Critical Points

&

Primary Photons

Gennady Kozlov
jinr

❖ Introduction

- We introduce a novel (primary) photon production mechanism stemming from the ***Conformal Anomaly*** of QED x QCD and the existence of scalar ***dilaton*** fields in the early stage after collisions between heavy ions.
- We show that in the vicinity of ***Critical Point*** this mechanism can provide escape of primary (soft) photons through the decays of dilatons.
- The yield of primary photons contributes with a couple of % to the yield from light hadrons decays.
- The latter may indicate one is close to the Critical Point.
- No escape of primary photons is seen when the Critical Point is approached.

❖ *Quantum anomalies*

- Manifestation of quantum anomalies in collective dynamics of excited matter (quark gluon plasma?)
- Background fields presence. Scalars (dilaton fields).
- Quantum anomalies lead to non-conservation of currents
- Conformal SVV anomaly:

  - scale (dilatation) current S_μ

  - two vector currents V_μ.

  There is violation of conformal invariance of QCD by quantum effects

❖ Critical point(s)

$$\left.\begin{matrix} CP \\ Phase\ transitions \end{matrix}\right\} search\ do\ operate\ with\ observables\ (matter\ fields\ ?$$

$$\uparrow$$

$$symmetry\ breaking\} \qquad \begin{matrix} conformal \\ chiral \end{matrix}$$

$High\ T, \mu_B$: conformal sector does influence *baryonic to anomaly* ($q's, g's$ are free)

$$[CONFORMAL\ SECTOR] \leftarrow\ ?\ \rightarrow [SM\ SECTOR]$$

$$\left.\begin{matrix} Early\ Universe \\ Early\ time\ after\ HIC \end{matrix}\right\} \partial_\mu S^\mu = \theta^\mu_\mu \approx 0,\ S^\mu = \theta^{\mu\nu} x_\nu,\ \ x_\mu \rightarrow \lambda x_\mu$$

- **In nature: $m_i \neq 0$, $Conforml\ Anomaly\ (CA)\ goverved \leftarrow \beta(\alpha) \neq 0$, α running**
  - **QCD vacuum disordered**
  - **Scale invariance destroyed, $\mu = Me^{-2\pi/(b\alpha_S)}$ appearance**

❖ Symmetry breaking

$[\chi - Chiral\ Symmetry\ breaking\ spontaneously]$ $[Conformal\ Symmetry\ breaking\ explicitly]$

$[CP\ vicinity$
$Conformal\ symmetry\ breaking\ approximately]$
$\Downarrow$

Light Ps-Goldstone boson (*dilaton)*

Approximate dilatation symmetry if $\beta - function\ small;\ \alpha_S\ running\ slowly\ with\ \mu$

$$\beta(\alpha_S) \equiv \mu \frac{\partial \alpha_S(\mu)}{\partial \mu} = -\frac{b_0}{2\pi}\alpha_S^2 - \frac{b_1}{4\pi^2}\alpha_S^3 + \cdots$$

Conformality: CP/IR $\alpha_S^* = -\frac{2\pi b_0}{b_1},\ b_0 = \frac{(11N-2N_f)}{3}\ , IRFP\ if\ \frac{N}{N_f} = \frac{2}{11}$, Banks − Zaks

❖ Fluctuating dilaton field

$[\boldsymbol{CONFORMAL}] \Rightarrow \boldsymbol{breaking}\ [\boldsymbol{DILATON}] \Rightarrow \boldsymbol{CA}\ [\boldsymbol{PHOTONS}]$ **detection**

$\boldsymbol{\beta(\mu) = 0}$ $\boldsymbol{\beta(\mu) \neq 0}$ $\boldsymbol{Primary\ observables}$

- Probability distribution of an order parameter field –

  DILATON field, associated with *Critical Mode* that develops

  infinite correlation length $\xi \sim m^{-1}$

❖ Dilaton

- **Dilaton natural object in theory with approximate scale symmetry**
- **Dilaton mass $<$ $\Lambda_{confinement}$**
- **No dilaton state(s) in QCD**

Origin: $L = \sum_i g_i(\mu) O_i(x), \qquad [O_i(x)] = d_i$

Including of dilaton field χ with the replacement: $g_i(\mu) \to g_i[\mu(\chi)](\chi)^{4-d_i}$

***L* invariance under $x^\mu \to e^\lambda x^\mu$, $O_i(x) \to e^{\lambda d_i} O_i(e^\lambda x)$, $\chi(x) \to e^\lambda \chi(e^\lambda x)$**

- **Dilaton χ is formed at the scale $\geq \Lambda_{confinement}$,**
  e.g., glueball $\chi = O^{++}$, $m_\chi \sim O(\Lambda_{confinement})$

❖ Model

$$\mathrm{L} = -\mathrm{C}\,(\partial A) + \frac{1}{2}\kappa C^2 - I^{\mu}\left(A_{\mu} + e^{-\sigma}\partial_{\mu}\sigma\right) + \bar{q}\left(i\hat{\partial} - m_q - g\hat{A}\right)q$$

To avoid the non-linearized term $\sim e^{-\sigma}\partial_{\mu}\sigma \Rightarrow \chi(x) = f e^{-\sigma(x)}$

$$\searrow$$

$$\sim O\left(\Lambda_{\text{scale symm breaking}}\right)$$

$$\chi(x)\ \text{spontaneously "slipped" from}\ \langle\chi(x)\rangle^{HOT}_{CP} = 0 \rightarrow \langle\chi(x)\rangle = f$$

❖ Dilaton fluctuating

Dilaton $\chi(x)$ *is the ground potential of* $A_\mu(x)$:

$$f^{-1}\partial_\mu\chi(x) = \partial_\mu\varphi(x) = A_\mu\,(x)$$

- *Fluctuation of dilaton is seen through its propagator*

LD invariance under:

$$\chi \to \chi + f\alpha,\ A_\mu \to A_\mu + \partial_\mu\alpha, \qquad C \to C,\ I_\mu \to I_\mu, \qquad q \to qe^{ig\alpha}$$

❖ Additional Anomaly term: $-L_A = \varphi\left(\theta^\mu_{\mu q} + \theta^\mu_{\mu\, anom}\right)$

$$\theta^\mu_{\mu q} = \sum_q m_q \bar{q} q \qquad \theta^\mu_{\mu\, anom} = \frac{\alpha}{8\pi} b_{EM} F^2_{\mu\nu} + \frac{\alpha_S}{8\pi} b_0 G^{a\,2}_{\mu\nu}$$

❖ Basic equations

$$\kappa C = (\partial A), \;\; \partial_\mu \varphi = A_\mu,$$

$$-(\partial I) = \theta^\mu_{\mu q} + \theta^\mu_{\mu\, anom}, \; (\partial I) = 0 \; if \; no \; \boldsymbol{CA}$$

$$\left(i\hat{\partial} - m_q - g\hat{A}\right)q - \varphi \sum_q m_q q = 0$$

$$-J_\mu - I_\mu + \partial_\mu C + \varphi \, \frac{\alpha}{2\pi} b_{EM} \partial^\nu F_{\mu\nu} = 0, \quad J_\mu = \bar{q} g \gamma_\mu q$$

❖ Conformal sector

If $\left.\begin{matrix} strong \\ EM \end{matrix}\right\}$ are in Conformal sector

$$\Downarrow$$

$$\sum_{light} b_0 = -\sum_{heavy} b_0$$

Mass of the dilaton spits light and heavy states sectors

$$\frac{\alpha_S}{8\pi} b_0^{light} = \frac{\beta(g)}{2g} G_{\mu\nu}^{a\,2}, \qquad b_0^{light} = -11 + \frac{2}{3} n_L$$

- The only n_L $particles$ $(m < m_\varphi)$ are $included$ in $\beta - function$

For $m_\varphi \sim O(\Lambda_{conf})$, $n_L = 3 \Rightarrow 14$ $times$ $increase$ for φgg $couplings$ $compared$ to SM $Higgs$

❖ Light dilatons

$$\Delta^2\Delta^2\varphi(x) = \kappa\,\eta(x)$$

$$\eta = -\,\theta^{\mu}_{\mu\,anom} - \theta^{\mu}_{\mu\,tree}$$

$$\left.\begin{array}{c} If\ no\ anomaly \\ no\ quarks \\ weak\ EM \end{array}\right\}$$

$$\lim_{m^2\to 0}(\Delta^2 + m^2)^2\varphi(x) \approx 0$$

$$\downarrow$$

$$dipole\ field$$

$$confinement - like\ pattern$$

$$[\varphi(x), \varphi(y)]_- = p\,\Delta_m(z) + q\,\Delta'_m(z), \qquad z = x - y;\ \ p, q\ \neq 0$$

❖ Properties of the commutator

$$[\varphi(x), \varphi(y)]_- = p\,\Delta_m(z) + q\,\Delta'_m(z), \qquad z = x - y;\;\; p, q \neq 0$$

$$\Delta_m(x) = \frac{1}{(2\pi)^2}\int_{\mathcal{R}^4} e^{ikx}\,[\delta_m^+(k) - \delta_m^-(k)]dk$$

$$\Delta'_m(x) = \frac{1}{(2\pi)^2}\int_{\mathcal{R}^4} e^{ikx}\,[\delta'^+_m(k) - \delta'^-_m(k)]dk$$

$$\delta_m^{\pm}(k) = \theta(\pm k^0)\delta(k^2 - m^2)$$

$$\delta_m'^{\pm}(k) = \theta(\pm k^0)\delta'(k^2 - m^2)$$

❖ Propagator of dilaton

❖ Vicinity of CP: $G(k) \approx -\frac{1}{2} i\kappa \frac{\partial}{\partial k^\mu} \left[\frac{k^\mu \ln(-l^2 k^2 - i\epsilon)}{(-k^2 - i\epsilon)^2} \right]$

➢ Dilaton fluctuation length: $l = \frac{1}{2\mu} e^{\gamma - 1/2} \to \infty \; as \; \mu \to 0 \; at \; CP$

❑ Vicinity of CP. *Divergence at* $k = 0$? $NO!$

Weak derivative:

$$\int G(k)\, f(k)\, d^4k = \frac{1}{2} i\kappa \int d^4k \frac{\ln(-l^2 k^2 - i\epsilon)}{(-k^2 - i\epsilon)^2} \times k^\mu \frac{\partial}{\partial k^\mu} f(k)$$

↓

regular test function

Extra power of k^μ $explicitly\ eliminates\ the\ divergence\ at\ k = 0$

❖ Primary (soft) photons. Origin.

Dilatons unstable → $primary\ (soft)\ photons$

High T:

CA acts as a source of primary photons, not produced in hadronic decays

Low T:

dilatons disappear, abundance of (no-primary) photons due to decays of light hadrons

Light dilaton, low mass, primary photons induced effectively by gluon operators.

Low energy effective theory at scales $< \Lambda_{conformal}$

$$\langle \gamma\gamma | \theta^{\mu}_{\mu}(q) | 0 \rangle \approx 0$$

$$\left\langle \gamma\gamma \left| \frac{b_0^{light}}{8\pi} G^{a\,2}_{\mu\nu} \right| 0 \right\rangle = - \left\langle \gamma\gamma \left| \frac{b_{EM}}{8\pi} F^{2}_{\mu\nu} \right| 0 \right\rangle, \ \vec{q} = 0$$

❖ Primary photons escape.

❑ ***Close to CP***: $R_{\gamma\gamma} = \frac{\Gamma(\Phi \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)} = \left(\frac{3F_{anom}}{2N_c}\right)^2 \left(\frac{f_\pi}{f}\right)^2 \left(\frac{m}{m_\pi}\right)^3$

➢ ***CA contribution***:

$$F_{anom} = -\left(\frac{2n_L}{3}\right)\left(\frac{b_{EM}}{b_0^{light}}\right),\ b_{EM} = -4\sum_{q:u,d,s} e_q^2 = -\frac{8}{3}$$

✓ Dilaton mass at IRFP: $m \approx \sqrt{1 - \frac{N_f}{N_f^c}}\ \Lambda \quad \Rightarrow\ R_{\gamma\gamma} \approx 4\ \%$

CP: $F_{anom} \to 0,\ as\ n_L \to 0\ \Rightarrow\ R_{\gamma\gamma} \to 0$

❖ 2d order phase transitions, $N_f \to N_\gamma^c, \quad \Lambda \to 0$:

$NO\ Primary\ Photons$ evidence through the detector

❖ Observables.

- If CP is situated in some regions accessible to Heavy Ion Collisions one should identified it observables

- The signature of CP is ***non-monotonous behavior of observable fluctuation*** that increase very rapidly

❖ For ***CP*** evidence $r_{\varphi\gamma\gamma} = C_{EM}\,\Gamma(\pi^0 \to \gamma\gamma)\left(\frac{\Lambda}{n_L}\right)^2 \xi^3$

correlation length ↙

$$C_{EM} = (4\pi)^3 \left(\frac{3b_0^{light}}{\alpha b_{EM}}\right)^2$$

✓ $r_{\varphi\gamma\gamma}$ *scheme independent in terms of* Λ

- At ***CP*** $r_{\varphi\gamma\gamma} \to \infty\ as\ n_L \to 0, and\ \xi\ sharply\ increasing$

❖ Correlation length

$$\xi = 2\,\mu\,Q\left(\frac{vB}{2\pi^2}\right)^{2/3} ln^{-1}\left(\frac{1}{\overline{\mu_0}}\right)$$

Ground state $\overline{\mu_0}$: $\quad \sum_f \overline{n_f} = \sum_f \frac{1}{\mu_0^{-1} e^{F(f)\beta} - 1} = N$

- $Critical\ temperature \qquad T_c = \frac{1}{2m}\left(\frac{2\pi^2}{v\,B}\right)^{2/3}$

- We expect the non-monotonous increasing of fluctuations of primary photons once is going from ***UV*** to ***IR***

- Measurement of photon fluctuations can be used to determine whether quantum system is in the vicinity of ***CP*** or not

❖ T- dependence of correlation length

- Weak interactions of primary photons with medium.
- That is the reason primary photons is the ***"thermometer"*** of the temperature to excited state of matter (quark-gluon plasma?)
- The fluctuation rate of primary photons is scaled with the temperature as

$$\sim \frac{\Gamma(\pi^0 \to \gamma\gamma)\,\Lambda^2}{m^3}\left(\frac{\boldsymbol{T}}{T_c}\right)^{\mathbf{3}}, \qquad T < T_c$$

❖ Conclusions

1. Novel approach to approximate scale symmetry breaking
2. Evidence of Phase Transitions and Critical Point is seen in Conformal sector window
3. CP found followed by IRFP where Primary Photons are detected
4. Origin of Primary photons is Conformal Anomaly through decays of dilatons
5. In experimental scanning the observables, the deviation of escape $R_{\gamma\gamma}\ from\ 4\%\ to\ zero\ indicates\ the\ CP\ appearance$
6. At CP no escape of Primary Photons is seen