High Energy Heavy Ion Collisions at the CERN SPS

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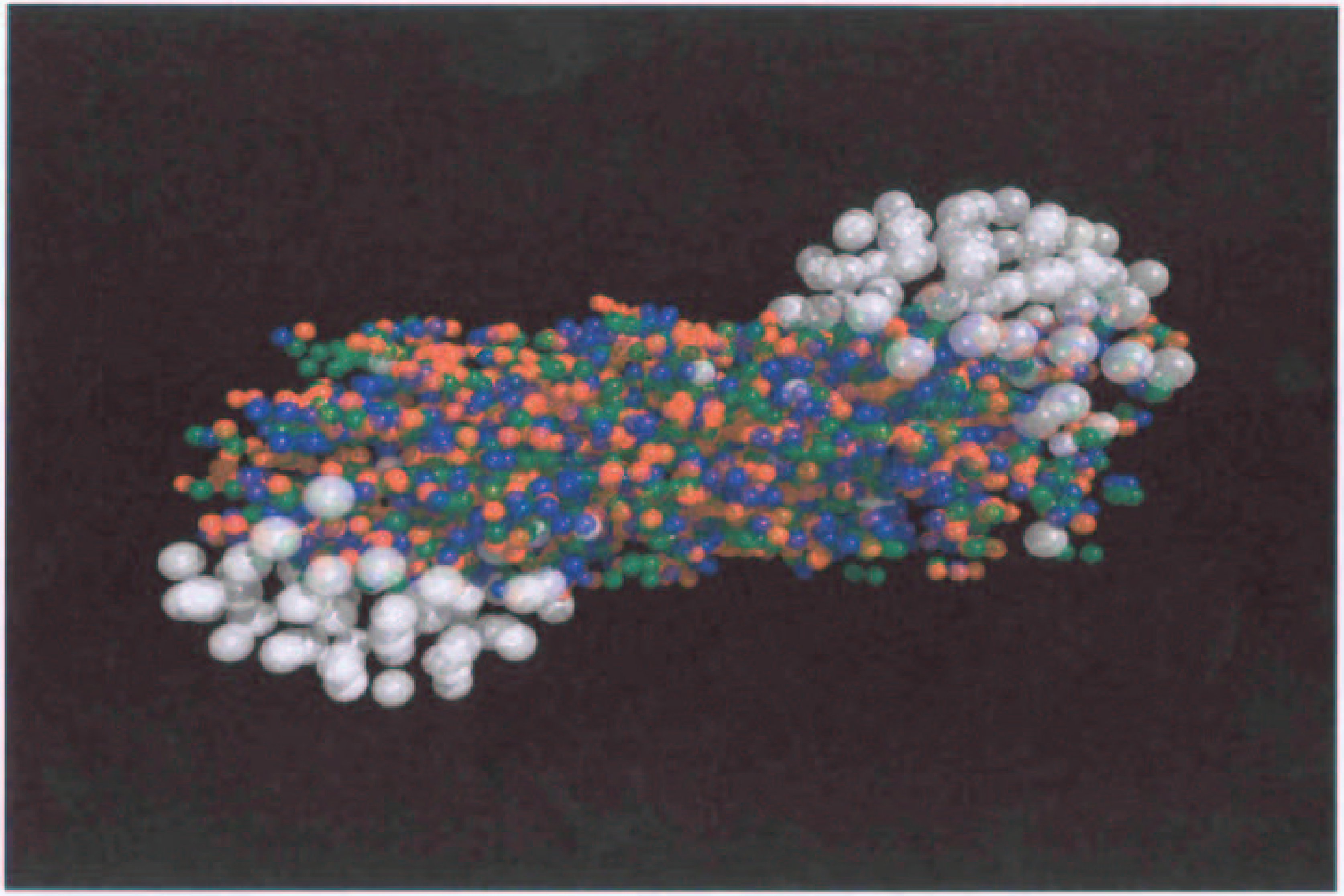
- Motivation - the QCD Phase Transition
- the SPS Heavy Ion Program - Summary of Results
  - Yields of Produced Hadrons
  - Particle Spectra and Correlations
  - Low Mass Electron Pairs
  - Direct Photons
  - Charmonia
- Outlook - the Colliders and the Hot QCD Plasma



Quarks

up — down

mass 5–7 MeV

charm — strange

500 MeV — 150 MeV

top — bottom

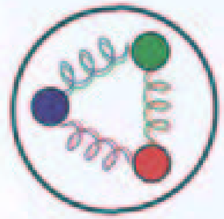
Gluons

... mediate interaction between quarks

Quarks are bound by strong interaction into

Hadrons

Mesons — ***Baryons***



quark–antiquark — 3 valence quarks

mass scale set by constituent quark masses (u,d=300 MeV)

Motivation

- Hadronic Matter: physical vacuum with bags containing quarks and gluons

  quarks and gluons are confined

  chiral symmetry spontaneously broken

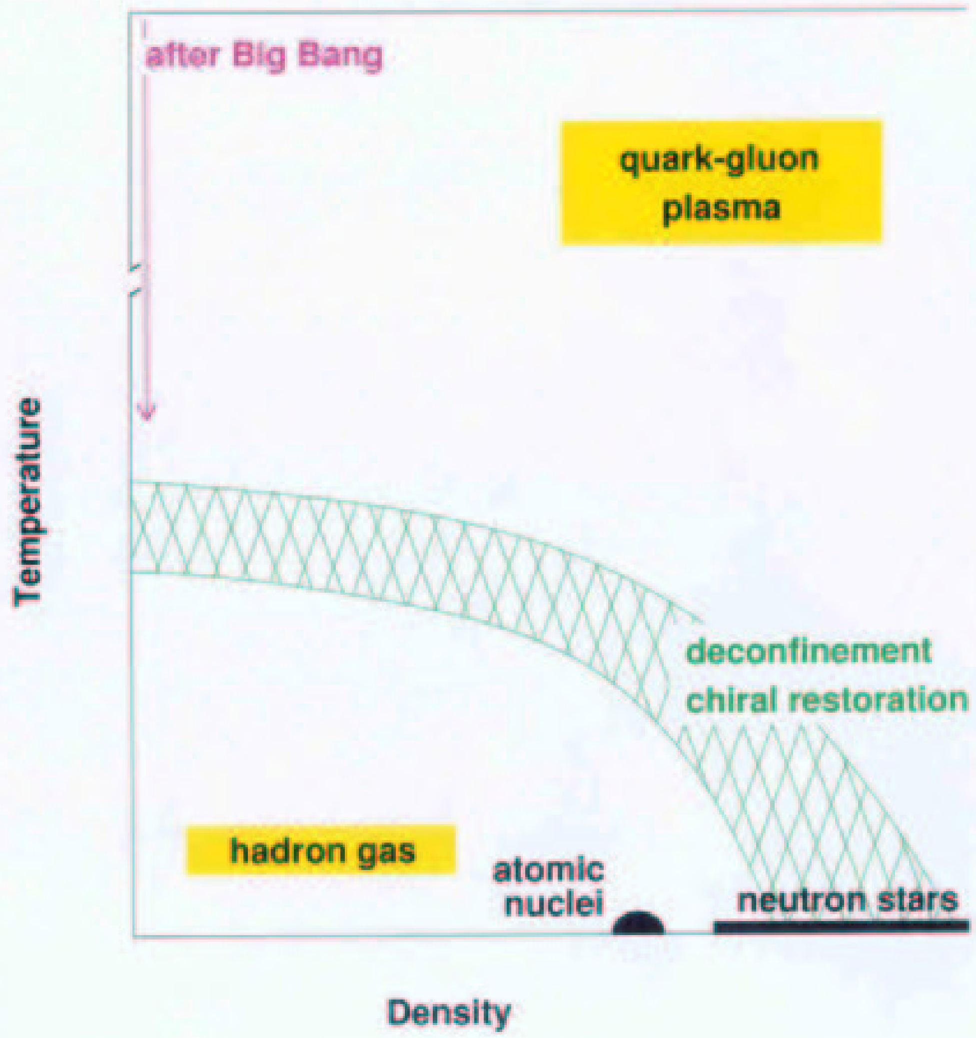
- Quark-Gluon Plasma: perturbative vacuum with deconfined massless quarks and gluons

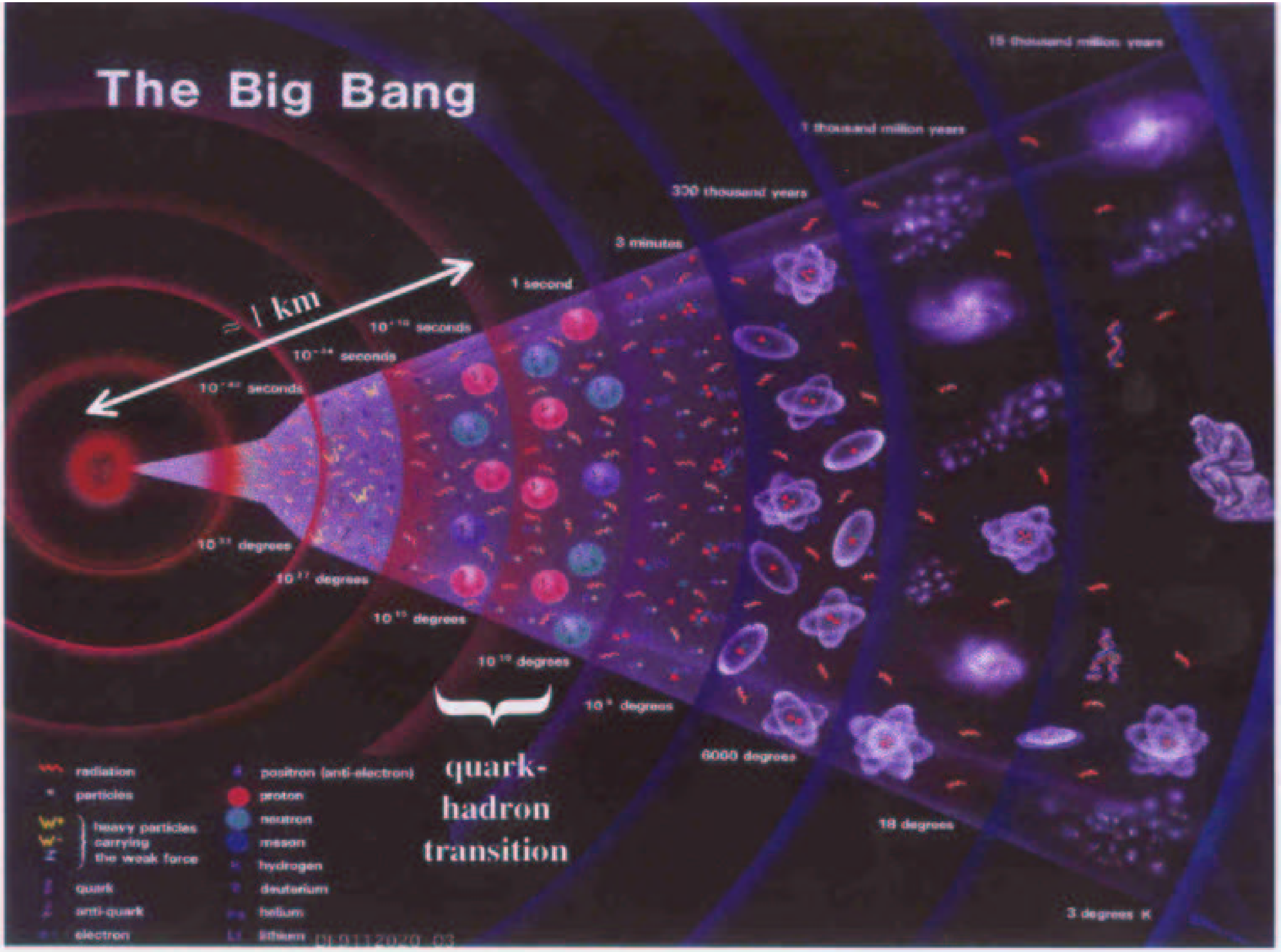
  confinement lifted

  chiral symmetry restored

  constitutents carry color charge → 'plasma'

- At some critical temperature and density there is a phase transition

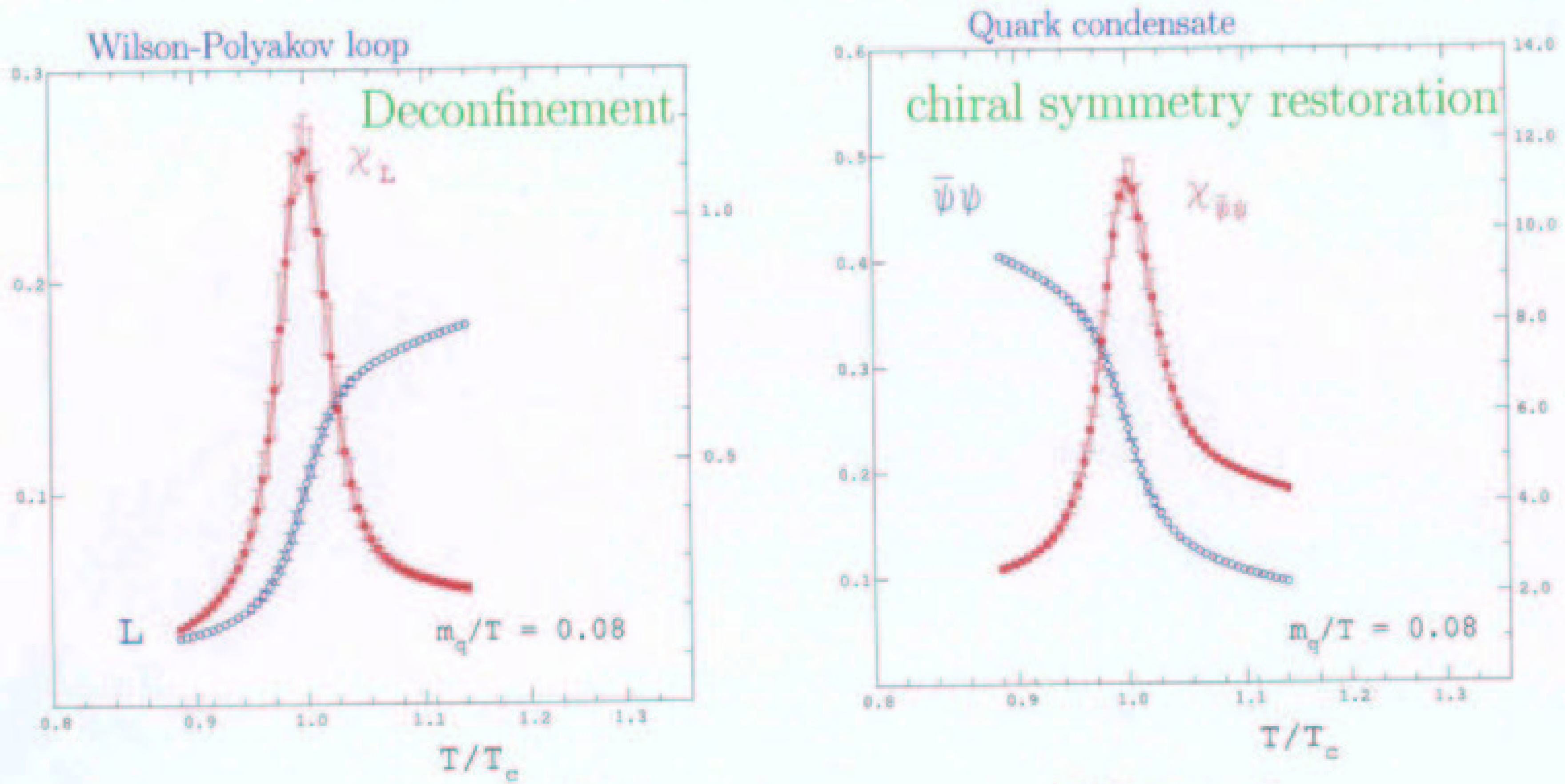




The Big Bang
≈ 1 km
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10²⁷ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
quark-
hadron
transition
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

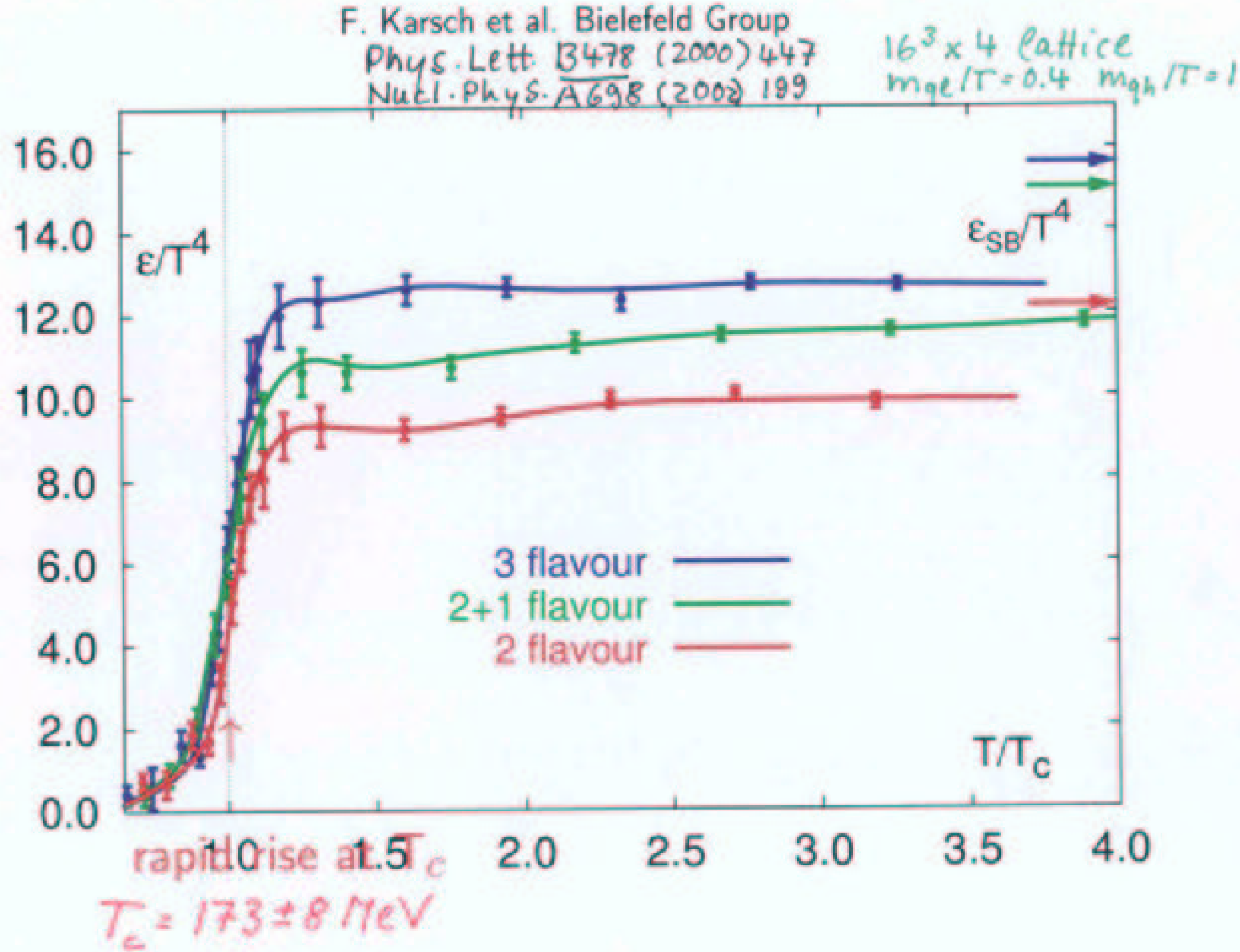
The QCD Phase Transition

Lattice QCD - Bielefeld Group - $8^3 \times 4$ lattice, 2 light quark flavors



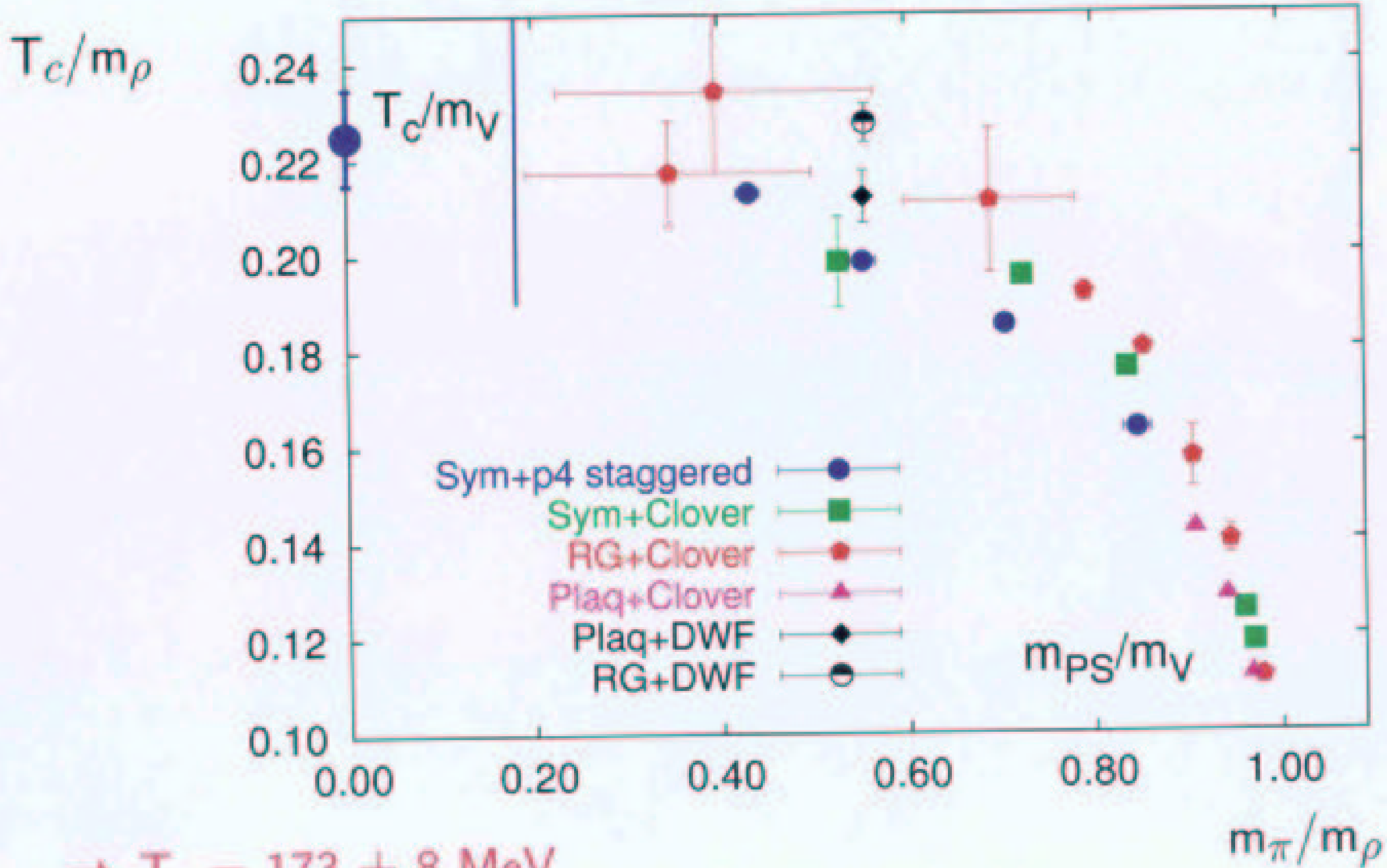
susceptibilities χ are a measure of fluctuations

Energy Density from Finite Temperature Lattice QCD



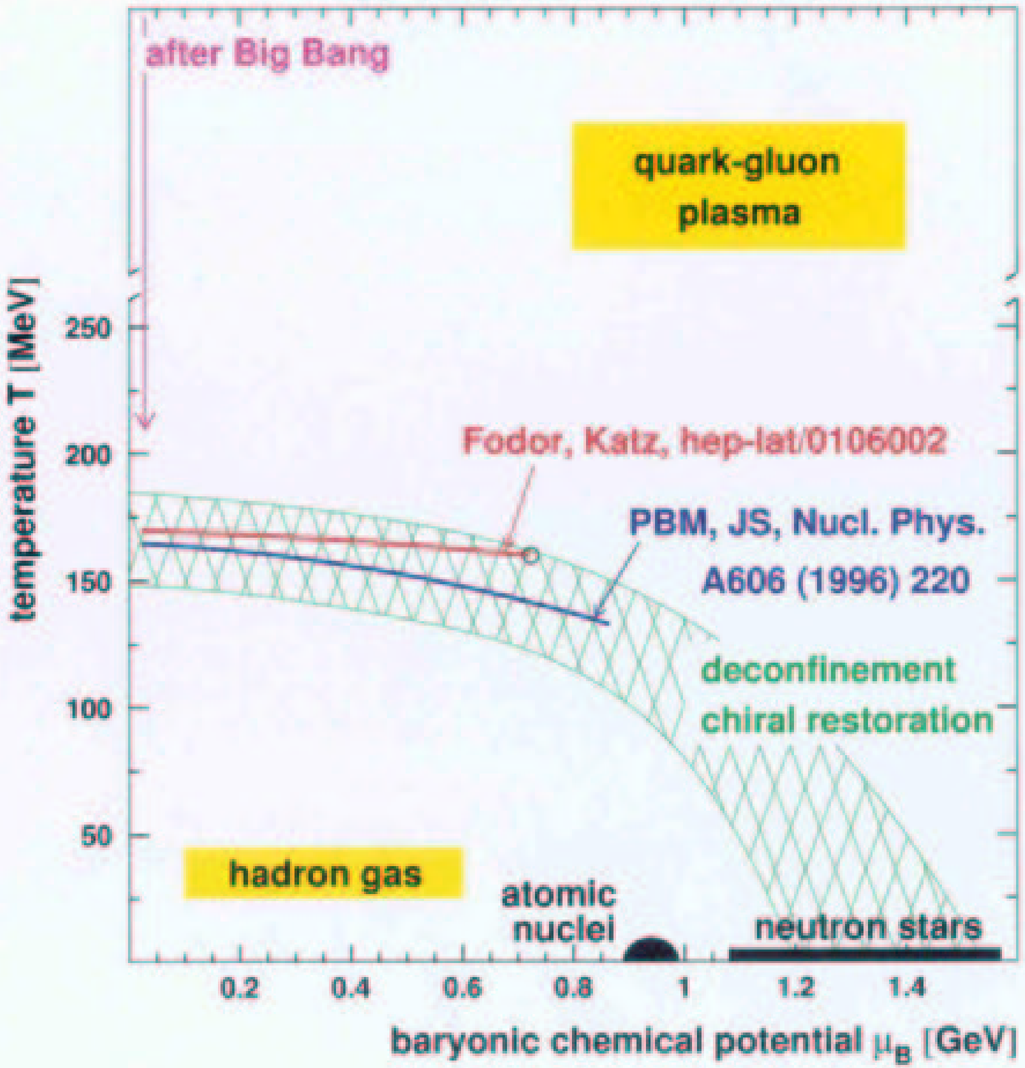
Critical Temperature from Lattice QCD

F. Karsch, Nucl. Phys. **A698** (2002) 199; E. Laermann, Proc. Hirschegg 2002



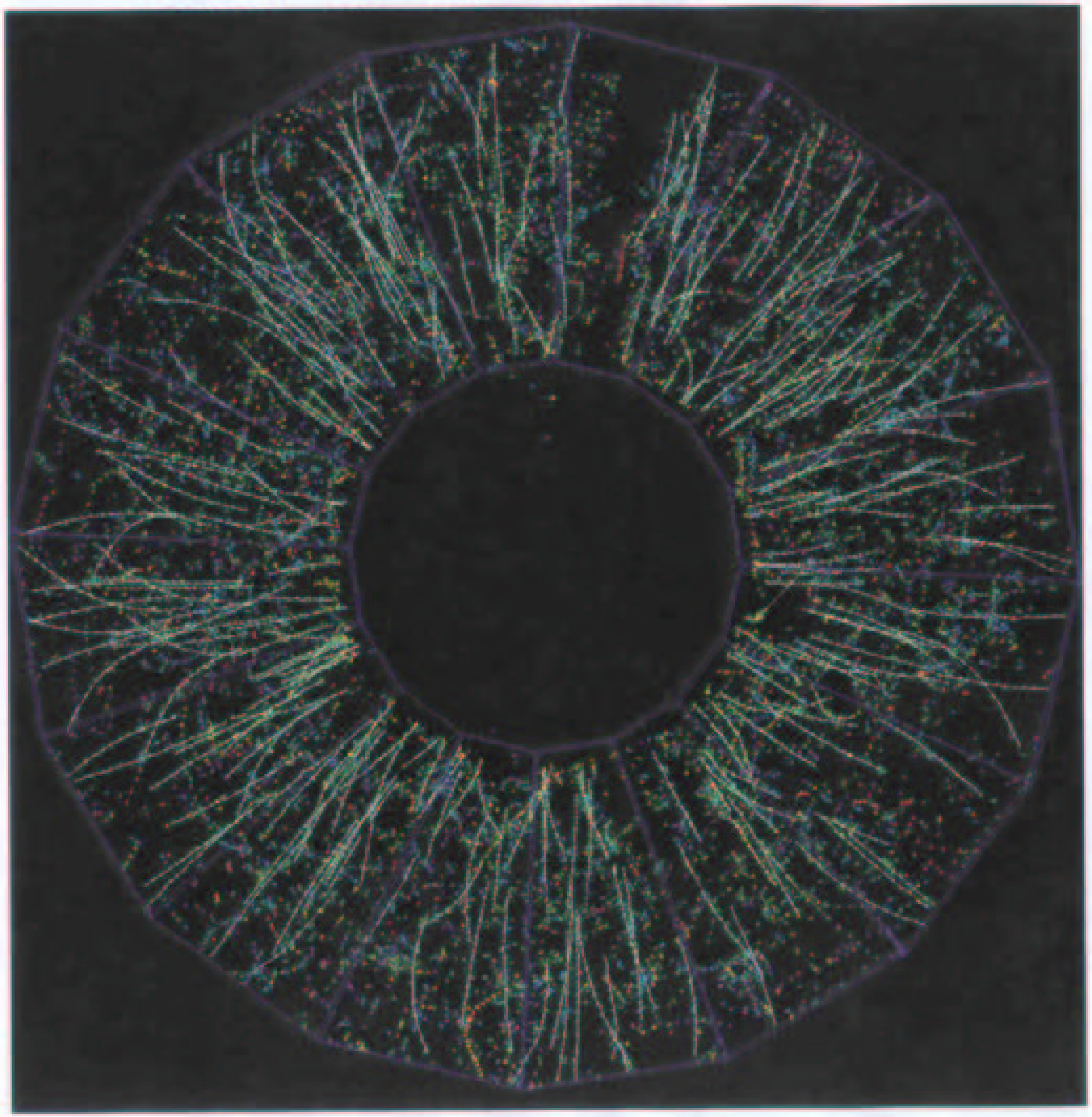
➡ $T_c = 173 \pm 8$ MeV
critical energy density $\epsilon_c = 0.44$-0.88 GeV/fm^3

The Phase Diagram of Nuclear Matter



	fixed target		collider	
	AGS	SPS	RHIC	LHC
beam momentum	29·Z GeV/c	450·Z GeV/c	ea250·Z GeV/c	ea7000·Z GeV/c
projectile	p...Au	p...Pb	p...Au	p...Pb
energy available in c.m. system	Au+Au 600 GeV	Pb+Pb 3200 GeV	Au+Au 40 TeV	Pb+Pb 1150 TeV
hadrons produced per collision	900	2400	7500	60000

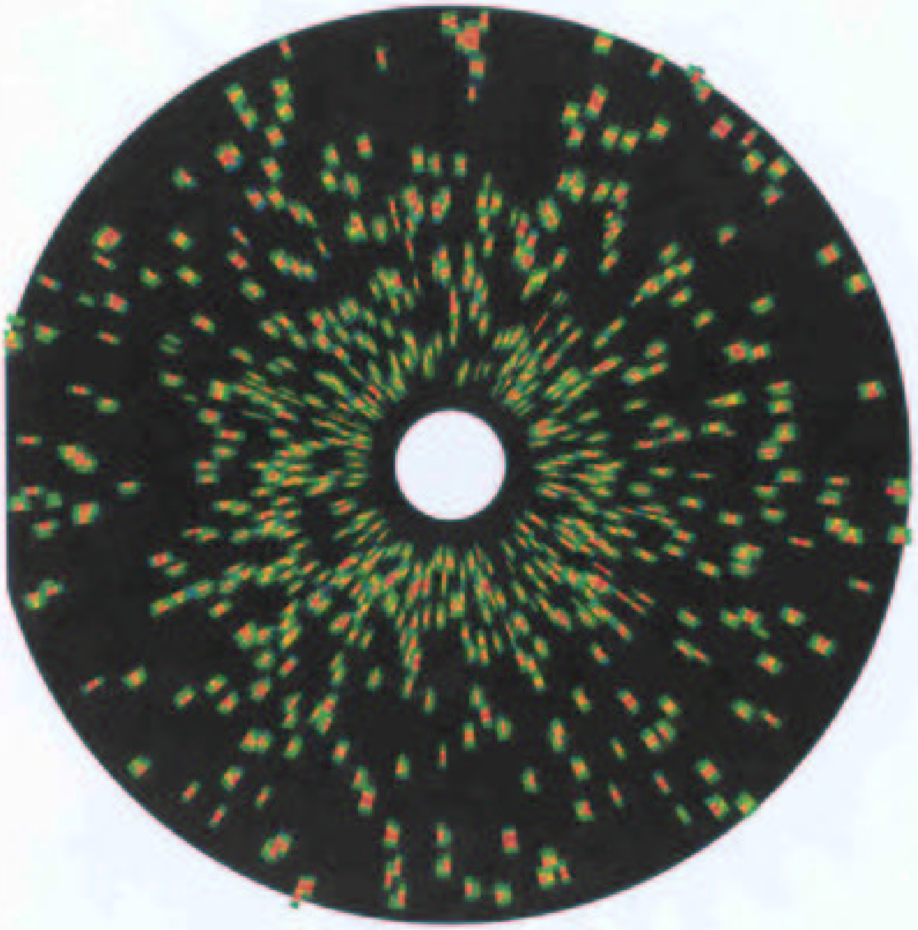
central Pb + Au collision 158 A GeV



CERES TPC
10 m³ gas detect.

4 Million
read-out pixels

CERES Radial SDD Event Display

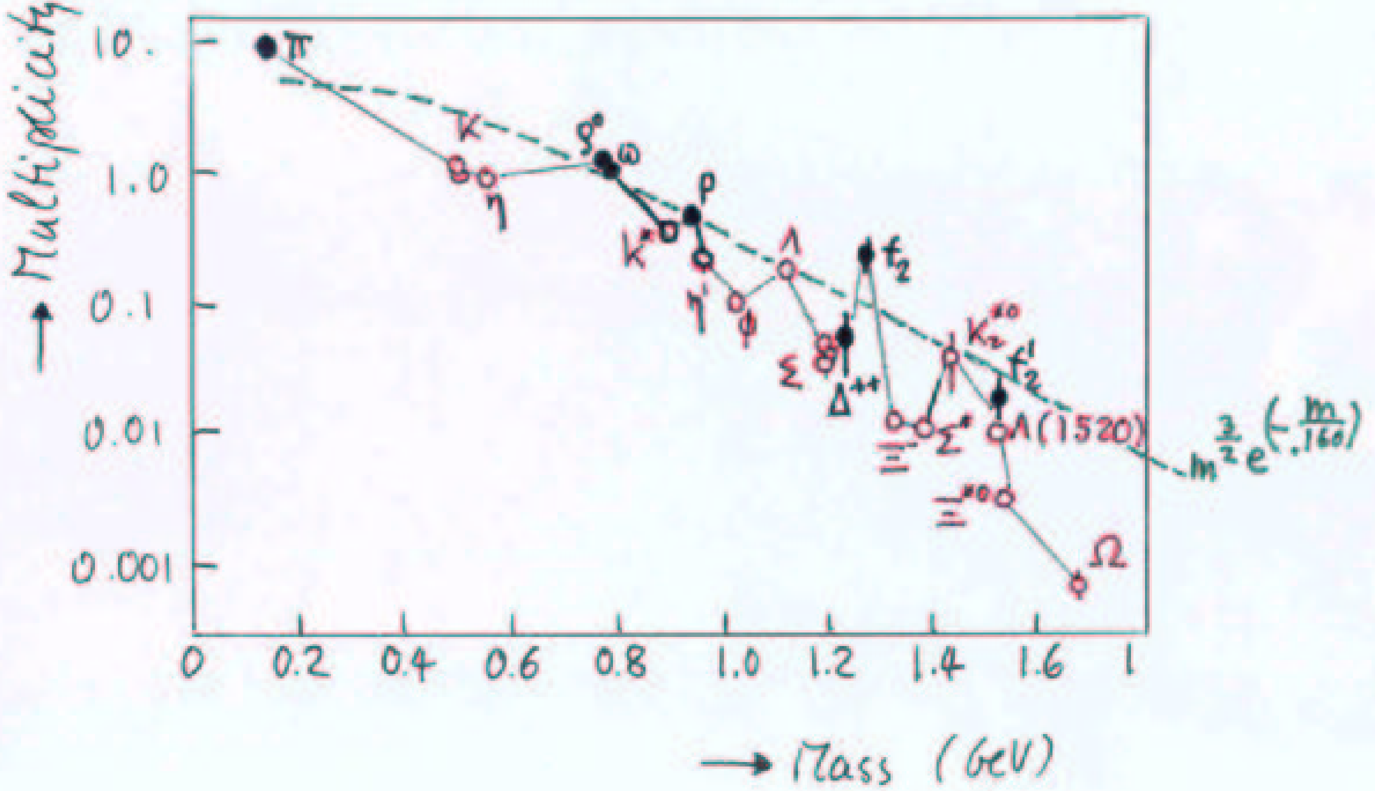


Radius: 4" (active area of 55 cm^2)

Thickness: 280 μm of Si

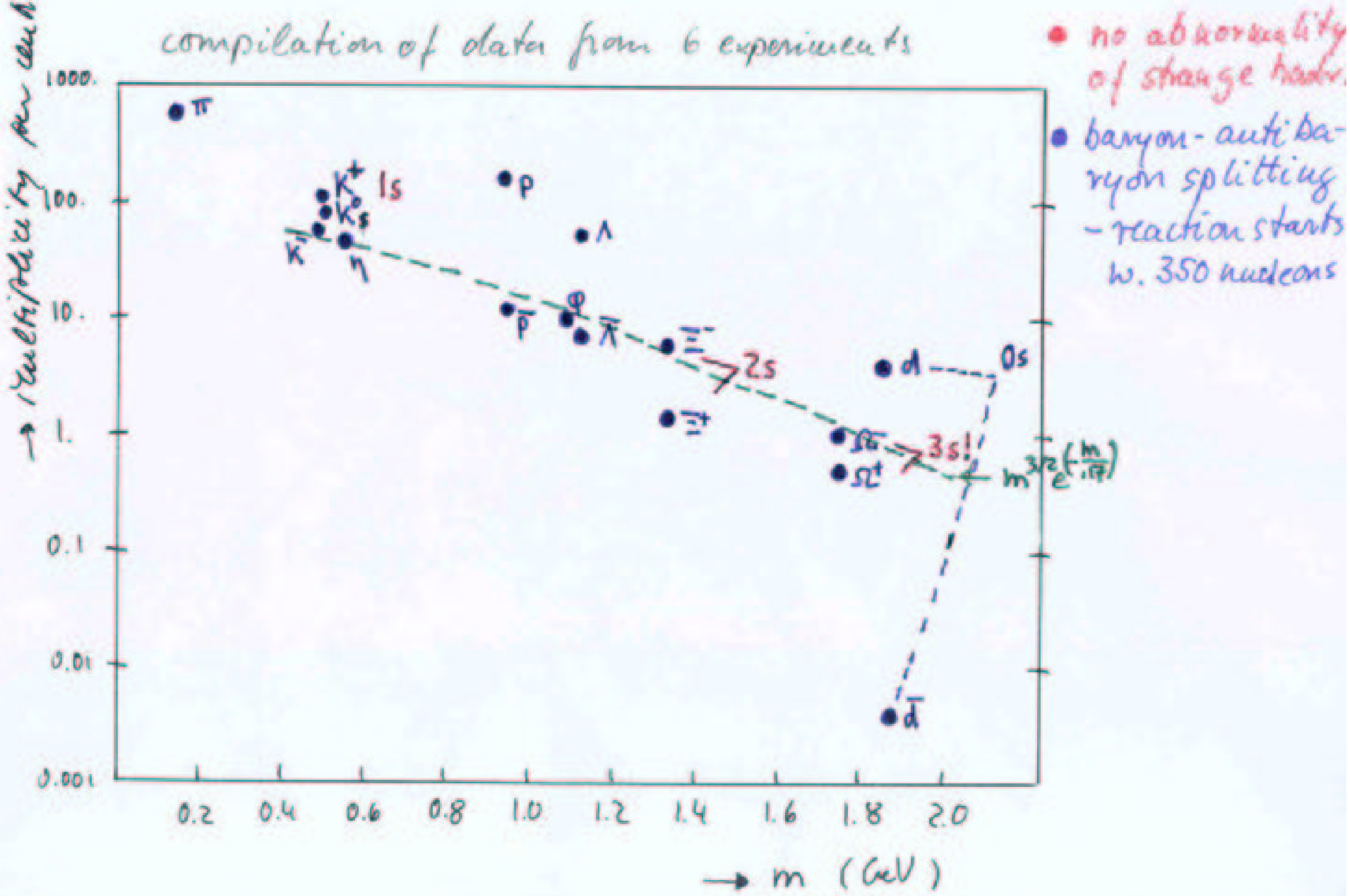
Granularity: 360 anodes x 256 time bins

Particle Production in e^+e^- Collisions at $\sqrt{s} = 91.2$ GeV (LEP)



- • general trend : exponential decrease w. mass
- ○ in addition : strangeness suppression

Particle Production in PbPb Collisions



CERN SPS Data and Thermal Model

P. Braun-Munzinger, I. Heppe, J.Stachel, Phys.Lett.**B465** (1999) 15

Grand Canonical Ensemble:

$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,\mathrm{d}p}{exp[(E_i(p)-\mu_i)/T]\pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

free parameters:
- T = 0.170 ± 0.005 GeV
- μ_b = 0.270 ± 0.010 GeV

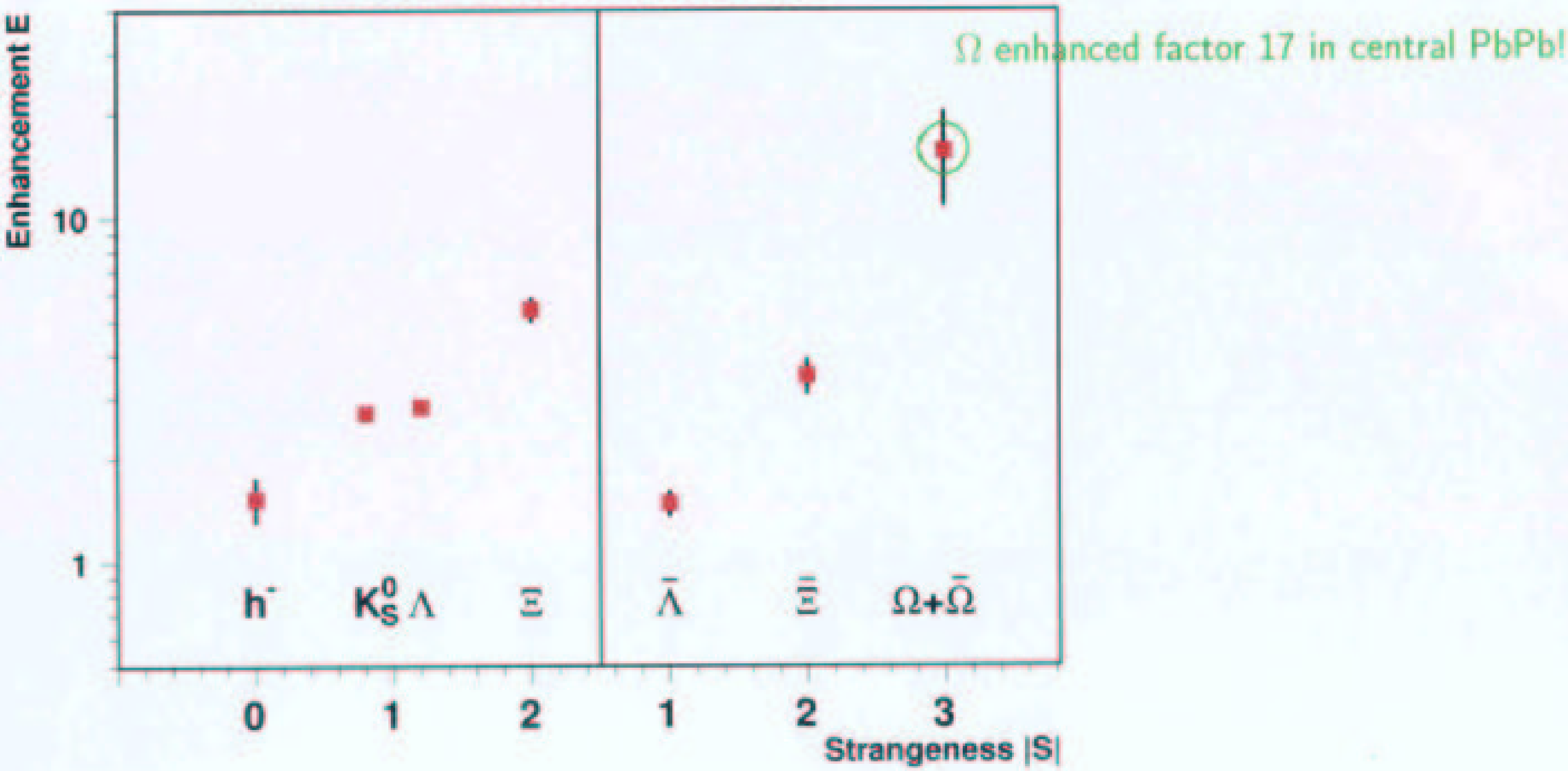
fixed by conservation laws:
- μ_s = 0.074 GeV from ΔS=0
- μ_{I_3}=0.005 GeV from ΔQ=0

central 158 A GeV/c Pb + Pb collisions

Strangeness Enhancement in 158 A GeV/c Pb + Pb Collisions

$$\text{Enhancement E} = \frac{\text{yield(PbPb)}/N_{\text{part}}(\text{PbPb})}{\text{yield(pBe)}/N_{\text{part}}(\text{pBe})}$$

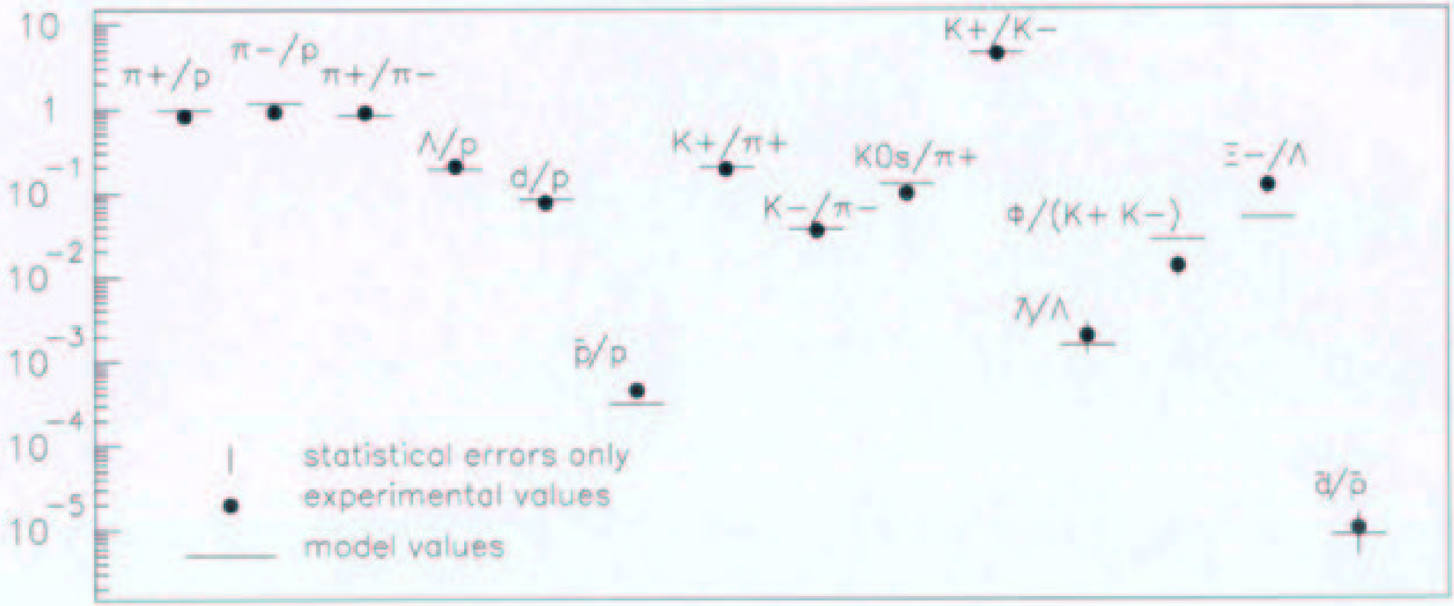
WA97 Phys. Lett. **B449** (1999) 401



Hadron Yields at AGS and Thermal Model

P. Braun-Munzinger, I. Heppe, J. Stachel, Phys. Lett. **B465** (1999) 5
and I. Heppe, Diploma thesis, U. Heidelberg 1998

central 14.6 A GeV/c Si + Au collisions
thermal model parameters: T = 125 MeV, μ_b = 540 MeV



yields for 11.5 A GeV/c Au + Au are very similar

Yields of Light Nuclei at AGS and Thermal Model

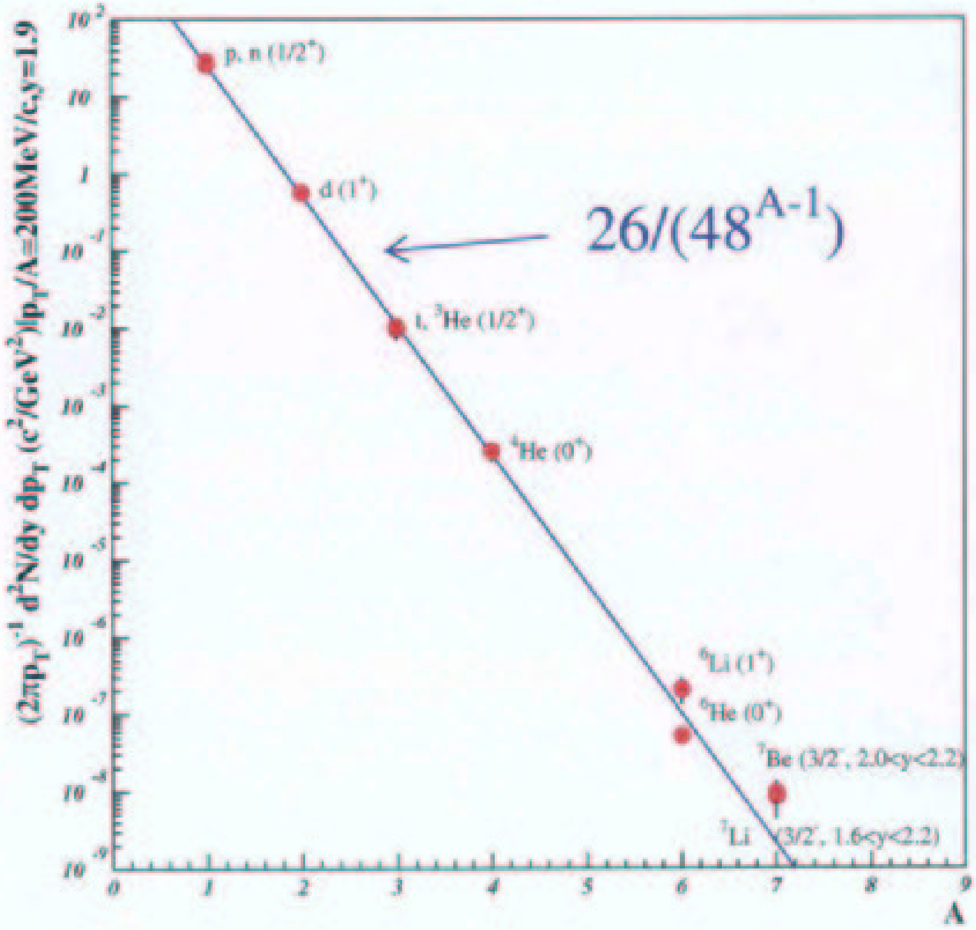
Addition of every nucleon → penalty factor R_p=48
but data are at very low p_t
p_t int. with A-dependent slope → R_p =26

Grand Canonical Ensemble:
$R_p \approx \exp[(m_n \pm \mu_b)/T]$
for T=125 MeV and μ_b = 540 MeV
→ R_p= 23 good agreement!

also good for antideuterons
data: R_p=2±1 10^5 GC: R_p=1.3 10^5

P.Braun-Munzinger, J.Stachel
J.Phys.**G28**(2002)1971

E864 Collaboration, Phys. Rev. **C61** (2000) 064908

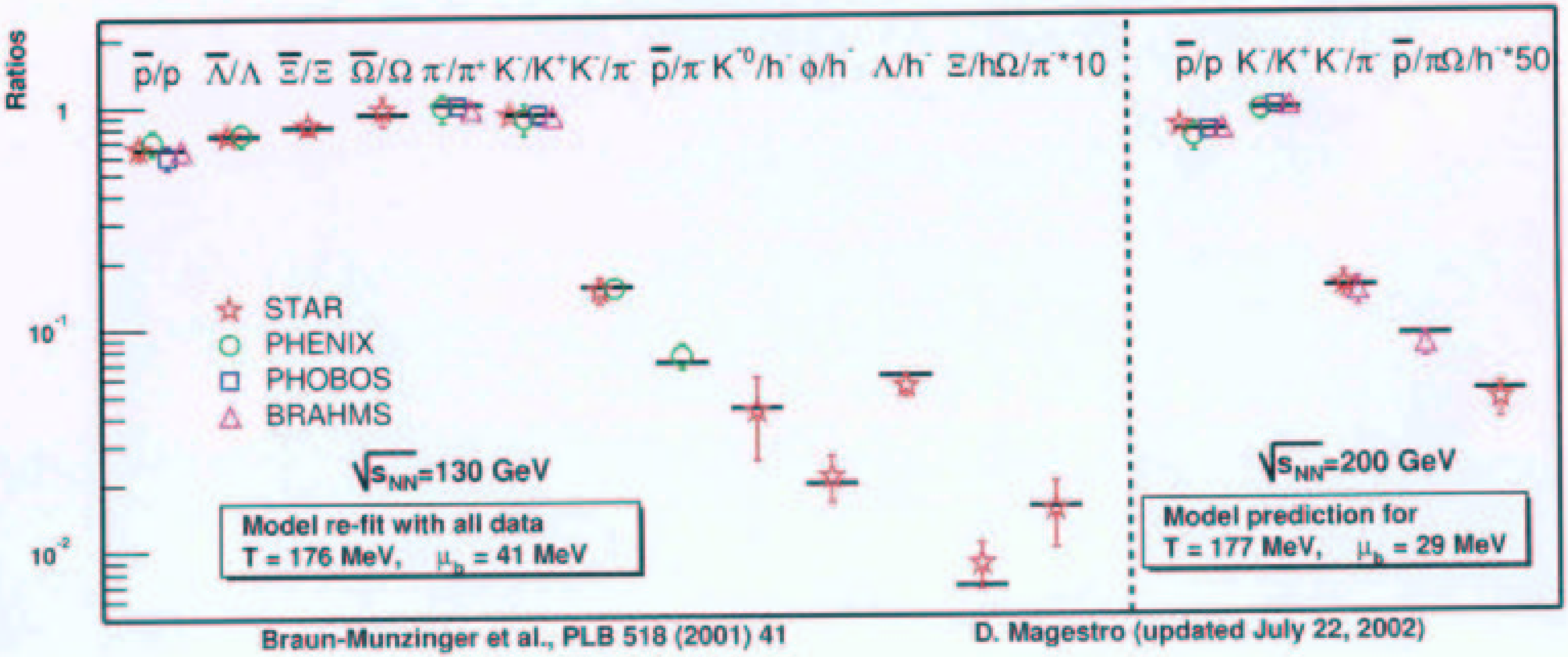


RHIC Data and Thermal Model

P.Braun-Munzinger, D. Magestro, K. Redlich, J.Stachel, Phys. Lett. B518 (2001) 41

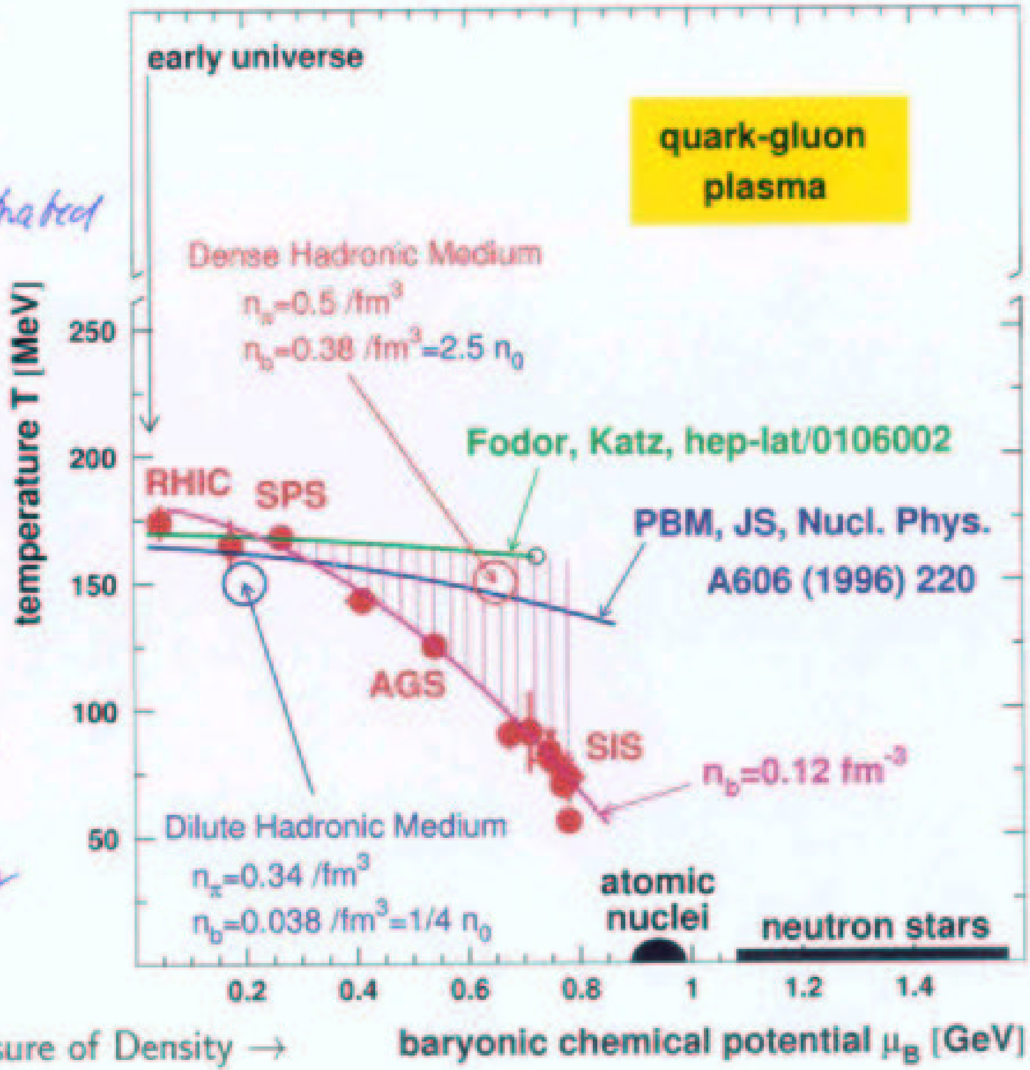
$$T = 0.174 \pm 0.007\,\mathrm{GeV} \;\; \mu_b = 0.046 \pm 0.005\,\mathrm{GeV}$$

central Au + Au collisions, data from all experiments combined



Phase Diagram of Nuclear Matter

1. hadron yields equilibrated
2. For full energy SPS and above: hadron yields frozen at phase boundary
3. how is equilibrium achieved? at SPS and RHIC not with hadronic cross sections
⟺ QGP much more efficient equilibrator



Measure of Density →

Estimate of Initial Conditions

energy and baryon density a la Bjorken:

$$\epsilon = \frac{1}{A_\perp}\frac{dE_t}{d\eta}\frac{d\eta}{dz} \quad \text{and} \quad \rho_b = \frac{1}{A_\perp}\frac{dN_b}{d\eta}\frac{d\eta}{dz}$$

$d\eta/dz$ typically 1 fm for AGS and SPS

- AGS 11 A GeV/c Au+Au

$$dE_t/d\eta = 200\text{GeV} \quad dN_b/d\eta = 150$$

$\rightarrow \epsilon = 1.4$ GeV/fm^3 and $\rho_b = 1.0/\text{fm}^3 \approx 6\rho_0$

$T_i = 170$ MeV

- SPS 158 A GeV/c Pb+Pb

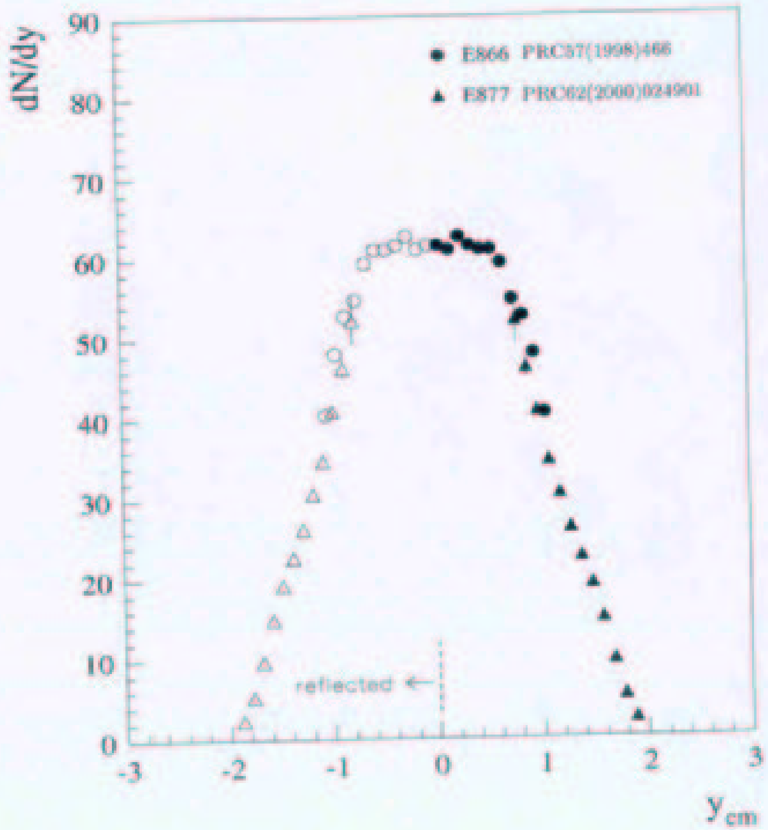
$$dE_t/d\eta = 450\text{GeV} \quad dN_b/d\eta = 80$$

$\rightarrow \epsilon = 3$ GeV/fm^3 and $\rho_b = 0.5/\text{fm}^3 \approx 3\rho_0$

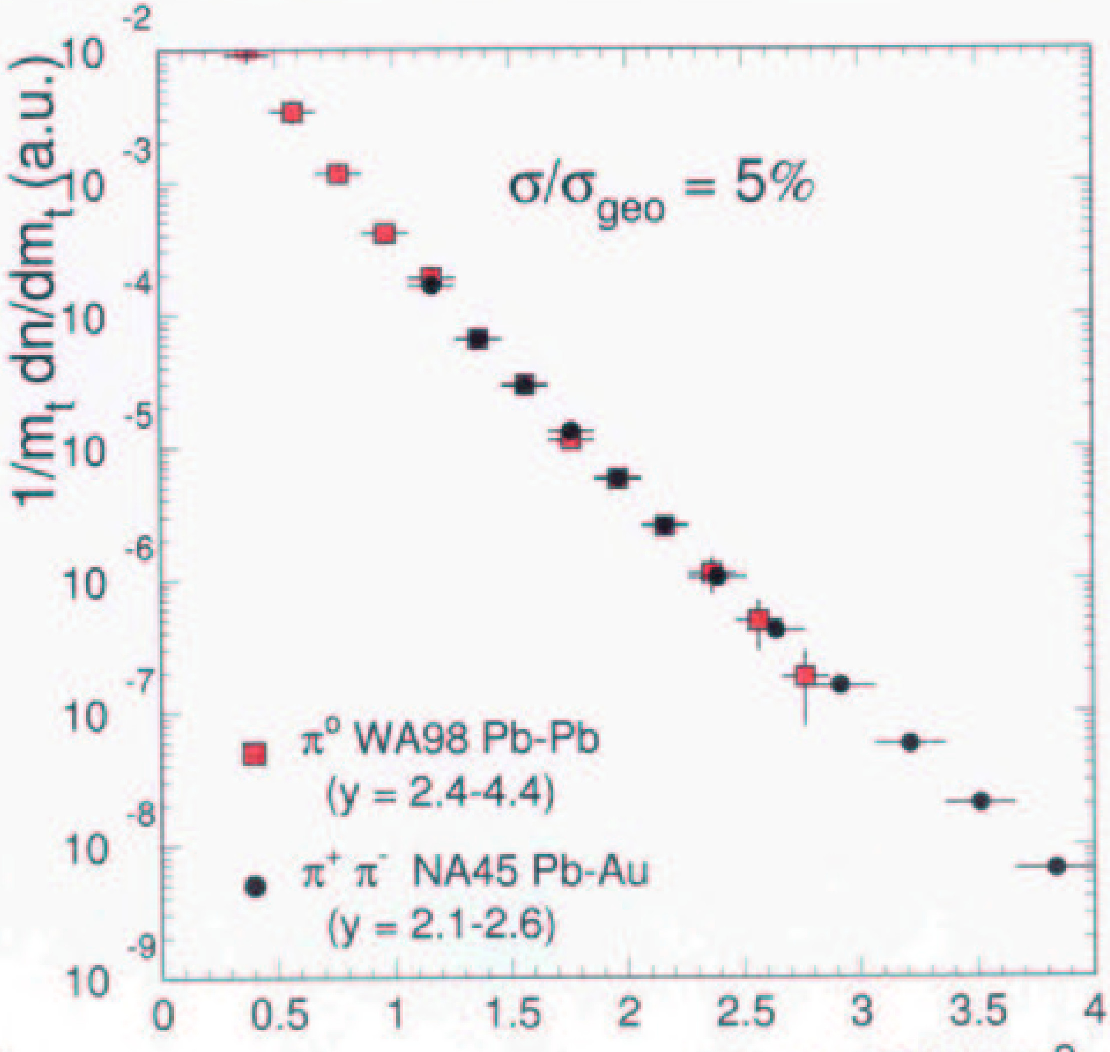
$T_i = 210$ MeV

$p = 0.7$ GeV/fm^3 $= 10^{35}$ Pa

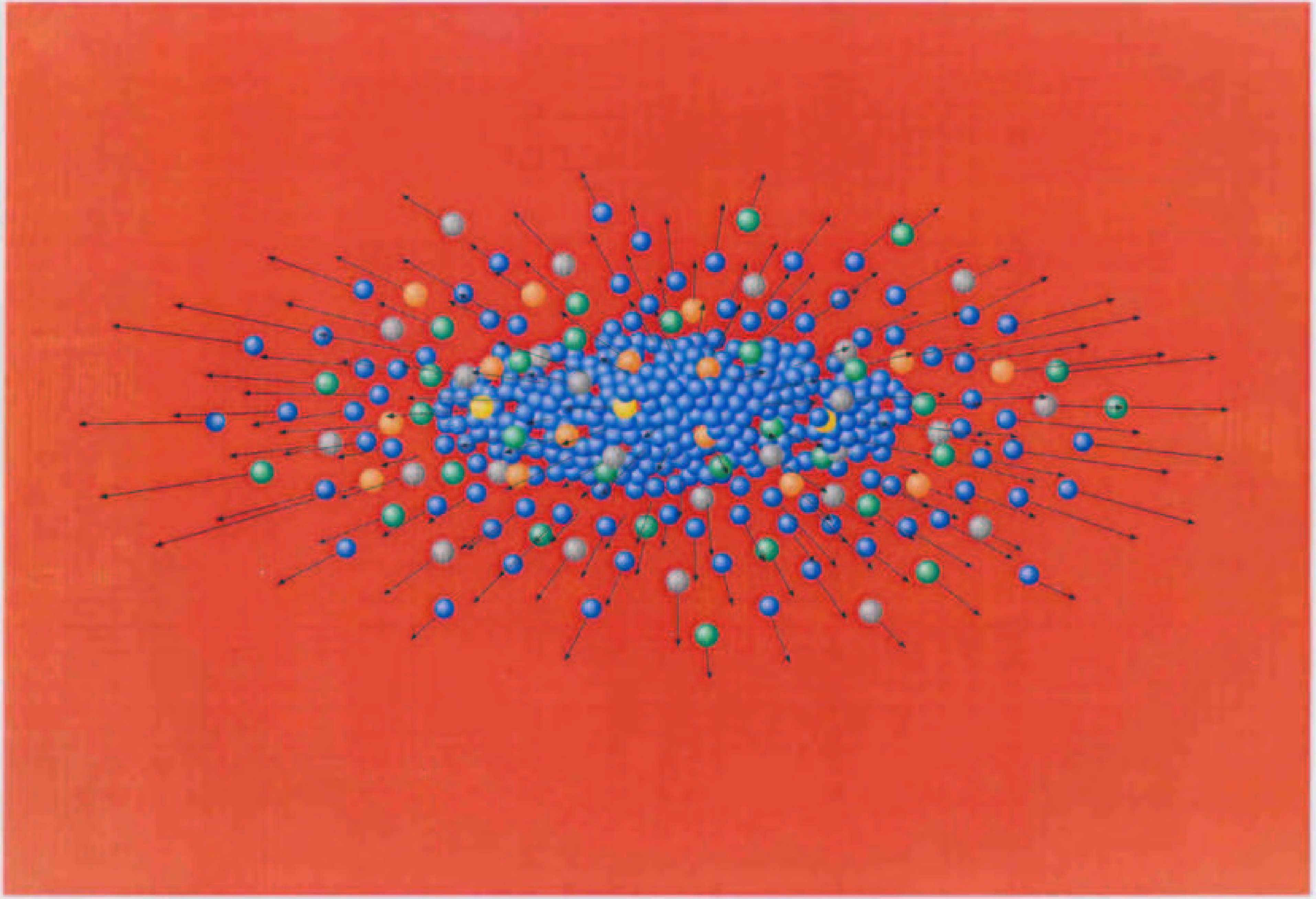
proton rapidity distribution 11 A GeV/c Au + Au



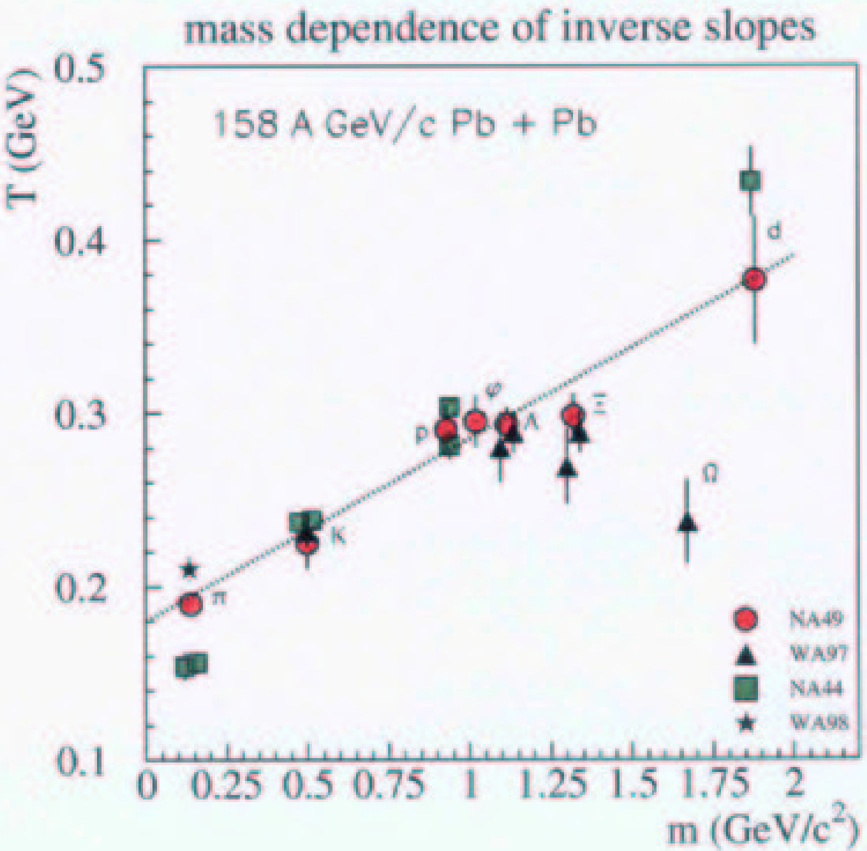
Particle Transverse Momentum Spectra



$$m_t = \sqrt{m_0^2 + p_t^2}$$



Slope Constants of Transverse Momentum Spectra

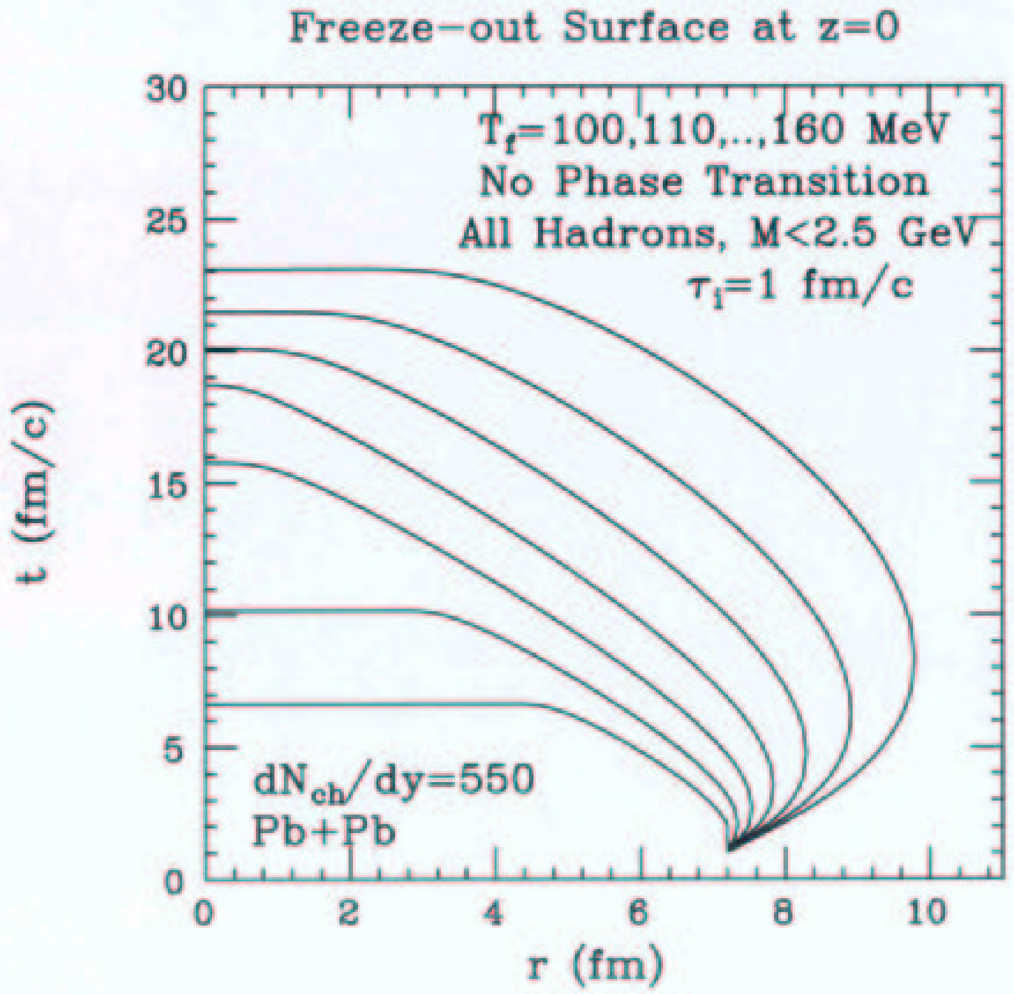


slope constants grow with mass - too large for real temperatures!

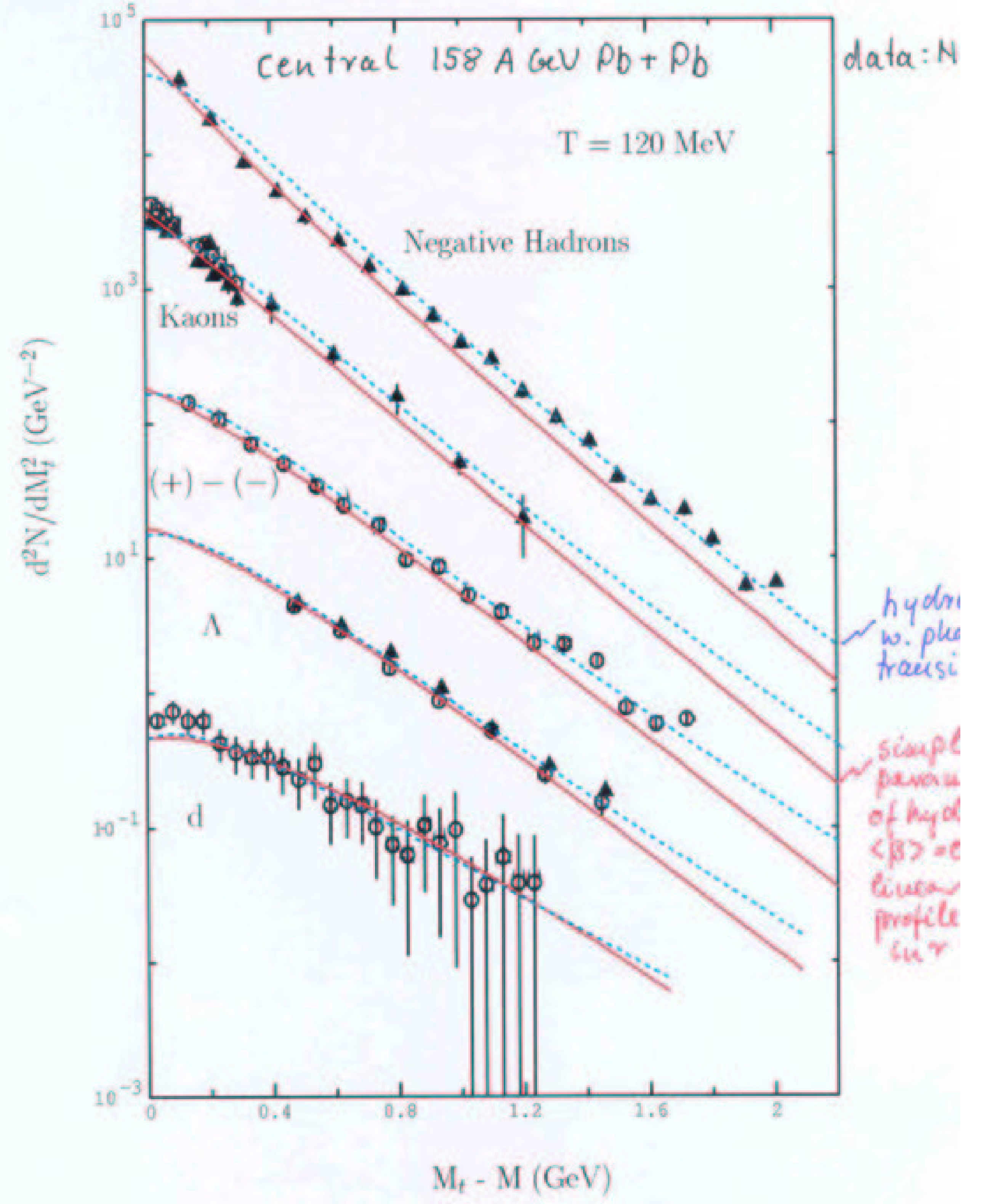
Hubble Expansion of Nuclear Fireball

Hydrodynamic Evolution of the Fireball

Cleymans, Redlich, Srivastava, Phys. Rev. C55 (1997) 1431



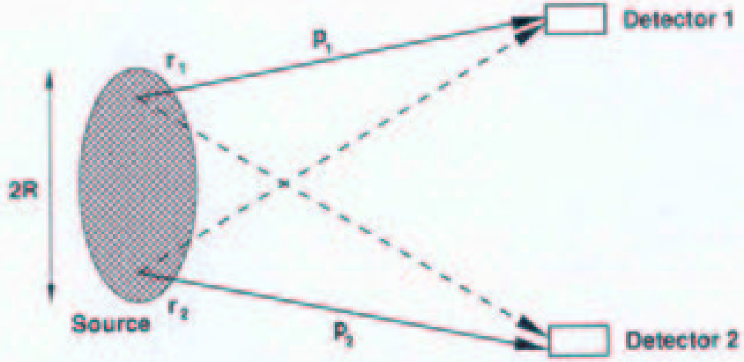
freeze-out time vs radius for different temperatures



central 158 A GeV Pb + Pb
data: N
T = 120 MeV
Negative Hadrons
Kaons
(+) − (−)
Λ
d
d²N/dM²t (GeV⁻²)
Mt - M (GeV)

Pion HBT interferometry

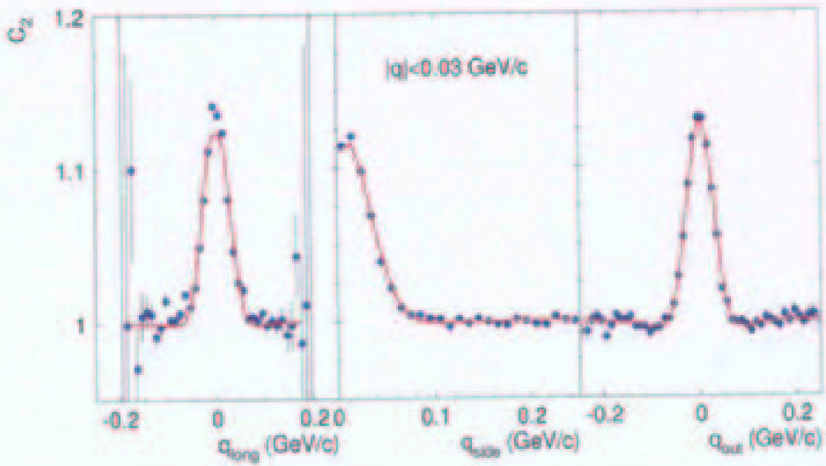
When phase space volume smaller than $\Delta p_x \Delta x \approx \hbar$ is considered, chaotic system of identical non-interacting particles exhibits quantum fluctuations following Bose-Einstein or Fermi statistics



First application in astrophysics (Hanbury-Brown and Twiss)
→ size of stars

$$C_2 \propto \frac{\mathrm{d}^6 N/\mathrm{d}\vec{p_1}\mathrm{d}\vec{p_2}}{\mathrm{d}^3 N/\mathrm{d}\vec{p_1}\cdot\mathrm{d}^3 N/\mathrm{d}\vec{p_2}} = 1 \pm \chi(\vec{p_1} - \vec{p_2})$$

in heavy ion physics typical dimensions 1-10 fm
→ momentum differences of 20-200 MeV/c



more complications, but also more information for non-static source:
duration of emission, space-momentum correlations due to expansion, strong & EM interaction, decays of resonances ...
measure C_2 as function of Δp_x, Δp_y, Δp_z for all y, p_t, m

Longitudinal expansion

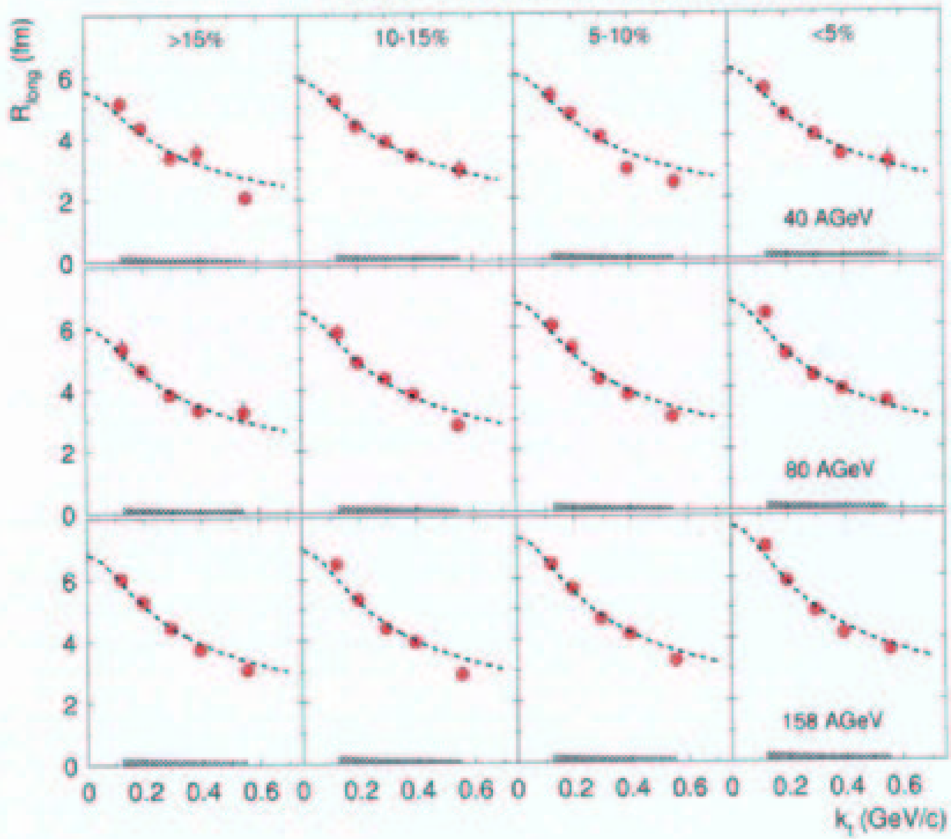
Duration of expansion (lifetime) τ of the system can be estimated from the transverse momentum dependence of R_{long}:

$$R_{\mathrm{long}} \approx \tau \cdot \sqrt{\frac{T_f}{m_t}}$$ Y. Sinyukov

➡ $\tau = 6 - 8$ fm/c

for $T_f = 120$ MeV

• CERES collaboration, nucl-ex/0207005



Transverse expansion

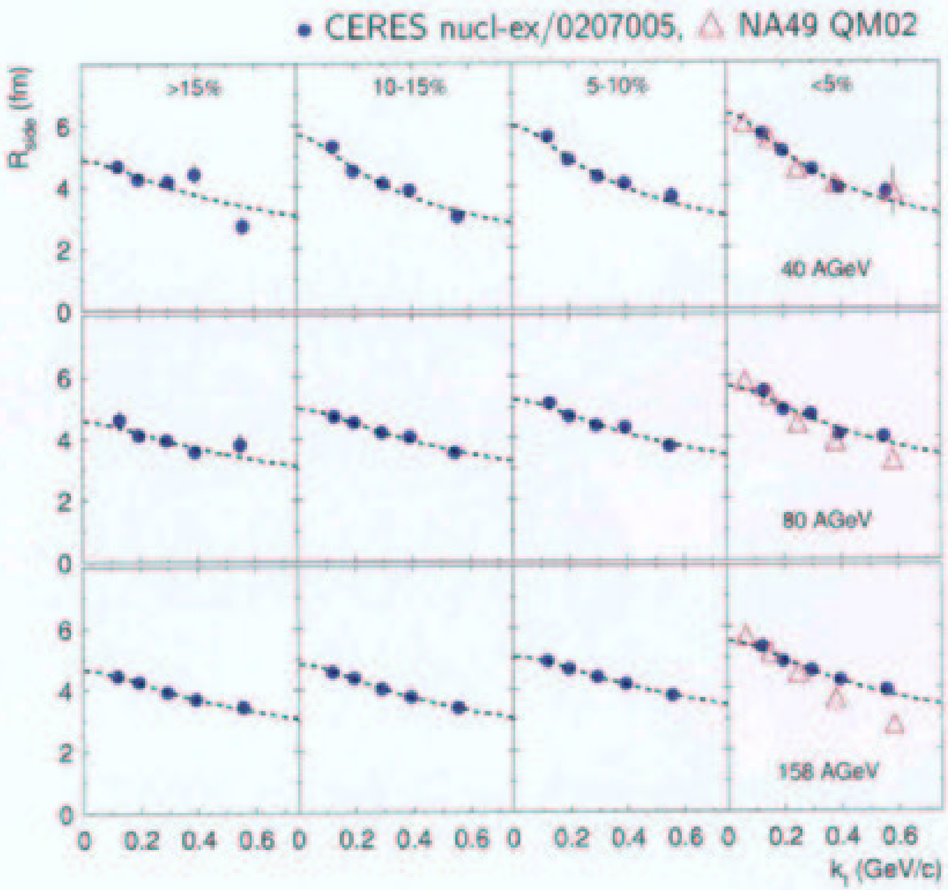
Transverse momentum dependence of R_{side} allows determination of geometric source size R_{geo} and average transverse flow velocity β_t:

$$R_{\mathrm{side}} \approx R_{\mathrm{geo}}/(1 + m_t \cdot F(T_f, \beta_t))^{\frac{1}{2}}$$

U. Heinz *et al.*

➡ $\beta_t \approx 0.55$

for $T_f = 120$ MeV

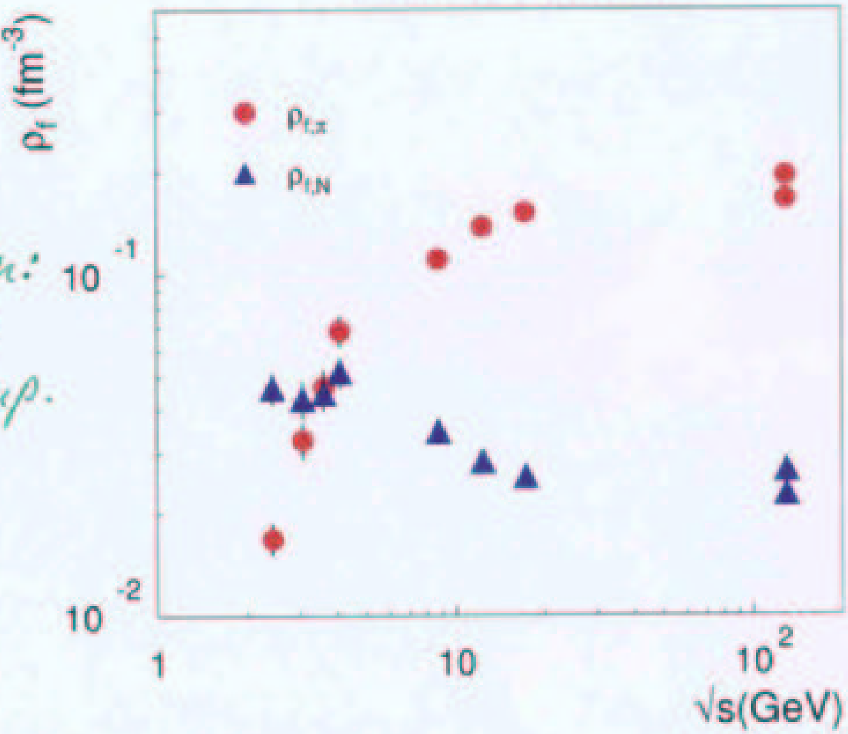


Freeze out density

fireball decouples at
a nucleon density of
1/4 - 1/7 nuclear matter dens.

using ππ and πN cross section:
when mean free path > 2.5 fm
collisions too infrequent as comp.
to expansion rate

CERES nucl-ex/0207008



Effects of Restoration of Chiral Symmetry

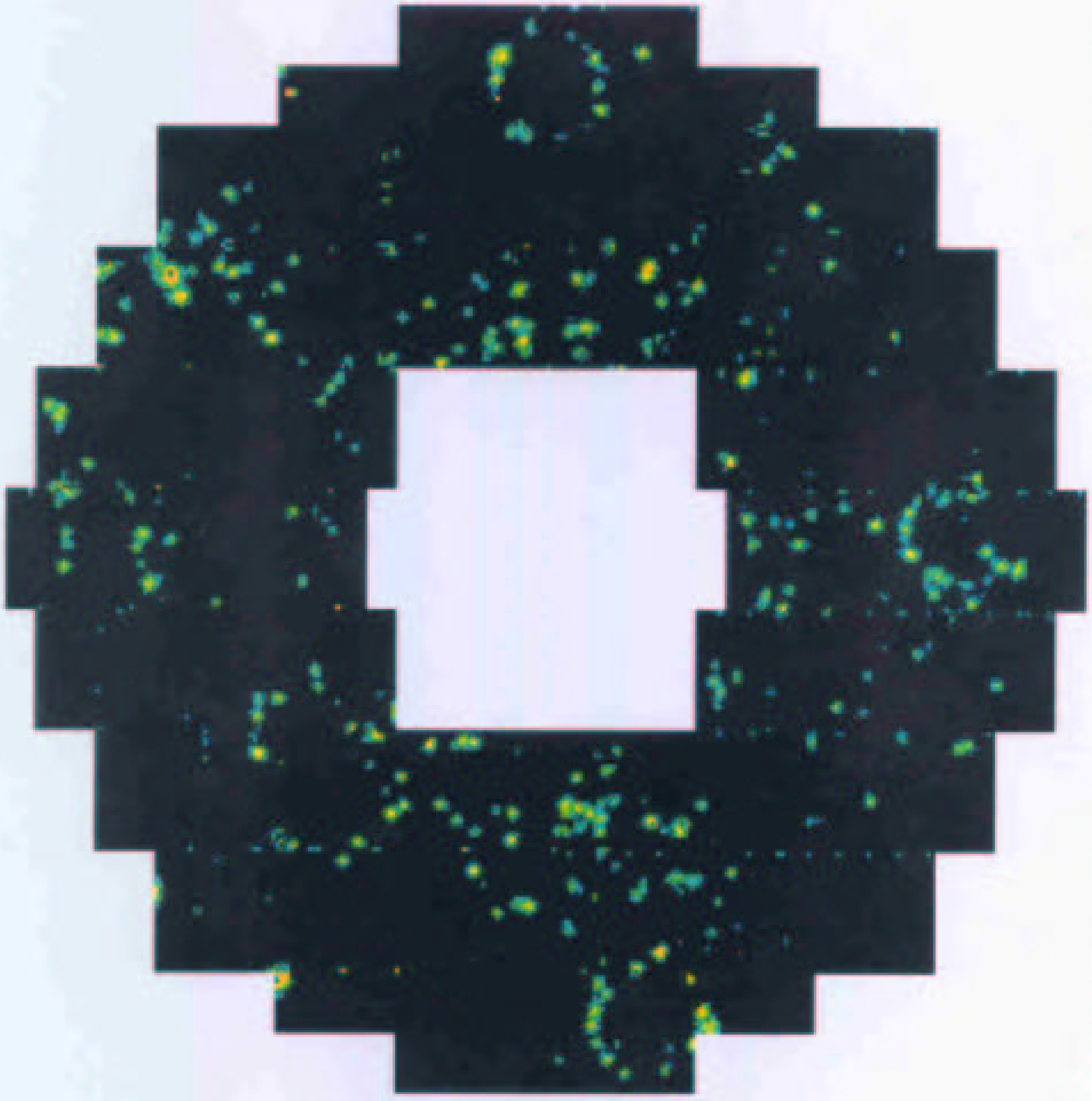
- chiral symmetry of QCD $\rightarrow$ hadronic spectrum of degenerate chiral partners (doublets as π/σ or ρ/ω)
- spontaneous breaking of symmetry $\rightarrow$ large masses and splitting in mass
- restoration of chiral symmetry $\rightarrow$ chiral partners become degenerate, masses ?

most visible effect expected for ρ meson:

- mass 770 MeV
- decays quickly $\Gamma = 150$ MeV, $\tau = 1.3$ fm/c
- decays with 4.4 10^{-5} probability to e^+e^-
- e^+e^- leave interaction zone unchanged

CERES / NA45

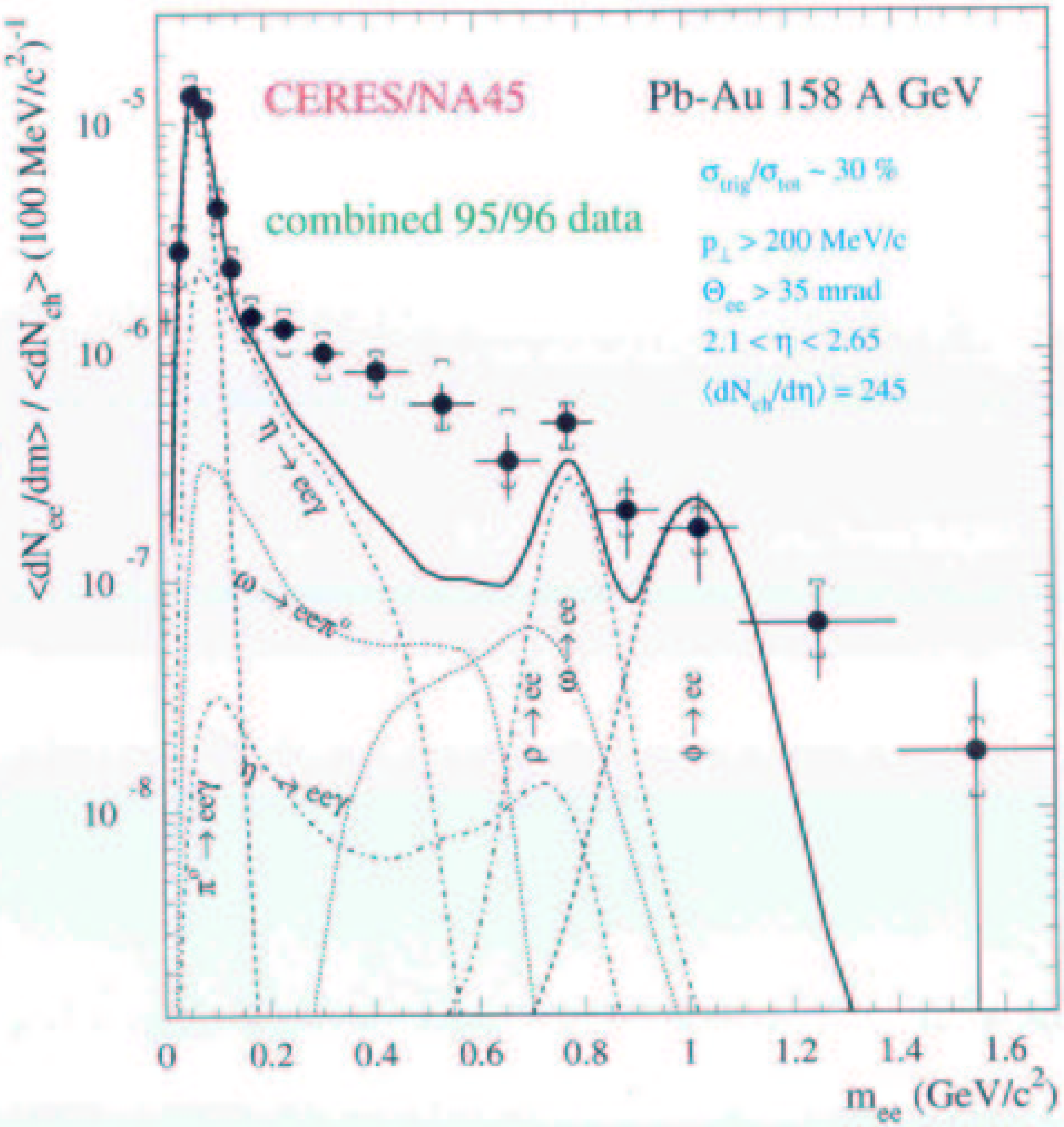
RICH 1 wirechamber w. TMAE
& pad readout



Electron Pair Mass Spectrum in Pb+Au

Data: CERES/NA45
Nucl. Phys. **A661** (1999) 23c
Phys. Lett. **B422** (1998) 405

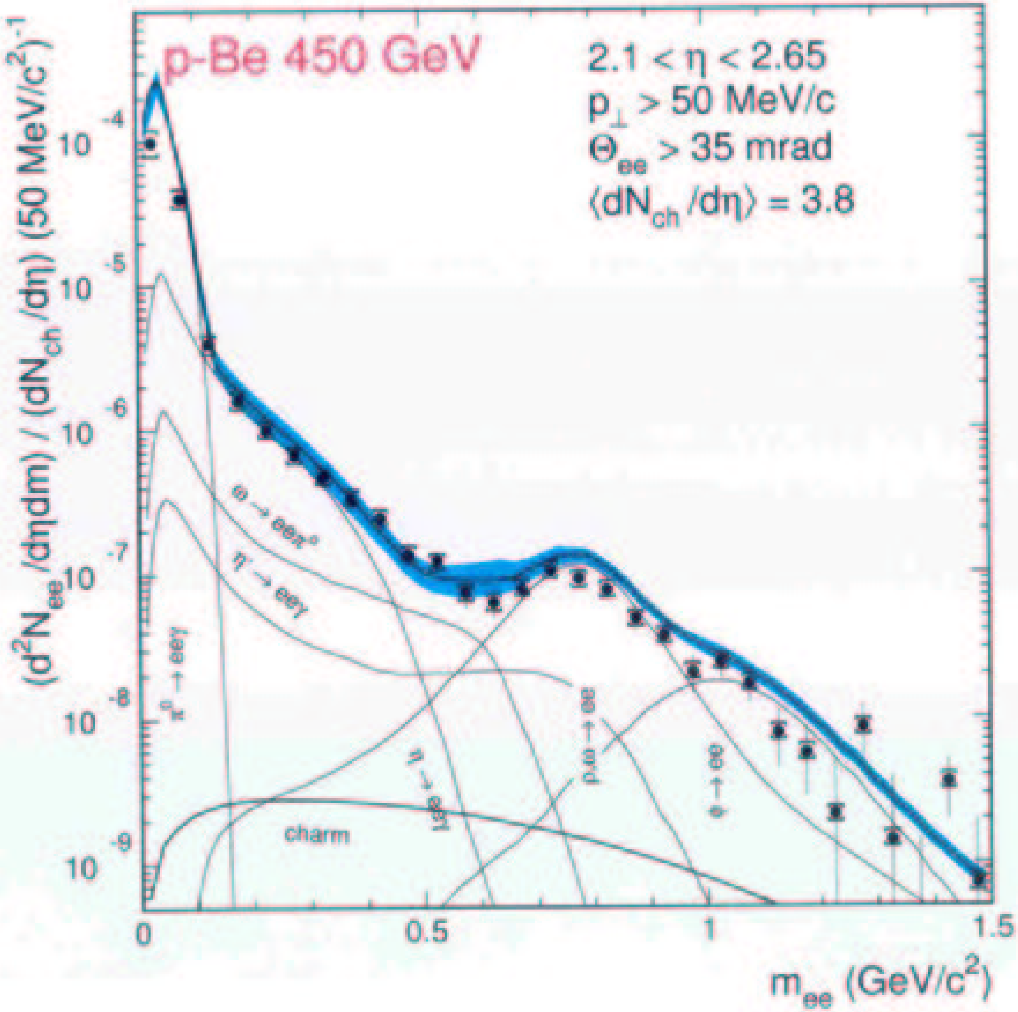
data enhanced over expectation
from hadronic decay
by factor 2.9 ± 0.3 (stat.) ± 0.6 (syst.)



Electron Pair Mass Spectrum in Nucleon-Nucleon Collisions

Data: CERES/NA45
Eur. Phys. J. **C4** (1998) 231 and 249

data reproduced by expectation
from hadronic decays
within 10-20 %



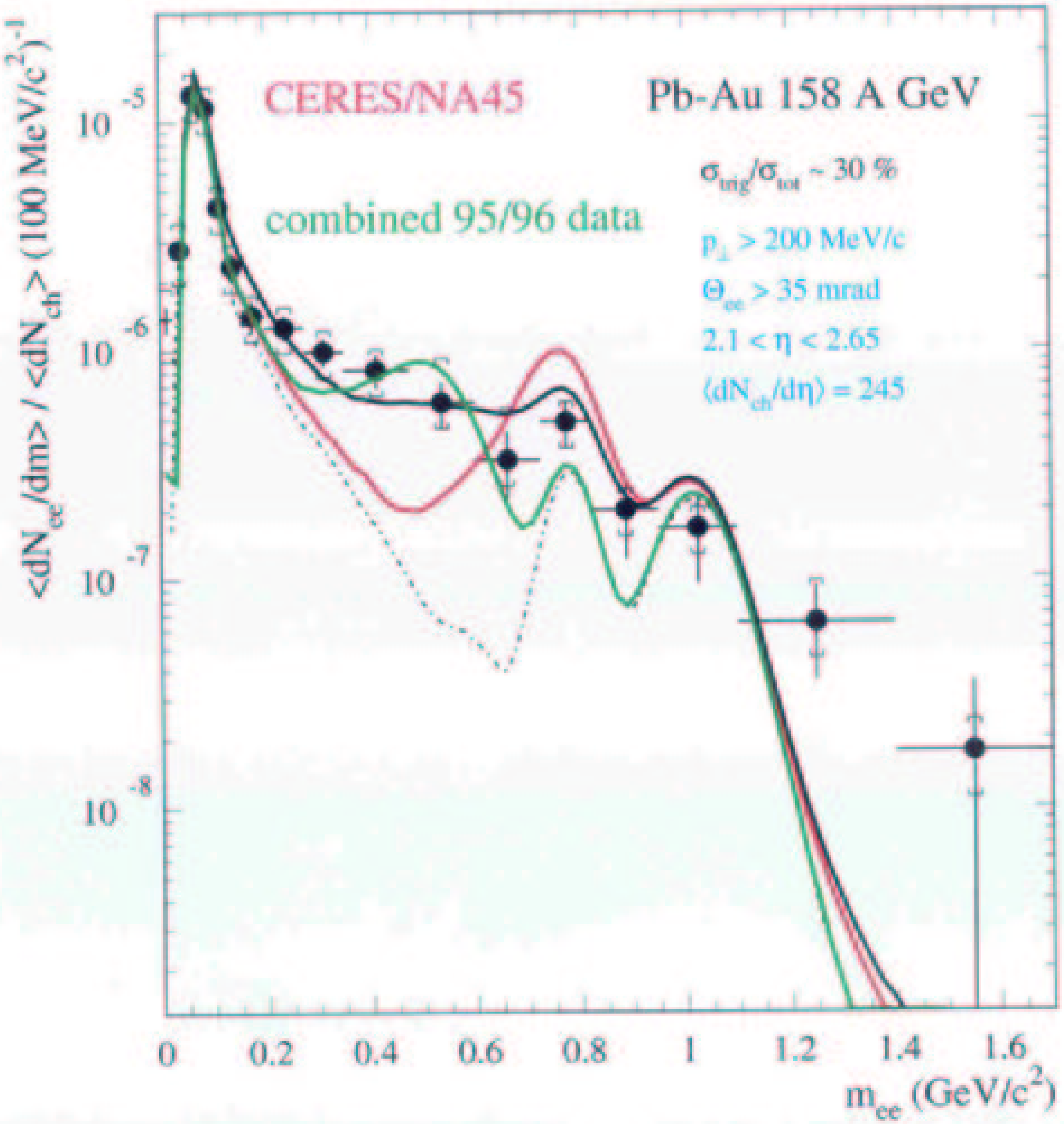
Comparison of Electron Pair Spectrum to Calculations

Data: CERES/NA45

Calculations: R. Rapp, J. Wambach

- pion-annihilation included
- Brown-Rho scaling of masses
- Rapp-Wambach in-medium modification

Enhancement due to temperature and density induced medium modification of ρ

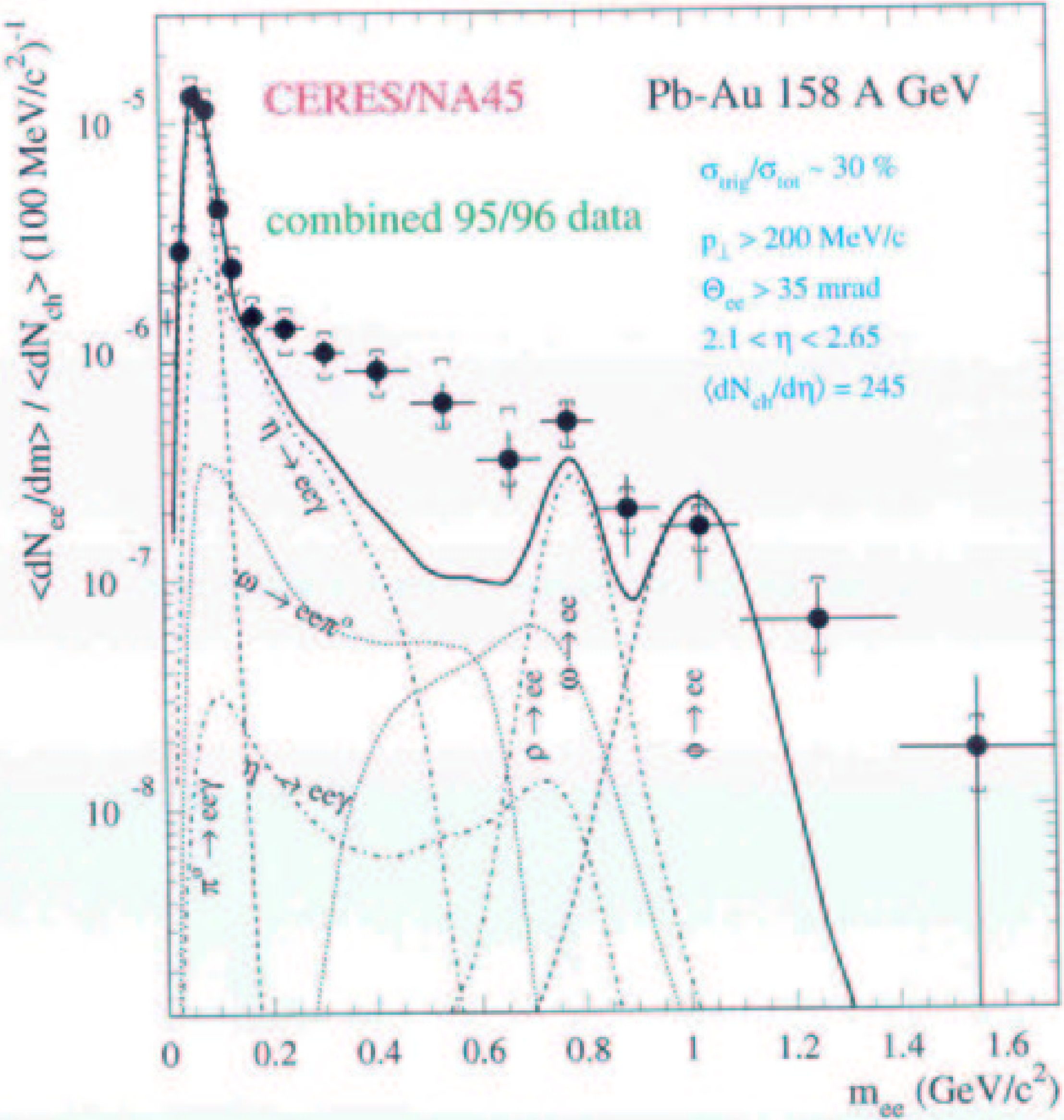


Electron Pair Mass Spectrum in Pb+Au at 40 A GeV/c

Data: CERES/NA45
Ph.D. thesis S. Damjanovic
and nucl-ex/0111009

data enhanced over expectation
from hadronic decay
by factor 5.1 ± 1.3 (stat.) ± 1.0 (syst.)

effect even larger
than at 158 A GeV!



Comparison of Electron Pair Spectrum to Calculations

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- pion-annihilation included
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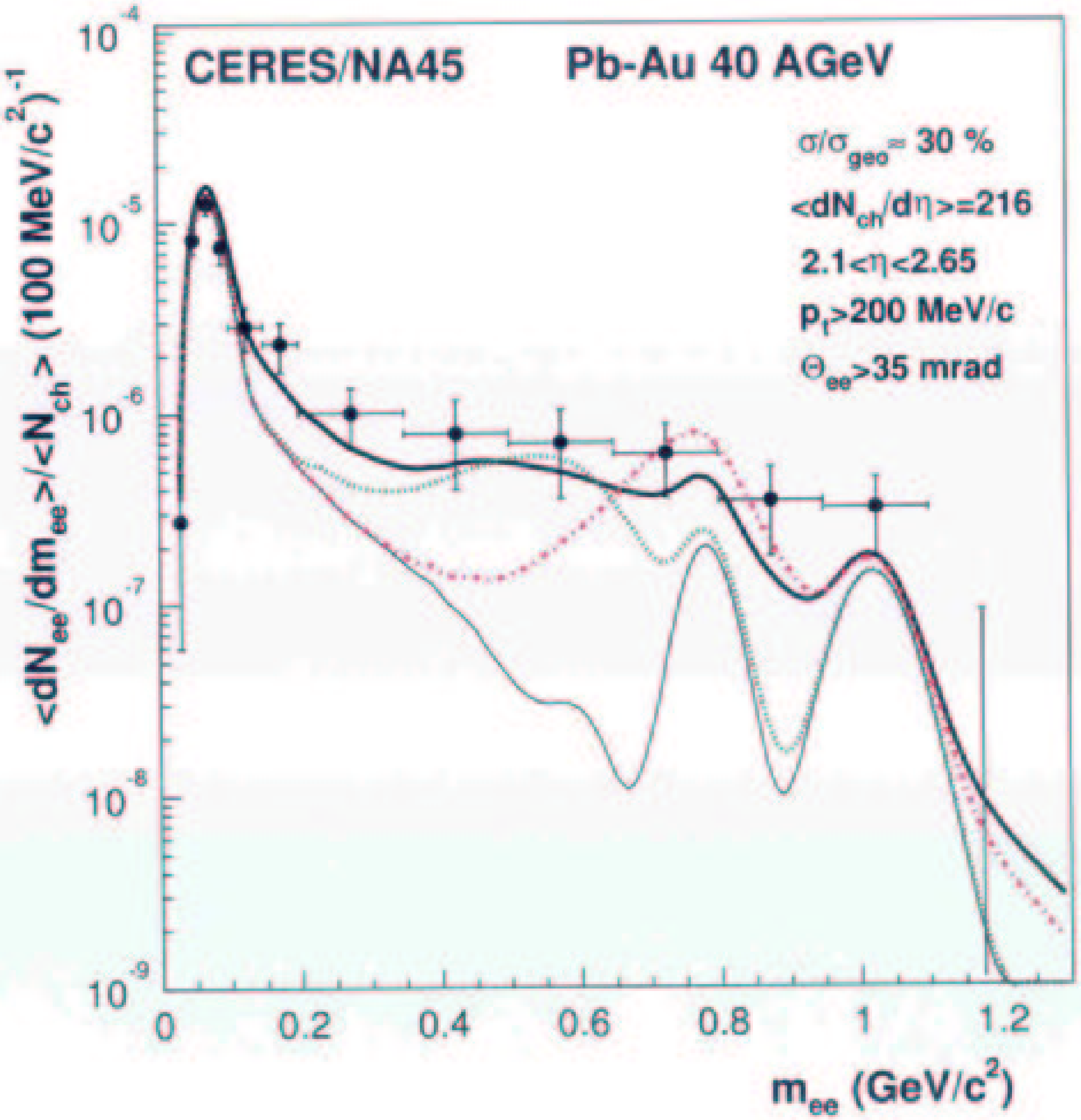
Same type of medium modification accounts for data

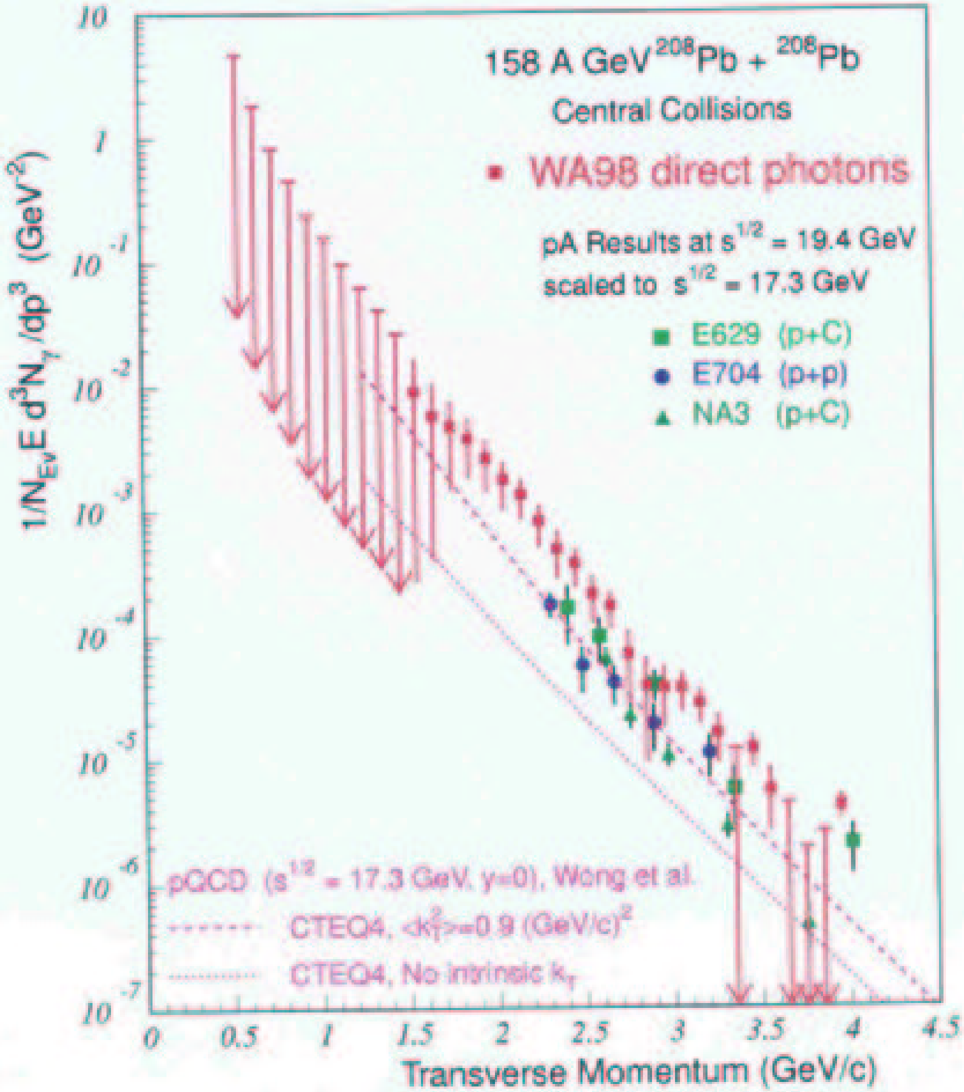


Direct Photons in Pb+Pb Collisions

Data: WA98
Phys. Rev. Lett. **85** (2000) 3595

p-p and p-A scaled to A-A

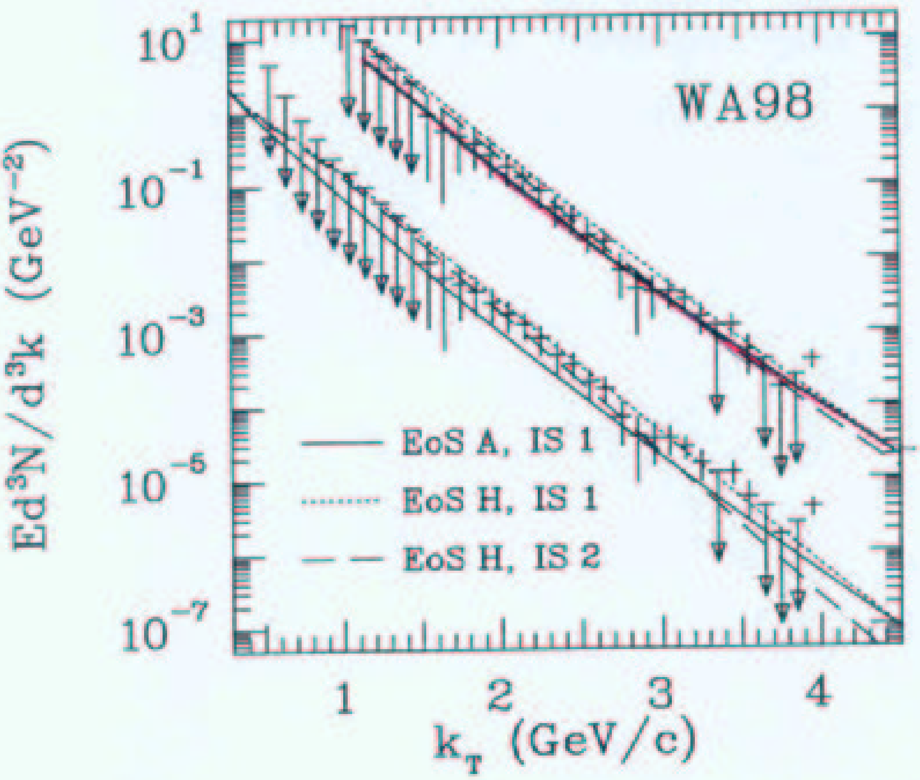
excess over hard scattering even for relatively large k_t broadening



P. Huovinen, P.V. Ruuskanen, S.S. Räsänen, nucl-th/0111052

- using all orders in multi-loop expansion as derived in P. Arnold, G. D. Moore and L. G. Yaffe, hep-ph/0109094, and hep-ph/0111107.
- finite initial longitudinal size, hydro tuned to reproduce rapidity distributions and spectra

	IS 1		IS 2		BI (0.3)	BI (1.0)
	EoS A	EoS H	EoS A	EoS H	EoS A	EoS A
$T_{\max}$ (MeV)	325	275	265	245	364	244
$\overline{T}(z=0)$ (MeV)	255	234	214	213	301	214

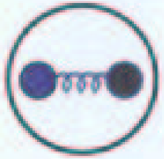


Thermal photon emission for different EoS and initial state with the contribution of initial pQCD photons (upper set, scaled by factor 100) and without (lower set).

➡ EOS with phase transition and initial condition IS1 gives very good description of data

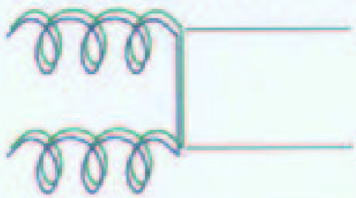
Charm production and J/ψ – suppression

Hadrons with charm–anticharm valence quarks



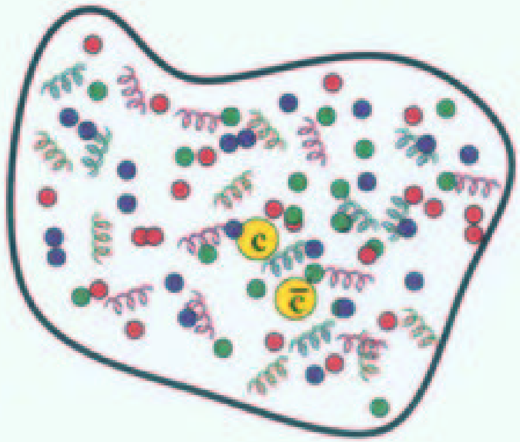
	J/ψ	ψ'
	r=0.45 fm	r=0.9 fm
	mass=3097 MeV	3686 MeV

production of charm–anticharm quarks by gluon fusion in the early stage of the collision



typically 1 $c\bar{c}$–pair per 6 Pb+Pb collisions
about 1 in 118 would evolve into a J/ψ
about 1 in 7200 into a ψ'

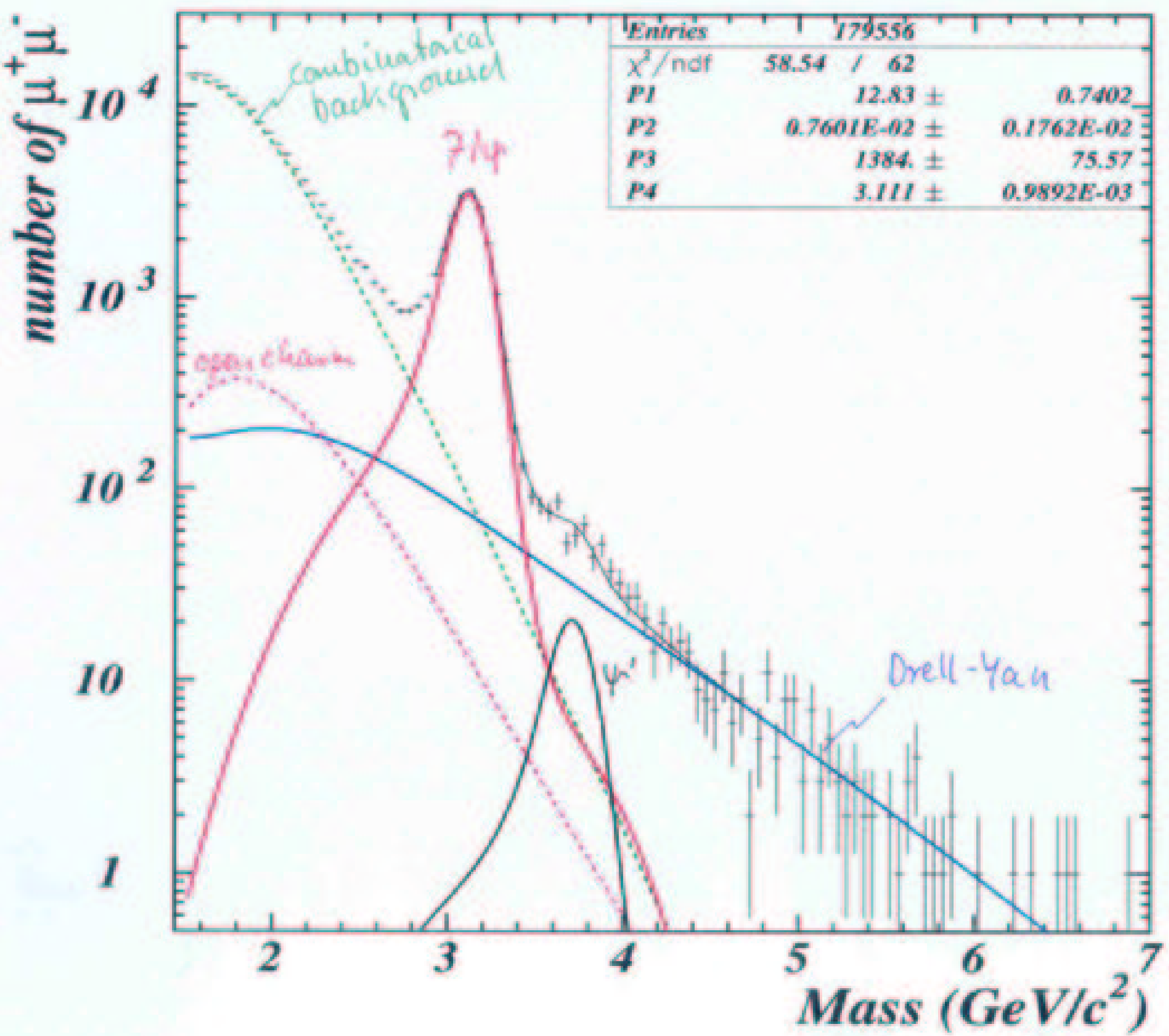
but in Quark–Gluon–Plasma c and $\bar{c}$ do not find each other
"attractive interaction is screened"



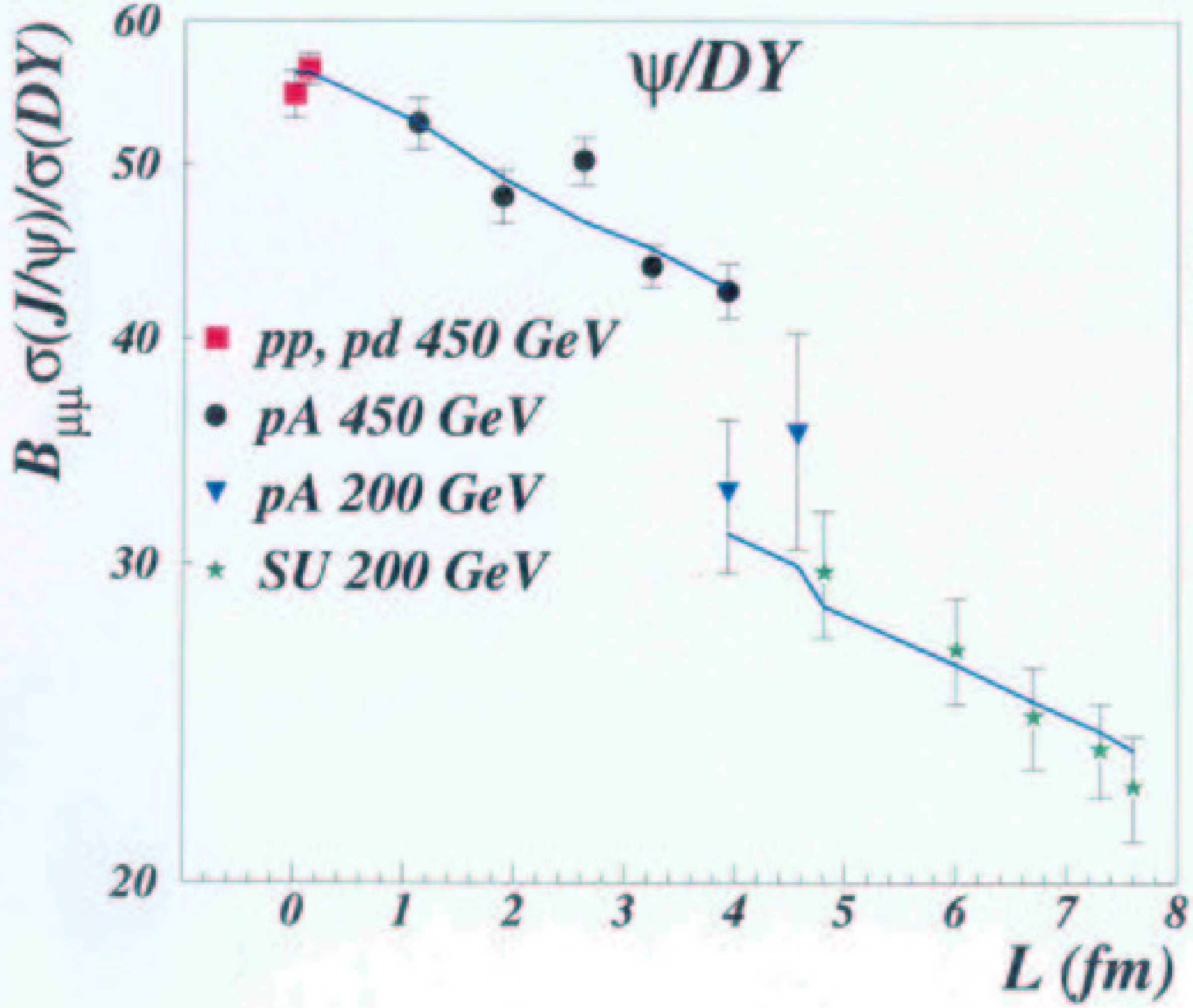
expect significantly less J/ψ
and ψ' than without Quark–Gluon–Plasma

Detection: 7% of all J/ψ -> $\mu^+\mu^-$

NA50 invariant mass spectrum

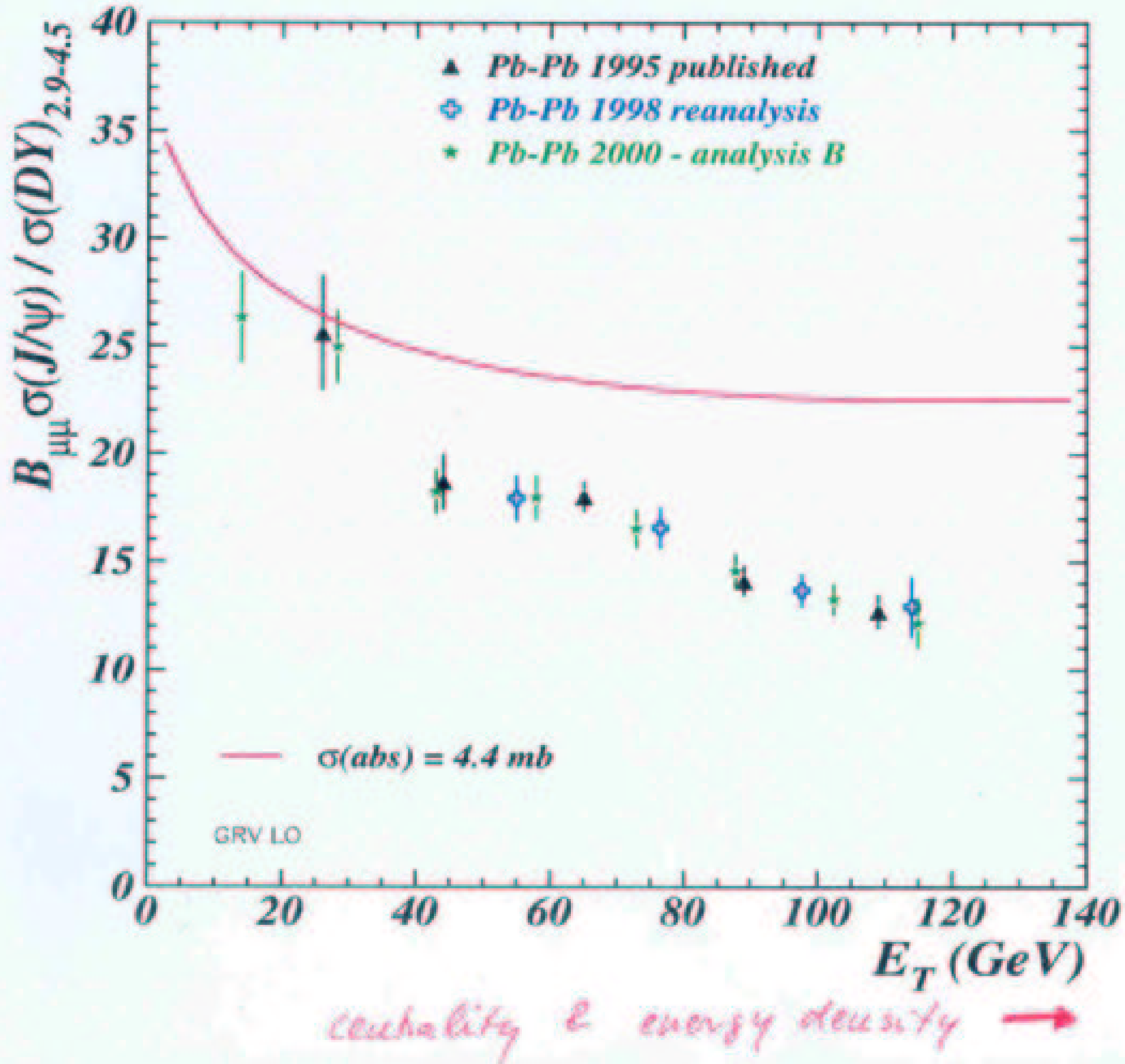


Absorption of J/ψ in nuclear medium

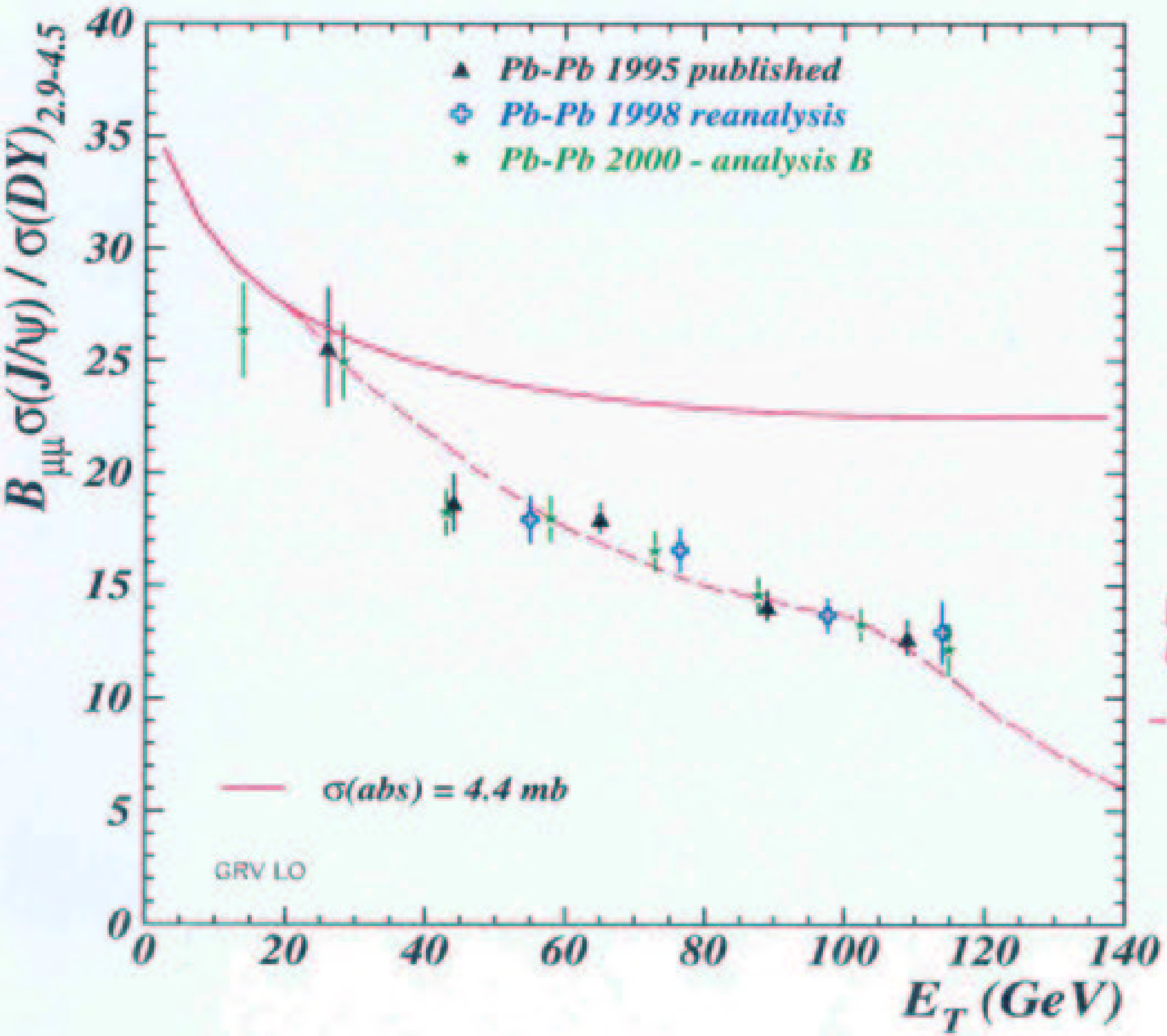


$\sigma_{abs} = 4.4 \pm 0.5$ mb

J/ψ suppression: new NA50 results, L. Ramello, QM2002 proceedings



J/ψ suppression: new NA50 results, L. Ramello, QM2002 proceedings



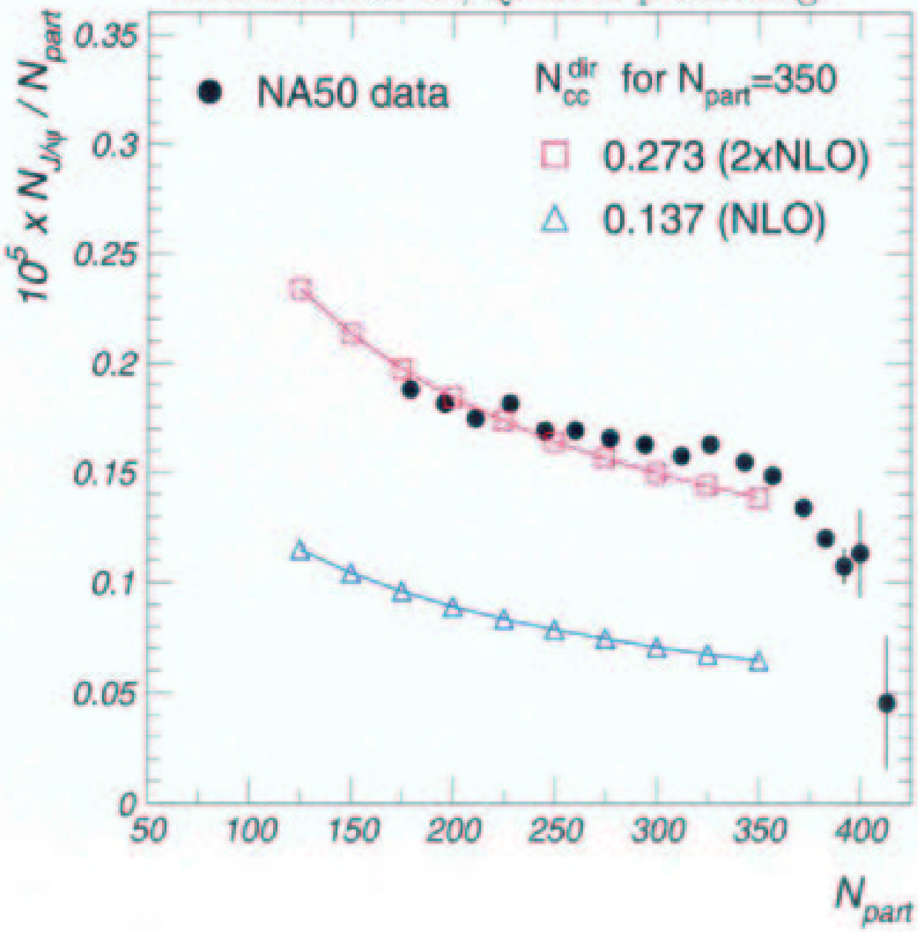
Blaizot, Dinh, Ollitrault
nucl-th/0007020:
--- adding QGP absorption
50% of J/ψ melts at 3.3 fm^{-2}
(χ_c)
100% at 4.2 fm^{-2}
+ density fluctuations
at high E_T

Statistical hadronization: idea and results (SPS)

P.Braun-Munzinger, J.Stachel, PLB 490 (2000) 196 ; NPA 690 (2001) 119c

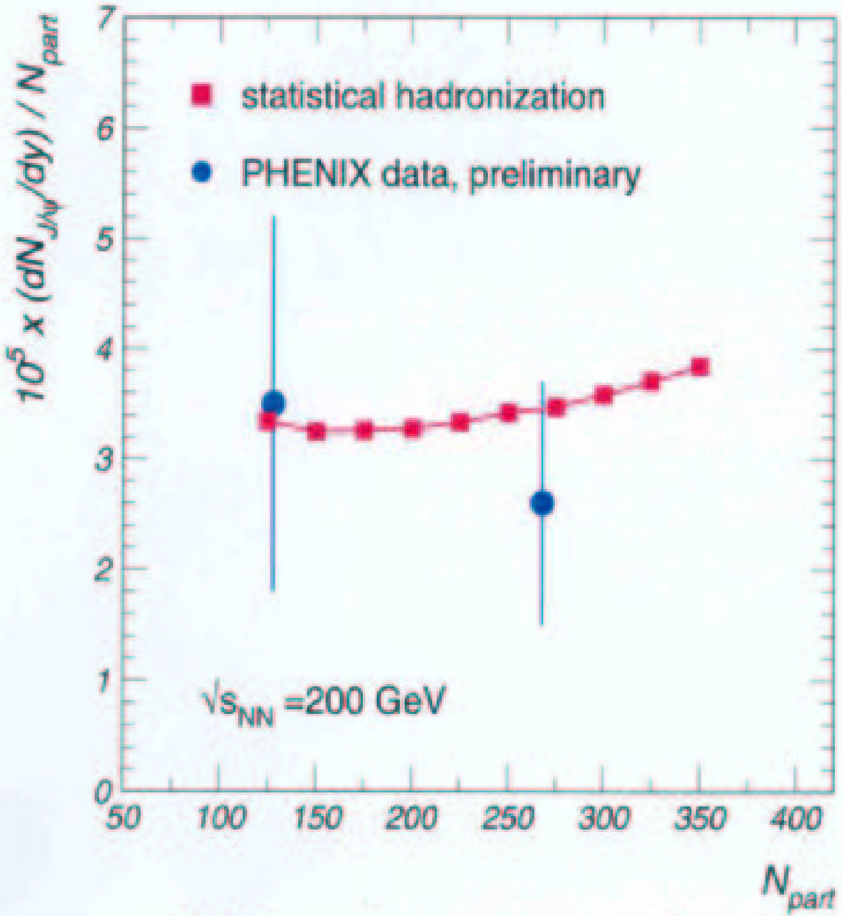
- all charm quarks are produced in primary hard collisions
- charmed hadrons (open and hidden) are formed at freeze-out (at SPS and beyond, freeze-out is at phase boundary)
- full screening (no J/ψ is preformed in QGP)
- could be a signal of deconfinement

A.Andronic et al., QM2002 proceedings

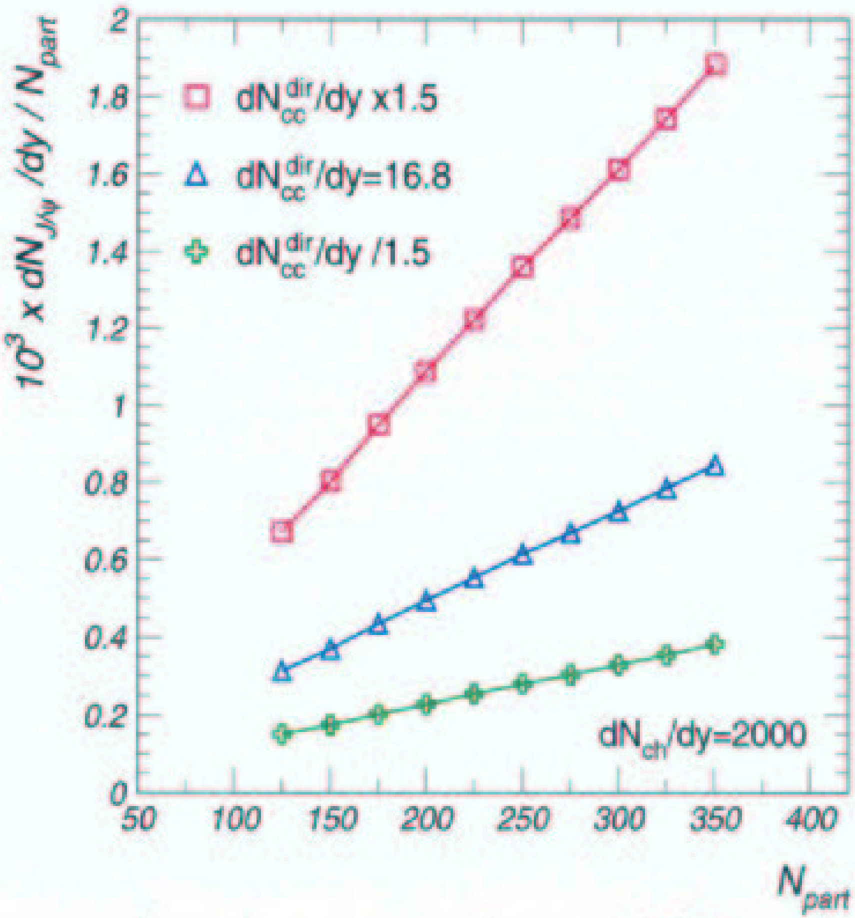


Predictions for RHIC and LHC ($\mathrm{d}N_{J/\psi}/\mathrm{d}y$)

RHIC



LHC



LHC: enhancement by a factor larger than 5 compared to pQCD

High Energy Heavy Ion Collisions at the CERN SPS

Johanna Stachel

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- Motivation - the QCD Phase Transition *now from LQCD: $T_c = 178 - 8$ MeV and dropping for $\mu > 0$*
- the SPS Heavy Ion Program - Summary of Results *15 years of experimentation →*
  - Yields of Produced Hadrons *hadron yields at full SPS energy equilibrated frozen at phase boundary*
  - Particle Spectra and Correlations *strong collective transverse expansion $\langle\beta\rangle \simeq 0.5$*
  - Low Mass Electron Pairs *properties of ρ changed at high density & T ↔ chiral sym. restor.*
  - Direct Photons *contribution beyond initial scat., $\langle T_i \rangle_{\tau_0} \simeq 255$ MeV $\simeq 1.5\, T_c$*
  - Charmonia *most consistent interpretation: signal of deconfinement (+ statistical hadronization)*
- Outlook - the Colliders and the Hot QCD Plasma *probe properties of QGP*
  much higher T_i, longer lifetime

new probes at high energy: jets, photons, heavy quarks, ...

RHIC now

LHC from 2007