Critical Points & Primary Photons

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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 $S_\mu$
  - two vector currents $V_\mu$.

There is violation of conformal invariance of QCD by quantum effects
**Critical point(s)**

\[ CP \]

Phase transitions \{ search do operate with observables (matter fields?) \}

\[ \uparrow \]

symmetry breaking \{ conformal chiral \}

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

\[
\begin{align*}
\text{Early Universe} & \quad \{ \partial_\mu S^\mu = \theta^\mu_\mu \approx 0, \quad S^\mu = \theta^{\mu\nu} x_\nu, \quad x_\mu \to \lambda x_\mu \}
\end{align*}
\]

- **In nature:** \( m_i \neq 0 \), *Conformal Anomaly (CA) governed* \( \leftarrow \beta(\alpha) \neq 0 \), \( \alpha \) *running*
- QCD vacuum disordered
- Scale invariance destroyed, \( \mu = Me^{-2\pi/(b\alpha_s)} \) *appearance*
Symmetry breaking

\[ \chi - \text{Chiral Symmetry breaking} \quad \text{spontaneously} \quad \text{Conformal Symmetry breaking} \quad \text{explicitly} \]

\[ CP \text{ vicinity} \quad \text{Conformal symmetry breaking approximately} \]

\[ \downarrow \]

Light Ps-Goldstone boson \textit{(dilaton)}

Approximate dilatation symmetry if \( \beta - \text{function small; } \alpha_s \text{ running slowly with } \mu \)

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

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

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Fluctuating dilaton field


\[ \beta(\mu) = 0 \quad \beta(\mu) \neq 0 \quad \text{Primary observables} \]

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 \( \Lambda_{\text{confinement}} \)
- No dilaton state(s) in QCD

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

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

\( L \) invariance under 
\[ x^\mu \rightarrow e^\lambda x^\mu, \quad O_i(x) \rightarrow e^{\lambda d_i} O_i(e^\lambda x), \quad \chi(x) \rightarrow e^\lambda \chi(e^\lambda x) \]

- **Dilaton** \( \chi \) is formed at the scale \( \geq \Lambda_{\text{confinement}} \)
  - e.g., glueball \( \chi = O^{++} \), \( m_\chi \sim O(\Lambda_{\text{confinement}}) \)
\[ L = -C \left( \partial A \right) + \frac{1}{2} \kappa C^2 - I^\mu \left( A_\mu + e^{-\sigma} \partial_\mu \sigma \right) + \bar{q} \left( i \hat{\partial} - m_q - g \hat{A} \right) q \]

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

\( \Rightarrow \sim O(\Lambda_{\text{scale symm breaking}}) \)

\( \chi(x) \) spontaneously “slipped” from \( \langle \chi(x) \rangle_{\text{HOT}} = 0 \) → \( \langle \chi(x) \rangle_{\text{CP}} = f \)

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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:

$$\chi \rightarrow \chi + f\alpha, \quad A_\mu \rightarrow A_\mu + \partial_\mu\alpha, \quad C \rightarrow C, \quad I_\mu \rightarrow I_\mu, \quad q \rightarrow q e^{ig\alpha}$$

Additional Anomaly term:

$$-L_A = \varphi(\theta_{\mu q}^\mu + \theta_{\mu \text{anom}}^\mu)$$

$$\theta_{\mu q}^\mu = \sum_q m_q \bar{q} q \quad \theta_{\mu \text{anom}}^\mu = \frac{\alpha}{8\pi} b_{EM} F_{\mu\nu}^2 + \frac{\alpha_s}{8\pi} b_0 G_{\mu\nu}^2$$
\section*{Basic equations}

\[ \kappa C = (\partial A), \quad \partial_\mu \varphi = A_\mu, \]

\[ - (\partial I) = \theta^\mu_{\mu q} + \theta^\mu_{\mu \text{anom}}, \quad (\partial I) = 0 \text{ if no CA} \]

\[ (i \hat{\partial} - m_q - g \hat{A}) q - \varphi \sum_q m_q q = 0 \]

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

If $\text{strong}_{\text{EM}}$ are in Conformal sector

$$\Sigma_{\text{light}} b_0 = -\Sigma_{\text{heavy}} b_0$$

Mass of the dilaton splits light and heavy states sectors

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

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

For $m_\phi \sim O(\Lambda_{\text{conf}})$, $n_L = 3 \Rightarrow 14$ times increase for $\phi gg$ couplings compared to SM Higgs
Light dilatons

\[ \Delta^2 \Delta^2 \varphi(x) = \kappa \eta(x) \]

\[ \eta = - \theta_\mu \, \text{anom} - \theta_\mu \, \text{tree} \]

If no anomaly

no quarks
weak EM

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

\[
\downarrow
\]

dipole field
confinement – like pattern

\[
[\varphi(x), \varphi(y)]_- = p \, \Delta_m(z) + q \, \Delta_m'(z), \quad z = x - y; \; p, q \neq 0
\]
Properties of the commutator

\[ [\varphi(x), \varphi(y)]_\text{\scriptsize{\textpm}} = p \Delta_m(z) + q \Delta'_m(z), \quad z = x - y; \quad p, q \neq 0 \]

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

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

\[ \delta^\pm_m(k) = \theta(\pm k^0)\delta(k^2 - m^2) \]

\[ \delta'^\pm_m(k) = \theta(\pm k^0)\delta'(k^2 - m^2) \]
Propagator of dilaton

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

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

\[
\downarrow
\]
regular test function

Extra power of \( k^\mu \) 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 \(< \Lambda_{conformal}\)

\[\langle \gamma \gamma | \theta^\mu_\mu (q) | 0 \rangle \approx 0\]

\[\langle \gamma \gamma | \frac{b^\text{light}}{8\pi} G^a_{\mu \nu} | 0 \rangle = - \langle \gamma \gamma | \frac{b_{EM}}{8\pi} F^2_{\mu \nu} | 0 \rangle, \quad \tilde{q} = 0\]
Primary photons escape.

**Close to CP:**

\[
R_{\gamma\gamma} = \frac{\Gamma(\Phi \to \gamma \gamma)}{\Gamma(\pi^0 \to \gamma \gamma)} = \left( \frac{3F_{\text{anom}}}{2N_c} \right)^2 \left( \frac{f_\pi}{f} \right)^2 \left( \frac{m}{m_\pi} \right)^3
\]

**CA contribution:**

\[
F_{\text{anom}} = - \left( \frac{2n_L}{3} \right) \left( \frac{b_{EM}}{b_{0\text{light}}} \right), \quad b_{EM} = -4 \sum_{q:u,d,s} e_q^2 = -\frac{8}{3}
\]

**Dilaton mass at IRFP:**

\[
m \approx \sqrt{1 - \frac{N_f}{N_f^C}} \Lambda \quad \Rightarrow \quad R_{\gamma\gamma} \approx 4\% 
\]

**CP:**

\[
F_{\text{anom}} \to 0, \text{ as } n_L \to 0 \quad \Rightarrow \quad R_{\gamma\gamma} \to 0
\]

**2d order phase transitions,** \( N_f \to N_f^C, \quad \Lambda \to 0: \)

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 $r_{\varphi\gamma\gamma} = C_{EM} \Gamma(\pi^0 \rightarrow \gamma\gamma) \left( \frac{\Lambda}{n_L} \right)^2 \xi^3$

  correlation length

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

  $r_{\varphi\gamma\gamma}$ scheme independent in terms of $\Lambda$

- At CP $r_{\varphi\gamma\gamma} \rightarrow \infty$ as $n_L \rightarrow 0$, and $\xi$ sharply increasing
Correlation length

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

Ground state $\mu_0$: \[ \sum f n_f = \sum f \frac{1}{\mu_0^{-1} e^{F(f) / \beta} - 1} = N \]

Critical temperature \[ T_c = \frac{1}{2m} \left( \frac{2\pi^2}{v_B} \right)^{2/3} \]

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

\[
\sim \frac{\Gamma(\pi^0 \rightarrow \gamma \gamma)}{m^3} \Lambda^2 \left( \frac{T}{T_c} \right)^3, \quad T < T_c
\]
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