Decoherence in high energy collisions as renormalization group flow

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Shi-Jia Lin[1, 2]

[1] Department of Physics and Center for Field Theory and Particle Physics, Fudan University, Shanghai, 200438, China ,
[2] Department of Physics, University of Chicago, Chicago, IL 60637, USA

Introduction

- Observations such as top-quark **spin entanglement** demonstrate quantum effects at high energies[1].
- However, the quark pairs are **open quantum systems**, as unresolved soft & collinear photon/gluon radiation inevitably causes **decoherence**.

SCET Factorization

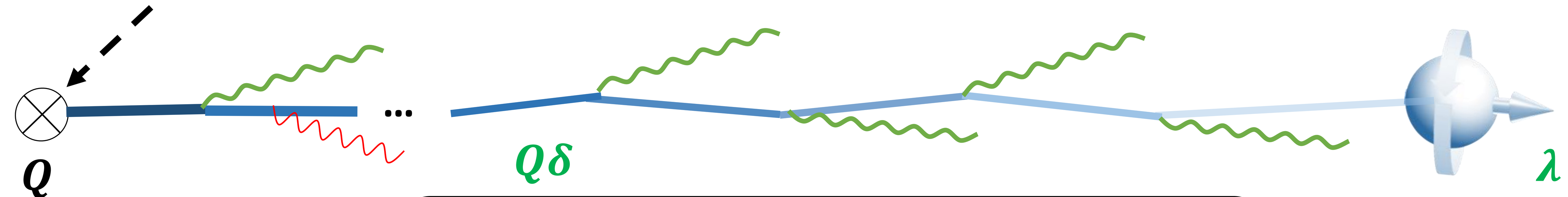
- Using SCET factorization theorems, the production density matrix of the fermion pair is factorized:

$$\hat{R} = \hat{J}_f(Q\delta,\lambda,\mu)\hat{R}_{\text{hard}}(Q,\mu)\hat{J}_{\bar{f}}(Q\delta,\lambda,\mu)S(Q\beta,\delta,\mu)$$

At leading order, soft emissions are spin-independent and thus **do not** induce decoherence[4-5].

OPE

$$\hat{C}_{\bar{f}}(Q\delta,\mu)\hat{D}_{\bar{f}}(\lambda,\mu)$$

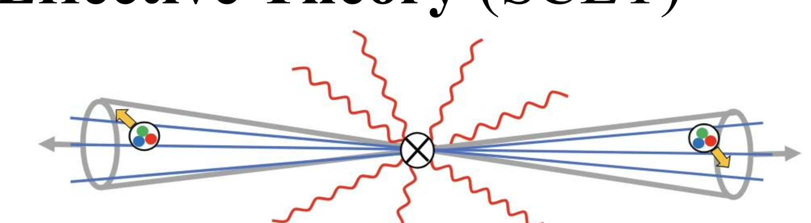


$$\hat{R} = \hat{D}_f(\lambda,\mu)\hat{R}_{\text{eff}}(Q\delta,\mu)\hat{D}_{\bar{f}}(\lambda,\mu)$$

$$\hat{R}_{\text{eff}}(\mu) \equiv S(Q\beta,\delta,\mu)\hat{C}_f(Q\delta,\mu)\hat{R}_{\text{hard}}(Q,\mu)\hat{C}_{\bar{f}}(Q\delta,\mu)$$

Effective Field Theory for Decoherence

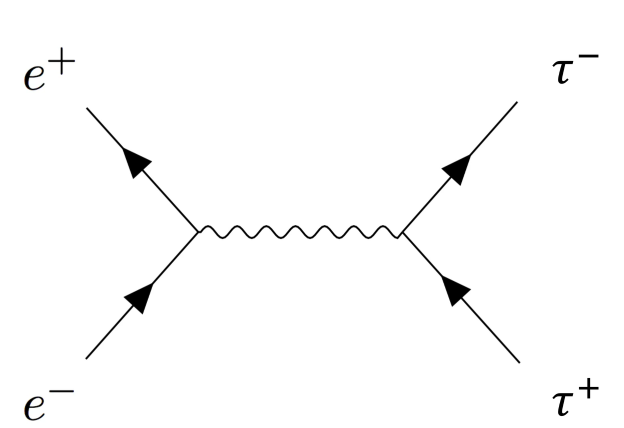
- Radiation should be considered **unresolved** if either **soft** or **collinear.**
- We introduce the energy and angular resolution parameters, similar **to Sterman-Weinberg cone jet** definition[2].
- We apply **Soft Collinear Effective Theory** (SCET) [3].



$\delta = \tan(\alpha/2)$ $\quad 2E_{\text{out}} < Q\beta$

At scale Q: Production

- The fermion pair is produced at an energy scale Q much higher than an IR scale λ.
- The spin state of two spin-1/2 particles can be characterized by a two-qubit density operator $\hat{\rho}_{\text{hard}} = \frac{\hat{R}_{\text{hard}}}{\text{Tr}[\hat{R}_{\text{hard}}]}$.
- eg. $e^+ + e^- \to \tau^- + \tau^+$



$$\hat{\rho}_{\text{hard}}(Q,\mu) = \frac{1}{4}\left(\hat{I}_2\otimes\hat{I}_2 + \frac{\sin^2\theta}{1+\cos^2\theta}\hat{\sigma}_1\otimes\hat{\sigma}_1 + \frac{\sin^2\theta}{1+\cos^2\theta}\hat{\sigma}_2\otimes\hat{\sigma}_2 - \hat{\sigma}_3\otimes\hat{\sigma}_3\right)$$

From $Q\delta$ to λ: Collinear Emission

- From scale $Q\delta$ to λ, the fermion pair emits collinear photons.
- Solution to the Renormalization Group Equation(RGE)

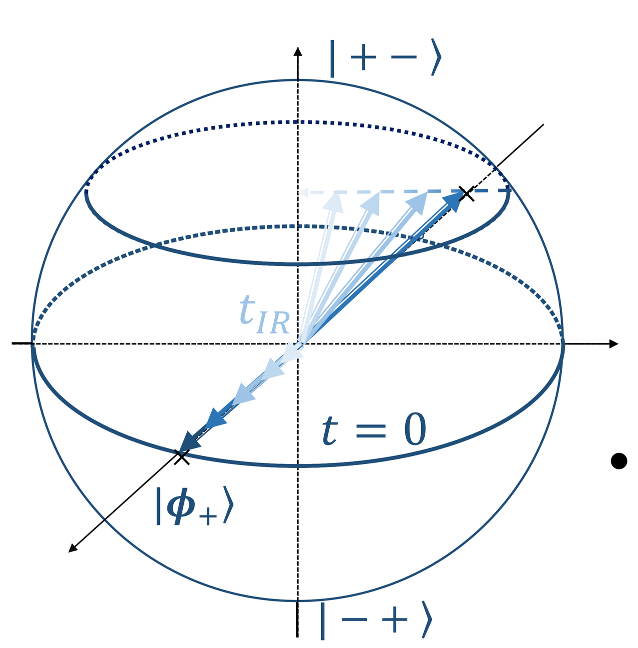
$$\hat{R}_{\text{eff}}(t) = \hat{U}_f(t,0)\,\hat{R}_{\text{eff}}(0)\,\hat{U}_{\bar{f}}(t,0) \qquad t \equiv \log(Q\delta/\mu)$$

- The evolution functions: $U^{\mathcal{P}}(t,0) = \exp\left(\int_0^t \mathrm{d}t\,\gamma^{\mathcal{P}}\right)$, γ^P as anomalous dimension.

> - The **RGE** encapsulates decoherence from collinear radiation, whose **Kraus representation** can be determined.
> - **Anomalous dimensions** determine the information loss.

- eg. collinear photon emission ↔ **phase-flip** channel

$$U^U = U^L = 1,\ U^T = \exp\left(-\frac{\alpha}{2\pi}t\right) \leftrightarrow \hat{K}_{(i,j)} = \hat{K}_i^{\ell^-}\otimes\hat{K}_j^{\ell^+}$$



$$\hat{K}_0^{\ell^-} = \hat{K}_0^{\ell^+} = \sqrt{1-p^2}\,\mathbb{I},$$

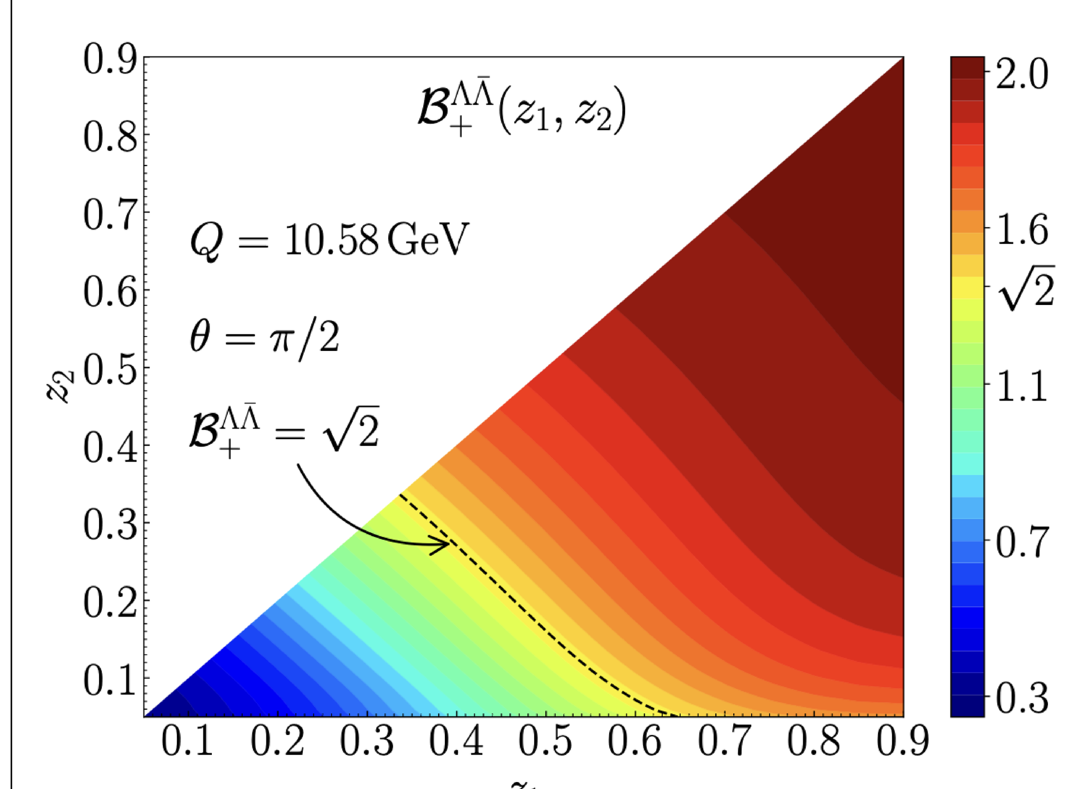
$$\hat{K}_1^{\ell^-} = \hat{K}_1^{\ell^+} = p\,\hat{\sigma}_3, \quad p = \sqrt{\frac{1}{2}\left[1-\exp\left(-\frac{\alpha}{2\pi}t\right)\right]}$$

- Final-state concurrence for general cases

$$\mathcal{C}_{\text{final}} \leq \mathcal{C}(0)\left(\frac{Q\delta}{\lambda}\right)^{-\frac{\alpha}{\pi}}$$

At scale λ: Measurement

- When the state is evolved to scale λ, the final stage of the process is **the projection of the evolved spin state onto definite experimental outcome**.
- eg. Defining spin measurement operators as $\hat{M}_f(\boldsymbol{S}_f) \equiv \hat{D}_f\hat{P}_f$ to contain final state projection and the spin measurement.



(arXiv:2507.15387, decoherence in QCD)

Summary

- Developed a systematic framework for computing spin decoherence from final-state radiations in high-energy processes by unifying SCET with open quantum system formalism.
- Demonstrated that renormalization group evolution constitutes a quantum channel, where the RG flow parameter drives a Markovian loss of quantum coherence.
- Framework extends naturally to QCD, including subleading- power soft effects, etc.

Reference

[1] G. Aad et al. (ATLAS), Nature 633, 542 (2024).
[2] G. F. Sterman and S. Weinberg, Phys. Rev. Lett. 39, 1436 (1977).
[3] T. Becher, M. Neubert, L. Rothen, and D. Y. Shao, Phys. ev. Lett. 116, 192001 (2016)
[4] F. E. Low, Phys. Rev. 96, 1428 (1954).
[5] M. Gell-Mann and M. L. Goldberger, Phys. Rev. 96, 1433 (1954).