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

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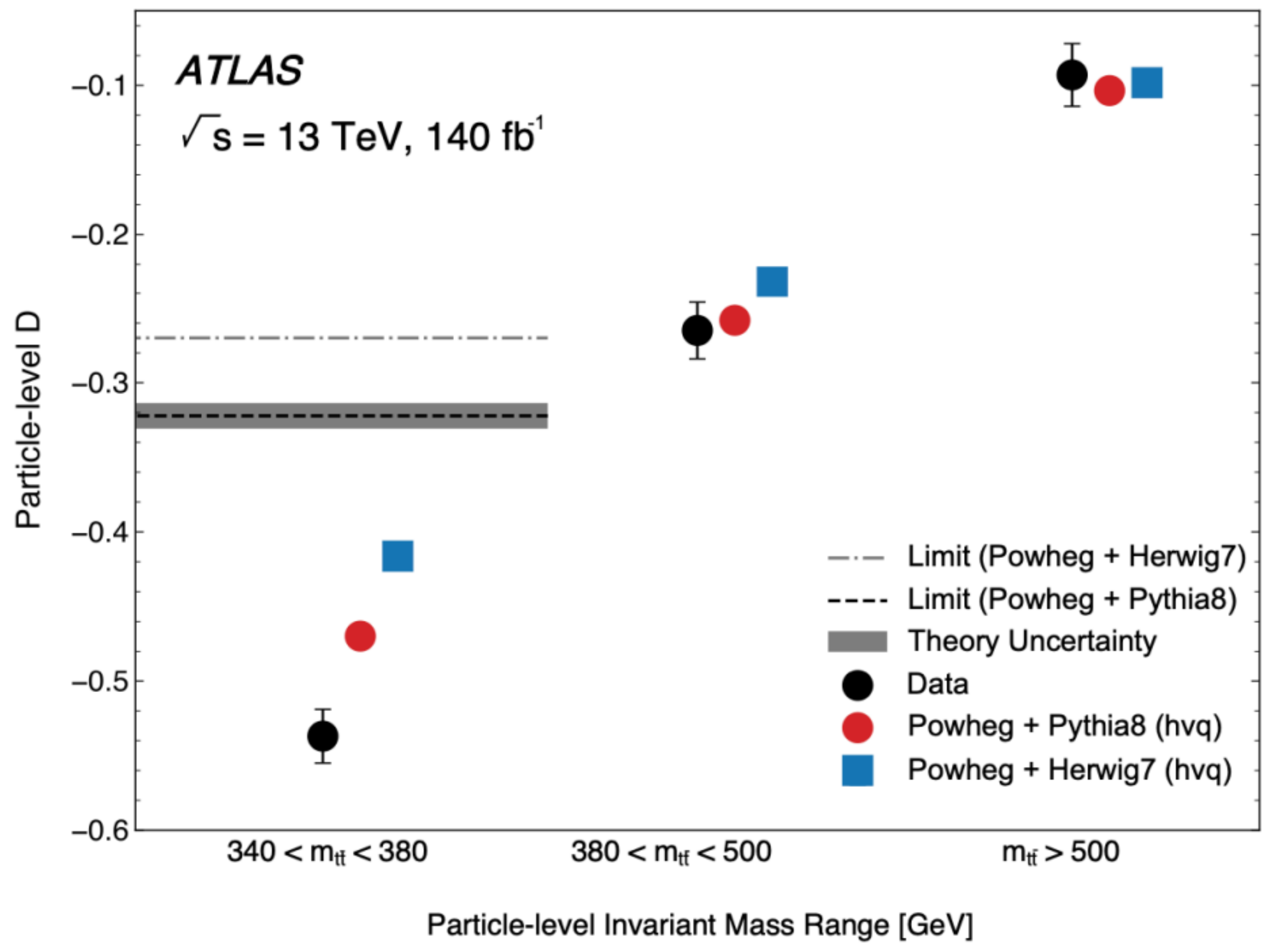
Testing Quantum Entanglement in $t\bar{t}$ at LHC

Reconstructing Density matrix Experimentally From decay products



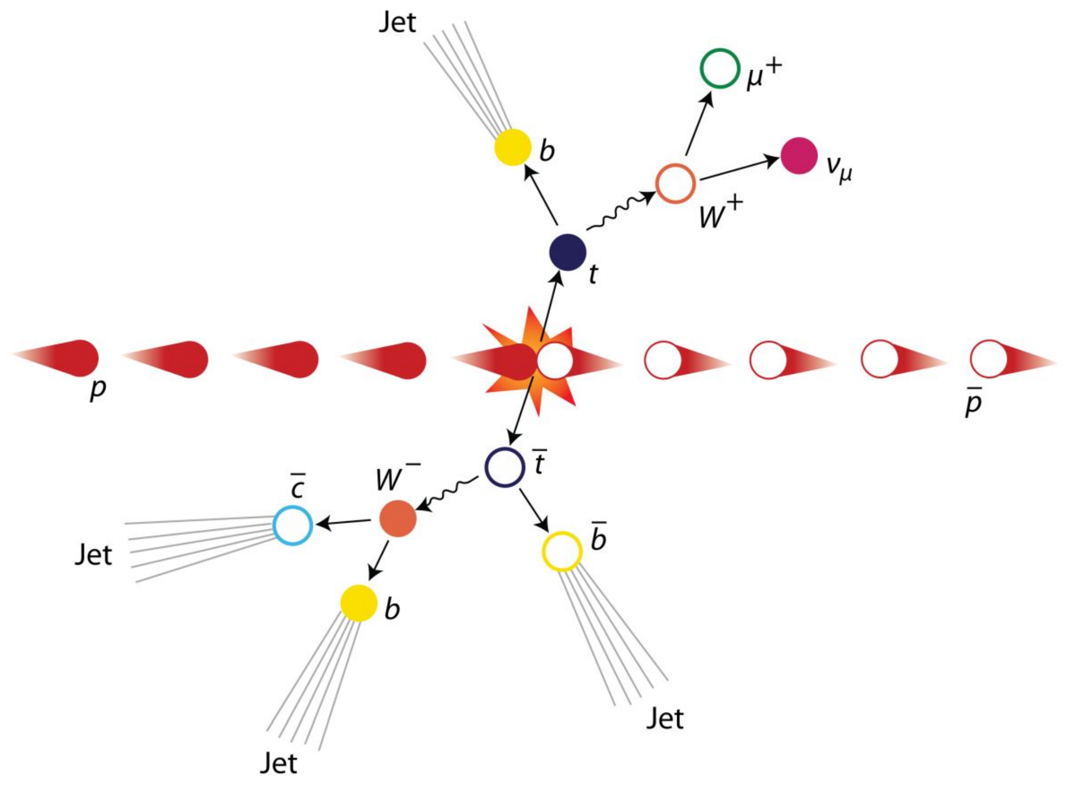
ATLAS Nature 2024

Spin correlation matrix

$$\hat{\rho} = \frac{1}{4}\left(\hat{I}_2 \otimes \hat{I}_2 + \sum_{i=1}^{3} B_i^+ \hat{\sigma}_i \otimes \hat{I}_2 + \sum_{i=1}^{3} B_i^- \hat{I}_2 \otimes \hat{\sigma}_i + \sum_{i,j=1}^{3} C_{ij} \hat{\sigma}_i \otimes \hat{\sigma}_j \right)$$

- **Top quark decays before hadronization**
- **Spin information is preserved in decay products**
- **Charged leptons are optimal spin analyzers**

$$t \to b\, \ell^+\, \nu, \qquad \bar{t} \to \bar{b}\, \ell^-\, \bar{\nu}$$



- **Angular Correlations of the two leptons —— Spin correlation of the top quark pair**

$$\langle \hat{\ell}_+^i \hat{\ell}_-^j \rangle \propto C_{ij}$$

Testing Quantum Entanglement in $t\bar{t}$ at LHC

Calculating Density matrix Theoretically From helicity amplitudes

Spin correlation matrix

$$\hat{\rho} = \frac{1}{4}\left(\hat{I}_2 \otimes \hat{I}_2 + \sum_{i=1}^{3} B_i^+ \hat{\sigma}_i \otimes \hat{I}_2 + \sum_{i=1}^{3} B_i^- \hat{I}_2 \otimes \hat{\sigma}_i + \sum_{i,j=1}^{3} \boxed{C_{ij}} \hat{\sigma}_i \otimes \hat{\sigma}_j\right) .$$

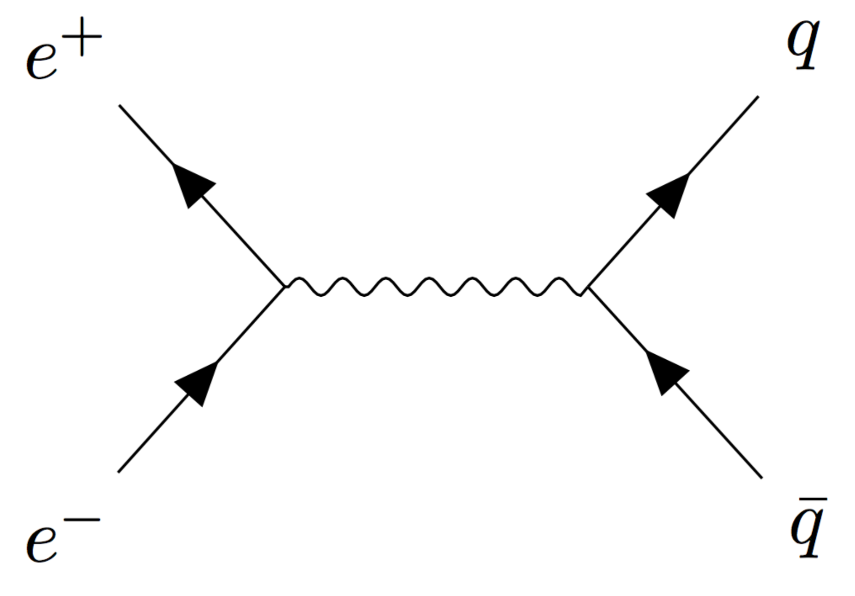
$$|\mathrm{out}\rangle = \sum_{\lambda_1,\lambda_2} \mathcal{M}_{\lambda_1\lambda_2}(s,\Theta)\,|\lambda_1;\lambda_2\rangle \quad \Rightarrow \quad \rho_{\lambda_1\lambda_2\lambda_1'\lambda_2'} = \mathcal{M}_{\lambda_1\lambda_2}\mathcal{M}^*_{\lambda_1'\lambda_2'}$$

At 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 measure the concurrence

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

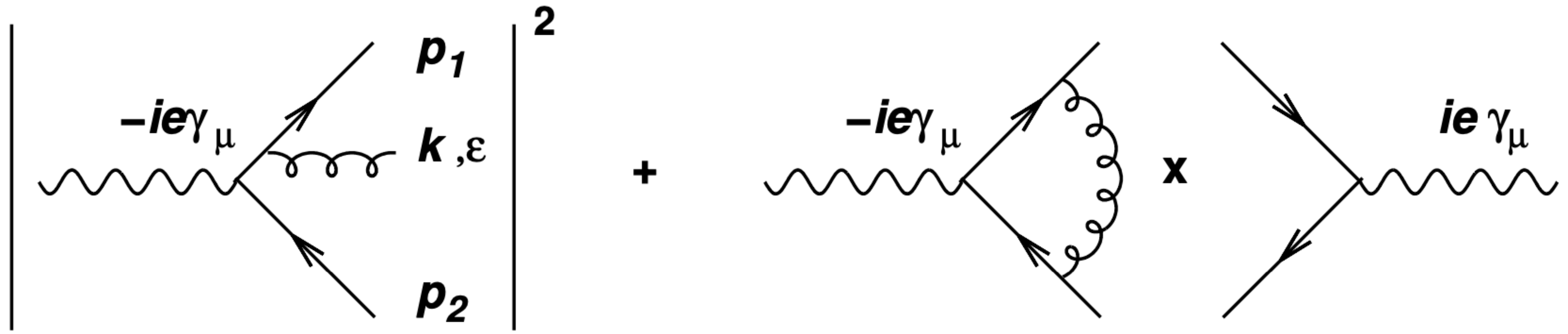
At the central scattering region, $\mathcal{C}[\rho_{\mathrm{LO}}] = 1$ $\quad \frac{1}{\sqrt{2}}(|+-\rangle + |-+\rangle)$



$t\bar{t}$ as an open system

Aoude, Barr, Maltoni, Satrioni '25

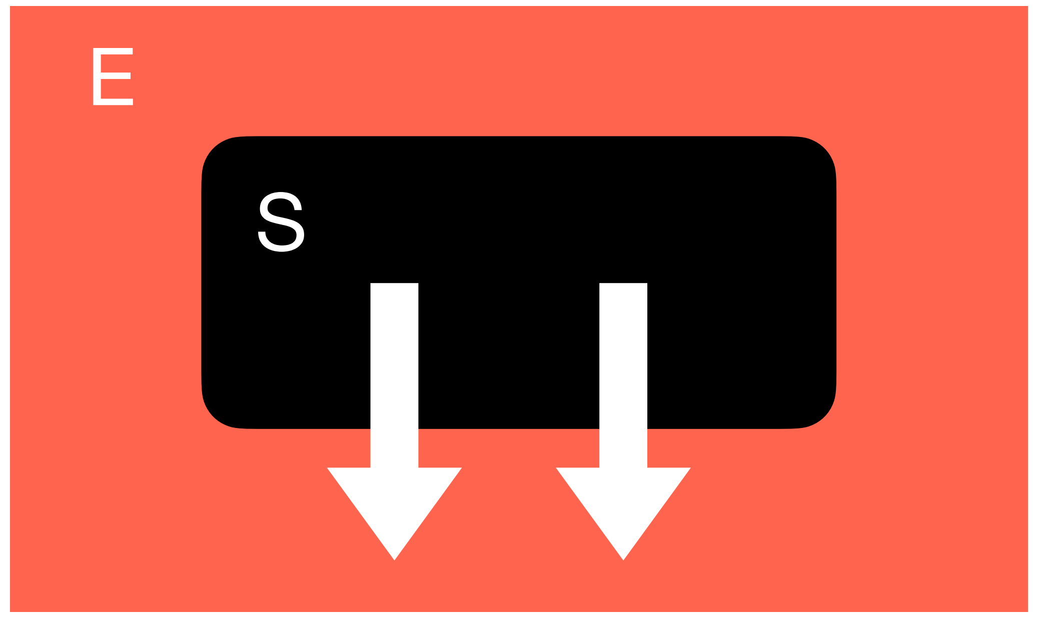
- Top quarks may radiate gluons or photons in the short period of time before decaying, leading to a reduction in quantum spin information, i.e., decoherence.



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

Kraus operators: Kraus representation theorem

Kraus operators and master equations for an open system



$$
\begin{tikzcd}
\rho_A(t_0)\otimes\rho_B(t_0) \arrow[r, "U(t_1,t_0)"] \arrow[d, "\mathrm{Tr}_B"'] & \rho_{AB}(t_1) \arrow[d, "\mathrm{Tr}_B"] \\
\rho_A(t_0) \arrow[r, "\mathcal{E}_{(t_1,t_0)}"] & \rho_A(t_1)
\end{tikzcd}
$$

Kraus operators: Kraus representation theorem

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

Master equation: Lindblad operators

$$\dot{\rho} = -i[H,\rho] + \sum_k \left(L_k \rho L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho\} \right)$$

Decoherence Models for a Single Qubit

- Bit-flip Channel

$$|0\rangle \leftrightarrow |1\rangle$$

$$\mathcal{E}(\rho) = |\alpha|^2 \sigma_x \rho \sigma_x^\dagger + (1-|\alpha|^2)\rho$$

- Phase-flip Channel

$$\mu|0\rangle + \nu|1\rangle \leftrightarrow \mu|0\rangle - \nu|1\rangle$$

$$\mathcal{E}(\rho) = |\gamma|^2 \sigma_z \rho \sigma_z^\dagger + (1-|\gamma|^2)\rho$$

“QED/QCD preserves helicity in for massless fermions”

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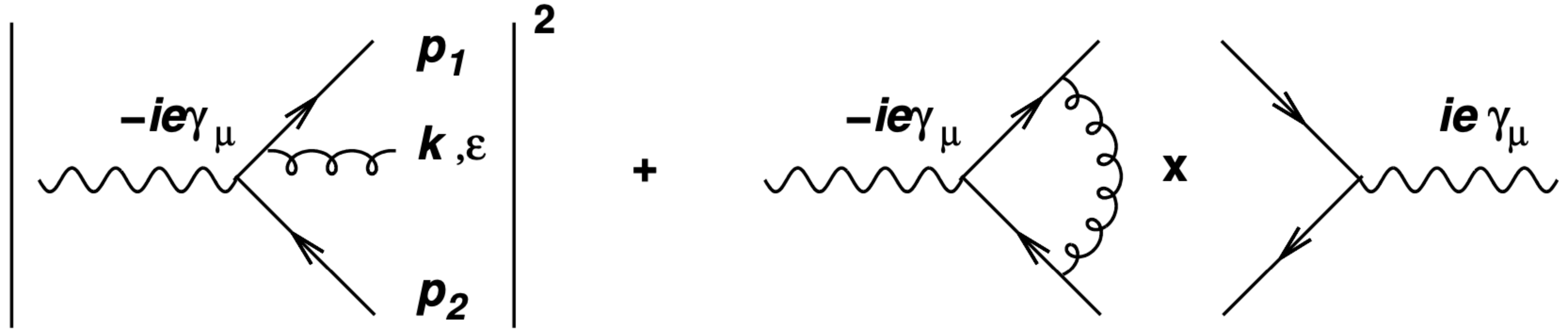


$$\rho^{\mathrm{red}}_{\mathrm{LO+NLO}} = \mathsf{p}_{\mathrm{LO}}\,\mathbb{1}\rho_{\mathrm{LO}}\mathbb{1} + \bar{\mathcal{E}}_{\mathrm{V}}[\rho_{\mathrm{LO}}] + \bar{\mathcal{E}}_{\mathrm{R}}[\rho_{\mathrm{LO}}]$$

$$\bar{\mathcal{E}}_{\mathrm{V}}[\rho_{\mathrm{LO}}] = \mathsf{p}_{\mathrm{V}}\mathbb{1}\rho_{\mathrm{LO}}\mathbb{1} \qquad \bar{\mathcal{E}}_{\mathrm{R}}[\rho_{\mathrm{LO}}] = \sum_j K_j \rho_{\mathrm{LO}} K_j^\dagger$$

Virtual

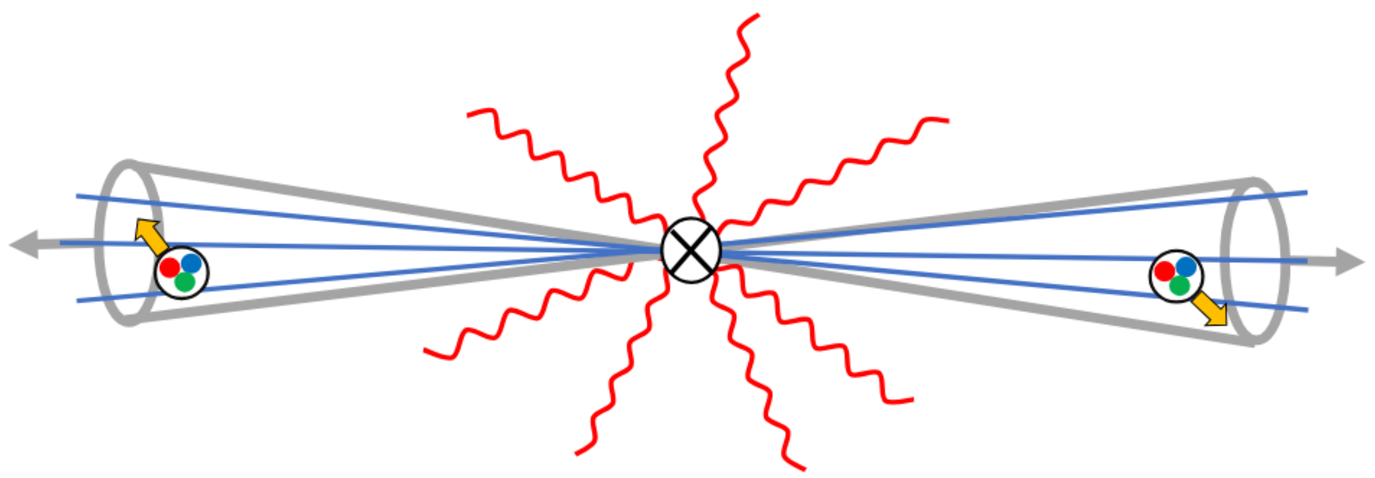
Real: ~~hard~~, collinear, ~~soft~~

Effective Field Theory for decoherence

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

- **Radiation should be considered unresolvable if either soft of collinear**
- **We apply Soft Collinear Effective Theory (SCET)**
- **We introduce the energy and angular resolution parameters, which is similar to Sterman-Weinberg cone jet definition** (Sterman, Weinberg ’77)

Two fermion events:



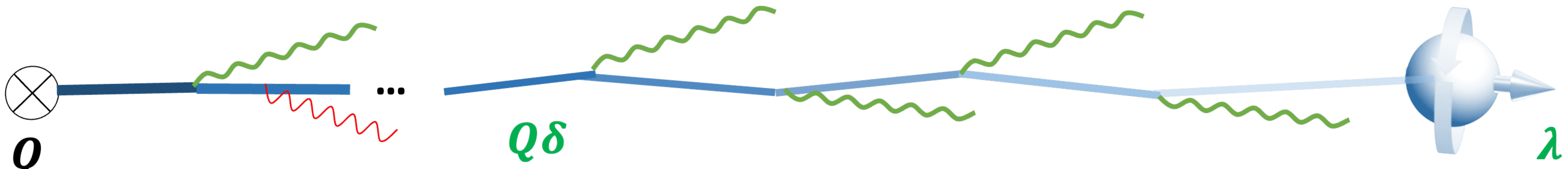
- Using SCET factorization theorems, the production density matrix of the fermion pair is factorized:

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

OPE

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

At leading order, soft emissions are spin-independent and thus **do not** induce decoherence



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

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

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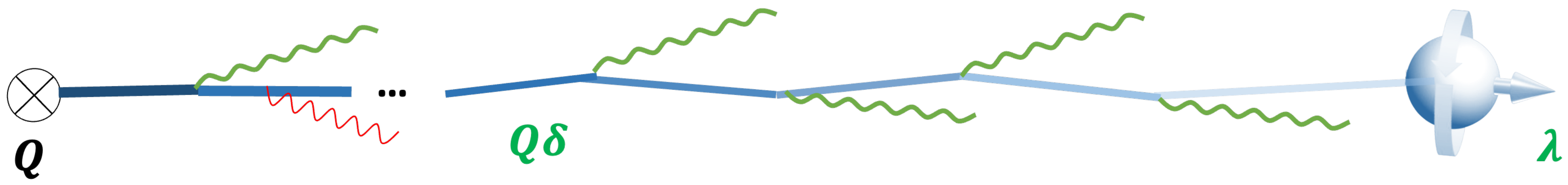
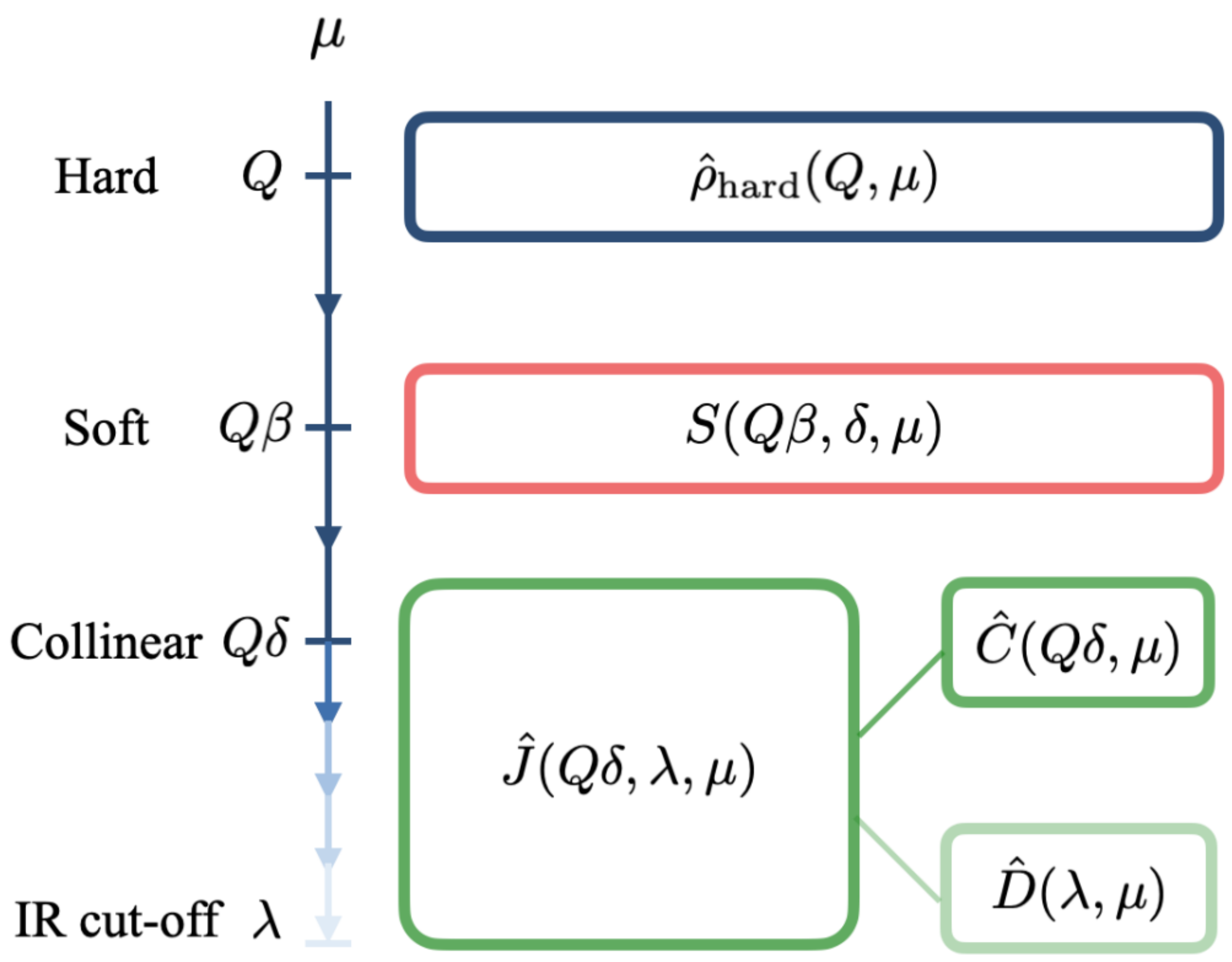
$$\hat{R} = \hat{J}_f(Q\delta, \lambda, \mu)\hat{R}_{\rm hard}(Q,\mu)\hat{J}_{\bar{f}}(Q\delta, \lambda, \mu)S(Q\beta, \delta, \mu)$$





- 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

$$\sum_X \langle 0|\psi|fX\rangle\langle fX|\bar{\psi}|0\rangle$$

Spin decomposition

$$\hat{J}_f = \mathcal{J}_f^U\,\hat{I}\otimes\hat{I} + \mathcal{J}_f^L\hat{\sigma}_z\otimes\hat{\sigma}_z + \mathcal{J}_f^T(\hat{\sigma}_x\otimes\hat{\sigma}_x + \hat{\sigma}_y\otimes\hat{\sigma}_y)$$

- **J^U : unpolarized**
- **J^L : longitudinal polarized**
- **J^T : transverse polarized**

Effective Field Theory for decoherence

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- **Refactorization via an operator product expansion**

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

- **Define a scale-dependent effective production matrix**

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

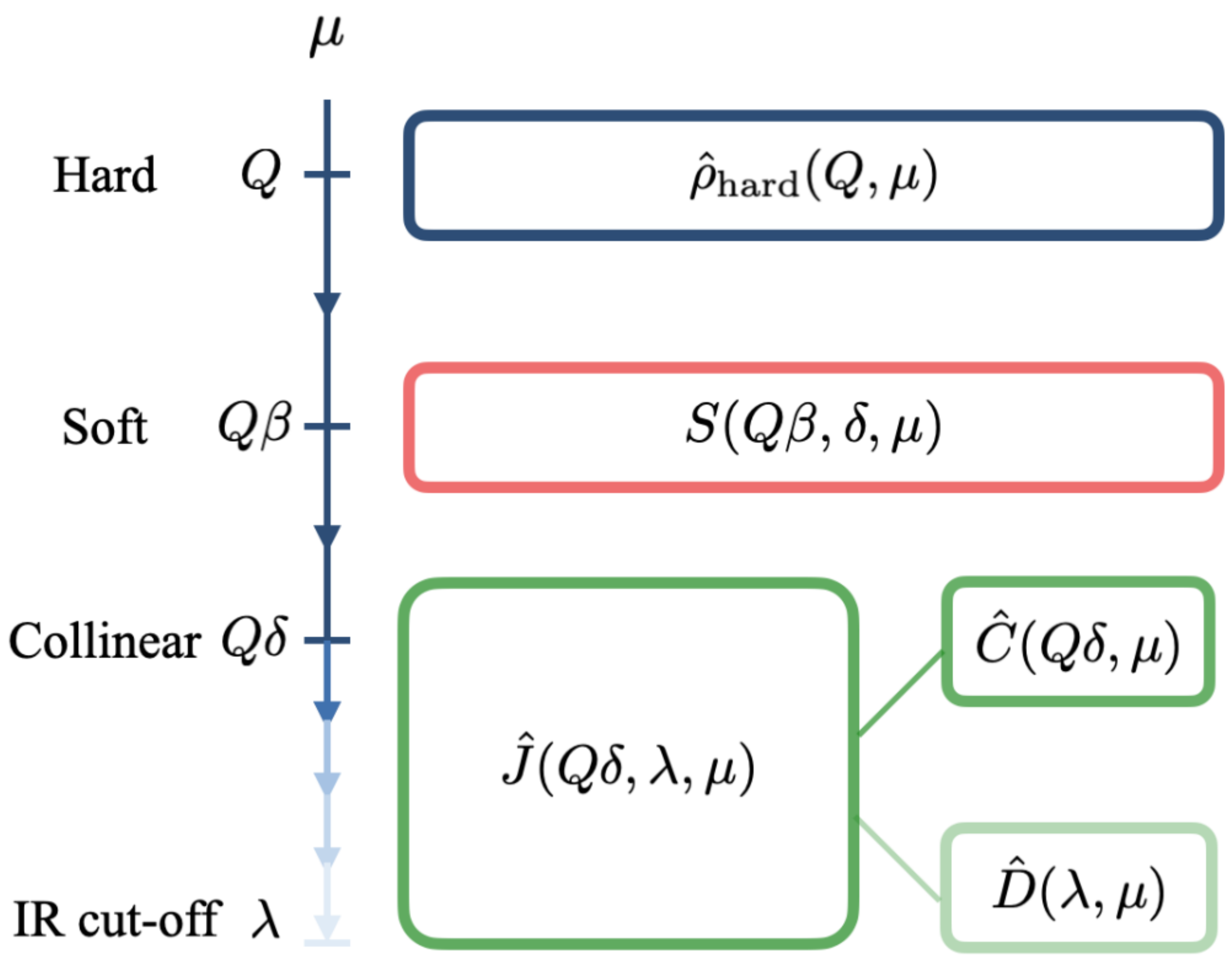
- **Renormalization group eqn**

$$t \equiv \log(Q\delta/\mu).$$

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

$$U^{\mathcal{P}}(t, 0) = \exp\left(\int_0^t \mathrm{d}t\, \gamma^{\mathcal{P}}\right) \qquad \gamma^{\mathcal{P}} \equiv \frac{\alpha}{\pi} P^{\mathcal{P}}_{ff}$$

1st Mellin moment of splitting function



decoherence = RG flow

anomalous dimensions determine the information loss

Effective Field Theory for decoherence

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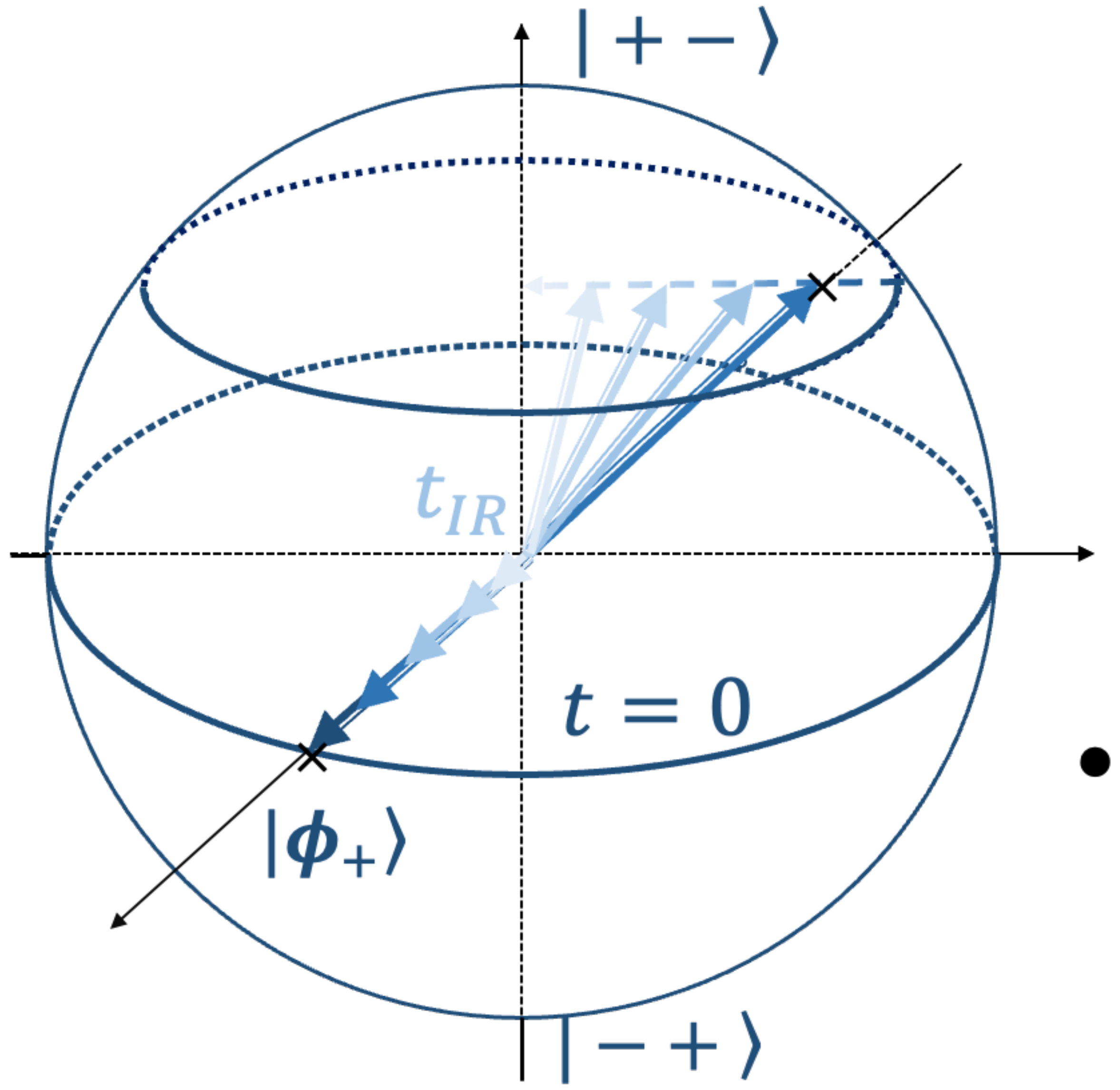
- collinear photon emission ↔ **phase-flip** channel

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



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

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

- Final-state concurrence for general cases

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

Effective Field Theory for decoherence

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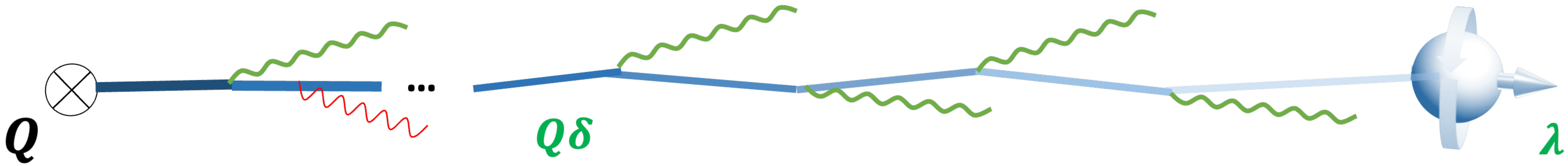
$$\hat{R} = \boxed{\hat{J}_f(Q\delta, \lambda, \mu)}\,\boxed{\hat{R}_{\rm hard}(Q, \mu)}\,\boxed{\hat{J}_{\bar{f}}(Q\delta, \lambda, \mu)}\;\boxed{S(Q\beta, \delta, \mu)}$$

OPE

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



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

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

At scale Q: Production	From $Q\delta$ to λ: Collinear Emission	At scale λ: Measurement
✔	✔	✘

Measurement operator

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- **The final stage of the process is the projection of the evolved spin state onto a definite experimental outcome**

- **Define spin-dependent measurement operator** $\hat{M}_f(\boldsymbol{S}_f) \equiv \hat{D}_f \hat{P}_f$

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

- **Decoherence from fragmentation and hadronization**

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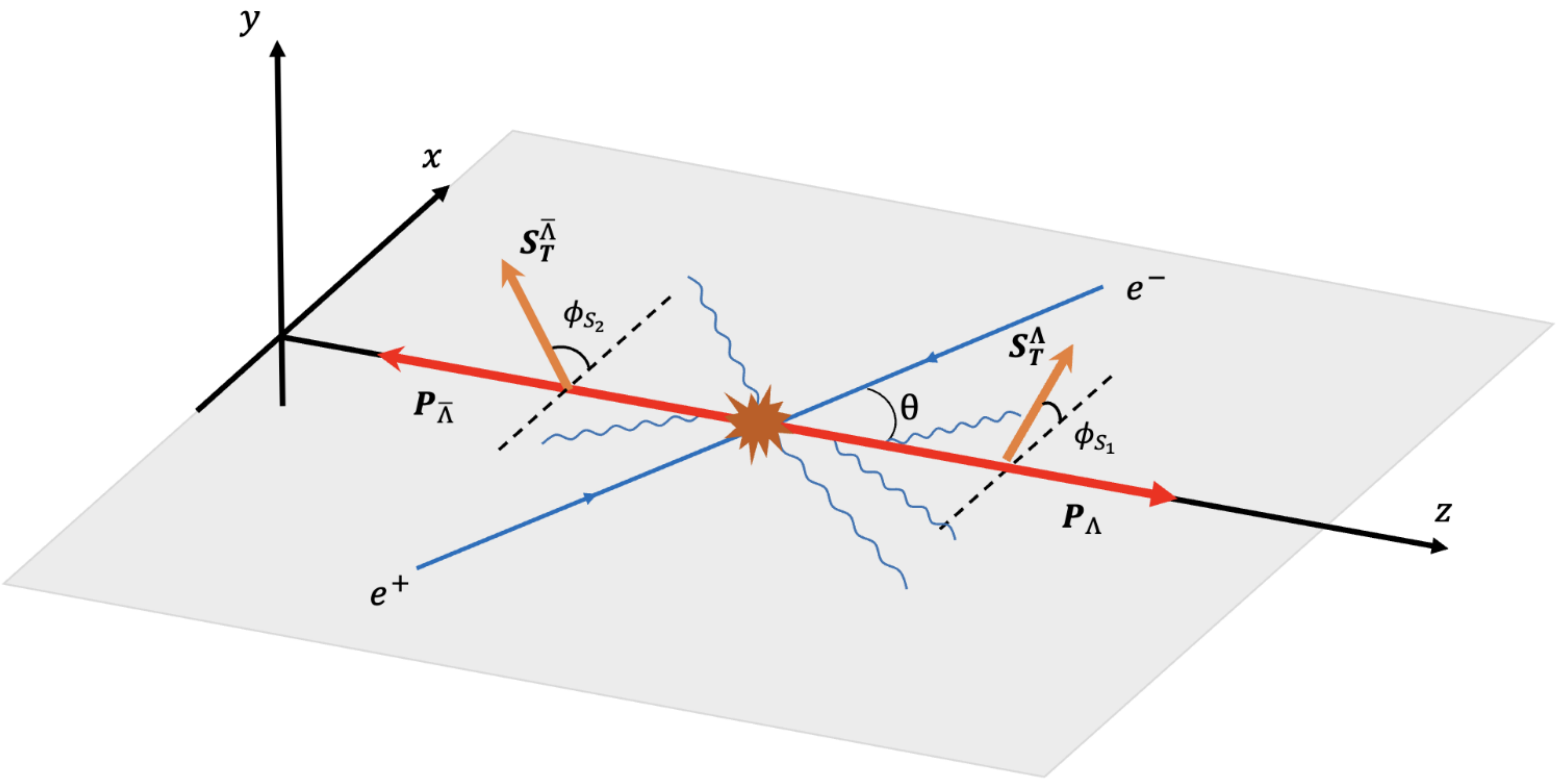

Spin correlation in Λ pair production with a thrust cut

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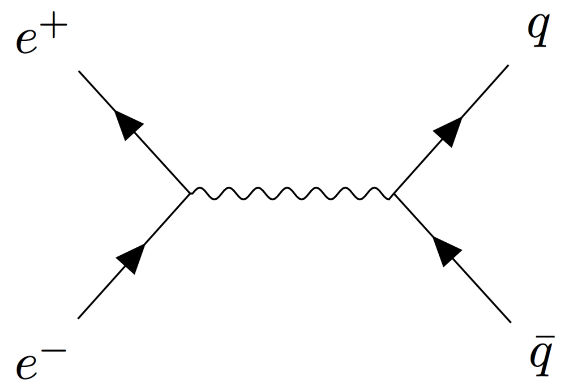
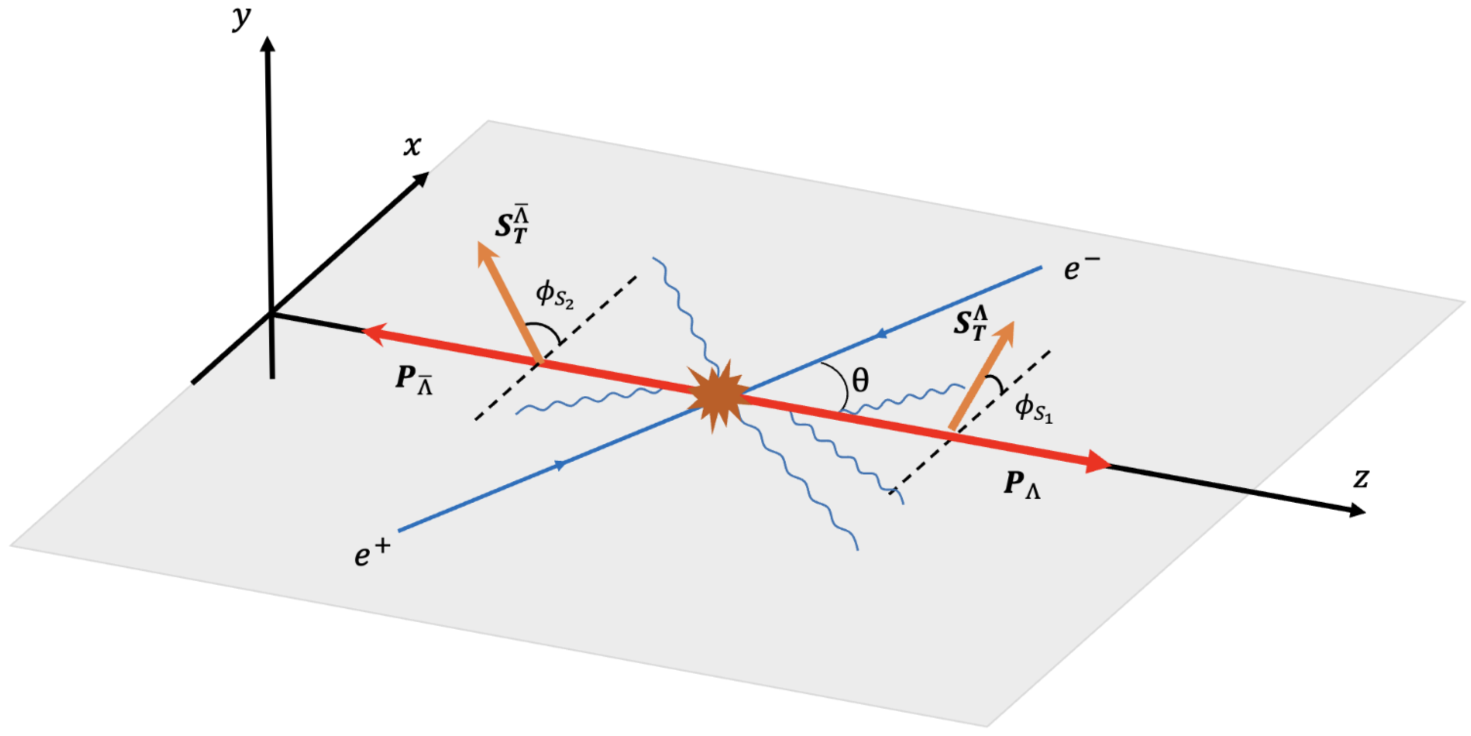
Bell variable
Parton-level

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



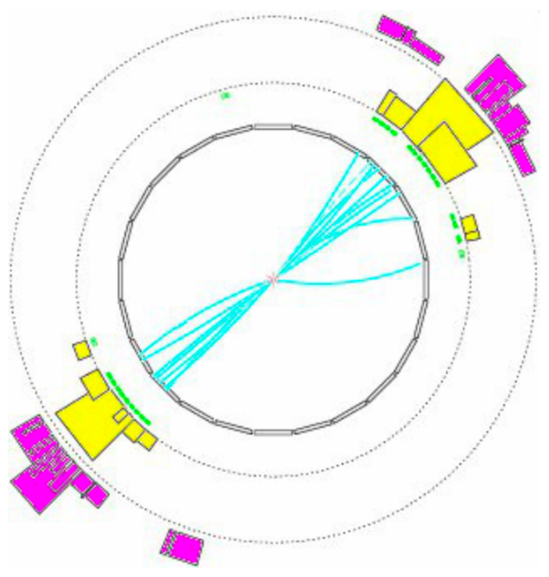
Bell variable
Hadron-level

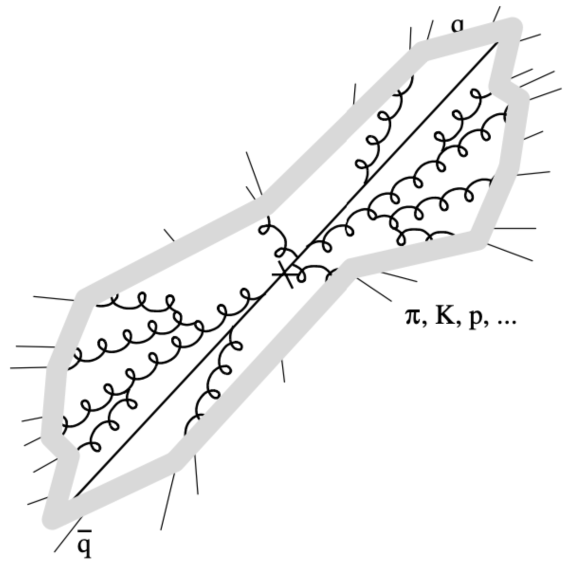
$$\mathcal{B}_{+}^{\Lambda\bar{\Lambda}} = \frac{2\,\mathrm{d}\sigma^T}{\mathrm{d}\sigma^U}$$

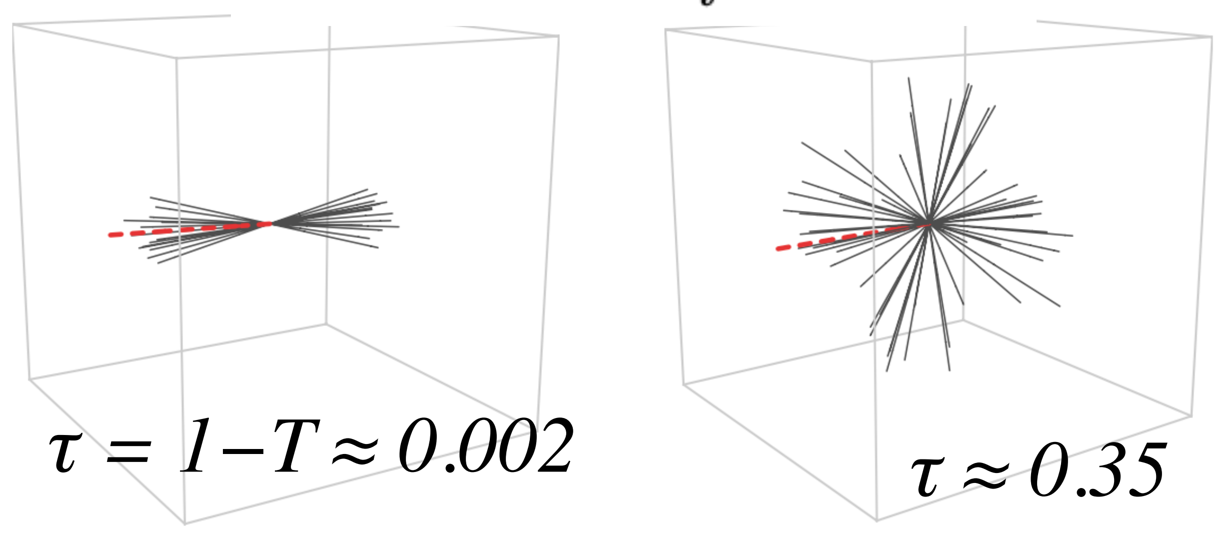


- **We apply the event shape thrust (T) to select two-jet configuration**

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







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

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

$$\begin{aligned}
\frac{\mathrm{d}\sigma^{\mathcal{P}}(\tau_{\rm cut})}{\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega} &= \int_0^{\tau_{\rm cut}} \mathrm{d}\tau\,\frac{\mathrm{d}\sigma^{\mathcal{P}}}{\mathrm{d}\tau\,\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega}\,,\\
&= \frac{\mathrm{d}\sigma_0^{\mathcal{P}}}{\mathrm{d}\Omega}\exp\left[4C_F S(\mu_h,\mu_J) + 4C_F S(\mu_s,\mu_J) - 2A_H(\mu_h,\mu_s) + 4A_J(\mu_J,\mu_s)\right]\left(\frac{Q^2}{\mu_h^2}\right)^{-2C_F A_{\rm cusp}(\mu_h,\mu_J)}\\
&\times H(Q^2,\mu_h)\,\widetilde{S}_T\left(\partial_\eta,\mu_s\right)\\
&\times \sum_q e_q^2\,\widetilde{\mathcal{G}}^{\mathcal{P}}_{\Lambda/q}\left(z_1,\ln\frac{\mu_s Q}{\mu_J^2}+\partial_\eta,\mu_J\right)\widetilde{\mathcal{G}}^{\mathcal{P}}_{\Lambda/\bar{q}}\left(z_2,\ln\frac{\mu_s Q}{\mu_J^2}+\partial_\eta,\mu_J\right)\left(\frac{\tau_{\rm cut}Q}{\mu_s}\right)^{\eta}\frac{e^{-\gamma_E\eta}}{\Gamma(1+\eta)}\Bigg|_{\eta=4C_F A_{\rm cusp}(\mu_J,\mu_s)}
\end{aligned}$$

Spin correlation in Λ pair production with a thrust cut

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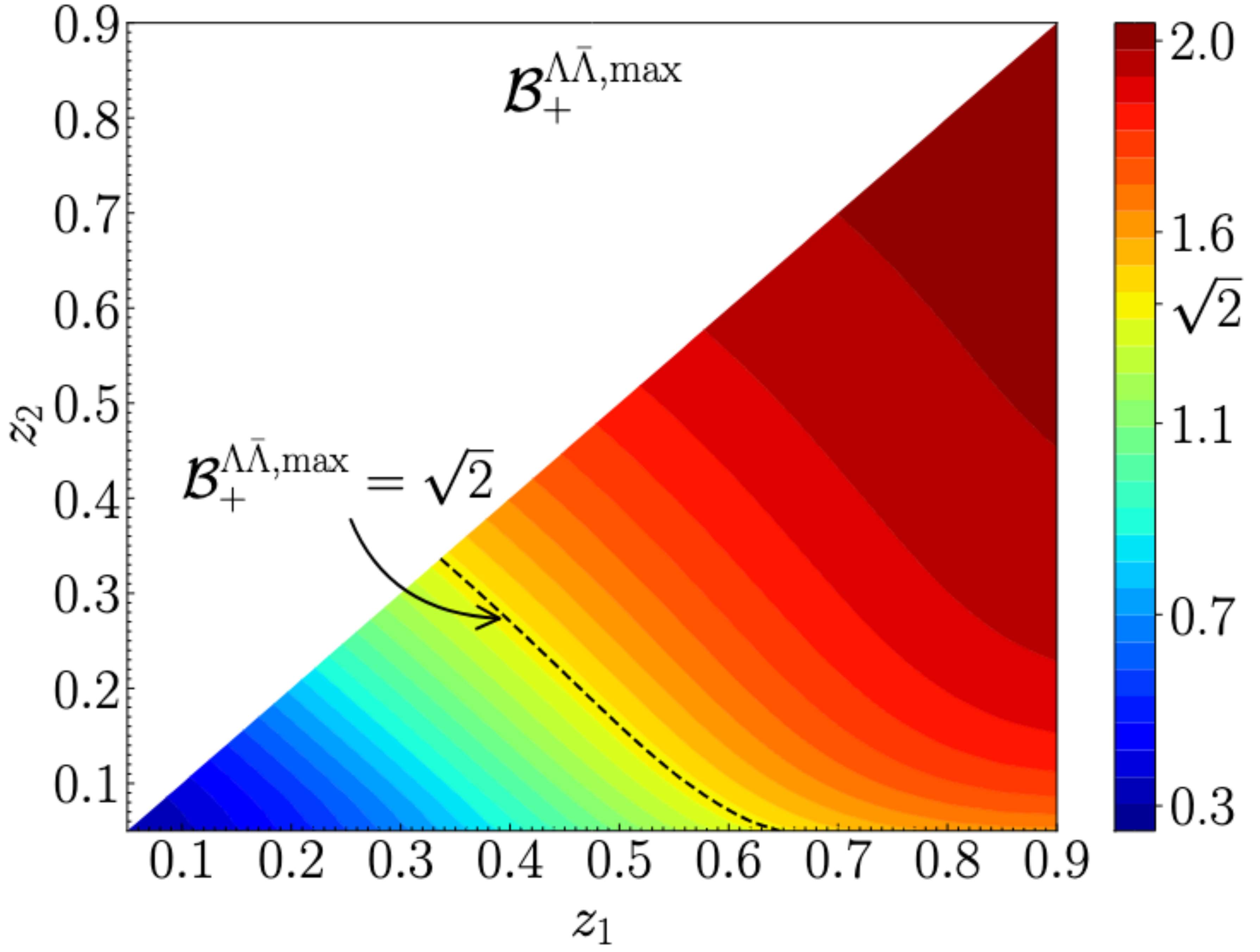
- **For the non-perturbative Λ FFs, we employ the DSV parameterization for the unpolarized Λ FF** (de Florian, Stratmann, Vogelsang '97)
- **We can utilize theoretical positivity bounds to define their maximal contribution** (Soffer '94; Vogelsang '97)

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

- **We start from the ideal partonic baseline of a maximally entangled** $\mathcal{B}_+^{q\bar{q}} = 2$
  - **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**



Summary

- **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.**
- **We work under the assumption that the process is Markovian to a good approximation. At the same time, there could be important non-Markovian effects.**

- **K0 K0bar system** (Bertlmann ’04) **ΛΛbar system** (Wu, Qian, Yang, Wang ’24)
- **“Infrared quantum information” Soft radiation decrease momentum entanglement** (Carney, Chaurette, Neuenfeld, Semenof ’17)
- **Decoherence and precision calculation** (Aoude, Barr, Maltoni, Satrioni ’25)
- **Decoherence and renormalization group flow** (Lin, Liu, DYS, Wei ’25, Gu, Lin, DYS, Yang, Wang’25)
- **Decoherence and decoupling in effective field theory** (Burgess, Colas , Holman, Kaplanek ’25)
- **Black hole horizons decohere superpositions** (Biggs, Maldacena ’24)

Open Quantum Systems: Dissipative Dynamics from Quarks to the Cosmos

December 1, 2025 - December 12, 2025

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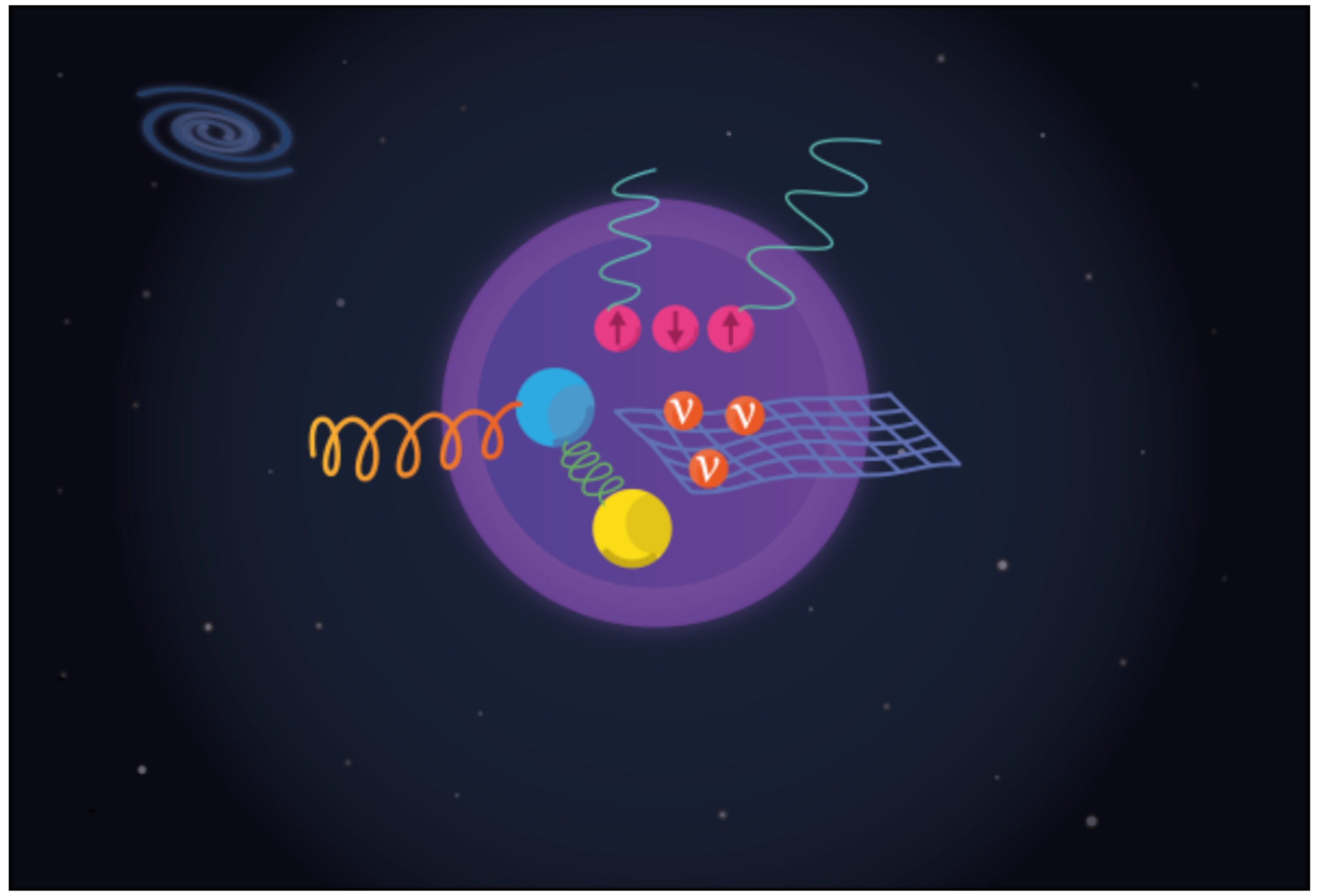

The application deadline for this event has passed.

Thank You