Panoramic Tour around the Quark-Gluon Plasma

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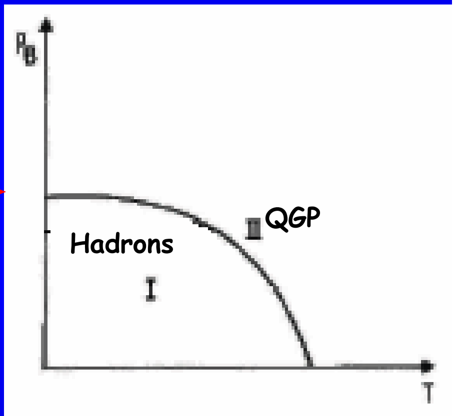
Old days …

Brief History of the Field

- **Motivation:**
  $\approx$ Mid 70's → existence of a new state of matter was predicted @ high temperatures (above T_c) / densities

Preliminary phase diagram:

Collins & Perry, PRL 34 (1975) 1353
Cabbibo & Parisi, PLB59 (1976) 67



Inspired theoretical & experimental efforts in

– Relativistic Heavy Nuclei (Ions) collisions:

80's & 90's:
- AGS/BNL: A+B a $14.6\ GeV/n$ ($\sqrt{s_{NN}} \approx 5.4\ GeV$)
- SPS/CERN: S+Pb, Pb+Pb a 158 GeV/n ($\sqrt{s_{NN}} \approx 17\ GeV$)

Starts: 2000
- RHIC/BNL: Au+Au $\sqrt{s} \approx 130,\ 200\ GeV$
- d+Au, p+p, Cu+Cu

Brief History of the Field

- **Motivation:**
  - ≈ Mid 70's → existen
    predicted @ high t

  Inspired theoretical & ex
  - Relativistic Heavy

80's & 90's
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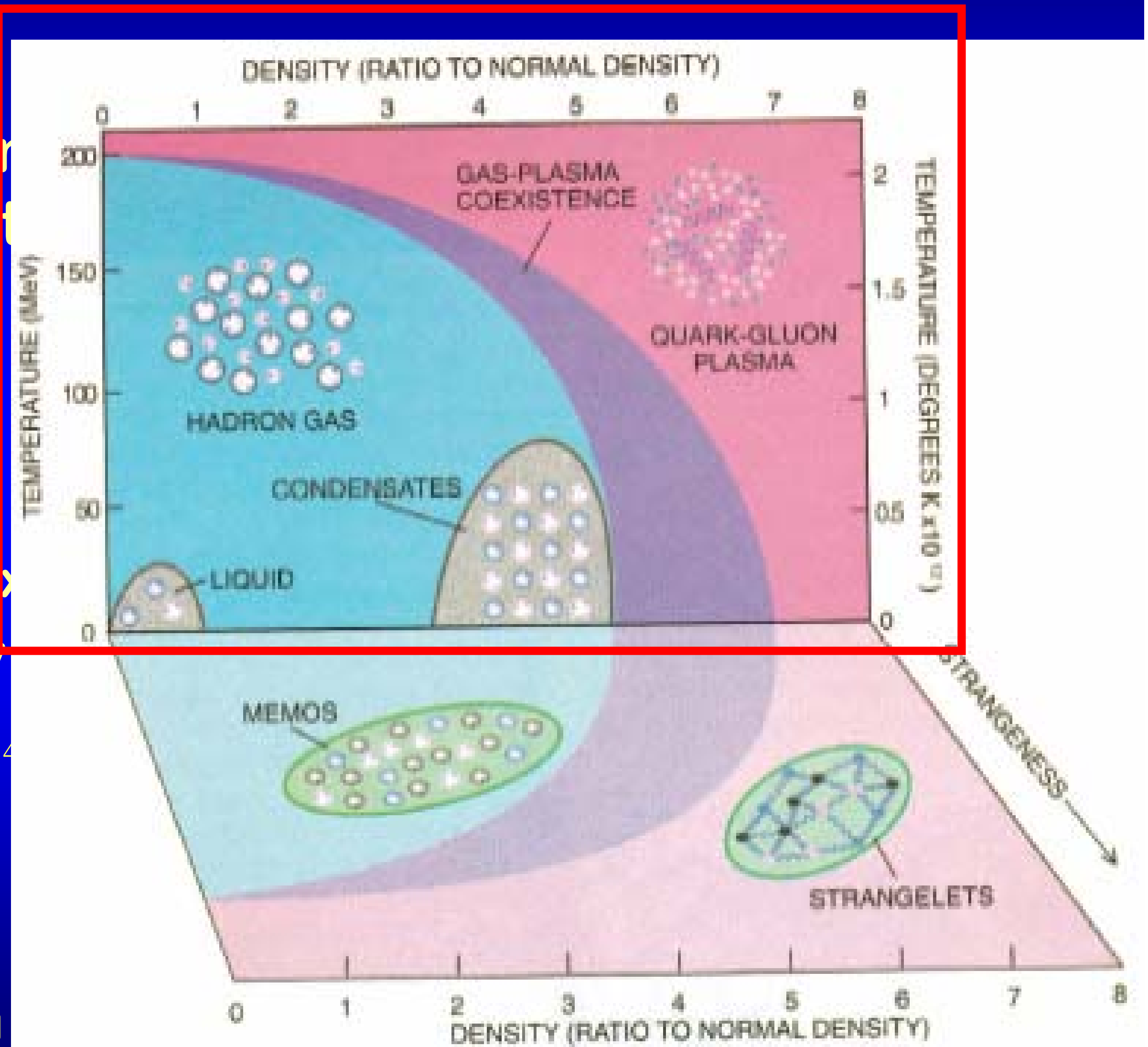
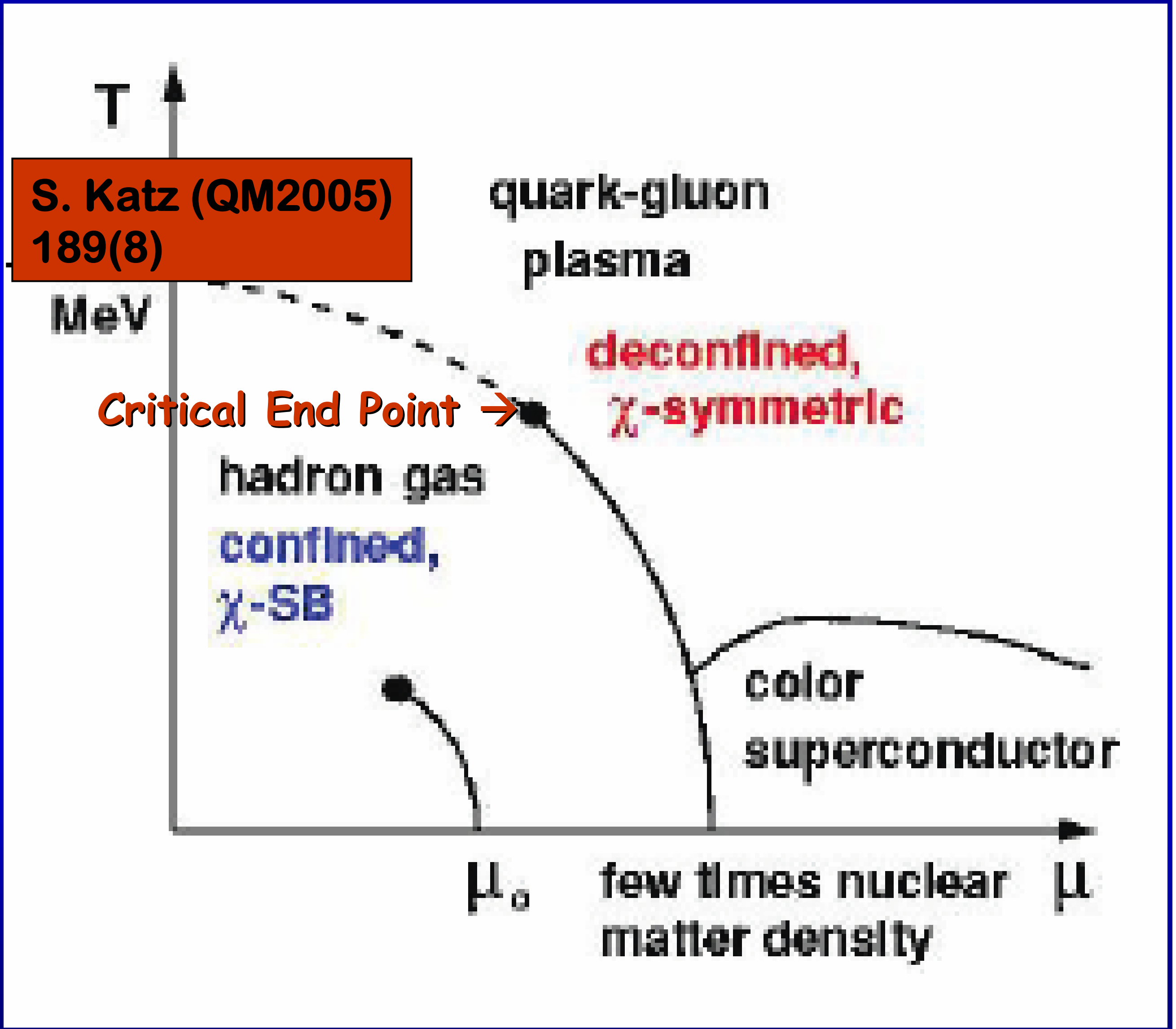


Lattice QCD: recent results

- $T_c \approx T_\chi$
- $T_c \approx$ 170 MeV
- Crossover ($m_u = m_d; m_s \rightarrow \infty$)
- Critical Point
- Order of the transition → not yet definied



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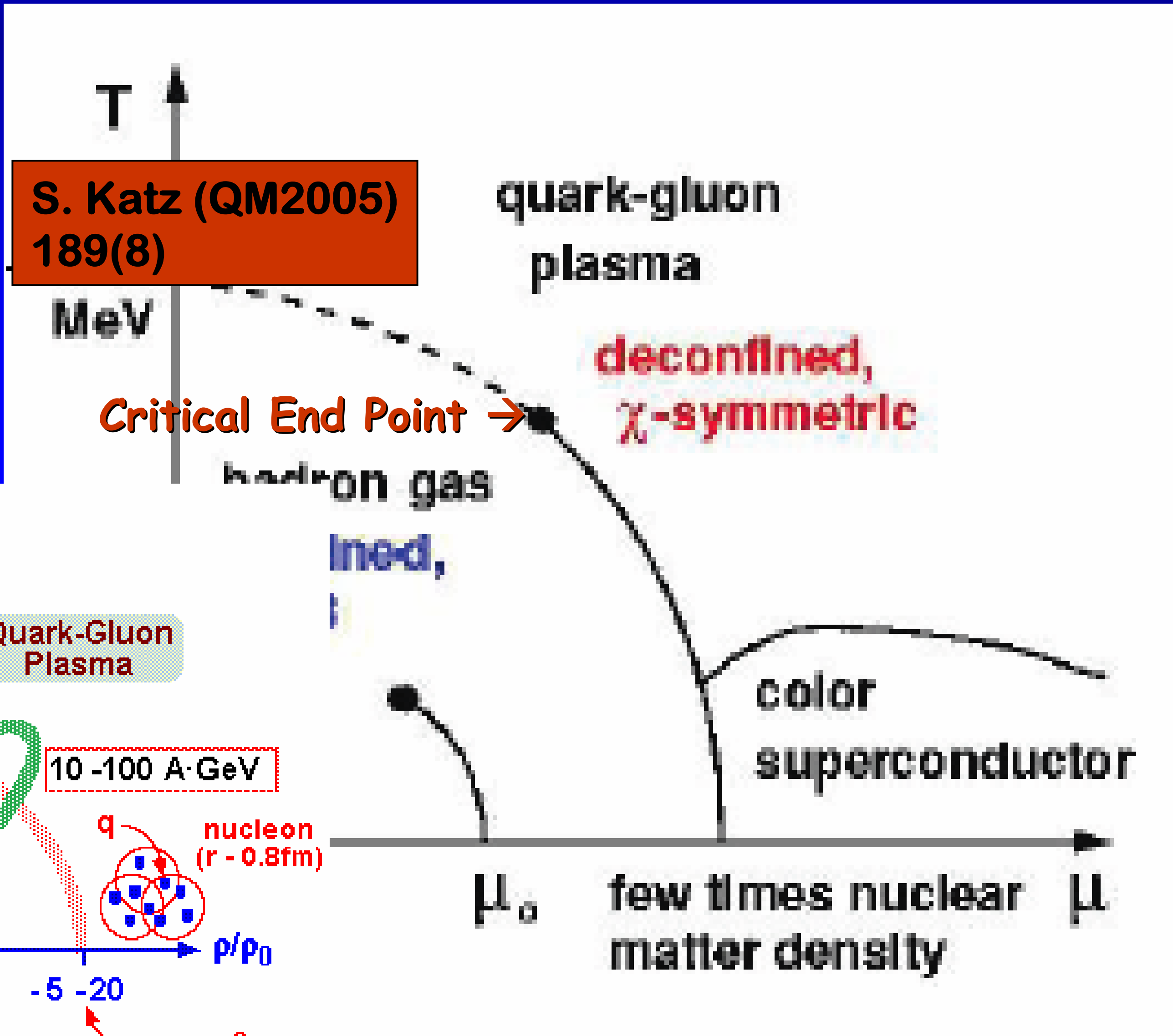
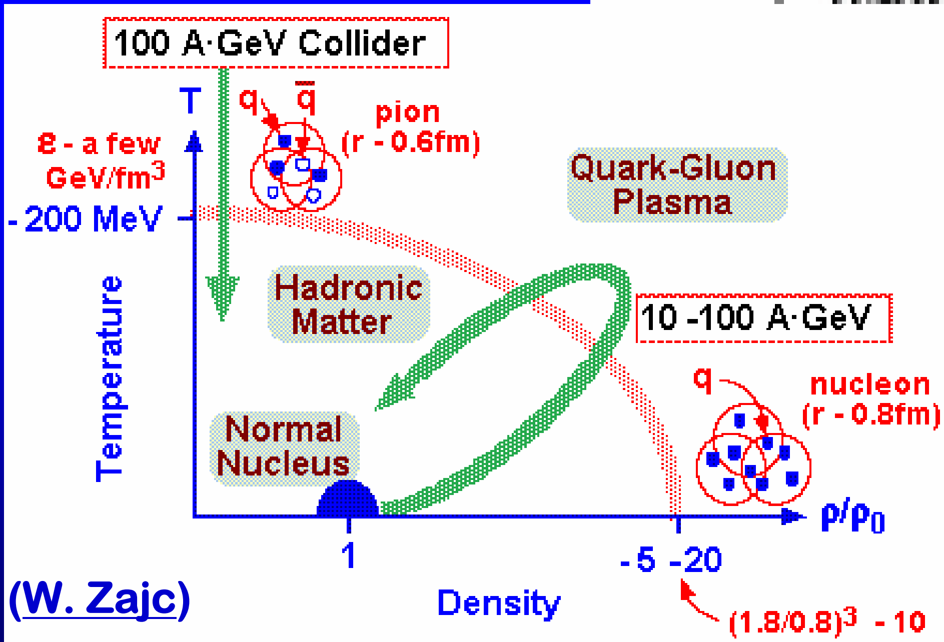




(W. Zajc)

Probes of QGP formation

R
E
L.

H
E
A
V
Y

I
O
N

C
O
L
L.

– 1) Phase diagrams ε *vs.* T (EoS near T_c) or $<p_T>$ vs. T (particles with large p_T emitted at high T)

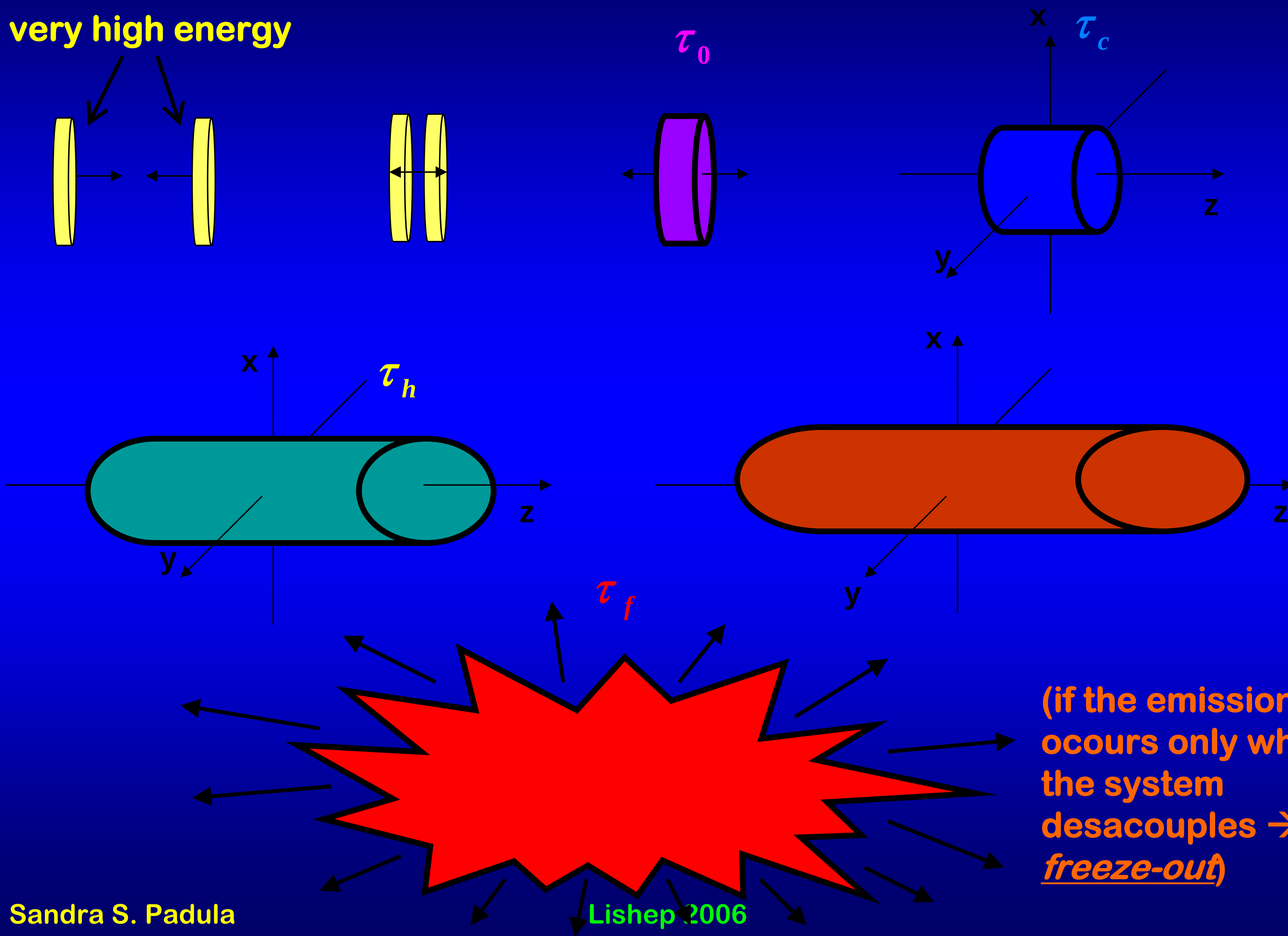
– 2) J/ψ Suppression $\longleftrightarrow$ *screening* of the $c\,\overline{c}$ pair

– 3) direct γ*'s*, direct $\ell^+\ell^-$ pairs $\longrightarrow$ systems in different stages of evolution

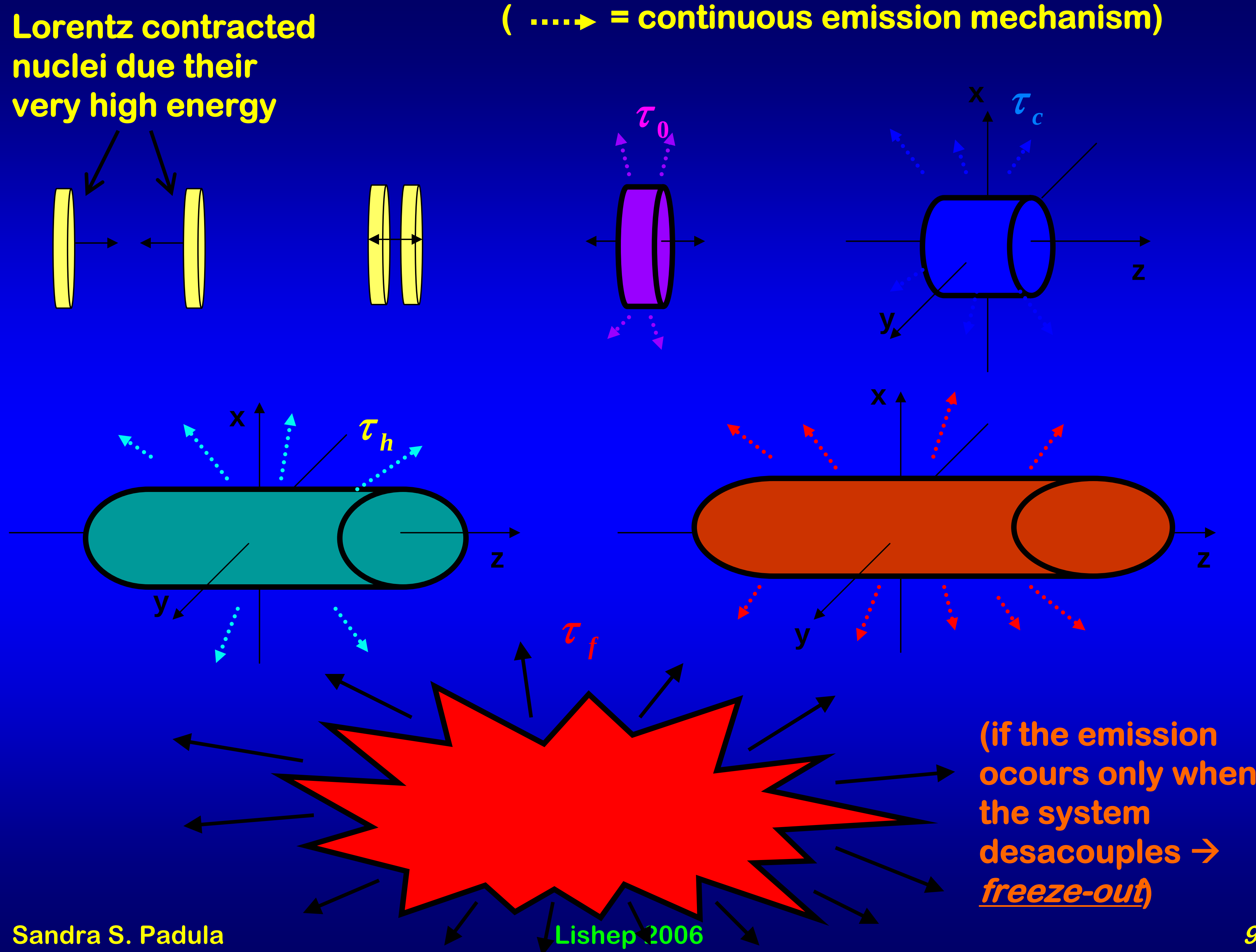
– 4) HBT (interferometry of identical π's): big volumes were expected

[at AGS & SPS energies → all were compatible with alternative (conventional) explanation, i.e., hadronic ressonance gas]

Lorentz contracted nuclei due their very high energy



(if the emission ocours only when the system desacouples → ***freeze-out***)


Lorentz contracted nuclei due their very high energy
(····▶ = continuous emission mechanism)
τ_0
τ_c
τ_h
τ_f
x
y
z
(if the emission ocours only when the system desacouples → *freeze-out*)

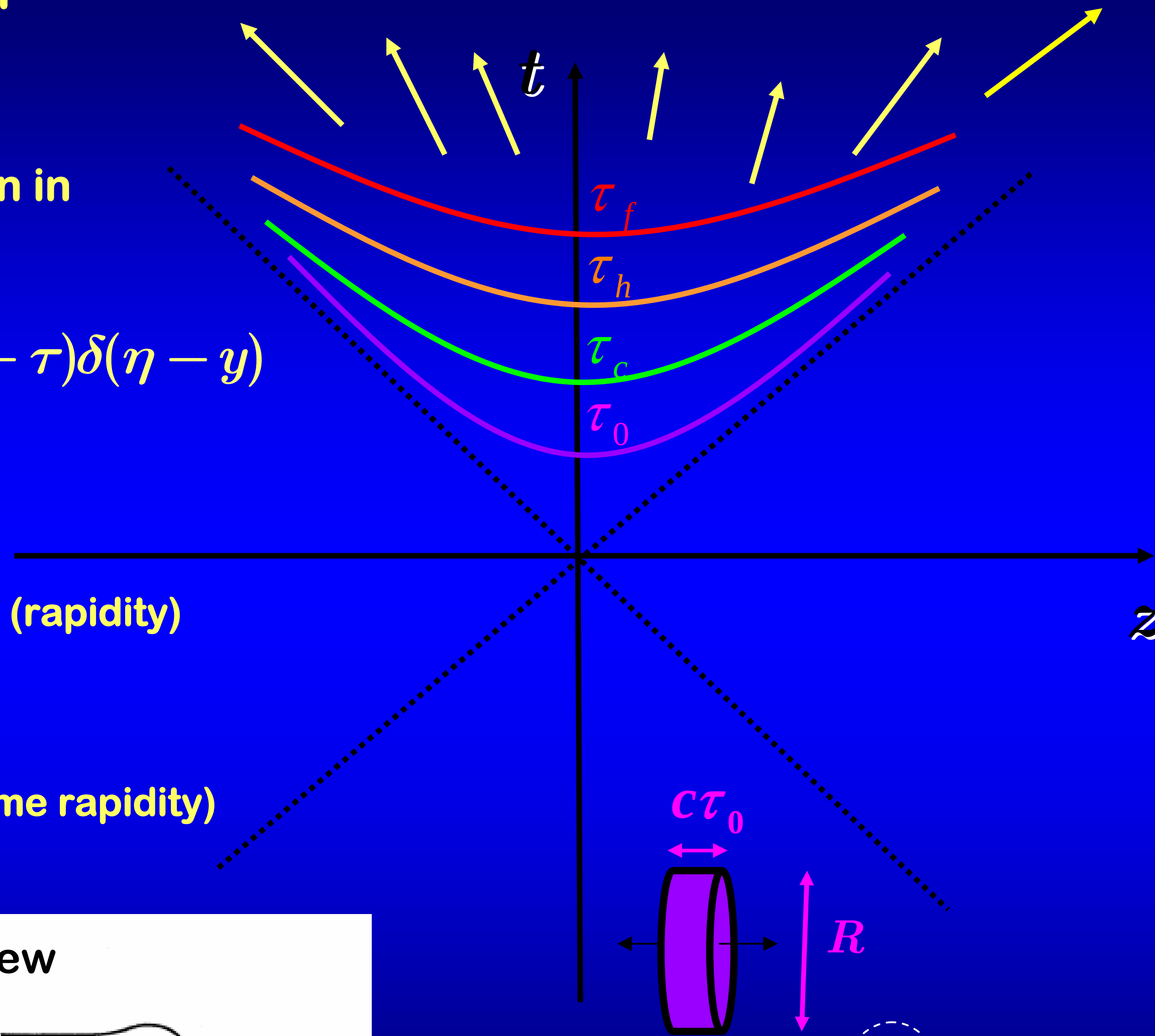
Ideal Bjorken Model

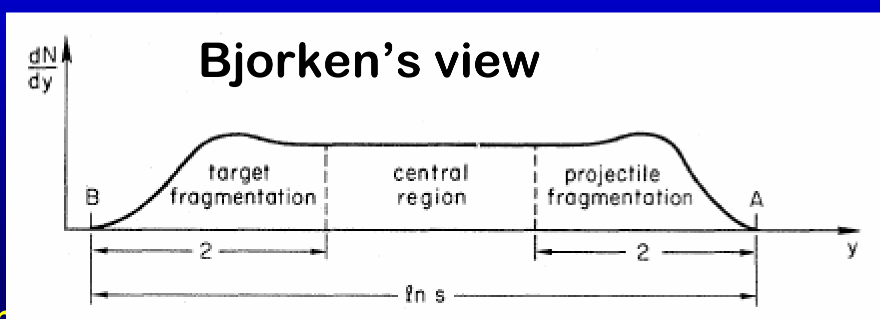
Freeze-out distribution in Phase-space

$$f(x,p) \propto \left(\frac{dN}{dy}\right)\frac{1}{\tau}\delta(\tau_f-\tau)\delta(\eta-y)$$

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$ **(rapidity)**

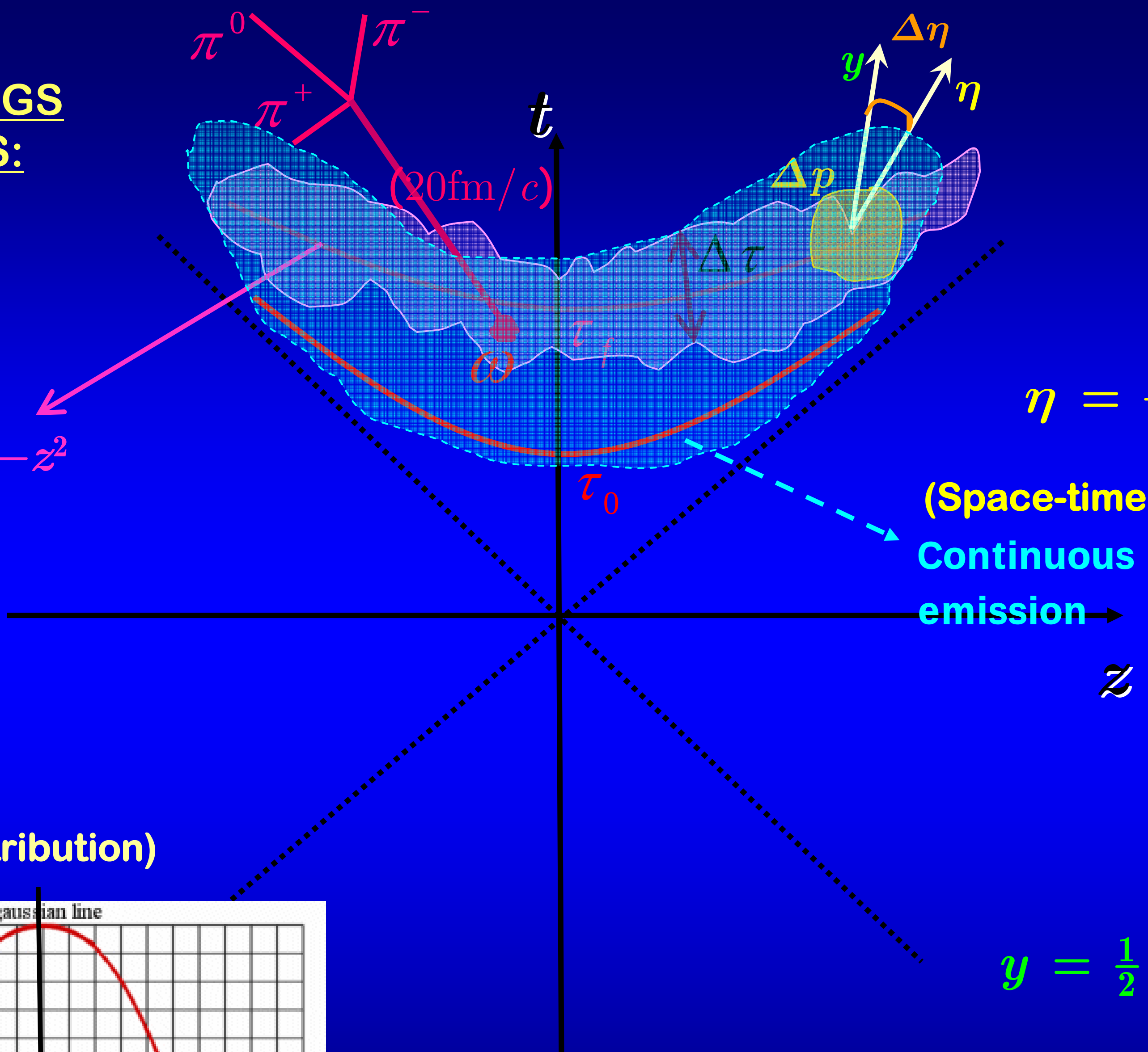
$$\eta=\frac{1}{2}\ln\frac{t+z}{t-z}$$ **(Space-time rapidity)**





$$\varepsilon_0 = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dN}{dy} \leftrightarrow \frac{dE_T}{dy}$$

At the AGS and SPS:



$\tau^2 = t^2 - z^2$

$$\eta = \frac{1}{2}\ln\frac{t+z}{t-z}$$

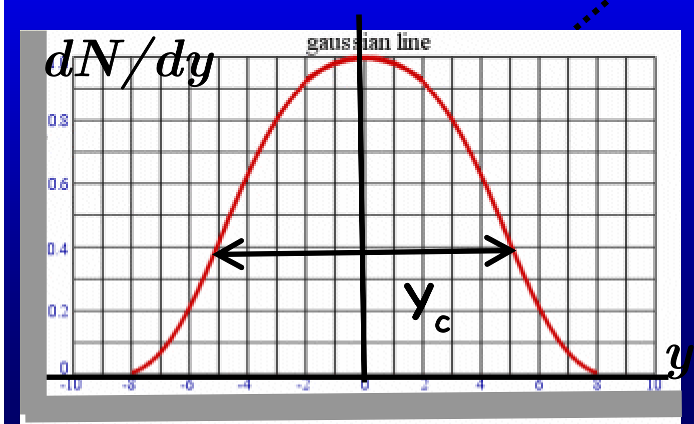
(Space-time rapidityl)

Continuous emission

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

(rapidity)

(rapidity distribution)



1) Phase diagrams ε vs. T (EoS near T_c)

Early expectation by Bjorken [P.R. D27 (1983) 140]

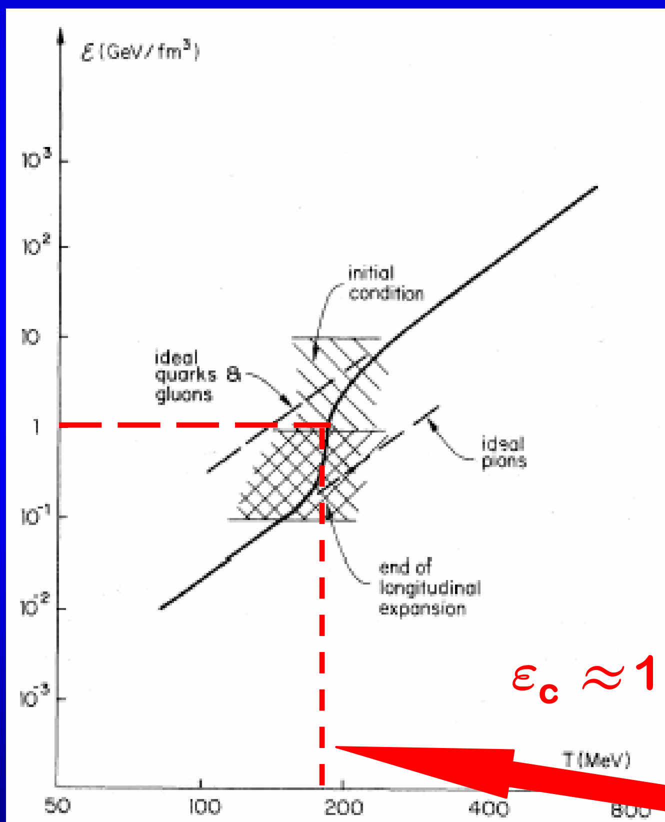
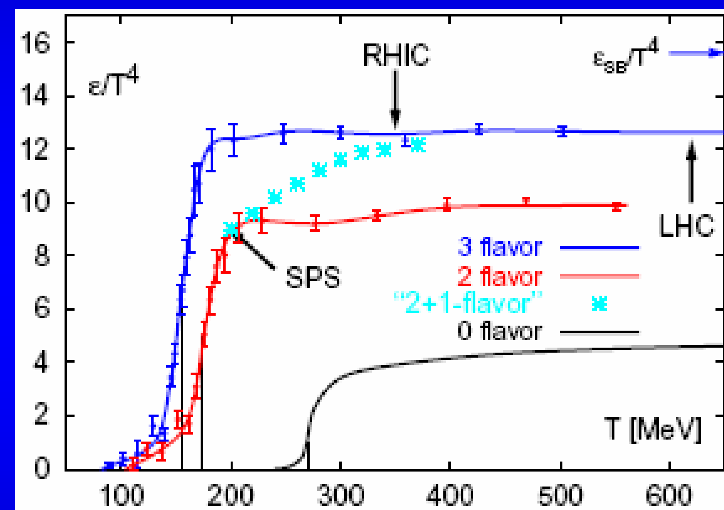


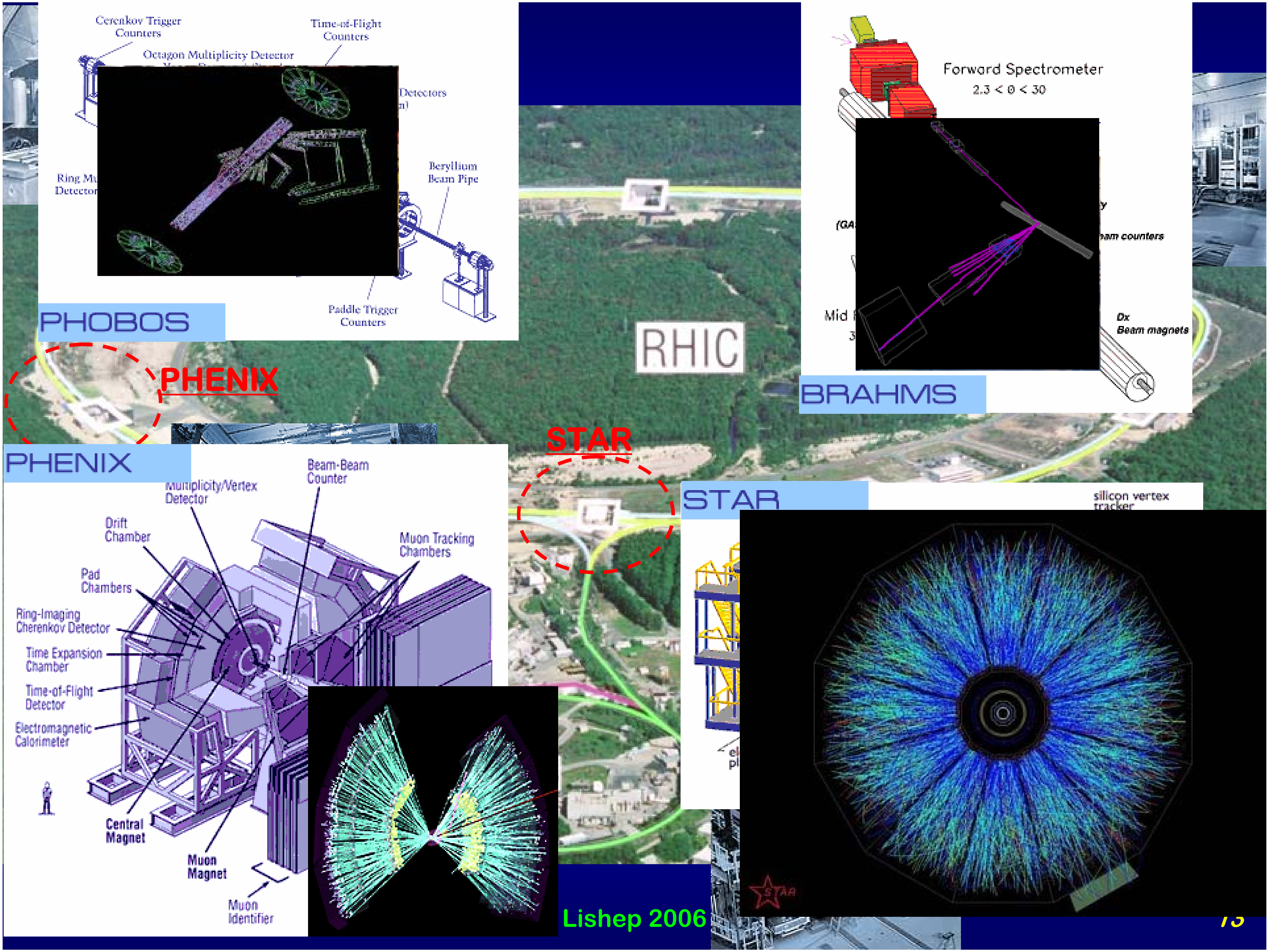
FIG. 8. Energy density versus temperature.

$\varepsilon_c \approx 1$ GeV/fm^3

Lattice QCD results [F. Karsch, Lett. Not. Phys, 583 (2002) 209] for the ε / T^4 as a function of T



- By then, L-QCD predicted $T_c \approx$ 170 MeV
- At QM2005 → L-QCD: $T_c \approx$ 189 (8) MeV



PHOBOS
Cerenkov Trigger Counters
Time-of-Flight Counters
Octagon Multiplicity Detector
Beryllium Beam Pipe
Paddle Trigger Counters
RHIC
Forward Spectrometer
2.3 < θ < 30
Dx
Beam magnets
BRAHMS
PHENIX
PHENIX
STAR
STAR
silicon vertex tracker
Beam-Beam Counter
Multiplicity/Vertex Detector
Drift Chamber
Muon Tracking Chambers
Pad Chambers
Ring-Imaging Cherenkov Detector
Time Expansion Chamber
Time-of-Flight Detector
Electromagnetic Calorimeter
Central Magnet
Muon Magnet
Muon Identifier

Estimated initial density ε_0

$$\varepsilon_0 \approx 100\varepsilon_0 = 15\ \mathrm{GeV/fm^3}$$

- Bjorken extrapolation (final → initial state)

$$\varepsilon_0 = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dN}{dy} \leftrightarrow \frac{dE_T}{dy}$$

$$E_T / N_\pi = 0.5 GeV \ ; \ dN/dy \sim 1000$$

$$\tau_0 = 1 fm/c; V = (1 fm)\pi R^2 \approx 154 fm^3$$

$$\varepsilon_{Bj} \approx 3.2\ GeV/fm^3 \approx 20\varepsilon_A$$

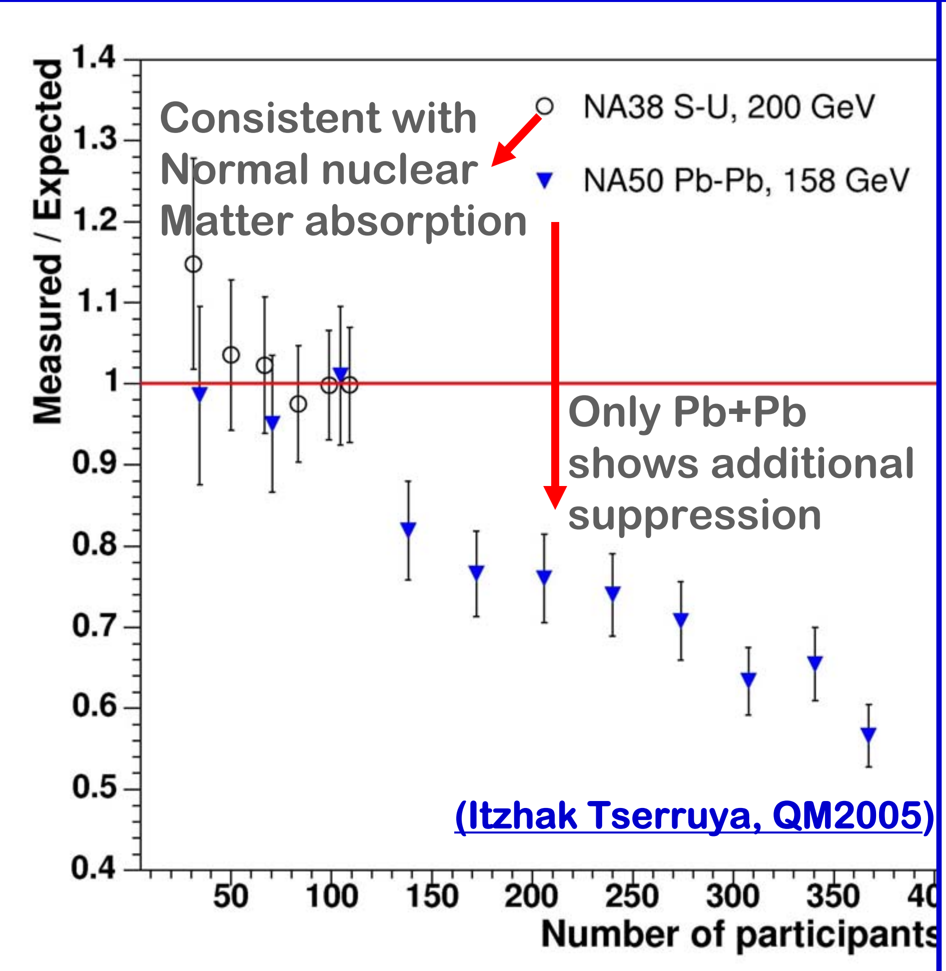
$$\tau_0 = 0.2 fm/c; V = (0.2 fm)\pi R^2 \approx 154 fm^3$$

$$\varepsilon_{Bj} \approx 16\ GeV/fm^3 \approx 100\varepsilon_A$$

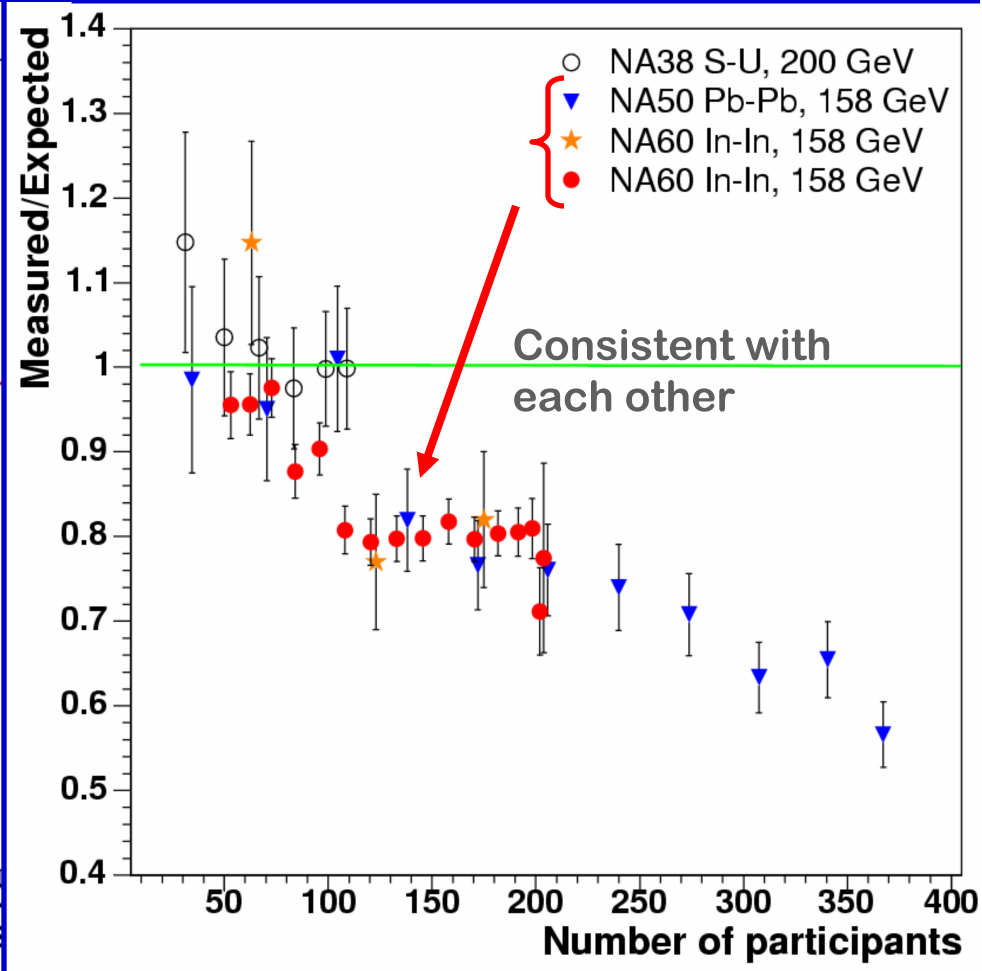
2) J/ψ Suppression $\longleftrightarrow$ *screening* of the $c\,\bar{c}$ pair

NA50 J/ψ → reanalysis of data:

Normal nuclear absorption derived from pA data only $\sigma = 4.18 \pm 0.35$ mb

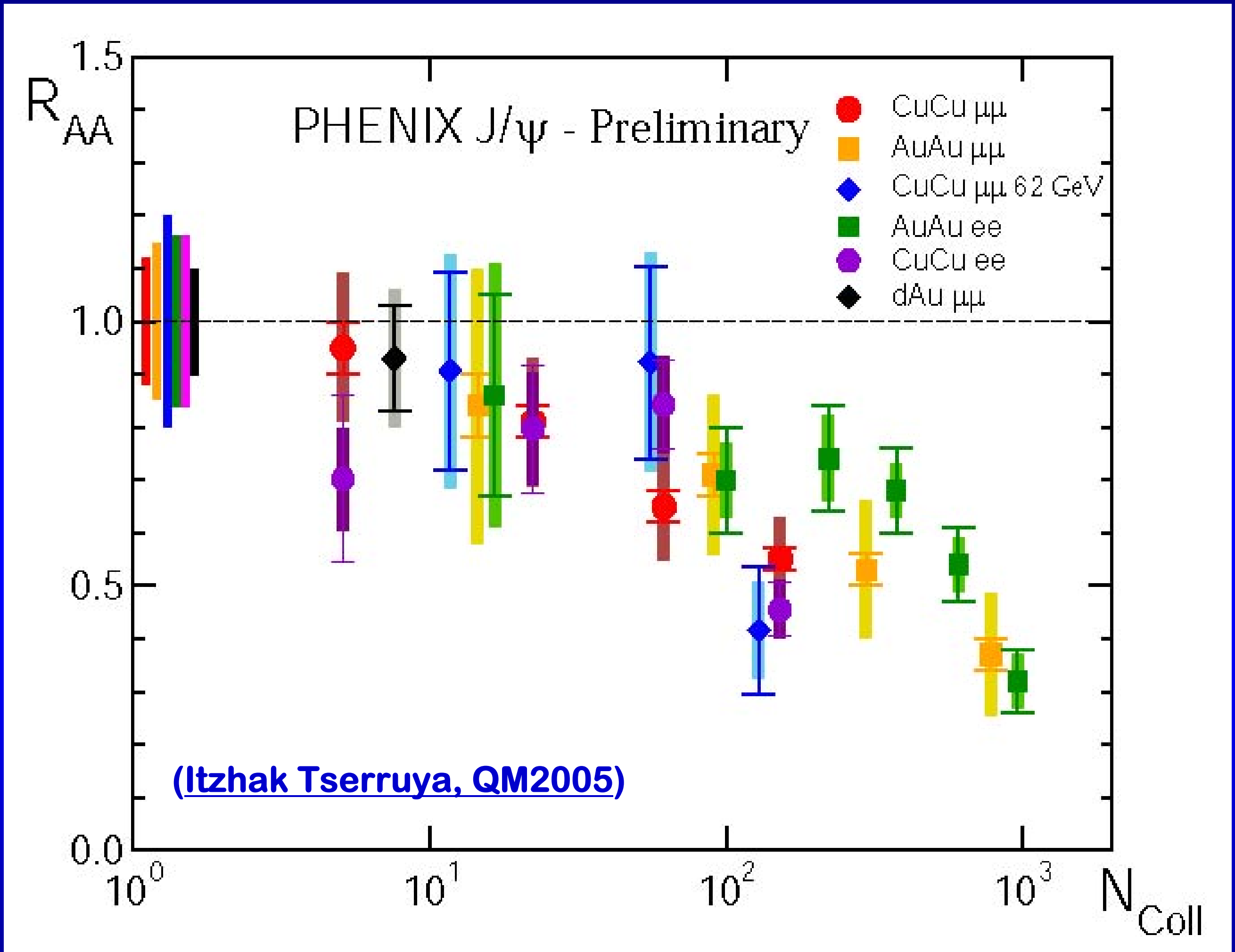


NA50 and NA60 together (final results at QM'05)



Systematic errors of ~8% not shown

J/ψ @ RHIC (new!)



$J/\psi \to \mu\mu$

(muon arm)

$1.2 < |y| < 2.2$

$J/\psi \to ee$

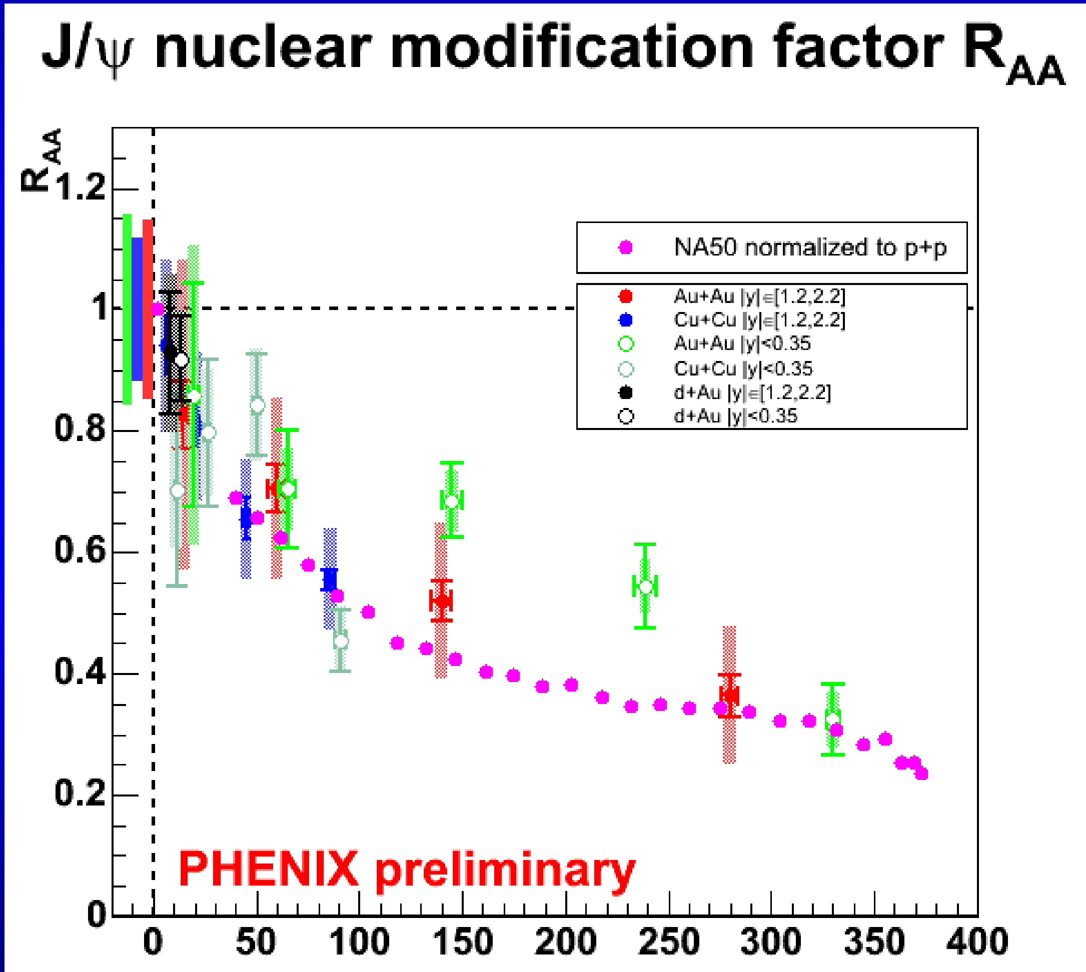
(central arm)

$-0.35 < y < 0.35$

Central events: factor ~3 suppression

Same trend shown by data within error bars for all species (even at 62 GeV)

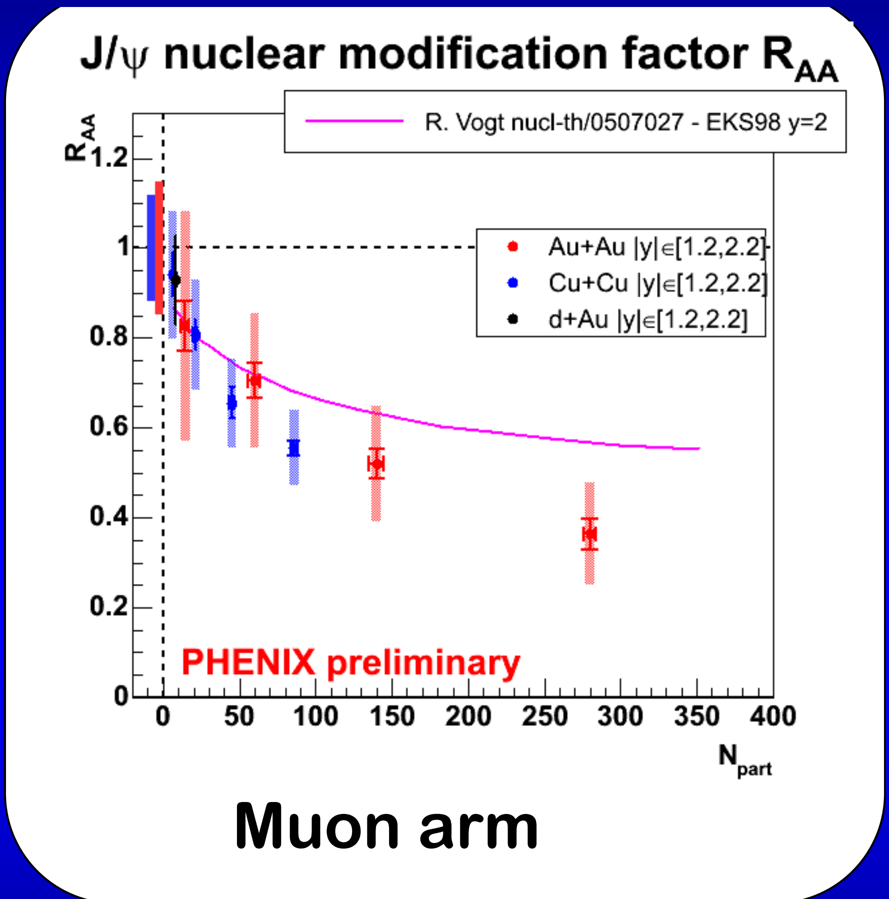
R_{AA} vs N_{part}: PHENIX and NA50

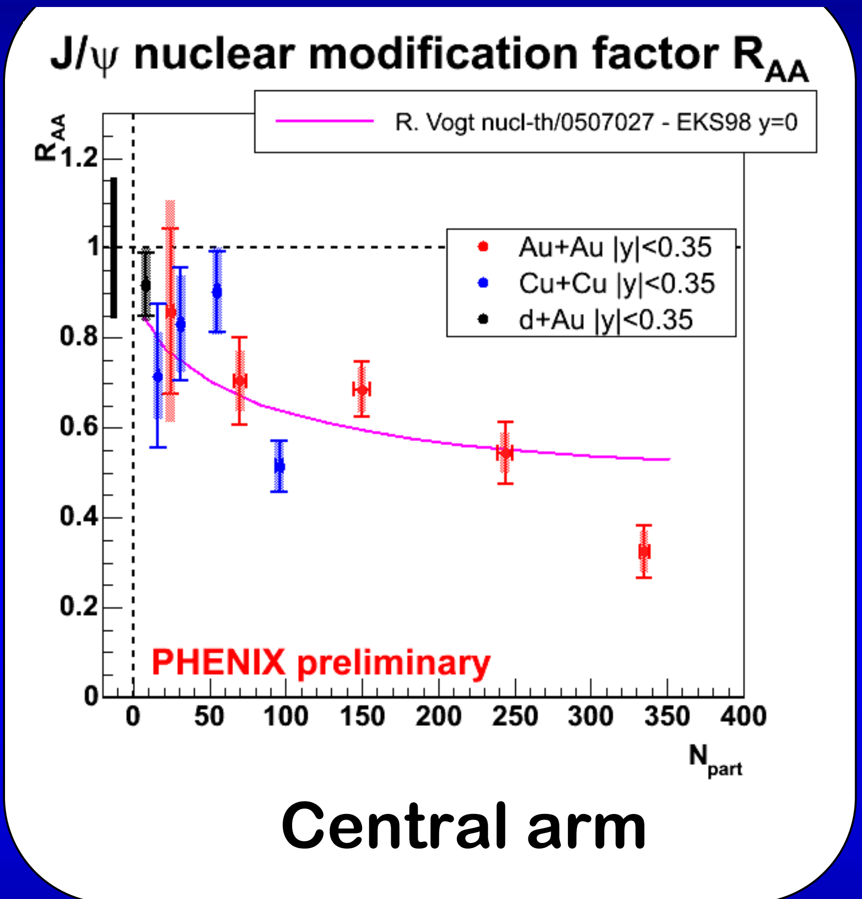


(Itzhak Tserruya, QM2005)

- NA50 data normalized to NA50 p+p point.
- Similar suppression in NA50 ($\sqrt{s} = 17$ GeV) data and in PHENIX ($\sqrt{s} = 200$ GeV)

Comparison to theory type I: normal nuclear absorption

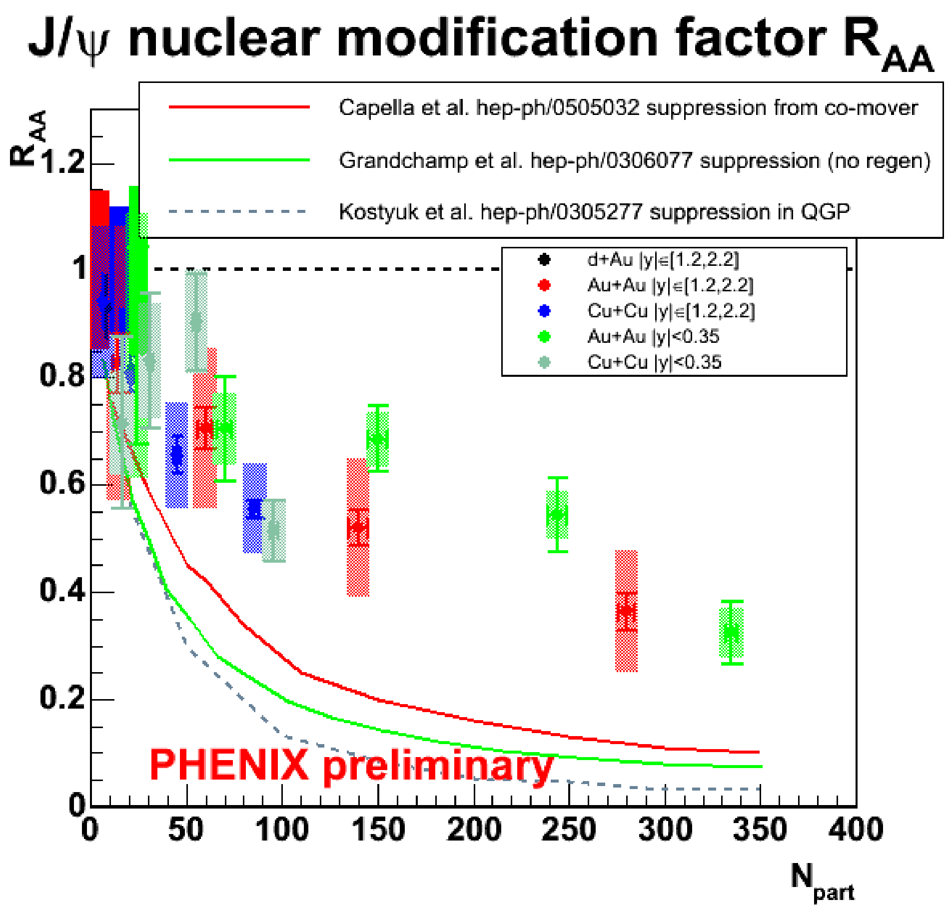


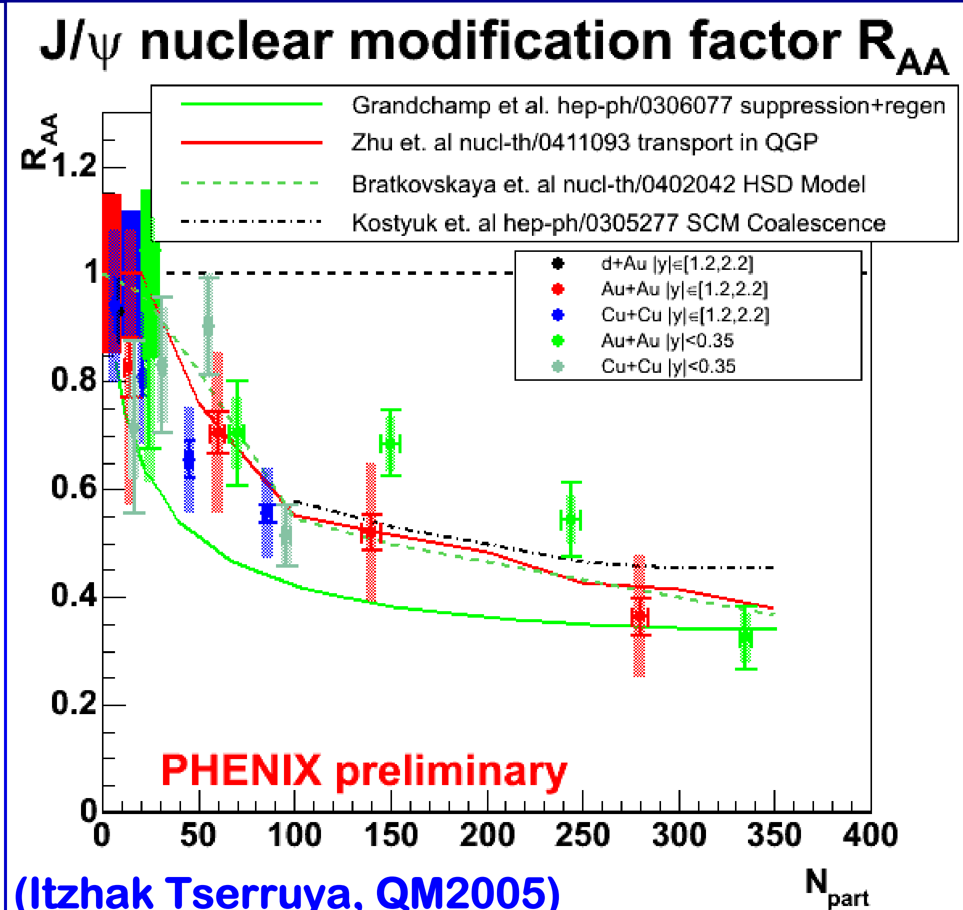


(Itzhak Tserruya, QM2005)

Cold nuclear matter absorption model in agreement with d+Au: tendency to underpredict suppression in most central AuAu and CuCu events

Comparison to theories type II & III





(Itzhak Tserruya, QM2005)

Models that were successful in describing SPS data fail to describe data at RHIC - too much suppression -

Adding recombination: much better agreement with the data

Alternative: melting of χ_c & ψ' (but not of J/ψ)

- Produced J/ψ: direct → 60%; χ_c → 30%; ψ' → 10%
- Proposal by M. Nardi (QM05):
  - Observed J/ψ suppression total melting of excited charmonium states (mainly χ_c & ψ') , no recombination
  - Supported by L-QCD:

$$T_{\psi'}^{diss} \approx T_{\chi_c}^{diss} \approx 1.1 T_c \;\; ; \;\; T_{J/\psi}^{diss} \approx (1.5-2) T_c$$

  - If this turns to be a good explation is true → only at LHC there will be temperatures high enough to melt J/ψ directly

3) Direct γ *'s*

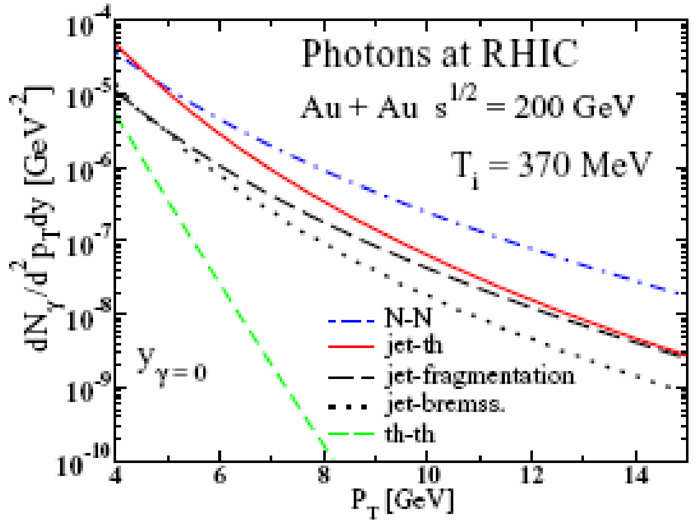
- **Spectrum of γ *'s* produced in A+A collisions → sources:**

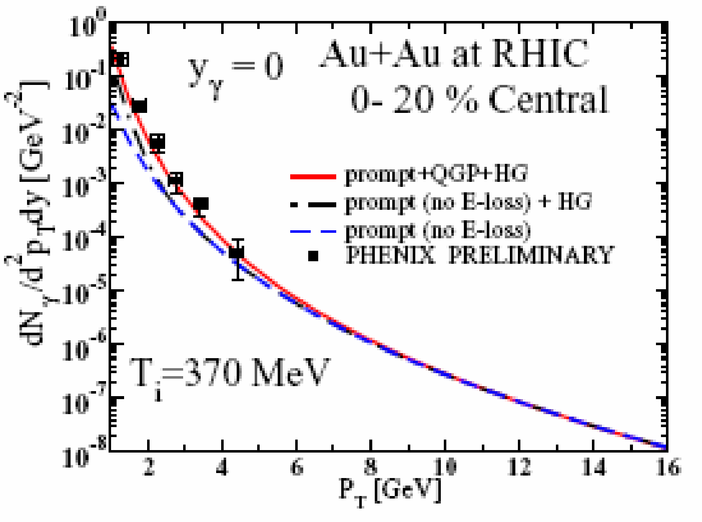
Active in pp collis.
- ***Direct γ's produced by parton Compton and annihilation proc.***
- ***Fragmentation γ's produced by bremsstrahlung of FS partons***
- ***Fragmenting jets → now subjected to energy loss (due to interaction with dense QCD medium)***
- ***γ's produced by medium-induced bremsstrahlung of hard partons traveling the dense medium***
- ***Conversion of leading partons to γ's* (significant contribution)**

Contributing sources **Total production of γ's @ RHIC**

Sources of high-p_T photons at mid-rapidity in central A+A coll.

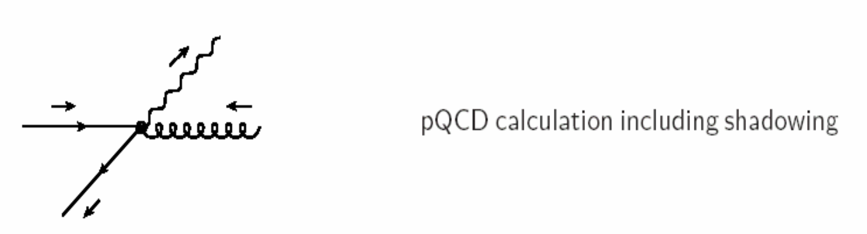
(C. Gale, QM'05)



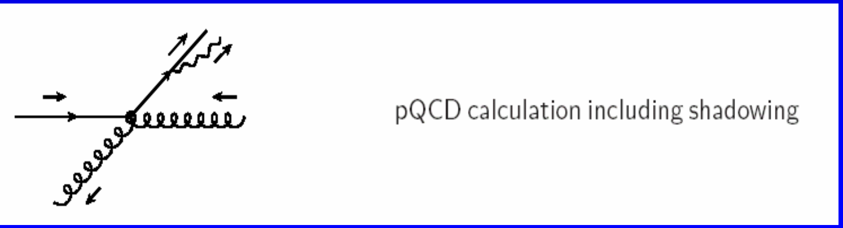


Photon sources

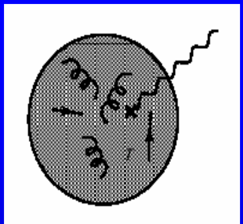
- Hard direct photons



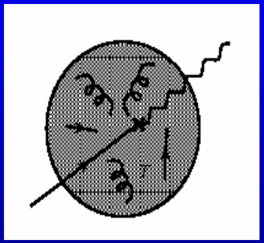
- EM bremsstrahlung



- Thermal photons from hot medium



- Jet-photon conversion

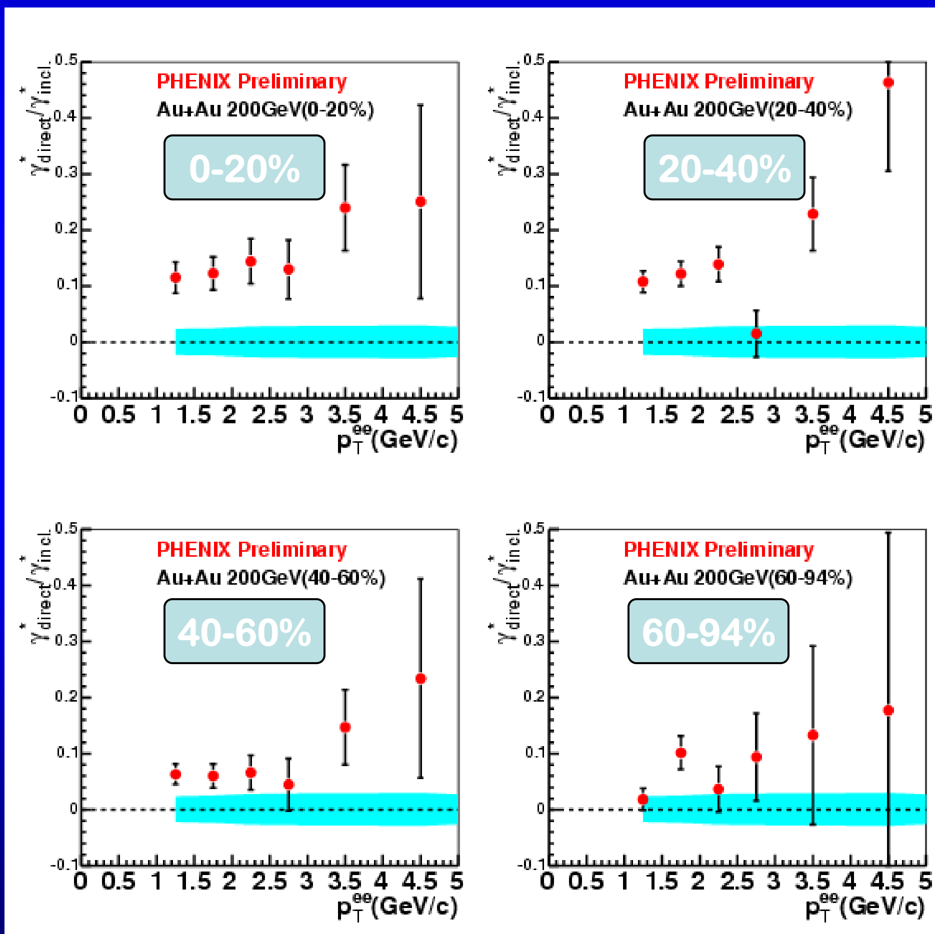


- Jet in-medium bremsstrahlung

(C. Gale, QM2005)

New approach on searching direct γ's (Phenix)

$\gamma^*_{direct} / \gamma^*_{inclusive}$



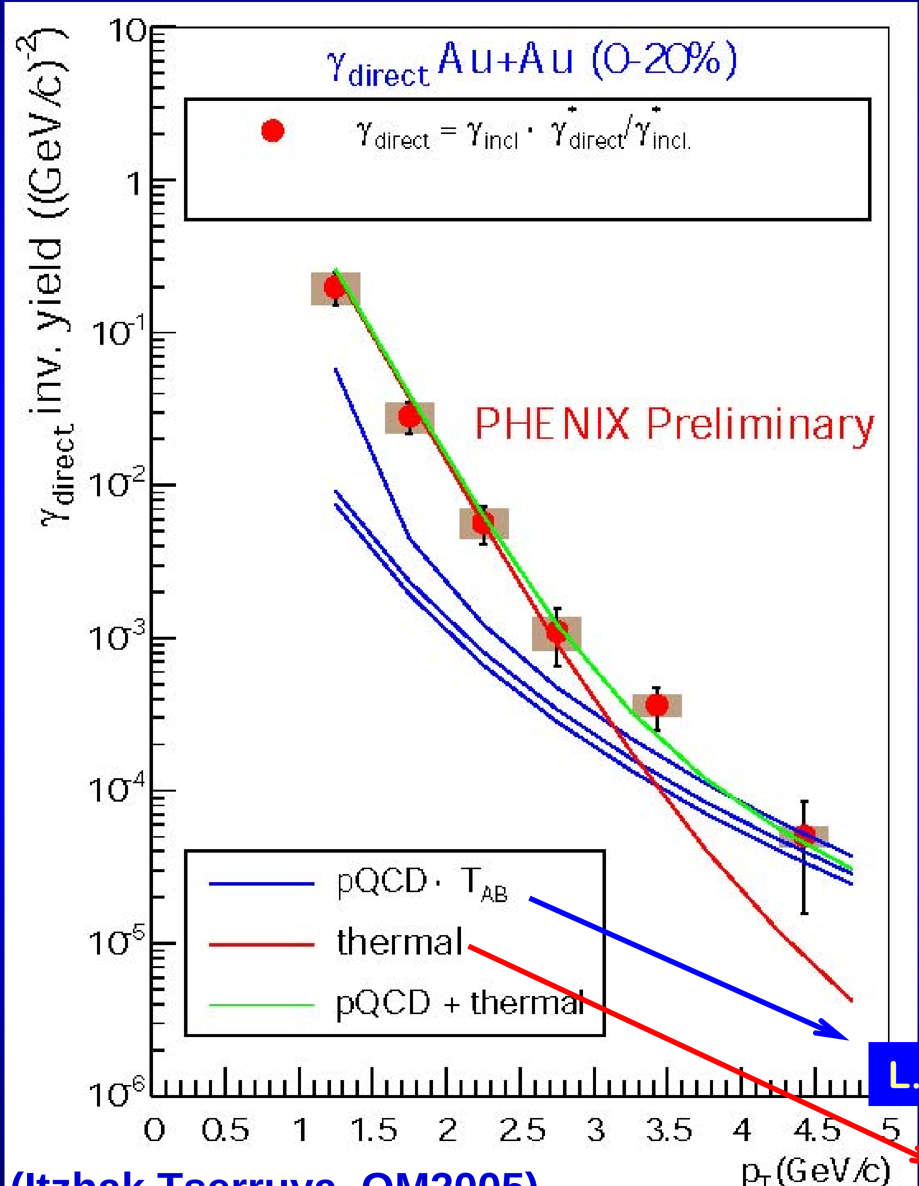
– Using: any source of real γ emits virtual $\gamma*$ with very low mass →

– low mass e^+e^- yield is translated (after removing hadronic sources) into spectrum of direct γ, assuming that

$$\frac{\gamma^*_{direct}}{\gamma^*_{incl.}} = \frac{\gamma_{direct}}{\gamma_{incl.}}$$

(Itzhak Tserruya, QM2005)

Yield of direct γ's



(Itzhak Tserruya, QM2005)

$$\gamma_{direct} = \gamma_{incl.}(\gamma^*_{direct} / \gamma^*_{incl.})$$

— Preliminary results compatible with a spectrum obtained by conventional analysis of real γ's

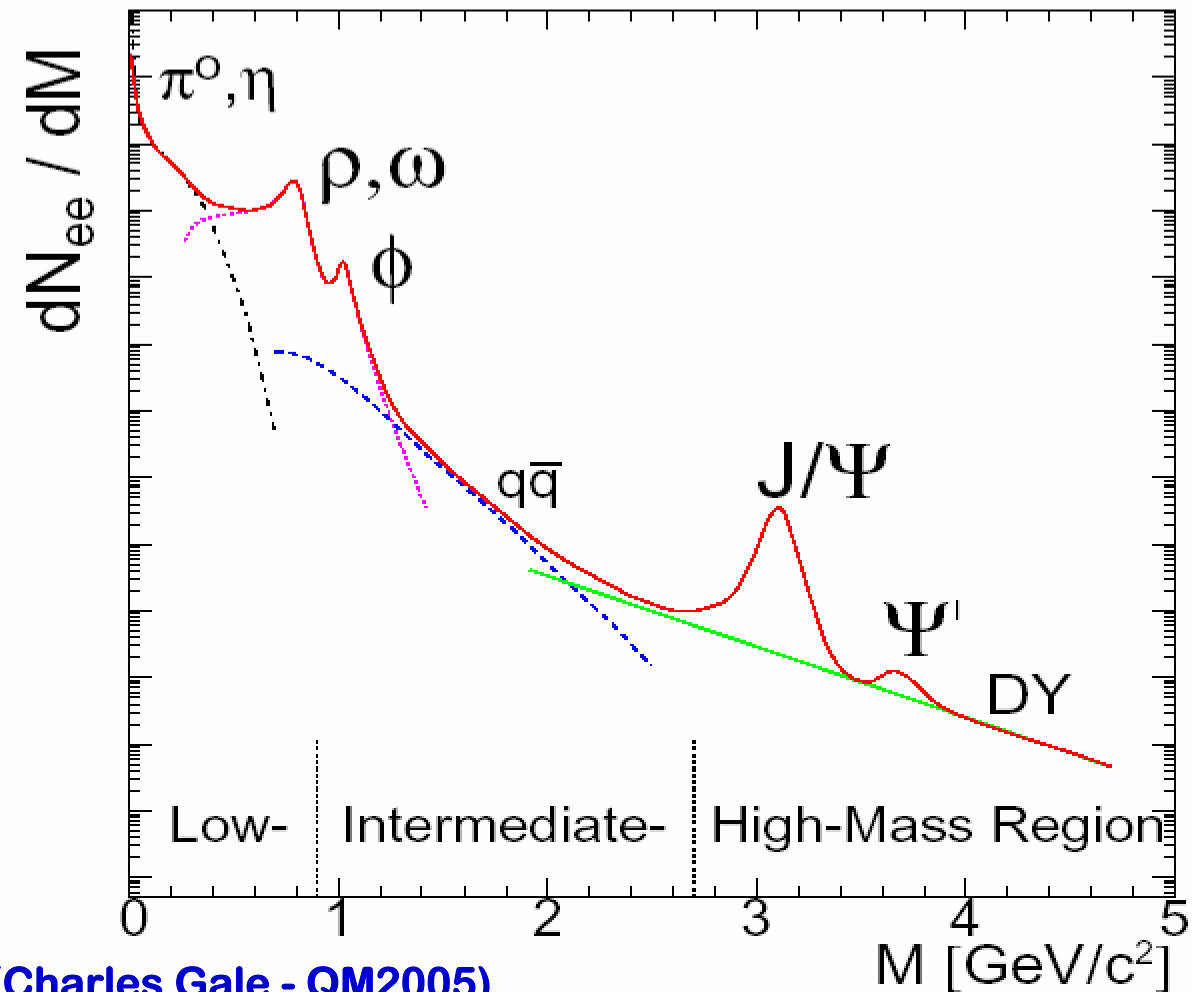
— But error bars are small and allow to go down to $p_T \approx$ 1GeV/c
→ 2 essential ingredients that will help make evident the yield in p_T range 1- 4 GeV/c over NLO pQCD

Then interpreted as emission from the medium → QGP?

L.E.Gordon and W. Vogelsan, PR D48, 3136 (93)

d'Enterria, D. Perresounko, nucl-th/0503054
2+1 hydro ; T_0=590 MeV ; τ_0=0.15 fm/c

3) Direct $\ell^+\ell^-$ pairs: what is expected

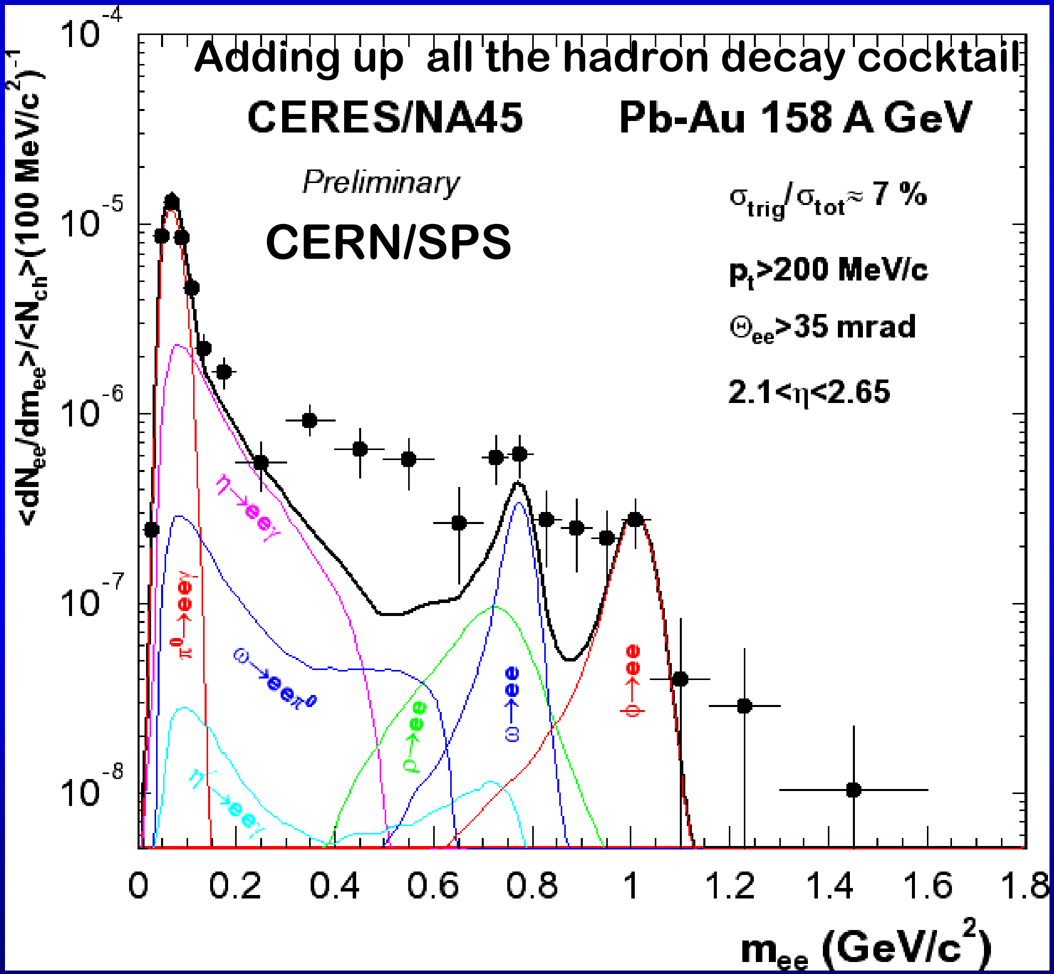


(Charles Gale - QM2005)

- **Low masses receive significant contribution from radiative decays**
- **High masses dominated by DY**
- **Intermediate mass region interesting from QGP perspective, $D\bar{D}$ [Shuryak (78), Shor (89)]**

CERES low-mass e^+e^- mass spectrum

Almost final results from the 2000 run Pb+Au at 158 GeV per nucleon



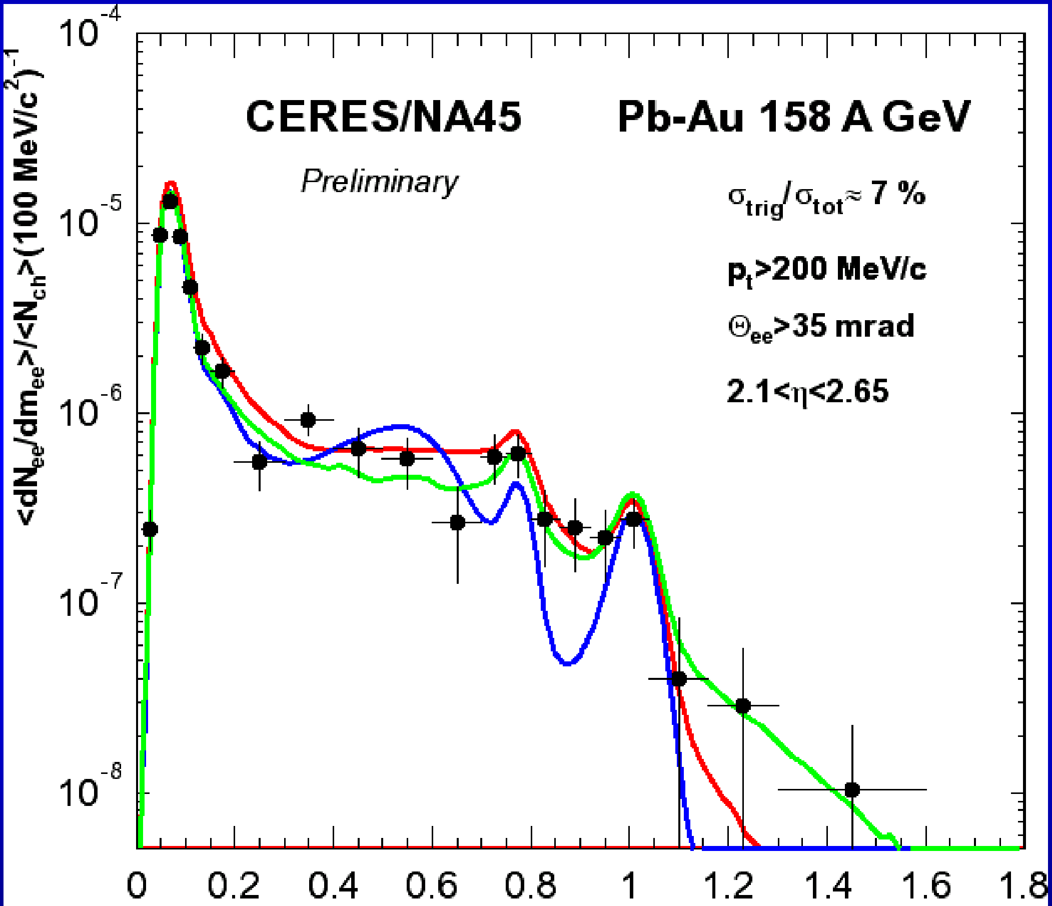
Clear enhancement over hadron decay cocktail for

m_{ee} > 0.2 GeV:
2.43±0.21 (stat)

0.2 GeV<m_{ee}< 0.6 GeV:
2.8±0.5 (stat)

(Itzhak Tserruya, QM2005)

Comparing e^+e^- mass spectrum models



(Sergey Yurevich, CERES)

calculation by R.Rapp , using Rapp/Wambach medium modification of rho spectral function

calculation by R.Rapp using Brown-Rho scaling

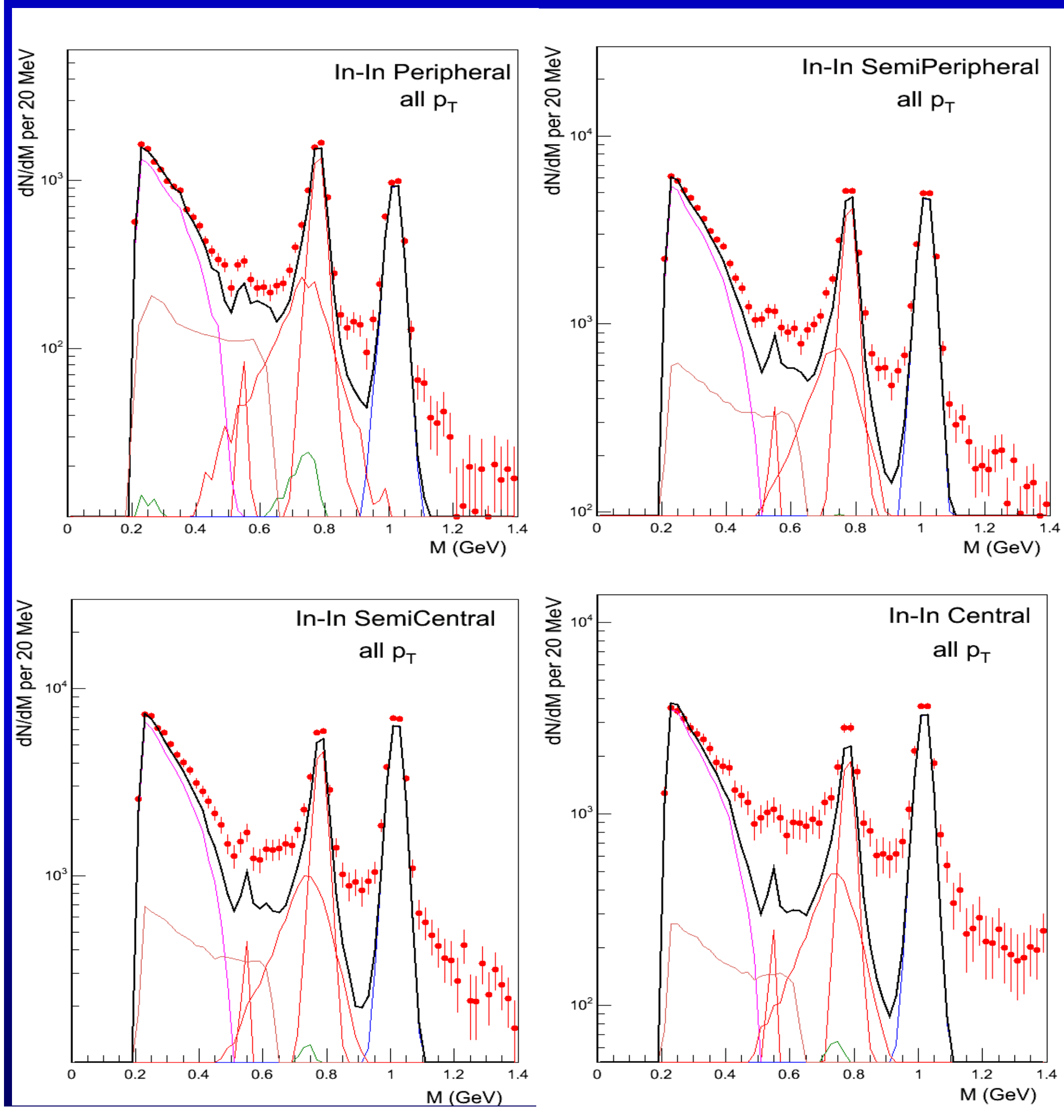
B. Kämpfer, calculation with thermal emission

(naturally, any of the above added to the cocktail)

(Charles Gale - QM2005)

NA60 Low-mass dimuons

NA60 data sum of all cocktail sources



— Clear excess of low mass with centrality

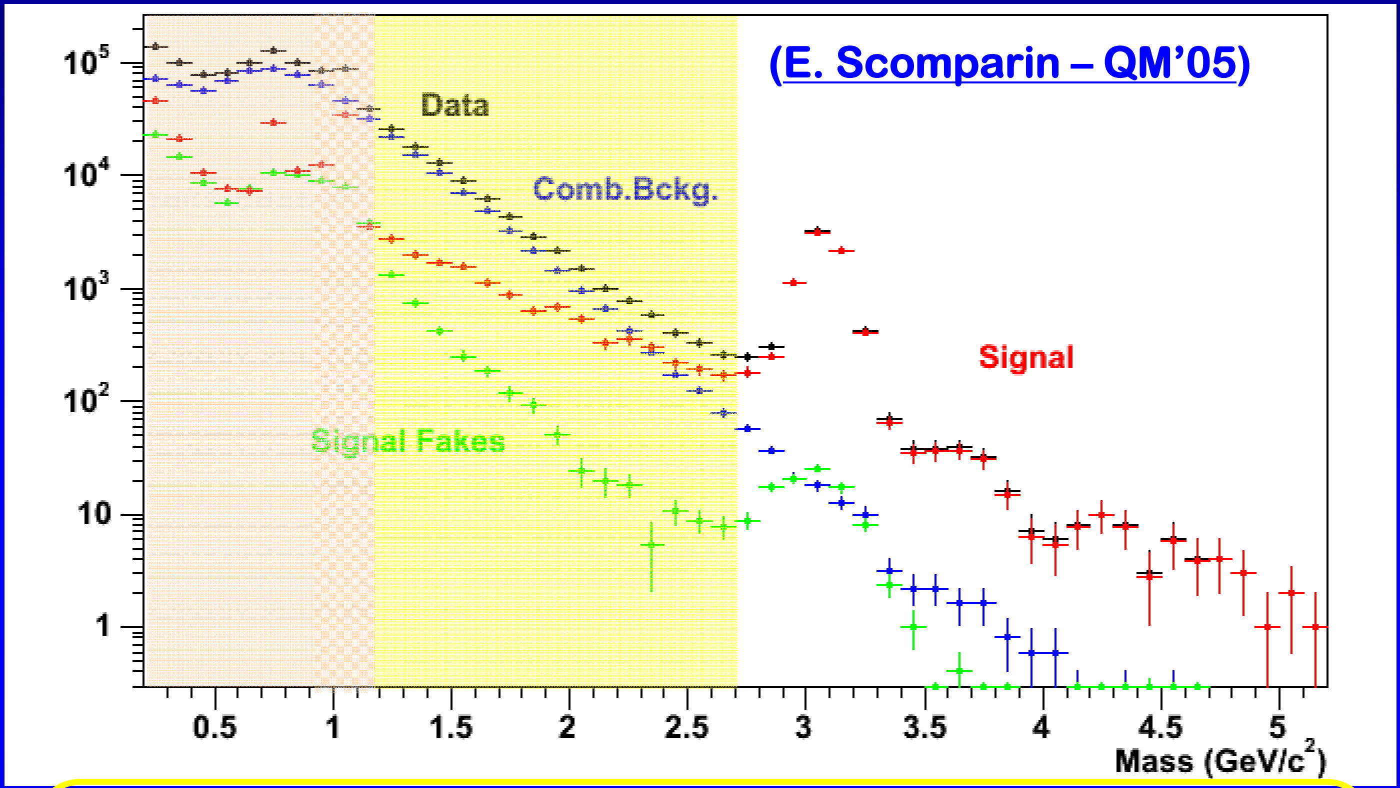
— confirms & is consistent with CERES

— rising with centrality

— more pronounced at low pT

(E. Scomparin – QM'05)

NA60: In-In @158 Gev/nucleon



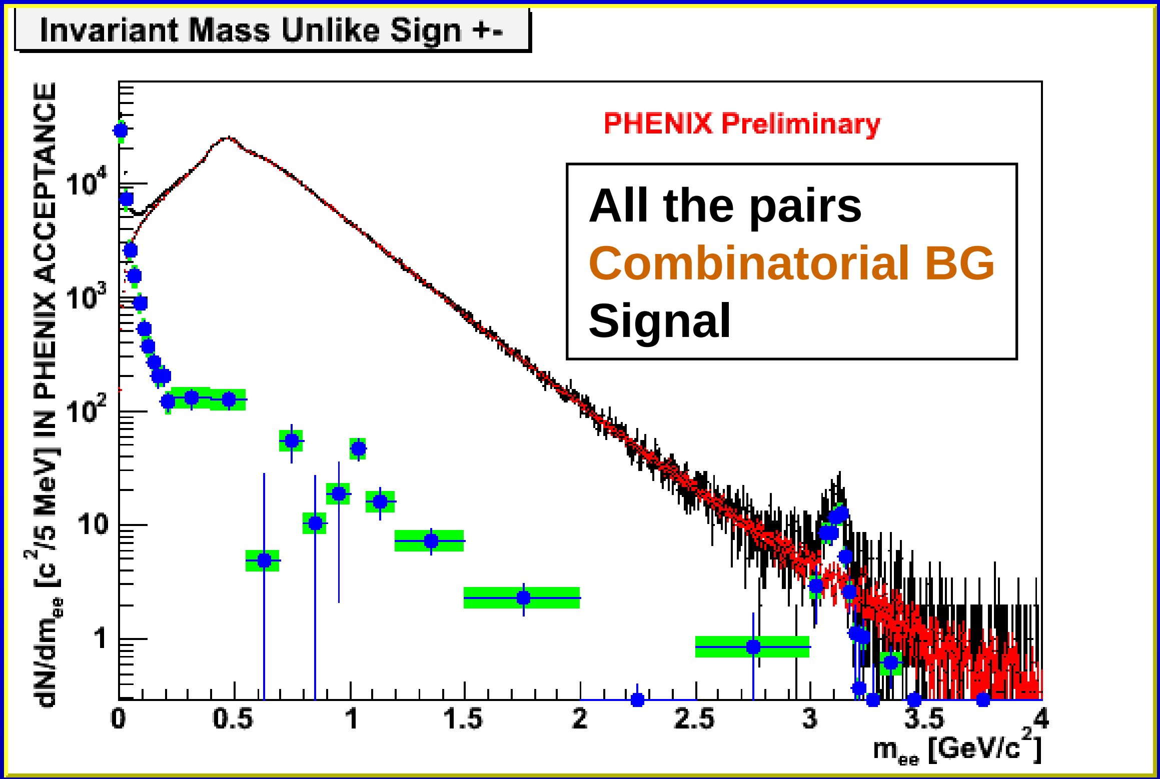
Low-mass region

- Lepton pair excess at SPS energies confirmed
- Mass shift of the intermediate ρ ruled out
- Broadening of the intermediate ρ describes data

Intermediate-mass region

- Enhancement of $\mu^+\mu^-$ yield confirmed
- Consistent with an enhanced prompt source
- Not consistent with an enhancement of open charm

Low-mass dileptons in PHENIX

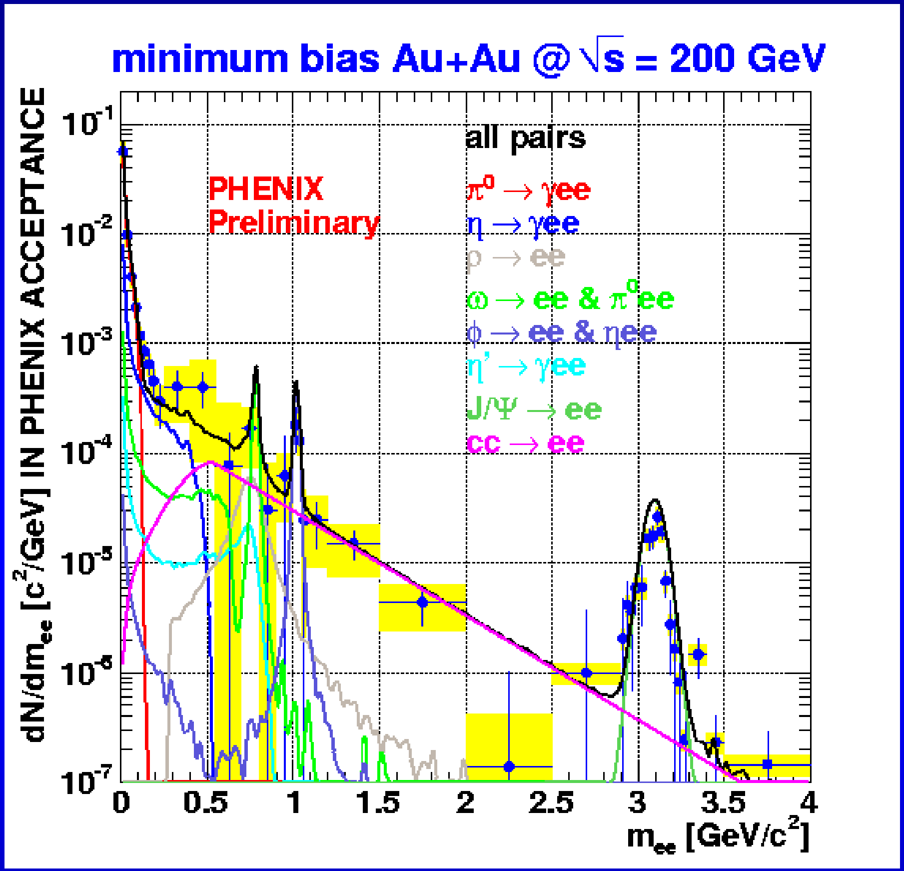


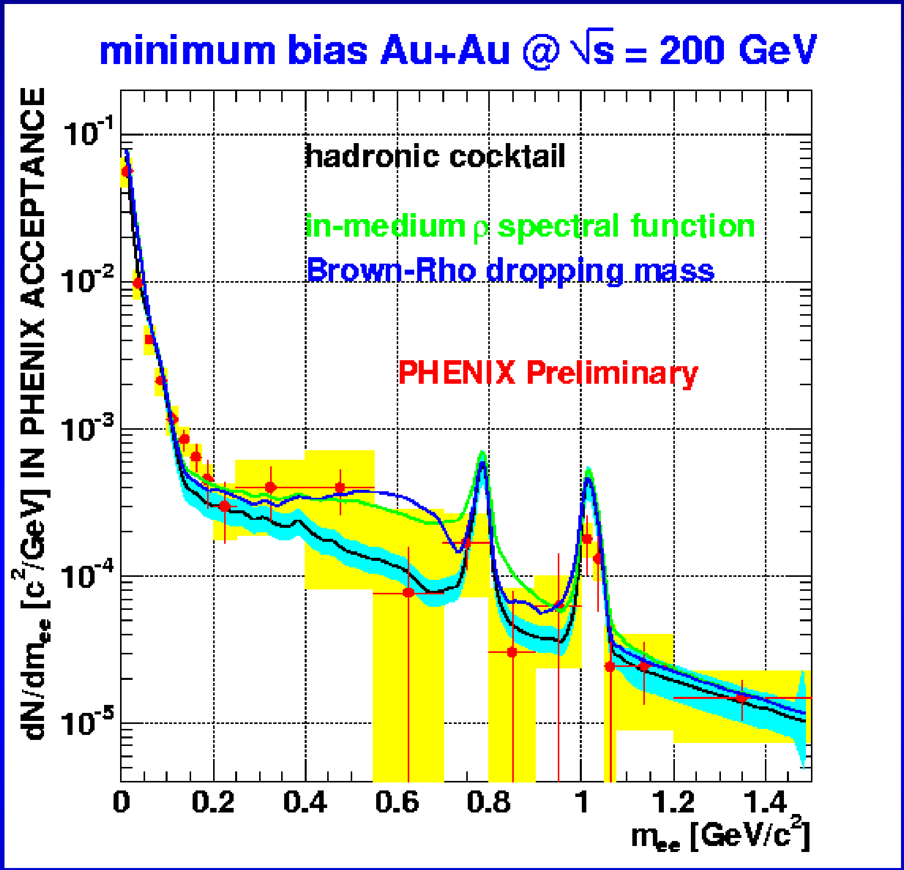
(Itzhak Tserruya, QM2005)

Integral:180,000
above p0:15,000

BG determined by event mixing technique, normalized to like sign yield

Comparison to cocktail and models



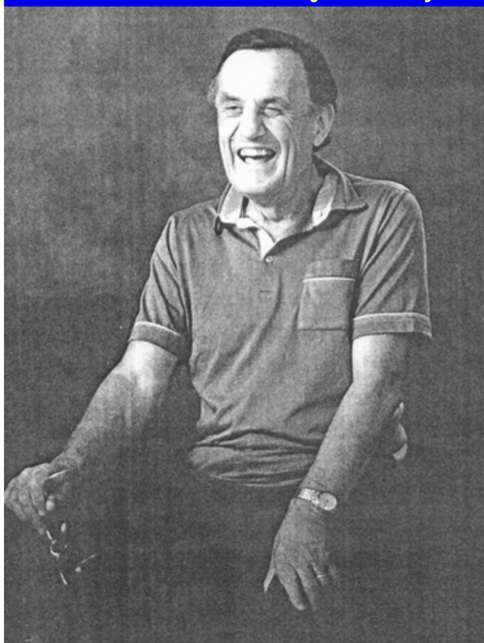


- Yellow band: total systematic error
- Horizontal bars =bin width

(Itzhak Tserruya, QM2005)

4) Hanbury Brown – Twiss (interferometry of identical particles)

- **HBT** → ingenius method conceived in the 1950's for measuring stellar radii in radio-astronomia (Cygnus & Cassiopea) and later in optical astronomy (Syrius)



R. Hanbury Brown
(1916-2002)

<u>1959</u> $\mapsto$ unexpected empirical observation by G. Goldhaber, S. Goldhaber, Lee & Pais: in $\bar{p}p$ collisions at $1.05\ GeV/c$, Bevatron (LBL) → search for $\rho^0 \to \pi^+\pi^-$, by looking into the mass-distribution of $\pi^+\pi^-$ and of $\pi^\pm\pi^\pm$ → correlation between identical π's!!

$$C(Q^2) = 1 + e^{Q^2 r^2}; Q^2 = -q^2 = -(k_1 - k_2)^2 = M_{12}^2 - (m_1 - m_2)^2$$

Simplest Example

Source space-time distribut.

$$f(x,p) = \rho(x)\ g(p)$$

$$\rho(x) \approx \exp[-x^2/(2R)^2]$$

↕

2-π Correlation Function

(simetrization ⇔ identical particles
+ source chaoticity ⇔ random phases)

$$C(k_1,k_2) = 1 \pm |\tilde{\rho}(q)|^2 = 1 \pm \exp(-q^2 R^2)$$

Fourier transform of the source distribution

R= radius of emitting source

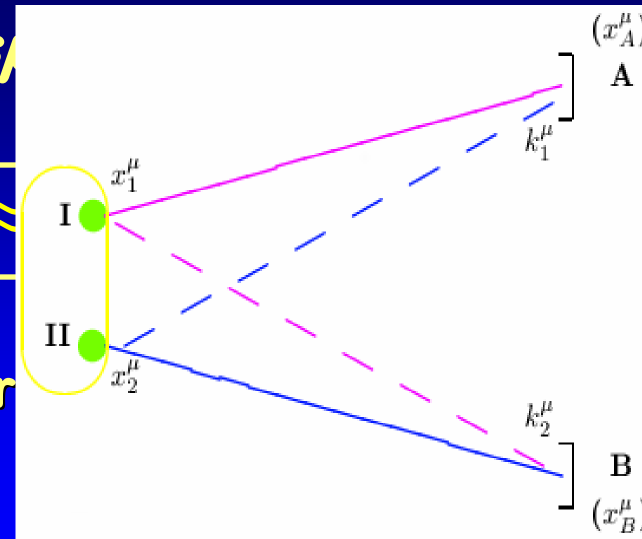
$$q^\mu = k_1^\mu - k_2^\mu$$

(simetrization without FSI)

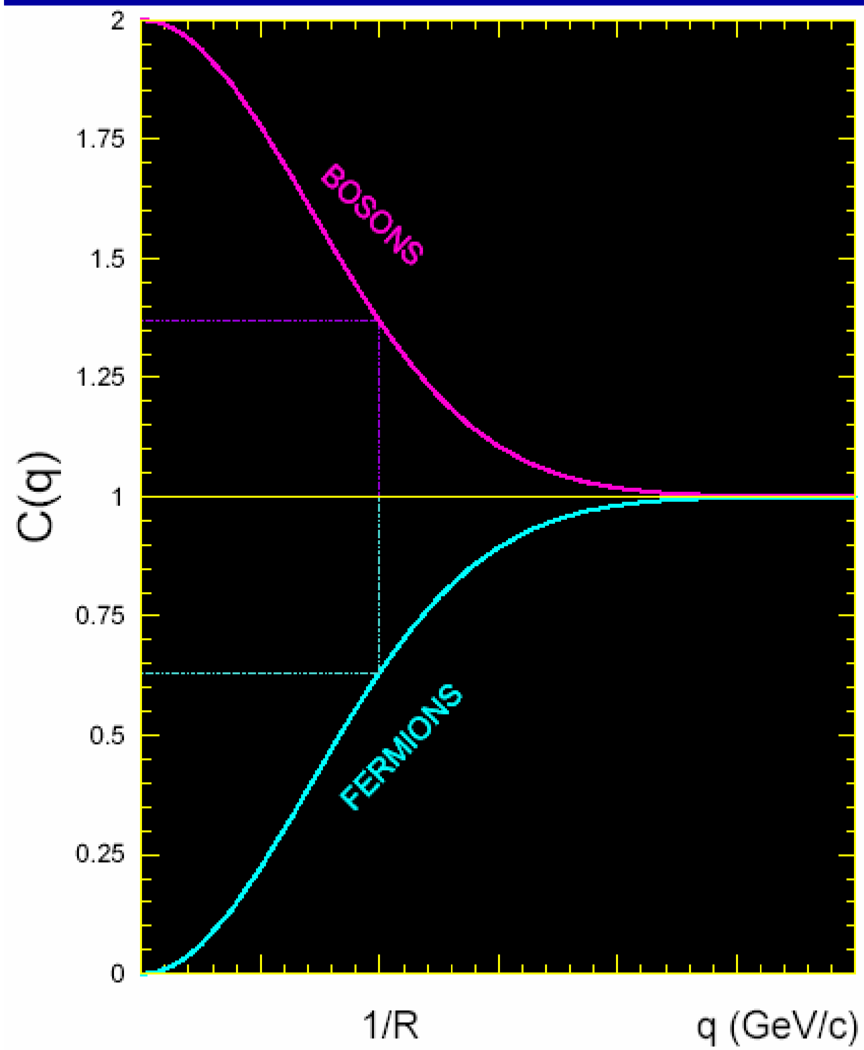
Simplest Example

Source s

$\rho(x) \approx$



2-π Cor



(simetrization

+ source chaoticity ⇔ random phases)

$$C(k_1,k_2) = 1 \pm |\tilde{\rho}(q)|^2 = 1 \pm \exp(-q^2R^2)$$

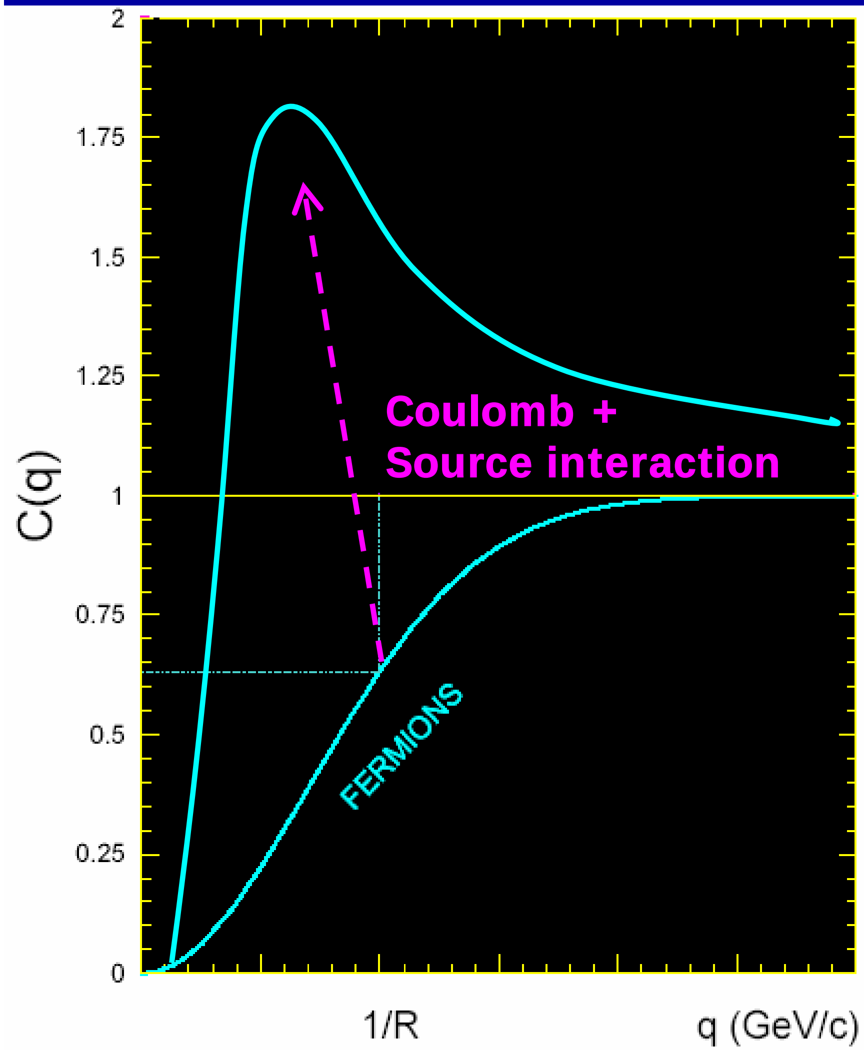
Fourier transform of the source distribution

R= radius of emitting source

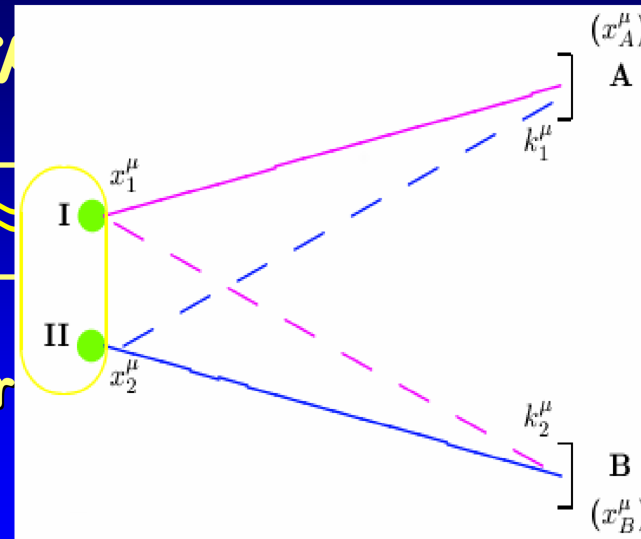
$$q^\mu = k_1^\mu - k_2^\mu$$

(simetrization without FSI)

Simplest Example



Source s



$\rho(x) \approx$

2-π Cor

(simetrization

+ source chaoticity ⇔ random phases)

$$C(k_1,k_2) = 1 \pm |\tilde{\rho}(q)|^2 = 1 \pm \exp(-q^2 R^2)$$

Fourier transform of the source distribution

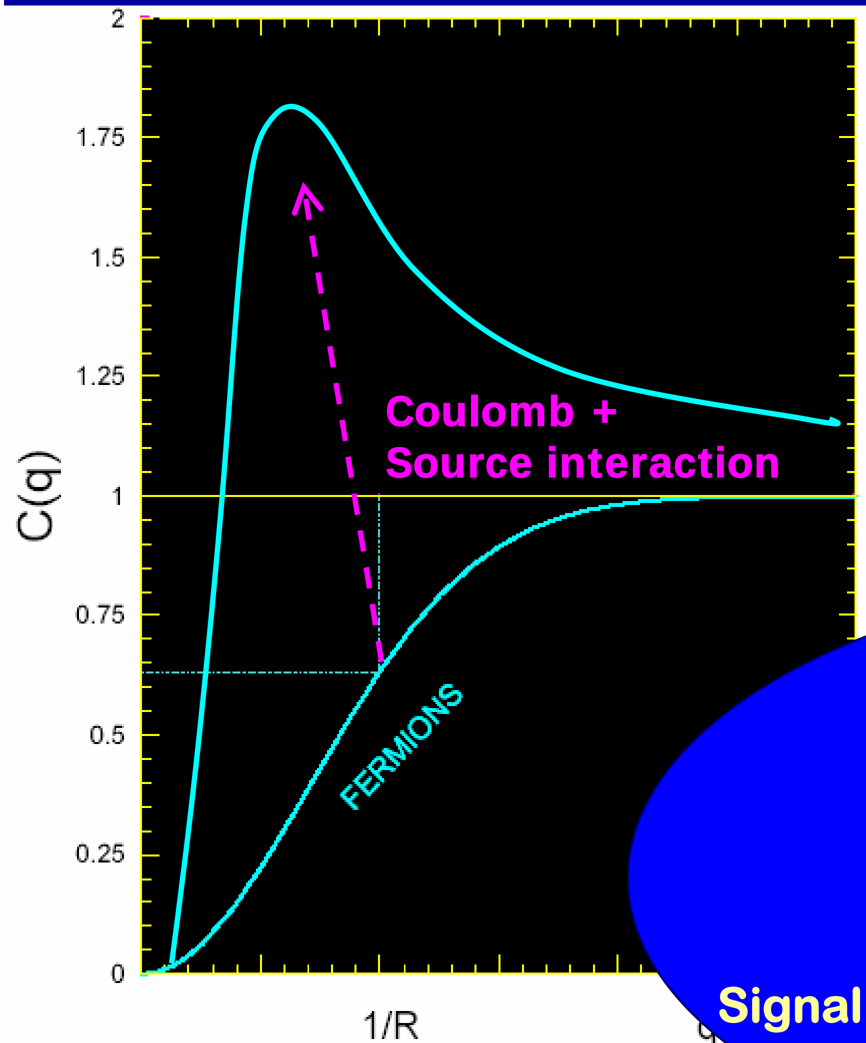
R= radius of emitting source

$$q^\mu = k_1^\mu - k_2^\mu$$

← ferminic case: including interaction

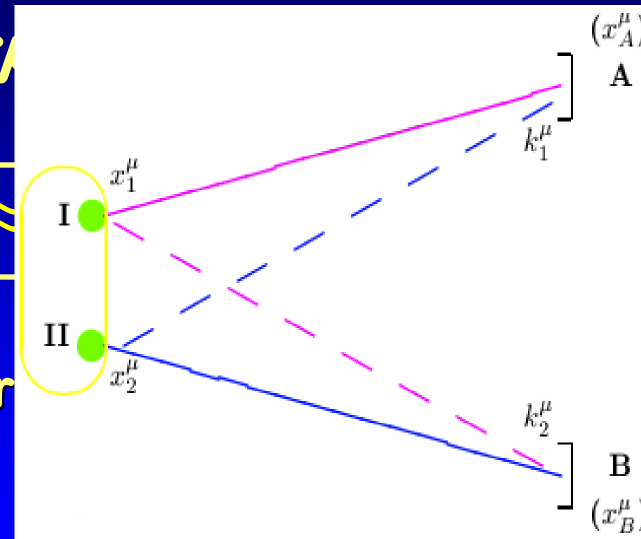
Simplest Example

Source s



$\rho(x) \approx$

2-π Cor



(simetrization

+ source chaoticity ⇔ random phases)

$$C(k_1,k_2) = 1 \pm |\tilde{\rho}(q)|^2 = 1 \pm \exp(-q^2R^2)$$

ius of

Experimantal definition of the Correlation Function

$$C(k_1,k_2) = \frac{A(q)}{B(q)}$$

Signal (particles from same event)

Background (particles from ≠ events)

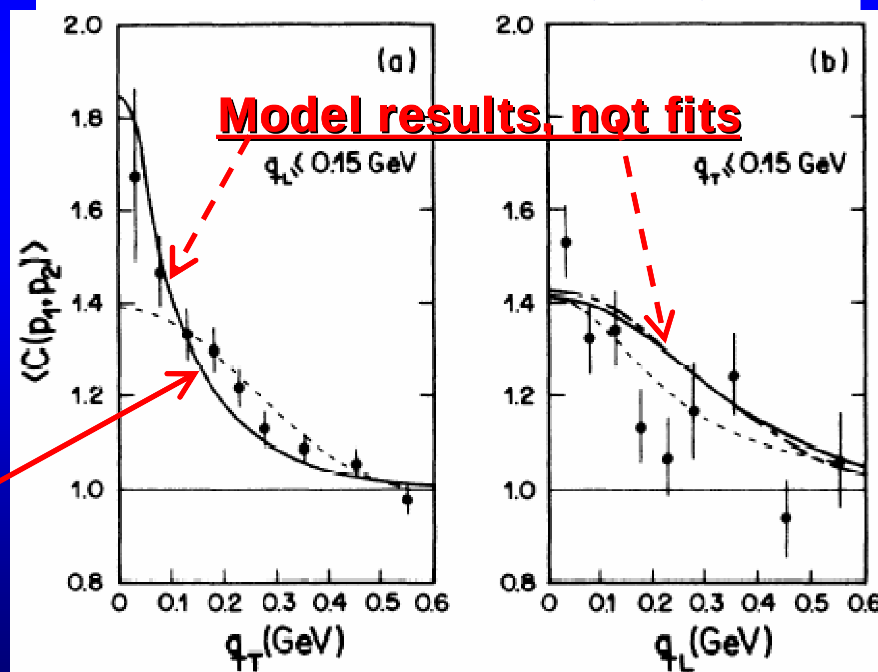
(simetrization without FSI)

First Contact

Main hypotheses:

- **QGP formation ⊕ 1st order phase-transition**
- **Expanding system (1-D hydrodynamics)**

[Y. Hama & SSP, P.R.D 37(1988) 3237]

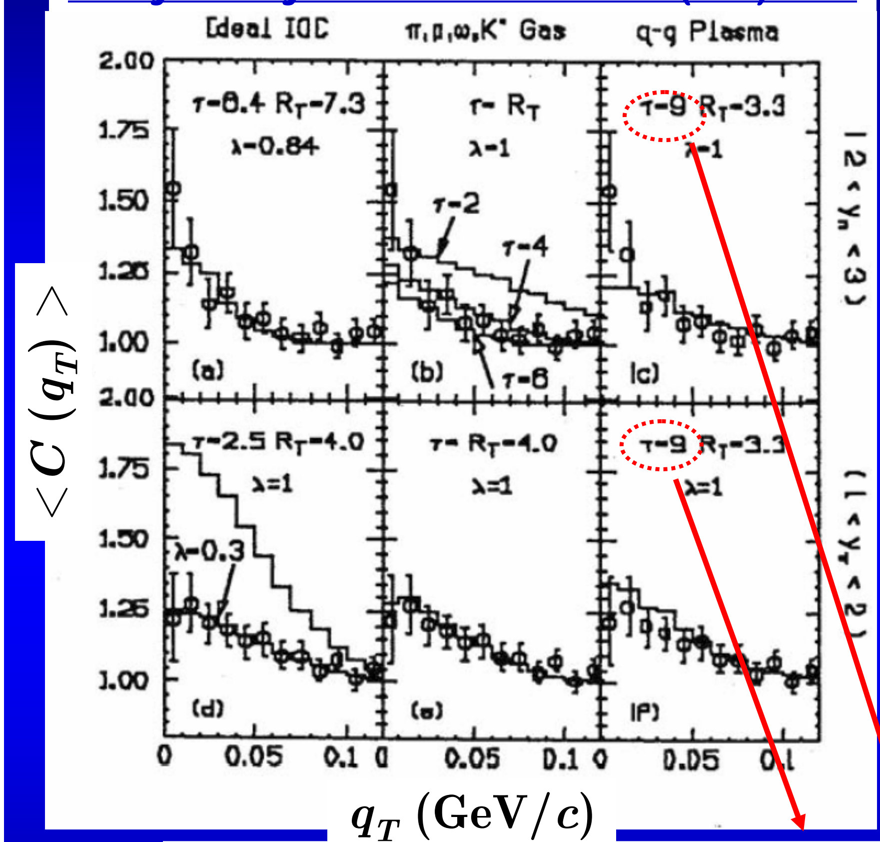


➡ Comparison with exp. Data on pp & $\bar{p}p$ collisions - CERN/ISR ($\sqrt{s}$=53 GeV)

* **Sole model able of describing data trend: evidencing expansion effects (clear non-Gaussin behavior)**

Testing CERN/NA35 vs. (non) ideal IOC

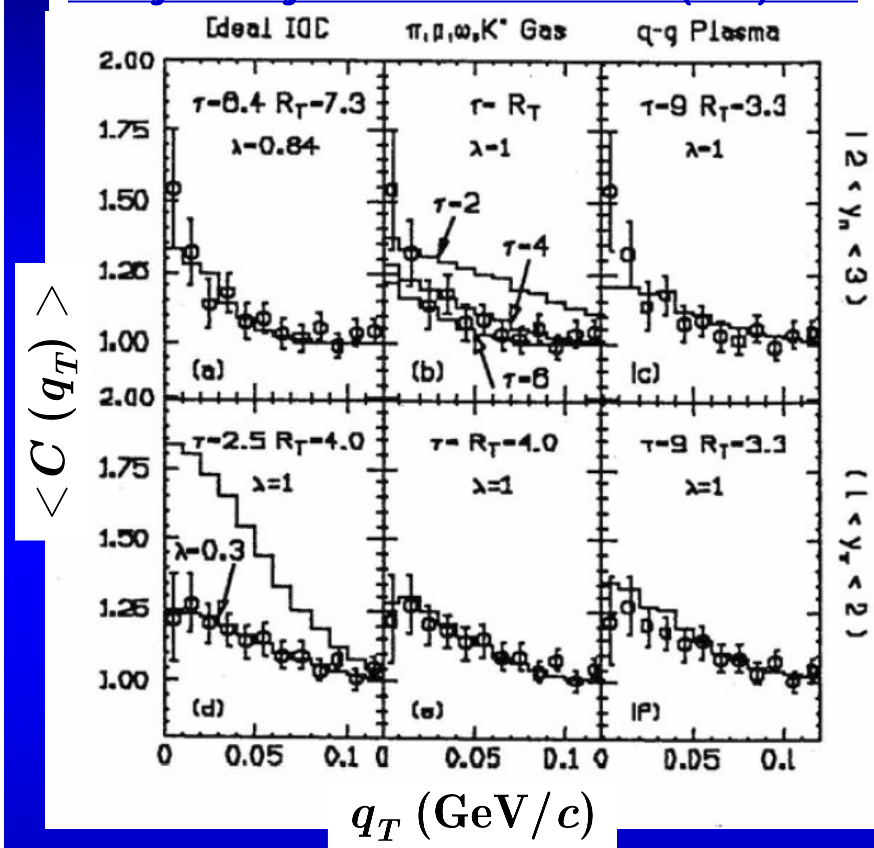
M.Gyulassy & SSP: P.L. B217 ('89) 181

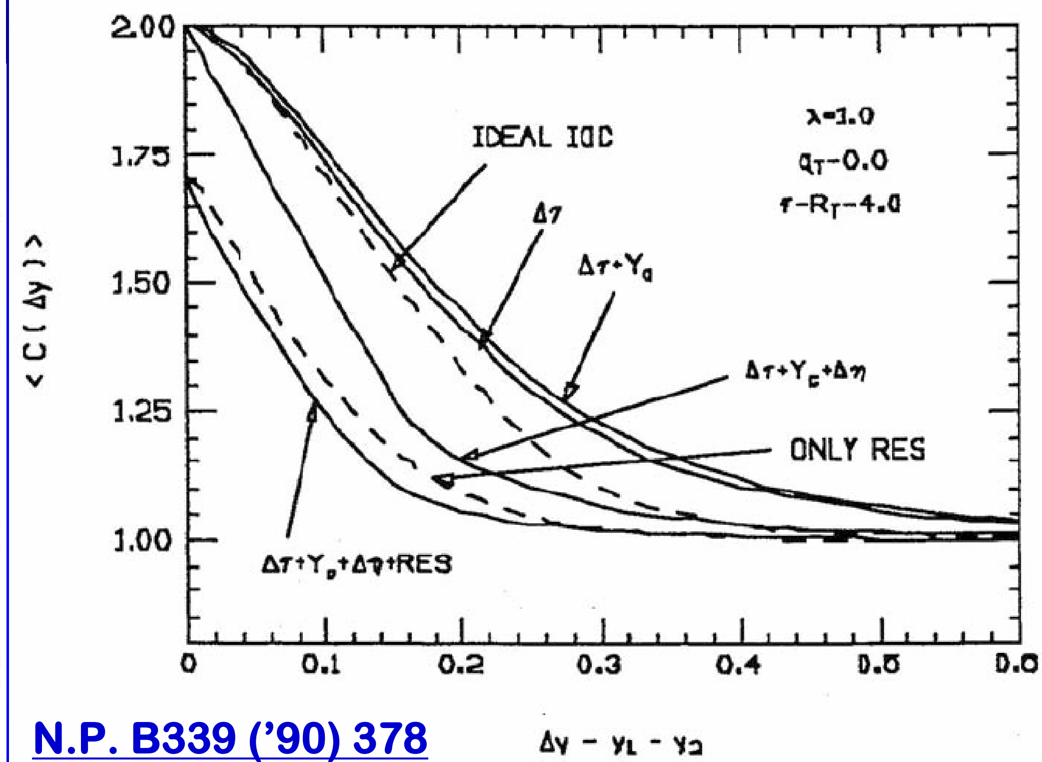


Large proper-times expected for QGP scenario

Testing CERN/NA35 vs. (non) ideal IOC

M.Gyulassy & SSP: P.L. B217 ('89) 181





N.P. B339 ('90) 378

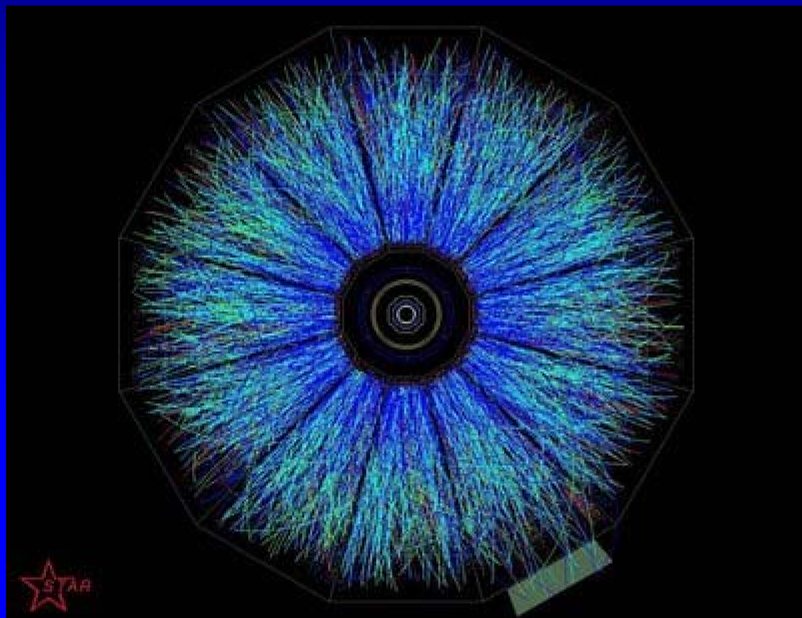
- 3 distinct scenarios:
  - Ideal IOC but $\lambda < 1$
  - Non-ideal + resonances
  - Quasi-ideal & QGP

Equivalently good description of data

- Correlation function reflects geometrical and dynamical effects
  - Resonances:

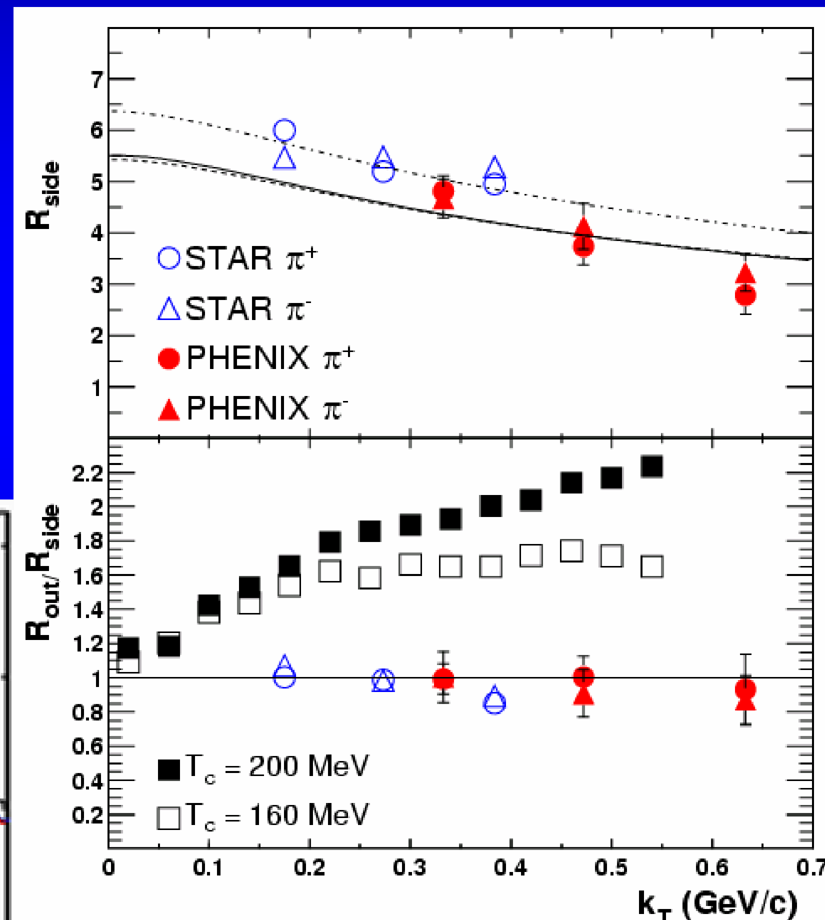
    $f_{\pi/r} \rightarrow r = \pi, \rho, \omega, K, \eta, \eta$"
  - Fluctuations in (emission) times
  - $< x_\perp . p_\perp >$ (transversal "flow"), ...

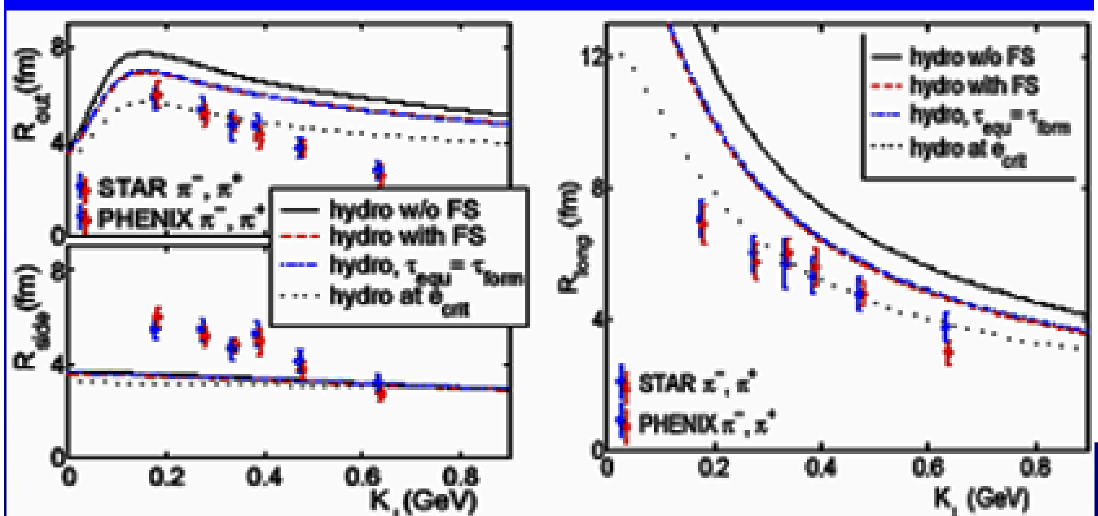
HBT → RHIC puzzle



Hydro+uRQMD

Soff, Bass et al. NPA 715 (03) 801



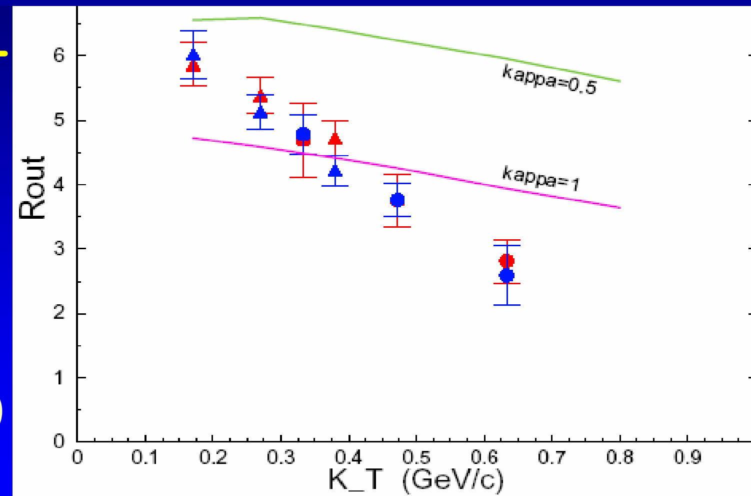


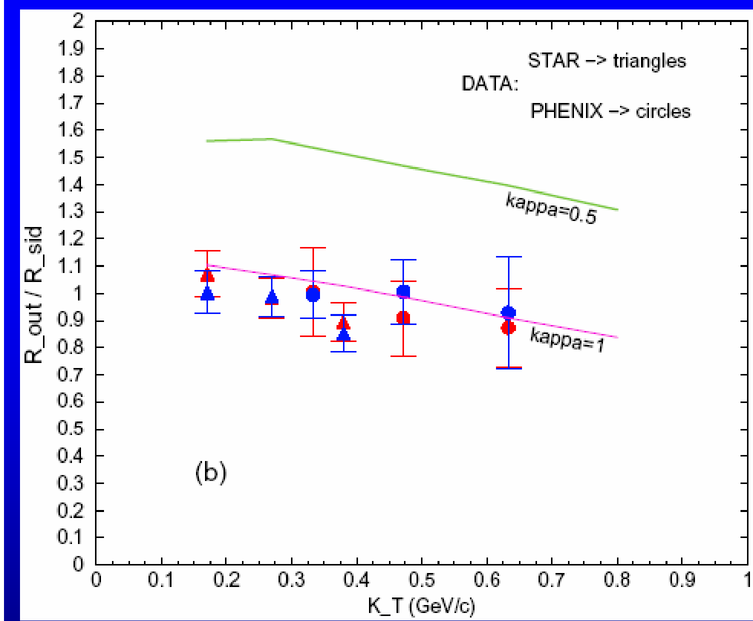
(best results require freeze-out at hadronization point ↓)

First tentative explanations

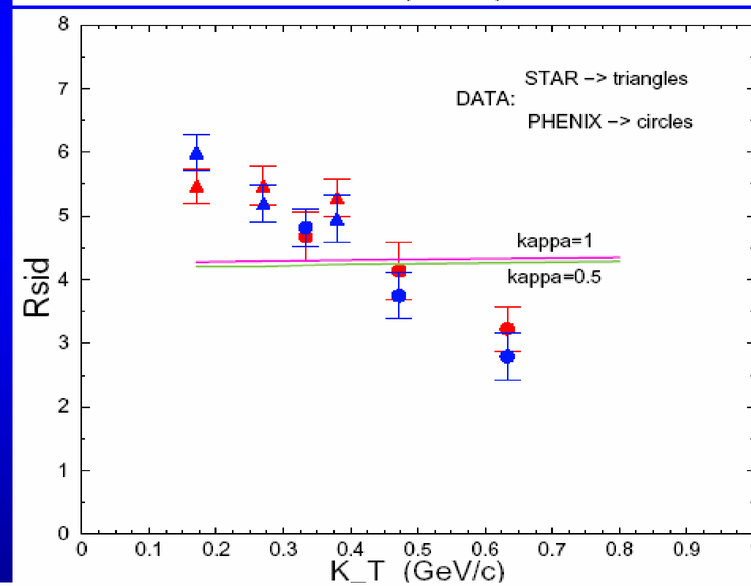
L.McLerran & SSP → opaque source ⊕ black-body radiation w/emissivity $\mathcal{K}$ (π's only) ⊕

- QGP formed in initial state @ RHIC
- Ideal Bjorken Hydrodyn. (1+1) (no ⊥ flow)
- PhaseTransition starts: τ_c (T_c); ends τ_h (T_c)
- Hadrons expands further, untill τ_f (T_f)
- At T_f → sistema desacopla-se (emissão vol.)





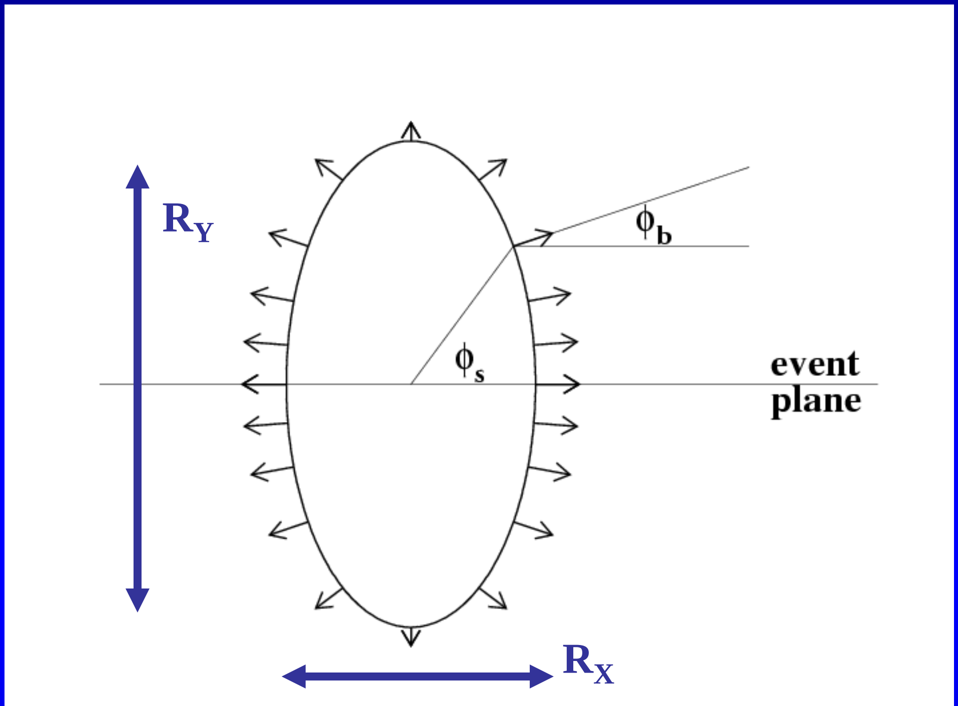
$T_0 \approx 411$ MeV
$T_c = 175$ MeV
$T_f = 150$ MeV



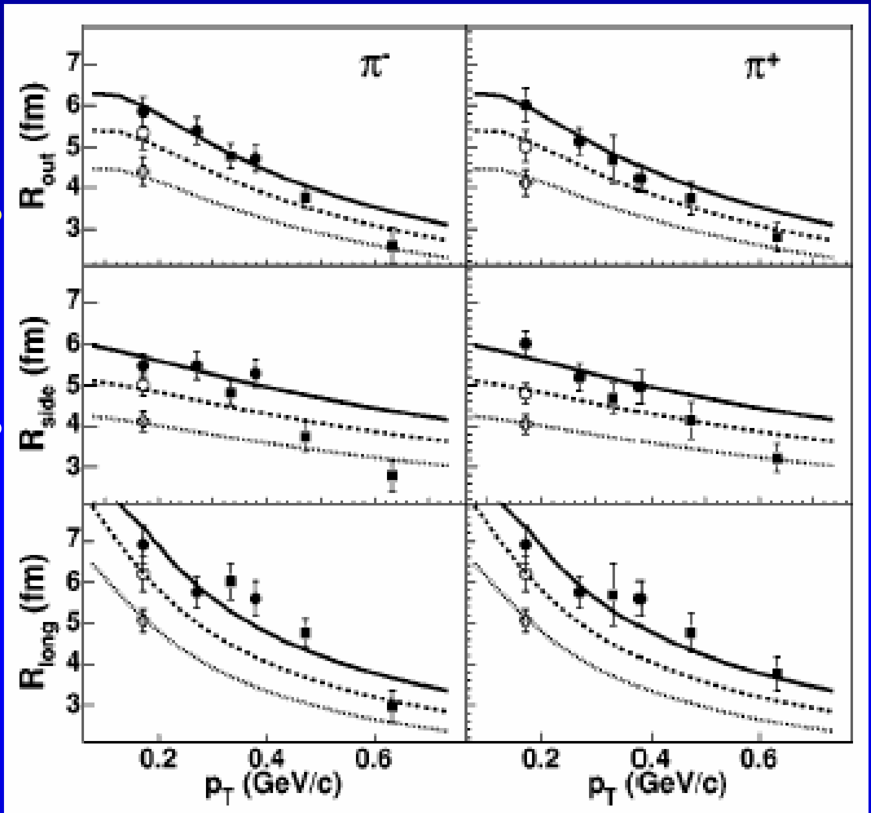
$\mathcal{K}$ calc $\approx 4\ \mathcal{K}_{\text{blackbody}}$
Requires ⊥ flow (?)

κ	τ_0 (fm/c)	τ_c (fm/c)	τ_h (fm/c)	τ_f (fm/c)	$\mathcal{S}/\mathcal{N}$ ($\tau_0 \le \tau \le \tau_f$)	$\mathcal{V}/\mathcal{N}$ (at τ_f)
1	0.160	1.54	5.73	6.97	0.844	0.156
0.5	0.160	1.75	8.37	10.5	0.758	0.242

Blast wave model



[F. Retière & M.A Lisa PRC 70 044907 (2004)]



$$
\begin{aligned}
S(x,p)\,d^4x &= \frac{1}{(2\pi)^3}\, m_\perp \cosh(y-\eta)\, \exp\left(-\frac{p_\mu u^\mu - \mu}{T}\right)\, \theta(R_B - r) \\
& \quad \frac{1}{\sqrt{2\pi\Delta\tau^2}}\, \exp\left(-\frac{(\tau-\tau_0)^2}{2\Delta\tau^2}\right)\, \tau\, d\tau\, d\eta\, r\, dr\, d\phi\,, \\
u^\mu &= (\cosh\eta_t \cosh\eta,\ \sinh\eta_t \cos\phi,\ \sinh\eta_t \sin\phi,\ \cosh\eta_t \sinh\eta) \\
\eta_t &= \sqrt{2}\,\eta_f\, \frac{r}{R_B}\,.
\end{aligned}
$$

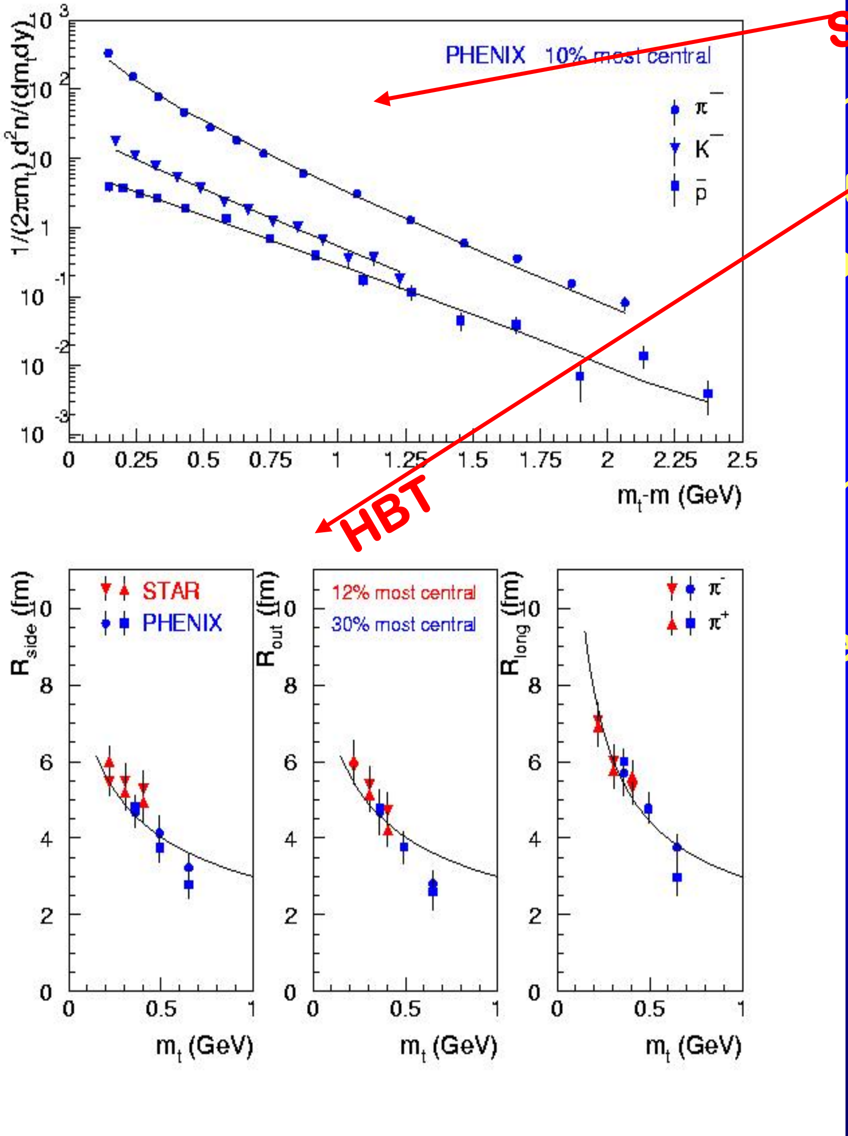
Buda-Lund Model

- Separation of the emission source core and the halo
- Core: hydrodynamic evolution
- Halo: decay products of long-lived resonances

- Analytic expressions for all the observables
- 3-D expansion, local thermal equilibrium, symmetry
- Recovers known hydro solutions in non-relativistic limit
  (implies density inhomogeneity !)

Buda-Lund Model

T. Csörgö & B. Lorstad



B-L fit to Phenix and Star data

n source core and the halo

BL-H source parameters	Fit I.		Fit II.	
T_0 [MeV]	174	$\pm$ 12	140	fixed
$\langle u_t \rangle$	1.03	$\pm$ 0.14	0.98	$\pm$ 0.14
R_G [fm]	9.3	$\pm$ 1.0	9.2	$\pm$ 1.0
τ_0 [fm/c]	6.7	$\pm$ 0.3	7.6	$\pm$ 0.2
$\Delta\tau$ [fm/c]	0.2	$\pm$ 2.8	0.1	$\pm$ 1.4
$\Delta\eta$	2.5	fixed	2.5	fixed
$\langle \Delta T/T \rangle_r$	0.46	$\pm$ 0.16	0.17	$\pm$ 0.06
$\langle \Delta T/T \rangle_t$	3.0	$\pm$ 0.9	1.0	$\pm$ 0.2
μ_0^{π} [MeV]	0	fixed	0	fixed
μ_0^{K} [MeV]	50	$\pm$ 16	76	$\pm$ 9
μ_0^{p} [MeV]	391	$\pm$ 35	422	$\pm$ 12
χ^2/NDF	84/69=1.22		100/70=1.43	
CL	11.3%		1.1%	

Hydrodynamics

- Initial interactions among the constituents should be strong to fulfill requirement of matter in local thermal equilibrium
- Needs IC + (QCD) EoS →

$$\partial_\mu T^{\mu\nu} = \partial_\mu \{u^\mu u^\nu [\varepsilon(T) + p(T)] - g^{\mu\nu} p(T)\} = 0$$

- Hydrodynamical model works nicely at RHIC:
- Great surprise: strongly coupled QGP but which behaves almost as a perfect fluid (although the viscosity behaves smoothly near T_c) → sQGP (T. D. Lee)
- Best description so far seems to be Hydrodynamics of QGP coupled to microscopic evolution of the HG

Hydrodynamics

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- Needs IC + (QCD) EoS →

$$\partial_\mu T^{\mu\nu} = \partial_\mu\{u^\mu u^\nu[\varepsilon(T) + p(T)] - g^{\mu\nu} p(T)\} = 0$$

- Hydrody
- Great su n behaves almost a behaves smoothl
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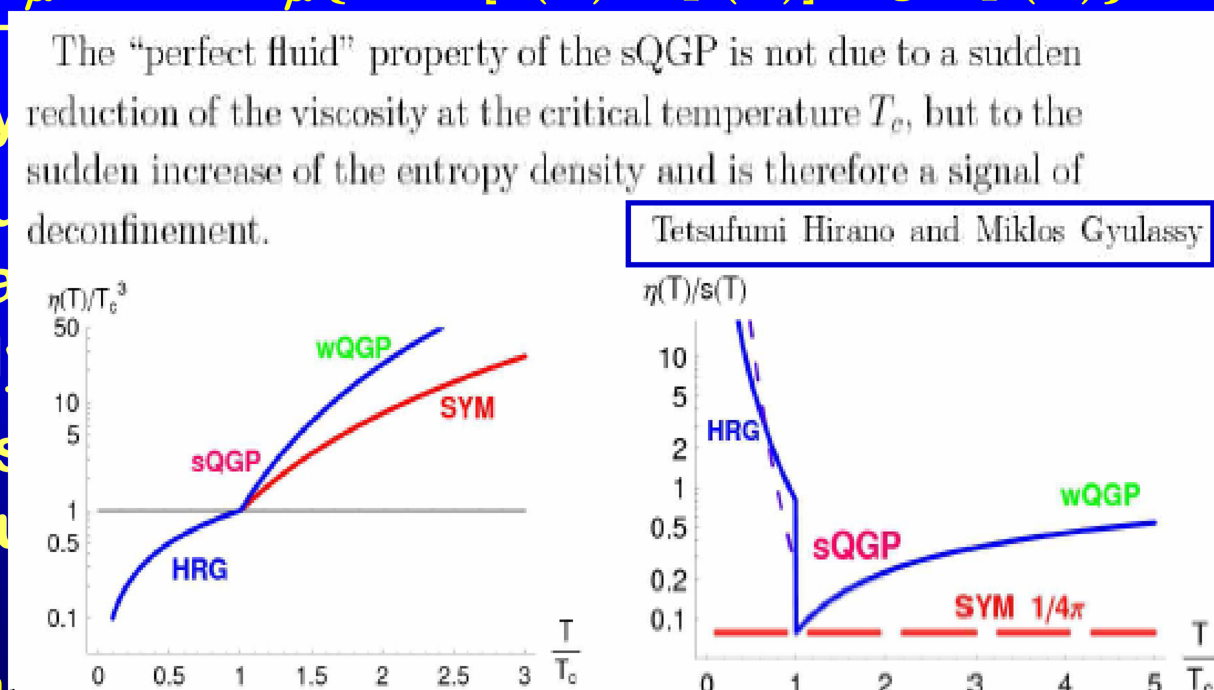
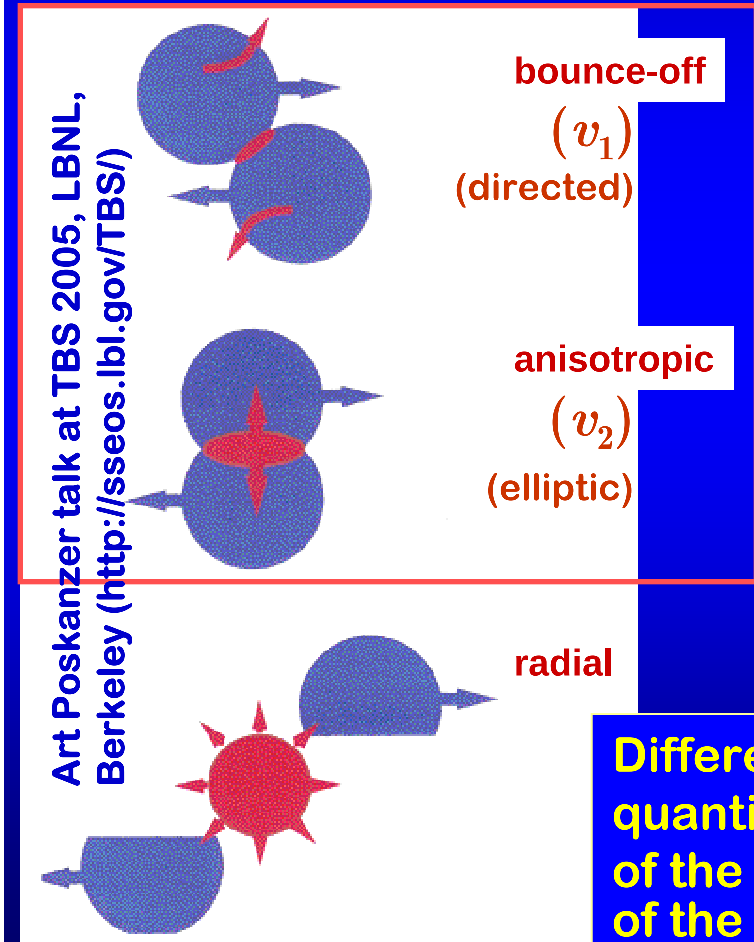
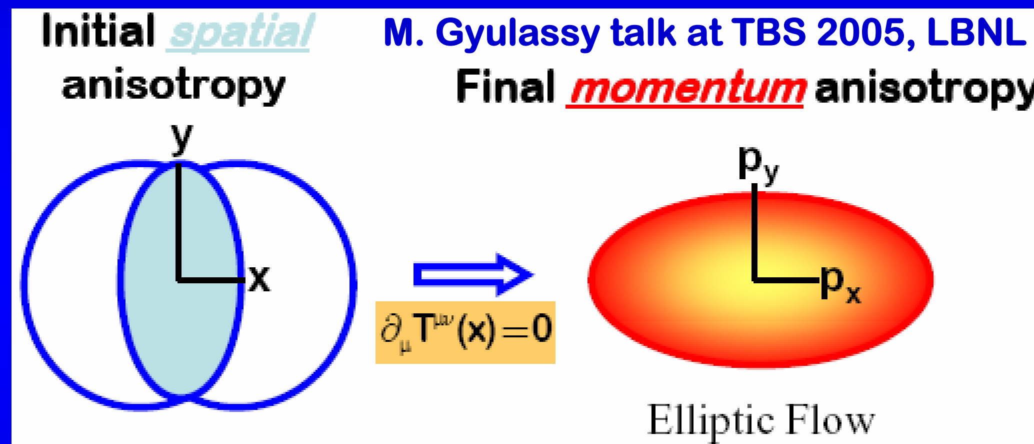

The "perfect fluid" property of the sQGP is not due to a sudden reduction of the viscosity at the critical temperature T_c, but to the sudden increase of the entropy density and is therefore a signal of deconfinement.

Tetsufumi Hirano and Miklos Gyulassy

Flow ↔ collective dynamics

- A collective flow is a motion characterized by space-momentum correlations of dynamical origin → 2 signatures:

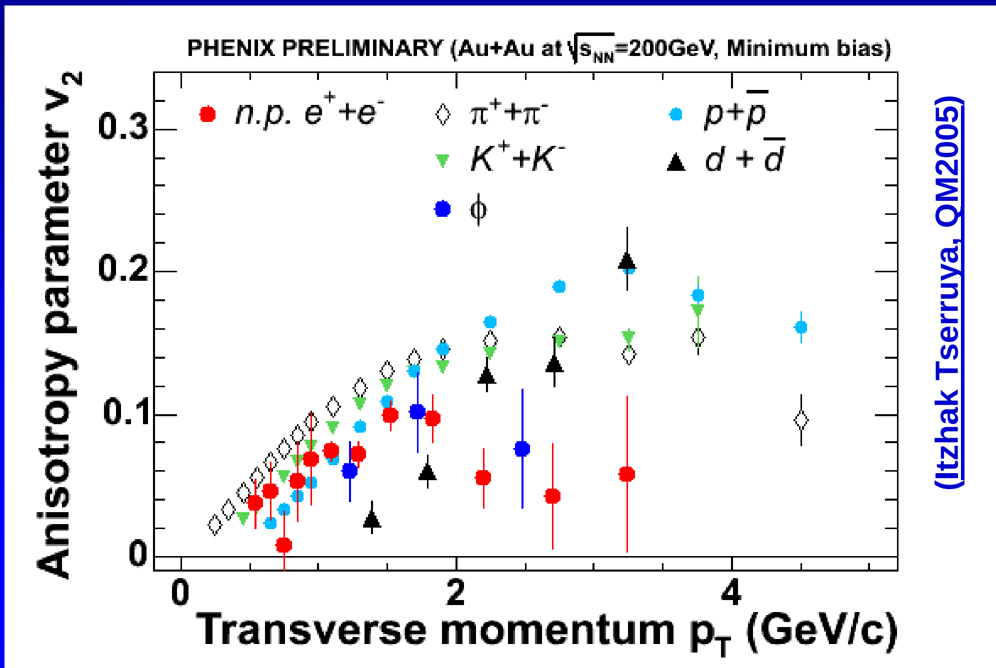




$$\frac{dN_h(N_p)}{dy\,dp_T^2\,d\phi} = \frac{dN_h(N_p)}{dy\,dp_T^2}\,\frac{1}{2\pi} \times \left(1 + 2v_1(y, p_T, N_p, h)\cos\phi + 2v_2(y, p_T, N_p, h)\cos 2\phi + \cdots\right)$$

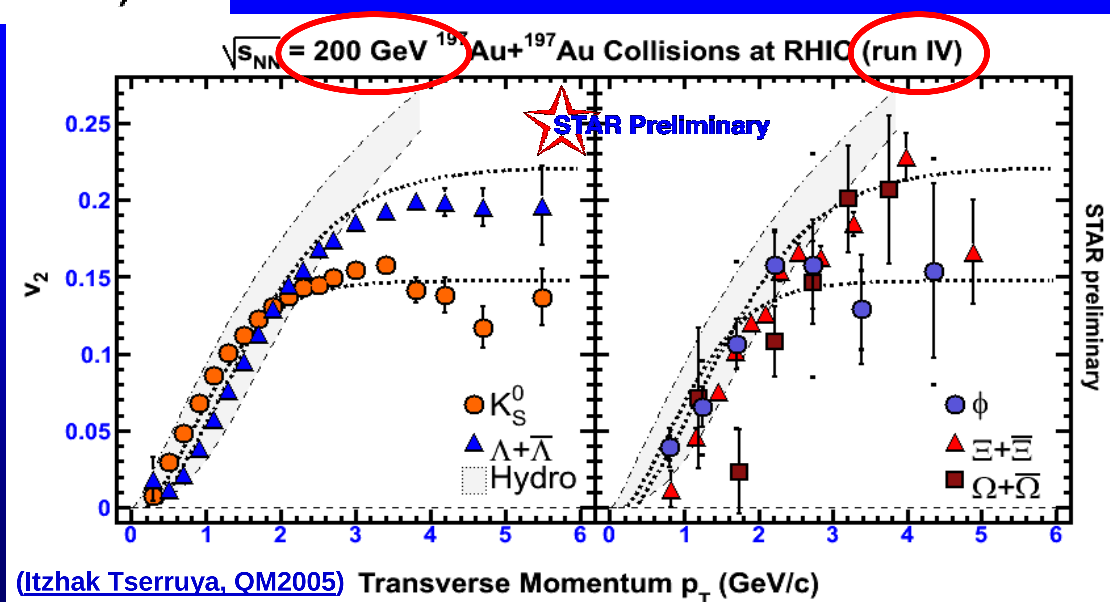
Different type of collective flows → conveniently quantified in terms of first few (2) Fourier components of the azimuthal angle (i.e., angle aroundthe beam axis of the collision): v_1, v_2, …

Every particle flows



- Large v_2 of heavier particles: ϕ, Ξ, Ω, d.
- Even open charm flows (measured through single electrons)
- Strong interactions at early stage → early thermalization

Miklos Gyulassy says: " … The QCD fingerprint at RHIC → conclusive evidence for long wavelength flow with unique fine structure v_2 consistent with P_{QPG} …"



Sandra S. Padula

Jet quenching

Color Glass Condensate

Cu+Cu vs. Au+Au

•
•
•

Theory side: $\phi\phi$ Back-to-Back Correlations (in-medium mass-shift and squeezed states)

Important references on RHIC data

- Since the beginning of RHIC's operation → about 90 published experimental papers
- Quark Matter Proceedings (2000, 2002, 2004 and 2005)
- Rikken/BNL workshop (2004) →
  Nuclear Physics A 750 (2005)
- "Hunting the Quark-Gluon Plasma", assessments by the experimental collab.,
  BNL-73847-2005 Formal Report