EXPLODING SPHALERONS IN QCD

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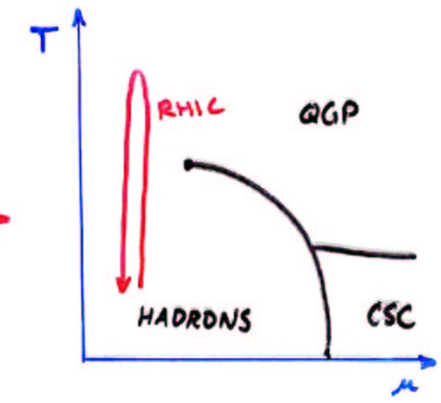
MOTIVATION

RHIC COLLISIONS "MELT" THE VACUUM



VAC → QGP → VAC

THE QCD VACUUM IS NON-TRIVIAL.

CLASSICAL TURNING STATES CONNECT VACUUM INSTANTONS TO RHIC COLLISIONS.

THE INSTANTON LIQUID MODEL USES AN ENSEMBLE OF CLASSICAL TOPOLOGICAL FIELD CONFIGURATIONS TO SPONTANEOUSLY BREAK CHIRAL SYMMETRY – THE DOMINANT FEATURE OF THE QCD VACUUM. (SHURYAK SCHÄFER DIAKONOV PETROV...)

ALSO REPRODUCES HADRONIC CORRELATORS OBSERVED IN LATTICE QCD (USUALLY)

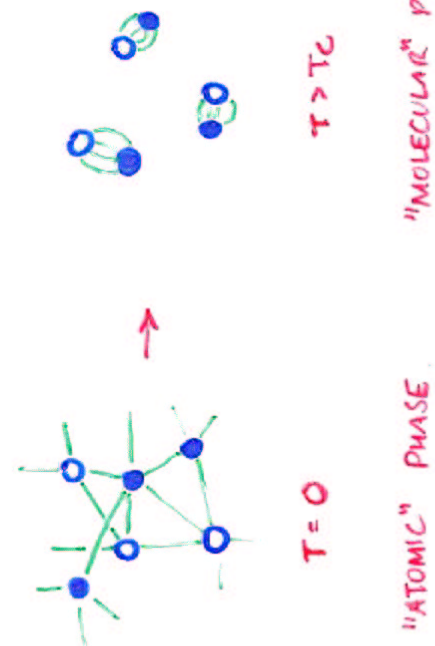
USES 2 MAIN PARAMETERS:

AVERAGE SIZE $\rho \simeq \frac{1}{3}$ fm

DILUTENESS $\rho^4 n \simeq 0.01$

ARE INSTANTONS "MELTED" AT RHIC?

CHIRAL SYMMETRY RESTORATION IN THE ILM:

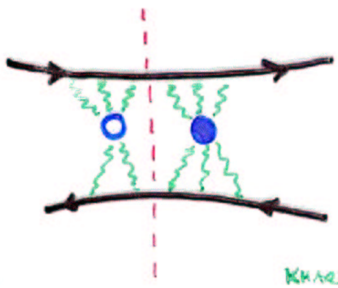


SCHÄFER, SHURYAK, VERBAARSCHOT

BUT THIS IS AN EQUILIBRIUM SCENARIO;
PROBABLY NOT VALID AT RHIC FOR $t \sim 0.5$ fm.
WHAT ABOUT THIS EARLY STAGE ($t < 1$ fm)?

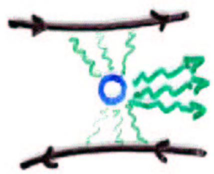
INSTANTON-PARTON SCATTERING

CALCULABLE CONTRIBUTIONS TO QUASI-ELASTIC AND INELASTIC CROSS SECTIONS σ_{qq}, σ_{gg}, σ_{gq}.



KHARZEEV KOVCHEGOV LEVIN, NOWAK SHURYAK ZAHED (2001)

CUTTING THIS DIAGRAM IS RELEVANT AT RHIC DUE TO LARGE PARTON DENSITY.

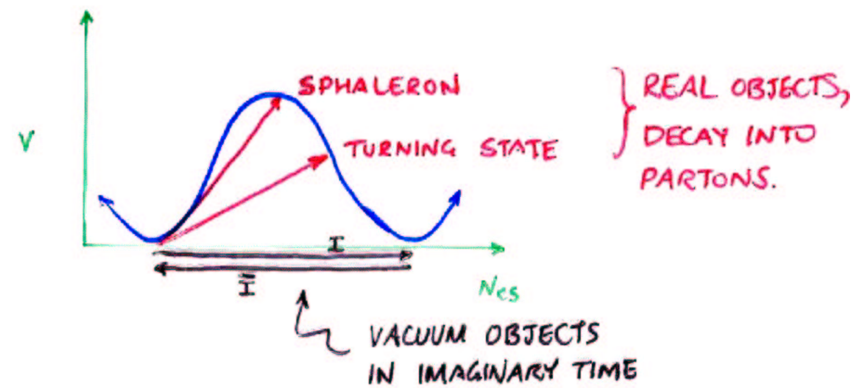


WHAT IS THIS OBJECT?

WHAT DOES IT PRODUCE?

WE CALL IT A TURNING STATE.

THE REASON:



CONJECTURE: VACUUM INSTANTONS ARE EXCITED INTO REAL (PURE MAGNETIC) CONFIGURATIONS, WHICH DECAY INTO PARTONS.

SIMILAR TO SPHALERONS IN EW

KUZMIN RUBAKOV SHAPOSHNIKOV
ARNOLD McLERRAN
RATRA YAFFE
RINGWALD KHOZE
ESPINOSA
ZAKHAROV
ZADROZNY
HELLMUND KRIPFGANZ
KLINKHAMER MANTON

PHENOMENOLOGICAL LIBERTIES

(FOR A SCALE-INVARIANT THEORY)

AN OLD PROBLEM: INSTANTONS DO NOT CONFINE.

NO MASS GAP FOR GAUGE FIELDS

FOR $r \gg \rho$

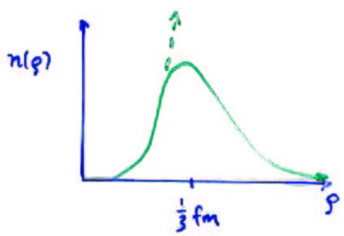
$$A(r) \sim \frac{1}{r^n}$$

INSTEAD OF

$$A(r) \sim e^{-Mr}$$

A PROBLEM IN VACUUM PHENOMENOLOGY, WHERE

WE IMPOSE A SIZE DISTRIBUTION



TURNING STATES ARE

- CLASSICAL
- PURELY MAGNETIC
- UNSTABLE (SADDLE-POINT)

SOLUTIONS TO THE YANG-MILLS EQUATIONS

WITH A CONSTRAINT:

- FINITE AVERAGE SIZE ρ.
  CAN BE SOLVED ANALYTICALLY, BUT
  POWER-LAW TAILS AT $r \gg \rho$.

-OR-

- FINITE MASS m
  CAN BE SOLVED NUMERICALLY, SIMILAR TO
  ELECTROWEAK, BUT NOT GAUGE INVARIANT.

THEY PRODUCE COHERENT GLUONS - NO ADDITIONAL POWERS OF α ARE NEEDED FOR MULTIPLE GLUONS.

WITTEN'S $O(3)$ ANSATZ (1977):

$$A_i^a(x) = \frac{1-\phi_1}{r}\epsilon_{iaj}\hat{x}_j + \frac{\phi_2}{r}(\delta_{ai} - \hat{x}_a\hat{x}_i) + A_1\hat{x}_a\hat{x}_i$$

$$A_0^a(x) = A_0\hat{x}_a \qquad r = \sqrt{\vec{x}^2}$$

WITH SCALAR FUNCTIONS

$$\phi_1(r,t) \quad \phi_2(r,t) \quad A_1(r,t) \quad A_0(r,t)$$

AND MINKOWSKI 1+1 D ACTION, IN $A_0 = 0$ GAUGE:

$$S = \frac{4\pi}{g^2}\int dt\,dr\Big[\dot{\phi}_1^2 + \dot{\phi}_2^2 + \frac{r^2}{2}\dot{A}_1^2 - \phi_1'^2 - \phi_2'^2 + - \frac{(1-\phi_1^2-\phi_2^2)^2}{2r^2} - 2A_1(\phi_1\phi_2' - \phi_1'\phi_2) - A_1^2(\phi_1^2+\phi_2^2)\Big]\left(1+\frac{r^2}{\rho^2}\right)$$

$$- m^2\left[(1+\phi_1)^2 + \phi_2^2 + \frac{r^2}{2}A_1^2\right]$$

CONSTRAIN WITH SIZE

CONSTRAIN WITH MASS

MAGNETIC SOLUTIONS HAVE

$$A_1 = \phi_2 = 0$$

$$\phi_1(r, t=0)$$

CONSTRAINING WITH SIZE:

$t=0$ STATIC SOLUTION

$$\phi_1(r,0) = \frac{\rho^2 - r^2}{\rho^2 + r^2}$$

$$E = \frac{3\pi^2}{g^2\rho} \simeq 2.7\ \text{GeV}$$

$$\Delta N_{cs} = \frac{1}{2}$$

$t>0$ EXPLOSION: LÜSCHER, SCHECHTER (1977)

EXPANDING SHELLS OF RADIATION

SEE ALSO FARHI, ET. AL. (1995)

AT LARGE TIMES

$$\mathcal{E}(r,t) = \frac{2}{g^2\rho^2}\left[\frac{\rho^2}{\rho^2 + (r-t)^2}\right]^3$$

SUCH THAT

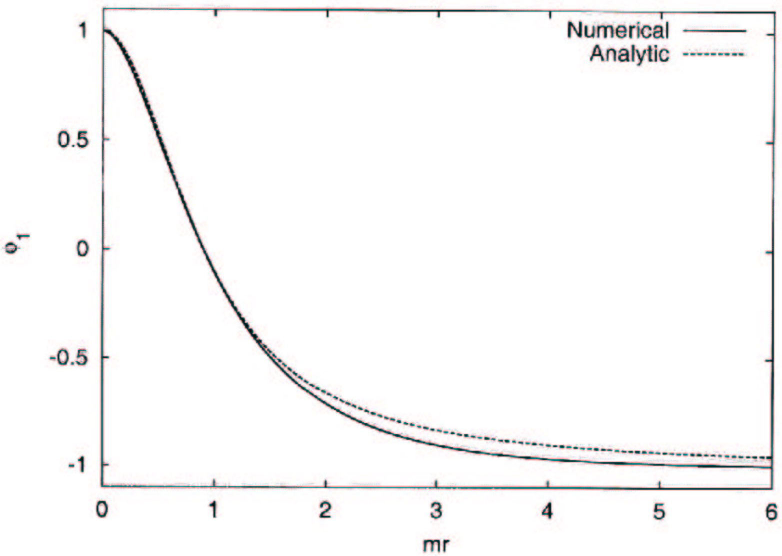
$$E(t) = \int_0^\infty dr\,\mathcal{E}(r,t)$$

CONSTRAINING WITH A MASS: SIMILAR TO KLINKHAMER + MANTON (1984)

$t=0$ SOLUTION

$$\phi_1'' - \frac{\phi_1}{x^2}(\phi_1^2-1) - (\phi_1+1) = 0$$

$x = mr$



PROFILE IS AT $\frac{1}{2}$ $r=0$ VALUE AT $mr = 0.9$

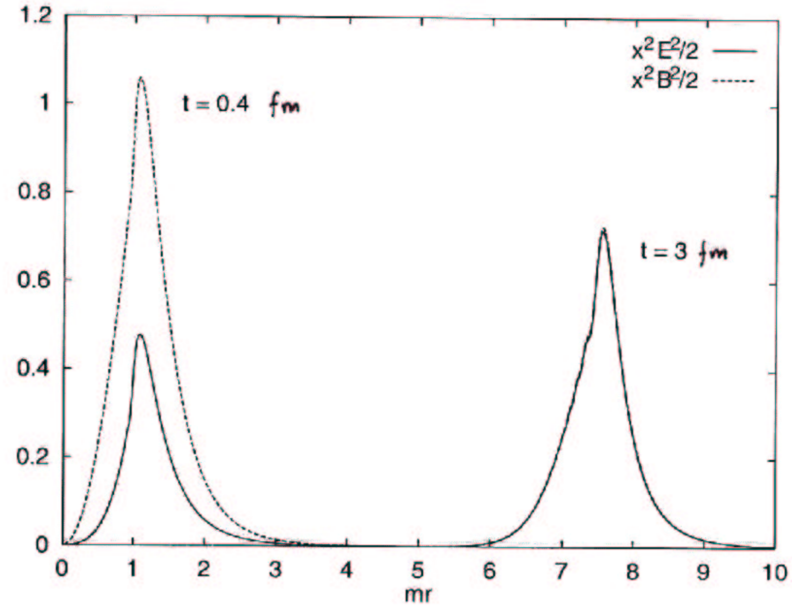
OR $m = 0.9\, \rho_{INST}^{-1} \simeq 540$ MeV

AND $E_{TS} = 5.1\, m \simeq 2.8$ GeV

AT $t=0$, WE SET $m=0$ AND EVOLVE IN TIME.

THE EXPLOSION PROCEEDS QUICKLY

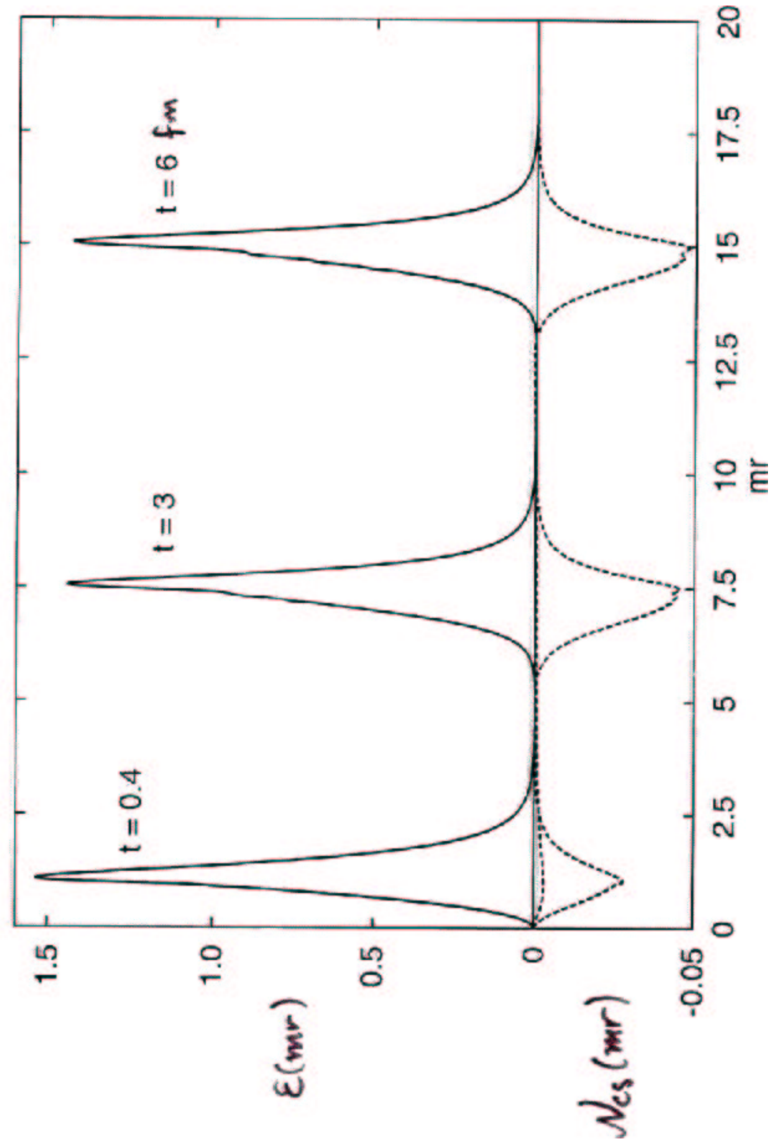
$$\frac{E(r)^2}{B(r)^2} > 0.95 \quad \text{FOR ALL} \quad t > 1.4 \text{ fm}$$



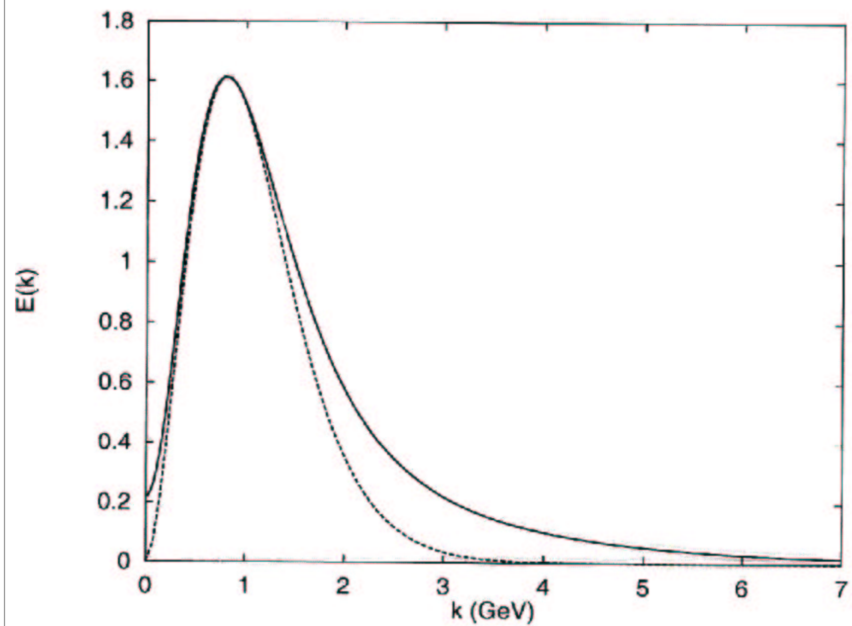
SOLVED ON A 2D LATTICE, $\Delta x = 0.01$

$\Delta mt = 5 \cdot 10^{-4}$

SHELLS OF GAUGE FIELD MOVING AT V=C



FOURIER DECOMPOSITION OF FIELDS AT LATE TIME GIVES THE MOMENTUM SPECTRUM OF PROMPT GLUONS:



THE DASHED LINE IS A THERMAL SPECTRUM WITH $T = 285$ MeV

HOW PROMINENT AT RHIC? WE NEED $\sigma_{qq}^{Inst}, \sigma_{qg}^{Inst}, \sigma_{gg}^{Inst}$.

CAN BE ESTIMATED FROM SEMI-HARD HADRON CROSS SECTIONS, INDUCED BY INSTANTONS.

$Q^2 \simeq 1 \text{ GeV}^2 \qquad \sqrt{s} \sim 100 \text{ GeV}$

THE POMERON REGIME:

$$\sigma_{hh'}(s) = \sigma_{hh'}^{0} + X_{hh'} \ln s$$

WE COMPUTED $X_{hh'}$ WITH INSTANTONS.

NOTE:

- $X_{pp} \neq X_{p\pi} \neq X_{p\gamma}$, ETC. NOT A "UNIVERSAL" POMERON FIT.
- DILUTENESS PARAMETER $n\rho^4 \simeq 0.01$ NATURALLY ACCOUNTS FOR THE SMALL POMERON INTERCEPT.
- SMALL POMERON SIZE, CLOSER TO $\rho \simeq \frac{1}{3}$ fm THAN $R_{HADRON} \simeq 1$ fm.

MAIN ASSUMPTIONS OF THE MODEL:

- ADDITIVE PARTONS

INTEGRATED GRV STRUCTURE FUNCTIONS AT $Q^2 = 1 \text{ GeV}^2$ OVER $x = [0.01, 1]$.

PROTON = $1.7\, u_{val} + 0.9\, d_{val} + 1.16\, u{+}d_{sea} + 4.1\, g$
= 3.7 QUARKS + 4.1 GLUONS

PION = 2.3 QUARKS + 3.1 GLUONS

PHOTON = α(1.2 QUARKS + 1.9 GLUONS)

WITH $\sigma_g^{Inst} = 2\, \sigma_q^{Inst}$ WE FIND

		PDG
$\frac{1}{\alpha}\frac{X_{\gamma N}}{X_{NN}}$	= 0.60	0.43
$\frac{X_{\pi N}}{X_{NN}}$	= 0.73	0.63
$\frac{1}{\alpha}\frac{X_{\gamma N}}{X_{\pi N}}$	= 0.69	0.68

- A MODIFIED INSTANTON PROFILE (MASS, AGAIN)

$$A(x) \sim \frac{1}{x^2+\rho^2} \rightarrow \frac{1}{x^2+\rho^2}\, e^{-Mx}$$

TO BE FIT.

WITH

- SHADOWING FACTOR TO ENFORCE UNITARITY — KOPELIOVICH, ET AL., HÜFNER + POVH
- HADRONIC FORM FACTORS — HÜFNER + POVH

WE FIT

$X_{pp} = 0.174\ fm^2$ WITH $M = 500$ MeV

AND COMPUTE

		PDG
$X_{p\pi}$	$= 0.132\ fm^2$	$0.111\ fm^2$
$X_{p\gamma}$	$= 5.65 \cdot 10^{-4}\ fm^2$	$5.51 \cdot 10^{-4}\ fm^2$
$X_{\gamma\gamma}$	$= 1.72 \cdot 10^{-6}\ fm^2$	$1.45 \cdot 10^{-6}\ fm^2$

USING THE COMMON

$$\sigma_{qq}^{Inst} = 1.7 \cdot 10^{-3}\ fm^2$$

AND AT RHIC...

Au-Au AT RHIC:

PARTONS ("EFFECTIVE QUARKS") PER NUCLEON:

$$N_q + 2N_g \simeq 12$$

NUMBER OF PARTONIC COLLISIONS:

$$N \simeq \sigma_{qq}\, n_q^2\, \pi \left(\frac{3}{2\pi}\frac{AN}{n_q}\right)^{4/3}$$

LEADS TO

$$\frac{dN_{TS}}{dy} \simeq 76$$

PROMPT GLUE

$$\frac{dN_g}{dy} \simeq 76 \times 4 \simeq 300$$

PROMPT QUARKS (SHURYAK + ZAHED, hep-ph/0206022)

$$\frac{dN_q}{dy} \simeq 76 \times 2N_f \approx 380$$

TOTAL

$$\frac{dN}{dy} \approx 700$$

RHIC:

$$\frac{dN_{Hadrons}}{dy} \approx 1000$$

CONCLUSIONS:

REMEMBER THE VACUUM!

- HEAVY-ION COLLISIONS MIGHT EXCITE NON-PERTURBATIVE GLUE AND PRODUCE PROMPT PARTONS.

- INSTANTON / TURNING STATE MECHANISM PRODUCES APPROPRIATE PARTON MULTIPLICITY.