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SMR.1317 - 32

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

QCD AND QUARK-GLUON PLASMA

Lectures IV & V

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E. Shuryak

Lecture 4

Hot/dense Hadronic Matter in Heavy Ion Collisions

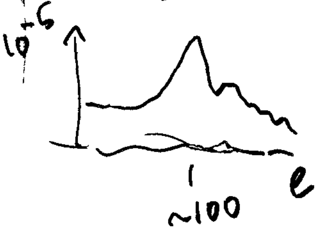
See proceedings of
Quark Matter
conferences
Nucl. Phys A (Supplementos + some volumes)

Heavy Ion collisions

- Introduction: AGS, SPS and now RHIC era
- The particle composition is thermal. Chemical vs thermal freeze-outs → phase diagram
- Collective effects: radial and elliptic flows Examples from RHIC/SPS
- Dileptons and photons → duality of q-h
- J/Psi suppression
- The initial stage at RHIC: perturbative or non-perturbative?

Two explosions:
the Big Bang versus the Little one

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



1 event only! $\sim 10^7$ events !!

Common q's: e.g: How entropy has been produced?

Motivations

Theory: $\boxed{\text{QCD vacuum}}$ = complicated matter filled by virtual quark and gluon fields

Either 'gentle' approach → correlators, elementary excitations

Or just trying to 'melt' it, into a simpler state ⇒ quark-gluon plasma

Experiment: $\boxed{\text{Why do we need RHIC and LHC?}}$ (why high energy?)

Reason #1: To produce q's and g's is not enough, one should also suppress negative non- pert. energy of the vacuum → $\boxed{\text{Large MIT bag!}}$

$$\varepsilon(T) = \underbrace{(\#\,\mathrm{DOF})(\mathrm{const}\cdot T^4)}_{\text{q and gluons inside}} + \underbrace{B}_{\text{minus negative energy outside}}$$

$$p(T) = \frac{1}{3}(\,---\,)\,T^4 - B$$

[Compare to a spot of normal metal inside the superconductor]

$\boxed{B \text{ is large}}$ $\left(\sim 1\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}\right) \gg m_N\, n_{\mathrm{nucl.matter}} \sim 0.15\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$

Reason #2 'Normal' QGP appears at

$$T \gtrsim (2\div 3)T_c$$
$$\varepsilon \gtrsim (10\text{-}100)\,\varepsilon_c$$

Reason #3 We need 'truly macroscopic' system

$\tau_g \sim \frac{1}{3}$ fm/c; $2R_\perp \sim 10$ fm; However, longitudinal expansion $t_\parallel \sim$ (few fm/c)

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 (AGS,SPS) QGP or strings? It is not soft at RHIC!
- 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?

Interplay between suppression and thermal production

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

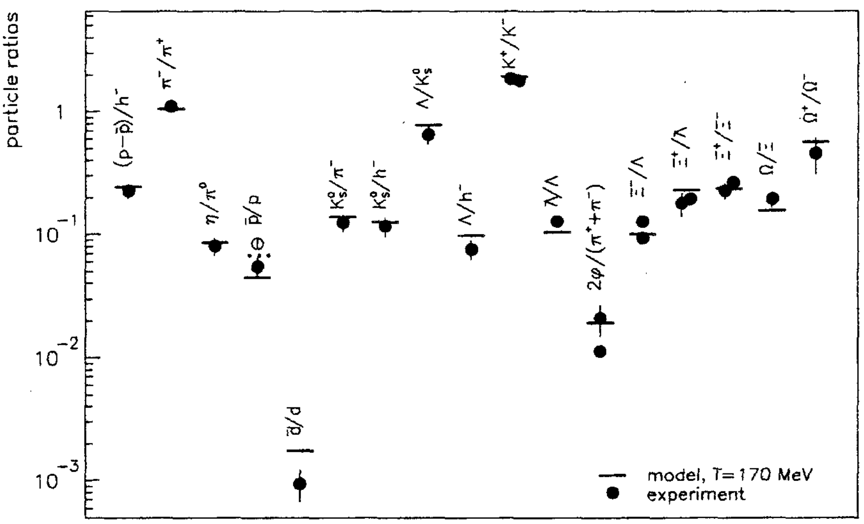


Figure 1: The ratios fitted to thermal model for PbPb at SPS (from J.Stachel)

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

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

DILEPTONS

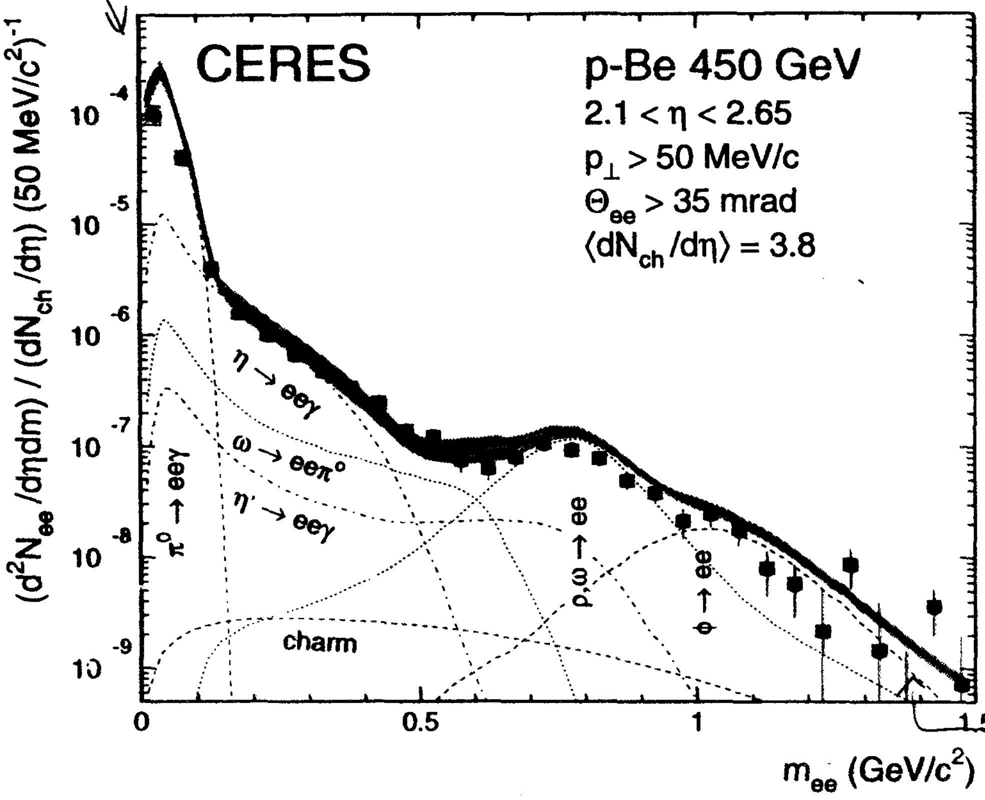
Old ideas: QCD phase transition causes "melting" of all hadrons $(\rho, \omega, \phi, J/\psi)$
Dileptons are "penetrating probes"
ES - 1978

Good news: all SPS dilepton experiments (HELIOS-3,CERES,NA50) see significant dilepton enhancement, compared to "naive" expectations. The effects are stronger at small p_t, clearly indicating matter effects [illegible]
CERES sees qualitative change of shape of the vector spectral density for $M < m_\rho$ as compared to the vacuum.

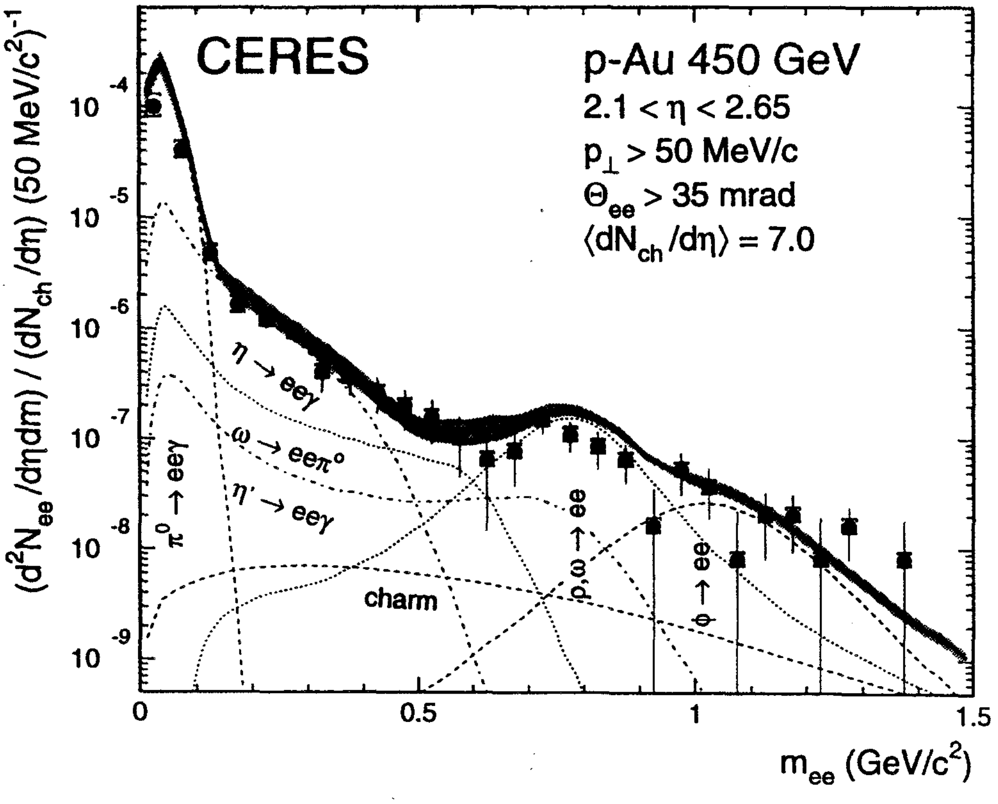
Bad news: Most radiation is not from QGP but from the "mixed phase". We still do not quite understand it... More details are needed.

strongly cut by detector acceptance

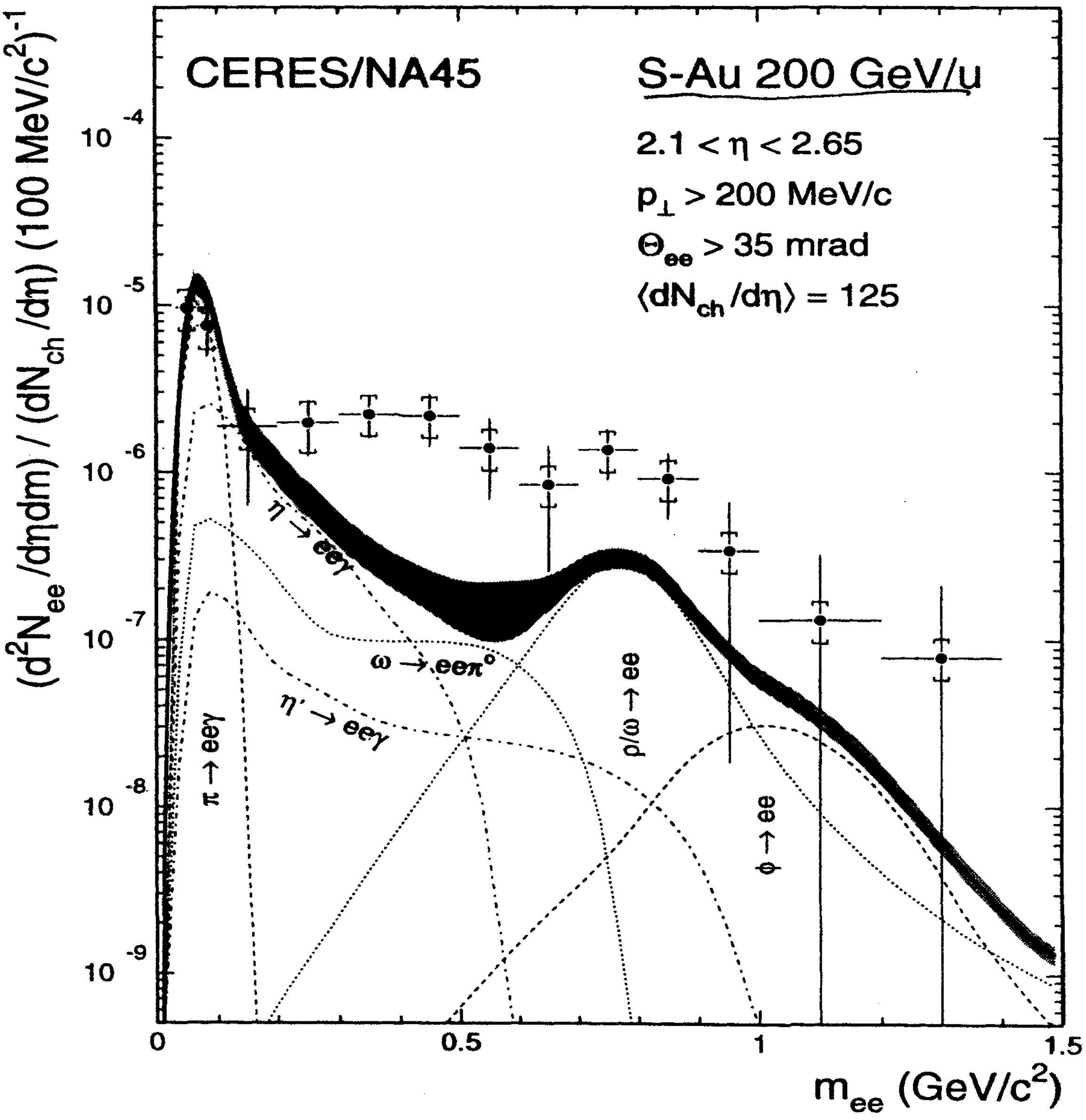
Previous CERES Results



note large width → resolution

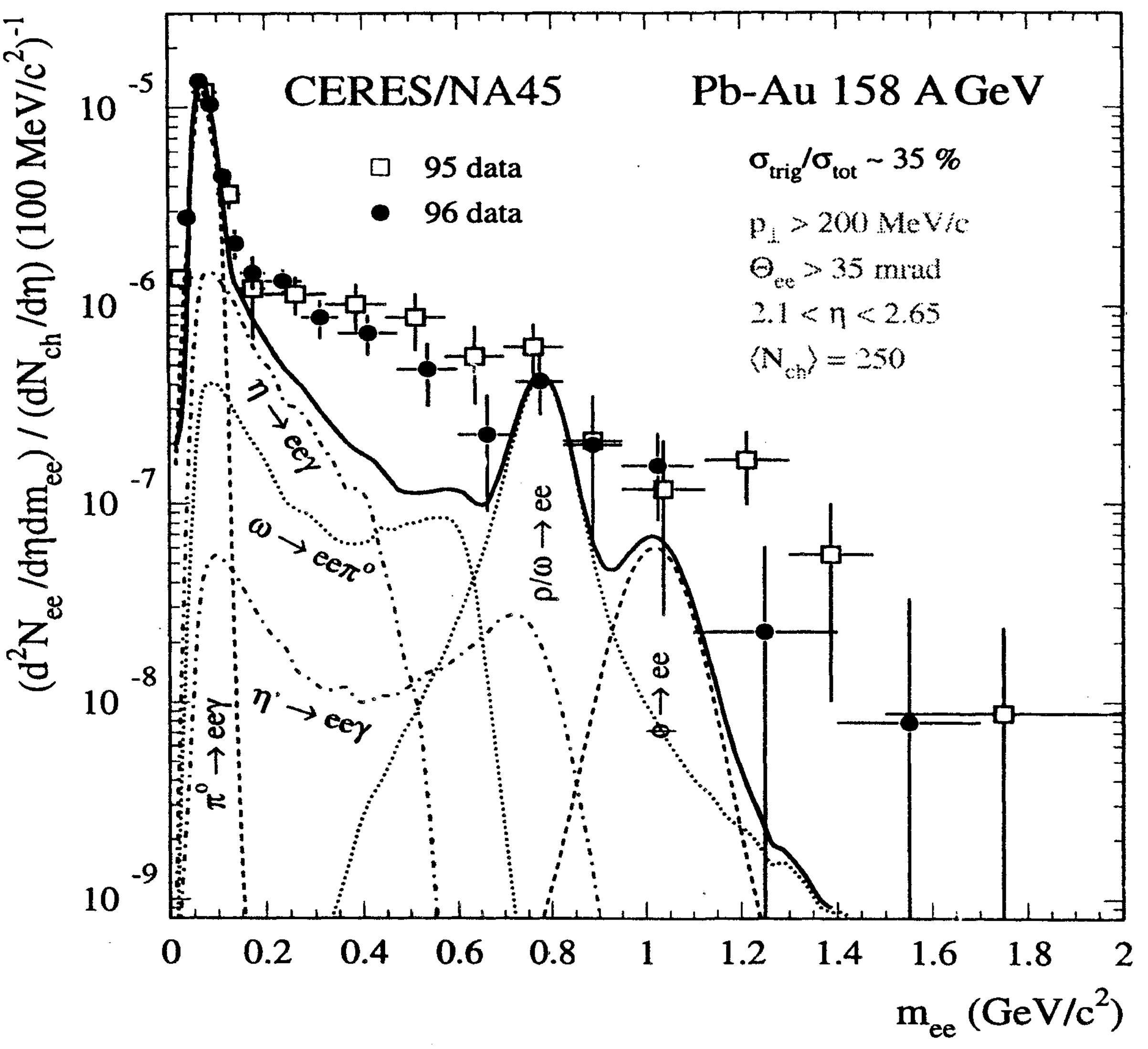


Previous CERES Results



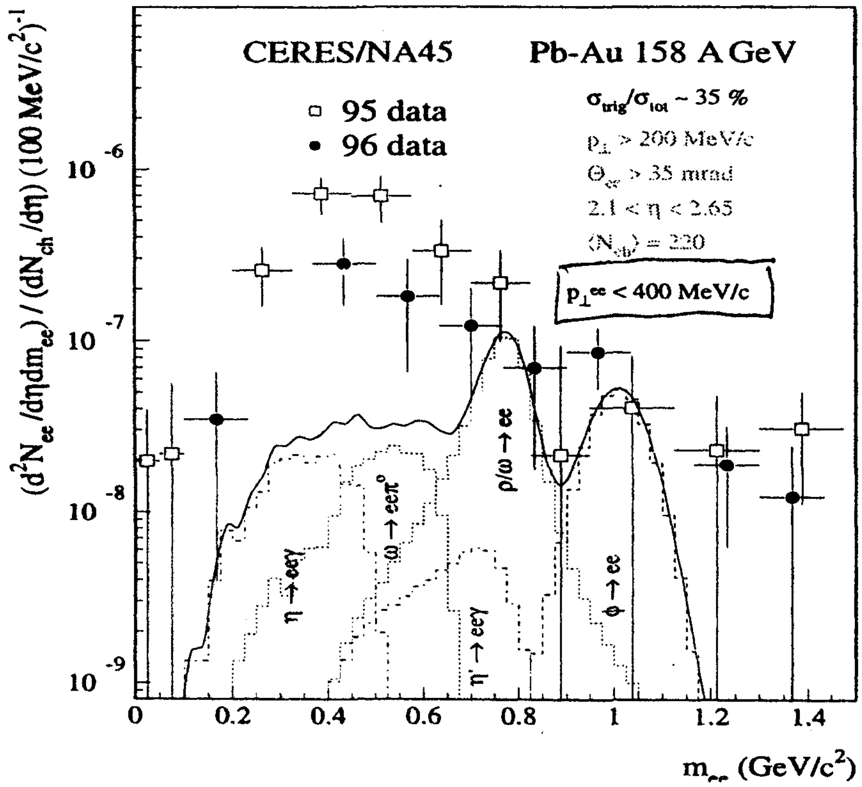
B.Leukeit, Paris 98
Aug. 24

e^+e^- pair mass spectrum

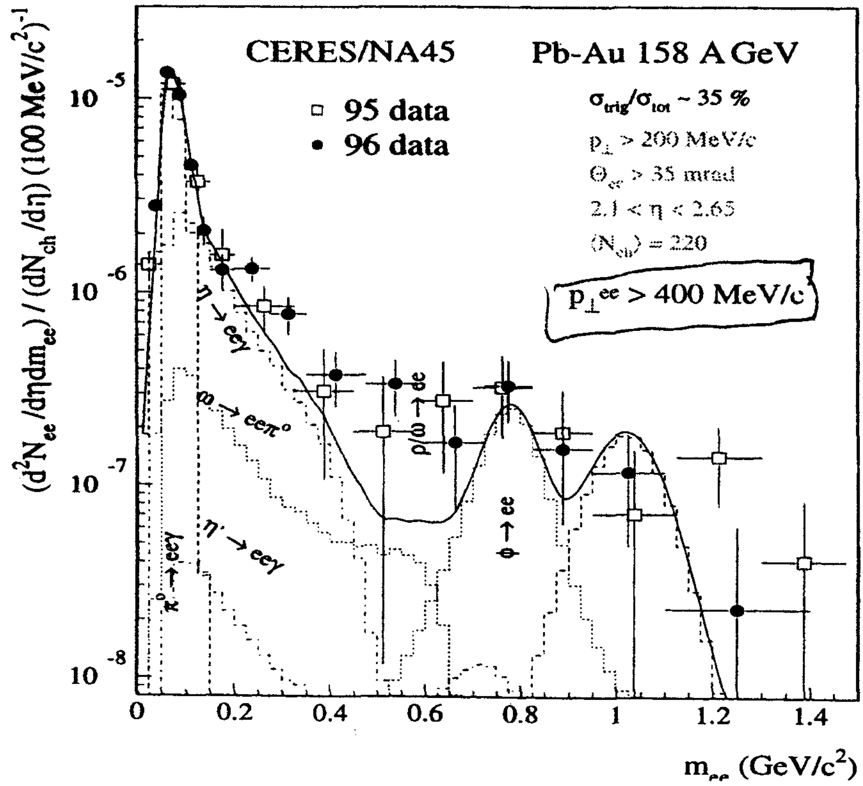


- particle ratios for hadronic cocktail taken from pp collisions
- rapidity and pt distributions taken from HI-collisions
- enhancement over pp-scaled sources ($0.25 < m_{ee} < 0.7$ GeV/c^2) :
  3.3 ± 0.7(*stat.*) ± 0.7(*syst.*) (96' data set)
  4.9 ± 1.1(*stat.*) ± 1.0(*syst.*) (95' data set)

e^+e^- pair mass spectrum



Large effect



No (or little) effect

R.Rapp QM99

RATES

CROSS SECTION

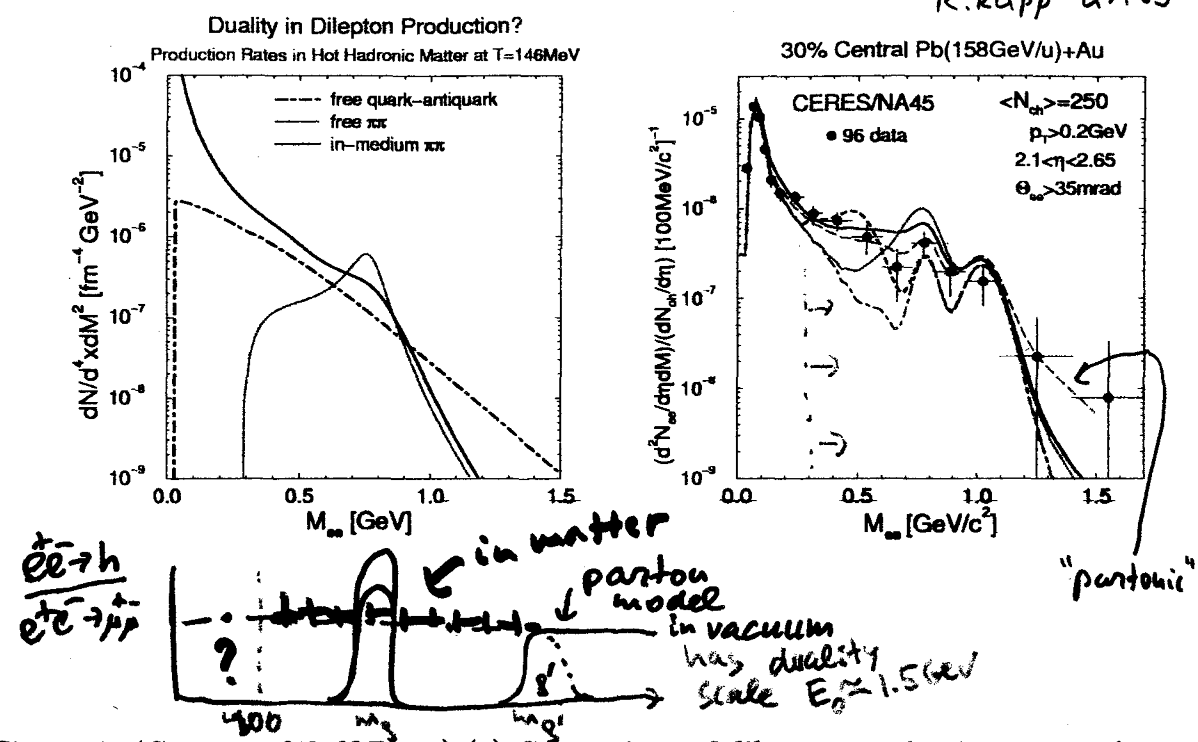
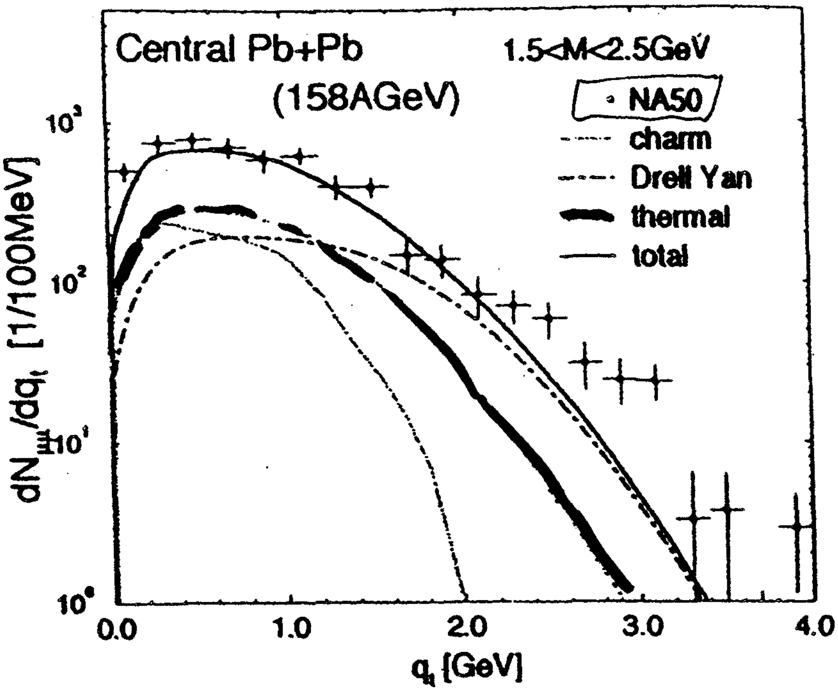


Figure 4: (Curtesy of Ralf Rapp) (a) Comparison of dilepton production rates: thermal pion gas, "partonic" (dash-dotted) "realistic" one (from Rapp et al). (b) Comparison of CERES 96 data for mass spectrum of the observed dileptons with several theoretical calculations: no in-matter production (dash-dotted), 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) ?

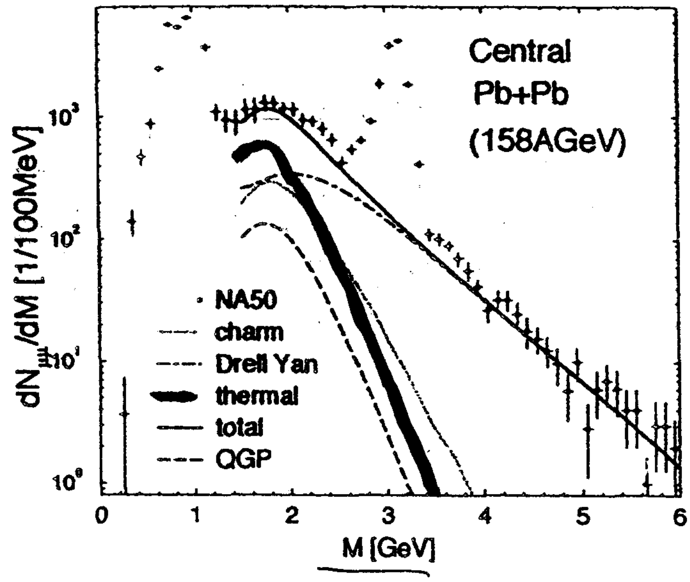
R. Rapp, E. Shuryak
PL B473 (2000) 13



Intermediate Mass Dileptons

ω & φ

ψ
↓



NA50
$(\mu^+\mu^-)$
exp.
at CERN

J/ψ suppression as QGP signature

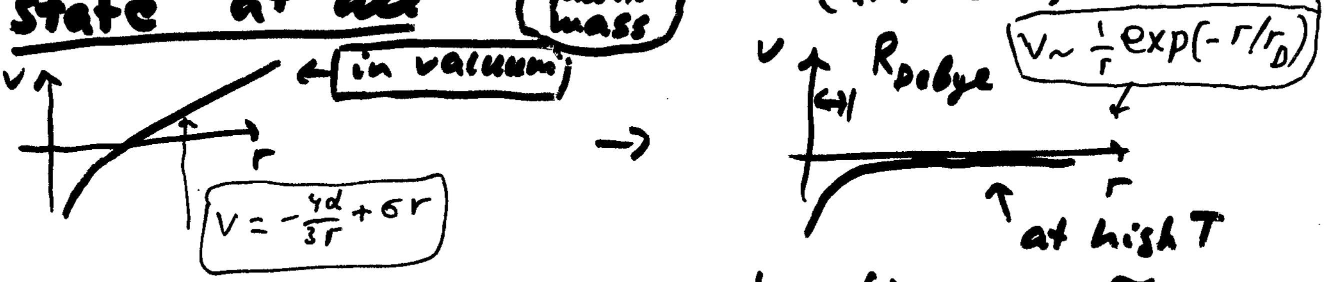
- **All hadronic states, including vector mesons $\rho, \omega, \varphi, J/\psi, \Upsilon$ to disappear in dilepton spectra at high T**
- "Photoeffect"-like excitation in QGP
  $$g + \psi \to \bar{c}c \,,\quad g + \Upsilon \to \bar{b}b$$

(ES 78)

M.Peskin
D.Kharzeev
- - -

- **Above certain $T(m)$ there is <u>no bound</u> state at <u>all</u>** quark mass

(T.Matsui, H.Satz 1986)



- deconfinemen $\sigma = 0$
- charge screening

- **Such T is different for different states**

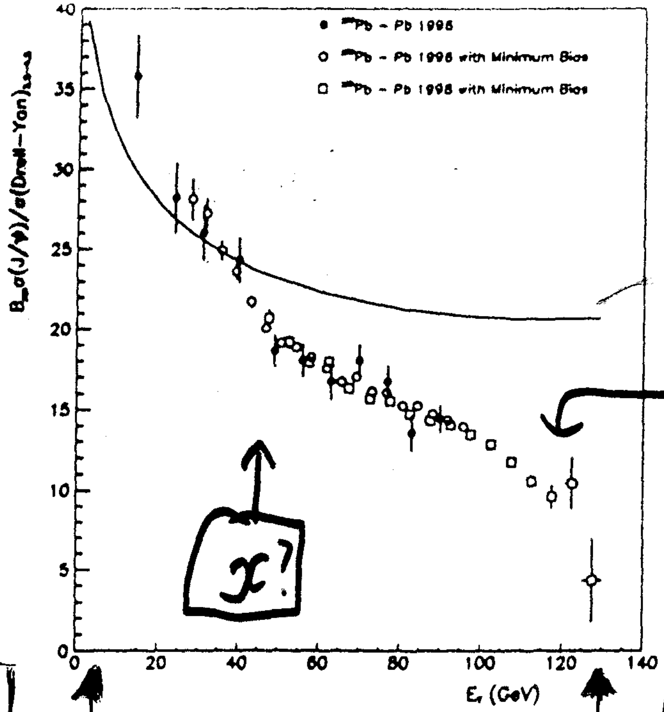
$$T_{\chi,\psi'} < T_{\psi} < T_{\chi_b \Upsilon'} < T_{\Upsilon}$$

Thus quarkonium signal is a <u>thermometer</u>

- Note: $T_{\chi,\psi'}$ from calculation are below T_c → suppose to disappear in QGP right away

- **J/ψ (and others) are <u>believed to</u> have small cross sections on $N, \pi \ldots$ $\sigma \sim$ few mb. If so, they cannot be affected by hadronic stage**

NA50 → QM99



"nuclear absorption", works for light ions

ψ melting (?)

Two changes of curvature

~40% of ψ are from χ (at least in pp)

χ?

peripheral more dilute matter...

most central denser one...

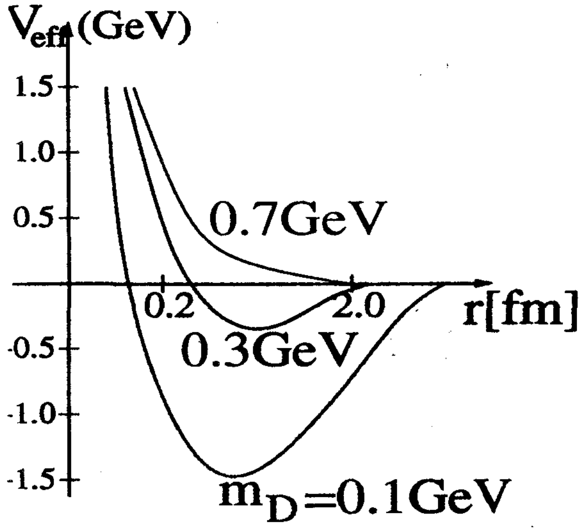
Figure 20. The ratio of the J/ψ to Drell-Yan cross-sections for Pb-Pb reactions. The curve shows the "normal" suppression due to nuclear absorption as deduced from the measurements done with lighter projectiles or targets.

J/Ψ Production and Suppression

L. [redacted]
R. Rapp
hep-ph

(a) 'Standard' Picture

[Matsui + Satz '86, ...], [E. Shuryak '78 ...]



J/Ψ produced primordially

→ robust in hadron gas

→ dissolved in QGP (Debye screening, gluon diss., ...)

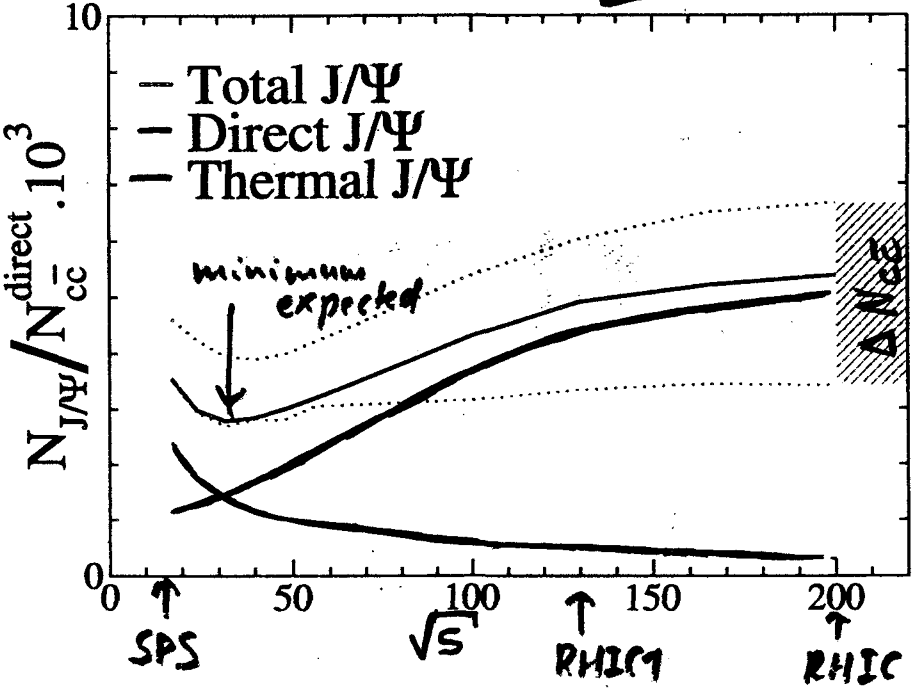
⇒ suppression increases with T_{ini}, T_{QGP}

(b) Statistical Production at T_c

[Gazdzicki et al. '00 Braun-Munzinger et al. '00, ...]

$\bar{c}$ quarks 'coalesce' into J/Ψ at hadronization

⇒ combine (a) + (b) [L. Grandchamp + R.R. in prep.]



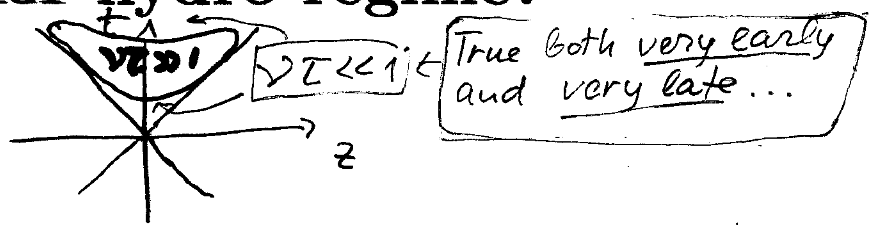
J/Ψ enhancement at RHIC ?!

The immediate issues to be addressed at RHIC

- Are AuAu collisions at RHIC a (Little) Bang, or a Fizzle?

(Or, ~~in other words: Have we produce~~d a new form of matter or a very nice firework?)

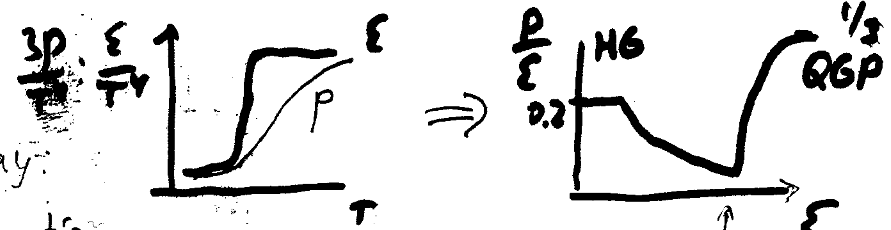
~~Or, in technical language, what is the~~ Collision Rate $\nu(\tau)$? ~~Is there a place for~~ hydro regime?



True both very early and very late...

Or, in ~~primitive but practical language, what is the~~ Effective Pressure p? ~~How it relates to the~~ energy density ϵ?

Lattice EoS in Hydro-friendly way:



The softest point

$p/\epsilon \sim \frac{\text{force}}{\text{mass}} \sim$ acceleration

Is the system of ($\sim 1000\,\pi$) large enough, to use it? What is the smallest # ?

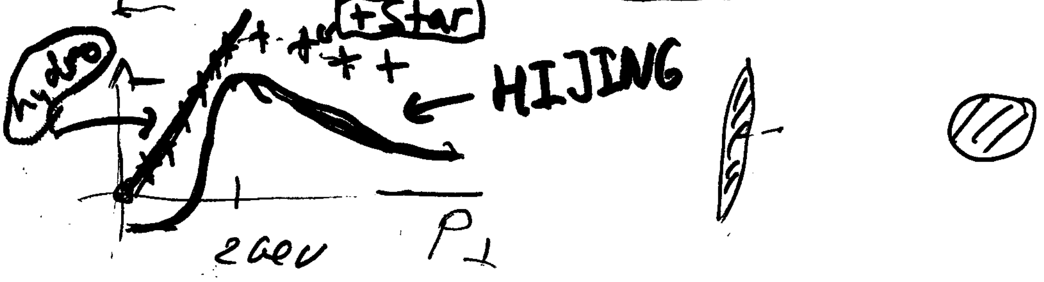
- **How one can tell the Bang from a Fizzle?**

There are 3 effects one can discuss: (i) longitudinal work; (ii) radial transverse flow; and (iii) elliptic flow. Let me concentrate on the last one first:

- Fizzle does not have any correlation between space and momentum, but hydro does (indeed HIJING without rescatterng has nearly zero (slightly negative) v_2)

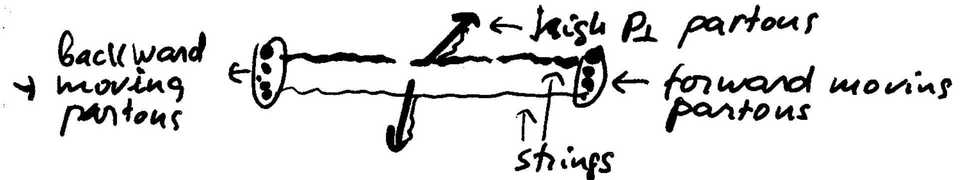
string models like UrQMD also do not produce pressure at early time, and get respectively smaller v_2 at RHIC than at SPS

Those are eliminated because STAR data show v_2 twice that at SPS!



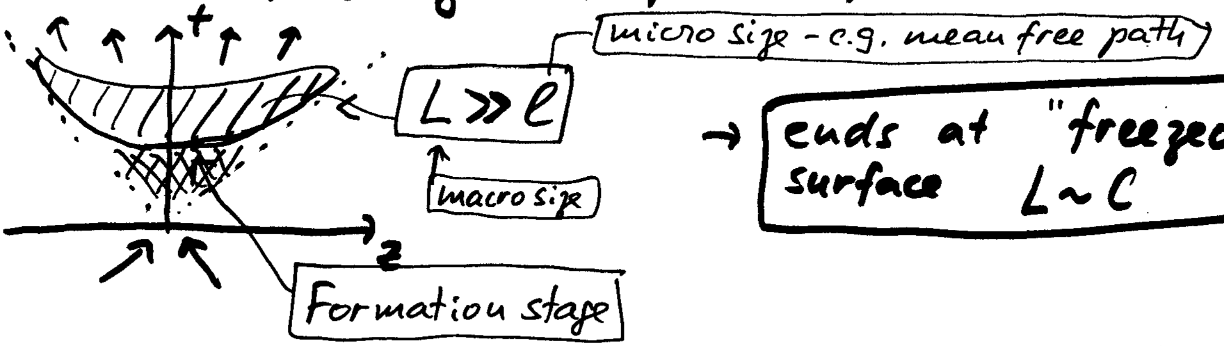
Introduction to a Collective Flow

- In e^+e^- and pp collisions ⇒ "dilute" or collisionless regime



→ String fragmentation is ≈ independent (Lund-type models)

- But in AA (at large A and small b) — impact param.
  we hope to be in a dense regime
  thus creating "new form of matter"



→ ends at "freezeout" surface $L \sim C$

- It looks complicated, But it is in fact simpler than pp case, Because in red area **Thermo-**, and **Hydrodynamics should hold!**

(Landau, 1953)

$$\partial_\mu T_{\mu\nu} = 0 \qquad T_{\mu\nu} = (\varepsilon + p) u_\mu u_\nu - p g_{\mu\nu}$$

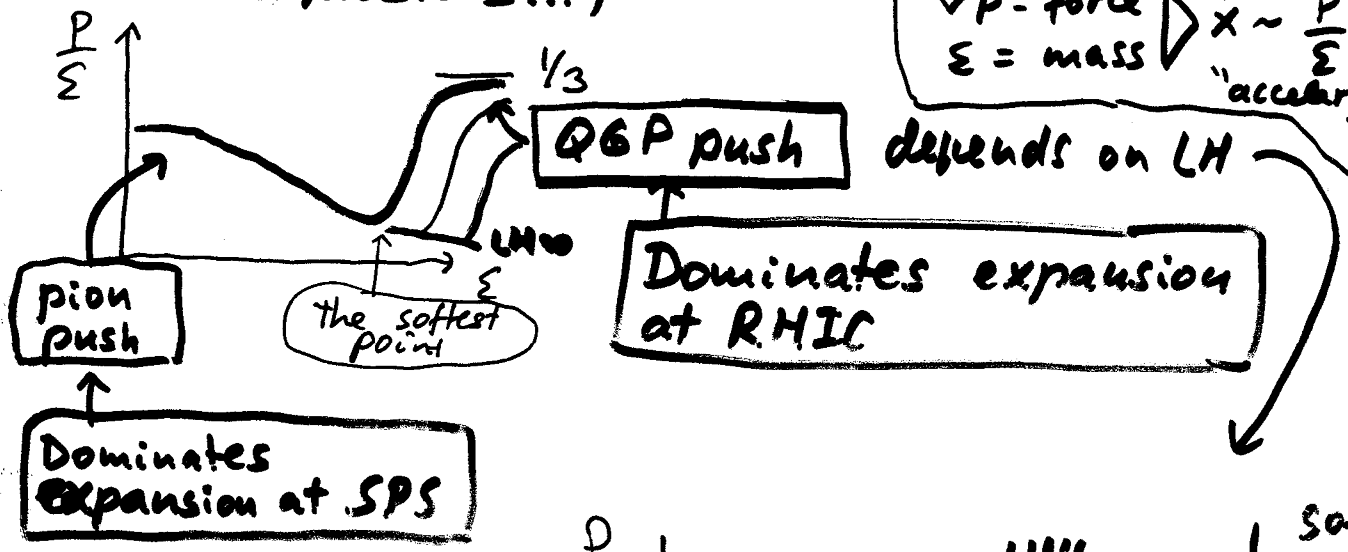
↑ ↑ 4-velocities, $\varepsilon(p)$ or $p(\varepsilon)$ is EoS

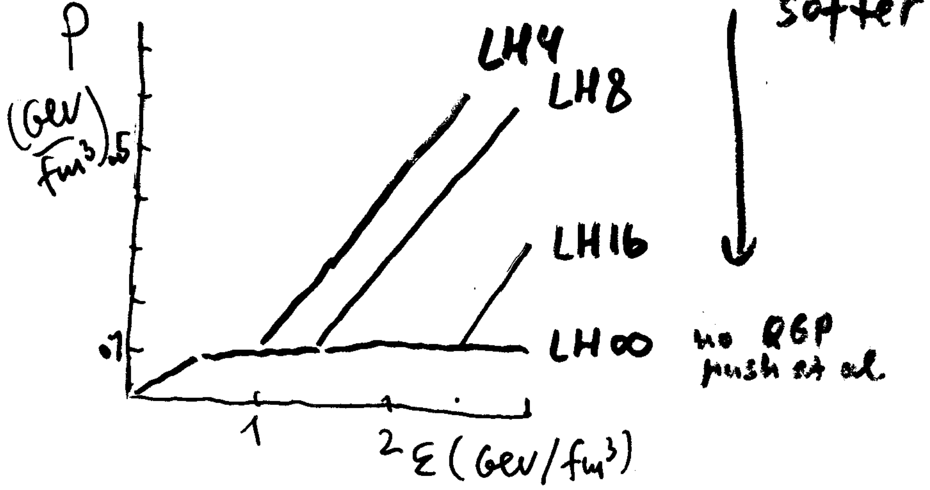
So, one has to know very little, e.g. $p/\varepsilon = 1/3$ in QGP

Another form of EoS

(more convenient to understand hydro explosions...)

∇p = force
ε = mass
$\Rightarrow \ddot{x} \sim \frac{p}{\varepsilon}$ "acceleration" ratio



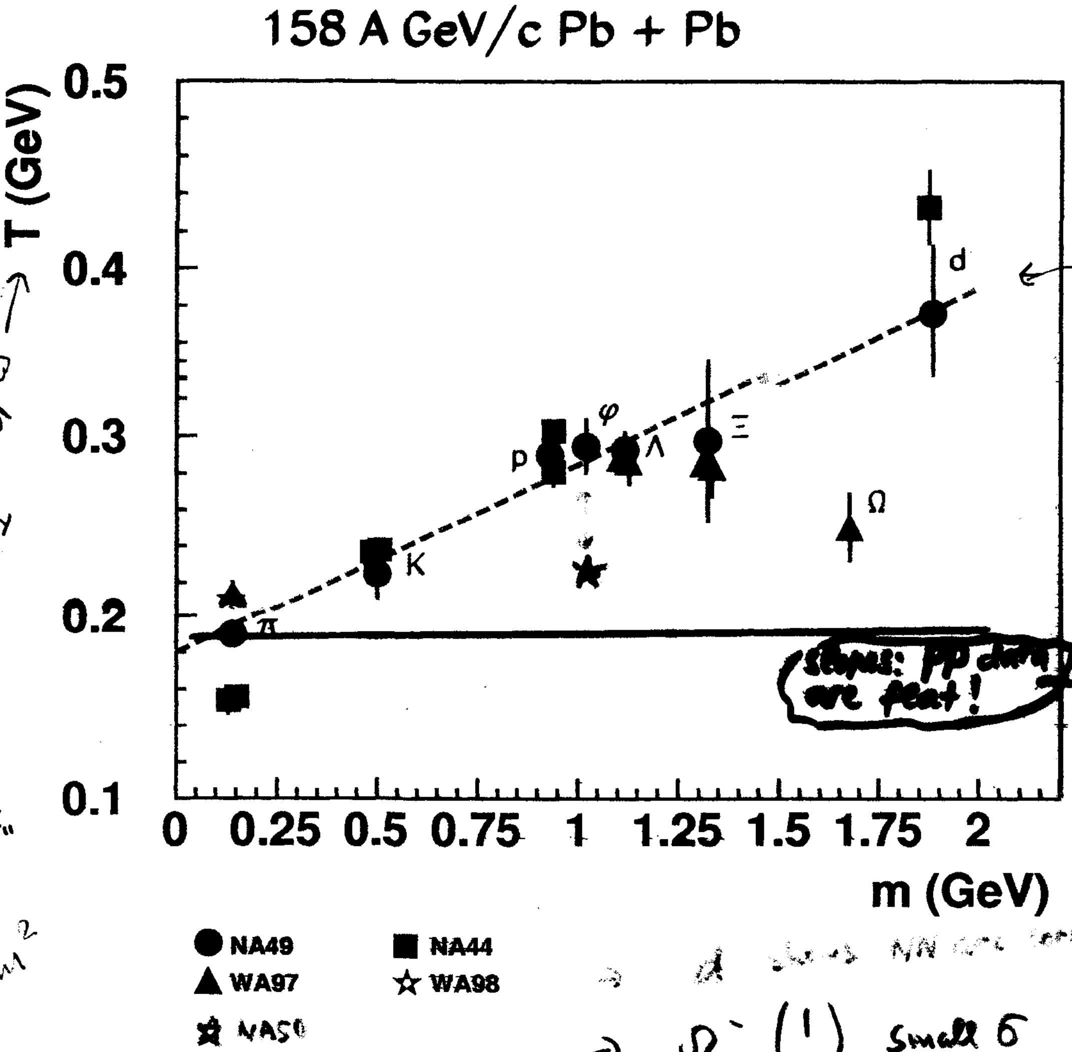


To demonstrate sensitivity to EOS we will show below results for variable Latent Heat

$$LH8 = \begin{matrix}0.4\\0.8\\ \vdots\end{matrix}\ \frac{GeV}{fm^3}\ \text{etc}$$

tra had confirmed such v_t and T_f selection Heinz et al

mass dependence of inverse slopes



slopes: pp data are flat!

actually, $m_\perp$ slopes → "T"

$\frac{d\sigma}{dm_\perp^2} \sim e^{-\frac{m_\perp}{\text{"}T\text{"}}}$

$m_\perp^2 = p_\perp^2 + m^2$

← flow effect grows with A!

"$M_\perp$" scaling
No flow in pp
→ ES. 197

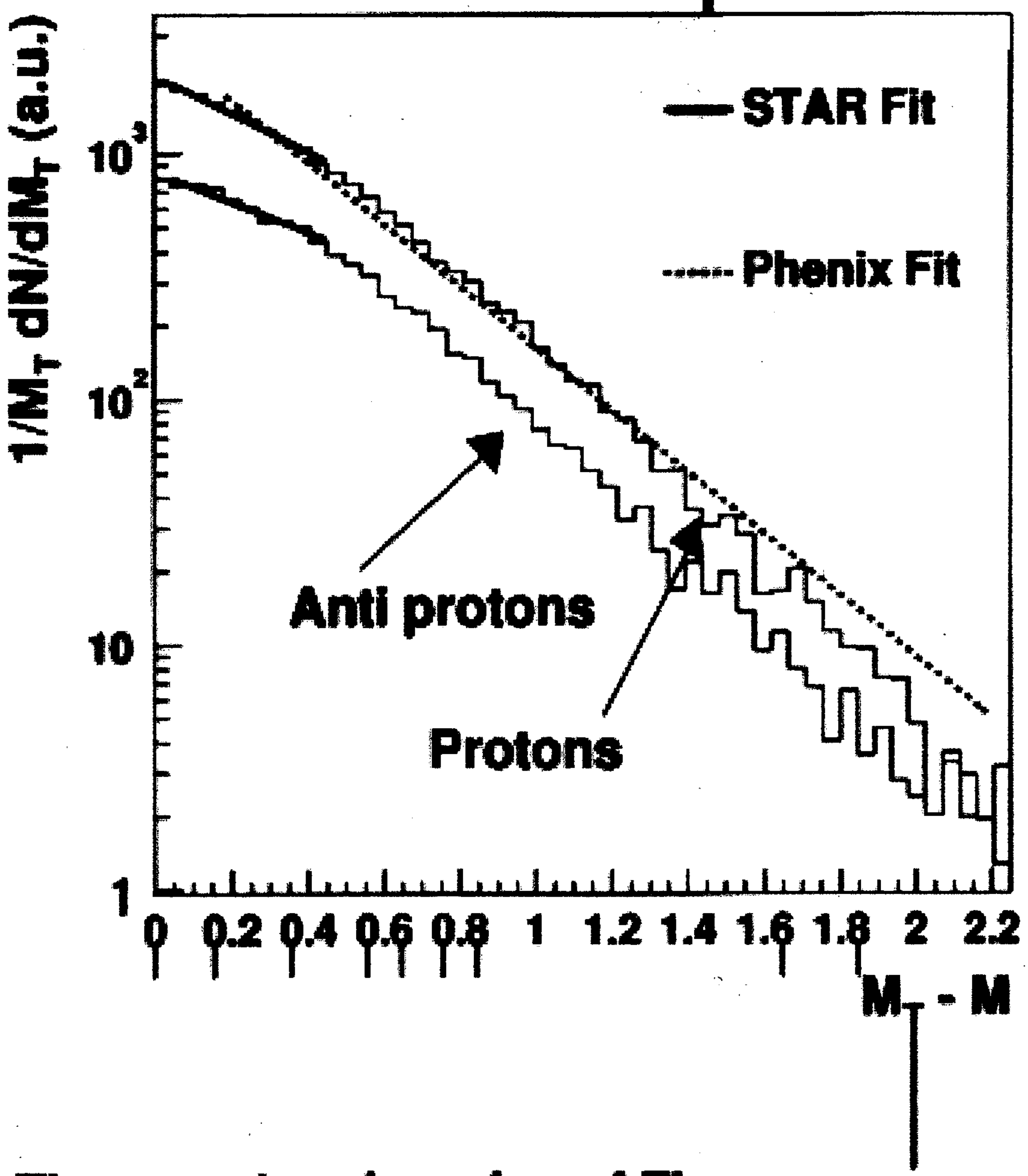
→ d shows NN are correlated

→ Ω^- (!) small σ

→ φ (?) K eaten

NA49 and NA50 seem to see different slopes

RHIC Radial Flow comparisons



The curvature is a sign of Flow

$E\frac{dN}{d^3p} \sim e^{-\frac{M_T}{T_{slope}}}, \quad m_\perp^2 = p_\perp^2 + m^2$

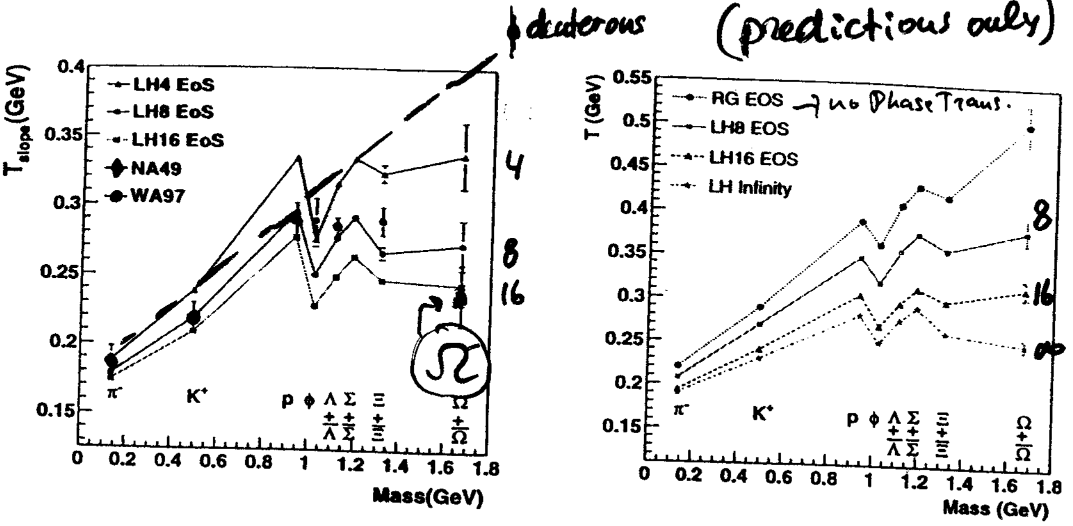
Slopes: how sensitive they are to EOS?

Cern SPS

RHIC (predictions only)

Differential freezeout (according to σ_h)

example: Ω^- (H. Sorge)



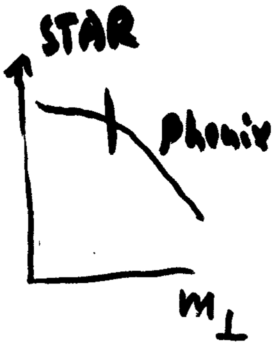


Figure 1. (a) A compilation of slope parameters(see e.g.[9]) at the SPS compared to model predictions for different EoSs. The slope parameters are fit from 0< $M_T - m$ <0.9 GeV, corresponding to the WA98 acceptance. (b) Model predictions for slope parameters at RHIC for different EoSs. The slope parameters are fit over the range 0< $M_T - m$ <1.6 GeV and do depend on the fit range used.

STAR (small $p_\perp$) Phenix (large $p_\perp$)

p spectra have non-trivial shape:

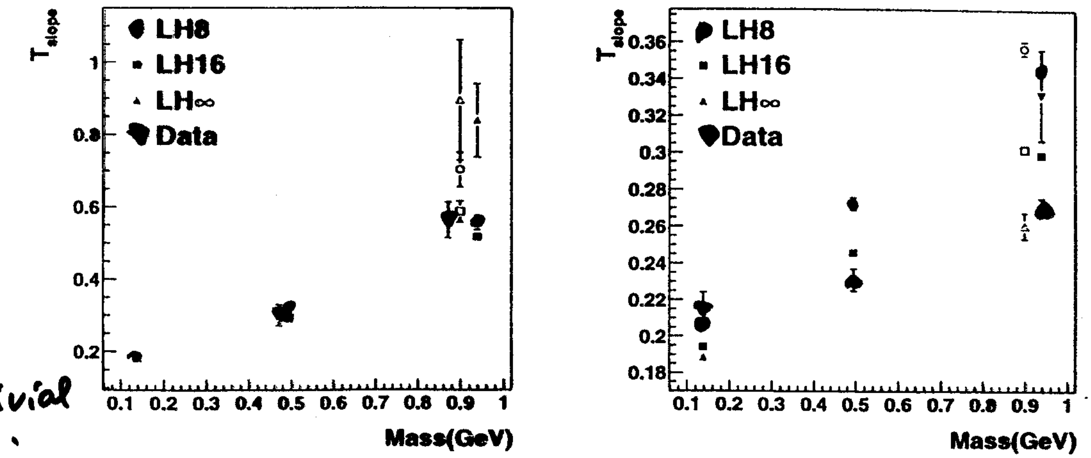


Figure 2. Slope parameters for π^-, K^-, p and $\bar{p}$ reported in these proceedings by the STAR(a) and PHENIX(b) collaborations[5,7]. The open(closed) symbols show model predictions for anti-protons(protons). The STAR collaboration fits the π^-, K^- and $\bar{p}$ spectra over the ranges, 0.12 GeV< $M_T - m$ <0.45 GeV, 0.04 GeV< $M_T - m$ <0.34 GeV and 0.04 GeV< $M_T - m$ <0.45 GeV respectively. The PHENIX collaboration fits the π^- and p spectra over the ranges, 0.19 GeV< $M_T - m$ <0.87 GeV and 0.175 GeV< $M_T - m$ <2.2 GeV respectively.

Ph.D.
D.Teaney, ES

~~The Hydro-to-Hadrons~~ H2H ~~Mode~~l*

Basically No parameters

- ~~Transfer from~~ hydro ~~to hadronic cascade~~ (RQMD without strings) ~~was done in order not to worry about~~ freeze-out of different species, resonance decays etc ⇒ "differential freezeout", different for each species

★ ⁈

- ~~But, is the transfer smooth enough? Is EoS of RQMD and our hadronic matter~~ the same)? Yes, we checked ~~The radial flow changes little, but elliptic one is (surprisingly) more sensitive.~~ → Yes

?

- ~~Can one see the~~ transfer surface ~~at all? Yes, with HBT one~~ can see through the clouds, ~~finding~~ bright shiny QGP surface ~~beneath the (RQMD-generated)~~ atmosphere. ~~Is it an artifact or not~~? It probably is...

  (The fraction of π, K, N, ϕ going through without a single collision is .2,.35,0.05,0.9.)

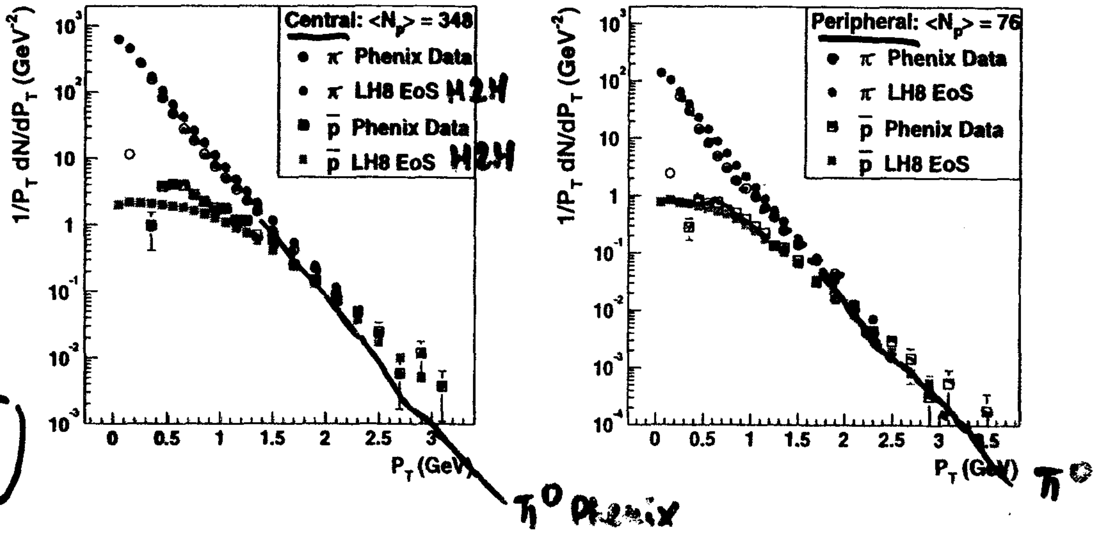
---

* Similar model, But for central collisions only, have been made previously By Dumitru, Bass et al.
hydro+ UrQMD

$\boxed{\text{The } \bar{p} > \pi^- \text{ anomaly}}$

(same for $p > \pi^+$ at $p_t > 2$ GeV)
we did not plot K → they are in between)

FIGURES



■
• H2H
$LH = 0.8 \frac{GeV}{fm^3}$

$\boxed{\text{QGP push is needed!}}$

- Vitev + Gyulassy ⟹ Hard processes (jet fragm.) cannot explain it
  $\bar{p}/\pi^- \sim 0.1 \div 0.4 < 1$ and $p_\perp$-indep.

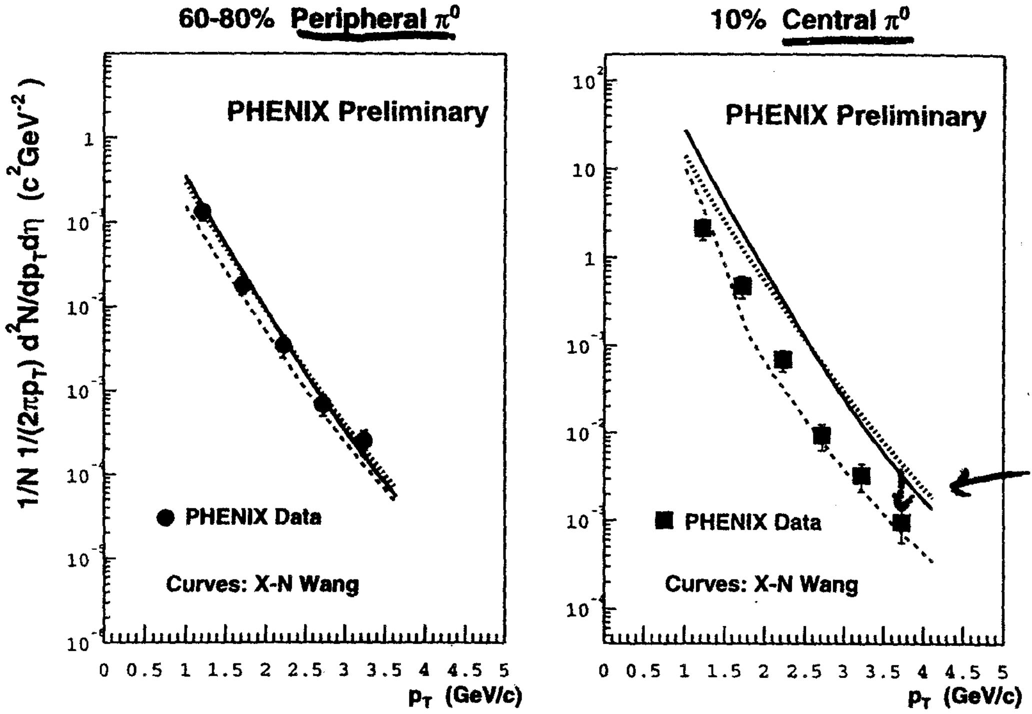
- Thermodynamics → $\begin{cases} \text{small } p_\perp & \frac{\bar{p}}{\pi} \sim \exp(-\frac{m_{\bar{p}}}{T}) \ll 1 \\ \text{large } p_\perp & \frac{\bar{p}}{\pi^-} \to 2 \quad (\text{stat. weights!}) \end{cases}$

- Hydrodynamics, $p_\perp \to \infty$ $\text{slope} = T\sqrt{\frac{1+v_\perp}{1-v_\perp}} \approx 2T$
  so flow drops out from $\bar{p}/\pi^-$ ratio at large $p_\perp$, → 2

- H2H model (we used before for <u>elliptic</u> and <u>radial</u> flow at $p_\perp < 1$ GeV) works! Even down by <u>3 orders of magn.</u>

Jet quenching !

⇓



← presumed jet quenching ~ 1/5

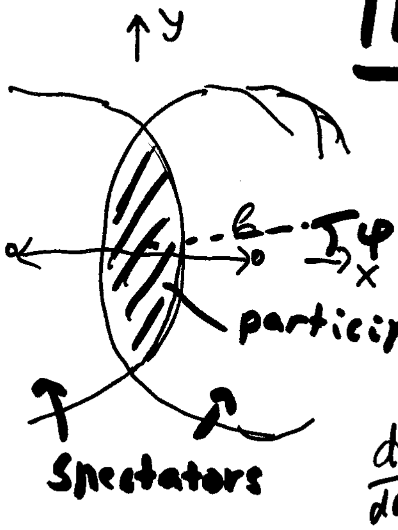
Figure 3. Comparison of PHENIX π^0 spectra to theoretical calculations under three scenarios and for two centralities. The points are the same as on Figure 1. The curves are calculations of X-N. Wang [1]. Solid lines are a pQCD calculation for pp scaled by the mean number of binary collisions. The dotted lines add shadowing and p_T broadening. The dashed lines add a $dE/dx = 0.25$ GeV/fm parton energy loss.

- Gyulassy et al: such suppression means $\Rightarrow \frac{L}{\lambda} \simeq 3$ or $\frac{dN_g}{dy} \simeq 1000$ (AuAu Central)
- Independent study of $v_2(p_\perp > 2\,\mathrm{GeV})$ give the same estimate

How they are produced ?

Absent for
independent
pp, or parton-parto

The elliptic flow



The "almond" has initial spatial deformation $\frac{\langle y^2-x^2\rangle}{\langle y^2+x^2\rangle} = \varepsilon$

$$\Downarrow$$

$\frac{dN}{d\varphi} \sim (1 + 2v_2\cos 2\varphi)$ final momentum deform.

$\longrightarrow v_2 =$ [illegible] $\langle \cos 2\varphi \rangle$

At SPS $v_2 \cong 2\%$ for all π at $b = 6\,fm$

- Important, because it can help us to separate initial from final state effects...

Predictions before RHIC:

- String-based models (RQMD, UrQMD)

  $\frac{v_2(RHIC)}{v_2(SPS)} \sim \frac{1}{2}$ only late rescattering by that time less almond

- pQCD-like models (HIJING) ⟹ very small and specific $p_\perp$ dep.

← shadowing

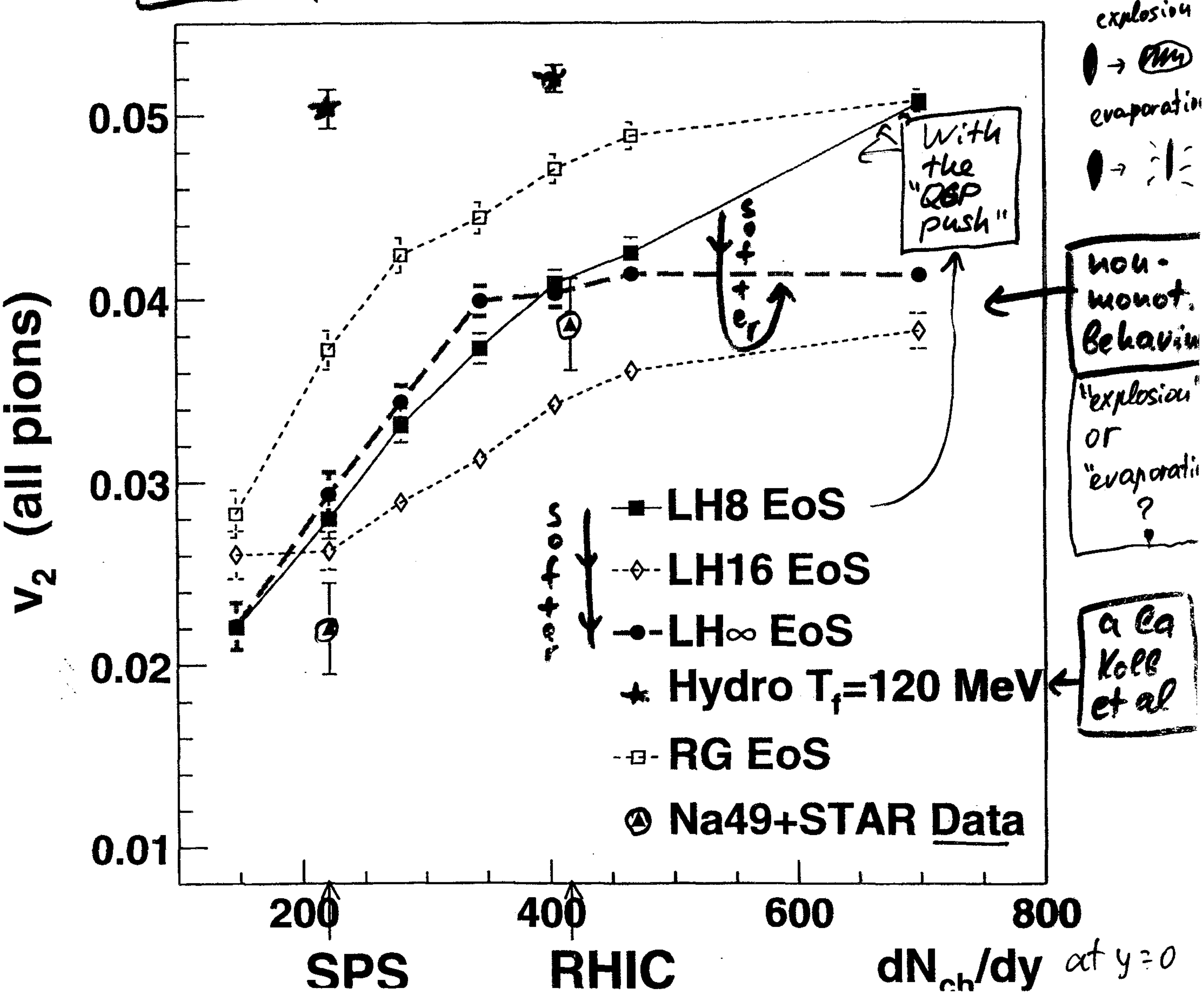
↖ opposite sign due to [illegible] multiplication in matter

- Hydro predicted → D. Teaney, ES Kolb + Heinz + ... QM99

  $\frac{v_2(RHIC)}{v_2(SPS)} \sim 2$ due to QGP push at early time

How magnitude of the <u>elliptic flow</u> depends on initial entropy density (or $\frac{dN_\pi}{dy}$) ?

$\boxed{b = 6\ fm}$



at y=0

softer

softer

With the "QGP push"

explosion

evaporation

non-monot. behaviour

"explosion" or "evaporation" ?

a la Kolb et al

How good is hydro ?

(v.s. "few scattering model" H Heiselberg et al)

At RHIC deviation from hydro only for very peritheral, $N_p / N_{part.}^{max} < 0.1$

at SPS start at ~ 0.6

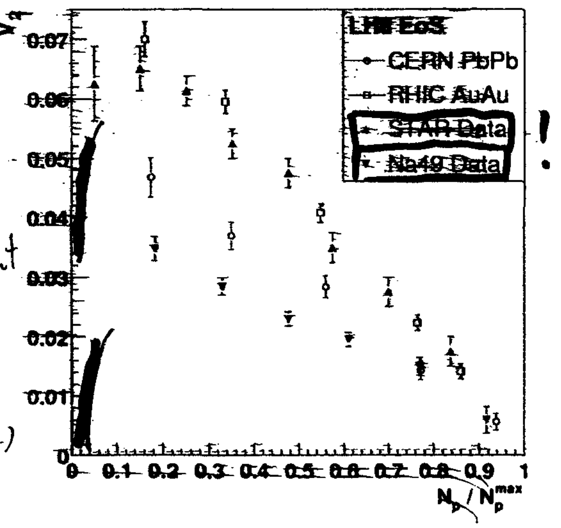
hydro: $V_2 \sim \varepsilon \sim (N_p \cdot N_p^{max})$

small density limit: $V_2 \sim N_p$

not seen

where is the transparent region?

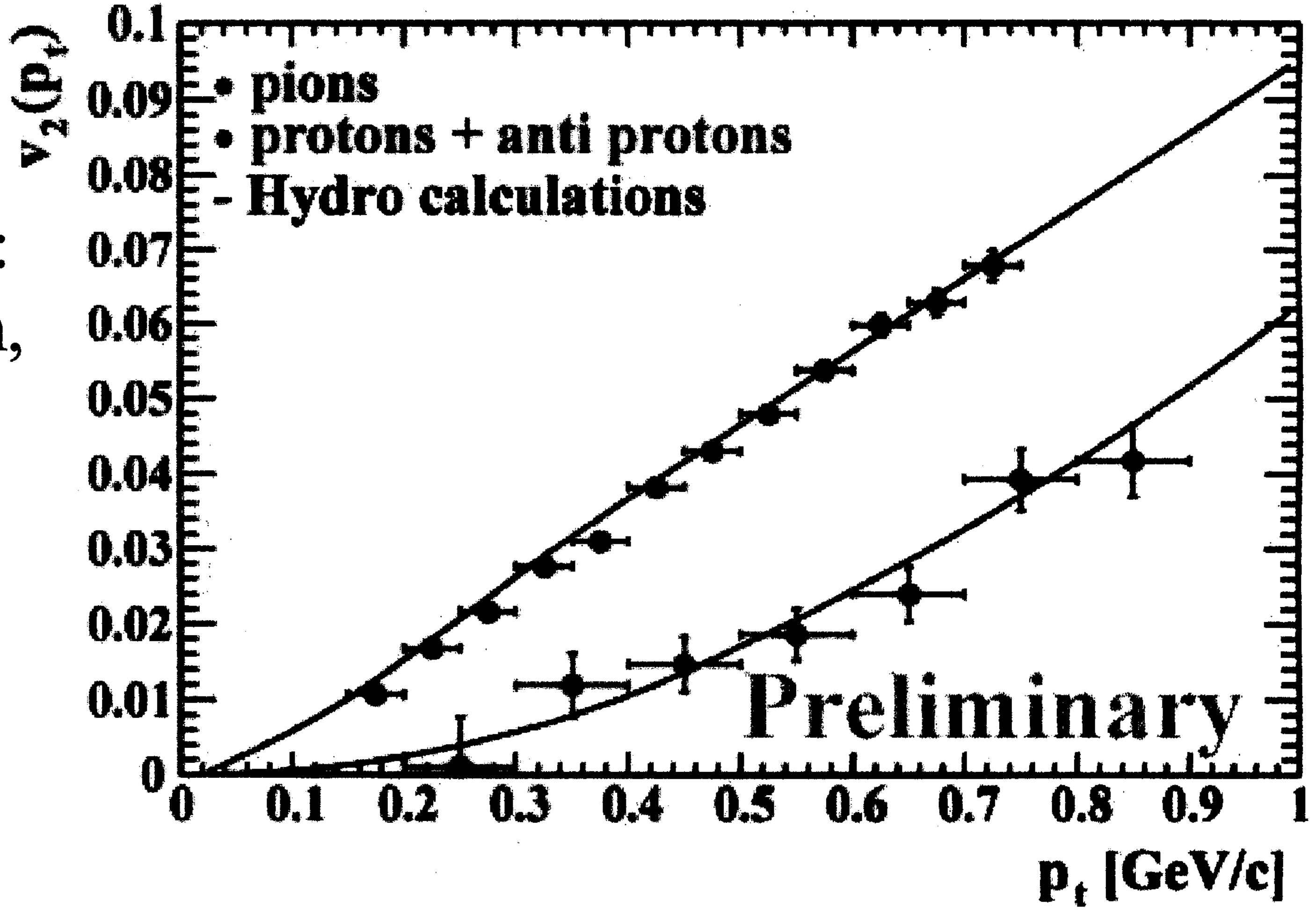
Heiselbers...



~~Figure 3: v2 versus impact parameter b, described experimentally by the number~~ of ~~participant nucleons, for RHIC STAR and SPS NA49 experiments. Both are compared~~ to our results, for ~~EoS LH8.~~

A Hydro view of the world

- Hydro calculations: P. Huovinen, P. Kolb and U. Heinz



If v_2 is normalized to spatial deformation → const (B)

?

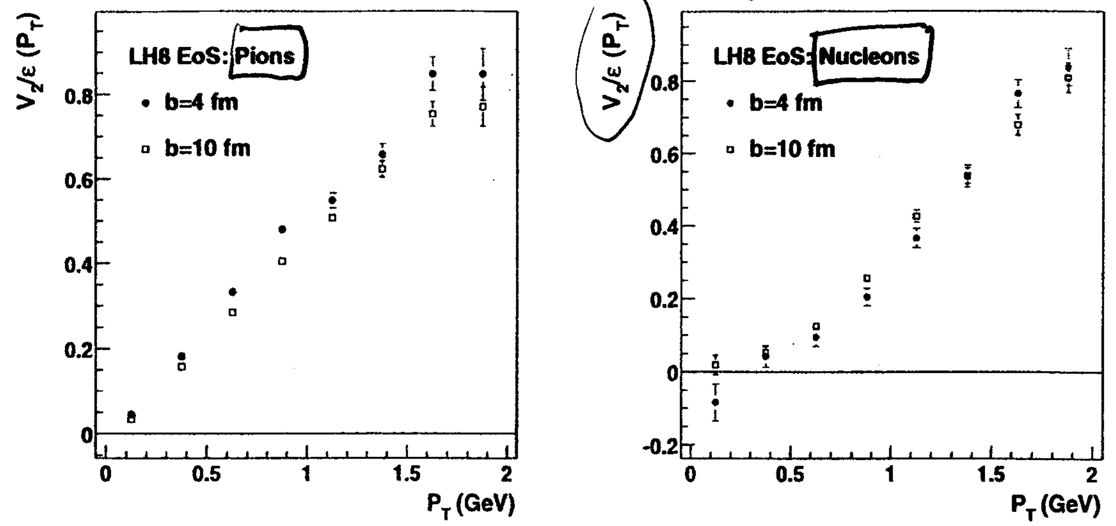
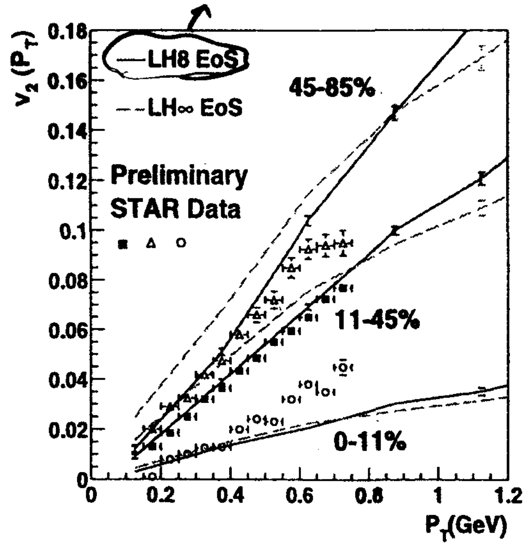


FIG. 26: The b dependence of elliptic flow for pions, kaons nucleons

with QGP push

H2H model (curves) vs STAR data



peripheral

mid-central

central

and $P_\perp$

FIG. 27: The b dependence of elliptic flow for pions, [redacted]

Most difference

Gyulassy, Vitev, Wang
nucl-th/0012092

▨ Star data

favor $\frac{dN^g}{dy} \simeq 1000$!!

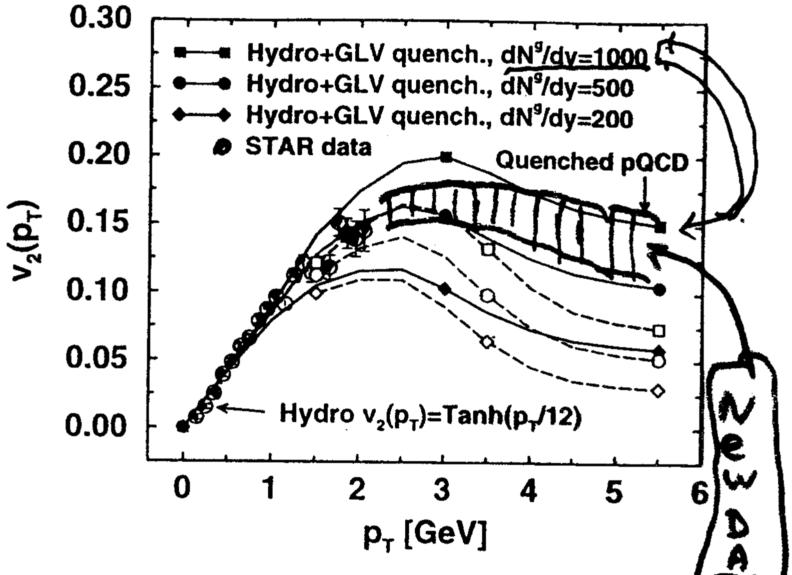


FIG. 4. The interpolation of $v_2(p_T)$ between the soft hydrodynamic [12] and hard pQCD regimes is shown for $b = 7$ fm. Solid (dashed) curves correspond to cylindrical (Wood-Saxon) geometries.

HIJING → 200
(= pert. partonic reactions, $P^2_{cutoff} \sim 2\,\text{GeV}^2$)

$\frac{dN_\pi}{dy} \simeq 1000$ also

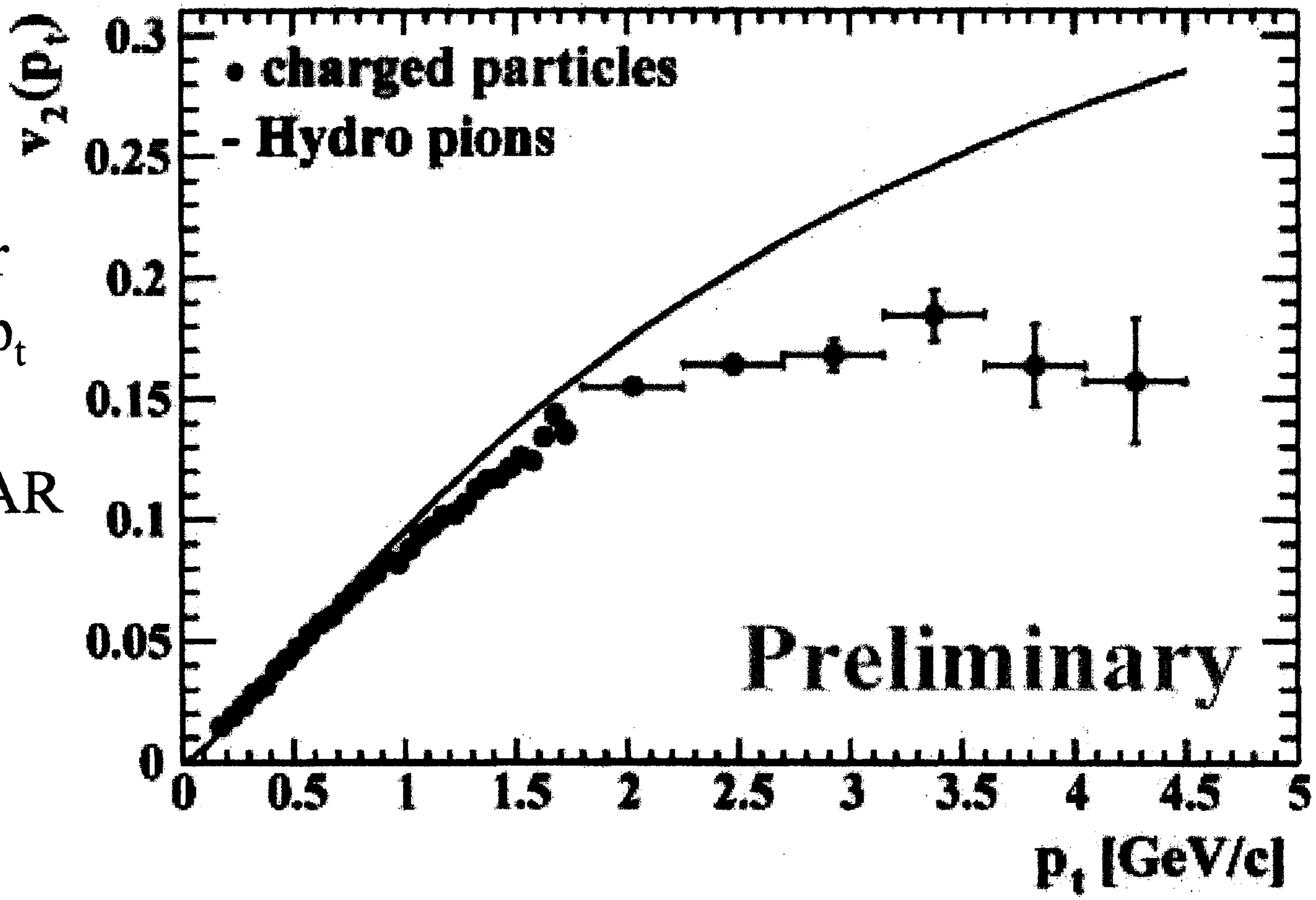
Conclusion

Like in the Big Bang,
in the Little one
the whole entropy is there
even at earliest time we
can measure it!

How is it produced?

Charged particle anisotropy
$0 < p_t < 4.5$ GeV/c

- Only statistical errors
- Systematic error 10% - 20% for $p_t = 2 - 4.5$ GeV/c
- More in the STAR high-pt talk (James Dunlop, PS2, this afternoon)



Major observations from the first RHIC run

- New component in multiplicity which was not there at CERN SPS $\sqrt{s} = 17$ GeV $\left[\begin{array}{l} N \sim (\#\text{ of collisions}) \\ \text{not }\#\text{ of participants} \end{array} \right.$

  "semi-hard" scale, $Q \sim 1$ GeV

- Much more visible collective effects radial and elliptic flow
  - → QGP scenario, not string or perturbative ones EOS like derived on the lattice, $L \approx 0.8 \frac{GeV}{fm^3}$

- Large $p_\perp$ hadronic spectra (π^0 from Phenix) show jet quenching ($\sim 1/5$!) in central coll.

- Its dependence on asymuthal angle φ at $p_t > 2$ GeV allows an estimate of $\frac{dN_{gluons}}{dy}$ (at early times)

  $\frac{dN_g}{dy} \simeq 1000$ (at $b=0$) $\Rightarrow$ as large # as π's !

  (Vitev, Wang, Gyulassy 01)

Summary:

- Not only we definitely have QGP at RHIC

but

- we have to explain now how this large entropy can be produced so quickly

E. Shuryak

Lecture 5

Understanding a Pomeron via Instantons

Instanton/sphaleron mechanism of high energy hadronic and heavy ion collision

E.V.Shuryak
SUNY Stony Brook

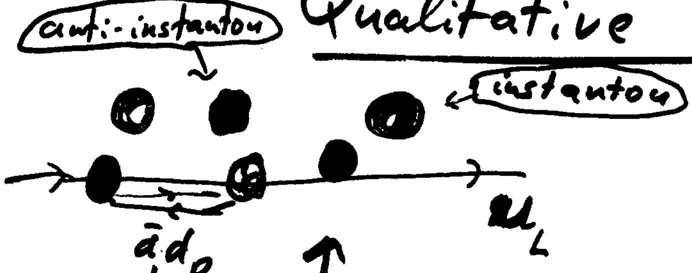
+ I. Zahed
M. Nowak
G. Carter
D. Ostrovsky

- – Introduction: the "substructure scale"
- – Instanton liquid, properties, counting rules
- – Elastic scattering
- – Inelastic scattering: multi-gluon production, unitarization
- – Evaluating Soft Pomeron parameters, Δ, α'
- X – The Sphaleron and its decay
- – Instanton/sphaleron mechanism for heavy ion collisions at RHIC
- Sphaleron + (fermions from 't Hooft vertex)
  ⇒ What are hadronic final states?
  ⇒ Do they have special features?
  ⇒ Can those be found experimentally?

Qualitative Pictures

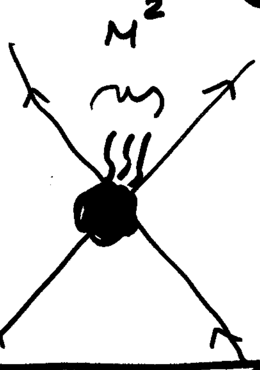
ES, Zahed
Kharzeev, Kovchegov, levin

Follows closely electroweak developments of early 1990's
Zakharov, Ringwald, Khose...



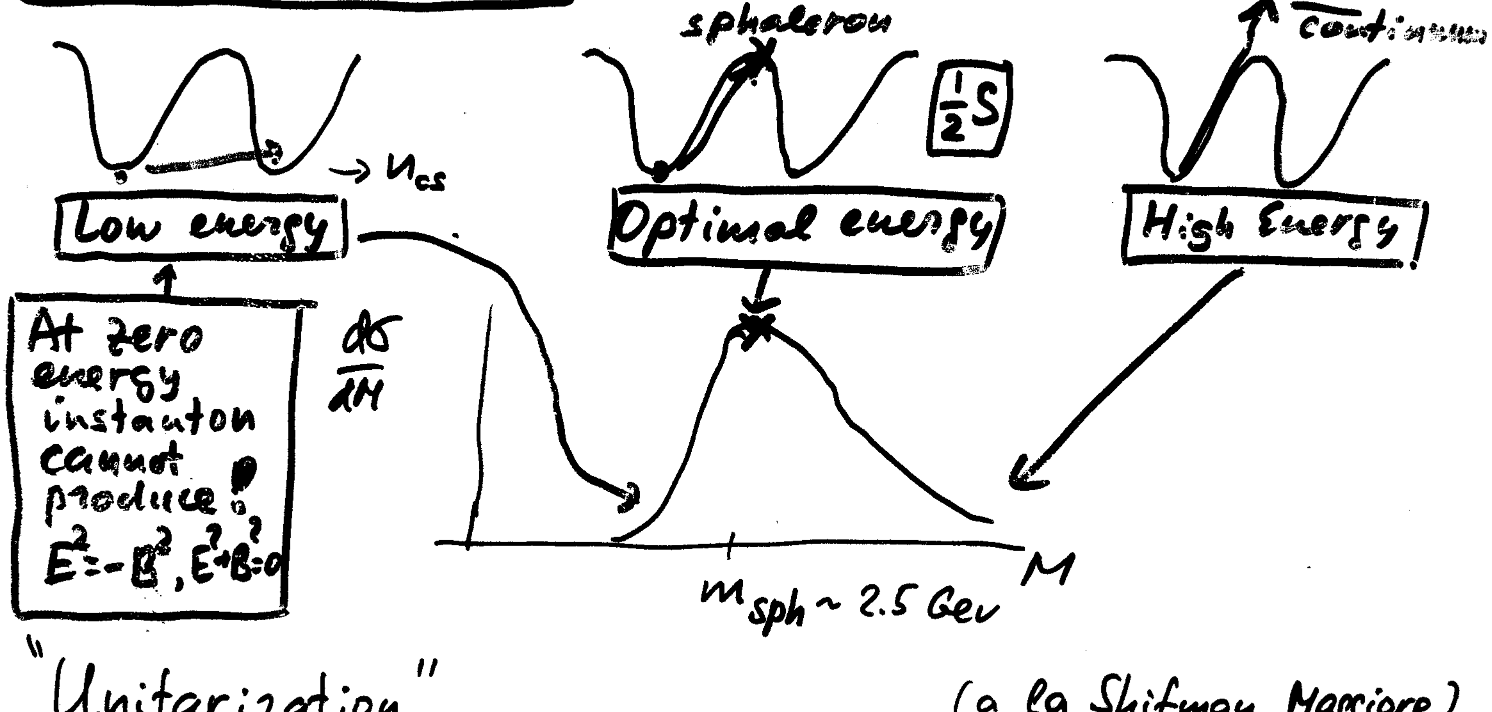
One quark in the instanton vacuum...

Quark moves through the instanton vacuum (Note: Sea quarks are opposite in flavor and chirality!) and becomes a constituent quark, $m_{eff} \simeq 400$ MeV



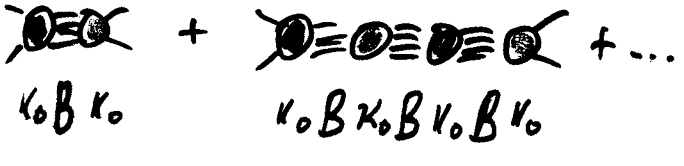
Two quarks collide near the instanton...

If 2 partons collide ⇒ Instantons transform some of their field into a different form which is emitted



At zero energy instanton cannot produce!
$E^2 = -B^2$, $E^2 + B^2 = 0$

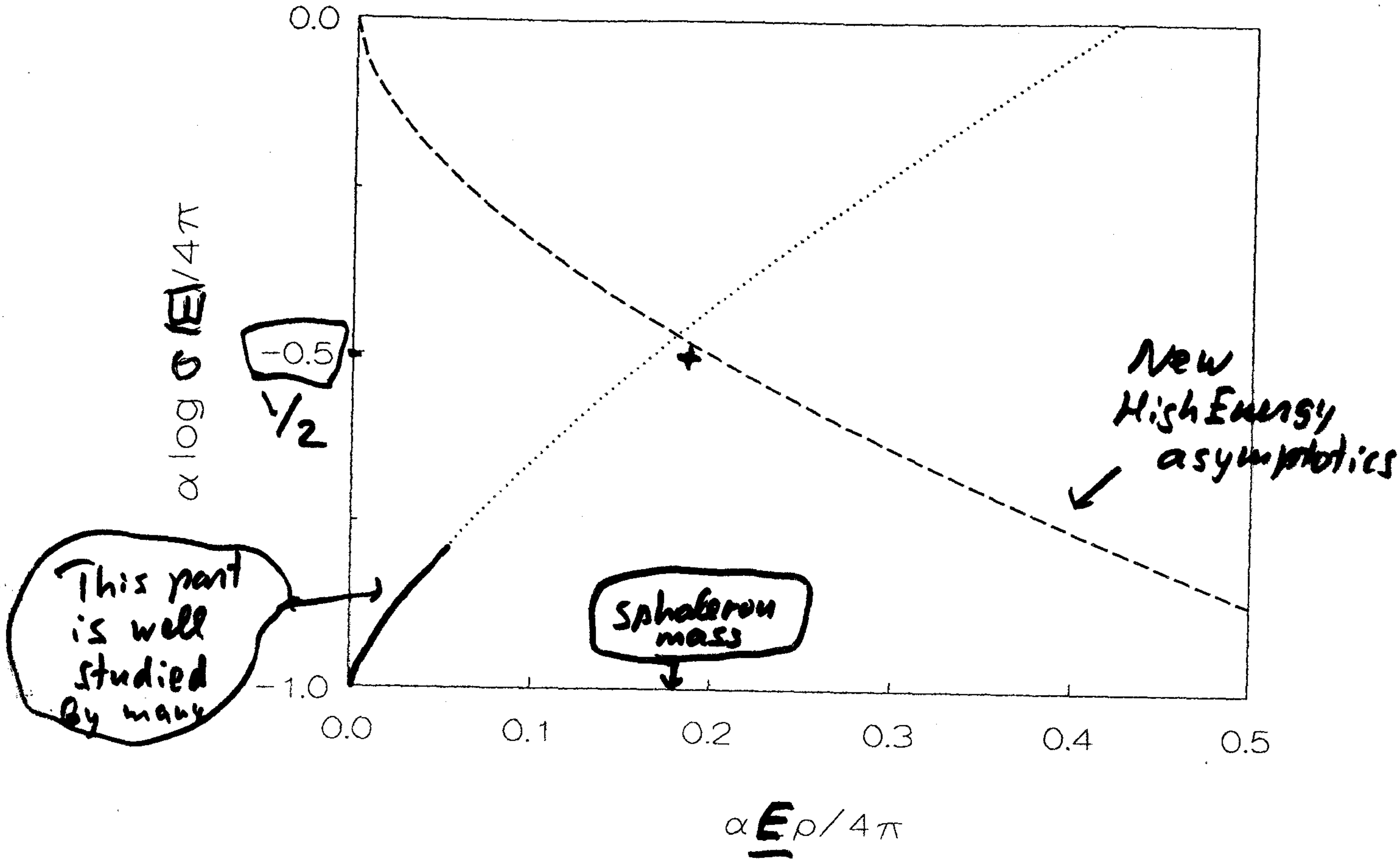
"Unitarization"



(a la Shifman, Maggiore)

$$\frac{K_0 B(M)}{1 + K_0^2 B^2(M)}$$

contains multi[illegible] phase space and grows with M



D. Diakonov, V. Petrov → arXiv:hep-ph/9307356 28 Jul 1993

NOTE E is the gg (actually WW) energy

using a different path in the [redacted] space of all configurations...

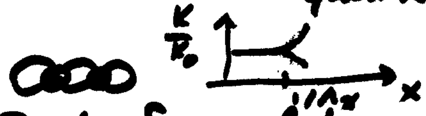
Scales of non-perturbative QCD

① The "chiral scale" $\Lambda_\chi \sim 1$ GeV

Separates the region where effective low energy approaches are suppose to work

↓ - Chiral Lagrangians
- NJL (1961)

(a)  ← cutoff $k < \Lambda_\chi$
so $\frac{1}{\Lambda_\chi}$ ~ size of const. quark

(b) 

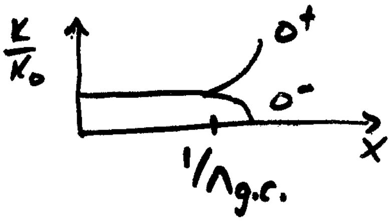
π, η', σ, δ correlators

generated by instantons!

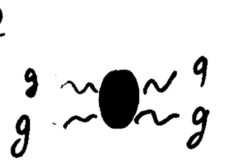
② The "glueball continuum" scale (NSVZ-81)

at which correlators for $G_{\mu\nu}^2$ and $G\tilde{G}$ deviate from pert. th.

$\Lambda_{\text{glueball cont.}} \sim (3 \div 4)$ GeV



Increased compared to Λ_χ because instantons are small and semiclassical



$\sim \left(\frac{8\pi^2}{g^2}\right)^2 \sim 10^2$ relative to

③ The 3-ed kind of non-pert. scale

appears when we want to separate $\boxed{\text{color}}$!

Parton distribution in tr. plane

- – The non-perturbative objects in the QCD vacuum (and inside hadrons) are not some shapeless soft fields, with typical momenta of the order of $\Lambda_{QCD} \sim 1 fm^{-1}$.

- – Instead we have semi-classical small-size instantons $\rho \sim 1/3 fm$ (E.S.82 and recent lattice data) and very thin QCD strings: the string energy (action) is concentrated in a radius of .2 fm (.4 fm) in transverse directions (see review by G.Bali). Both are small compared to typical hadronic size, suggesting a substructure inside hadrons.

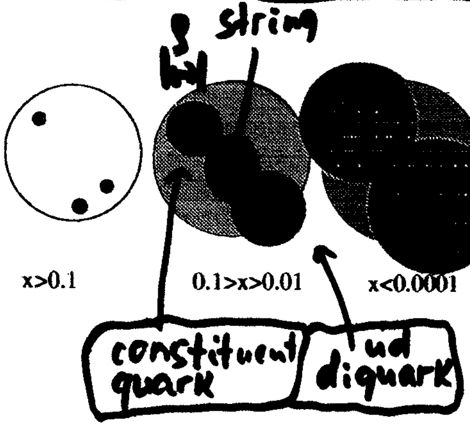


Figure 1:

Finally, at x→0 it becomes an universal "color glass"

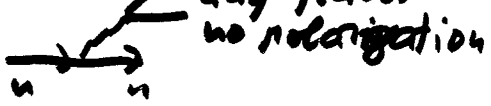
For nuclei, large $A^{1/3}$ (McLerran Venugopalan) helps also...

Small "Beads" of such glass may be already there inside the nucleon...

- – A snapshot of parton distribution in a transverse plane inside the nucleon should look like indicated in Fig1, for different x regions. Parton clusters originate from "scars" in the vacuum, perturbed by valence quarks and strings, and therefore they must have the same transverse dimensions.

- – The non-perturbatively produced sea quarks are supposed to be more concentrated inside the constituent quarks (enhanced polarization is here) while the string is supposed to be

unlike



Simplified Instanton Counting rules

- – Numerical parameters characterizing the QCD vacuum (ES 1982): instanton (plus anti-instanton) density

$$n_0 \approx 1\,/\mathrm{fm}^4 \qquad R = n^{-1/4} \approx 1\,\mathrm{fm}$$

and the mean instanton size

$$\rho_0 \approx 1/3\,\mathrm{fm}$$

yield the dimensionless diluteness

$$\kappa_0 = n_0 \rho_0^4 \approx 0.01$$

of the instanton vacuum. The mean instanton action is

$$S_0 = 2\pi/\alpha_s \approx 10 - 15 \quad \gg 1$$

.

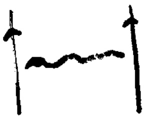
- – For comparison we note that in the electroweak theory the diluteness factor is 10^{-84}, as action is order of magnitude larger
- – Each time an instanton is inserted it costs a small factor κ_0. However, there are no

coupling constants, and so each time we compare the results with their perturbative counterparts we get powers of the large action S_0, with a net gain per gluon involved.

- – Numerically the instanton-induced effects should dominate the perturbative effects from third order and on ($\kappa_0 S_0^2 \approx 1$), while they comparable to second order.

Example 1: (1st order)

qq potential (or quasi-elastic scatt. ampl.)



$\sim \frac{\alpha_s}{R}$ $\boxed{\gg}$

$\sim (n\rho^4)\frac{1}{\rho}$

Example 2 (2nd order)

Dipole - dipole pot. / scatt. amplitude

(I. Zahed, ES 2000)

$\sim \frac{\alpha_s^2 (d^4 \tau^2)}{R^7}$ $\boxed{\ll}$

Casimir-Polder

$\frac{1}{\rho}(n\rho^4)(d/\rho)^4$

Below we discuss much higher order effects!

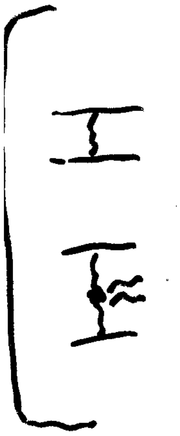
etc:

Instanton-induced Inelastic Collisions in QCD

Based on M.Nowak, E.Shuryak and I.Zahed

also Kharzeev, Levin 2000

Generalities



- – i. **initial stage:** Partons are initially described by some wave-function. Assumed to move along the eikonalized straight Wilson lines
- –ii. **prompt stage:** As partons pass each other color of through-going partons could be changed (quasi-elastic), or new partons/hadro could appear (inelastic). Confinement is ignored since the time is short
- –iii. **final stage:** All produced partons fly away, [redacted] dragging longitudinal color strings of matching color. String breaking happens with probability one, thus cross sections are not affected. These eventually produce the hadronic final state.

Lund-like models

Only the basic process involving prompt inelastic quark-quark scattering is discussed.

The Eikonal Approximation → quasi elastic

(color exchanges included)

↳ E.S, I.Zahed PRD (2000)

Quasi-elastic amplitude

$$\mathcal{T}_{AB,CD}(s,t) \approx -2is \int d^2b\; e^{iq_\perp\cdot b} \times\langle\, (\mathbf{W}_1(b)-\mathbf{1})_{AC}\,(\mathbf{W}_2(0)-\mathbf{1})_{BD}\,\rangle\,, \qquad (1)$$

where

$$\mathbf{W}_{1,2}(b) = \mathbf{P}_c\mathrm{exp}\left(ig\int_{-\infty}^{+\infty} d\tau\, A(b+v_{1,2}\tau)\cdot v_{1,2}\right)\,. \qquad (2)$$

The averaging is over the gauge configurations using the QCD action. AB and CD are the incoming and outgoing color and spin of the quarks.

Scattering at high-energy in <u>Minkowski</u> geometry follows from scattering in <u>Euclidean</u> <u>geometry</u> by analytically continuing $\boxed{\theta \to -iy}$ in the regime $y \approx \log(s/m^2) \gg 1$. The Minkowski scattering amplitude at high-energy can be altogether continued to Euclidean geometry through

$$\mathcal{T}_{AB,CD}(\theta,q) \approx 4m^2\,\underline{\sin}\,\theta \int d^2b\; e^{iq_\perp\cdot b} \times\langle\, (\mathbf{W}(\theta,b)-\mathbf{1})_{AC}\,(\mathbf{W}(0,0)-\mathbf{1})_{BD}\,\rangle\,, \qquad (3)$$

where

$$\mathbf{W}(b,\theta) = \mathbf{P}_c\mathrm{exp}\left(ig\int_{\theta} d\tau\, A(b+v\tau)\cdot v\right)\,, \qquad (4)$$

with $v = p/m$. The line integral in (4) is over a straight-line sloped at an angle θ away from the vertical.

Can be done analytic. for the instanton

the two-instanton contribution to the color inelastic part

$$\mathbf{W}(\theta, b) = \cos\alpha - i\boldsymbol{\tau}\cdot\hat{\boldsymbol{n}}\sin\alpha \ , \tag{5}$$

where

$$n^a = \mathbf{R}^{ab}\,\eta^b_{\mu\nu}\,\dot{x}_\mu(z-b)_\nu = \mathbf{R}^{ab}\,\mathbf{n}^b \ , \tag{6}$$

and $\underline{\alpha = \pi\gamma/\sqrt{\gamma^2+\rho^2}}$ with

$$\begin{aligned}\gamma^2 =&\quad n\cdot n = \mathbf{n}\cdot\mathbf{n}\\ =&\quad (z_4\sin\theta - z_3\cos\theta)^2 + (b - z_\perp)^2 \ .\end{aligned} \tag{7}$$

The one-instanton contribution to the parton-parton scattering amplitude survives only in the color-changing channel a situation reminiscent of one-gluon exchange.

- Why the cross section grows?

$$\sigma = \underbrace{\overset{\pi r_*^2}{\overset{\shortparallel}{\sigma_0}}} \left[1 + (\Delta(0) + \alpha'|t|) \underset{\text{grows}}{\underline{\ln s}} + \dots \right)$$

The part which is constant with s
$\sigma_0 \approx \frac{1}{9}\sigma_{NN} \Rightarrow r_* = \frac{1}{3}fm$

$\Delta(0) \simeq 0.08$ "Pomeron intercept" (Landshoff et al)

$\alpha' \approx 0.25\, GeV^{-2}$

- Why $\Delta(0)$ is so small?

$$\Delta(0) \simeq \underset{O(1)}{\#} \underbrace{\left(\frac{\pi^2}{2} n \rho^4\right)}_{0.06}$$

instanton diluteness

current calculation (ES + I. Zahed, in progress)
$\Delta(0) \simeq 0.[illegible]2$

- Why α' is so small?

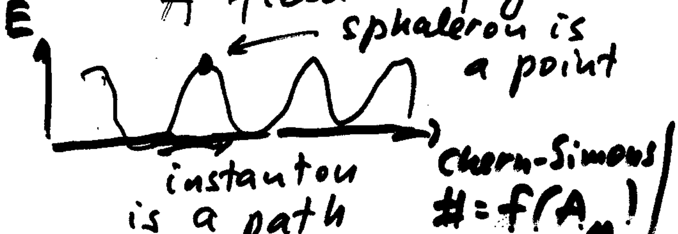
$$\alpha' = \frac{1}{(2\,GeV)^2} = (0.1\, fm)^2$$

Because instantons are small!
current estimate $\alpha' \simeq 0.5\, GeV^{-2}$

- What is produced in the process?

A field config. called ~~the~~ "sphaleron" ~ to magnetic one

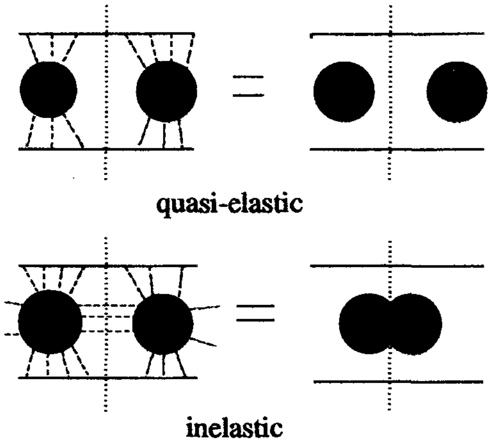
Klinkhammer Manton



$$E_{sph} \simeq \frac{3\pi^2}{g^2\rho} \simeq \underline{2.5\,GeV}$$

Basically a set of glueballs (if zero color but not necessarily so...)

- No odderon! Instanton is SU(2) object
Odderon requires d^{abc} | in SU(2) $\bar{q} \approx q$



(Not all diagrams are still included: e.g. interf. between "absorbed" and "produced" gluons)

Figure 1: Schematic representation of the amplitude squared, with (without) gluon lines are shown in the left (right) side of the figure. The dotted vertical line is the unitarity cut. The upper panel illustrates the quasi-elastic (at the parton level) amplitudes where only color is exchanged as detailed in [?]. The lower panel depicts inelastic processes in which some gluons cross the unitarity cut, and some gluons are absorbed in the initial stage.

M. Nowak,
I. Zahed
ES → PRD
in press

Inelastic Scattering

The imaginary part of the quark-quark inelastic amplitude follows from unitarity. Schematically,

$$\mathrm{Im}\,\mathcal{T}_{if} = \mathcal{T}_{in}\,\sigma_{nn}\,\mathcal{T}^{*}_{nf}\ , \qquad (8)$$

where σ_{nn} accounts for the phase space of the propagating quarks and emitted intermediate gluons. The total cross section follows then from the optical theorem $\sigma = \mathrm{Im}\,\mathcal{T}/s$.

The functional integration is understood over gauge-fields (to be saturated by instantons in Euclidean space after proper analytical continuation)

Zakharov + ...

Khoze-Ringwald resummed

$\oint \to e^{-S}$

resummed eikonalized gluon exchanges

$$
\begin{aligned}
\mathcal{W} \approx \quad & n_0^2 \sum_{CD} \int d^4z\, d\mathbf{R}\, d\mathbf{R}'\; e^{iQ_E z}\, e^{-\underline{\mathbf{S}(z,\mathbf{R}\mathbf{R}'^{-1})}} \\
& \times \int d^3x\, d^3y\, d^3x'\, d^3y' e^{-iq_{1\perp}(x-x')-iq_{2\perp}(y-y')} \\
\to \quad & \times((\cos\alpha - 1)_{AC} - i\mathbf{R}^{a\alpha}\, \mathbf{n}^{\alpha}\, (\tau^a)_{AC} \sin\alpha\ ) \\
\to \quad & \times((\cos\underline{\alpha} - 1)_{BD} - i\mathbf{R}^{b\beta}\, \underline{\mathbf{n}}^{\beta}\, (\tau^b)_{BD} \sin\underline{\alpha}\ ) \\
\to \quad & \times((\cos\alpha' - 1)_{AC} + i\mathbf{R}'^{a'\alpha'}\, \mathbf{n}'^{\alpha'}\, (\tau^{a'})^*{}_{AC} \sin\alpha'\ ) \\
\to \quad & \times((\cos\underline{\alpha'} - 1)_{BD} + i\mathbf{R}'^{b'\beta'}\, \underline{\mathbf{n}}'^{\beta'}\, \tau^{b'*}_{BD} \sin\underline{\alpha'}\ )\ ,
\end{aligned}
\tag{9}
$$

where the variables x, x' are defined on a tilted Wilson line of angle θ with x_4, and y, y' on an untilted Wilson line running along y_4.

The result is

$$
\begin{aligned}
\mathcal{W}(Q, q_{1\perp}, q_{2\perp}) &= (16\pi^5)^{\frac{1}{2}}\ \mathbf{K}(q_{1\perp}, q_{2\perp}) \\
\times \mathrm{Im}\ n_0^2 &\int_0^\infty dR \left(\frac{R}{Q}\right)^{\frac{3}{2}} \int_0^\pi d\chi \sin^6\chi\, e^{QR-\mathbf{S}(R,\cos^2\chi)}\ ,
\end{aligned}
\tag{10}
$$

with the induced kernel

$$
\mathbf{K}(q_{1\perp}, q_{2\perp}) = |\mathbf{J}(q_{1\perp}) \cdot \mathbf{J}(q_{2\perp}) + \mathbf{J}(q_{1\perp}) \times \mathbf{J}(q_{2\perp})|^2\ , \tag{11}
$$

We have introduced our generic instanton-induced form-factor

$$
\mathbf{J}(q_\perp) = \int dx_3\, dx_\perp\, e^{-iq_\perp x}\, \frac{x_\perp}{|x|} \sin\left(\frac{\pi\, |x|}{\sqrt{x^2 + \rho_0^2}}\right)\ . \tag{12}
$$

Color rotation angle

$$
\begin{aligned}
\mathbf{J}(q_\perp) = \quad & -i\frac{\hat{q}_\perp}{\sqrt{q_\perp}} \int_0^\infty dx\, J_{3/2}(q_\perp x) \\
& \times \left((2\,\pi x)^{3/2} \sin\left(\frac{\pi\, |x|}{\sqrt{x^2 + \rho_0^2}}\right)\right)\ .
\end{aligned}
\tag{13}
$$

Soft Pomeron from Instantons

The instanton contribution to the inelastic process, yields a logarithmically growing cross section

$$\sigma(s,t) \approx \pi\,\rho_0^2\,\left(\#\,\kappa_0 \ln s + \ldots\right)\ . \tag{17}$$

Hence,

$$\sigma(s,t) \approx \pi\,\rho_*^2\,(\alpha_s/\pi)^2 + \pi\,\rho_0^2\,\Delta(t)\ln s \tag{18}$$

with

$$\Delta(0) = \kappa_0\,\frac{64}{15}\,\frac{1}{(2\pi)^8}\int dq_{1\perp}\,dq_{2\perp}\,\mathbf{K}(q_{1\perp},q_{2\perp})\ . \tag{19}$$

$$\Delta(0) = \kappa_0\,\frac{64}{15}\,\frac{1}{(2\pi)^8}\left(\int_0^\infty dq\,\mathbf{G}^2(q)\right)^2\ , \tag{20}$$

where we have defined the scalar form-factor **G** as

$$\mathbf{J}(q) = -i\,\frac{\hat{q}}{\sqrt{q}}\,\frac{\mathbf{G}(q)}{\sqrt{2\pi}}\ . \tag{21}$$

A numerical estimate of (20) can be made using the parameterization (**??**) which removes the unphysical singularity at $q_\perp = 0$. The result is

$$\underline{\Delta(0) = 9.48\,\kappa_0 \approx 0.12\ ,} \tag{22}$$

which is close to the phenomenological intercept of 0.093 → 0.16 or so, if unitarity corrections done (B. Kopeliovich et al.)

Effective power $\boxed{\Delta(b) = \frac{d \ln \Gamma}{d \ln S}}$

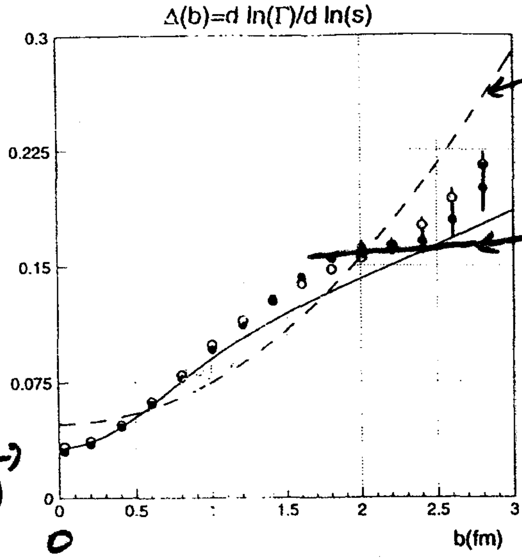
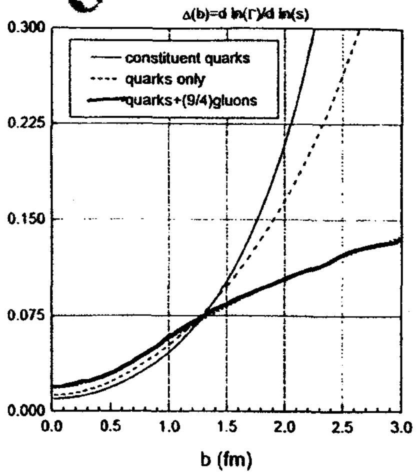


Figure 9: *The exponent Δ(b) found by the fit to each point of Fig. 8 with power dependence on energy at each value of b. The black and open points correspond to the fits with parameterizations I and II respectively. Our predictions with Eq. (53) are shown by solid curve. The dashed curve demonstrates prediction of a single Regge pole model without any unitarity corrections.*

From Kopeliovich et al hep-ph/0009008 (using total + elastic data)



▬ = our results $\boxed{q+g}$

(G. Carter, D. Ostrovsky, ES → in progress)

$$\sigma_{hh'}(s) = \sigma^0_{hh'}(s_0) + X_{hh'} \log\frac{s}{s_0}$$

TABLE III. Instanton deformation parameter (c) and $X = d\sigma_{tot}/d\ln(s)$ on quark level (subscript qq) and for different models of hadrons. Superscript stands for screening model

	constituent quarks	quarks only	quarks + 9/4gluons	PDG → data
c	0.257	0.387	0.784	
$X_{qq}^{w/o}$, fm^2	$2.52 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$1.28 \cdot 10^{-3}$	
X_{qq}^{pp}, fm^2	$1.94 \cdot 10^{-2}$	$7.38 \cdot 10^{-3}$	$8.79 \cdot 10^{-4}$	
input → X^{pp}, fm^2	0.174*	0.174*	0.174*	← 0.174
$X_{qq}^{p\pi}$, fm^2	$2.05 \cdot 10^{-2}$	$7.85 \cdot 10^{-3}$	$9.39 \cdot 10^{-4}$	
$X_{p\pi}$, fm^2	0.123	0.105	0.129	← 0.111
$X_{\gamma p}^{p\pi}$, fm^2	0	$6.51 \cdot 10^{-4}$	$6.39 \cdot 10^{-4}$	← $5.51 \cdot 10^{-4}$
$X_{\gamma\gamma}^{p\pi}$, fm^2	0	$2.29 \cdot 10^{-6}$	$2.19 \cdot 10^{-6}$	← $1.45 \cdot 10^{-6}$

* This is our method of fixing c.

Assumptions of our model are:

- $N^h_{q,g} = \int_{0.01} dx\,(\text{pdf}(x))$ ↑ latest GRV, lead. ord. for N, π, γ; $Q^2 \sim 1\,\text{GeV}$
- $\sigma(tot) = 2 \int d^2b\, \Gamma(b,s)$

  $\Gamma = 1 - \exp(\chi_0 + \chi_1)$

  ↑ related to σ_0 | ↑ related to X, or $\log S$ part

Main result: $X_{qq} \simeq 10^{-3}\,\text{fm}^2$

about 300 times less than πg^2! ⇒ Rare events

"Ready to fall"

Sphaleron: mass and decay

- **Magnetic** object $\vec{B}^a(r)$ $\qquad \vec{D}\vec{B}=0$, $\vec{D}\times\vec{B}=0$

$B_i^a \sim n^a n_i$ hedgehog, like monopole but no magnetic charge $\qquad A_i^a \sim \epsilon^{aim} r^m f$

(Klinkhamer, Manton 1984) in electroweak theory

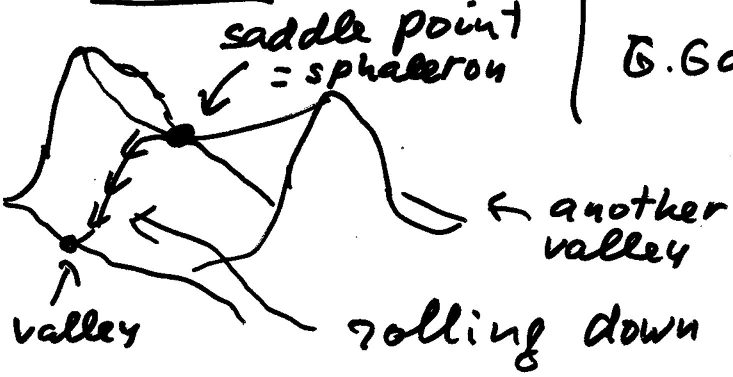
$M \sim 14$ TeV, in $\lambda \to \infty$ limit Higgs decouples

$M \approx \frac{30}{g^2 \rho} \sim 2.5$ GeV in QCD, if $\rho = 1/3$ fm

- Decay

J. Zadrozny, PL, 1992 for EW

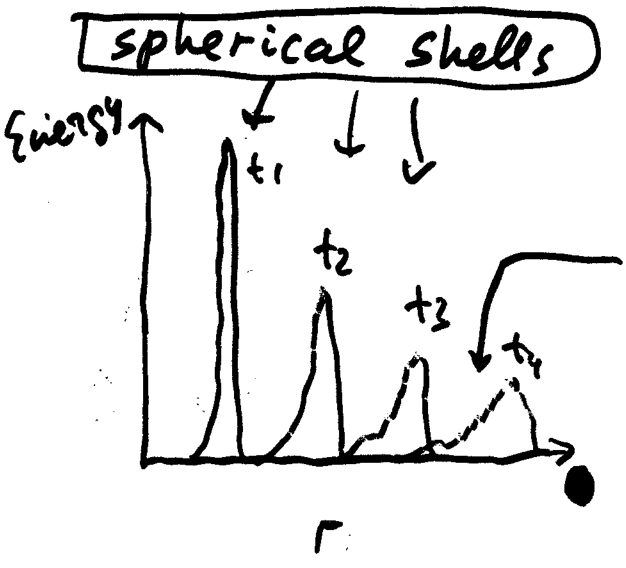
G. Carter + ES → in progress for QCD



Recall that in $A_0=0$ gauge $\vec{E}=\frac{\partial \vec{A}}{\partial t}$

$\uparrow$ momentum

(but $\vec{E}^2$ is gauge inv.)

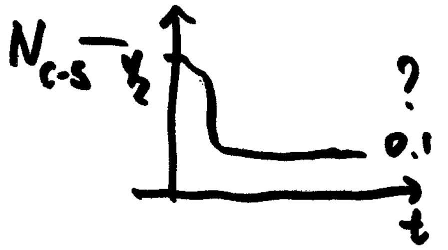


ripples are not my shaky hand but a trace of e^{ikr}

momentum $k \to$ const | $r \to \infty$

$|C_k|^2$ occupation numbers → const

Puzzle:



EW sphalerons → ~50 W+Z about 200 GeV each

QCD sphalerons → 3-4 gluons ~600 MeV each

Why QGP is produced so early ?

- –One possible solution to this puzzle can be a significantly lower cutoff scale in AA collisions, compared to $p_0 = 2\,GeV$ fitted from pp data. ("saturation" at 1GeV ?)

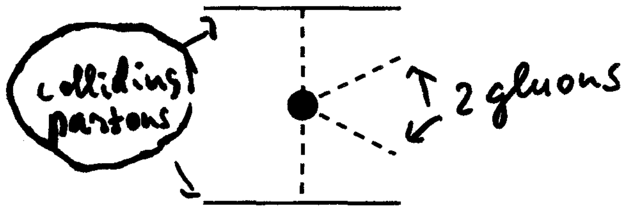
- – An alternative scenario: *non−perturbative* mechanism of multi-gluon production, involving classical topological objects, *instantons and sphalerons*.

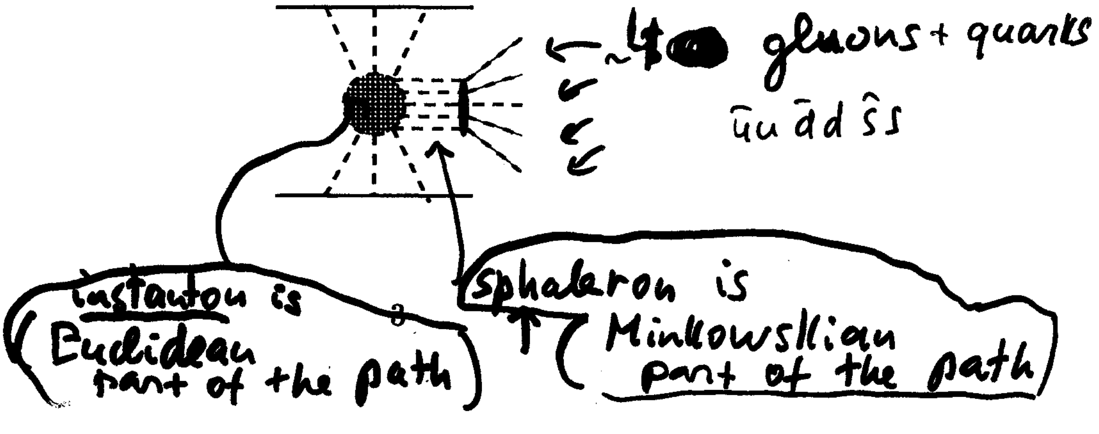
- – The cross sections of hadron-hadron collisions ($\bar{p}p, pp, \pi p, Kp, \gamma N$ and even $\gamma\gamma$) start to grow slowly with the collision energy s at $s > 10^3 GeV^2$.

$$\sigma_{hh'}(s) = \sigma_{hh'}(s_0) + log(s/s_0)X_{hh'}\overset{\xleftarrow{}\ 0.09\ \text{small number}}{\Delta} + ..(2)$$

- – The physical origin of it remains an outstanding open problem. Multiple suggestions include perturbative resummations and non-perturbative models, none of them is really quantitative. It is hardly surprising, since the momenta scale is $\alpha'(0) \approx 1/(2\,GeV)^2$ at the "substructure scale". Thus soft Pomeron should be applied not at the hadronic level, but for hadronic substructure, effective quarks and/or gluons normalized at that scale

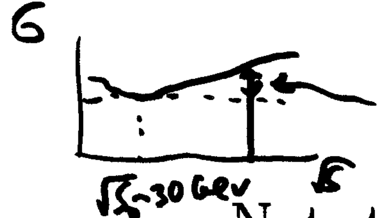
- – A qualitative difference between constant and logarithmically growing parts of the cross section. The former can be explained by prompt color exchanges (Low and Nussinov). It nicely correlates with the flux tube picture of the final state.
- – The growing part of the cross section cannot be generated by t-channel color exchanges and is associated with production of some objects, with the log(s) coming basically from their longitudinal phase space.





- – Bypassing dynamical calculations, we can evaluate (an upper limit) the probability of the sphaleron production by assuming it to be behind the logarithmic growth of the cross section.

extra multiplicity per rapidity!



$$x(s) = \Delta \frac{X_{NN}}{\sigma_{hh'}(s_0)} log(s/s_0) \qquad (3)$$

Note that phenomenological values at RHIC $x(\sqrt{s} = 56\,Gev) = 0.05 \pm 0.03, x(\sqrt{s} = 130\,Gev) = 0.09 \pm 0.03$ [?] are well reproduced. The threshold value at $s_0 = 1000\,GeV^2$ is above the highest SPS but below the lowest RHIC energy, it explains why it has not been seen before.

- – For RHIC appropriately normalized (at the scale $Q \sim 1\,GeV$) structure functions lead to $N_p^N \approx 6$, which fixes cross section per parton with prompt production of "objects" $\frac{d\sigma_{prompt}}{dy} = \underline{0.005\,fm^2}$, about $1/100$ of geometric $\pi\rho^2$.

- – As the total number of parton-parton collisions in *central* AA collision is large, about 10^4, we get the resulting rapidity density of "objects"

$$\frac{dN_{prompt}}{dy} = (\frac{X_{NN}\Delta}{\pi\rho^2})\frac{A^{4/3}}{(N_p^N)^{2/3}} \sim 200(4)$$

(about the same as HIJING minijets)

- – So far, two possible mechanisms of prompt production were not really distinguishable: now we ask what happens next... Min-jets fly away with little interaction while sphalerons explode into several ($\sim 5 - 7$) q+gluons in time $\tau \sim \rho$ which is long compared to $1/M \approx g^2\rho/30 \sim 1/2.5GeV$ but ! short on the scale of expansion.
- – we conclude that the number of produced q/gluons by this mechanism can be as large as $dN_g/dy \sim 1000$, which is comparable to the total entropy! (It cannot be higher)

Phenomenological Summary

Mini-jets vs Instanton-induced Clusters

• In hh'

→ Both can explain growth of $\sigma(s)$, multiplicity rise ...

CORRELATION
→ Mini-jets can be looked for as clusters in (Θ, φ) statistically ...
→ Instanton-induced clusters, $M = 2.5-3$ GeV, isotropic
$\Delta y \sim 1$, but $\Delta\varphi = 2\pi$

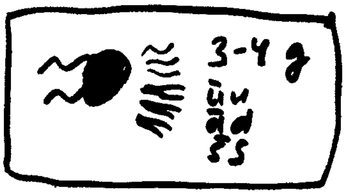
HBT
→ Mini-jets are expected to fragment as string fragm.
→ Standard $\lambda_{HBT} \approx 0.5$ and standard η/π, η'/π, K/π
→ Enhanced η', η, K, λ_{HBT} decreases, as observed!
in pp at large multiplici

• In AuAu etc

→ Both can explain multiplicity growth, and why there appears new component at RHIC $\sim N_{coll}(B)$ (instead of $\sim N_{part}(B)$)

→ Minijets with a cutoff from pp fit (HIJING) lead to $\frac{dN}{dy} \sim 200$ minijets (central AuAu at RHIC)
It is not enough for collective effects and jet quenchin
Lower the cutoff? Higher Order processes?

→ Instanton-induced reactions (into QGP, no hadrons) with similar cross section



leads to: much higher entropy!
and may solve quark production problem