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CERN

Cours/Lecture Series

1983 – 1984 ACADEMIC TRAINING PROGRAMME

SPEAKER : M. GYULASSY / LBL, Berkeley
TITLE : Searching for the quark-gluon plasma at CERN and elsewhere
DATES : June 25, 26, 27, 1984
TIME : 11.00 hours
PLACE : Auditorium

ABSTRACT

Three lectures are aimed at clarifying the new physics potential of very high energy nuclear collisions. At energy densities only ten times higher than that of ordinary nuclei, hadronic matter may dissolve into new quark-gluon plasma state. Current speculations on the nature of that phase are reviewed. We address in detail the problem of generating the required energy densities in nuclear collisions. The stopping power of nuclei and nuclear transparency at high energies are discussed. The essential role of forthcoming CERN experiments in this regard with $^{16}0$ beams from 10 to 200 GeV per nucleon are emphasized. Production of baryon rich plasmas using heavier nuclei and low baryon density plasmas at higher energies are discussed. Finally, we present a critical analysis of proposed signatures of the plasma.

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Academic Training Programme CERN June 25-27, 1984

by Miklos Gyulassy (LBL)

Lecture I

Searching for the QCD Plasma at CERN and elsewhere

Monday
1. Thermodynamics of Dense Matter
   $\epsilon \sim 10\epsilon_{Nuc}$ interesting
2. Achieving $10\epsilon_{Nuc}$ via U+U at $10\frac{GeV}{A}$
   high ρ_B plasmas

Tuesday
3. Nuclear transparency
   new p+A data and interpretations
   $\rightarrow$ need for ^{16}O+Pb at CERN
4. Achieving $10\epsilon_{Nuc}$ beyond 1 TeV/A
   low ρ_B plasmas

Wed.
5. Diagnostic Tools

Thermometers	$\mu^+\mu^-$, γ
Barometers	$\langle p_\perp \rangle$
Seismometers	$\frac{dN}{dy}$ fluctuations

Ref: BNL Workshop Nuc. Phys. A418 1984

atives 83 { HEPAP → NO CBA .4+.4 TeV pp
→ YES SSC 20+20 TeV pp

NUSAC → NO LAMPF II K factory
→ YES RNC 30+30 GeV/A U+U
Relativistic Nuclear Collider

Lure of SSC : Higgs, ℓ^*, q^*, W^*

Lure of RNC: QCD Plasma

$\bar{p}p$ = poor man's e^+e^- → probe $d \ll \Lambda_{QCD}^{-1}$

UU = poor man's big bang → probe $d \gg \Lambda_{QCD}^{-1}$

Current frontiers:

micro – ν, t, W macro – T < 100 MeV

Next interesting scale

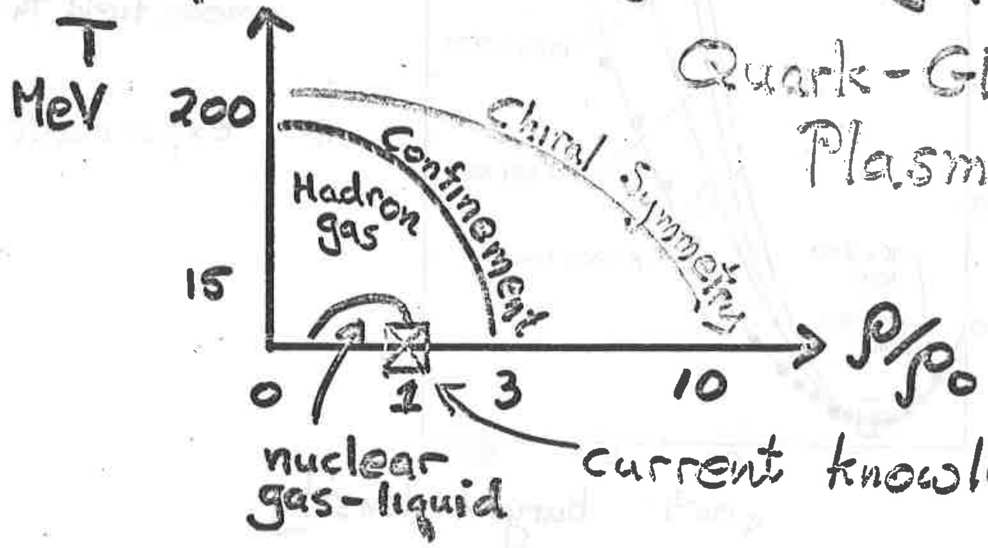
$m \sim 1$ TeV $\sim 10\, m_W$ T ~ 200 MeV

$\hookrightarrow \epsilon \sim 10\, \epsilon_{Nuc} \sim 2\ \frac{GeV}{fm^3}$

Nuclear and Hadronic Matter Physics

Goal is to learn about:

1. Temperature, Baryon density phase diag.

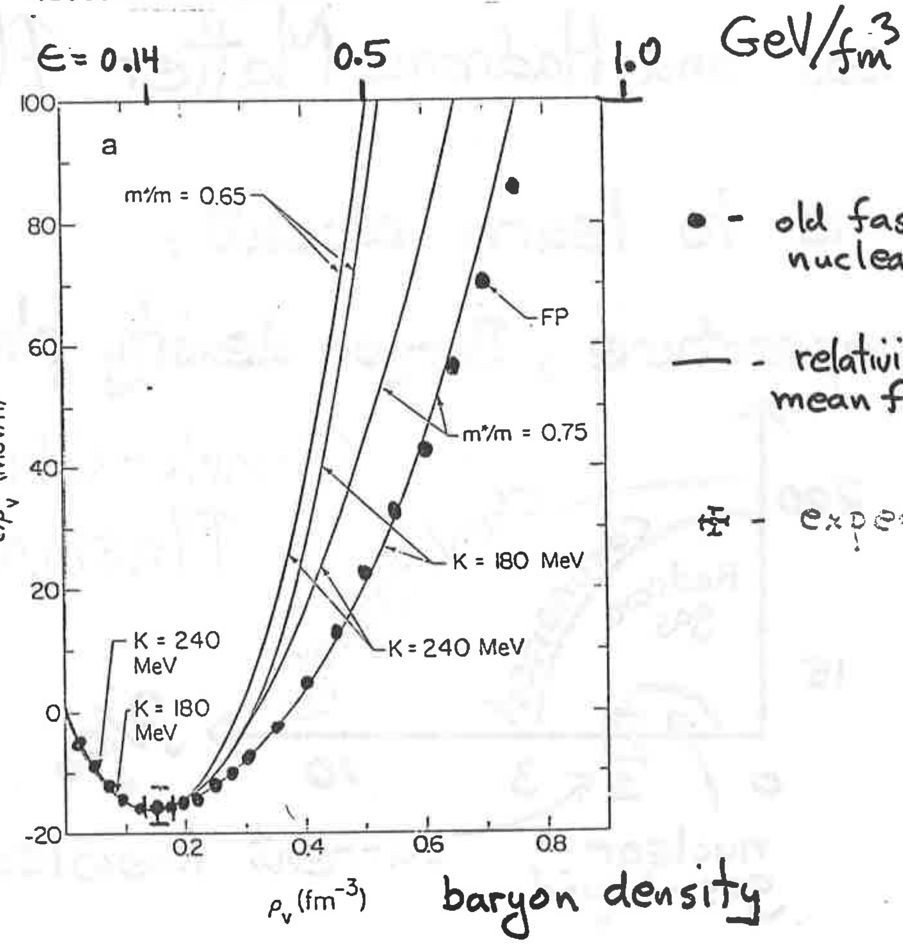


2. Thermodynamics of matter:
   energy density, pressure, entropy
   $\varepsilon(\mu,T)$, $p(\mu,T)$, $\sigma(\mu,T)$

3. Transport properties
   stopping power $-dE/dx$
   viscous, thermal conductivity coef.
   particle production/absorbtion mech.

SYSTEMATICS OF NUCLEAR MATTER PROPERTIES
IN A NON-LINEAR RELATIVISTIC FIELD THEORY

J. BOGUTA and H. STOCKER



$\frac{E_B}{A}$

binding energy

• - old fashion nuclear theory

— - relativistic mean field th.

experiment

baryon density

possible density isomers Boguta, Glendenning

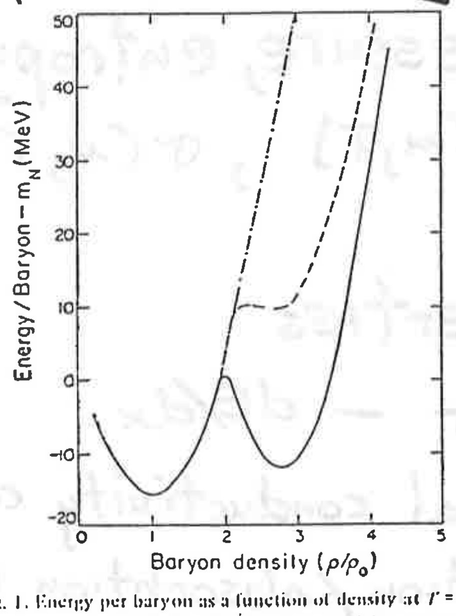


Fig. 1. Energy per baryon as a function of density at $T = 0$. The dot–dash curve is for the case when no delta resonances are included. The solid curve is for $\varkappa_S/\varkappa_{SN} = 1.4$ and the broken curve is for $\varkappa_S/\varkappa_{SN} = 1.35$.

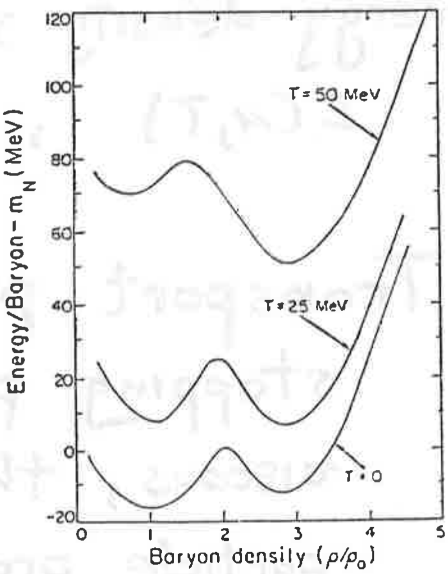


Fig. 2. Ground state and thermal excitations of nuclear matter for $\varkappa_S/\varkappa_{SN} = 1.4$ and $T = 0$, 25 MeV and 50 MeV.

How far can nuclear/hadron theory be pushed?

before 1979 – Statistical Bootstrap — Hagedorn, Frautschi …

exponential resonance spectrum

$$\rho(m) \sim \frac{1}{m^3} e^{m/m_\pi}$$

$\Rightarrow$ energy density $\epsilon_{SB} \xrightarrow[T \to m_\pi]{} \infty$

$\Rightarrow$ can push hard!

After 1979 – Finite Volume Correction — Rafelski, Hagedorn

$$V(m) = \frac{m}{4B} \qquad B \sim 200 \frac{\text{MeV}}{\text{fm}^3} \text{ is vacuum pressure}$$

$$\epsilon = \frac{\epsilon_{SB}}{1 + \epsilon_{SB}/4B} \xrightarrow[T \to m_\pi]{} 4B < \infty \;!$$

$\Rightarrow$ hadron theory exists only up to

$$\epsilon_c \sim 4B \approx 1 \text{ GeV/fm}^3 \;!!$$

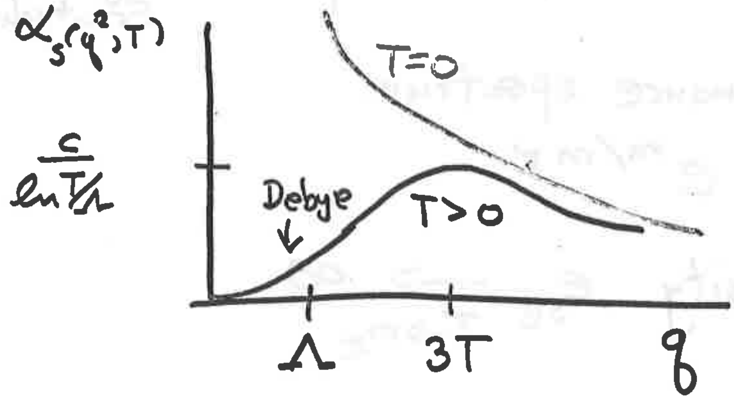
Matter from the QCD side

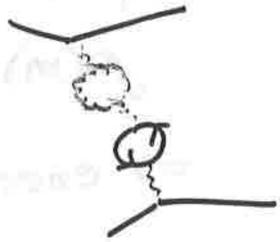
Asymptotic Freedom

Kapusta, Gendenshtein, Soni, ...

$$\Rightarrow \alpha_s(q^2, T) = \frac{4\pi}{(11 - \frac{2}{3} n_f) \ln q^2/\Lambda^2 + aT^2/q^2}$$

electric screening





$\alpha_s \to 0$ for $T/\Lambda \to \infty$

$\Rightarrow$ asymptotic properties are simple ideal Stefan Boltzman gas (plasma)

$$\epsilon(T) = KT^4 (1 + O(\alpha_s))$$

!! Warning: magnetic sector unshielded $m_g = 0 + O(g^2)T$

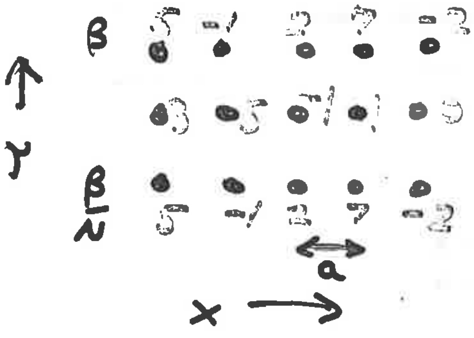
But for $T \sim \Lambda \sim 100 - 500$ MeV α_s becomes large

$\Rightarrow$ expect qualitative change for

$$T \sim \Lambda_{QCD} \Rightarrow \epsilon_c \sim 12 \Lambda^4 \sim 2 \frac{GeV}{fm^3}$$

QCD Thermodynamics on a Lattice

Partition function $Z = Tr\, e^{-\beta H}$ $\quad \beta = \frac{1}{T}$



$$= \lim_{N\to\infty} \sum_{1\cdots N} \langle 1|1-\tfrac{\beta}{N}H|2\rangle \cdots \langle N|1-\tfrac{\beta}{N}H|1\rangle$$

$$= \int \Pi\, dA^{\alpha}_{\mu}(x_i,\tau_i)\; e^{-\frac{\beta}{N}\sum_i a \sum_j \mathcal{L}_{QCD}(x_i, ja)\,\tau = \frac{i\beta}{N}}$$

$$A(x,\beta) = A(x,0)$$

$\sim 10^4$ dimensional integral via Monte Carlo

Free energy of <u>static</u> $q\bar{q}$ pair at $x = y_1$ and y_2

$$H_{ex} = \int d^3x\, J^{\mu\alpha}_{ex} A_{\mu\alpha}$$

$$J_{ex} = \delta_{\mu 0} \frac{\lambda^\alpha}{2}\left[\delta(x-y_1) - \delta(x-y_2)\right]$$

$$e^{-F_{q\bar{q}}(y_1\, y_2)/T} = \frac{1}{Z} Tr\, e^{-\beta(H_0 + H_{ex})}$$

$$= \langle L(y_1) L^{+}(y_2)\rangle$$

$$L(x) = tr_\lambda \exp\left\{ i\int_0^\beta d\tau\, A_0^\alpha(x,\tau) \lambda^\alpha/2 \right\}$$

= thermal Wilson line integral

For $|y_1 - y_2| \to \infty$ $\quad \langle L_{y_1} L^{+}_{y_2}\rangle \xrightarrow{\text{deconf.}} \langle L_{y_1}\rangle \langle L^{+}_{y_2}\rangle = \text{con}$

If $\langle L\rangle = 0$ then $\quad F_{q\bar{q}} \to \infty \Rightarrow$ confinement

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North-Holland, Amsterdam

COLOUR SCREENING IN SU(N) GAUGE THEORY AT FINITE TEMPERATURE

Helmut SATZ

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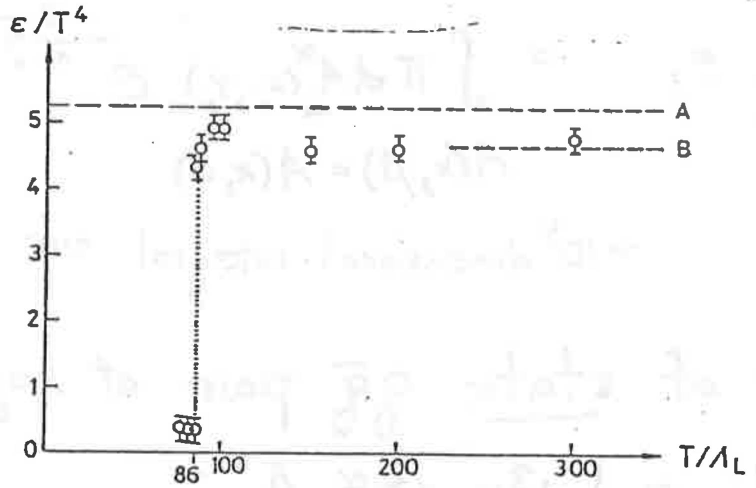

FIGURE 3

Energy density ε of the SU(3) Yang-Mills system, evaluated on an 8^3x3 lattice, with finite lattice corrections, compared to the ideal gas limit without (A) and with (B) colour neutrality correction

$e^{-\text{"}M_q\text{"}/T} \sim$

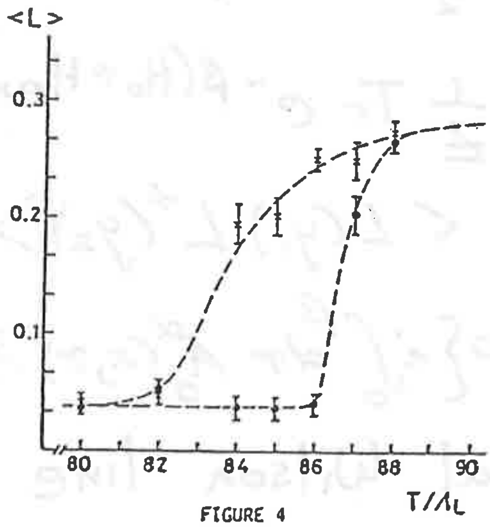

FIGURE 4

Order parameter <L> of the SU(3) Yang-Mills system, evaluated on an 8^3x3 lattice, with ordered (x) and with random (•) starting configuration

9

With light fermions maybe 2^{nd} order

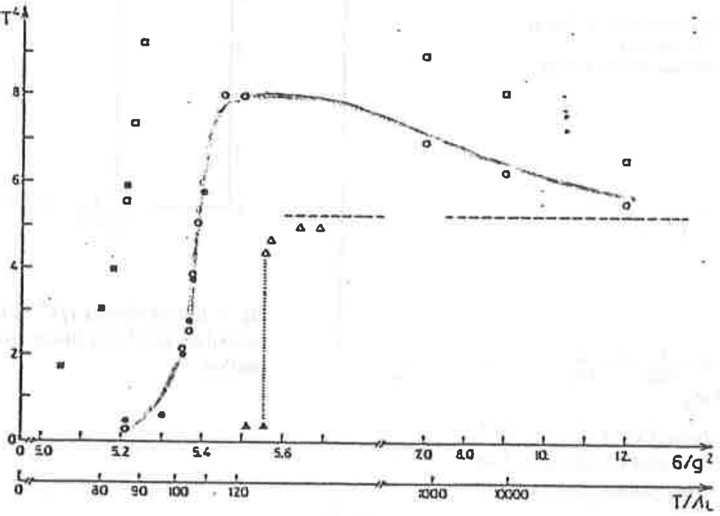

FIGURE 7

Energy density of the gluon sector, with virtual quark loops, as function of $6/g^2$ and of T/Λ_L, for $\varkappa$=0.20 (squares), 0.15 (circles), 0 (triangles); for $\varkappa$=0 the T/Λ_L scale does not apply. Open symbols denote ordered, solid ones disordered start; the dashed line is the ideal gas limit.

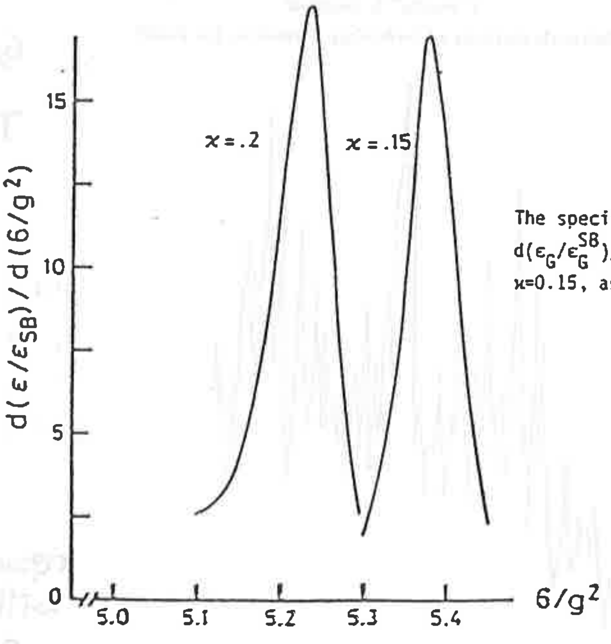

FIGURE 8

The specific heat measure $d(\varepsilon_G/\varepsilon_G^{SB})/d(6/g^2) \sim c_V$, for $\varkappa$=0.15, as function of $6/g^2$

SU(3) no internal quark loops

Kogut, ...

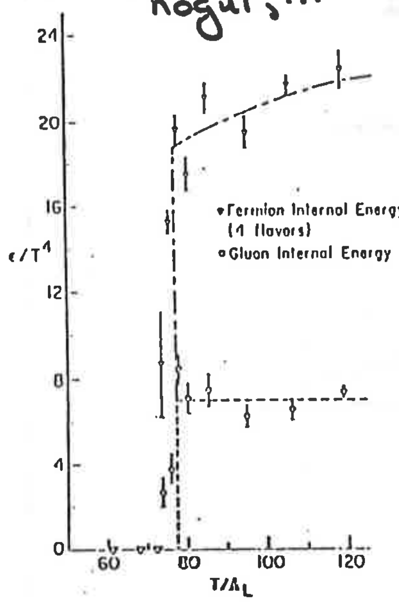

FIG. 3. Gluon and quark internal energies, ϵ_g/T^4 and ϵ_f/T^4, vs T/Λ_L. The free-field limits on a 4×8^3 lattice are approximately 7.5 for gluons and 24.5 for quarks.

Satz, ...

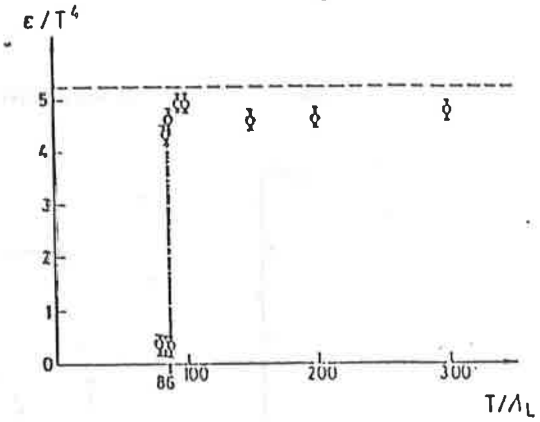

Fig. 4. Energy density ϵ/T^4 as function of temperature, calculated on an $8^3 \times 3$ lattice, using the renormalization group relation.

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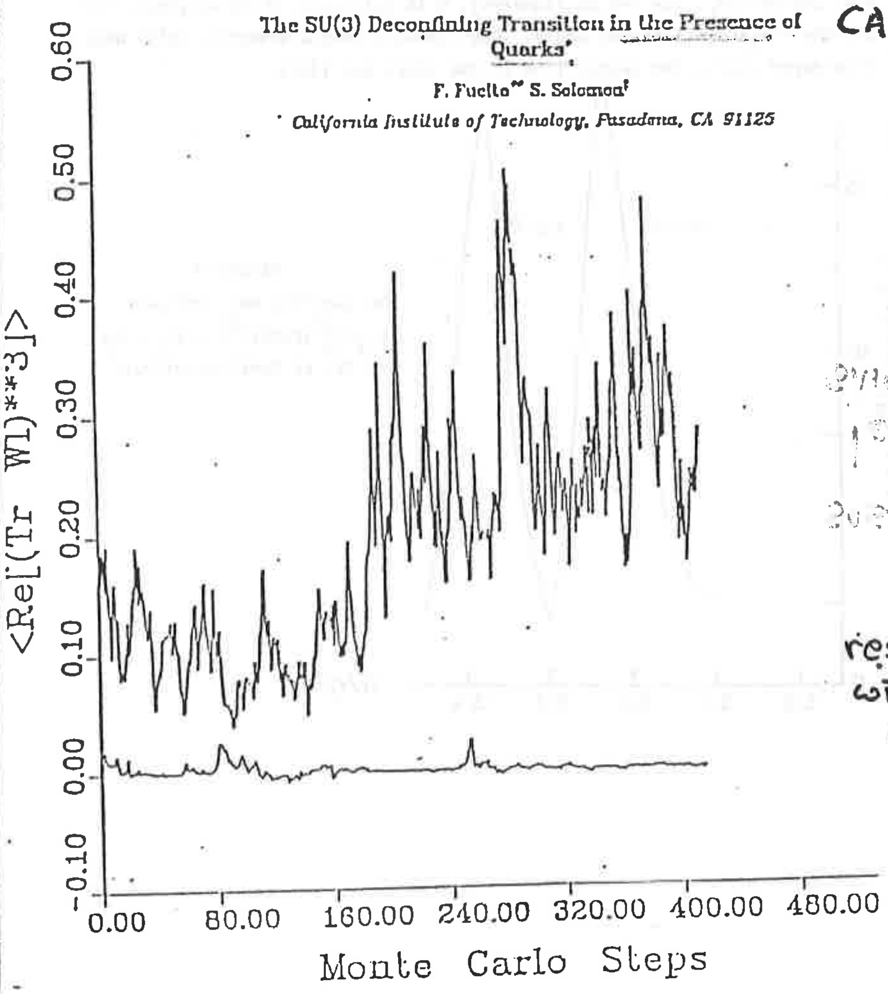
The SU(3) Deconfining Transition in the Presence of Quarks*

F. Fucito** S. Solomon†
California Institute of Technology, Pasadena, CA 91125



$6/g_c^2 = 5.6 \pm .1$

$T_c/\Lambda_L = 300 \pm 50$

evidence for 1st order even with quarks

results disagree with hopping para expansion ??

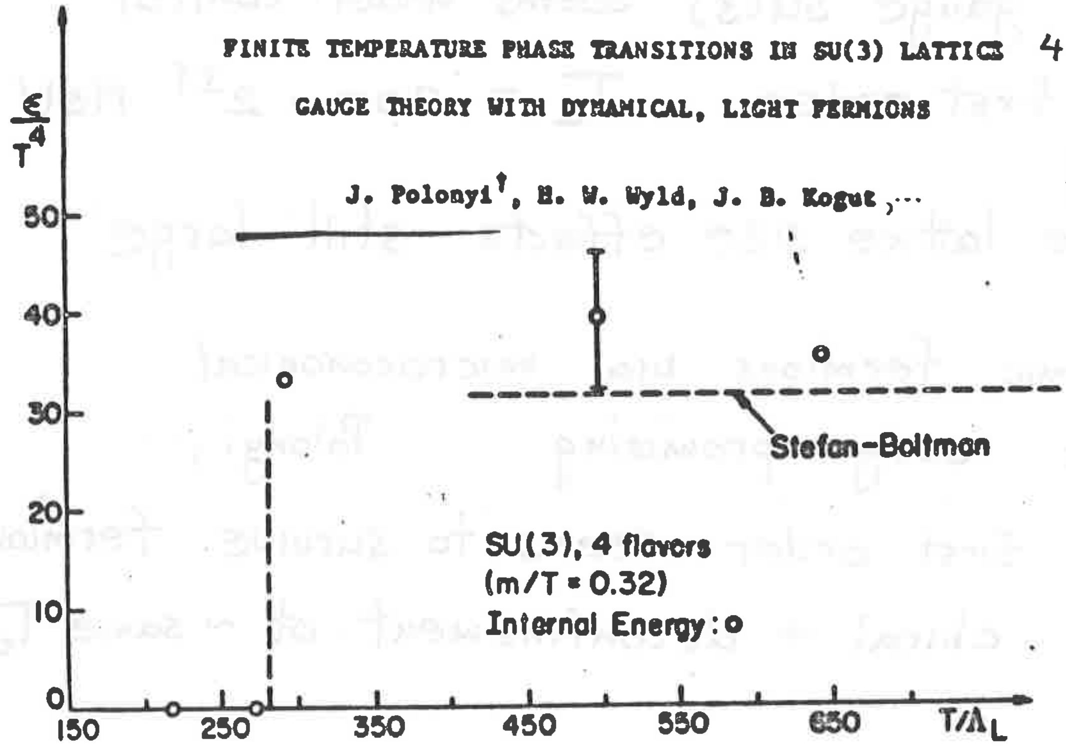
ILL-(TH)-84-22
May 1984

FINITE TEMPERATURE PHASE TRANSITIONS IN SU(3) LATTICE GAUGE THEORY WITH DYNAMICAL, LIGHT FERMIONS

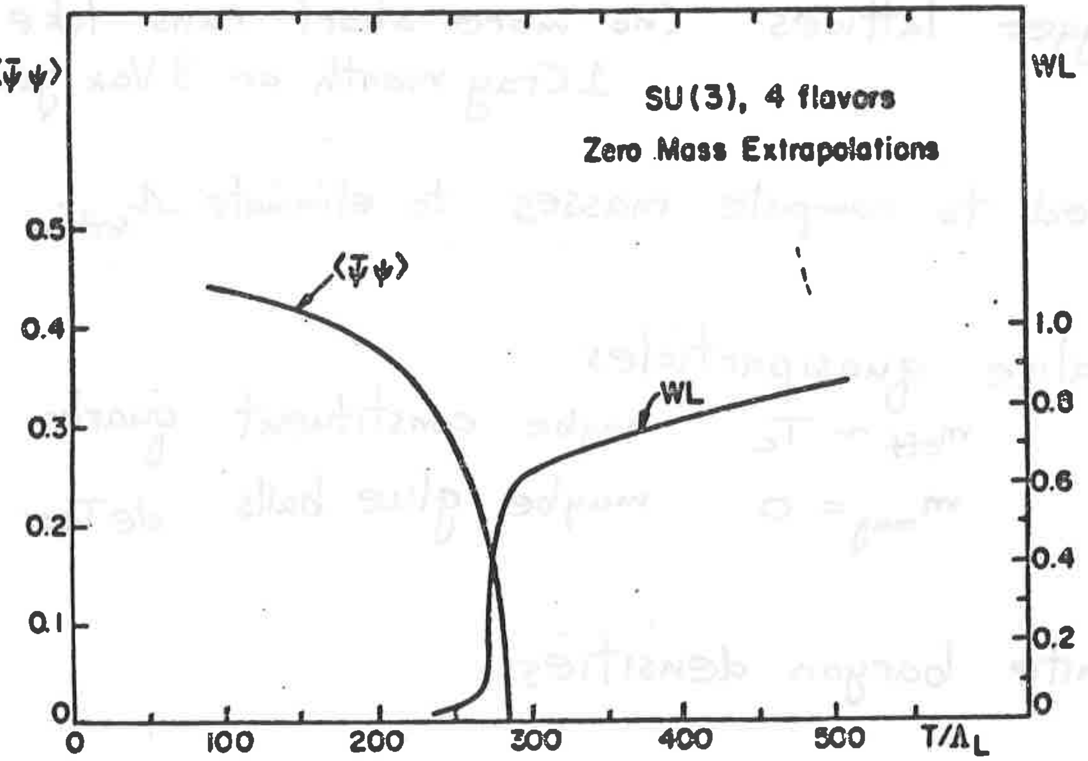
4×8^3

J. Polonyi[†], H. W. Wyld, J. B. Kogut, ...

$\frac{\Lambda_L}{\sqrt{\sigma}} \sim 10^{-3}$



$T_c \approx 280 \Lambda_L$
$\approx .28 \sqrt{\sigma} \cdot 2^{\pm}$
~100-300 MeV



Status of the Lattice

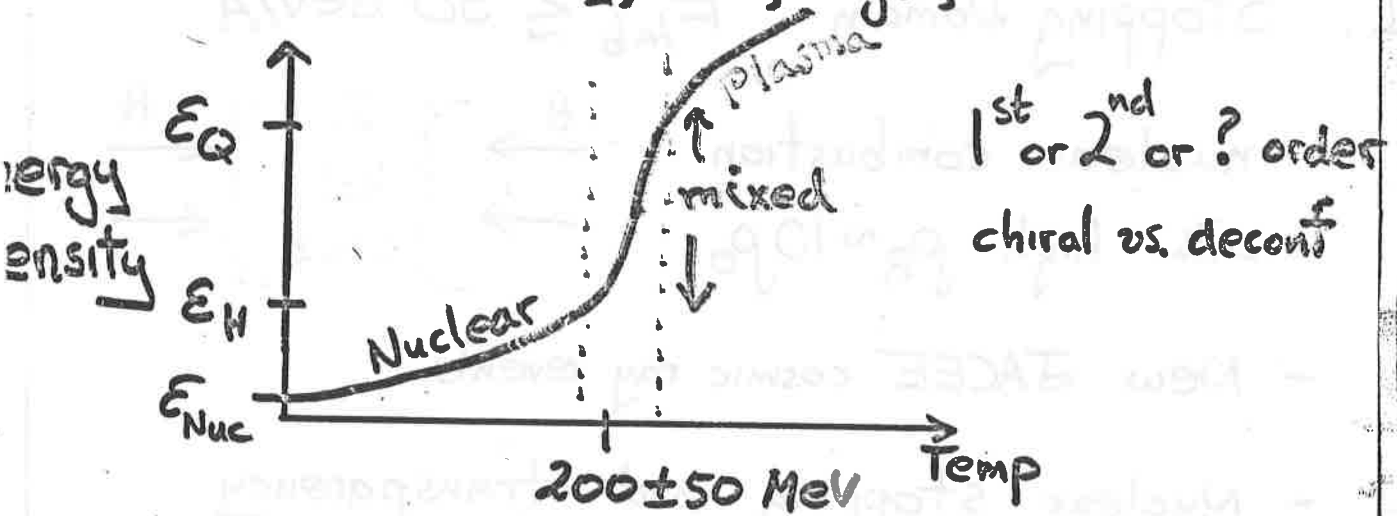
- pure gauge SU(3) seems under control
  first order $T_c = 200 \times 2^{\pm 1}$ MeV
- finite lattice size effects still large
- dynamic fermions via microcononical
  look very promising Polonyi, ...
  first order seems to survive fermions
  chiral + deconfinement at ~ same T_c

Future:

- bigger lattices (no more short runs like
  1 Cray month or 3 Vax years)
- need to compute masses to eliminate $\Lambda_{lattice}$
- analize quasiparticles
  $m_{eff} \sim T_c$ maybe constituent quarks
  $m_{mag} = 0$ maybe glue balls deTar
- finite baryon densities

Phase Characteristics

Lattice QCD   Montvay, Satz, Kogut, ...



$$\varepsilon_{Nuc} = m_N \rho_0 \approx 0.15 \ \mathrm{GeV/fm^3}$$

$$\varepsilon_H \sim (3\text{-}5)\, \varepsilon_{Nuc} \sim \tfrac{1}{2} \ \mathrm{GeV/fm^3}$$

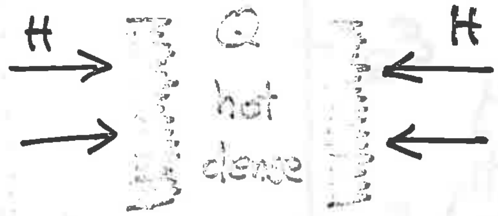
$$\varepsilon_Q \sim 10\, \varepsilon_{Nuc} \sim 1\text{-}2 \ \mathrm{GeV/fm^3}$$

To get into plasma phase requires an increase of ε_{Nuc} by a factor ~ 10 !

Getting $\epsilon \gtrsim 10\,\epsilon_{Nuc}$ via Nuclear Collisions

1. Stopping Domain $E_{lab} \lesssim 50$ GeV/A

- nuclear combustion with high $\rho_B \sim 10\rho_0$



- New JACEE cosmic ray events

- Nuclear stopping and transparency
  new $p + A \rightarrow p + X$ Busza, ...

- Fragmentation asymptotics $E_{lab} > 100$ GeV/A

2. Scaling Domain $E_{lab} \gtrsim 1$ TeV/A

low ρ_B plasmas

initial conditions
evolution
cosmic ray data

$\epsilon_0 \propto (dN/dy)^{1+c_0^2}$

Relativistic Combustion Theory

Landau, Steinhard

MG, K. Kajantie, H. Kurki-Suonio, L. McLerran

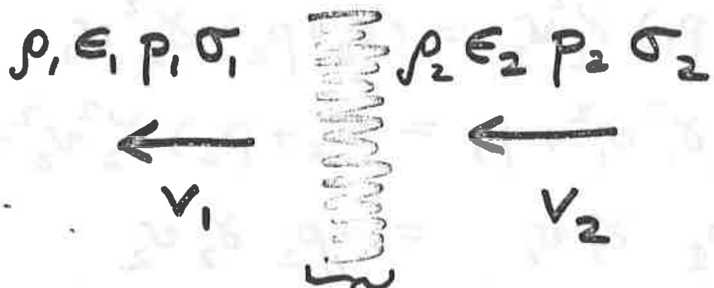
Nuc Phys B237 (84) 477

Nothing but energy-momentum + baryon conserv.

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu \rho^\mu = 0$$

plus assumption of local equilibrium

and stationary boundary



$\Delta T^{0z} = 0$

$\Delta T^{zz} = 0$

$\Delta \rho^z = 0$

d = shock or flame thickness

Local Equilibrium except in shock zone

$$\Rightarrow T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p\, g^{\mu\nu} \underset{\text{rest frame}}{\Rightarrow} \begin{pmatrix} \epsilon & & & 0 \\ & p & & \\ & & p & \\ 0 & & & p \end{pmatrix}$$

$$\rho^\mu = \rho u^\mu$$

u^μ = matter flow velocity

$= (\gamma, \gamma \underline{v})$

$= (\cosh y,\ 0_\perp,\ \sinh y)$

ϵ = energy density

p = pressure

σ = entropy density

ρ = baryon density

$\Big\}$ functions of local T, μ

Solution of $\partial_\mu T^{\mu\nu} = \partial_\mu \rho^\mu = 0$

$$\left.\begin{aligned} \partial_0 T^{0z} + \partial_z T^{zz} &= 0 \\ \partial_0 T^{00} + \partial_z T^{z0} &= 0 \\ \partial_0 \rho^0 + \partial_z \rho^z &= 0 \end{aligned}\right\} \xRightarrow[\text{frame}]{\text{shock}} \begin{aligned} \partial_z T^{zz} &= 0 \\ \partial_z T^{z0} &= 0 \\ \partial_z \rho^z &= 0 \end{aligned}$$

$$\xleftarrow[v_1]{} \quad \} \quad \xleftarrow[v_2]{}$$

Integrate $\partial_z F = 0$: $\int_{-\infty}^{\infty} dz\, \partial_z F = F_2 - F_1 = 0$

1 $\quad (\epsilon_1 + p_1)\gamma_1^2 v_1 = (\epsilon_2 + p_2)\gamma_2^2 v_2$

2 $\quad (\epsilon_1 + p_1)\gamma_1^2 v_1^2 + p_1 = (\epsilon_2 + p_2)\gamma_2^2 v_2^2 + p_2$

3 $\quad \rho_1 \gamma_1 v_1 = \rho_2 \gamma_2 v_2$

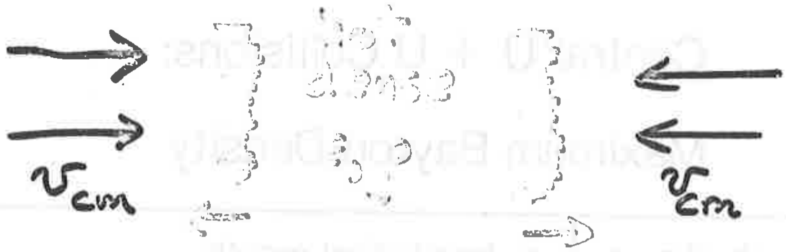
Use 1+2 to solve for v_1, v_2

$$\gamma_1 v_1 \equiv u_1' = \sinh y_1 = \left[\frac{(p_1 - p_2)}{(\epsilon_1 - p_1 - \epsilon_2 + p_2)} \, \frac{(\epsilon_2 + p_1)}{(\epsilon_1 + p_1)} \right]^{1/2}$$

$$\gamma_2 v_2 = \gamma_1 v_1 (1 \leftrightarrow 2)$$

$$\frac{\rho_1}{\rho_2} = \frac{\gamma_2 v_2}{\gamma_1 v_1} = \left[\frac{\epsilon_1 + p_2}{\epsilon_2 + p_2} \, \frac{\epsilon_1 + p_1}{\epsilon_2 + p_1} \right]^{1/2}$$

Application to Nuclear Shocks:



cold nuclear matter
$\epsilon = \epsilon_N,\ p = 0$
ρ_0

Conservation of energy in cm

$$\epsilon = (\gamma_{cm} m_N)\,\rho$$

Shock compression

$$\rho/\rho_0 = \left[\frac{\epsilon_N + p}{\epsilon + p}\ \frac{\epsilon_N + p_N}{\epsilon + p_N}\right]^{1/2} \qquad \underline{p_N = 0}$$

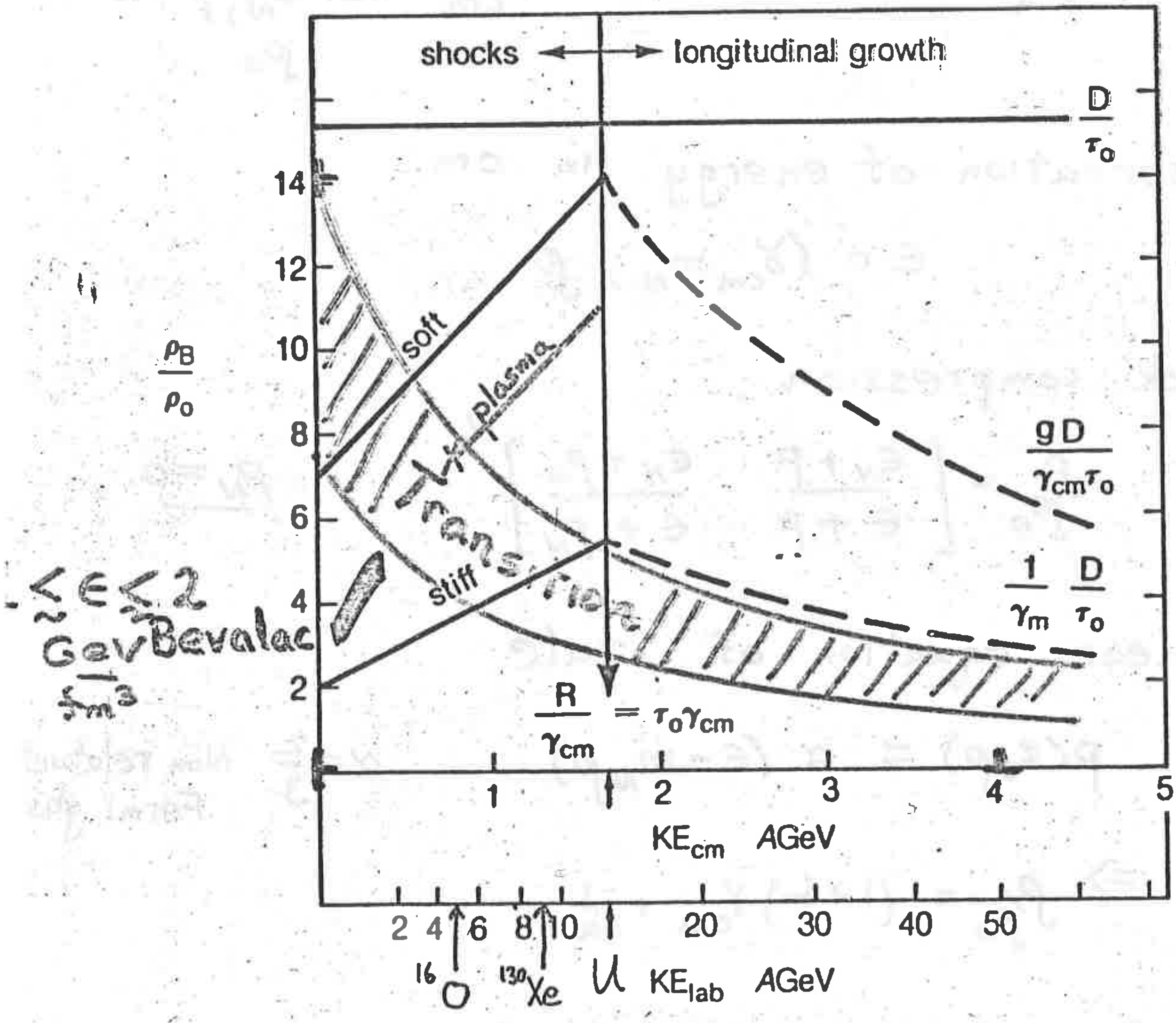
Nuclear equation of state

$$p(\epsilon, \rho) \approx \alpha\,(\epsilon - m_N \rho) \qquad \alpha = \frac{2}{3} \text{ Non relativist Fermi gas}$$

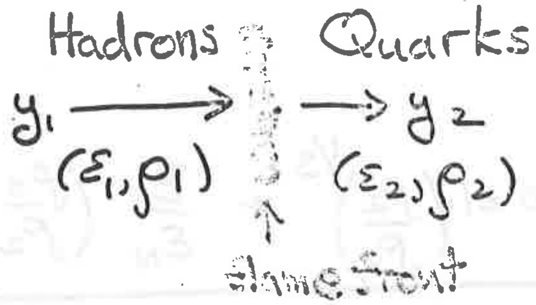
$$\Rightarrow \rho/\rho_0 = \left(1 + \frac{1}{\alpha}\right)\gamma_{cm} + \frac{1}{\alpha}$$

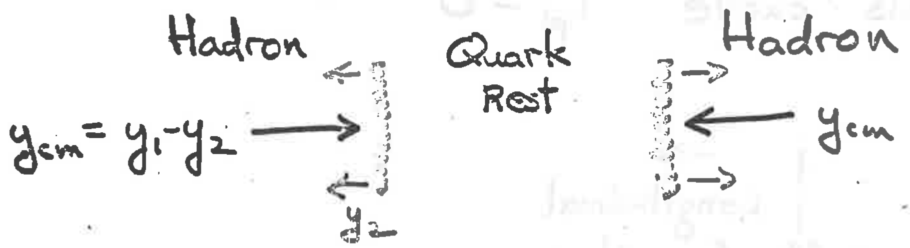
Central U + U Collisions:

Maximum Bayron Density



Hadron Combustion (inverse deflagrations)





Cold hadrons $\rightarrow$ Plasma requires minimum kinetic energy to melt non-perturbative vacuum

$$\varepsilon_2 = \varepsilon_{SB}(T, \mu) + \underbrace{B}_{\text{vac. energy density}}$$

$$B \sim (1-3)\, m_N \rho_0$$

$$p_2 = \frac{1}{3}\varepsilon_2 - \frac{4}{3}B$$

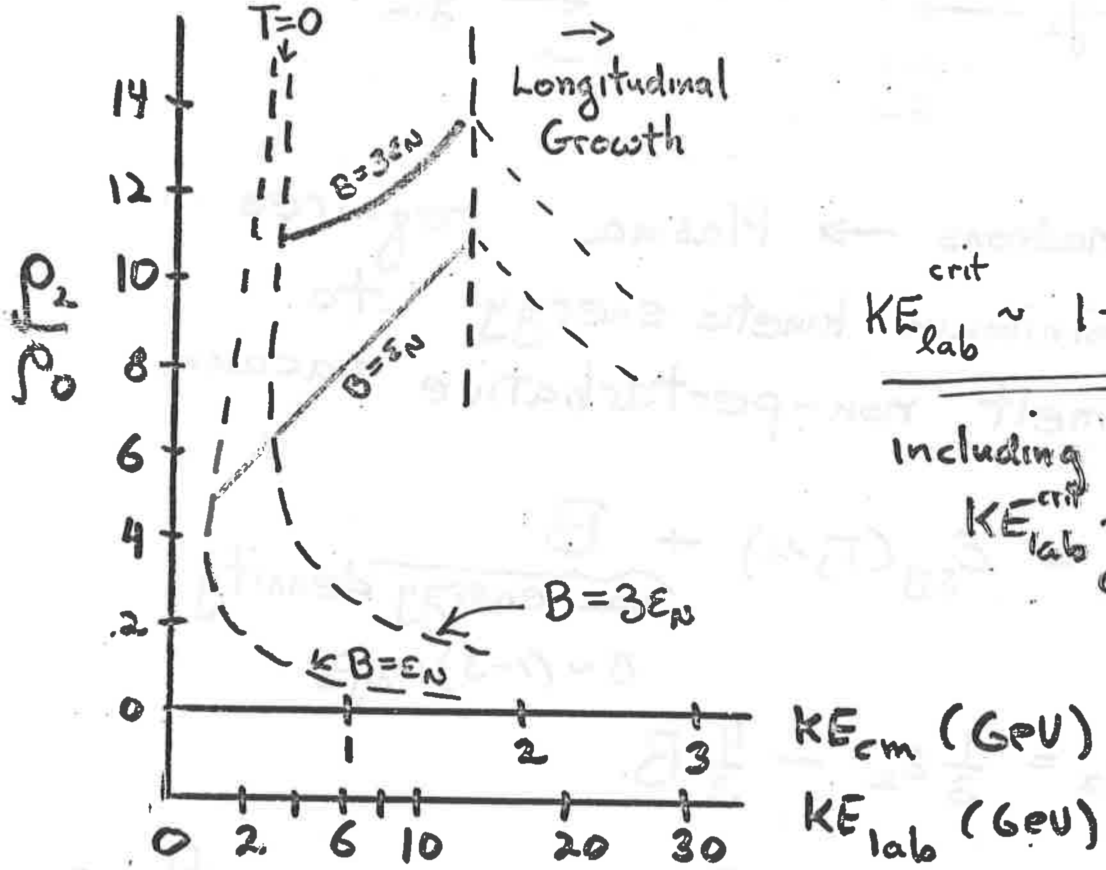
Continuity of $T_{\mu\nu}$, j_μ across flame

$$\Rightarrow \quad \frac{\rho_2}{\rho_0} = \left[\frac{\varepsilon_2 + p_1}{\varepsilon_1 + p_2} \; \frac{\varepsilon_2 + p_2}{\varepsilon_1 + p_1}\right]^{1/2}$$

$$= \frac{1}{2\gamma_{cm}}\left[4\left(\gamma^2 + \frac{B}{\varepsilon_0}\right) - 3 + \sqrt{\left(4\left(\gamma^2 + \frac{B}{\varepsilon_0}\right) - 3\right)^2 - 16\frac{B}{\varepsilon_0}\gamma^2}\right]$$

$$\Rightarrow \quad \underbrace{\gamma_{cm}^{crit} = 0.61\left(\frac{\rho_2}{\rho_0}\right)^{1/3} + \frac{B}{\mathcal{E}_N}\left(\frac{\rho_0}{\rho_2}\right)}_{\text{on this curve } T_{pl}=0}$$

Biro
Zimanyi



$KE_{lab}^{crit} \sim 1-3$ GeV

Including interaction
$KE_{lab}^{crit} \sim 5$-8 GeV
(Stöcker)

Finite Nuclei Limit on Stopping Domain

There exists characteristic proper interaction time

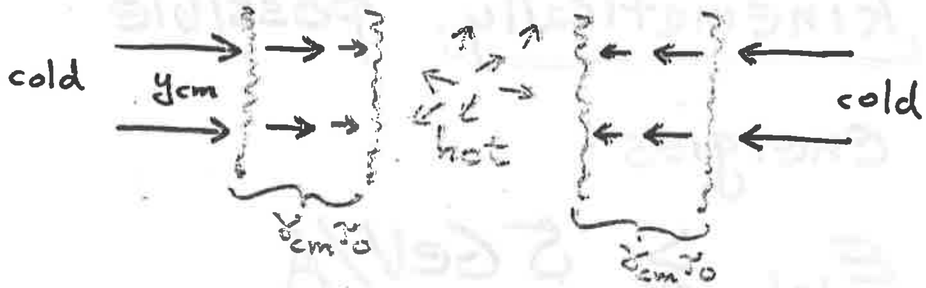
$$\tau_0 \sim \hbar/p_\perp \sim \Lambda_{QCD}^{-1} \sim 1\ \mathrm{fm}/c$$

Time dilation in cm frame

$$\Rightarrow \Delta t_{cm} = \gamma_{cm}\tau_0 \approx \tau_0 \frac{e^{y_{cm}}}{2}$$

$\Rightarrow$ Minimum stopping distance $= \gamma_{cm}\tau_0$

Minimum shock thickness $= \gamma_{cm}\tau_0$



To form shock in finite nuclei $R < 7\,\mathrm{fm}$

must have

$$\underline{\gamma_{cm}\tau_0 < \frac{R}{\gamma_{cm}}} = \text{lorentz contracted nuclei}$$

Highest energy where shock can form

$$\frac{E}{A}_{lab} \approx 2\gamma_{cm}^2 m_N = \left(\frac{2R}{\tau_0}\right)\mathrm{GeV} \sim 10\text{-}50\ \mathrm{GeV}$$

Summary of Stopping Domain

1. By $E_{lab} \sim 10$ GeV/A
   nuclear shocks can reach

   $$\epsilon \sim 10\,\epsilon_0 \qquad \rho \sim 10\,\rho_0$$

2. Burning of nuclear matter
   to quark-gluon plasma
   is kinematically possible
   for energies

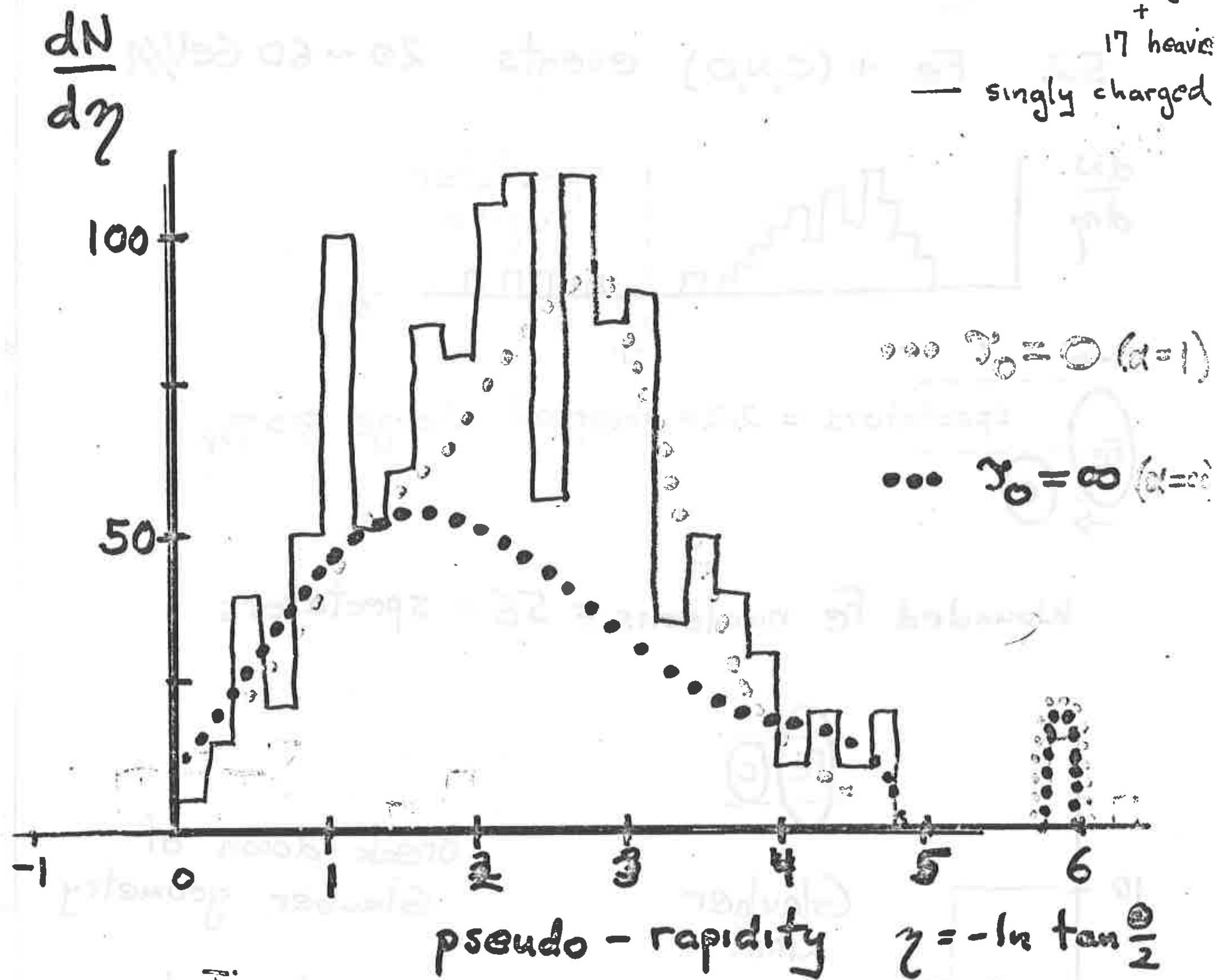
   $$E_{lab} \gtrsim 5 \text{ GeV/A}$$

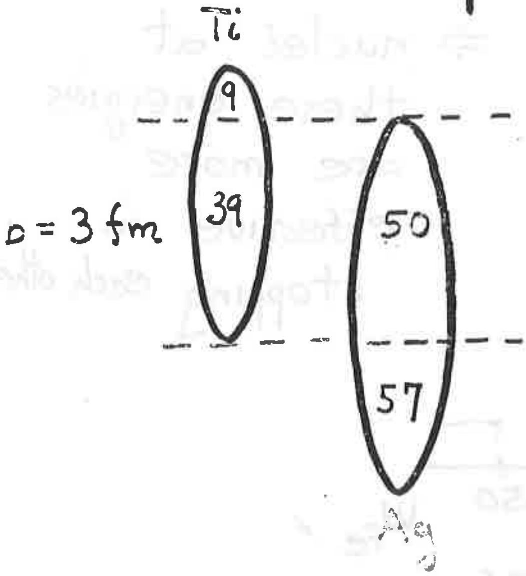
3. Assumption of stationary
   flame front with thickness
   less than R/γ_{cm}
   probably breaks down
   for $E_{lab} \gtrsim 10$ GeV/A

Preliminary

JACEE III

$^{22}_{48}\mathrm{Ti}$ (26 GeV/A) + $^{47}_{107}\mathrm{Ag}$ → 255 charges + 17 heavies





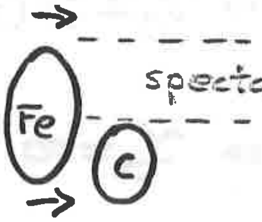
$\gamma_{cm} = 3.8$

$\bar{\nu}_{Ti} = 2.9$

$\bar{\nu}_{Ag} = 3.9$

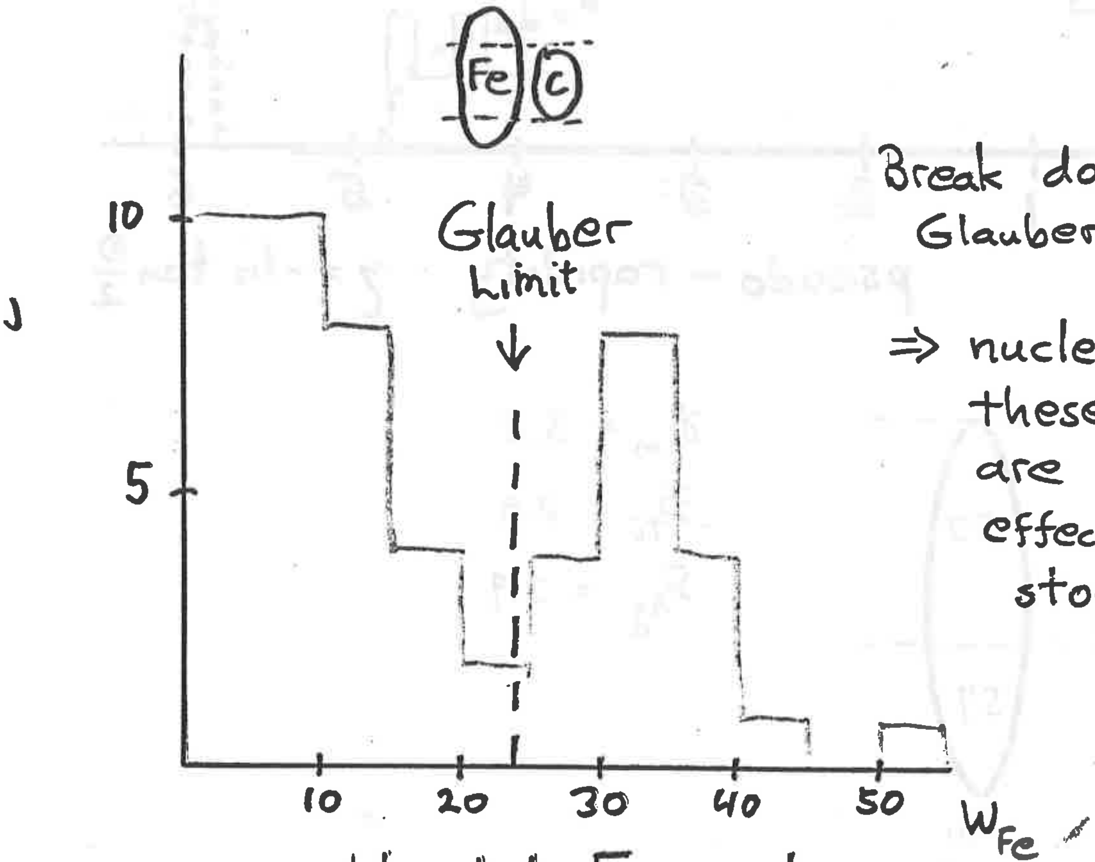
Preliminary JACEE III

52 Fe + (C,N,O) events 20 ~ 60 GeV/A



spectators = 2.2× observed charge $\eta > \eta_{sp}$

Wounded Fe nucleons = 56 − spectators



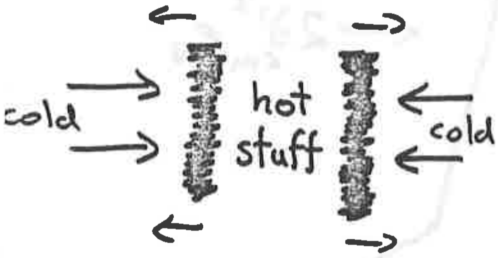
Wounded Fe nucleons

Break down of Glauber geometry

⇒ nuclei at these energies are more effective in stopping each other

Why is Nuclear Stopping of Interest?

In stopping domain nuclear shocks can form in which



$$\rho_B \approx \left(1+\frac{1}{c_0^2}\right)\gamma_{cm}\rho_0 \sim (2-4)\gamma_{cm}\rho_0$$

$$\epsilon = \gamma_{cm} m_N \rho_B \sim (2-4)\gamma_{cm}^2\,\epsilon_{Nuc}$$

Up to what energies $E_{lab} \approx 2\gamma_{cm}^2 m_N$ can finite nuclei stop baryons?

first guess: $\underbrace{\ell_{stop} \sim \gamma_{cm}\, r_0}_{\text{time dilation}} < \underbrace{\frac{R}{\gamma_{cm}}}_{\text{lorentz contraction}}$

$$\Rightarrow E_{max}^{lab} \sim \left(\frac{2R}{r_0}\right) \text{GeV} \sim 10\,\text{GeV}$$

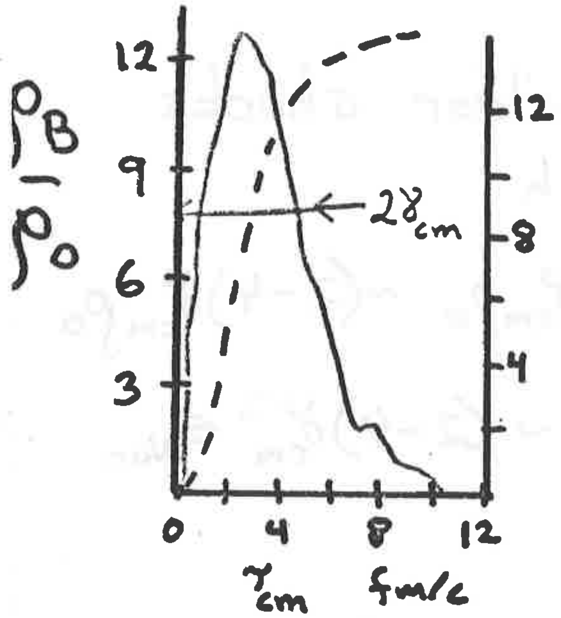
But what if $r_0 \sim \frac{1}{5}$ fm ?

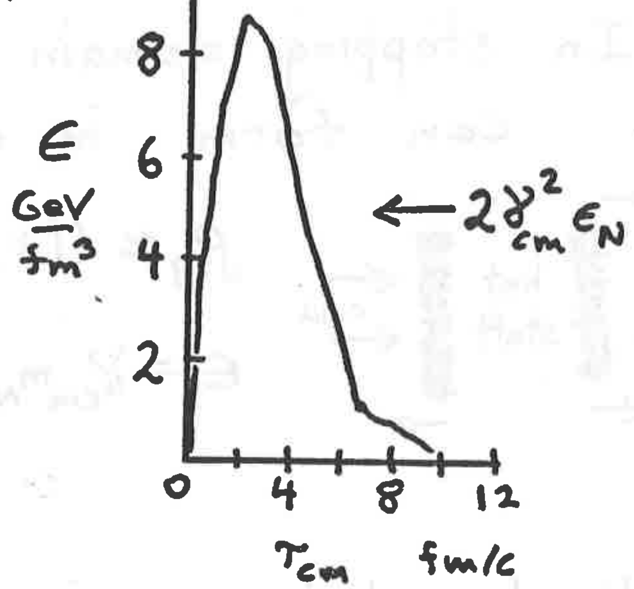
$\epsilon_{max} \sim 100\ \epsilon_{Nuc}$ could be reached!

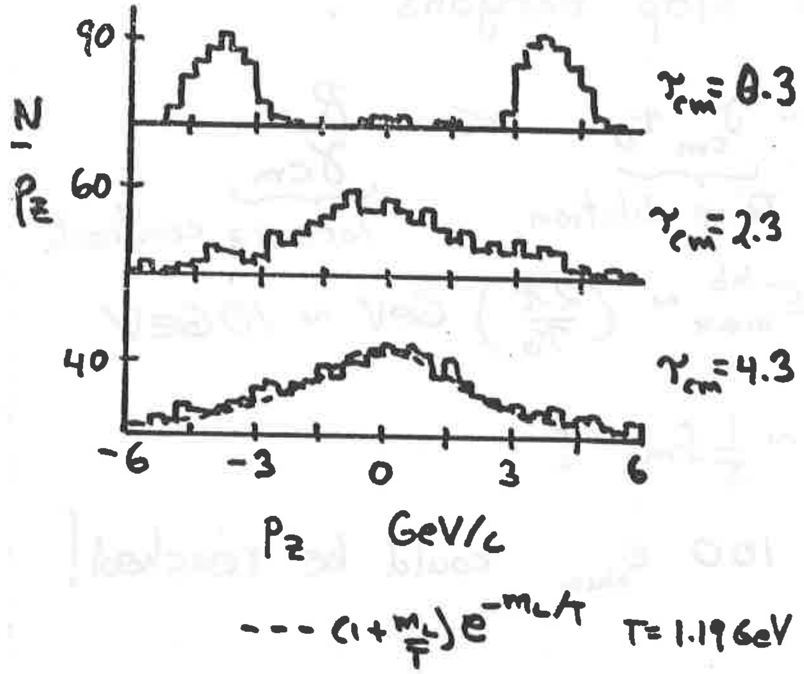
Evolution of central core in b=0 U+U

$E_{lab} = 30$ GeV/A $KE_{cm} = 3$ GeV/A

(Isotropic elastic , $\tau_c = 0$, billiard model)







U+U big enough for equilibrium

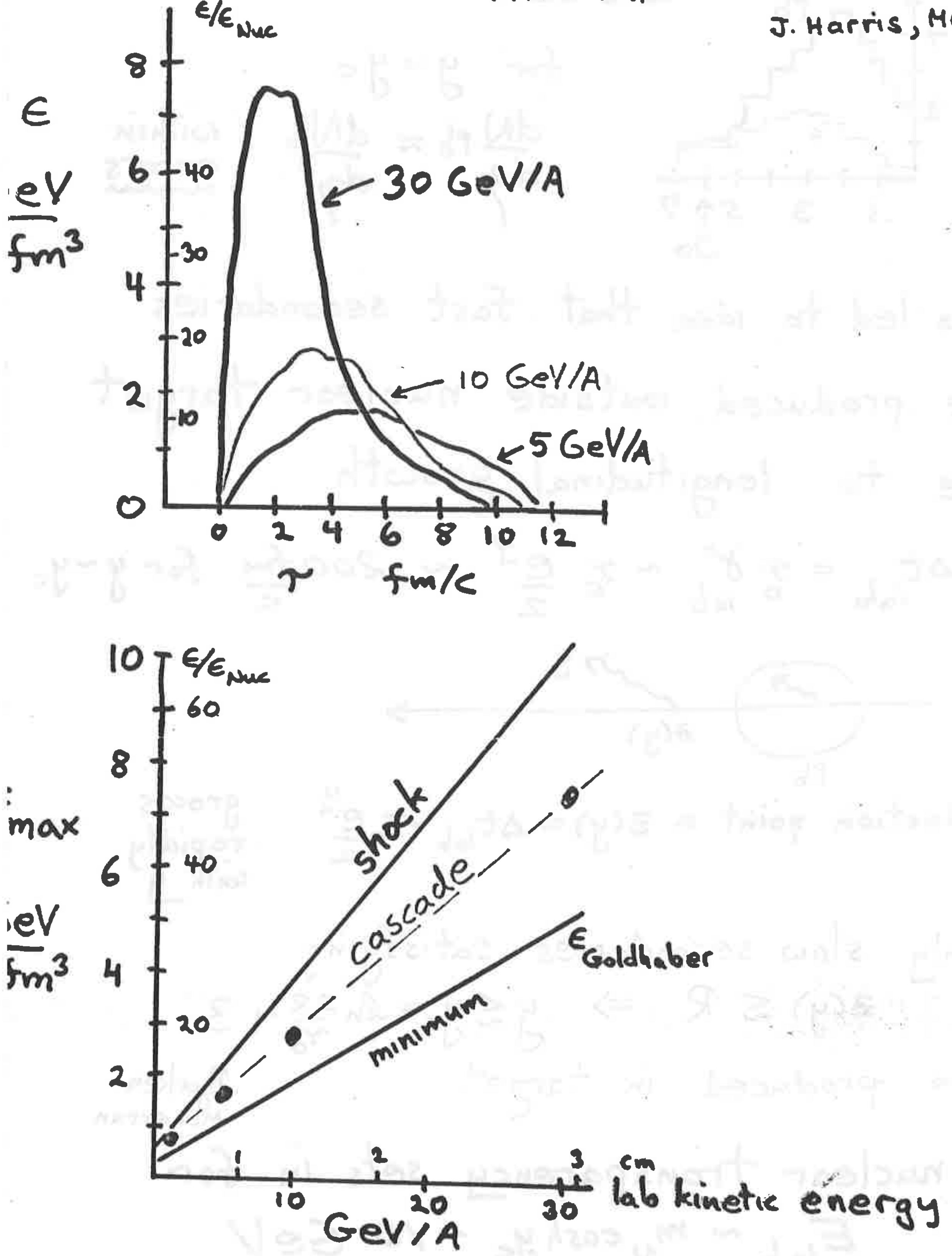
High (ρ, ϵ) lasts for $\Delta\tau \sim 4$ fm/c

Beam Energy Dependence

central core $b=0$ U + U $r_0 = 1$

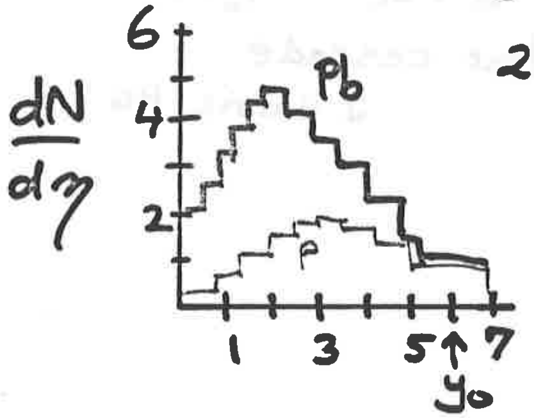
intra-nuclear cascade

J. Harris, MG



Nuclear Transparency :

pseudo-rapidity p+A data before 1983



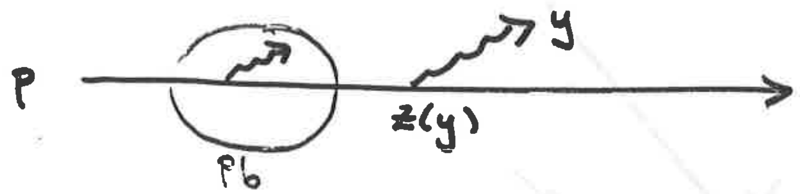
200 GeV

for $y \sim y_0$

$\frac{dN}{d\eta}_{Pb} \approx \frac{dN}{d\eta}_p$ within errors

This led to idea that fast secondaries are produced outside nuclear target due to longitudinal growth

$$\Delta t_{lab} = \tau_0 \gamma_{lab} \sim \tau_0 \frac{e^y}{2} \sim 200 \frac{fm}{c} \text{ for } y \sim y_0$$



production point $= z(y) \approx \Delta t_{lab} \sim \tau_0 \frac{e^y}{2}$ grows rapidly with y

∴ Only slow secondaries satisfying

$$z(y) \lesssim R \Rightarrow y \lesssim y_c = \ln \frac{2R}{\tau_0} \sim 3$$

are produced in target

Bjorken
McLerran

$\Rightarrow$ nuclear transparency sets in for

$$E_{lab} \sim m_N \cosh y_c \sim 10 \text{ GeV}$$

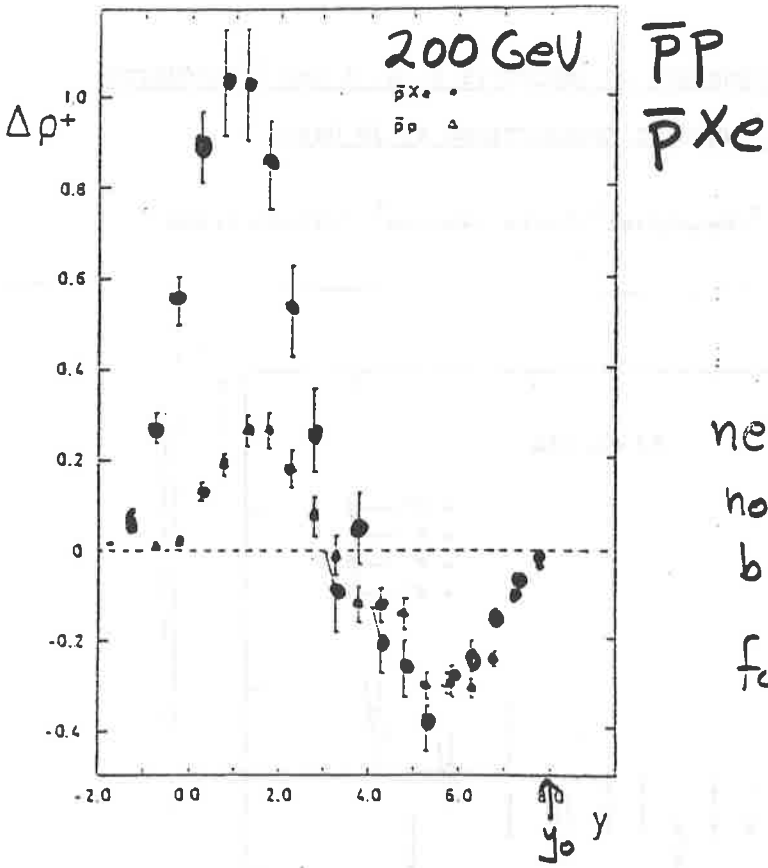


Fig 11. The average net charge versus rapidity for $\bar{p}$Xe (circles) and $\bar{p}$p (triangles) interactions[8].

net charge not affected by Nucleus for $y \gtrsim 3$

Does not necessarily mean leading particle $\bar{p}$

$\bar{p} \rightarrow \pi^-$ + slow [redacted]

see Busza $pA \rightarrow p$

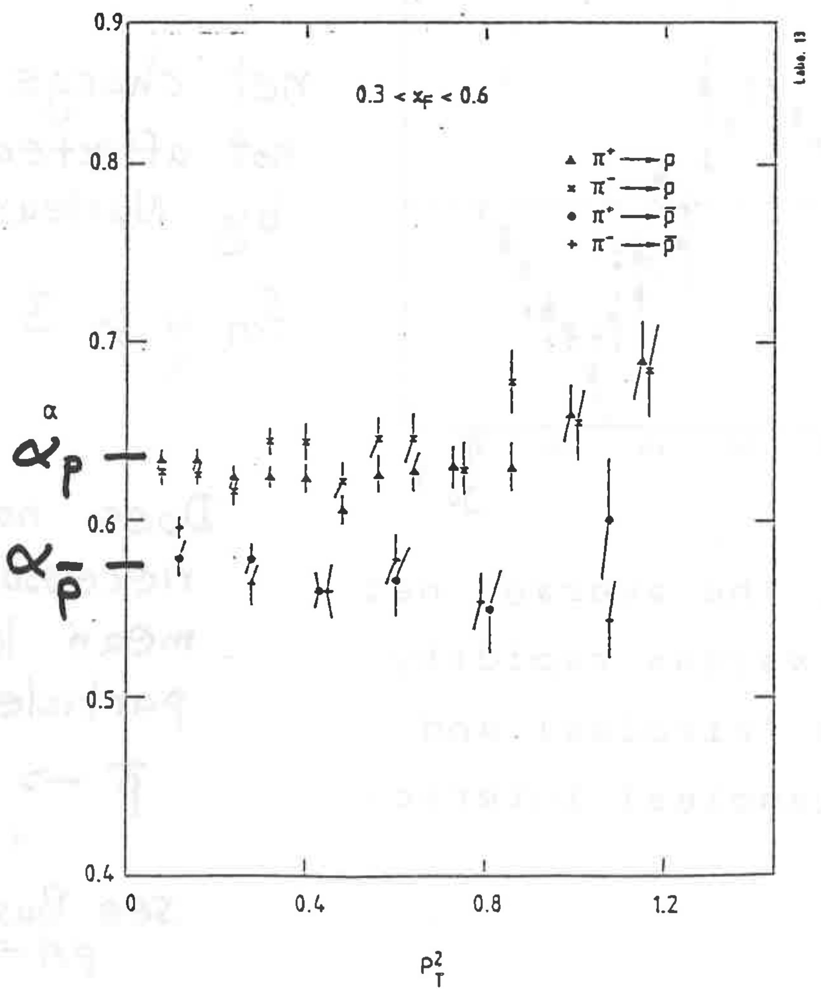
6c

CERN/EP 84-51
13 April 1984

STUDY OF THE A-DEPENDENCE OF INCLUSIVE p, $\bar{p}$, Λ AND $\bar{\Lambda}$ PRODUCTION

IN $\pi^{\pm}$-NUCLEUS INTERACTIONS AT 30 GeV/c

CERN[1]-Lisbon[2]-Neuchâtel[3]-Paris[4]-Warsaw[5] Collaboration



$\pi^+ \to u \to p \to$

$\pi^- \to \bar{u} \to \bar{p} \,\times \to$

Assume $\bar{u} \to \bar{p}$ has formation length L

Fit $L\,(15\text{GeV}) = 20 \pm 10$ fm $= 15\,\tau_0$

$\alpha_p > \alpha_{\bar{p}}$

because

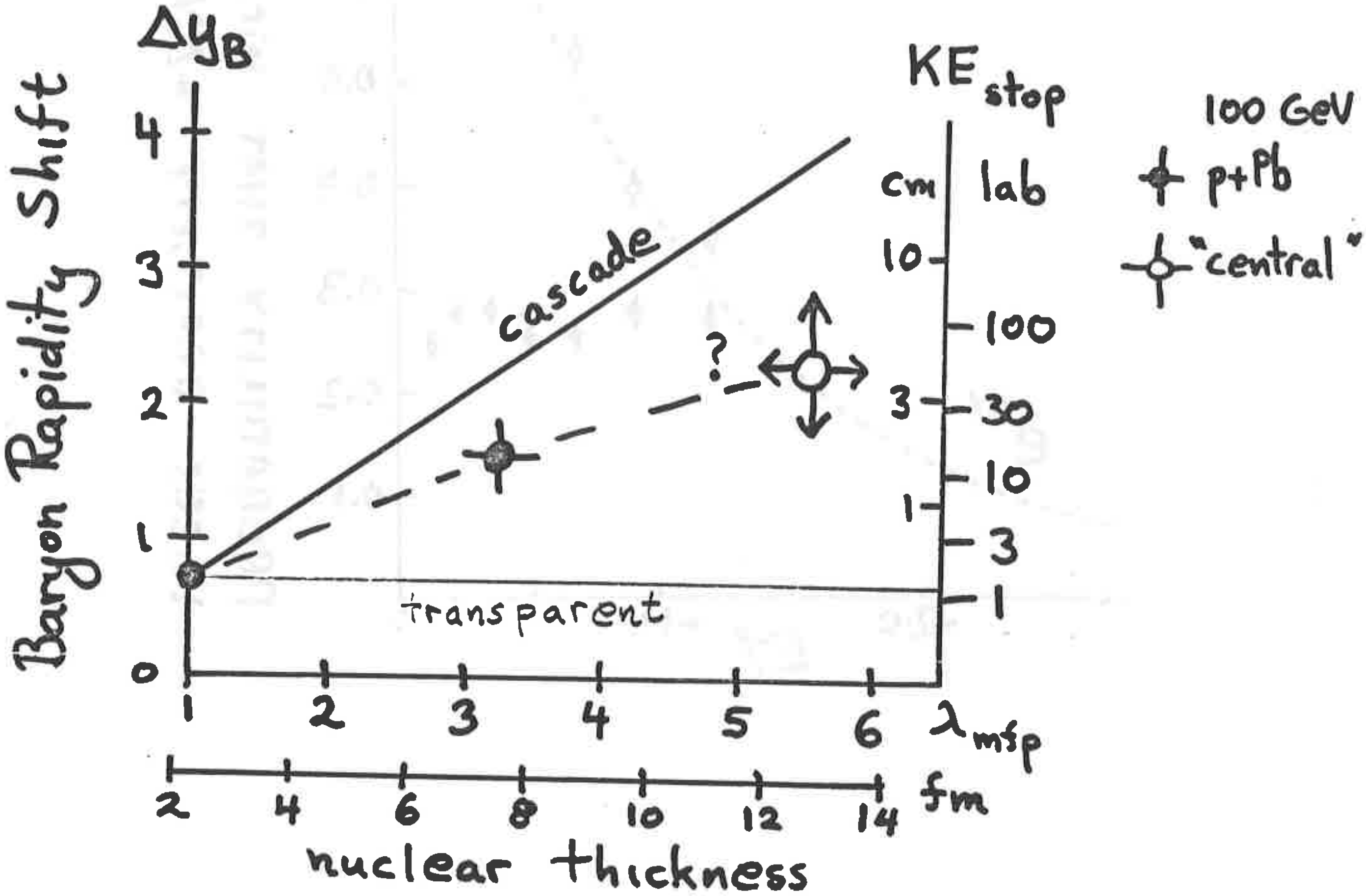
both $\bar{u}$ and $\bar{p}$ could annihilate!

$\tau_0 \sim 1$ fm/c

Nuclear Stopping Power:

New $p + A \to p + X$ data Busza, et al. 1983

$\Rightarrow$ nuclei are much more effective in stopping baryons than previously assumed

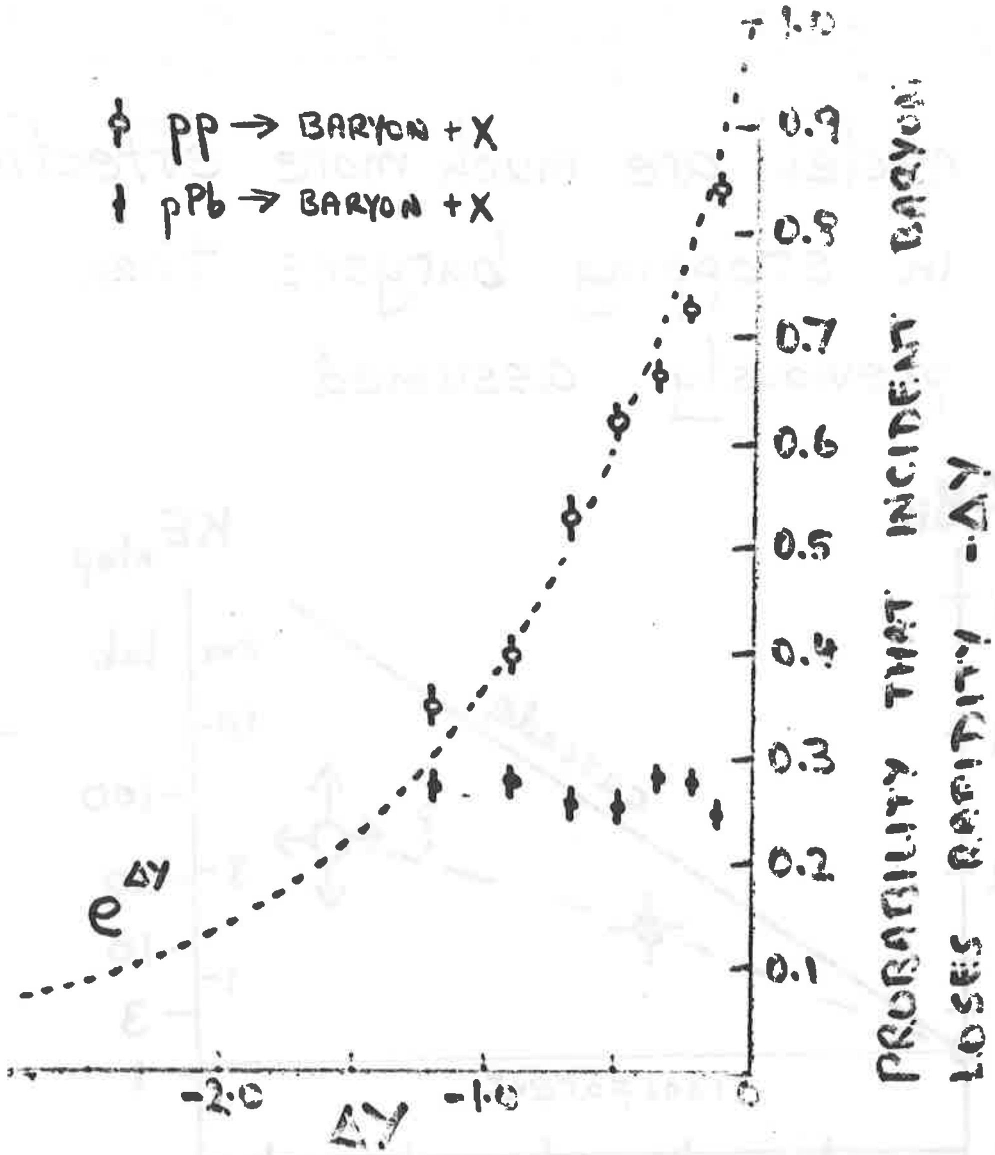


Baryons stop in cm for A+A collisions when lab kinetic energy per nucleon is

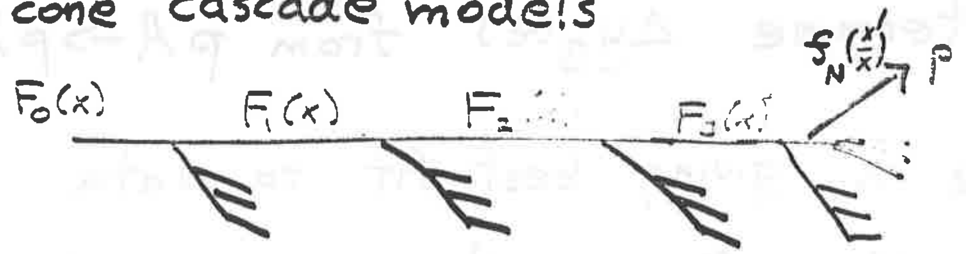
$$KE_{lab} < KE_{stop} = m_N (\cosh 2\Delta y_B - 1) \sim 50\ \text{GeV/A}$$

for U+U

W. BUSZA & A. GOLDHABER



Light cone cascade models



$$x\frac{dN}{dx} = \sum_{i=1}^{\infty} p_i \int_x^1 dx' \, F_{i-1}(x') f_N\left(\frac{x}{x'}\right)$$

p_i = prob of scattering with i target nucleons

$F_i(x)$ = probability that baryon cluster has fractional momentum x after i collisions

$$f_N(x) = \frac{1}{\sigma_{NN}} x \frac{d\sigma}{dx}^{pp\to pX} \approx x = \text{proton fragmentation function}$$

Recursion:

$$F_{i+1}(x) = \int_x^1 \frac{dx'}{x'} P\left(\frac{x}{x'}\right) F_i(x')$$

$$\int_0^1 dx \, P(x) = 1 \qquad \int_0^1 dx \, F_i(x) = 1$$

Dynamic Input:

$P(x)$ = scattering prob of losing momentum fraction $1-x$

$$= \begin{cases} \alpha x^{\alpha-1} & \text{Kinoshita, Minaka, Sumiyoshi} \\ 1 & \text{Wong} \\ c + (1-c)\delta(1-x) & \text{Hwa ; Csernai Kapusta} \end{cases}$$

To determine $\Delta y_B(z)$ from $pA \to pX$

1. Find α giving best fit to data

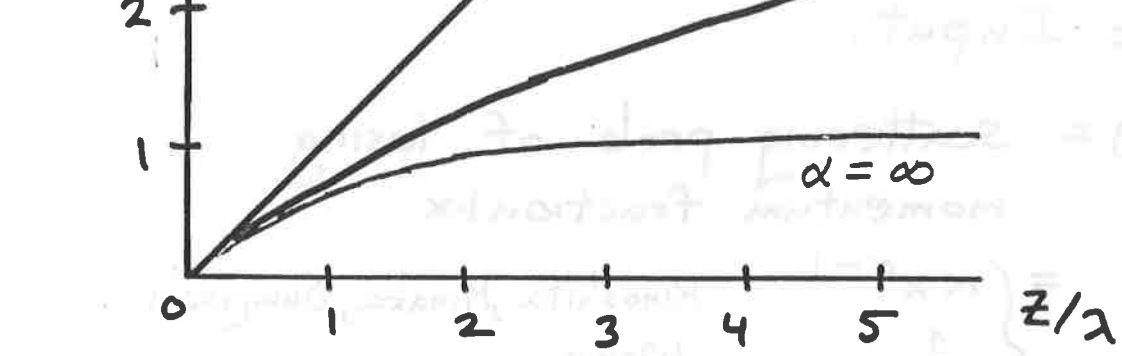
$$x\frac{dN}{dx}^{pA} = x \sum_{i=2}^{\infty} P_i(A) \int_x^1 \frac{dx'}{x'} \frac{\alpha^{n-1}}{(n-2)!} x'^{\alpha-1} \left(\ln\frac{1}{x'}\right)^{n-2}$$

$$+ P_1(A)\, x$$

Good nuclear densities must be used to calculate $P_i(A)$

2. Knowing α

$$\Delta y_B(z) = \frac{1}{\alpha}\left(\frac{z}{\lambda}\right) + \frac{\alpha-1}{\alpha}\left(1-e^{-z/\lambda}\right)$$



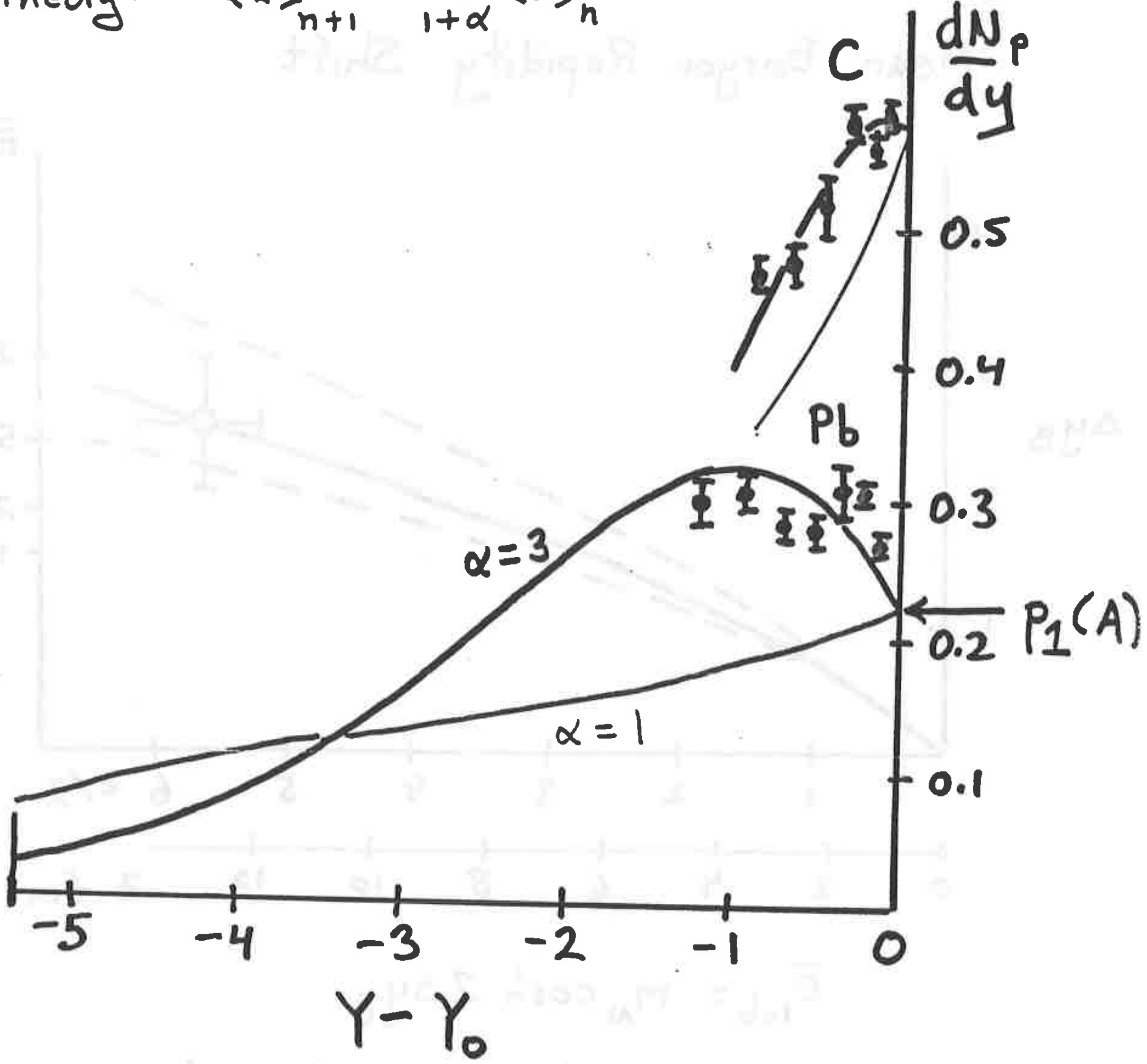
11 a

Date, MG, Sumiyoshi

$p + A \to p + X$ 100 GeV

data: Busza et. al.

theory: $\langle x \rangle_{n+1} = \frac{\alpha}{1+\alpha} \langle x \rangle_n$



$g(p_\perp) = N\left(e^{-ap_\perp^2} + e^{-bp_\perp}\right)$

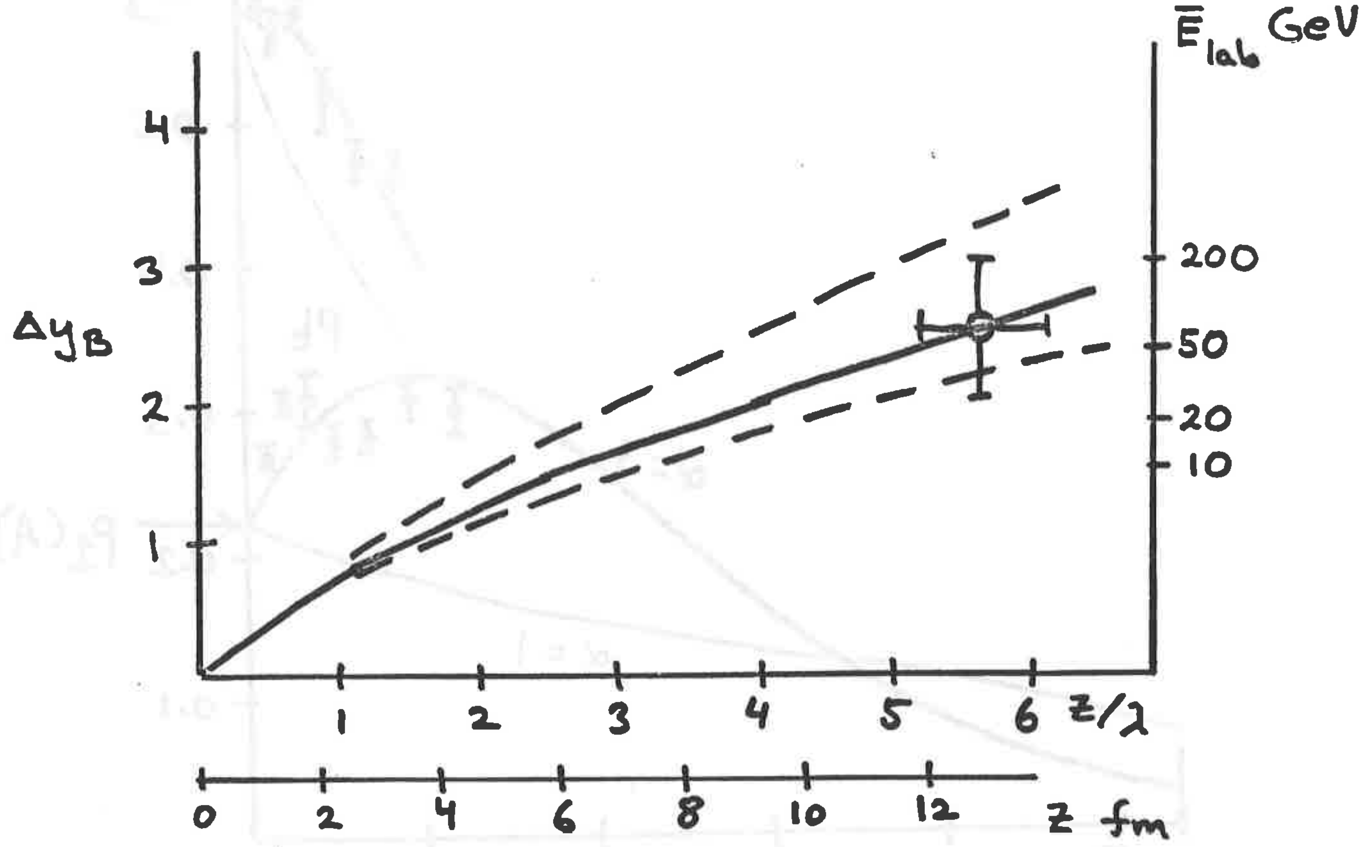
$a = 4.5 \text{ GeV}^{-2}$ $b = 4 \text{ GeV}^{-1}$

Nuclear Stopping Power

Busza - Goldhaber

$\alpha = 3 \pm 1$ Sumiyoshi, Date, MG
Hufner Klar
Csernai Kapusta

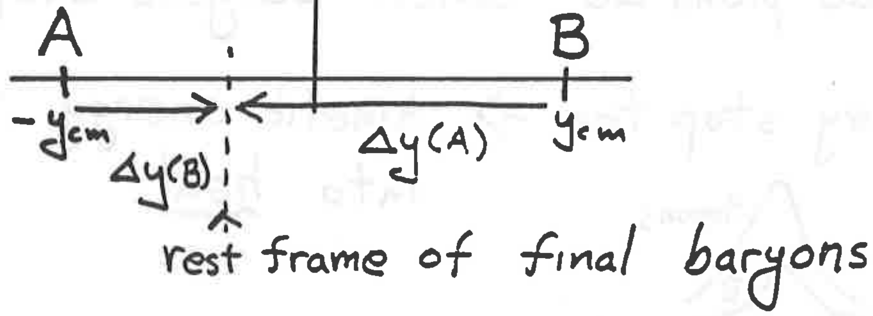
Mean Baryon Rapidity Shift



$$\bar{E}_{lab} = m_N \cosh 2\Delta y_B$$

= max energy for stopping baryons in A+A collisions in the cm frame

Application to Asymmetric Systems



If $2y_{cm} = y_{lab} = \Delta y(A) + \Delta y(B)$
then nuclei stop each other in
frame moving with $\Delta y(B)$ in lab

Maximum laboratory energy for stopping baryons

$$E_{max}(A+B) = m_N \cosh\left(\Delta y(2R_A) + \Delta y(2R_B)\right)$$

$$\approx 2\,\text{GeV}\left[e^{A^{1/3}+B^{1/3}}\right]^{1/\alpha}$$

E_{max}	$\alpha = 2$	3	4
$^{238}U + U$	983	125	44
$^{16}O + U$	156	37	18

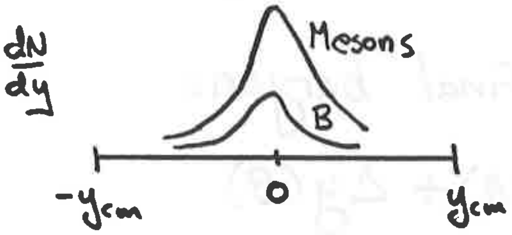
* Uncertainty in $\alpha = 3 \pm 1 \Rightarrow$ very large uncertainty in E_{max}

** This is where PS, SPS experiments $^{16}O + A$ are crucial!

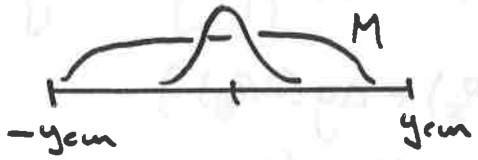
Baryon vs. Energy Stopping

What do pions do when baryons stop?

1. They stop too ⇒ kinetic energy turned into heat



OR 2. Only baryons stop and fast pions carry away the energy



← due to long formation lenghts $z \sim r_0 e^{y/2}$

* There is no data to decide!

need $p + A \to \pi$ + trigger proton + no neutron + X

simple inclusive is inconclusive !!

for $^{16}O + A$ need semi-exclusive data

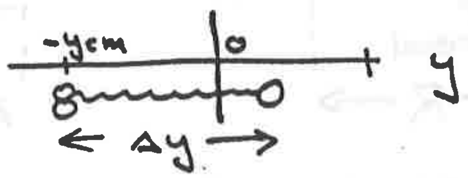
Help, Carlo!

* This is the bread and butter on the way for searching for QCD plasma

Hadronization of Strings

Total energy per target string initially all kinetic

$$E_s \cong m_\perp \frac{e^{\Delta y}}{2}$$



Maximum length of string = stopping distance of end

$$V(\ell_s) = E_s \Rightarrow \ell_s = \frac{E_s}{\sigma} \quad \leftarrow \text{longitudinal growth}$$

$$\gamma_0 = \frac{m_\perp}{\sigma} \approx \frac{1}{2}\,\text{fm}$$

Determine Δy from $p + A \to p + X$ Busza, et al

$$F_{n+1}(x) = \int_x^1 \frac{dx'}{x'} P\left(\frac{x}{x'}\right) F_n(x') \quad ; \quad P(x) = \alpha x^{\alpha - 1}$$

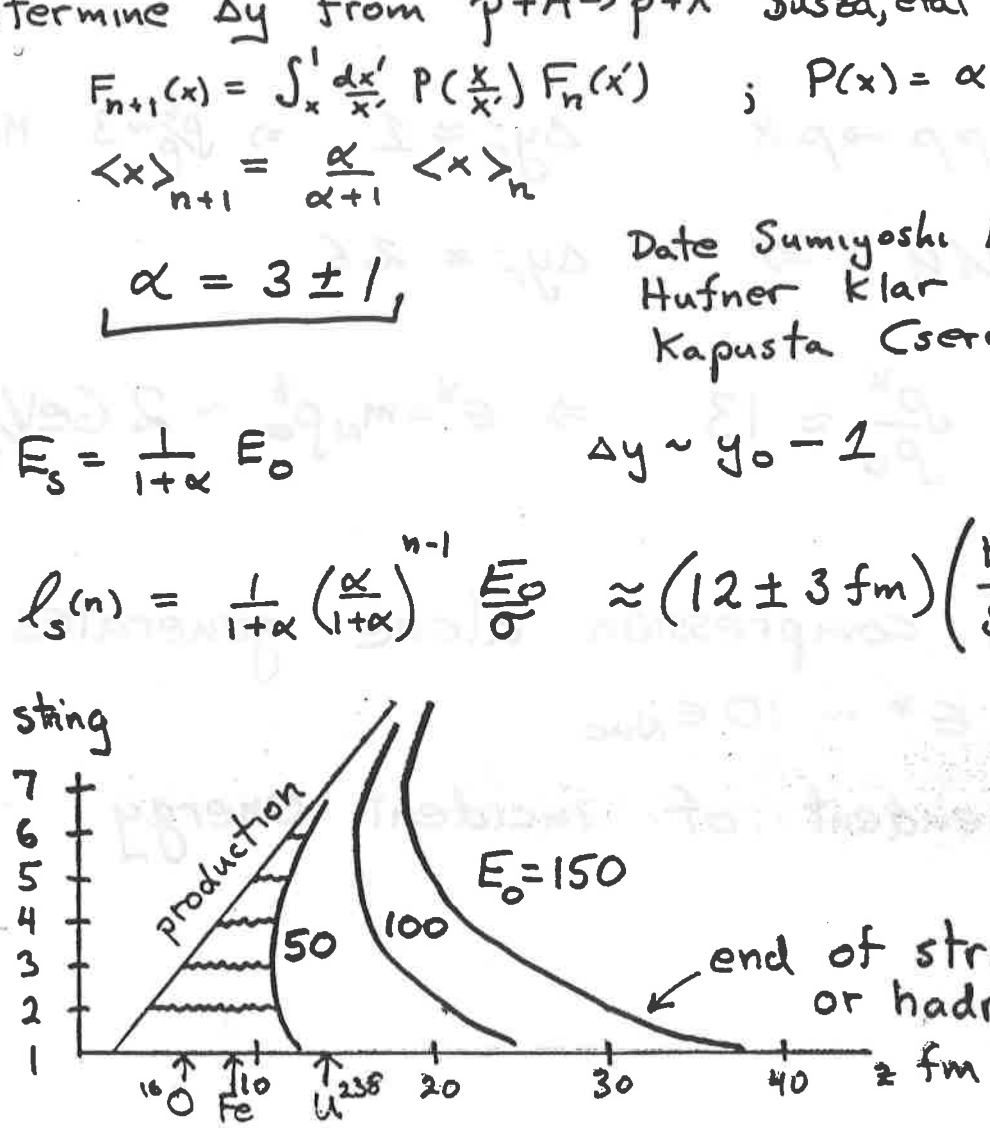
$$\langle x \rangle_{n+1} = \frac{\alpha}{\alpha+1} \langle x \rangle_n$$

$$\underbrace{\alpha = 3 \pm 1}$$

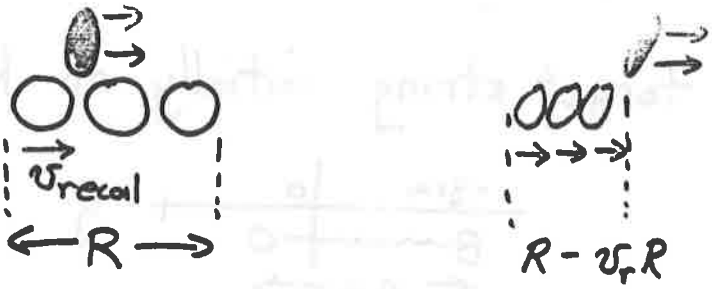
Date Sumiyoshi MG
Hufner Klar
Kapusta Csernai

$$E_s = \frac{1}{1+\alpha} E_0 \qquad \Delta y \sim y_0 - 1$$

$$\ell_s(n) = \frac{1}{1+\alpha}\left(\frac{\alpha}{1+\alpha}\right)^{n-1} \frac{E_0}{\sigma} \approx (12 \pm 3\,\text{fm})\left(\frac{E_0}{50\,\text{GeV}}\right)\left(\frac{3}{4}\right)^{n-1}$$



What happens if pions are not stopped?



McLerran, ...

Recoil compression $\rho/\rho_0 = \frac{1}{1-v_r}$ in lab

In recoil rest frame $\rho^*/\rho_0 = \frac{1}{\gamma_r}\frac{1}{(1-v_r)} = e^{\Delta y_r}$

In $pp \to pX$ $\Delta y_r \approx 1$ $\Rightarrow \rho^*/\rho \sim 3$ McLerran

But UU $\Rightarrow$ $\Delta y_r \approx 2.6$

$$\frac{\rho^*}{\rho_0} \approx 13 \quad \Rightarrow \epsilon^* = m_N \rho_0^* \sim 2\ \mathrm{GeV/fm^3}$$

Recoil compression alone generates

$\epsilon^* \sim 10\, \epsilon_{Nuc}$

independent of incident energy

Making Baryon Rich Matter with $\epsilon \gtrsim 10\,\epsilon_{Nuc}$

Stopping Regime

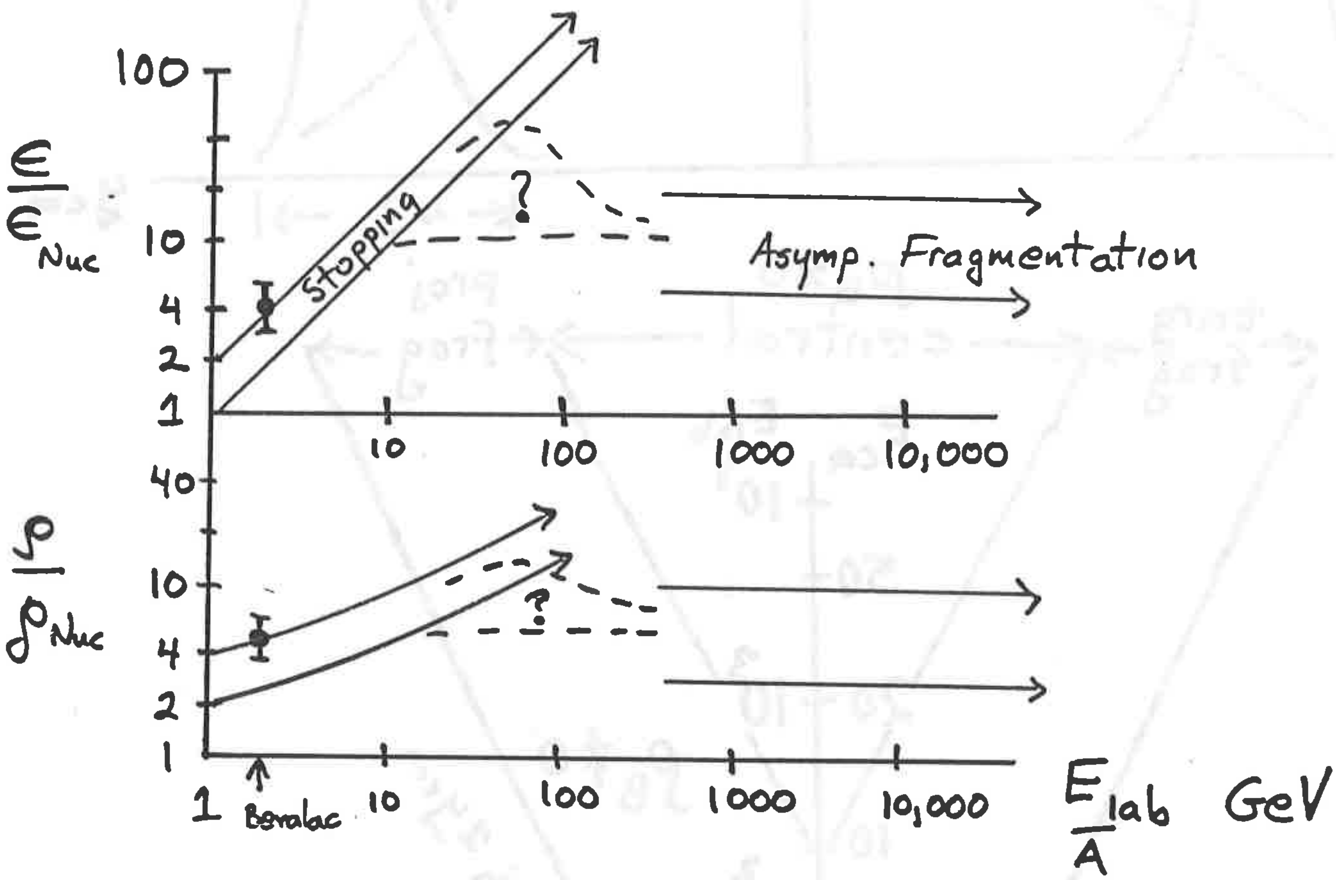
$\rho_B = (2-4)\,\gamma_{cm}\,\rho_0$

$\epsilon = (2-4)\,\gamma_{cm}^2\,\epsilon_{Nuc}$

Asymptotic

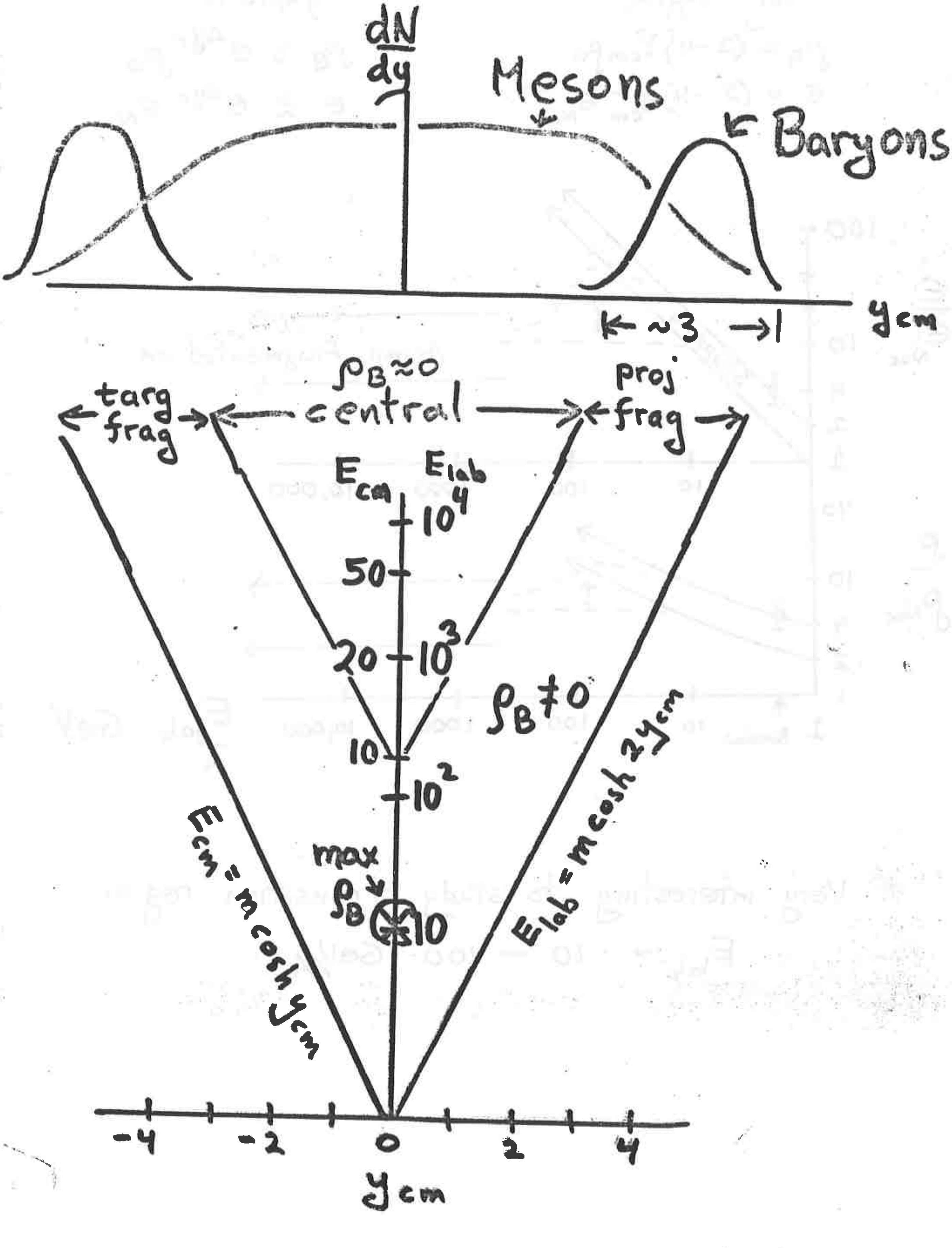
$\rho_B \gtrsim e^{\Delta y_r}\,\rho_0$

$\epsilon \gtrsim e^{\Delta y_r}\,\epsilon_N$



* Very interesting to study transition region

$E_{lab} \sim 10 - 100$ GeV/A



dN/dy
Mesons
Baryons
y_{cm}
← ~3 →
$\rho_B \approx 0$
targ frag
central
proj frag
E_{cm}
E_{lab}
10^4
50
20
10^3
$\rho_B \neq 0$
10
10^2
max ρ_B
10
$E_{cm} = m \cosh y_{cm}$
$E_{lab} = m \cosh 2y_{cm}$
-4
-2
0
2
4
y_{cm}

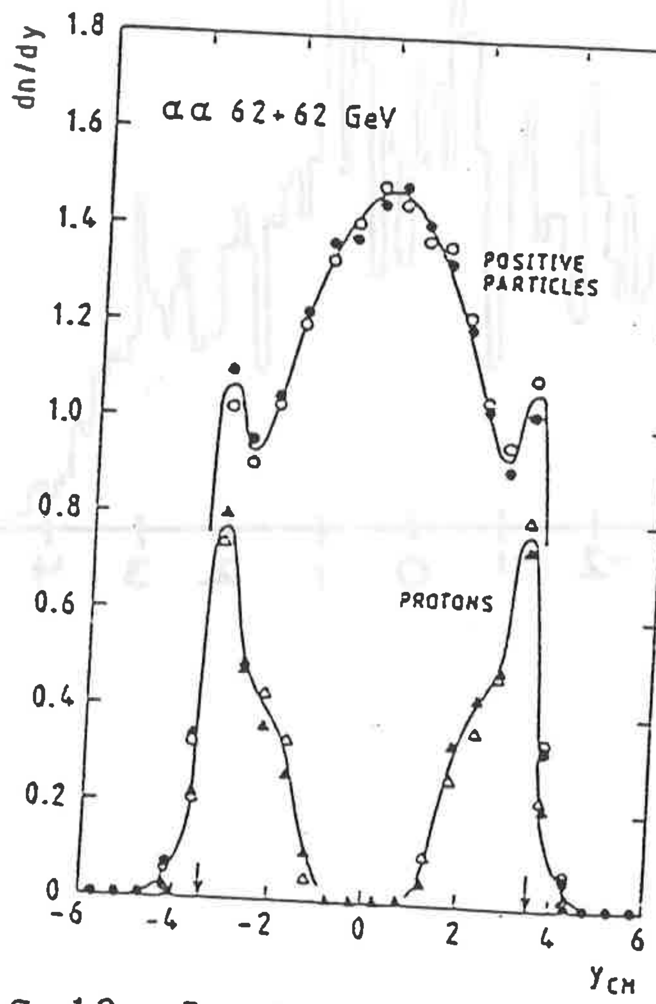
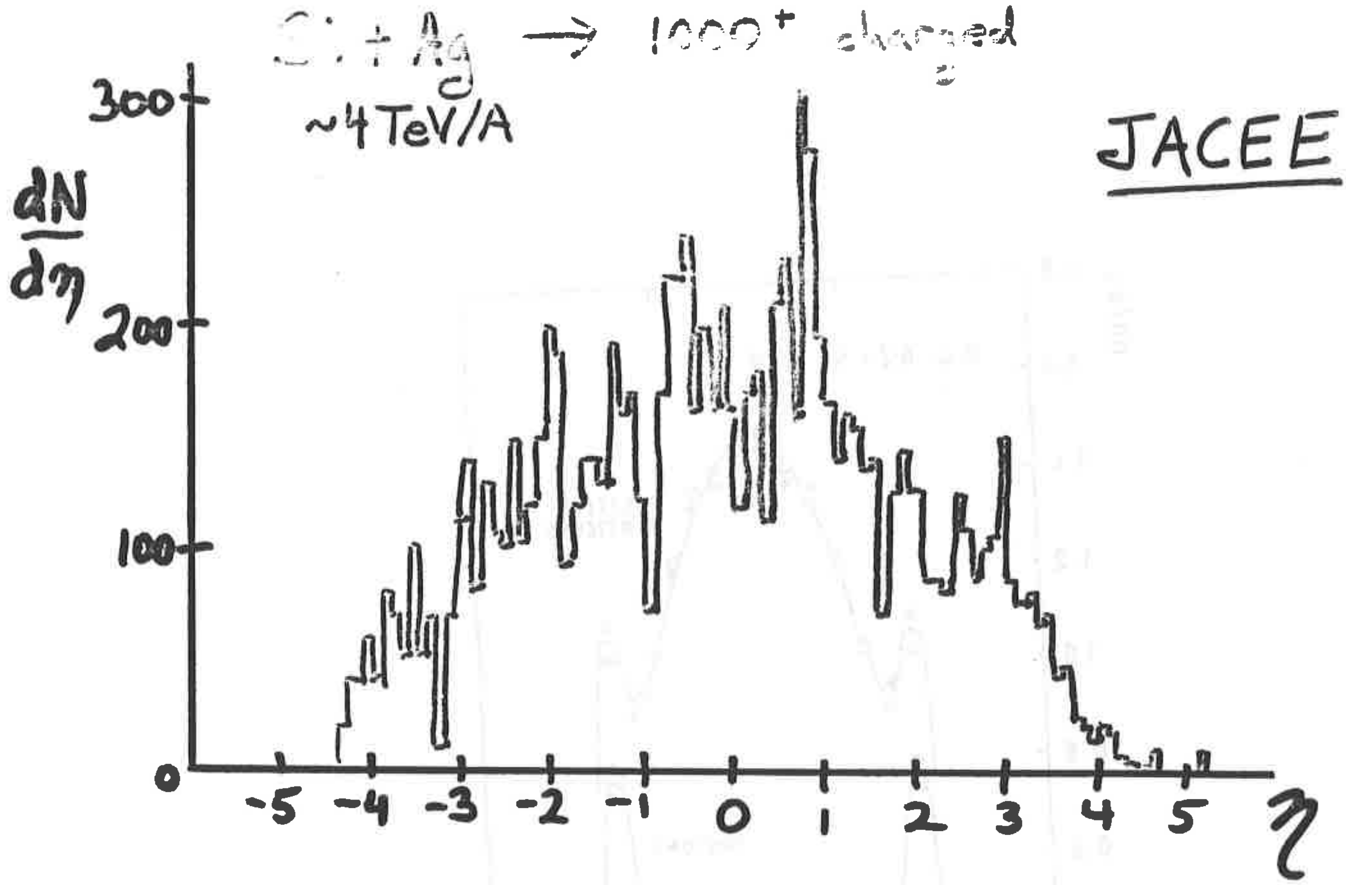


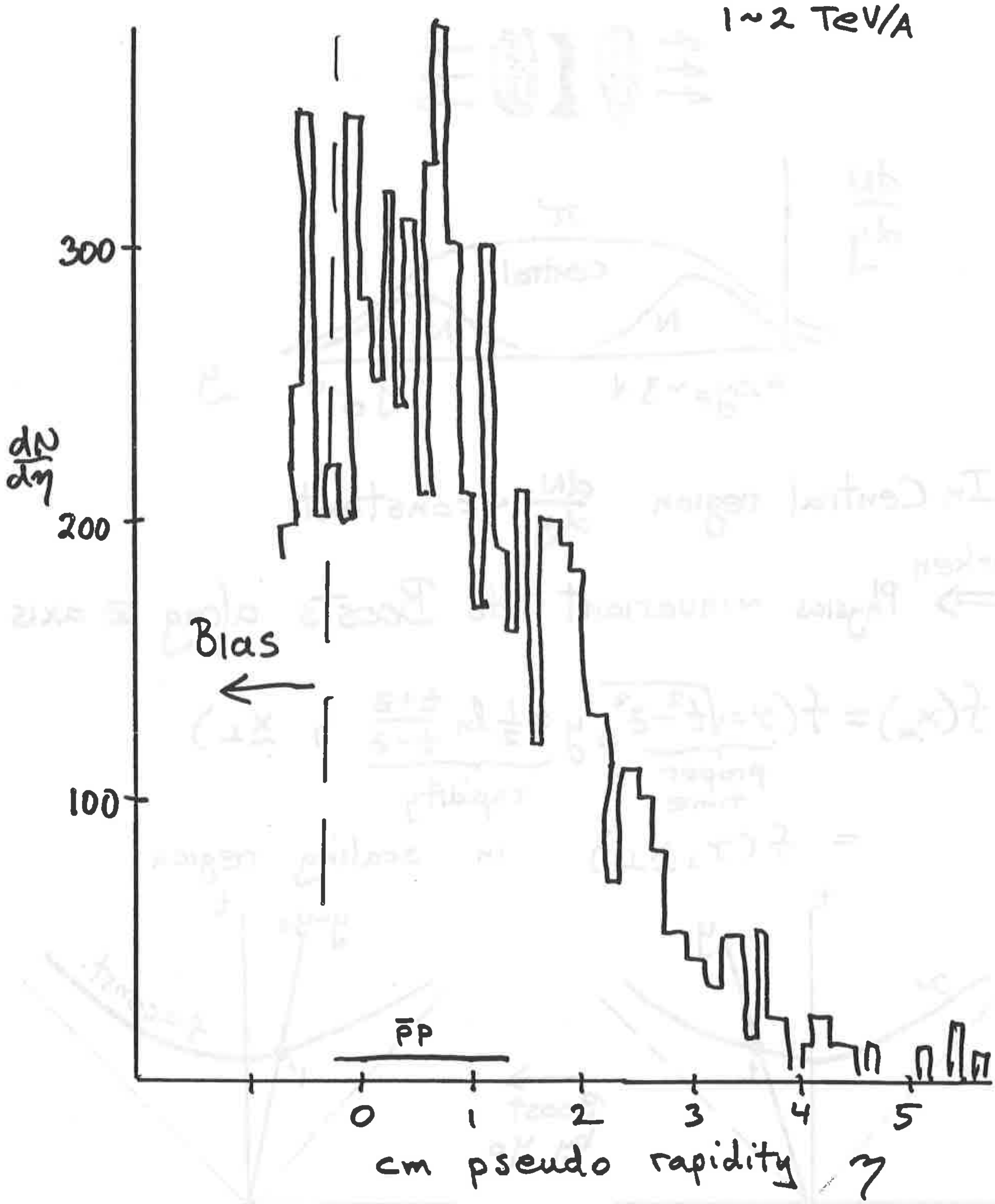
Fig 12. Rapidity density of positive particles and protons in αα interactions at $\sqrt{s}$ =31.2 GeV[27].



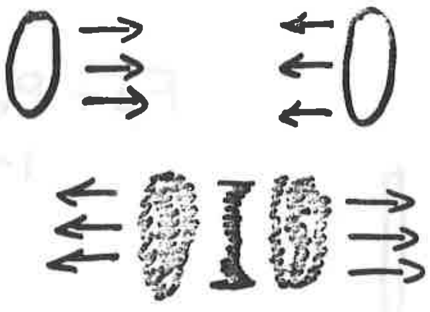
Si + Ag → 1000+ charged
~4 TeV/A
JACEE
dN/dη
300
200
100
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
η

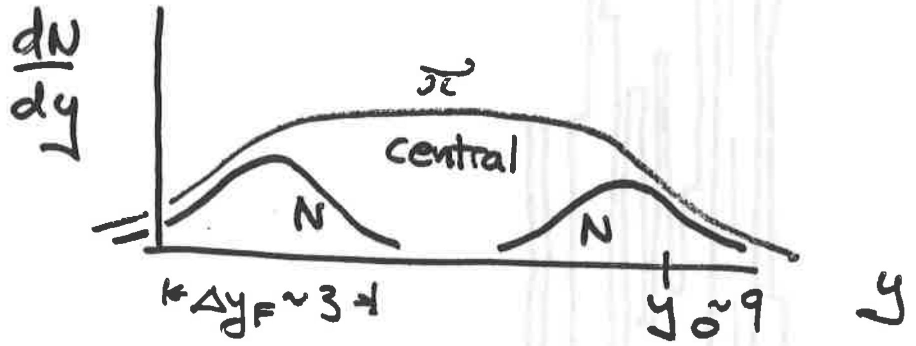
Preliminary JACEE III

Fe + Pb → 1000 ± 100 ch
1~2 TeV/A



Nuclear Collisions $E_{lab} \gtrsim 1\,\mathrm{TeV/A}$



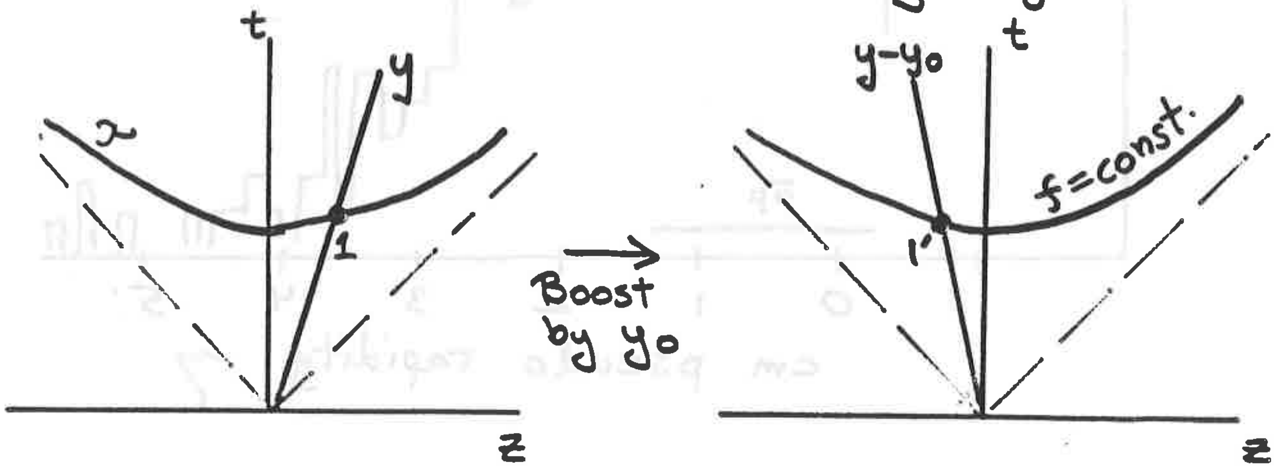


In Central region $\frac{dN}{dy} \sim$ constant

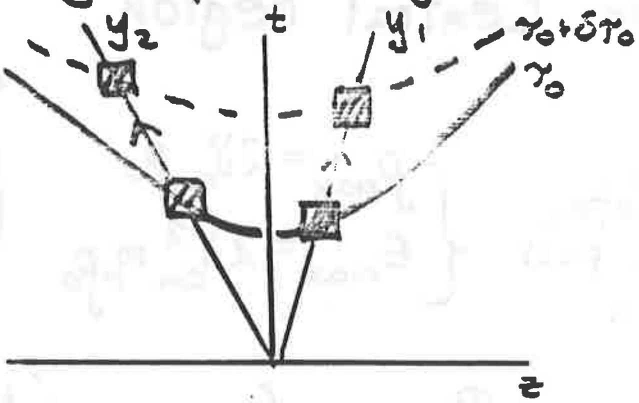
$\overset{\text{Bjorken}}{\Longrightarrow}$ Physics ~ invariant to Boosts along z axis

$$f(x_\mu) = f(\underbrace{\tau = \sqrt{t^2 - z^2}}_{\text{proper time}},\ y \underbrace{= \tfrac{1}{2}\ln\tfrac{t+z}{t-z}}_{\text{rapidity}},\ \underset{\sim}{x}_\perp)$$

$$= f(\tau, \underset{\sim}{x}_\perp) \quad \text{in scaling region}$$



Very Rapid Longitudinal Expansion



particles produced at $\tau = \tau_0$ and $z = z_0$ move away from $z=0$

$$y = \frac{1}{2}\ln\frac{t+z}{t-z} \qquad \tau = \sqrt{t^2-z^2}$$

$$v_z = \tanh y = \frac{z}{t} = \frac{z}{\sqrt{\tau_0^2+z^2}}$$

"Hubble" constant $= \left.\frac{\partial v_z}{\partial z}\right|_{z=0} = \frac{1}{\tau_0} \sim 10^{17} H_{\text{cosmos}}$ $(t\sim\mu\text{sec})$

Volume element doubles every time τ doubles

$\Rightarrow \quad \epsilon(\tau) = \epsilon(\tau_0)(\tau_0/\tau) \qquad$ if $dE=0$

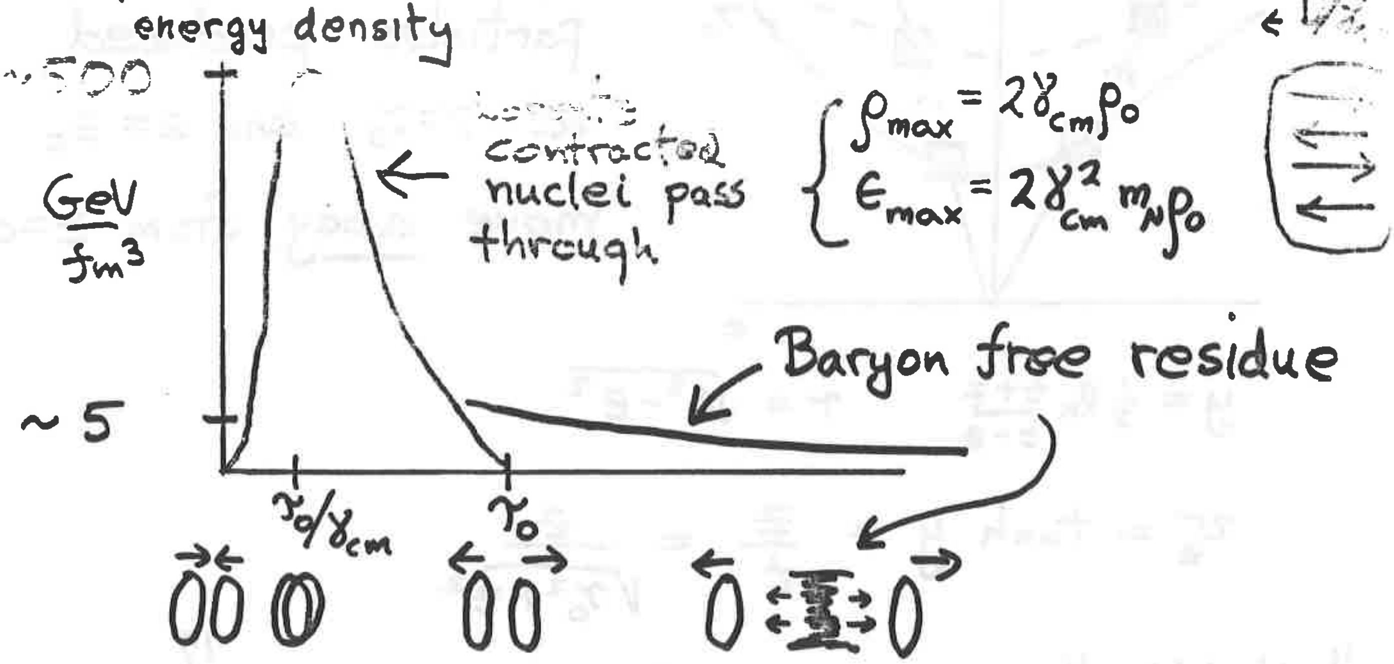
If expansion is isentropic $dS=0 \Rightarrow pdV$ work

$$\partial_\mu T^{\mu\nu}=0 \Rightarrow \frac{\partial\epsilon}{\partial\tau} + \frac{\epsilon+p}{\tau} = 0 \Rightarrow \epsilon(\tau)=\epsilon(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{1+c_s^2}$$

* Energy density ↓ by at least a factor of 2 between τ_0 and $2\tau_0$

* Plasma produced in highly non-static environment

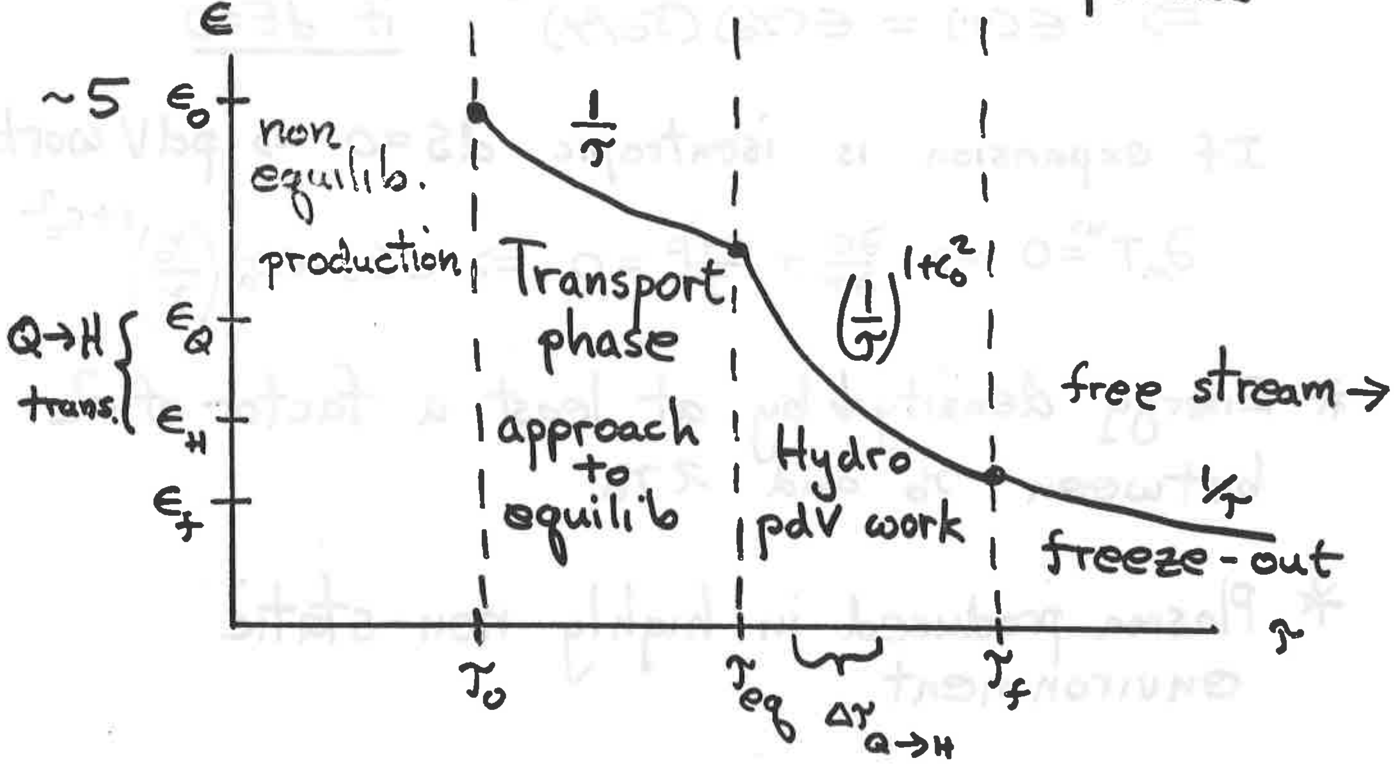
Proper time history in Central region



$$\begin{cases} \rho_{max} = 2\gamma_{cm}\rho_0 \\ \epsilon_{max} = 2\gamma_{cm}^2 m_N \rho_0 \end{cases}$$

Within first fm/c ~ τ_0, ϵ falls by a factor $\underline{e^{y_0} \sim 100}$!

* We are interested in 1% residue = quark-gluon plasma



Navier-Stokes equation in scaling regime

$n_B = 0$ and $f(x_\mu) = f(\tau)$

$$\underline{\frac{d\epsilon}{d\tau} + \frac{\epsilon+p}{\tau} = \frac{1}{\tau^2}\left(\frac{4}{3}\eta+\zeta\right)}$$

Emelyanov 65
Kajantie, ...

Note:

1. Heat conduction does not enter

2. Only combination $\frac{4}{3}\eta + \zeta$ enters

3. Entropy density $\sigma = \frac{\epsilon + p}{T}$ obeys

$$\frac{d}{d\tau}(\tau\sigma) = \frac{1}{\tau T(\tau)}\left(\frac{4}{3}\eta+\zeta\right) \geq 0$$

$$\tau_f\sigma_f = \tau_0(\sigma_0 + \delta\sigma) \qquad \delta\sigma = \frac{1}{\tau_0}\int_{\tau_0}^{\tau_f}\frac{d\tau}{\tau}\frac{\left(\frac{4}{3}\eta+\zeta\right)}{T(\tau)} \geq 0$$

Relation to dN/dy (T. Matsui, M6)

dimensionally $n \sim T^3$ $\quad \sigma \sim T^3$

$\Rightarrow \quad n = \frac{1}{c}\sigma \qquad c \approx 4 \qquad$ Landau

$$N = \int dy \frac{dN}{dy} = \int d^4x\, \delta(\tau-\tau_f)\, n(\tau, x_\perp) = \int dy\, d^2x_\perp\, \tau_f\, n(\tau_f, x_\perp)$$

$$\Rightarrow \quad \frac{dN}{dy} = A_\perp \tau_f\, n(\tau_f) = \frac{1}{4} A_\perp \tau_f\, \sigma(\tau_f)$$

$$= \frac{1}{4} A_\perp \tau_0 (\sigma_0 + \delta\sigma)$$

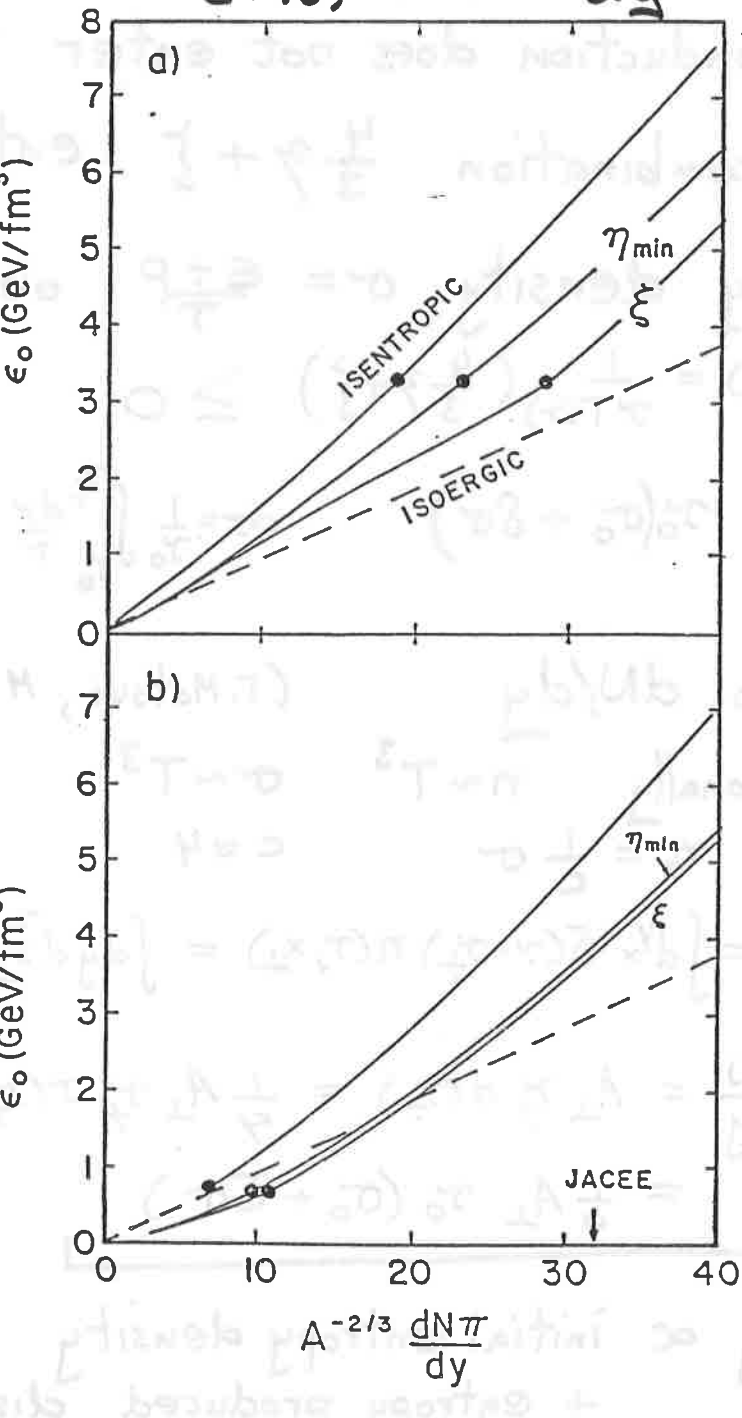
Final $dN/dy \propto$ initial entropy density
+ entropy produced dissipatively

P. Danielewicz, MG

Navier Stokes $\frac{dN}{dy} = \frac{1}{4} A_\perp \tau_0 (\sigma(\tau_0) + \delta\sigma_\eta)$

$$\sigma(\tau_0) = \frac{\epsilon + p}{T}\Big|_{\tau=\tau_0} \qquad \delta\sigma_\eta = \frac{1}{\tau_0}\int_{\tau_0}^{\infty} \frac{d\tau}{\tau} \frac{(4/3\,\eta + \zeta)}{T(\tau)}$$

$\epsilon(\tau_0)$ vs. dN/dy



full work $\tau\sigma$ = cont

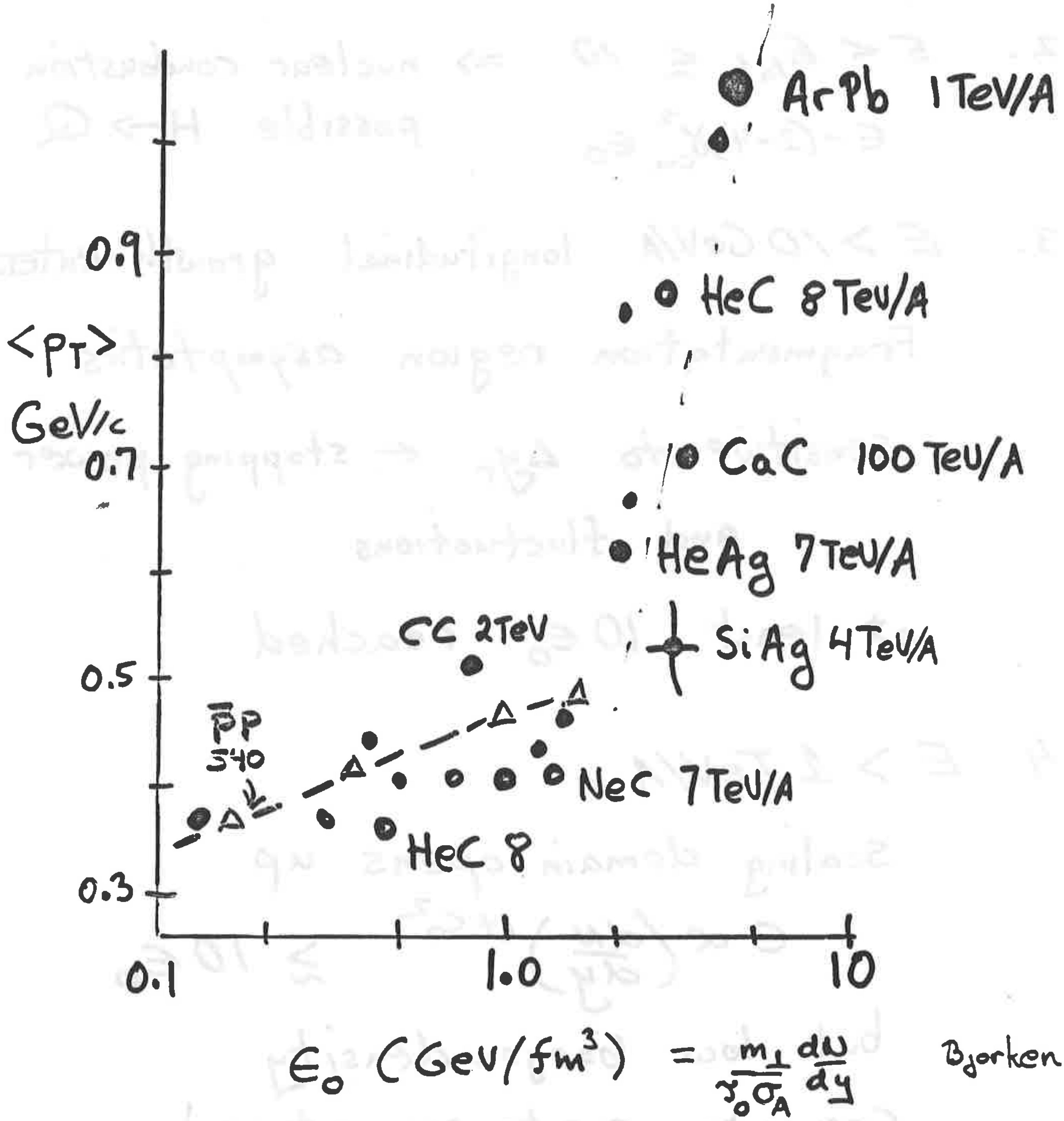
} viscous reheatin

no work $\tau\epsilon$ = cons

Fig. 2

Miyamura Compilation of Cosmic Ray Data

JACEE



Where are we?

1. For $E_{lab} < 5\,GeV/A \Rightarrow$ nuclear shocks in U+U

2. $5 < E_{lab} \lesssim 10 \Rightarrow$ nuclear combustion possible $H \rightarrow Q$
   $\epsilon \sim (2-4)\gamma_{cm}^2 \epsilon_0$

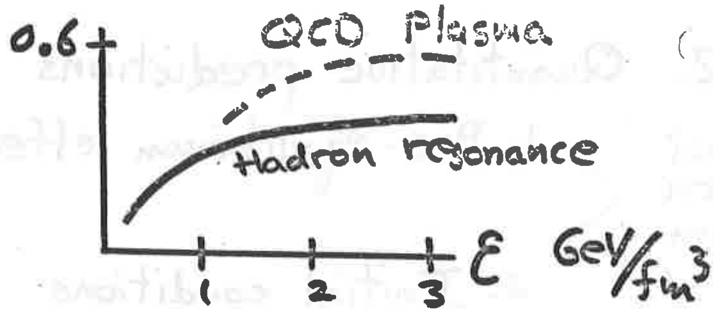
3. $E > 10\,GeV/A$ longitudinal growth enter.
   Fragmentation region asymptotics
   sensitive to $\Delta y_r \leftarrow$ stopping power and fluctuations
   at least $10\,\epsilon_0$ reached

4 $E > 1\,TeV/A$
   Scaling domain opens up
   $$\epsilon \propto \left(\frac{dN}{dy}\right)^{1+c_0^2} \gtrsim 10\,\epsilon_0$$
   but low baryon density
   Cosmic ray events provocative!

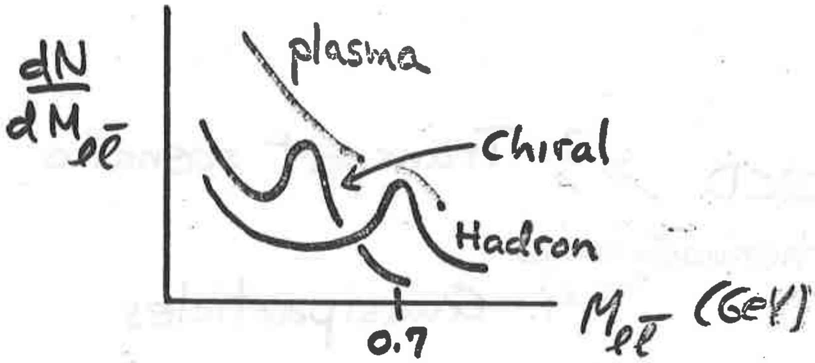
Lecture 3 by Miklos Gyulassy CERN 6/27/84

Diagnostic Tools

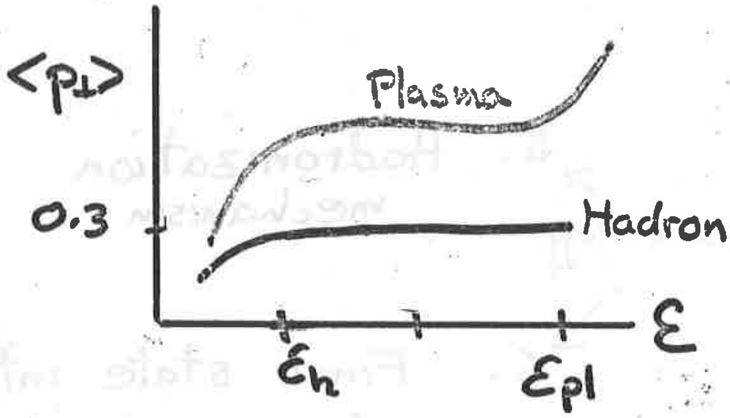
1. Stangeness fraction
   Rafelski
   Glendenning



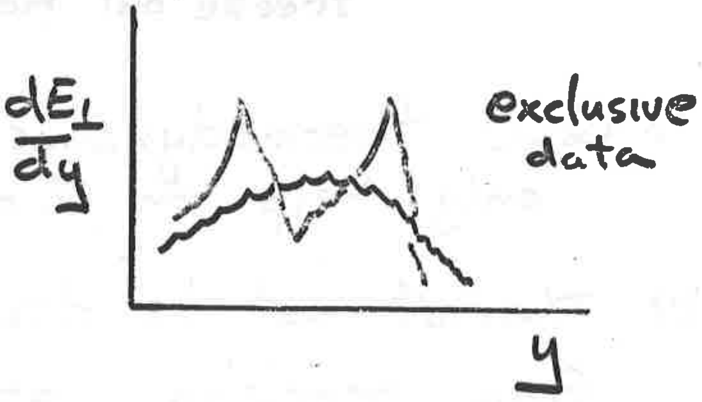
2. Dilepton pairs
   Chin
   Pisarski
   McLerran



3. $\langle p_\perp \rangle$ vs ε
   Shuryak
   Van Hove



4. $\frac{dE_\perp}{dy}$ fluctuations
   M.G., McLerran
   Takagi



General Remarks on the search for QCD plasma

1. This is an exploratory and phenomenological science

2. Quantitative predictions depend on many unknowns

must learn from pA, OA →

1. Pre-equilibrium effects { hard collisions, initial state inter.
2. Initial conditions { fluctuations, variations with b and $\Sigma_\perp$

QCD thermodynamics →

3. Transport scenario { chemical equilibration, viscocities
4. Quasiparticles { m_{eff}, ω_{pl}, sound, screening in time dependent environment

phenomenology →

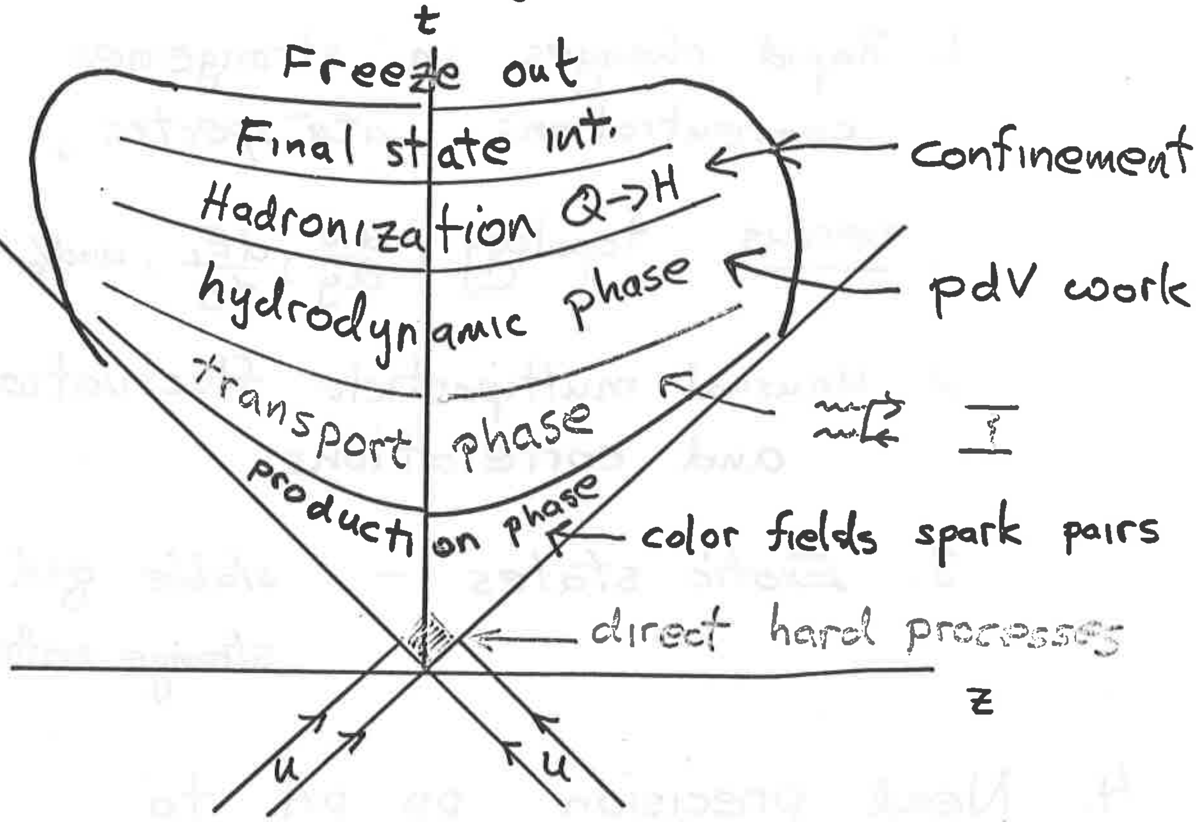
5. Hadronization mechanism { recombination, spinoidal, deflagrations
6. Final state interactions freeze out mechanism

* QCD thermodynamics (on a lattice) only help on 2 out of 6

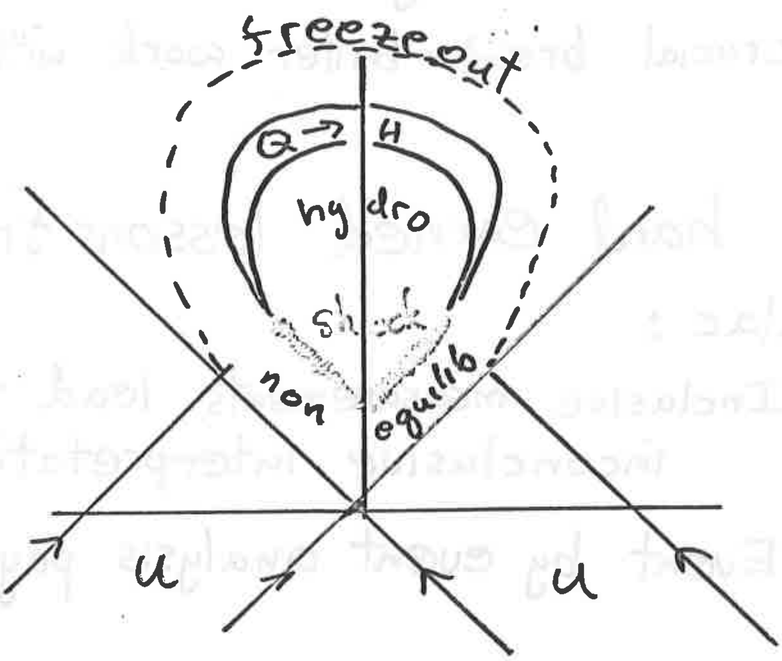
** The rest must be deduced phenomenologically from precision pp pA BA data.

Space-Time evolution of nuclear reactions

$E_{lab} > 1\,TeV/A$ Scaling domain



$E \lesssim 10\,GeV/A$ Stopping domain



3. Must concentrate on <u>qualitative</u> phenomena

1. Rapid changes in strangenes concentrations, $\mu^+\mu^-$ spectra, $\frac{dN}{dp_\perp^2}$, ...

<u>versus</u> topology, $\frac{dN}{dy}$, $\frac{dE_\perp}{dy}$, and/or A

2. Unusual multiparticle fluctuations and correlations

3. *Exotic* states − stable $q+A$ states
strange matter $S\approx -A$

4. Need precision pp pA to develop <u>Monte Carlo</u> simulators (Ludlam) to establish backgrounds
* crucial bread + butter work with PS, SPS

5. Learn hard earned lessons from Bevalac:

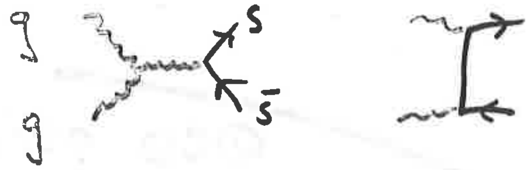
Inclusive measurements lead to inconclusive interpretations

Event by event analysis pays off!

Tasting the Plasma Flavors

Strangeness of *Rafelski*

1. $s\bar{s}$ abundance controlled by gluons



2. Unlike u d strangeness drops quickly <u>out</u> of chemical equilib

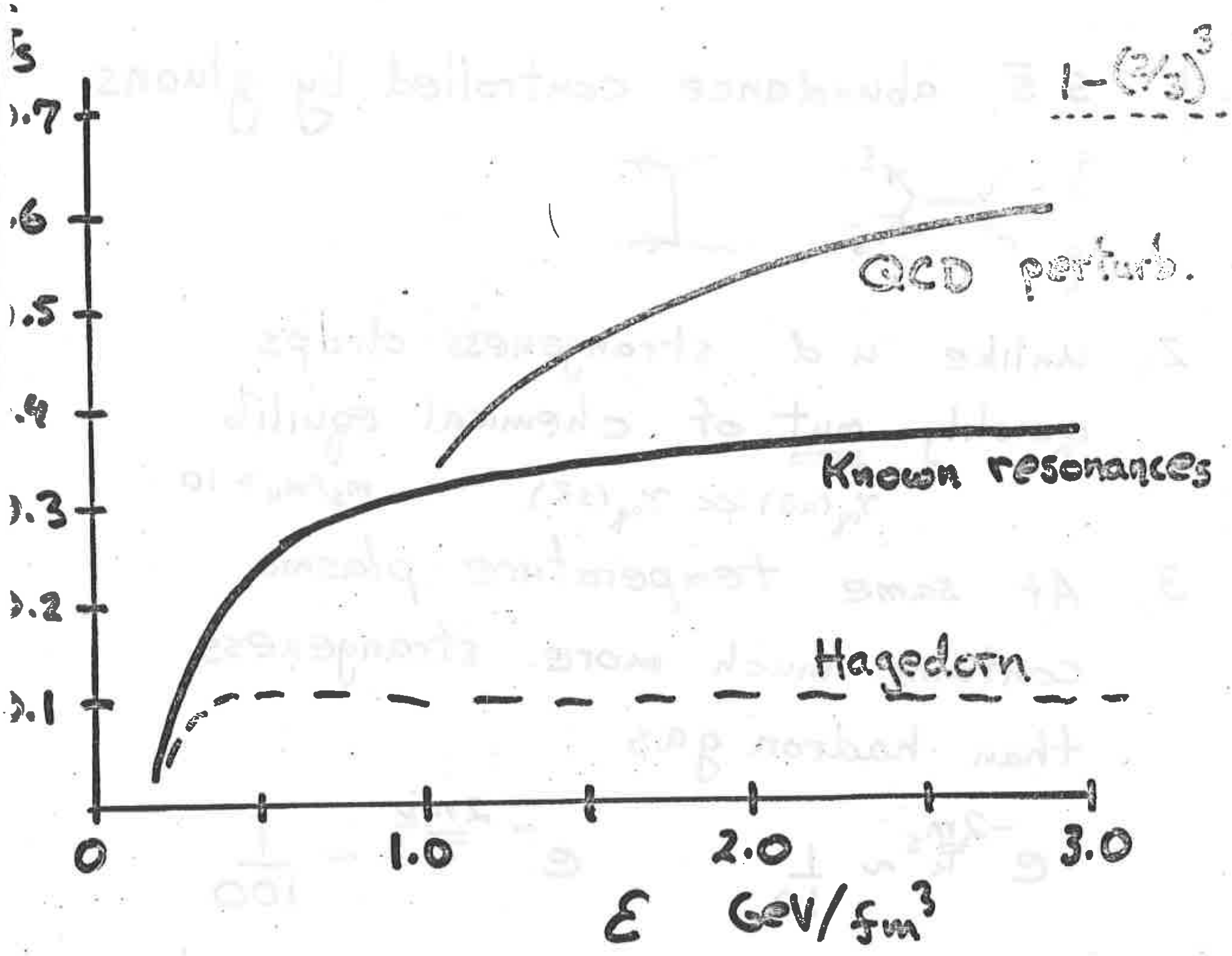
   $\tau_{eq}(u\bar{u}) << \tau_{eq}(s\bar{s})$ $\qquad m_s/m_u > 10$

3. At same temperature plasma contains much more strangeness than hadron gas

$$e^{-\frac{2m_s}{T_c}} \sim \frac{1}{10} \qquad e^{-\frac{2m_K}{T}} \sim \frac{1}{100}$$

✳✳ 4. Must select special event classes with same temperature profiles

   Events with fixed energy density, $\frac{dE_\perp}{dy}$, are not good enough: $T_Q \neq T_H$



$$f_s = \frac{N_\Lambda + N_\Sigma + \cdots}{N_N + N_\Lambda + N_\Sigma + \cdots} = \text{strange baryon fraction}$$

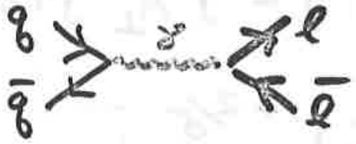
—— Anishetti Koehler McLerran

- - - - Glendenning Gyulassy

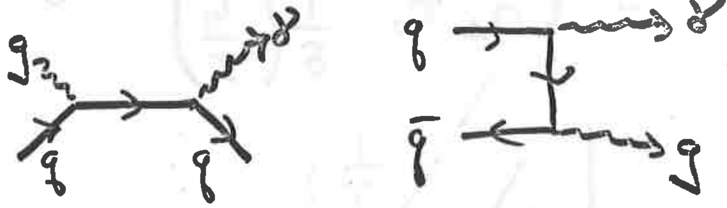
Plasma Diagnostics: Thermometers

(Feinberg, Shuryak, Domokos, Kajantie, Mietinen, ...)
↳ Sov. J. Nucl. Phys 28 (1978) 408

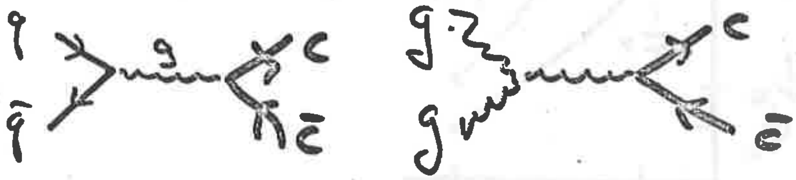
1. Dilepton



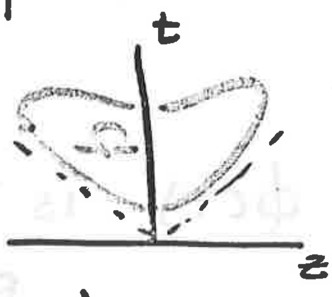
2. Direct Photons



3. Charm



Let $\Gamma(T,M)$ = production rate/volume per unit (mass, $p_\perp$, and/or x_F) at temperature T



$$\frac{d\sigma}{dM} = \sigma_{in} \int_\Omega d^4x\, \Gamma(T(x))$$

$$= \sigma_{in} \int_{T_{freeze}}^{T_0} dT\, \phi(T)\, \Gamma(T,M)$$

$$\underbrace{\phi(T) = \int_\Omega d^4x\, \delta(T - T(x))}$$ = Temperature Profile

Temperature Profile Function

$$\epsilon = \epsilon_0 \left(\frac{r_0}{r}\right)^{\alpha} \qquad \alpha = 1 \to \frac{4}{3} \qquad T = T_0 \left(\frac{r_0}{r}\right)^{\alpha/4 \equiv \delta}$$

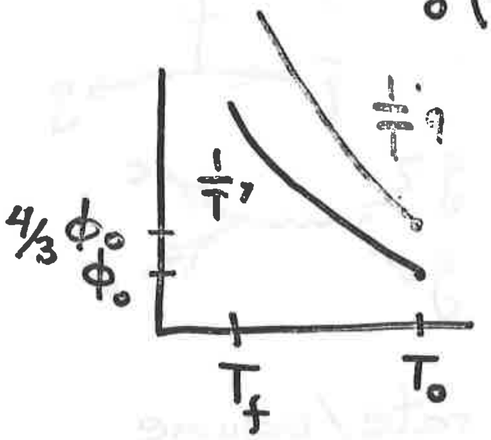
$$\delta \sim .25 - .33$$

$$\phi(T) = \int d^4x \, \delta\left(T - T_0\left(\frac{r_0}{r}\right)^{\delta}\right) = Y A_\perp \int r\,dr \, \delta\left(T - T_0\left(\frac{r_0}{r}\right)^{\delta}\right)$$

$$= Y A_\perp r_0^2 \, \frac{1}{\delta}\left(\frac{T_0}{T}\right)^{1+2/\delta}$$

$\to 7$ for isentropic

$\to 9$ for viscous

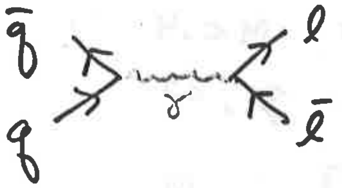


Note $\phi \propto A_\perp r_0^2 \sim R^2$ not R^4 !

Kajantie

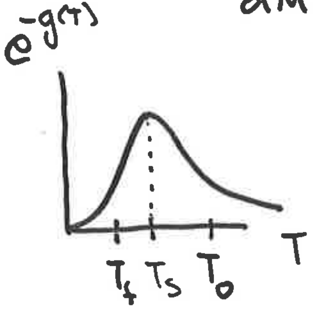
$\phi(T)$ is sensitive to dynamical path δ

Thermal Production Rates



$$\frac{d\Gamma(T)}{dM} = \frac{\sqrt{2}\,\alpha^2}{3\pi^{3/2}}(MT)^{3/2}\, e^{-\frac{M}{T}} \qquad \frac{M}{T} \gg 1$$

$$\frac{d\sigma}{dM} \propto \int_{T_f}^{T_0} dT\, \phi(T)\, \frac{d\Gamma(T)}{dM}$$



$$\propto \int_{T_f}^{T_0} dT\, \frac{1}{T^p}\, T^{3/2} e^{-M/T} = \int_{T_f}^{T_0} dT\, e^{-g(T)}$$

$$g(T) = \frac{M}{T} + (p - 3/2)\ln T \;; \quad g'(T) = -\frac{M}{T^2} + \frac{p - 3/2}{T}$$

stationary phase point $g'(T_s) = 0$

$$T_s = \frac{M}{p - 3/2} \qquad p = 7 - 9$$

By chosing M: $(p - 3/2)m_\pi < M < (p - 3/2)T_0$

$$\int_{T_f}^{T_0} dT\, e^{-g(T)} \propto \frac{e^{-g(T_s)}}{(g''(T_s))^{1/2}} \propto \frac{1}{M^{p-5/2}}$$

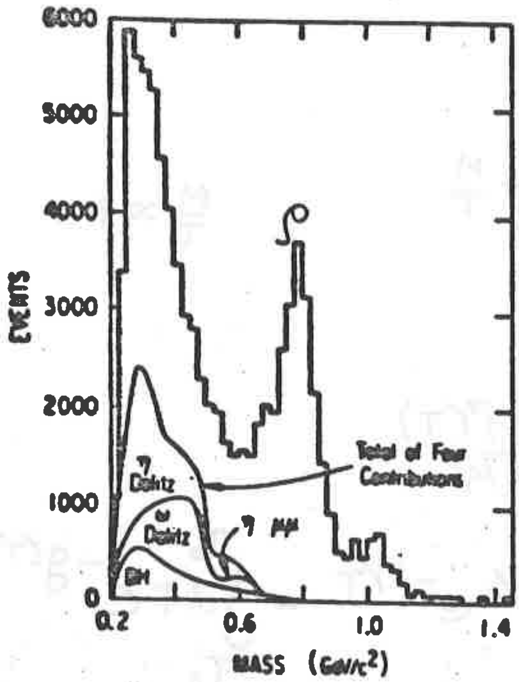
$\Rightarrow$ For pairs $m_\rho < M_{\mu^+\mu^-} \lesssim$ few GeV

$$\frac{d\sigma}{dM} \propto \frac{M^{3/2}}{M^{4.5-6.5}}$$

falls as power
not e^{-M/T_0}

Mclerran, ...

Backgrounds



1) Low mass $M < .4$

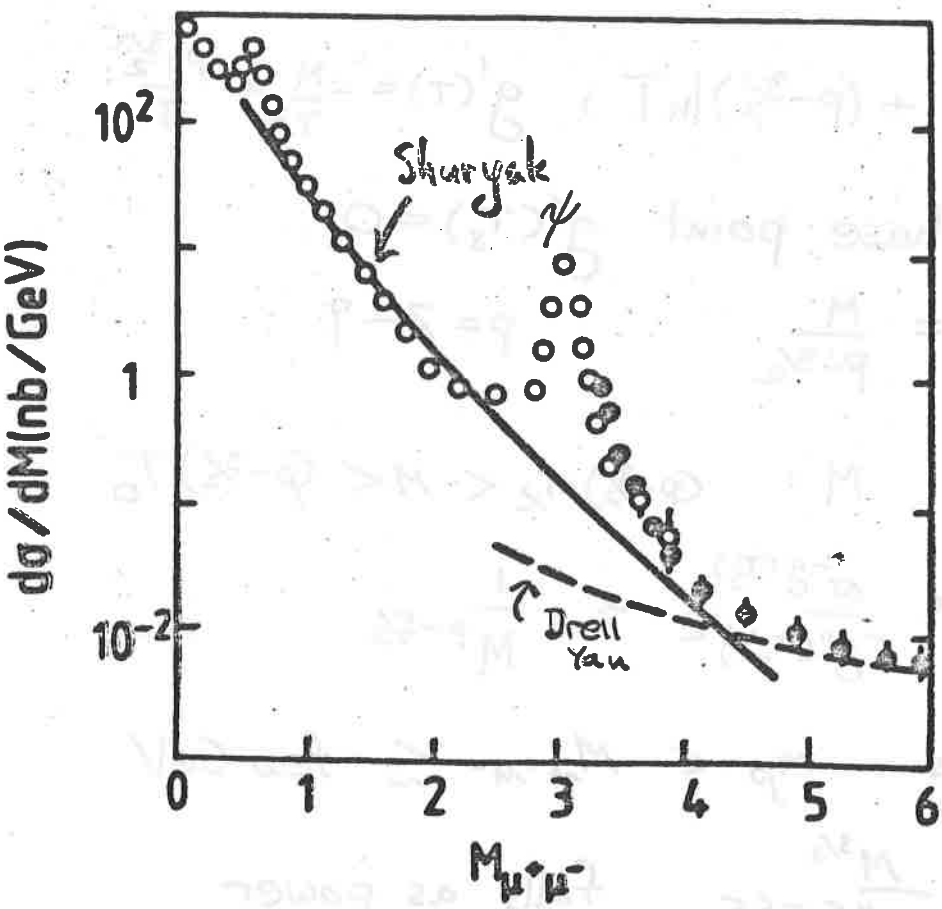
Dalitz η, ω

2) $m \sim 0.7$: ρ

$\pi^+\pi^- \to \ell\bar{\ell}$

3) $m > 2$ GeV

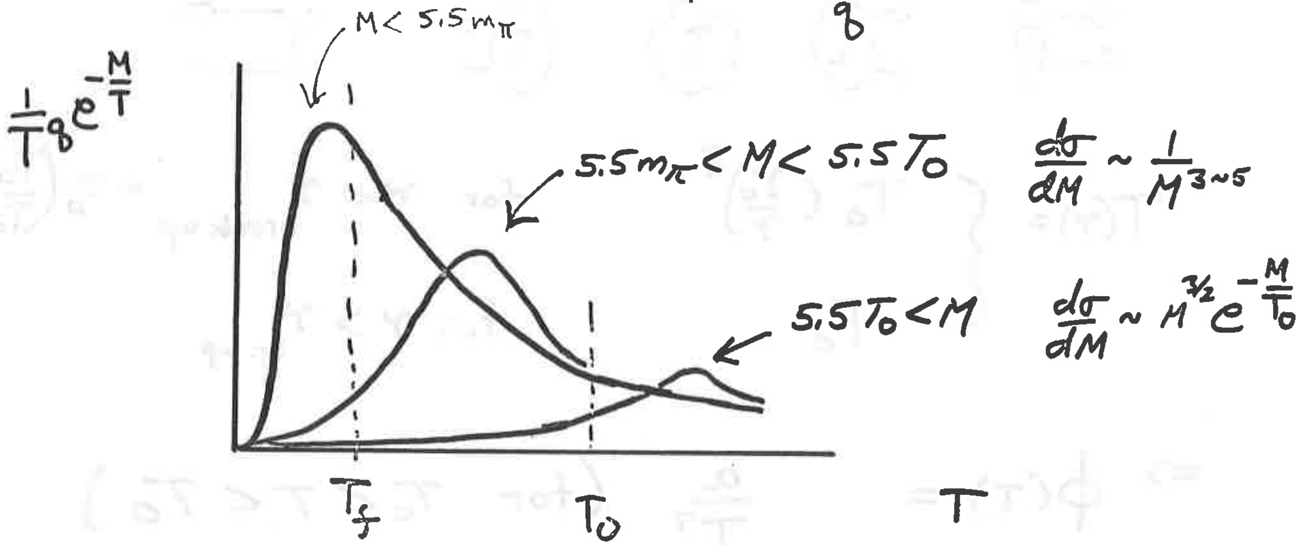
Drell - Yan



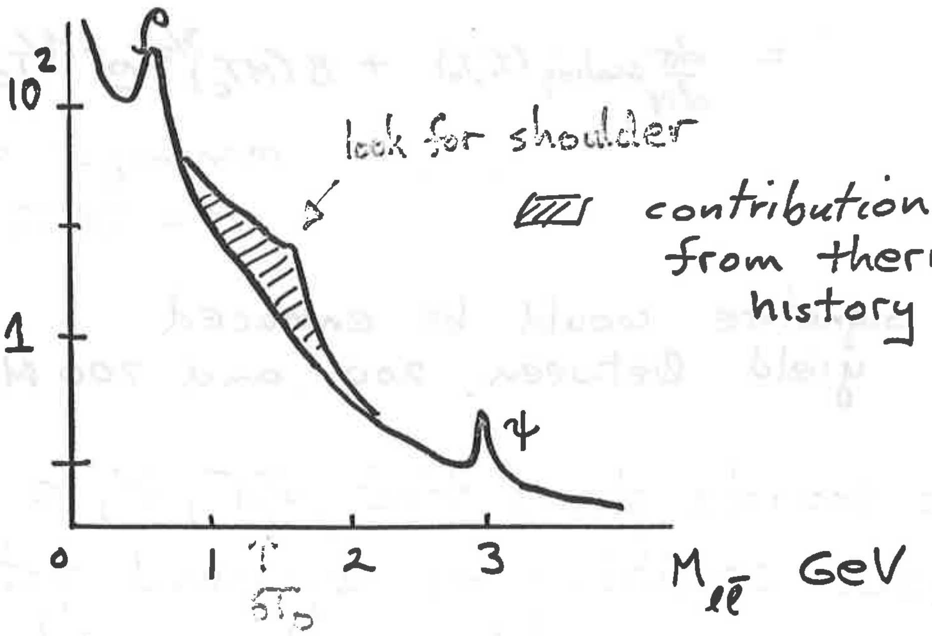
$T_0 \cong 500$ MeV

Measurement of $T_0 = T(\tau_0)$ McLerran

$$\frac{d\sigma}{dM_{\ell\bar{\ell}}} = A\, M^{3/2} \int_{T_f}^{T_0} dT \, \underbrace{\frac{1}{T^q} e^{-\frac{M}{T}}}_{\text{peaks } \frac{M}{q} = T} \qquad q = 5.5 \sim 7.5$$



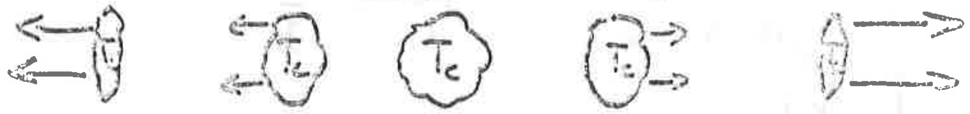
Note: change of behavior from power law to exponential at $M \sim 6T_0$



Altemate Van Hove scenario

Assume scaling dynamics ok for $T > T_c$

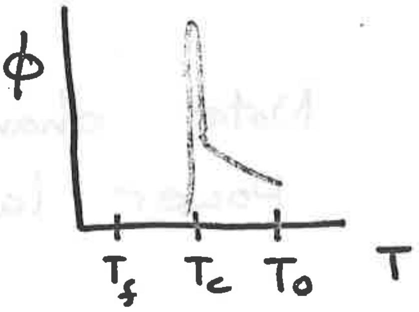
But system breaks up at T_c



$$T(\tau) = \begin{cases} T_0 \left(\frac{\tau_0}{\tau}\right)^{\delta} & \text{for } \tau < \tau_{\text{break up}} = \tau_0 \left(\frac{T_0}{T_c}\right)^{1/\delta} \\ T_c & \text{for } \tau > \tau_{\text{br. up}} \end{cases}$$

$$\Rightarrow \phi(T) = \frac{a}{T^7} \quad (\text{for } T_c < T < T_0)$$

$$+ \, b\, \delta(T - T_c)$$



$$\Rightarrow \frac{d\sigma}{dM} = \int \phi(T) \frac{d\Gamma}{dM}(T)$$

$$= \frac{d\sigma}{dM}_{\text{scaling}}(T_c, T_0) + B\,(MT_c)^{3/2} e^{-M/T_c}$$

maximizes at
$M = 3/2\, T_c \sim m_{\rho}/2$

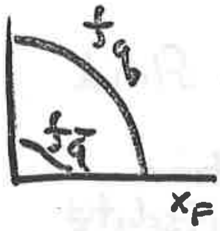
Signature would be enhaced yield between 200 and 700 MeV

✳ This example shows that $\mu^+\mu^-$, γ, ... depend sensitively on dynamical path and hadronization mechanism!

Open Problem: Contribution from approach to equilibrium

$$\Gamma(x) = \int d^3p\, d^3p' \left[\sigma_{q\bar{q}\to\ell\bar{\ell}}\, v\right] f_q(p,x)\, f_{\bar{q}}(p',x)$$

1) For $0 < \tau < \tau_0 \sim 1\,\mathrm{fm}/c$ Quantal Stage



$f_q(p,x)$ = structure function (wigner density) of nuclei

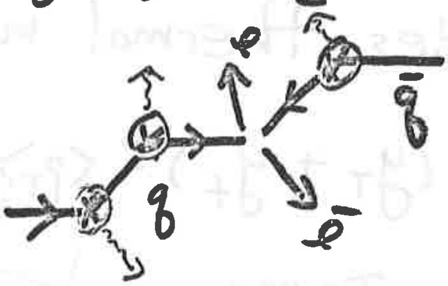
* This gives Drell - Yan part

2) For $\tau > \tau_c \sim 1-2\,\tau_0$ Local Equilibrium

$$f_q(p,x) = \left(e^{-\omega/T(\tau)} + 1\right)^{-1} \qquad T(\tau) = T_0\left(\frac{\tau_0}{\tau}\right)^{1/3}$$

* This gives thermal part

3) For $\tau_0 < \tau < \tau_c$ Approach to Equilib



$f_p(p,x) = ??$

Requires Monte Carlo cascade!

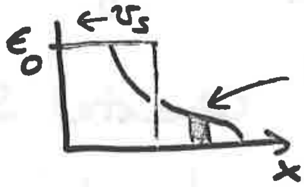
$$\frac{d\sigma}{dM} \propto \int d^4x\, \Gamma = \Gamma_{DY} + \underline{\Gamma_{int}} + \Gamma_T$$

$\langle p_\perp \rangle$ Barometer (Van Hove, Shuryak)

Naïve Wrong idea $\langle p_\perp \rangle \cong 2T_f$ = thermometer

* $\langle p_\perp \rangle$ involves both thermal and collective motion

1-dim example



fluid cell at x has flow rapidity $y(x)$

Flow comes from pdV work done by fluid

$$y(\epsilon) = \int_\epsilon^{\epsilon_0} \frac{c_0\, d\epsilon}{\epsilon + \underbrace{p(\epsilon)}_{\simeq c_0^2 \epsilon \text{ ideal gas}}}$$

general solution Landau + Lifschitz

If fluid breaks up at density $\epsilon = \epsilon_f$

then final flow velocity is

$$y_f = y(\epsilon_f) = \frac{c_0}{1+c_0^2} \ln P_0/P_f$$

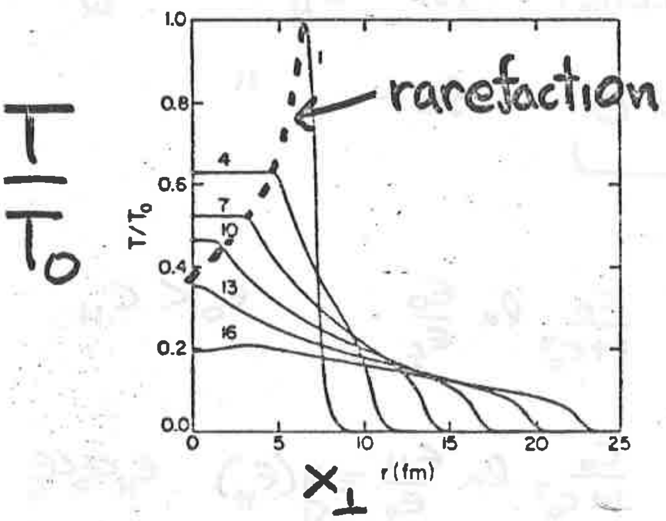
$\Rightarrow$ y_f is barometer

Observed $\langle p_T \rangle$ includes thermal motion

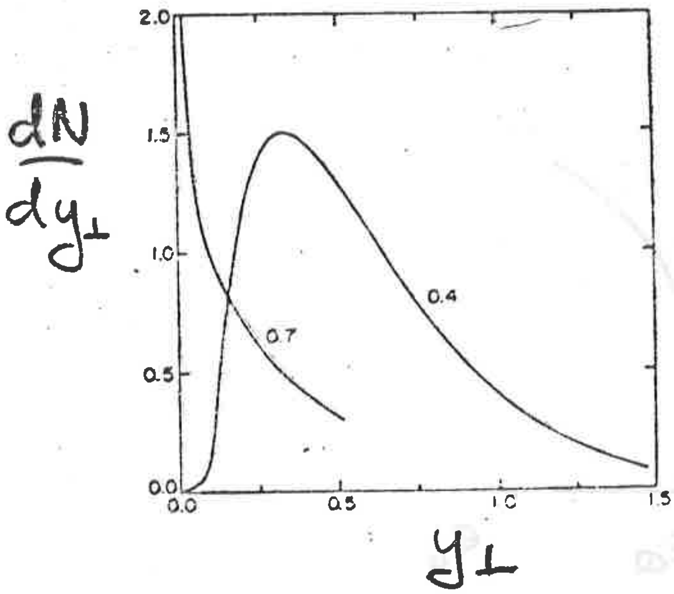
$$\langle p_T \rangle = m \sinh(y_T + y_f) \cong \underbrace{\langle p_T \rangle_{\text{thermal}}\, e^{y_f}}_{\text{Doppler shifted}}$$

typically $y_T \approx 1.5$ for $T = m_\pi$

Transverse Expansion: Baym, Friman, Blaizot, Soyeur, Czyż



Because of longitudinal expansion, center core could freeze out with
$v_\perp = 0$



Note: small $y_\perp$ can lead to large $p_\perp$

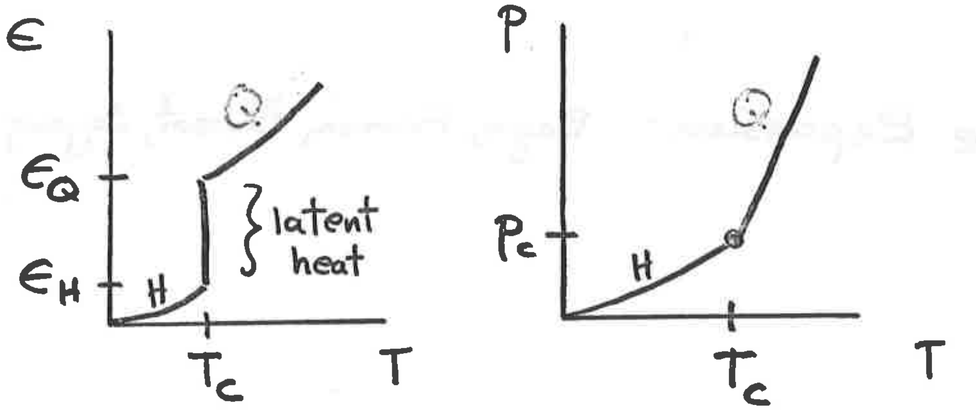
$p_\perp = m_\perp \, sh(y_T + y_\perp)$

$y_T \approx 1.5 \Rightarrow p_\perp \approx 0.3$ GeV

$y_T + y_\perp \approx 2 \Rightarrow p_\perp \approx 0.5$ "

Need to build in transition $Q \to H$

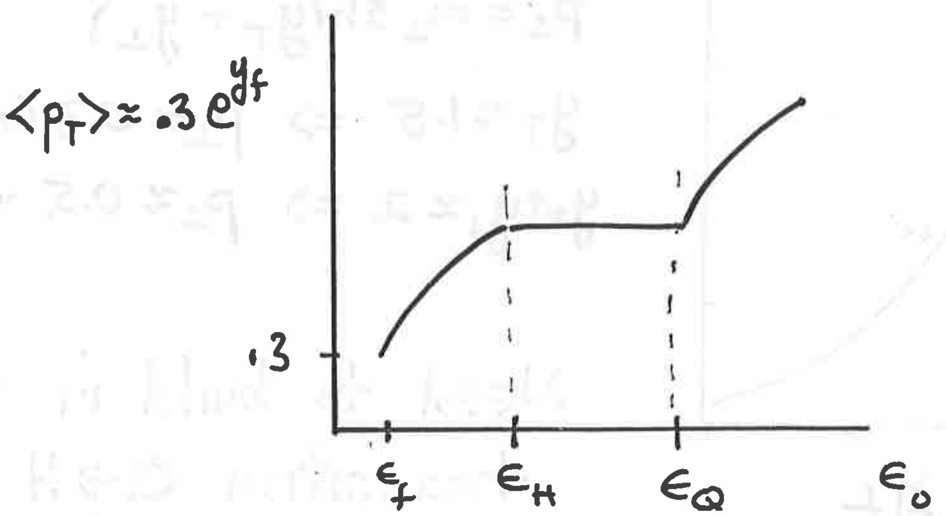
What if there is a first order transition?

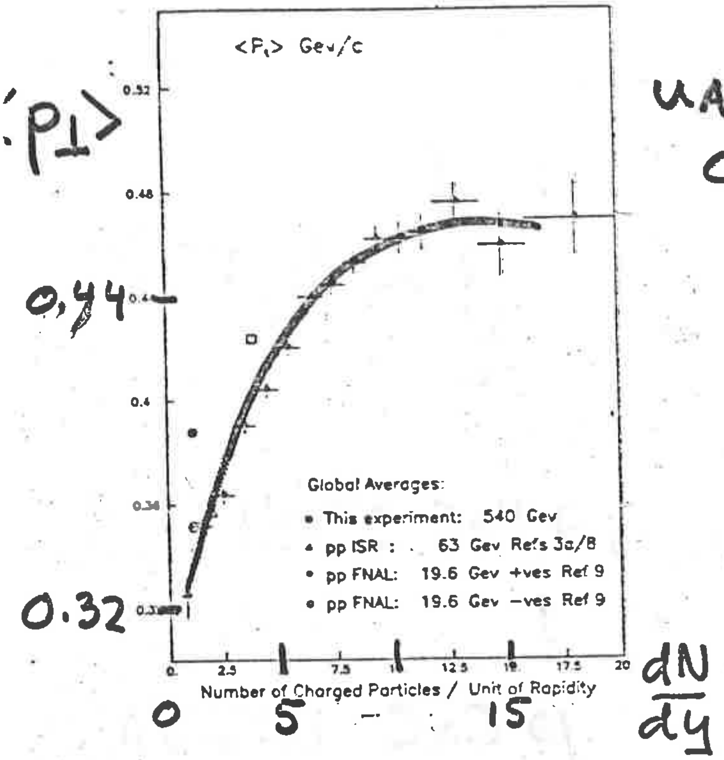


First order $\Rightarrow$ $p = p_c = \text{const}$ for $\epsilon_H < \epsilon < \epsilon_Q$

$$\Rightarrow \underbrace{c_0^2 = \frac{\Delta p}{\Delta \epsilon} = 0}\quad \text{for} \quad ''$$

$$y_f = \int_{\epsilon_f}^{\epsilon_0} \frac{c_0(\epsilon)\,d\epsilon}{\epsilon + p(\epsilon)} = \begin{cases} \dfrac{c_0}{1+c_0^2}\ln\dfrac{\epsilon_0}{\epsilon_f} & \epsilon_0 < \epsilon_H \\[2ex] \dfrac{c_0}{1+c_0^2}\ln\dfrac{\epsilon_H}{\epsilon_f} \equiv y(\epsilon_H) & \epsilon_H < \epsilon_0 < \epsilon_Q \\[2ex] y(\epsilon_H) + \dfrac{c_0}{1+c_0^2}\ln\dfrac{\epsilon_0 - B}{\epsilon_Q - B} & \epsilon_0 > \epsilon_Q \end{cases}$$

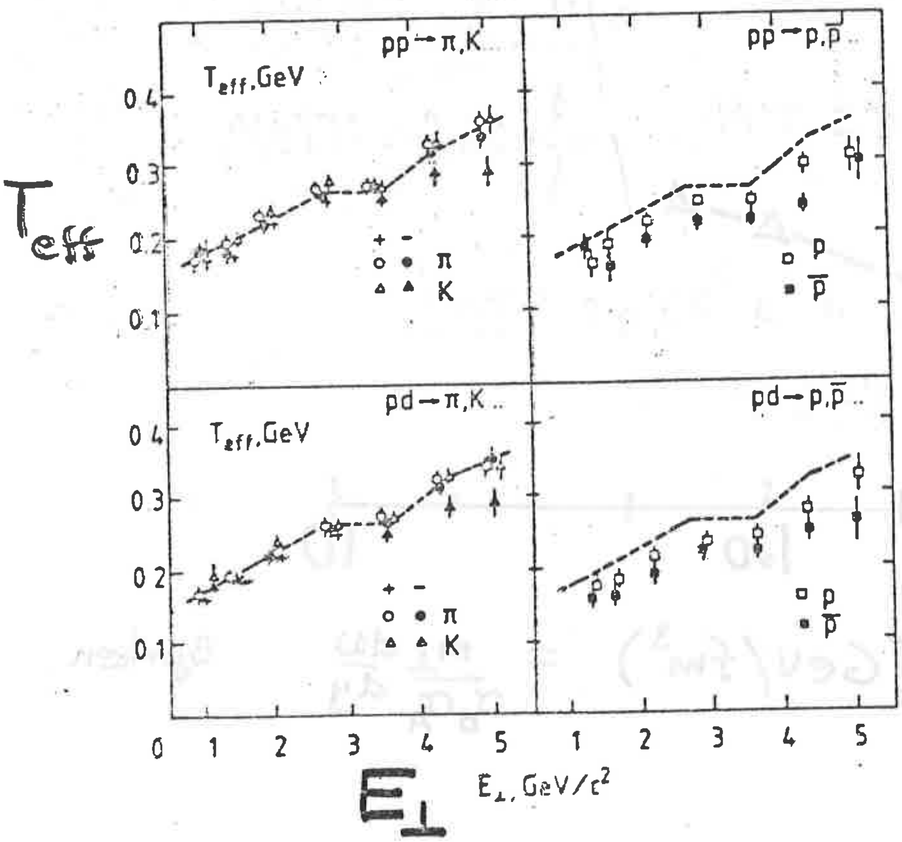




UA1 $p\bar{p}$

CERN-EP/82-125

* must see upturn if this is signature of transition

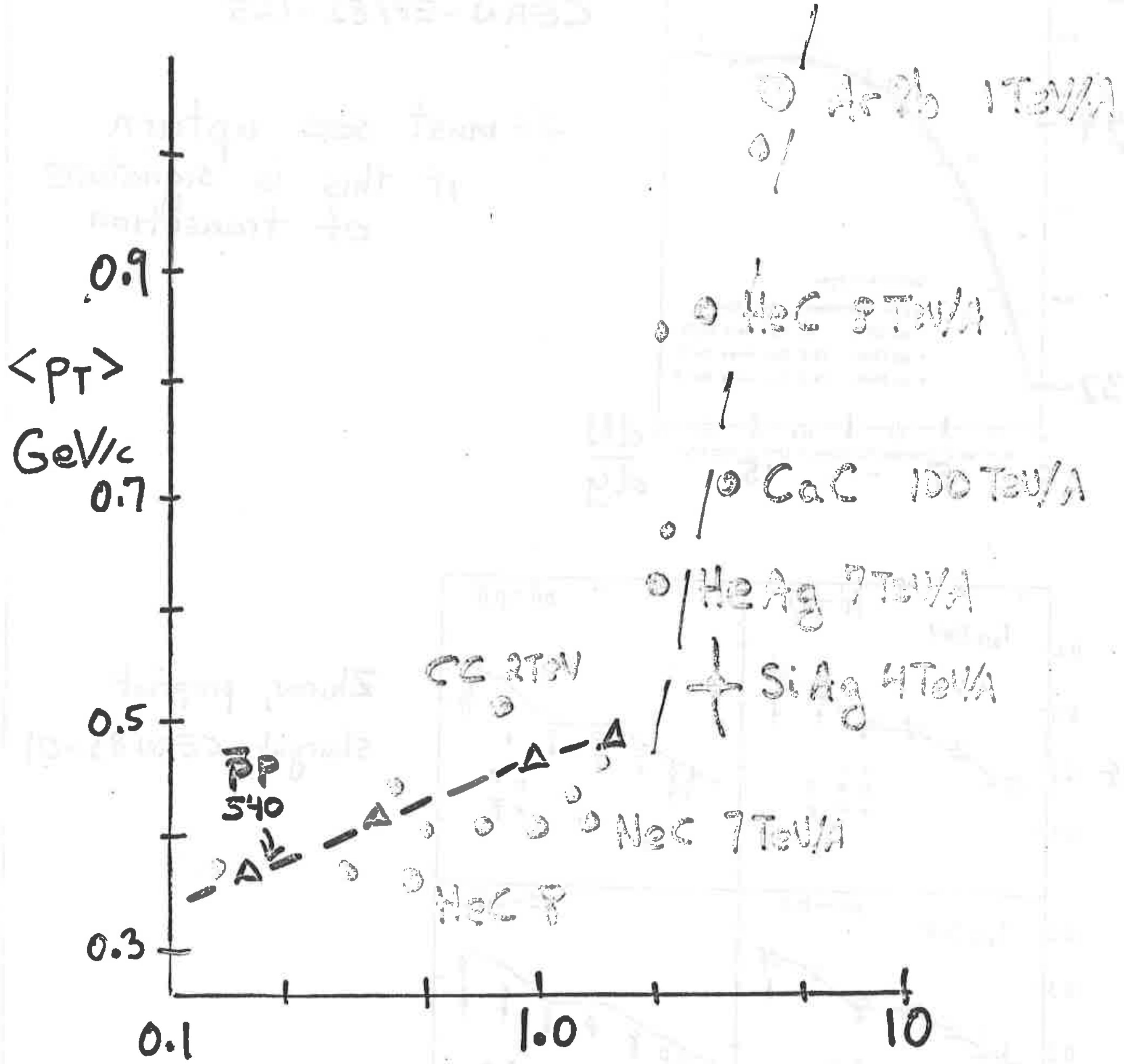


Zhirov, preprint

Shuryak, CERN 83-01

Miyamura Compilation of Cosmic Ray Data

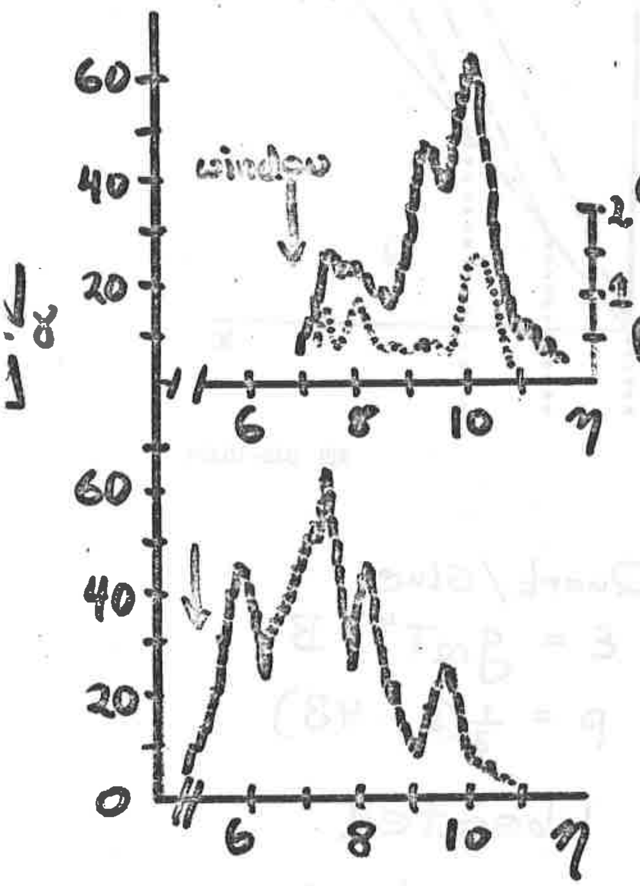
JACEE



ϵ_0 (GeV/fm^3) $= \frac{m_\perp}{\tau_0 \sigma_A} \frac{dN}{dy}$ Bjorken

Rapidity Clustering $\Delta y \sim 1$ in Cosmic Rays

Nuv. Cim. 69 295 (82)



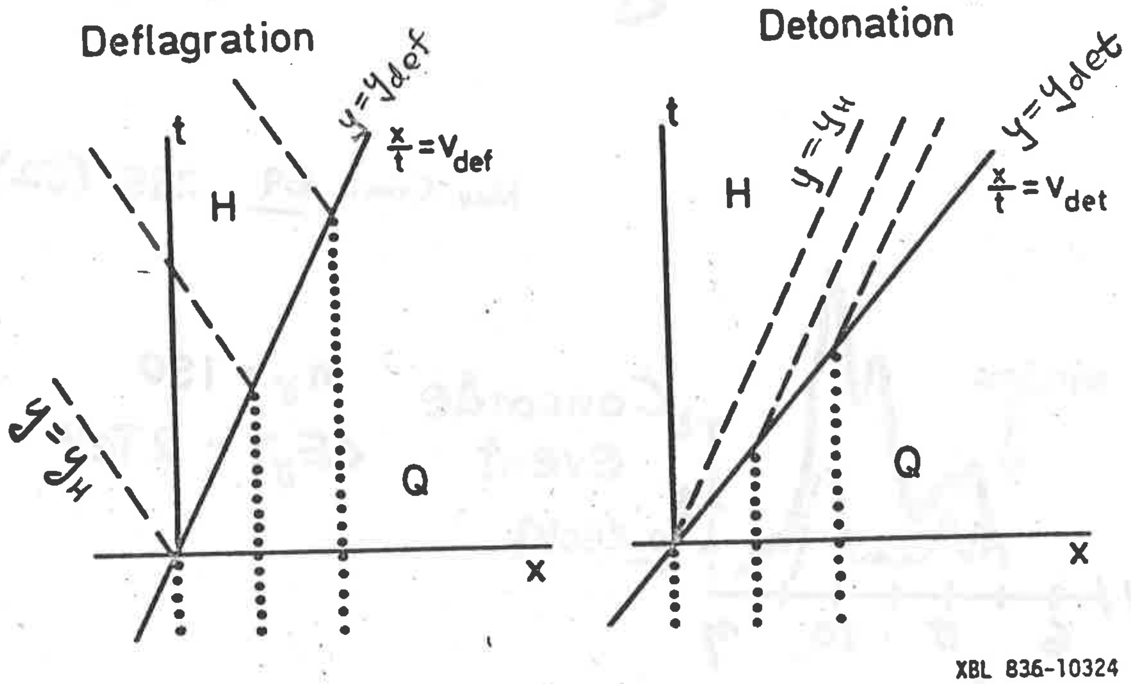
Concorde event $n_\gamma \sim 150$ $\langle E_\gamma \rangle \sim 2$ TeV

Texas Lone Star $n_\gamma \sim 200$ $\langle E_\gamma \rangle \sim 1$ TeV

Indications that clustering correlated with isotropic high $p_\perp \sim 1$ GeV

Signatures of Strong First Order Transitions

MG, K. Kajantie, Kurki-Suonio, McLerran ; Van Hove



Bag Model Eq. of State:

Hadrons

$\varepsilon = g_H T^4$

$p = \frac{1}{3}\varepsilon$

Quark/Glue

$\varepsilon = g_Q T^4 + B$

$p = \frac{1}{3}(\varepsilon - 4B)$

Latent heat $\Delta\varepsilon = 4B$ is liberated

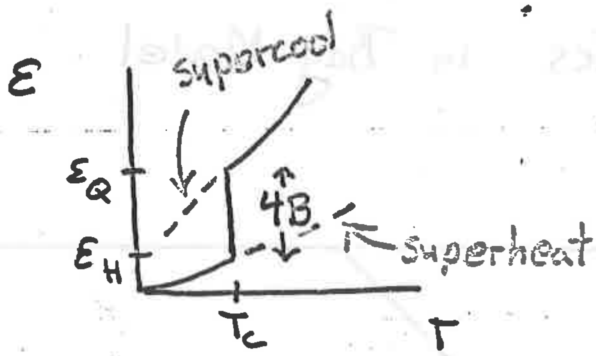
Energy goes into accelerating hadrons

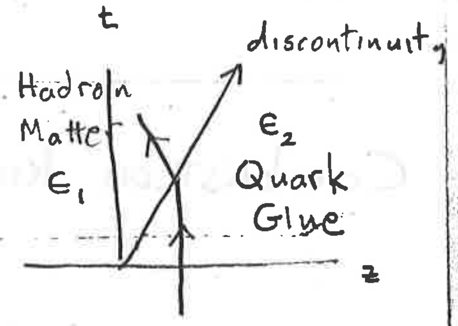
$y_{det(def)}$, y_H, ε_H

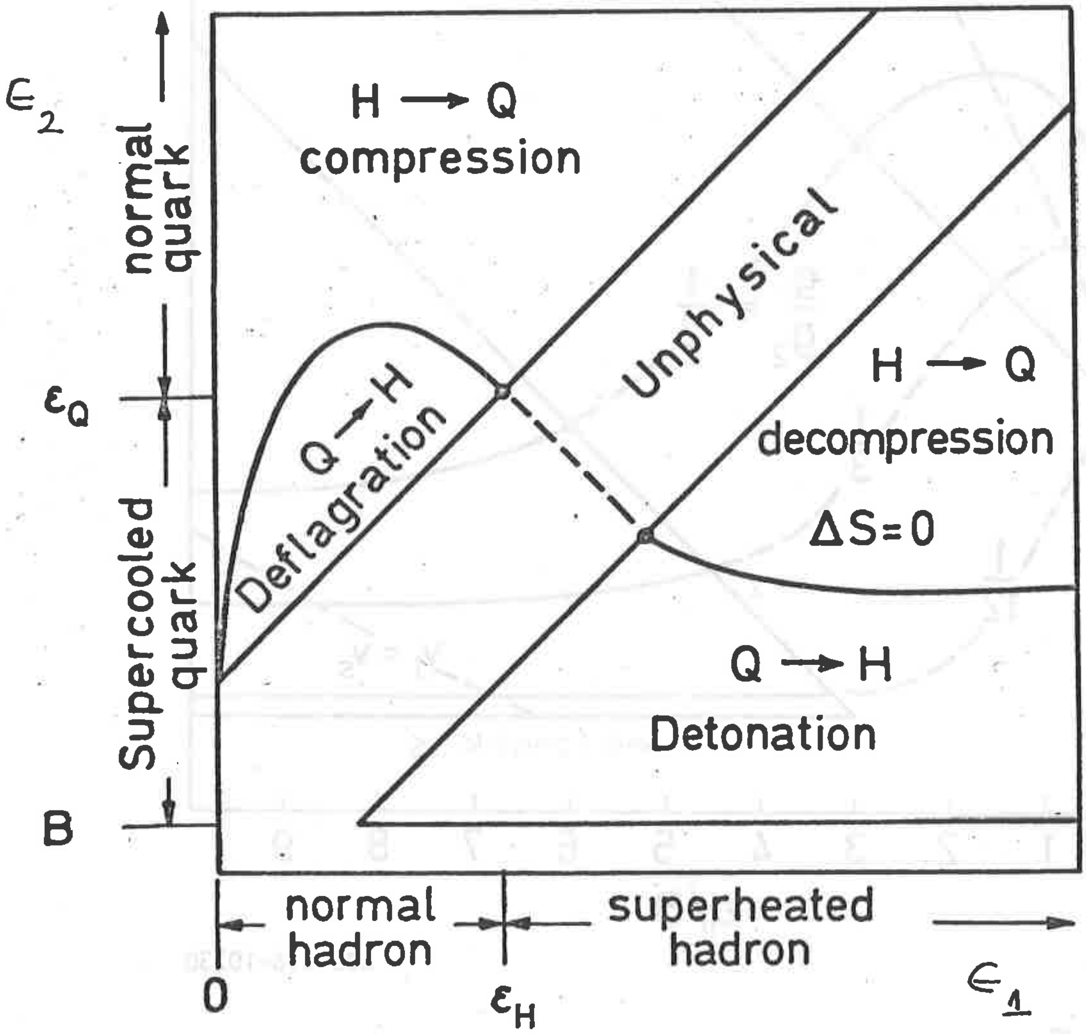
fixed by conservation laws $\partial_\mu T^{\mu\nu} = 0$

plus equation of state

as function of plasma ε_Q







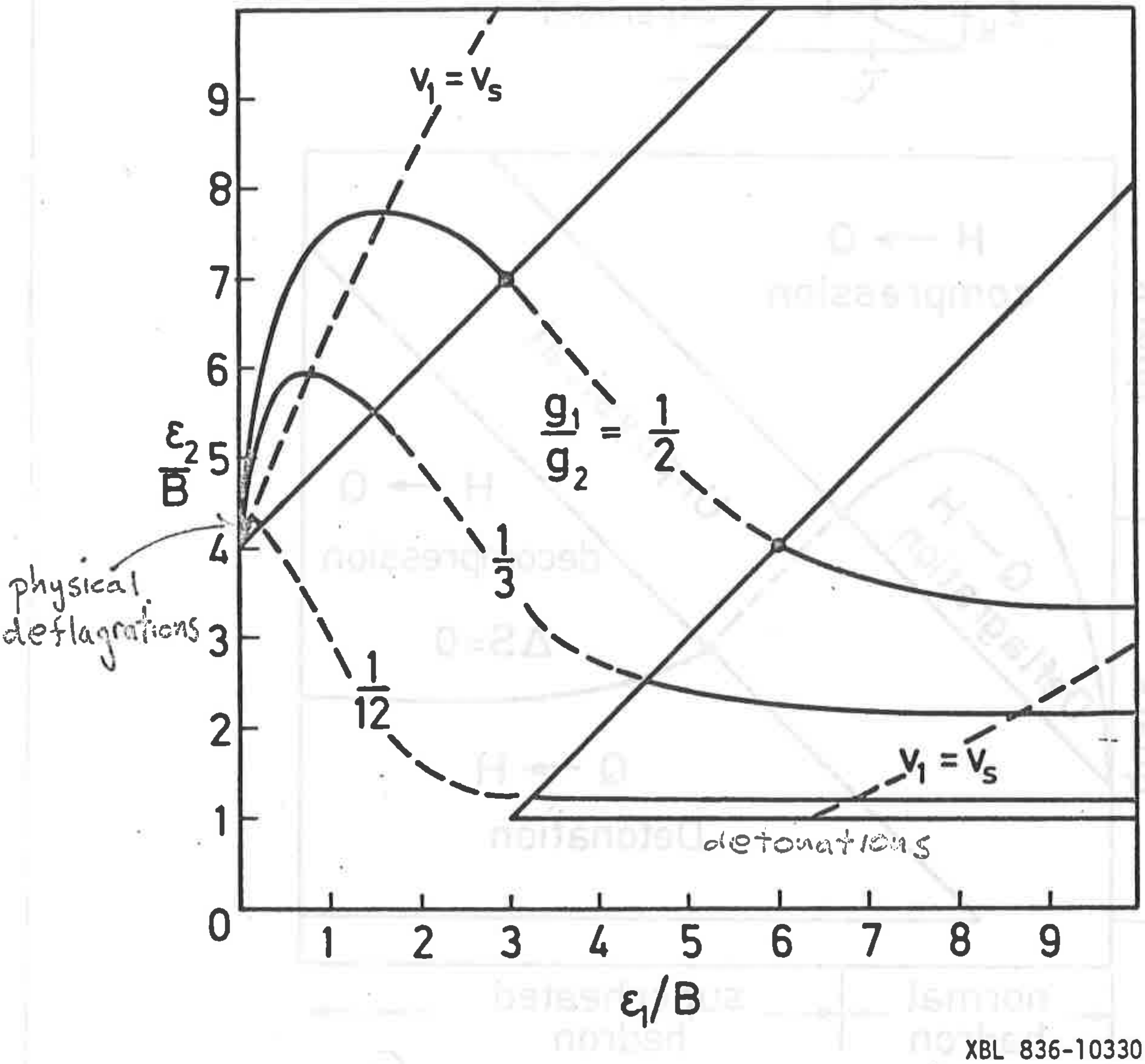
XBL 856-10329

Deflagrations do not tolerate supercooling

* Detonations require large "

<u>and</u> large superheating

Combustion kinetics in Bag Model



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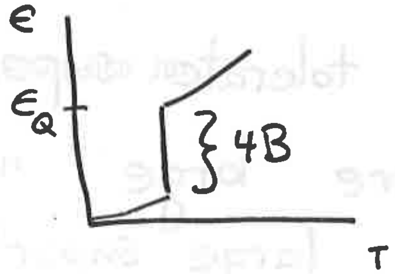
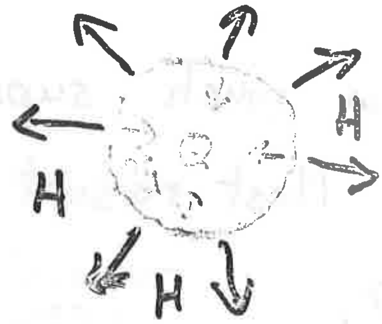
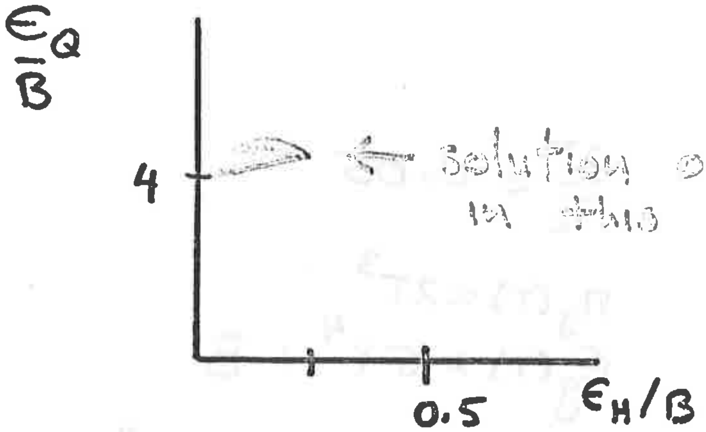
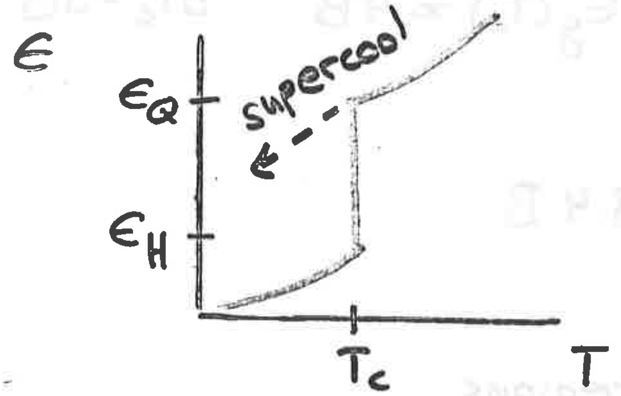


Surface Deflagrations

Van Hove



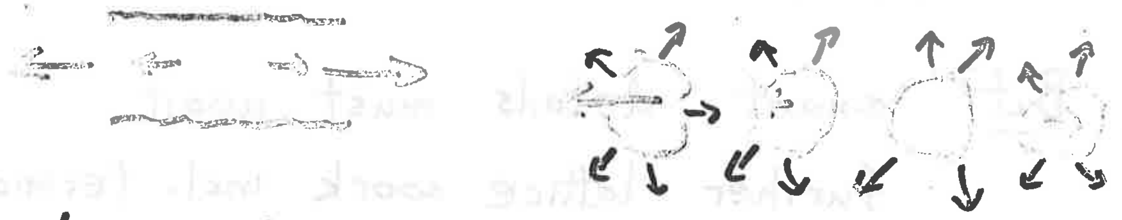




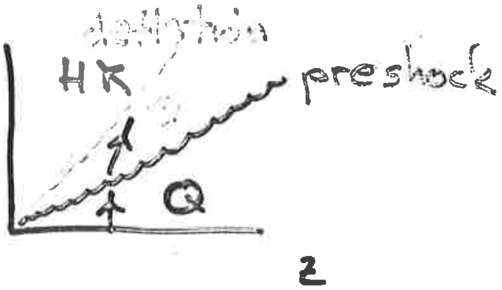
Rapid longitudinal expansion supercools plasma!

$\Rightarrow$ ordinary deflagration not possible

1. Van Hove solution: Plasma breaks up into droplets with $\epsilon \approx \epsilon_Q$

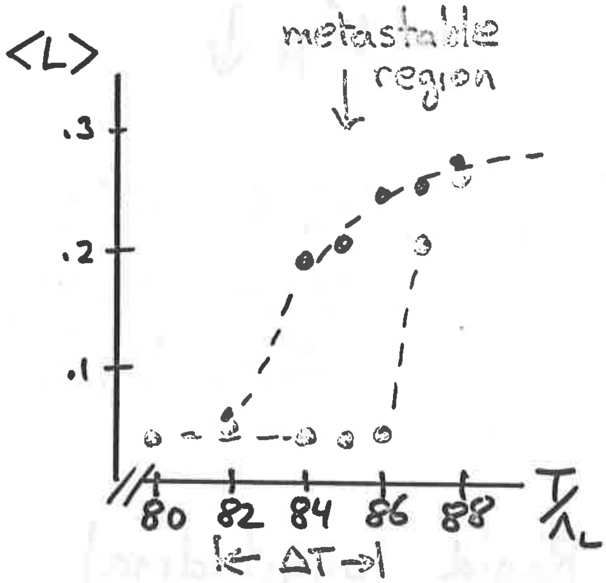


2. Our's: surface breaks into $\underline{2}$ fronts +



How much supercooling can occur?

Must resort to lattice calculations.



$\frac{\Delta T}{T_c} \approx 0.05$

$n_g(T) \approx 2T^3$

$\epsilon_g(T) \approx 5T^4 + B$

$\epsilon_g(T_c) \approx 4B \qquad 5T_c^4 \approx 3B$

$$\frac{\epsilon_g(T_c \times 0.95)}{\epsilon_g(T_c)} < 3.4\,B$$

⇒ supercooling to ϵ regions where deflagrations are prohibited can occur

<u>But</u> exact details must await further lattice work incl. fermions

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Nuclear Physics A418 (1984) 447c-465c
North-Holland, Amsterdam

COLOUR SCREENING IN SU(N) GAUGE THEORY AT FINITE TEMPERATURE

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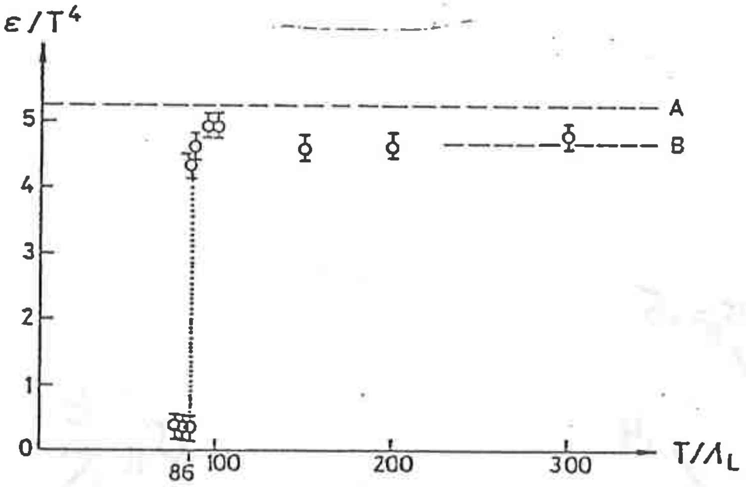


FIGURE 3

Energy density ε of the SU(3) Yang-Mills system, evaluated on an 8^3x3 lattice, with finite lattice corrections, compared to the ideal gas limit without (A) and with (B) colour neutrality correction

$e^{-\text{"}M_q\text{"}/T} \sim$

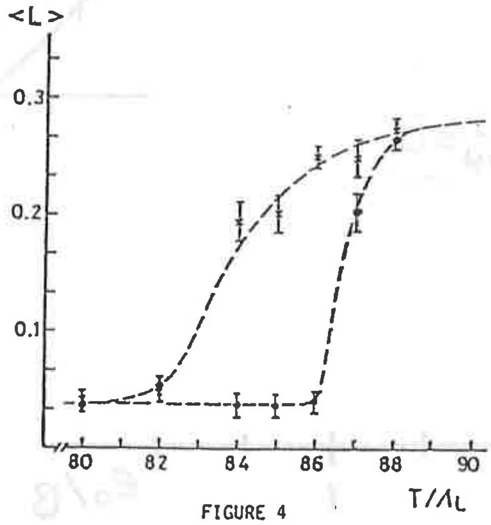
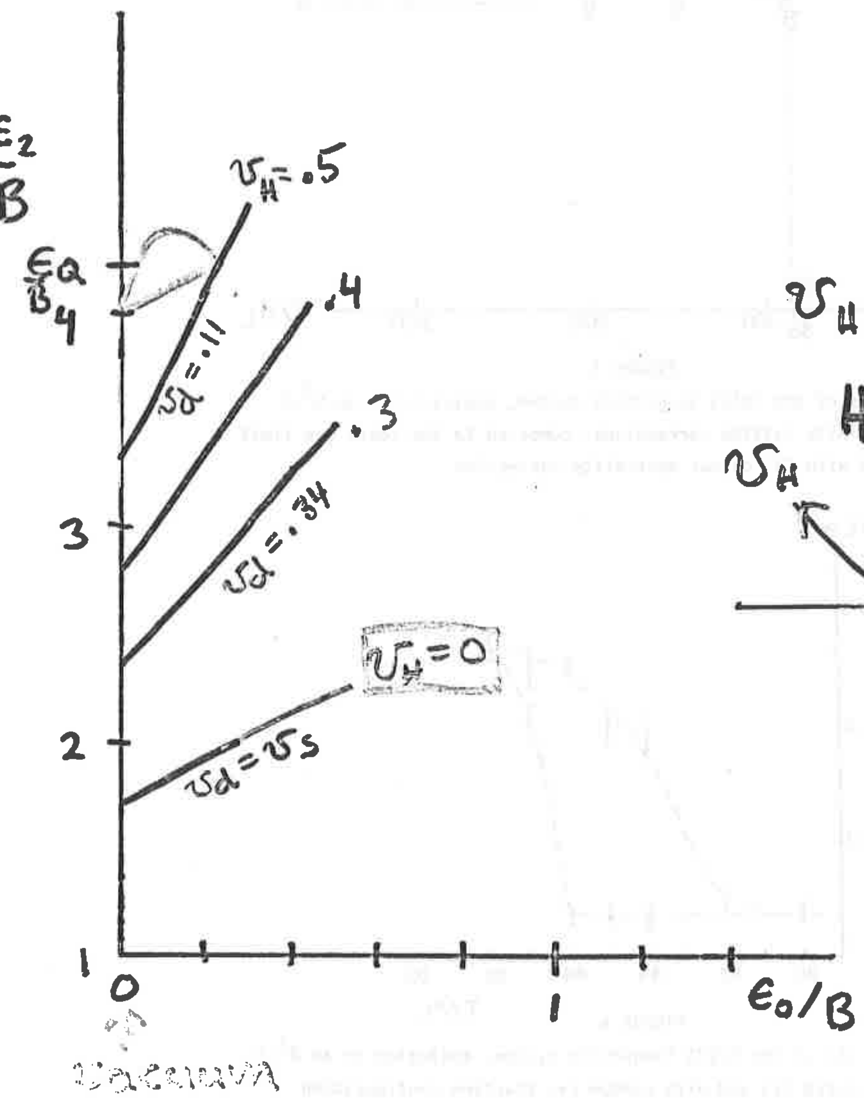


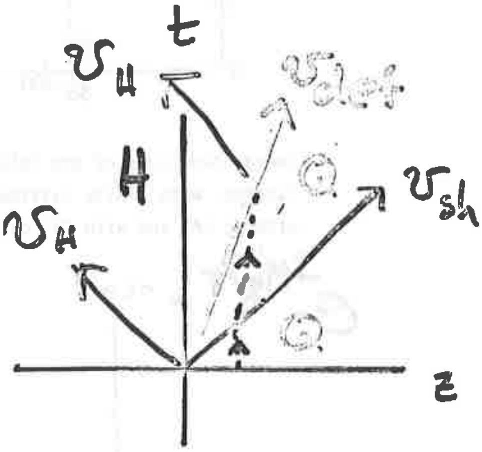
FIGURE 4

Order parameter <L> of the SU(3) Yang-Mills system, evaluated on an 8^3x3 lattice, with ordered (x) and with random (•) starting configuration

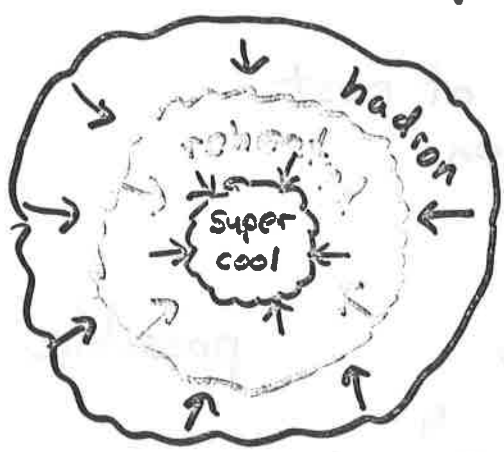
Split Surface Deflagrations

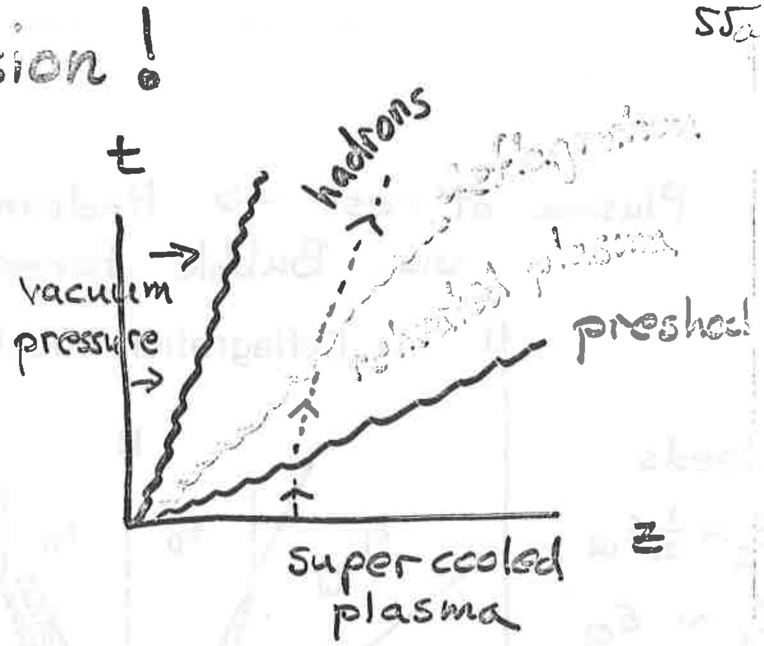
shows existence of imploding surface





Surface Implosion!





For $\epsilon < \frac{\epsilon_Q}{3}$ vacuum pressure

$$p_{vac} = B \approx 200 \text{ MeV/fm}^3$$

causes plasma to implode!

This is exactly opposite expected from usual hydrodynamic expansion

large $p_\perp$ from large pressure

But bounce at $r=0$ could produce supernova effect with large $p_\perp$

Detailed $\frac{dN}{dp_\perp^2}$ very interesting!

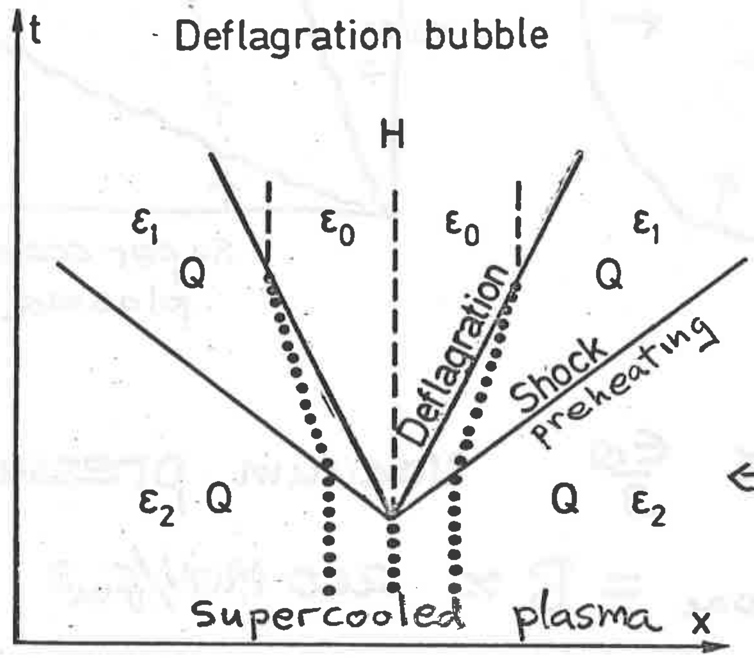
Plasma at rest → Hadrons at rest
via Bubble formation

Needs

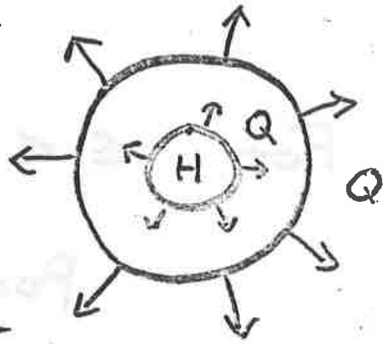
$\varepsilon_2 \sim \frac{1}{2} \varepsilon_Q$

$\varepsilon_1 \sim \varepsilon_Q$

$\varepsilon_0 \sim \frac{1}{2} \varepsilon_H$



possible

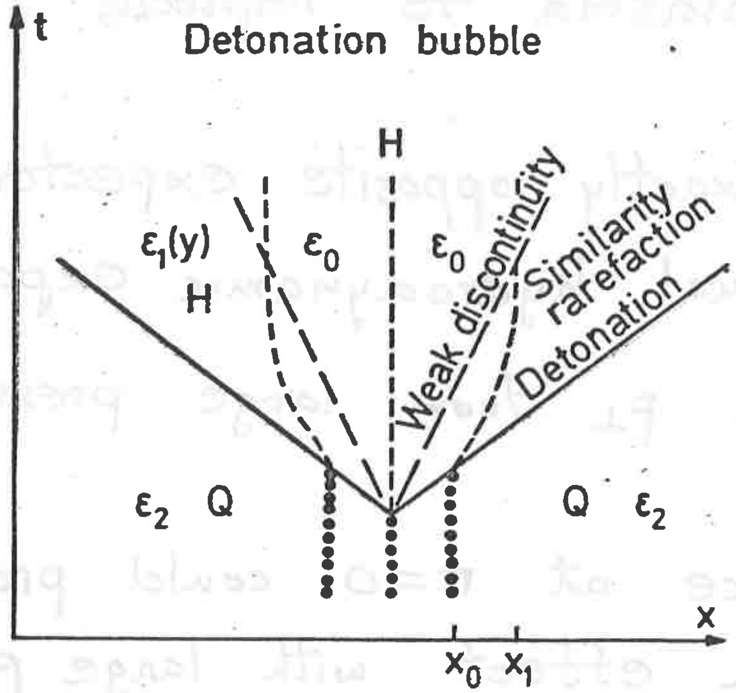


Needs

$\varepsilon_2 \sim \frac{1}{4} \varepsilon_Q$

$\varepsilon_1 \sim 10 \varepsilon_H$

$\varepsilon_0 \sim \frac{1}{2} \varepsilon_H$



not likely

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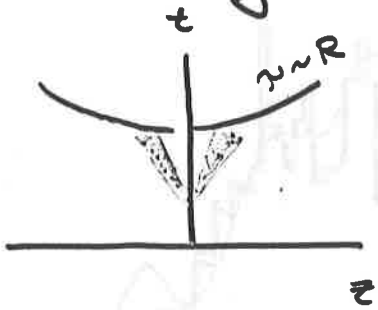
Signatures of Combustion Phenomena $Q \to H$

1. Conversion of latent heat into collective motion

$$\langle p_\perp \rangle \sim 0.5 - 0.8 \text{ GeV}$$

2. Bursting bubbles $\Rightarrow \frac{dN}{dy}$ fluctuations

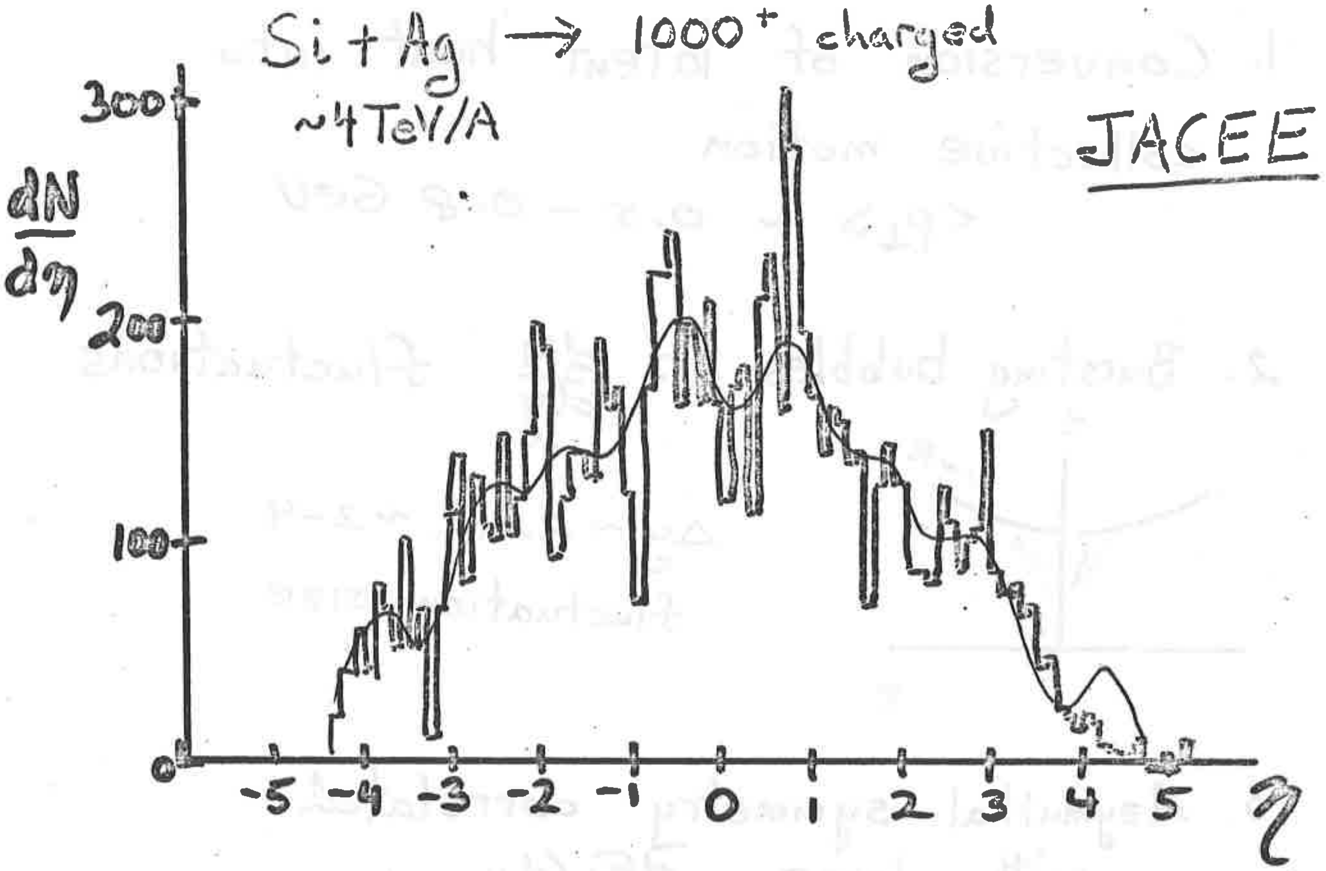


$\Delta y \sim 2 \ln R \sim 2-4$

fluctuation size

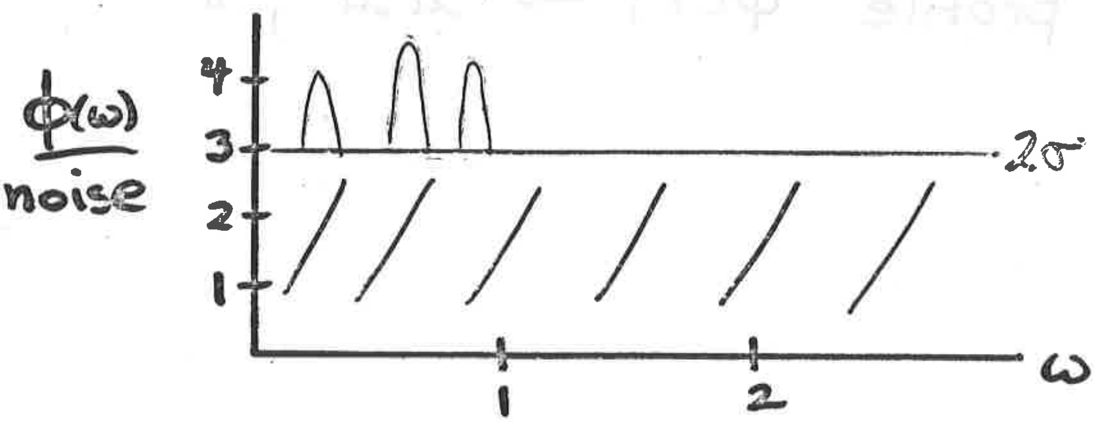
3. Azymuthal symmetry correlated with large $dE_\perp/dy$

* 4. Can differentiate droplet mechanism from supercooling via temperature profile $\phi(T) \to \mu^+\mu^-, \gamma$



Power Spectrum Analysis : F. Takagi

$$\phi(\omega) = \frac{1}{2Y}\left|\int_{-Y}^{Y} d\eta \left(f(\eta) - f_0(\eta)\right) e^{2\pi i \omega \eta}\right|^2$$



1. QCD thermodynamics (lattice, perturb. th) Statistical bootstrap ; Nuclear Theory all point to the critical energy scale
$\epsilon \sim 10\,\epsilon_{Nuc} \sim$ few GeV/fm^3

2. This scale is accessible with nuclear collisions
stopping domain ~10 GeV/A $\rho_B \sim 10\rho_c$
scaling domain ~ 1 TeV/A $\rho_B < \rho_c$
transition ~100 GeV unsettled
⇒ PS, SPS light ion studies are timely and interesting

3. The variety of phenomena that could be observed is rich and growing

Obviosly, experiments are needed!

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