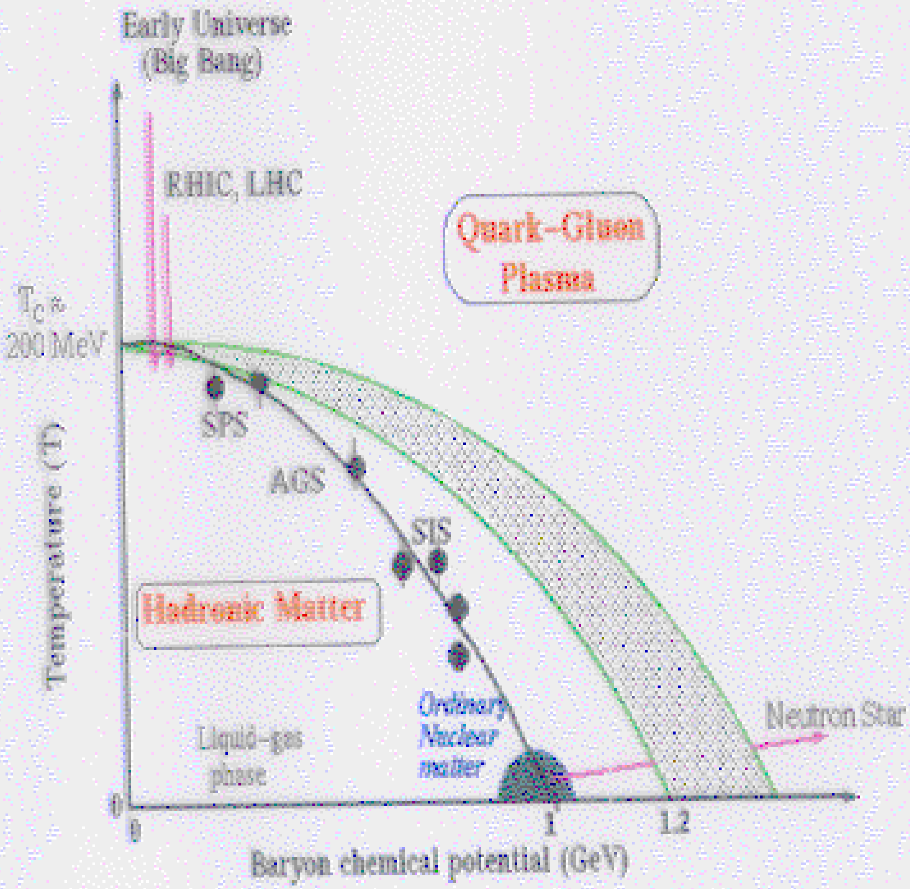
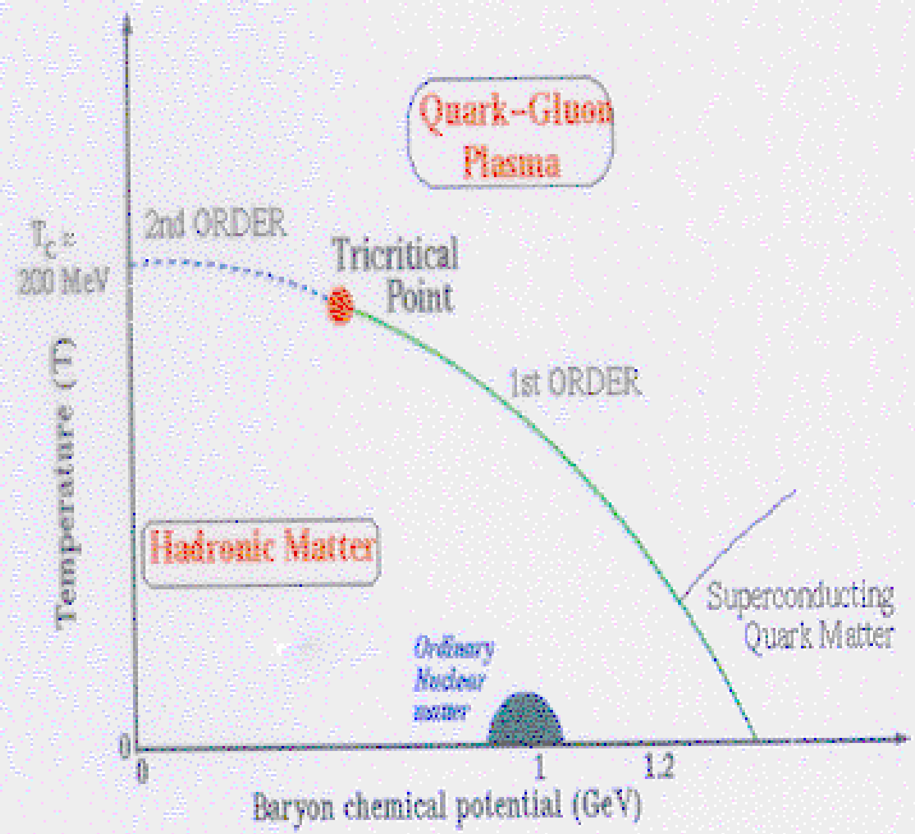
HIC03, Canada
2003' JUNE

ELECTROMAGNETIC
signals



PHASE TRANSION

HADRON → QGP → HADRON



Quark–Gluon Plasma
2nd ORDER
Tricritical Point
1st ORDER
$T_c \approx$ 200 MeV
Temperature (T)
Hadronic Matter
Superconducting Quark Matter
Ordinary Nuclear matter
0
0
1
1.2
Baryon chemical potential (GeV)

	SPS	RHIC	LHC
$\sqrt{s}/A$ (GeV)	17	200	5500
ΔY	6	11	17
dN_{ch}/dy	400	700-1500	3000-8000
$\tau_{\rm tr}^{\rm PbPb}$ (fm/c)	1	0.1	0.005 ← Transit Time
$\tau_0^{\rm QGP}$ (fm/c)	1	~ 0.2	0.1
$\varepsilon(\tau_0)$ (GeV/fm^3)	3	60	1000
$\tau_{\rm QGP}$ (fm/c)	$\lesssim 2$	2-4	$\gtrsim 10$
$\tau_{\rm fo}$ (fm/c)	~ 10	20-30	30-40
$V_{\rm com}(\tau_{fr})$	$8V_{\rm Pb}$	$90V_{\rm Pb}$	$400V_{\rm Pb}$

Table 1: Some characteristics of the heaviest systems produced in AA at SPS, RHIC and LHC ($A \sim 200$). From the top: cms-energy $\sqrt{s}$, available total rapidity interval ΔY, charged particle multiplicity dN_{ch}/dy at $y = 0$, the transit time $\tau_{\rm tr}$ of the Lorentz-contracted nuclei, the formation time $\tau_0^{\rm QGP}$ of the QGP (lower limit), the initial energy density $\varepsilon(\tau_0)$ at the time of formation of the QGP, lifetime of the QGP phase τQGP , freeze-out time $\tau_{\rm fo}$ at $z = 0$, "comoving" volume $V_{\rm com}(\tau_{fr})$ along the freeze-out surface. $V_{\rm Pb}$ denotes the rest frame size of a lead nucleus. The value $dN_{ch}/dy = 400$ is a measured one .

OUTLINE

(i) Electromagnetic Signals from **hot/dense hadronic matter** : Chirality of the medium

(ii) e.m. signals from QGP + Hot/Dense + Cold .....

(iii) Interferometry : γ, μ^+....

(IV) Quark-hadron phase transition : μ sec. univ

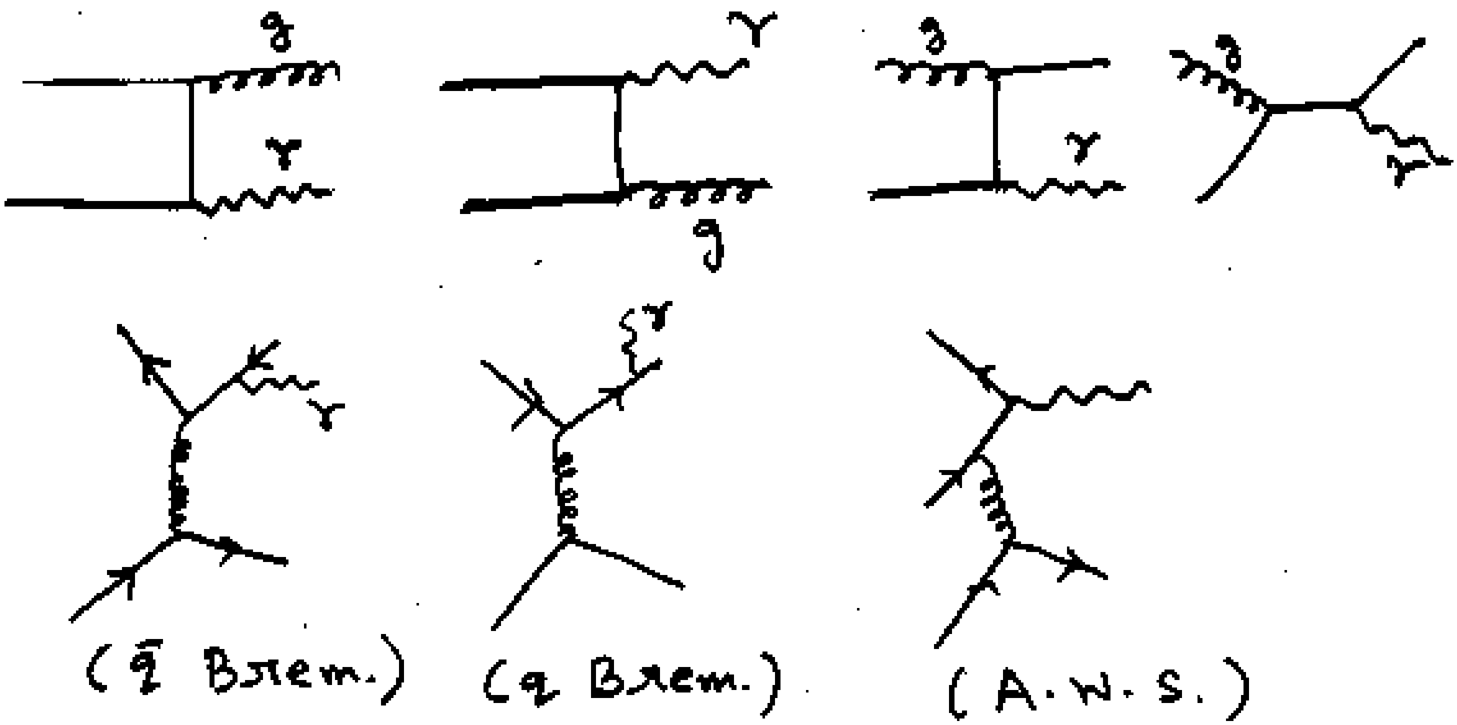
MACHO : CDM

Collaborators: J. Alam, C. Gale, D. K. Srivastava, S. Raha, S. Sarkar, B. Muller et. al ...

- Ultra-Relativistic Heavy Ion Collisions:
- (i) A + A → Hadronic Matter
- (ii) A + A → [Hadronic Matter]*
- (iii) A + A → QGP → Mix. Phase → Hadronic Matter*
  - Electromagnetic γ, l^+l^-
    - * large mean free path
    - * negligible final state interactions
    - * emitted at all stages.
- Sources of real **PHOTONS**:
  - Decay photons $\pi^0 \to \gamma\gamma, \quad \eta \to \gamma\gamma$
  - Prompt photons $(A + B \to \gamma + X)$
  - Thermal Photons
    - * from quark matter
    - * from hadronic matter
- Sources of **DILEPTONS** (virtual photons):
  - Dalitz (e.g. $\pi^0 \to \gamma e^+e^-$).
  - Drell-Yan $(A + B \to l^+l^- + X)$; D meson decays
  - Thermal Dileptons
    - * from quark matter
    - * from hadronic matter

• **From QGP** (QCD Compton, Annihilation, Bremsstrahlung & $q\bar{q}$ annihilation with scattering):

(Kapusta et al, 1991; Baier et al 1992; Aurenche et al 1998.)



$$E\frac{dR}{d^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}\,T^2\exp(-E/T)\left[\ln\left(\frac{2.912\,E}{g^2\,T}\right)\right.$$
$$\left. +4\frac{(J_T - J_L)}{\pi^3}\{\ln 2 + \frac{E}{3T}\}\right]$$

where $J_T \simeq 4.45$, $J_L \simeq -4.26$ and

$$\alpha_s = \frac{6\pi}{(33-2n_f)\ln(\kappa T/T_c)} \quad ;\kappa = 8$$

$\alpha_s(T = 200MeV) \sim 0.3 \Rightarrow g^2 \sim 4$

$g << 1 \Rightarrow \alpha_s << 0.08$

HOT HADRONS / Dense

→ Effective Lagrangian approach.

$$\mathcal{L}_{VNN} = g_{VNN}\left[\bar{N}\gamma_\mu \tau^\alpha N V^\mu_\alpha - \frac{\kappa_V}{2M}\bar{N}\sigma_{\mu\nu}\tau^\alpha N \partial^\nu V^\mu_\alpha\right]$$

$$\tau_\alpha = \{1, \vec{\tau}\}$$

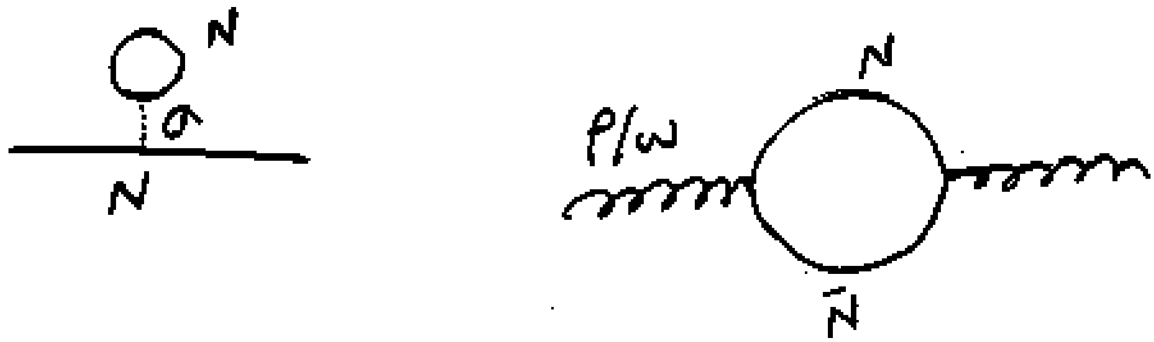
$$V^\mu_\alpha = \{\omega^\mu, \vec{\rho}^\mu\}$$

QHD → QCD

Self Energy   P. Roy et. al Nucl. Phys. A 653 (1999)

- **Quantum Hadrodynamics(QHD)**

$$\mathcal{L}^{\text{int}}_{VNN} = g_{VNN}\left(\bar{N}\gamma_\mu\tau^a N V^\mu_a - \frac{\kappa_V}{2M_N}\bar{N}\sigma_{\mu\nu}\tau^a N\partial^\nu V^\mu_a\right)$$



- **Universal Scaling Hypothesis**

$$\frac{m_V^*}{m_V} = \frac{f_V^*}{f_V} = \frac{\omega_0^*}{\omega_0} = \left(1 - 0.2\frac{n_B}{n_0}\right)\left(1 - \frac{T^2}{T_c^2}\right)^\lambda,$$

$$\lambda = 1/6, \quad \text{Brown} - \text{Rho, Scaling}$$

(Brown & Rho, 1991)

Thermal photons from hot hadronic matter

Essential components are π ρ η ω, a_1

$$\mathcal{L} = -g_{\rho\pi\pi}\vec{\rho}^{\mu} \cdot (\vec{\pi} \times \partial_{\mu}\vec{\pi}) - eJ^{\mu}A_{\mu} + \frac{e}{2}F^{\mu\nu}\,(\vec{\rho}_{\mu} \times \vec{\rho}_{\nu})_3,$$

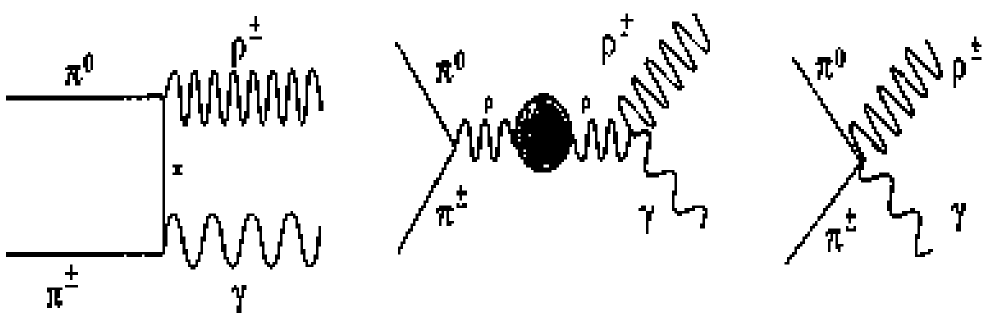
where

$$J^{\mu} = (\vec{\rho}_{\nu} \times \vec{B}^{\nu\mu})_3 + (\vec{\pi} \times (\partial^{\mu}\vec{\pi} + g_{\rho\pi\pi}\vec{\pi} \times \vec{\rho}^{\mu}))_3$$

To $O(e^2 g_{\rho\pi\pi}^2)$ imaginary part leads to rates for

$$\pi\pi \rightarrow \rho\gamma$$
$$\pi\rho \rightarrow \pi\gamma$$
$$\rho \rightarrow \pi\pi\gamma$$

For example:

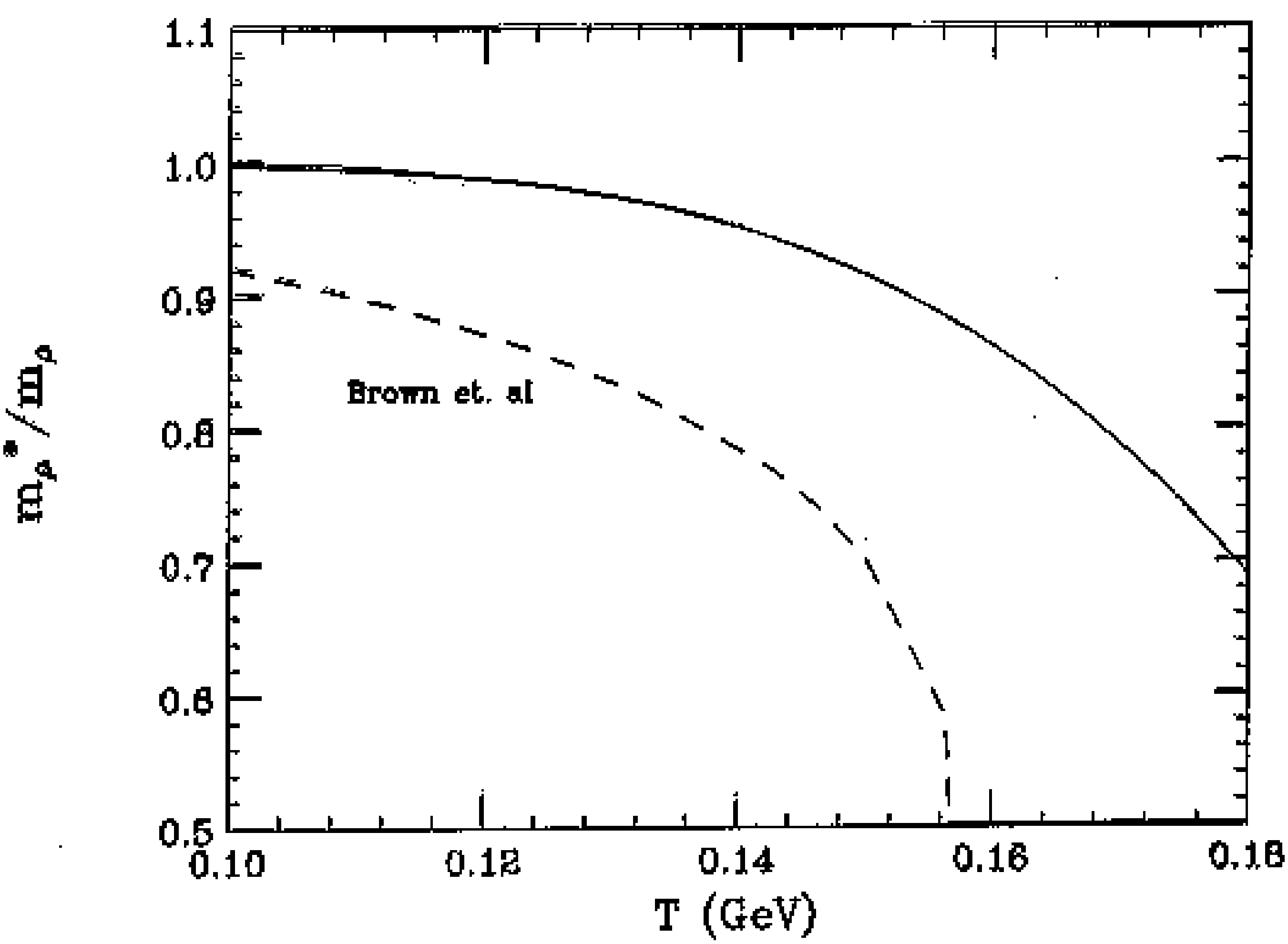


(a) (b) (c)

We also include

$$\pi\eta \rightarrow \pi\gamma$$
$$\pi\pi \rightarrow \eta\gamma$$
$$\omega \rightarrow \pi\gamma$$

$\mathcal{L}_{\pi\rho a_1}$ is taken from Guaged Linear Sigma Model.



1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.10
0.12
0.14
0.16
0.18
m_ρ^*/m_ρ
T (GeV)
Brown et. al

Medium Effects

- Quantum Hadrodynamics(QHD)

The effective mass of ρ/ω can be parametrized as:

$$m_\rho^* = m_\rho \left[1 - 0.127\left(\frac{T(\mathrm{GeV})}{0.16}\right)^{5.24}\right]$$
$$m_\omega^* = m_\omega \left[1 - 0.044\left(\frac{T(\mathrm{GeV})}{0.16}\right)^{7.09}\right]$$

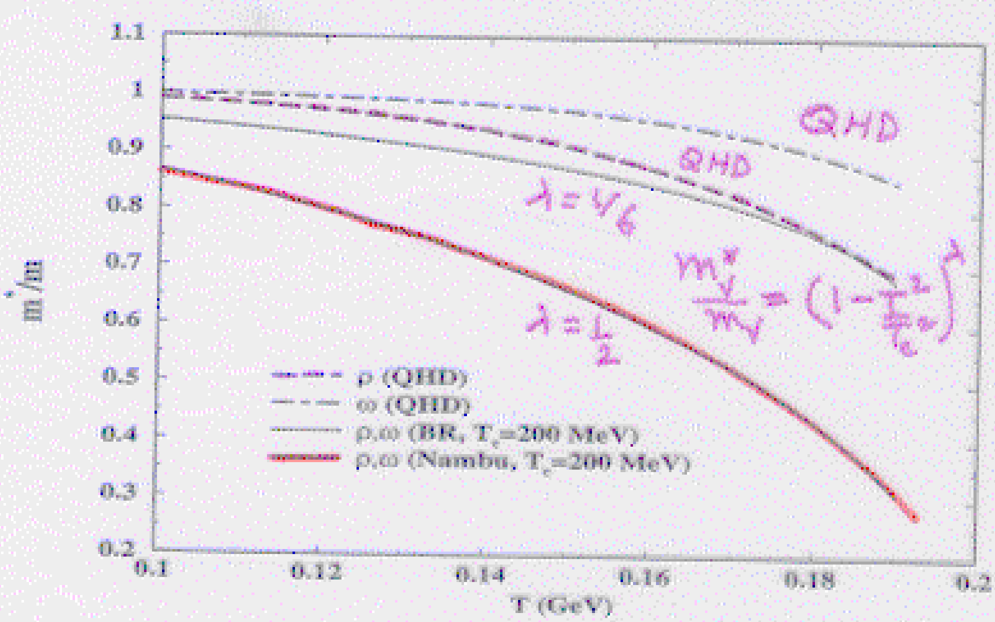
(Sarkar et. al. 1999)

- Universal Scaling Hypothesis

$$\frac{m_V^*}{m_V} = \frac{f_V^*}{f_V} = \frac{\omega_0^*}{\omega_0} = \left(1 - \frac{T^2}{T_c^2}\right)^\lambda ,$$

$\lambda = 1/6(1/2)$ Brown − Rho(Nambu) Scaling

(Brown & Rho, 1996)



Medium effects : (Finite Temp. field th.)

P. Roy et. al Nucl. Phys A 653 (1999)

S. Sarkar, P. Roy, J. Alam, B. S.
Phys. Rev. 60 (1999)
& Annals of Phys.
To appear

$$\frac{m_V^*}{m_V} = \frac{f_V^*}{f_V} = \frac{\omega_0^*}{\omega_0} = \left[1 - \frac{T^2}{T_c^2}\right]^{1/2}$$

⇒ Nambu Scaling

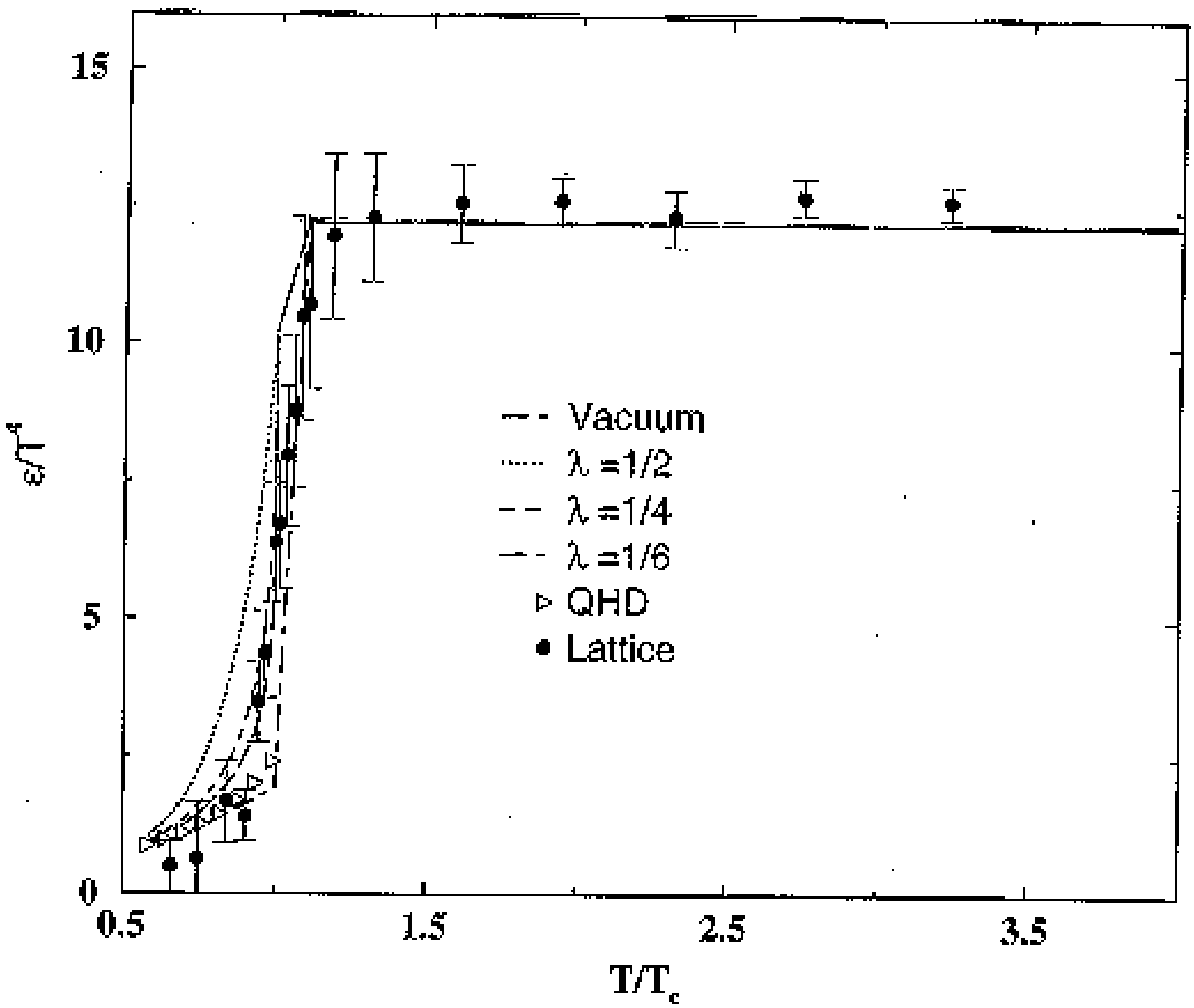
f_V ~ Coupling between electromag. current & vector meson field

→ ω_0 Continuum threshold

Shall not

$$\frac{m_V^*}{m_V} \neq \frac{m_N^*}{m_N}$$

J. Alam
S. Sarkar
T. Hatsuda
T. Nayak
B. S. (2000)



15
10
5
0
0.5
1.5
2.5
3.5
ε/T^4
T/T_c
Vacuum
λ =1/2
λ =1/4
λ =1/6
QHD
Lattice

EOS and Space Time Evolution

- Quark Gluon Plasma:

$$\begin{aligned}
\epsilon_{QGP} &= 3\frac{\pi^2}{90} g_{QGP} T^4 + B; \\
P_{QGP} &= \frac{\pi^2}{90} g_{QGP} T^4 - B \\
s_{QGP} &= 4\frac{\pi^2}{90} g_{QGP} T^3
\end{aligned}$$

- Hadronic Matter (π, ρ, ω, η, a_1 and N)

$$\begin{aligned}
\epsilon_H &= \sum_i g_i \int \frac{d^3p}{(2\pi)^3}\, E_i\, f(E_i, T) \\
P_H &= \sum_i g_i \int \frac{d^3p}{(2\pi)^3}\, \frac{p^2}{3\,E_i}\, f(E_i, T)
\end{aligned}$$

$$s_H = \frac{\epsilon_H + P_H}{T} \equiv 4a_{\rm eff}(T)\, T^3 = 4\frac{\pi^2}{90} g_{\rm eff}(m^*(T), T) T^3$$

$$\text{Sound Velocity, } c_s^{-2} = \frac{T}{s_H}\frac{ds_H}{dT} = \left[\frac{T}{g_{\rm eff}}\frac{dg_{\rm eff}}{dT} + 3\right]$$

$$T \sim \frac{1}{\tau^{c_s^2}}$$

$c_s < c_s^{ideal}$ $\Rightarrow$ Slow Cooling.

Photon Emission

A + A $\Rightarrow$ QGP $\Rightarrow$ Mixed $\rightarrow$ Hadronic Phase : SPS, RHIC

A + A $\rightarrow$ Hadronic Matter : SPS

- **QGP:** $q\bar{q} \Rightarrow g\gamma$, $qg \rightarrow q\gamma$,
  $q\bar{q}q \Rightarrow q\gamma$, $qg \rightarrow qg\gamma$ etc.

- **Hadronic Matter:** $\pi\pi \rightarrow \rho\gamma$, $\pi\rho \rightarrow \pi\gamma$, $\rho \Rightarrow \pi\pi\gamma$,
  $\pi\eta \rightarrow \pi\gamma$, $\pi\pi \Rightarrow \eta\gamma$, $\omega \Rightarrow \pi\gamma$

- **Space-Time Evolution:** (3+1)d Hydrodynamics

- **Equation of State:** Bag Model for QGP

  All Hadrons upto mass 2.5 GeV

- **Initial Conditions:** T_i=200 MeV, τ_i=1 fm/c for SPS

  T_i=265 MeV, τ_i=0.6 fm/c for RHIC

- **Criticial Temperature:** 170 MeV

- **Freezeout Temperature:** 120 MeV

• **Space Time Evolution:**

(3+1)D Hydrodynamics - Initial Conditions:

$$\frac{dS}{\pi R_A^2 \tau_i dy} \propto \frac{dN}{\pi R_A^2 \tau_i dy} = \left(\frac{45\zeta(3)}{2\pi^4}\right) 4a_{\rm eff} T_i^3$$

$$\frac{dN}{dy} = \frac{45\zeta(3)}{2\pi^4} \pi R_A^2 4 a_{\rm eff} T_i^3 \tau_i$$

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

$T_i \sim 200\,(196)$ **MeV for Hadronic Matter (QGP).**

$$\epsilon(\tau_i, r) = \frac{\epsilon_0}{\exp(r - R_A)/\delta + 1}$$

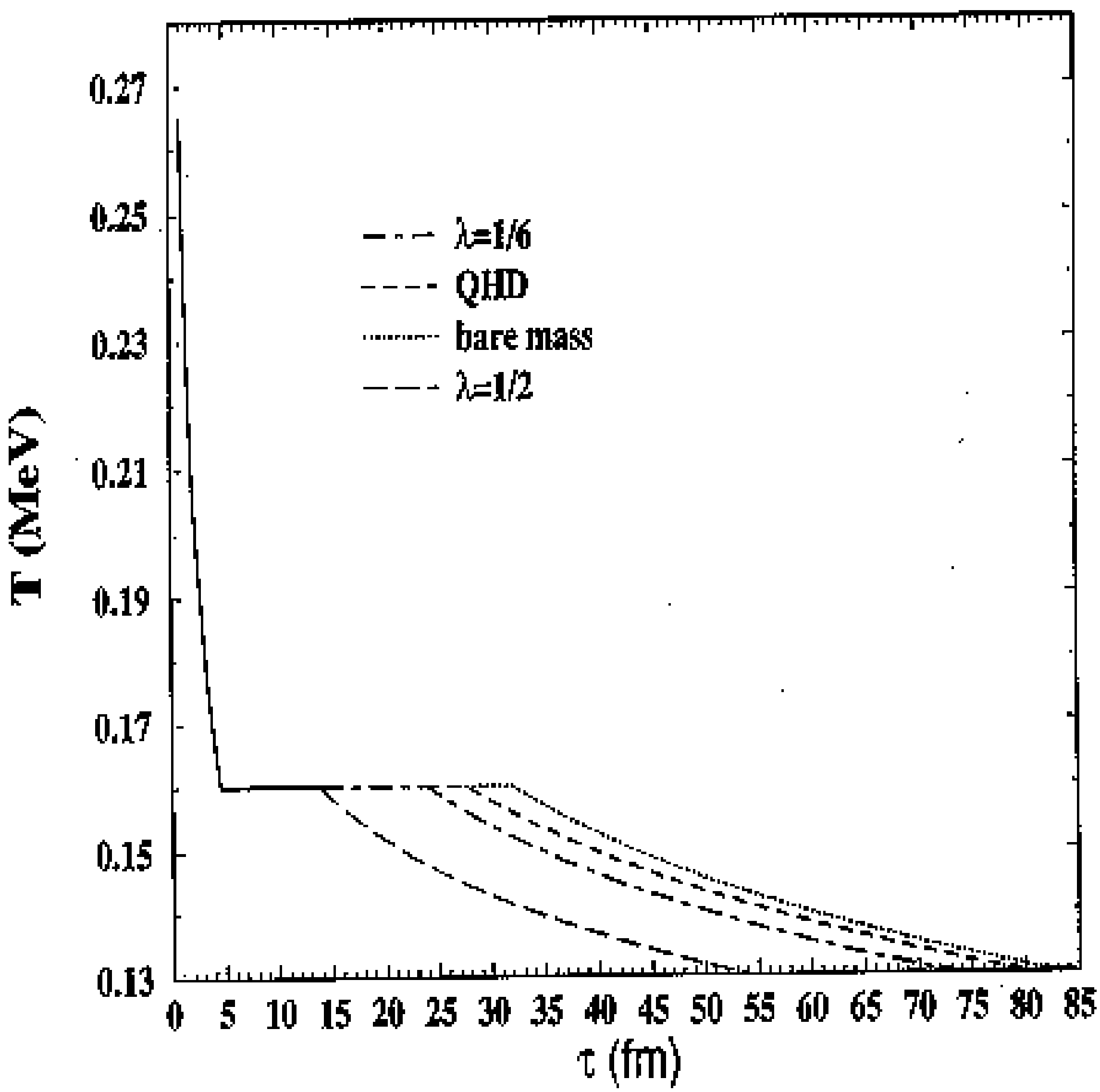
$$v_r(\tau_i, r) = v_0 \left(\frac{r}{R_A}\right)^\alpha$$

initial radial velocity

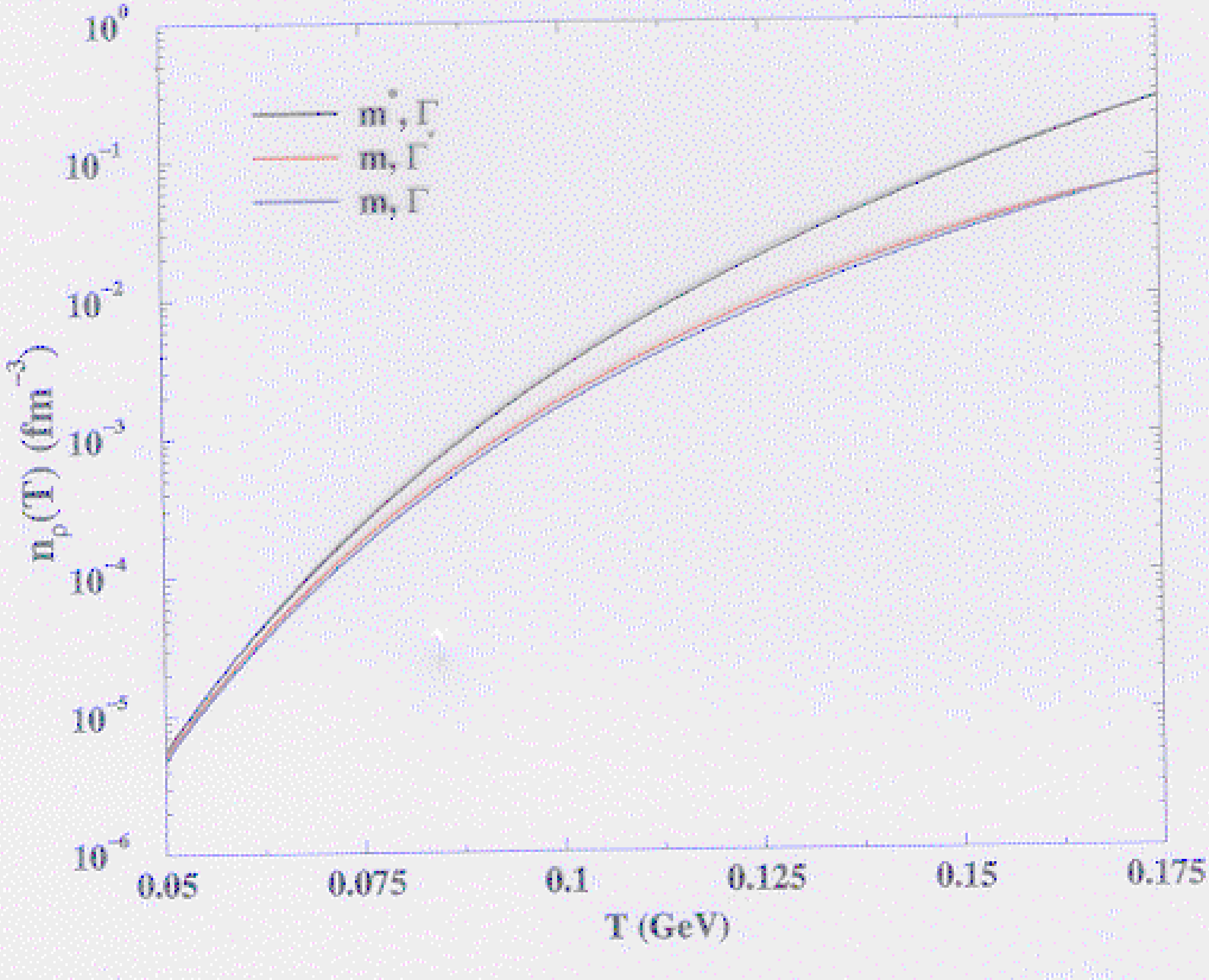
Temperature Profile from Transport Model:

$$T(\tau) = (T_i - T_\infty)\, e^{-\tau/t_0} + T_\infty$$

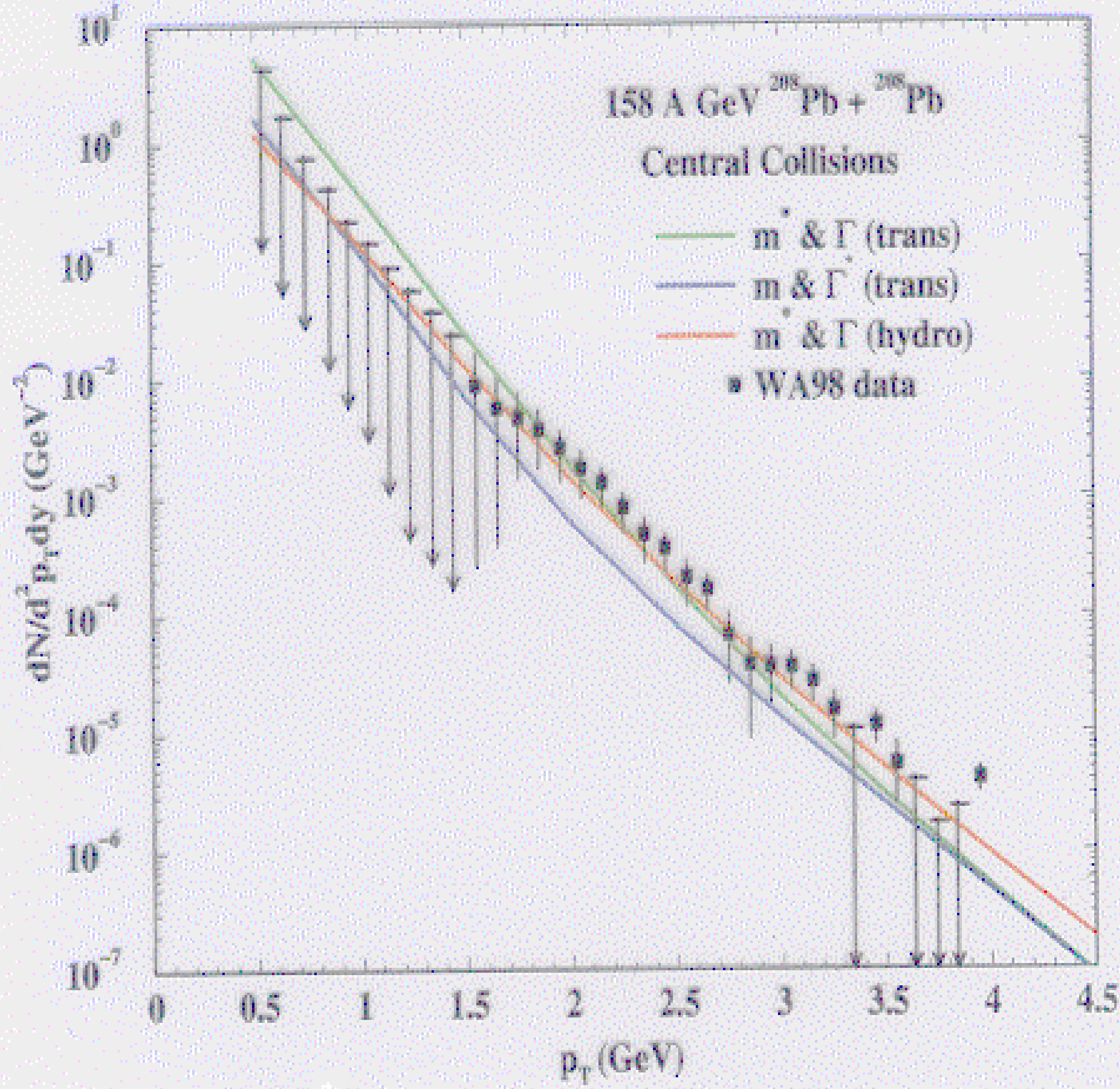
(Rapp et al, 1997.)



λ=1/6
QHD
bare mass
λ=1/2
T (MeV)
0.27
0.25
0.23
0.21
0.19
0.17
0.15
0.13
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85
τ (fm)



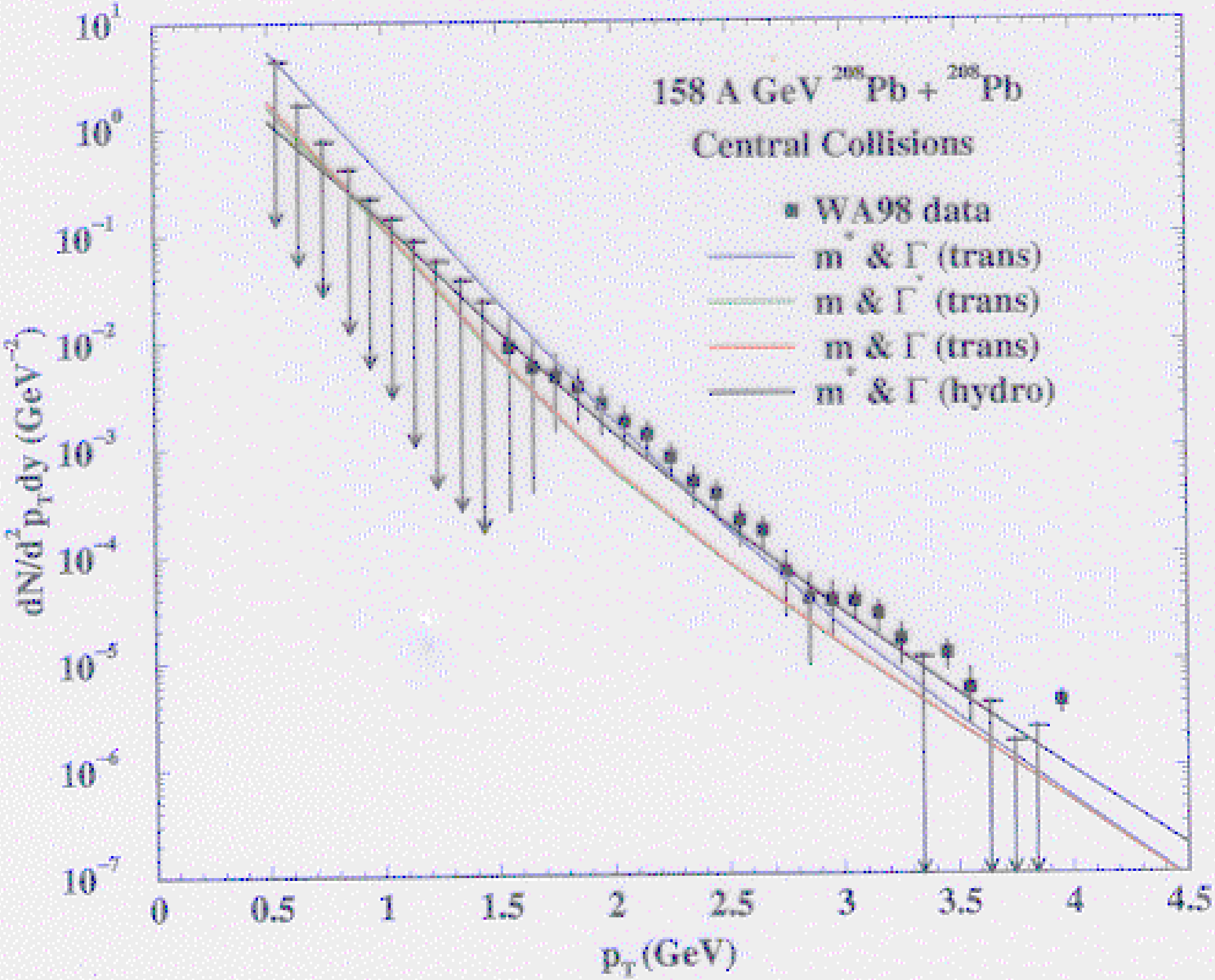
m*, Γ
m, Γ*
m, Γ
$n_\rho(T)$ (fm^{-3})
T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.05
0.075
0.1
0.125
0.15
0.175



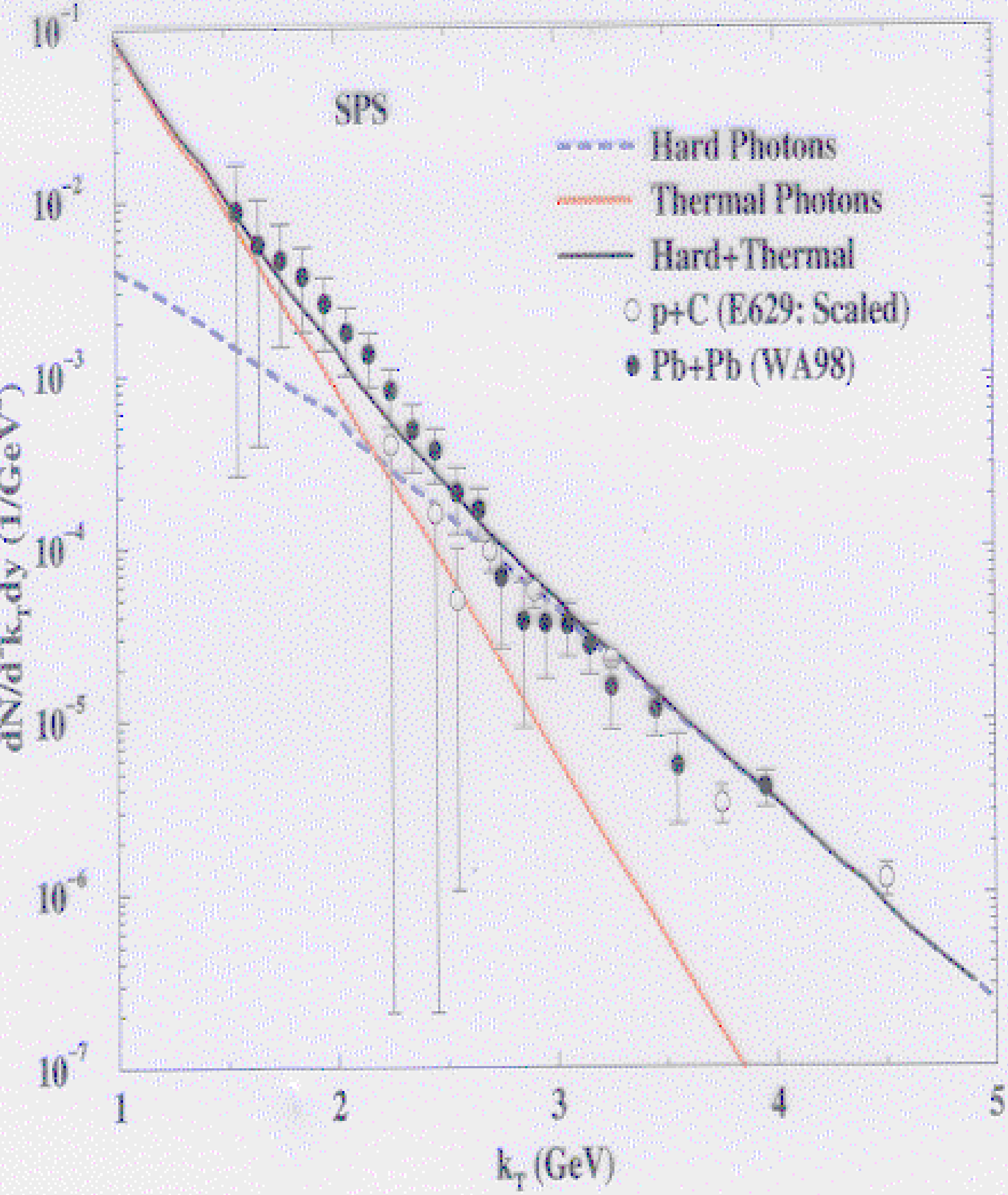
Trans: $T(\tau) = (T_i - T_F)\, e^{-\tau/\tau_0} + T_F$

Broadening / Mass Shift

$$\frac{dN}{d^3k\, d^3x\, ds} = \frac{g}{(2\pi)^3} \frac{1}{\exp\left[\frac{\sqrt{k^2+s}}{T}\right] - 1} \times \left[\frac{1}{\pi} \frac{\mathrm{Im}\,\Pi}{(s - m^2 - \mathrm{Re}\,\Pi)^2 + (\mathrm{Im}\,\Pi)^2}\right]$$



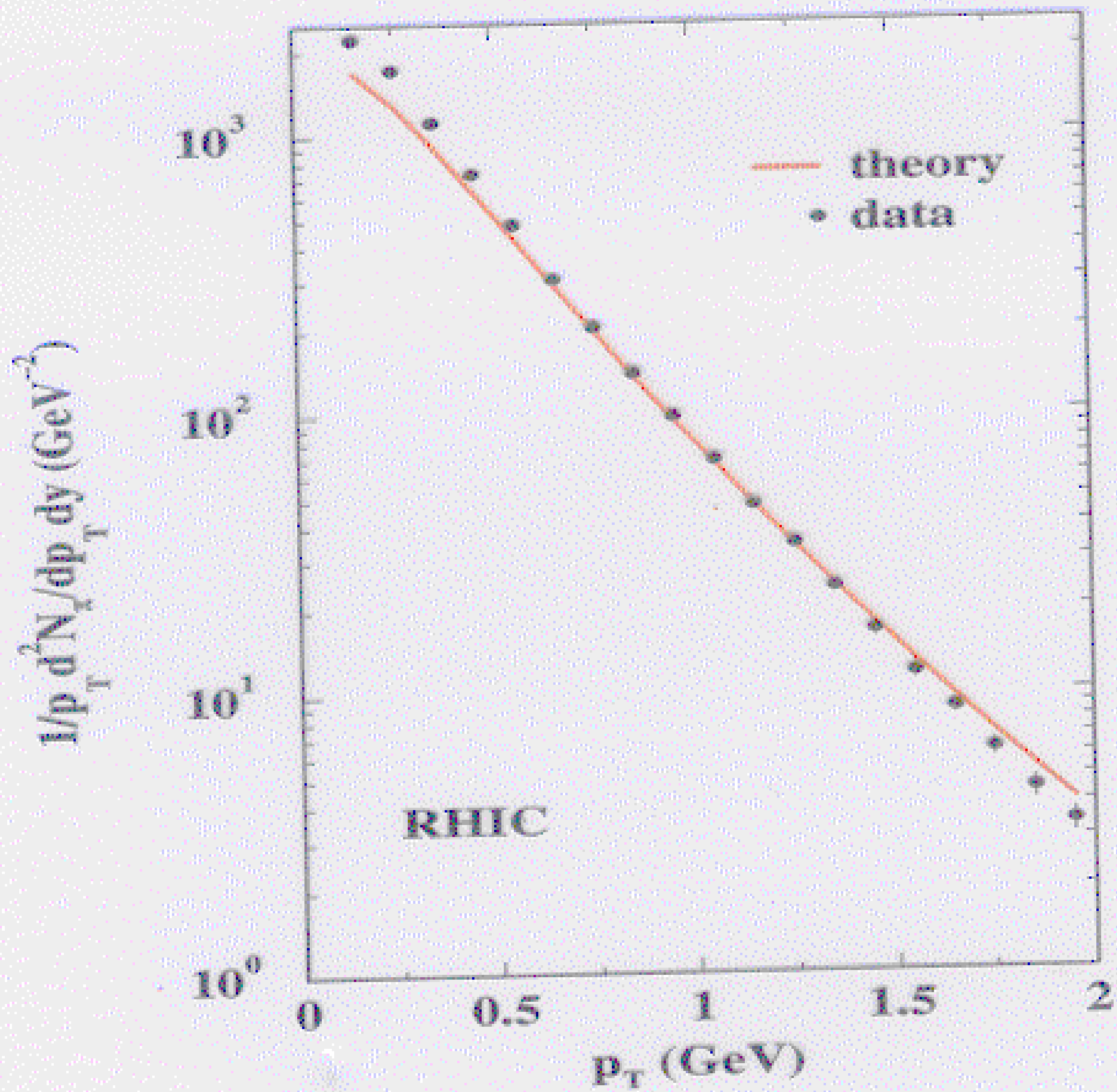
158 A GeV 208Pb + 208Pb
Central Collisions
WA98 data
m* & Γ (trans)
m & Γ* (trans)
m & Γ (trans)
m* & Γ (hydro)
dN/d2pTdy (GeV-2)
pT (GeV)



SPS
Hard Photons
Thermal Photons
Hard+Thermal
p+C (E629: Scaled)
Pb+Pb (WA98)
dN/d²k_T dy (1/GeV²)
k_T (GeV)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
1
2
3
4
5

k_T window ←

Freeze-Out



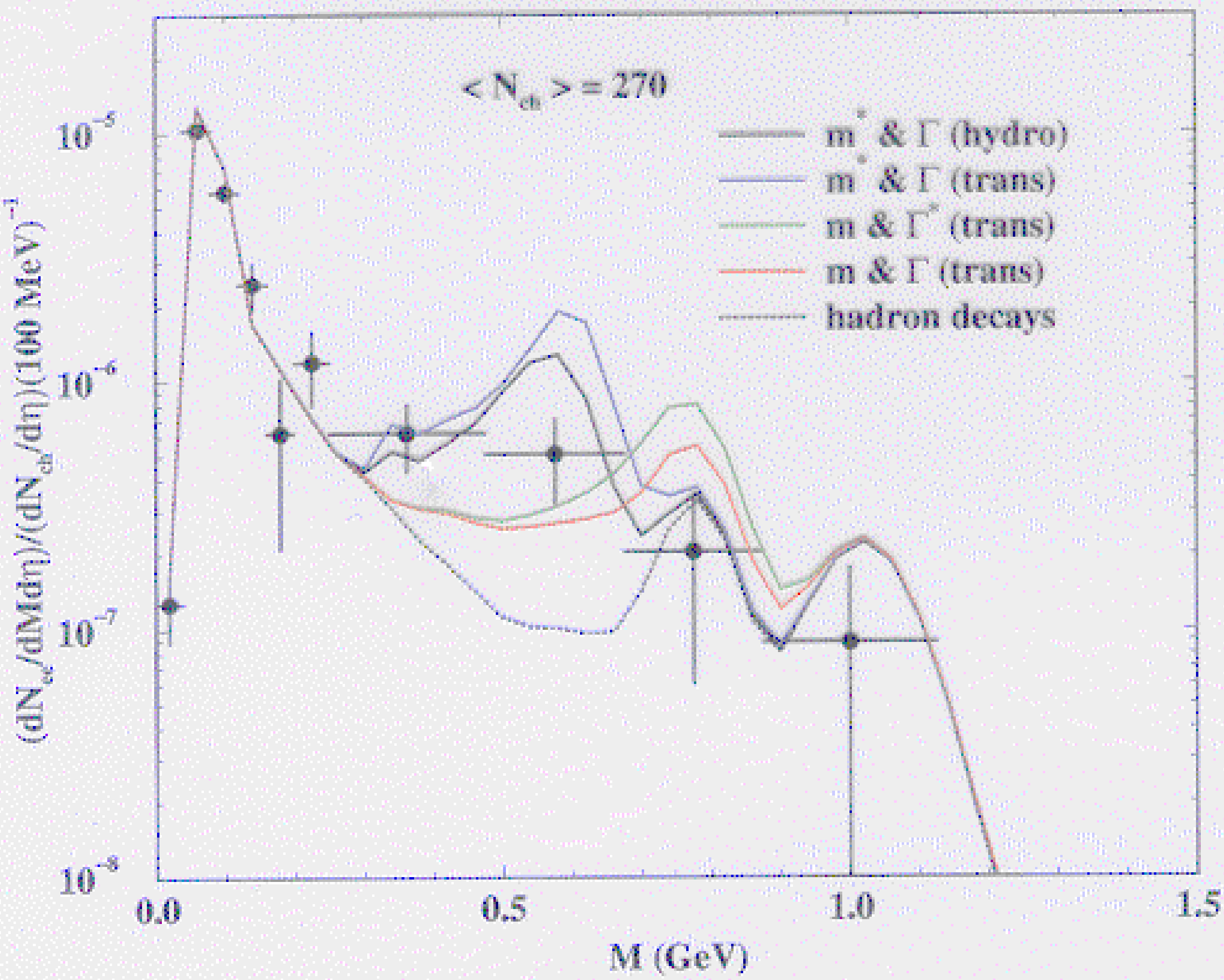
$$\frac{dN}{p_T\, dp_T\, dy} = \frac{g}{\pi}\int r\, dr\, \tau_F(r)\left[m_T I_0(x) K_1(y) - \frac{\partial \tau_F}{\partial r} I_1(x) K_0(y) \right]$$

$$x = p_T \sinh y_T / T_F$$
$$y = p_T \cosh y_T / T_F$$

$T_F \sim 120\,MeV$

Patra, Alam, Roy, Sarkar, Sinha

Nucl. Phys. A 2002



< N_ch > = 270
m* & Γ (hydro)
m* & Γ (trans)
m & Γ* (trans)
m & Γ (trans)
hadron decays
(dN_ee/dMdη)/(dN_ch/dη)(100 MeV)^-1
10^-5
10^-6
10^-7
10^-8
0.0
0.5
1.0
1.5
M (GeV)

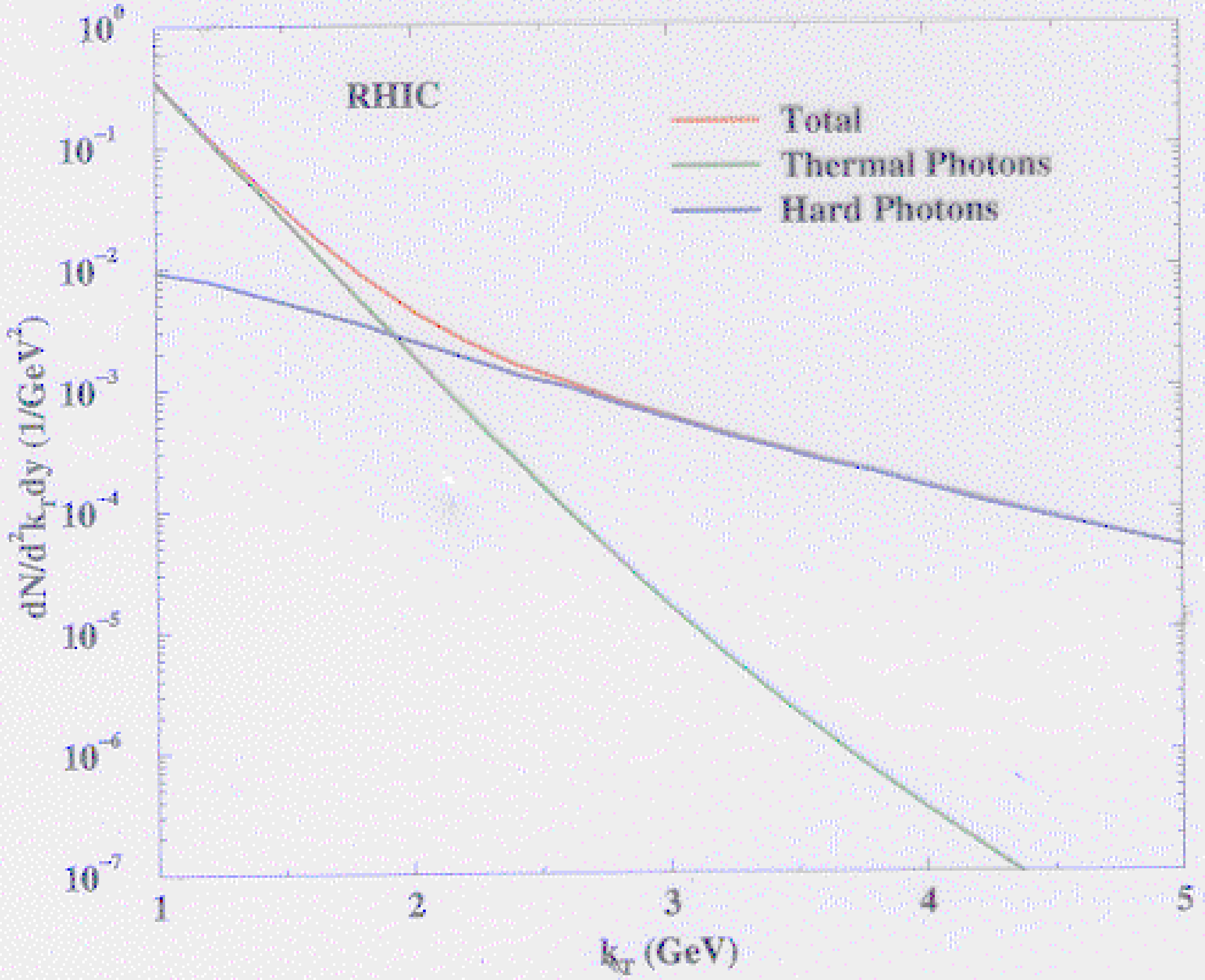
Summary:

• In order to reproduce the WA98 photon data either a substantial reduction in vector meson masses or the formation of QGP in the initial stage with $T_i \sim 200$ MeV is necessary. A simple hadronic model is inadequate to reproduce the data.

• Enhancement of the lepton pairs in the invariant mass region $\sim 0.3 - 0.6$ GeV measured by CERES and the hadronic spectra obtained by NA49 can be reproduced by the same framework.

• Invariant mass distribution of the lepton pair is sensitive to both the pole shift and the broadening of the spectral function. Photon spectra is insensitive to the broadening.

• New method is required to evaluate photon emission rate from QCD plasma, HTL approximation is not applicable at SPS,.... energies.


RHIC
Total
Thermal Photons
Hard Photons
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$dN/d^2k_T dy$ (1/GeV^2)
1
2
3
4
5
k_T (GeV)

(a) Photon Interferometry

(b) Global Interferometry:

$\gamma, \mu^+, \mu^-, K^+, K^-, \pi^+, \pi^-, p \ldots\ldots$

Correlation function ⇒ (i) Corrected two loop correction for photons.

(ii) Chirality of the medium

(iii) E.O.S contains hadronic mass ~ 2.5 GeV

(IV) Initial conditions, freeze out conditions & E.O.S reproduce WA98 Single photon spectra ⇒ Not arbitrary

⟶

Significance of Simul. $\gamma, \mu^+, \mu^- : \mu^+\mu^- \ldots$

⇒ T^4 : B.S. (1983)

- Intensity (or HBT) Interferometry is the only known way to obtain direct experimental information on the space-time structure of a particle emitting source

- It is hence a powerful tool to study the geometry of the evolving reaction zone in relativistic heavy ion collisions

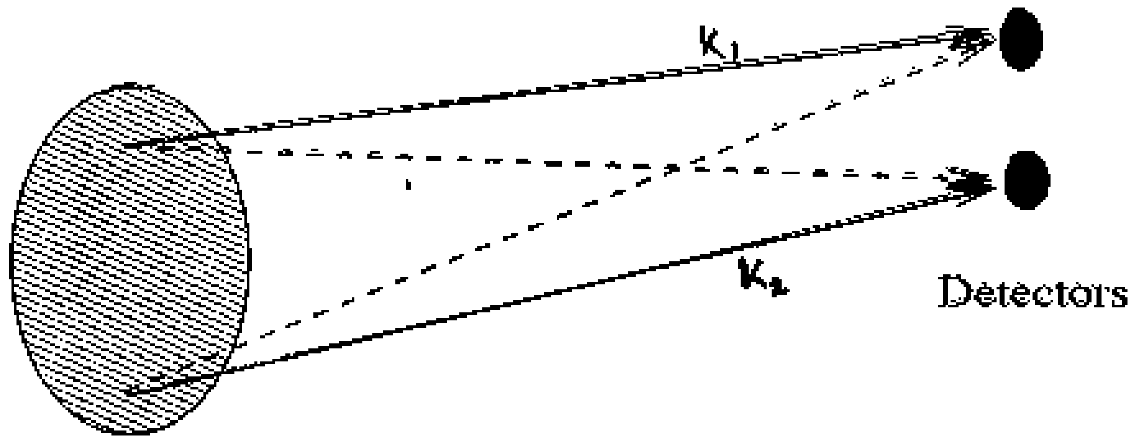
- HBT Interferometry concerns the study of momentum correlations of identical paricles measured in coincidence

- Hadronic correlators involving pions, kaons and protons have been studied extensively. These reflect the space-time extent of the source at freezeout

- Photons are emitted at all stages of the collision and undergo minimal rescattering - should provide dynamical information about the size of the hot zone

  - low yield
  - large background

Formulation



$$C_2(\vec{k_1}, \vec{k_2}) = \frac{P(\vec{k_1}, \vec{k_2})}{P(\vec{k_1})P(\vec{k_2})}$$

$$P(\vec{k}) = \int d^4x \; \omega(x, k)$$

source function $\omega(x, k) = E\frac{dN_\gamma}{d^4x \; d^3k}$

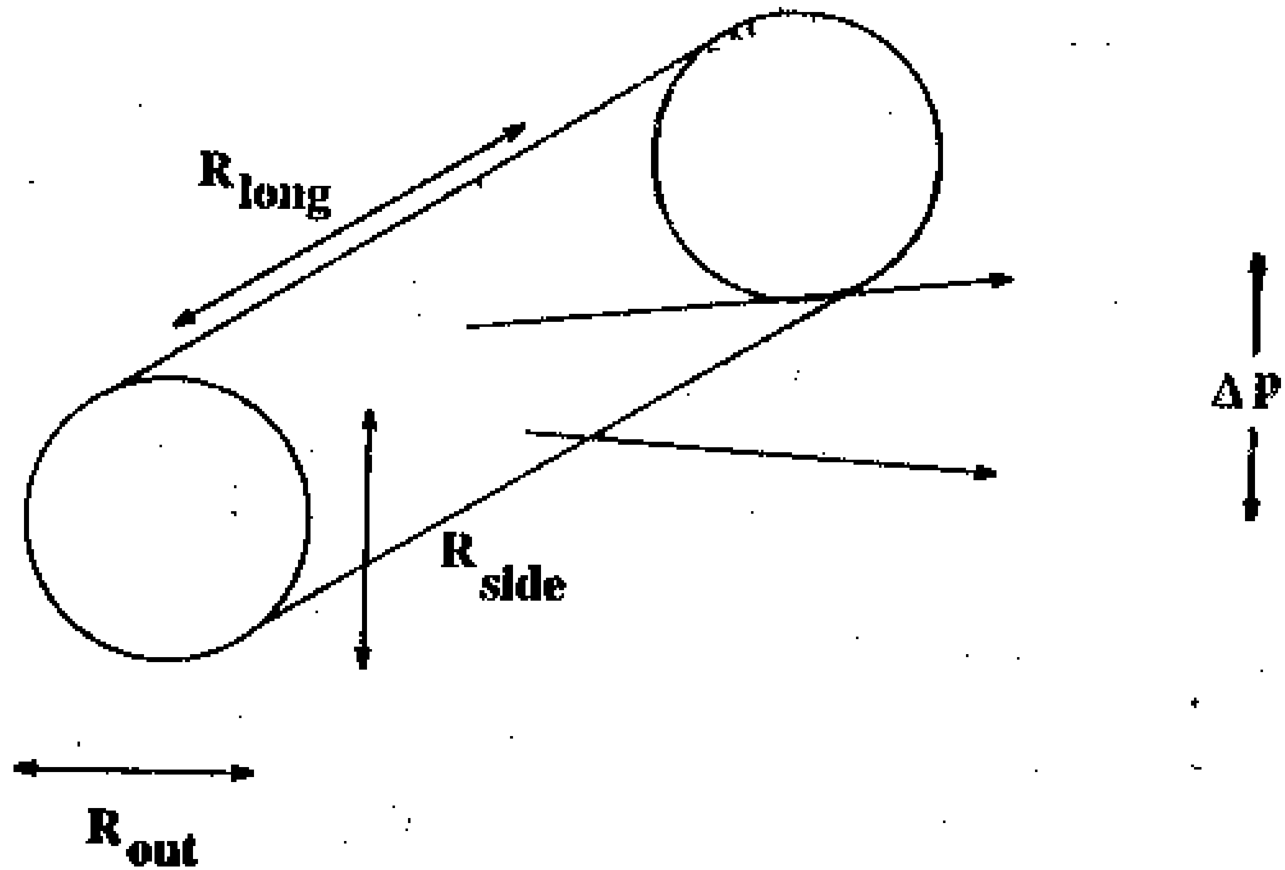
$$P(\vec{k_1}, \vec{k_2}) = P(\vec{k_1})P(\vec{k_2}) + \int d^4x \, d^4y \;\; \omega(x, K) \; \omega(y, K) \;\; \cos[(x - y) \cdot q]$$

$$K = \frac{k_1 + k_2}{2} \quad ; \qquad q = k_1 - k_2$$

$$k_i^\mu = (k_{iT} \cosh y_i, \; \vec{k_i}) \;\; ; \quad \vec{k_i} = (k_{iT} \cosh y_i, \; k_{iT} \cos \psi_i, \; k_{iT} \sin \psi_i, \; k_{iT} \sinh y_i)$$

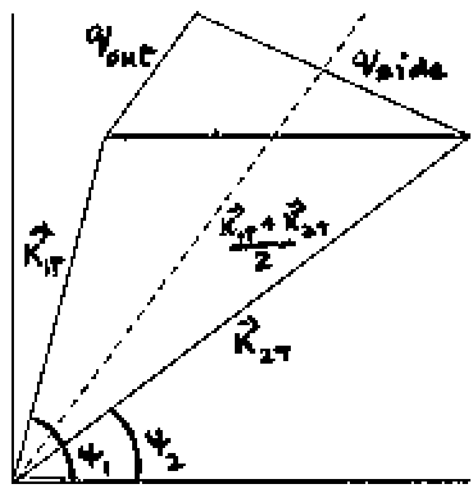
coherent source, $C_2(\vec{k_1}, \vec{k_2}) = 1 \quad \Longrightarrow$ **no correlation**

chaotic source, $1 \; \leq \; C_2(\vec{k_1}, \vec{k_2}) \; \leq \; 2$



R_{long}
R_{side}
R_{out}
ΔP

Kinematic Variables



Transverse Momentum Plane

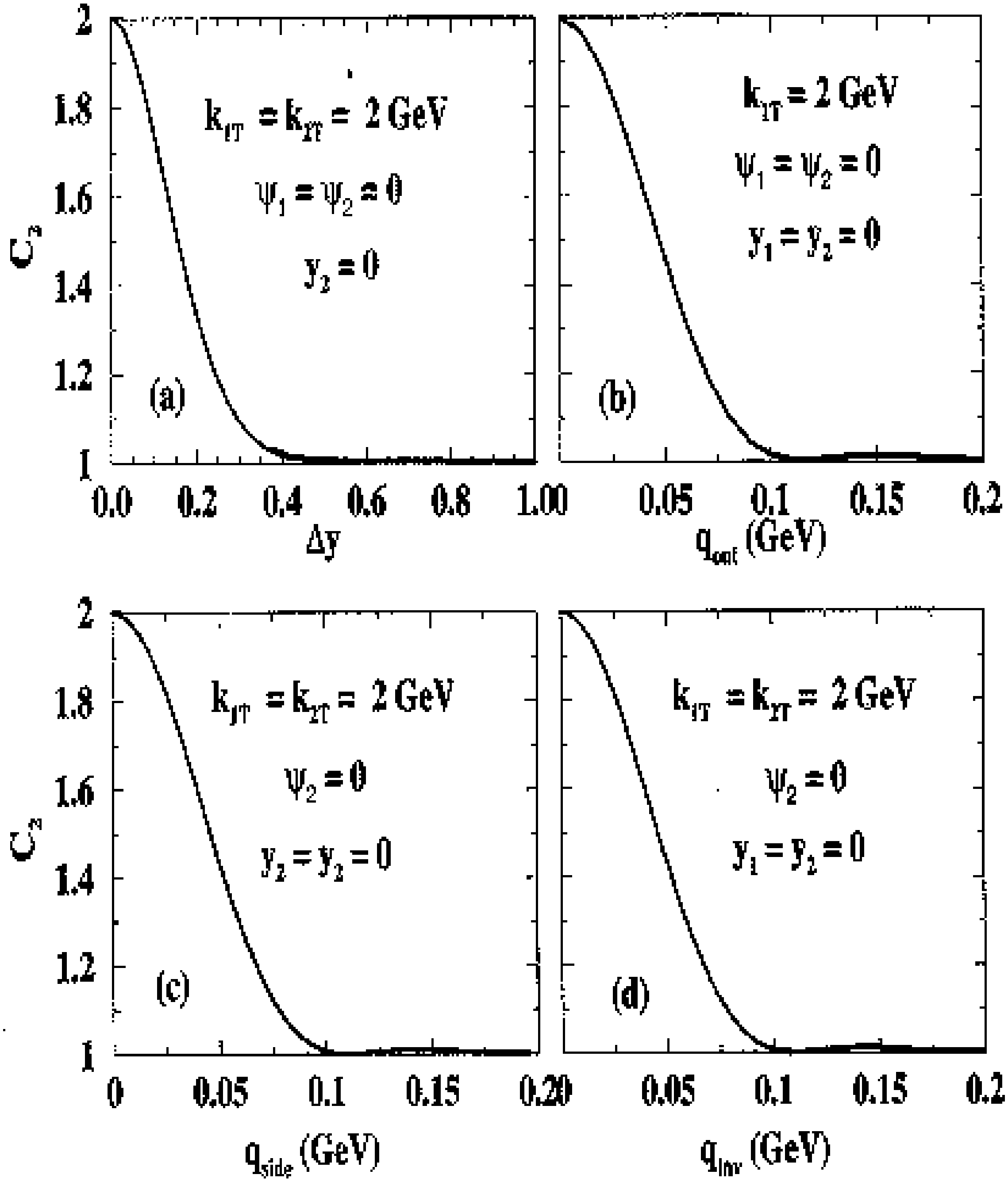
$$\vec{q}_T = \vec{k}_{1T} - \vec{k}_{2T} \quad ; \qquad \vec{K}_T = \frac{(\vec{k}_{1T} + \vec{k}_{2T})}{2}$$

$$q_{out} = \frac{\vec{q}_T \cdot \vec{K}_T}{|K_T|} = \frac{(k_{1T}^2 - k_{2T}^2)}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}k_{2T}\cos(\psi_1 - \psi_2)}}$$

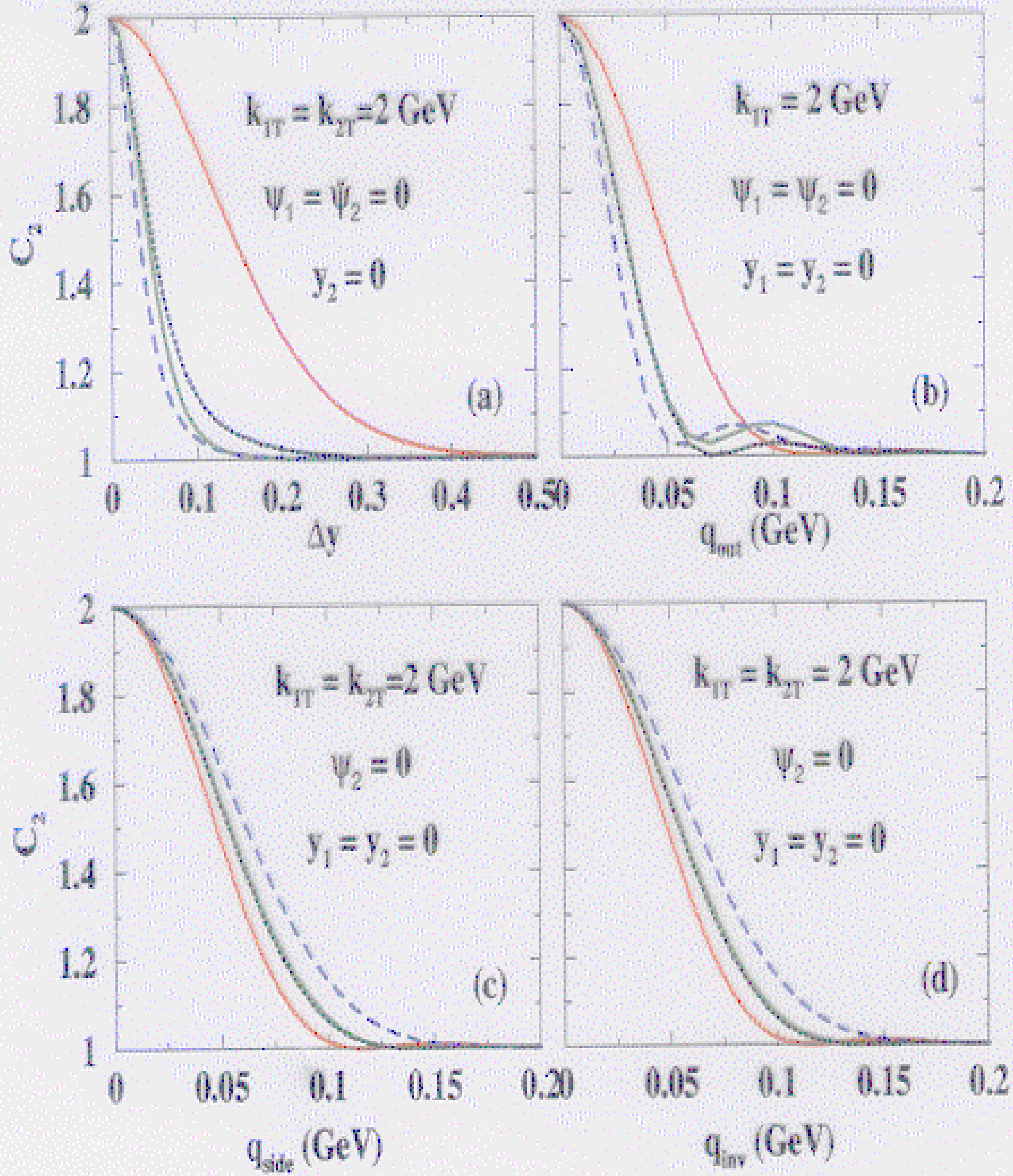
$$q_{side} = \frac{\left|\vec{q}_T \times \vec{K}_T\right|}{|K_T|} = \frac{2k_{1T}k_{2T}\ \sin(\psi_1 - \psi_2)}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}k_{2T}\cos(\psi_1 - \psi_2)}}$$

$$q_{long} = k_{1z} - k_{2z} = k_{1T}\sinh y_1 - k_{2T}\sinh y_2$$

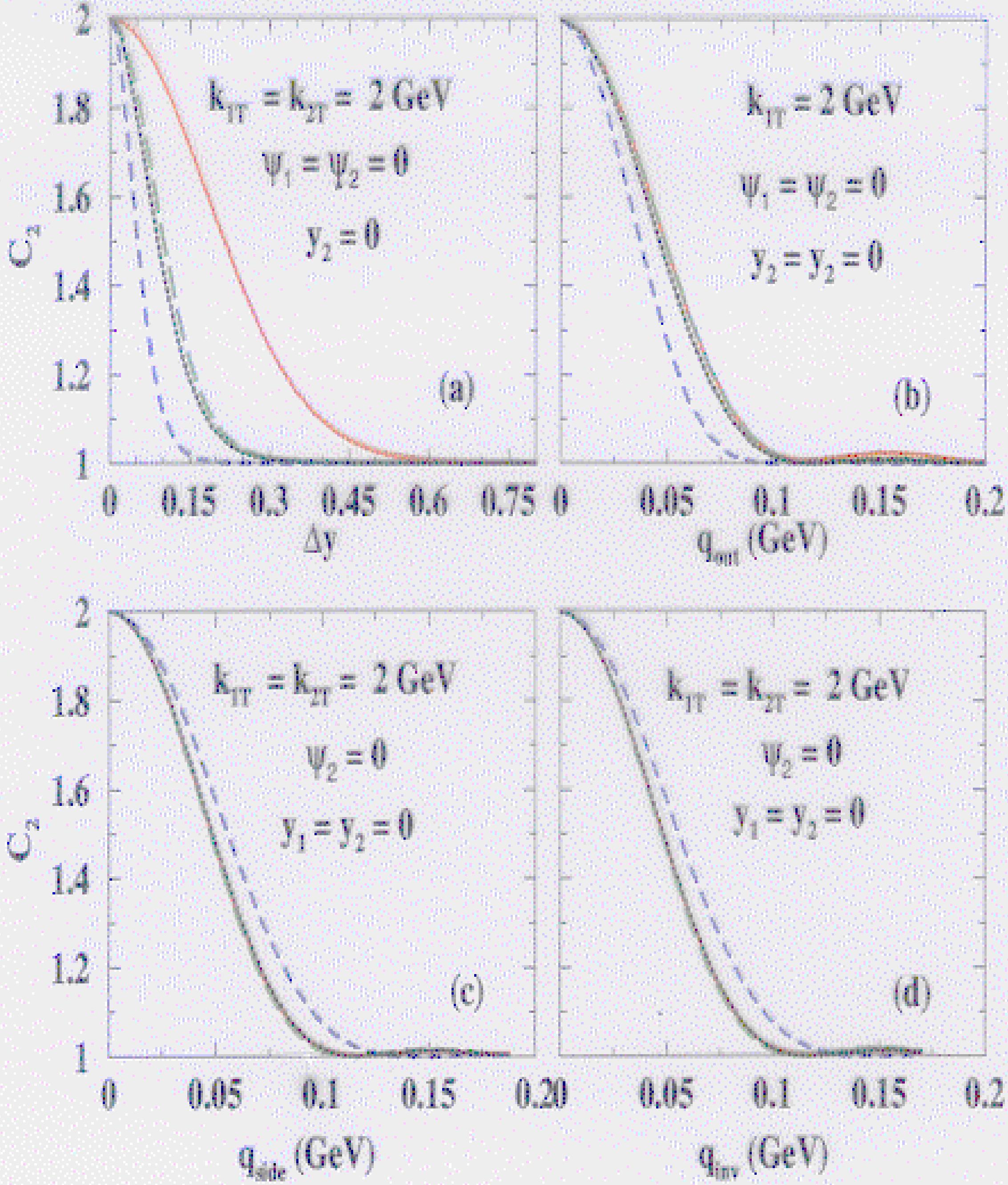
$$\begin{aligned} q_{inv}^2 &= q_{out}^2 + q_{side}^2 + q_{long}^2 - q_0^2 \\ &= 2k_{1T}k_{2T}[\cosh(y_1 - y_2) - \cos(\psi_1 - \psi_2)] \end{aligned}$$



$k_{1T} = k_{2T} = 2$ GeV
$\psi_1 = \psi_2 = 0$
$y_2 = 0$
(a)
$k_{1T} = 2$ GeV
$\psi_1 = \psi_2 = 0$
$y_1 = y_2 = 0$
(b)
$k_{1T} = k_{2T} = 2$ GeV
$\psi_2 = 0$
$y_2 = y_2 = 0$
(c)
$k_{1T} = k_{2T} = 2$ GeV
$\psi_2 = 0$
$y_1 = y_2 = 0$
(d)
C_2
Δy
q_{out} (GeV)
q_{side} (GeV)
q_{inv} (GeV)



$k_{1T} = k_{2T}$=2 GeV
$\psi_1 = \psi_2 = 0$
$y_2 = 0$
(a)
C_2
Δy
k_{1T} = 2 GeV
$\psi_1 = \psi_2 = 0$
$y_1 = y_2 = 0$
(b)
q_{out} (GeV)
$k_{1T} = k_{2T}$=2 GeV
$\psi_2 = 0$
$y_1 = y_2 = 0$
(c)
C_2
q_{side} (GeV)
$k_{1T} = k_{2T}$ = 2 GeV
$\psi_2 = 0$
$y_1 = y_2 = 0$
(d)
q_{inv} (GeV)



(a)
$k_{1T} = k_{2T} = 2$ GeV
$\psi_1 = \psi_2 = 0$
$y_2 = 0$
C_2
Δy
(b)
$k_{1T} = 2$ GeV
$\psi_1 = \psi_2 = 0$
$y_2 = y_2 = 0$
q_{out} (GeV)
(c)
$k_{1T} = k_{2T} = 2$ GeV
$\psi_2 = 0$
$y_1 = y_2 = 0$
q_{side} (GeV)
(d)
$k_{1T} = k_{2T} = 2$ GeV
$\psi_2 = 0$
$y_1 = y_2 = 0$
q_{inv} (GeV)

Parametrization: $C_2 = 1 + \exp(-R_k^2 q_k^2)$

$K_T \sim$ **2 GeV**

		R_{inv}	R_{out}	R_{side}	R_{out}/R_{side}
SPS	**Hadron***	**3.7**	**3.6**	**3.7**	**~1**
SPS	**QGP**	**3.5**	**3.6**	**3.5**	**~1**
RHIC	**QGP**	**3.0**	**5.5**	**3.0**	**1.8**

$R \Longrightarrow$ **scale of homogeneity**

< **geometric size for expanding systems**

Alam et al.
C67 '2003

$R_{side}/R_{out} \sim 1$ for SPS

$R_{side}/R_{out} < 1$ for RHIC

Summary

- We evaluate the two-photon correlation function for SPS and RHIC energies

- For SPS, constraints from the single-photon spectra have been used

- We find that R_{out}/R_{side} ~1 for SPS both for a QGP and hot hadronic gas initial state

- For RHIC, R_{out}/R_{side} >1