NEUTRINOS FROM THE LAB, THE SUN, AND THE COSMOS

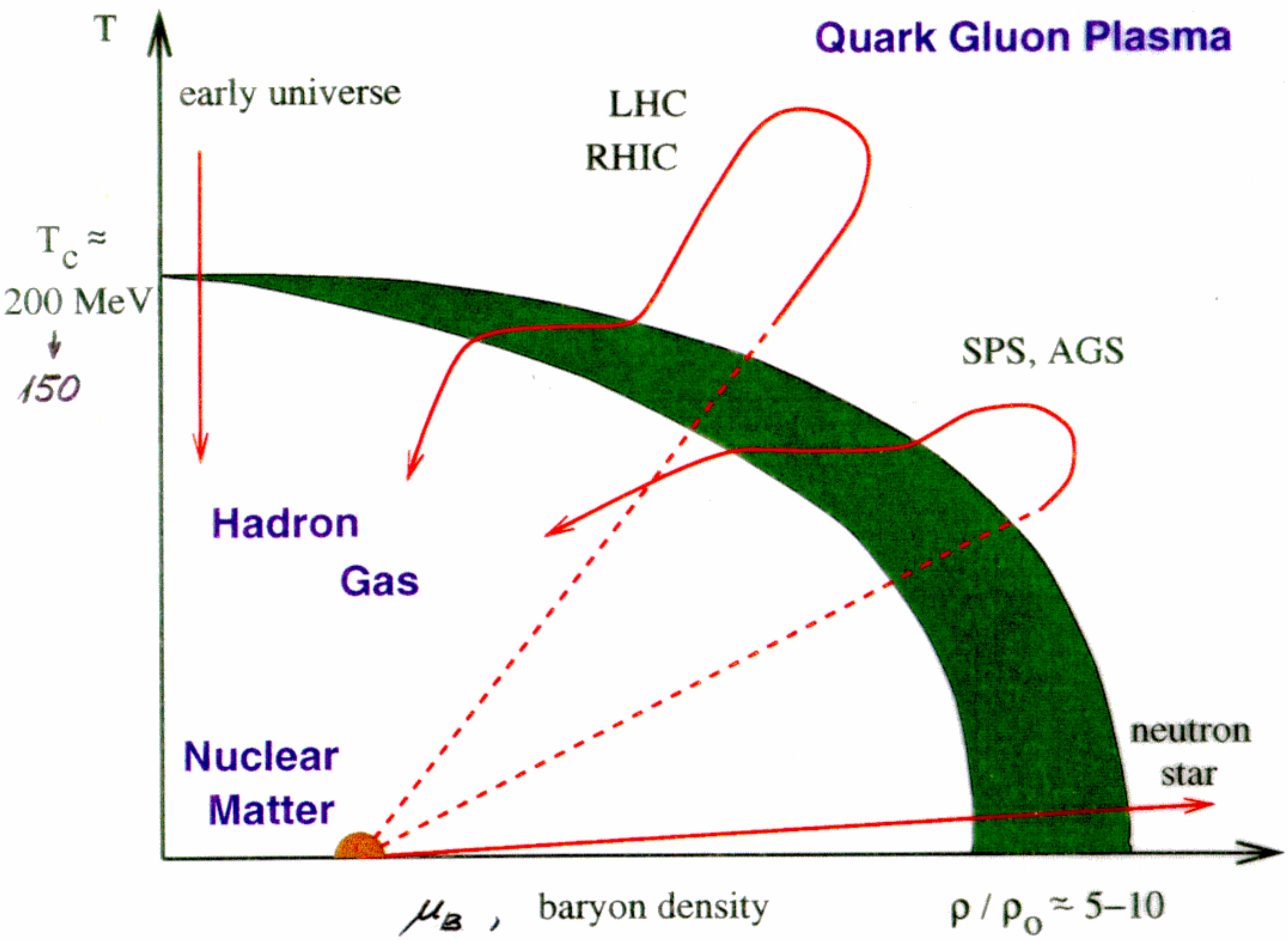
XXVIII SLAC SUMMER INSTITUTE
14-25 AUGUST 2000

Hans Specht

Quark Matter Formation at SPS Energies

Stanford Linear Accelerator Center
Stanford, California

Phase Diagram of Nuclear Matter



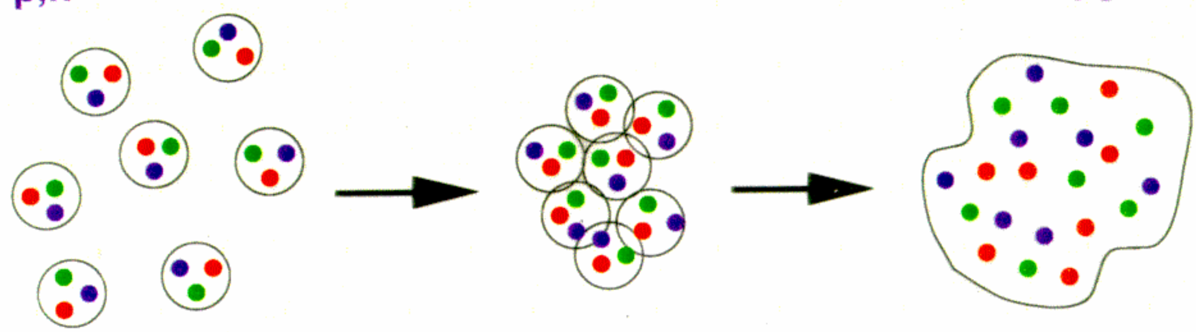
- QGP in Astrophysics

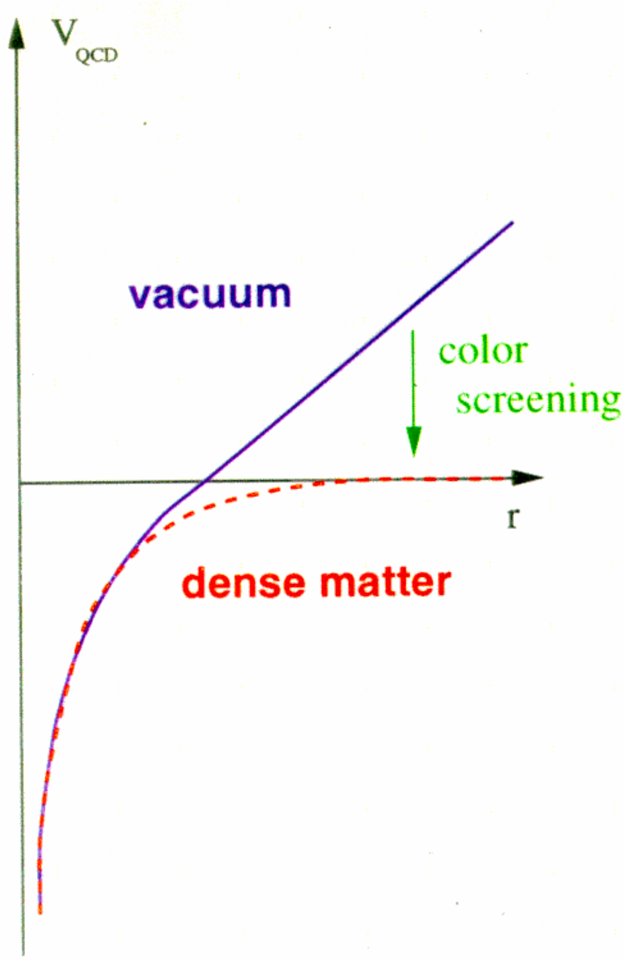
  early universe for times $< 10^{-6}$ seconds
  possibly in the interior of neutron stars

- QGP as transient state in heavy ion collisions

  verify experimentally existence of QGP
  study QCD confinement of quarks to hadrons
  study how hadrons get their masses

Nuclear Matter at High Temperature and Density





QCD potential:

- **in vacuum:**
  - linear increase with distance from color charge
  - strong attractive force
  - confinement of quarks to hadrons baryons (qqq) and mesons $(q\bar{q})$

- **in dense matter:**
  - screening of colour charges (similar to Debye screening in dense atomic matter)
  - potential vanishes for large distance
  - deconfinement of quarks → QGP

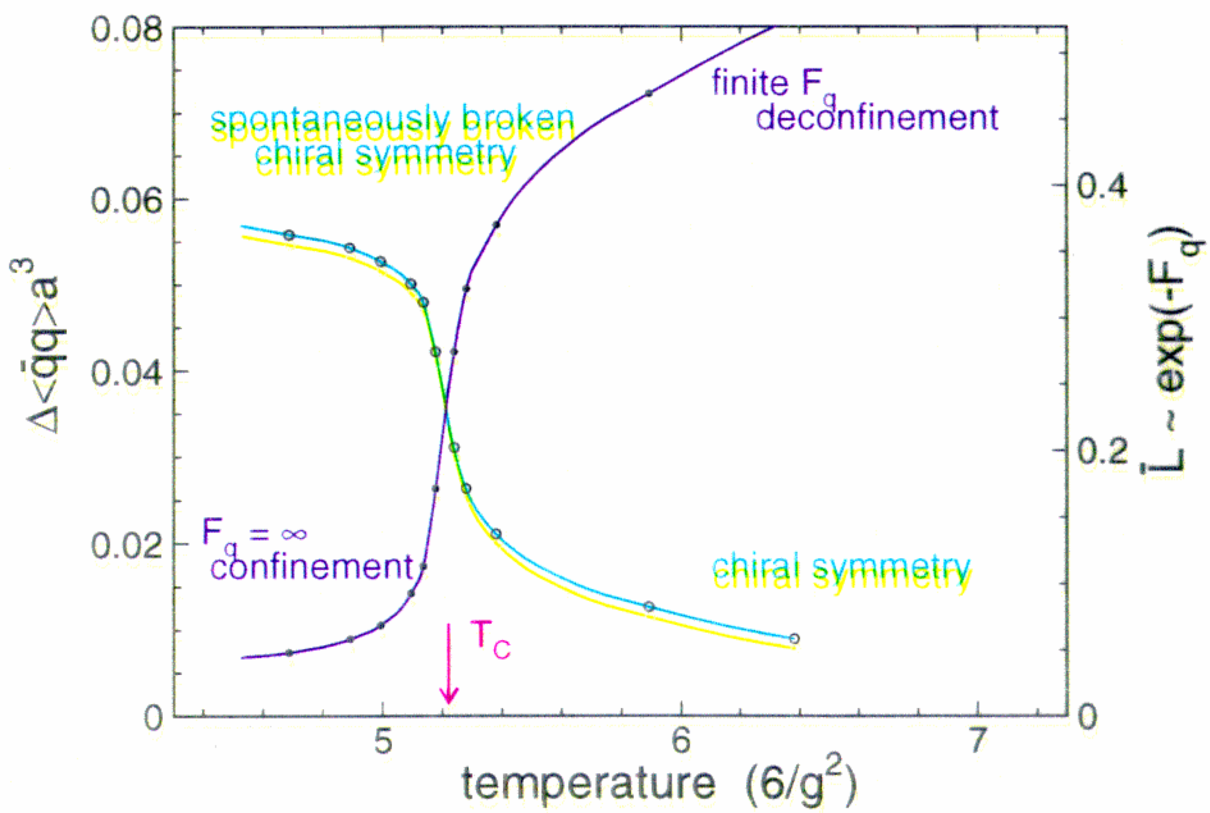
QCD Calculations on Lattice

- perturbative QCD calculations applicable only for
  large momentum transfer → small coupling
- for small momentum transfer → large coupling only solution
  numerical QCD calculations on lattice

Results from lattice QCD establish the phase transition

observe change of order parameter:

deconfinement:	Polyakov loop	$\bar{L} \sim e^{-F_q}$
chiral symmetry:	chiral condensate	$\langle \bar{q}q \rangle$



$T_C \sim$ ~~150 — 200~~ MeV/c^2

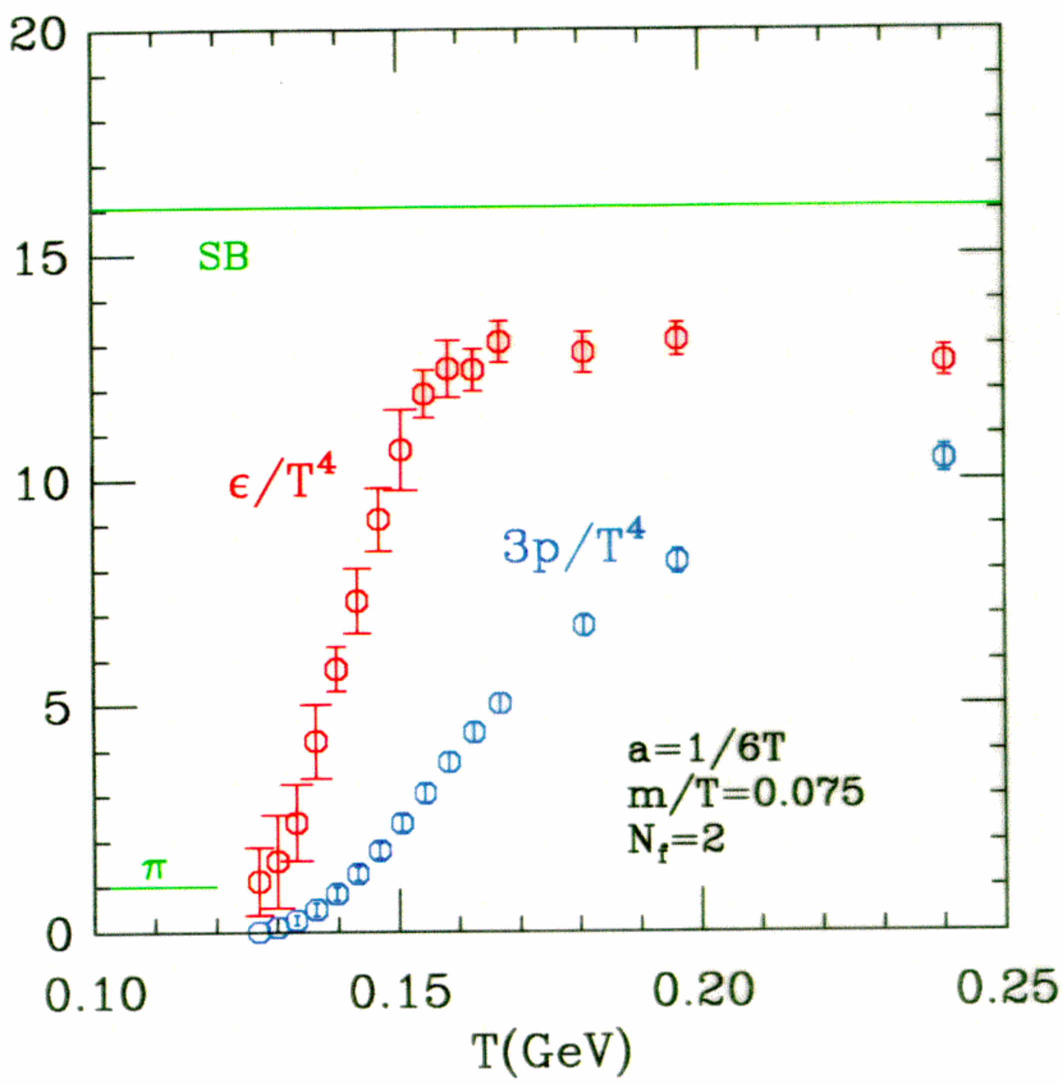
140 – 170

LATTICE QCD

2 (light) flavors

energy density ε and pressure p

(T. Blum et al., Phys. Rev. D51 (1995) 5153)



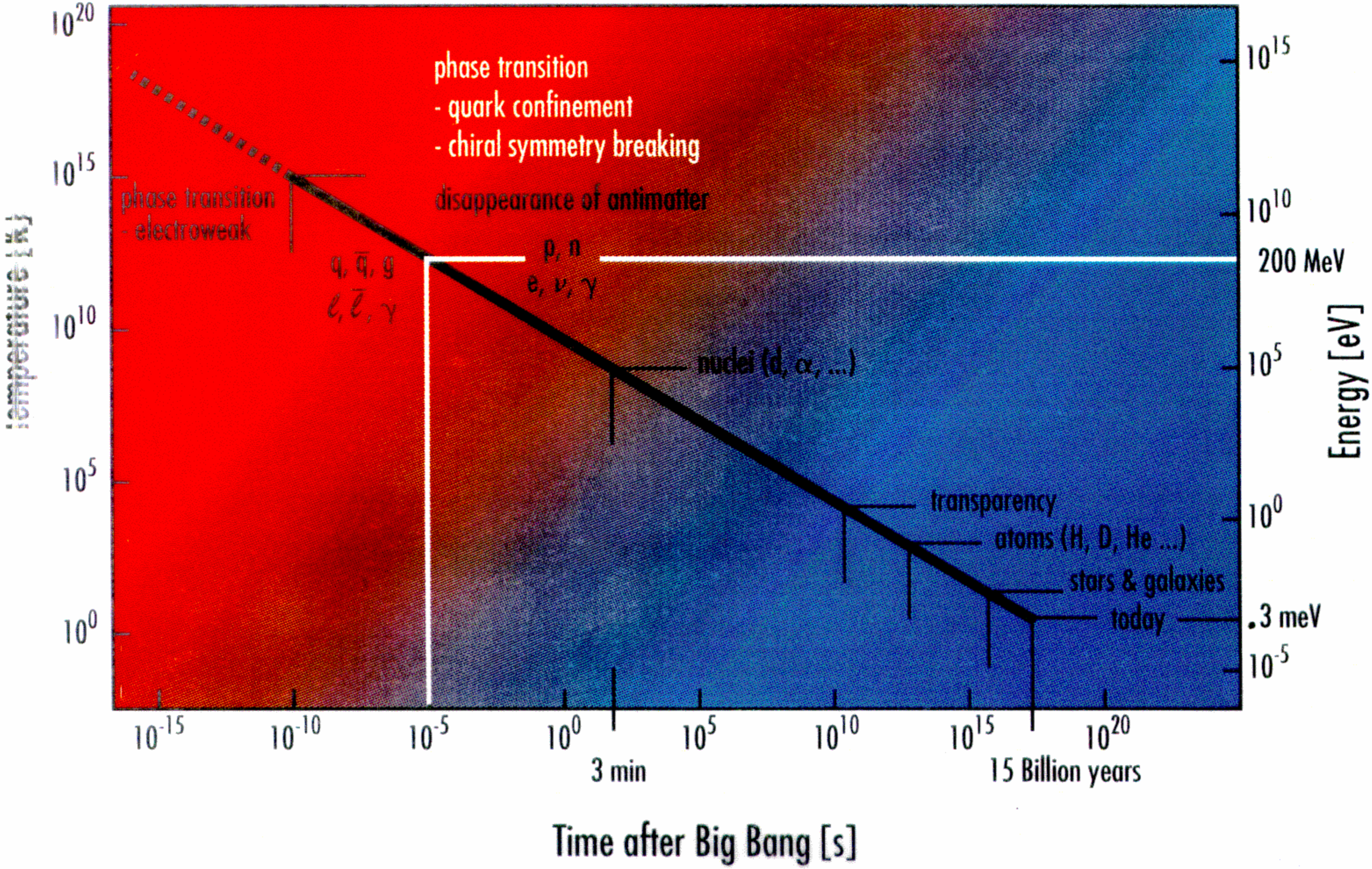
present critical values:

T_c ~ 140-170 MeV

ε_c ~ 1-2 GeV/fm³

H. J. Specht, SSI 2000

The development of the UNIVERSE



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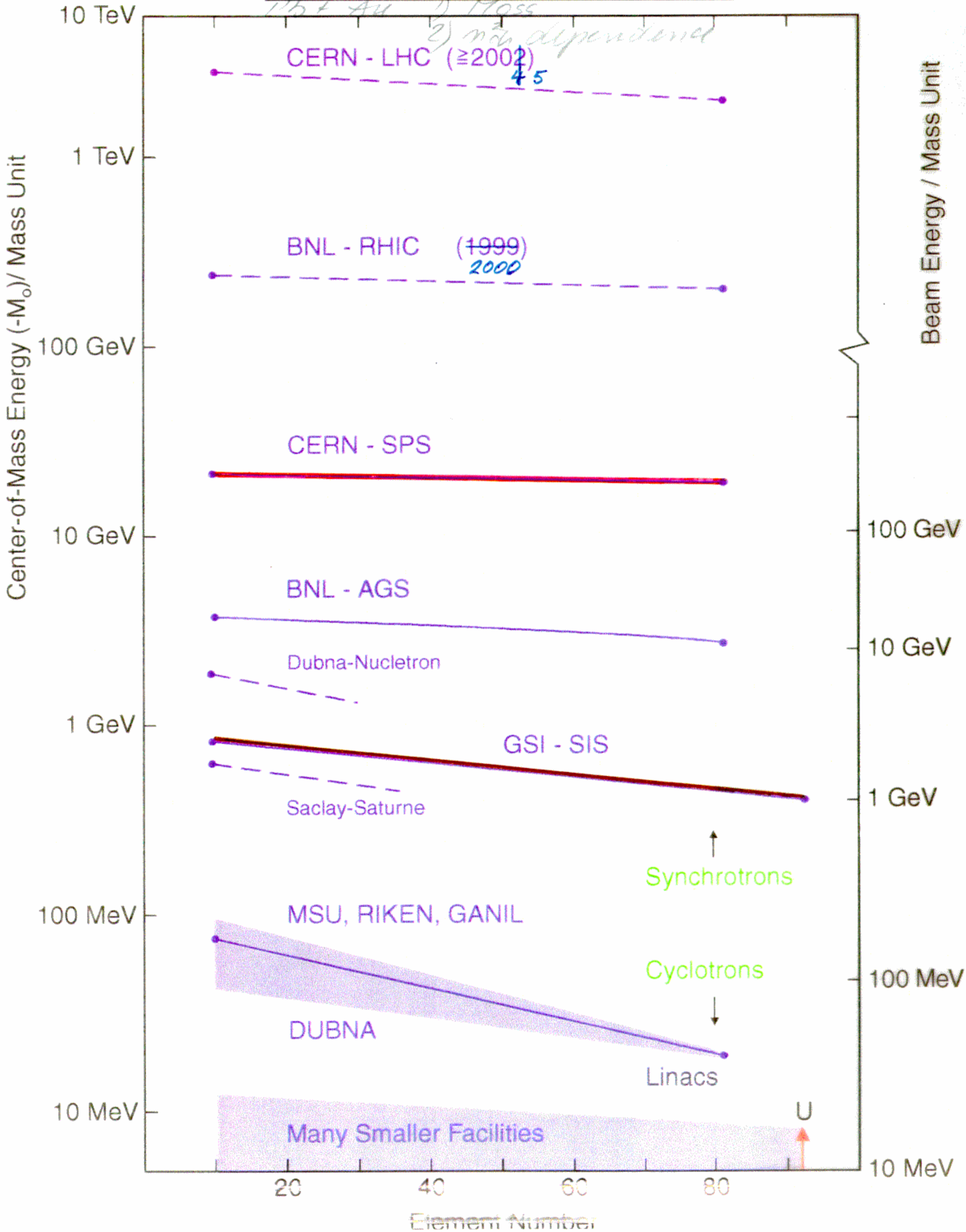
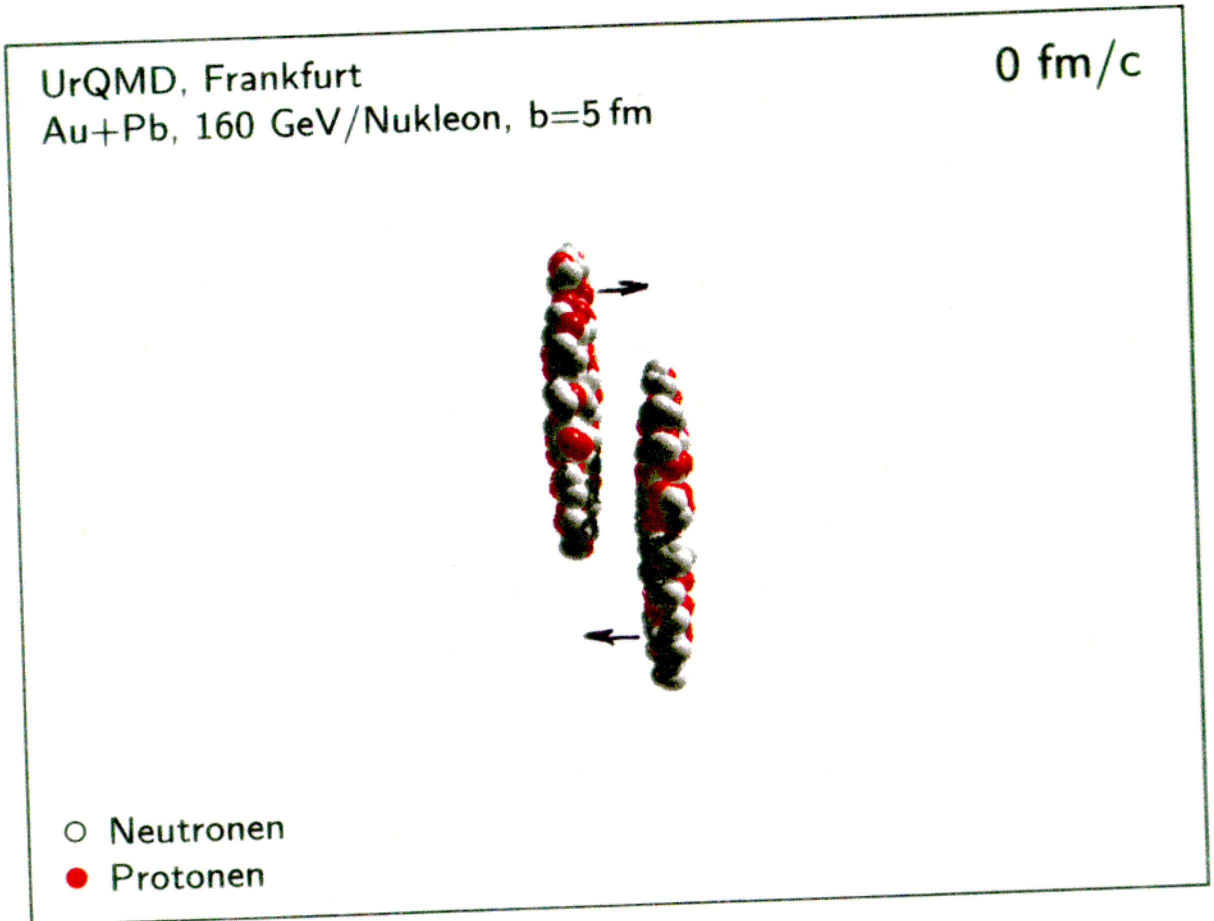
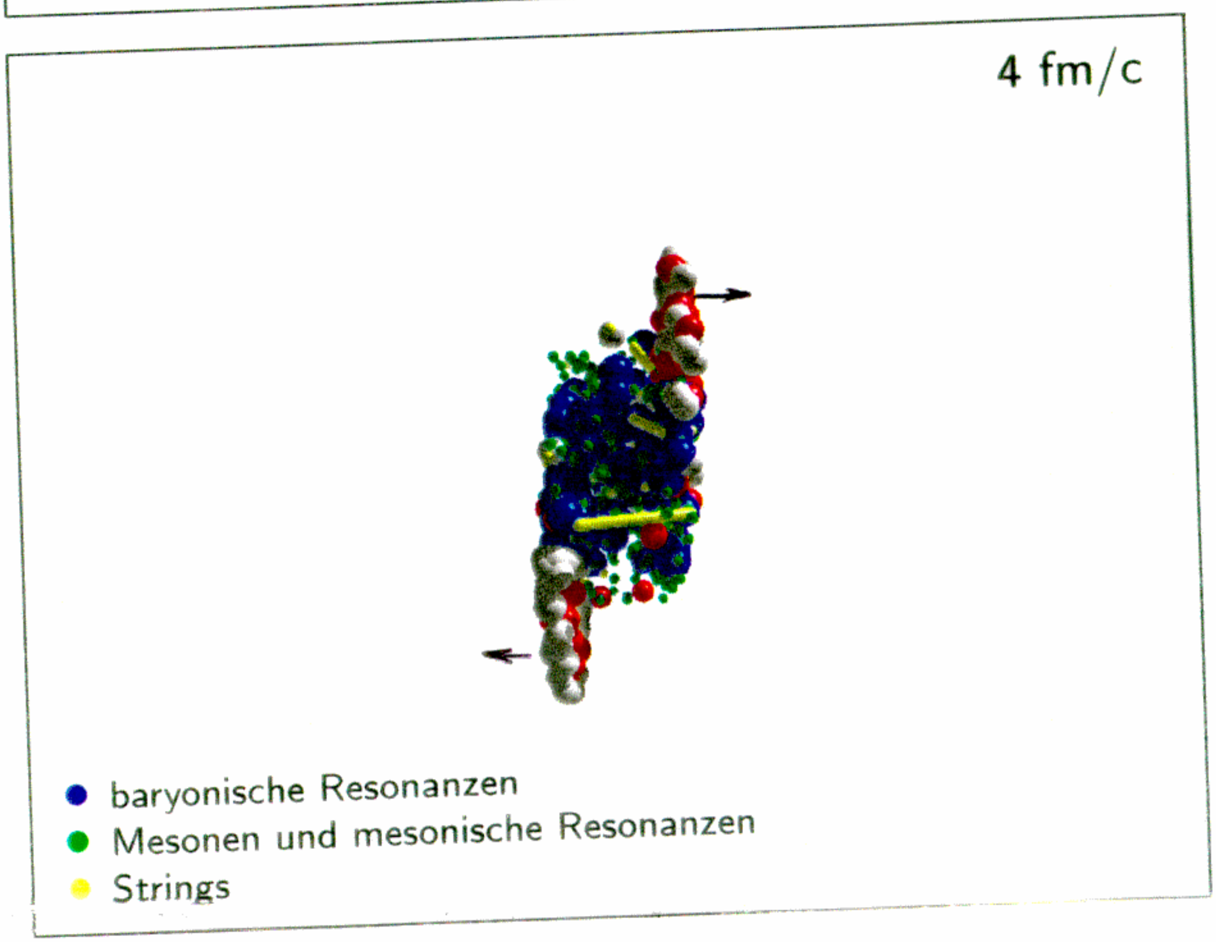
Heavy Ion Facilities Worldwide

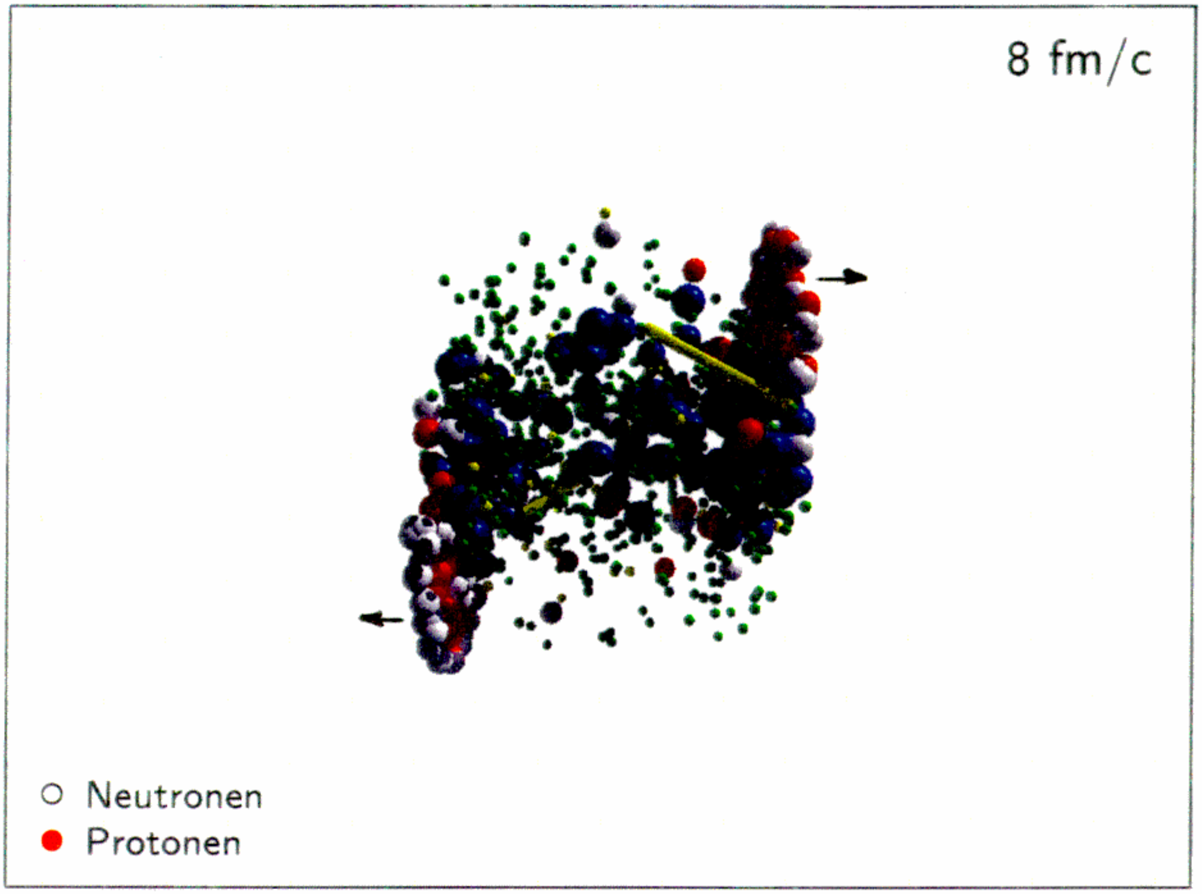


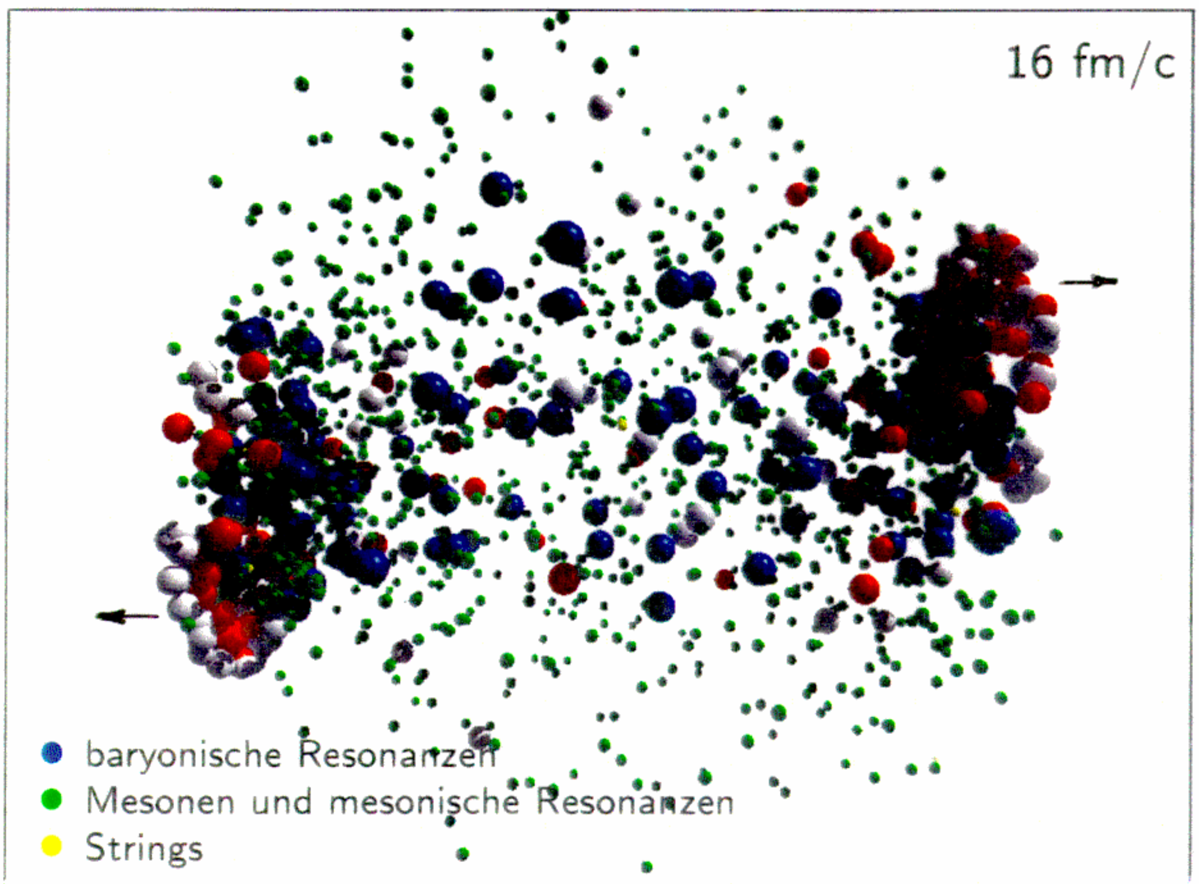
	AGS	SPS
Beam Momenta:	29·Z GeV/c	450·Z GeV/c
Beams:	p,Si,Au	p,S,Pb
Energy available in cm:	Au+Au 600 GeV	Pb+Pb 3200 GeV
Total Hadron Multiplicity:	900	2400
Pion : Nucleon Ratio	1:1	6:1
Produced : Constituent Baryons	1:1000	1:10

Henning Weber

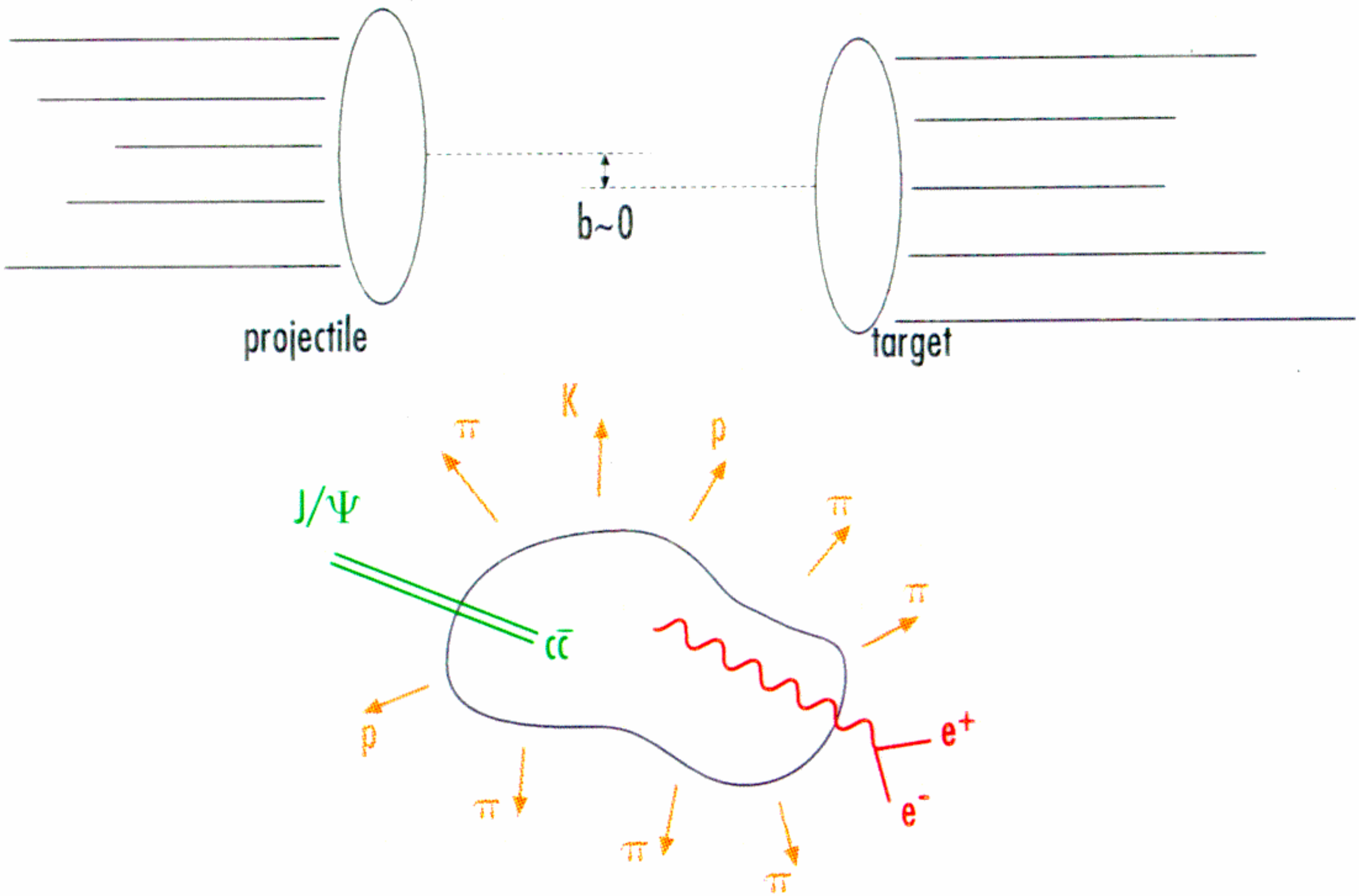





8 fm/c
Neutronen
Protonen


16 fm/c
baryonische Resonanzen
Mesonen und mesonische Resonanzen
Strings

Schemativ View of a Heavy Ion Collision



nearly 2000 particles are produced (central Pb + Pb)

light hadrons (π, K, p...)

most frequent (> 99%); produced "late"
sensitive to global properties (b, R, T_f, m_f)
sensitive to deconfinement?

heavy hadrons (J/Ψ =cc̄)

very rare (≪ 10^{-4} of hadrons); produced "early"
sensitive to interior properties (deconfinement)

photons and leptons (γ, e^+e^-...)

rare (<10^{-4} of hadrons); produced "any time"
sensitive to interior properties (chiral restoration)

exotica

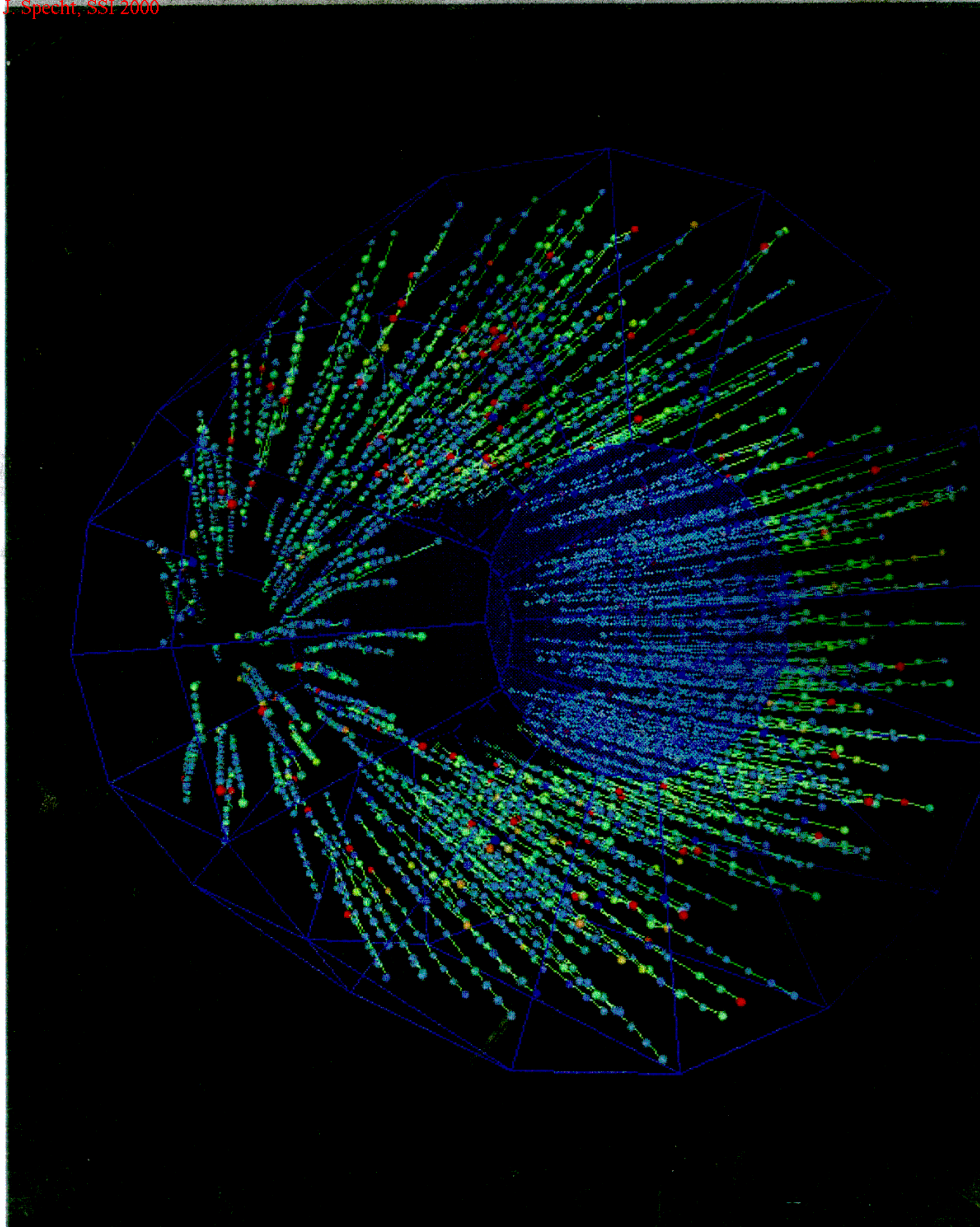
strange quark droplets?

SPS Pb-Beam Programme

- Experiments

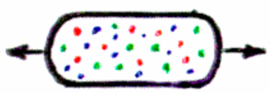
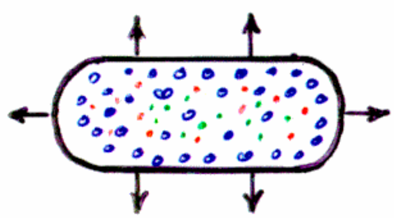
⊙	NA49	4π hadron experiment
⊙	WA97	hyperons
⊙	WA98	γ, π^0, η
•	NA44	HBT
⊙	NA45	e^+e^-
⊙	NA50	$\mu^+\mu^-$
•	NA52	strangelet research

- smaller experiments



CERES/NA45 TPC

Quark matter formation at SPS energies: "proof by circumstantial evidence"

system evolution	evidence
collision	(event selection)
	
quark matter formation	energy density 3 GeV/fm^3; T = 200 MeV
	• thermal photons/dileptons (?)
	memory effects in hadron yields:
	J/ψ suppression
	strangeness enhancement
collective expansion of fireball under pressure	memory effects in hadron spectra
	asymptotic: $\langle v/c \rangle \sim 0.4$
	
freeze-out at phase boundary in chemical equilibrium	thermal analysis of hadron yields (includ. memory effects)
	T = 170 MeV; μ_B = 0.27 GeV
chiral transition close to phase boundary (?)	• excess in low-mass dileptons

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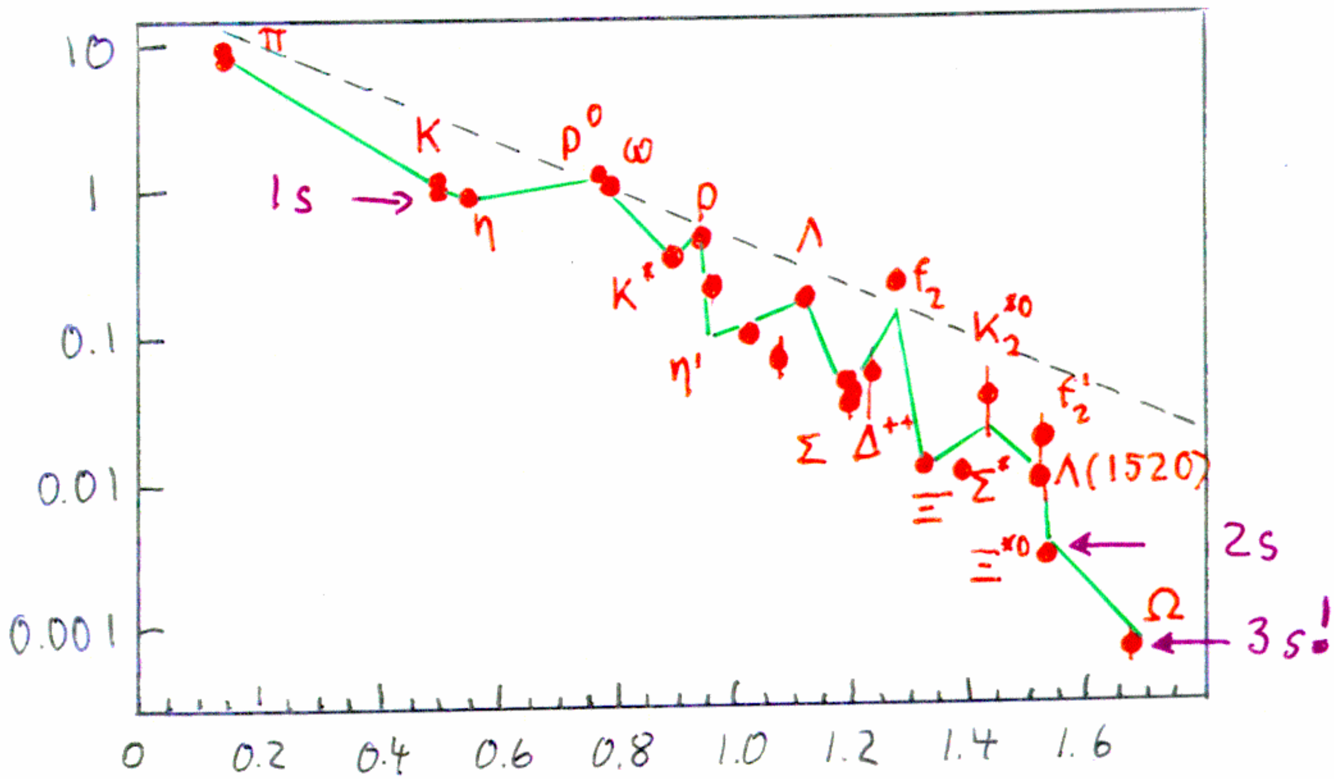
Particle Production in e^+e^- Collisions at $\sqrt{s}$ = 91.2 GeV (LEP)



generell trend:

exponential decrease with mass

inverse slope parameter ~ 160 MeV

(for uppermost yields)

additional feature:

strangeness suppression

suppression factor rises with S

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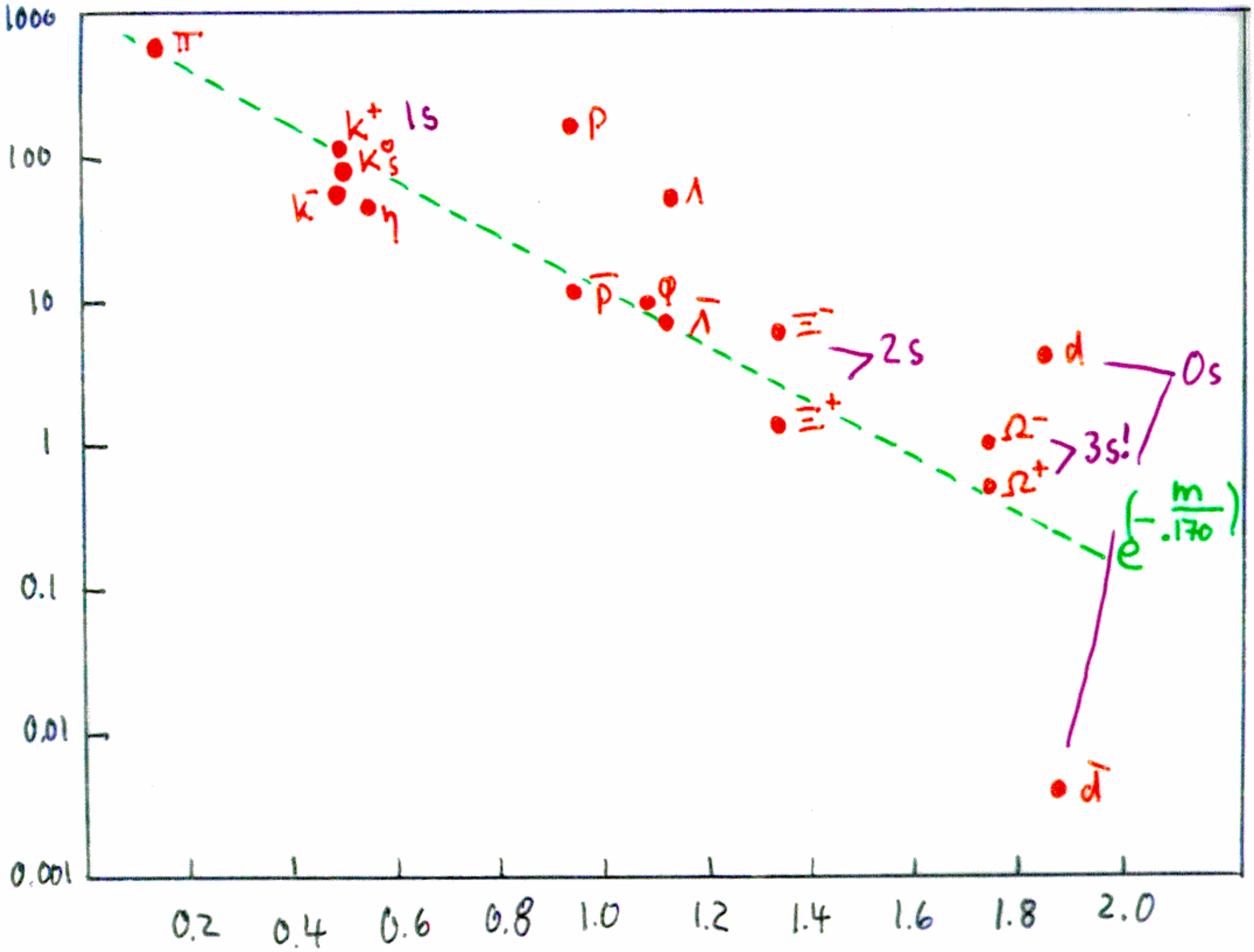
Particle Production in Pb-Pb Collisions at $\sqrt{s}$ = 18 GeV/nucl. (CERN SPS)



generell trend:

- exponential decrease with mass
- inverse slope parameter ~ 170 MeV

additional features:

- <u>no strangeness suppression</u>
- baryon - antibaryon splitting due to net baryons (> 400 nucl.)

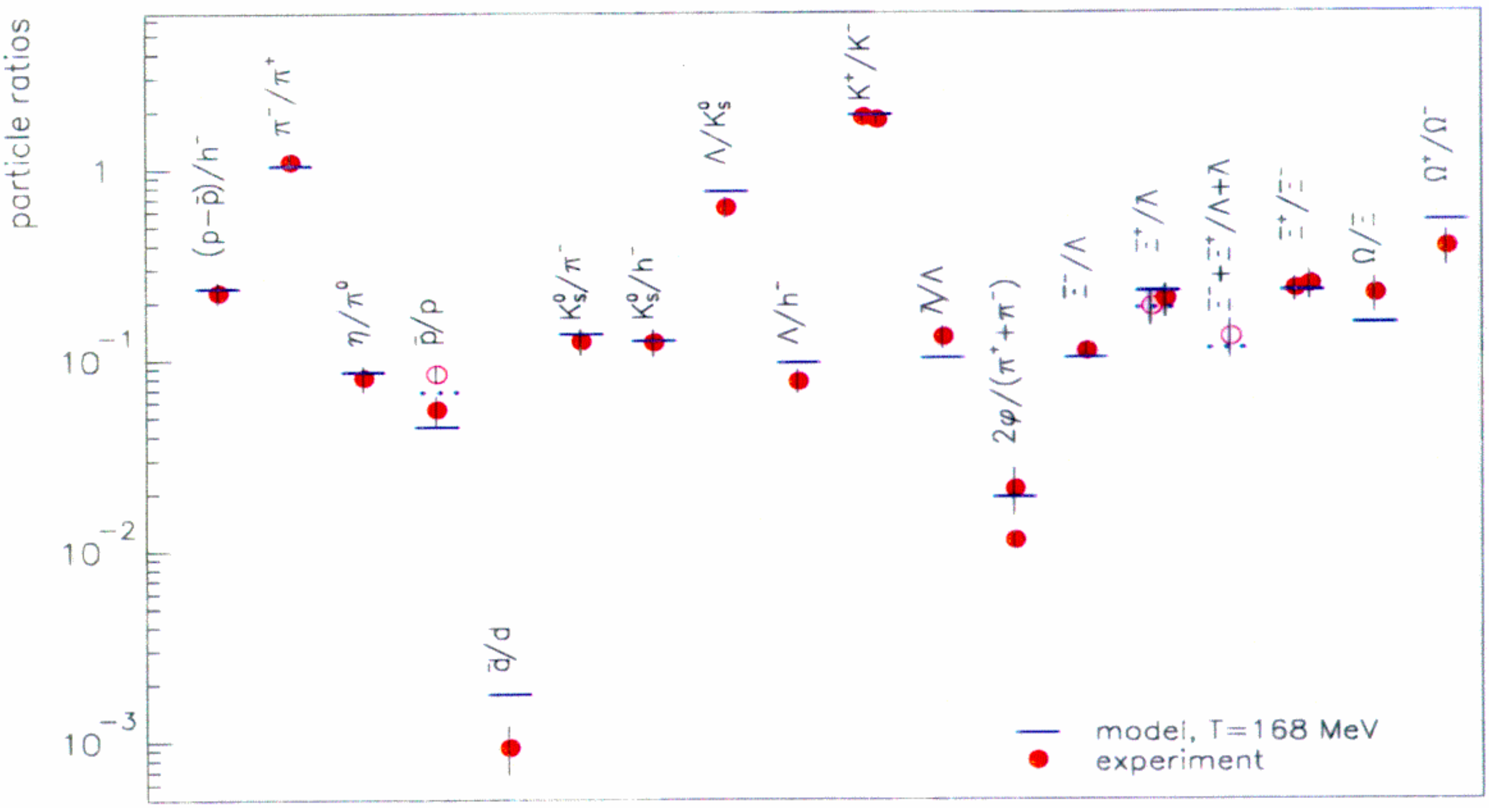
CERN SPS Data and Thermal Model

P.Braun-Munzinger, I. Heppe, J.Stachel, nucl-th/9903010, Phys. Lett. B

$T = 0.165 - 0.170$ GeV driven by $K^0_s/\bar{\Lambda}$, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, Ξ^+/Ξ^-
$\mu_b = 0.265 - 0.274$ GeV driven by p/π

$\mu_s = 0.071$ GeV *from* $\Delta S = 0$

$\mu_{I_3} = 0.005$ GeV *from* $\Delta Q = 0$

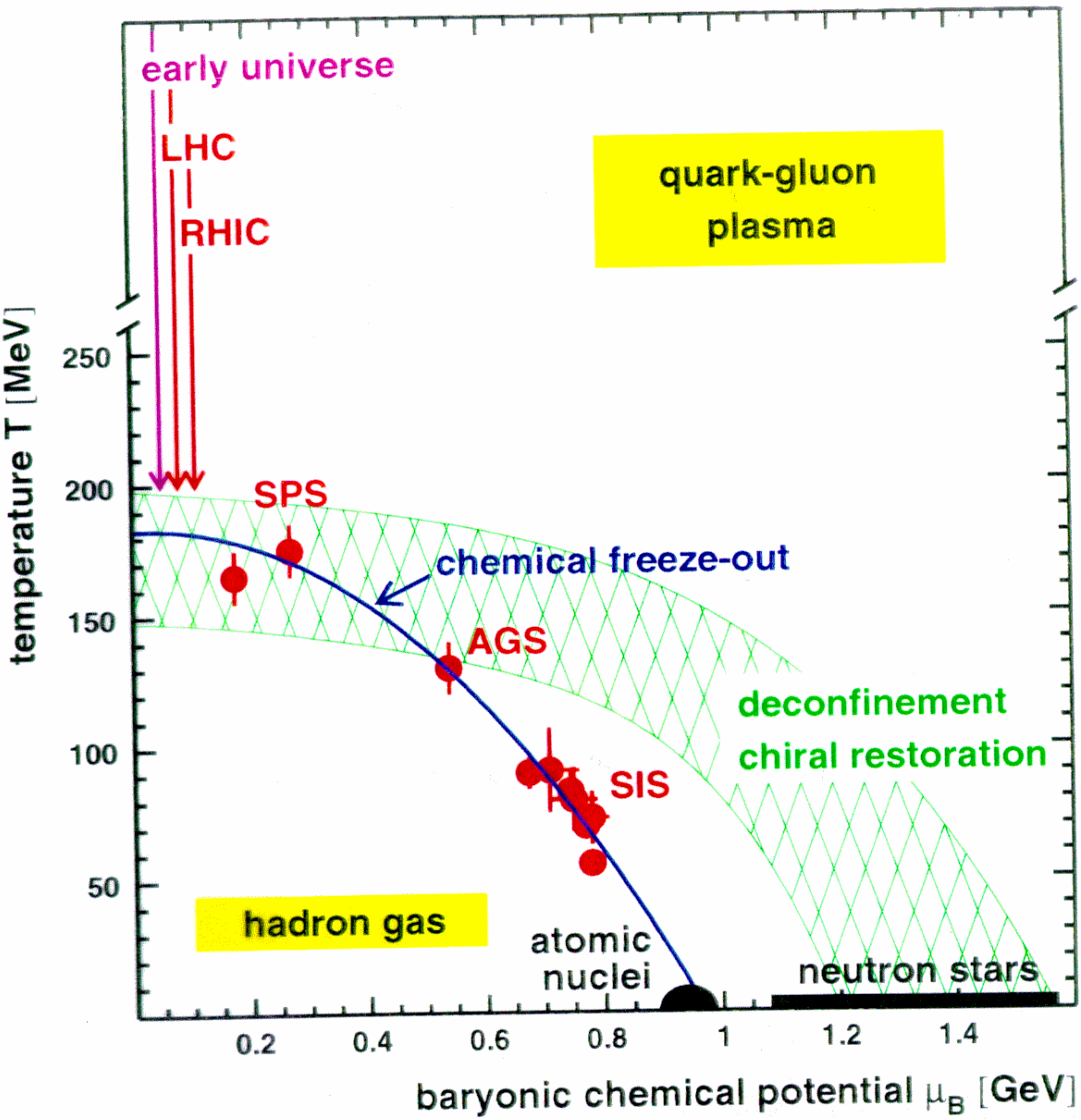


— model expectations for a statistical ensemble in chemical equilibrium

grand canonical

$$\rho_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{\exp[(E_i - \mu_B B_i - \mu_S S_i - \mu_{I_3} I_i^3)/T] \pm 1}$$

essentially 2 parameters to be fitted (T, μ_B)



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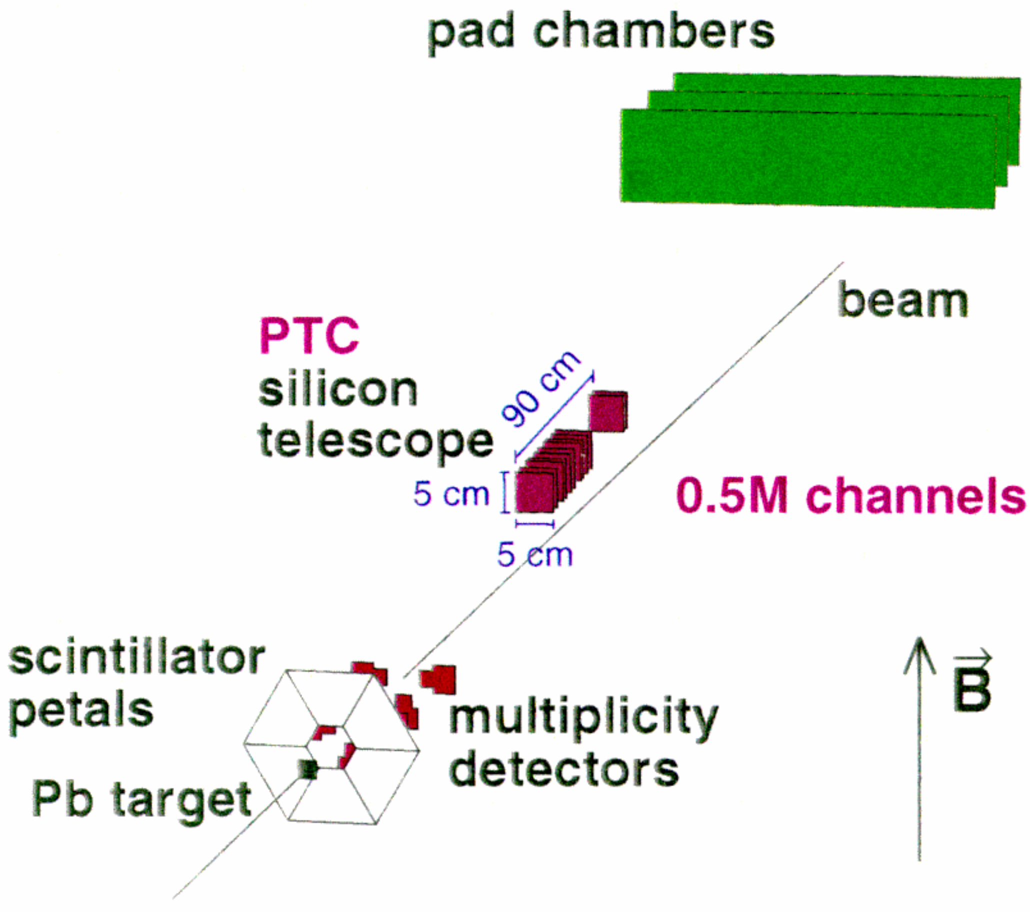
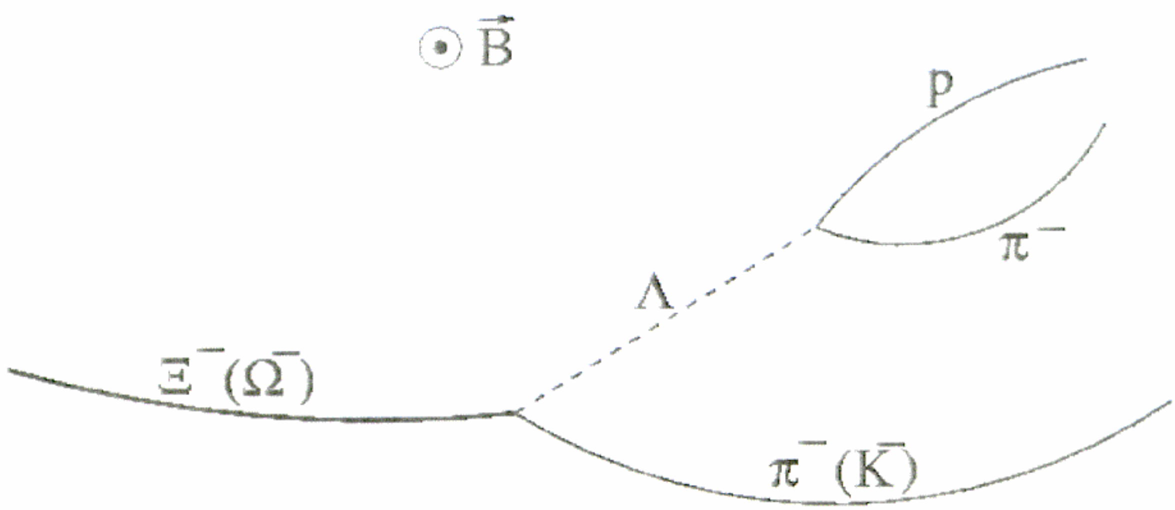
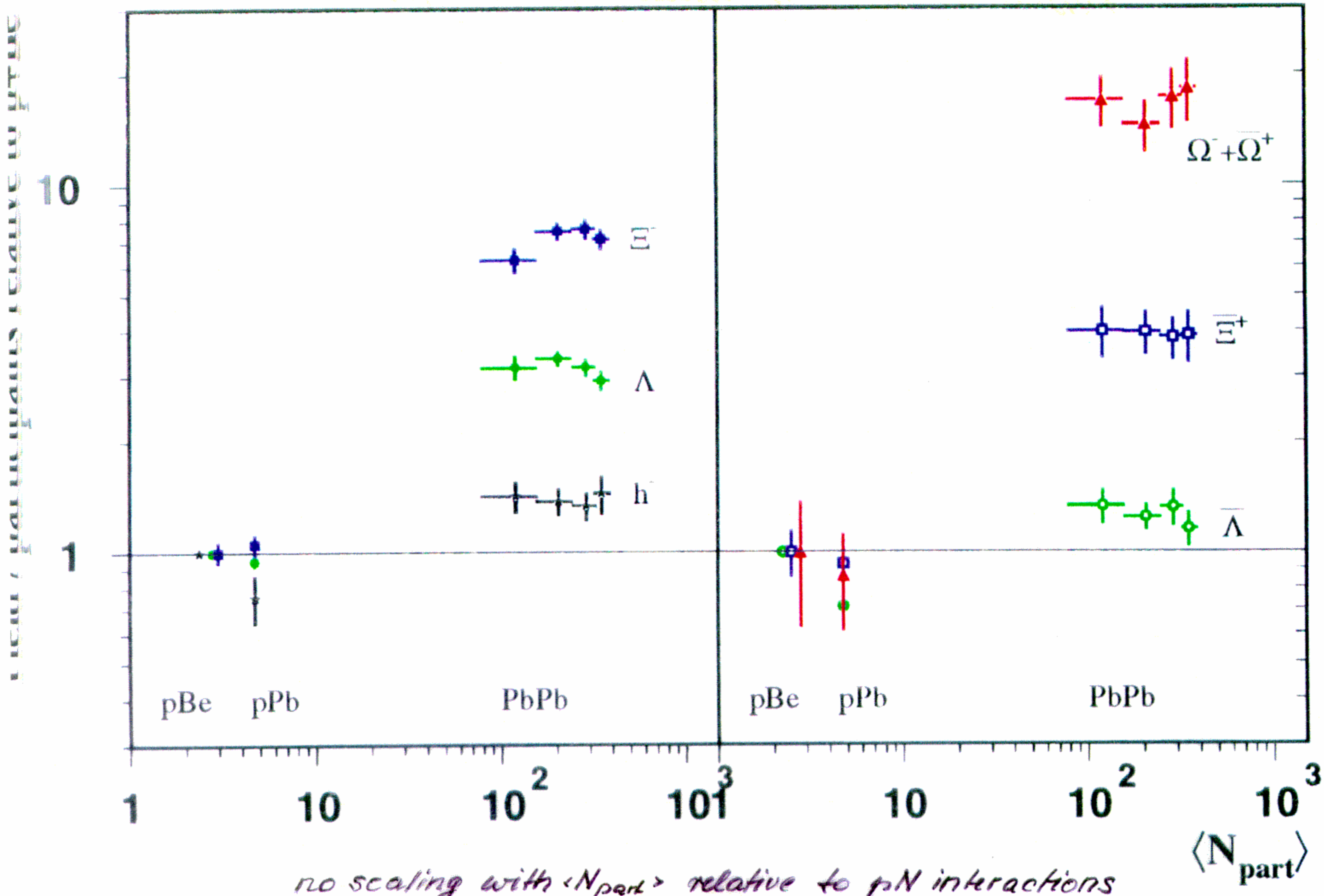
WA97 set-up
in the Omega magnet




⊙ $\vec{B}$
p
π^-
Λ
$\Xi^-(\Omega^-)$
$\pi^-(K^-)$

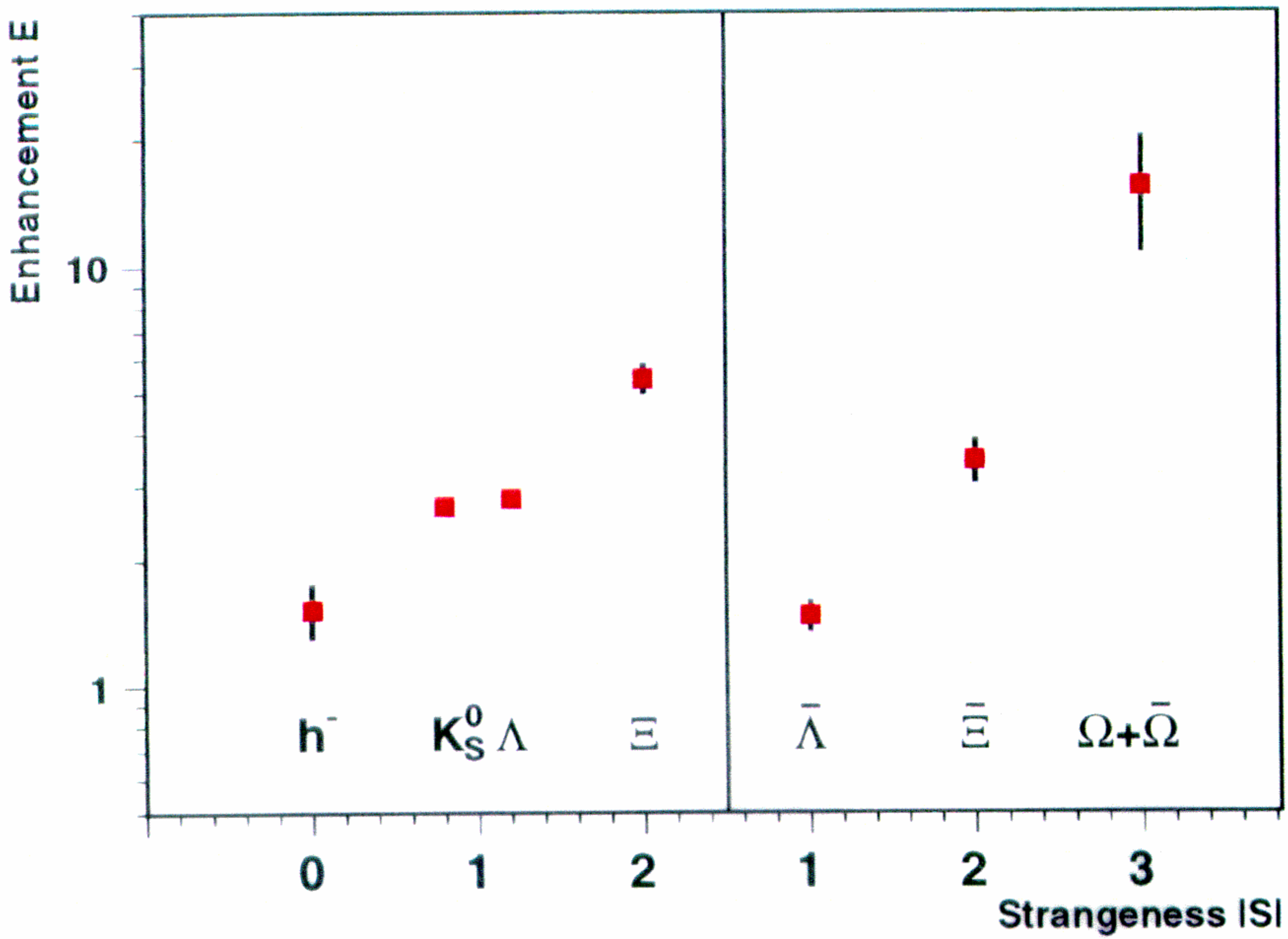
WA 97



no scaling with $\langle N_{part} \rangle$ relative to pN interactions

→ enhancement up to factor > 15 !

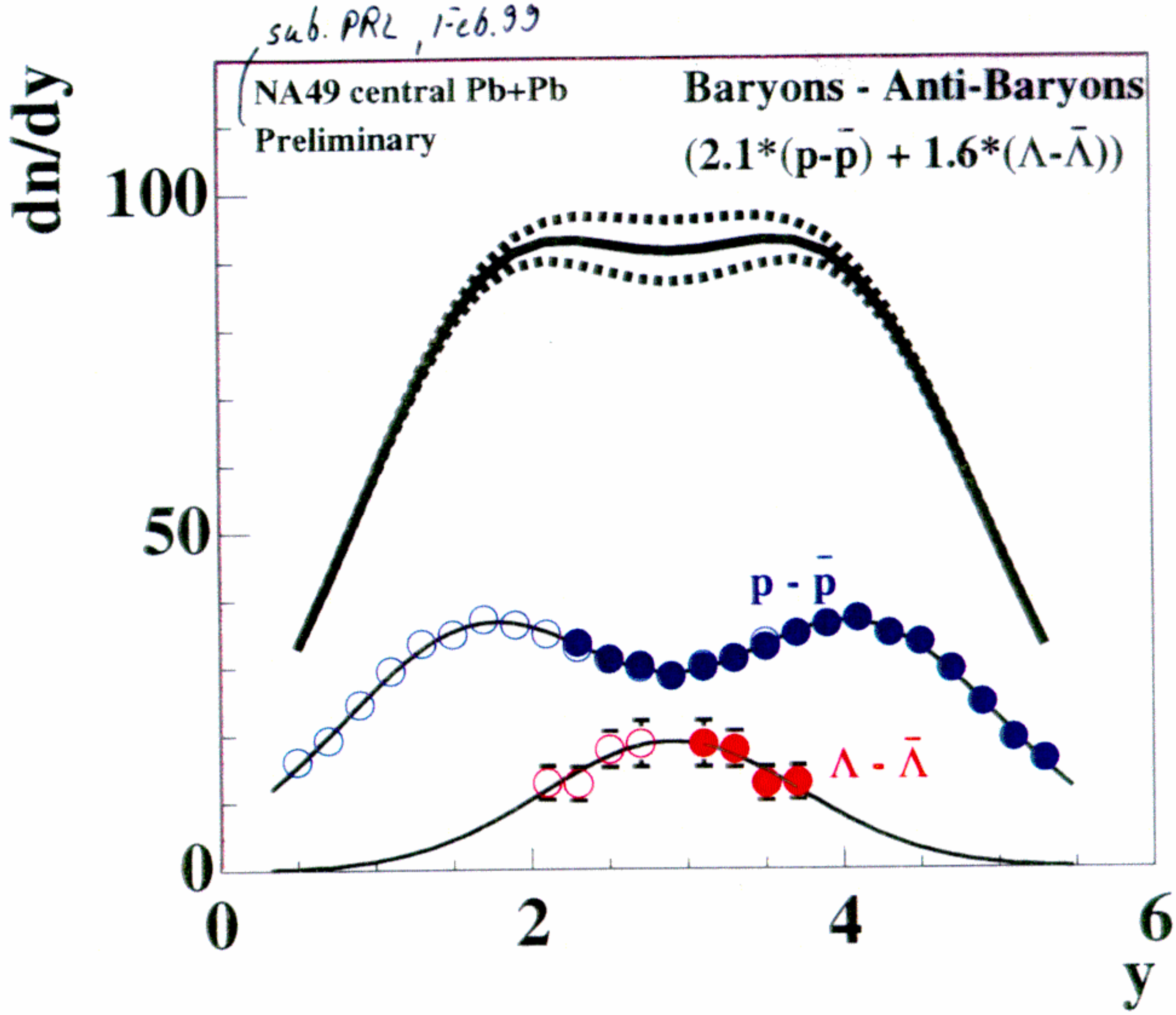
WA 97

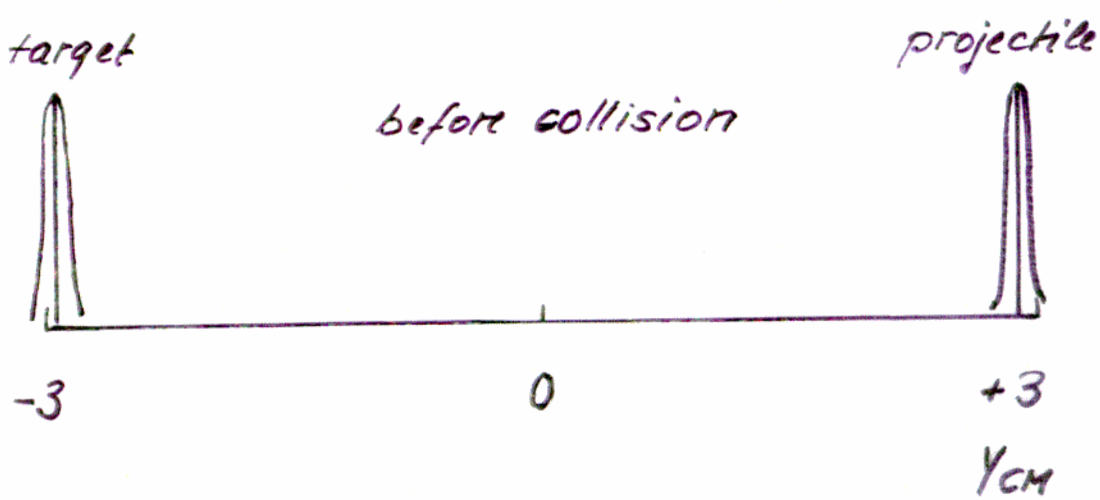


enhancement <u>increases</u> with |S|, in conflict
with hadronic rescattering models (high M, low σ)
"natural" in quark matter (high σ for $s\bar{s}$ prod.)

Baryon Stopping

SPS Energy





→ very high degree of stopping !

from transverse energy resp. particle production:

Estimation of Energy Density

Highly model-dependent

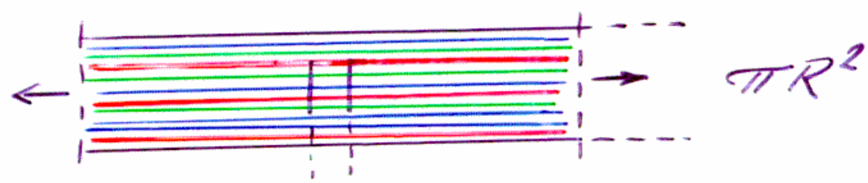
3 approaches:

(i) The Fermi Model

(ii) The Landau Model

(iii) The Shuryak-Bjorken Model

ad (iii):



$\Delta y \cdot \tau$

comoving energy density at time of hadronization τ

$$\varepsilon = \frac{\Delta E_T}{\Delta y \cdot \tau} \cdot \frac{1}{\pi r_0^2 A^{2/3}} \quad (E_T = \Sigma p_{T_i} c)$$

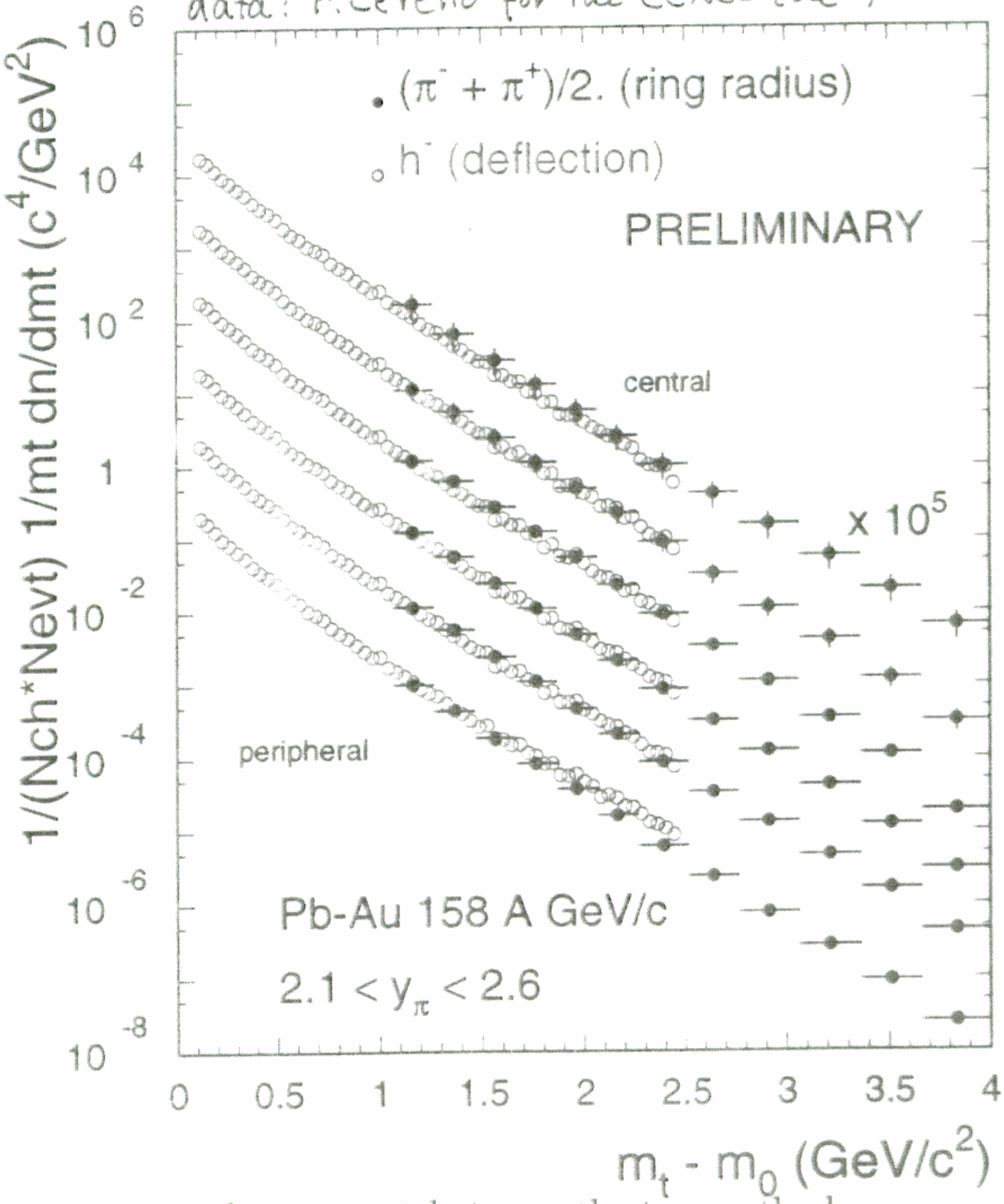
Results roughly ($\tau \approx 1$ fm/c):

$\varepsilon_{initial} \leq 2 - 4$ GeV/fm^3 $> \varepsilon_{crit}$

π^+, π^- and h^- spectra

- corrected for efficiency and momentum resolution
- h^-, mostly π^- with < 10% K^- and $\bar{p}$ and small contamination (~ 1%) of electrons

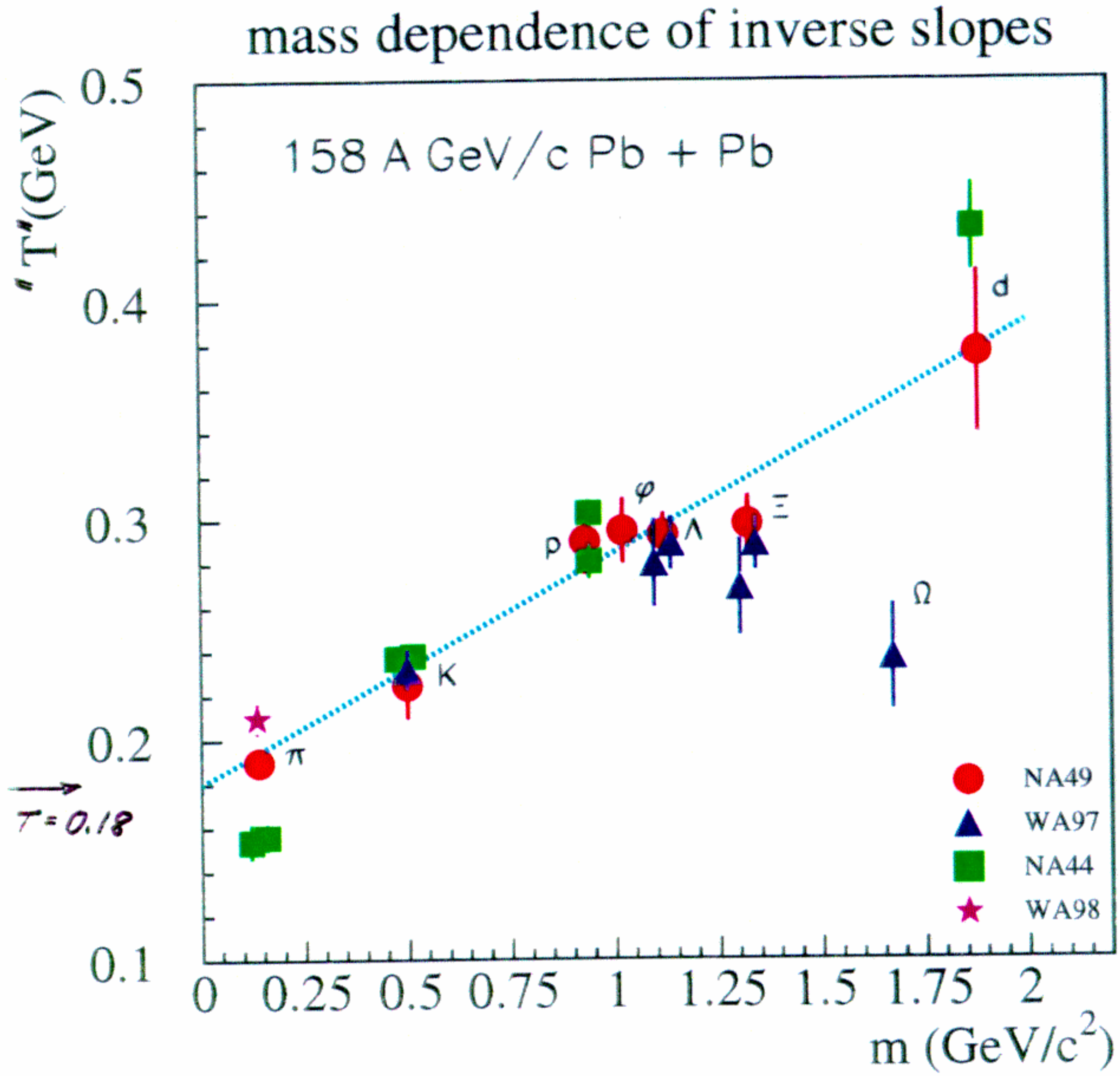
data: F. Ceretto for the CERES coll., Proc. QM97, Nucl. Phys A in print.



- very good agreement between the two methods

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

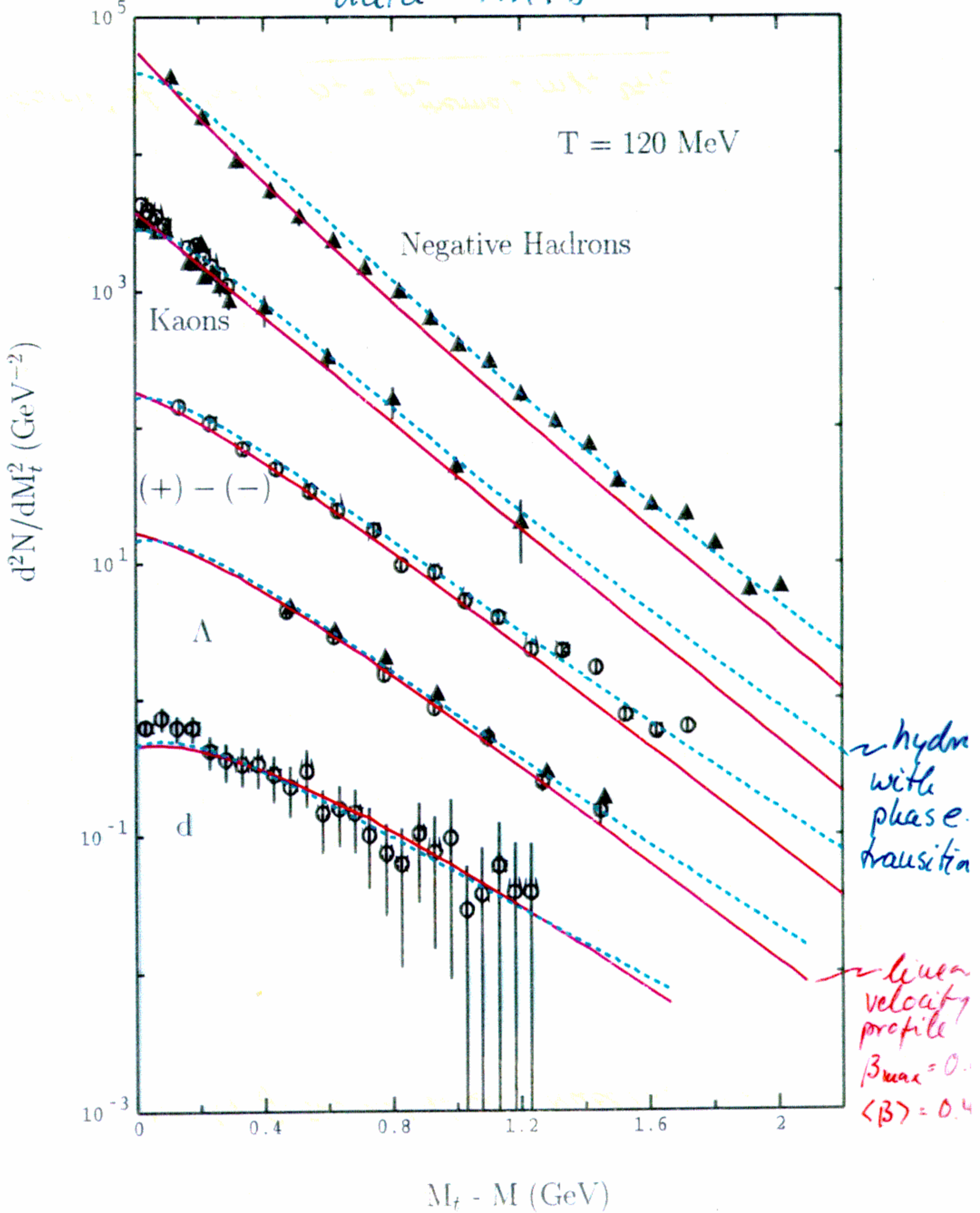
compilation by J. Stachel et al., Nucl. Phys. A654 (99) 119c



"spirit" of plot: $p_T = p_T^{thermal} + m\gamma_T v_T/c$

central 158 A GeV/c Pb+Pb at SPS

data : NA49

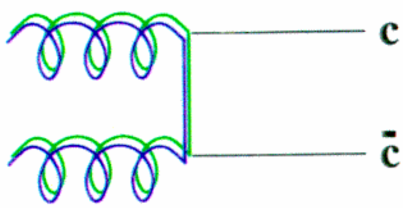


Charm production and J/ψ suppression

Hadrons with charm-anticharm valence quarks

	J/ψ	ψ'
	r=0.3 fm	r=0.6 fm
	mass=3097 MeV	3686 MeV

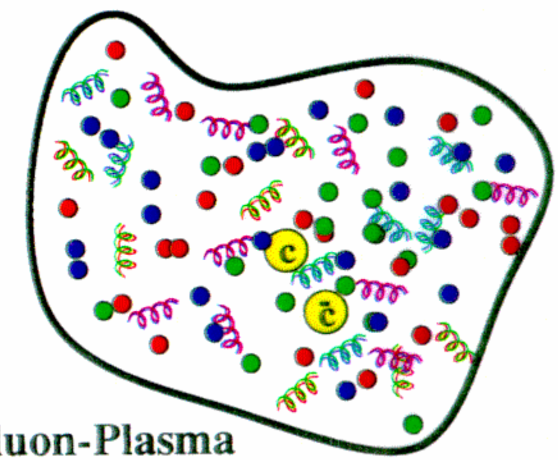
production of charm-anticharm quarks by gluon fusion



in the early stage of the collision

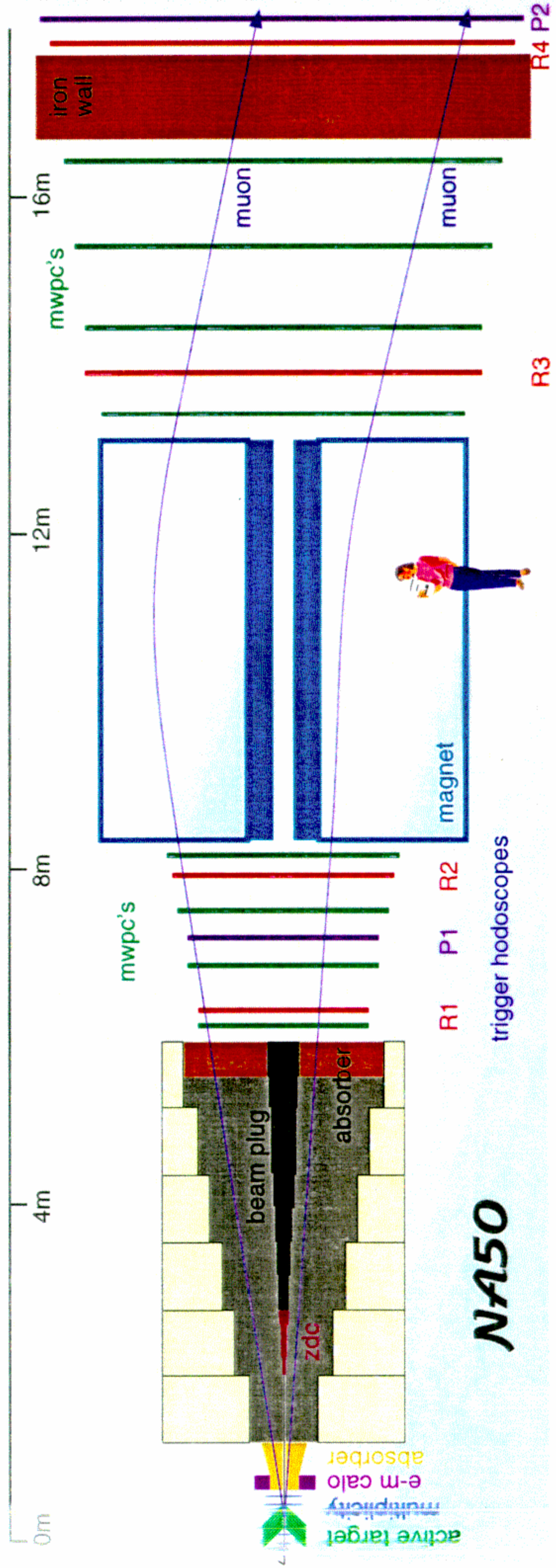
typically 1 $c\bar{c}$-pair per 6 Pb+Pb collisions
about 1 in 118 would evolve into a J/ψ
about 1 in 7200 into a ψ'

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

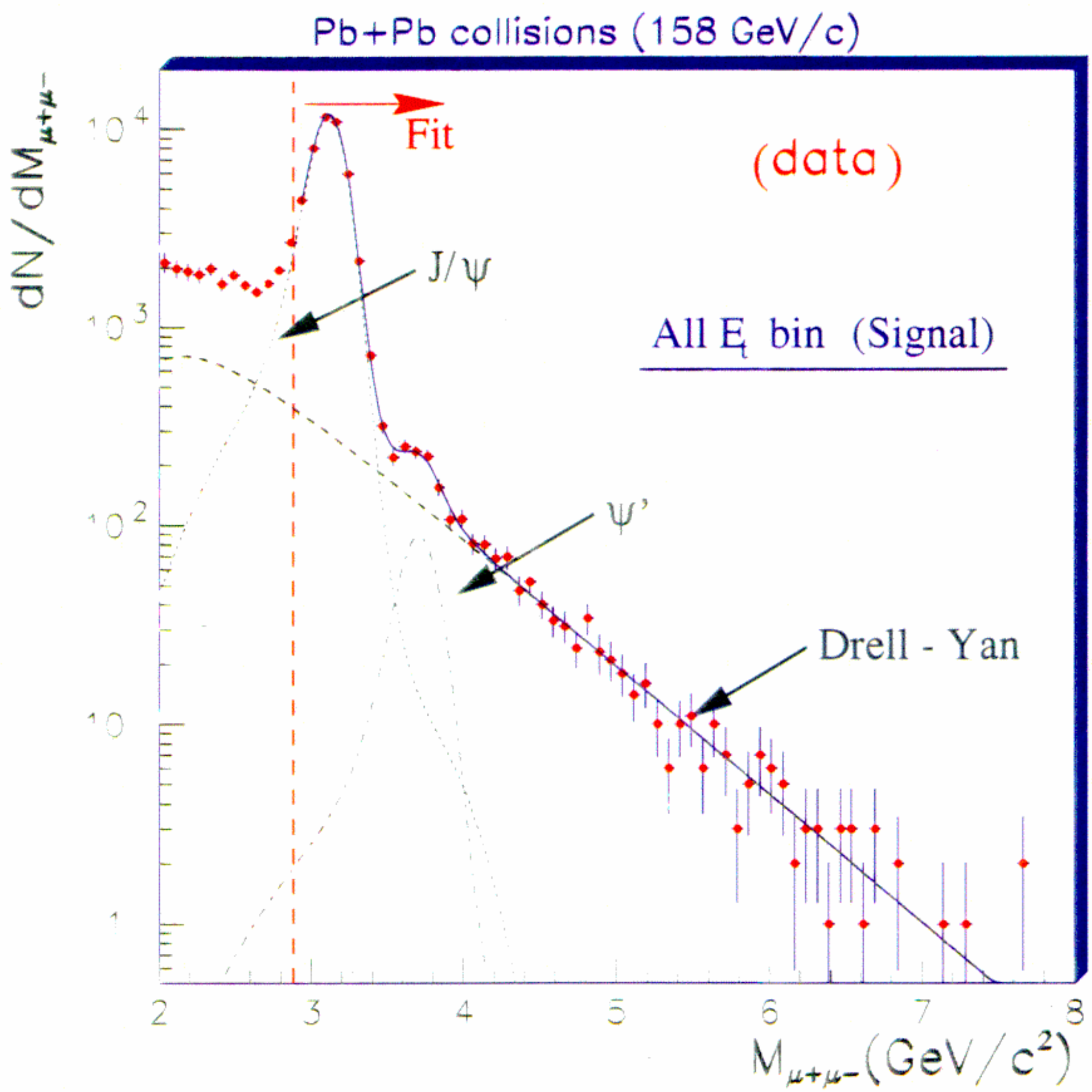


expect significantly less J/ψ
and ψ' than without Quark-Gluon-Plasma

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

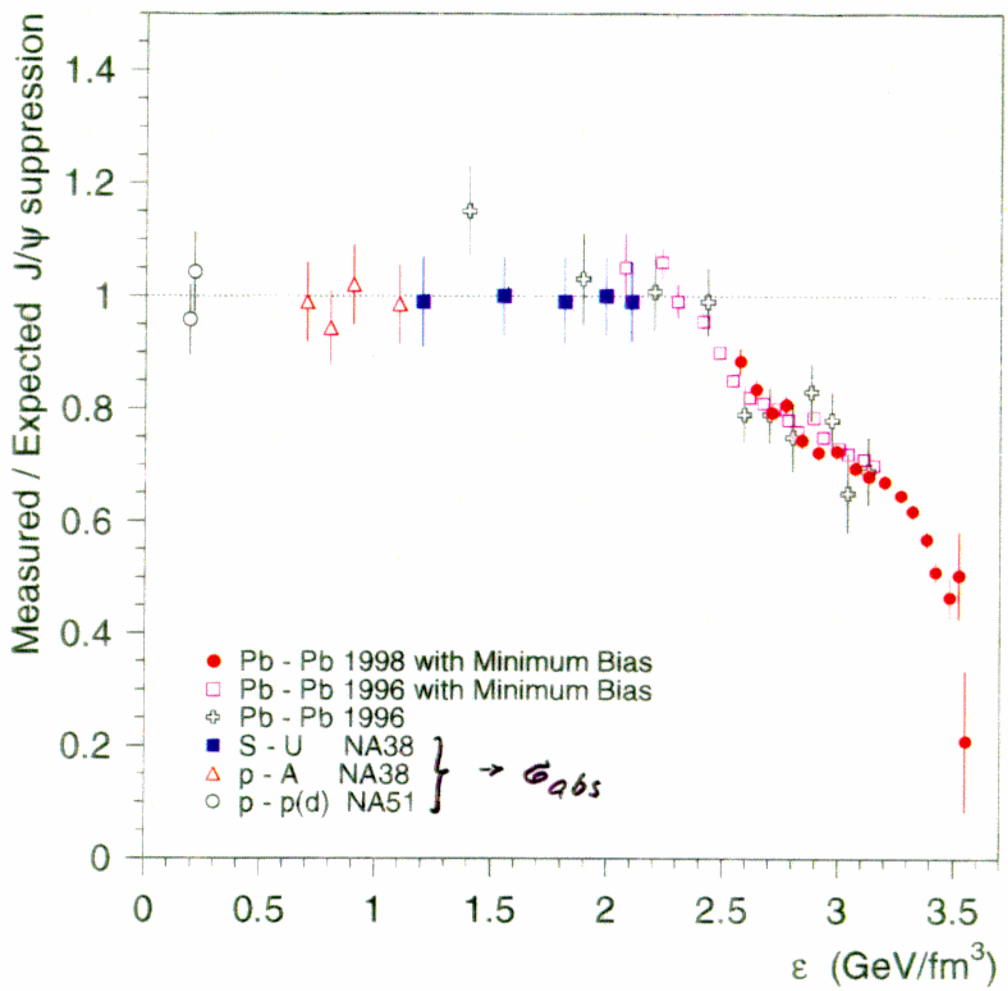

0m
4m
8m
12m
16m
iron wall
R4 P2
muon
muon
mwpc's
R3
magnet
mwpc's
R2
P1
R1
trigger hodoscopes
beam plug
absorber
zdc
NA50
absorber
e-m calo
multiplicity
active target

Fit of dimuon mass distribution



J/ψ suppression compared to expectations

NA50

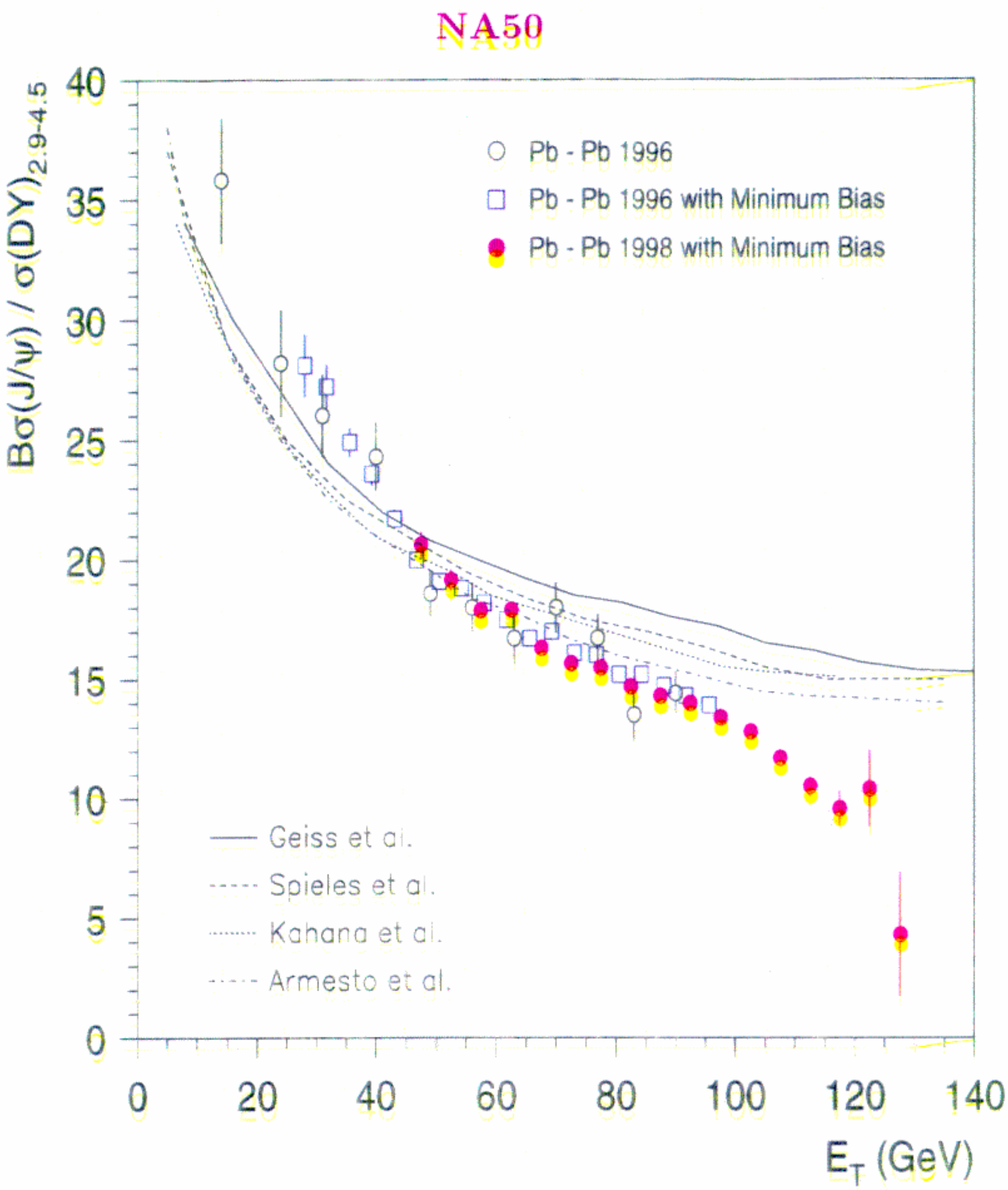


"expected suppression":
absorption of the $(c\bar{c}g)$ precursor state to the J/ψ in (normal) nuclear matter;
$\sigma_{abs} \sim 6$ mb

→ additional suppression in Pb-Pb

data: Phys. Lett. B477/2000/28

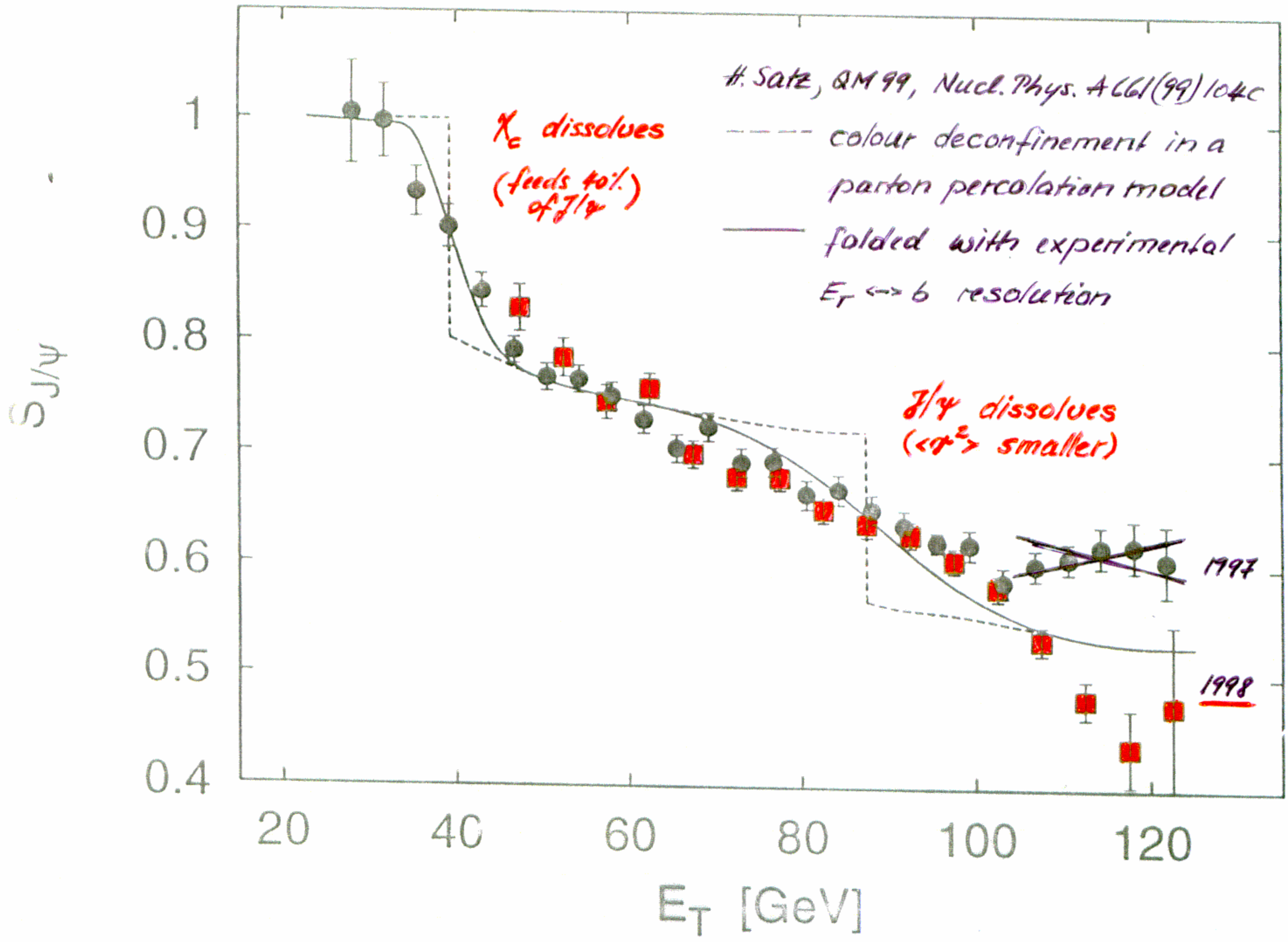
J/ψ yield and suppression in hadronic models



"hadronic models":
destruction of J/ψ by co-moving pions, strings, etc.

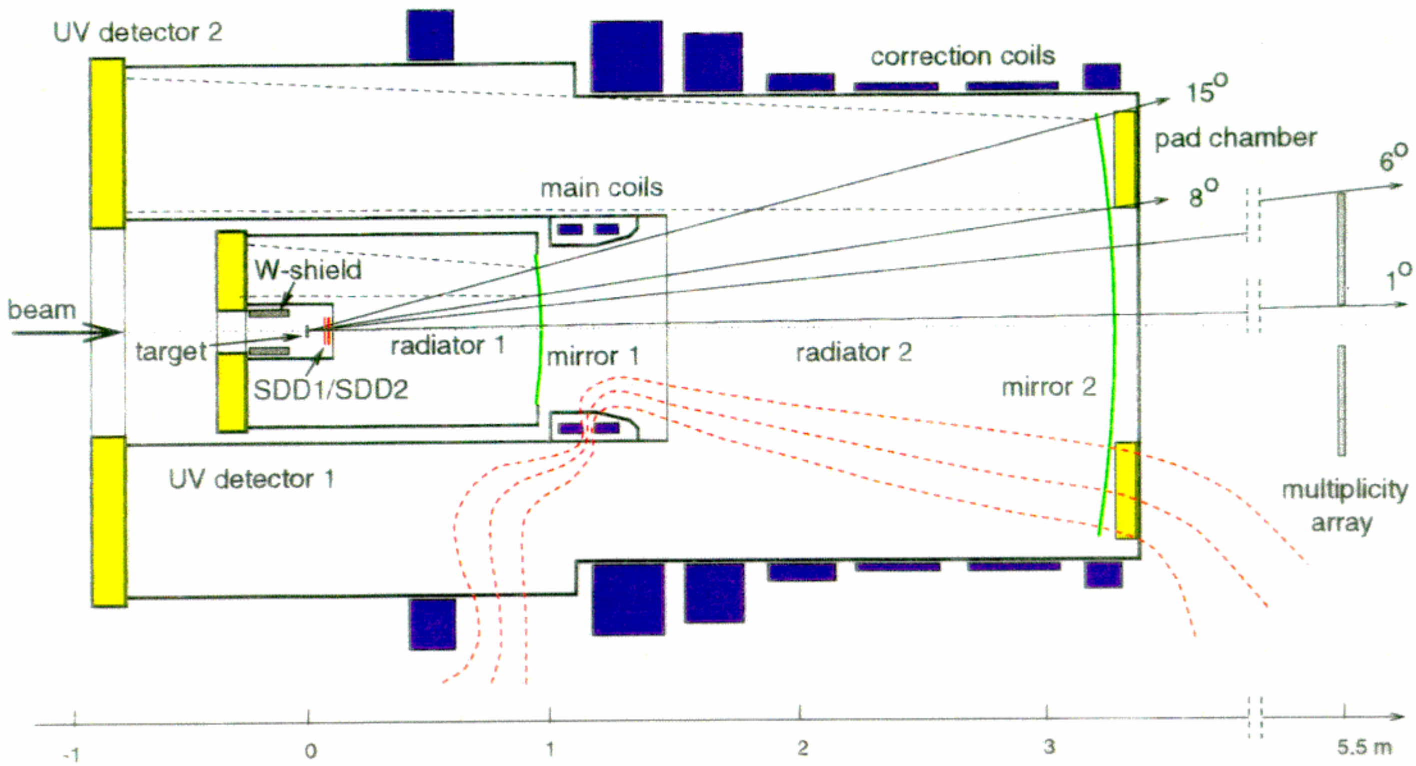
→ additional suppression in Pb-Pb caused by quark matter formation?

data: Phys. Lett. B477 (2000) 28



J/ψ survival probability as function of the measured transver

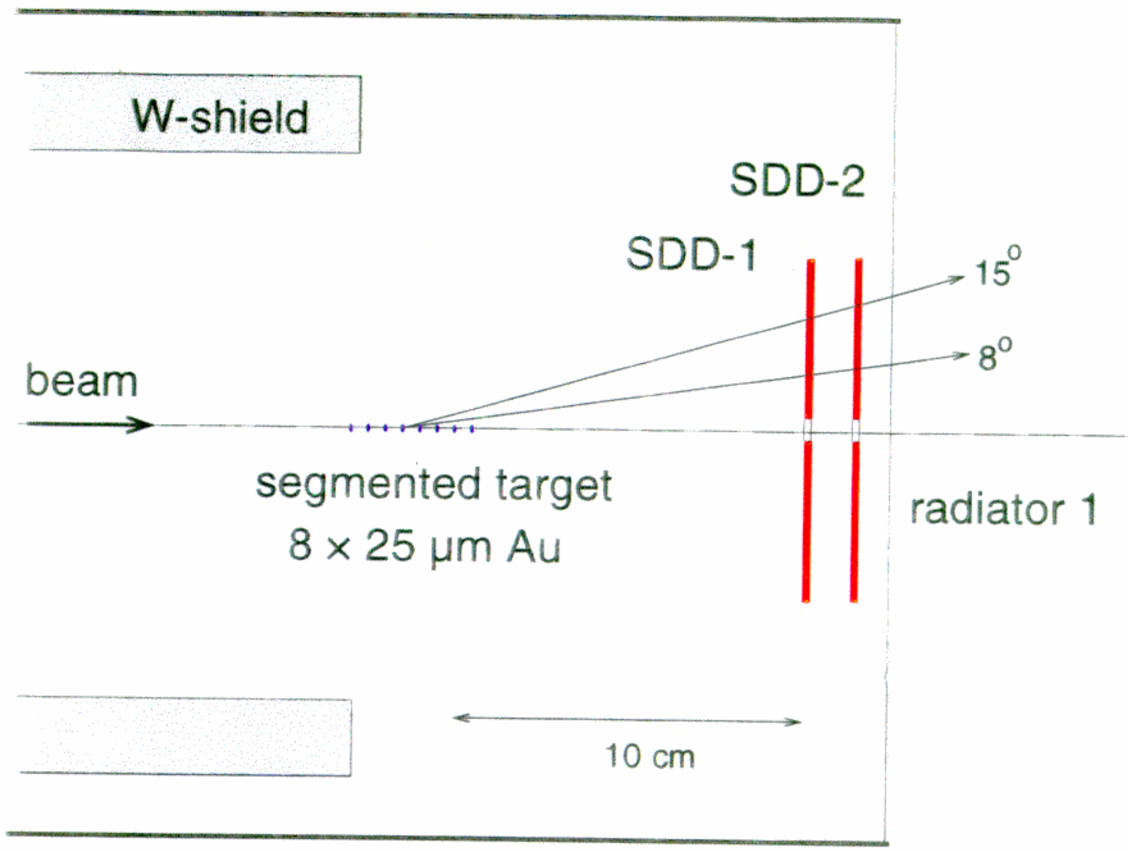
The CERES Experiment



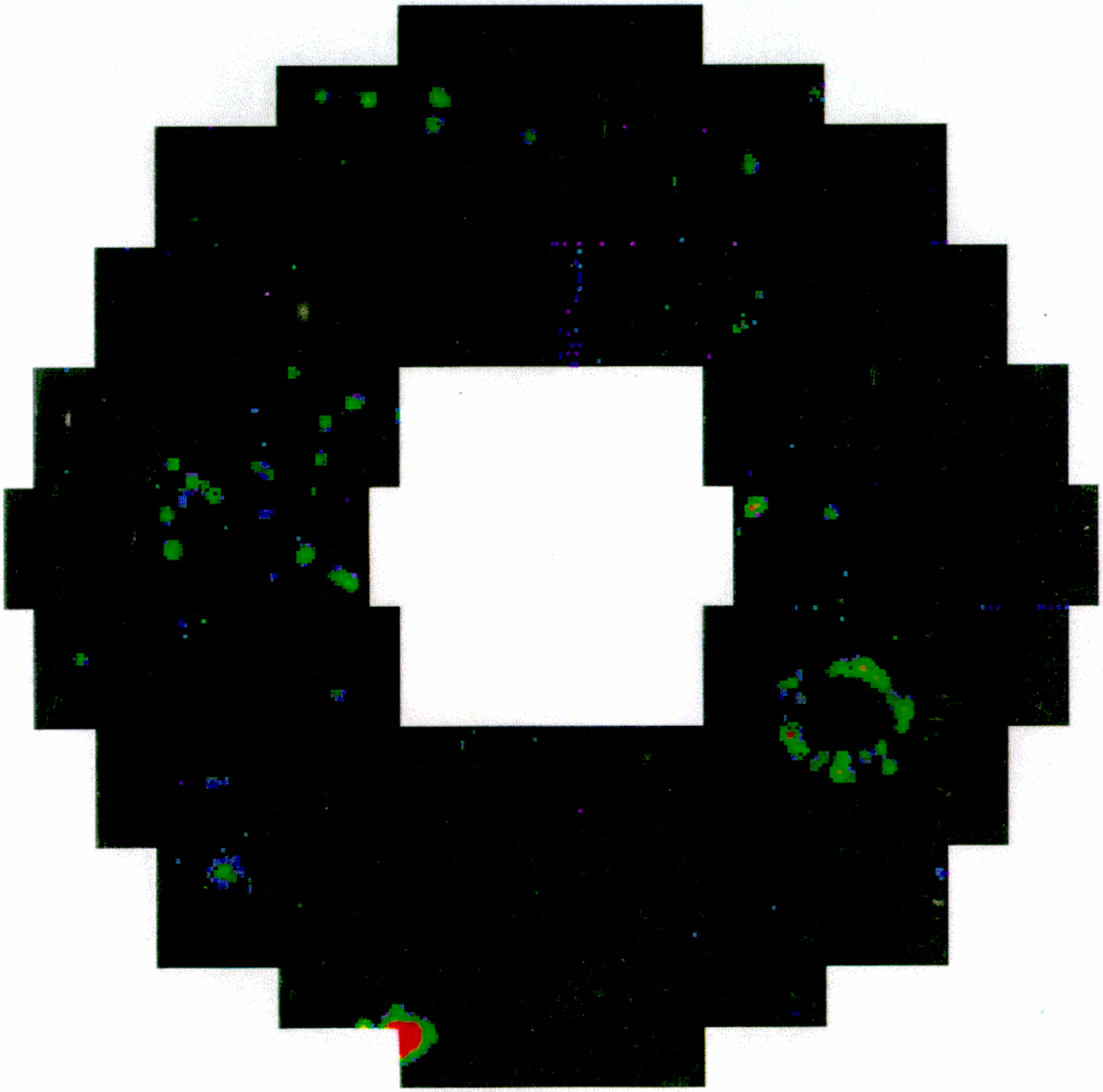
full φ acceptance, central rapidity coverage ($\mathbf{2.1 < \eta < 2.65}$)

- two RICH detectors ; CH_4 radiator gas ($\gamma_{thr} = \mathbf{31}$)
  - UV detectors upstream of the target
- magnetic field shaping
  - momentum measurement
  - deflection in azimuthal direction
  - straight tracks within the radiators
- Padchamber; tracking
  - additional point in the tracking scheme
  - high momentum measurement (with SDD)

CERES Target Setup



- segmented target
  - minimize conversion length to ~0.3% $X/X_\circ$
- two radial silicon drift detectors (SDD)
  - measure vertex and dN_{ch}/dy
  - provide tracking to RICH-1
  - conversion and Dalitz rejection (dE/dx)
- W-shield
  - absorb slow particles in UV-detector acceptance



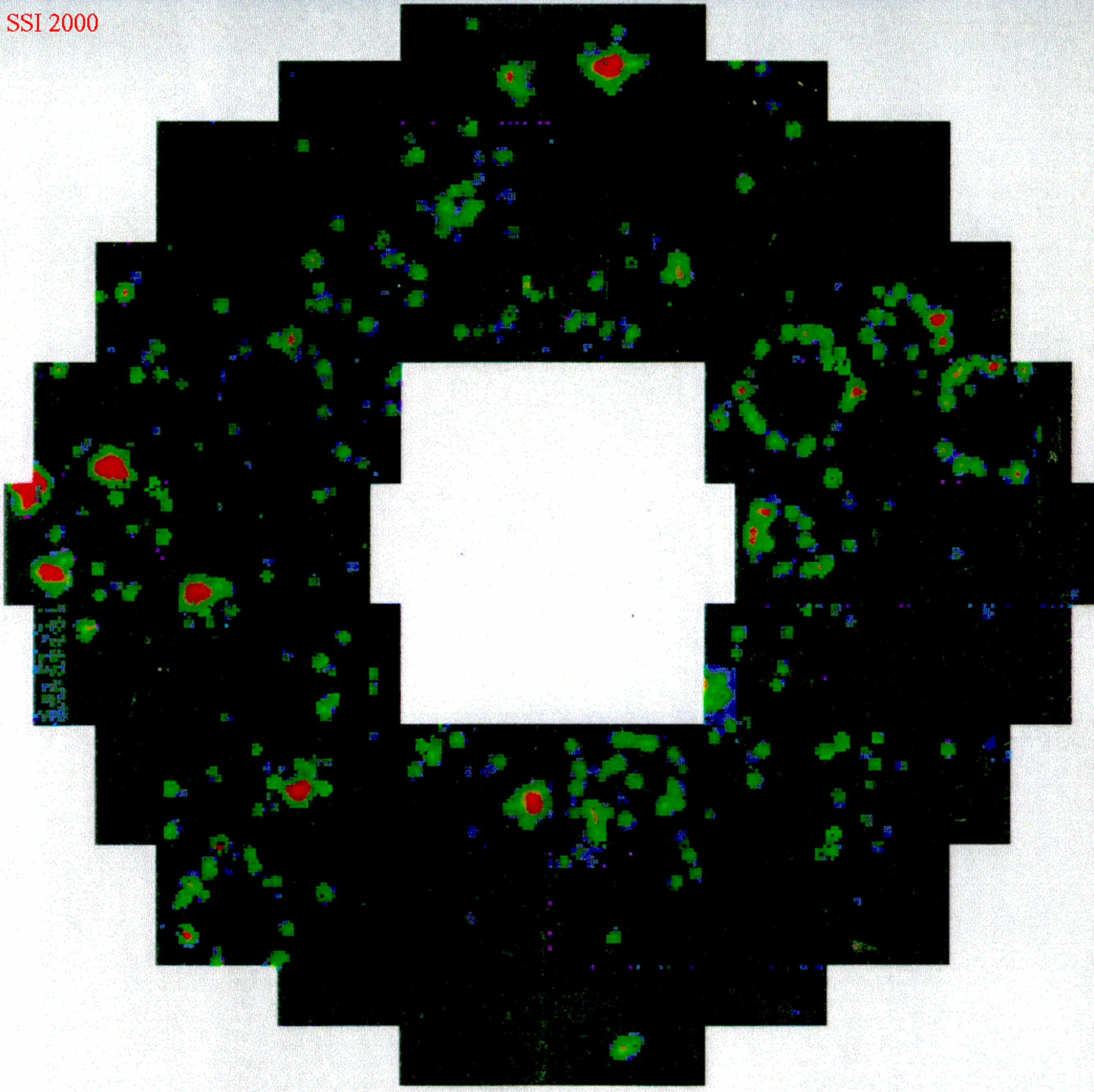
Run:	46
Burst:	950
Event:	15997
Date:	941103
Time:	222629
Time in Burst:	920 ms
Trigger:	/mult/flt/n2
Multiplicity:	653
Total # of pads:	6216

RICH1 View

160 GeV/u Pb+Au

$\frac{dN^{ch}}{d\eta} \sim 50$ (periph)

H. J. Specht, SSI 2000



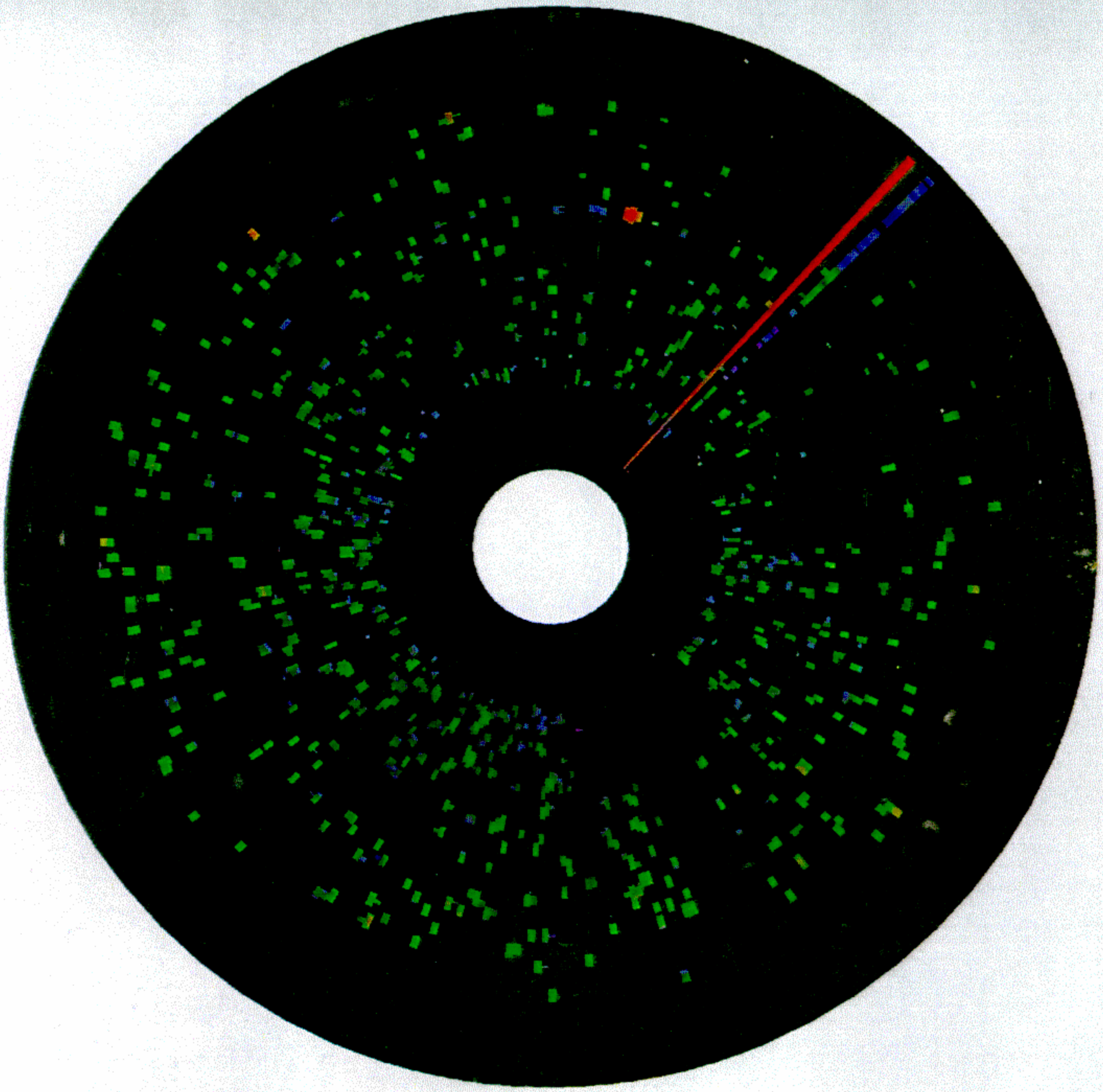
RICH1 View

Run:	46
Burst:	55
Event:	919
Date:	941103
Time:	173948
Time in Burst:	2710 ms
Trigger:	/mult/flt/n2
Multiplicity:	1210
Total # of pads:	7972
Lower threshold:	24
Event Length:	24222
Data Source:	o-ceres07.cern.ch

160 GeV/u Pb + Au

$\frac{dN_{ch}}{dy} \sim 600$ (central)

CERES/NA45@CERN



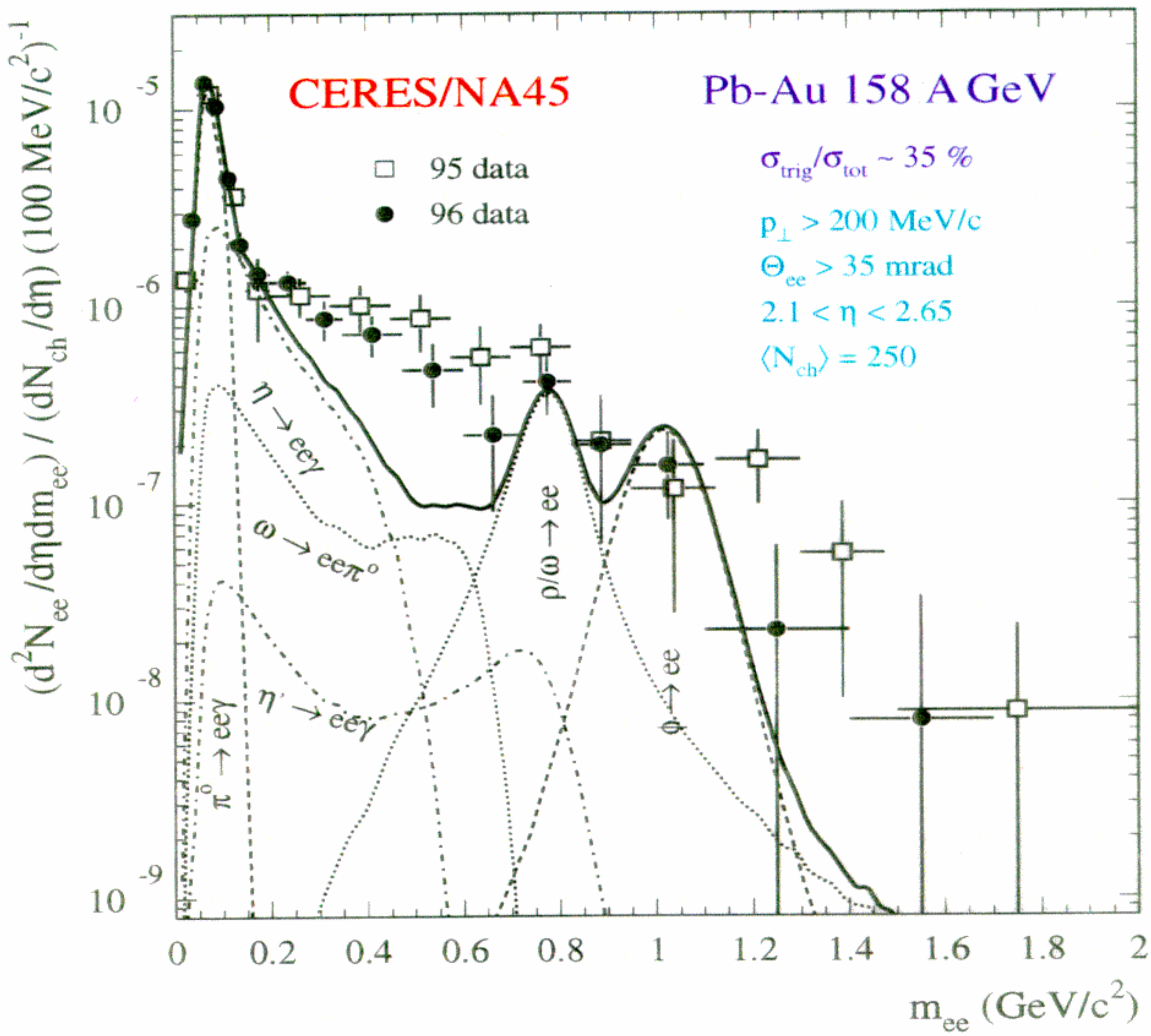
SIDC2 View

Run:	46
Burst:	55
Event:	919
Date:	941103
Time:	173948
Time in Burst:	2710 ms
Trigger:	/mult/flt/n2
Multiplicity:	1210
Total # of cells:	16183
Lower threshold:	10
Event Length:	24222
Data Source:	o-ceres07.cern.ch

$\frac{dN_{ch}}{dy} \sim 600$

e^+e^- pair mass spectrum

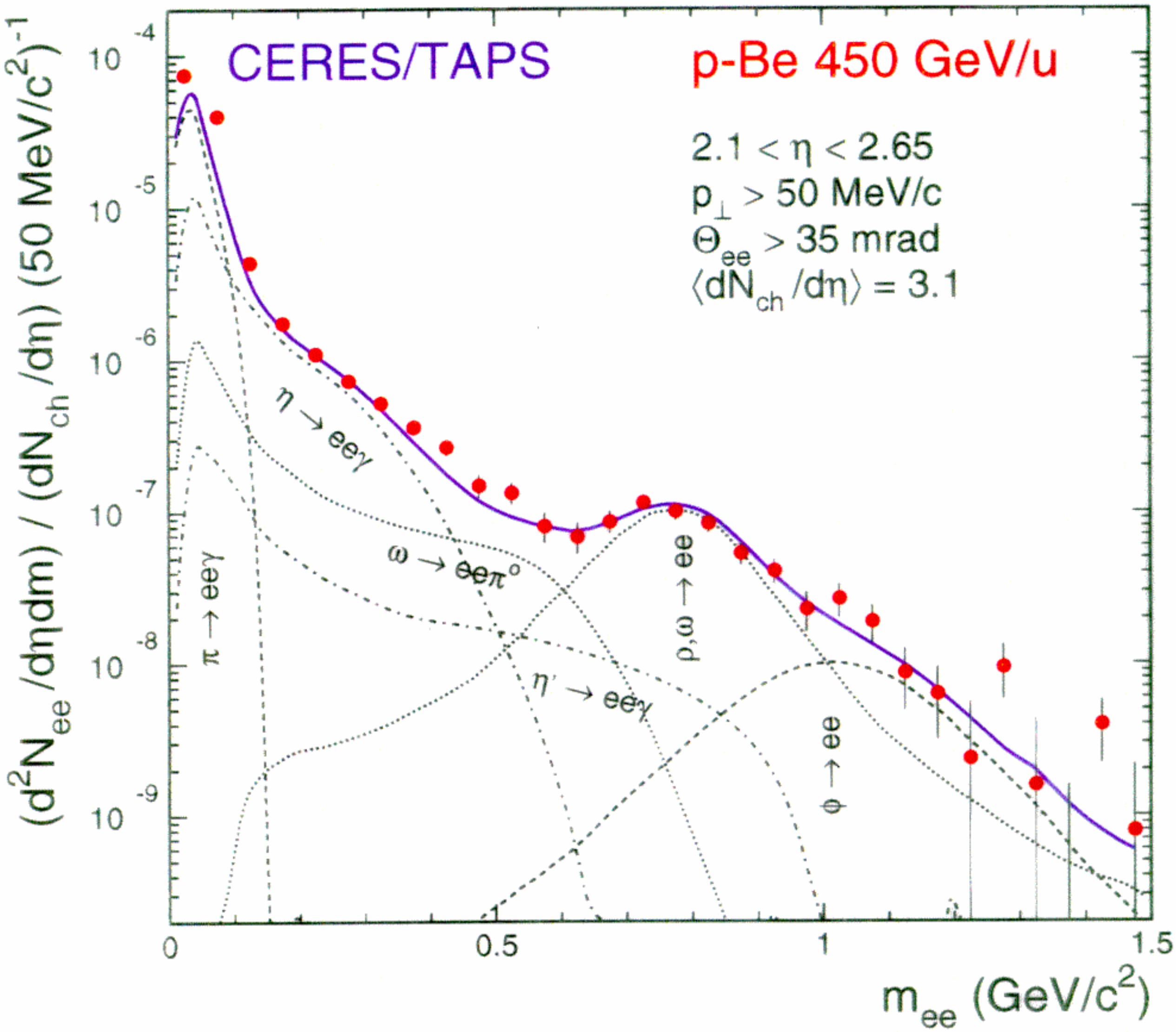
B. Lenkeit et al., INPC Paris (98)



- particle ratios taken from a thermal model fitted to measured ratios in Pb-Pb ($T = 175MeV, \mu_B = 270MeV$)
- rapidity and pt distributions following measured systematics in Pb-Pb
- enhancement ($0.25 < m_{ee} < 0.7$ GeV/c^2) :
  $2.6 \pm 0.5(stat.) \pm 0.6(syst.)$ (96' data set)
  $3.9 \pm 0.9(stat.) \pm 0.9(syst.)$ (95' data set)

Low mass Dileptons from p-Be Collisions

HELIOS-1: hadron decays account for all dileptons



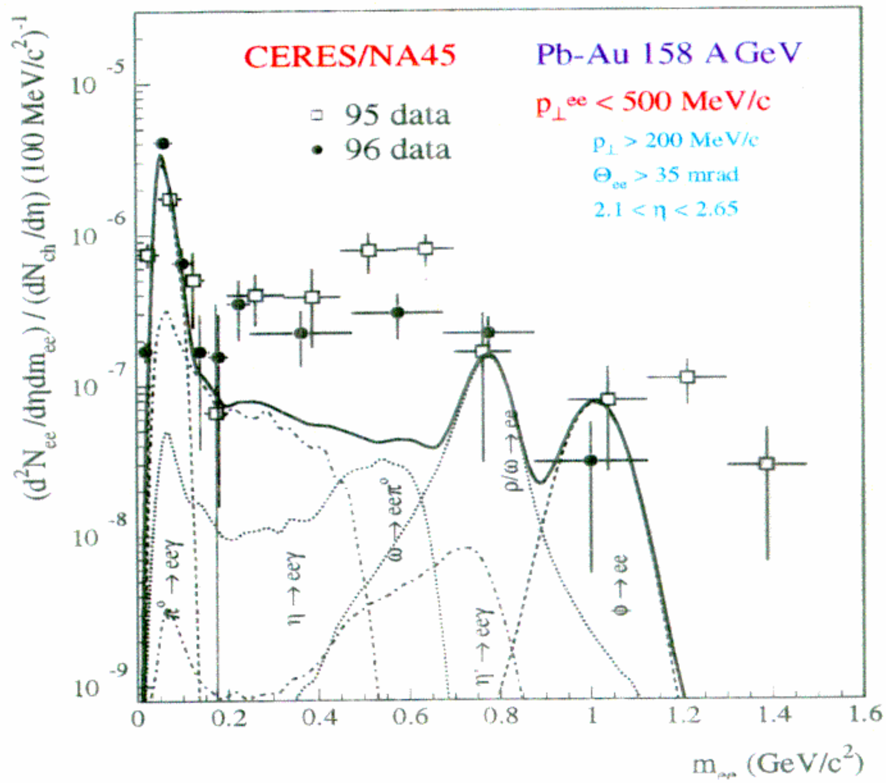
10% - 20% precision

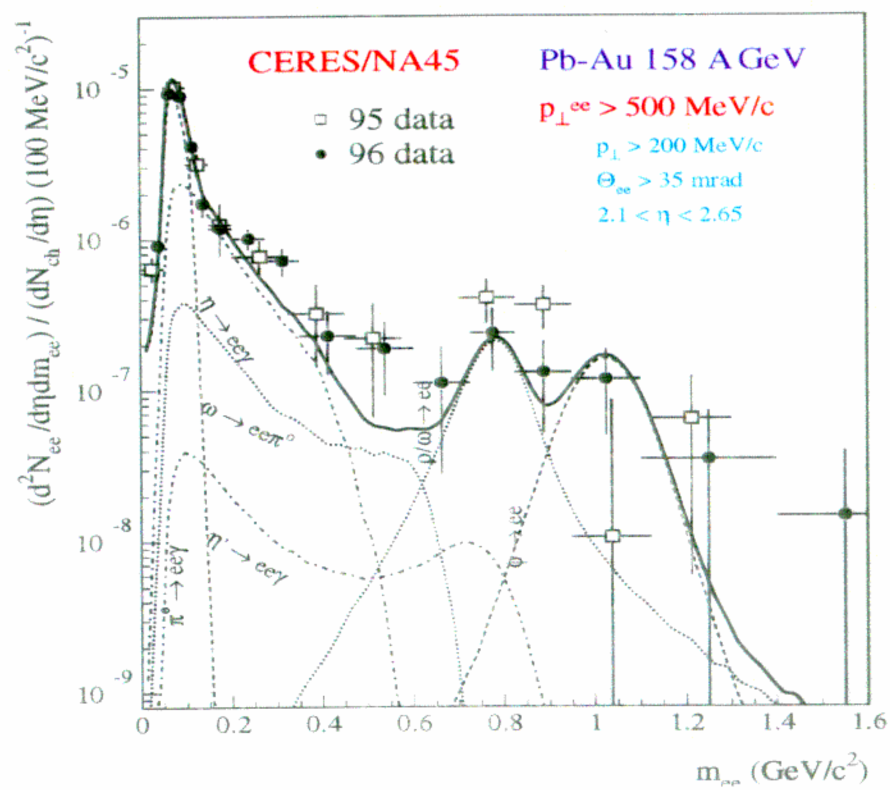
- measure e^+e^- and γ in coincidence
- normalize expected sources to exclusive reconstructed $\eta \to e^+e^-\gamma$
- more precise data on hadron production ($\eta \to \gamma\gamma, \omega \to \pi^\circ\gamma\gamma$)

Are there deviations from conventional sources after all?

(e.g. $300 < m < 600$ MeV/c^2)

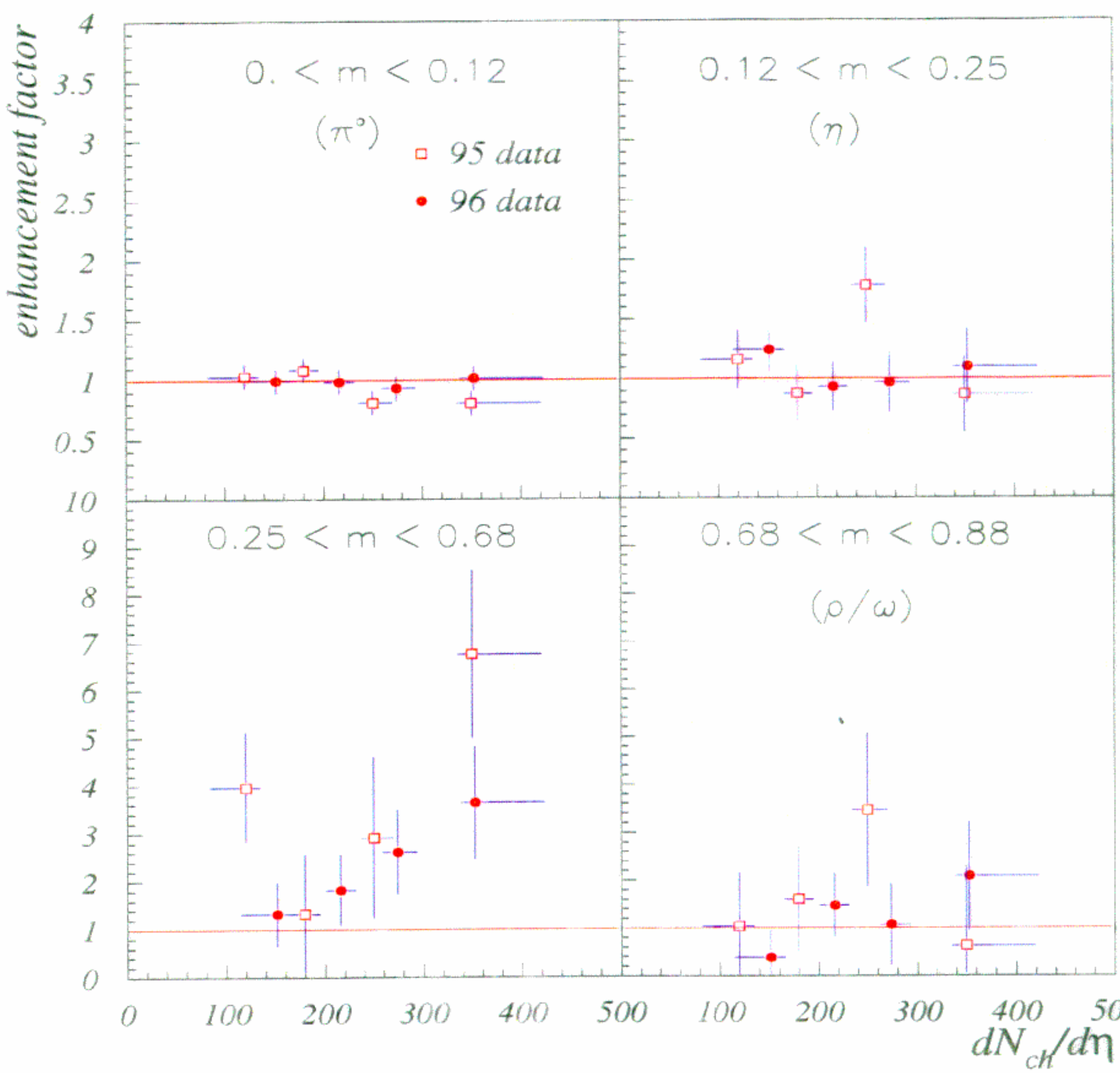
e^+e^- pair mass spectrum





Centrality dependence

enhancement factor = $N^{e^+e^-}$ / $N^{e^+e^-}$ (hadronic sources)

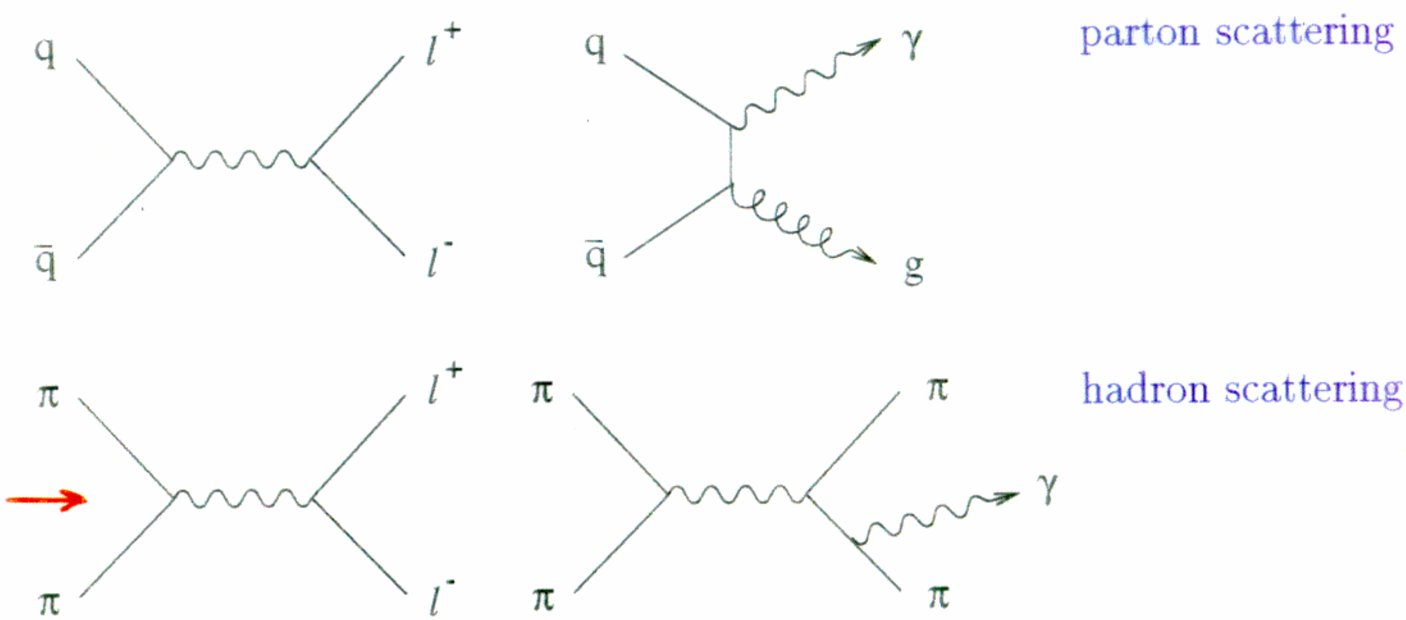


increase of pair yield stronger than linear with multiplicity in the mass range between 2 × pion mass and the Rho/Omega peak

Electromagnetic Radiation from Hot Matter

origins mostly from particle scattering in the 'fireball'

typical examples:



yield depends on local particle density squared

need model calculation to correlate local density and dN_{ch}/dy

yield from hot matter $\propto (dN_{ch}/dy)^2$

hadron decays after freeze-out $\propto dN_{ch}/dy$

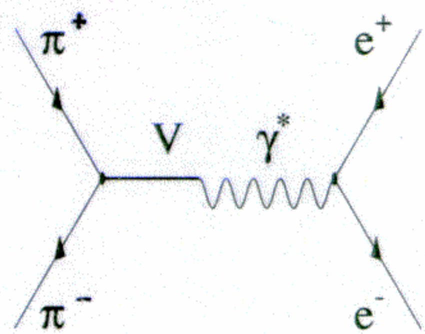
deviation from linear dN/dy-dependence:

a signature for new physics

Other Continuum Radiation

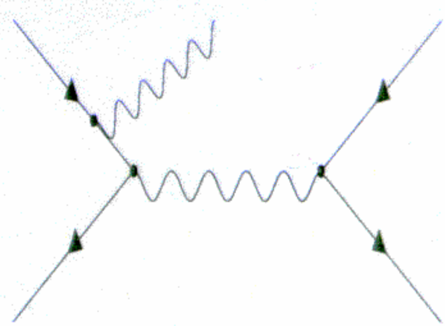
- $\pi\pi$-annihilation ($T \geq T_C$)
  threshold at $2\, m_\pi$ $= 2 \cdot 140\ \mathrm{MeV}/c^2$
  π-formfactor $\rightarrow$ ρ-enhancement

$V \approx \rho$



$m_\rho = 770\ \mathrm{MeV}/c^2$
$\tau = 1.3\ \mathrm{fm}/c$
$J^{PC} = 1^{--}$

- bremsstrahlung (at any stage of collision)

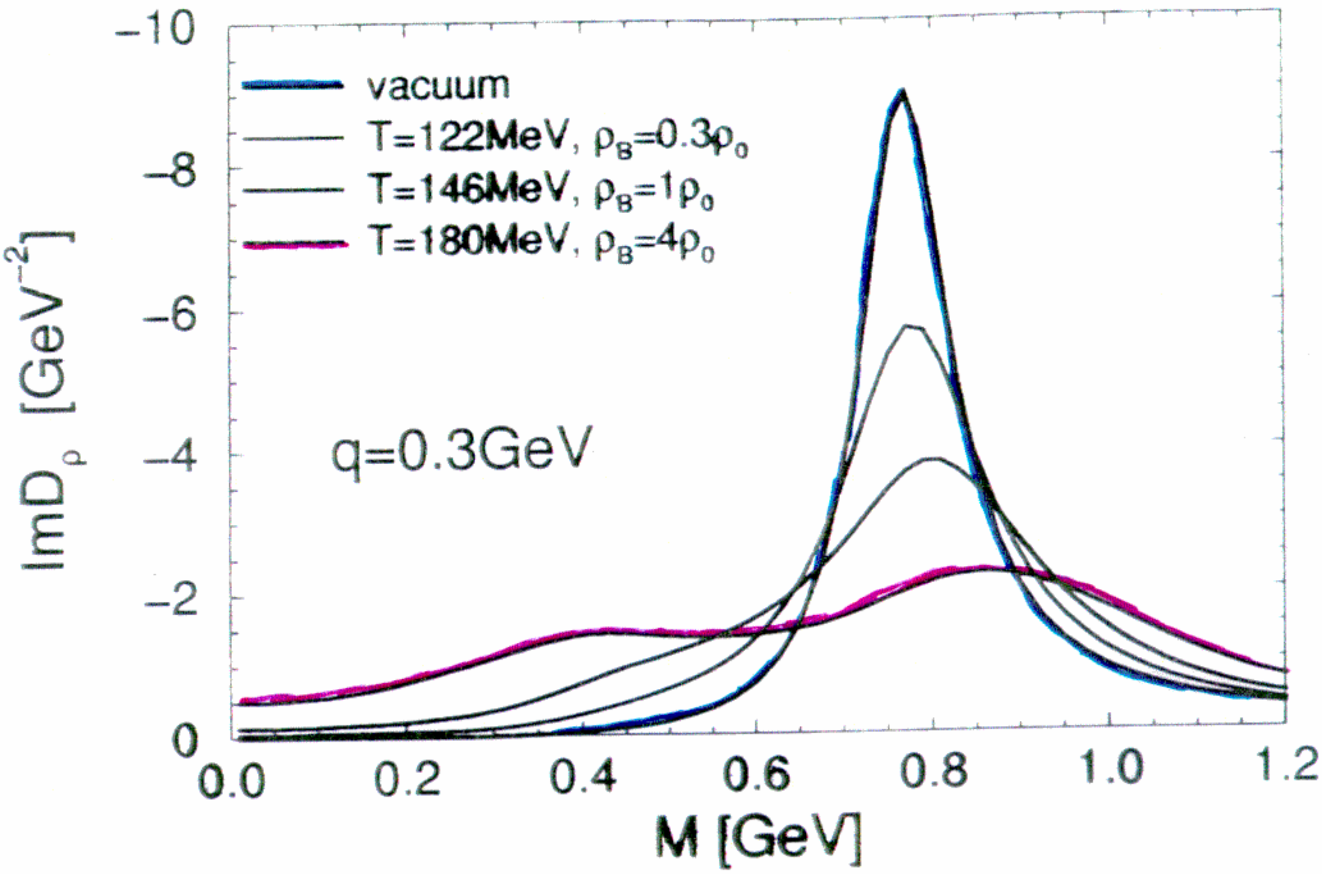


- dalitz decays (hadronization)

calculations very model dependent

R. Rapp & J. Wambach; see e.g. hep-ph/9909229
Adv. Nucl. Phys. (in print)

ρ Spectral Function in Hot Hadronic Matter

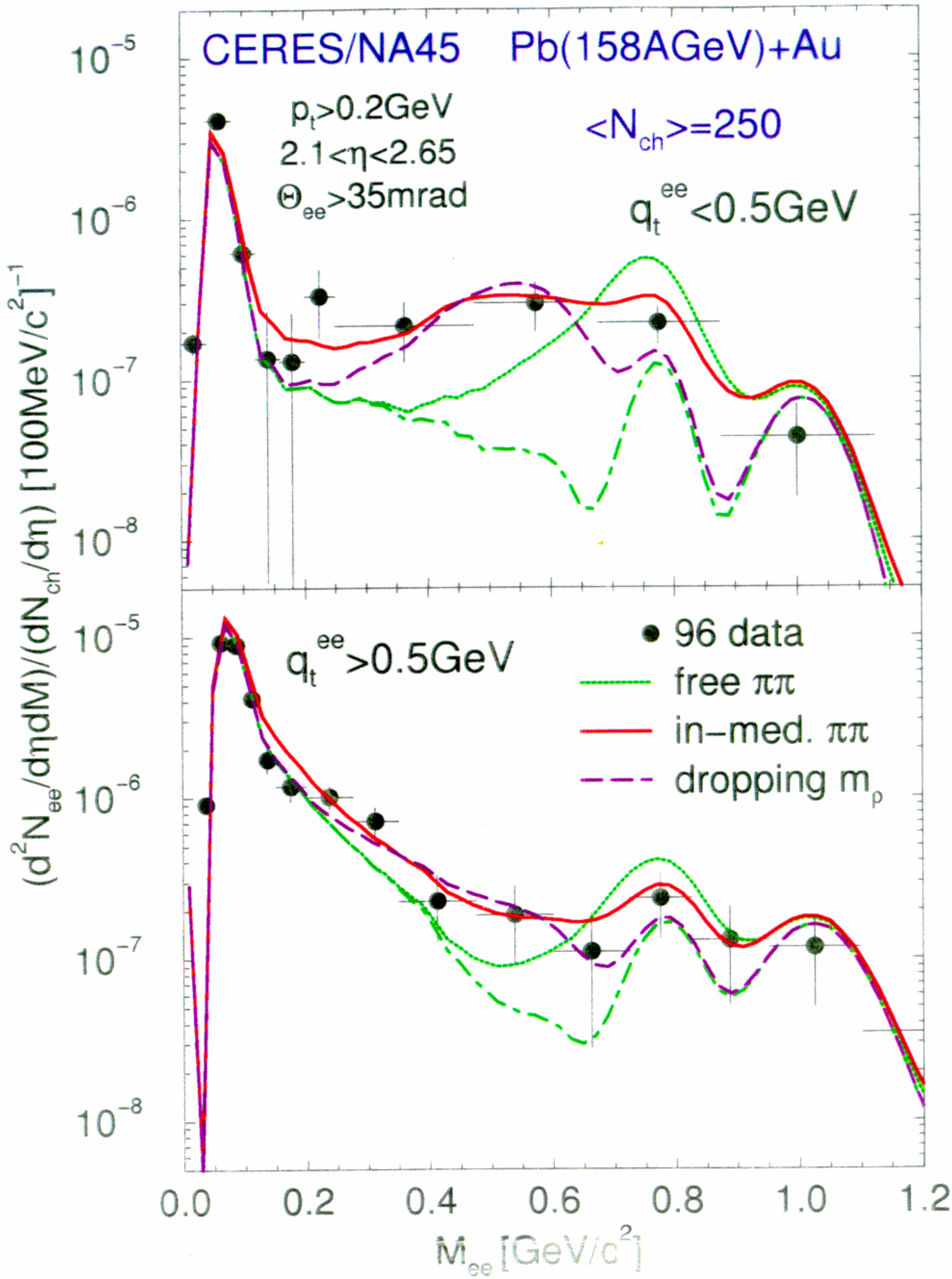


<u>Enhancement at $M = 0.4$ GeV [$\rho_B = \rho_0$, $T = 146$ MeV, $\mu_\pi = 0$] is due to:</u>

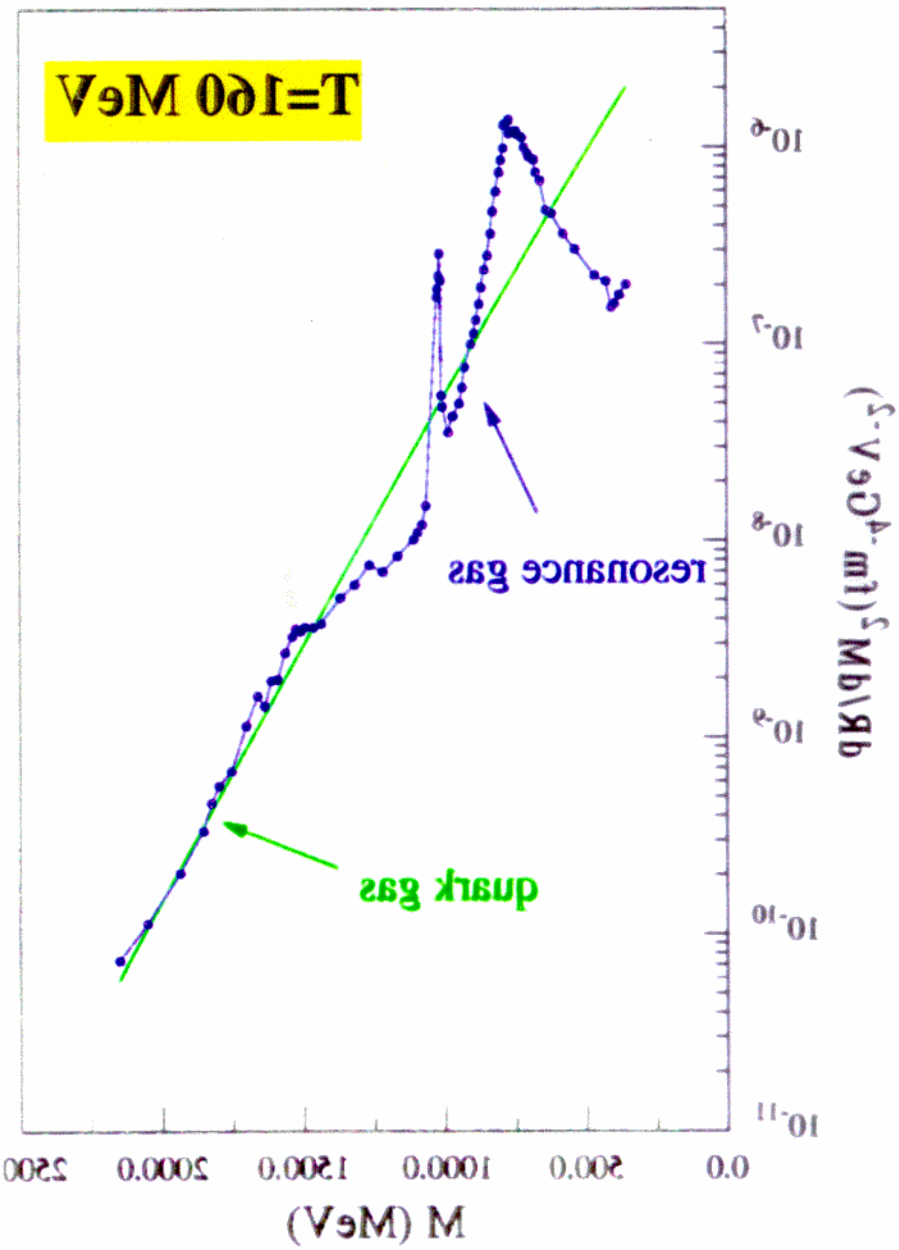
s-wave Rhosobars	~ 35 %
Meson-Resonances / Bose enhancement	~ 30 %
Pisobars in π-Cloud	~ 20 %
p-wave Rhosobars	~ 10 %

⇒ 'residual' coherence effect 5-10 %

Rapp and Wambach
Nucl. Phys. A661 (1999) 33c
(see also hep-ph 9909229; Adv. Nucl. Phys. E)



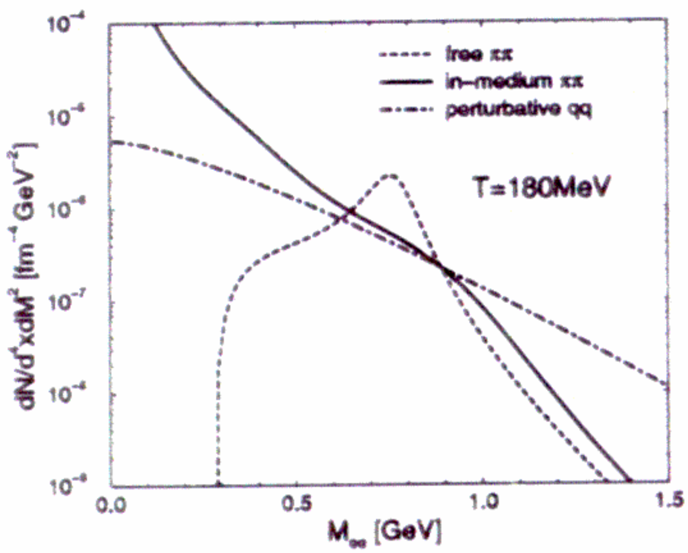
Rapp and Wambach
hep-ph/9909229 ; Adv. Nucl. Ph. E



Rapp and Wambach; hep-ph/9909229

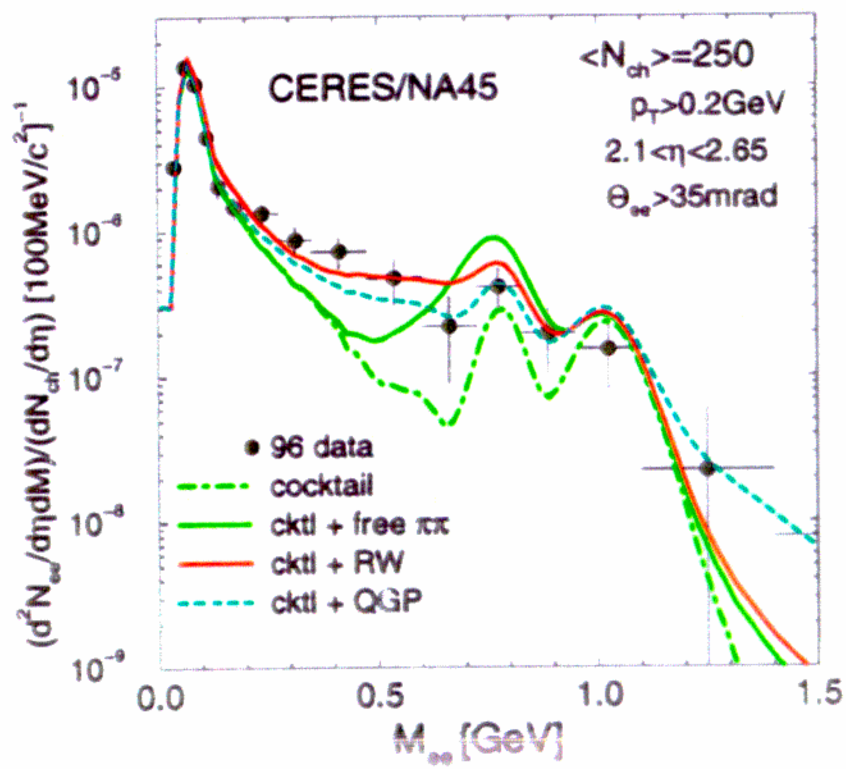
Quark-Hadron Duality ?

hadronic rates vrs. plasma rates

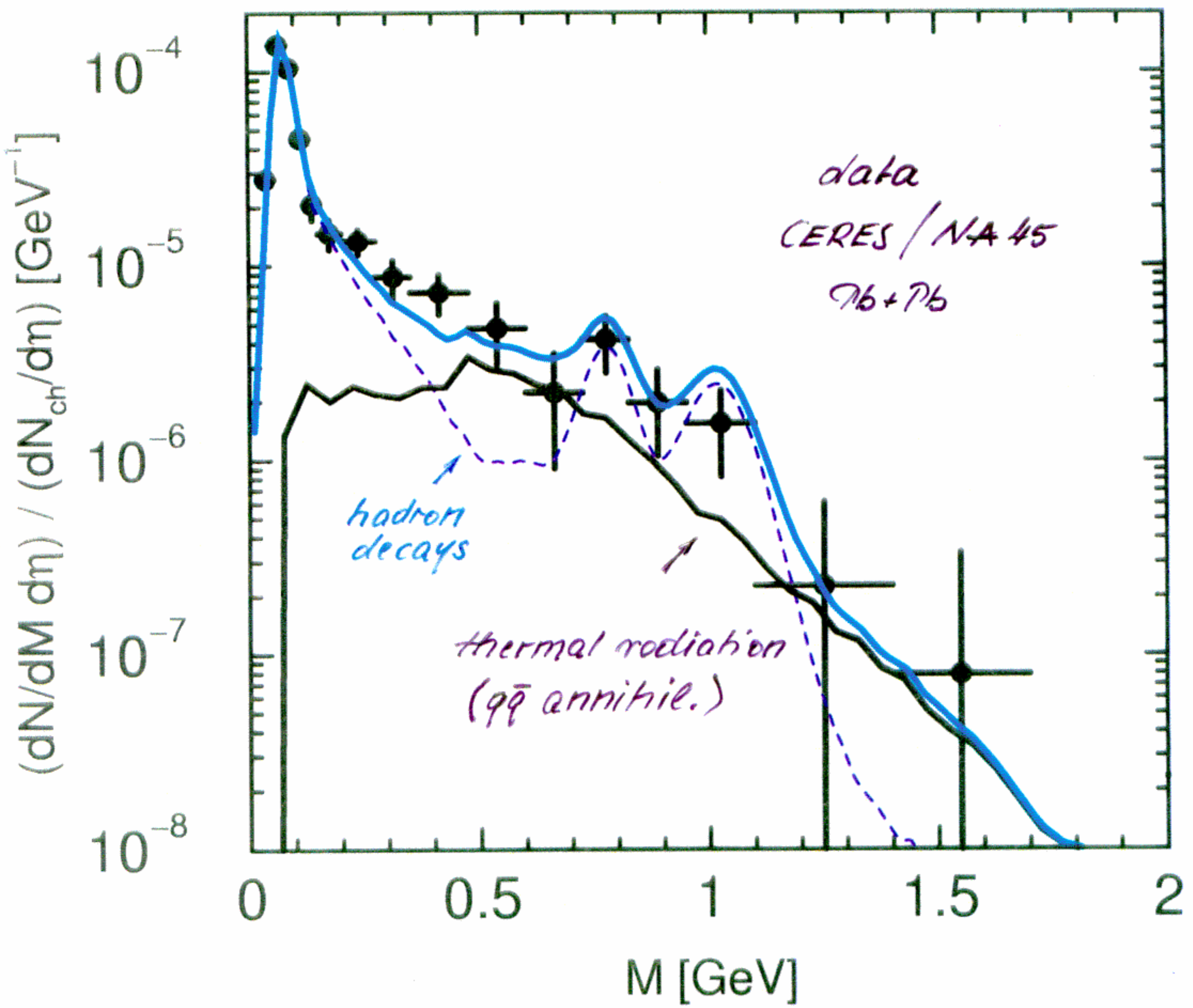


'soft dileptons' from the plasma ?

30% Central Pb(158GeV/u)+Au



Galmeister, Kämpfer, Pavlenko
Phys. Lett. B473 (2000) 20

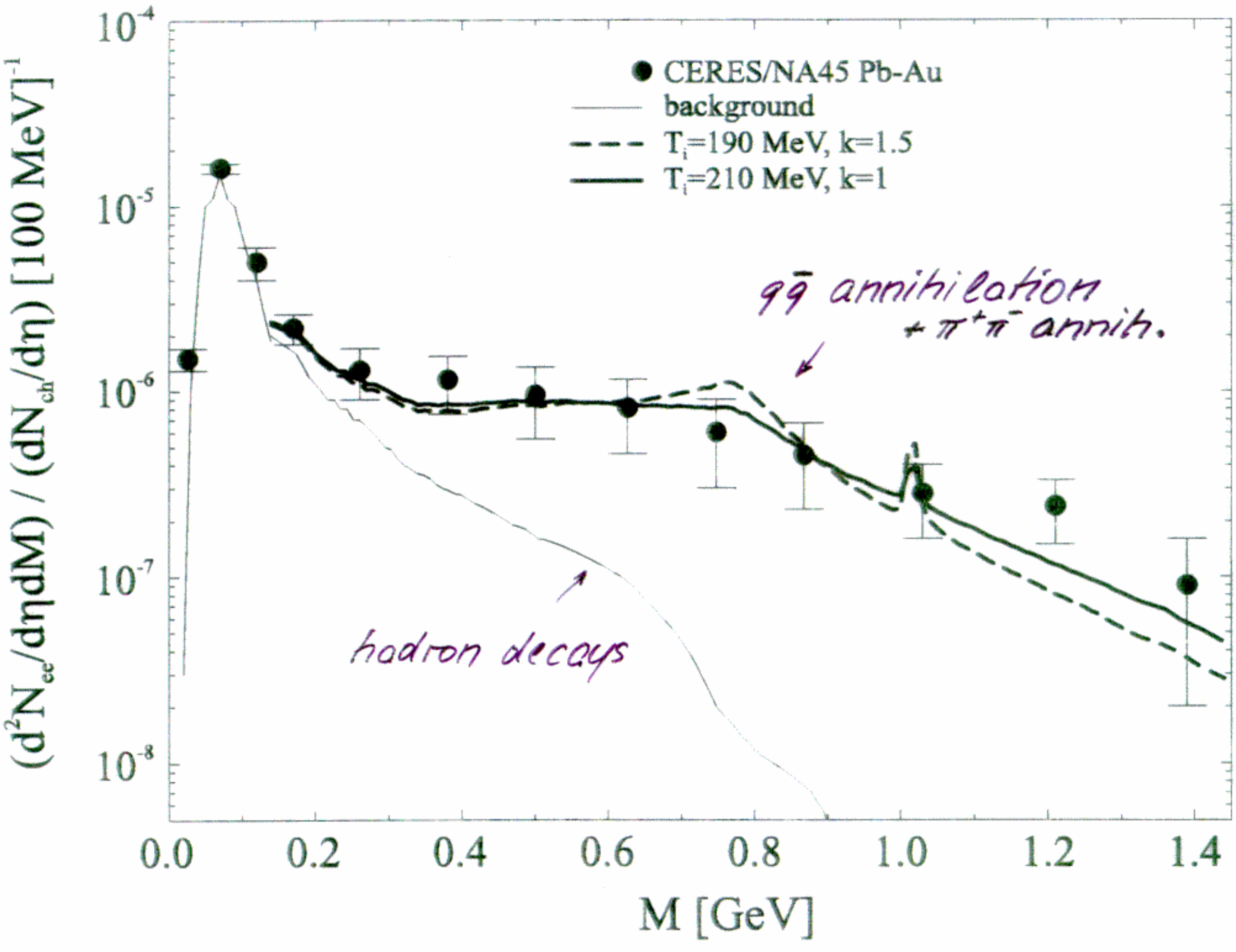


T_i = 210 MeV

T_f = 130 MeV

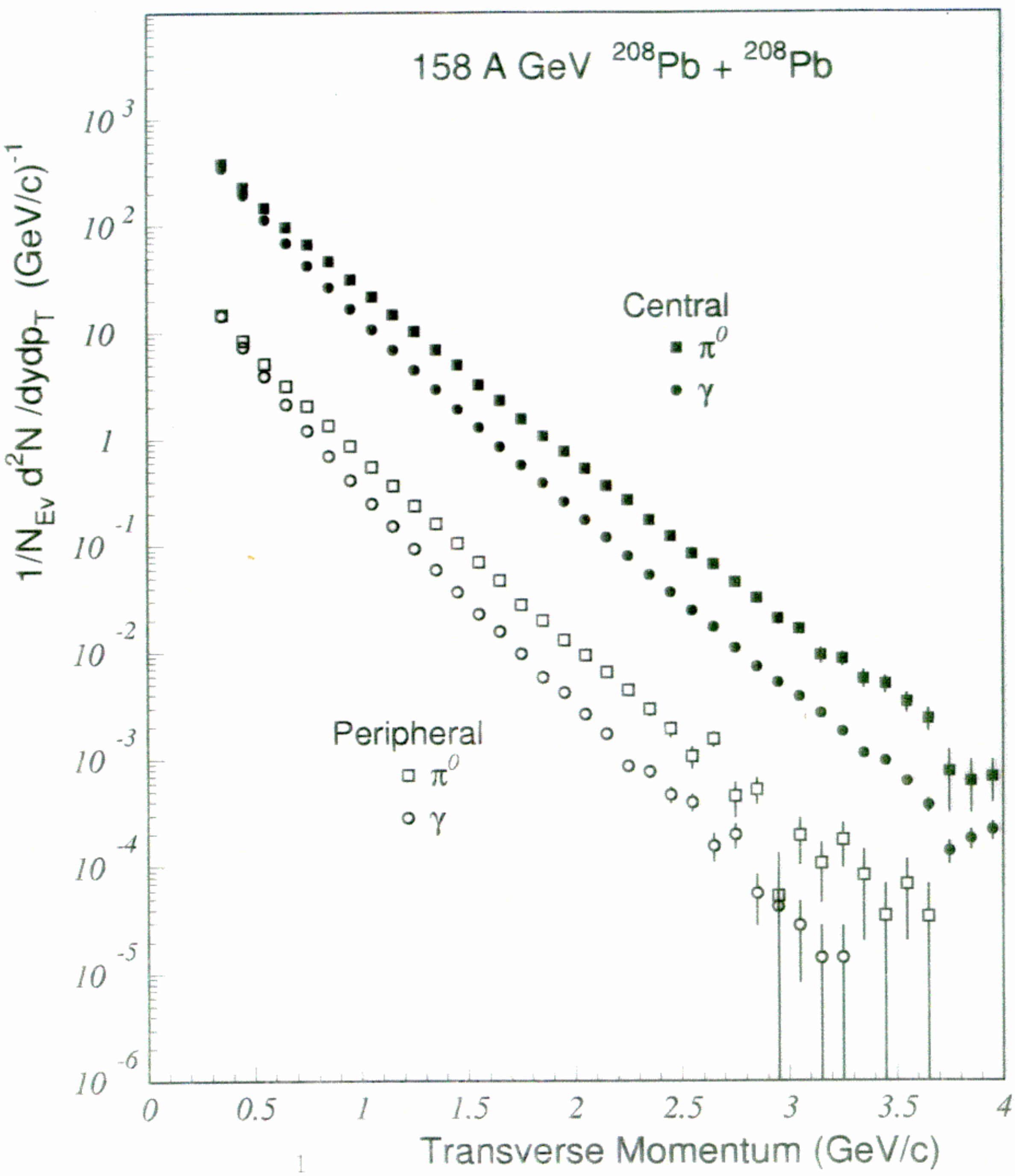
Schneider + Weise
hep-ph/0008083 9 Aug 2000

dileptons from $q\bar{q}$ annih. + $\pi^+\pi^-$ annih.



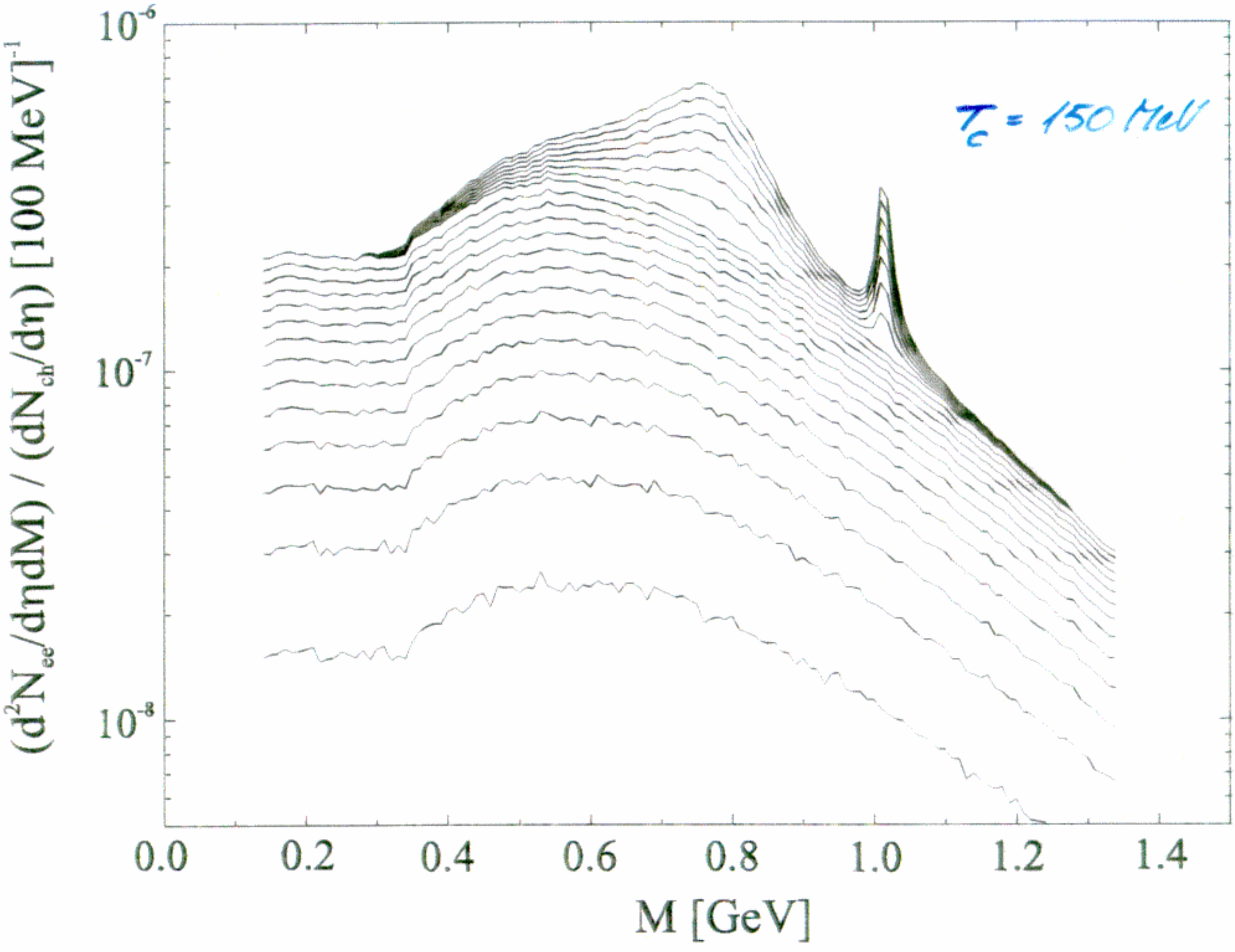
T_i = 190/210 MeV
ρ_i = 2.55 ρ_0 → T_c = 150 MeV

WA 98/nucl-ex/0006008
(13 June 2000)



Schneider + Weise

hep-ph/0008083 9 Aug 2000

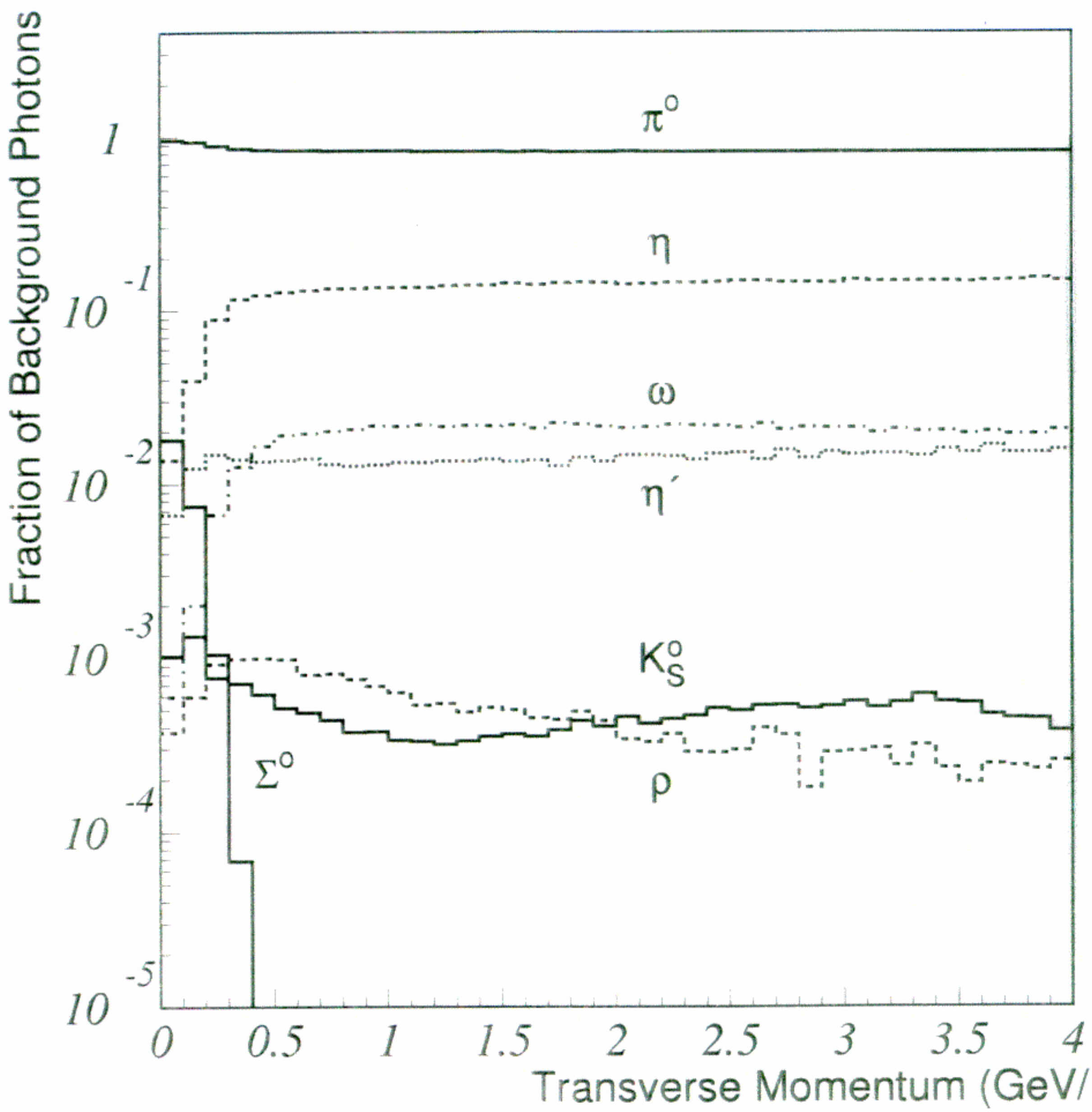


time evolution of accumulated dileptons from $q\bar{q}$ and $\pi^+\pi^-$ annihilation

fireball expansion from $t_i = 0$ to $t_f = 10$ fm/c (time steps of $\Delta t = 0.5$ fm/c)

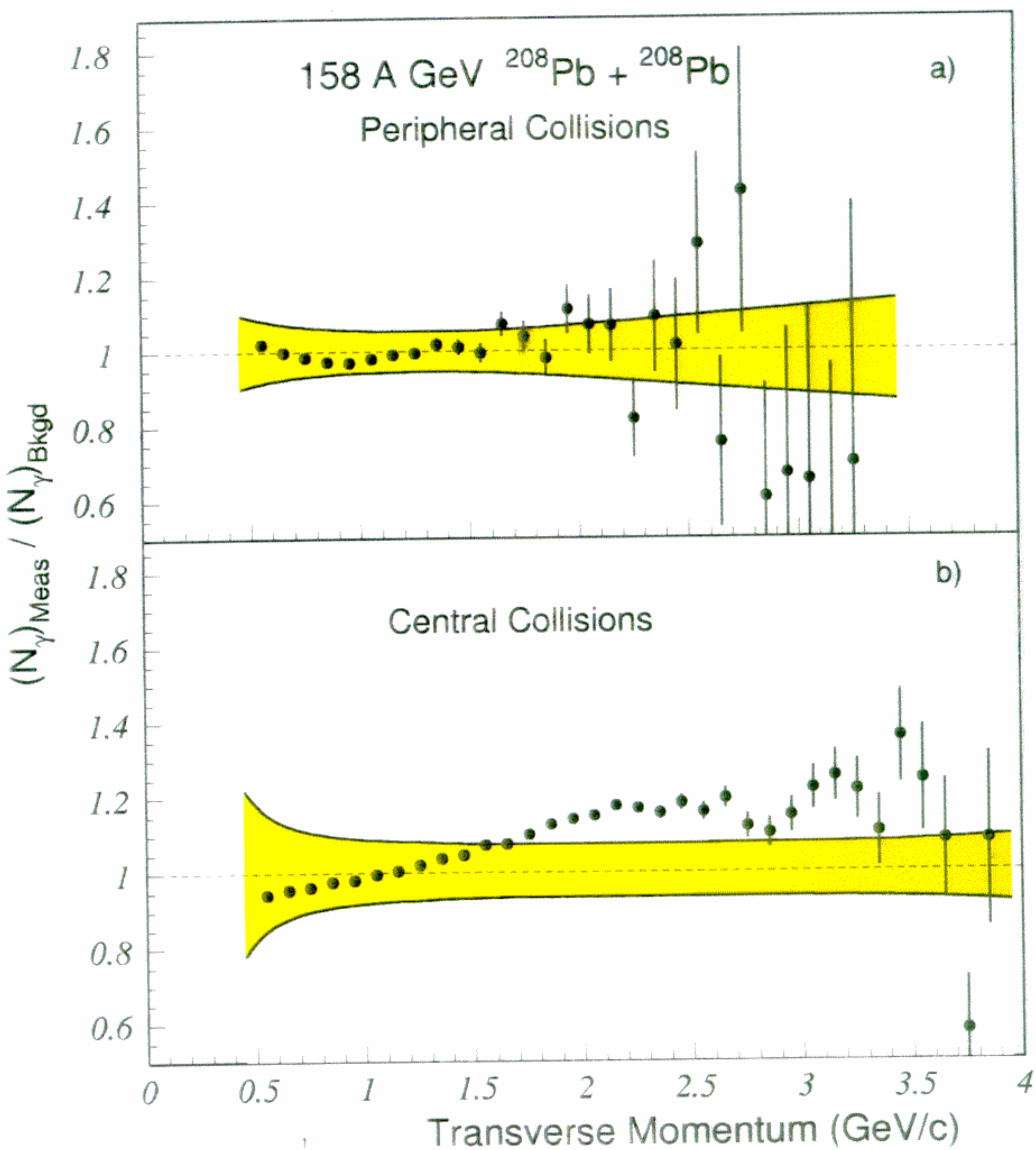
WA 98

nucl-ex/0006007 13 June 2000



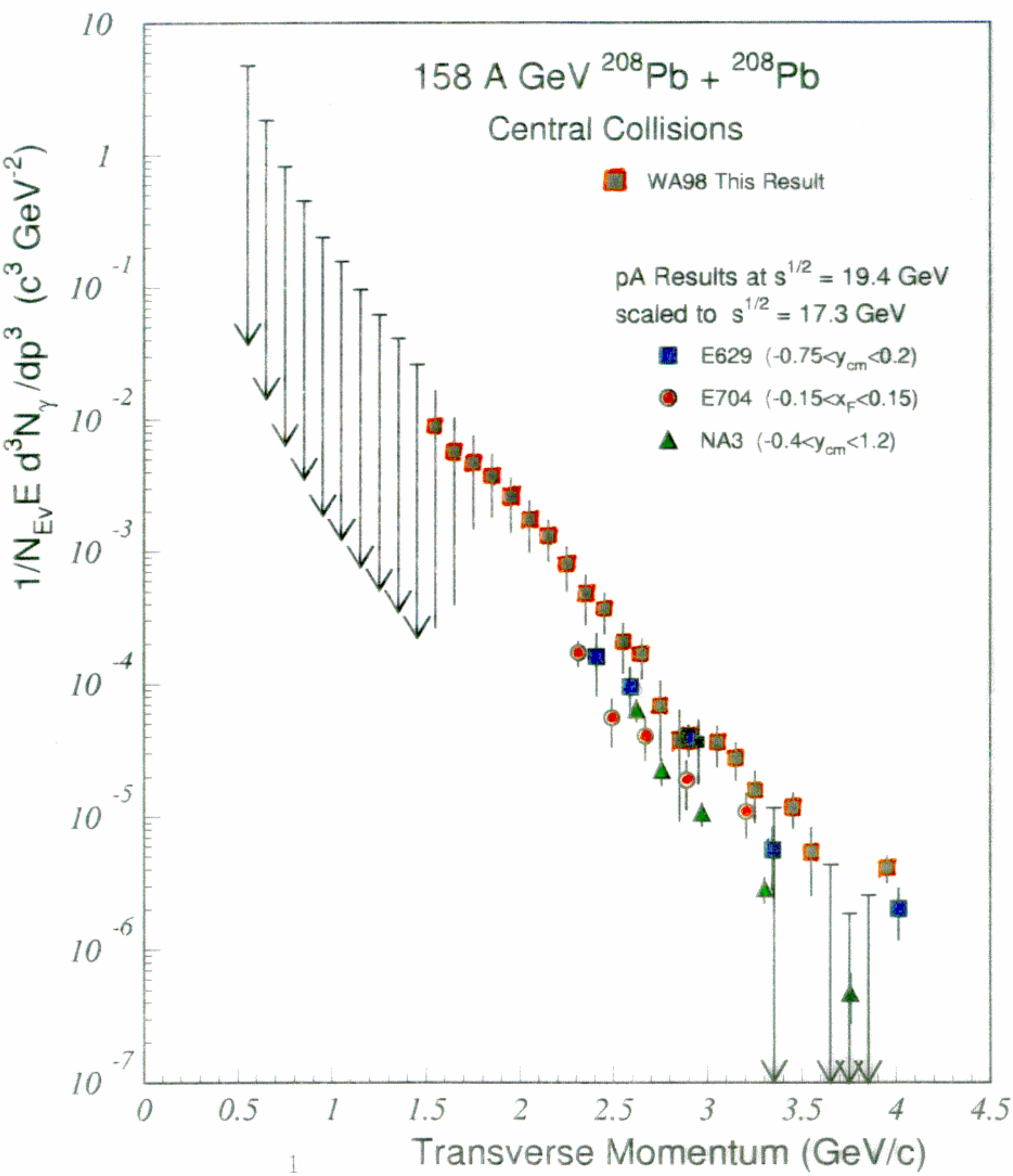
WA 98

nucl.-ex/0006008 13 June 2000

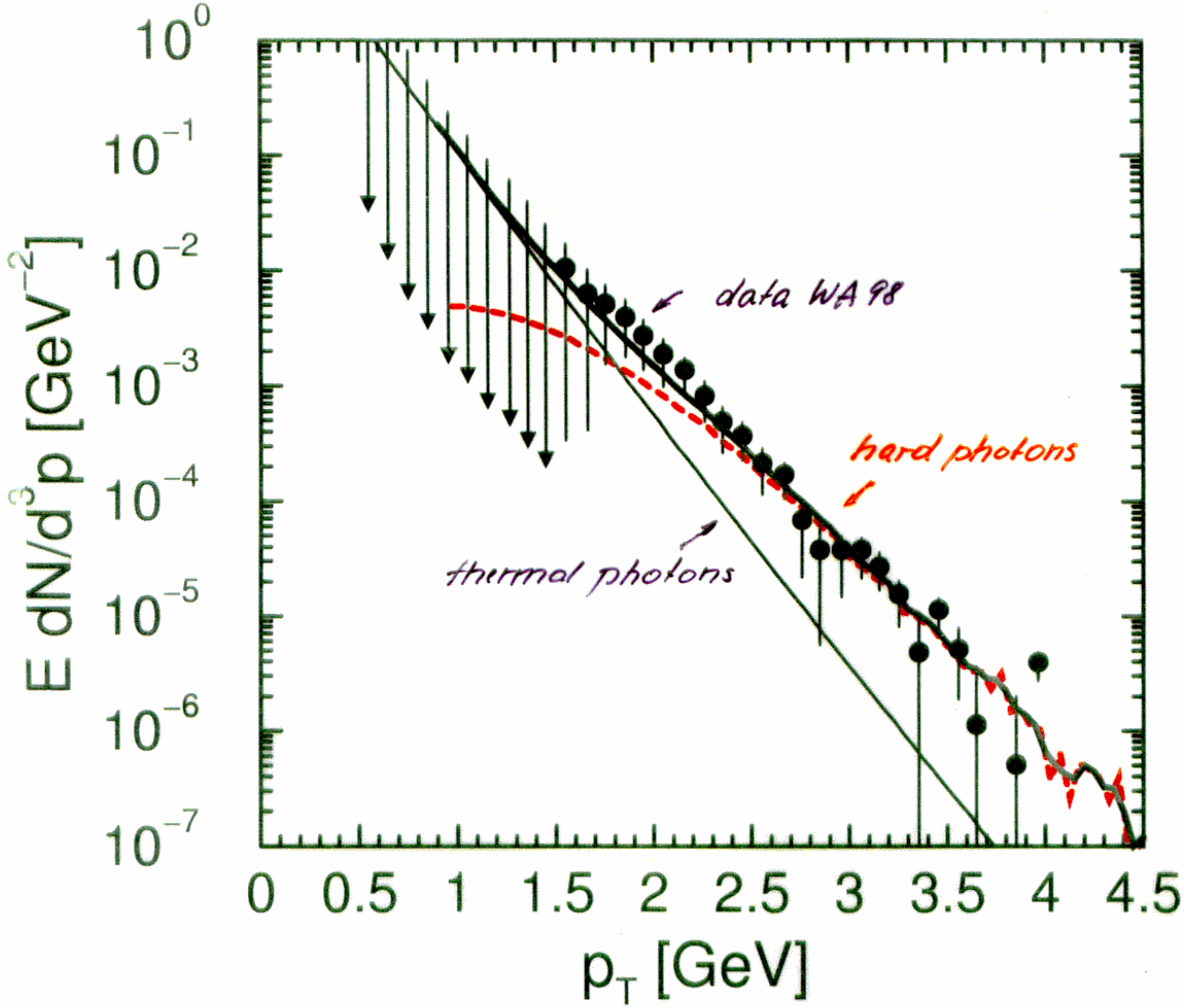


WA 98

nucl-ex/0006008 13 June 2000



Gallmeister, Kämpfer, Pavlenko
hep-ph/0006134; Phys Rev. C (2000)



thermal emission: same parameters as required to describe CERES and NA50 dileptons

(T_{eff} ~ 170 MeV; $V_4 = 3.3 \cdot 10^4$ fm^4)