开放量子系统的退相干与重整化群

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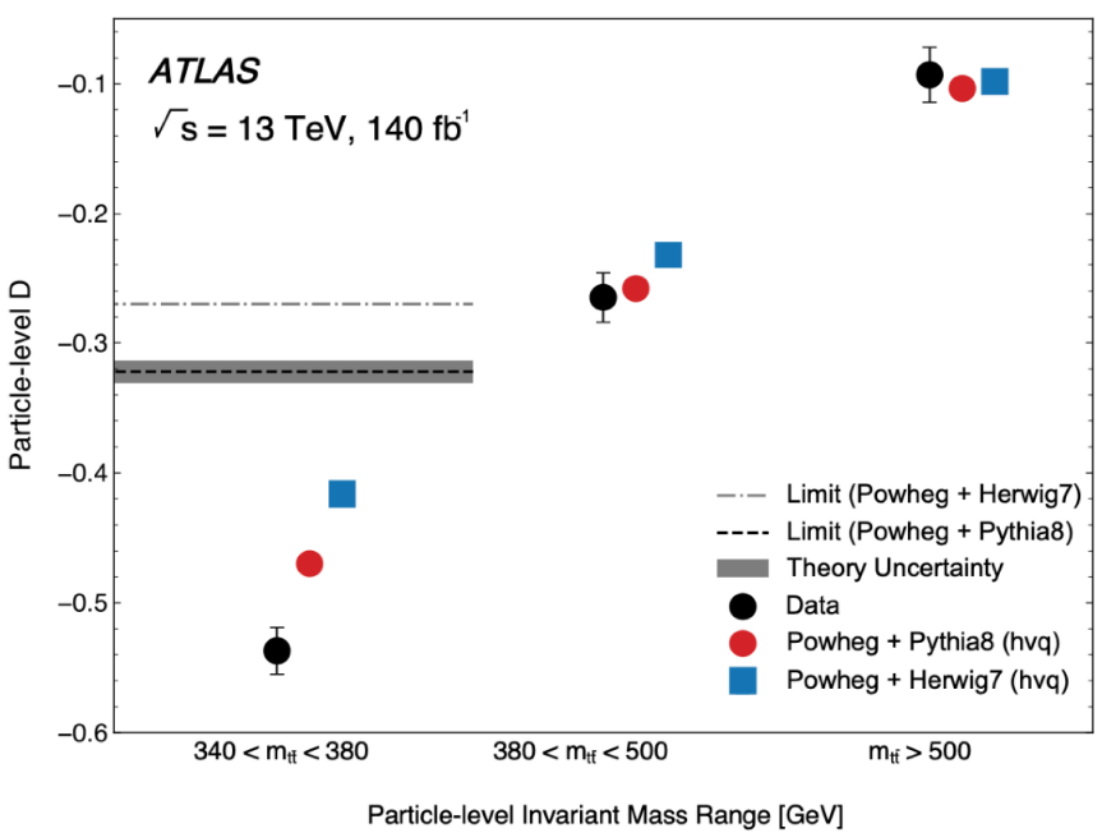
第四届高能物理理论与实验融合发展研讨会　　大连　　Sep 20 2025

Quantum information science meets high energy physics

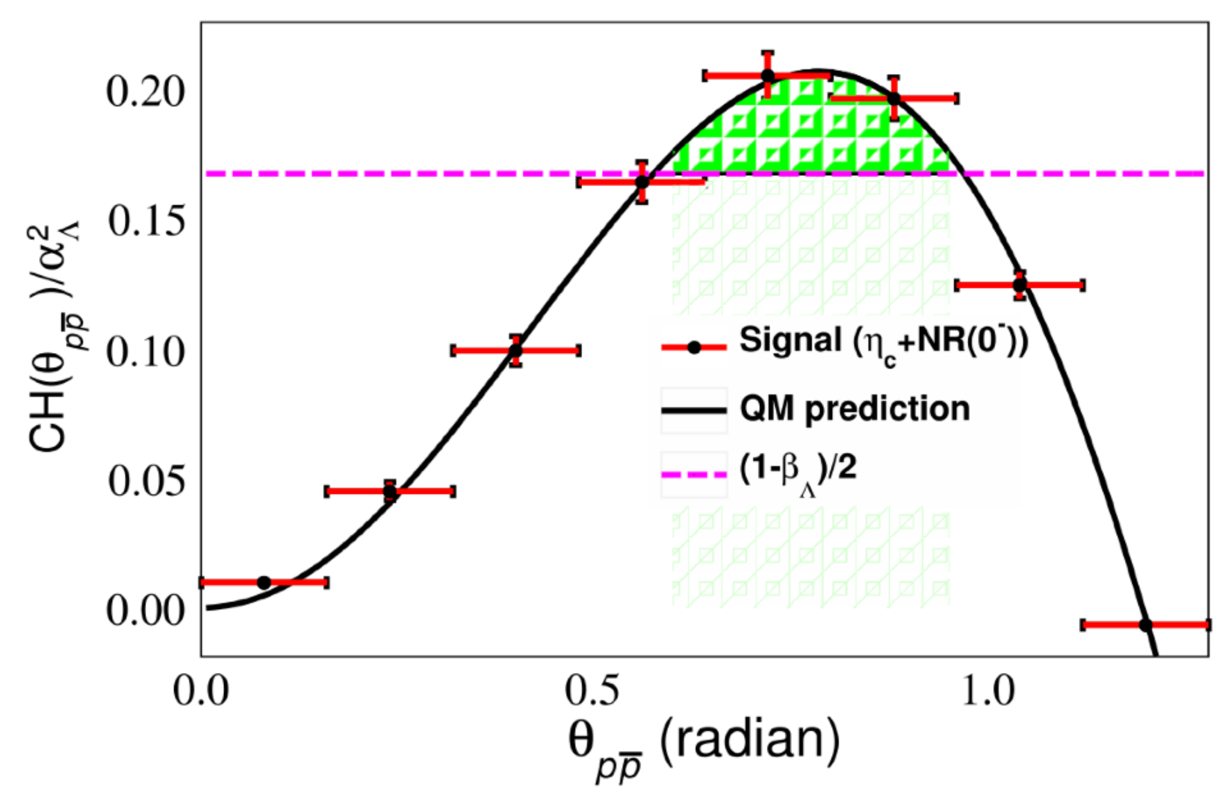
- **The study of quantum information in high-energy collider physics is rapidly transitioning from a theoretical curiosity to an experimental reality.** "Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics"— A recent review 2504.00086

See Li and Yan's talks

- **Recent breakthroughs, such as the observation of spin entanglement in top-quark pairs, have established particle colliders as novel laboratories for studying quantum mechanics at unprecedented energy scales.**



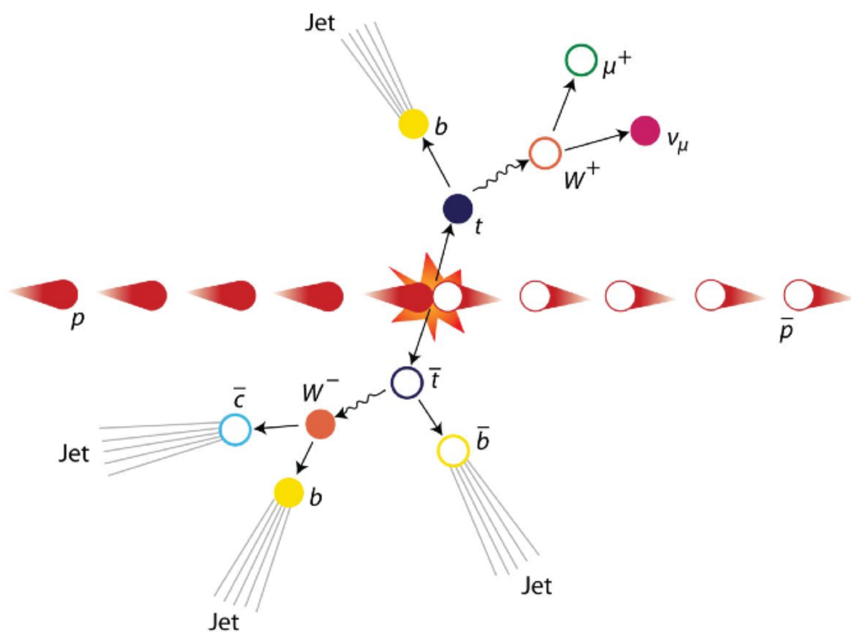
ATLAS Nature 2024

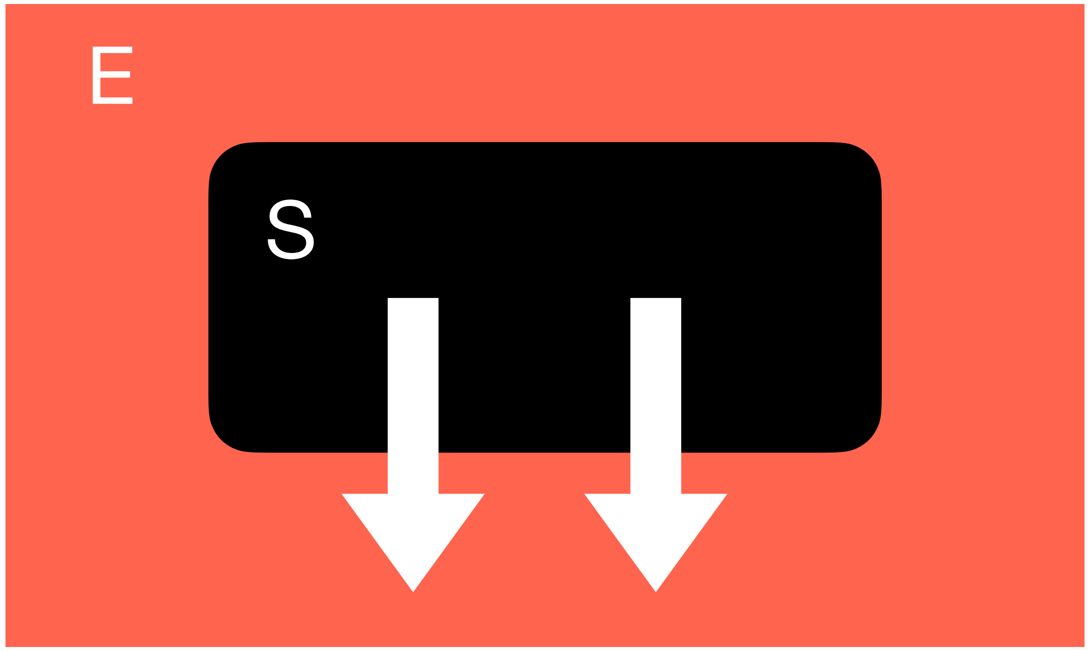


BESIII Nature Communications 2025

Decoherence in high energy collisions

- **We assume QFT is the underlying description and do not address debates concerning tests of local hidden variable theories at colliders** Li, Shen, Yang '24; Bechtle, Breuning, Dreiner, Duhr '25; Abel, Dreiner, Sengupta, Ubaldi '25 …
- **In the above measurements at the LHC, entangled top quark pairs can not be treated as a closed 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.**





Some decoherence effects in open system

- **K0 K0bar system** (Bertlmann ‘04) **Λ Λbar 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 in progress)
- **Decoherence and decoupling in effective field theory** (Burgess, Colas , Holman, Kaplanek ’25)
- **Black hole horizons decohere superpositions** (Biggs, Maldacena ’24)

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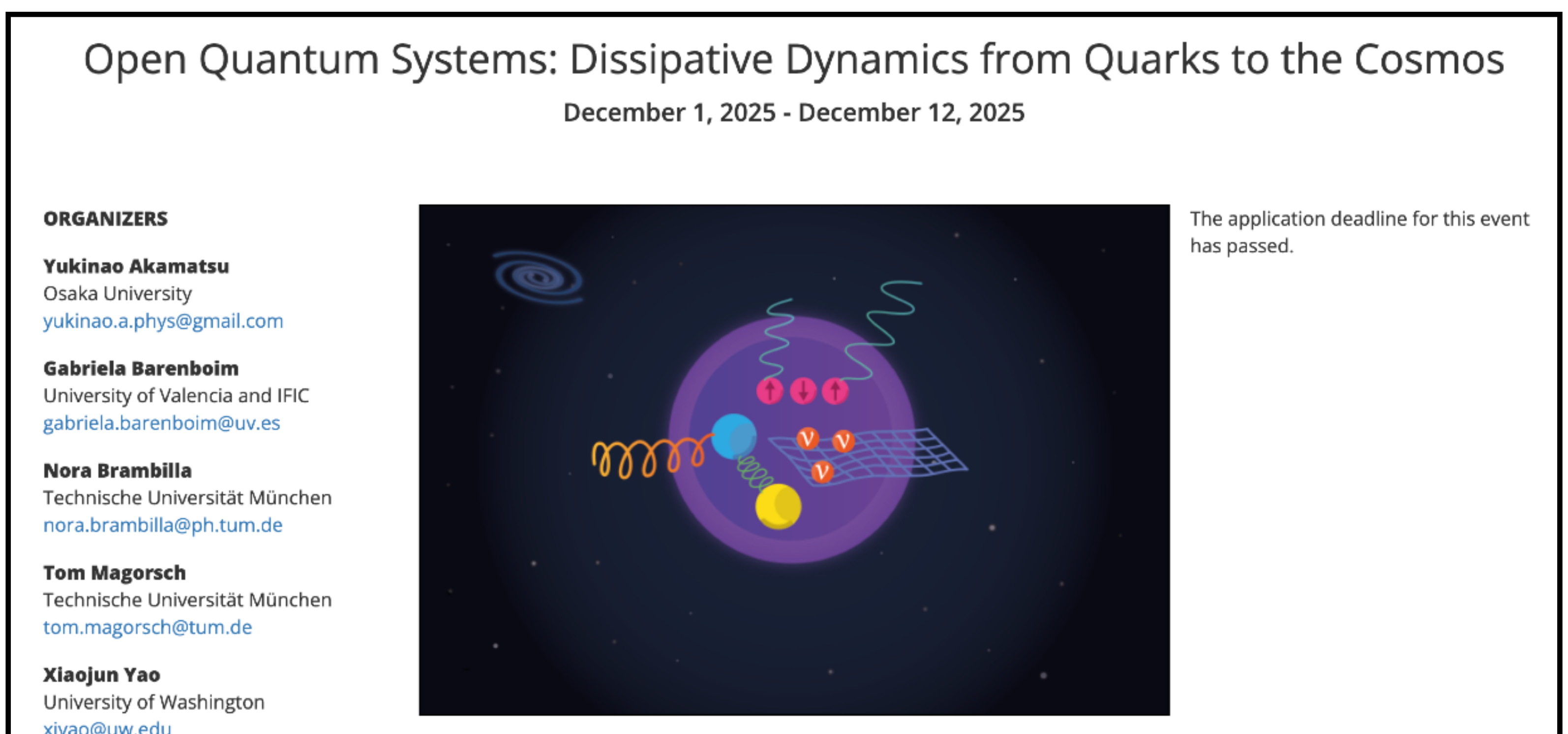


Concurrence at LO (closed system)

- **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**

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

Spin correlation matrix

- **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**

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

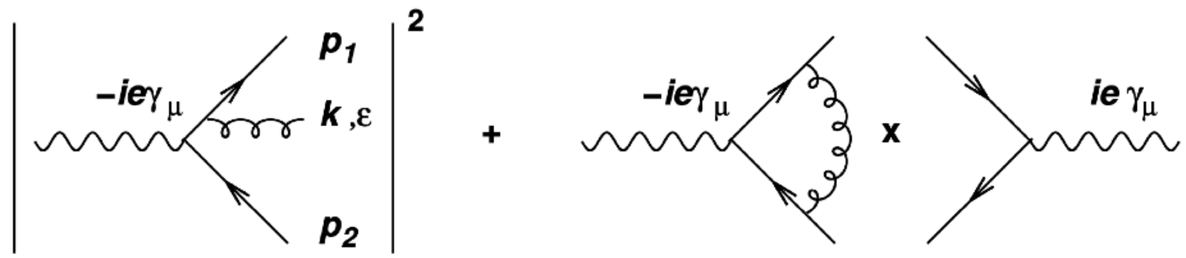
Quantum maps for open systems and perturbative calculation

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.**
- **To obtain the reduced density matrix, we need to trace over the emitted radiation**

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

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

Virtual

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

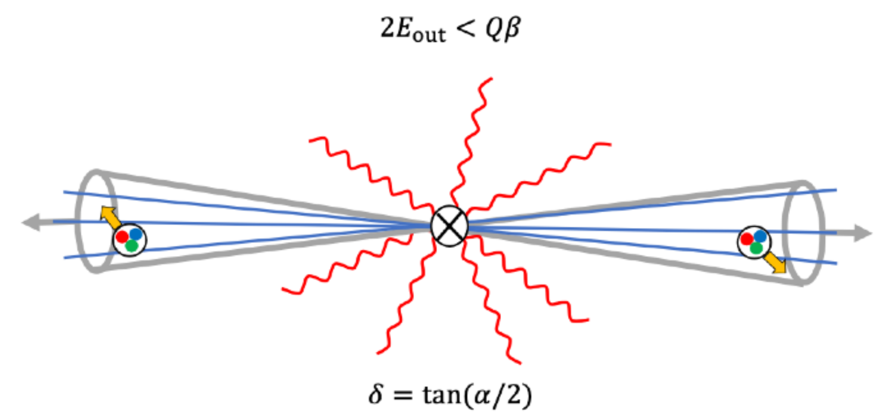
Real: ~~hard~~, collinear, ~~soft~~

Effective field theory for decoherence

J.Y. Gu, S.J. Lin (林士佳), DYS, L.T. Wang, S.X. Yang (杨斯翔) 2509.XXXXX

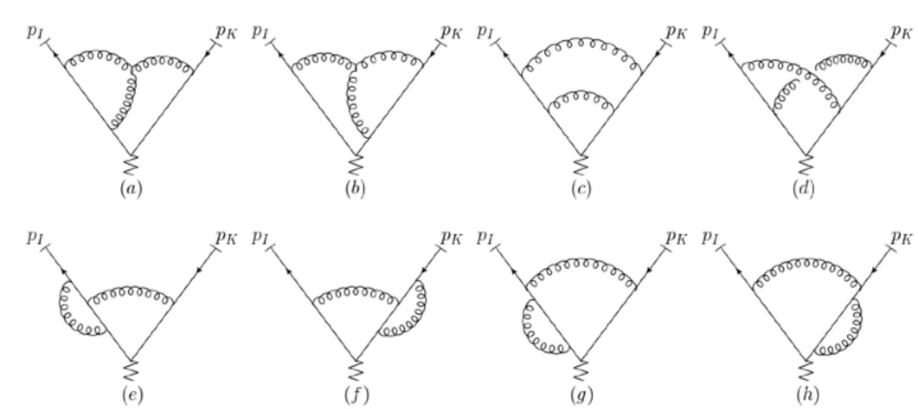
- **Radiation should be considered unresolvable if either soft of collinear**
- **We introduce the energy and angular resolution parameters, which is similar to Sterman-Weinberg cone jet definition** (Sterman, Weinberg ’77)

Two fermion events:



- **We apply soft collinear effective theory (SCET) + Jet Effective Theory (JET)** (Becher, Neubert, Rothen, DYS ’16 PRL)
- **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**

$$\hat{\rho}_{\rm hard}(Q,\mu) = \frac{1}{4}\Big(\hat{I}\otimes\hat{I} + P_i^+\,\hat{\sigma}_i\otimes\hat{I} + P_j^-\,\hat{I}\otimes\hat{\sigma}_j + C_{ij}\,\hat{\sigma}_i\otimes\hat{\sigma}_j\Big)$$



Factorization of the density operator

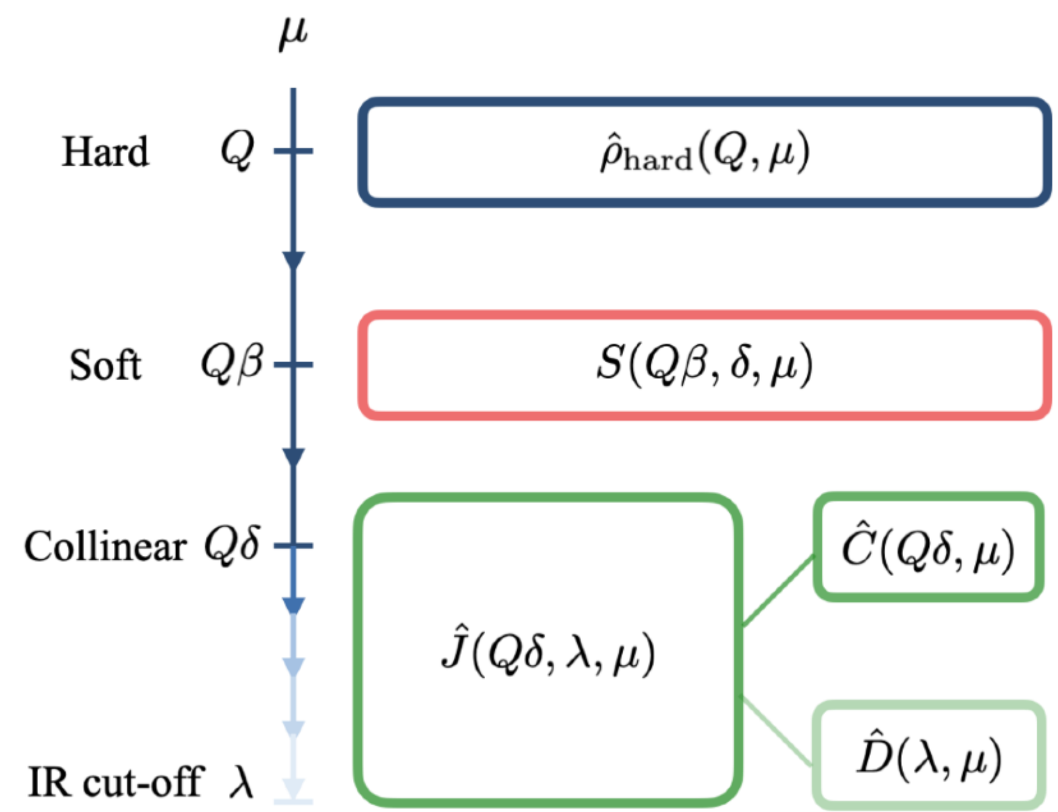
- **This jet definition allows us to apply the factorization theorems of SCET**

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

- **Soft function S accounts for large-angle soft radiation. At the leading power, soft emissions are spin-independent and thus do 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**

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



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**

Factorization of the density operator

- **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 scale-dependent effective production matrix**

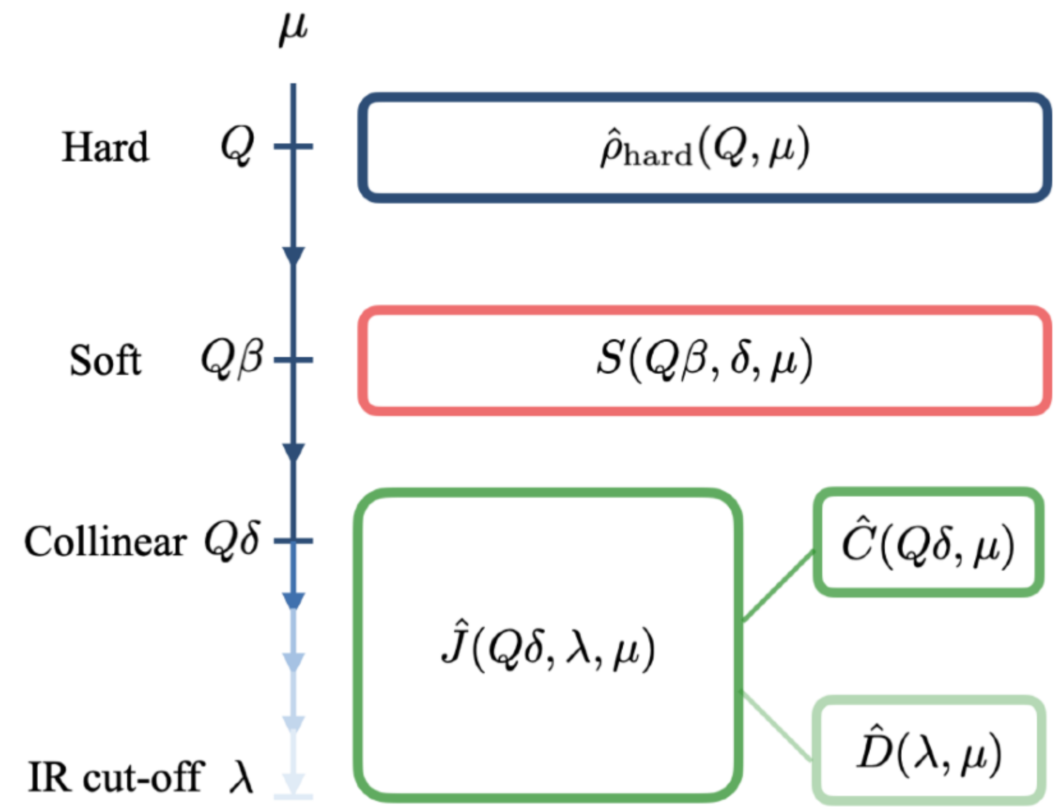
$$\hat{R}_{\text{eff}}(\mu) \equiv S(Q\beta, \delta, \mu)\hat{C}_f(Q\delta, \mu)\hat{R}_{\text{hard}}(Q, \mu)\hat{C}_{\bar{f}}(Q\delta, \mu)$$

- **Renormalization group eqn** $t \equiv \log(Q\delta/\mu)$

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

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

$\gamma^{\mathcal{P}} \equiv \frac{\alpha}{\pi} P^{\mathcal{P}}_{ff}$ 1st Mellin moment of splitting function



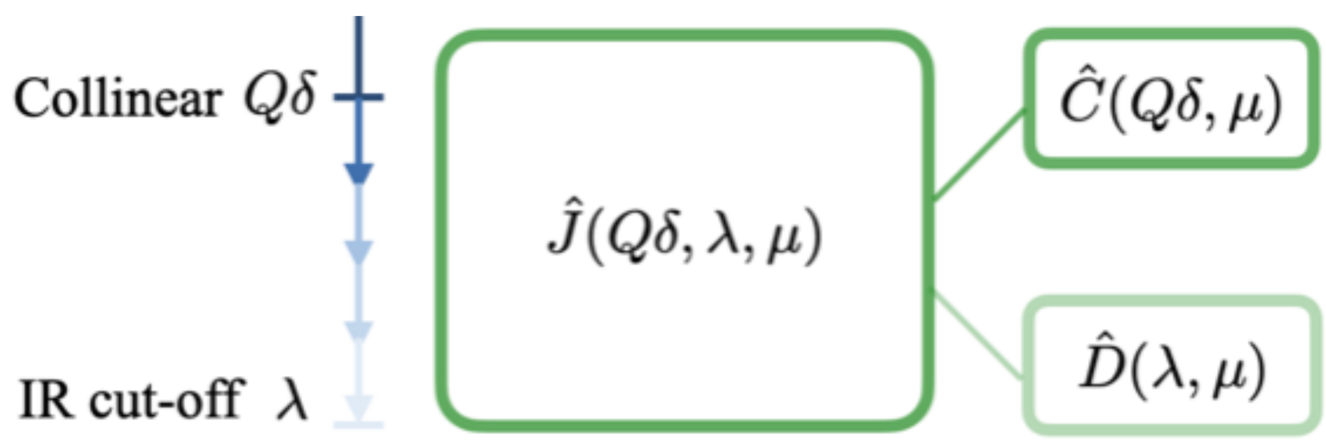
decoherence = RG flow
anomalous dimensions determine the information loss

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 $\hat{M}_f(\boldsymbol{S}_f) \equiv \hat{D}_f \hat{P}_f$

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

- 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

- **We use QED as an example: IR cut-off = lepton mass** $\lambda = m$
- **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**

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

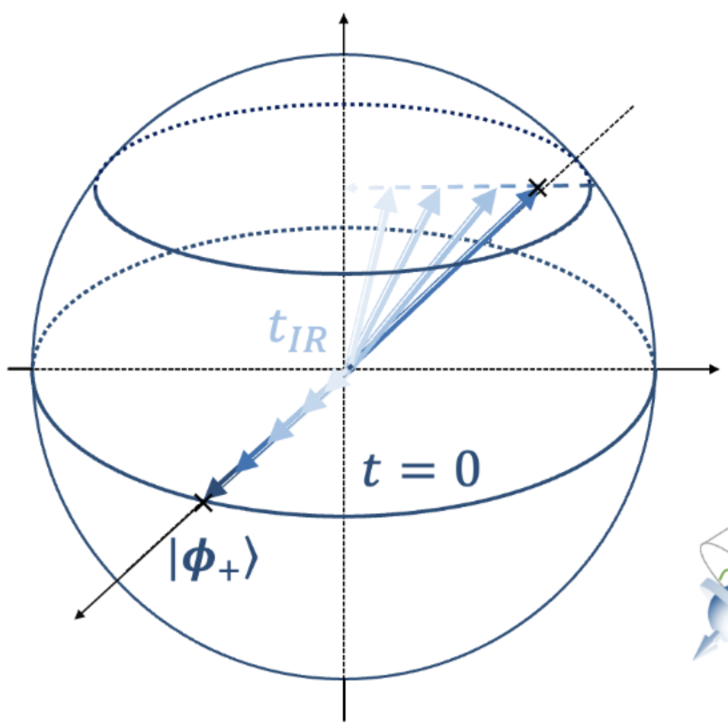
$$\hat{L}_1 = \sqrt{\alpha/4\pi}\,\hat{\sigma}_3 \otimes \mathbb{I} \qquad \hat{L}_2 = \sqrt{\alpha/4\pi}\,\mathbb{I} \otimes \hat{\sigma}_3$$

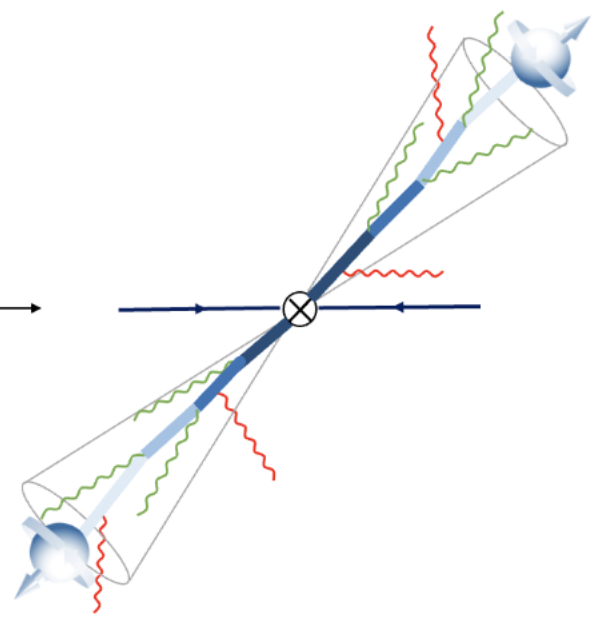
- **Quantum trajectory interpretation: each ”jump” corresponds to an unresolved collinear photon emission from either of the fermion legs, which induces a stochastic phase-flip**
- **Decay of all off-diagonal terms**

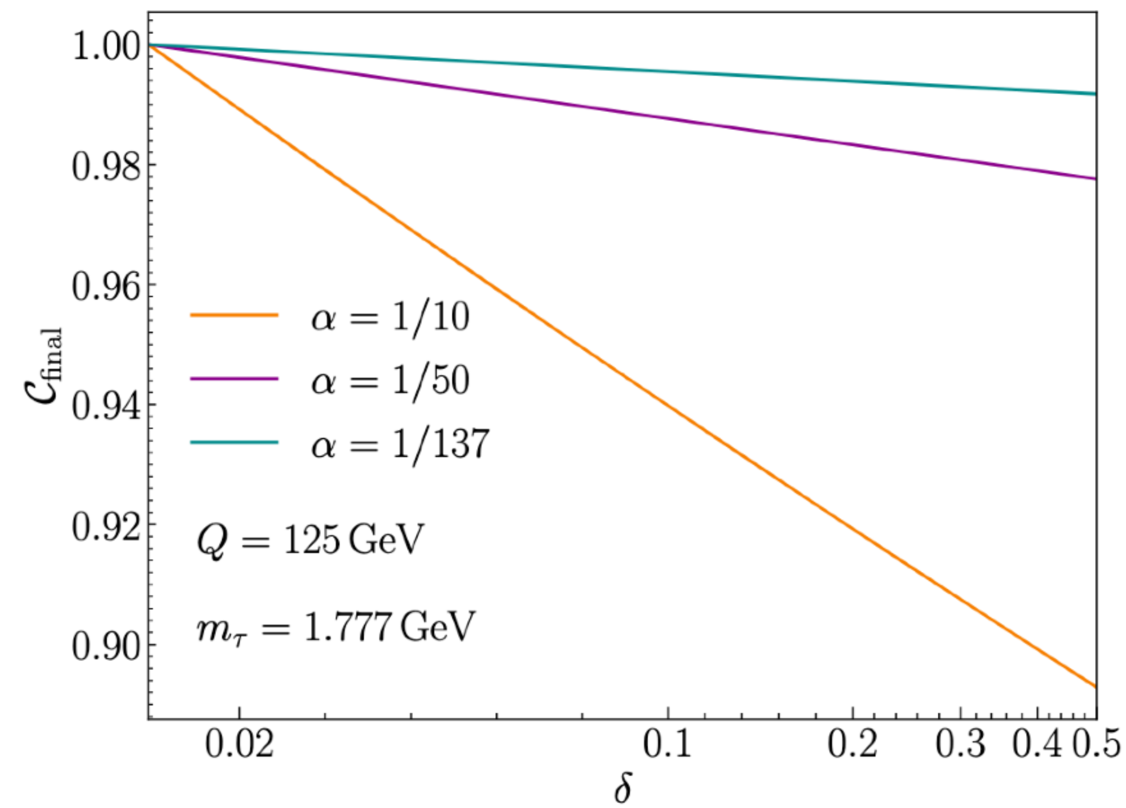
$$\frac{\hat{\rho}_{\text{eff}}^{ij}(t)}{\hat{\rho}_{\text{eff}}^{ij}(0)} = \begin{cases} 1 & i=j \quad (\text{diagonal})\,, \\ e^{-\frac{\alpha}{\pi}t} & ij = 14, 23, 32, 41 \quad (\text{anti-diagonal})\,, \\ e^{-\frac{\alpha}{2\pi}t} & \text{else}\,. \end{cases}$$

RG flow as a phase-flip channel

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







$|\phi_+\rangle = (|{+}{-}\rangle + |{-}{+}\rangle)/\sqrt{2}$

- **The concurrence after passage through a two-sided channel is bounded**

$$C[(\$_1 \otimes \$_2)\rho_0] \leq C[(\$_1 \otimes \mathbb{1})|\phi^+\rangle\langle\phi^+|]\, C[(\mathbb{1} \otimes \$_2)|\phi^+\rangle\langle\phi^+|]C(\rho_0)$$

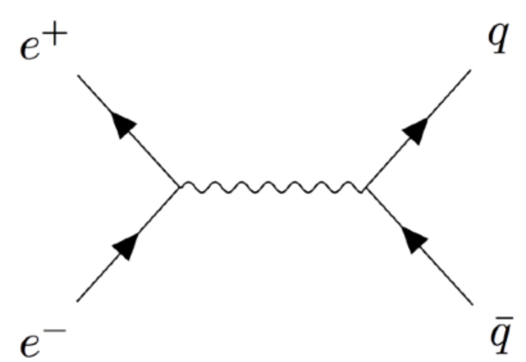
Konrad *et.al*. Nature Physics 2007

- **For the most general case, we have an inequality**

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

Spin correlation in Λ pair production with a thrust cut

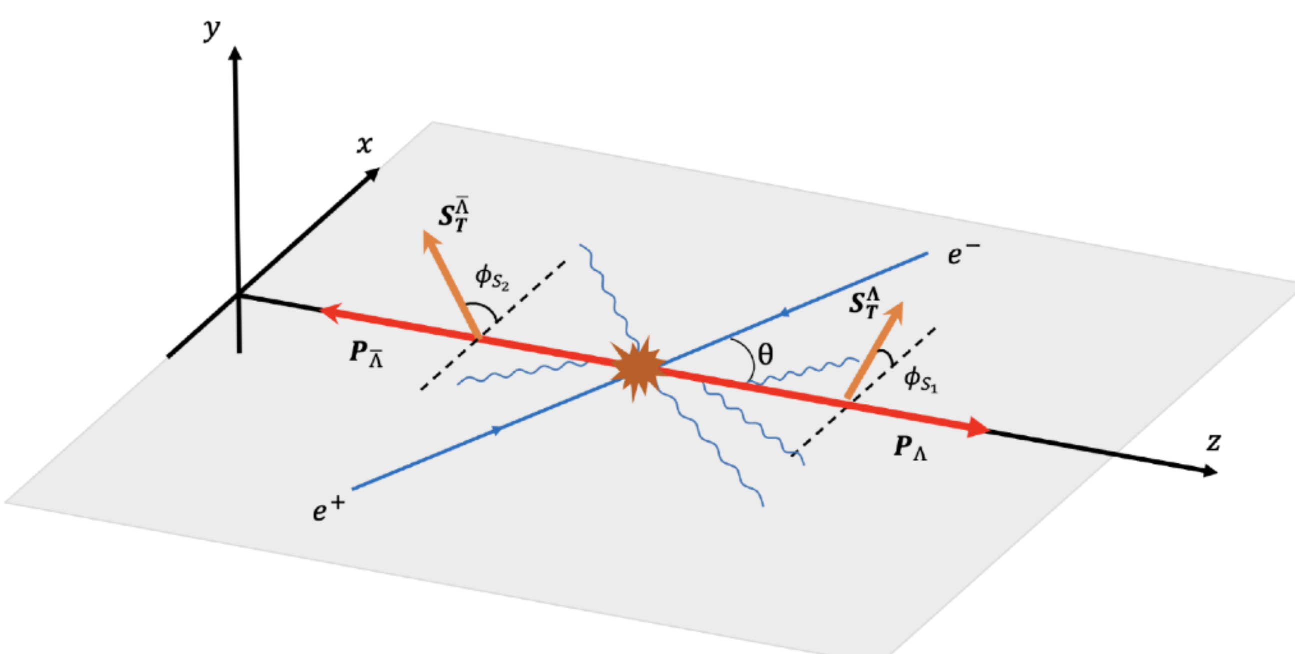
S.J. Lin (林士佳), M.J. Liu (刘铭钧), DYS, S.Y. Wei ‘25



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:

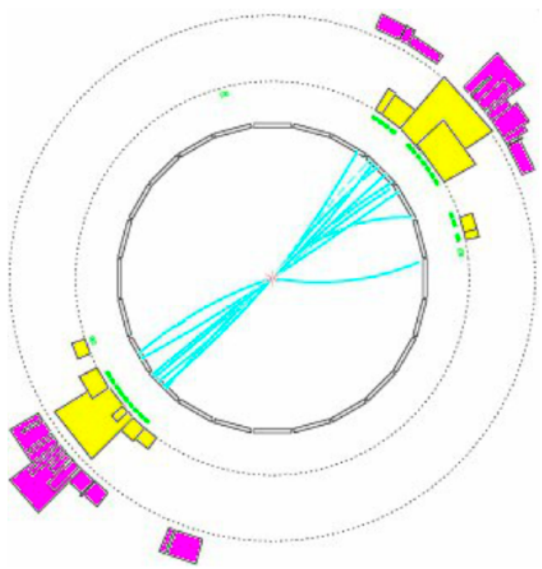
Boer, Jakob, Mulders ‘97

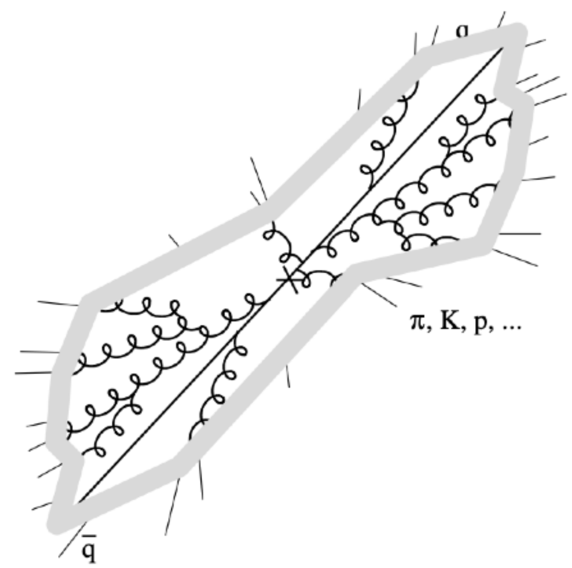
$$\frac{\mathrm{d}\sigma(\boldsymbol{S}^\Lambda, \boldsymbol{S}^{\bar{\Lambda}})}{\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega} = \sum_q e_q^2 \Bigg[\frac{\mathrm{d}\sigma_0^U}{\mathrm{d}\Omega}\,\mathcal{D}^U_{\Lambda/q}(z_1,\mu)\,\mathcal{D}^U_{\bar{\Lambda}/\bar{q}}(z_2,\mu) + P_z^\Lambda P_z^{\bar{\Lambda}}\,\frac{\mathrm{d}\sigma_0^L}{\mathrm{d}\Omega}\,\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

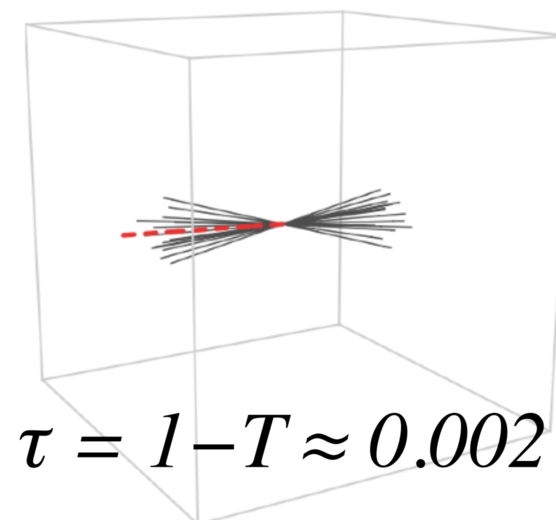
Spin correlation in Λ pair production with a thrust cut

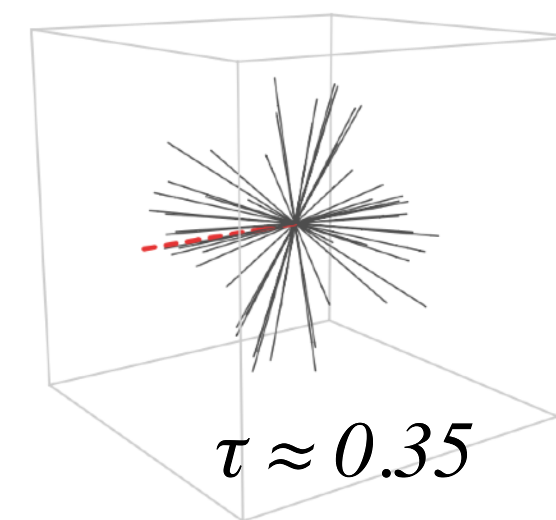
S.J. Lin (林士佳), M.J. Liu (刘铭钧), DYS, S.Y. Wei '25

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

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

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

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

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

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

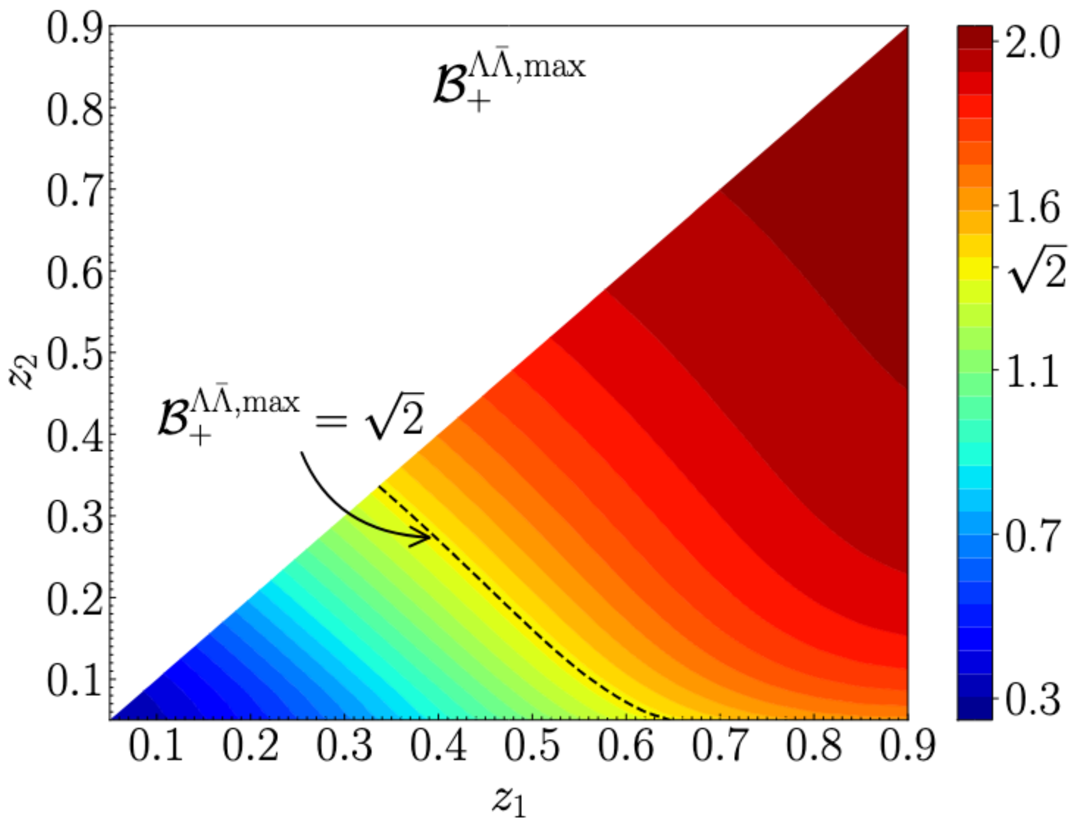
Bell nonlocality and decoherence

S.J. Lin (林士佳), M.J. Liu (刘铭钧), DYS, S.Y. Wei '25

- **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)

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

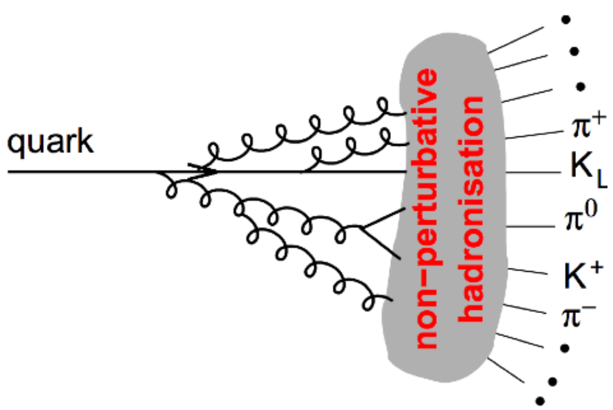
- **We start from the ideal partonic baseline of a maximally entangled** $\mathcal{B}_+^{q\bar{q}} = 2$

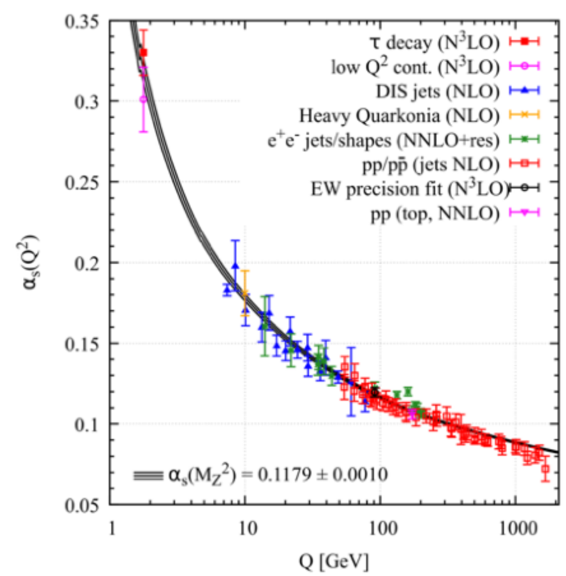


- **We observe that under these ideal hadronization assumptions, the Bell variable is suppressed below the partonic maximum of 2**
- **As expected, this decoherence is reduced at large z, where the hadron carries most of the parent parton's spin information**

Quantum information theory for hadronization

Parton (quark or gluon) fragmentation and hadronization





Jets are emergent property of QCD

- **Soft-collinear singularity**
- **Asymptotic freedom**
- **Color string breaks**

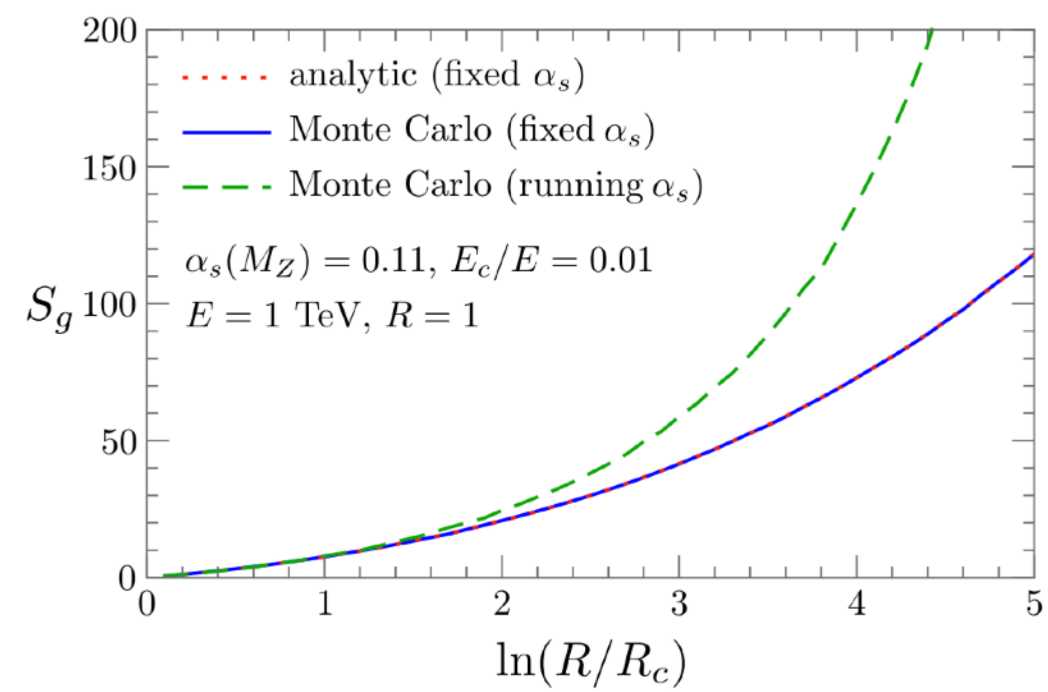
Dynamics of jets formation: from short to long distance in quantum field theory

E.g. Jet entropy Neill, Waalewijn '19 PRL

Reduced density matrix

$$\rho = \sum_{n=1}^{\infty} \int_H d\Pi_n \, (p_J) \, \frac{1}{\sigma} \frac{d\sigma}{d\Pi_n} \, |p_1, p_2, \ldots p_n\rangle \, \langle p_1, p_2, \ldots, p_n| \, ,$$

Renyi entropy $$S_\alpha = \frac{\ln \, \mathrm{tr}[\rho^\alpha]}{1-\alpha} = \frac{1}{1-\alpha} \ln \sum_{n=0}^{\infty} \mathrm{tr}[\rho_n^\alpha]$$

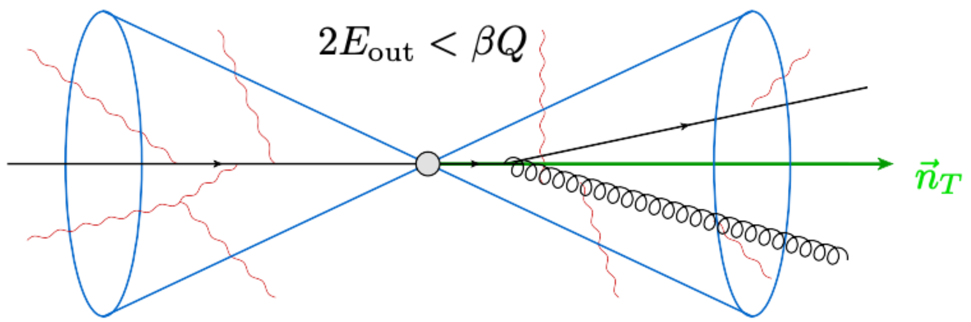


Gap fraction and open quantum system evolution

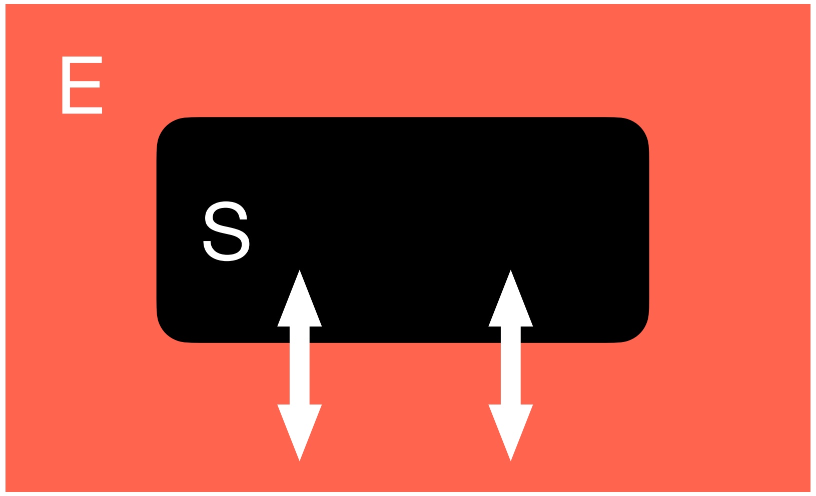
Becher, Neubert, Rothen, DYS '16 PRL

EFT contains two modes:

$$\text{hard:} \quad p_h \sim Q\,(1,1,1)$$
$$\text{soft:} \quad p_s \sim Q\beta\,(1,1,1)$$



1. no collinear singularity, only single logs
2. method of region to verify at two-loop level



Hard parton described by collinear field

gauge invariant: $\chi_i(0) = W_i^\dagger(\bar{n}_i)\,\frac{\not{n}_i\bar{\not{n}}_i}{4}\,\psi_i(0)$

Perform decoupling transformation: $\Phi_i = \boldsymbol{S}_i(n_i)\,\Phi_i^{(0)}$

$$\boldsymbol{S}_i(n_i) = \mathbf{P}\exp\left(ig_s\int_0^\infty ds\, n_i\cdot A_s^a(sn_i)\,\boldsymbol{T}_i^a\right)$$

Factorization for gap between jets in e+e-

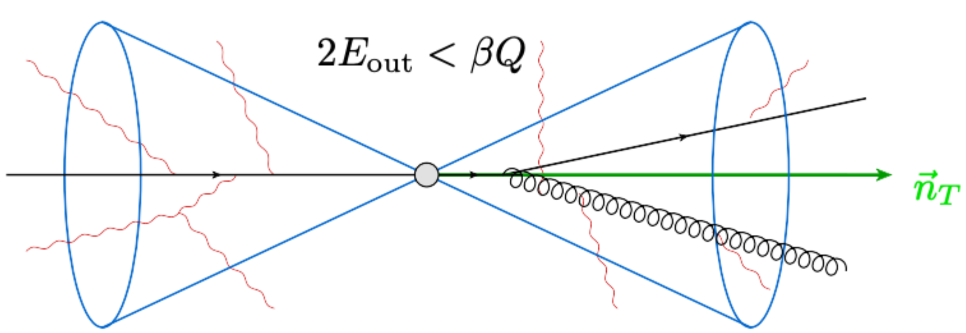
(Becher, Neubert, Rothen, DYS, ’15 PRL, ’16 JHEP; Caron-Huot ’15 JHEP)

Hard function
m hard partons along
fixed directions $\{n_1, \ldots, n_m\}$
$\boldsymbol{\mathcal{H}}_m \propto |\mathcal{M}_m\rangle\langle\mathcal{M}_m|$

$$\mathrm{Tr}[\rho\,\mathcal{O}]$$

Soft function
squared amplitude
with *m* Wilson lines

$$\sigma(Q, Q_\Omega) \sim \sum_{m=2}^{\infty} \prod_{i=1}^{m} \int \frac{d\Omega(\vec{n}_i)}{4\pi} \mathrm{Tr_c}\left[\mathcal{H}_m(\{\vec{n}_1, \cdots, \vec{n}_m\}, Q, \mu)\mathcal{S}_m(\{\vec{n}_1, \cdots, \vec{n}_m\}, Q_\Omega, \mu)\right]$$



Factorization for gap between jets in e+e-

(Becher, Neubert, Rothen, DYS, '15 PRL, '16 JHEP; Caron-Huot '15 JHEP)

Hard function
m hard partons along
fixed directions {n_1, …, n_m}
$\boldsymbol{\mathcal{H}}_m \propto |\mathcal{M}_m\rangle\langle\mathcal{M}_m|$

$\mathrm{Tr}[\rho\,\mathcal{O}]$

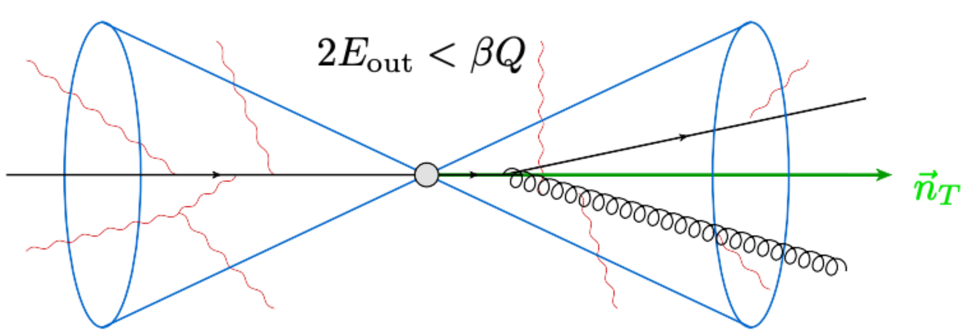
Soft function
squared amplitude
with m Wilson lines

Color Trace **Hard scale** **Soft scale**

$$\sigma(Q,Q_\Omega) \sim \sum_{m=2}^{\infty}\prod_{i=1}^{m}\int\frac{d\Omega(\vec{n}_i)}{4\pi}\,\mathrm{Tr}_c\left[\mathcal{H}_m(\{\vec{n}_1,\cdots,\vec{n}_m\},Q,\mu)\mathcal{S}_m(\{\vec{n}_1,\cdots,\vec{n}_m\},Q_\Omega,\mu)\right]$$

# of jet not fixed

Integrate the angles for hard partons



All-order evolution of leading Super-Leading Logs

(Becher, Neubert, DYS '21 PRL + Stillger'23 JHEP)

All-order structure: Kampe de Feriet function (a two-variable generalization of the generalized hypergeometric series, the general sextic equation can be solved in terms of it)

$$\Sigma(v,w) = \sum_{m=0}^{\infty}\sum_{r=0}^{\infty} \frac{(1)_{m+r}(1)_m\left(\frac{1}{2}\right)_r}{(2)_{m+r}\left(\frac{5}{2}\right)_{m+r}} \frac{(-w)^m(-vw)^r}{m!\,r!}$$

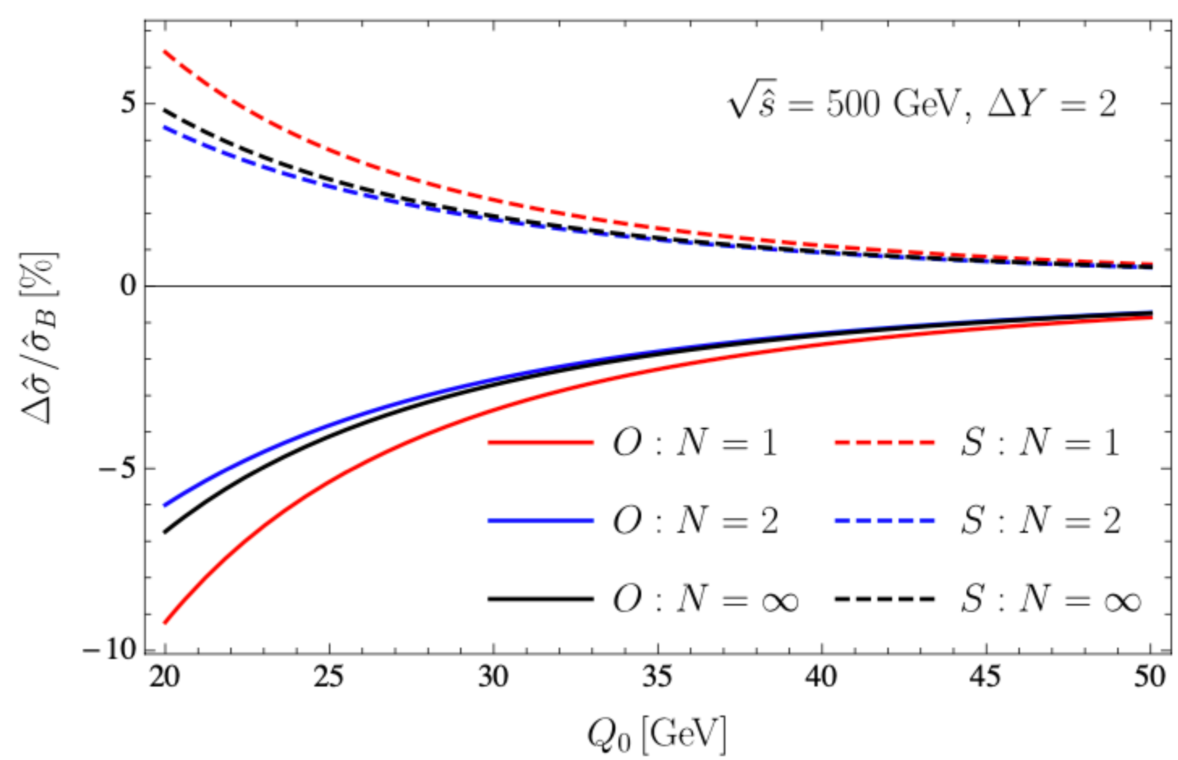
$$= {}^{1+1}F_{2+0}\left(\begin{matrix} 1 : 1, \frac{1}{2} ; \\ 2, \frac{5}{2} : \quad ; \end{matrix}\, , -w, -vw\right)$$

$$w = \frac{N_c \alpha_s(\bar{\mu})}{\pi} \ln^2\left(\frac{\mu_h}{\mu_s}\right)$$

Sudakov suppression of the superleading logarithms is weaker than the one present for global observables

Global logs ⟶ $e^{-\omega}$

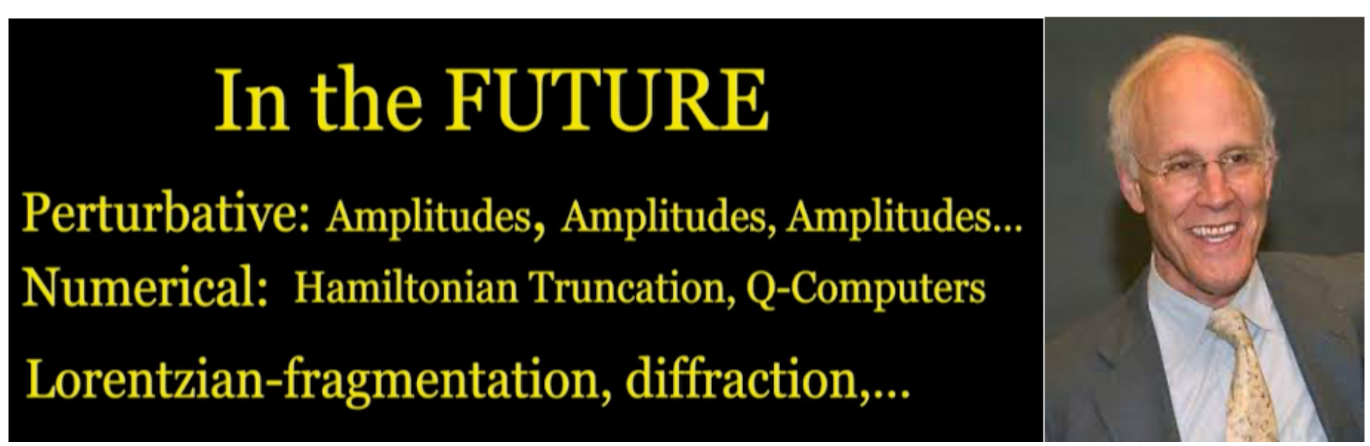
Superleading logs $\xrightarrow{\omega \to \infty}$ $\frac{1}{\omega}$



Red: Four loop **Blue: Five loop** **Black: all order**

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.**
- **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** $\hat{L} \propto \hat{\sigma}_i \otimes \hat{\sigma}_j$
- **Quantum information science meets Lorentzian fragmentation**



Thank you