From UV to IR, tracking information loss in open quantum systems

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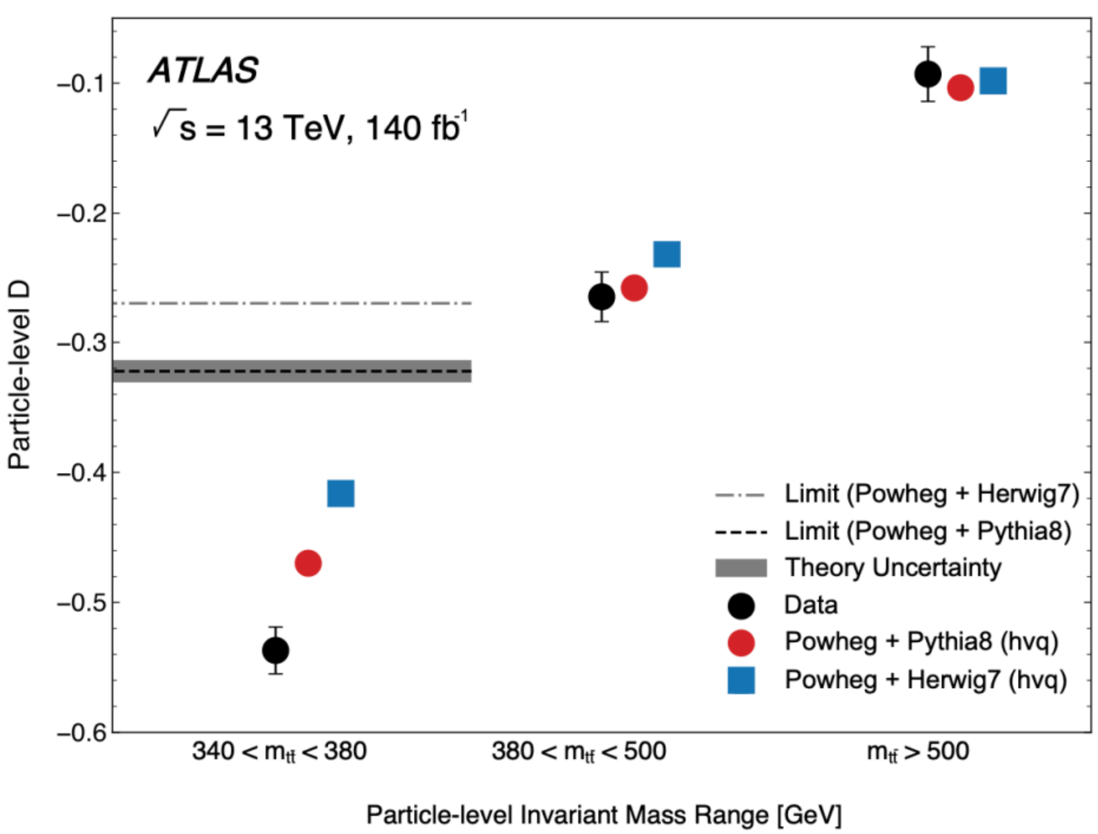
Quantum information science meets high energy physics

- **Over the past few decades, entanglement has been observed in various macroscopic systems, but its exploration in the high-energy regime remains relatively limited.**

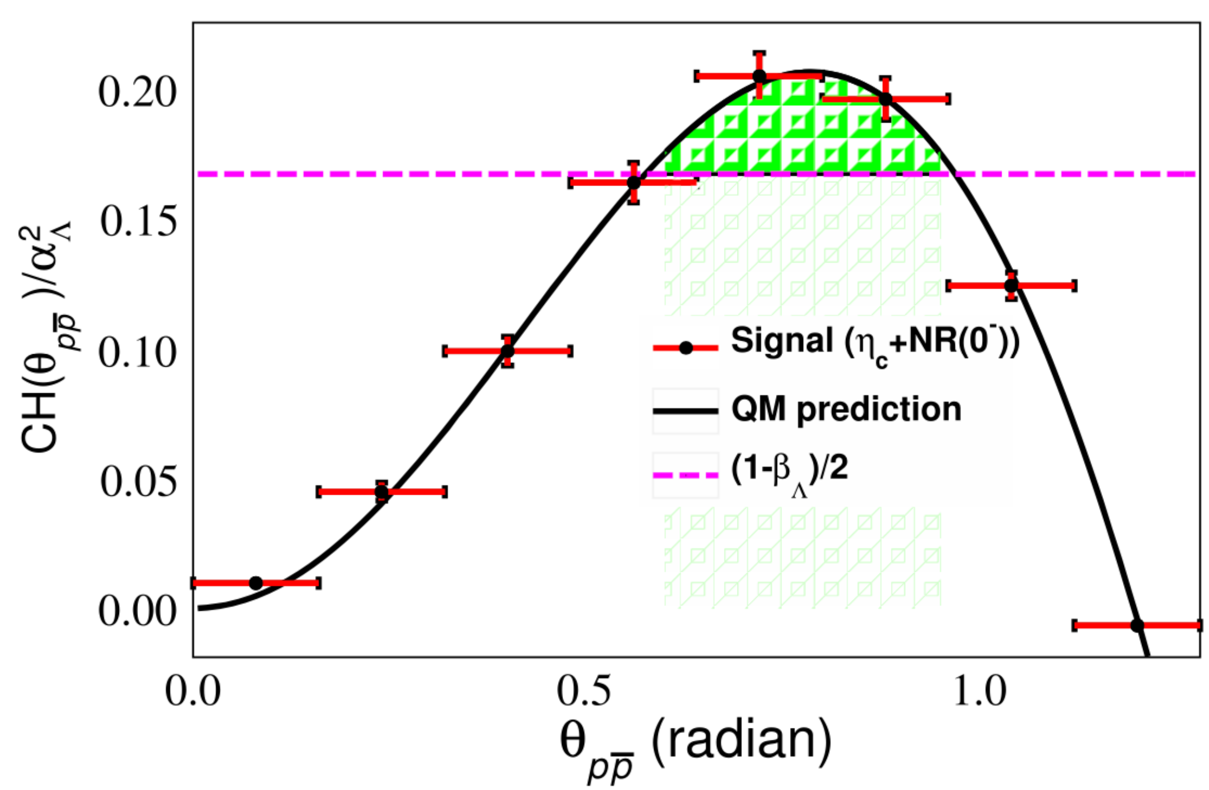
- **The study of quantum information in high-energy collider physics is rapidly transitioning from a theoretical curiosity to an experimental reality.**— A recent review 2504.00086

- **A recent breakthrough came when the ATLAS and CMS collaborations observed quantum entanglement by measuring the spin correlations of top quark pairs at the LHC.**

ATLAS Nature 2024

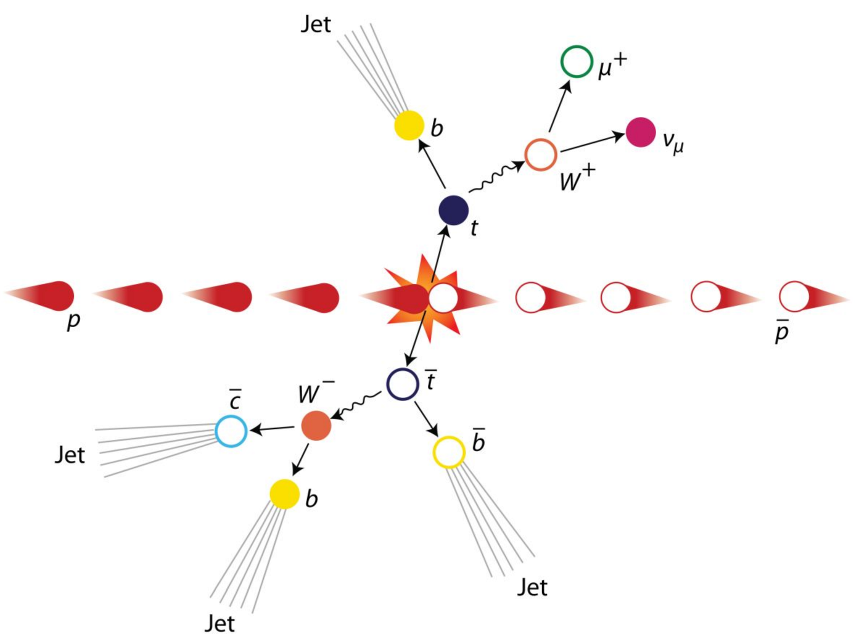


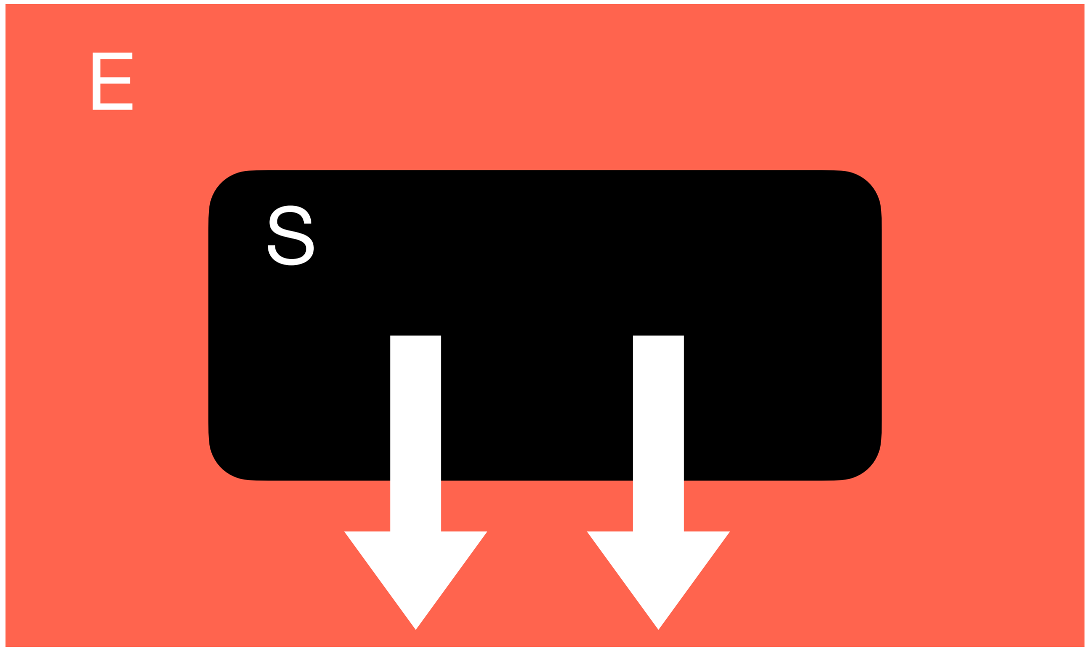
BESIII Nature Communications 2025



Decoherence in high energy collisions

- **Bell inequality at colliders ?** Li, Shen, Yang '24; Bechtle, Breuning, Dreiner, Duhr '25; Abel, Dreiner, Sengupta, Ubaldi '25 …
- **The Large Hadron Collider can be viewed as an open quantum system.**
- **Top quarks may radiate gluons or photons in the short period of time before decaying, leading to a reduction in quantum spin information, i.e., decoherence.**
- **Decoherence can be studied by recognizing that realistic quantum systems are always embedded in some environment.**
- **This interaction with the system results in 'leakage of information' to the environment, decreasing the entanglement between the components of the system.**





Concurrence at LO

- **Consider QED process** $e^+e^- \to f\bar{f}$

- **The spin state of a lepton pair can be characterized by a two-qubit density operator**

$$\hat{\rho} = \frac{1}{4}\left(\hat{I}_2 \otimes \hat{I}_2 + B_i^+ \hat{\sigma}_i \otimes \hat{I}_2 + B_i^- \hat{I}_2 \otimes \hat{\sigma}_i + C_{ij} \hat{\sigma}_i \otimes \hat{\sigma}_j\right)$$

- **At the LO**

$$\rho_{\mathrm{LO}} = \frac{1}{4}\left(\hat{I}_2 \otimes \hat{I}_2 + \frac{\sin^2\theta}{1+\cos^2\theta}\hat{\sigma}_1 \otimes \hat{\sigma}_1 + \frac{\sin^2\theta}{1+\cos^2\theta}\hat{\sigma}_2 \otimes \hat{\sigma}_2 - \hat{\sigma}_3 \otimes \hat{\sigma}_3\right)$$

- **To probe entanglement, one can calculate the concurrence C**

$$\mathcal{C}[\rho_{\mathrm{LO}}] = \frac{\sin^2\theta}{1+\cos^2\theta}$$

- **Maximum entanglement cosθ = 0**

$$\mathcal{C}[\rho_{\mathrm{LO}}] = 1 \qquad \frac{1}{\sqrt{2}}(|+-\rangle + |-+\rangle)$$

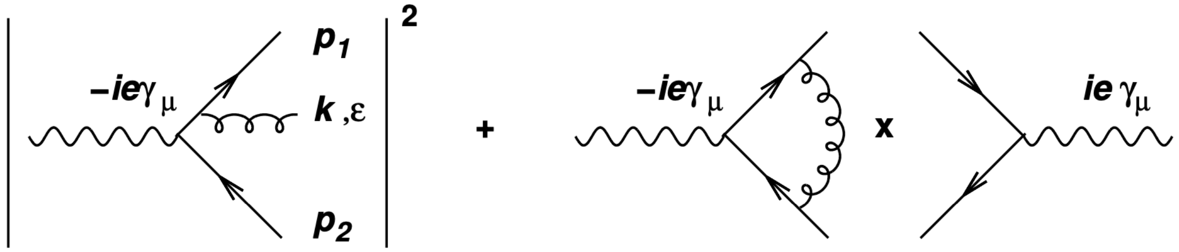
Quantum maps for open systems

Aoude, Barr, Maltoni, Satrioni '25

- The evolution of an open system can represented by a quantum map (channel)

$$\mathcal{E}[\rho] = \sum_j K_j \rho K_j^\dagger, \qquad \sum_j K_j^\dagger K_j = \mathbb{1},$$

Kraus operators: Kraus representation theorem



- The virtual corrections lead to the same final state Hilbert space while the real emission leads to the extra Hilbert space of the environment.

$$\rho^{\text{red}}_{\text{LO+NLO}} = \mathrm{p}_{\text{LO}}\, \mathbb{1}\rho_{\text{LO}}\mathbb{1} + \bar{\mathcal{E}}_{\text{V}}[\rho_{\text{LO}}] + \bar{\mathcal{E}}_{\text{R}}[\rho_{\text{LO}}]$$

$$\bar{\mathcal{E}}_{\text{V}}[\rho_{\text{LO}}] = \mathrm{p}_{\text{V}} \mathbb{1}\rho_{\text{LO}}\mathbb{1}$$

Virtual

$$\bar{\mathcal{E}}_{\text{R}}[\rho_{\text{LO}}] = \sum_j K_j \rho_{\text{LO}} K_j^\dagger$$

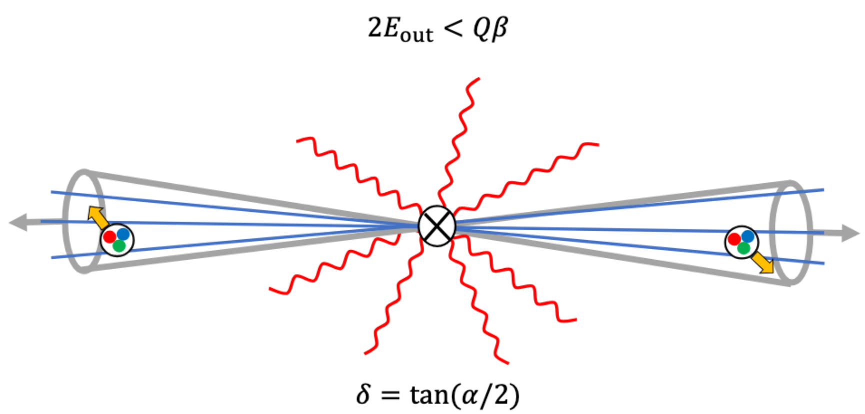
Real

Effective field theory for decoherence

J.Y. Gu, S.J. Lin, D.Y. Shao, L.T. Wang, S.X. Yang 2510.13951

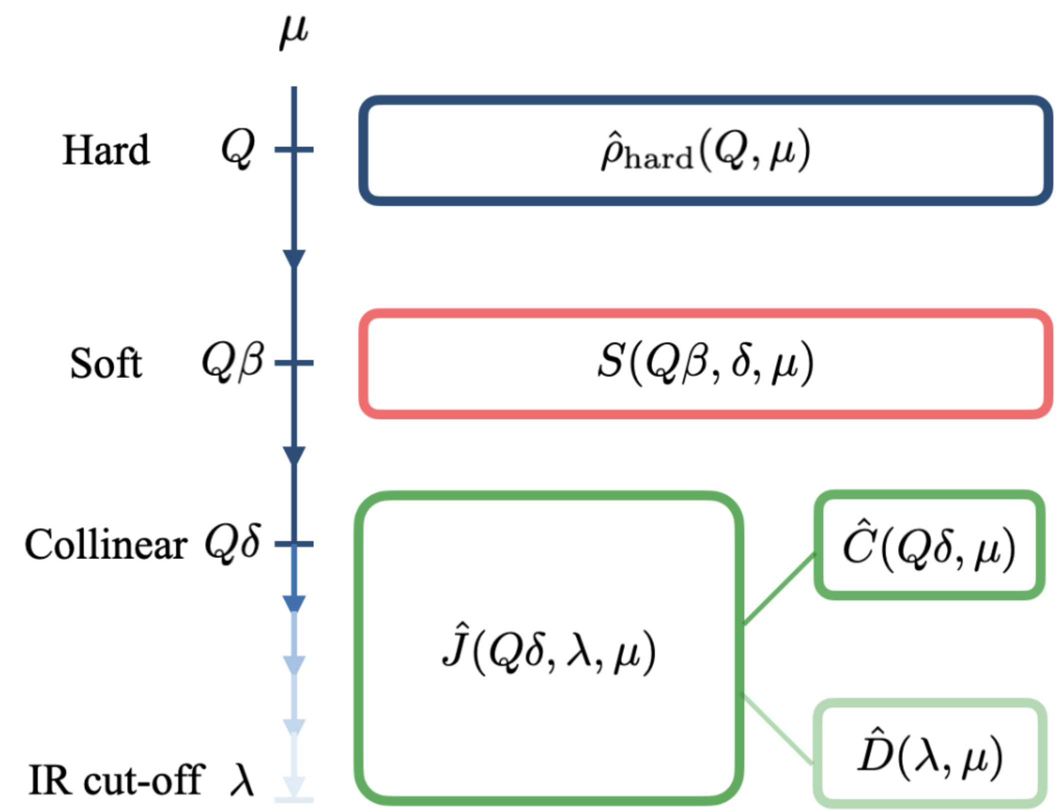
- We introduce the energy and angular resolution parameters, which is similar to Sterman-Weinberg cone jet definition (Sterman, Weinberg ’77)

Two particle state events:



- The initial spin state generated by the short-distance hard scattering $\hat{\rho}_{\rm hard}(Q,\mu)$
- Apply a standard multiplicative renormalization scheme to regularize both UV and IR divergences
- $\hat{\rho}_{\rm hard}(Q,\mu) = \dfrac{1}{4}\Big(\hat{I}\otimes\hat{I} + P_i^+\,\hat{\sigma}_i\otimes\hat{I} + P_j^-\,\hat{I}\otimes\hat{\sigma}_j + C_{ij}\,\hat{\sigma}_i\otimes\hat{\sigma}_j\Big)$
- Our production matrix can be factorized as
- $\hat{R} = S(Q\beta,\delta,\mu)\hat{J}_f(Q\delta,\lambda,\mu)\hat{R}_{\rm hard}(Q,\mu)\hat{J}_{\bar{f}}(Q\delta,\lambda,\mu)$

Factorization of the density operator



- Soft function **does not induce decoherence.**
- The fragmenting jet operators J_f project the hard scattering state onto the Hilbert space of the observed particles. This effectively traces over unobserved collinear radiation, and induces decoherence
- $\hat{J}_f = \mathcal{J}_f^U\, \hat{I}\otimes\hat{I} + \mathcal{J}_f^L \hat{\sigma}_z\otimes\hat{\sigma}_z + \mathcal{J}_f^T\,(\hat{\sigma}_x\otimes\hat{\sigma}_x + \hat{\sigma}_y\otimes\hat{\sigma}_y)$
- Refactorization via an operator product expansion

$$\hat{J}(Q\delta,\lambda,\mu) = \hat{C}(Q\delta,\mu)\hat{D}(\lambda,\mu)$$

Fragmentation operator

- Define a effective production matrix $\hat{R}_{\text{eff}}(\mu) \equiv S(Q\beta,\delta,\mu)\hat{C}_f(Q\delta,\mu)\hat{R}_{\text{hard}}(Q,\mu)\hat{C}_{\bar{f}}(Q\delta,\mu)$
- Renormalization group eqn $t \equiv \log(Q\delta/\mu)$.

$$\hat{R}_{\text{eff}}(t) = \hat{U}_f(t,0)\,\hat{R}_{\text{eff}}(0)\,\hat{U}_{\bar{f}}(t,0)$$

$$U^{\mathcal{P}}(t,0) = \exp\left(\int_0^t \mathrm{d}t\,\gamma^{\mathcal{P}}\right)$$

decoherence = RG flow
anomalous dimensions determine the information loss

Measurement operator

- The final stage of the process is the projection of the evolved spin state onto a definite experimental outcome
- Define spin-dependent measurement operators $\hat{M}_f(\boldsymbol{S}_f) \equiv \hat{D}_f \hat{P}_f$

$$\mathrm{d}\sigma(\boldsymbol{S}_f, \boldsymbol{S}_{\bar{f}}) \propto \mathrm{Tr}\left[\hat{M}_f(\boldsymbol{S}_f, t)\, \hat{R}_{\mathrm{eff}}(t)\, \hat{M}_{\bar{f}}(\boldsymbol{S}_{\bar{f}}, t)\right]$$

- Physics at different scales separated
  - Decoherence from collinear radiation are encapsulated in the RGE of the effective density matrix
  - Infrared physics of the final-state projection is contained entirely within the measurement operators (e.g. fragmentation function in QCD)

Kraus operator and Lindblad master equation

- The Kraus operators in QED

$$\hat{K}_{(i,j)} = \hat{K}_i^{\ell^-} \otimes \hat{K}_j^{\ell^+}$$

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

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

- Lindblad equation and jump operator

$$\frac{\mathrm{d}\hat{\rho}_{\mathrm{eff}}}{\mathrm{d}t} = -\frac{\alpha}{2\pi}\hat{\rho}_{\mathrm{eff}} + \frac{\alpha}{4\pi}\left[(\hat{\sigma}_3\otimes\mathbb{I})\,\hat{\rho}_{\mathrm{eff}}\,(\hat{\sigma}_3\otimes\mathbb{I}) + (\mathbb{I}\otimes\hat{\sigma}_3)\,\hat{\rho}_{\mathrm{eff}}\,(\mathbb{I}\otimes\hat{\sigma}_3)\right]$$

$$\hat{L}_1 = \sqrt{\alpha/4\pi}\,\hat{\sigma}_3\otimes\mathbb{I} \qquad \hat{L}_2 = \sqrt{\alpha/4\pi}\,\mathbb{I}\otimes\hat{\sigma}_3$$

- Each "jump" corresponds to an unresolved collinear photon emission from either of the fermion legs, which induces a stochastic phase-flip

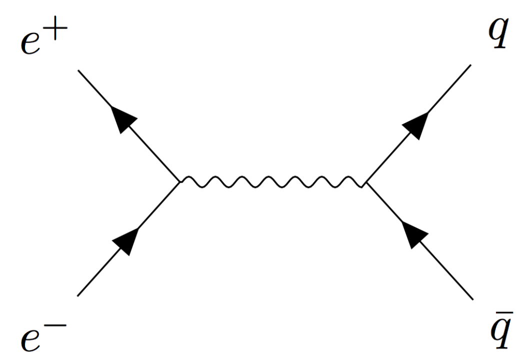
- Decay of all off-diagonal terms

$$\frac{\hat{\rho}_{\mathrm{eff}}^{ij}(t)}{\hat{\rho}_{\mathrm{eff}}^{ij}(0)} = \begin{cases} 1 & i=j \quad (\text{diagonal})\,, \\ e^{-\frac{\alpha}{\pi}t} & ij = 14, 23, 32, 41 \quad (\text{anti-diagonal})\,, \\ e^{-\frac{\alpha}{2\pi}t} & \text{else}\,. \end{cases}$$

- Concurrence in QED $\mathcal{C}(t) = \mathcal{C}(0)e^{-\frac{\alpha}{\pi}t}$

Spin correlation in Λ pair production with a thrust cut

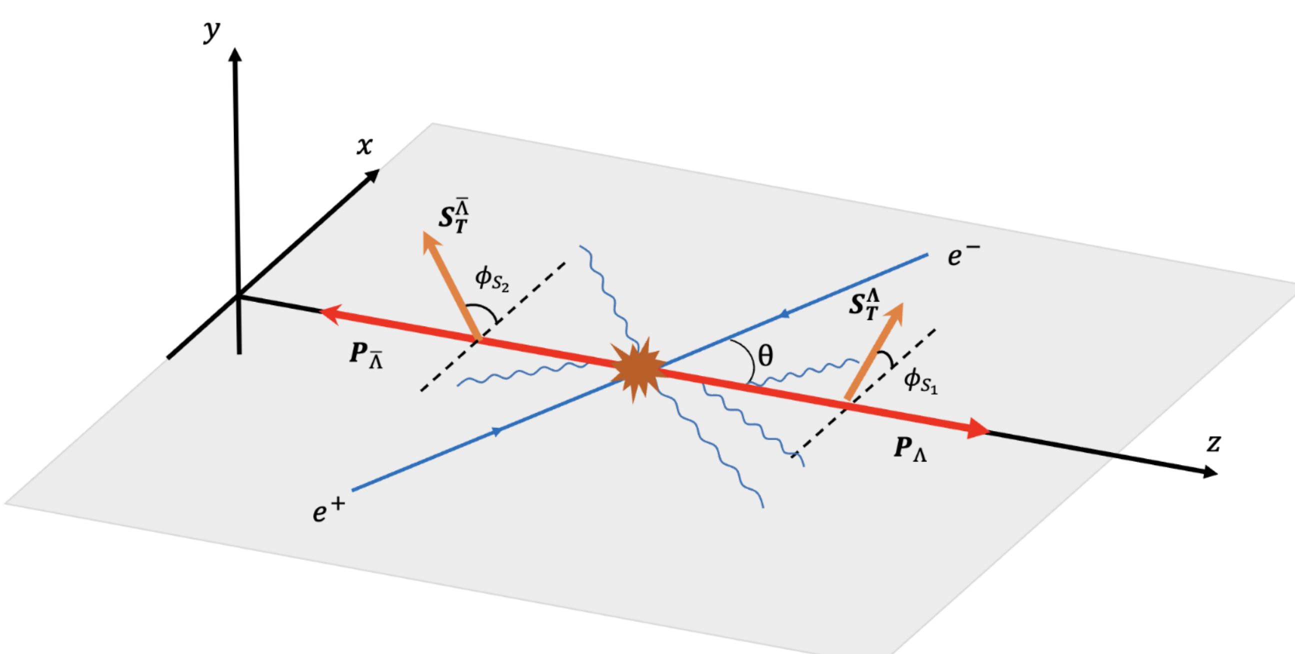
S.J. Lin, MJL, D.Y. Shao, S.Y. Wei '25



Bell variable

Parton-level

$$\mathcal{B}_+^{q\bar{q}} = \frac{2\sin^2\theta}{1+\cos^2\theta}$$



Bell variable

Hadron-level

$$\mathcal{B}_+^{\Lambda\bar{\Lambda}} = \frac{2\,\mathrm{d}\sigma^T}{\mathrm{d}\sigma^U}$$

Parton model:

$$\frac{\mathrm{d}\sigma(\boldsymbol{S}^\Lambda,\boldsymbol{S}^{\bar{\Lambda}})}{\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega} = \sum_q e_q^2\Bigg[\frac{\mathrm{d}\sigma_0^U}{\mathrm{d}\Omega}\,\mathcal{D}^U_{\Lambda/q}(z_1,\mu)\,\mathcal{D}^U_{\bar{\Lambda}/\bar{q}}(z_2,\mu) + P_z^\Lambda P_z^{\bar{\Lambda}}\,\frac{\mathrm{d}\sigma_0^L}{\mathrm{d}\Omega}\,\mathcal{D}^L_{\Lambda/q}(z_1,\mu)\,\mathcal{D}^L_{\bar{\Lambda}/\bar{q}}(z_2,\mu)$$
$$+|\boldsymbol{S}_T^\Lambda||\boldsymbol{S}_T^{\bar{\Lambda}}|\cos(\phi_{S_1}+\phi_{S_2})\,\frac{\mathrm{d}\sigma_0^T}{\mathrm{d}\Omega}\,\mathcal{D}^T_{\Lambda/q}(z_1,\mu)\,\mathcal{D}^T_{\bar{\Lambda}/\bar{q}}(z_2,\mu)\Bigg]$$

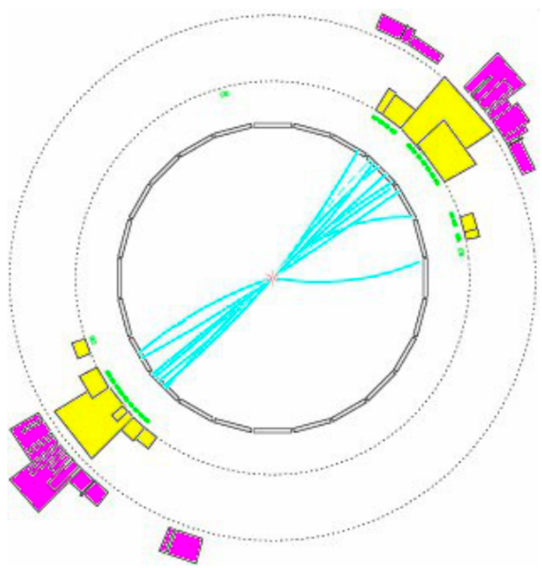
Boer, Jakob, Mulders '97

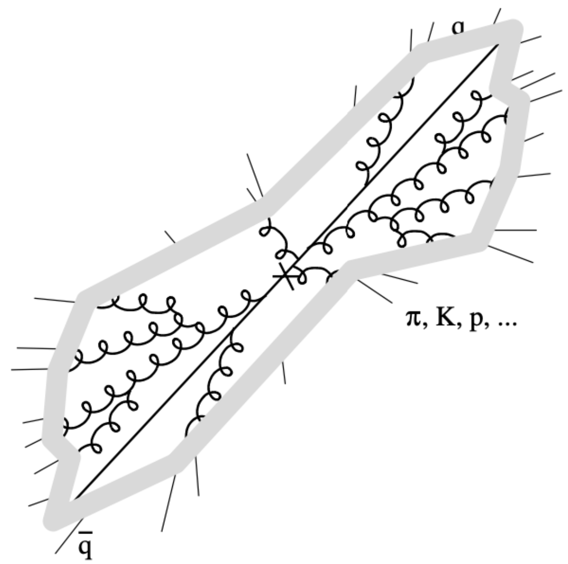
Spin correlation in Λ pair production with a thrust cut

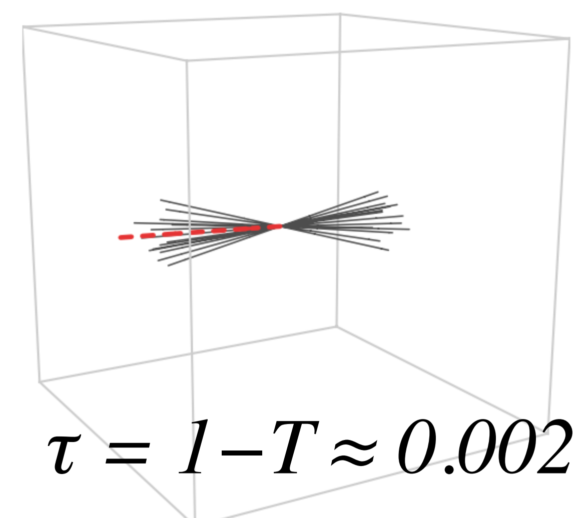
S.J. Lin, MJL, D.Y. Shao, S.Y. Wei ‘25

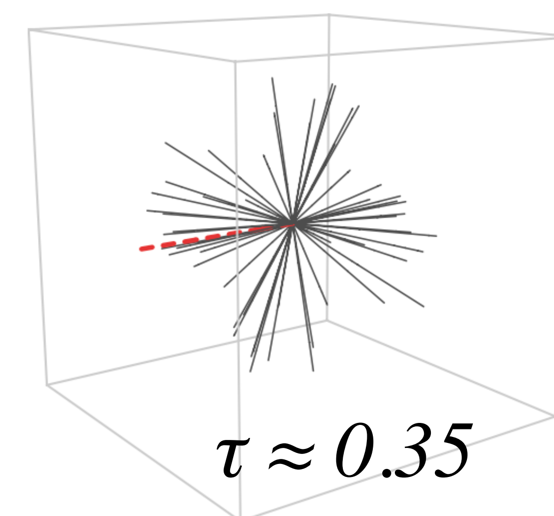
- **We apply the event shape thrust (T) to select two-jet configuration**

$$T = \frac{1}{Q}\max_{\vec{n}_T} \sum_i |\vec{n}_T \cdot \vec{p}_i|$$









- **The factorized cross section in Laplace space is**

$$\frac{\mathrm{d}\sigma^{\mathcal{P}}}{\mathrm{d}\tau\,\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_0^{\mathcal{P}}}{\mathrm{d}\Omega} H\left(Q^2,\mu\right) \int_{\gamma-i\infty}^{\gamma+i\infty} \frac{\mathrm{d}u}{2\pi i} \frac{e^{u\tau/e^{\gamma_E}}}{e^{\gamma_E}} S_T\left(\frac{u}{Q},\mu\right) \times \sum_q e_q^2\, \mathcal{G}_{\Lambda/q}^{\mathcal{P}}\left(z_1, \frac{u}{Q^2},\mu\right) \mathcal{G}_{\Lambda/\bar{q}}^{\mathcal{P}}\left(z_2, \frac{u}{Q^2},\mu\right) .$$

- **Polarized fragmenting jet functions**

$$\mathcal{G}_{\Lambda/q}^{\mathcal{P}}\left(z, \frac{u}{Q^2},\mu\right) = \sum_j \int_z^1 \frac{\mathrm{d}x}{x} \mathcal{J}_{jq}^{\mathcal{P}}\left(\frac{z}{x}, \frac{u}{Q^2},\mu\right) \mathcal{D}_{\Lambda/j}^{\mathcal{P}}(x,\mu)$$

Spin correlation in Λ pair production with a thrust cut

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- **The resummation predictions on the polarized cross section**

$$\boxed{\mu_h = Q, \quad \mu_J = Q\sqrt{\tau_{\rm cut}}, \quad \mu_s = Q\tau_{\rm cut}.}$$

$$\frac{\mathrm{d}\sigma^{\mathcal{P}}(\tau_{\rm cut})}{\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega} = \int_0^{\tau_{\rm cut}} \mathrm{d}\tau\, \frac{\mathrm{d}\sigma^{\mathcal{P}}}{\mathrm{d}\tau\,\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega}\,,$$

$$= \frac{\mathrm{d}\sigma_0^{\mathcal{P}}}{\mathrm{d}\Omega} \exp\left[4C_F S(\mu_h,\mu_J) + 4C_F S(\mu_s,\mu_J) - 2A_H(\mu_h,\mu_s) + 4A_J(\mu_J,\mu_s)\right] \left(\frac{Q^2}{\mu_h^2}\right)^{-2C_F A_{\rm cusp}(\mu_h,\mu_J)}$$

$$\times H(Q^2,\mu_h)\, \widetilde{S}_T(\partial_\eta,\mu_s)$$

$$\times \sum_q e_q^2\, \widetilde{\mathcal{G}}^{\mathcal{P}}_{\Lambda/q}\left(z_1, \ln\frac{\mu_s Q}{\mu_J^2} + \partial_\eta, \mu_J\right) \widetilde{\mathcal{G}}^{\mathcal{P}}_{\bar\Lambda/\bar q}\left(z_2, \ln\frac{\mu_s Q}{\mu_J^2} + \partial_\eta, \mu_J\right) \left(\frac{\tau_{\rm cut} Q}{\mu_s}\right)^{\eta} \frac{e^{-\gamma_E \eta}}{\Gamma(1+\eta)}\bigg|_{\eta = 4C_F A_{\rm cusp}(\mu_J,\mu_s)}.$$

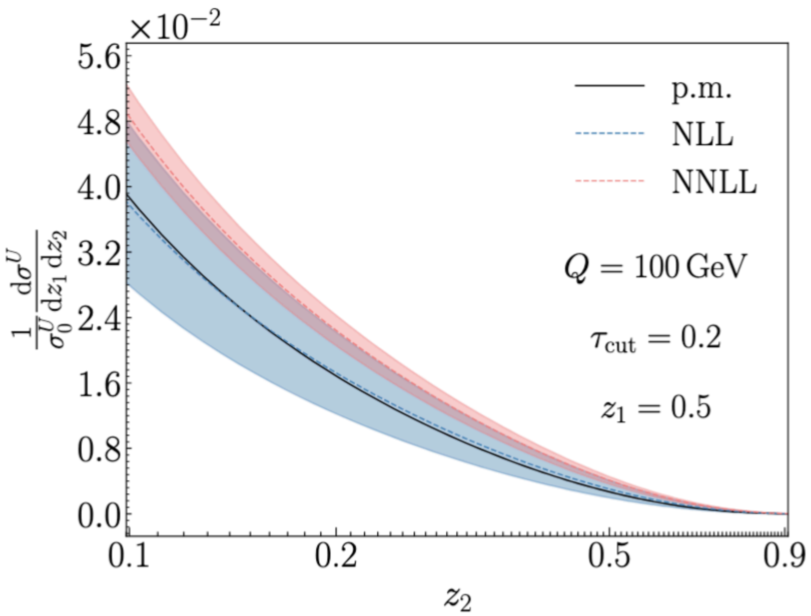
- **For the non-perturbative Λ FFs, we employ the DSV parameterization for the unpolarized Λ FF** (de Florian, Stratmann, Vogelsang '97)

- **We can utilize theoretical positivity bounds to define their maximal contribution** (Soffer '94; Vogelsang '97)

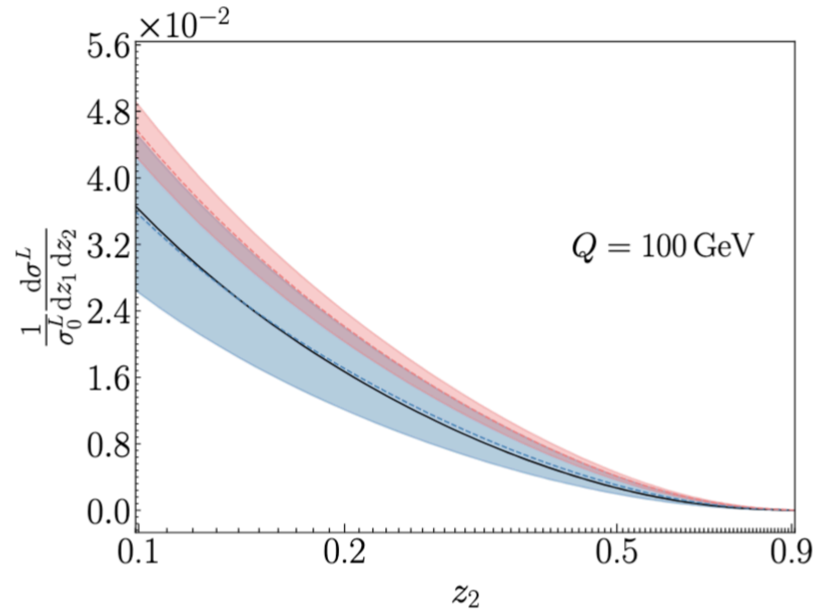
$$|\mathcal{D}^L(z,\mu_0)| \le \mathcal{D}^U(z,\mu_0)\,, \qquad |\mathcal{D}^T(z,\mu_0)| \le \frac{1}{2}\left[\mathcal{D}^U(z,\mu_0) + \mathcal{D}^L(z,\mu_0)\right]$$

Bell nonlocality and decoherence

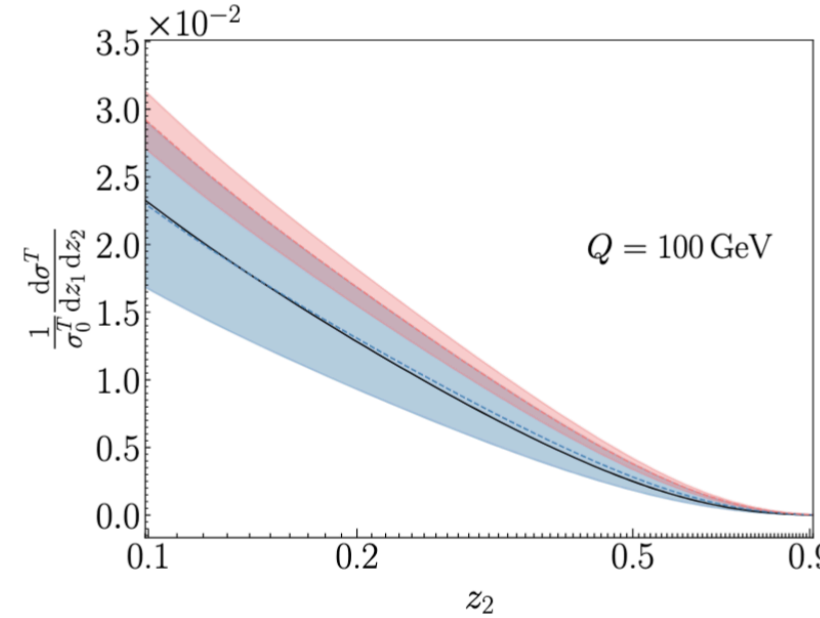
S.J. Lin, MJL, D.Y. Shao, S.Y. Wei ‘25



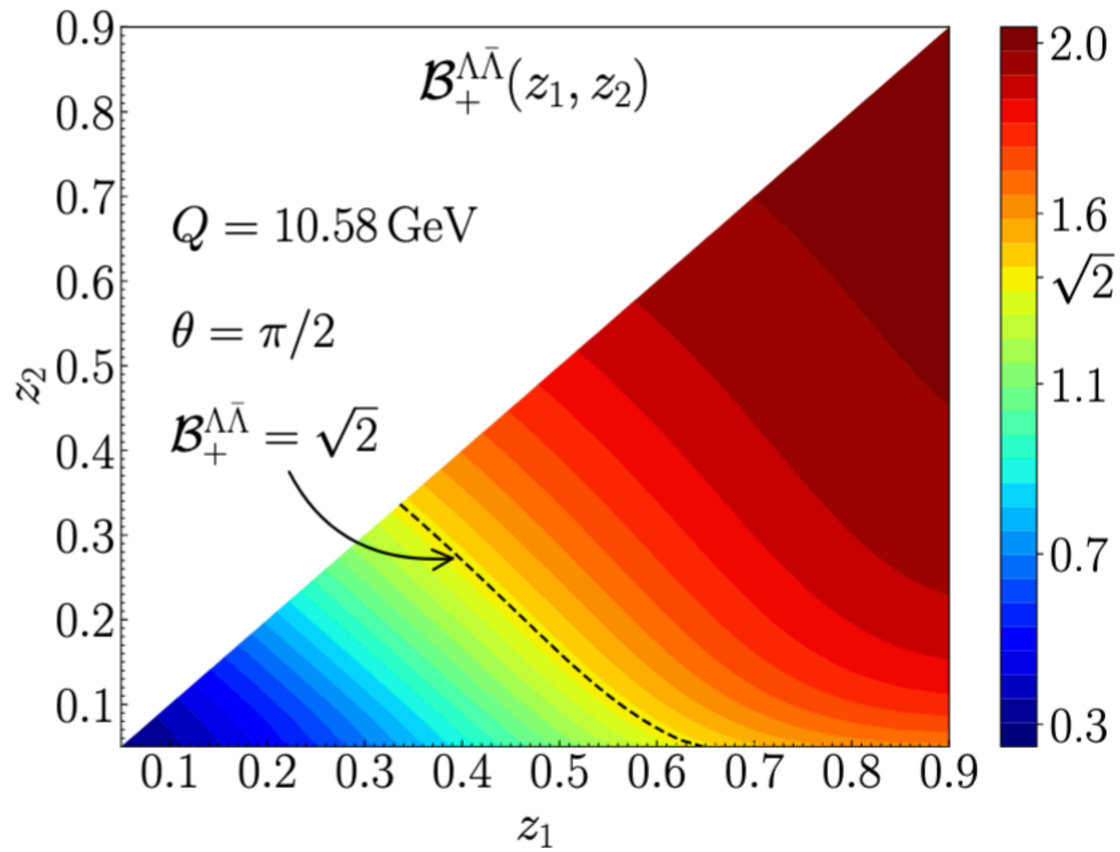
Unpolarized



Longitudinally polarized



Transversely polarized



- We observe that under these ideal hadronization assumptions, the Bell variable is suppressed below the partonic maximum of 2
- As expected, this decoherence is reduced at large z, where the hadron carries most of the parent parton’s spin information

Bell nonlocality and decoherence

S.J. Lin, MJL, D.Y. Shao, S.Y. Wei '25

- We construct three corresponding models for the polarized FFs:

  - Scenario 1 (Static quark model scenario)

$$\mathcal{D}_s^T(z,\mu_0) = z\,\mathcal{D}_s^U(z,\mu_0) \text{ and } \mathcal{D}_u^T(z,\mu_0) = \mathcal{D}_d^T(z,\mu_0) = 0$$

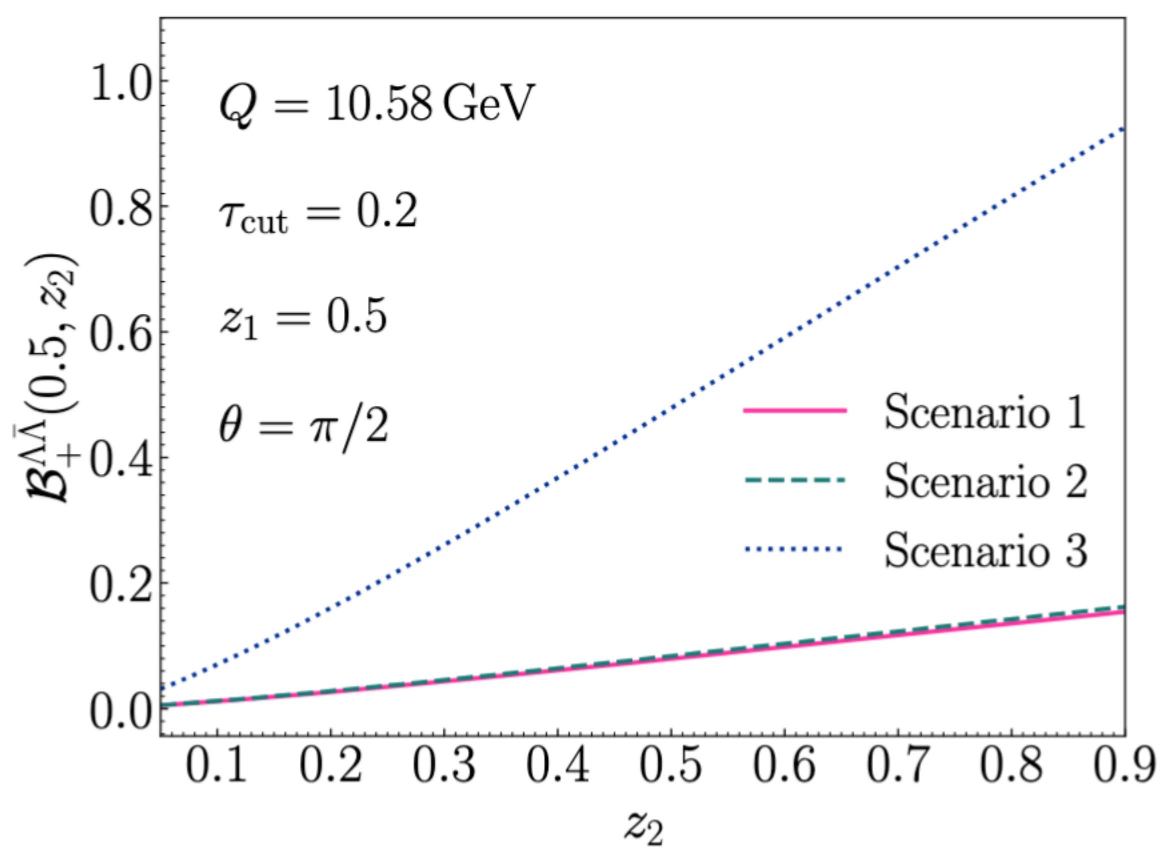
  - Scenario 2 (Burkardt-Jaffe scenario)

$$\mathcal{D}_{u/d}^T(z,\mu_0) = -0.1\,z\,\mathcal{D}_{u/d}^U(z,\mu_0) \text{ and } \mathcal{D}_s^T(z,\mu_0) = z\,\mathcal{D}_s^U(z,\mu_0)$$

  - Scenario 3 (SU(3) symmetric scenario)

$$\mathcal{D}_{u/d/s}^T(z,\mu_0) = z\,\mathcal{D}_{u/d/s}^U(z,\mu_0)$$

- The results from Scenario 1 and Scenario 2 are comparable.
- In all three scenarios, the hadronic Bell variable remains far below the violation threshold.



Summary and outlooks

- We have established a systematic framework for calculating spin decoherence by unifying SCET with the formalism of open quantum systems.
- Our central finding is that the renormalization group evolution constitutes a quantum channel, where the RG flow parameter, rather than time, drives a Markovian loss of quantum coherence.
- Using the thrust event shape, we studied hyperon—antihyperon production, linked experimentally accessible spin correlations to the Bell inequality, and confirmed decoherence effects during hadronization.
- Quantum information science meets fragmentation.

Thank you