V. Results on π interferometry source size

VI. Results on dileptons J/ψ suppression

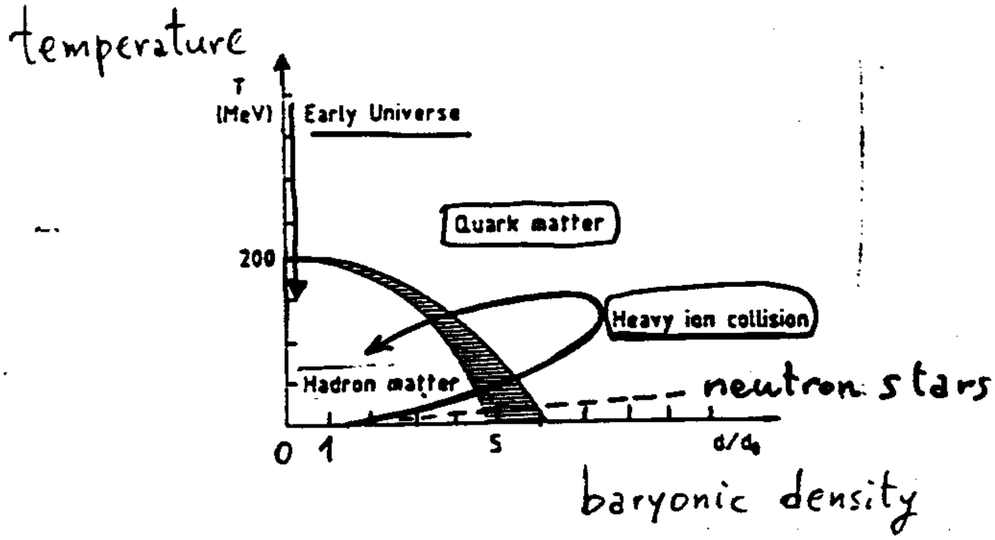
I. PHYSICS INTEREST

- STUDY OF NUCLEAR MATTER AT HIGH TEMPERATURE AND/OR DENSITY OVER "LARGE" VOLUMES, I.E. STRONG INTERACTION THERMODYNAMICS
- LATTICE QCD CALCULATIONS SUPPORT A PHASE TRANSITION TO QUARK-GLUON PLASMA (QGP) LINKED TO DECONFINEMENT AND CHIRAL SYMMETRY RESTORATION
- EQUATION OF STATE OF DENSE NUCLEAR MATTER
- LINKS TO COSMOLOGY & ASTROPHYSICS:
  EARLY UNIVERSE (10^{-5}s AFTER BIG BANG)
  NEUTRON STARS, BLACK HOLES

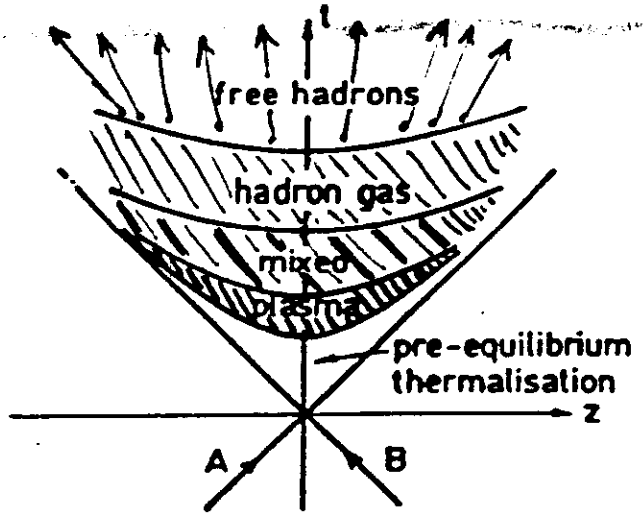
* SIGNATURES OF QGP FORMATION ARE OBSCURED BY THE SUBSEQUENT COOLING AND HADRONIZATION, SO ONE NEEDS TO UNDERSTAND SIMULTANEOUSLY A-A, p-A AND $\overset{(-)}{p}p$ DATA TO ISOLATE SIGNATURES OUT OF TRIVIAL SUPERPOSITION OF NUCLEON-NUCLEON INTERACTIONS

* TO THIS EFFECT AN EXTENSIVE USE IS MADE OF QCD-INSPIRED MONTE CARLO GENERATORS

PHASE DIAGRAM



SPACE-TIME PICTURE



- LATTICE QCD CALCULATIONS INDICATE A FIRST ORDER PHASE TRANSITION FROM HADRON GAS TO QGP, BOTH FOR PURE GAUGE THEORY ($N_F = 0$) AND WITH 2 OR 4 DEGENERATE QUARK FLAVORS

- THE NATURE OF THE TRANSITION DEPENDS ON THE RATIO m_q / T : IT IS "CHIRAL" FOR $m_q / T \lesssim .1$, AND OF DECONFINEMENT TYPE FOR $m_q / T > 1$

- THE CRITICAL TEMPERATURE T_c IS $\lesssim 200$ MeV, DECREASING AS N_F INCREASES

- THE JUMP IN ENERGY DENSITY (AND ENTROPY DENSITY) AT $T = T_c$ IS CLOSE TO THE DIFFERENCE OF STEFAN-BOLTZMANN VALUES BETWEEN A HADRON GAS ($g_h = 3$ FOR MASSLESS PIONS) AND A GAS OF FREE QUARKS AND GLUONS

- THE CRITICAL ENERGY DENSITY ε_c IS PROPORTIONAL TO T_c^4, SO ITS NUMERICAL VALUE HAS LARGE UNCERTAINTY :

$$\varepsilon_c \approx 1 \div 3 \text{ GeV/fm}^3$$

<u>recall</u>: $\varepsilon = 0.15$ GeV/fm³ IN NUCLEI

$\varepsilon = 0.5$ GeV/fm³ IN NUCLEONS

QM '88

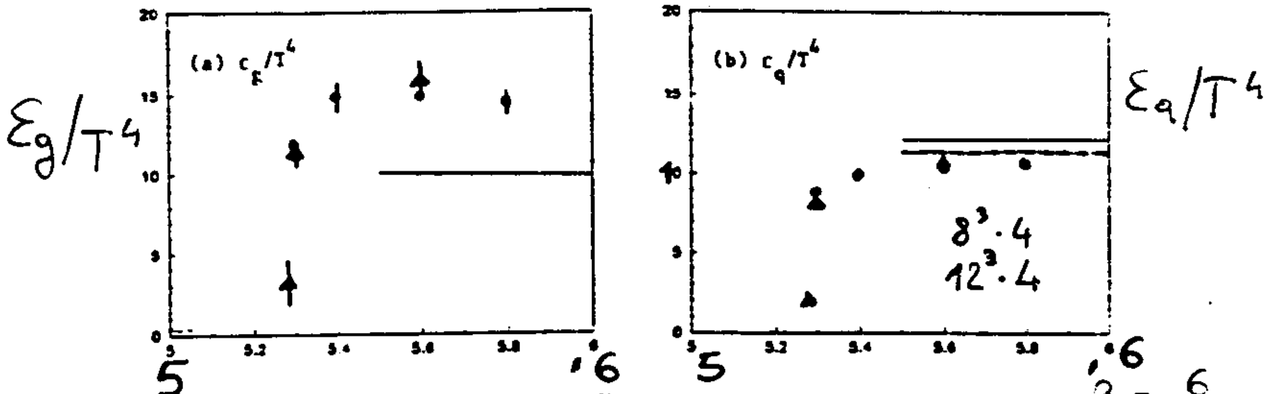


Fig. 4

The gluon (a) and the quark (b) part of the energy density as a function of β. The triangles and circles are for 8^3 and 12^3 spatial volume, both with $N_t = 4$. The lines are weak-coupling prediction to order g^2 on the same size of the lattice (solid for 8^3 and dashed for 12^3). For the gluon part, the two lines overlap. From ref. 42.

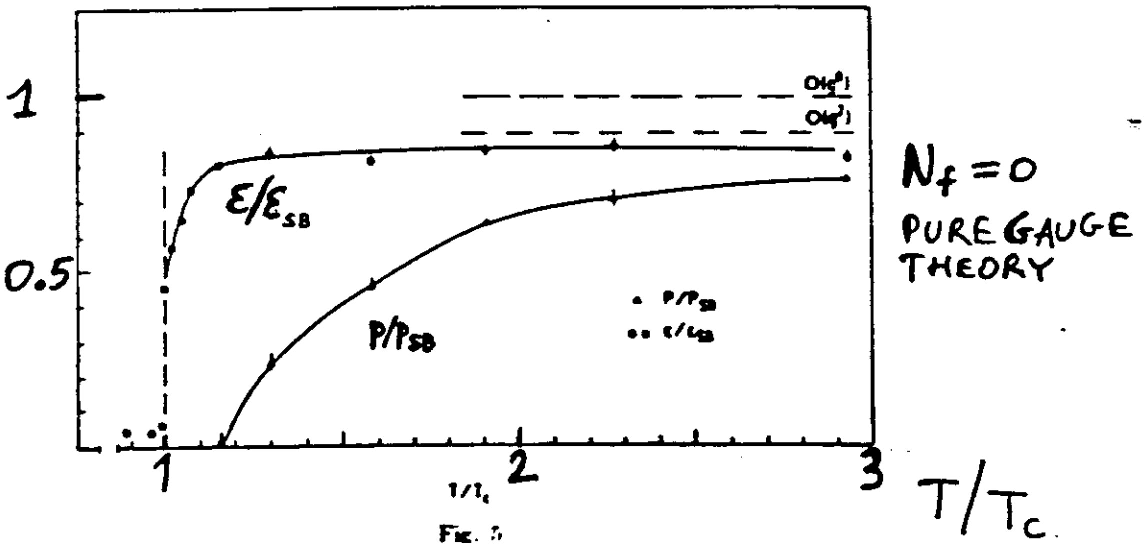
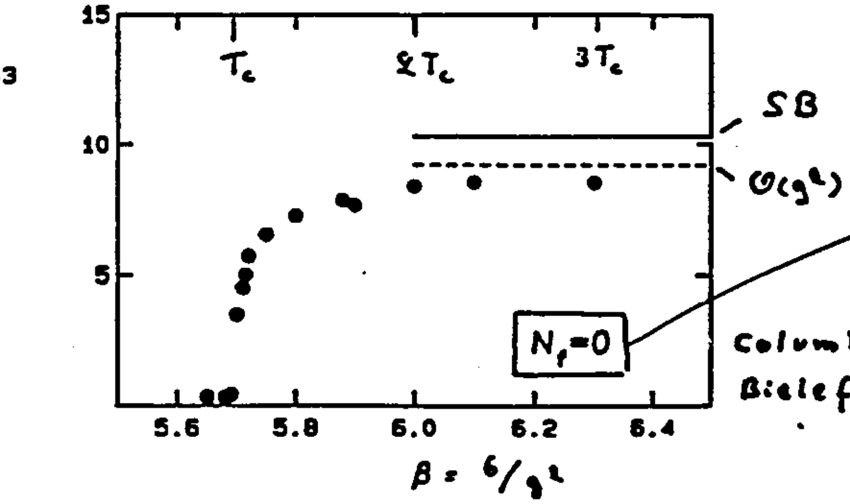


Fig. 5

The gluon energy density and the pressure in the pure gauge theory normalized by the lowest order lattice weak-coupling value. The ratio T/T_c takes into account empirical violation of scaling. The circles and triangles are from ref. 45 ($12^3 \times 4$), and the squares from ref. 46 ($24^3 \times 4$). The latter assumed $p = 0$ to obtain the energy density. From F. Karsch[44].

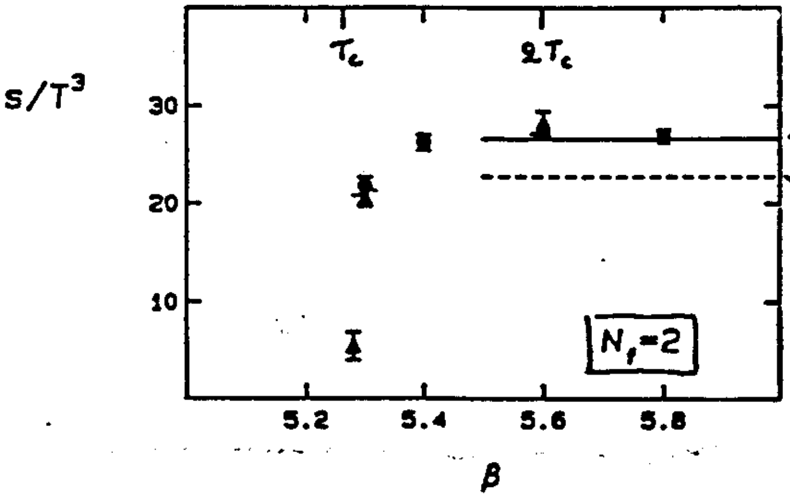
Peterson QM '90



EXACT, FAST ALGORITHM

Columbia Bielefeld

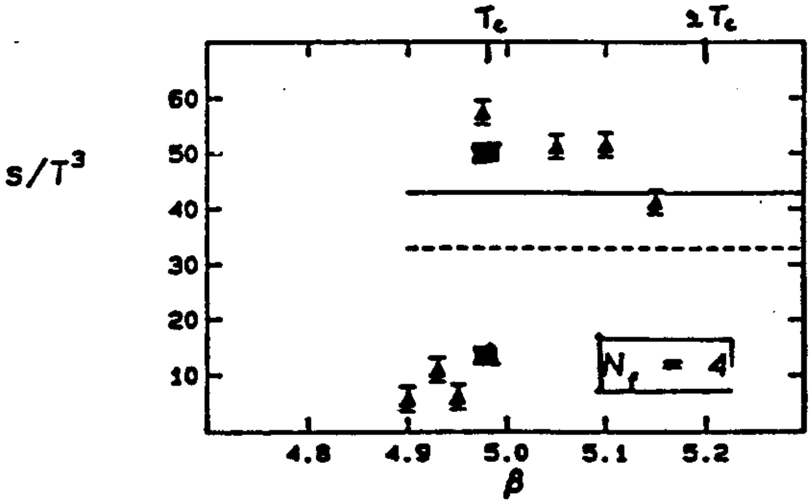
$$s = \frac{\varepsilon + P}{T}$$



SB

$\mathcal{O}(g^2)$

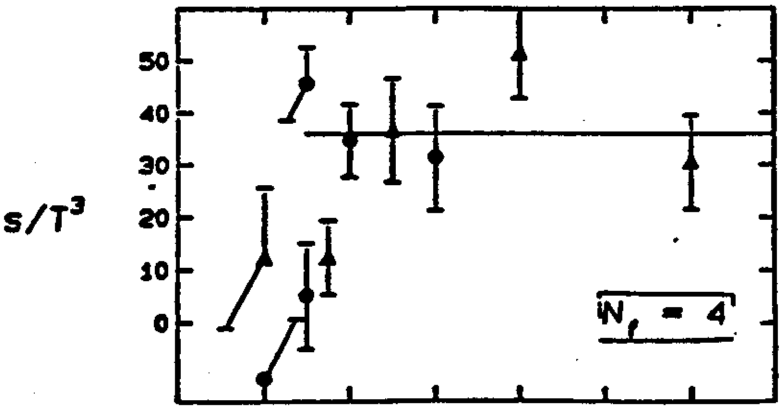
Karsch-Wyld



Karsch-Stamatescu

Kogut et al Columbia

$N_\tau = 8$



SB

MT_c

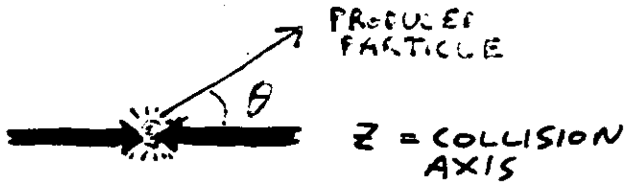
KINEMATICS

- ONE-PARTICLE INCLUSIVE DISTRIBUTIONS ARE OFTEN MEASURED IN TERMS OF RAPIDITY:

$$y = \frac{1}{2}\ln\frac{1+\beta_z}{1-\beta_z} \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

AND TRANSVERSE MOMENTUM:

$$p_T = p\sin\theta$$

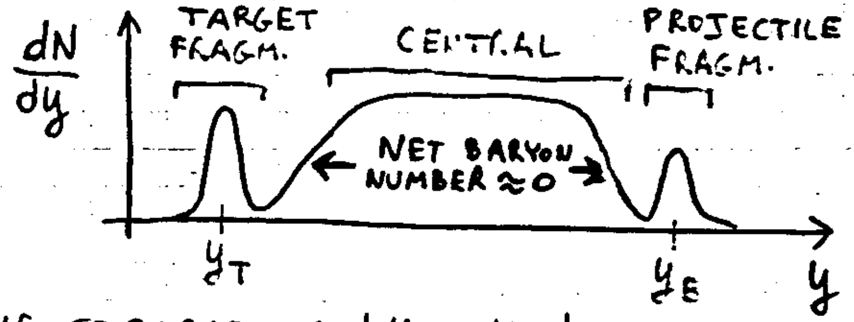


- THE RAPIDITY y TRANSFORMS ADDITIVELY FOR LONGITUDINAL LORENTZ BOOSTS WITH VELOCITY β'_z:

$$y' = y + \tanh^{-1}(\beta'_z)$$

(NOTE THAT $\beta_z = \tanh y$), SO DISTRIBUTIONS IN y ARE INVARIANT IN FORM WHEN GOING, E.G., FROM THE C.M. TO THE LABORATORY SYSTEM.

- OBSERVED PARTICLES ARE CLASSIFIED IN 3 REGIONS:



THE SEPARATION $|y_B - y_T|$ INCREASES LOGARITHMICALLY WITH BEAM ENERGY (AT SPS, 200 GeV/N, IT'S ~ 6 UNITS).

- RAPIDITY IS OFTEN APPROXIMATED BY AN EASILY MEASURABLE QUANTITY, PSEUDORAPIDITY:

$$\eta = -\ln(\operatorname{tg}\theta/2) \equiv \frac{1}{2}\ln\frac{p+p_z}{p-p_z}$$

FOR RELATIVISTIC PARTICLES ($p \approx E$) ONE HAS $\eta \approx y$.

* BJORKEN MODEL (LONGITUDINAL, BOOST-INVARIANT HYDRODYN. EXPANSION) PREDICTS RAPIDITY PLATEAU IN THE CENTRAL

CONDITIONS NEEDED TO PRODUCE QGP :

* HIGH ε BY COMPRESSION AND/OR HEATING
  → RELATIVISTIC PROJECTILES

* LARGE VOLUMES / LIFETIMES TO HAVE A THERMODYNAMICAL SYSTEM
  → HEAVY IONS

THESE CONDITIONS ARE "VERIFIED" BY STUDYING GLOBAL FEATURES LIKE TRANSVERSE ENERGY AND MULTIPLICITY → SECTION III

SPECIFIC SIGNATURES :

◆ EQUILIBRATION, COLLECTIVE FLOW
→ via $p_\perp$ spectra, particle ratios $(K/\pi, \dots)$
$\langle p_\perp \rangle$ vs. dN/dy → SECTION IV

◆ SOURCE SIZE (AND LIFETIME)
→ via HBT interferometry → SECTION V

◆ PARTICLES EMITTED BY QGP IN EARLY STAGES
→ thermal photons, dileptons

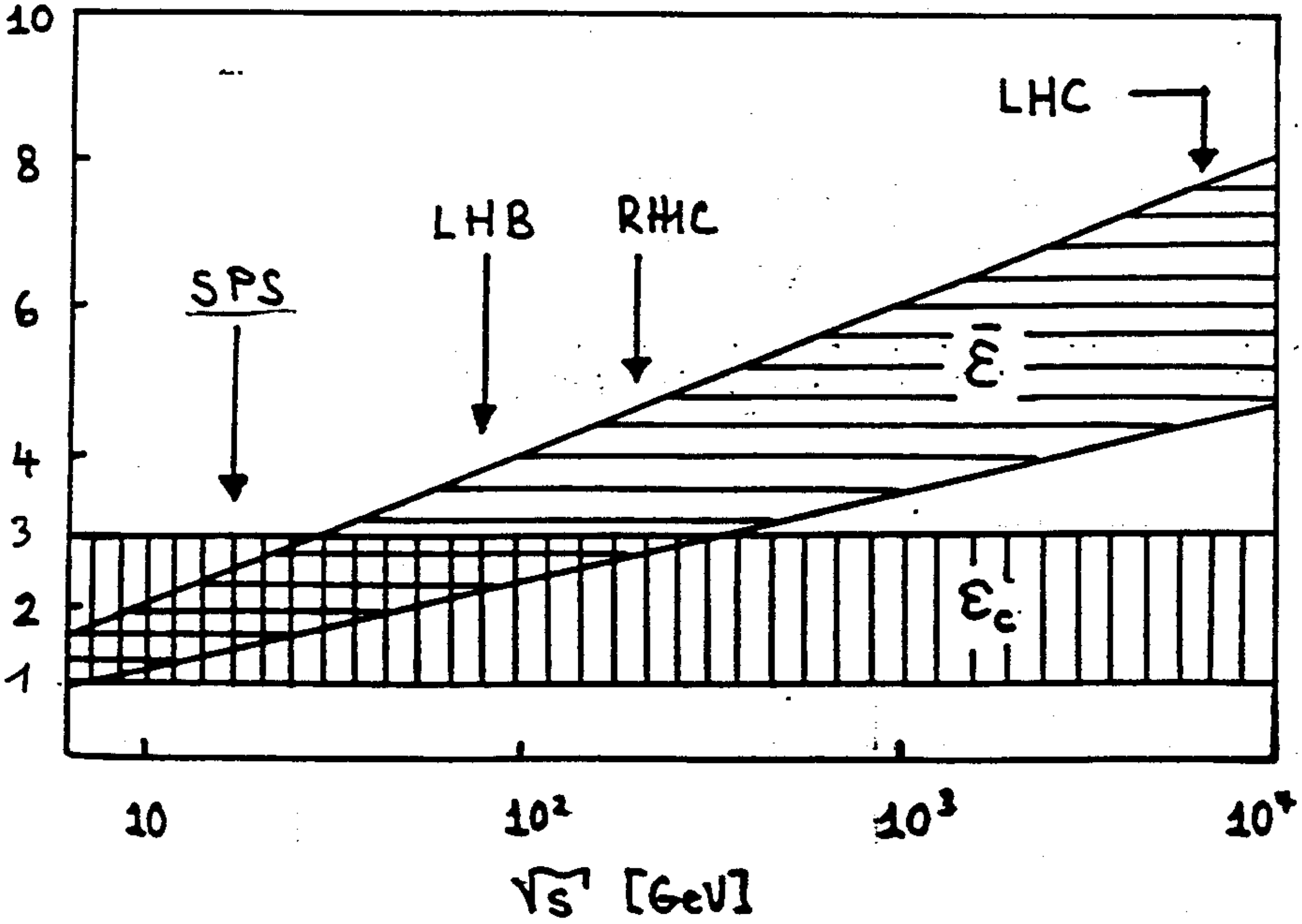
◆ "MELTING" OF HEAVY $q\bar{q}$ STATES
→ J/ψ, ψ', Υ, ... suppression → SECTION VI

◆ RAPIDITY FLUCTUATIONS (JACEE)

◆ INTERMITTENCY ?

Bjorken average ε for central Pb-Pb collisions

$$\varepsilon\,[\mathrm{GeV/fm^3}] \simeq 0.0884\, A^{\alpha-2/3} \ln\sqrt{s} \;;\; A=208,\ \alpha=1.0\div1.1$$



$$\varepsilon = \frac{\langle m_T \rangle}{\pi R^2 \tau}\left(\frac{dN}{dy}\right)$$

m_T = transverse mass $\simeq 0.5$ GeV

$R = r_0 A^{1/3}$ $r_0 \sim 1.2$ fm

τ = formation length ~ 1 fm

$$\left(\frac{dN}{dy}\right)_{AA} = A^{\alpha}\left(\frac{dN}{dy}\right)_{pp}$$

II. BEAMS AND EXPERIMENTS

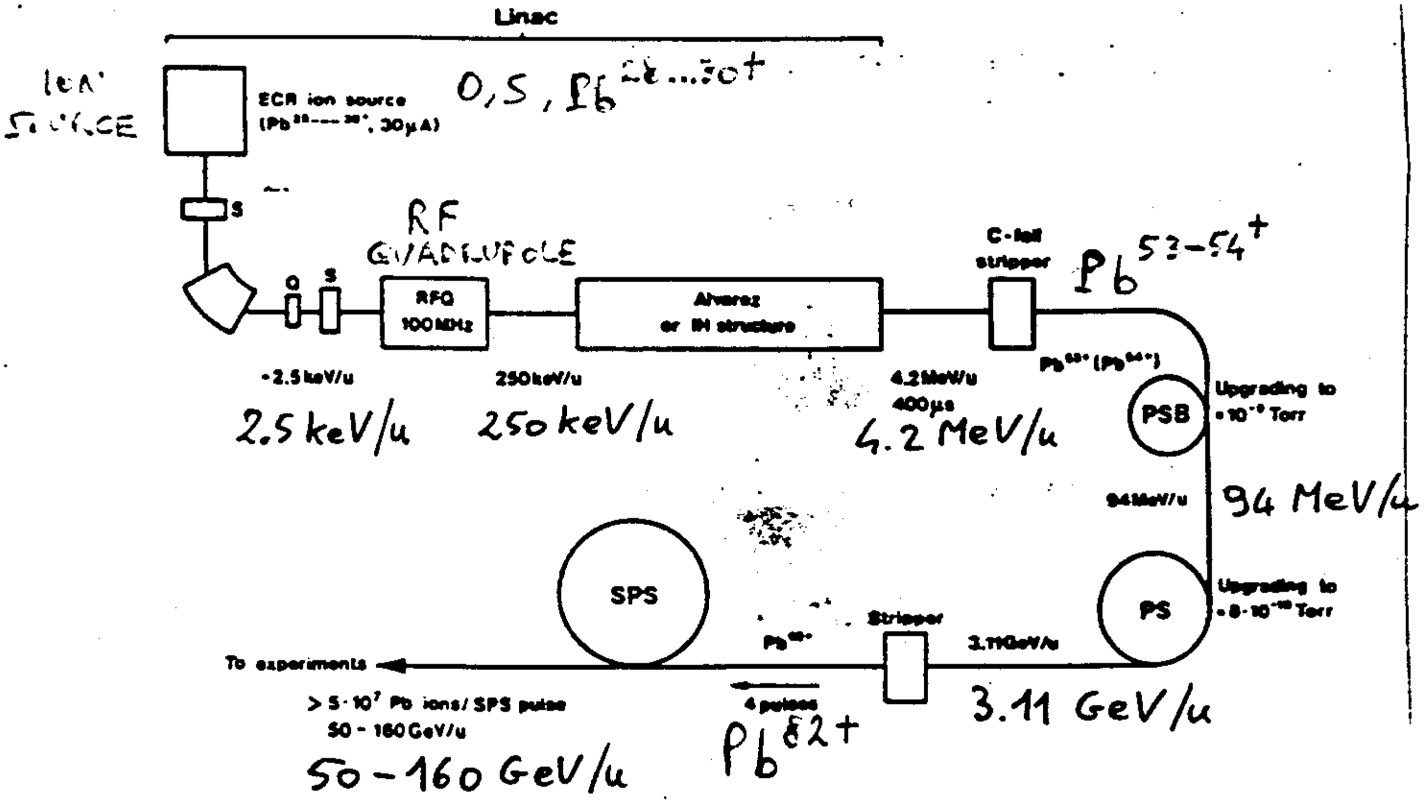
- PRESENT AND FUTURE ACCELERATORS:

	IONS	E/nucleon GeV	$\sqrt{s_{NN}}$ GeV	INTENSITY ions/pulse	AVAILABLE FROM
BNL/AGS	up to ^{28}Si	14.5	5	10^9	1986
CERN/SPS	^{16}O, ^{32}S	60/200	10/19	$10^9/5\times10^7$	1986/87
BNL/AGS BOOSTER	up to ^{197}Au	14.5	5	10^8-10^9	1991
CERN/SPS	up to ^{208}Pb	160	17	4×10^8	1993 ?
BNL/RHIC	up to ^{197}Au	100	200	$\mathcal{L}=2\times10^{26}$	1997 ?
CERN/LHC	up to ^{208}Pb	3150	6300	$\mathcal{L}=10^{27}$	1998 ?

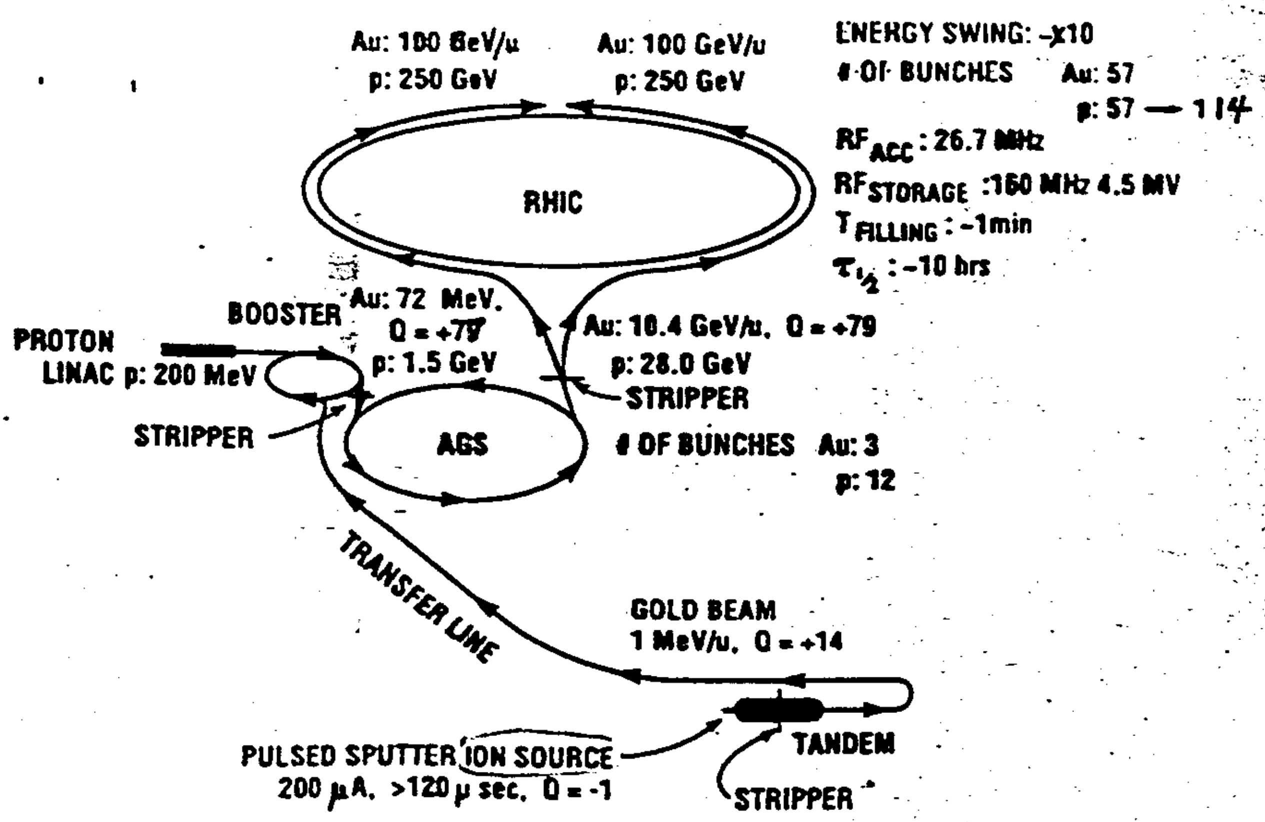
BNL/AGS EXPERIMENTS:

EXPERIMENT	DETECTOR	MEASURES
E802	ZERO DEGREE CALORIM.	E_{ZD}
	Pb-GLASS CALORIM.	$dE_T/d\eta$
	MAGN. SPECTROM.	$p, \bar{p}, d, \pi^\pm, K^\pm$
E810	TIME PROJECTION CHAMBER	p, θ of charged particles
E814	NaI/U CALORIMETER	E_T, N_{CH}
	TARGET CALORIM.	neutrons and protons
	SILICON MULT. CTR.	in forward direction
	PARTICIPANT CALO.	
	FORWARD SPECTROM. AND CALORIMETER	

CERN LINAC - PS - SPS COMPLEX



BNL RHIC ACCELERATION CONFIGURATION



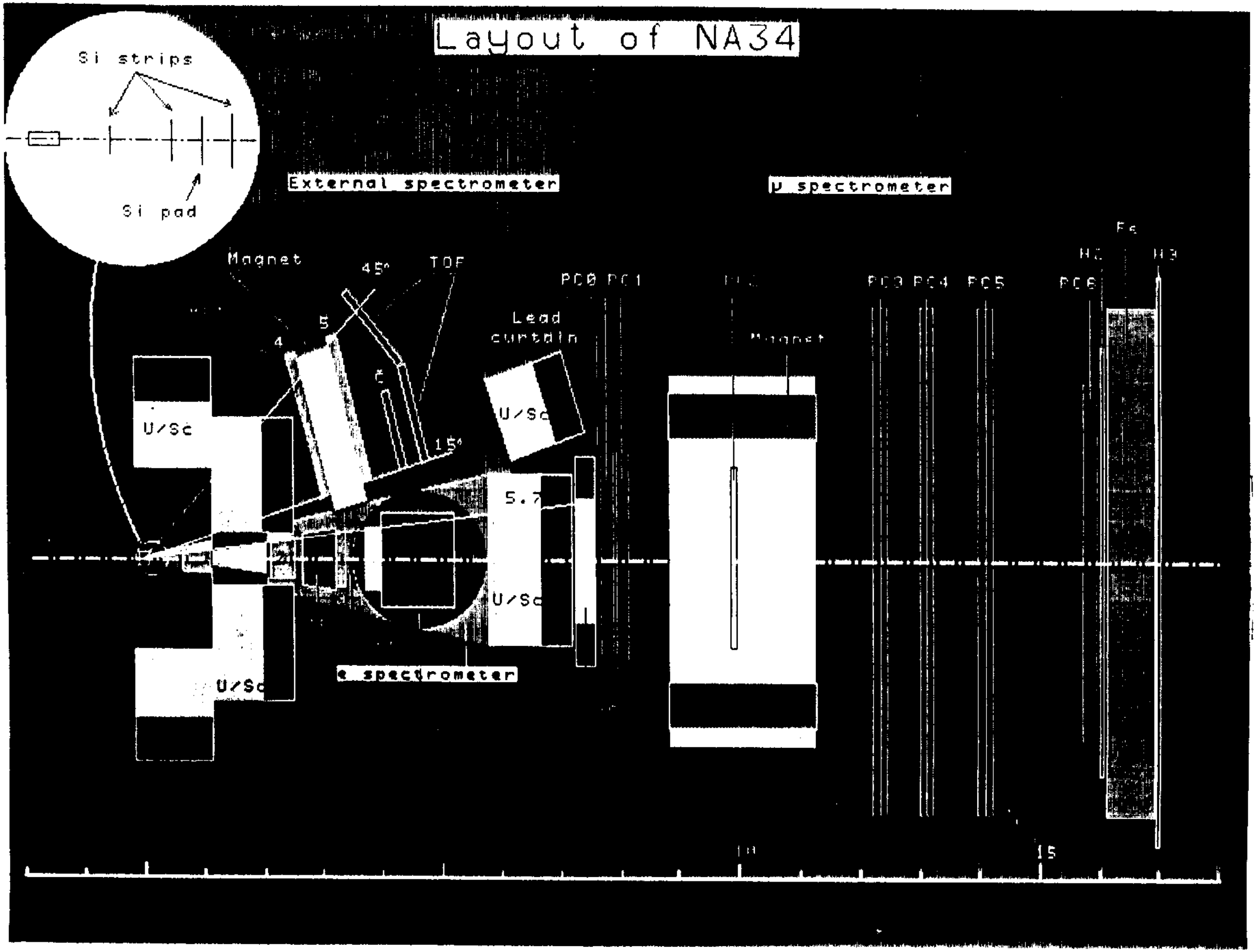
CERN/SPS EXPERIMENTS :

EXPERIMENT	DETECTOR	MEASURES
NA34 (HELIOS)	U/Sc. CALORIMETER	E_T , $dE_T/d\eta$
	U/Liq.Ar CALORIM.	
	SILICON COUNTERS	$dN^{ch}/d\eta$
	EXTERNAL SPECTROM.	$\pi^\pm, K^\pm, \bar{p}, \gamma$
	MUON SPECTROM.	LOW MASS MUON PAIRS
NA35	ZERO DEGREE CALORIM.	E_{ZD} , E_T
	RING CALORIMETER	
	PHOTON POSITION DET.	
	STREAMER CHAMBER	$\pi^\pm, p, K^0, \Lambda, \bar{\Lambda}$
NA36	TIME PROTECTION CHAMBER	$K^0, \Lambda, \bar{\Lambda}, \Xi, \Omega$
NA38	E.M. CALORIMETER	E_T
	MUON SPECTROMETER	$\mu\mu$ (HIGH MASS)
WA80	ZERO DEGREE CALORIM.	E_{ZD} , E_T
	MID-RAPIDITY CALORIM.	
	MULTIPLICITY DETECTORS	N_{CH} , $dN^{CH}/d\eta$
	Pb-GLASS PHOTON DET.	γ, π^0
WA85	"Ω" SPECTROMETER	$K^0, \Lambda, \bar{\Lambda}, \Xi$
NA44*	FOCUSSING SPECTROM.	INTERFEROMETRY WITH $\pi, K, \bar{p}$
NA45*	e^+e^- SPECTROMETER WITH RICH'S	LOW MASS e^+e^-

* FIRST RUN : AUGUST 1990

IN ADDITION, A LARGE NUMBER OF "SMALL" EXPERIMENTS USE EMULSIONS AND/OR PLASTICS TO MAKE A GENERAL SURVEY OF INTERACTIONS (NO TRIGGER IS USED).

THE HELIOS-EMULSION COLLABORATION COMBINES NUCLEAR EMULSIONS WITH THE NA34 APPARATUS.



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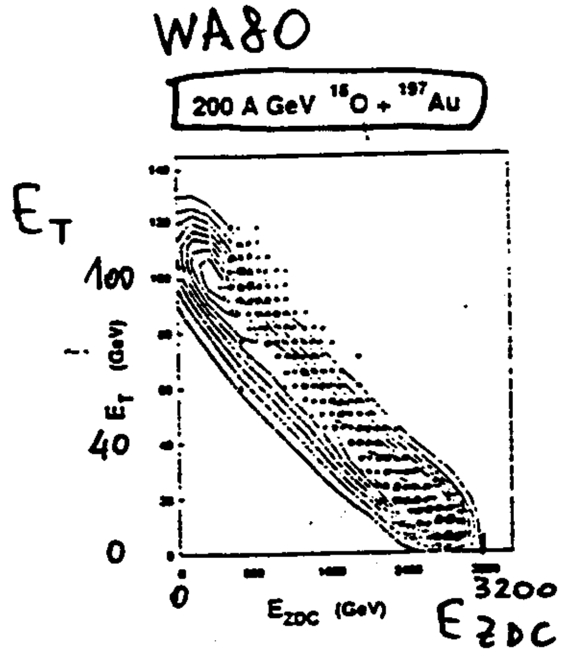


E_T, N_{CH} ARE ANTICORRELATED WITH E_{ZDC}

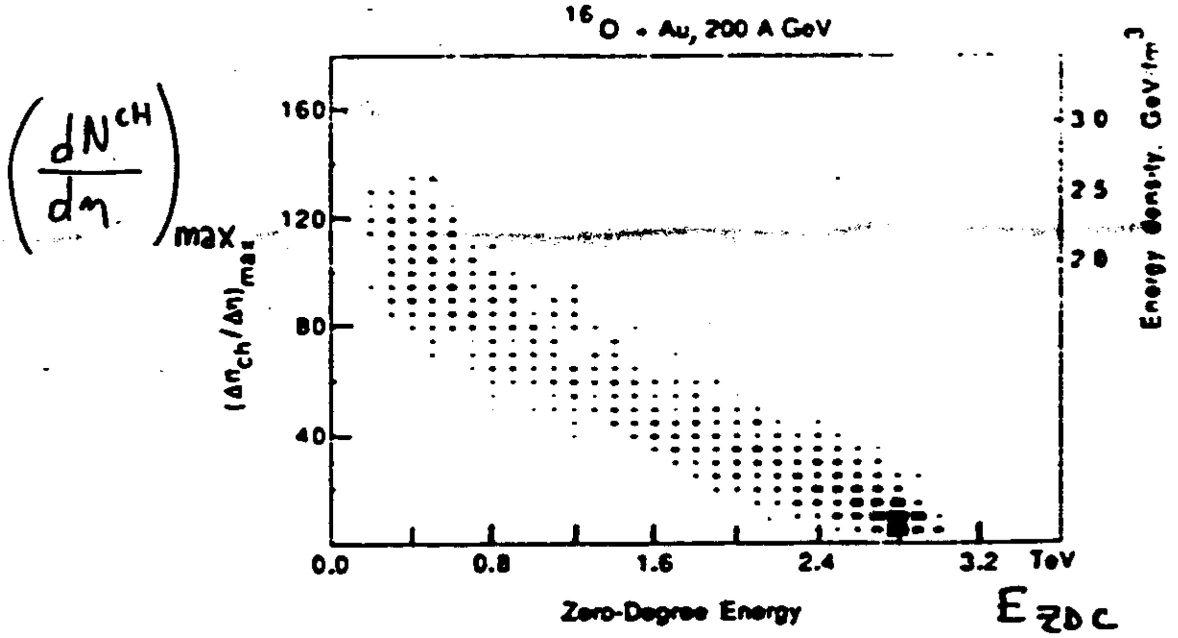


Fig. 8. The density of charged particles in the pseudo-rapidity interval $2.65 < \eta < 3.15$ for $^{16}O + Au$ at 200 A GeV $(\Delta n_{ch}/\Delta \eta)_{max}$, as a function of the energy measured in the ZDC, E_{ZDC}. On the scale to the right we show the corresponding energy densities, derived as described in the text

DIFFERENTIAL CROSS SECTIONS.

- CROSS-SECTIONS IN E_T AND N_{CH} HAVE BEEN MEASURED FROM MANY EXPERIMENTS ON A VARIETY OF NUCLEI, BOTH AT BNL AND CERN ENERGIES: → FIG.

THEY ARE ESSENTIALLY UNDERSTOOD ON THE BASIS OF RATHER SIMPLE GEOMETRICAL MODELS.

▶ nucleus-nucleus collision = superposition of N effective nucleon-nucleon interactions, where N is calculated via the overlap integral Ω of the two nuclear densities at the appropriate impact parameter b → FIG.

▶ E_T (or N_{CH}) cross-section fitted with 2 free parameters:

ε_0 = average E_T per nucleon-nucleon int.

ω = variance $/\varepsilon_0^2$

(E_T at a given impact parameter is assumed gaussian distribute with average $N\varepsilon_0$ and variance $\omega N\varepsilon_c^2$)

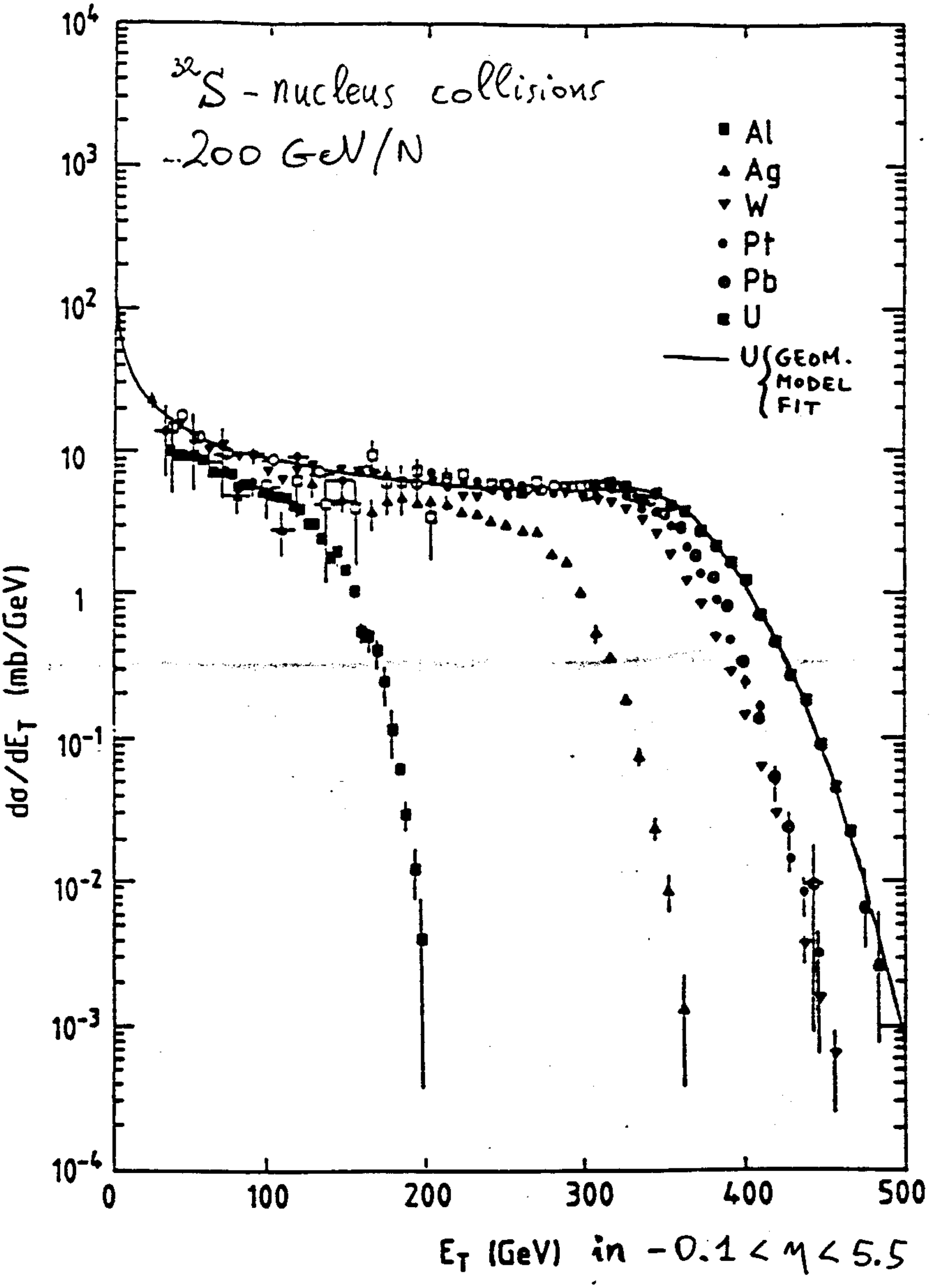
RESULTS OF GEOMETRICAL MODEL FITS FOR $\boxed{\text{HELIOS}}$ ^{32}S DATA AT 200 GeV/N OVER THE LARGEST COVERAGE $(-0.1<\eta<5.5)$:

S →	Al	Ag	W	Pb	U
ε_c	1.88 ± .06	1.71 ± .02	1.67 ± .005	1.68 ± .03	1.63 ± .02
ω	1.1 ± .3	1.84 ± .3	1.83 ± .06	1.35 ± .15	2.37 ± .2
ω_d	—	0.22	0.81	—	1.75
ω_{true}	1.1	1.62	1.10	1.35	0.62

▶ ε_c is rather constant for various nuclei (recall that $\langle E_T\rangle \sim 1.4$ GeV in p-p collisions at $\sqrt{s} = 20$ GeV)

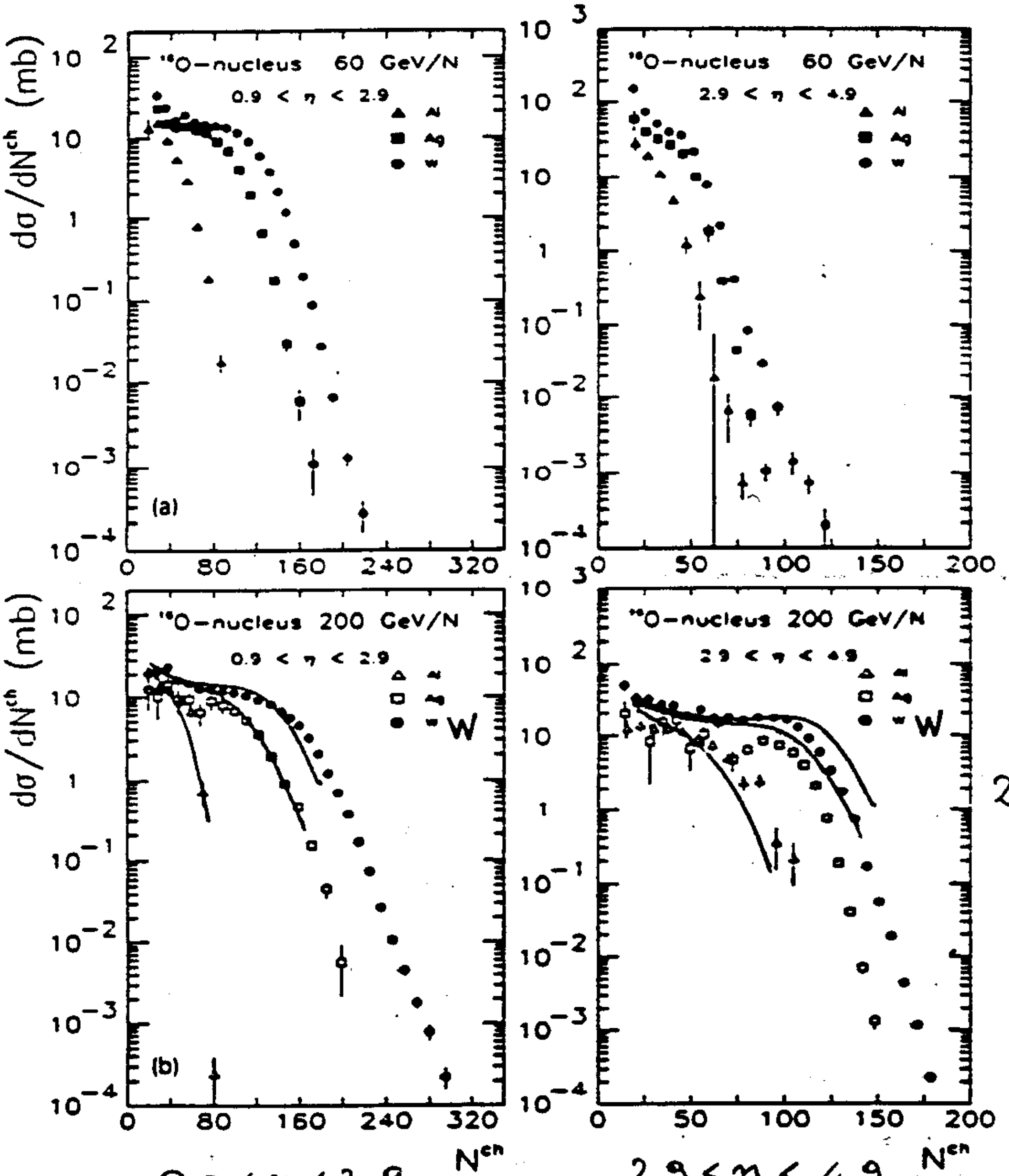
▶ $\omega_W, \omega_U > \omega_{Pb}$ due to nuclear shape: in high E_T events a non-spherical nucleus is aligned (effective $A \sim 400$ for $^{32}S \rightarrow {}^{238}U$!).
Values of ω are less dispersed when the effect of nuclear deformation ω_d is taken out.

HELIOS



^{32}S - nucleus collisions
..200 GeV/N
■ Al
▲ Ag
▼ W
• Pt
● Pb
■ U
U { GEOM. MODEL FIT
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$d\sigma/dE_T$ (mb/GeV)
0
100
200
300
400
500
E_T (GeV) in $-0.1 < \eta < 5.5$

^{16}O - nucleus collisions HELIOS



60 GeV/N

200 GeV/N

$0.9 < \eta < 2.9$

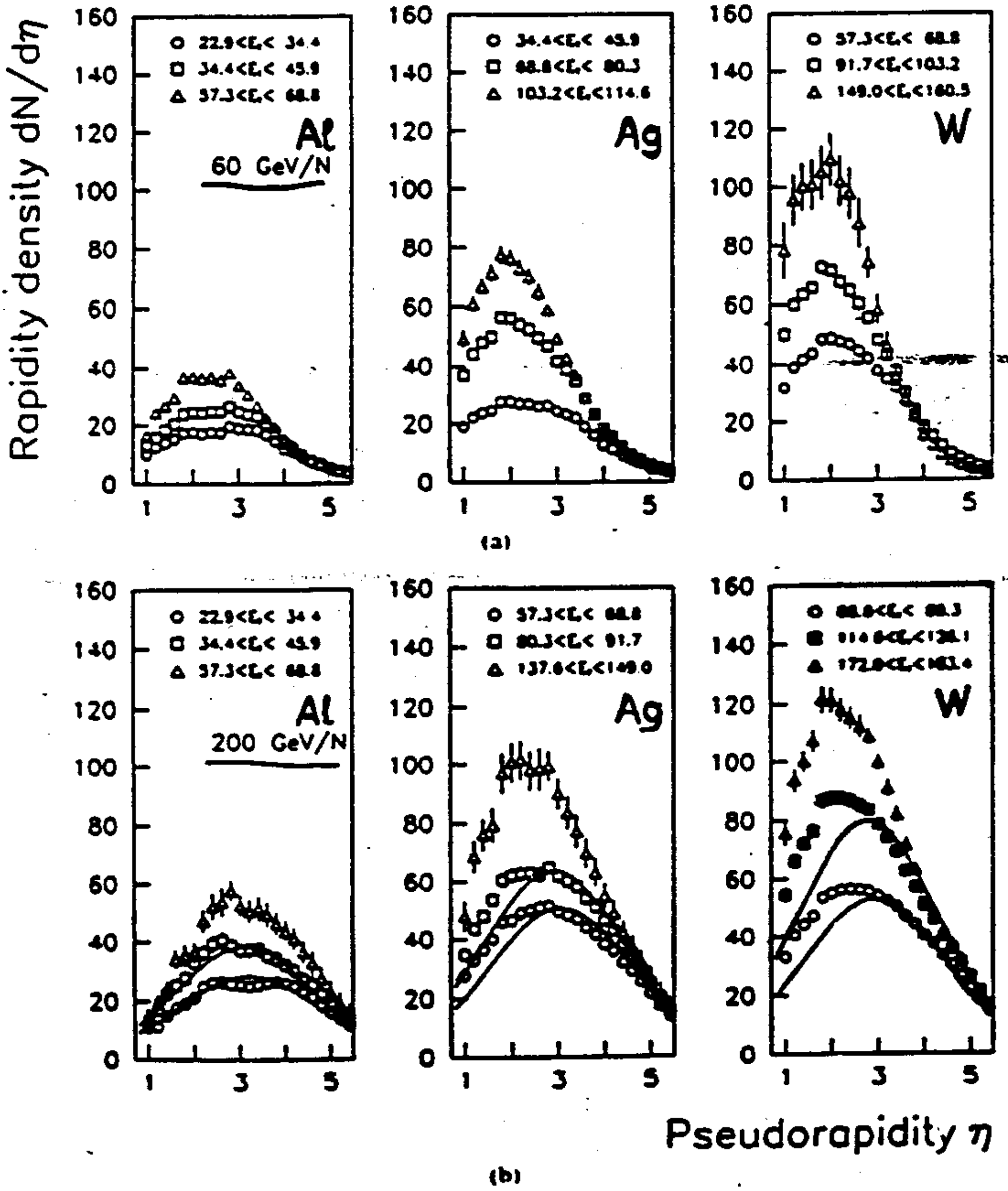
$2.9 < \eta < 4.9$

Fig. 3. Charged-particle differential cross section $d\sigma/dN_{ch}$ in the backward and restricted forward regions: (a) at 60 GeV per nucleon, (b) at 200 GeV per nucleon. The error bars are statistical only; the global systematic error on the multiplicity scale is 5%. The lines indicate IRIS predictions.

PSEUDORAPIDITY DISTRIBUTIONS
as a function of "centrality":
$dN^{ch}/d\eta$

HELIOS

T. Åkesson et al. / Multiplicity distributions 61



PLATEAU
CENTRAL
TAIL

Fig. 4. Distribution of pseudorapidity density for three selected windows in E_T within the trigger region: (a) at 60 GeV per nucleon; (b) at 200 GeV per nucleon. The errors shown are statistical only. The lines indicate IRIS predictions.

(centrality selected by "backward" E_T $(-0.1<\eta<2.9)$)

- NO RAPIDITY PLATEAU, DISTRIBUTIONS VERY CLOSE TO GAUSSIANS (AS PREDICTED BY LANDAU HYDRODYN. MODEL).

MOMENTS OF $dN^{ch}/d\eta$ DISTRIBUTIONS:

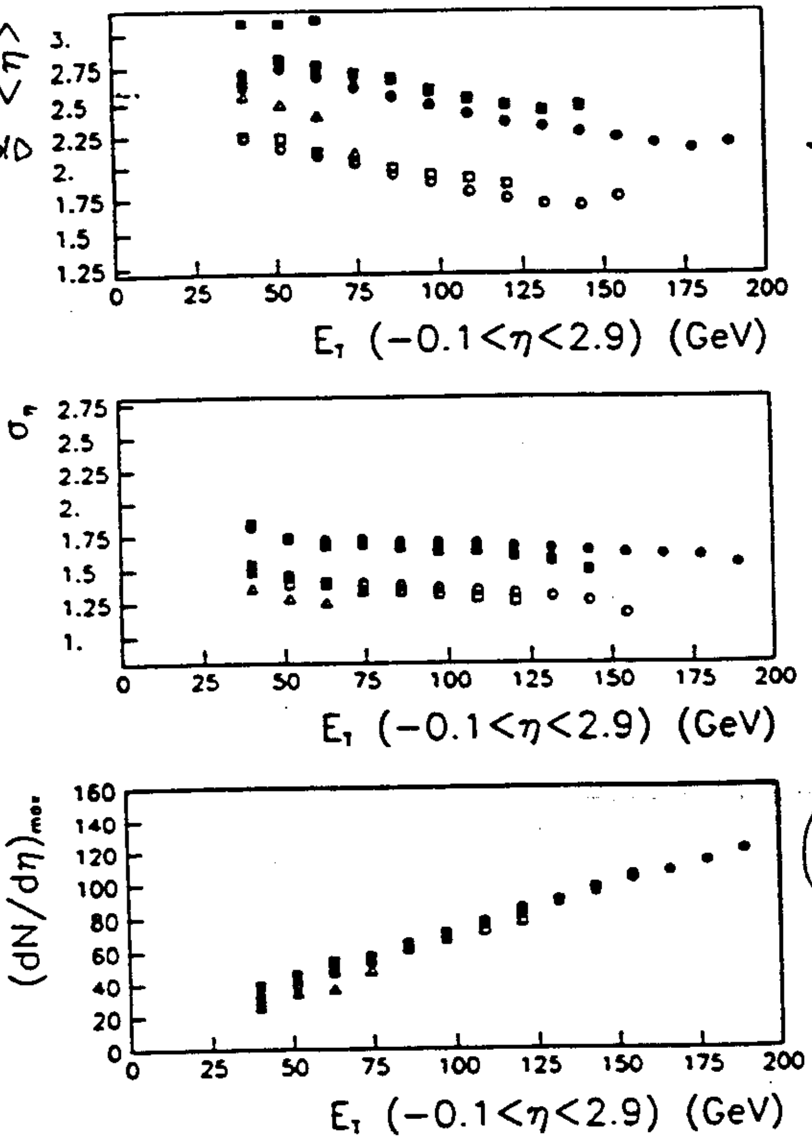
HELIOS

	60 GeV	200 GeV
O+ Al	△	▲
Ag	□	■
W	○	●

CENTROID

WIDTH

MAXIMUM



$\langle\eta\rangle$ moves back with increasing centrality due to changing participants' kinematics

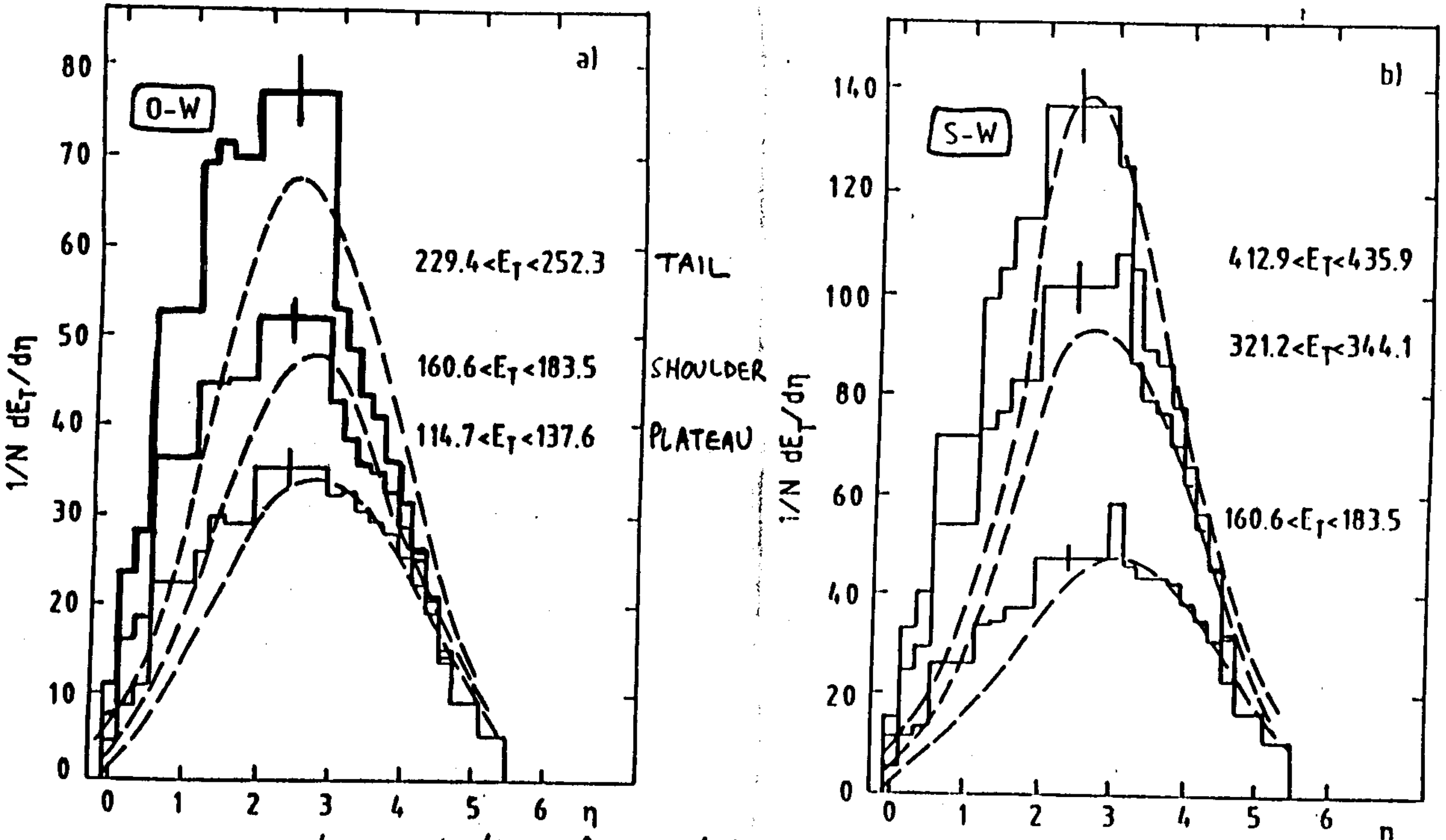
σ_η decreases by about 10% for very central collisions

$\left(\frac{dN^{ch}}{d\eta}\right)_{max}$ is very close to linear vs. E_T

Fig. 5. Evolution of mean η, standard deviation, and maximum pseudorapidity density with E_T for Ag targets (squares) and W targets (circles), at 60 GeV (open symbols) and 200 GeV (closed symbols) per nucleon.

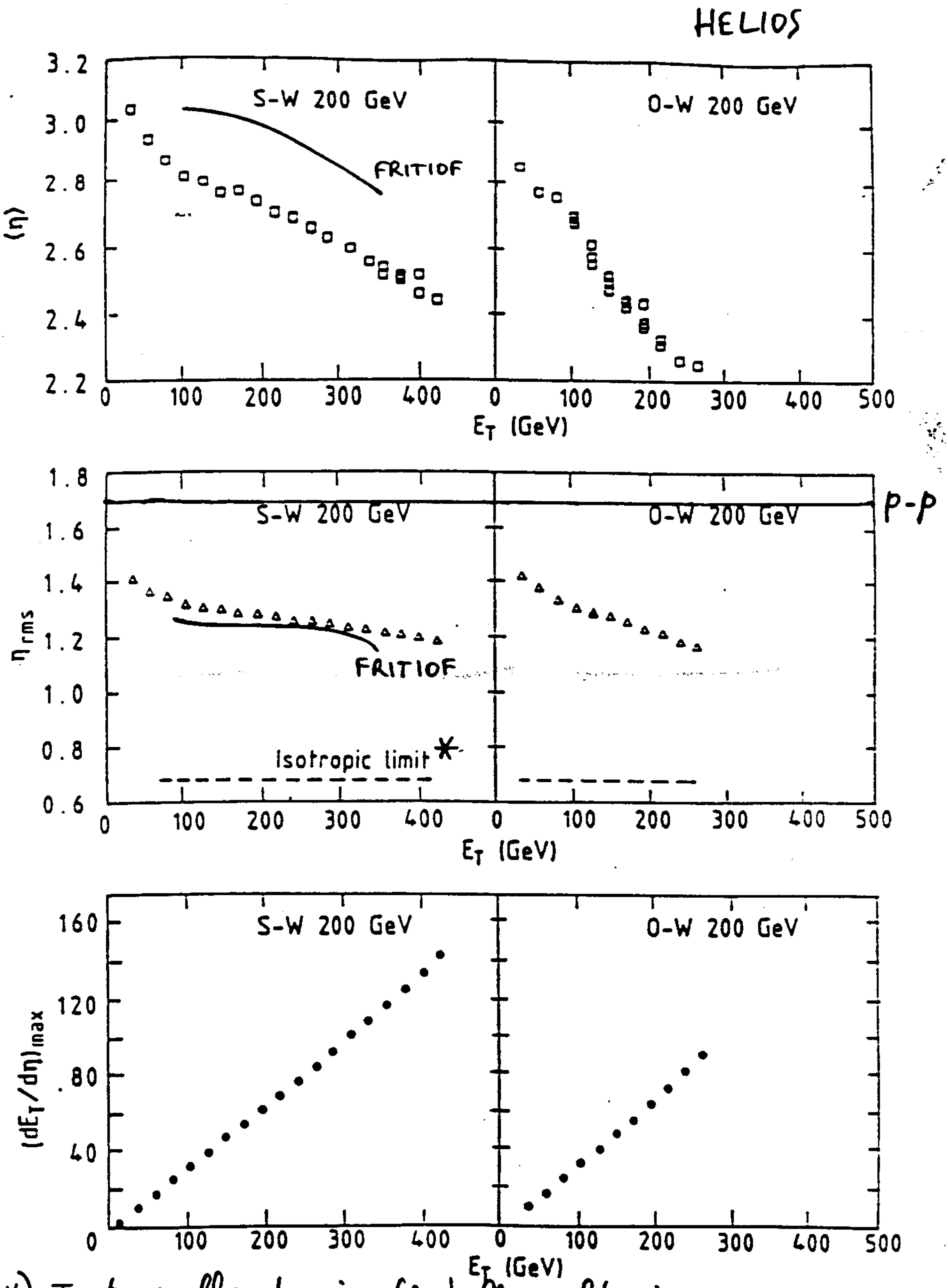
$dE_T/d\eta$

HELIOS



— — — IRIS at same $d\sigma/dE_T$ value as data

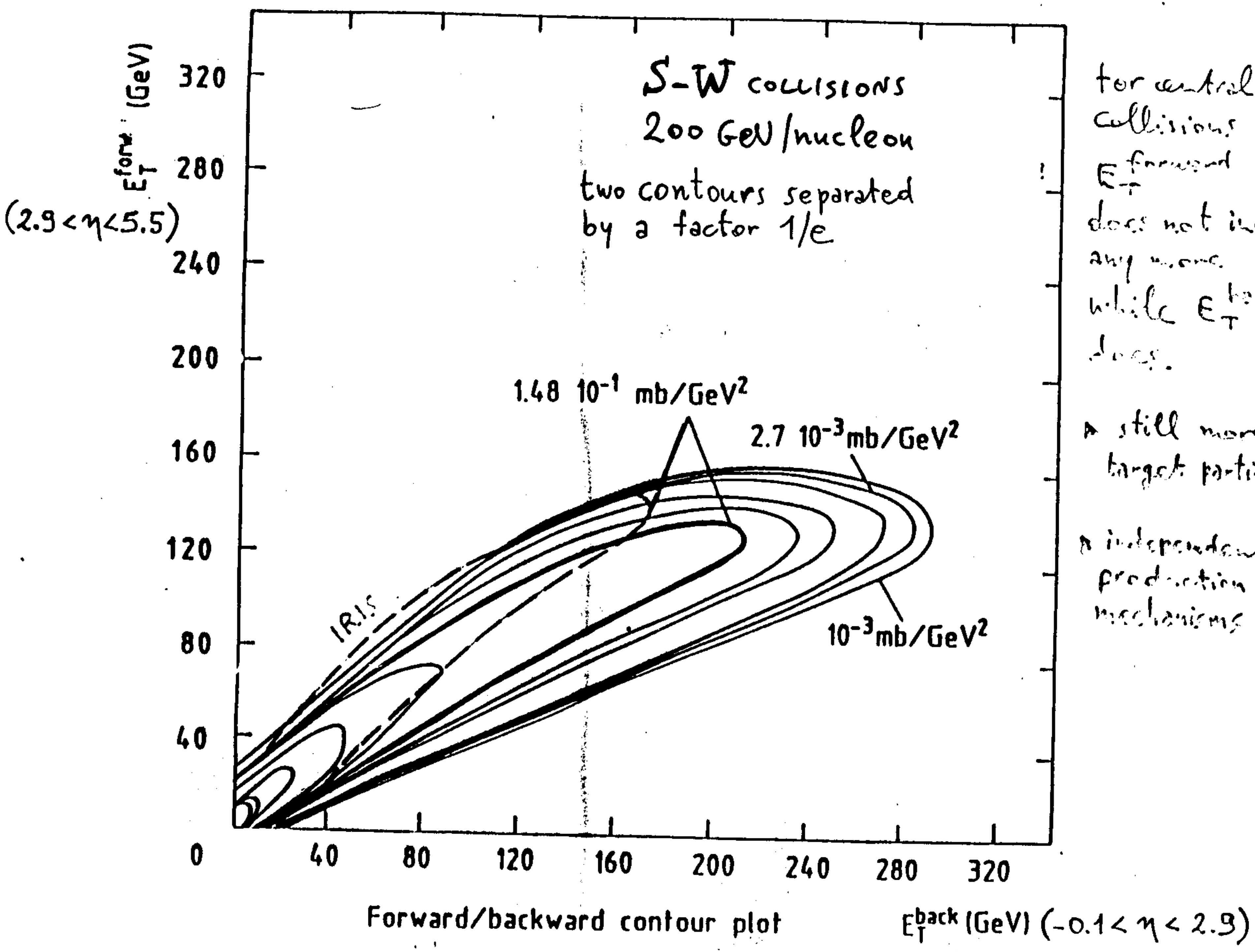
MOMENTS OF $dE_T/d\eta$ DISTRIBUTIONS:



*) Isotropically decaying fireball would give :

$dE_T \; = \; 1 \; \Rightarrow \; \eta \; = 0.7$

HELIOS



Forward/backward contour plot

for central collisions $E_T^{forward}$ does not increase any more while E_T^{back} does.

→ still more target participants]

→ independent production mechanisms ?

EVALUATION OF STOPPING AND ENERGY DENSITY

- Stopping defined via observed E_T :

$$\mathcal{S} = \frac{E_T}{E_T^{max}}$$

where E_T^{max} is proportional to the available energy $E^{max} = E^{cm} - (A_P + A_T) m_N$ with a coefficient dependent on the assumed "fireball" kinematics :

$$E_T^{max} = \frac{\pi}{4} E^{max} \quad \text{isotropic fireball}$$

$$c\, E^{max} \quad (c < \pi/4) \quad \text{Landau fireball}$$

- **HELIOS** data on stopping fraction $\left\{ \begin{array}{l} E_T \text{ at } d\sigma/dE_T = 10^{-2}\ mb/GeV^{*} \\ E_T \text{ at } d\sigma/dE_T = 10^{-4} \times \text{PLATEA} \end{array} \right.$

BEAM ENERGY ↓	TARGET:	Al	Ag	W
^{16}O-60		0.7	0.8	0.9
^{16}O-200		0.5	0.6	0.7 0.88
^{32}S-200		0.45 0.56	0.55 0.84	0.65 0.88

* $dE_T/d\eta$ from isotropic firebal

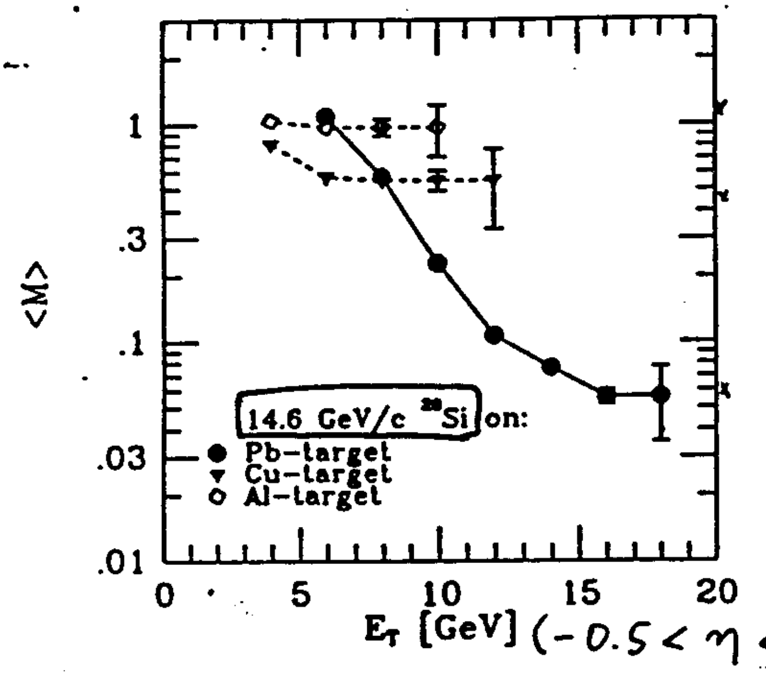
◆ $dE_T/d\eta$ from dat

- $\mathcal{S}_{FB}$ is probably an underestimate of $\mathcal{S}$ (Landau fireball is more realistic)
- stopping decreases with E_{beam} ($\mathcal{S} \sim 1$ at AGS energies, $10 \div 15$ GeV/nucleon) and increases with A_T
- nuclear transparency is not there !

BARYONS AND STOPPING

E814 $Y \geq 3$, $P_T \lesssim .25$ GeV/c
E814 PRELIMINARY

Average Multiplicity of Beam Rapidily Neutrons



BEAM RAPIDITY PROTONS GIVE SAME RESULT

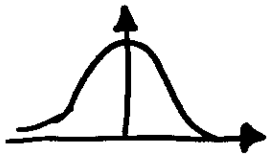
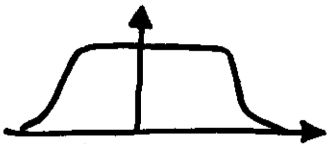
- DEFINING TRANSPARENCY AS:

$$T = \frac{\langle M_p \rangle + \langle M_n \rangle}{A_p}$$

$\boxed{\text{E814}}$ GETS $T = 1/350$ FOR Pb TARGET, WHICH CORRESPONDS TO A MEAN FREE PATH OF $\lambda = 2.4$ fm IN THE LABORATORY.

- AT CERN/SPS ENERGIES, NA35 AND WA80 OBTAIN (FROM BARYON DISTRIBUTIONS) INDICATIONS FOR LESS STOPPING THAN AT 14.6 GeV/N.

- evaluation of energy density ϵ is again "model" dependent:

MODEL	dN/dy	ENERGY DENSITY
ISOTROPIC FIREBALL	 $\sigma_y = 0.88$	$\epsilon_{FB} = \frac{\gamma_{cm} E_T}{V}$
LANDAU MODEL (LONGIT. EXPANSION)	 $\sigma_y \propto \ln\sqrt{s}$	
BJORKEN MODEL (ULTRARELATIVISTIC)	 plateau	$\epsilon_{BJ} = \frac{(dE_T/d\eta)_{max}}{\underbrace{\pi r_0^2 A_P^{2/3}}_{\perp\ \text{area}}\ \overset{\nwarrow \sim 1\ \text{fm/c}}{\tau}}$

- $\boxed{\text{HELIOS}}$ data, taking (arbitrarily) E_T at $\frac{d\sigma}{dE_T} = 10^{-2}$ mb/GeV:

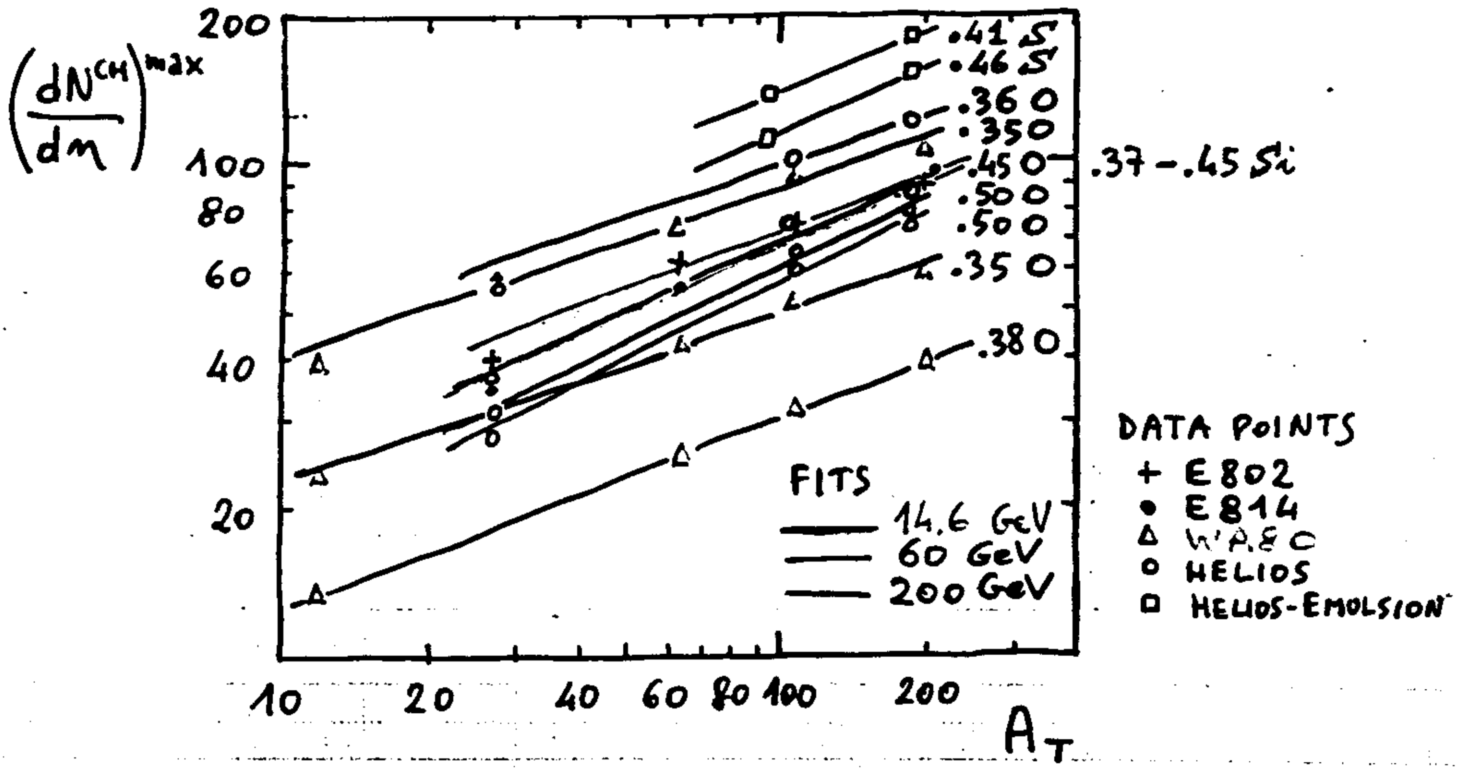
BEAM ENERGY ↓ / TARGET →	Al	Ag	W
$^{16}O - 60$	2.8 1.2	1.8 2.0	1.6 2.6
$^{16}O - 200$	7.6 1.6	5.1 2.6	4.6 3.3
$^{32}S - 200$	8.1 1.3	6.3 2.6	5.6 3.3

ϵ_{FB}
ϵ_{BJ} GeV/f

- large uncertainties, true $\epsilon \approx$ Landau?
- significant increase with E_{BEAM}
- increasing A_P is compensated (in ϵ_{BJ}) by increase of transverse area
- we are reaching (with the most extreme collisions) the hoped for values of ϵ !

PROJECTILE AND TARGET MASS DEPENDENCE

- PARAMETRIZE A_T - DEPENDENCE OF $(dN^{CH}/d\eta)_{max}$ AS A_T^{α}:



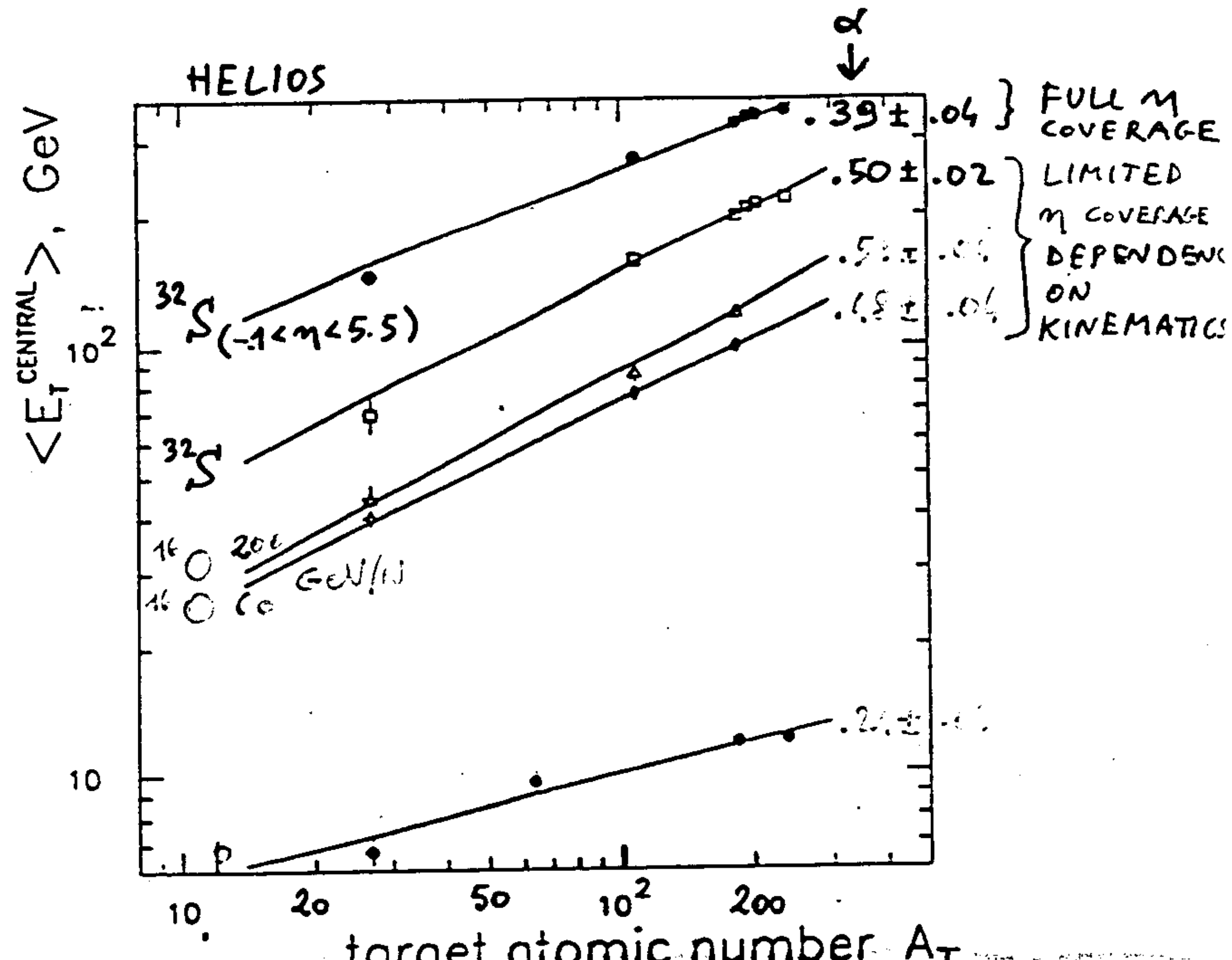
$\alpha \simeq 0.35 - 0.50$, WITH NO CLEAR DEPENDENCE ON BEAM ENERGY OR PROJECTILE.

▶ MODELS BASED ON NUCLEON - NUCLEON COLLISIONS PREDICT $\alpha = 0.33$, THE LARGER VALUES MIGHT INDICATE RESCATTERING EFFECTS.

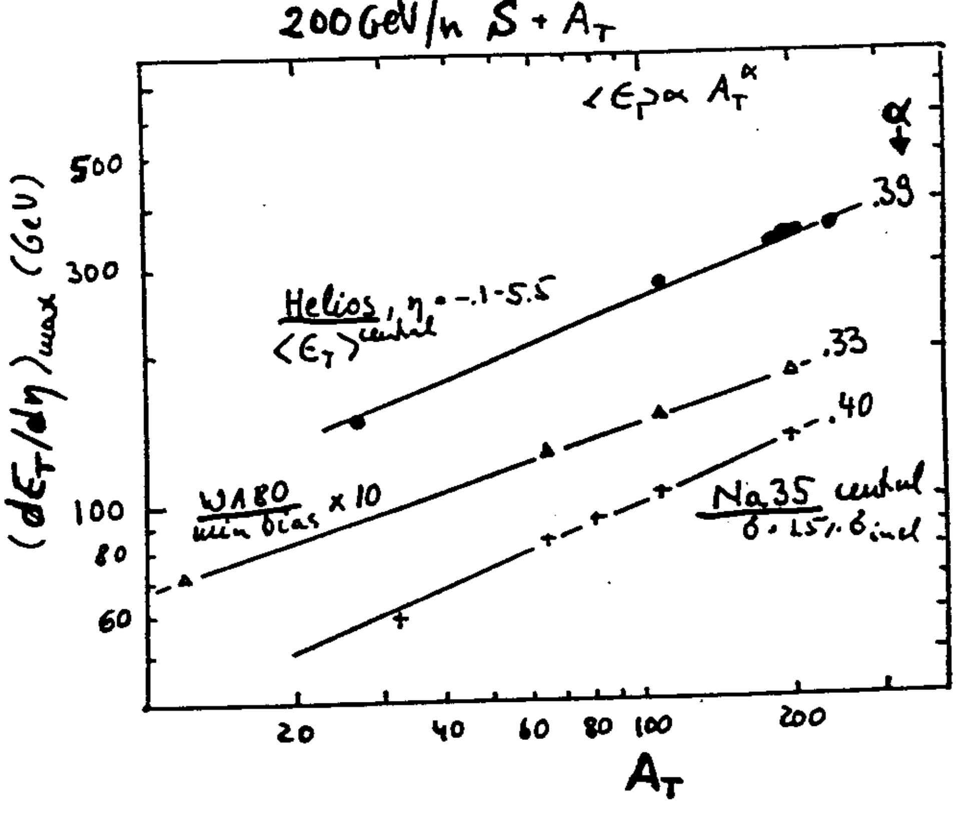
- E_T PRODUCTION VS. PROJECTILE MASS A_P: COMPARING ^{16}O AND ^{32}S ON HEAVY TARGETS AN INCREASE OF A FACTOR 1.62 - 1.80 IS OBSERVED.

▶ SCALING WITH $A_P^{2/3}$ (PROJECTILE TRANSVERSE AREA) WOULD GIVE A FACTOR 1.58, WHILE IF ALL OVERLAPPING NUCLEONS PARTICIPATE ONE GETS $A_P^{5/6}$ SCALING AT HIGH ENERGY, I.E. A FACTOR 1.78.

- E_T PRODUCTION VS. TARGET MASS A_T:



▶ INCOMPLETE STOPPING! FULL STOPPING WOULD GIVE E_T INDEPENDENT OF A_T FOR LARGE ENOUGH A_T.
FULL STOPPING PLUS HYDRODYN. EXPANSION PREDICTS $\alpha = 1/6$.



IV. P_T DISTRIBUTIONS & PARTICLE RATIOS

- P_T DISTRIBUTIONS ARE EXPECTED TO PROVIDE INFORMATION ON BOTH COLLECTIVE FLOW OF PARTICLES (FOLLOWING THERMALIZATION) AND THE EQUATION OF STATE.

- THE INVARIANT CROSS-SECTION $E\, d^3\sigma/dp^3$ MAY BE WRITTEN (IGNORING THE y-DEPENDENCE):

$$\frac{1}{p_T}\frac{dN}{dp_T} \quad \text{OR} \quad \frac{1}{m_T}\frac{dN}{dm_T} \qquad (m_T^2 = p_T^2 + m^2)$$

FOR A THERMALIZED SYSTEM AT TEMPERATURE T:

$$\frac{1}{p_T}\frac{dN}{dp_T} \sim C\, m_T^{1/2} e^{-m_T/T}$$

$$\Rightarrow \frac{1}{m_T^{3/2}}\frac{dN}{dm_T} \sim C\, e^{-m_T/T}$$

IMPLYING THE <u>SAME</u> EXPONENTIAL DISTRIBUTION FOR <u>ALL</u> PARTICLES: m_T SCALING (CONCEPT FROM pp COLLISIONS).

- A COLLECTIVE FLOW (E.G. TRANSVERSE EXPANSION FOLLOWING THE INITIAL LONGITUDINAL EXPANSION IN HYDRODYNAMICAL MODELS) WOULD BREAK THE EXPONENTIAL FORM, AND WOULD AFFECT MORE THE HEAVIER PARTICLES (THEY WOULD GET MORE MOMENTUM $p = mv\gamma$ FROM THE SAME COLLECTIVE VELOCITY v).

▶ IT IS <u>NOT</u> CLEAR THAT m_T SCALING $\Rightarrow$ THERMALIZATION, HOWEVER, SINCE IT APPLIES ALSO TO pp COLLISIONS WHERE THERMALIZATION IS DOUBTFUL.

E802

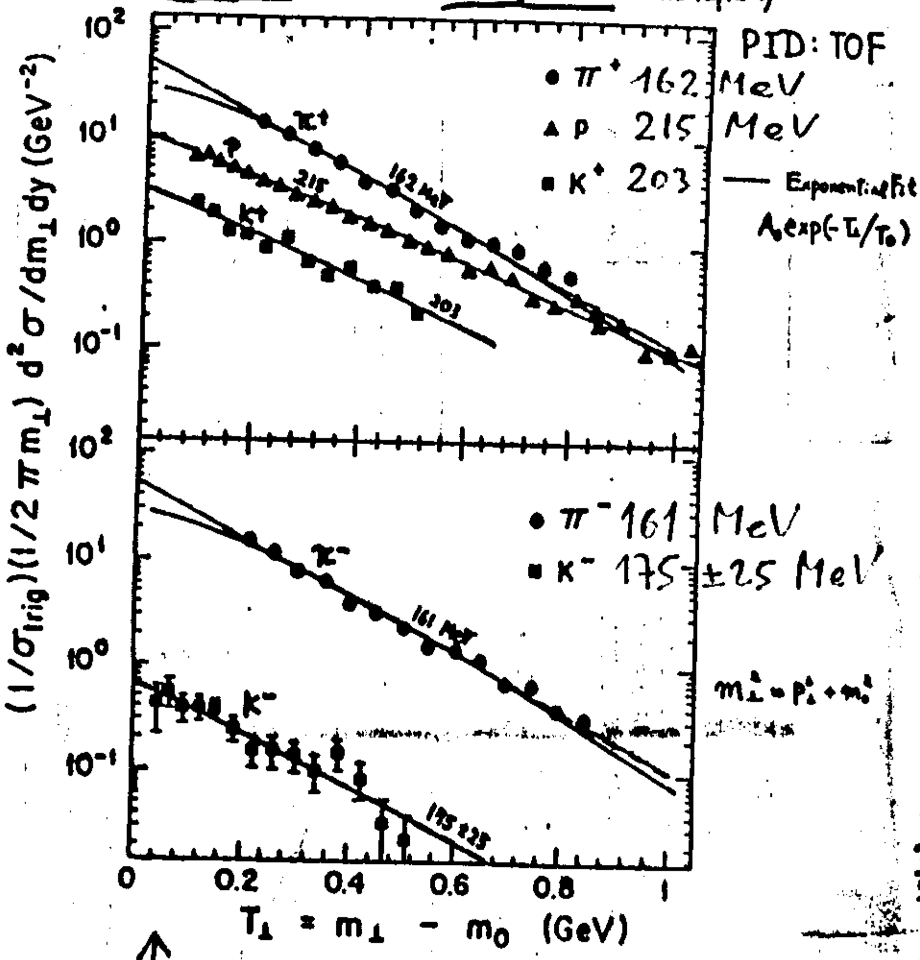
CENTRAL Si+Au

PRL64(90)249 ✓

14.6 A·GeV/c $^{28}Si + ^{197}Au$

Central Trigger $1.2 < y < 1.4$: Mid rapidity

PID: TOF



↑

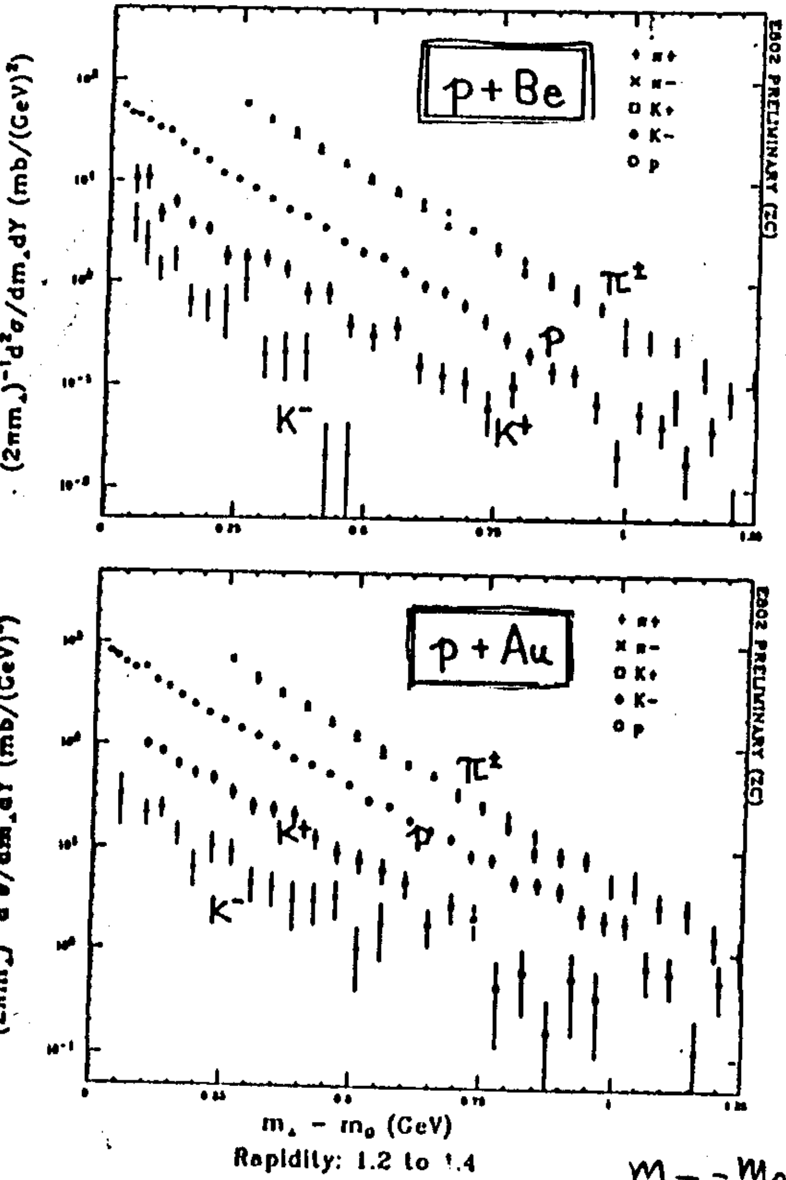
$m_T - m_0$

m_T slopes are not the same !

Particle spectra from 14.6 GeV/c p+Be, p+Au (min. bias)

Extended PID : TOF + GASČ

(π/K sep up to 5 GeV/c)



m_T slopes are all ~ same like in p-p

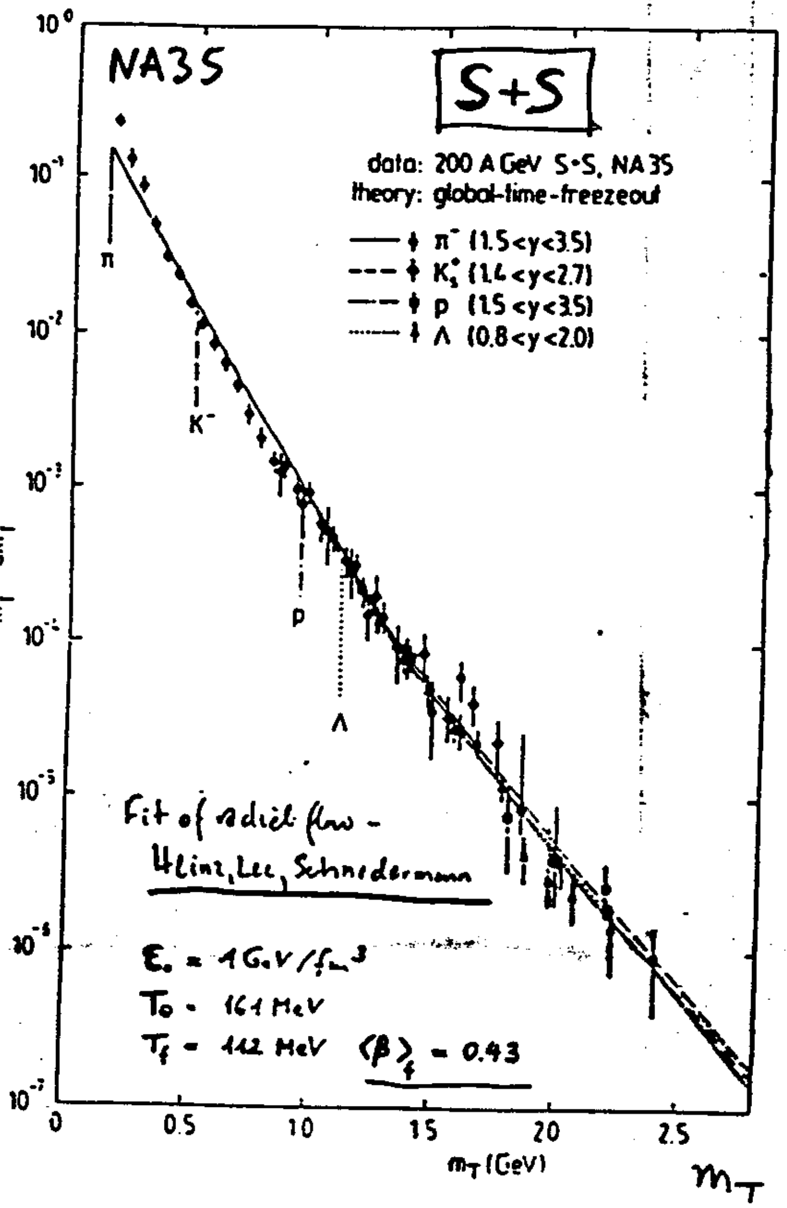
$T \sim 150$ MeV

protons maybe flatter ?

$m_T - m_0$

- MODELS INCLUDING RADIAL COLLECTIVE FLOW AFTER FREEZE OUT ARE COMPATIBLE WITH DATA

$$\frac{1}{m_T^{3/2}} \frac{dN}{dm_T}$$



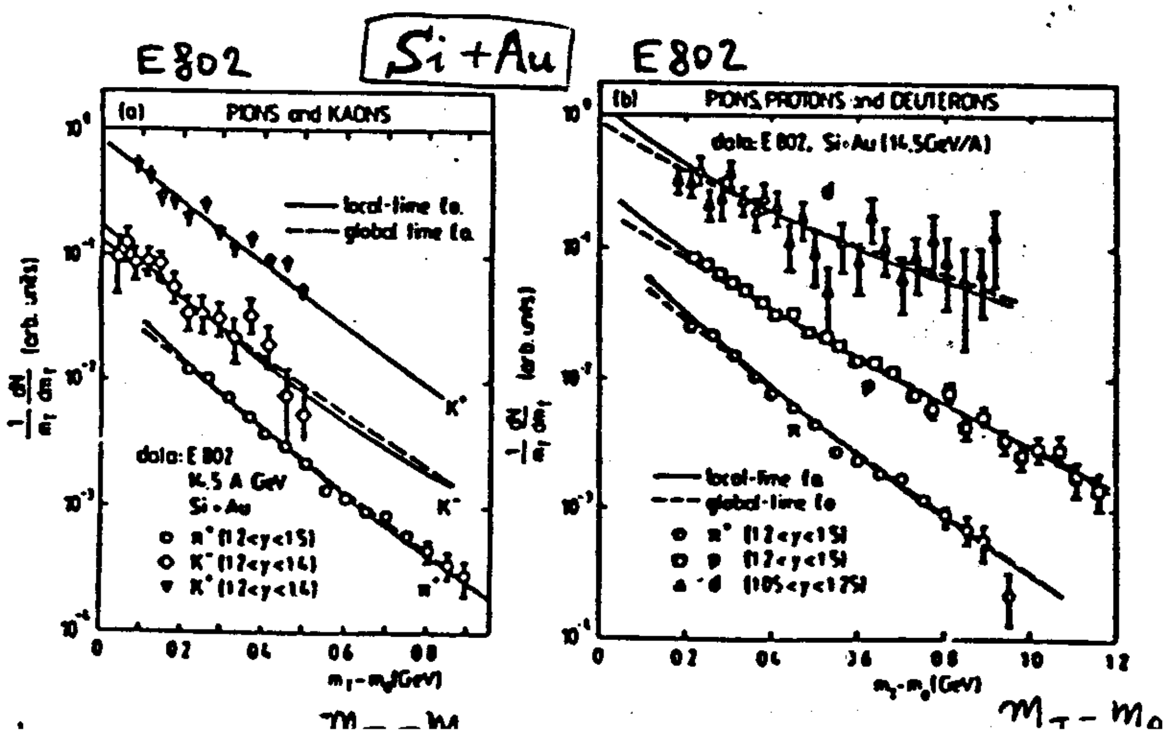
Fit of radial flow - Heinz, Lee, Schnedermann

$E_0 = 1\,GeV/fm^3$

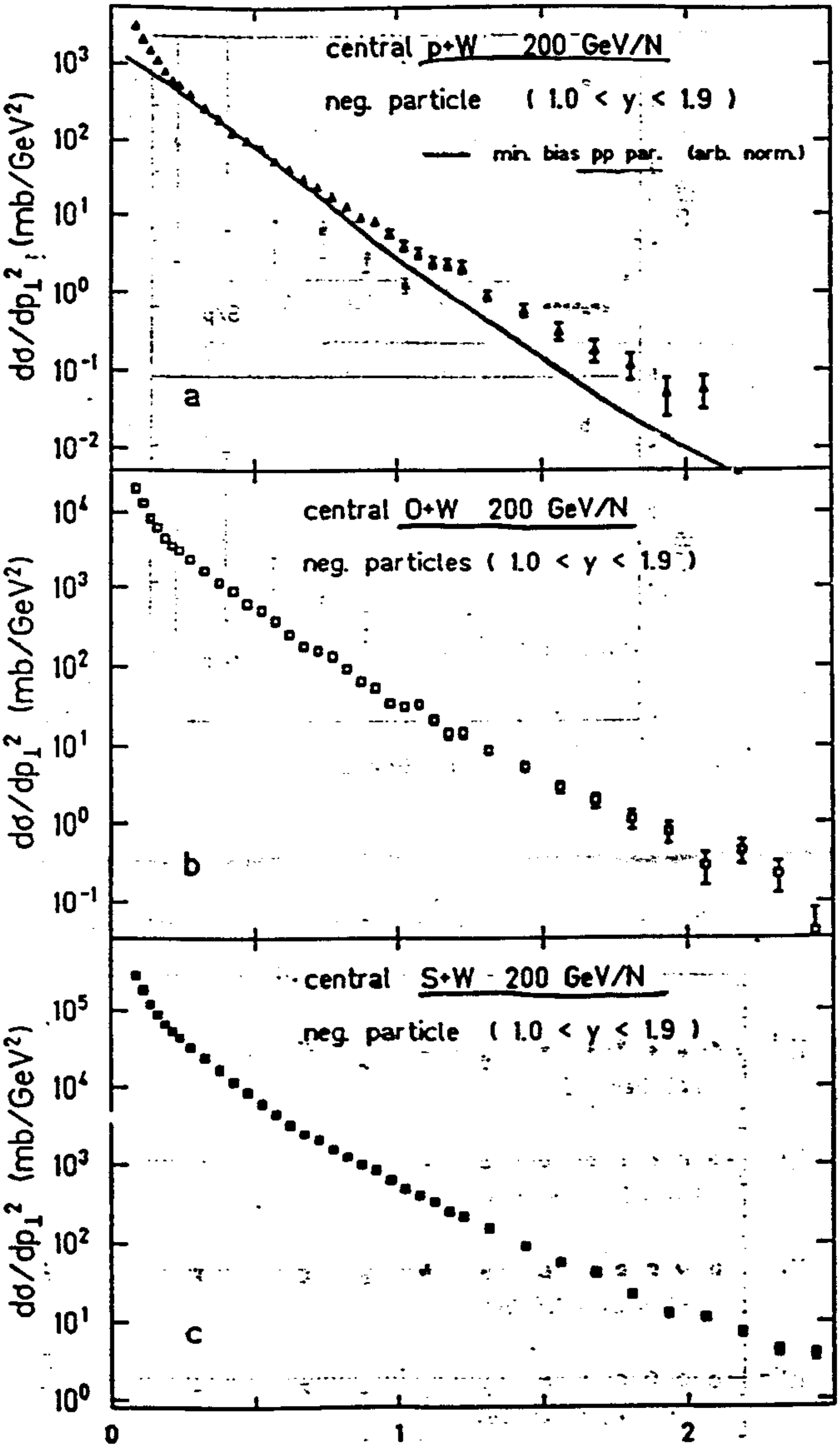
$T_0 = 161\,MeV$

$T_f = 142\,MeV$ $\langle\beta\rangle_f = 0.43$

pions have curvature at low m_T; other particles follow an exponential.



HELIOS
NEGATIVE PARTICLES



low $p_\perp$ excess
mysterious

high $p_\perp$ (>1G
excess w.r.
is well-kn
Cronin effect
$\frac{dN}{dp_\perp^2} \propto A^{n(p_\perp)}$
interpreted as
PARTONIC MULTI
SCATTERING
or
RESCATTERING
WITH SPECTATORS

target: resatt., Δ, N* decays
central: collective exp.
cold QGP

- HYDRODYNAMICAL CALCULATIONS FOR HEAD-ON COLLISIONS OF EQUAL-A NUCLEI

KATAJA ET AL.

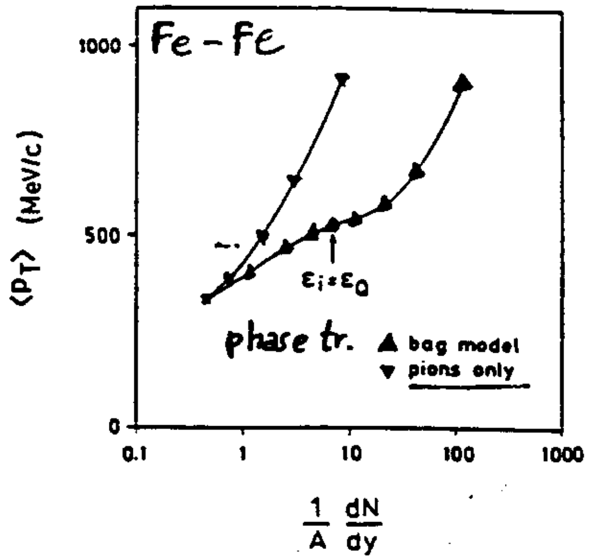


FIG. 6. Average p_t with and without phase transition. In the latter case the matter is assumed to be produced as hot pion gas. At the point indicated by $\epsilon=\epsilon_Q$, pure plasma state at T_c is reached at τ_c.

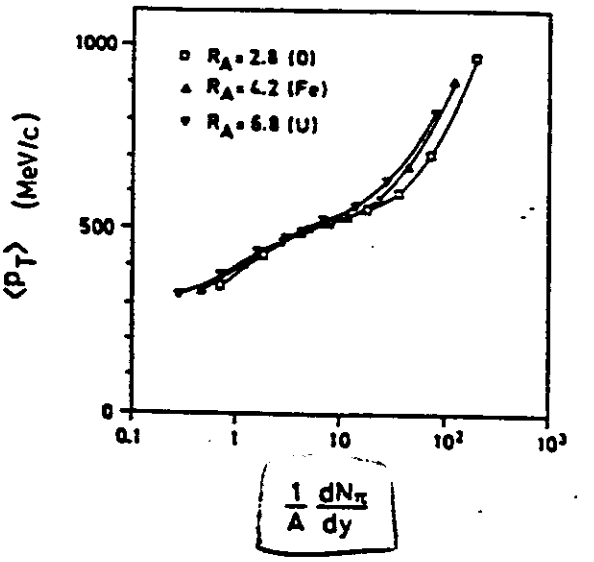
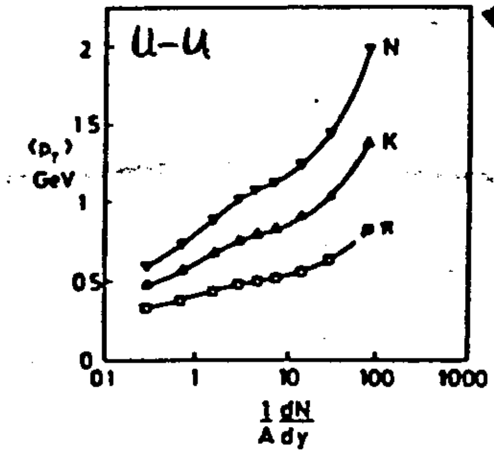


FIG. 7. Average p_t as a function of normalized multiplicity $(1/A)dN/dy$ for U-U ($R_A=6.8$), Fe-Fe ($R_A=4.2$), and O-O ($R_A=2.8$ fm) collisions.

APPROXIMATE SCALING VS. A IF dN/dy IS DIVIDED BY A.



STRONGER ⟨$p_\perp$⟩ GROWTH FOR HEAVIER PARTICLES.

- INFORMATION ON THE EQUATION OF STATE IS OBTAINED BY PLOTTING ⟨p_T⟩ (RELATED TO TEMPERATURE) VS dN/dy (RELATED TO ENTROPY DENSITY).
- THE QGP (WITH A BAG MODEL EQUATION OF STATE) PRODUCES LOWER ⟨p_T⟩ PARTICLES THAN A PION GAS, FOR THE SAME RAPIDITY DENSITY dN/dy.
- THE EXPANSION WILL INCREASE ⟨p_T⟩ BEYOND THERMAL VALUES, SOFTENING THE DIFFERENCE BETWEEN QGP AND HADRON GAS.

E-735 (FNAL) $\bar{p}p$ at $\sqrt{s} = 1.8$ TeV

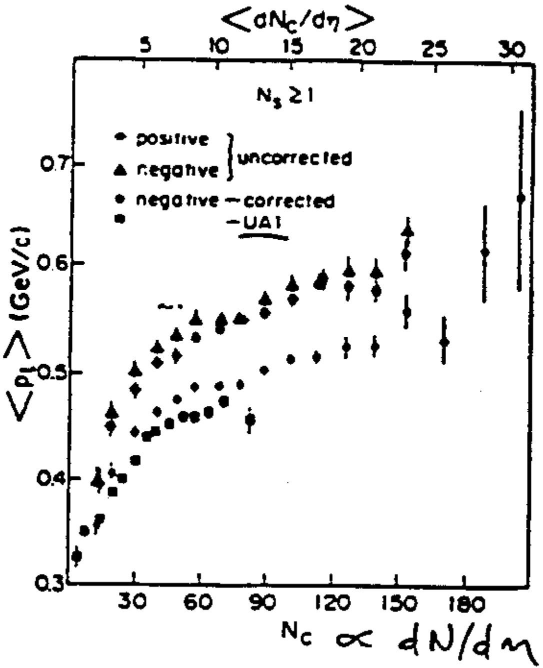


FIG. 4. $\langle p_t \rangle$ as a function of N_c and $\langle dN_c/d\eta \rangle$ for all positive tracks and all negative tracks averaged over the interval 0.15 GeV/c $< p_t <$ 3.0 GeV/c. The corrected $\langle p_t \rangle$ of negative particles includes unobserved particles with $p_t <$ 0.15 GeV/c (see text). The last few uncorrected data points are omitted for clarity. The UA1 data (Ref. 5) are from $\sqrt{s}$ = 540 GeV/c.

plateau = mixed phase ?

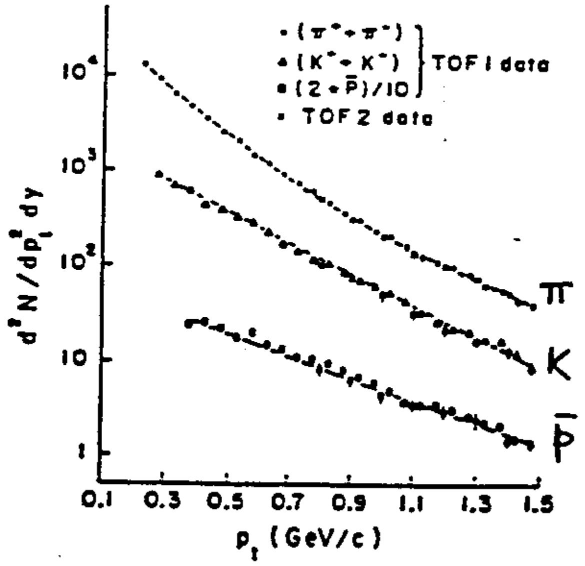


FIG. 1. Plot of inclusive d^2N/dp_t^2dy as a function of p_t for pions, kaons, and antiprotons. The particles are mass identified using two independent hodoscopes, TOF1 and TOF2 (see text), and the results from both detectors are shown as a consistency check. The curves shown correspond to fits (described in the text) in the regions $0.2 < p_t < 1.5$ GeV/c (pions), $0.25 < p_t < 1.5$ GeV/c (kaons), and $0.35 < p_t < 1.5$ GeV/c (antiprotons).

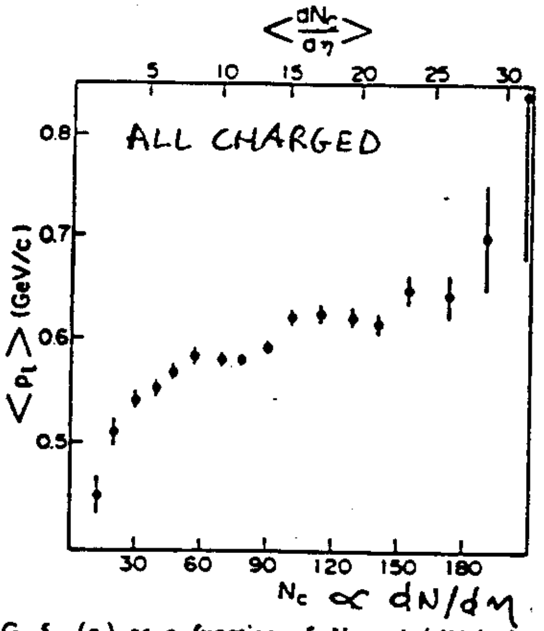


FIG. 5. $\langle p_t \rangle$ as a function of N_c and $\langle dN_c/d\eta \rangle$ for all charged particles with $N_s \geq 2$, averaged over the interval 0.15 GeV/c $< p_t <$ 3.0 GeV/c.

"plateau" values for $\langle p_T \rangle$

π ~ 375 MeV/c
K ~ 525
$\bar{P}$ ~ 625

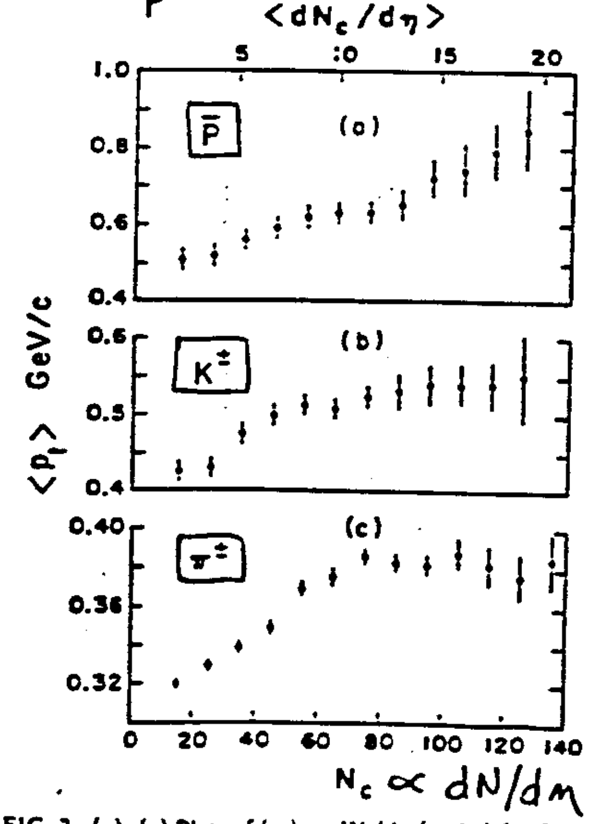
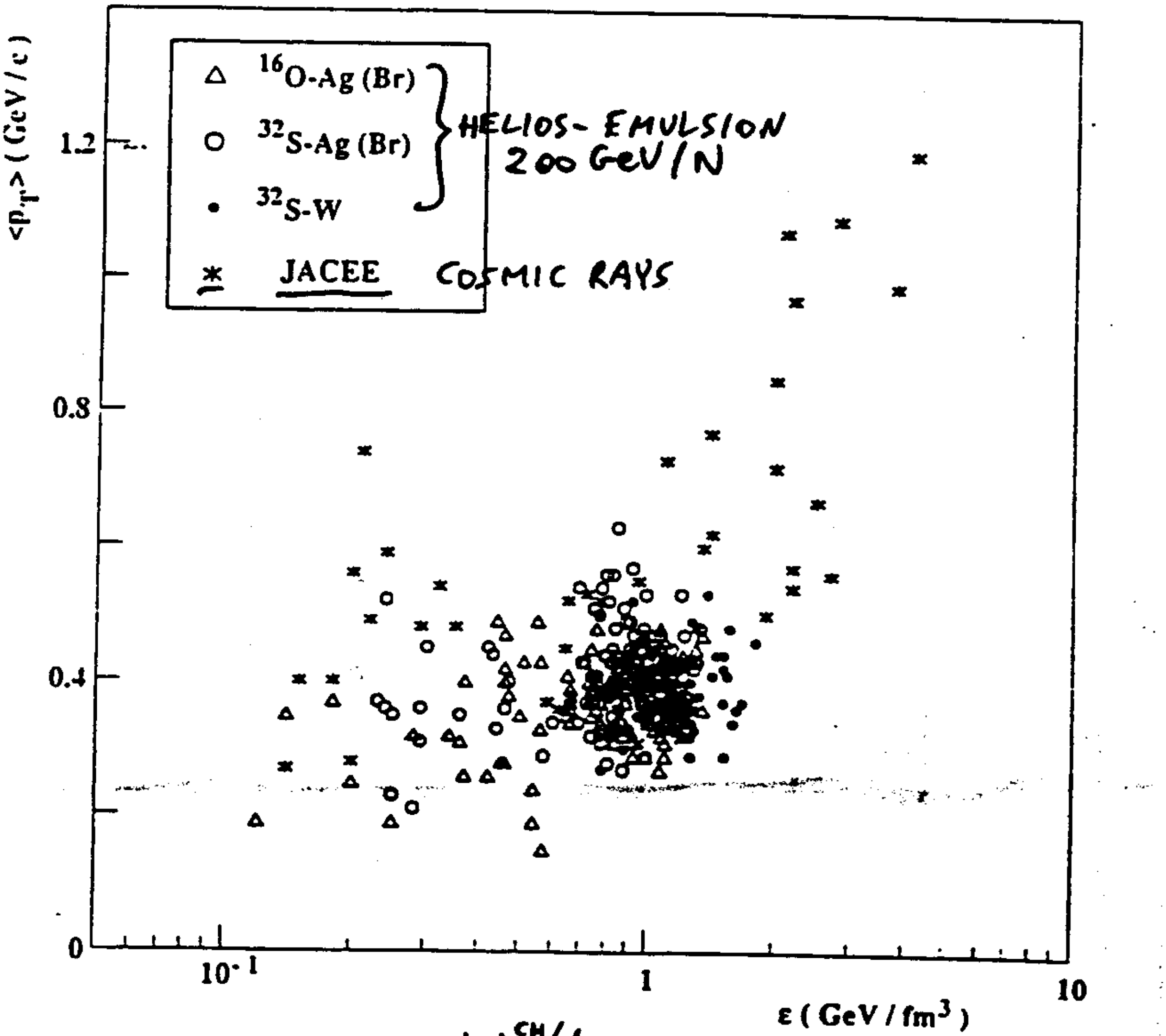


FIG. 2. (a)-(c) Plots of $\langle p_t \rangle$ vs $dN_c/d\eta$ (or N_c) for $\bar{p}$, kaons, and pions, respectively, for particles with $p_t < 1.5$ GeV/c.



$$\varepsilon = \frac{3}{2}\,\frac{\langle m_T\rangle \; dN^{ch}/d\eta}{\pi R_0^2 \, A_p^{2/3}\cdot 2\tau_0}$$

Bjorken formula

$$\langle m_T\rangle = \sqrt{\langle p_T\rangle^2 + m_\pi^2}$$

$$\tau_0 = 1 \text{ fm}/c$$

- HELIOS-EMULSION DATA DO NOT REACH AS HIGH ε AS JACEE DATA
- JACEE DATA SEEM TO RISE TOO RAPIDLY TO FIT QGP ; HOWEVER AN IDEAL PION GAS FIT GIVES UNREALISTICALLY HIGH TEMPERATURE.

PARTICLE RATIOS

- STRANGE PARTICLES ARE A VERY INDIRECT PROBE OF QGP SINCE THEY ARE FORMED RATHER LATE; A HADRON GAS HAS STRANGENESS ABUNDANCES VERY SIMILAR TO THE QGP (UNLESS THERE ARE NON-EQUILIBRIUM EFFECTS).

- IN ANY CASE, K/π RATIOS PROVIDE INFORMATION ABOUT THE CHEMICAL EQUILIBRIUM OF THE HADRON GAS, AND CAN BE USED TO EXTRACT THE TEMPERATURE AND BARYON DENSITY AT DECOUPLING.

- K^+/π^+ has been measured to increase gradually from pBe to pAu to central SiAu collisions (E802) while K^-/π^- does not increase much. → FIG.

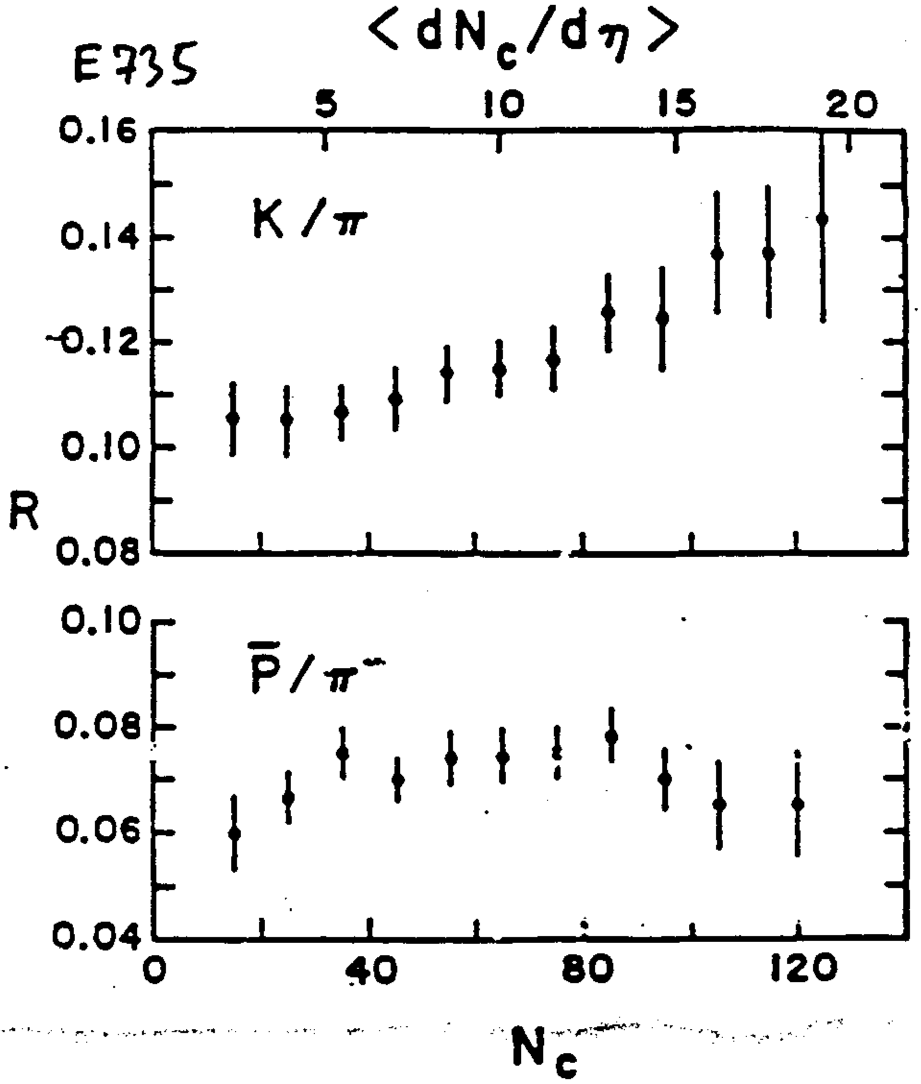
- These data are fitted by a Chemically Equilibrated Hadron gas model with $T \sim 105$ MeV and $n_B \sim 0.05$ baryons/fm^3 → FIG.

- At CERN energies, NA35 and WA85 have measured $\Lambda, \bar{\Lambda}, K^0_S$ production; WA85 also measured Ξ and Ξ production. Large ratios $\bar{\Lambda}/\Lambda$ and $\bar{\Xi}/\Xi$ have been reported:

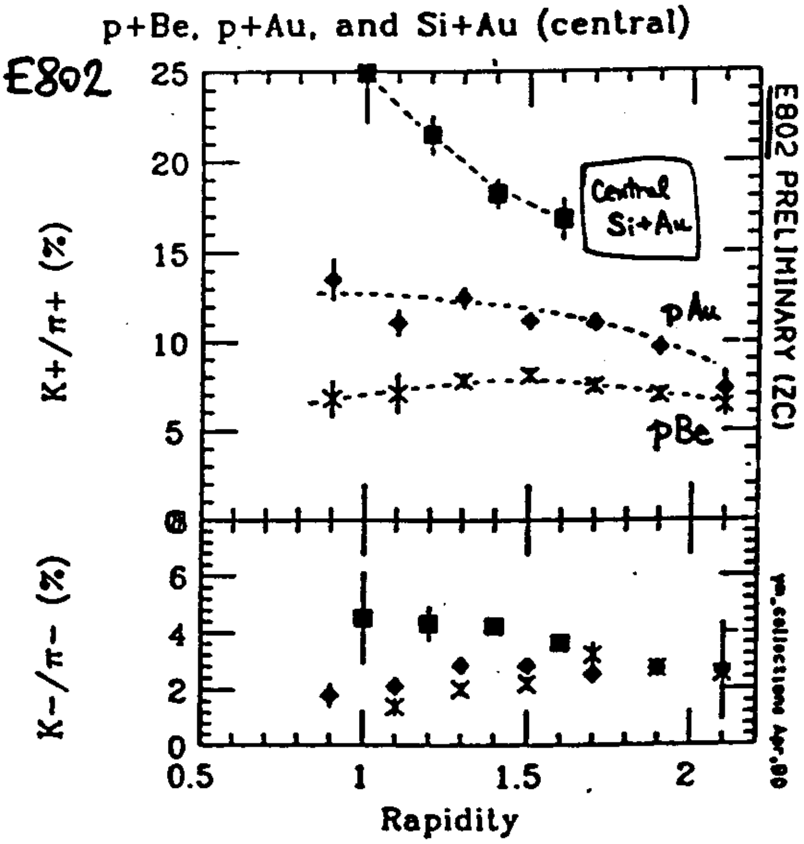
$$0.16 \leq \bar{\Lambda}/\Lambda \lesssim 0.39 \quad , \quad 0.36 \lesssim \bar{\Xi}/\Xi \lesssim 0.5$$

- The CERN data require higher values of parameters:
  $T \sim 180$ MeV, $n_B \sim 0.12$ baryons/fm^3
  in the CLEHG model.
  So far, a consistent picture is missing.

E735



E802



CENTRAL Si +Au

$\langle \frac{K^+}{\pi^+} \rangle = 19\ \%$

$\langle \frac{K^-}{\pi^-} \rangle = 3.6\%$

CLEYMANS QM '90 CLEHG Model $\left\{ \begin{array}{l} \text{resonance prod.} \\ \text{baryon repulsion} \end{array} \right.$

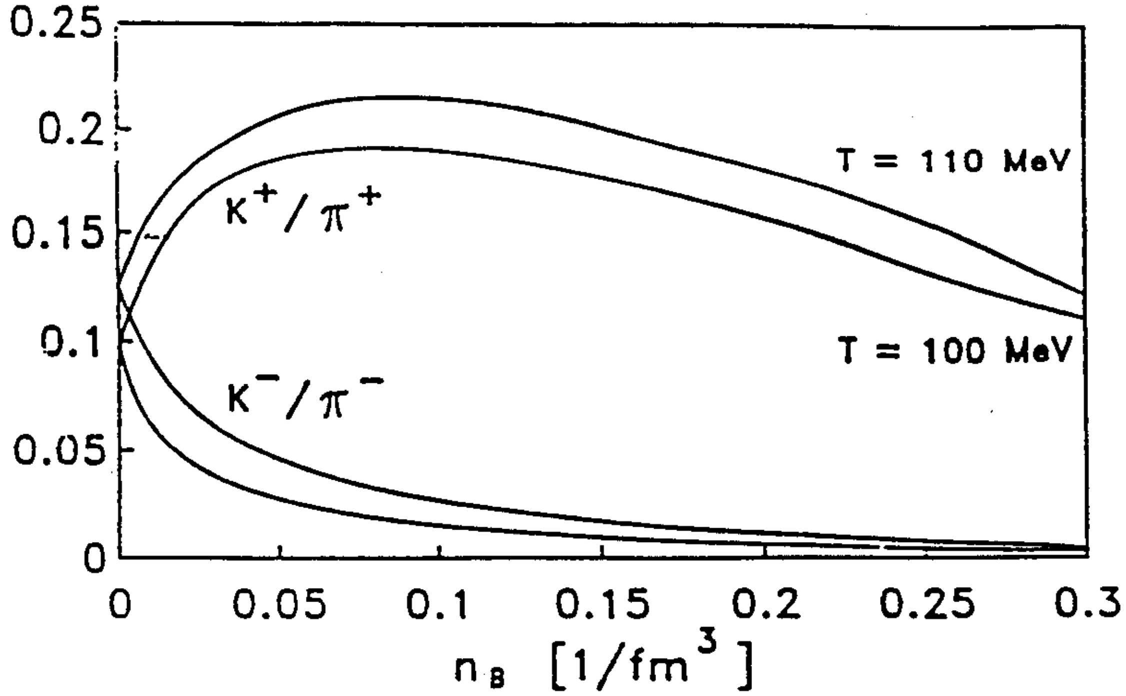


Figure 4: Dependence of the K/π ratios on the baryon density for different values of the temperature T.

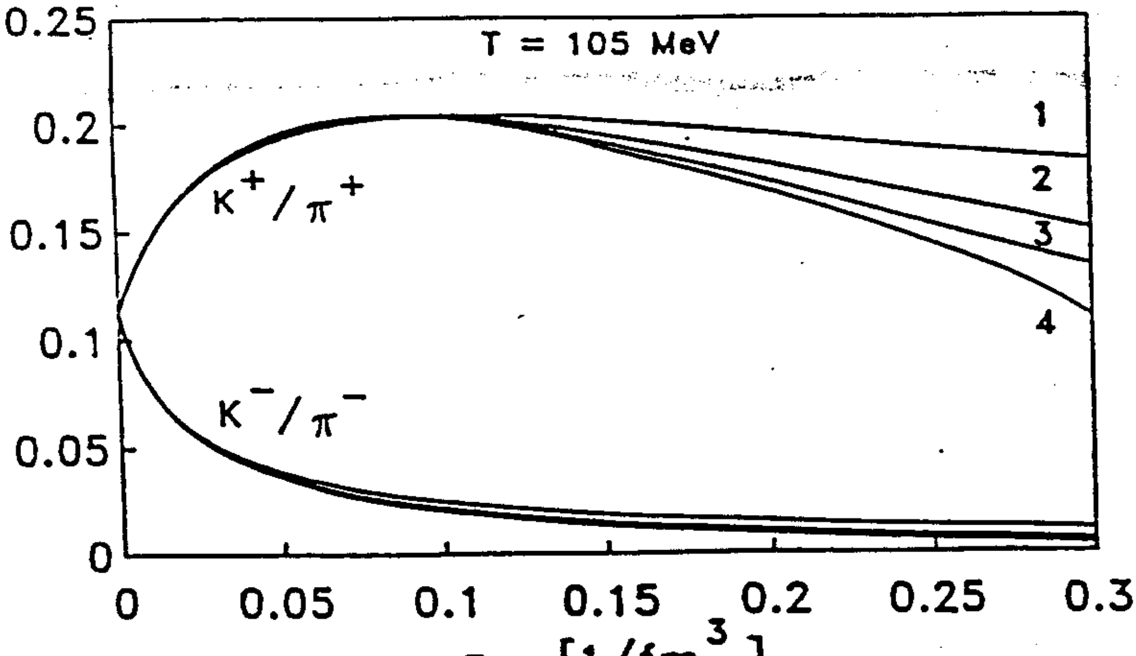


Figure 5: Dependence of the K/π ratios on different choices for the volume corrections : no corrections (1), purely geometric (2), depending on the energy density (3) and on the baryon density (4).

basic idea: $K^+/\pi^+ \sim \frac{\bar{s}u}{\bar{d}u} \sim \frac{\bar{s}}{\bar{d}} \sim \frac{e^{-m_s/T}}{e^{-\mu/T}}$ μ = chemical potential

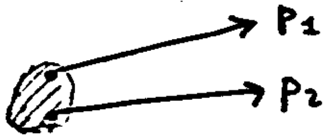
$K^-/\pi^- \sim \frac{e^{-m_s/T}}{e^{\mu/T}}$

[illegible] (by increasing n_B)

V. PION INTERFEROMETRY

- PRINCIPLE: WHEN 2 IDENTICAL BOSONS (E.G., 2 PIONS) ARE DETECTED, THE BOSE-EINSTEIN CORRELATION IN 4-MOMENTUM SPACE HAS A MAGNITUDE INVERSELY PROPORTIONAL TO THE SIZE OF THE SOURCE IN COORDINATE SPACE. ONE HAS TO MEASURE:

$$C_2(p_1,p_2)=\frac{N_2(p_1,p_2)}{N(p_1)\,N(p_2)}$$



- PRACTICAL DIFFICULTIES:
  - i) RESONANCES
  - ii) FINAL STATE INTERACTIONS (NEUTRAL BOSONS ARE BETTER!) → GAMOW CORRECTION
  - iii) BACKGROUND → USE EVENT MIXING TO ESTIMATE IT
  - iv) SPACE-TIME GEOMETRY OF COLLISION → USE MODELS

- THE SIMPLEST MODEL IS A SOURCE DESCRIBED BY GAUSSIANS SEPARABLE IN SPACE AND TIME:

$$C_2(Q_T,Q_L)=1+\lambda\exp(-Q_T^2R_T^2/2)\exp(-Q_L^2R_L^2/2)$$

WITH Q_L (Q_T) = LONGITUDINAL (TRANSVERSE) MOMENTUM DIFFERENCE, λ = CHAOTICITY PARAMETER, R_L (R_T) = LONGITUDINAL (TRANSVERSE) SOURCE SIZE.

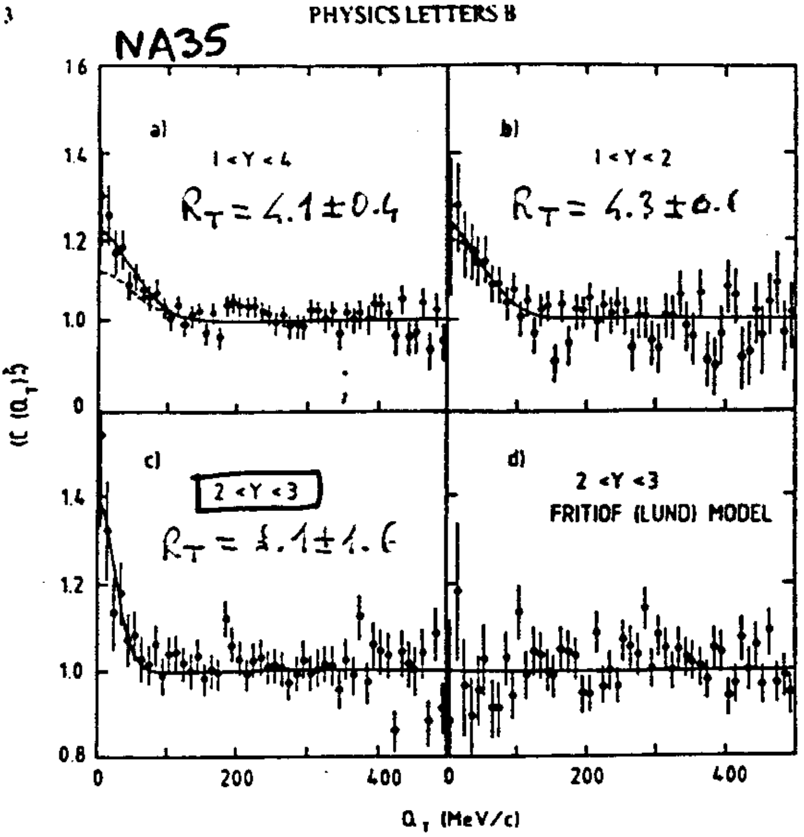
- NA35 RESULTS INDICATE AN INCREASE OF R_T AND R_L FOR π^- COMING FROM THE CENTER-OF-MASS REGION; R_T HAS VALUES OF MORE THAN TWICE THE TRANSVERSE PROJECTILE SIZE.

  THIS WOULD INDICATE A LARGE-RADIUS, NEARLY SPHERICAL THERMALIZED SOURCE IN THE CENTRAL REGION.

$^{16}O + Au$
200 GeV/N

105 central events

($E_{ZDC} < 300$ GeV)



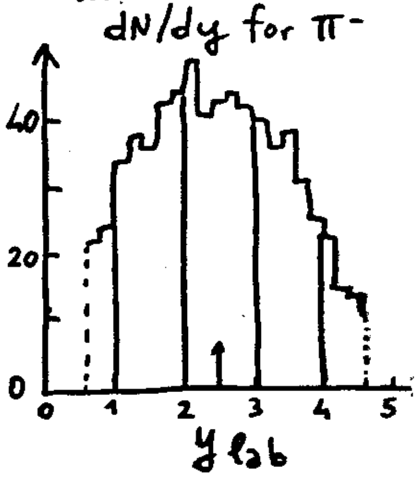
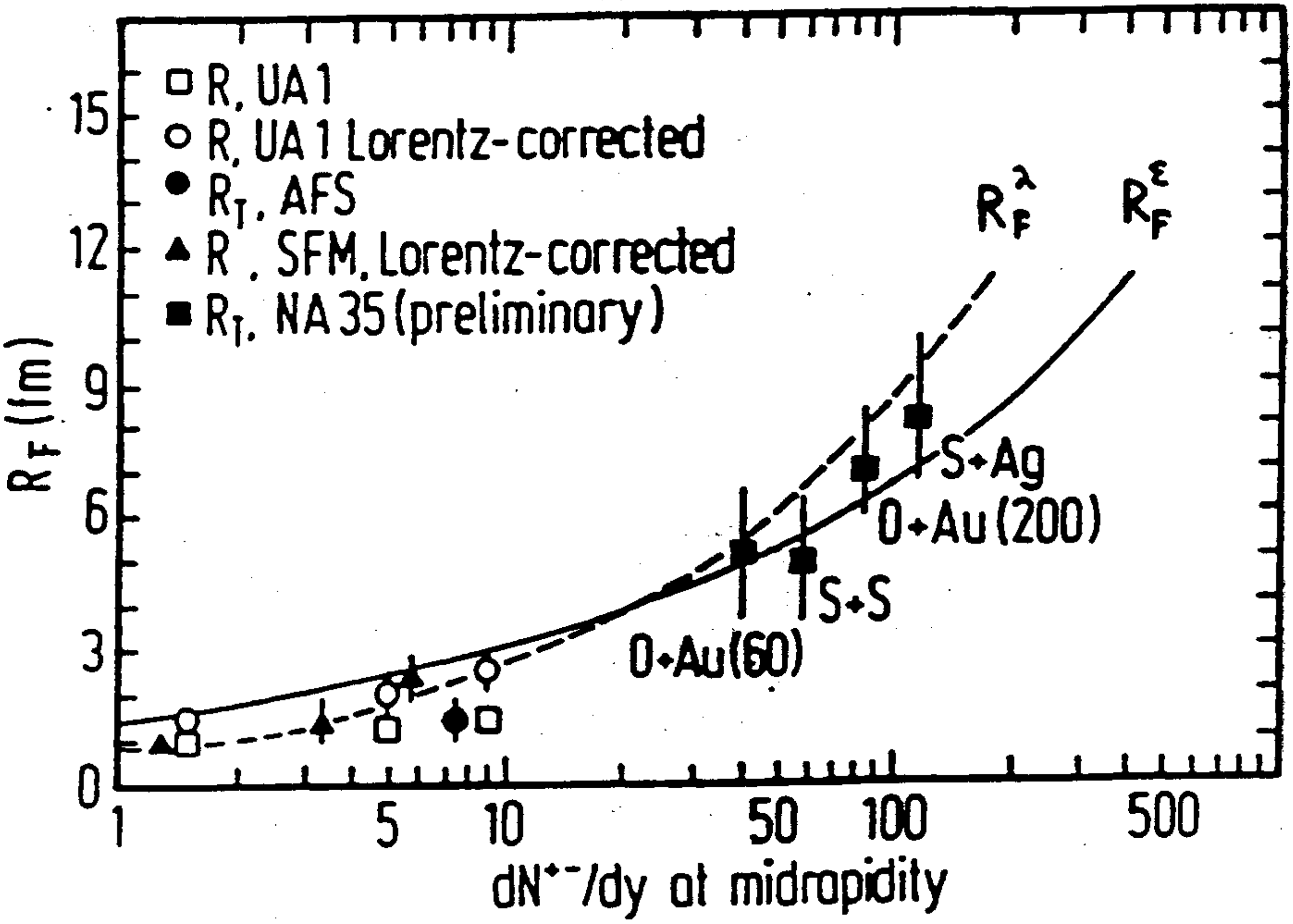


Fig. 2. Correlation function projected on to the Q_T-axis (for pairs with $Q_L < 100$ MeV/c) for different rapidity intervals: (a) $1 < y < 4$, (b) $1 < y < 2$, and (c) $2 < y < 3$, data; (d) $2 < y < 3$, Fritiof calculation. The projected gaussian fit is shown (solid curve) for each case, and in (a) the dashed curve shows the fit to the non-Gamow-corrected correlation function.



VI. DILEPTONS

KAJANTIE et al.

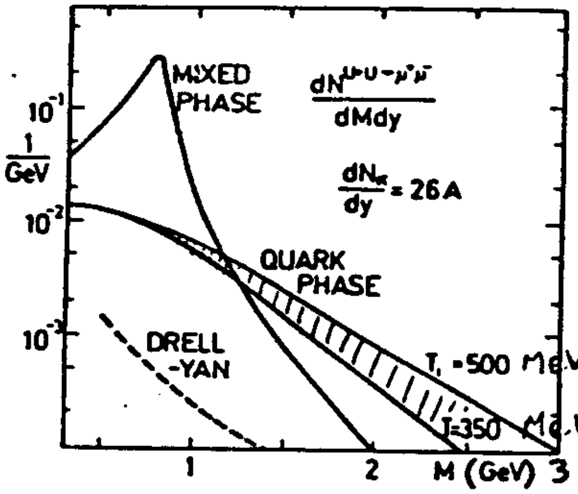


Figure 11 Mass distribution of dileptons at $y \approx 0$ from two flows with the same dN_π/dy but different T_i.

U+U central collisions most favourable case!

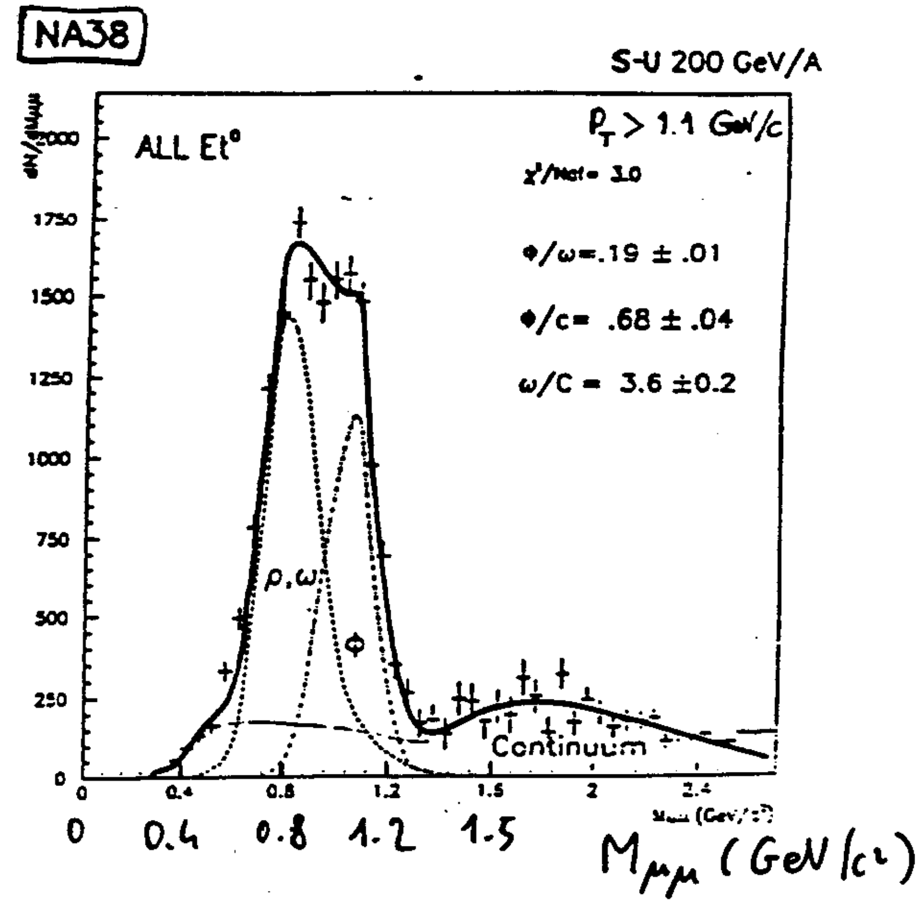
$T_c = 200$ MeV

- DILEPTONS ARE EXPECTED FROM THE QGP PHASE WITH $1 \lesssim M \lesssim 3$ GeV (RATE $\propto (dN^\pi/dy)^2$), AND FROM THE MIXED PHASE WITH $M \approx 1$ GeV AFTER THE MATTER HAS COOLED DOWN TO T_c.

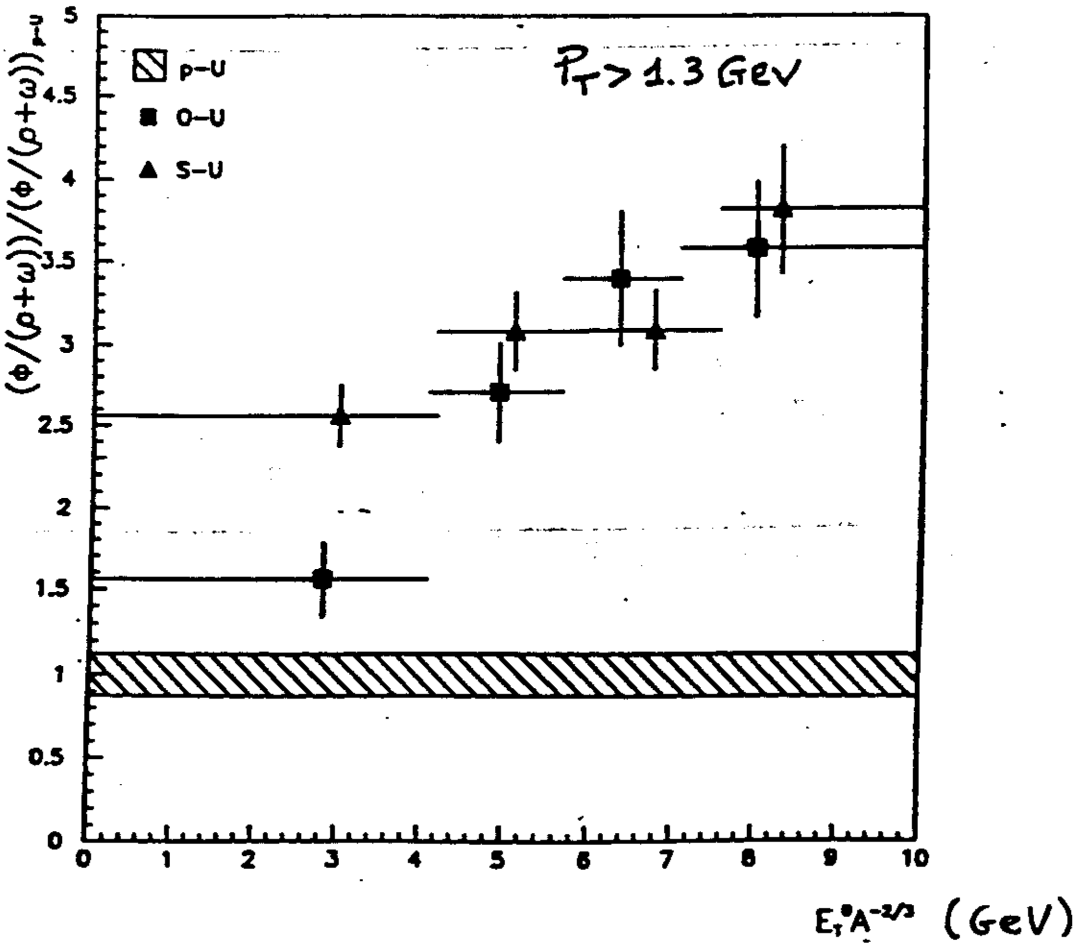
- NO EVIDENCE HAS BEEN REPORTED SO FAR WITH ^{16}O AND ^{32}S PROJECTILES, BUT DATA ARE STILL TOO PRELIMINARY

- NA38 FINDS AN ENHANCEMENT OF ϕ PRODUCTION W.R.T. ρ, ω IN O-U, S-U COLLISIONS (COMPARED TO p-U COLLISIONS). → FIG.

- THE ENHANCEMENT HAS BEEN INTERPRETED QUANTITATIVEL BY POSTULATING THAT THE ϕ ONLY REACHES CHEMICAL EQUILIBRIUM IN DENSE NUCLEAR MATTER (MORE RESCATTERING), WHILE THE ρ AND ω MESONS REACH ALWAYS CHEMICAL EQUILIBRIUM, BEING MADE OF LIGHT u, d QUARKS (Koch, Heinz and Pišút).


NA38
S-U 200 GeV/A
$P_T > 1.1$ GeV/c
ALL Et°
χ^2/Ndf = 3.0
φ/ω=.19 ± .01
φ/c= .68 ± .04
ω/C = 3.6 ±0.2
dN/dM
0
250
500
750
1000
1250
1500
1750
2000
ρ,ω
φ
Continuum
0
0.4
0.8
1.2
1.6
2
2.4
0
0.4
0.8
1.2
1.5
$M_{\mu\mu}$ (GeV/c²)

φ/(ρ+ω) RATIO


(φ/(ρ+ω))/(φ/(ρ+ω))$_{p-U}$
$P_T > 1.3$ GeV
▨ p–U
■ O–U
▲ S–U
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
1
2
3
4
5
6
7
8
9
10
$E_T^0 A^{-2/3}$ (GeV)

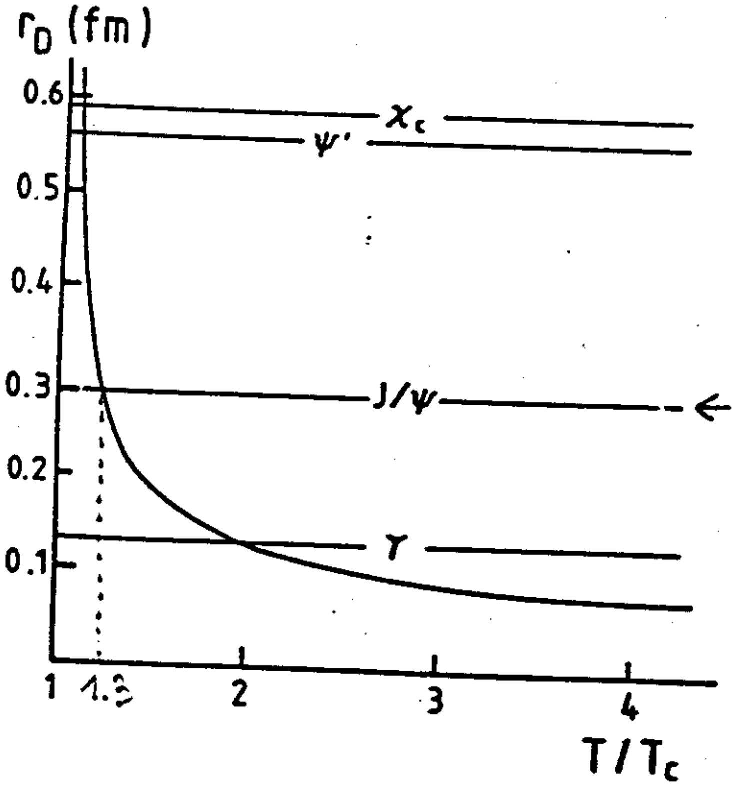
J/ψ SUPPRESSION IN QGP (Matsui & Satz, 1986)

- DECONFINEMENT IS A CONSEQUENCE OF COLOR CHARGE SCREENING, CHANGING THE VACUUM POTENTIAL $V_0(r)$ OF A $q\bar{q}$ PAIR INTO:

$$V(r) = V_0(r)\, e^{-r/r_D} \qquad (r_D = \text{Debye radius})$$

- BOUND STATES OF HEAVY QUARKS ($c\bar{c}$, $b\bar{b}$), HAVING A SMALL BOHR RADIUS, SURVIVE INSIDE QGP UNLESS T IS SUCH THAT $r_D < r_{Bohr}$
- IF QGP IS FORMED, $c\bar{c}$ ($b\bar{b}$) PAIRS "FLY APART" AND CANNOT COMBINE INTO J/ψ (Υ) UNTIL HADRONIZATION, WHEN THE CHANCE OF FINDING A c (b) PARTNER IS LOWER.

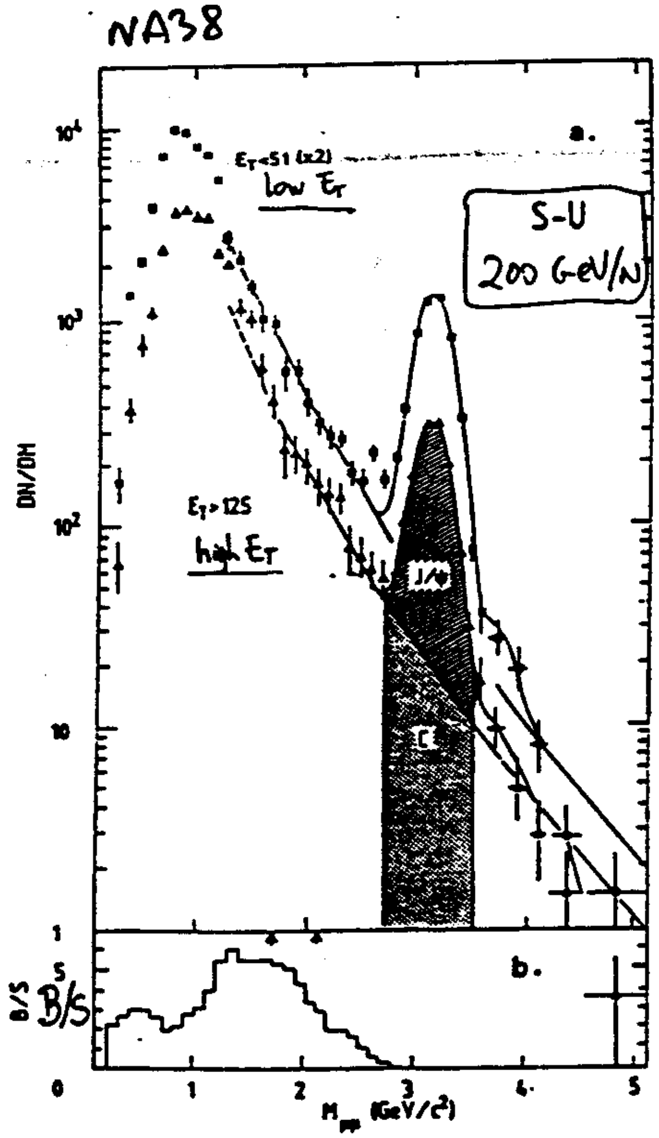
⇒ J/ψ PRODUCTION SHOULD BE SUPPRESSED IN CENTRAL COLLISIONS COMPARED TO PERIPHERAL COLLISIONS, AND MORE SUPPRESSED AT LOW P_T(J/ψ) SINCE AT HIGH P_T THE $c\bar{c}$ PAIR CAN EASILY ESCAPE THE PLASMA.

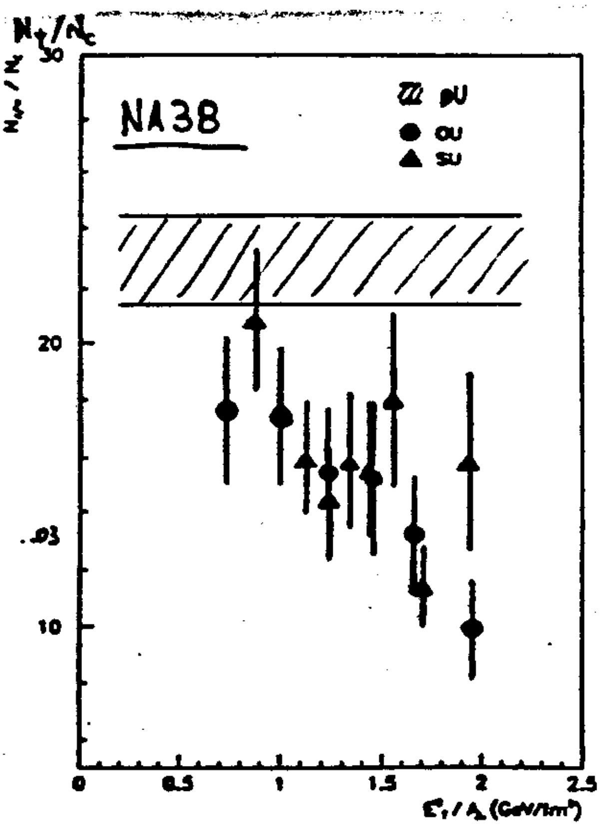


← screening length r_D needed to dissociate the J/ψ

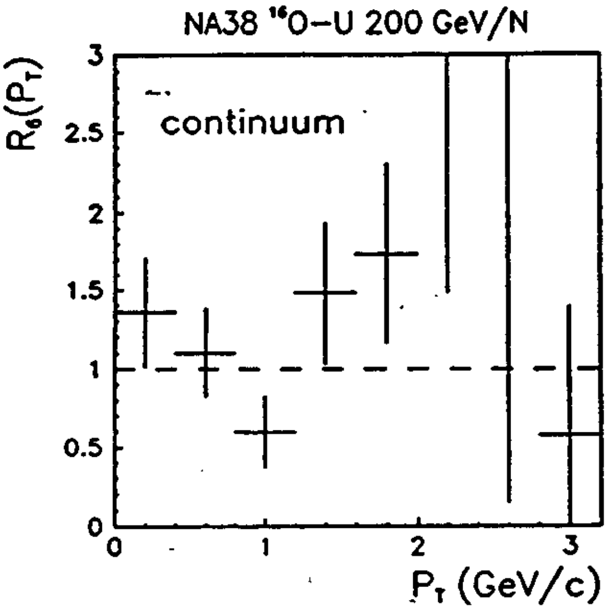
Fig. 5: Screening lengths r_D as function of the temperature, together with the dissociation values of some heavy quark bound states. From Ref. 11, Ref. 13 and Ref. 16.

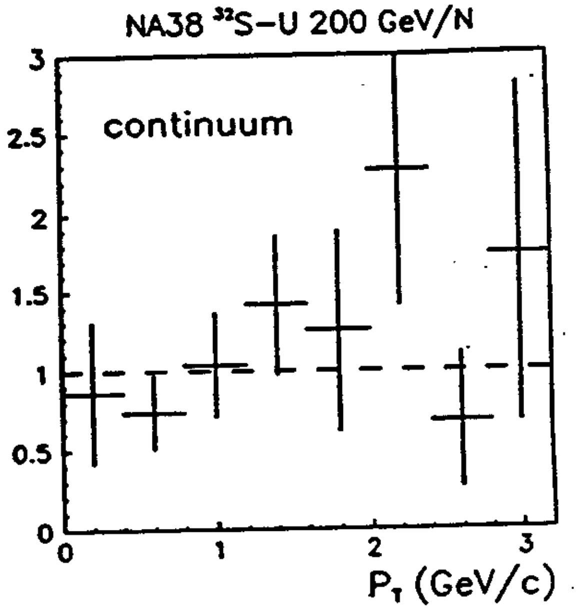
- NA38 OBSERVES J/ψ (AND ψ') SUPPRESSION IN HIGH E_T O-U AND S-U COLLISIONS, WHILE NO EFFECT IS SEEN IN p-U.
- THE PREDICTED p_T-DEPENDENCE OF THE SUPPRESSION IS OBSERVED AND AGREES QUANTITATIVELY WITH THE MODEL.
- ALTERNATIVE EXPLANATIONS, ESSENTIALLY BASED ON J/ψ ABSORPTION IN DENSE HADRONIC MATTER, PREDICT A DIFFERENT p_T-DEPENDENCE AND REQUIRE VERY HIGH HADRON DENSITIES.

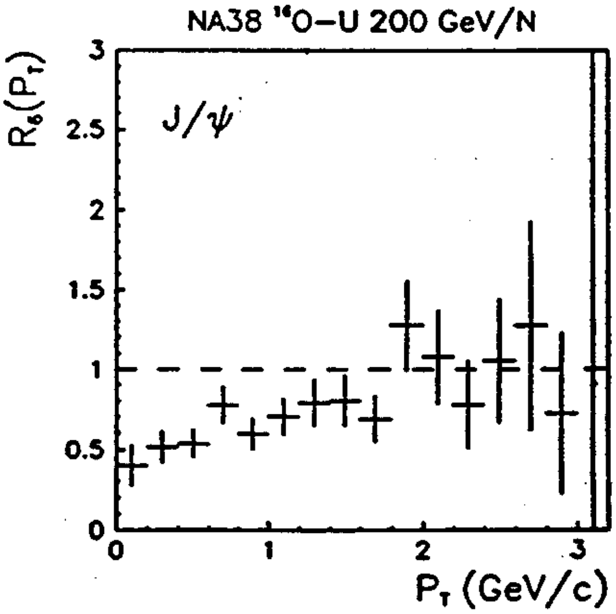


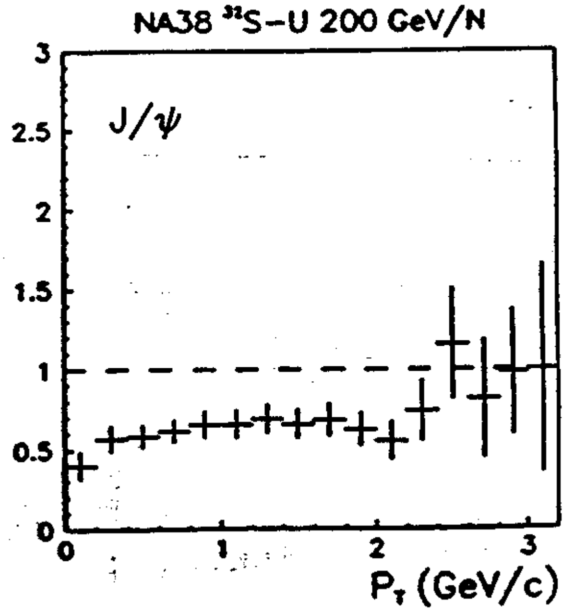


NA38


NA38 ^{16}O–U 200 GeV/N
$R_6(P_T)$
continuum
3
2.5
2
1.5
1
0.5
0
0
1
2
3
P_T (GeV/c)


NA38 ^{32}S–U 200 GeV/N
continuum
3
2.5
2
1.5
1
0.5
0
0
1
2
3
P_T (GeV/c)


NA38 ^{16}O–U 200 GeV/N
$R_6(P_T)$
J/ψ
3
2.5
2
1.5
1
0.5
0
0
1
2
3
P_T (GeV/c)


NA38 ^{32}S–U 200 GeV/N
J/ψ
3
2.5
2
1.5
1
0.5
0
0
1
2
3
P_T (GeV/c)

CONCLUSIONS

1. The energy density ε has the right order of magnitude to form QGP in "extreme" collisions
2. The stopping power is still high at 200 GeV/N
3. Global features of collisions are essentially understood with simple geometrical considerations
4. THERE IS A POSSIBLE INDICATION OF A MIXED PHASE FROM $\langle p_T \rangle$ vs. dN/dy
5. THERE IS EVIDENCE FOR A LARGE, THERMALIZED SYSTEM FROM 2π INTERFEROMETRY
6. J/ψ SUPPRESSION HAS BEEN ESTABLISHED IN O-U, S-U COLLISIONS, ALTERNATIVE MECHANISMS DON'T REPRODUCE QUANTITATIVELY THE EFFECT

MORE WORK MUST BE DONE ON:

- LOW MASS DILEPTONS NA34, NA45
- K/π, $\bar{\Lambda}/\Lambda$, $\bar{\Xi}/\Xi$ RATIOS WA85
- INTERFEROMETRY NA44

➡ LARGER VOLUMES Pb (CERN), Au (BNL) beam

➡ LARGER ENERGY DENSITY RHIC, LHC