How Quantum Mechanics of the gauge fields helps us understand RHIC Puzzles

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- – New "firework" scenario in brief
- – QM of YM beyond instantons: going uphill toward the Turning States
- – Explosion of the Turning States
- – How many Mini-bangs inside a central AuAu collisions ?
- – The RHIC Puzzles
- – Entropy and Jet Quenching

The "Firework Scenario", in brief

- – Non-perturbative tunneling dominate the QCD vacuum and are described by instantons, classical paths under a barrier
- – Partons start interact non-perturbatively already at the semi-hard scale, $M = 2 - 3GeV$ perturbing instantons and dumping non-zero energy into them
- – This energy eventually appears in form of specific **gluomagnetic objects I would call the Turning States**
- – **The news is: those are very explosive and rapidly decay into a spherically expanding shell of coherent field, which eventually becomes 4 gluons and about 2.5 quarks, in average.**

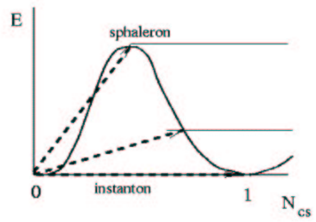
- – Multiple production (about 80 in central AuAu at RHIC) is expected, and random color field from soft partons (like in McL-V model) are supplemented by these spherical shells.

- – Jets fly through those spherical shells of field and get a kick from its coherent field, with much large probability than from random QGP/color condensate: enhanced (jet quenching) follows.
- This also provides (early extra push) to hydro expansion, and obviously helps to explain (early entropy production)

Few independent developments contributed:

- –(Baryon-number violating) instanton-induced processes in electroweak theory A.Ringwald, Nucl.Phys. B330 (1990) 1, O.Espinosa, Nucl.Phys. B343 (1990) 310; L.McLerran, A.Vainshtein V.I.Zakharov, A.Muller, M.Maggiore and M.Shifman, D. Diakonov and V. Petrov...1! : extremely interesting but too small to be seen!
- – QCD application: "pomeron from instantons" D. E. Kharzeev, Y. V. Kovchegov and E. Levin,M. A. Nowak E. V. Shuryak and I. Zahed, - 2000,G.W.Carter,D.Ostrovsky and E.V.Shuryak -2001
- – the fate of turning states in pp and AA collisions is different: large early entropy E.Shuryak, PL 2001.
- – explosion of turning states G.W.Carter,D.Ostrovsky and E.V.Shuryak-2002,early analytic studies by M.Luescher and Schehter- 1977
- – Jet quenching by exploding shells E.V.Shuryak and I.Zahed-2002
- – Indirect influence of discussions of generation of classical YM field in heavy ion collisions L.McLerran, R.Venugopalan and others

Quantum Mechanics of YM fields



- – The figure shows the process in a quantum mechanical way. The energy of Yang-Mills field versus the Chern-Simons number, related to the so called topological current

$$N_{CS} = \int d^3x K_0$$

$$K_\mu = -\frac{1}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}(\mathcal{G}^a_{\nu\rho}\mathcal{A}^a_\sigma - \frac{g}{3}\epsilon^{abc}\mathcal{A}^a_\nu\mathcal{A}^b_\rho\mathcal{A}^c_\sigma)$$

is a periodic function, with zeros at integer points.

- – The instanton (shown by the lowest dashed line) is a transition between such points. Note it is a path with zero energy, and it starts and ends at nothing.

- – However if some nonzero energy is deposited into the process during the transition, the virtual path (the dashed line) leads to a turning points, where it emerges from under the barrier into real

(Minkowskian) world. At this point canonical momentum (in the $A_0 = 0$ gauge) is "$\vec{p}$" $= \frac{d\vec{A}}{dt} = \vec{E} = 0$ so the field is only magnetic there.

- – From there starts the real time motion outside the barrier (shown by horizontal solid lines). The maximal cross section corresponds to the top of the barrier, called the sphaleron ="ready to fall" in Greek, according to Klinkhammer and Manton

Forced Tunneling
and Instanton-Antiinstanton configurations

- – Two different views on $\bar{I}I$ configurations. One: such fields occur in the YM vacuum and describe a virtual path over the barrier but ends up in the same well ($\delta Q = 0$).
- – Another:the corresponding action would rather control the *probability* of transition

$$P \sim |<0|M|turning\, state>|^2$$

into *turning states* excited from the vacuum by some external force. $D_\mu G_{\mu\nu} = j^{ext}_\nu$.

- – Simple sum of instanton and anti-instanton A_μ in singular gauge – known as the sum ansatz – has many bad qualities, such as infinite fields at the centers
- – the so called *ratio ansatz* (ES-1988) is better: for identical sizes and orientations is

$$g A^{ratio}_{a\mu}(x) = \frac{2\eta_{a,\mu,\nu} y_1^\nu \rho^2/y_1^2 + 2\bar{\eta}_{a,\mu,\nu} y_2^\nu \rho^2/y_2^2}{1 + \rho^2/y_1^2 + \rho^2/y_2^2}$$

- – These trial functions are simple enough to have analytic expressions for the field strength, see fig. above.
- – Due to $t \to -t$ symmetry, quantities which are odd under this transformation (like A_0 or electric field G_{0m}) should naturally vanish at t=0 3-plane
- – the resulting purely magnetic configuration at this central 3-plane t=0 is the *turning points* of these paths we want to

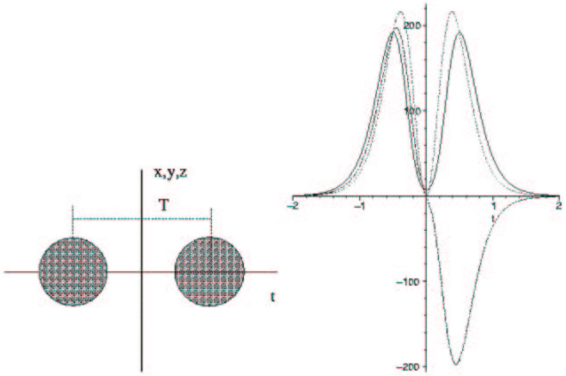
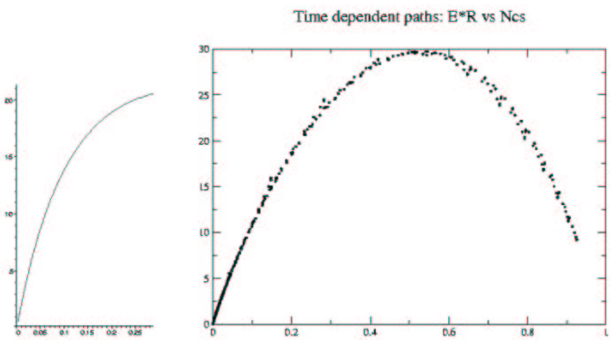


Figure 1: Instanton-antiinstanton configurations. (a) A schematic picture in the Euclidean space-time. The vertical thick line, t=0, corresponds to the location of the turning state. It also display the definition of inter-center distance T. (b) Actual distribution along the time axis of $2\vec{B}^2, 2\vec{E}^2, 2\vec{B}\vec{E}$ for the ratio ansatz, T=ρ, shown by the solid, dashed and short-dashed lines respectively. The curve for $\vec{B}\vec{E}$ is the only one which is t=odd.

study. Their energy E(T) and Chern-Simons numbers $N_{CS}(T)$ at t=0 can be calculated, plotting $E(N_{CS})$ one can get the profile of barrier

- – Alas, for the sum ansatz this idea does not produce reasonable results. When T decreases, the energy E(T) of the turning state (as well as the action for the whole configuration) becomes very large, while $N_{CS}(T)$ no longer changes.
- – The ratio ansatz turned somewhat better results, with finite (and even simple) field structure at all T including the coinciding $\bar{I}I$ centers ($T = 0$), but (see fig) it can only accomplish about 1/3 of the journey

  The *Normalized* energy E*R versus the Chern-Simons number, for ratio and Yung $\bar{I}I$ configurations



- – Going uphill: the Yung ansatz (approximately a solution of the so called “streamline equation” - Verbaarschot) The Yung ansatz for the field configuration is rather complicated, has no apparent t to -t symmetry but accomplish everything
- – As classic Yang-Mills theory has scale invariance one should evaluate the energy times the r.m.s. radius $E * R$ defined as

$$R^2 = \frac{\int d^3 r r^2 B^2}{\int d^3 r B^2}$$

Fig.shows indeed a parabolic-looking maximum near $N_{CS} = 1/2$.

The Turning States from Constrained Minimization

- – We look for the *minimal potential energy of static Yang-Mills field, consistent with constraints: (i) the given value of (corrected) Chern-Simons number. (ii) the given value of the r.m.s. size.*

$$< r^2 >= \frac{\int d^3 x r^2 \mathcal{B}^2}{\int d^3 x \mathcal{B}^2}$$

we introduce Lagrange multipliers and search for the minimum

- – *Surprisingly the analytical solution is found (by D.Ostrovsky): energy density has the profile*

$$B^2/2 = 24(1-\kappa^2)^2\rho^4/(r^2+\rho^2)^4$$

, total energy is

$$E_{stat} = 3\pi^2(1-\kappa^2)^2/(g^2\rho)$$

, and (corrected) Chern-Symons number

$$\tilde{N}_{CS} = \mathrm{sign}(\kappa)(1-|\kappa|)^2(2+|\kappa|)/4$$

. The sphaleron corresponds to $\kappa = 0$ and has mass about 2.5-3 GeV, if size is $\rho = 1/3$ fm.

Explosion of the Turning States

- – Solved both numerically (G.Carter) and analytically (as it was found by D.Ostrovsky based on work by Luescher and Schehter)
- – (Witten -77) action for spherical YM

$$\mathcal{A}^a_j = A(r,t)\Theta^a_j + B(r,t)\Pi^a_j + C(r,t)\Sigma^a_j \mathcal{A}^a_0 = D(r,t)\frac{x^a}{r}$$

with

$$\Theta^a_j = \frac{\epsilon_{jam}x^m}{r}, \qquad \Pi^a_j = \delta_{aj} - \frac{x_a x_j}{r^2}, \qquad \Sigma^a_j = \frac{x_a x_j}{r^2}$$

It is convenient to express functions $A, B, C,$ and D through the new set of r,t dependent parameters, which are related to the Abelian gauge ($A_{\mu=0,1}$) Higgs (ϕ, α) model on hyperboloid

$$A = \frac{1+\phi\sin\alpha}{r}, \quad B = \frac{\phi\cos\alpha}{r}, \quad C = A_1, \quad D = A_0.$$

$$S = \frac{1}{4g^2}\int d^3x dt[(\mathcal{B}^a_j)^2 - (\mathcal{E}^a_j)^2] =$$
$$4\pi\int dr dt\left((\partial_\mu\phi)^2 + \phi^2(\partial_\mu - a_\mu)^2 + \frac{(1-\phi^2)^2}{2r^2} - \frac{r^2}{2}(\partial_0 A_1 - \partial_1 A_0)^2)\right)$$

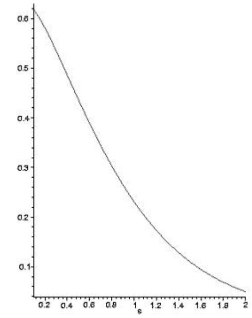
- – The solution is found in a complicated coordinates obtained from t,r by a conformal transformation item– solution for large times becomes simple transverse wave with a simple profile

$$4\pi r^2 e(r,t) = \frac{8\pi}{g^2\rho^2}(1-\kappa^2)^2\left(\frac{\rho^2}{\rho^2+(r-t)^2}\right)^3$$

- –the energy gluon distribution function is

$$n(\omega) = \frac{32}{g^2}(1-\kappa^2)^2\omega\rho^2 K_1^2(\omega\rho)$$

The corresponding energy spectrum $E(\omega) = \omega n(\omega)$ is shown in Fig.



the mean energy of the gluons

$$<\omega>= \frac{\int_M d\omega\omega n(\omega)}{\int_M d\omega n(\omega)} \approx .67\, GeV$$

Thus, a sphaleron of 3 GeV mass would decay into 4.5 gluons in average, in pure YM without quarks

Quarks: zero modes seem to be carried with the wave, materialized later with 1/2 probablity (for sphaleron)

Heavy Ion Collisions: Brief history

Pre-RHIC models and their predictions for RHIC

- – string production and breaking (RQMD) $\rightarrow$ low early pressure, small v2
- – QGP scenario (hydro at SPS) $\rightarrow$ high pressure above the transition region, large early pressure and V2
- – minijets (HIJING) $\rightarrow$ low collectivity, very small v2

RHIC era

- – v2 at RHIC is large and agrees with hydro
- – spectra also, including unexpected $\bar{p}/\pi^-, p/\pi^+ > 1$ at $p_t > 2$
- – But: HBT radii are smaller than in ideal hydro: early "extra push" seem to be needed
- – jet quenching is at least factor 1/3, but may be much stronger. No trace of jets in correlations also.
- – huge v2 (pt=2-6 GeV), incompatible with jet quenching idea at any absorption

How many "mini-bangs" are there in Heavy Ion Collisions ?

G. W. Carter, D. M. Ostrovsky,ES -hep-ph

- – We looked at high energy NN, πN, γN, and $\gamma\gamma$ cross sections which all *increase* with energy differently (in contrast to traditional "one Pomeron" fit) and asked if universal semi-hard parton-parton collisions can explain those

Ratio	Computed	PDG
$\frac{1}{\alpha}\frac{X_{\gamma N}}{X_{NN}}$	0.50	0.43
$\frac{X_{\pi N}}{X_{NN}}$	0.73	0.63
$\frac{1}{\alpha}\frac{X_{\gamma\gamma}}{X_{\gamma N}}$	0.69	0.68

Table 1: Cross Section ratios as computed in the text and reported by the Particle Data Group.

- – We also looked at shadowing in pp - growth index (power od s) at fixed impact parameter
- – We got Surprisingly small value for the non-pert.qq cross section:

$$\sigma_{qq} = 1.69 \times 10^{-3} fm^2$$

Heavy Ion Collisions

- – Assuming those correspond to sphaleron production we get

$$\frac{dN_{sph}}{dy} \approx 76$$

- – we tentatively take 3.5 gluons and 2.5 quarks/sphaleron which yields an average of six partons:
- – in central $AuAu$ collisions at RHIC about $76 \times 6 = 460$ partons per rapidity from sphaleron production.
- – This is roughly one half the maximal value, $dN_{partons}/dy \sim dN_{hadrons}/dy \sim 1000$, inferred from the final entropy limitations.

The jet quenching

ES and I.Zahed, in progress

- – Traditional treatment (Gyulassy et al, Dotshitzer et al,...) is random scattering on QGP partons including suppression from LPM effect: good in cold matter (HERA) but not enough for RHIC
- – Strong color field $G \sim 1/g\rho^2$ of the shell is coherent – field strengths of several gluons are added together – which increase the kick
- – It happens with high probablity: about 2 times for jet, while the cross section for $Q \sim 1GeV$ kick in Coulomb scattering is very small $\sim \pi\alpha_s^2/Q^2 \sim 1/100 fm^2$

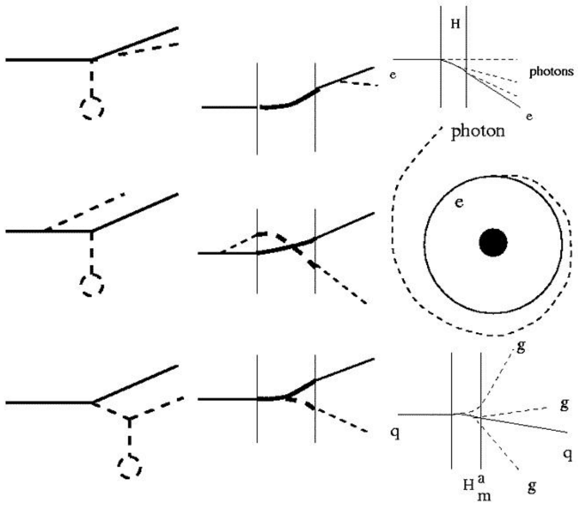


Figure 2: Three diagrams generating the QCD bremsstrahlung and syncrotron-type radiation. We also compare three cases: (a) in the usual magnet; (b) by a charge rotating ultrarelativistically in a gravity field (e.g. around a black hole); (c) the layer of gluomagnetic gauge field.

- –Energy loss due to QCD synchrotron-like radiation (the 3-ed diagram) is evaluated: 3 different cases

Conclusions

- – Vacuum instantons are killed in the collisions, but each leaves a remnant, which then explodes into QGP. (Instantons then are suppressed till T cools down to Tc again)
- – Details of the "forced path" in Euclid determines the cross section, but the objects themselves – the Turning States – can be obtained from constrained minimization.
- – Both their shape and further explosive behaviour are determined from classical YM and is under control, numerically and analytically.
- – They can help us with RHIC puzzles (entropy,jet quenching) and also add "explosive element" to the initial stage to get HBT radii

The exploding shells