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Soft photon production from real-time dynamics of jet fragmentation

Frashër Loshaj

Department of Physics & Astronomy
Stony Brook University

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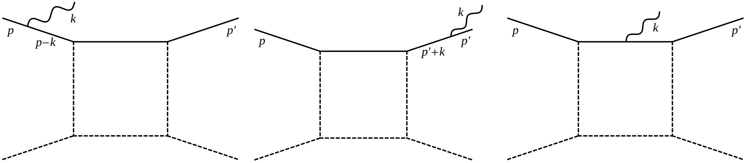
Outline

1. Introduction
2. Dynamics of jet fragmentation
3. Soft photon production
4. Summary and Outlook

Low Theorem

Scattering of two spin-zero particles, where one of them is charged



F.E. Low, Phys.Rev. 110 (1958) 974-977

- Total amplitude $M = M^{(1)} + M^{(2)}$;
  - $M^{(1)}$ - diagrams with photons attached to external propagators
  - $M^{(2)}$ - diagrams with photons attached to internal propagators.
- **Low Theorem**: as $k \to 0$, $M^{(1)} \sim 1/k, \ M^{(2)} \sim \text{constant}$.
- As a consequence, soft photons are mainly produced from initial and final charged particles.
- Soft photon yield can be computed from the hadron spectrum

$$\omega \frac{dN^{\gamma}}{d^3k} = \frac{\alpha}{(2\pi)^2} \sum_n \int d^3p_1 \cdots d^3p_n \sum_{i,j} \frac{-Q_iQ_j(p_i \cdot p_j)}{(p_i \cdot k)(p_j \cdot k)} \frac{dN^{hadr}}{d^3p_1 \cdots d^3p_n}$$

Anomalous soft photon production

- Contrary to expectations, nearly all experiments observe a significant enhancement of soft photon production (factor $2 \div 5$) - "Anomalous soft photon production."
- For example, DELPHI measurements of soft photons in Z^0 decay to hadrons. Photon spectrum similar to Bremsstrahlung, but by a factor of **four** larger [**Eur. Phys. J. C 67, 343 (2010)**].
- DELPHI measurements of e^+e^- to $\mu^+\mu^-$ show no deviation from Bremsstrahlung [**Eur. Phys. J. C 57, 499 (2008)**].
- Theoretical models: [**E. V. Shuryak, Phys. Lett. B 231, 175 (1989)**], [**P. Lichard and L. Van Hove, Phys. Lett. B 245, 605 (1990)**], [**G. W. Botz, P. Haberl and O. Nachtmann, Z. Phys. C 67, 143 (1995)**], [**C. -Y. Wong, Phys. Rev. C 81, 064903 (2010)**],[**Y. Hatta and T. Ueda, Nucl. Phys. B 837, 22 (2010)**], etc. None of them explain all the features of the phenomenon.
- Presents challenge to the foundation of the theory. The process needs to be understood in order to account for the background in soft photon production in heavy ion collisions for example.

Dynamical model of jet fragmentation

- String breaks, forming pairs of quark-antiquark, creating a space-time dependent electromagnetic current.
- Long distance QCD phenomena - strong coupling.
  - High energy jets - longitudinal (along jet axis) momentum large - use $1+1$ dimensional effective theory.
  - Picture of confinement in Abelian projection. Confinement due to condensation of magnetic monopoles and dual Meissner effect.
  - Hadronization - confinement in the presence of light fermions.
- Based on assumptions above, we consider QED_2 (Schwinger model).
- Properties
  - Confinement and charge screening,
  - Chiral symmetry breaking,
  - θ-vacuum.

$$\mathcal{L} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \bar{\psi} i \gamma^{\mu} \partial_{\mu} \psi - g \, \bar{\psi} \gamma^{\mu} \psi B_{\mu} - g j^{\mu}_{ext} B_{\mu}$$

Solution of the theory

- The theory is exactly soluble.
- It is easy to show this using bosonization:

$$j^\mu(x) = \bar{\psi}(x)\gamma^\mu\psi(x) = -\frac{1}{\sqrt{\pi}}\epsilon^{\mu\nu}\partial_\nu\phi(x)$$
$$j_5^\mu(x) = \bar{\psi}(x)\gamma^\mu\gamma^5\psi(x) = \frac{1}{\sqrt{\pi}}\partial^\mu\phi(x)$$

Equation of motion for ϕ

$$\boxed{(\Box + m^2)\phi = m^2\sqrt{\pi}\int^z dz' j^0_{ext}(t,z')}$$

$m = g/\sqrt{\pi}$.

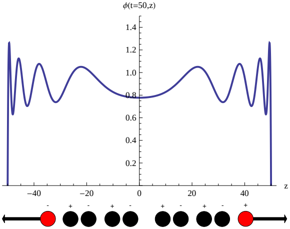
- Space-time evolution of electric field

$$E^{ind}(x) = G^{ind}_{01}(x) = -\frac{g}{\sqrt{\pi}}\phi(x).$$

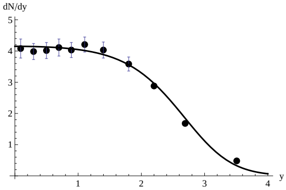
Jet fragmentation

D. E. Kharzeev and FL, Phys. Rev. D 87, 077501 (2013); FL and D. E. Kharzeev, Int. J. Mod. Phys. E 21, 1250088 (2012)

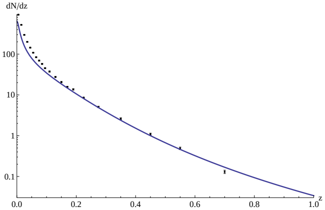
Quark-antiquark charge density: $j^0(x) = \delta(z - vt)\theta(z) - \delta(z + vt)\theta(-z)$



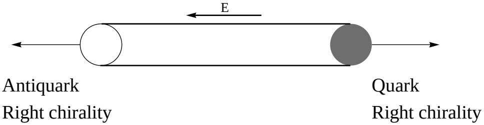
Quark fragmentation in the θ-vacuum.



(TPC/Two Gamma Collaboration), 1988.

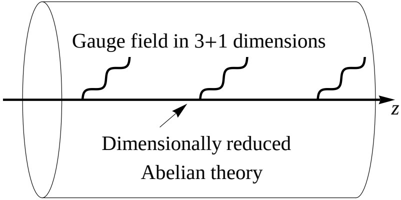


(OPAL Collaboration), 2003.



$$\Delta Q_5(t) = N_R - N_L = \frac{g}{\pi} \int d^2x \, E_{01}^{tot}(x) = 2[\cos(mt) - 1]$$

Anomaly induces oscillation of vector charge along jet axis.



$$\frac{dN_\gamma}{d^3p} = \left(B_{2/3} \left(\frac{2}{3}\right)^2 + B_{1/3} \left(\frac{1}{3}\right)^2 \right) \frac{1}{(2\pi)^3} \frac{1}{2p^0} e^2 \frac{4v^2}{(p_0^2 - v^2 p_z^2)^2} p_\perp^2 \left(1 + \frac{m^2}{p_\perp^2 - m^2}\right)^2$$

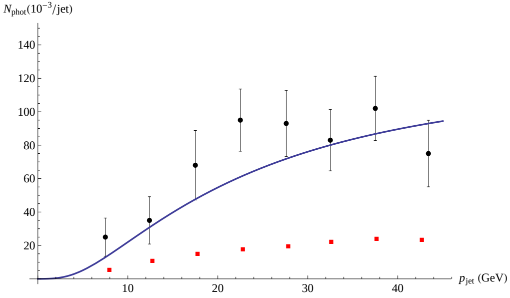
As $p_\perp \to 0$, $\frac{dN_\gamma}{d^3p} \to 0$ - Low theorem recoreved.

Phenomenology of soft photon production

- Quark-antiquark potential in the Schwinger model

$$V(r) = \frac{g\sqrt{\pi}}{2}\left(1 - e^{-\frac{g}{\sqrt{\pi}}r}\right)$$

- String tension $\kappa^2 = \frac{\pi}{2}m^2$, fluctuates [**A. Bialas, Phys. Lett. B 466, 301 (1999)**]:
$P(\kappa^2) = \sqrt{\frac{2}{<\kappa^2>}} e^{-\frac{\kappa^2}{2<\kappa^2>}}$.
- Finite width: $\frac{1}{p_\perp^2 - m^2} \to \frac{1}{p_\perp^2 - m^2 + i\gamma^2}$.



Data from [[**DELPHI Collaboration], Eur. Phys. J. C 67, 343 (2010)**]

D. E. Kharzeev and FL, arXiv:1308.2716 [hep-ph], to appear in PRD.

$$N_{phot} = \int dm \sqrt{\frac{\pi}{2}} P\left(\frac{\pi}{2}m^2\right) \times \left(\int d^3p \frac{dN}{d^3p}\right)$$

$$p_\perp < 80\,\text{MeV},\ 0.2 < E_\gamma < 1\,\text{GeV}$$

$$\gamma = \sqrt{m_R \Gamma_R} = 0.003\ \text{GeV}.$$

Typical values:
for η, $\gamma = 8 \cdot 10^{-4}$ GeV;
for ω, $\gamma = 8 \cdot 10^{-2}$ GeV.

Summary and Outlook

- We have modeled the propagation of the quark in QCD vacuum by using an exactly soluble $1+1$ dimensional Abelian gauge model.
- This simple model shares with QCD properties like confinement in the presence of light quarks, chiral symmetry breaking, axial anomaly and periodic θ-vacuum.
- This theory manifests coherent oscillations of the axial and vector (electric) charges coupled by the axial anomaly and induced by the propagating high energy quark.
- These oscillations lead to a strong enhancement of soft photons. By introducing an adjustable parameter, our model can describe the DELPHI data on the soft photon production.

- Would be interesting to generalize our study to a $3+1$ dimensional model.
- In heavy ion collisions, soft photons are very important for probing the properties of the quark gluon plasma. It is therefore crucial to account for the background coming from hard partons.