QCD in the extreme conditions

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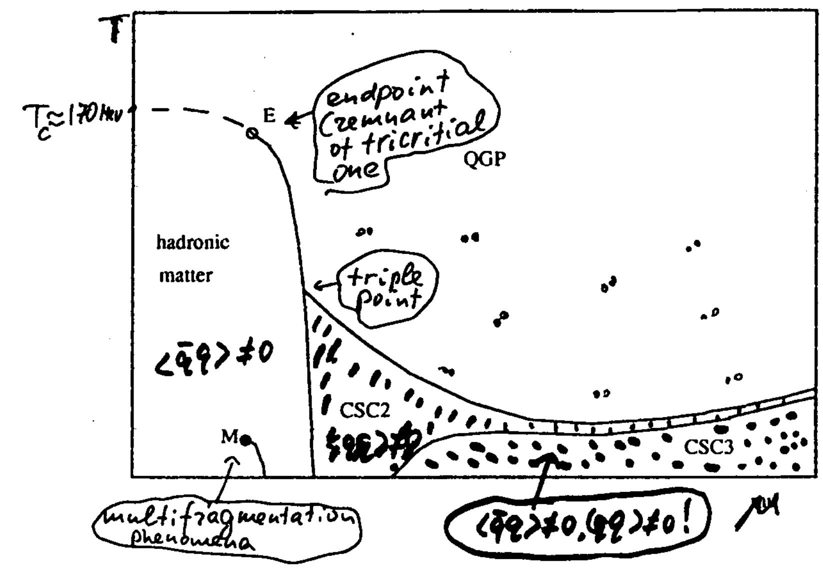
Lecture 1: The phases of QCD

- – **Prolog: Current** phase diagram as a map
- – Chiral symmetry breaking in vacuum and instantons
- – What happens at non-zero T: lattice, instanton molecules
- – Properties of Quark-Gluon Plasma
- – Color Superconductivity at high density
- – Color Superconductivity at very high density
- – Other "extreme conditions": increasing number of quark flavors, adjoint fermions, SUSY theories...

Before we start, we need some maps...
The theoretical version



- – **Progress was most signicant in the large density low T region. New phases: 2-flavor-like and 3-flavor-like Color Superconducors. (see talks by K.Rajagopal and T.Schaefer). Unfortunately the paths for heavy ion collisions do not cross them.**
- – **Another new element: the (remnant of) the QCD tricritical point (see talks by K.Rajagopal and M.Stephanov).** Strongly depends on m_s ...
- – "TRIALITY"

Instantons in QCD vacuum

d_L, $\bar{d}_R$

$A_\mu = \frac{2}{g} \frac{\eta^a_{\mu\nu} x^\nu}{x^2+\rho^2}$ describes tunneling between topologically different vacua...

[Polyakov et al (1975)]

oft (1976)]

(although different)

othetical Nambu-Jona-Lasinio tion, which is to create

$\langle\bar\psi\psi\rangle \neq 0$ $m_{const} \sim 350\text{-}400$ MeV pions and all that

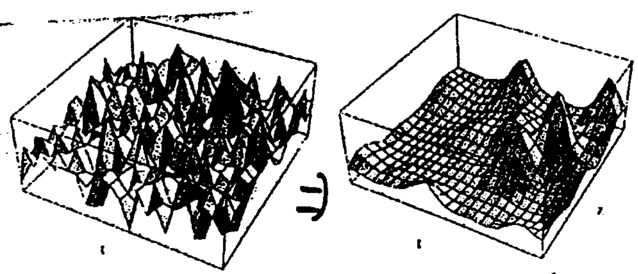
lso $\eta' \to$ (sign opposite!)

32) → Instantons create $\langle\bar\psi\psi\rangle$, etc !

$n = n_+ + n_- \simeq 1\ fm^{-4}$, $\rho \simeq \frac{1}{3}$ fm

ness parameter $n\rho^4 \sim (\frac{1}{3})^4 \ll 1$!

ction ops y -3 nders!



Before ↑ and ↗ after the fog goes away... (25 cooling steps)

Chu, Grandy, Negele, Huang - 94

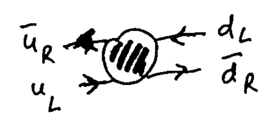
$\bar\rho = 0.35$ fm : $R \simeq 0.9$ fm ← Very close to my $\rho = 1/3$, $R = 1$ fm

+ many others

Chiral symmetry breaking and restoration

Few facts from the textbooks:

- – If quark masses are ignored, the QCD Lagrangian is a sum of independent left and right-handed parts. This generates two chiral symmetries, having rather different fate:
- – The $U(1)_A$ part is explicitly broken by anomaly, which (as G.t'Hooft and others explained) is driven by instantons. The measure of (rather significant!) strength of this effect is deviation of η' mass from that of a pion/kaon.



→ works repulsively for η'
→ But it also works attractively for π
→ does not work for ρ, ω...

- – The $SU(N_f)$ part is spontaneously broken, leading to non-zero quark condensate $< \bar{q}q >$, pions and all that. The reason for that is strong attraction between quark and antiquark in scalar channel, e.g. as assumed by Nambu-Jona-Lasinio (NJL) model (Nambu and Jona-Lasinio, 1961).

More recent findings(/claims) :

- – $SU(N_f)$ Chiral symmetry breaking is also caused by instantons. The same t'Hooft interaction which violates $U(1)_A$ is the attraction needed for it. However spontaneous breaking is not single-instanton effect, but a result of collective interaction of all instantons. (Therefore $< \bar{q}q > \sim \sqrt{n_{instantons}}$, not the first power.) (E.Shuryak 1982, D.Diakonov and V.Petrov, 1986.)
- – Lattice works of 80's have found chiral restoration phase transitions in QCD, at rather low temperature $T_c \approx 150 MeV$. Its order is still not clear, but it is sharp enough, transition to QGP happens in a narrow interval not larger than $\delta T \sim 10 MeV$.
- – Studies of susceptibilities, correlation functions, "screening masses" etc have shown that in scalar and pseudoscalar channels like π, σ, η' significant changes occur, and deviations from free quark behavior persist to the $T > T_c$ phase. However no large deviations in vector and axial channels are so far found.

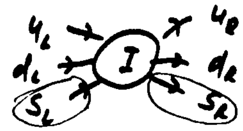
Interacting (III)

- – Instanton liquid model has reproduced (nearly) all those features of chiral restoration (Th.Schafer and Shuryak,96). In addition, it suggests a simple mechanism for chiral restoration: formation of instanton-anti-instanton molecules. Recently first direct observation of molecules were made on the lattice ((Ph. de Forcrand, 98))
- – Instantons were shown to generate Color Superconductivity at high density and relatively low $T < 50 MeV$. (Rapp,Schafer,Shuryak,Velkovsky, PRL 98, Alford, Rajagopal, Wilszek PLB 98) Unfortunately lattice simulations are not yet possible for non-zero chemical potential to study this region.
- – Existence of the "endpoint" second order transition in which sigma is truly massless, and especially its possible observation in heavy ion collisions was discussed (Stephanov,Rajagopal,Shuryak 98)

How to describe
the instanton-induced effects?

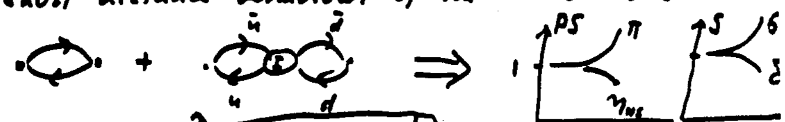
[W]ay #1: First integrate away the color field A_μ^a

⇒ 't Hooft effective interaction
(Like Nambu-Jona-Lasinio...)



[Ex]ample: short distance behaviour of the correlators

$\Pi(x)$ =



does not exist for V, A!

↑ 83 Paper, E.S.
check numbers...

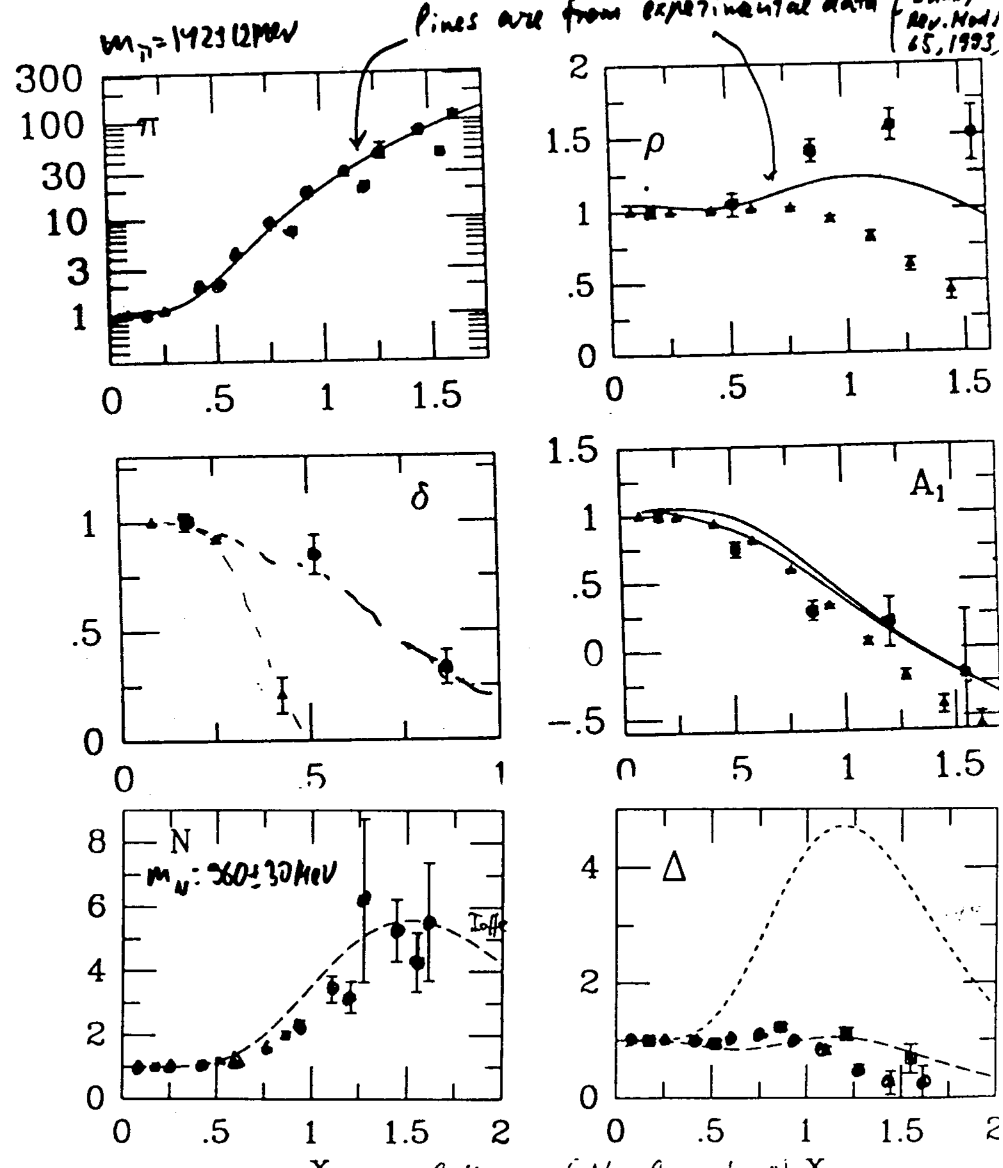
[Ex]ample: Sum of [diagrams] for π... is good!
(Diakonov, Petrov 86)

... but, how to solve it to **all** orders?

[W]ay #2 First do fermions, in 'atomic' approximation, then average over coll. variables

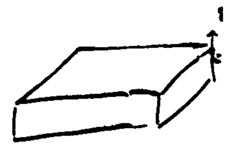
$$Z \sim \int d\Omega \, e^{-S_g} \left[\det(i\not{D})\right]^{N_f}$$

↑ collective coordinates 12/instanton
↑ gluonic interaction
↑ fermionic interaction



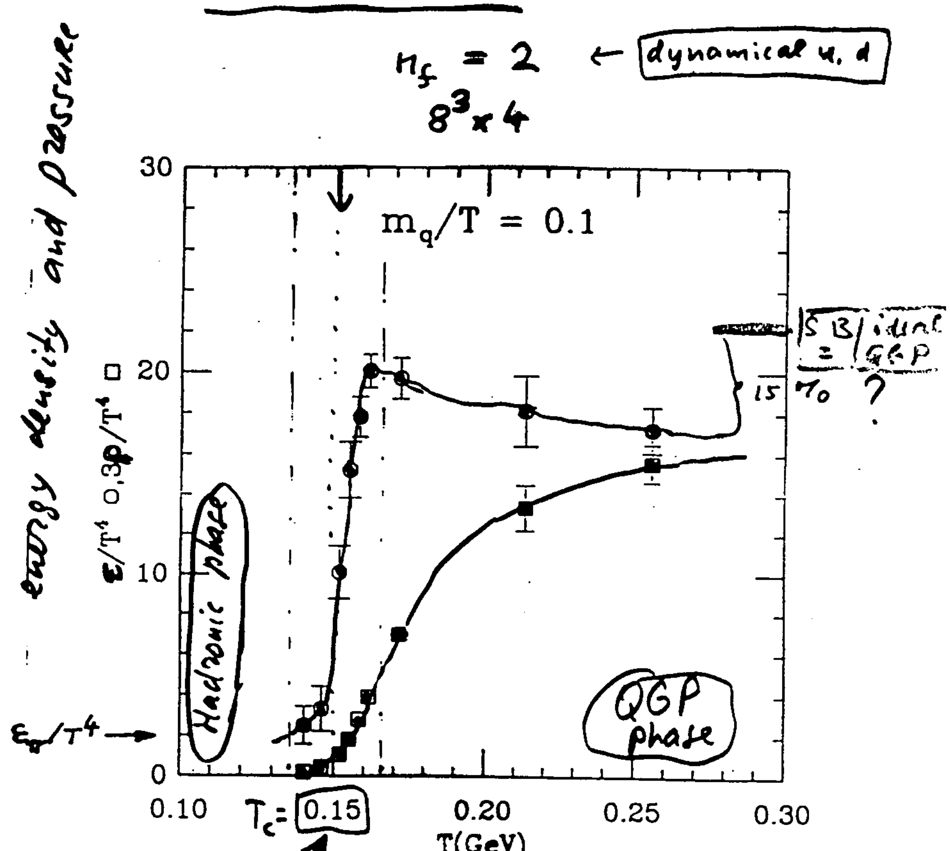
▪ - lattice (Negele et al)
▲ - RILM (Shuryak, Verbaarschot)
random instanton liquid model
Schaefer → Nucl. Phys. B. 93

QCD Thermodynamics on the lattice



$n_f = 2$ ← dynamical u, d

$8^3 \times 4$



the very small strip $\frac{\Delta T}{T_c} = 0.1$ or less is where all action is

= the mixed phase

What is going on there ?

MILC - Collaboration '94

T. DeGrand et al.

Comment:

Pure glue ⇒ "deconfinement"

$T_d \simeq 260$ MeV (Karsch et al)

QCD with light quar... "chiral restoration" ...

$T_c \simeq 150$ MeV

Both are surprisingly small ...

1. **Why they are so different ?**

Stay tuned...

2. **Energetics** is very different as can be seen from a QGP side

$p^{QGP} = (\#)\, T^4 + (B^{QGP} - B^{vac})$ should stay > 0 (smaller?)

* For pure glue ($T = T_d$) the first term is la... and matches the vacuum energy $B^{vac} \gtrsim 1$ GeV... so $p^{QGP}(T = T_d + \varepsilon)$ is small but positive

* For QCD ($T = T_c$) the first term is too s...

So, all non-perturbative fields cannot dis...

at $T \gtrsim T_c$: $B^{QGP} \gtrsim \frac{1}{2} B^{vac}$!

(G. Brown, V. Ko...)

"Hard glue", or **"epoxy"** does not melt

What is it made of ?

CHIRAL SYMMETRY RESTORATION

(based on T.Schaefer, E. Shuryak and J. Verbaarschot, The chiral phase transitions and the Instanton Molecules; SUNY-NTG-94-24,Stony Brook.) PRD(95)

– At growing T, quark motion becomes anisotropic
Example: zero mode of the "caloron" ($T \neq 0$ instanton)

$$\psi(\tau, r) \sim |\sin(\pi T \tau)/\cosh(\pi T r)|$$

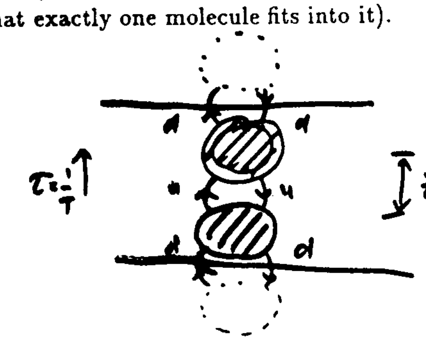
oscillatory in time, **exponentially decaying** in space.

– A "pairing" of instantons (leading to formation of $\bar{I}I$ molecules even at T=0) becomes much stronger, if I and $\bar{I}$ are at the same point

$$detD \sim |\sin(\pi T \tau)/\cosh(\pi T r)|^{2N_f}$$

– Rapid "polarization" of **even one** molecule was found at $T \approx T_c$, (which allows one to identify T_c as approximately the size of the "Matsubara box", such that exactly one molecule fits into it).

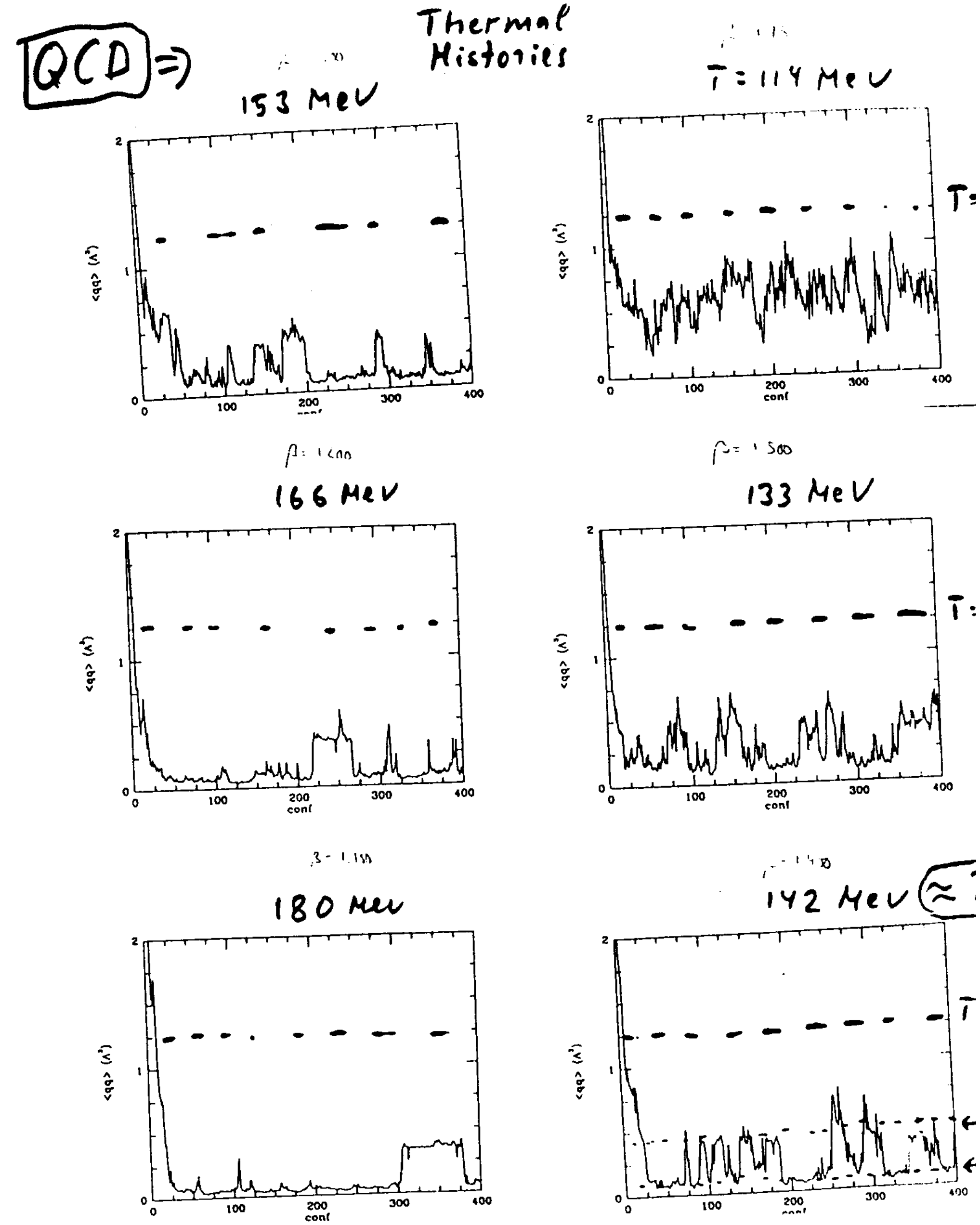
$\Delta\tau = \frac{1}{2T}$ half box
$\Delta\tau = 0$ same pouint



as maximum
T ≃ 110 MeV
: 140MeV it
nates !
c ≃ size of a molecule !

⟸ For $N_f = 2$ to 3
(not true for smaller and larger N_f ...)

QCD ⟹ Thermal Histories



⟹ weak 1-st order –

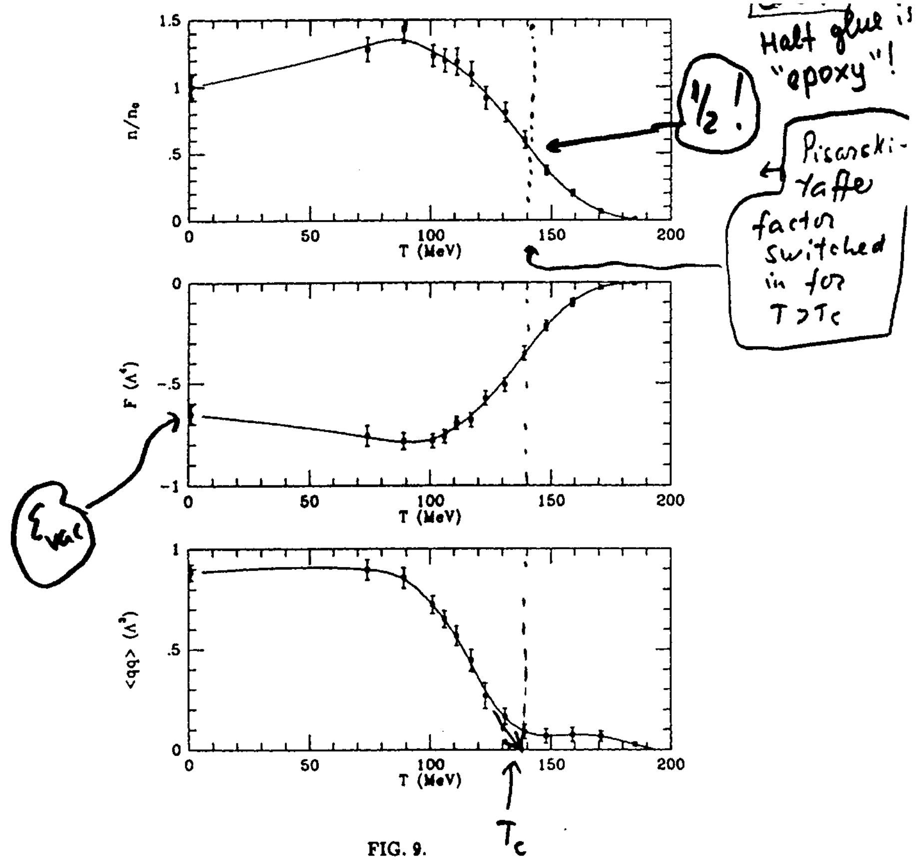


FIG. 9.

The quark condensate "melts" at $T = T_c$, but the gluon one does not! "Molecules" are the "epoxy"!

(glue which survives T_c!)

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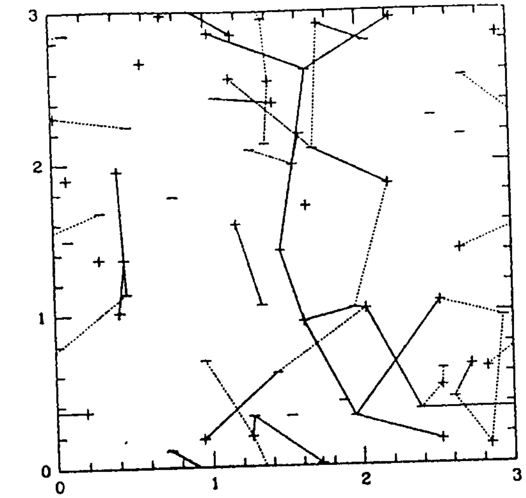
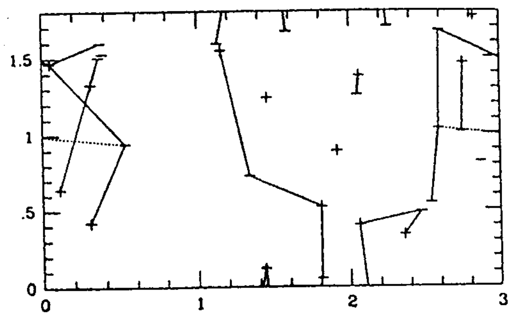
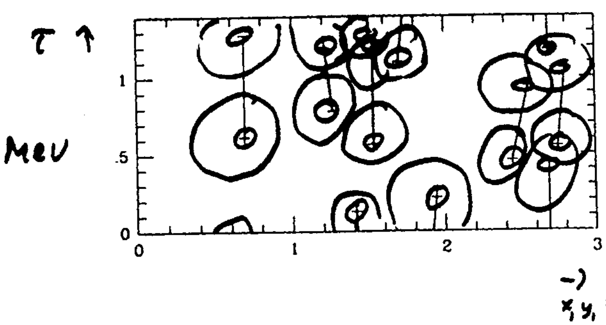
$T = 75$ MeV



$T = 123$ MeV ($T < T_c$)



$T = 158$ MeV ($> T_c$)



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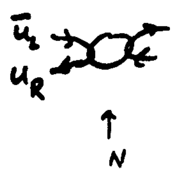
If instantons <u>do not</u> go away at $T \gtrsim T_c$, what interactions they produce?

Reminder: at $T < T_c$ it was 't Hooft Lagrangian



+ violates $U_A(1)$ ⟹ π and η′ correlators are <u>very</u> different, etc

"Molecules" produce other interactions

SSV Lagrangian (for 100% polarization)

$$\mathcal{L} = G\Big\{ \frac{2}{N_c^2}\big[(\bar\psi\tau^a\psi) - (\bar\psi\tau^a\gamma_5\psi)^2 - (\bar\psi\tau^a\gamma_0\psi)^2 - (\bar\psi\tau^a\gamma_\mu\gamma_5\psi)^2\big] + \frac{2\cdot 4}{N_c^2}(\bar\psi\gamma_0\gamma_5\psi)^2\Big\}$$

G ~ # of molecules

In general, NJL-type Lagrangian at $T \neq 0$ has 7 possible structures..., this has fixed factors

$U_A(1)$ symmetric ⟹ equally attractive for $(\vec\pi, \sigma)$, $(\eta', \vec\delta)$ channels

Transverse ρ, A_1 are <u>not</u> affected

Brief history

50's BCS...
60's Gorkov eqn
70's QGP, screening

- 70-80's: **Quarks of different colors are attracted perturbatively:** S. C. Frautschi (Erice1978), F. Barrois, Nucl. Phys. B129, 390 (1977), D. Bailin and A. Love, Phys. Rep. 107, 325 (1984). $\Delta \sim MeV$ **only...**

- T.Schaefer, E.S., J.Verbaarschot Nucl. Phys. B412, 143 (1994): **ud scalar diquarks are very deeply bound in the instanton model, being a very robust element of Nucleons (octet) baryons, as opposed to Δ (decuplet) ones.** Sorry: too many phenomenological hints to mention here: weak decays, formfactors, fluctuations of the N cross section...

- **First attempts to study instantons at finite density numerically** T. Schäfer, Phys. Rev D57 (1998) 3950.: **diquarks persist, even at high** μ: "polymers"

- -**Two papers** (**submitted** to **hep-ph** on the same day) **about** instanton-driven superconductivity for $N_f = 2, N_c = 3$ **appear:** R. Rapp, T. Schäfer, E. V. Shuryak and M. Velkovsky (RSSV) Phys. Rev. Lett. **81** (1998) 53. M. Alford, K. Rajagopal and F. Wilczek (ARW) Phys. Lett. B422 247 (1998). : large condensate $\Delta \sim 100$ MeV!
- - Color-flavor locking is proposed and verified for OGE in ARW hep-ph/9804403. It is also preferred by instantons RSSV,hep-ph 9904353 (probably always true).
- - Magnetic gluons overtake electric ones at large μ, the condensate grows with μ D.T. Son, Phys.Rev.D59:094019,1999;hep-ph/9812287
- - Transition between two CSC phases, as m_s changes, is discontinuous: the first order RSSV, Schafer+Wilczek, Rajagopal + Berges 99. Finalized the phase diagram (the mean field).

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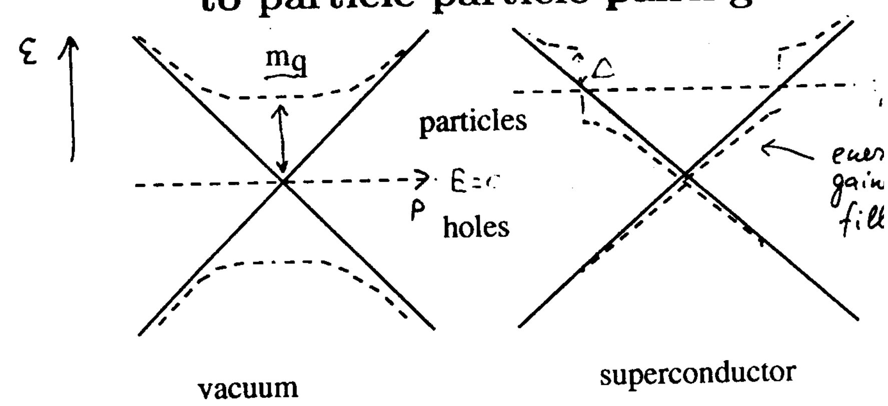
Why **transition** from **particle-hole** to particle-particle **pairing** ?



Energy versus momenta: the blue **dashed** line show the dispersion curve for vacuum and dense matter. It has discontinuity at two different places the surface of the Dirac sea and Ferm sphere.

* Cooper instability
Δ is helped by a ... ⇒
any coupling works...

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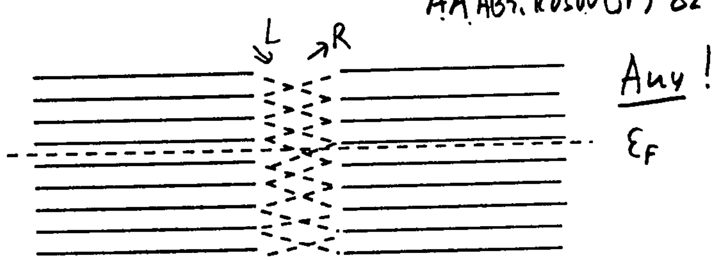
Why instantons?

- - It is the strongest **non-perturbative** effect **generally** → (my talks at Lattice 93,96)
- - Explanes quantitatively chiral symmetry breaking in vacuum. Gap is large: ($m_{constituent} = 330 - 400 MeV$)
- - Anomaly is not eliminated by adding $\mu\gamma_4$ to the Dirac operator[1]
AA Abrikosov (Jr) 82



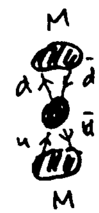
- - But at very high density instanton effect are suppressed by the Debye screening (E.S.1982)

$$dn(\rho, \mu) \approx dn(\rho, \mu = 0) exp(-N_f \rho^2 \mu^2)$$

[1] In random matrix models people have used a simple-minded approach: adding $\mu\gamma_4$ to the Dirac operator represented as a random matrix with some density of zero modes (leading to quark condensate). If μ is sufficiently large, eigenvalues move away from zero and chiral symmetry gets restored.

Instantons and triality

There are three attractive channels, which compete



- instanton-induced attraction in $\bar{q}q$ channel leads to χ-symmetry breaking, also η' mass – $U(1)$ problem

- instanton-induced attraction in qq leads to color superconductivity, It decreases with N_c as $1/(N_c - 1)$] same at N_c= / 1/2 in QCD

- light-quark-induced attraction of $\bar{I}I$ leads to pairing of instantons into "molecules". effect increases with N_f

⊛ The first two phases can be described by Mean Field Approx.
→ not the last!

Two colors: a very special theory

- The opposite to the large N_c limit: Baryons are degenerate with mesons: Pauli-Gursey symmetry (Unlike SUSY different number)
- symmetry breaking is $SU(2N_f) \to Sp(2N_f)$ For $N_f = 2$ the coset $K = SU(4)/Sp(4) = SO(6)/SO(5) = S^5$. 5 massless modes: pions plus scalar diquark S and its anti-particle $\bar{S}$
- RSSV1: finite μ breakes rotates the 5-dim sphere. Scalar diquark (not sigma meson) becomes massive. more in: Kogut, Stephanov and Toublan hep-ph/9906346
- Fermionic determinant is real: lattice simulations possible. Results by Karsh, Dagotto et al of mid-80's make sense! See recent work by S.Hands et al.

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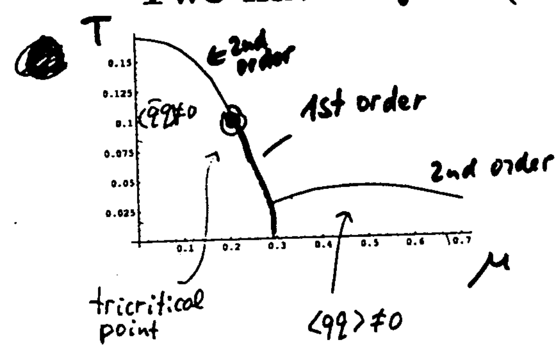
Two flavor QCD (CSC2)



Schematic (simple form-factor in 3-mo[…] instanton-induced Lagrangian

The phase diagram from Berges Rajagopal: Similar diagrams: RSS[…] Diakonov and Carter, Klevansky e[…] al.

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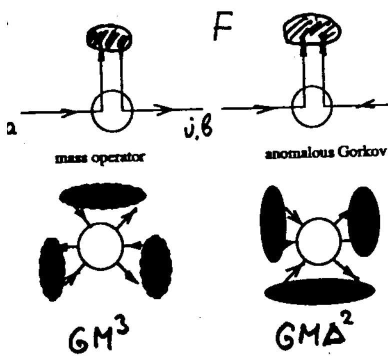
how the calculations are done: the mean field way



The mass operator include two types of diagrams: total energy of Fermi gas ("kinetic energy" is calcualated with it. *Note: condensates are matrices in C/F*

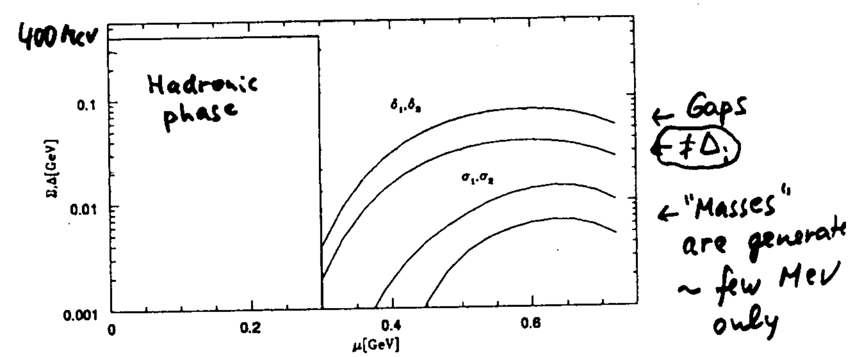
The ("potential energy") operator also two types of diagrams: For instantons and $N_f = 3$ it looks like this, where green area are $< \bar{q}q >$ and magenta $< qq >$ or its conjugate.

Then one minimizes the sum and get gap equations There are many because all masses/condensates are color-flavor matrices.

Approximations: (i) The coupling constant G is treated as constant.
(ii) No clustering included.

Three flavor QCD (CSC3)

$m_i = 0$ chiral limit



Color flavor locking (ARW2) is prefered by one-gluon-exchange
$\langle q_i^a C q_j^b \rangle = \bar{\Delta}_1 \delta_{ia}\delta_{bj} + \bar{\Delta}_2 \delta_{ib}\delta_{ja}$
$SU(3)_c SU(3)_f \to SU(3)_{diagonal}$
More complicated calculations (RSSV) show that instantons prefer it as well (and $\Delta_1 = -\Delta_2$)

The "continuity" issue

T.Schafer and F.Wilczek (98) pointed out that CSC3 phase has not only the same (?) symmetries as hadronic matter, but also very similar excitations:

The condensates conveniently mix color with flavor

quark language	hadronic language	comment
8 gluons →	8 massive vect. mes.	Meissner eff.
3*3 quarks →	8+1 "baryons"	Λ(1405)?
8 massless pions →	remain !	if $<\bar{q}q> \neq 0$
γ is combined with "hypercharge" g ↗	massless γ_{inside}	like γZ in SM
Singlet scalar $U(1)_b$ →	H condensate	???

(*) But: It is still not transparent for $\gamma_{outside}$ (something Weinberg/Salam should not have warried about) so it will levitate in an ordinary magnet, or reflect light from the surface...

→ Is it the correct condensation pattern of $N_f = 3$ nuclear matter?

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The one-gluon exchange

The operator $(\gamma_\mu t^a)(\gamma_\mu t^a)$: no chirality flip

Strength depends on momentum transfer Q (it is after all the Rutherford-like scattering)

Electric exchanges are Debye screened at $Q \sim g\mu$ (like instantons)

Magnetic ones got no screening at T=0, only Landau damping

(One has also to take care of time delay effects, since we now speak of relativistic bound state bound by exchanges of propagating quanta... Eliashberg eqn.)

T.D.Son, hep-ph/9812287 therefore found a "double log" in the gap equation

$$1 = const\, g^2 log^2 \Delta$$ | one log → the other

thus unusual answer: $\Delta \sim \mu exp(-\frac{3\pi^2}{\sqrt{2}g})$

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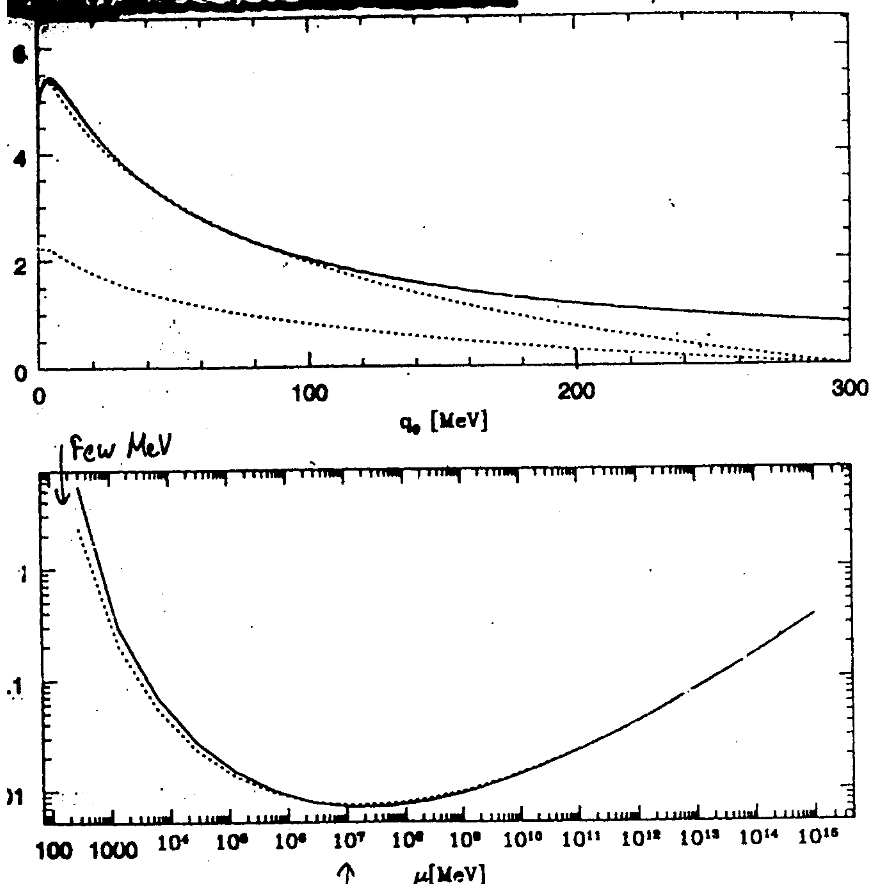
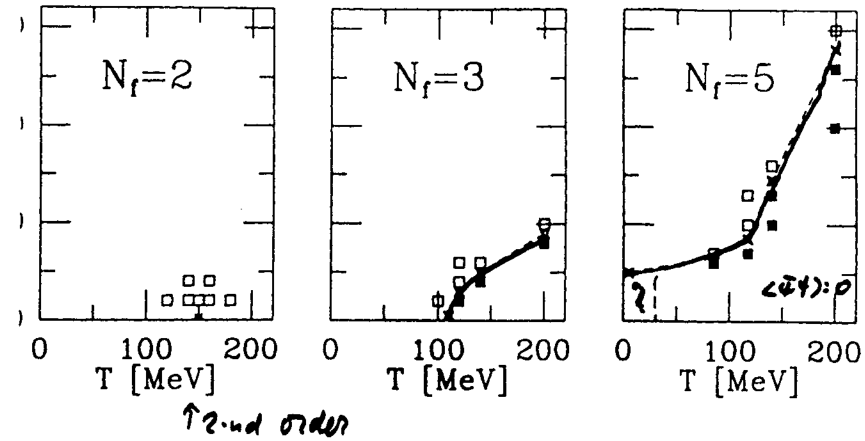
...HBERG EQUATION

T. Schafer following T. D. Son



T. Shafer + E.S. 95

FIG. 7.



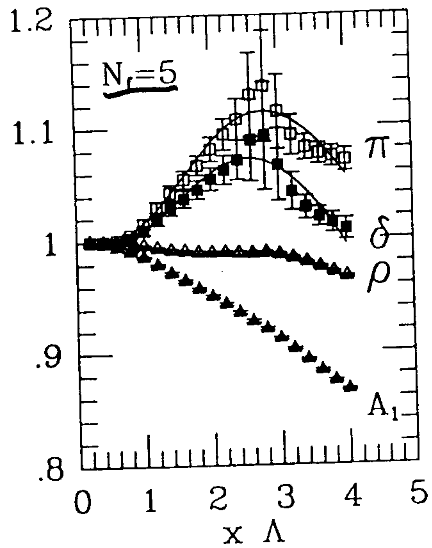
Phase diagram of IILM

at $N_f > 5$ and $m \to 0$ molecular vacuum $\langle\bar{\psi}\psi\rangle = 0$

But $(\pi - \sigma - \delta - \eta')$ $U(N) \times U(N_f)$ multiplet is Bound

($m \neq 0$, not Goldstone... of course

Are there bound states in the chirally symmetric phase?



$M_{quark} = 0.1\Lambda$ used (and fitted from the correlators)

$\Rightarrow$ So chiral sym. is not exact

Yes: $m_\pi = m_\delta = m_\sigma = m_{\eta'} = \ldots$
$= 1.4\Lambda \ (\pm 0.3\Lambda)$

All other channels (N, ...) are consistent with free quarks

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Conclusions

- The vacuum/hadrons are in th chirally broken phase, with $< \bar{q}q$ condensate generated by Redinsta tons
- At high $T > T_c \approx 160 MeV$ th Redcondensate melts: QGP
- At low T and high density Col Superconductivity is expected, wi $< \bar{q}q >$ condensate, also generate by instantons
- Chiral symmetry first disappe in the SCS2 and then reappear ag in CFL phase.
- It persists till indefinitely lar densities, with magnetically bou Cooper pairs. The gap grows large μ

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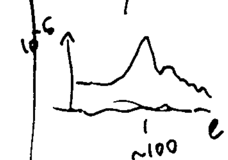
Lecture 2: Heavy Ion collisions: the Quark-Gluon Plasma search

- Prolog: Little Bang vs. the Big One
- The final state: observed spectra and phase diagram
- Radial and elliptic flows
- The "initial" state: has QGP been discovered at CERN?
- Dileptons: looking directly into hot matter
- The J/ψ, ψ' and ϕ stories

Two explosions: the Big Bang versus the Little one

	Big Bang	Little Bang
expansion	Hubble law $v \sim r$	same but anisotro
visible T	3K today, ~ 1 ev at freeze-out	170 MeV chemical 110-140 MeV ther
The *final* velocities status	Hubble constant, recently fixed to 10%	final radial flow $v_t = .5 - .6$
acceleration history conclusion	distant supernovae negative acceleration now?	Ω^- flow accelerates at the
dipole component	"directed flow" impact b motion of Solar system	
ellipticity		elliptic flow
angular harmonics	$l \leq 200$ with peak frozen plasma osc.	m=3-6 seen ???
	$\sim 10^{-5}$	$\sim .01$



1 event only! | ~ 10^7 events !!

2

Why study heavy ion collisions?

e.g. to see what happens with vacuum and hadrons near the phase transition

Elementary mechanics of a (fireball)

(= very big MIT bag)

QGP

$(16 + 3\cdot 3\cdot 2\cdot 2\cdot \frac{7}{8})$ ↙ adds to change the vac.

$\varepsilon = [(\# DOF)\, const \cdot T^4 + B]$

$p = [\frac{1}{3}(\# DOF)\, const \cdot T^4 - B]$

↑ expands against the vacuum pressure

1 GeV/fm³ $\left(B_{MIT} \sim 50 \frac{MeV}{fm^3}\right)$

energy diff. between and pert. vacua) ← That is why we need RHIC!

like atmospheric pressure, which is seen only if one can pump the air out, it is seen only if we go to new phase, QGP

...ish is produced by →
...ass to be moved is →

$$\frac{p}{\varepsilon} = \frac{\frac{1}{3} const(DOF) \cdot T^4 - B}{const(DOF) T^4 + B}$$

B makes the EOS softer

The phenomenological version of the map

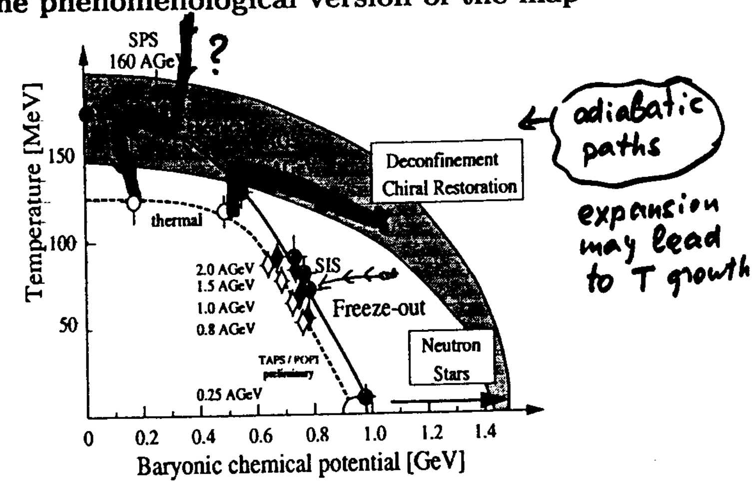


Figure 1: Solid (dashed) lines indicate chemical (thermal) freeze-out. Adopted from U.Heinz, hep-ph/9902424; The paths ~~and the second figure~~ are from C.M.Hung, E. Shuryak, Phys.Rev.C57:1891-1906,1998

- – Looking backward in time, from data one can identify "chemical" and "thermal" freeze-outs.
- – So we did found a new phase of matter at SPS, never seen before ! It is chemically frosen but kinetically equilibrated "resonance" gas.
- $\frac{S}{N} = const$, even in event generators, and close to thermal one (→ e.g. talk by L.Bravina on UrQMD at QM99)

Maybe non-equilibrium but quite adiabatic!

Particle composition

- \- Looking backward in time, from detector, is like looking at the Sun: $T \sim 6000^0$ only, although it is hotter inside... "thermal" freeze-out.
- \- one can also identify "chemical" freeze-out from particle ratios

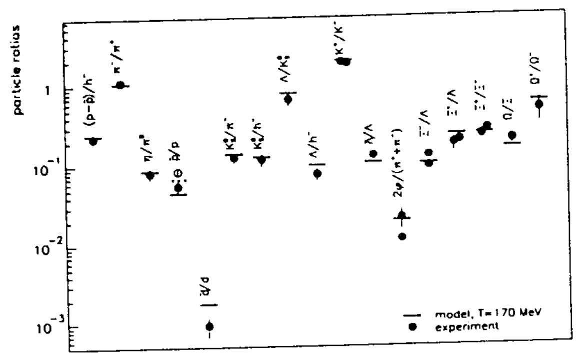


Figure 1: The ratios fitted to thermal model for PbPb at SPS (from J.Stachel)

hadronic chemistry	quark chemistry
fits many ratios very well $T \approx 170 - 190 MeV$, s quark suppression: small in PbPb Problems: why so high T? Can hadronic phase coexist ? Why vacuum masses are used?	more parameters fugacities (opposite for $\bar{q}q$) and "phase space occupancies" (same for $\bar{q}q$)

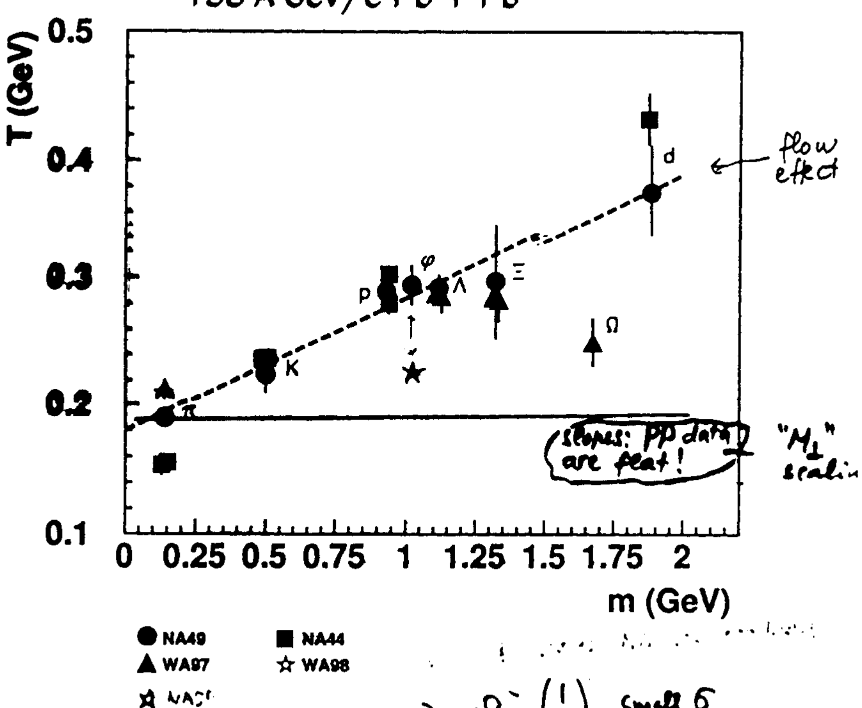
How hot is matter at the beginning in heavy ion collisions?

Is there such thing as a collective

- \- Pre-prehistory: Ancient debates if the AA spectra are just a superposition of NN's: different m_t slopes
- \- "Initial state" parton rescattering? No, the final state rescattering of hadrons - e.g.deuterons
- \-m_t slopes depend linearly on particle mass: this supports common flow idea $\langle p_\perp^2 \rangle \approx T + \frac{mv^2}{2}$
- \-"the larger the system, the further it cools" argument explained strong A and y dependence of v: large $v_t \approx .6$ and low $T_f \approx 120 MeV$ in PbPb followed.
- \-Fit to NA49 HBT radii plus spe

tra had confirmed such v_t and T_f selection Heinz et al

mass dependence of inverse slopes

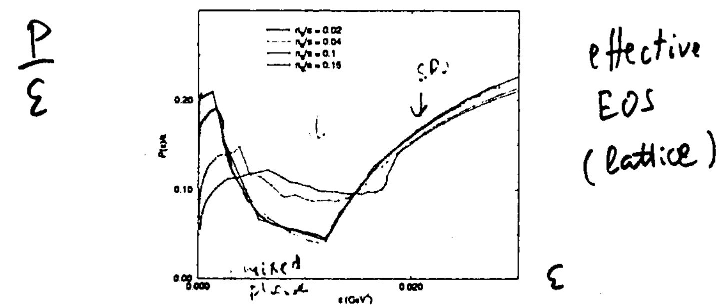


→ Ω^- (!) small σ

→ φ (?) K eaten

NA49 and NA50 seem to see different slopes

The softest point



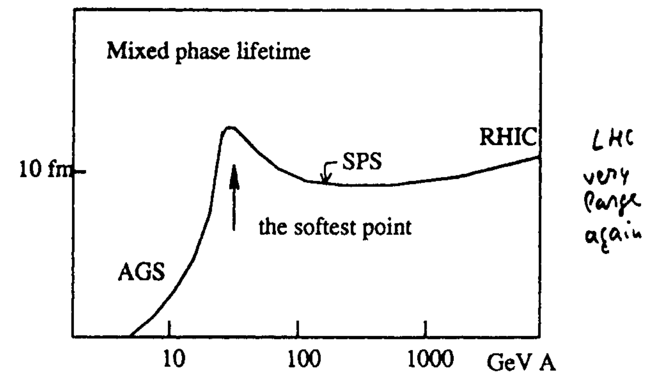
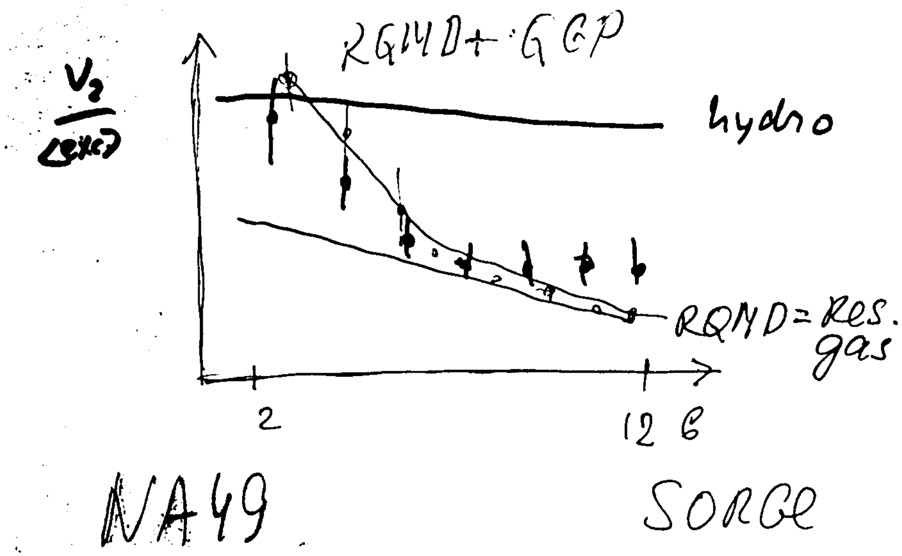


Figure 3: C.M.Hung, E. Shuryak, PRL 95

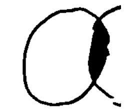
Next CERN SPS run is at 40 AGeV

→ took place in Oct 99



Elliptic flow

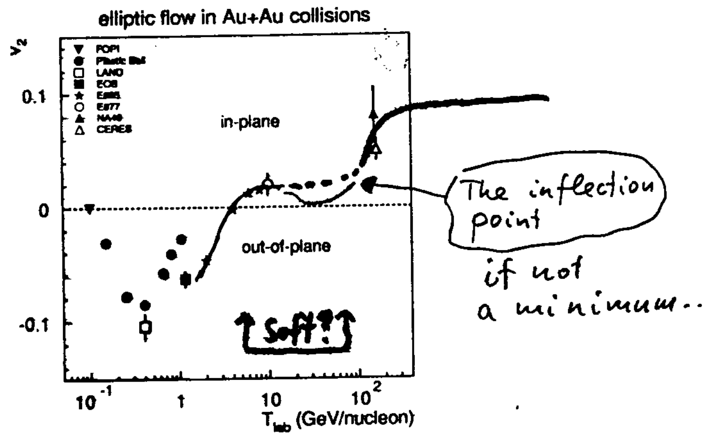
Sorry, I have no time to discuss the "directed flow" or the dipole component... The picture of the "initia almond" for non-central collisions



$$\frac{dN}{d\phi} = \frac{v_0}{2\pi} + \frac{v_2}{\pi}\cos(2\phi) + \frac{v_4}{\pi}\cos(4\phi) + \cdots$$

- **– At low energies "squize-out" was observed in ʒ direction, as spectators nuclei block the x direc tion.**
- **– First hydro studies for AGS/SPS domain shov significant v_2 in x direction Ollitrault Phys. Rev D46**, 229(1992); Phys. Rev. **D48**, 1132(1993)
- – ellliptic flow is developed earlier than the radial one H Sorge, Phys. Rev. Lett. **78**, 2309(1997). Furthermore, som interesting centrality dependence is found in H. Sorge, nucl th/9812057 (1998).
- – Detailed calculations for AGS energies, with softening du to QCD phase transition P. Danielewicz et al., Phys. Rev Lett. **81**, 2438(1998)
- – At high (RHIC/LHC) energies more complex evolution i x-y plane is found (called the "nutcracker" scenario), with foı mation of two "shells" which are physically separated in direction D.Teaney and E.Shuryak, nucl-th/9904006 The ɩ does not grow with energy, but v_4, v_6 are predicted to grow!

The status of experiments on elliptic flow can be summarized by the following figure:



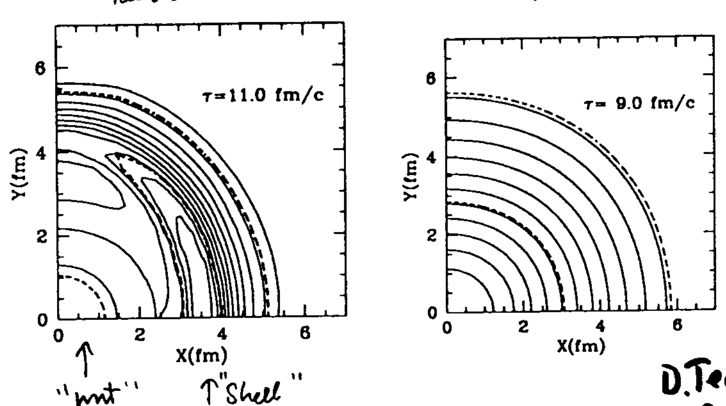
Data collected by J. Stachel

EOS, P.Danielewicz et al

- – Indication to softening of EOS at $E > 6$ GeV A
- – RQMD (and other event generators) seem to under-predicts its value at mid-rapidity (compared to NA49 data): A QGP push already? (note however the error bars and the CERES point).
- – Hydro calculations at higher energies D.Teaney and E.Shuryak, nucl-th/9904006 produce near constant ellipticity, wich is rapidly switched off at SPS energies
- –We may be lucky to see transition from soft to hard early EOS, inside the SPS energy domain, as an inflection point

RHIC as a nutcracker

- - At RHIC we have to tell an orange from the nut
- – Note that at CERN there is little difference with the initial shape
- – Simple EOS $p = .2\epsilon$ of the resonance gas creates large expansion but basically preserves the elliptic shape
- – "Realistic EOS" leads to formation of two shells, which then physically separate from each other! (The "nutcracker)



D.Teaney + ES

The "initial" state: is there a QGP at SPS?

There are several important observations:

- \- Particle composition cannot be explained by reactions in hadronic phase, the fitted $T > 170 MeV$ – Is it indeed the QGP boundary?
- \- The initial EOS is very soft – QGP or strings?
- \- Dilepton production is enhanced and the spectrum is changed – approaching the QGP rates, or just complicated hadronic reactions?
- \- J/ψ, ψ' production is further suppressed in central PbPb – Can we experimentally tell if it is not due to late hadronic absorbtion?

DILEPTONS

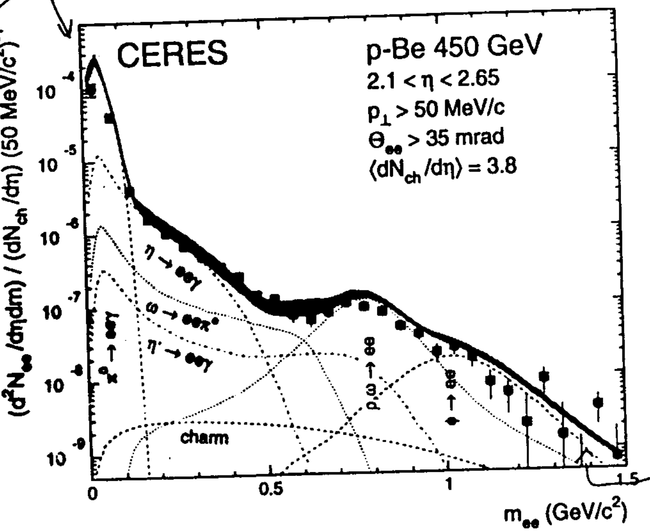
Old ideas: QCD phase transition ca "melting" of all hadrons $(\rho, \omega, \phi, J/\psi)$ Dileptons are "penetrating probes"

Good news: all dilepton experimen (HELIOS-3,CERES,NA50) see signi icant dilepton enhancement, compar to "naive" expectations. The effect are stronger at small p_t, clearly ind cating matter effects
CERES sees qualitative change of sh of the vector spectral density for M m_ρ as compared to the vacuum.

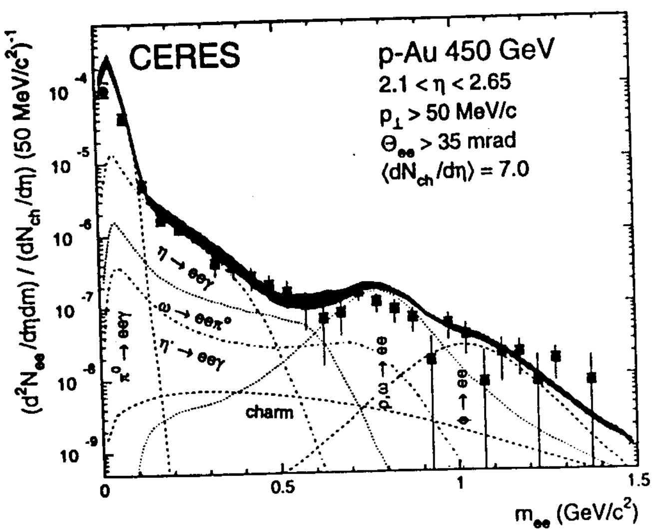
Bad news: Most radiation is not fr QGP but from the "mixed phase We still do not quite understand it More details are needed.

Previous CERES Results

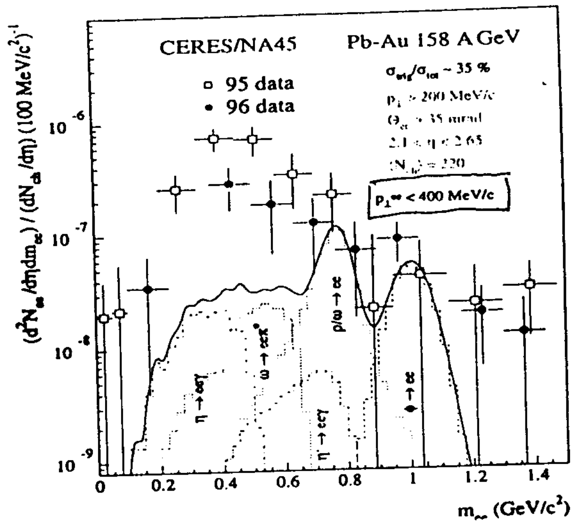
...ongly ...t by detector ...eptance



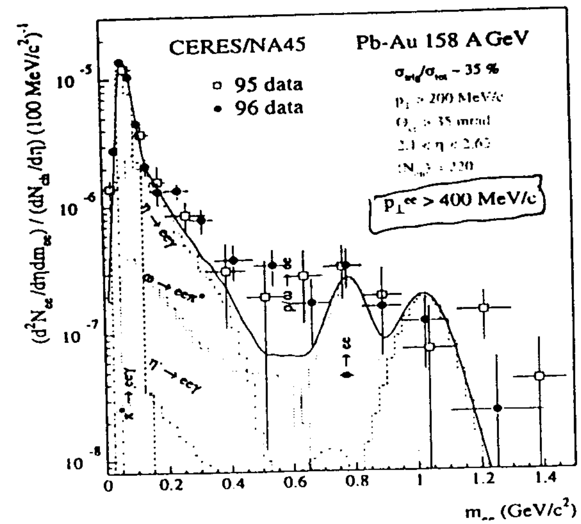
note large width → resolution



e^+e^- pair mass spectrum



Large effect



No (or little effect

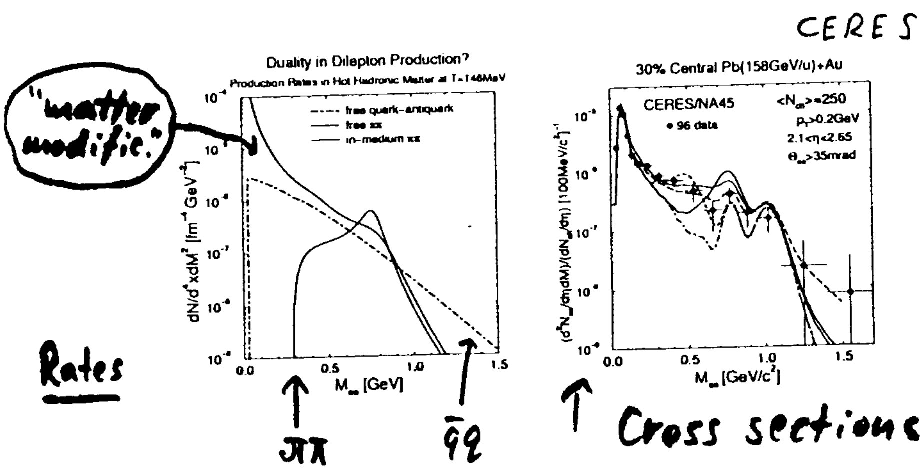


Figure 3: (Curtesy of Ralf Rapp) (a) Comparison of dilepton production rates: thermal pion gas, "partonic" (dash-dotted) "realistic" one (from Rapp et al). (b) Comparison of CERES 96 data for mass spectrum of the observed dileptons with several theoretical calculations: no in-matter production (dash-dotted), no in-matter modification (solid with ρ/ω peak), the Brown-Rho scaling (dashed with a peak at $M \approx .5$ GeV), hadronic rho widening (solid) and pure "partonic" rate (dashed).

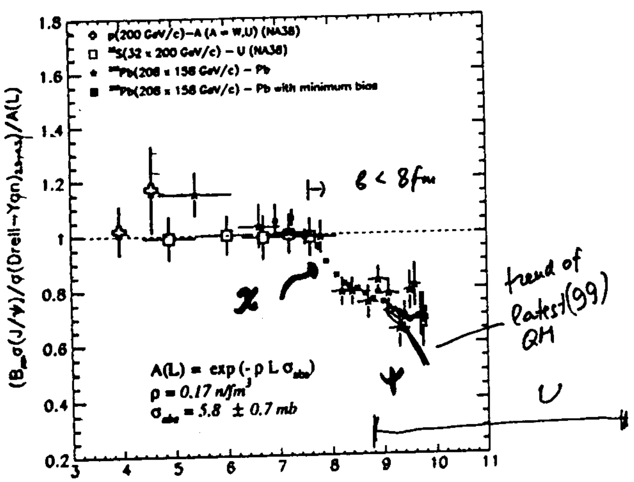
The main CERES-related physics issues are:
(i) to what extent the observed "ρ melting" indicate approach of the chiral symmetry breaking,
(ii) Does it really undercut the "resonance gas" picture (used in all event generators) ?

People who study/explain CERES data use vector meson masses shifted proportional to density with Walecka-type mean field model(G.Q. Li, C.M. Ko, G.E. Brown Nucl.Phys.A606:568-606,1996) , or resonance re-scattering on hadrons, mostly excited nucleons (R. Rapp, G. Chanfray, J. Wambach Nucl.Phys.A617:472-495,1997)

My point here: Note also one stril ing fact: for the most important mas $M = .3 - .6 GeV$ the "realistic" curv (obtained in a complicated hadroni based calculation) is not so far fro the "partonic" one, which correspon to just an ideal gas of quarks and ant quarks. So, we do find that the ine action between $\bar{q}q$ in the vector cha nel at $T \approx T_c$ is becoming weak.

Whatever the model, if vector spe tral density is modified, the Weinbe like sum rules (Kapusta,Shuryak 9 **demand that the axial one also chan At chiral restoration they should co side.**

J/ψ, ψ' SUPPRESSION



NA50 has found that PbPb collisions are different from pA-SS trend. Especially facinating is rapid variation of suppression at centrality $ET \sim 50$ GeV, or b> 8 fm. More data needed, simpler target, or other A, or energy...

What is the mechanism of this change?

- – gluonic photoeffect (Shuryak 78, Peshkin 80, Kharzeev, Satz,Nardi 95
- – the states in QGP simply do not exist (Matsui and Satz, 1986)
- – hadronic comovers (Gavin and Vogt, Kahana and Kahana)
- – change in the lifetime of the QGP due to the softest point (Shuryak and Teaney,1998)

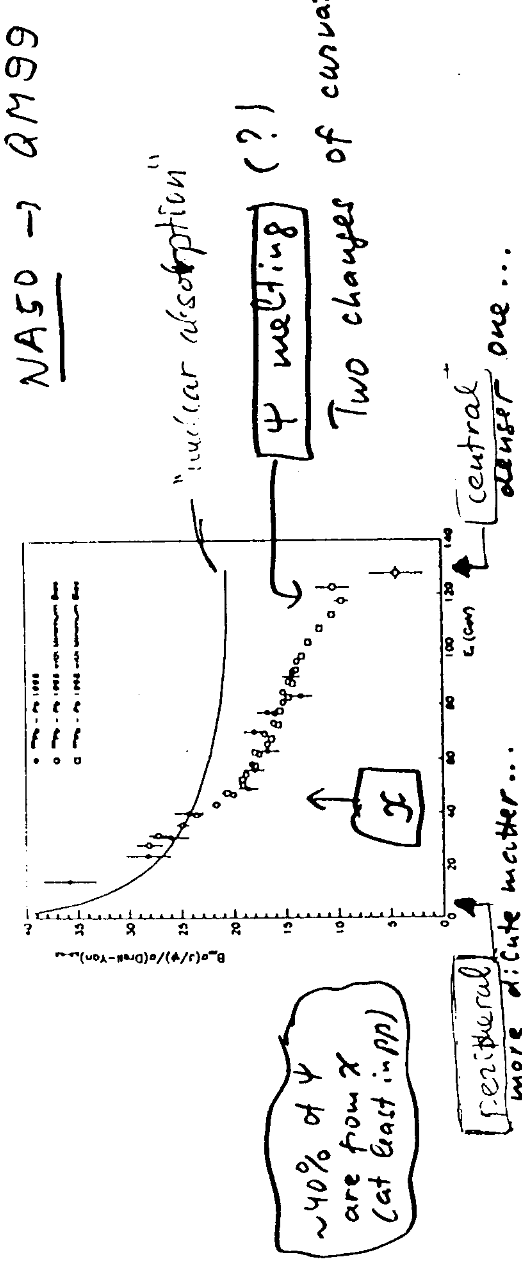


Figure 20. The ratio of the J/ψ to Drell-Yan cross-sections for Pb-Pb reactions. The curve shows the "normal" suppression due to nuclear absorption as deduced from the measurements done with lighter projectiles or targets.

Conclusions

- \- AA collisions produce a Bang not a fizzle. Radial flow at SPS develops late, mostly in hadronic phase.
- \- Early "QGP push is expected at at RHIC, and maybe seen already at SPS in ellipticity (NA49)
- \- At RHIC the non-central collisions leads to a "nutcracker".
- \- Dileptons see melting of ρ resonance and approach to "partonic rates" at small masses, or QGP-like radiation from hot matter
- \- The J/ψ seem to be suppressed in steps: the only observable with strong A and centrality dependence. two components (χ, ψ)