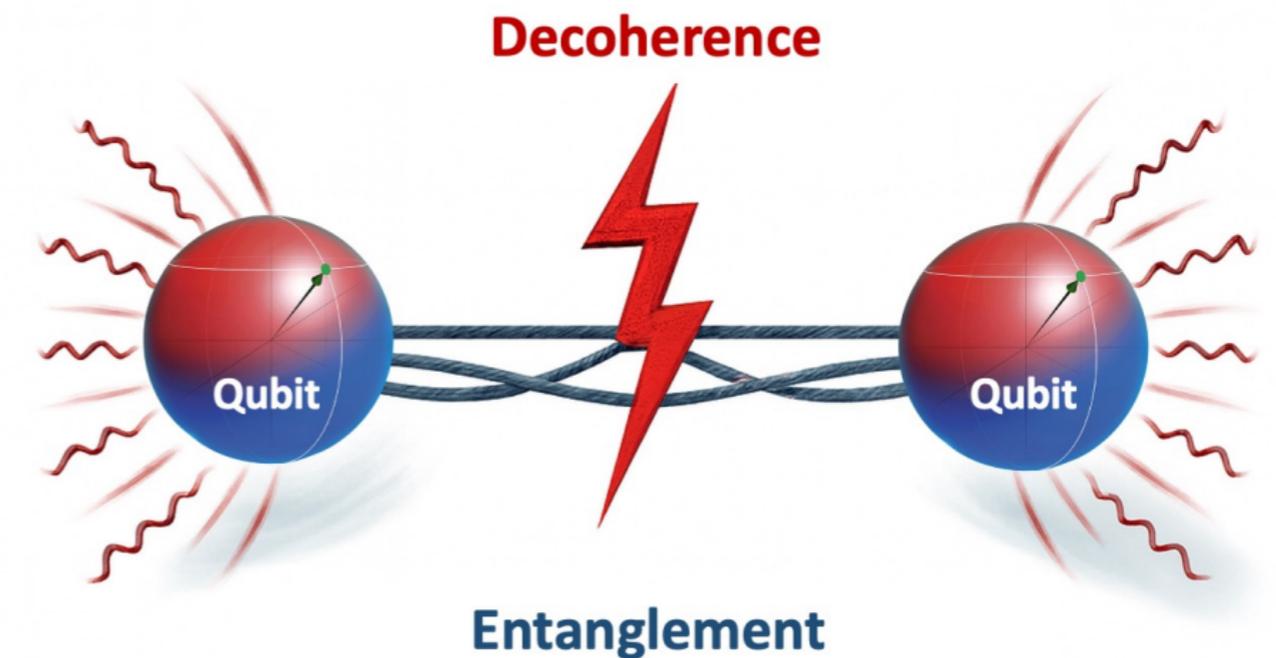# Decoherence as renormalization group flow: quantum information loss in high energy collisions

**Ding-Yu Shao**
**Fudan University**

Gu, Lin, DYS, Wang, Yang,  2510.13951

Lin, Liu, DYS, Wei,  JHEP11(2025)082

Fang, Yang, DYS, Zhou, PRL136(2026)021901

FP2026        HKUST        2026.01.15

# Decoherence in the double-slit experiment



Fig. 1-3. Interference experiment with electrons.

$$P_1 = |\phi_1|^2$$
$$P_2 = |\phi_2|^2$$

$$P_{12} = |\phi_1 + \phi_2|^2$$



Fig. 1-4. A different electron experiment.

$$P'_{12} = P'_1 + P'_2$$

《The Feynman Lectures on Physics》

# Decoherence in the double-slit experiment



Fig. 1-3. Interference experiment with electrons.



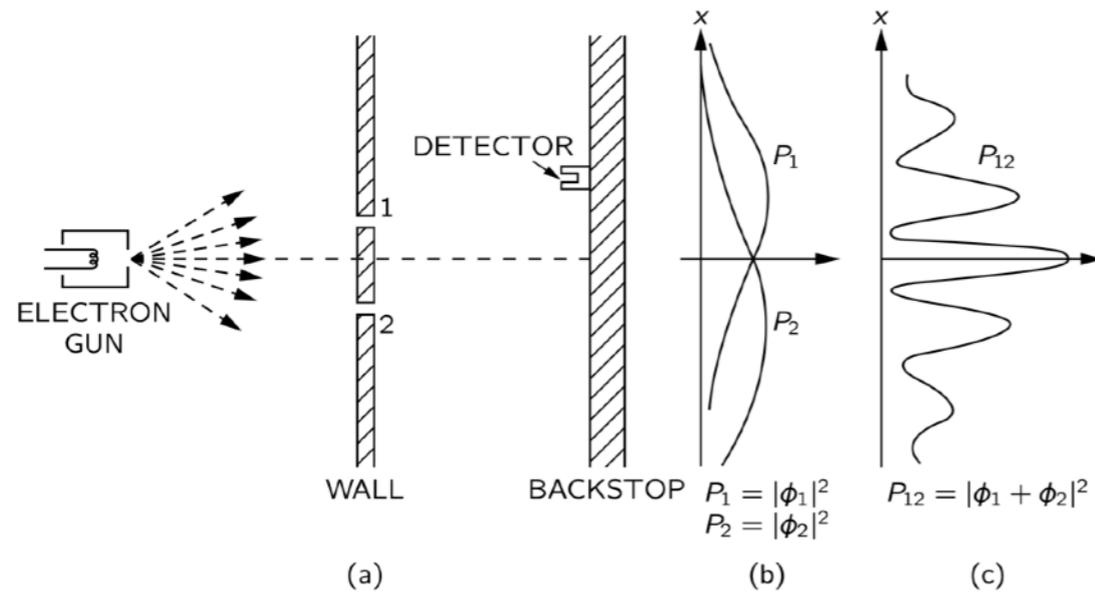Fig. 1-4. A different electron experiment.

《The Feynman Lectures on Physics》

**Pure state**

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|\psi_{\text{pure}}\rangle = \frac{1}{\sqrt{2}} (|\text{Slit } 1\rangle + |\text{Slit } 2\rangle)$$

$$\rho_{\text{pure}} = |\psi_{\text{pure}}\rangle\langle\psi_{\text{pure}}| = \frac{1}{2}\begin{pmatrix} 1 \\ 1 \end{pmatrix}\begin{pmatrix} 1 & 1 \end{pmatrix} = \begin{pmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{pmatrix}$$
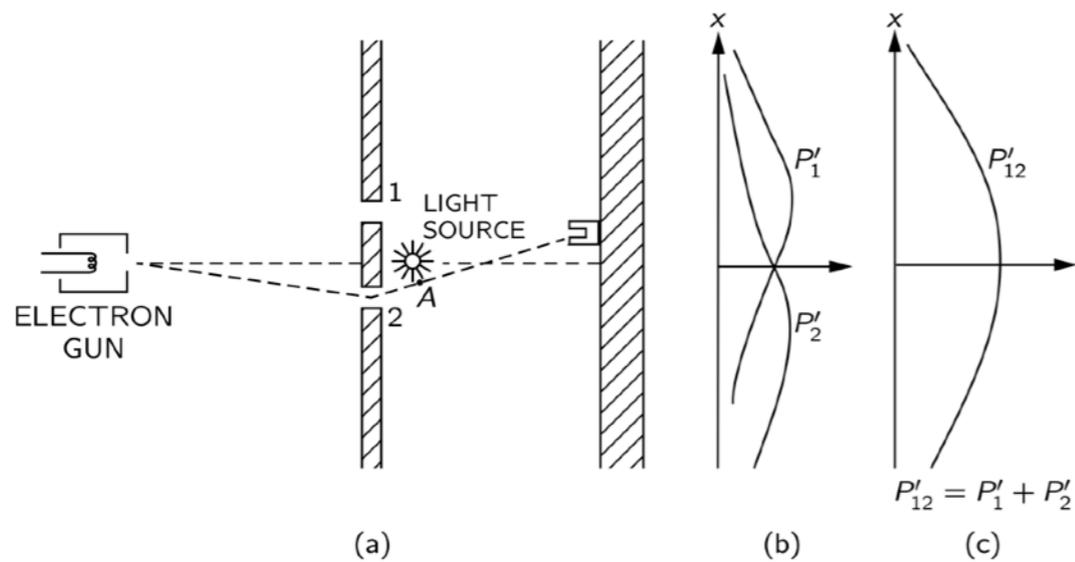
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《The Feynman Lectures on Physics》

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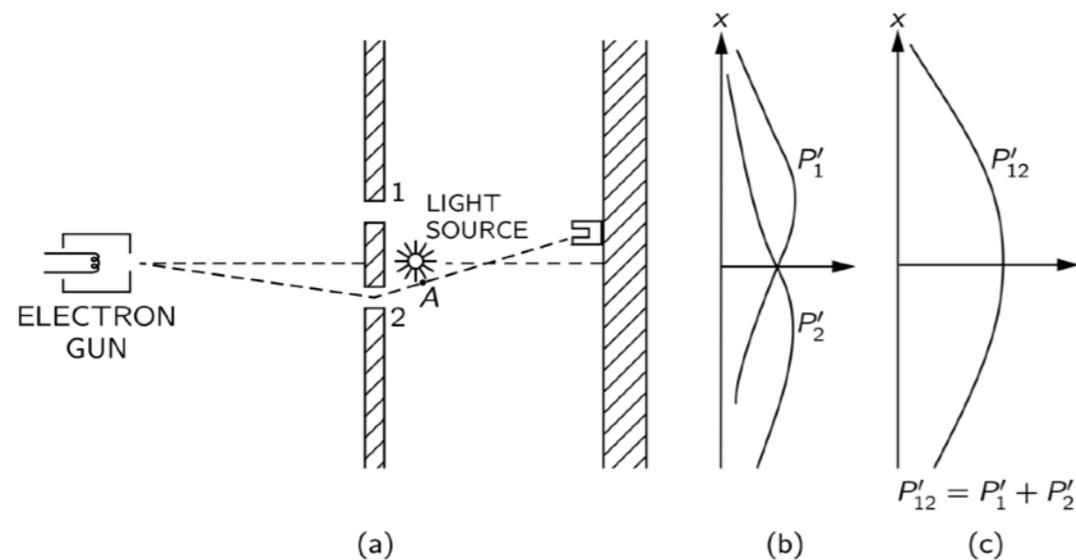$$\rho_{\text{pure}} = |\psi_{\text{pure}}\rangle\langle\psi_{\text{pure}}| = \frac{1}{2} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \end{pmatrix} = \begin{pmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{pmatrix}$$

**Mixed state**

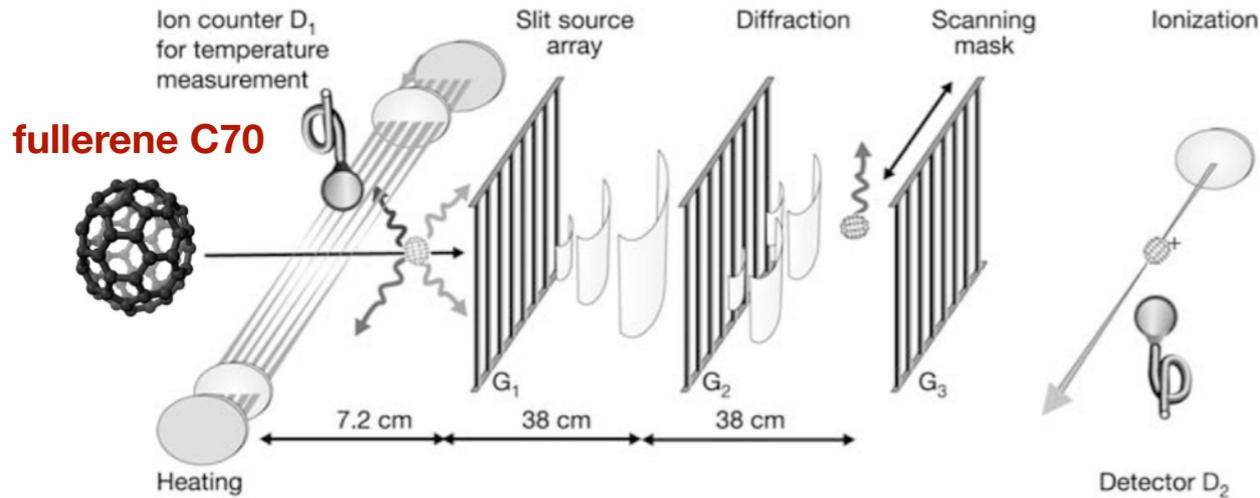$$\rho_{\text{mixed}} = \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix}$$

**Pure dephasing quantum channel**

$$\rho(t) = \begin{pmatrix} 1/2 & 1/2 \cdot e^{-\Lambda t} \\ 1/2 \cdot e^{-\Lambda t} & 1/2 \end{pmatrix}$$

**$\Lambda$ is the decoherence rate. It describes how fast the quantum coherence (the off-diagonal terms) disappears; decoherence time $t \approx 1/\Lambda$**

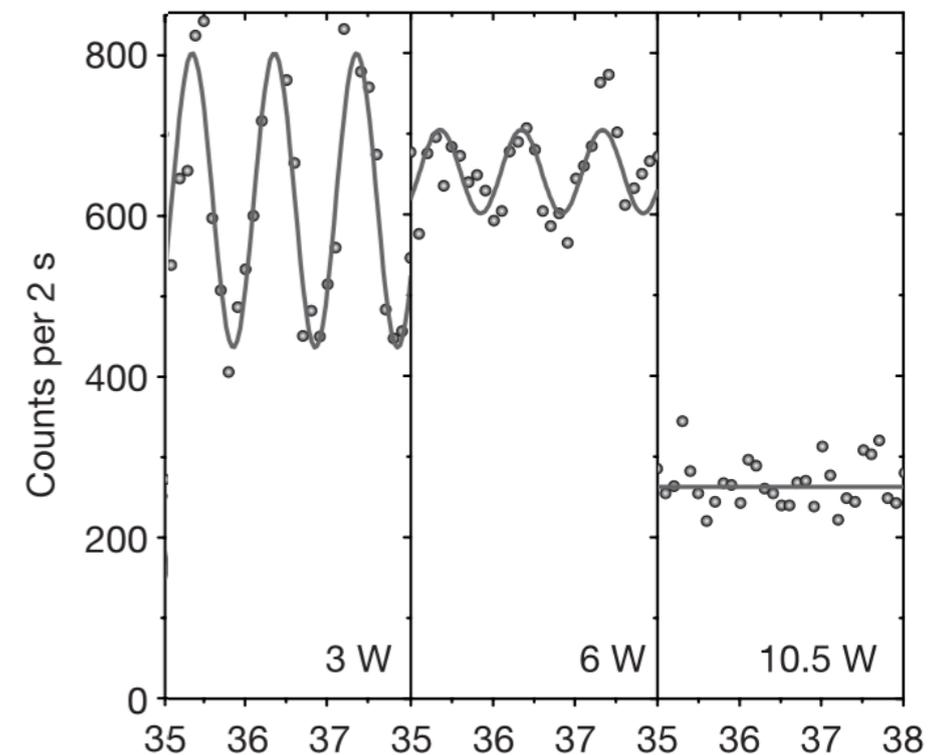# Decoherence by thermal emission of photons

Hackermuller, Hornberger, Brezger, Zeilinger, Arndt  Nature '04



**Setup: Heating & Interferometry**

- A Talbot-Lau interferometer

- Before entering the interferometer, C70 molecules pass through a laser beam to increase their internal temperature

- The internal temperature is varied from below 1,000 K (cold) up to 3,000 K (hot)

- **Cold Molecules:**

  - Molecules emit negligible radiation.

  - Result: Strong quantum interference is observed with a fringe visibility.

- **Hot Molecules:**

  - Molecules emit thermal photons that carry path information

  - Result: The interference fringe visibility drops to 0%.

- The decoherence mechanism is the thermal emission of photons by the molecule itself

# Decoherence by thermal emission of photons

Hackermuller, Hornberger, Brezger, Zeilinger, Arndt  Nature '04



**fullerene C70**
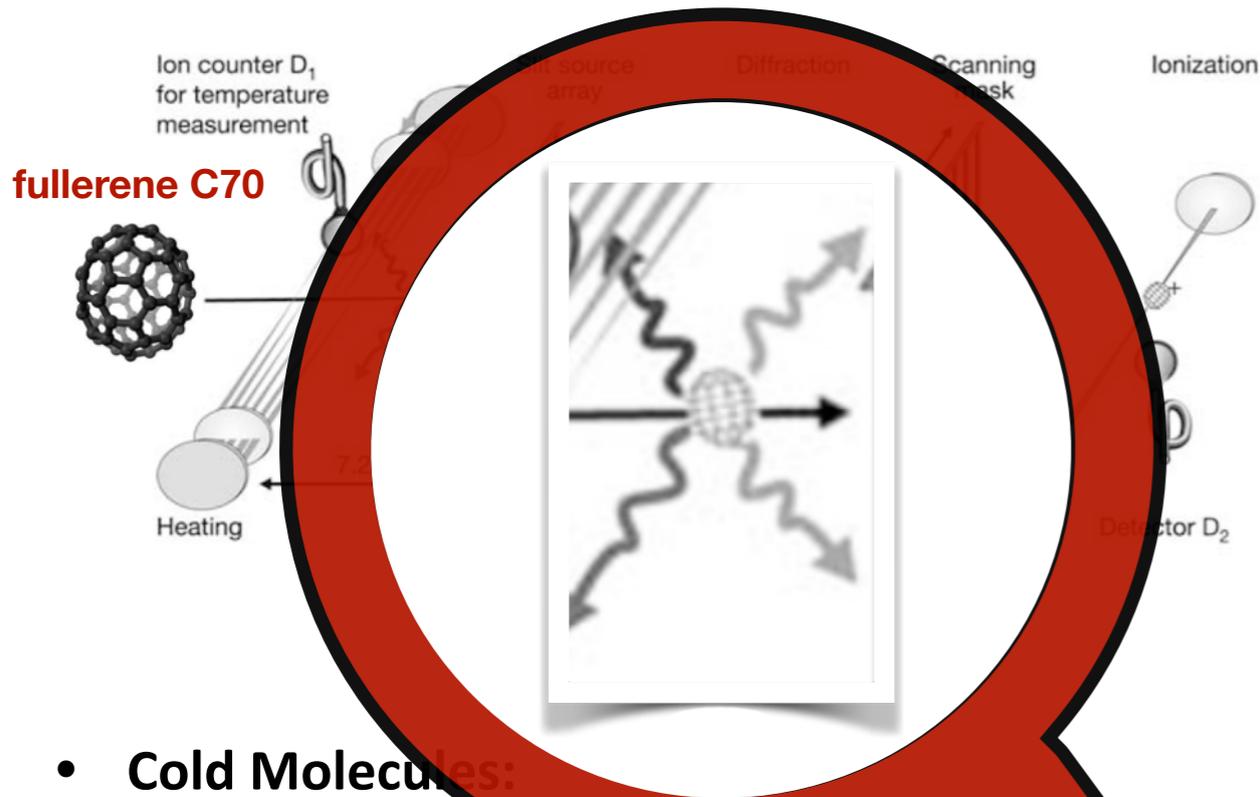
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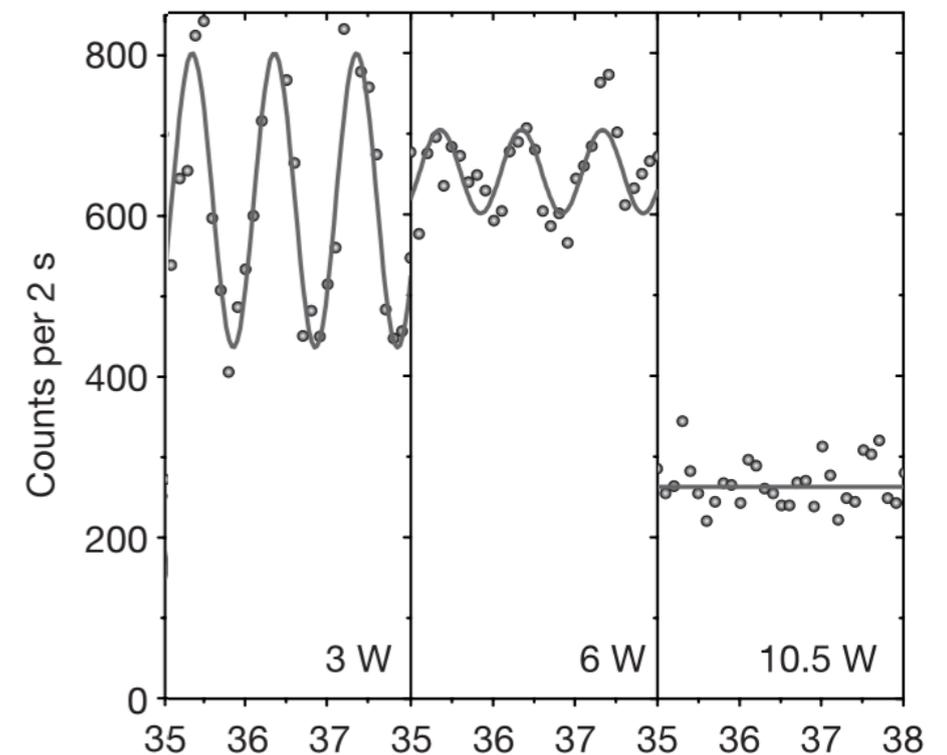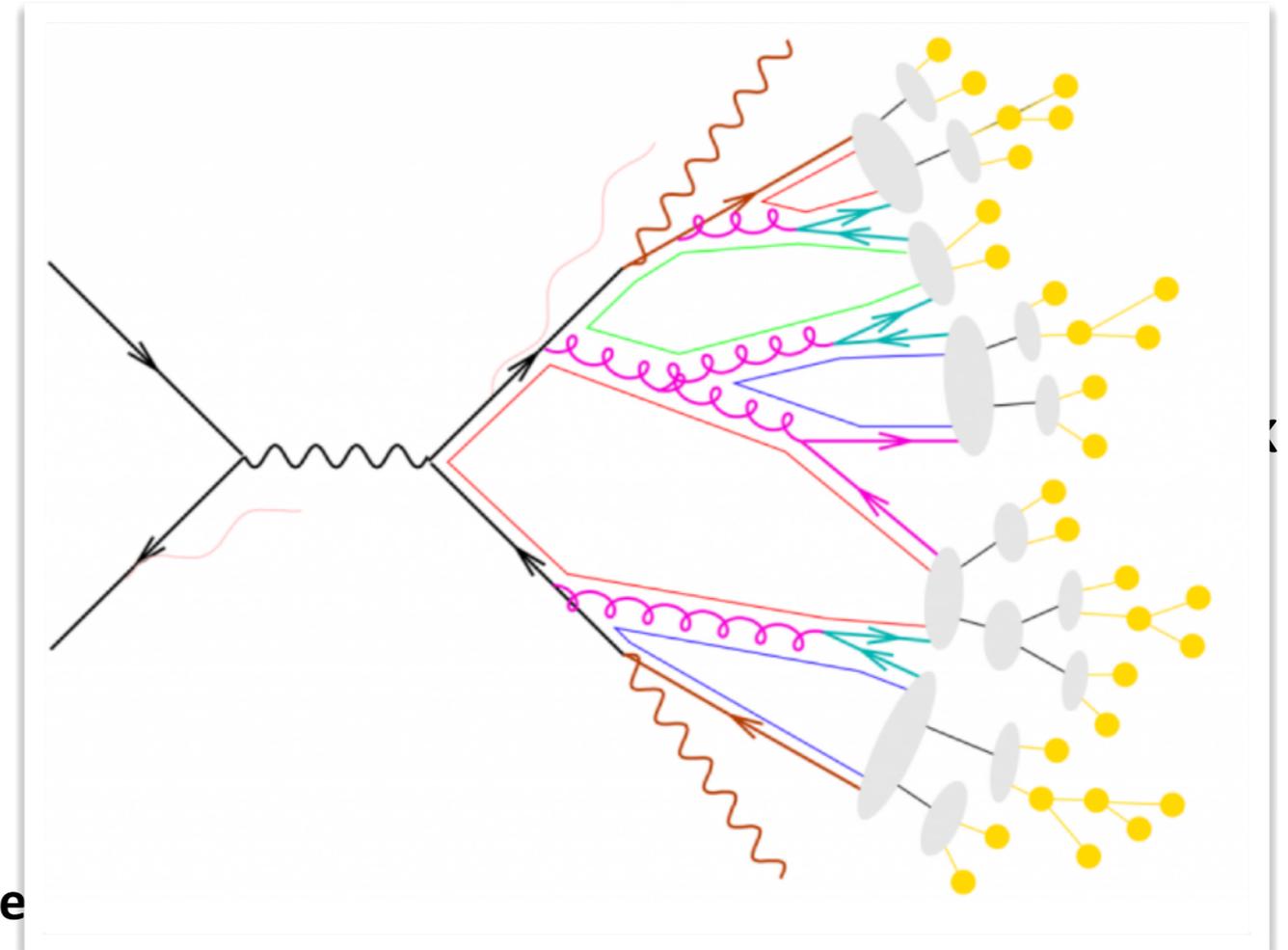
# Decoherence by thermal emission of photons

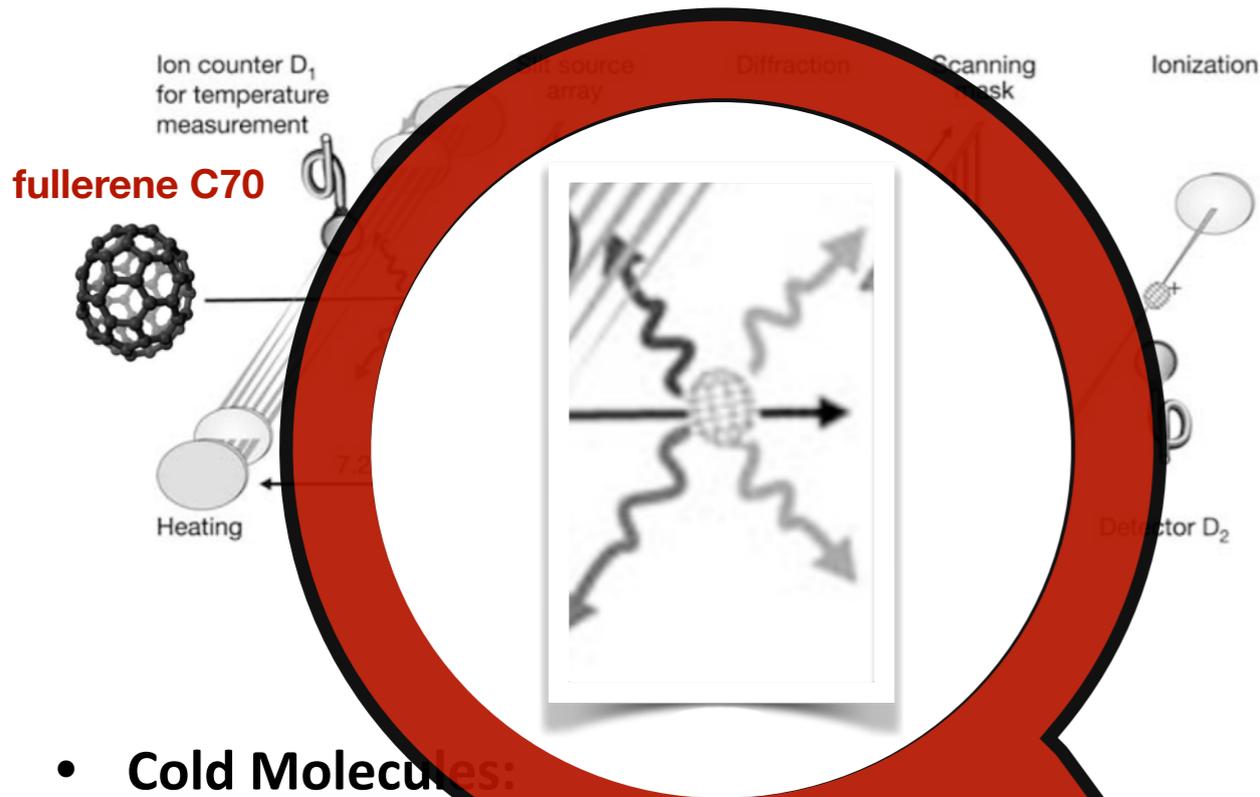Hackermuller, Hornberger, Brezger, Zeilinger, Arndt  Nature '04

fullerene C70

Ion counter $D_1$ for temperature measurement

Heating

Ionization

Detector $D_2$

- **Cold Molecules:**
  - **Molecules emit negligible radiation.**
  - **Result: Strong quantum interference is observed fringe visibility.**
- **Hot Molecules:**
  - **Molecules emit thermal photons that carry path information**
  - **Result: The interference fringe visibility drops to 0%.**
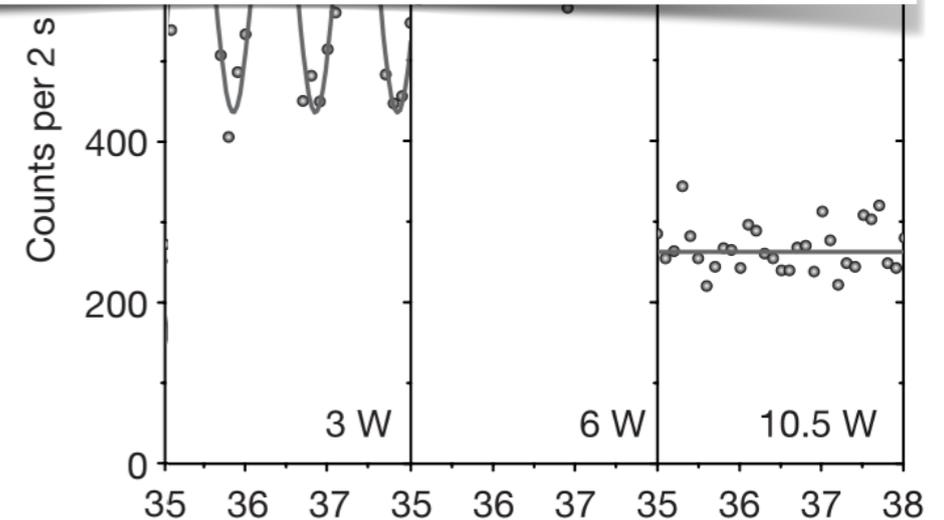- **The decoherence mechanism is the thermal emission of photons by the molecule itself**

Counts per 2 s

400

200

0

3 W          6 W        10.5 W

35  36  37  35  36  37  35  36  37  38

# Decoherence in high energy collisions

- **In the measurements at the colliders, entangled top quark pairs can not be treated as a closed system**



- **They may radiate gluons or photons before decaying, leading to a reduction in quantum spin information, i.e., decoherence.**

- **This interaction with the system results in leakage of information to the environment**

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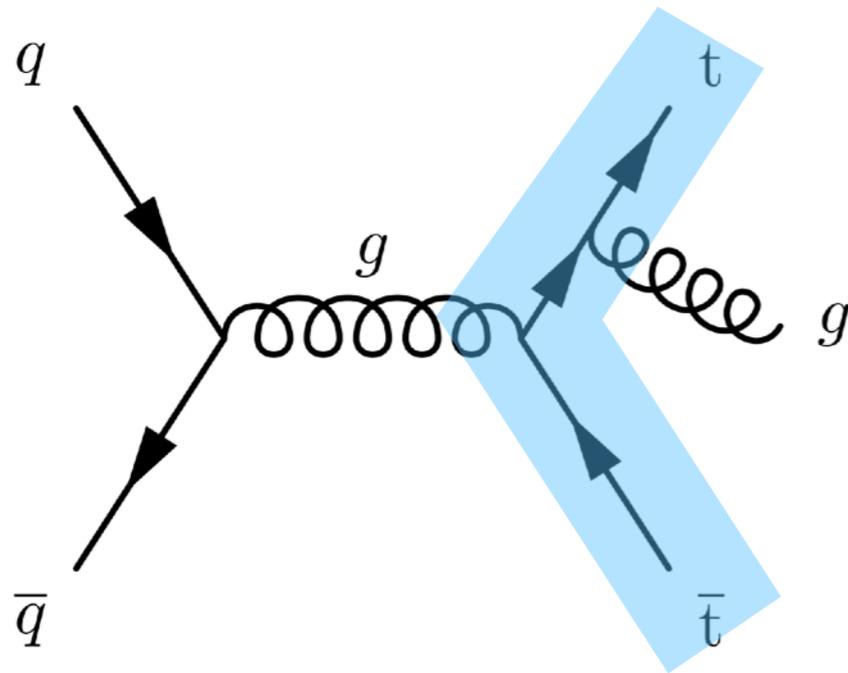
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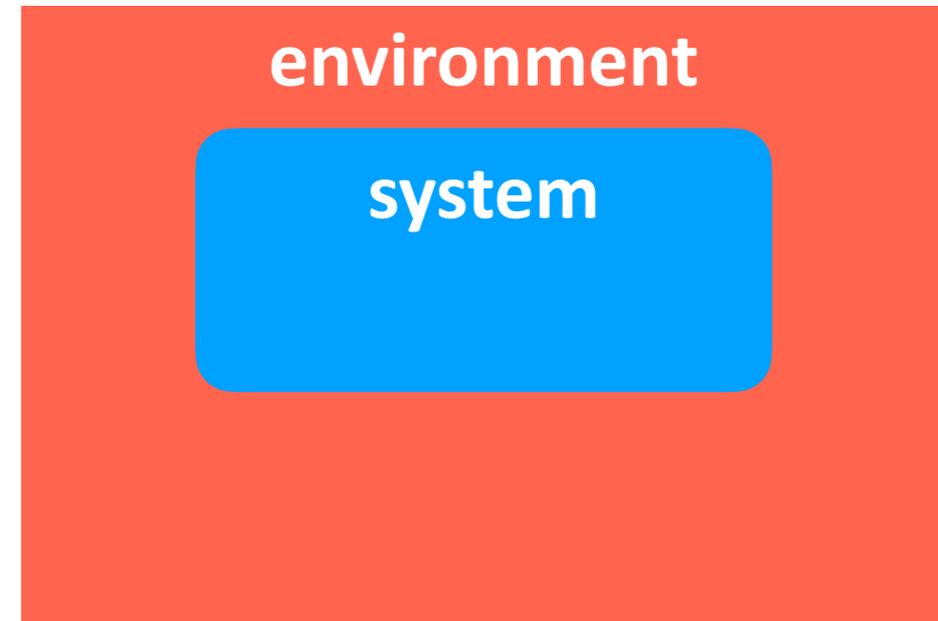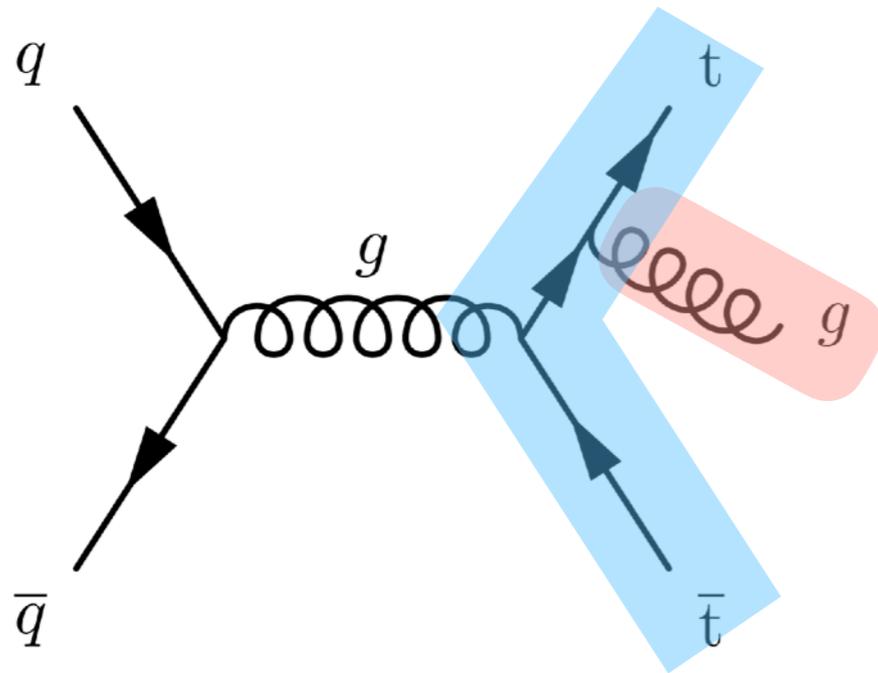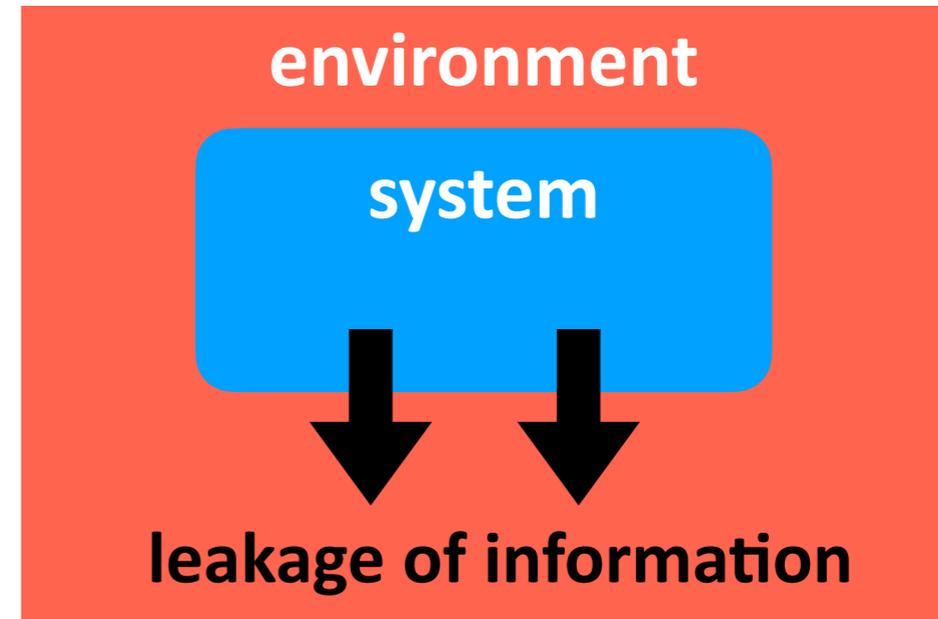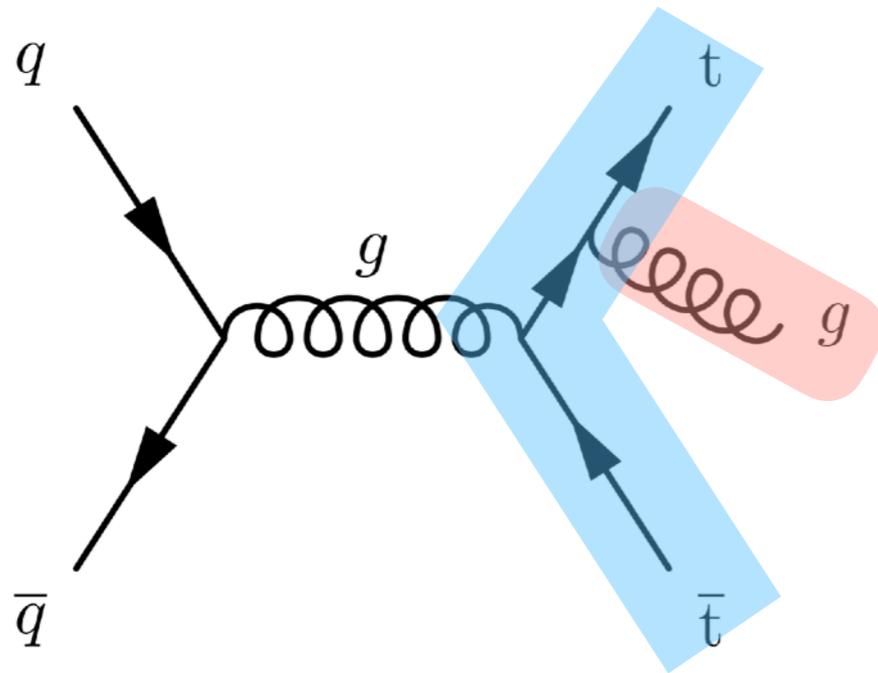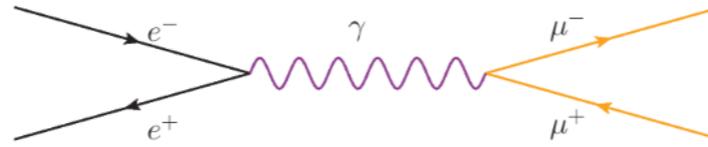


- **They may radiate gluons or photons before decaying, leading to a reduction in quantum spin information, i.e., decoherence.**

- **This interaction with the system results in leakage of information to the environment**

# Leading order results (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**

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

- **Maximum entanglement** $cos\vartheta = 0$

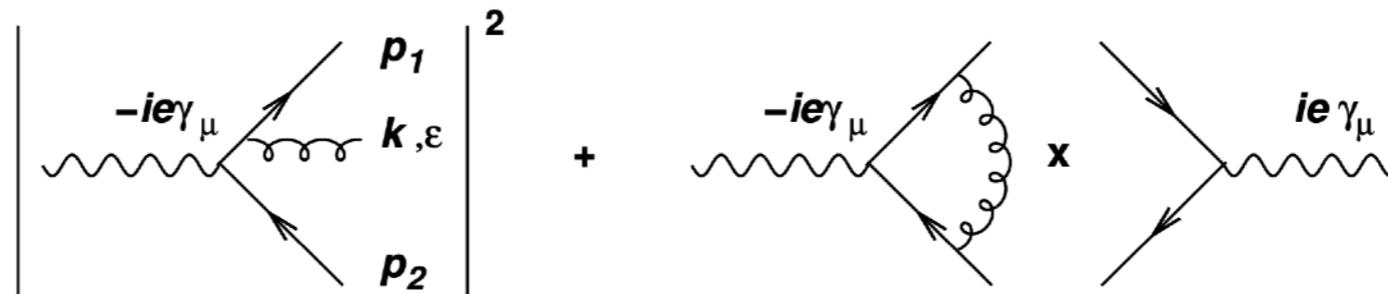$$\mathcal{C}[\rho_{\mathrm{LO}}] = 1 \qquad\qquad \frac{1}{\sqrt{2}}(|+-\rangle + |-+\rangle)$$

# 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**



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

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

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

**Virtual**             **Real: hard, collinear, soft**

# Effective field theory for decoherence
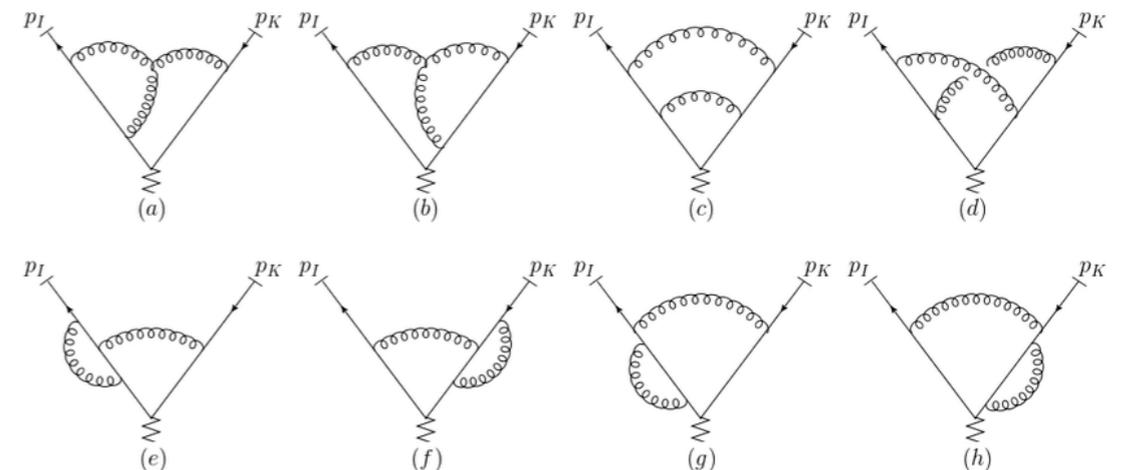
- **Radiation should be considered unresolvable if either soft of collinear**

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

**Two fermion events:**



$2E_{\text{out}} < Q\beta$

$\delta = \tan(\alpha/2)$

- **We apply soft-collinear effective theory (SCET) + jet effective theory (JET)** (Becher, Neubert, Rothen, DYS '16)

- **The initial spin state generated by the short-distance hard scattering** $\hat{\rho}_{\text{hard}}(Q, \mu)$

- **Apply a standard multiplicative renormalization scheme to regularize both UV and IR divergences**

$$\hat{\rho}_{\text{hard}}(Q, \mu) = \frac{1}{4}\left(\hat{I}\otimes\hat{I} + P_i^+ \,\hat{\sigma}_i \otimes \hat{I} + P_j^- \,\hat{I}\otimes\hat{\sigma}_j + C_{ij}\,\hat{\sigma}_i\otimes\hat{\sigma}_j\right)$$
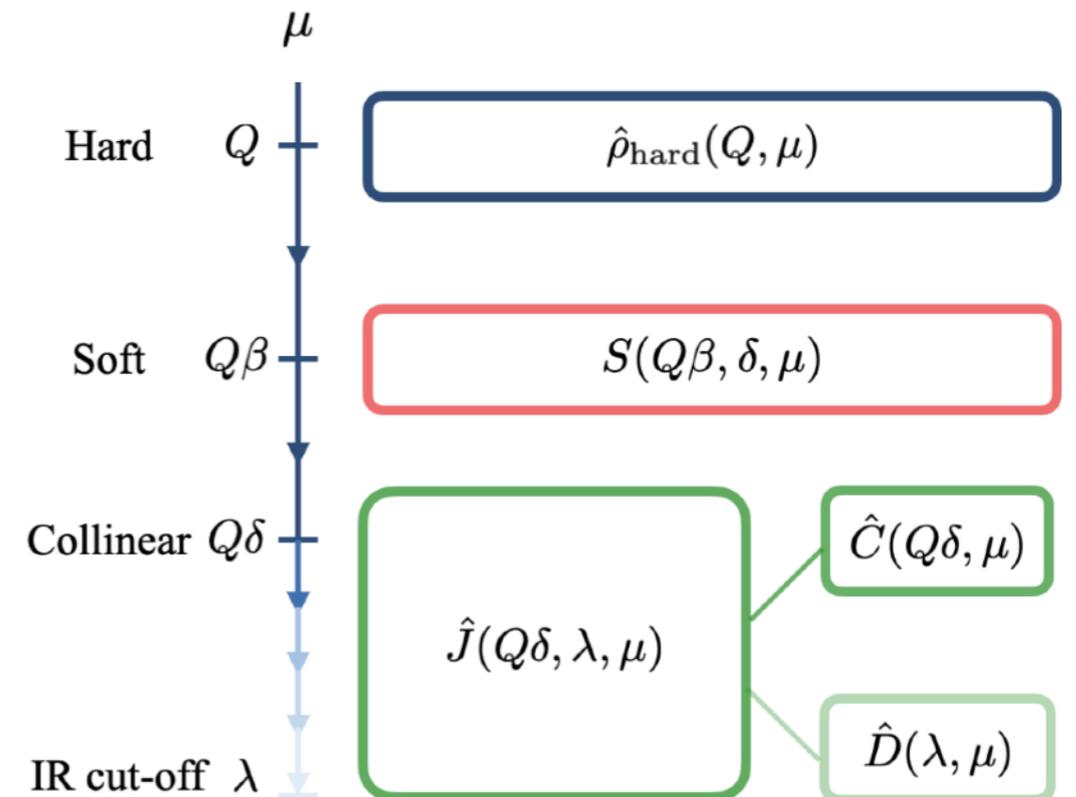
# Factorization of the density operator

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

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

- **Soft function $S$ accounts for large-angle soft radiation. At the leading power, soft emissions are spin-independent and thus <span style="color:red">do not induce decoherence</span>**

- **The fragmenting jet operators $\hat{J}_f$ project the hard scattering state onto the Hilbert space of the observed particles. This effectively traces over unobserved collinear radiation, and <span style="color:red">induces decoherence</span>**

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



**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

Chen, Goldstein, Jaffe & Ji '94

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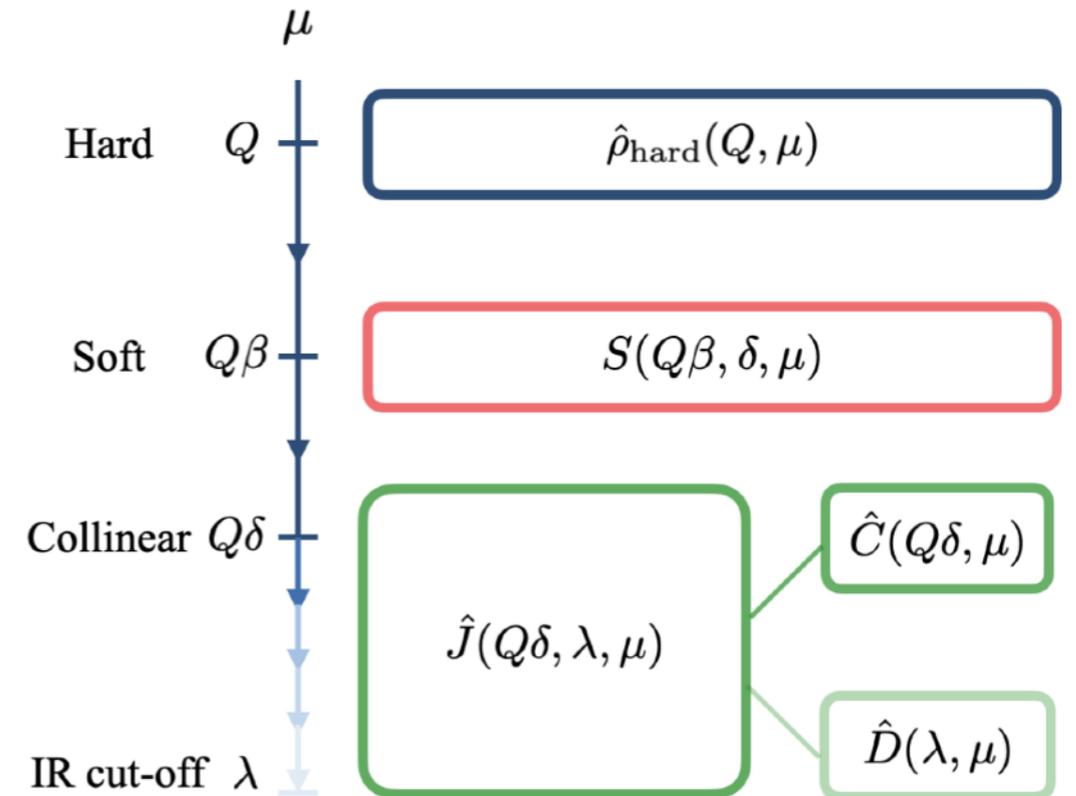
- **Define a scale-dependent effective production matrix**

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



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

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

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

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

**decoherence = RG flow**
anomalous dimensions determine
the rate of information loss

# Kraus operators in QED

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

- **The phase-flip channel: randomly applies a "phase flip" to a qubit**

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

- **The Kraus operators in QED** $\hat{K}_{(i,j)} = \hat{K}_i^{\ell^-} \otimes \hat{K}_j^{\ell^+}$

  - **For the phase-flip channel with probability** $p = \sqrt{\dfrac{1}{2}\left[1 - \exp\left(-\dfrac{\alpha}{2\pi}t\right)\right]}$ $\quad t \equiv \log(Q\delta/\mu).$

$$\hat{K}_0^{\ell^-} = \hat{K}_0^{\ell^+} = \sqrt{1 - p^2}\,\mathbb{I} \qquad \textbf{with probability 1 - } \boldsymbol{p^2}$$

$$\hat{K}_1^{\ell^-} = \hat{K}_1^{\ell^+} = p\,\hat{\sigma}_3 \qquad \textbf{with probability } \boldsymbol{p^2}$$

- **Decay of all off-diagonal terms**

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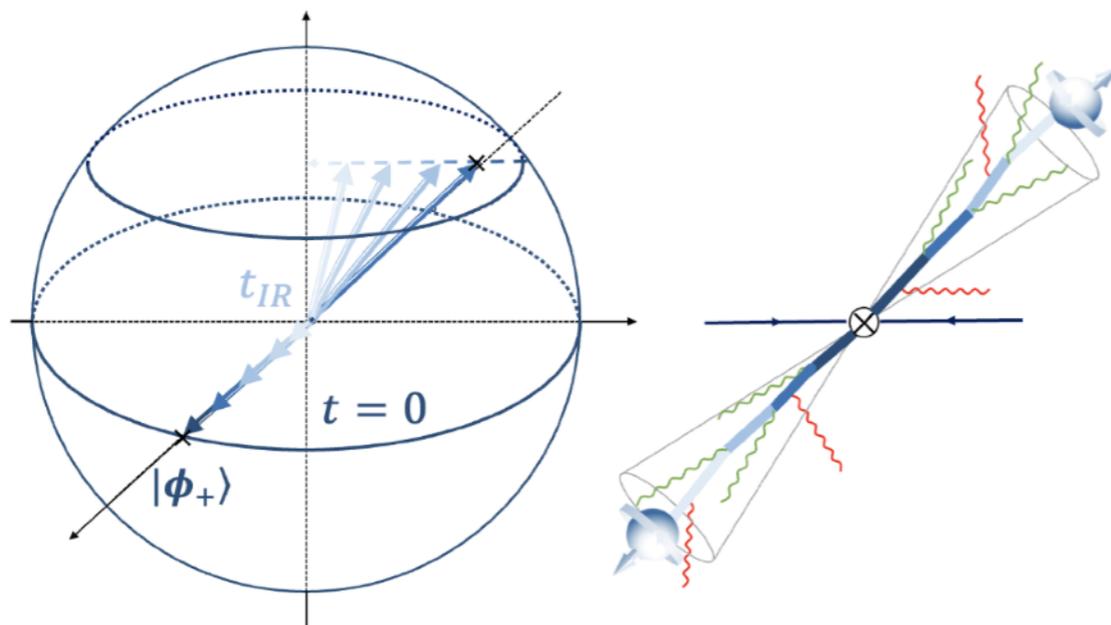
# Lindblad master equation

- **We use QED as an example: IR cut-off = lepton mass**

- **Gorini-Kossakowski-Sudarshan-Lindblad master equation and jump operators**

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

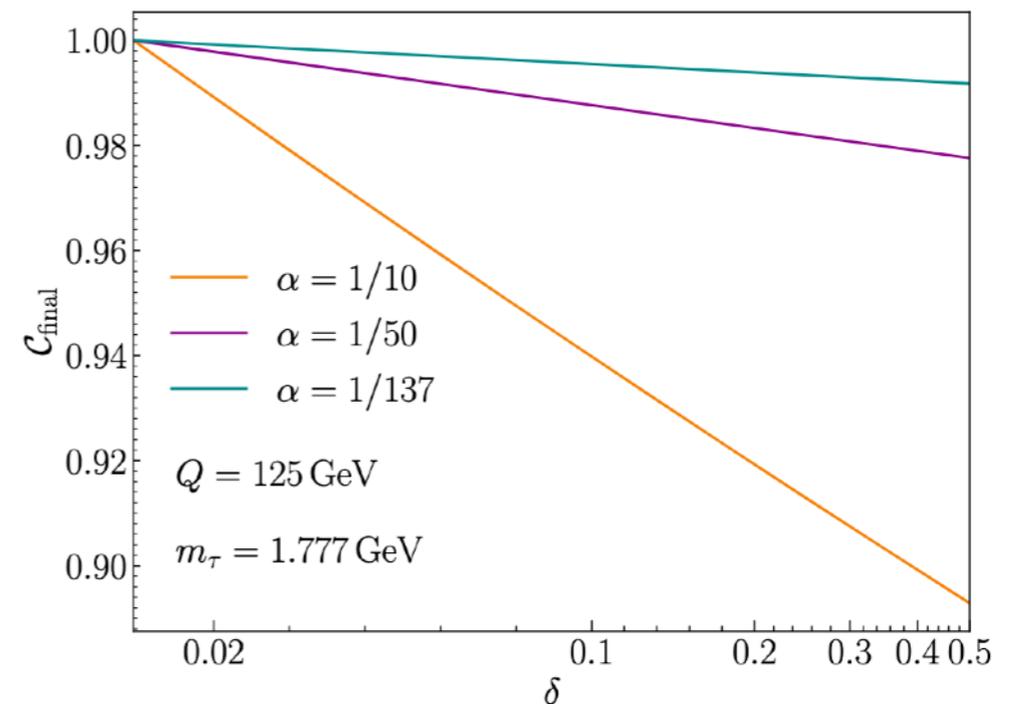$$\hat{L}_1 = \sqrt{\alpha/4\pi}\,\hat{\sigma}_3 \otimes \mathbb{I} \qquad\qquad \hat{L}_2 = \sqrt{\alpha/4\pi}\,\mathbb{I} \otimes \hat{\sigma}_3$$

- **Quantum trajectory interpretation: each "jump" corresponds to an unresolved collinear photon emission from either of the fermion legs, which induces a stochastic <span style="color:red">phase-flip</span>**



$$|\phi_+\rangle = (|+-\rangle + |-+\rangle)/\sqrt{2}$$
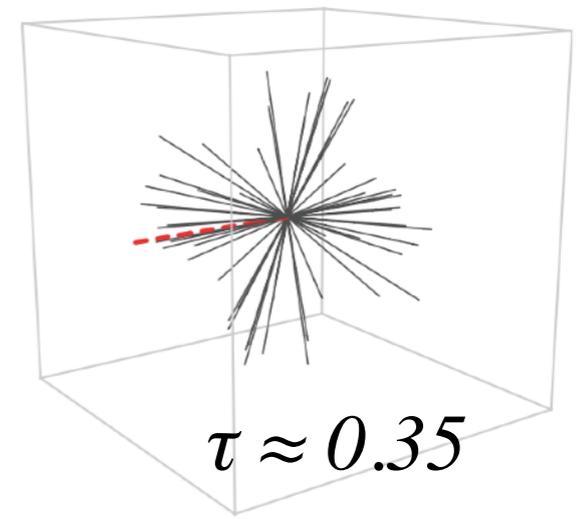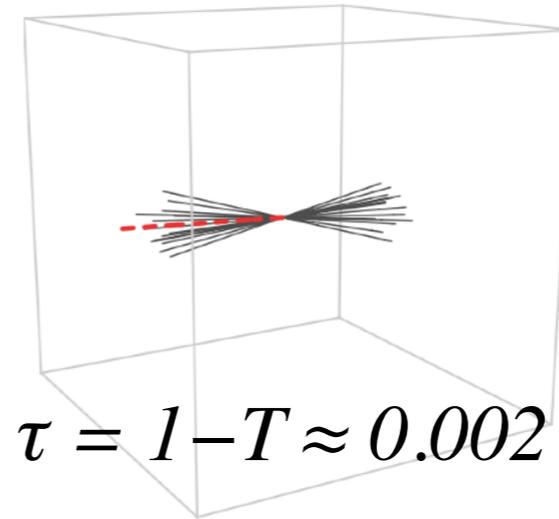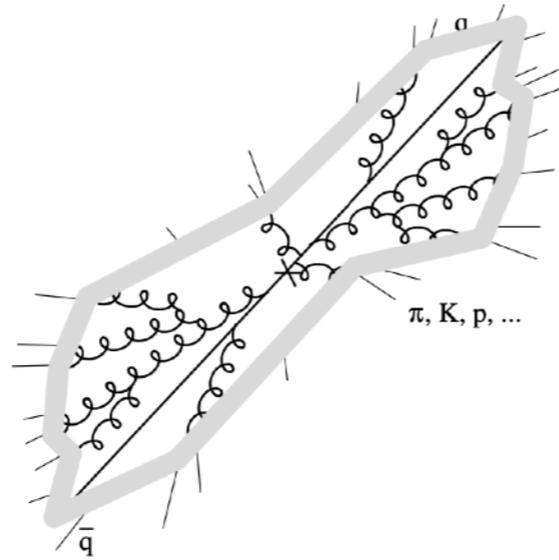
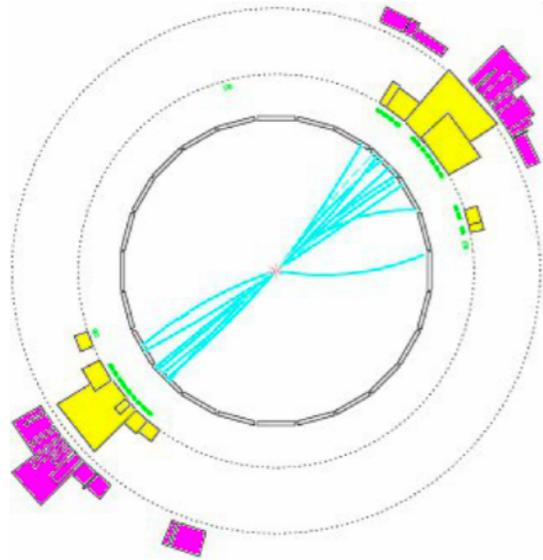**Concurrence** $\mathcal{C}(t) = \mathcal{C}(0)e^{-\frac{\alpha}{\pi}t}$

# Spin correlation in Λ pair production with a thrust cut

- **We apply the event shape thrust (T) to select two-jet configuration** $T = \dfrac{1}{Q}\max_{\vec{n}_T}\sum_i |\vec{n}_T \cdot \vec{p}_i|$



$$\tau = 1-T \approx 0.002 \qquad \tau \approx 0.35$$

- **The resummation formula on the polarized cross section (density matrix)**

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

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

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

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

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

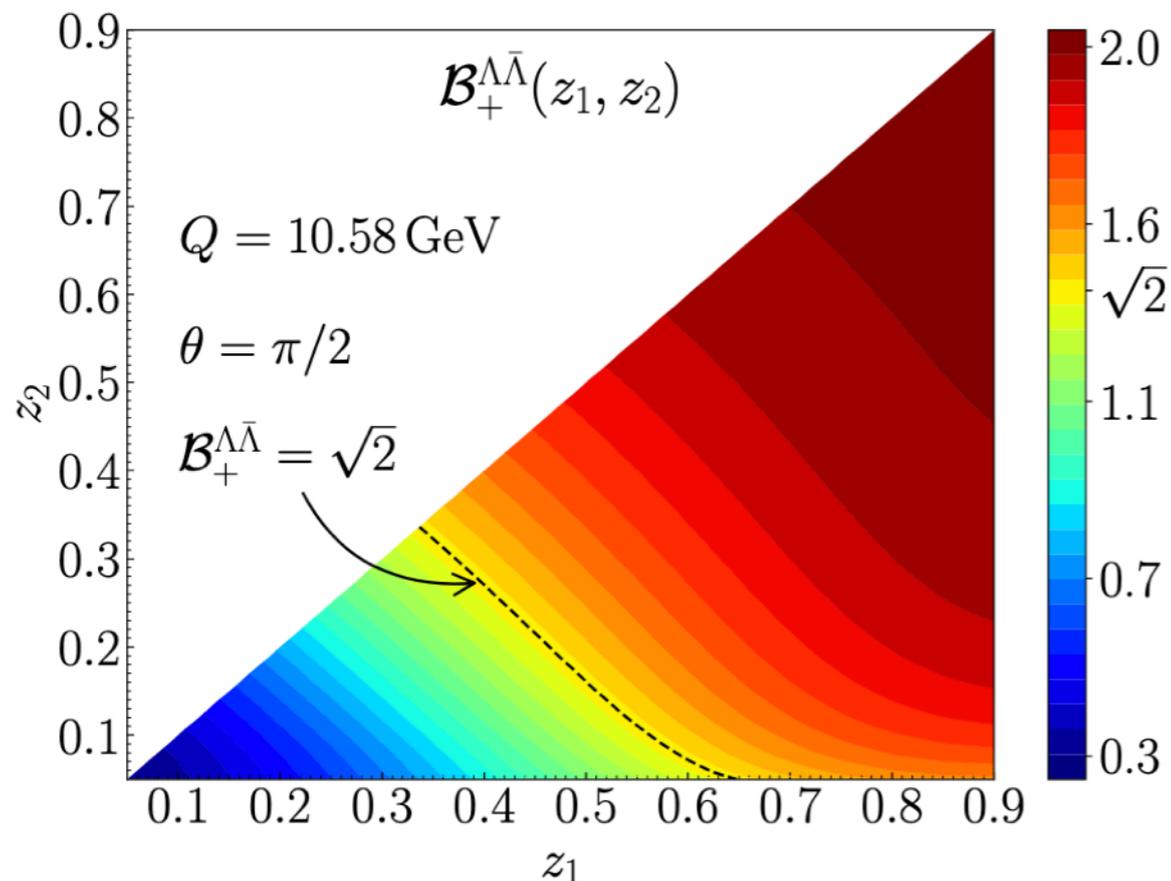# Bell nonlocality and decoherence

- **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**
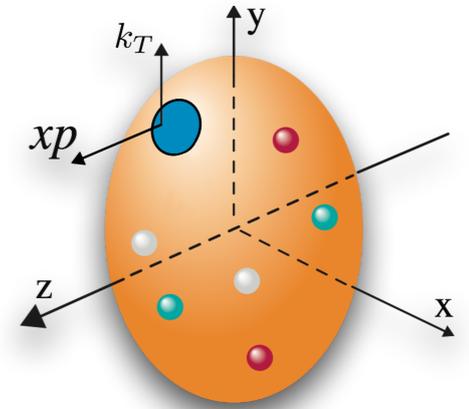
# Nucleon tomography with zero-jettiness

- **Transverse momentum distributions (TMDs) of nucleon encode the quantum correlations between hadron polarization and the motion and polarization of quarks and gluons inside it.**

Spin-dependent cross section:
$$\frac{\mathrm{d}\sigma(\vec{s}_T)}{\mathrm{d}\mathcal{PS}} = F_{UU} + \sin(\phi_s - \phi_q) F_{UT}^{\sin(\phi_s - \phi_q)}$$
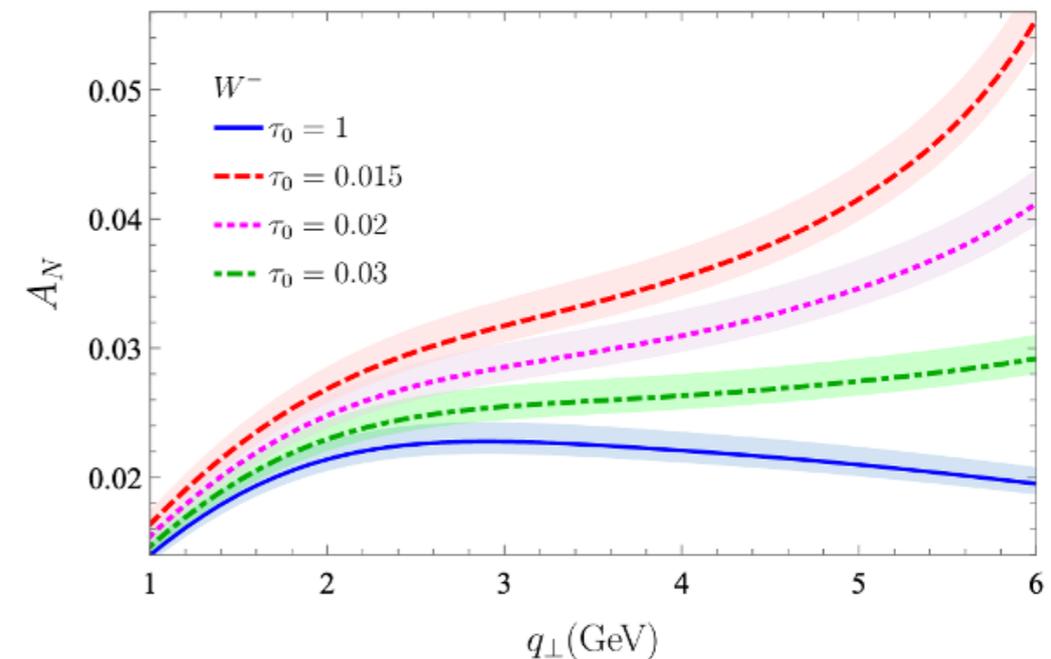
quark TMDs:  $f_q(x, k_T)$  $\qquad \frac{1}{M}\epsilon_{\alpha\beta}\, s_T^\alpha\, k_T^\beta\, f_{1T}^{\perp q}(x, k_T)$

- **However, at high energies, gluon radiation acts as environmental noise, causing quantum decoherence (Sudakov suppression) that obscures these signals.**

- **We introduce 0-jettiness into a tunable resolution scale for quantum coherence**

$$\tau \equiv \frac{2}{Q^2}\sum_i \min\{p_a \cdot l_i, p_b \cdot l_i\}$$

- **This framework predicts an order-unity enhancement of spin asymmetries (e.g., >80% at RHIC)**

# Summary and outlooks

- **Decoherence is inevitable**: Radiation creates an "environment" for the hard process

- **Decoherence is calculable**: RG evolution drives the loss of information

  - **We unified SCET/RGE (HEP) + Open quantum systems (QIS)**

  - **RG flow = Quantum channel**

  - **Energy Scale replaces Time as the driver of decoherence**

- **Outlook:**

  - **Subleading power corrections (e.g. NLP soft theorem)**

  - **Generalize to full evolution (momentum + flavor + spin + color + ...)**

  - **Investigate non-Markovian effects (beyond independent emissions)**

$$\dot{\rho}(t) = \int_0^t \mathcal{K}(t - t')\rho(t')dt' \qquad \mathcal{K}(t - t') \propto \delta(t - t')$$

# Thank you