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CERN

Cours/Lecture Series

1985-1986 ACADEMIC TRAINING PROGRAMME

LECTURERS L. VAN HOVE / CERN & W. WILLIS / CERN

TITLE Heavy Ions

DATES 18, 19, 20 February, 1986

TIME 11h to 12h

PLACE Auditorium

ABSTRACT

Lectures 1 & 2 : "Theoretical considerations", by L. VAN HOVE

Why study ultra-relativistic ion collisions ?

(a) To find out experimentally how nucleus-nucleus collisions differ from simple extrapolations of hadron-hadron collisions.

(b) To explore the possibility of producing the quark-gluon plasma that must have existed in the early Universe.

(c) Perhaps to produce and study it (in small, short-lived amounts).

The lectures will briefly cover the following topics :

(d) Theoretical expectations on the quark-gluon plasma and its behaviour in the early Universe - open questions.

(e) Theoretical predictions and uncertainties concerning (b) & (c).

(f) Some consequences for experiments concerning (a), (b) & (c).

Lecture 3, by W. WILLIS

In 1986 and 1987 the SPS will accelerate beams of oxygen and perhaps heavier nuclei. It is expected that central collisions of these projectiles with nuclear targets will lead to the generation of high energy densities over volumes which are large on the hadronic scale. A number of experiments are being set up to investigate this new domain of strongly interacting systems. The idea behind these experiments and their technical realization will be reviewed.

COPIES OF TRANSPARENCIES

SIS/H/344

(1) L. Van Hove, CERN

(pages 2 to 16)

Heavy Ions,

Why study ultra-relativistic ion collisions?

[Academic Training Programme
18-19 February 1986.]

(2) W. Willis, CERN

(pages 17 to 43)

Experimental Study of States
of High "Energy Density" At the SPS

[Academic Training Programme
20 February 1986]

Prospects on Ultrarelativistic Nuclear Collisions.

1. Introduction - Conventional aspects.

- Nucleus-nucleus collisions $\begin{cases} E_{lab} \gtrsim 200 \text{ GeV/N} \\ E_{cm} \gtrsim 20 \text{ GeV/NN} \end{cases}$

also hadron-nucleus collisions and lepton-nucleus collisions $\Big\} E_{lab} \gtrsim 200$ GeV

. What can be done? all that was done on protons, looking for nuclear effects.

- What was done already? $\begin{cases} \alpha\alpha, p\alpha \text{ at CERN-ISR} \\ \text{hadron-nucleus (FNAL, CERN-SPS)} \\ \mu\text{-nucleus}, \gamma\text{-nucleus } (\text{"}) \\ e\text{-nucleus (SLAC)} \end{cases}$

. Interesting nuclear effects found so far:

i) "soft" hadron-nucleus collisions (low p_t): NUCLEAR TRANSPARENCY (small A-dependence of fragmentation of hadron projectile)

ii) "hard" hadron-nucleus collisions (high p_t): CRONIN EFFECT, $E d^3\sigma/d^3p\Big|_{hA} = A^{\alpha} E d^3\sigma/d^3p\Big|_{hN}$ with $\alpha > 1$ for $p_t > 2$ GeV/c (also seen in $\alpha\alpha$ at ISR)

iii) deep inelastic lepton-nucleus collisions: EMC* EFFECT (quark distribution in nuclei is **not** "trivially" deducible from quark distribution in nucleons)

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* EMC = European Muon Collaboration

Theoretical prediction of a new state of matter, the "QUARK-GLUON PLASMA" (also called "quark matter").

- Constitution of hadronic matter according to QUANTUM CHROMODYNAMICS (QCD), a non-abelian gauge theory based on SU_3 (colour qu. nbs)
  - Spinor fields → QUARKS, SU_3 triplets, 5 (6?) "flavours"
  - gauge fields → GLUONS, SU_3 octets, no further int.^{e} qu. nb.
- CONFINEMENT property: hadronic systems in vacuum form SU_3 singlets ("colourless")

  Examples: baryon $= (qqq)_{singlet}$, meson $= (q\bar{q})_{singlet}$,

  where $q, \bar{q}$ may be "dressed" by a "sea" of $q\bar{q}$ pairs and gluons.

  - nucleus is also SU_3 singlet, containing 3A quarks and perhaps more ($q\bar{q}$ pairs).

    $q, \bar{q}$ distribution in nuclei is not the one in nucleon folded with Fermi distribution (EMC effect)

- At low density, hadronic matter forms HADRON GAS.
- Single hadrons occupy finite volume, $\gtrsim 1\,fm^3$.
- What about very dense hadronic matter as must occur
  - i) when nuclear matter is highly compressed (dense stellar objects)
  - ii) at high temperature, high density of hadrons being created by thermal agitation (early Universe).

Hadrons must then coalesce into a dense, continuous fluid of q's, $\bar{q}$'s and gluons, the QUARK-GLUON PLASMA.

i) Compress nuclear matter by factor 20:
Quark density $\sim 20 \times 3 \times 0.17\ fm^{-3} \sim 10\ fm^{-3}$.
ii) Heat matter to $T \sim 500$ MeV $\sim 6 \times 10^{12}$ K:
An ideal pion gas would have ~ 6 pions / fm^3,
i.e., a $q + \bar{q}$ density ~ $12\ fm^{-3}$.

Under such conditions, existence of Quark-Gluon Plasma seems inescapable (QGP also called Quark Matter).

- Can this new state of matter be produced on earth? Perhaps in ultrarelativistic nuclear collisions, a new domain of heavy ion physics, to be explored.

- 3 classes of problems, all affected by large uncertainties:
  - i) Expected properties of QGP and of QGP ↔ HG transition (HG = Hadron Gas).
  - ii) Compression and heating in nuclear collisions.
  - iii) Signals for QGP formation in " " .

- Much theoretical work, great quantitative uncertainties.
- Severe lack of data hampers work; experimental programmes to start soon at Brookhaven (15 GeV/nucleon up to ^{32}S) and CERN (225 GeV/nucleon up to ^{16}O).
- Impossibility to measure "colour conductivity"!

AGS + Booster: 15 GeV/nucleon up to gold
RHIC: colliding beams up to gold (^{197}Au) up to 100 GeV/nucleon.

(RHIC: Relativistic Heavy Ion Collider)

Quark-gluon plasma (QGP) and hadronic phase transition

One expects 2 phase transitions, but they may coincide:

- **Deconfinement transition**: QGP $\leftrightarrow$ HG (hadron gas)
- **Chiral transition**: restoration of chiral symmetry (from $\langle \psi_q \bar{\psi}_q \rangle \neq 0$ to $\langle \psi_q \bar{\psi}_q \rangle = 0$)

Theoretical work follows 2 approaches:

Continuum approach:

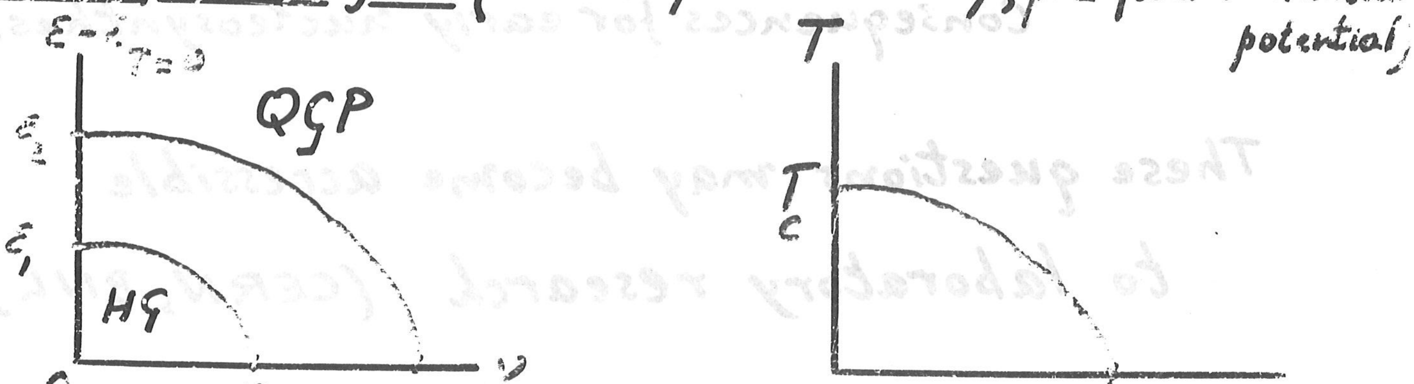
- describe HG from hadron phenomenology
- " QGP by ideal gas with perturbative and "plasmon corrections" based on QCD. (complexity of collective effects!)

Lattice approach: thermodynamics of QCD in lattice approximation by Monte Carlo integration.

- Pure SU_3 gauge field (self-interacting gluons) First order phase transition likely (hysteresis)
- Full QCD with quarks: Nature of transition unclear - but large change of energy density ε and entropy density σ, with small change of p, T, μ (?)

$$\varepsilon + p = T\sigma + \mu\nu, \quad \sigma = \partial p/\partial T, \quad \nu = \partial p/\partial \mu, \quad p = p(T,\mu)$$

Possible phase diagram (ν = net quark density, μ = quark chemical potential)

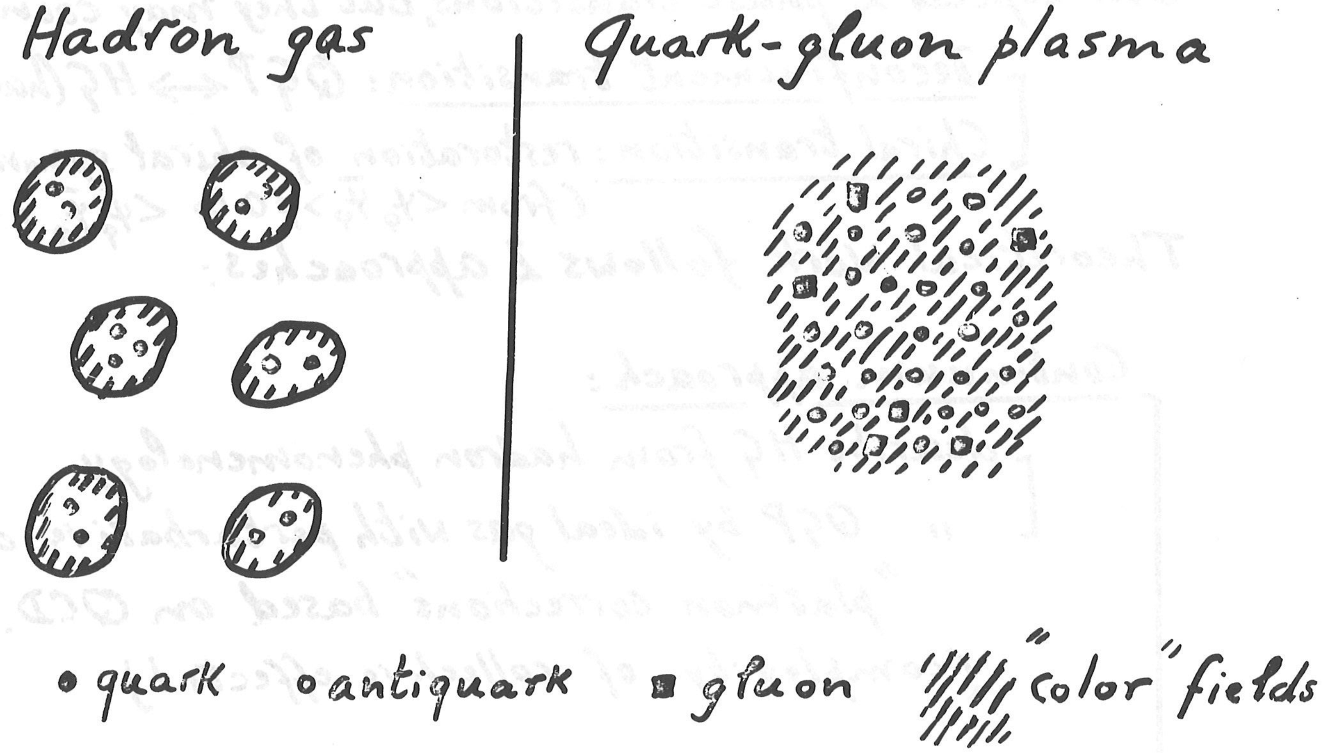


perhaps $\begin{cases} \varepsilon_2 \sim 2\varepsilon_1 \sim \text{a few GeV fm}^{-3} \\ \nu_2 \sim 2\nu_1 \sim \text{a few fm}^{-3} \text{ ?} \end{cases}$

perhaps $\begin{cases} T_c \sim 150\text{-}300 \text{ MeV} \\ \mu_c \sim 400\text{-}800 \text{ MeV ?} \end{cases}$

(1 MeV = 1.16×10^{10} K)

The hadronic phase transition.



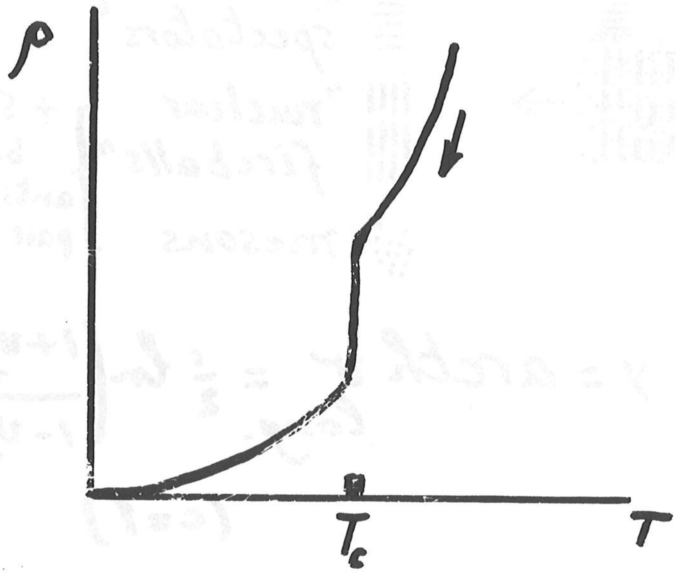
Phase transition in early Universe

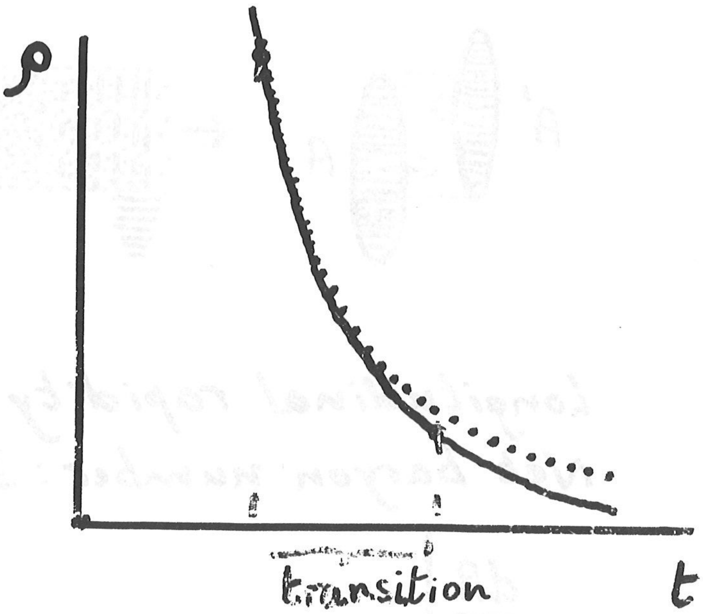
($t \sim 10^{-6} - 10^{-5}$ s , $T \sim 200$ MeV $\sim 2.4 \times 10^{12}$ K)

- Smooth or violent (supercooling)?
  ↳ gravitational waves?
  (present period ~ 1 year)
- Concentration of nucleons in plasma regions during phase transition?
  Consequences for early nucleosynthesis?

These questions may become accessible to laboratory research (CERN, BNL).

Hadronic phase transition in the expansion of the Universe.





(a = scale of expanding Universe)

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi}{3} G\rho \qquad \frac{d}{dt}(\rho a^3) + p\frac{da^3}{dt} = 0$$

$p \simeq p_c$ constant during transition

$(\rho + p_c)a^3 \simeq$ " " "

[1^{st} order trans assumed for simplicity]

$$\frac{d\rho}{dt} = -(24\pi G)^{1/2} \rho^{1/2}(\rho + p_c)$$

$$\rho \simeq p_c \left(\frac{\sqrt{\rho_1} - \sqrt{p_c}\tan\gamma(t-t_1)}{\sqrt{p_c} + \sqrt{\rho_1}\tan\gamma(t-t_1)} \right)^2$$

[$\gamma = (6\pi G p_c)^{1/2}$, t_1 = beginning of transition, $t_1 \sim 10^{-5}$ s = 3 km when $\rho(t_1) = \rho_1 = \rho$ [QGP + leptons + γ's] at T_c, p_c.

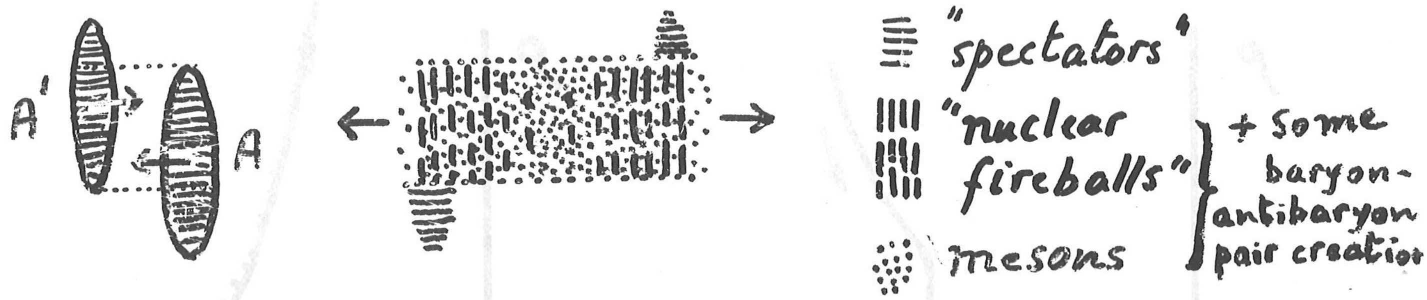
Transition ends at t_2 when $\rho(t_2) = \rho_2 = \rho$ [HG + lept. + γ.] at T_c, p_c

$\rho_2 \sim 0.5 - 0.7\, \rho_1$, $t_2 \sim 1.2 - 1.5\, t_1$.

At $t = t_1 + \delta t$, HG bubbles separated by $t_1^{1/3}(1\,fm)^{2/3} \sim 10^{-7}$ cm.

After percolation space structure may reach $t_1^{2/3}(1\,fm)^{1/3} \sim 1$ cm.

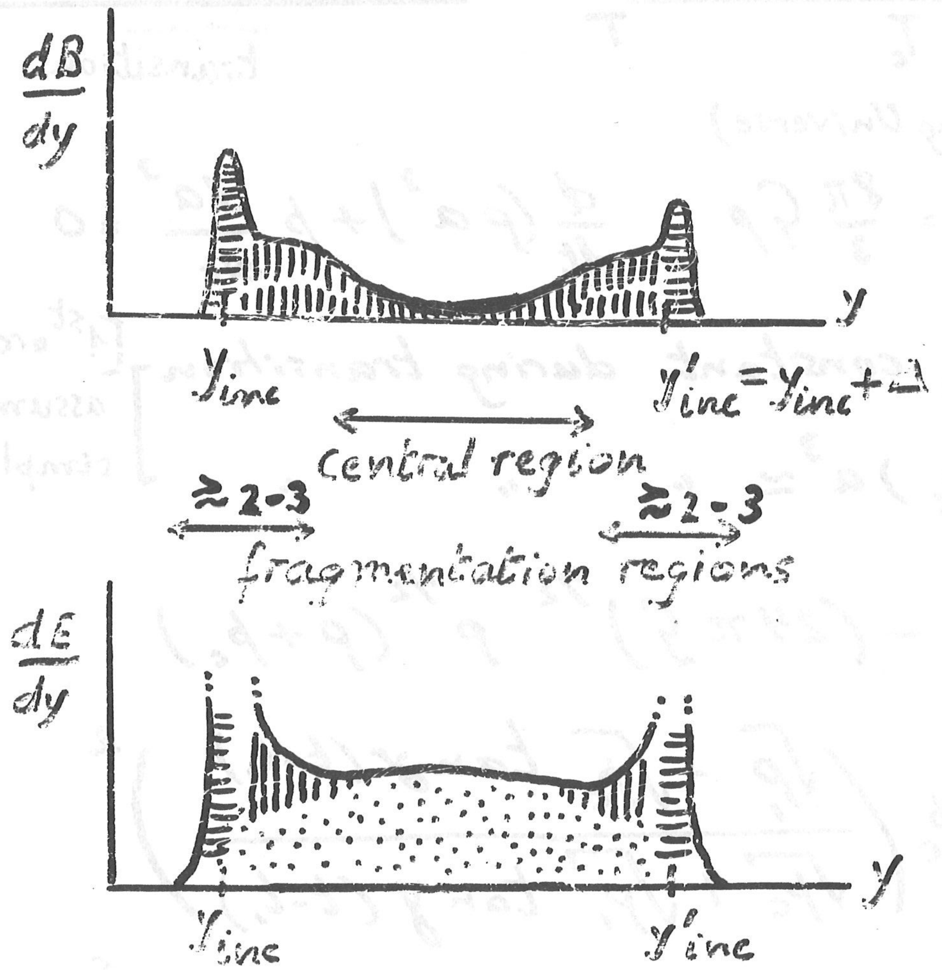
Ultrarelativistic nuclear collisions.



Longitudinal rapidity: $y = \operatorname{arcth} v_{long.} = \frac{1}{2} \ln\left(\frac{1+v_{long}}{1-v_{long}}\right)$

Net baryon number: B

$(c=1)$



$\left(\Delta = 6 \text{ for } E_{lab} = 200\,\text{GeV}/N\right)$

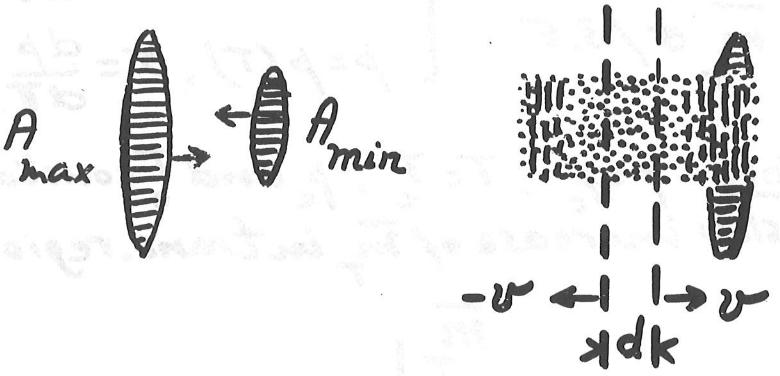
dE: comoving energy of particles in $(y, y+\Delta y)$

Fragmentation regions: compression gives $\nu \sim 2\nu_0 \sim 1\,\text{fm}^{-3}$, $\varepsilon \sim 1\,\text{GeV fm}^{-3}$? (maximum at $E_{lab} \sim 15$-$20\,\text{GeV}/N$?)

Central region: perhaps $\varepsilon \gtrsim 2\,\text{GeV fm}^{-3}$ at $E_{lab} \gtrsim 200\,\text{GeV}/N$
(Keeps growing with energy)

But: FLUCTUATIONS can help! ($\varepsilon \sim 10\,\text{GeV fm}^{-3}$ seen at $p\bar{p}$ collider

Estimate of early energy and entropy densities in central region



Thin slab of matter expanding longitudinally produces particles in rapidity interval $(y-\delta y/2,\ y+\delta y/2)$

In restframe of slab, $y=0$ and $v \sim \delta y/2$ for $\delta y \lesssim 1/2$

At early τ after collision began (measured in rest frame of slab), volume of slab is

$$V_\tau \sim \pi R_{min}^2\, d\ ,\ R_{min} = 1.2\, A_{min}^{1/3}\ fm\ ,\ d \sim 2v\tau \sim \tau\,\delta y$$

Early energy density: $\varepsilon_\tau V_\tau \sim \frac{dE}{dy}\,\delta y \sim \overline{m}_T\,\frac{3}{2}\,\frac{dn}{dy}\,\delta y$

$$\overline{m}_T \approx \sqrt{\overline{p}_T^{\,2} + m_\pi^2}\ ,\ dn/dy = \text{charged multiplicity}$$

(Bjorken) {Phys. Rev. D27 ('83) 140}

$$\boxed{\varepsilon_\tau \sim \frac{3}{2\pi(1.2)^2}\,\frac{\overline{m}_T}{\tau A_{min}^{2/3}}\,\frac{dn}{dy}\ \ GeV/fm^3\ ,\ \left\{\begin{array}{l}\overline{m}_T \text{ in } GeV\\ \tau \text{ in } fm/c\end{array}\right.}$$

(an underestimate)

Early entropy density: $\frac{2\pi^4}{45\,\zeta(3)}\,\frac{3}{2}\,\frac{dn}{dy}\,\delta y$

(Hwa + Kajantie) HU-TFT-85-2) Phys. Rev D...

$$\boxed{\sigma_\tau \sim \frac{1.2}{\tau A_{min}^{2/3}}\,\frac{dn}{dy}\ \ fm^{-3}\ ,\ \tau \text{ in } fm/c}$$

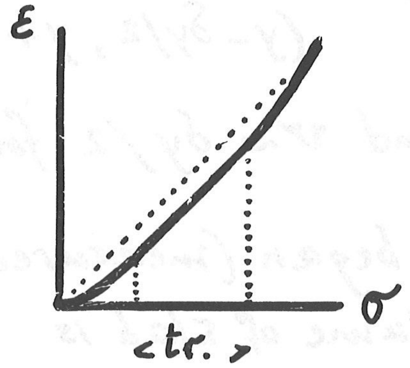
(an overestimate)

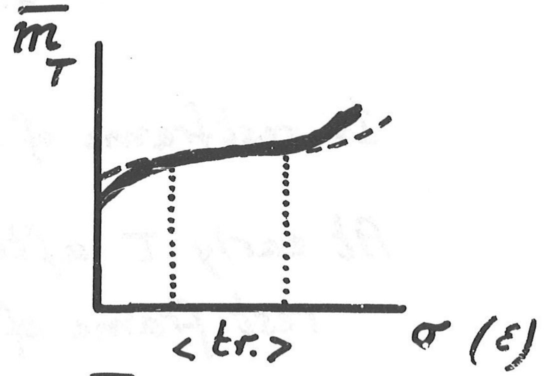
First order phase transition, central region (B=0)

Basic equations $\varepsilon + p = T\sigma$ $\left[\begin{array}{l} \varepsilon = \varepsilon(\sigma),\ T = \dfrac{d\varepsilon}{d\sigma} \\ p = p(T),\ \sigma = \dfrac{dp}{dT} \end{array}\right.$

$\varepsilon = \overline{m}_T\, \sigma / 3.5$

Transition region: $p = p_c$, $T = T_c$, p_c and T_c constant.
p_c small implies slow increase of $\overline{m}_T$ in trans. region.





---- $\overline{m}_T$ vs ε in appropriate units

Early net-baryon-number density

Early baryon number density: $\beta_\tau V_\tau \sim \dfrac{dB}{dy}\,\delta y$

$$\beta_\tau \sim \frac{1}{\pi (1.2)^2}\,\frac{1}{\tau A_{min}^{2/3}}\,\frac{dB}{dy}\ fm^{-3} \quad , \ \tau \text{ in } fm/c$$

(neutral baryons to be included in $\dfrac{dB}{dy}$)

NOTE: ε_τ, σ_τ and β_τ formulae need improvements:

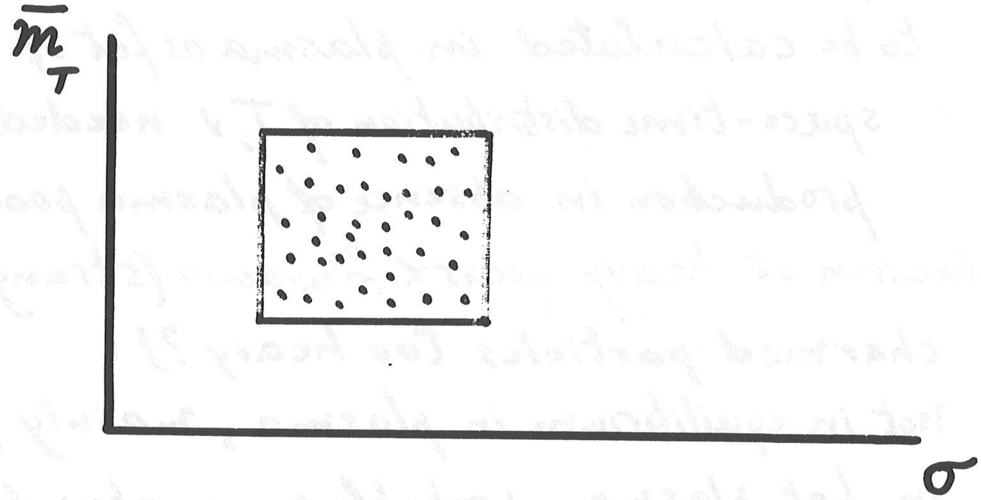
unknown displacements in rapidity for ε_τ, β_τ
+ unknown amount of entropy production for σ_τ

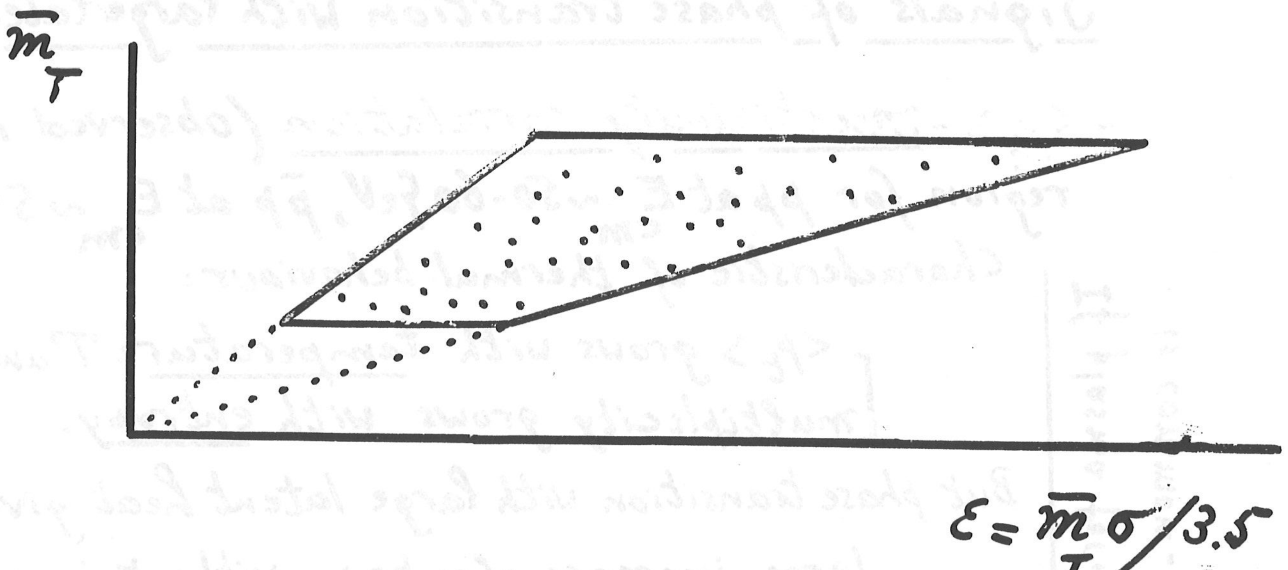
Note: ε_τ and β_τ have meaning without assuming thermalization, σ_τ assumes it.

Event-by-event analysis

(as in JACEE plot)

Assume $\bar{m}_T$ and σ uncorrelated:

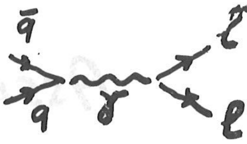




Signals for plasma formation.

"Traditional" signals:

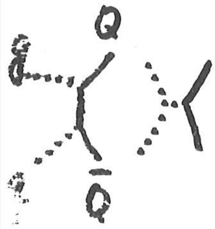
- direct e^+e^- and $\mu^+\mu^-$ pair production



- direct photon production:

etc | to be calculated in plasma as fct of T and ν, space-time distribution of T, ν needed, production in absence of plasma poorly known.

- production of heavy quark flavours (strange particles, charmed particles too heavy?):



not in equilibrium in plasma, mainly produced in hot plasma, probably more abundant than without plasma (production by gluons mainly).

Signals of phase transition with large latent heat:

- $\langle p_t \rangle$-multiplicity correlation (observed in central region for pp at $E_{cm} \sim 50$-60 GeV, $\bar{p}p$ at $E_{cm} \sim 540$ GeV):

If plasma formation is common.

Characteristic of thermal behaviour:

[$\langle p_t \rangle$ grows with temperature T and pressure p,
[multiplicity grows with entropy.

But phase transition with large latent heat gives large increase of entropy without increase of T, p

This might show as an anomaly in $\langle p_t \rangle$-mult. curve.

Also if pl. form. is exceptional.

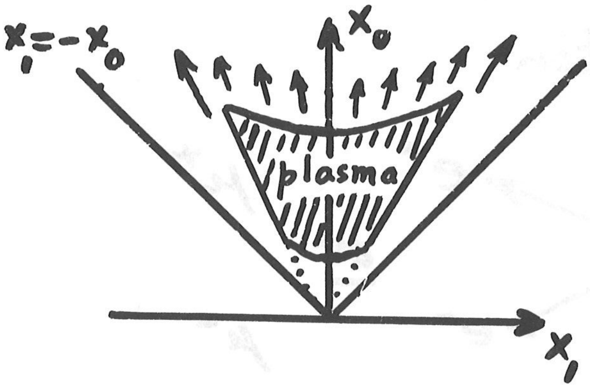
- multi-hadron fluctuations caused by instabilities in release of latent heat by plasma (plasma deflagration)

QGP ⇄ | HG →
Shock front

Cosmic ray evidence?

Dilepton emission by hot plasma ($T \gg T_c$)

L.D. McLerran, T. Toimela, Phys. Rev. D31 (1985) 545
R.C. Hwa, K. Kajantie, Helsinki prepr. HU-TFT-85-2 (1985)
Phys. Rev. D...



Dilepton (e^+e^- or $\mu^+\mu^-$)
mass M, p_T, y
transv. mass $M_T = \sqrt{M^2 + p_T^2}$

Emission by plasma:

$$dN/dM^2 dp_T^2 dy = \int_{plasma} d^4x \; dN_{pl}(T(x))/dM^2 dp_T^2 d[y - y(x)]$$

$dN_{pl}(T)/dM^2 dp_T^2 dy$: emission rate per unit volume × time by plasma of temperature T at rest

$$dN/dM^2 dp_T^2 dy = \int_{T_c}^{T_i} dT \int dy' \phi(T, y') \, dN_{pl}(T)/dM^2 dp_T^2 d(y - y')$$

[T_i = initial temp., T_c = transit. "], $\phi(T, y') = \int_{plasma} d^4x \; \delta[T(x) - T] \, \delta[y(x) - y']$

For $T \gg T_c$, plasma is almost ideal gas of quarks and gluons,

→ { i) $\phi \propto T^{-7}$ and indep. of y' (adiabatic longitudinal expansion, Lorentz invariant)

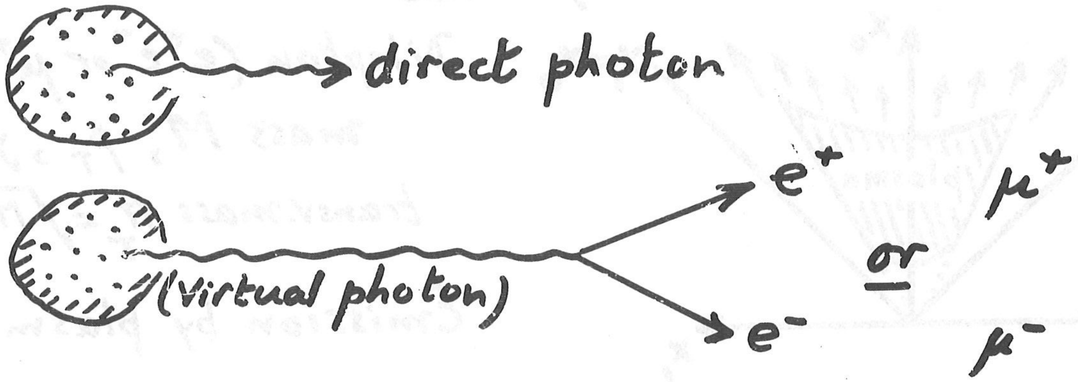
ii) $\dfrac{dN_{pl}(T)}{dM^2 dp_T^2 dy} = f(M_T/T, y)$, $f \propto e^{-M_T/T}$ for $T \ll M_T$ }

For $T_i \gg M_T \gg T_c$: $\dfrac{dN}{dM^2 dp_T^2 dy} \simeq \int dy' \dfrac{dN_{pl}(M_T)}{dM^2 dp_T^2 d(y - y')} \underbrace{\int_{M_T}^{T_i} \phi(T, y') \, dT}_{\propto M_T^{-6}}$

hence: $\boxed{dN/dM^2 dp_T^2 dy \propto M_T^{-6} \text{ indep. of } p_T^2/M^2}$

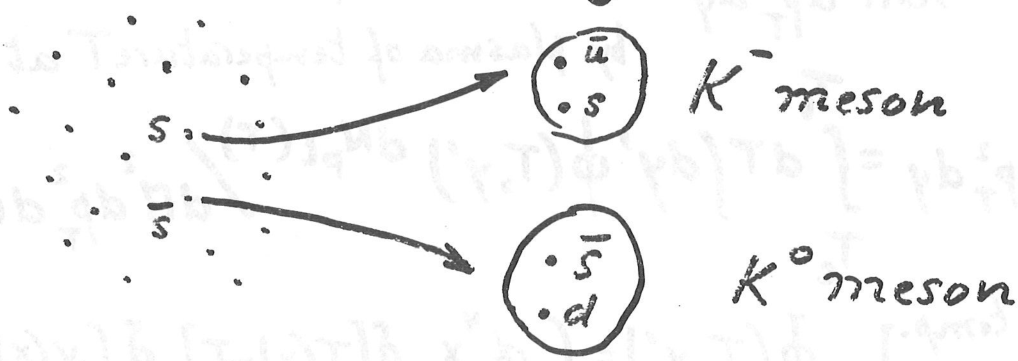
Signals for plasma formation.

i) electromagnetic signals emitted by plasma



(escape with negligible absorption)

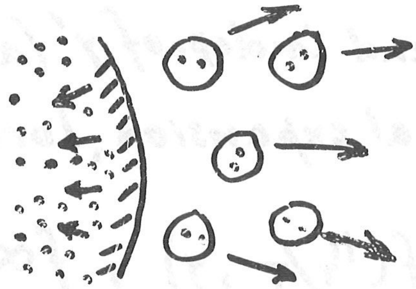
ii) strange quark pairs formed in plasma, emitted as strange hadrons



(also hyperon production)

iii) sudden liberation of latent heat at transition (deflagration)

In model calcul.: $v_{surface} \sim 0.15c$



$v_{HG} \sim 0 - 0.6c$

(produces entropy and fluctuations)

More generally:

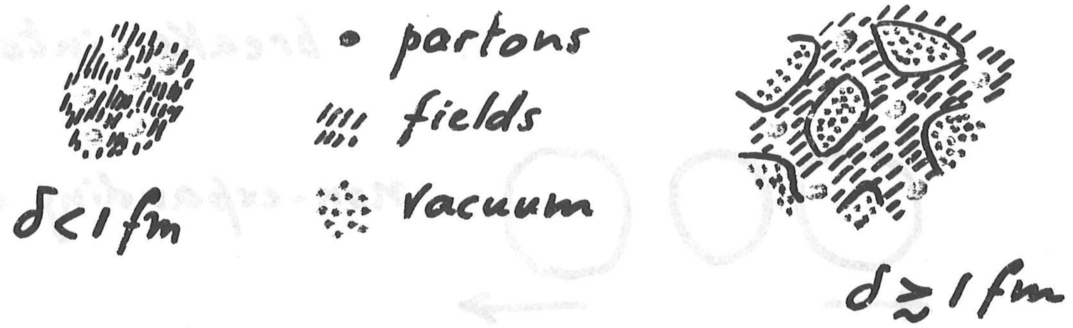
Plasma	→	Hadrons
high energy contents	→	high transverse motion
" entropy "	→	" multiplicity

Proposed Scenario for
Hadronization of expanding droplet of QG Plasma

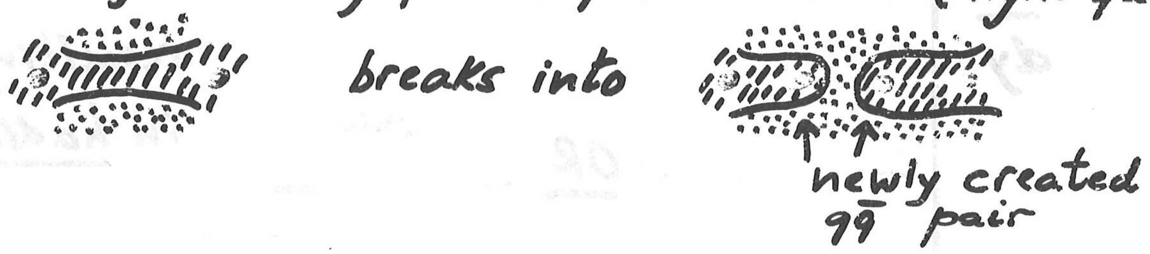
- δ : nearest neighbour distance between QCD "partons" (= quarks, antiquarks, gluons)

- For $\delta < 1$ fm colour confining fields (i.e. QCD gauge fields) cover all space in plasma.

- When $\delta \gtrsim 1$ fm the fields collapse into strings (= flux tubes) separated by vacuum (non-perturb. QCD vacuum)



- Some strings break by parton pair creation (light quarks)

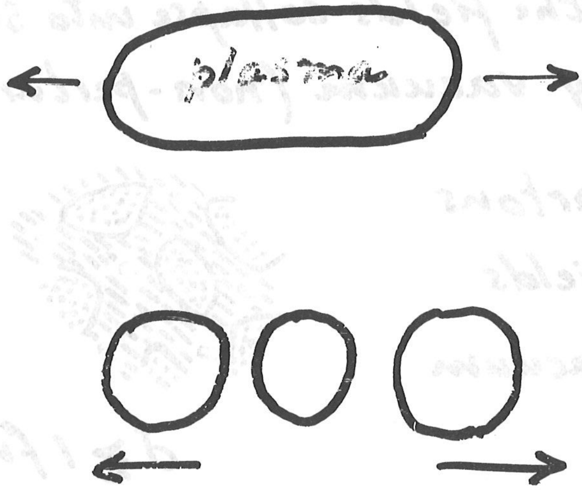


- An expanding droplet may break into smaller ones, and string tension stops expansion of the pieces

- Non-expanding plasma droplet can "deflagrate" by emitting a flow of hadron gas into vacuum.

(In larger expanding plasma, bubbles of vacuum would form)

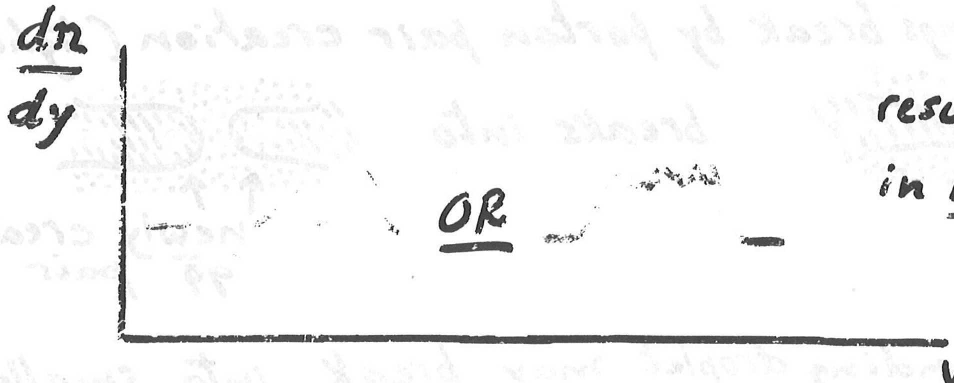
If plasma droplet (possibly after breaking up) hadronizes by deflagration, resulting rapidity distribution of hadrons should show maxima at rapidities of droplets



Expanding droplet

breaks into

non-expanding droplets



resulting maxima in hadron rap. dist

Expected width of maxima ~ $1 \div 1.5$

- The other signals for plasma formation (direct dileptons and photons, strange hadrons) should be concentrated in these maxima.
- Hadrons from plasma should have p_T somewhat larger than normal, with broad but fluctuating azimuthal distribution.

EXPERIMENTAL STUDY OF STATES OF HIGH 'ENERGY DENSITY' AT THE SPS

W. WILLIS

OR "SEARCH FOR Q. G. P." ??

BEAM OF SULFUR A = 32 × 225 GeV/u

= 7.2 TeV + FIXED TARGET

S^{32} ... U^{238}

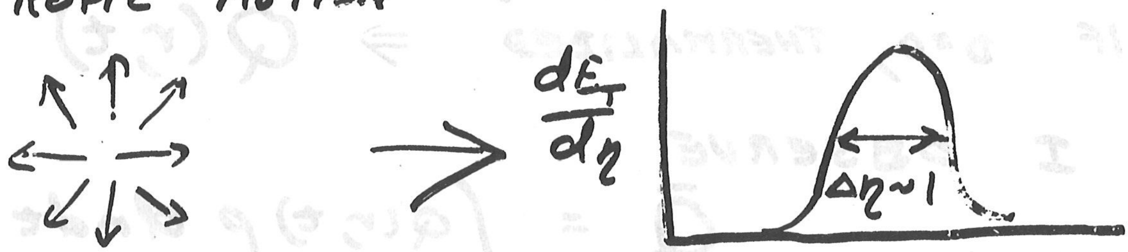
$\sqrt{s} \sim 1$ TeV

WE WANT "THERMALIZED ENERGY"

APPROPRIATE MEASURE? $E_T = \sum_i E_i \sin\theta_i$?

LONGITUDINAL MOTION **IRRELEVANT**

ISOTROPIC MOTION



$\eta = -\log \tan \frac{\theta}{2}$

⇒ **MEASURE IS E_T IN $\Delta\eta \sim 1$**

PEAK ANGLE : S^{32} - S^{32} ~ 5°

S^{32} - U^{238} → 30° ?

IN p-Pb WE HAVE $E_T(\Delta\eta \approx 1)$ > **30 GeV**

@ 200 GeV

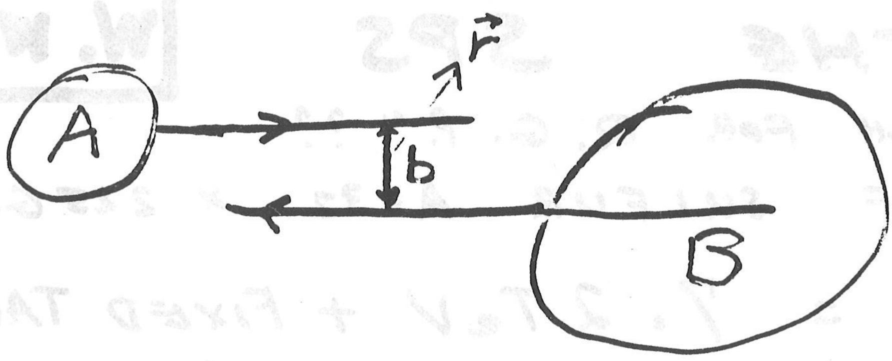
(OR ABOUT 15 GeV AT ~"CENTRAL" LEVEL)

WITH 32 PROJECTILES WE EXPECT **200 - 400 GeV**

OFTEN FACTOR 10× IN SCALE ⇒ DISCOVERY

EXPERIMENTAL OBSERVABLES AND TECHNIQUES

"CONVENTIONAL" PHENOMENA



MACROSCOPIC PHYSICAL OBSERVABLES HAVE MEANINGFUL TIME DEPENDENCE THUS ALSO $\vec{r}$ DEPENDENCE.

SO, FOR FIXED A, B, $\sqrt{s}$ IF NO FLUCTUATIONS OBSERVABLE

$$Q(b, \vec{r}, t)$$

IF $b=0$, THERMALIZED $\Rightarrow Q(r,t)$

BUT I OBSERVE

$$\bar{Q} = \int Q(r,t)\,\rho\; dr\,dt$$

ρ = WEIGHT

WHAT DO WE DO?

MANY OBSERVABLES Q_i^j, WHERE j DENOTES A CLASS, EG "TEMPERATURE" IN A CLASS, THERE ARE STILL MANY, DENOTED BY i, EG. TEMP. MEAS. BY π, K, e^+e^- ... USUALLY ρ_i's ARE DIFFERENT FUNCTIONS OF r, t

---

Q_i^j — DECONVOLUTES $\Rightarrow Q^j(r,t)$

Z PROJECTILE

MEASURED BY

IONIZATION OR CERENKOV

$\propto Z^2$

READOUT BY PMT - WATCH FOR RAD. DAM.

- ALL PRESENT EXPS. "COUNT BEAM"

A PROJECTILE

MEASURED BY

ENERGY IN CALORIMETER

$A_{TARGET} \equiv B$

MEASURED BY

ACTIVE TARGET

EMULSION, IONIZATION NEAR TINY TARGETS

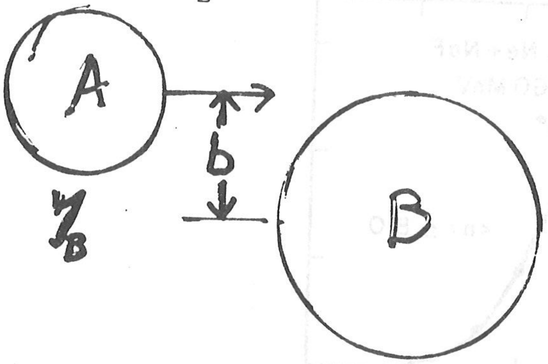
IF ELIMINATE SECONDARY INTERACTIONS

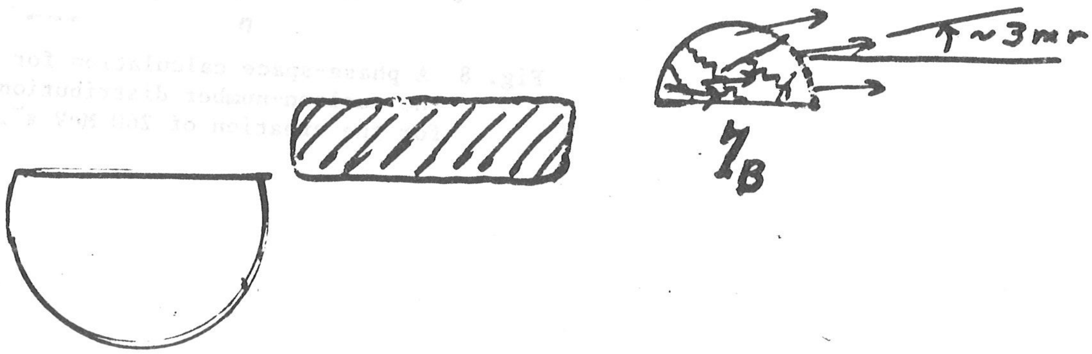
---

b 'IMPACT PARAMETER'

MEASURED BY

PROJECTILE FRAGMENTS





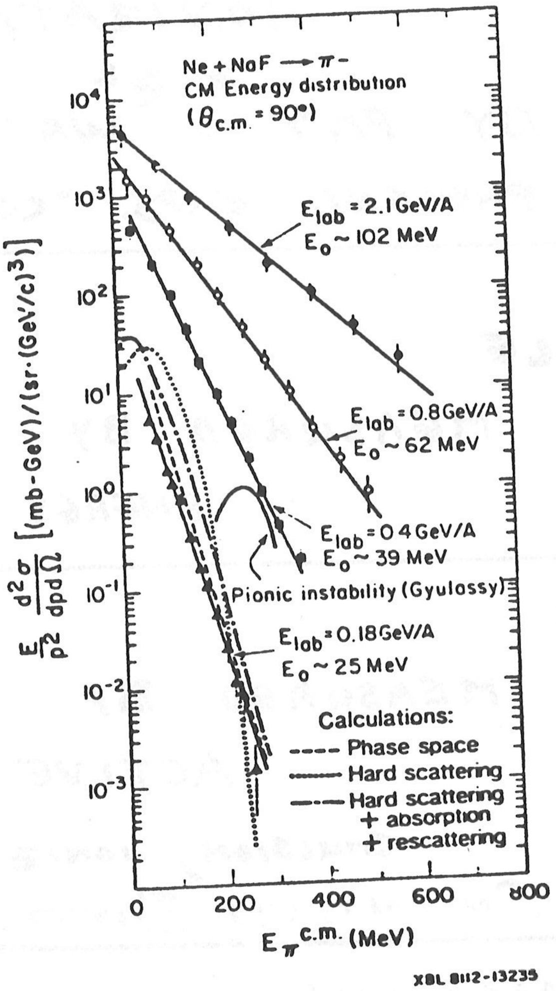


Fig. 7 Negative pion spectra at 90° at four different beam enrgies.

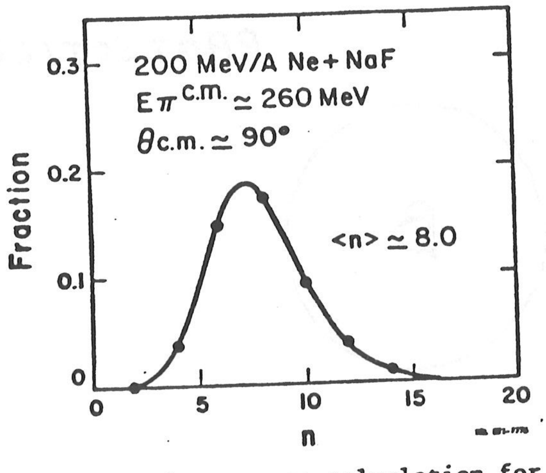


Fig. 8 A phase-space calculation for the nucleon-number distribution for the creation of 260 MeV π^-.

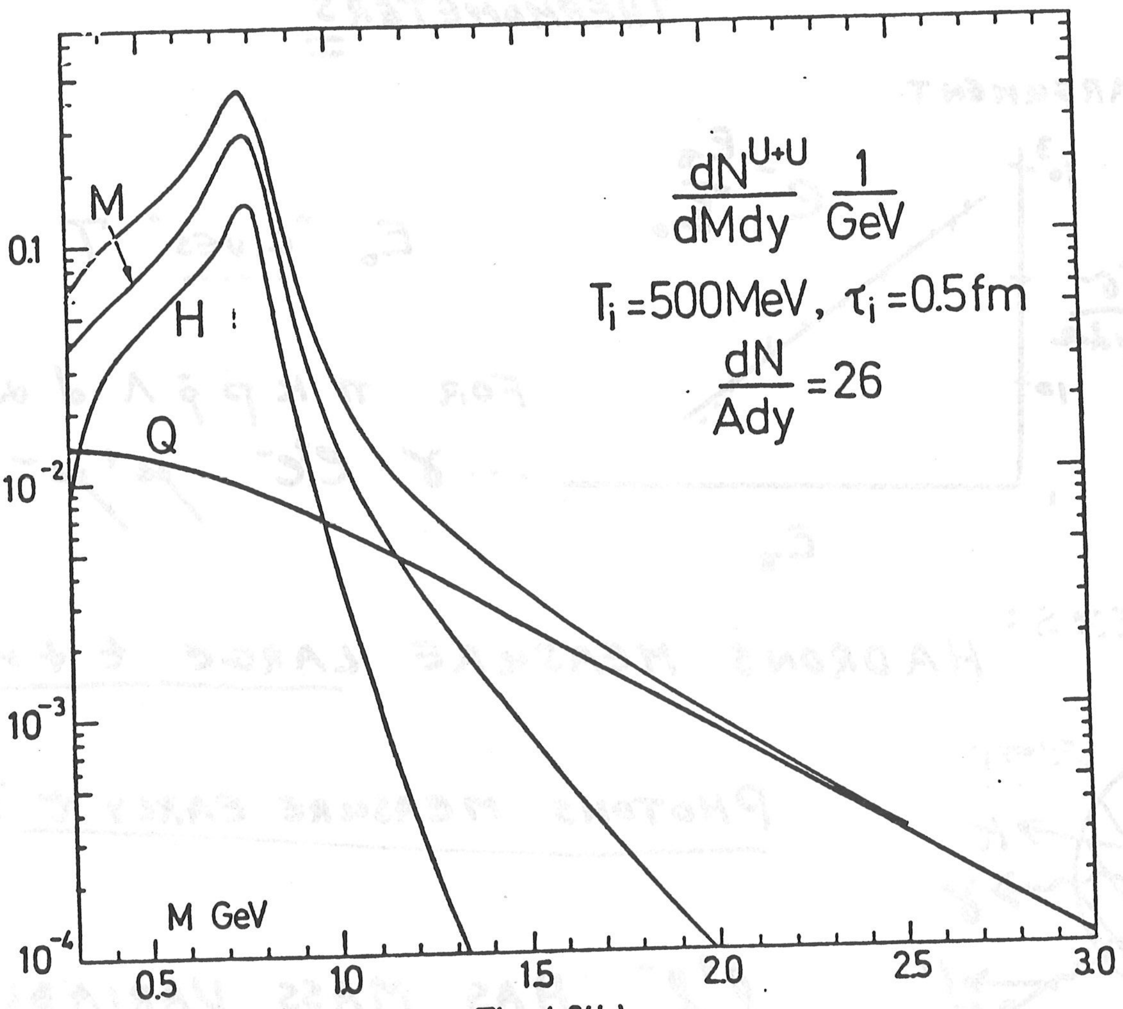

M
H
Q
$\frac{dN^{U+U}}{dMdy} \frac{1}{GeV}$
$T_i = 500 MeV, \tau_i = 0.5 fm$
$\frac{dN}{Ady} = 26$
0.1
10^{-2}
10^{-3}
10^{-4}
M GeV
0.5
1.0
1.5
2.0
2.5
3.0

Fig. 4.6(b)

PARTICIPANT ENERGY (+ LONGITUDINAL DIST.)

MEASURED BY

CALORIMETER WITH

GOOD ANGLE RESOLUTION: $\frac{dE_T}{d\eta}$

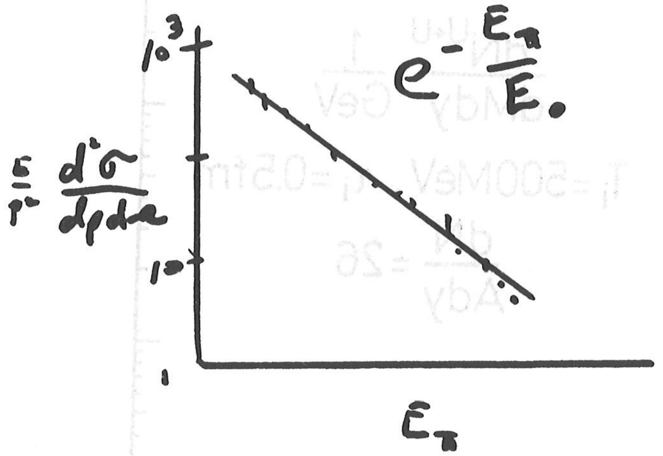
OR CHARGED MULTIPLICITY $\frac{dn_c}{d\eta}$

TEMPERATURE (DISTRIBUTIONS !?)

MEASURED BY

THERMOMETERS

OLD ARGUMENT



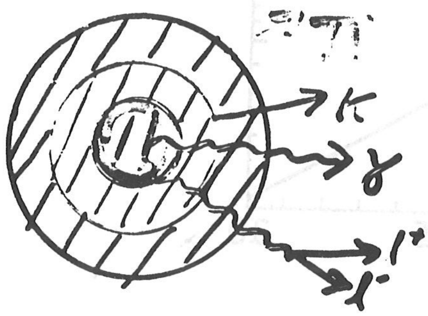
E_0 "GIVES" T

FOR π K p $\bar{p}$ Λ d α ...

... γ e^+e^- $\mu^+\mu^-$

PROBLEMS:

HADRONS MEASURE LARGE $t + r$?



PHOTONS MEASURE EARLY t ?

ALSO ϕ

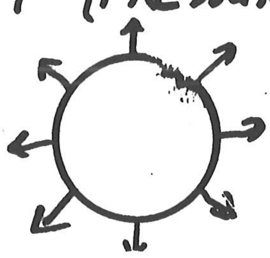
l^+l^- HAS MASS VARIABLE

AS WELL (NAIVE $m \sim T$)

*! IF T IS MEANINGFUL, SO IS P (PRESSURE)

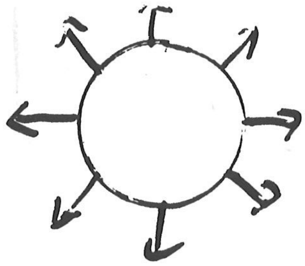
⇒ GIVEN FINITE SYSTEM

⇒ COLLECTIVE FLOW



⇒ BIG EFFECT ON E_0

EXPANSION VELOCITY



MEASURED BY A

SPEEDOMETER

THERMAL DISTRIBUTION <u>BOOSTED</u>
BY VELOCITY

TWO CASES * $m \ll \bar{p}_T$

· BOOST CHANGES $\bar{P}_T$, <u>FORM</u> <u>UNCHANGE</u>

(IF FOR π, $\bar{p}_T = .35$ GeV $\Rightarrow$ $\beta_\pi = .93$)

* $m \gg \bar{P}_T$

BOOST CHANGES $\bar{P}_T$ <u>AND FORM CHANGES</u>

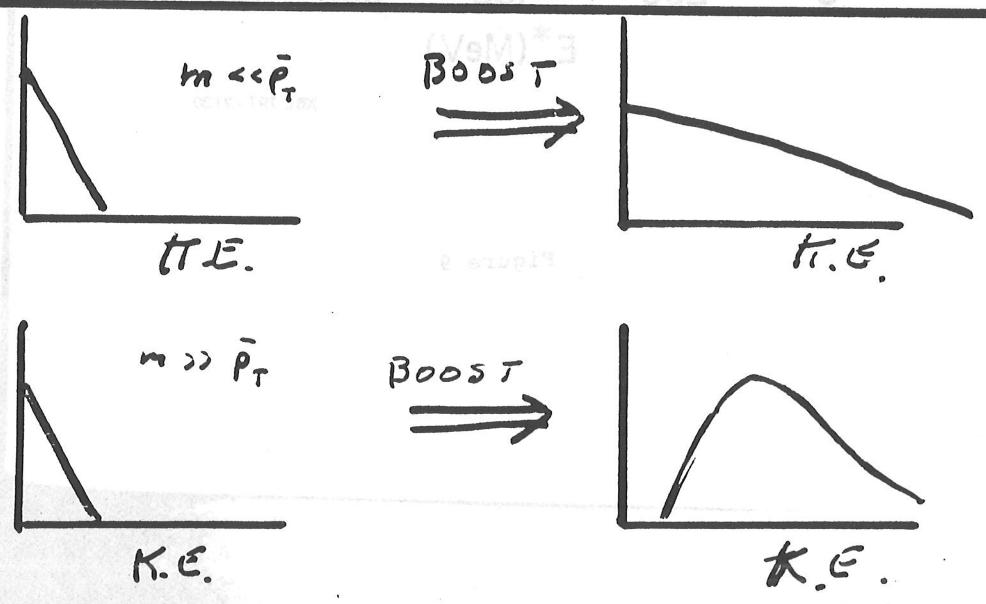
(IF FOR p, $\bar{P}_T = .5$ GeV $\Rightarrow$ $\beta_p \sim .5$

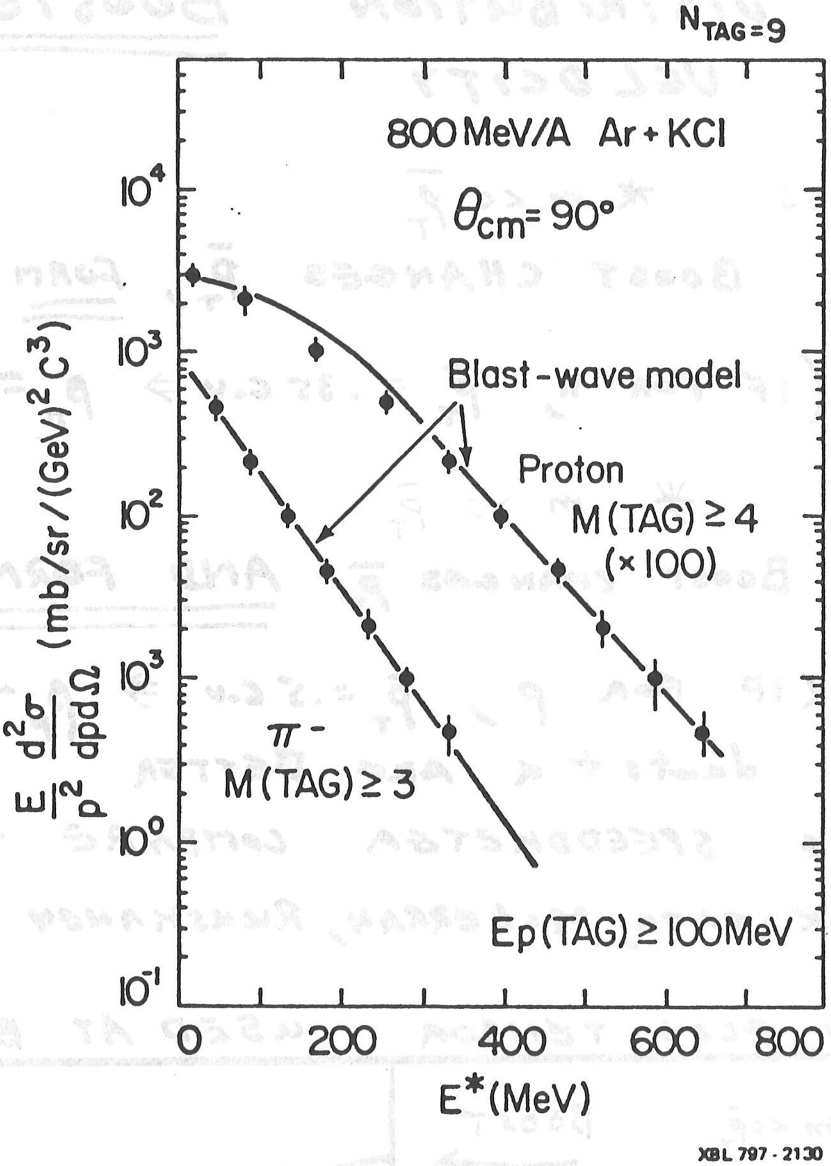
deuts + α ARE BETTER

$\Rightarrow$ POSSIBLE SPEEDOMETER COMPARE $\pi, p \cdots P_T$

KAJANTIE, KATAJA, McLERRAN, RUUSKANEN $\rho \to ee$

ENERGY FLOW TENSOR USED AT BEVALAC





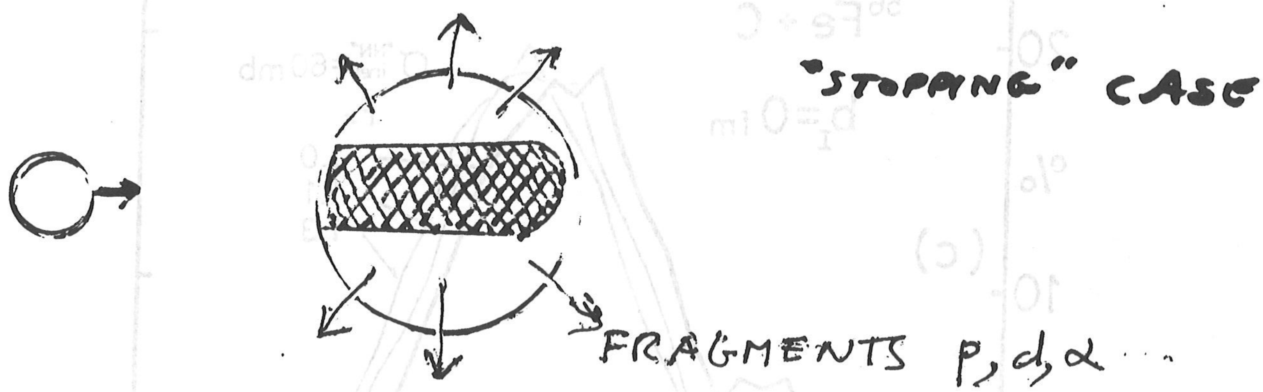
$N_{TAG}=9$
800 MeV/A Ar + KCl
$\theta_{cm}=90°$
Blast-wave model
Proton
M (TAG) ≥ 4
(×100)
π⁻
M (TAG) ≥ 3
Ep (TAG) ≥ 100MeV
$\frac{E}{p^2}\frac{d^2\sigma}{dp d\Omega}$ (mb/sr/(GeV)^{2}C^3)
E*(MeV)
XBL 797-2130

Figure 9

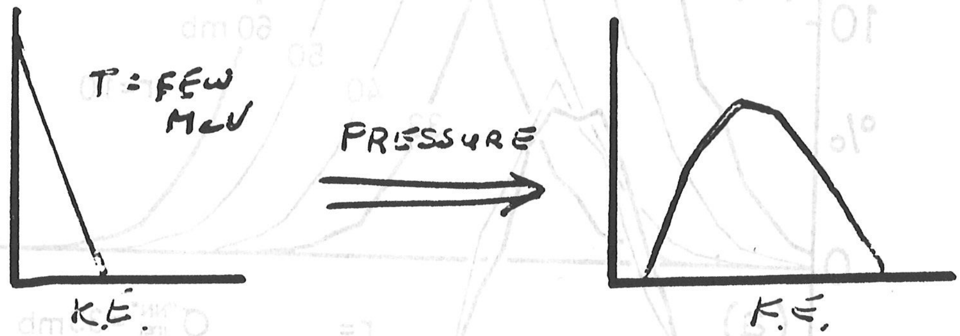
PRESSURE

MEASURED BY A

BAROMETER

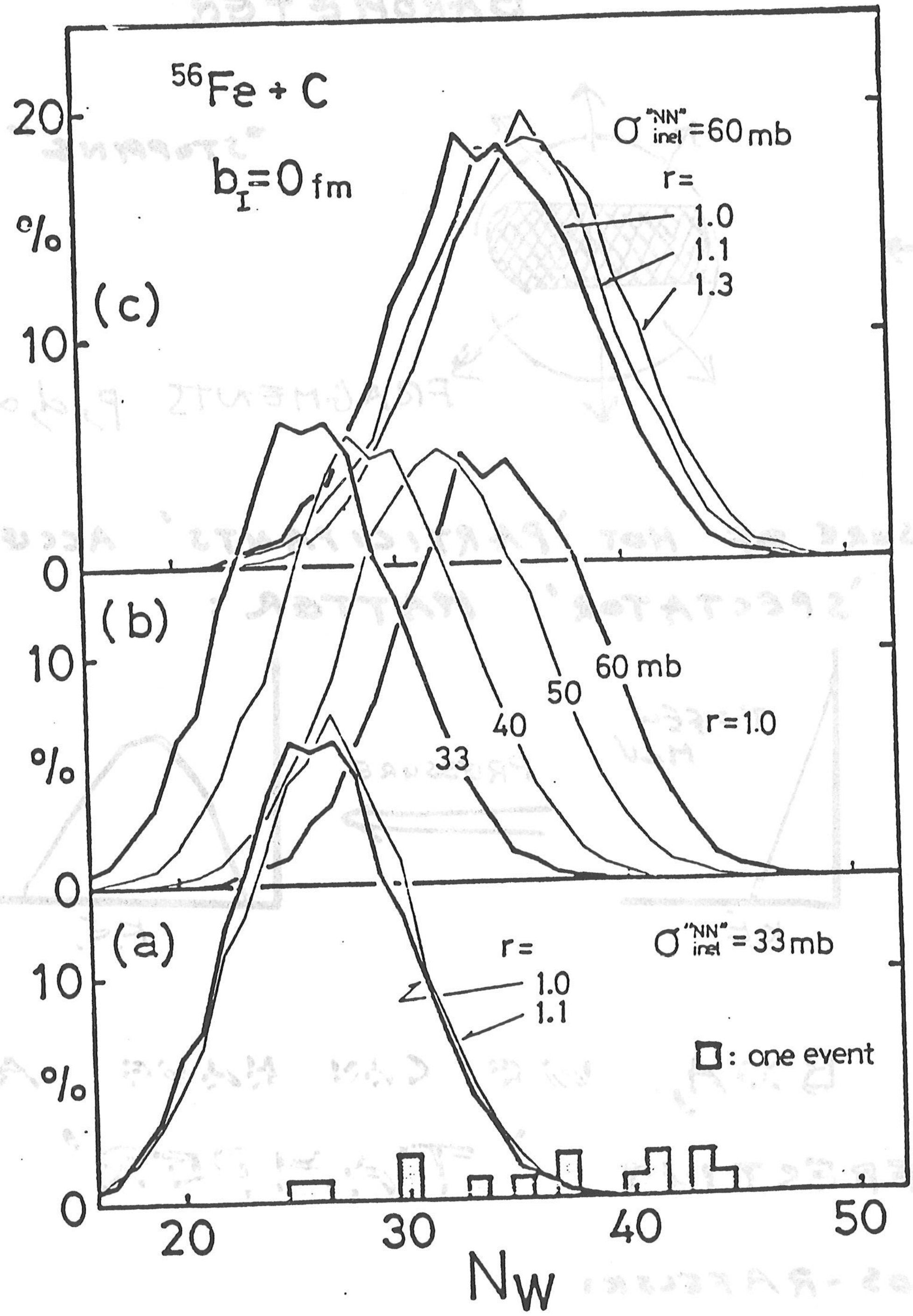


PRESSURE OF HOT 'PARTICIPANTS' ACCELERATES THE 'SPECTATOR' MATTER:



FOR B>>A, WE CAN HAVE AN EFFECTIVE 'TAMPER'

DANOS - RAFELSKI



⁵⁶Fe + C
b_I = 0 fm
σ"NN" inel = 60 mb
r=
1.0
1.1
1.3
(c)
20
10
%
0
(b)
10
%
60 mb
50
40
33
r=1.0
0
(a)
10
%
r=
1.0
1.1
σ"NN" inel = 33 mb
: one event
0
20
30
40
50
Nw

Fig. 3

JACEE-3

ICR 25-12-85

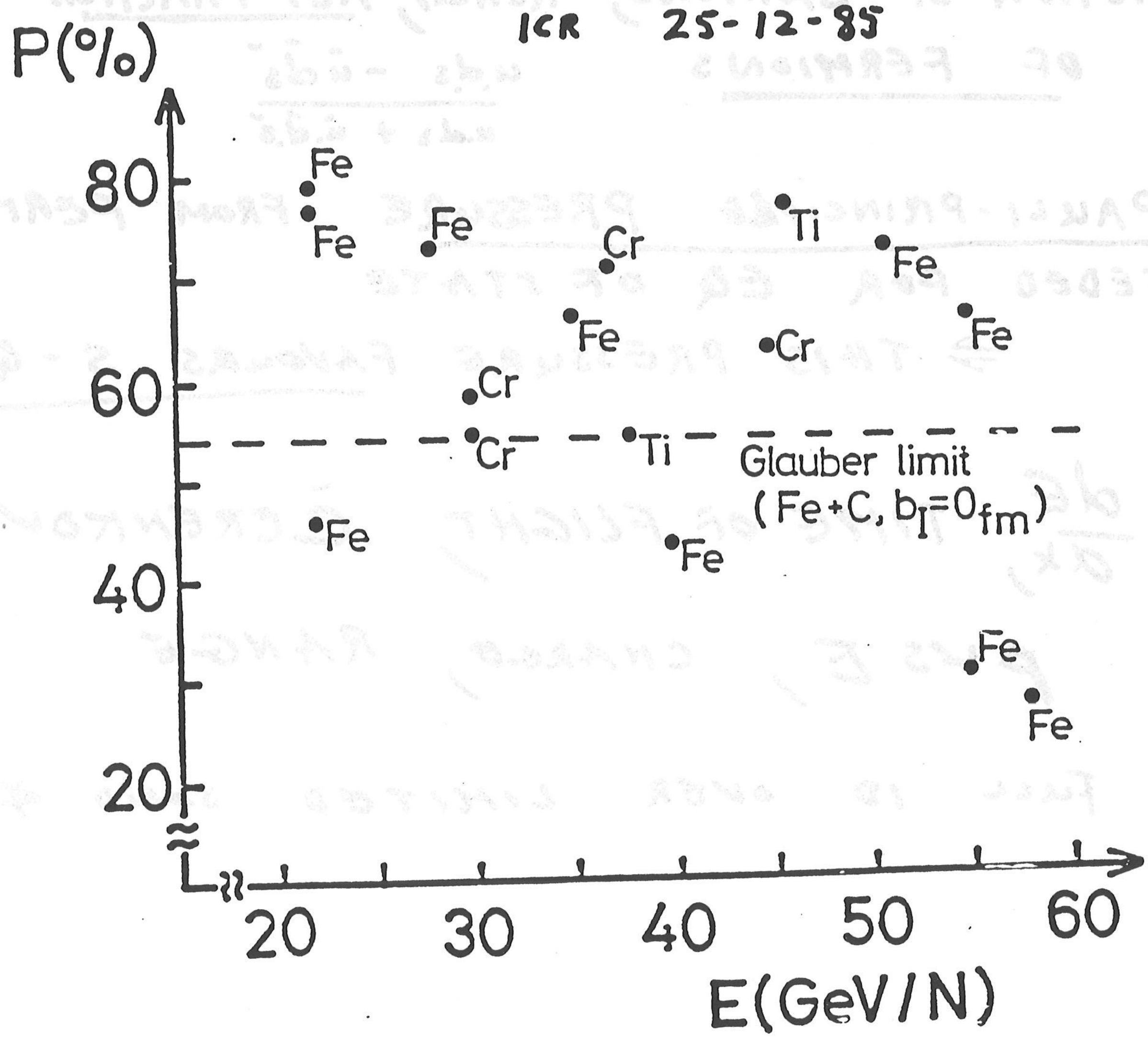


Fig.1

- FRACTION OF ENERGY IN BARYONS
- FRACTION OF $s/_{u+d}$ QUARKS

MEASURED BY PARTICLE IDENTIFIERS

FRACTION OF BARYONS, REALLY, NET FRACTION OF FERMIONS $\frac{u.d.s - \bar{u}\bar{d}\bar{s}}{u.d.s + \bar{u}.\bar{d}.\bar{s}}$

PAULI-PRINCIPLE PRESSURE FROM FERMI-SEA NEEDED FOR EQ OF STATE

$\Rightarrow$ THIS PRESSURE FAVOURS S-QUARKS

$\frac{dE}{dx}$, TIME OF FLIGHT, ČERENKOV

p vs E, CHARGE, RANGE

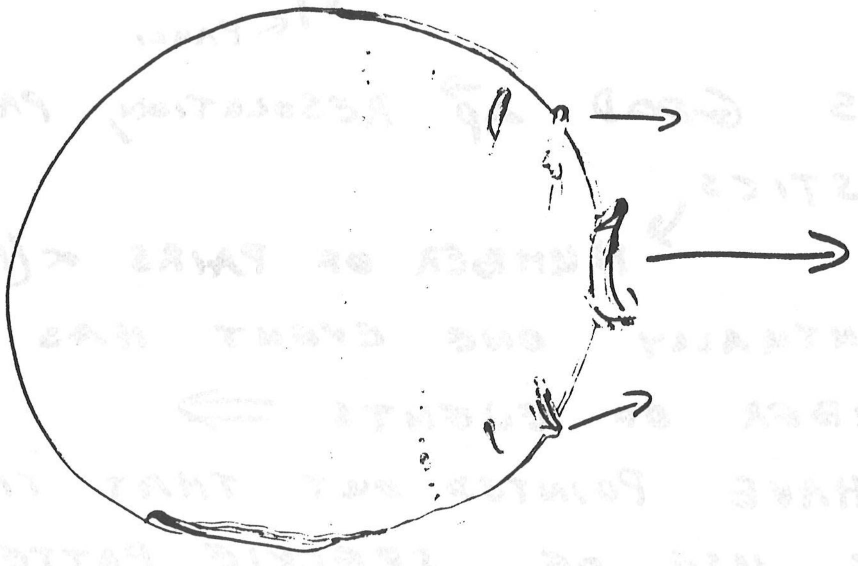
FULL ID OVER LIMITED SOLID ∡

INTERNAL WAVES, SHOCKS AND DEFLAGRATIONS

MEASURED BY A

SEISMOGRAPH

PREVIOUSLY DESCRIBED RADIAL FLOW, OR 'BLAST WAVE,' RADIALLY UNIFORM SO EXPLICIT VELOCITY MEAS. NECESSARY : INSTABILITIES DEVELOPE ~ ALONG A VECTOR



EASIER TO SEE, LIKE A JET, BUT NOT A PARTON JET, CALL THEM

SUPERJETS ($P_{JET} \gg \sqrt{s}_{pp}$)

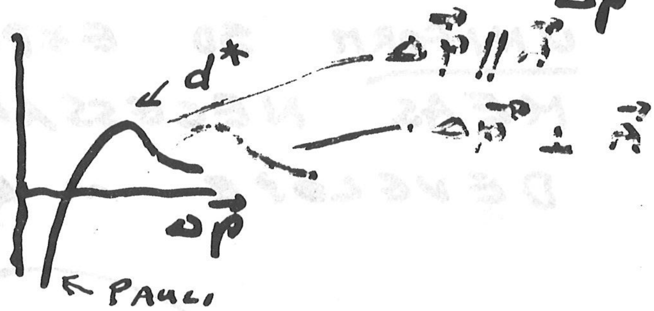
$$\frac{dE_T}{d\Omega}, \quad \frac{dn_c}{d\Omega}, \quad \frac{d}{d\Omega}\text{(PARTICLE FRACTION)}$$

$$\frac{d}{d\Omega}(\overline{P_T}) \quad - - -$$

SPATIAL DISTRIBUTIONS
MEASURED BY
INTERFEROMETERS

LIKE PARTICLES PRODUCE INTERFERENCE PATTERN WITH WIDTH $\Delta p \cdot R = \hbar$
(HANBURY BROWN, TWISS, GOLDHABER², PAIS)
HAS BEEN APPLIED TO

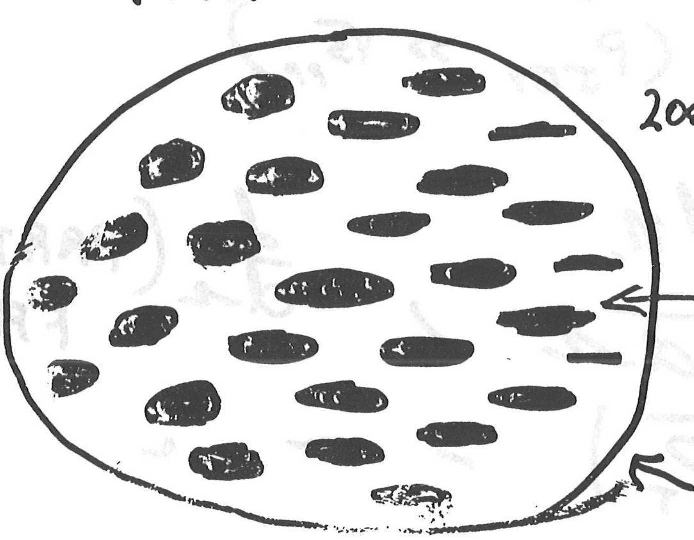
π, K, PROTON →



α's SHOULD BE GOOD

NEEDS GOOD $\vec{\Delta p}$ RESOLUTION, PARTICLE I.D.
STATISTICS ↘
NUMBER OF PAIRS ∝ (MULT.)²
EVENTUALLY ONE EVENT HAS THE RQD NUMBER OF EVENTS ⟹
I HAVE POINTED OUT THAT THIS ALLOWS THE USE OF SPECKLE PATTERN INTERFEROMETRY, A KIND OF PRIMITIVE **HOLOGRAM**

S + Pb →



$200 < p_\pi < 250$ MeV/c

π INTENSITY

$N_\pi \gtrsim 1000$

DETECTOR SURFACE

"EXOTIC" PHENOMENA

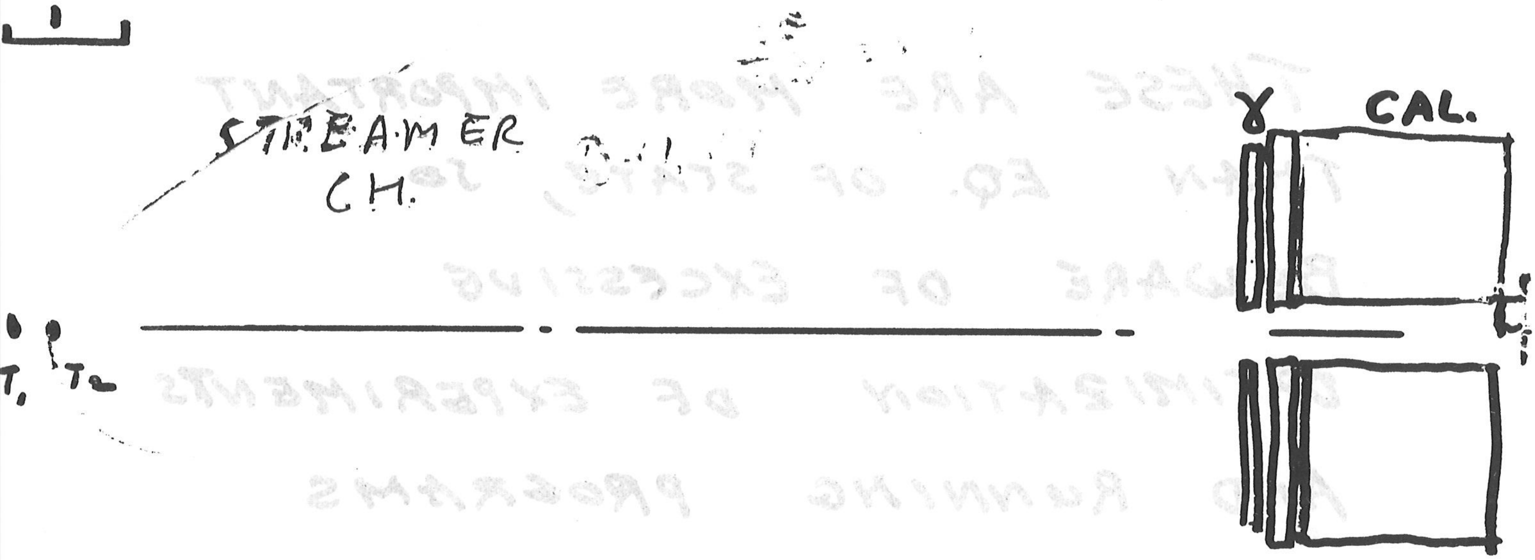
E.G. · SOMETHING NEW + QUASI STABLE
· CLEARLY ABNORMAL DYNAMICS

THESE ARE MORE IMPORTANT THAN EQ. OF STATE, SO BEWARE OF EXCESSIVE OPTIMIZATION OF EXPERIMENTS AND RUNNING PROGRAMS ON THE PHYSICS I'VE BEEN DESCRIBING.

NA 35

STREAMER CHAMBER (NA5, UA5)

CALORIMETER (NA5 + γ NA24)



~1% INT. L TARGET, + X_e EVENTS

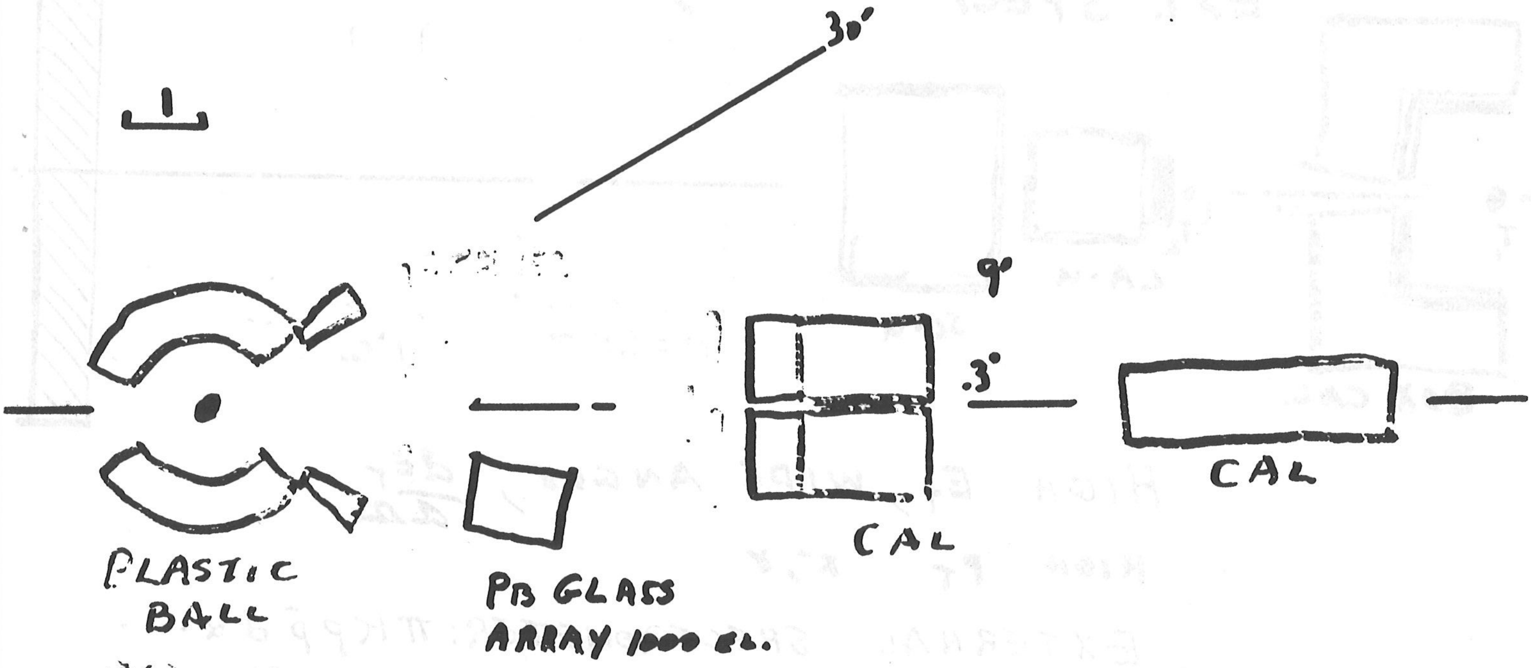
<u>EMPHASIS ON SYMMETRICAL COLLISIONS</u>
<u>FOR HEAVIER BEAMS</u>

HIGH P_T γ, π^0

"SUPER JET" TRIGGER

WA 80 PLASTIC BALL

PLASTIC BALL (BEVALAC)
NEW CAL., PB GLASS, MULTI PAD. CH.



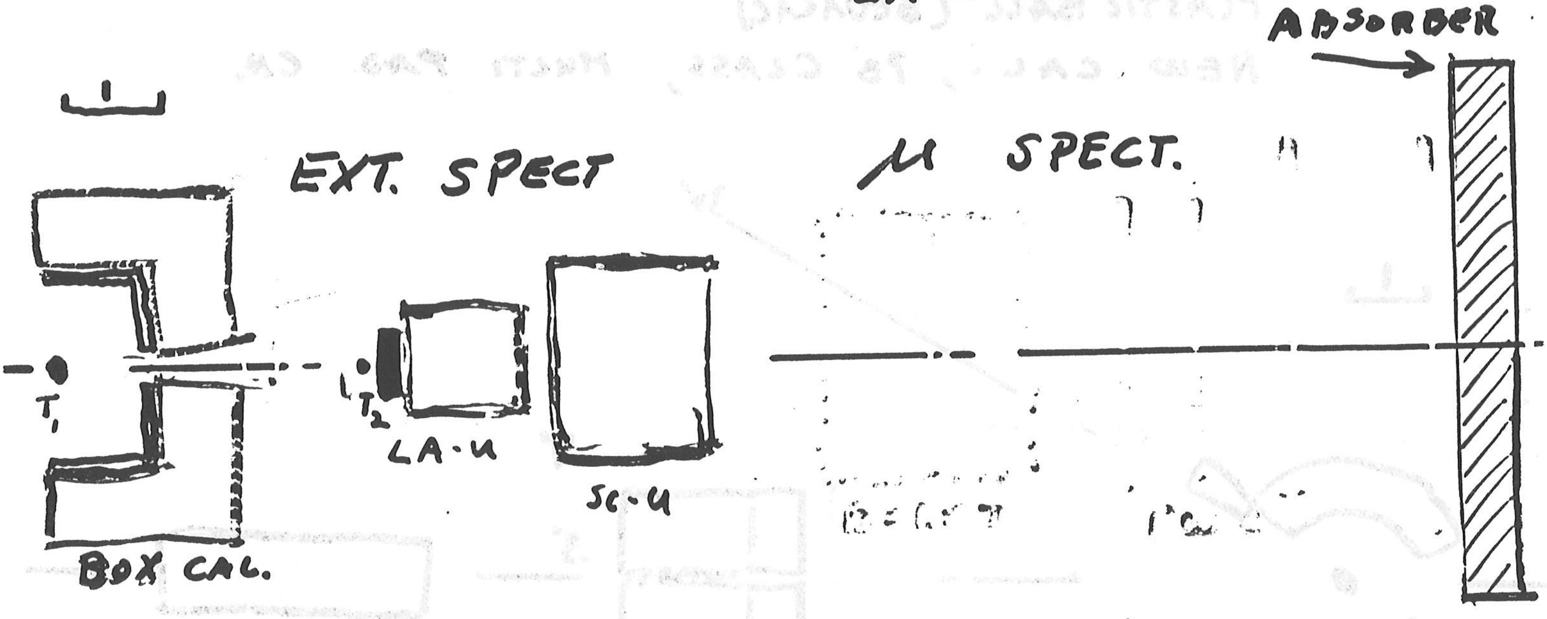
HIGH P_T γ, π^0

HIGH E_T, $\frac{dE}{d\Omega}$

VERY GOOD TARGET FRAG.!

HELIOS / NA-34-2

(NA3, AFS)
EXT. SPECTR.
LA-U CAL.

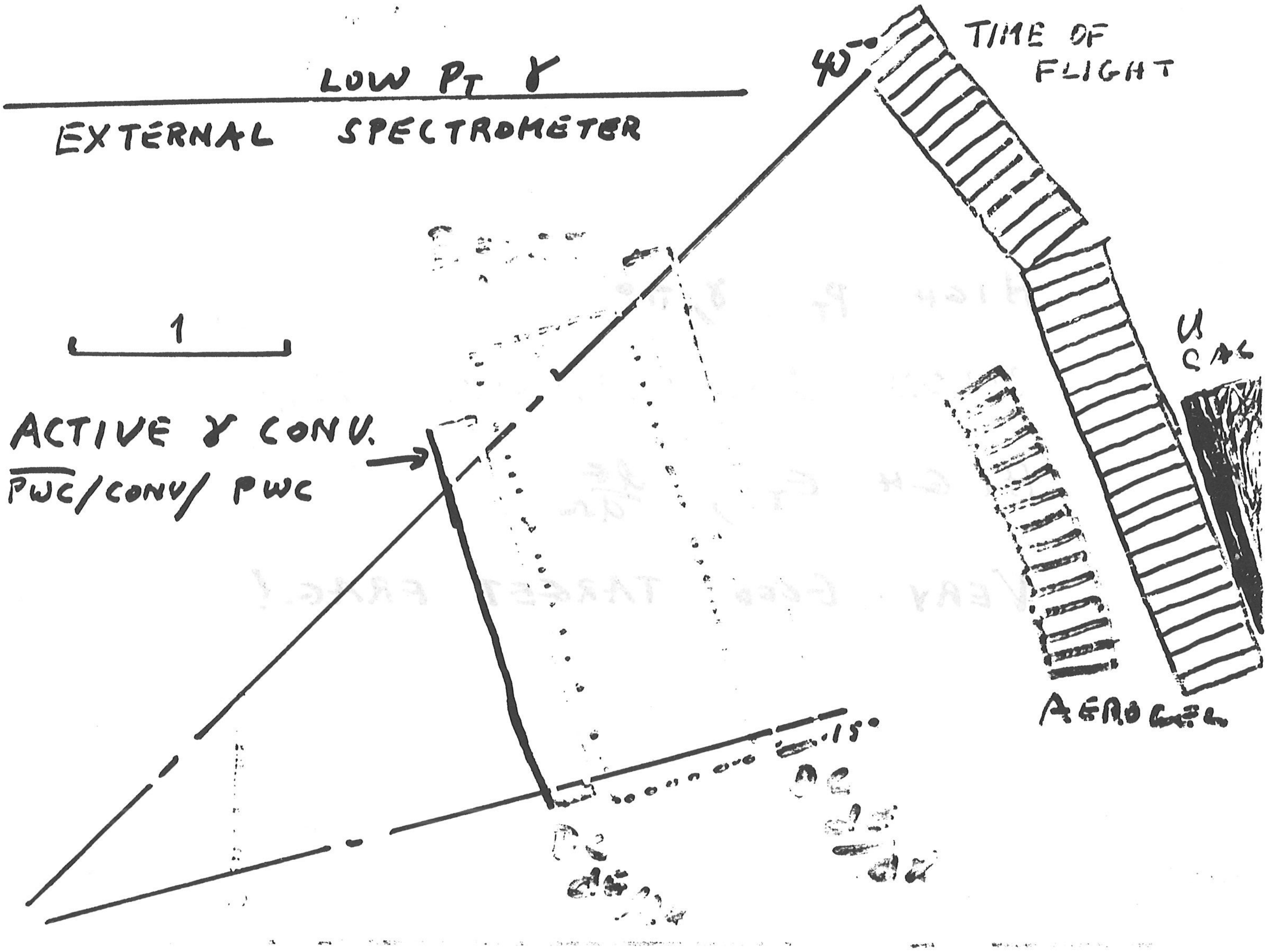


HIGH E_T, WIDE ANGLE, $\frac{dE_T}{d\Omega}$

HIGH P_T π^0, γ

EXTERNAL SPECTROMETER: $\pi K p \bar{p} d \alpha \ldots$

LOW P_T γ EXTERNAL SPECTROMETER



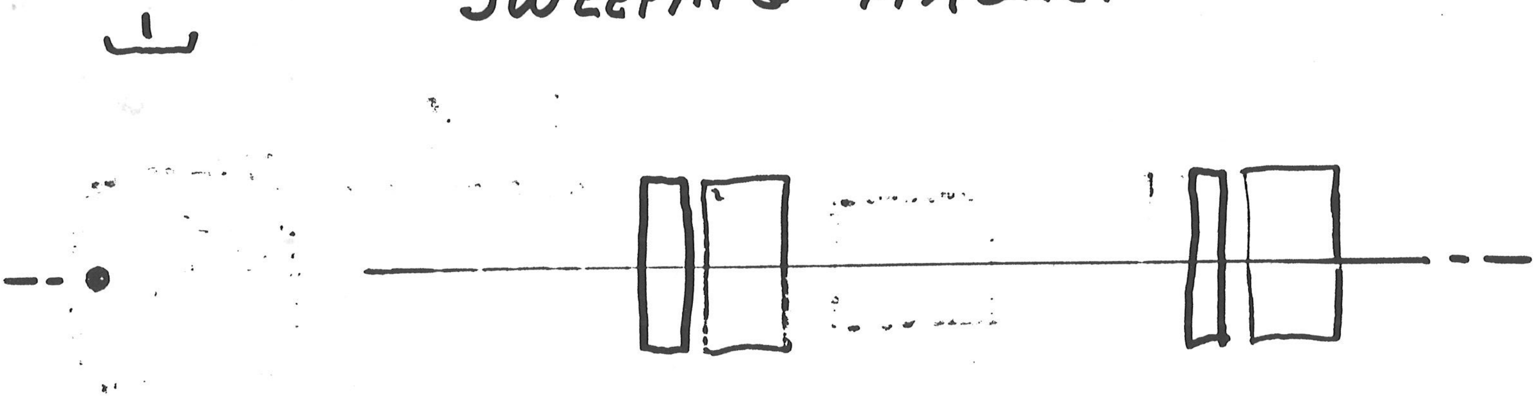
NA36 TIME PROJECTION CHAMBER (EHS+)

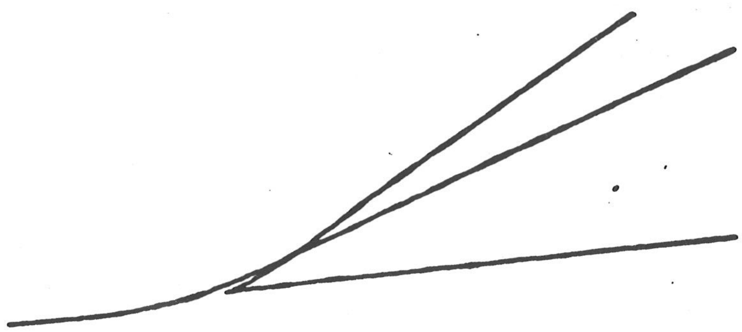
- RELATIVELY HIGH RATE, HIGH MULTIPLICITY CAPABILITY, ELECTRONIC DEVICE

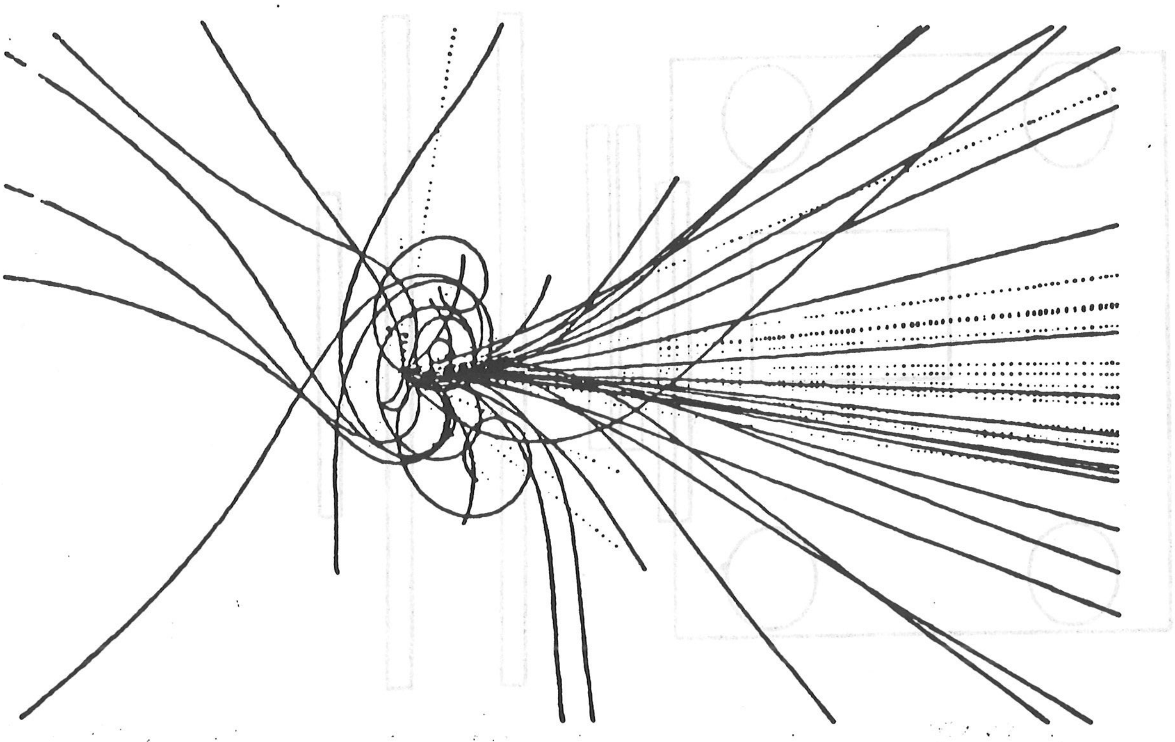
Λ K^0_S Σ^- Ξ^-

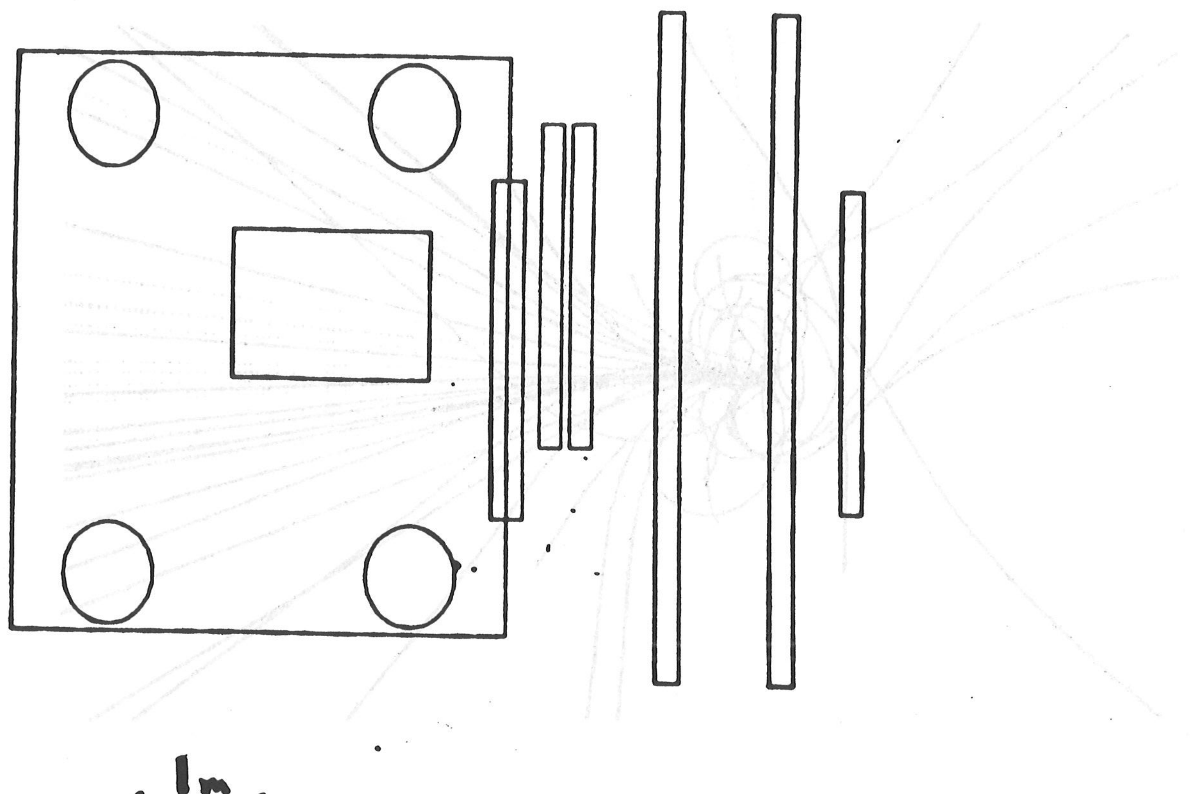
$\bar{\Lambda}$ $\bar{\Sigma}^-$ $\bar{\Xi}^-$

SWEEPING MAGNET





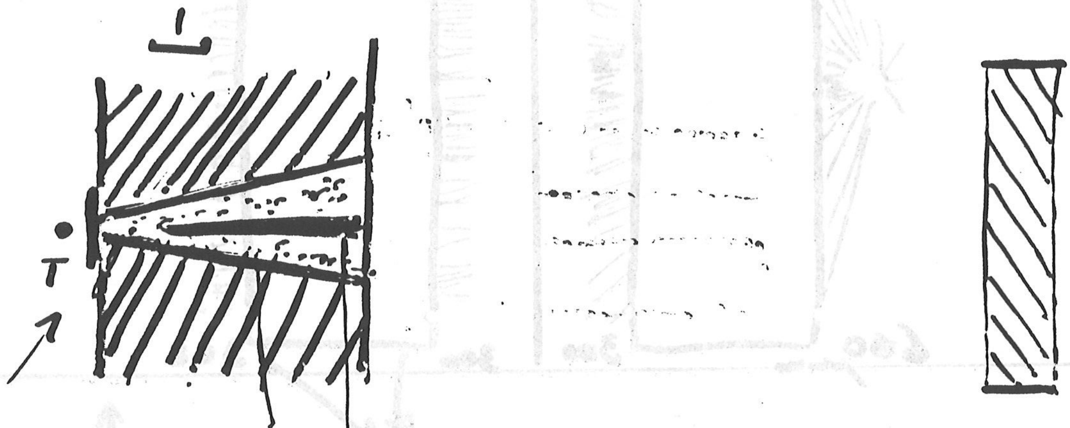



1m

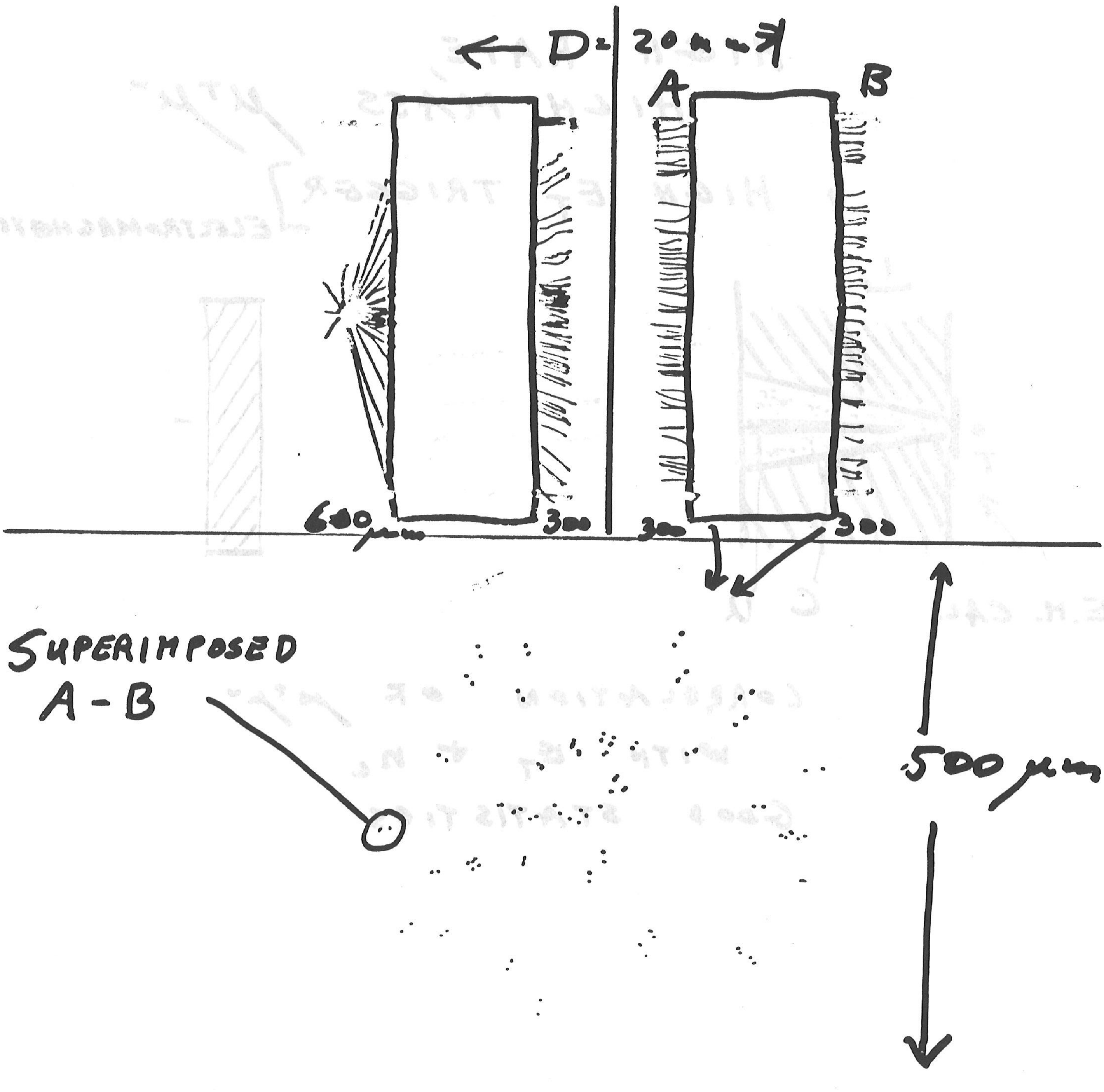
NA-38 MUON SPECTROMETER (NA10)

HIGH RATE,
HIGH MASS $\mu^+\mu^-$

+ HIGH E_T TRIGGER] ELECTROMAGNETIC



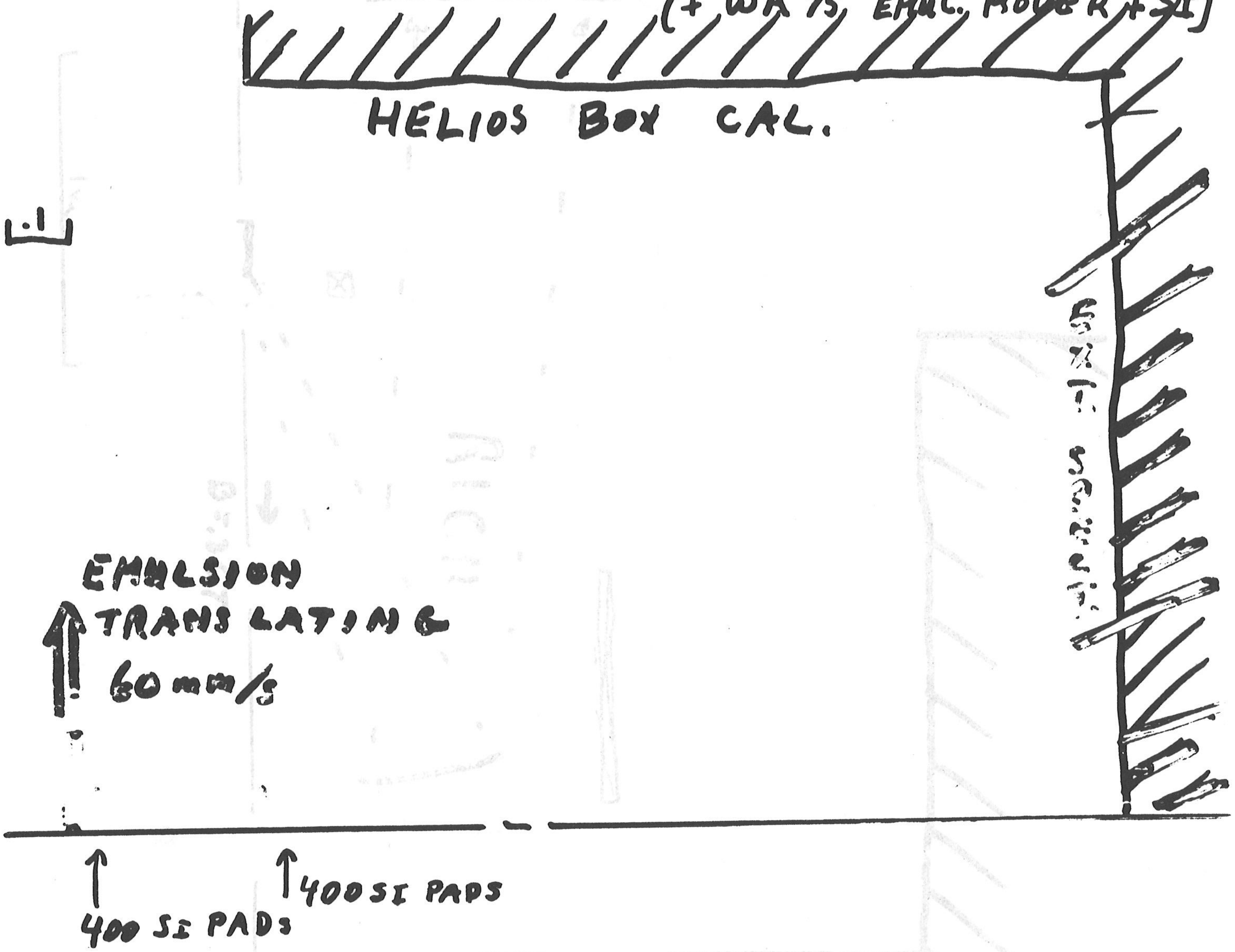
CORRELATION OF $\mu^+\mu^-$
WITH E_T + n_c
GOOD STATISTICS



MULTIPLICITY DIST.
PSEUDO-RAPIDITY DIST
FLUCTUATIONS
TARGET FRAGMENTS
PRODUCTION + INTERACTION
OF PROJECTILE FRAGMENTS
$z = 2 - 8$

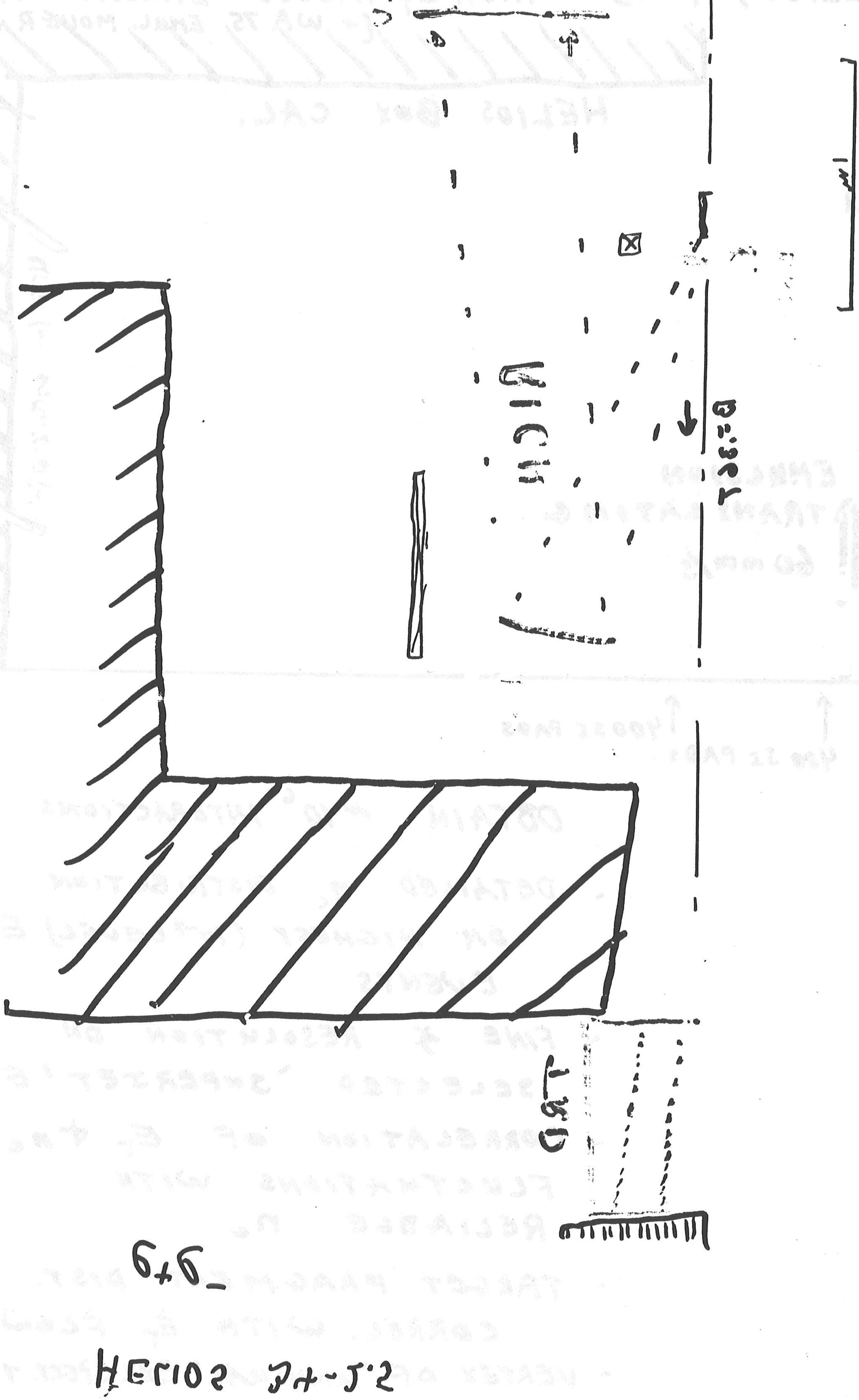
HELIOS / P213 HIGH E_T TAGGED EMULSION CH.

(+ WA 75, EMUL. MOVER + SI)



OBTAIN ~10^6 INTERACTIONS

- DETAILED n_c DISTRIBUTION ON HIGHEST (10^{-4} LEVEL) E_T EVENTS
- FINE η RESOLUTION ON SELECTED 'SUPERJET' EVENT
- CORRELATION OF E_T + n_c FLUCTUATIONS WITH RELIABLE n_c
- TARGET FRAGMENT DIST. CORREL. WITH E_T FLOW
- VERTEX OF 'UNUSUAL' EXT. SPECT. TRACKS



ASSERTION BECAUSE OF THE BIG JUMP IN ENERGY <u>AND</u> THE VERY POWERFUL ARRAY OF EXPERIMENTS AVAILABLE ALL AT ONCE,

THERE HAS NEVER BEEN THE FLOOD OF NEW INFORMATION AS THAT EXPECTED FROM THESE RUNS

WE MAY HOPE FOR SOME GOOD PHYSICS!