



**量子信息与人工智能：  
有效场论与重整化群研究的新启示与新范式**

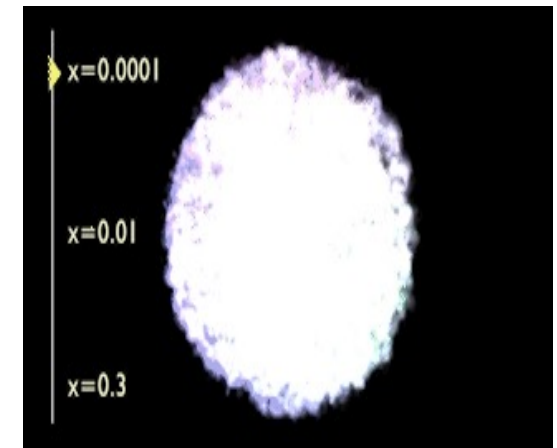
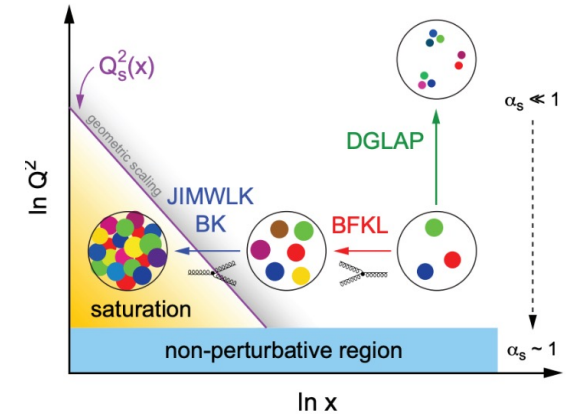
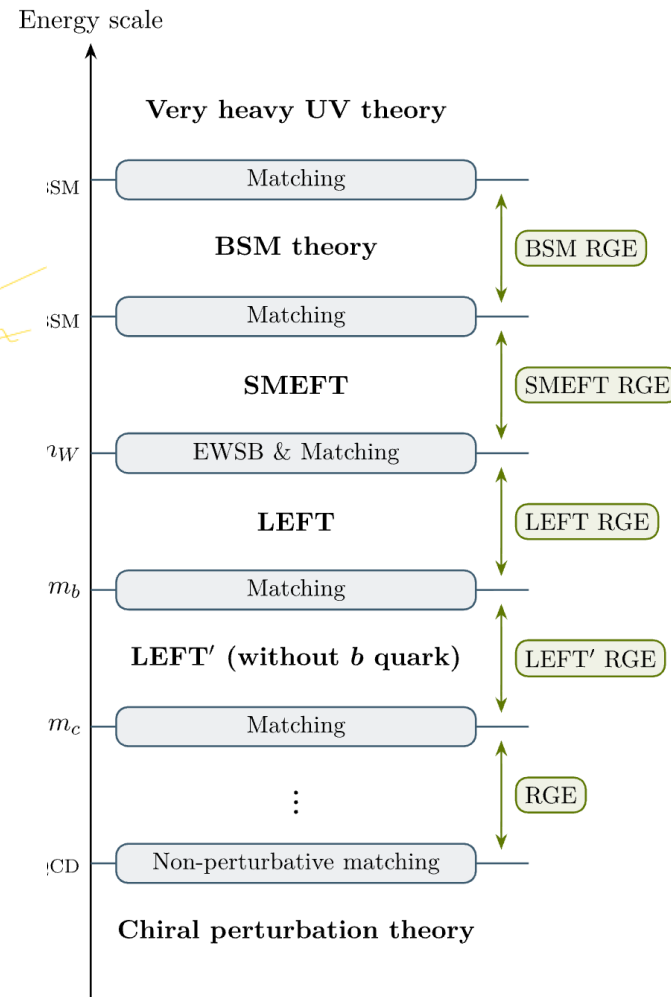
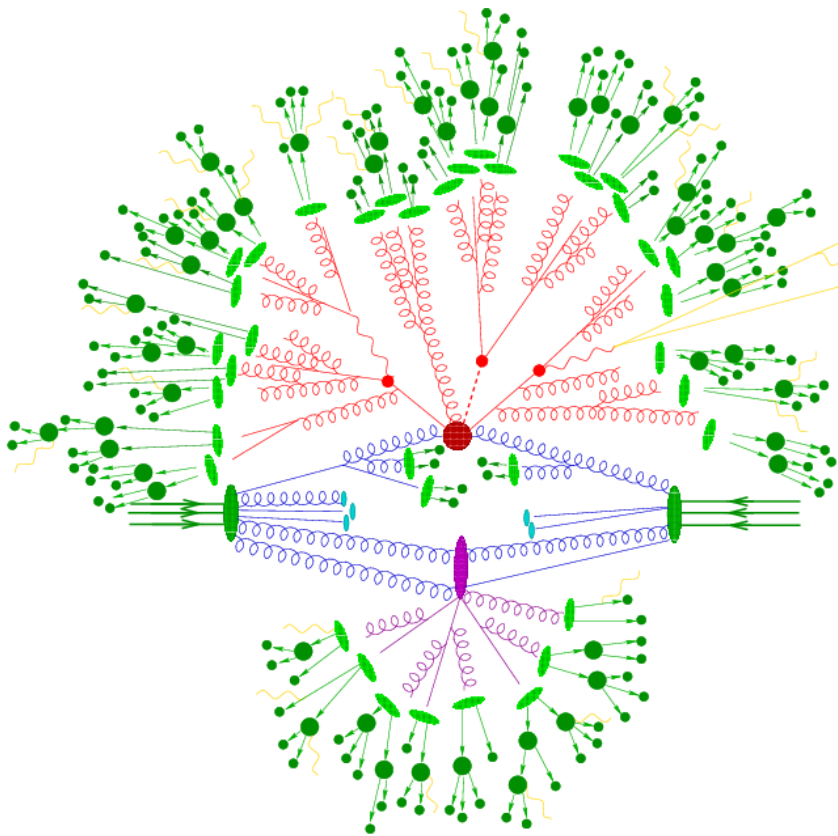
**邵鼎煜  
复旦大学**

**第二届TeV前沿物理研讨会暨第33届LHC Mini-Workshop**

**北京      2026年9月18-20日**



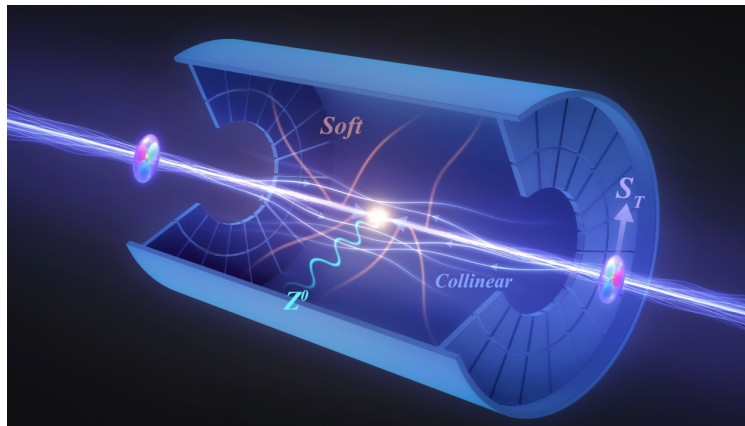
# Collider, EFT and RGE



# New insights

# QCD evolution and spin asymmetry

Spin dependent cross section



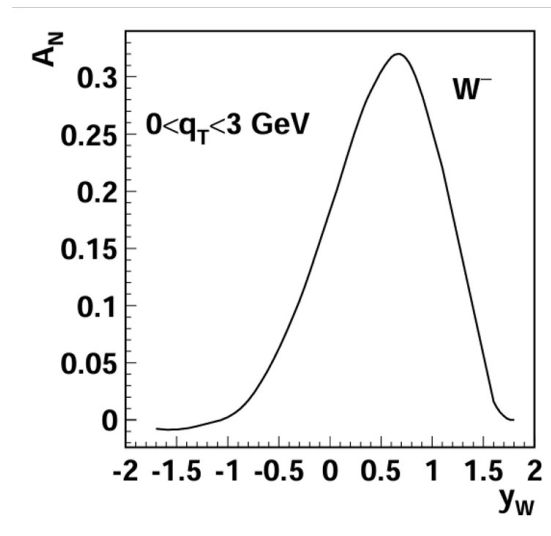
$$p + p^\uparrow \rightarrow V + X$$

$$\frac{d\sigma(\vec{s}_T)}{d\mathcal{PS}} = F_{UU} + \sin(\phi_s - \phi_q) F_{UT}^{\sin(\phi_s - \phi_q)}$$



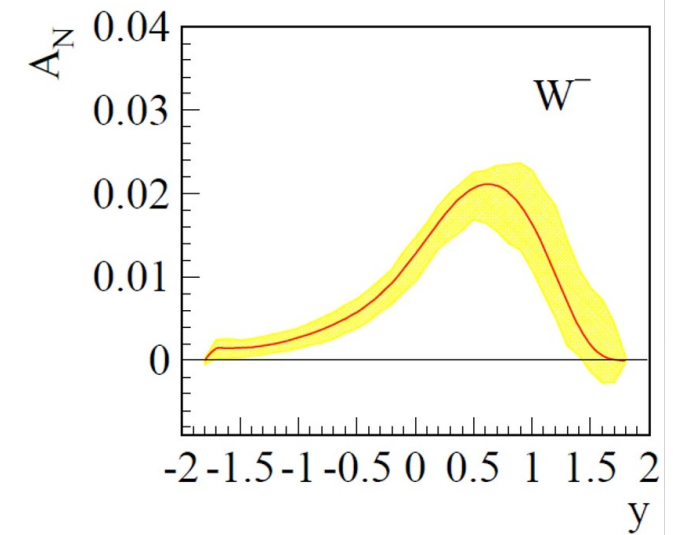
$$f_q(x, k_T) \quad \frac{1}{M} \epsilon_{\alpha\beta} s_T^\alpha k_T^\beta f_{1T}^{\perp q}(x, k_T)$$

Without evolution



Kang & Qiu '09

With evolution

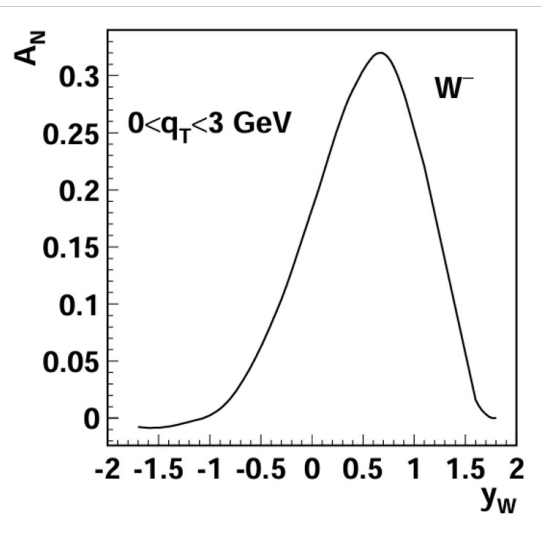


Echevarria, Idilbi, Kang, Vitev '14

**Evolution reduces the asymmetry**

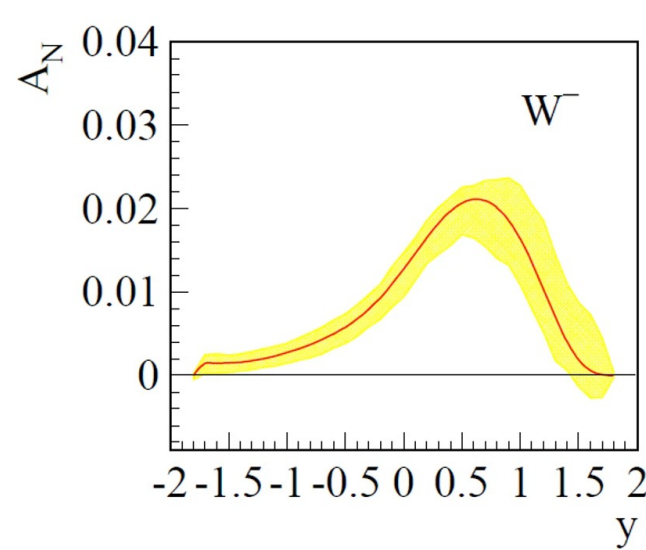
# Spin asymmetry, evolution and decoherence

## Without evolution



Kang & Qiu '09

## With evolution



Echevarria, Idilbi, Kang, Vitev '14

## Quantum information interpretation

- Soft and collinear radiation wash out observable quantum interference.
- Leading power soft radiation decohere the directions of the momenta and the gauge representations of the particles
- Leading power collinear radiation decohere the energies and the spin

Carney, Chaurette, Neuenfeld, Semenov '17

Neill, Waalewijn '19

Aoude, Barr, Maltoni, Satriani '25

S.J. Lin, M.J. Liu, DYS, S.Y. Wei '25

J.Y. Gu, S.J. Lin, DYS, S.X. Yang, L.T. Wang '25

**Evolution reduces the asymmetry  $|+\rangle\langle-|$**



# Effective field theory for decoherence

Lin(林士佳), Liu, DYS, Wei 25; Gu, Lin (林士佳), DYS, Yang(杨斯翔), Wang 25

- A systematic framework calculating decoherence in high energy collisions by combining SCET with the formalism of open quantum systems.
- The renormalization group evolution constitutes a quantum channel, where the RG flow parameter, rather than time, drives a Markovian loss of quantum coherence.

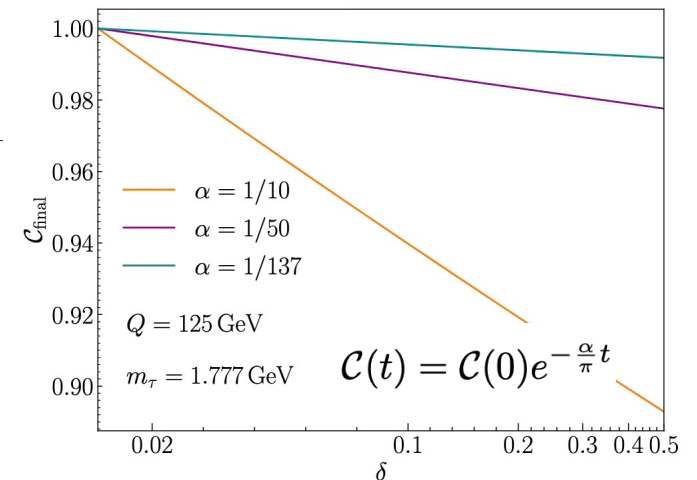
➤ E.g. Applications in QED processes  $e^+e^- \rightarrow l^+l^- + n\gamma$  **IR states unresolved**

- 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  $p = \sqrt{\frac{1}{2} \left[ 1 - \exp\left(-\frac{\alpha}{2\pi}t\right) \right]}$

$$\hat{K}_0^{\ell^-} = \hat{K}_0^{\ell^+} = \sqrt{1-p^2} \mathbb{I} \quad \hat{K}_1^{\ell^-} = \hat{K}_1^{\ell^+} = p \hat{\sigma}_3$$

- Decay of all off-diagonal terms

$$\hat{\rho}(t) = \begin{pmatrix} 1 & e^{-\frac{\alpha}{2\pi}t} & e^{-\frac{\alpha}{2\pi}t} & e^{-\frac{\alpha}{\pi}t} \\ e^{-\frac{\alpha}{2\pi}t} & 1 & e^{-\frac{\alpha}{\pi}t} & e^{-\frac{\alpha}{2\pi}t} \\ e^{-\frac{\alpha}{2\pi}t} & e^{-\frac{\alpha}{\pi}t} & 1 & e^{-\frac{\alpha}{2\pi}t} \\ e^{-\frac{\alpha}{\pi}t} & e^{-\frac{\alpha}{2\pi}t} & e^{-\frac{\alpha}{2\pi}t} & 1 \end{pmatrix}$$

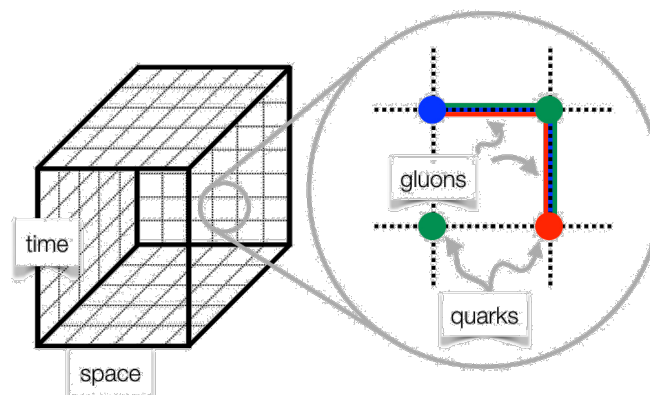
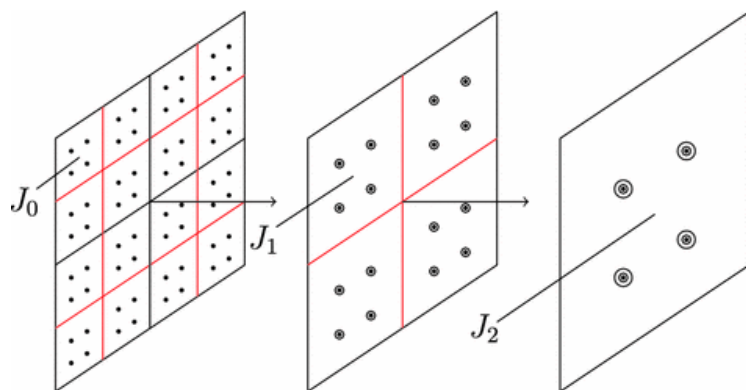


**decoherence = RG flow**  
anomalous dimensions in RGE  
determine the information loss

# **New paradigms**



K. G. Wilson



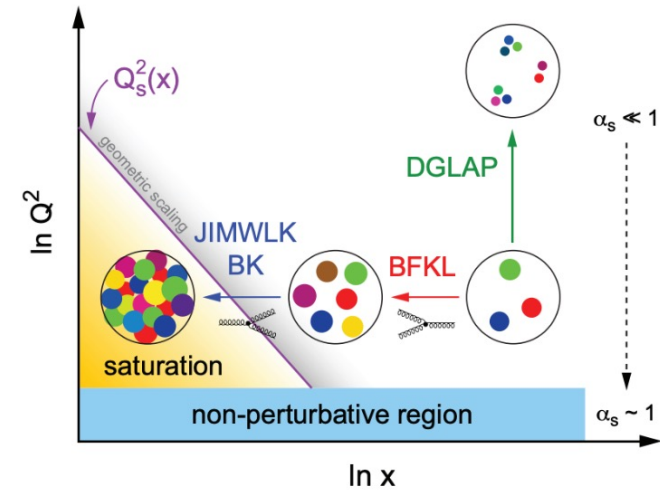
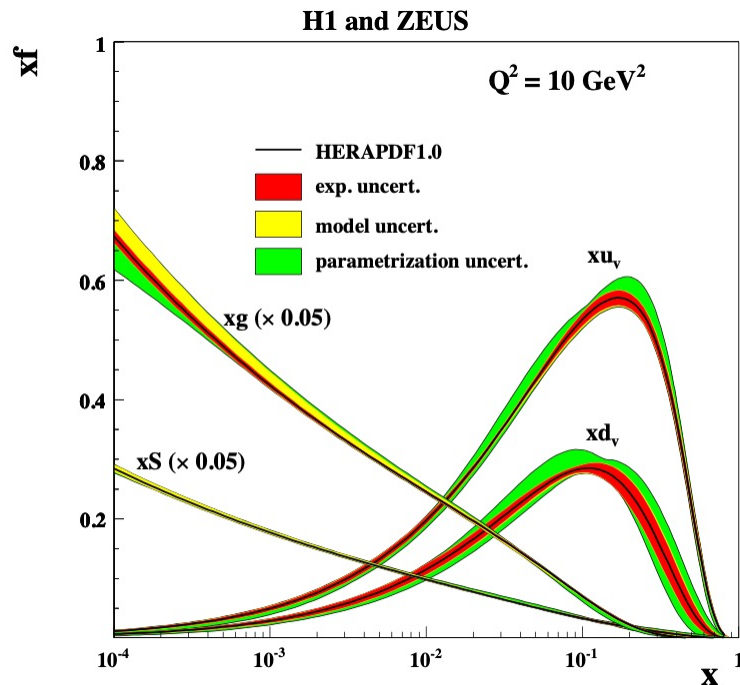
这些尺度的演化，能否被统一看成生成过程？

# **Transformer emulators for BK evolution**

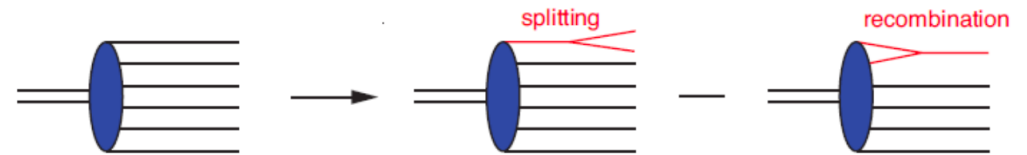
# Gluon saturation and small $x$ physics

DGLAP kernel:  $P_{gg}(x) \rightarrow \frac{1}{x}$  for  $x \rightarrow 0$

Gluon density rapidly increases at small- $x$



Non-linear evolution effect becomes important



BFKL (linear)  $\rightarrow$  BK / JIMWLK (nonlinear)



# Small $x$ factorization in SCET

- SCET factorization with Glauber operator Neill, Pathak, Stewart '23

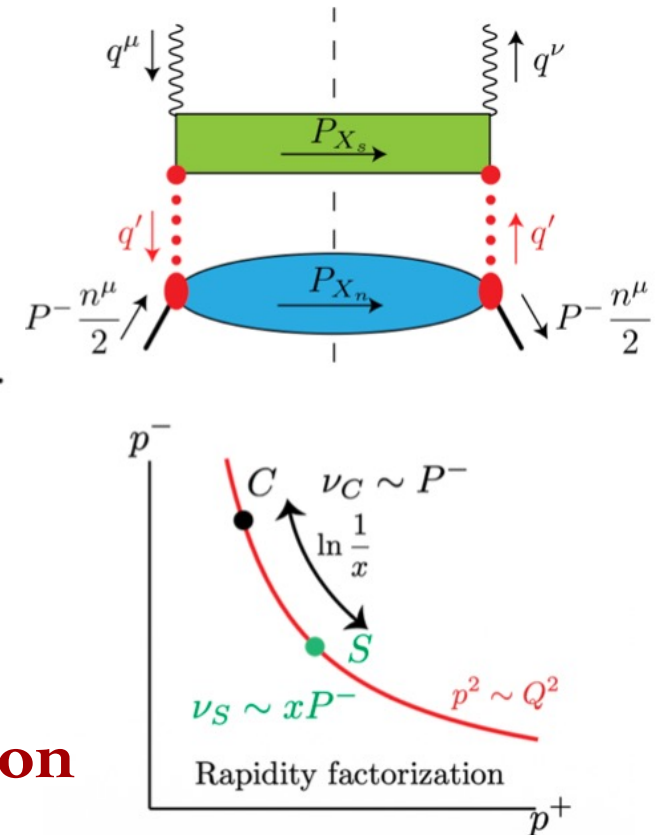
$$S_G^{ns} = 8\pi\alpha_s \sum_{i,j,A} \int d^d y \int d^d x \int \frac{d^d q'}{(2\pi)^d} \frac{e^{i(x-y)\cdot q'}}{\mathbf{q}'_{\perp}{}^2} \mathcal{O}_n^{iA}(x) \mathcal{O}_s^{j_n A}(y).$$

- Factorization formula

$$W^{\alpha\beta}(q, P) = \int d^{d-2} q'_{\perp} S^{\alpha\beta}\left(q, q'_{\perp}, \frac{\nu}{x_b P^-}, \epsilon\right) C\left(q'_{\perp}, P, \frac{\nu}{P^-}, \epsilon\right) + \dots$$

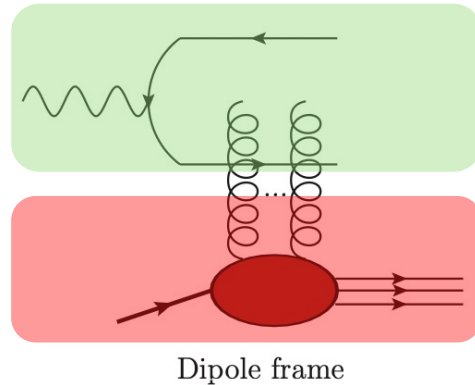
$$\frac{\nu_S}{\nu_C} = x_b$$

Small  $x$  Factorization = Rapidity Factorization



# Deep inelastic scattering at small $x$

- In the small- $x$  regime, DIS cross sections can be calculated within the dipole picture



$$\sigma^{\gamma^* p} = \frac{4\alpha_{\text{em}} N_c}{(2\pi)^2} \sum_f e_f^2 \int d^2\mathbf{r} d^2\mathbf{b} \int_0^1 dz \mathcal{K}_\lambda(\mathbf{r}, z) N(\mathbf{r}, \mathbf{b}, x),$$

- The dynamics of the strong interaction are encoded in the nonperturbative dipole amplitude  $N(\mathbf{r}, \mathbf{b}, x)$



# Balitsky-Kovchegov equation

- The small- $x$ , or rapidity, dependence of the dipole amplitude is governed by BK evolution

$$\frac{\partial N(|\mathbf{r}_{01}|, x)}{\partial Y} = \int d^2\mathbf{r}_2 K_{\text{BK}}(\mathbf{r}_0, \mathbf{r}_1, \mathbf{r}_2) [N(|\mathbf{r}_{02}|, x) + N(|\mathbf{r}_{12}|, x) - N(|\mathbf{r}_{01}|, x) - N(|\mathbf{r}_{02}|, x)N(|\mathbf{r}_{12}|, x)]$$

Non-linear  
gluon recombination

- Key challenge: time-consuming numerical BK evolution
- Some recent progress
  - GPU accelerated solution to BK equation Kutak, Li, Stasto, Straka '25
  - Fast BK solution with Transformer Gao, Kang, Penttala, DYS '25
  - Physics-informed global extraction of the dipole amplitude Dai, Li, Pang, Qin, Wei, Zhang, Zhao '26



# Fast BK solution with Transformer

Gao(高梅森), Kang, Penttala, DYS '25

- BK evolution requires a nonperturbative initial condition  $N(r, x_0)$
- We use a generalized McLerran-Venugopalan ansatz

$$N(r, x_0) = 1 - \exp \left[ - \left( \frac{r^2 Q_{s0}^2}{4} \right)^\gamma \ln \left( \frac{1}{\Lambda_{\text{QCD}} r} + e e_c \right) \right]$$

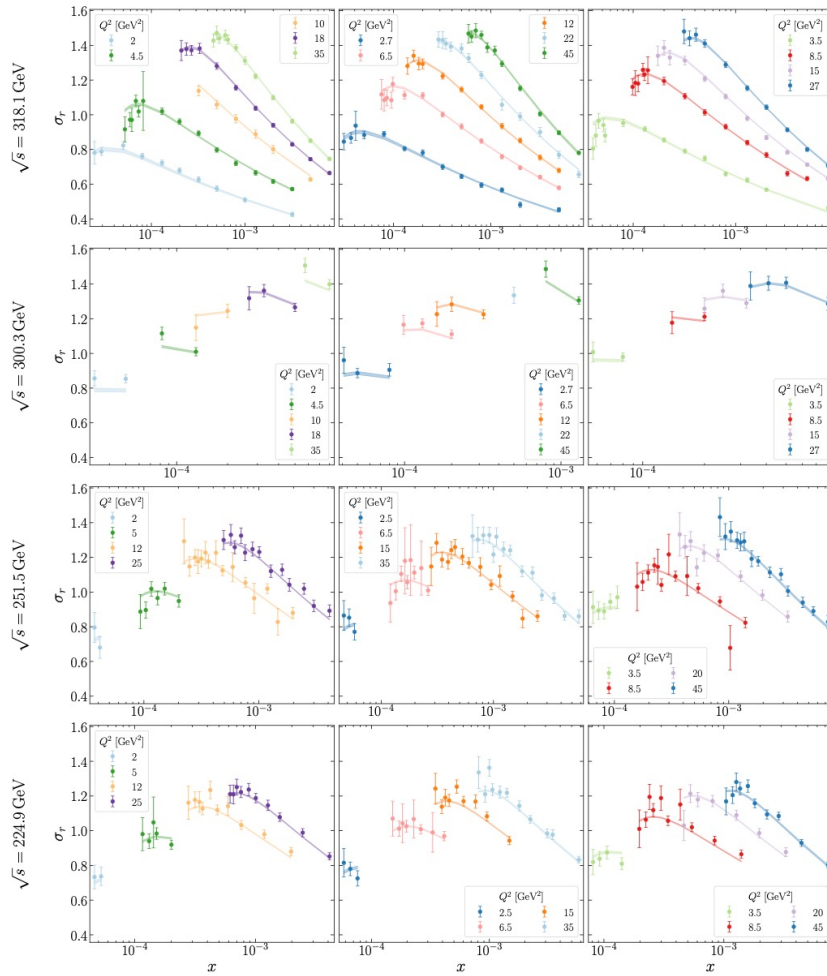
- We first generate a large set ( $O(10^7)$  points  $\{r, x, N\}$ ) of BK solutions
- Transformer network for  $N(r, x)$  emulation

$(\log_{10} Q_{s0}^2, \gamma, e_c, \log_{10} C, \log_{10} r, x)$



# Global-fit results

Gao, Kang, Penttala, DYS '25



| $x_0 = 0.01$                   |              |                           |                           |
|--------------------------------|--------------|---------------------------|---------------------------|
| Parameter                      | Prior Range  | 4-param ( $\gamma = 1$ )  | 5-param ( $\gamma$ free)  |
| $Q_{s0}^2$ [GeV <sup>2</sup> ] | [0.01, 0.11] | $0.063^{+0.001}_{-0.004}$ | $0.068^{+0.024}_{-0.015}$ |
| $e_c$                          | [0.5, 70.0]  | $29.0^{+8.7}_{-3.1}$      | $18.7^{+20.1}_{-9.6}$     |
| $C^2$                          | [2.0, 20.0]  | $4.45^{+0.99}_{-0.59}$    | $4.82^{+1.56}_{-2.63}$    |
| $\sigma_0/2$ [mb]              | [12.0, 20.0] | $14.5^{+0.6}_{-0.4}$      | $14.8^{+0.9}_{-2.4}$      |
| $\gamma$                       | [0.9, 1.3]   | 1.00 (fixed)              | $1.006^{+0.037}_{-0.019}$ |
| $\chi^2/\text{dof}$            | —            | 0.854                     | 0.857                     |

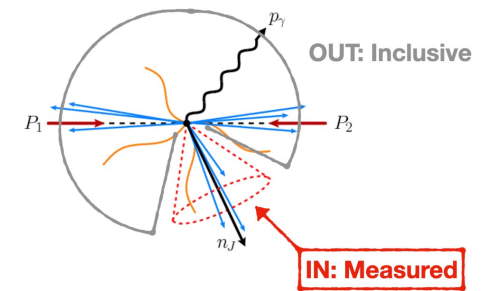
The fit provides a good description of the HERA data ( $\chi^2/\text{dof} \sim 0.85$ )

# **Auto Regressive Parton Shower Generator: Nested-GPT**



# Non-global logs and BMS equation

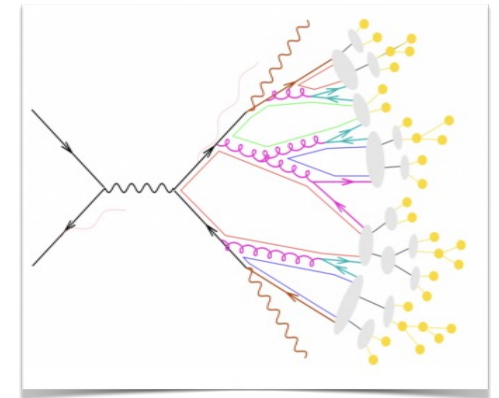
- Observables which are insensitive to emissions into certain regions of phase space involve additional non-global logs (NGLs) not captured by the standard resummation formula
  - Parton shower Dasgupta, Salam '01
  - BMS equation Banfi, Marchesini, Smye '02
  - EFT framework, Multi-Wilson framework Becher, Neubert, Rothen, DYS '16
- BMS eqn (Leading Log, large  $N_c$ )



$$Q \frac{\partial}{\partial Q} G_{ab}(Q) = \int \frac{d^2 \Omega_k}{4\pi} \bar{\alpha}_s W_{ab}(k) [u(k) G_{ak}(Q) G_{kb}(Q) - G_{ab}(Q)]$$

- A new generative paradigm: employ generative models to efficiently and accurately simulate the stochastic parton shower evolution

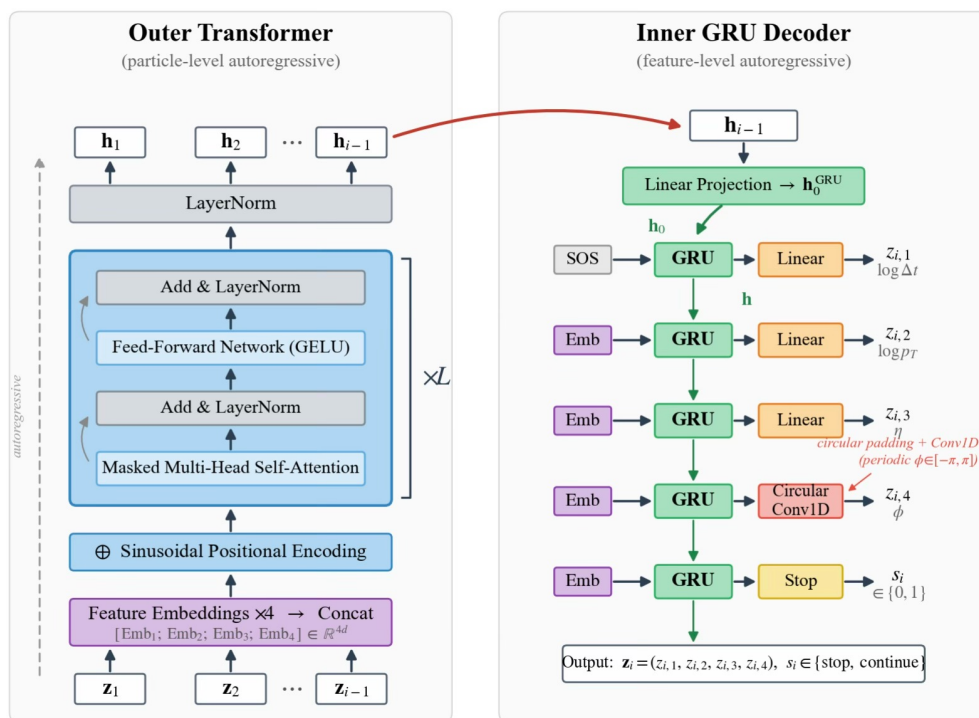
$$P(n, \{e_i\}) = \prod_i P(e_i | e_{<i}) P_{\text{stop}} \quad g \rightarrow gg \rightarrow ggg \rightarrow \dots$$



# Nested-GPT for variable-multiplicity parton showers

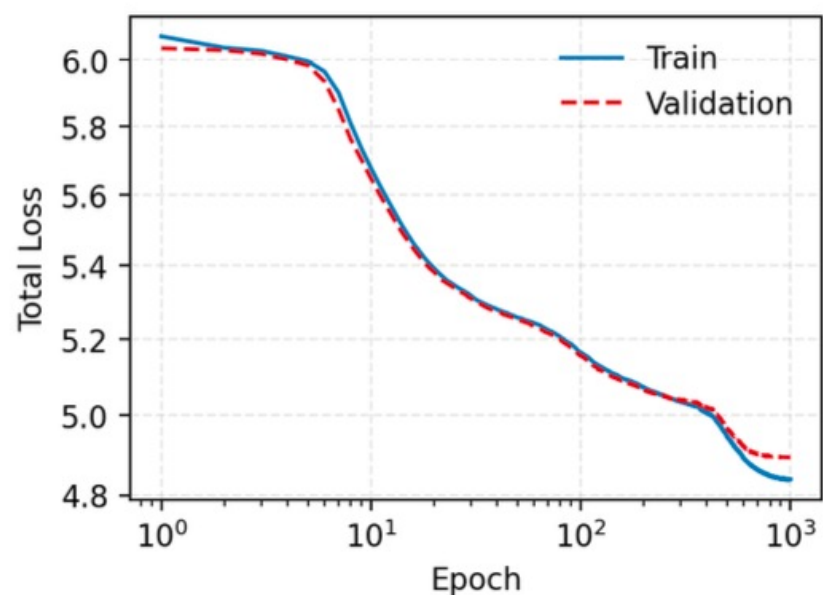
Li(李婉辰), DYS, Shi(施昊哲), Sun(孙宇轩) 2605.18360

- We introduce Nested-GPT, a hierarchical autoregressive Transformer architecture for simulating the variable-multiplicity parton-shower

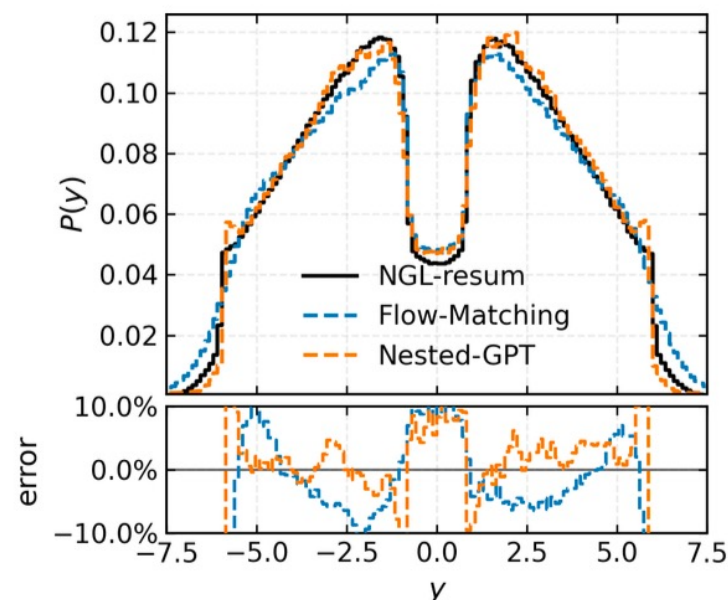


核心思想: 分层自回归架构

- Outer (Inter-Particle) Transformer: 使用因果注意力捕捉按 “shower time” 排序的粒子发射之间的长程依赖。通过 stop/continue decision token 动态学习序列何时终止, 用于模拟 Sudakov factor。
- Inner (Intra-Particle) GRU Decoder: 根据之前粒子的上下文, 自回归生成当前粒子的全部特  
 $(\log \Delta t, \log p_T, \eta, \phi)$
- Outcome: 生成的 “shower history” 序列自然满足物理上的时间有序性要求



Hierarchical learning: The model progresses from dominant inter-particle correlations (the shower structure) to correlations among intra-particle features, with overfitting setting in at around 1,000 epochs.



Nested-GPT achieves accuracy comparable to Flow-Matching and successfully generalizes from inclusive shower histories to unseen vetoed observables

## **An agentic calculation of NGLs @ 13 loops**



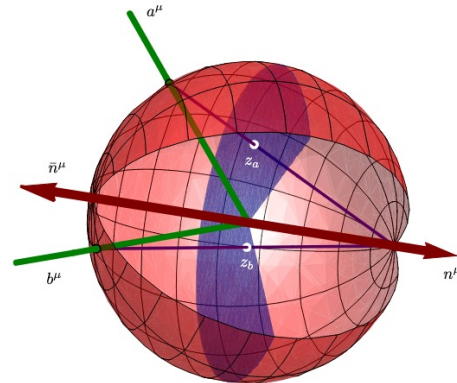
# BMS equation: Hidden symmetry and fixed-order analytic solutions

$$Q \frac{\partial}{\partial Q} G_{ab}(Q) = \int \frac{d^2 \Omega_k}{4\pi} \bar{\alpha}_s W_{ab}(k) [u(k) G_{ak}(Q) G_{kb}(Q) - G_{ab}(Q)]$$

Hidden  $PSL(2, R)$  symmetry

Stereographic projection onto the Poincaré disk

$$z = \tan \frac{\theta}{2} e^{i\phi}$$



Order-by-order analytic solution

$$g_{ab}(L) = 1 + \sum_{n \geq 2} L^n g_{ab}^{(n)}.$$

Analytic result through five loops

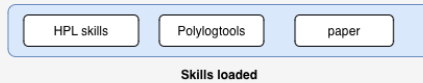
$$g_{n\bar{n}}(L) = 1 - \frac{\pi^2}{24} L^2 + \frac{\zeta(3)}{12} L^3 + \frac{\pi^4}{34560} L^4 + \left( -\frac{\pi^2 \zeta(3)}{360} + \frac{17 \zeta(5)}{480} \right) L^5 + \dots$$

Schwartz, Zhu 2014

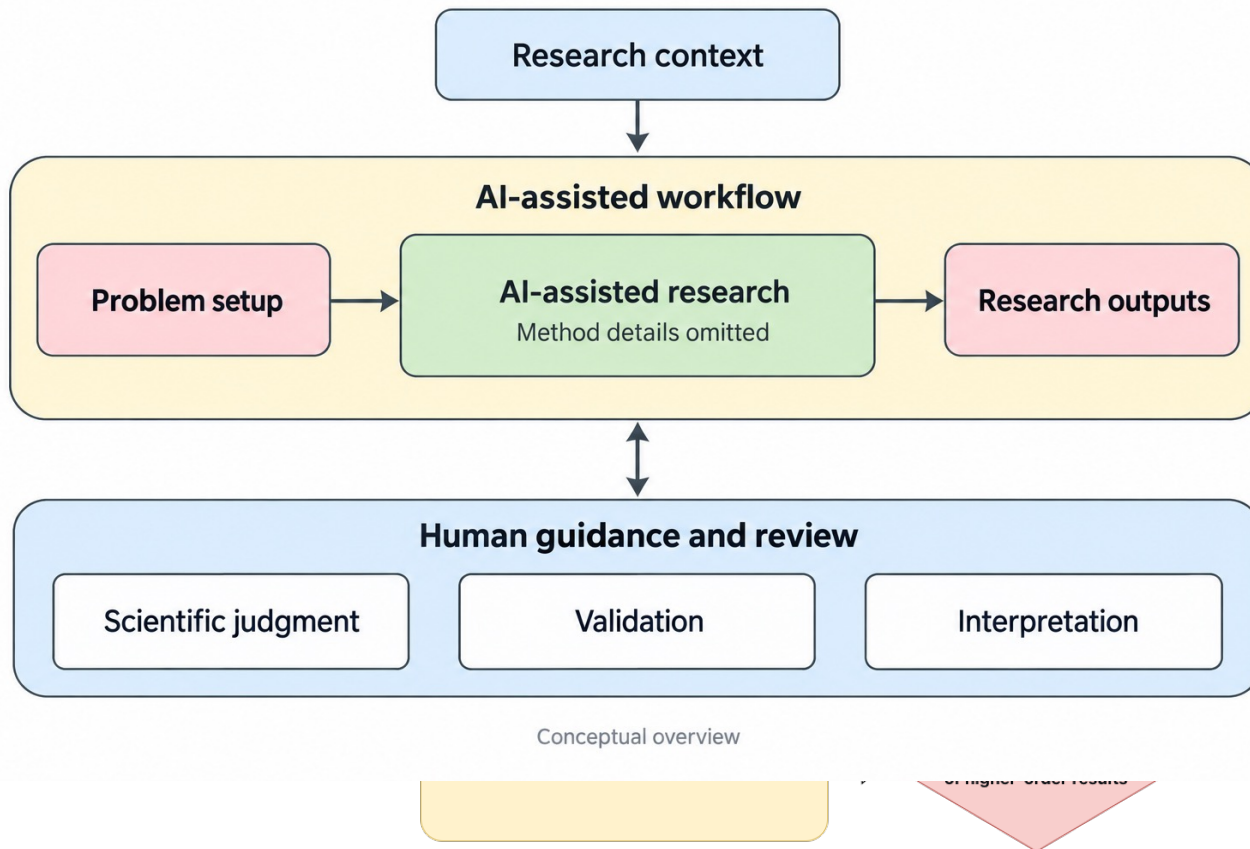
The hidden ( $PSL(2, R)$ ) symmetry reduces the angular dependence to one invariant, making the fixed-order BMS iteration analytically tractable through five loops.



# An agentic calculation of NGLs



## Human-guided AI research workflow



Kong(孔辰光), DYS, Sun(孙宇轩) in progress

$$g_{n\bar{n}}(t) = 1 + \sum_{k=2}^{13} c_k t^k + \mathcal{O}(t^{14})$$

$$t = \int_{\mu_R}^{\mu_L} \frac{d\mu}{\mu} \frac{N_c \alpha_s(\mu)}{\pi} \xrightarrow{\text{fixed coupling}} \frac{N_c \alpha_s}{\pi} \ln \frac{m_L^2}{m_R^2}$$

$$c_2 = -\frac{\pi^2}{24}, \quad c_3 = \frac{\zeta(3)}{12}, \quad c_4 = \frac{\pi^4}{34560}.$$

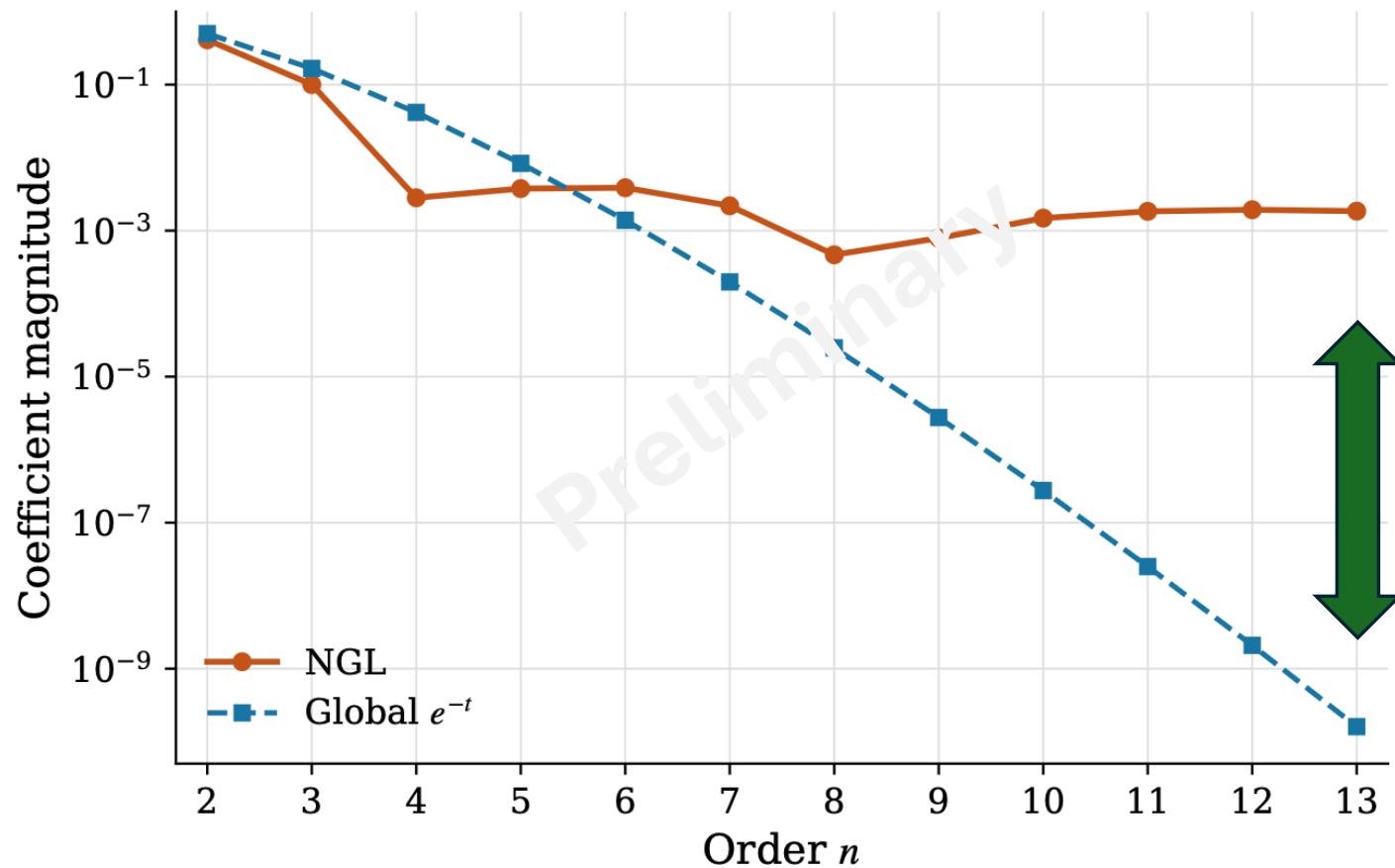
$$c_5 = -\frac{\pi^2 \zeta(3)}{360} + \frac{17 \zeta(5)}{480},$$

$$c_6 = -\frac{331 \pi^6}{65318400} + \frac{\zeta(3)^2}{1440},$$

$$c_7 = \frac{23 \pi^4 \zeta(3)}{691200} - \frac{221 \pi^2 \zeta(5)}{161280} + \frac{197 \zeta(7)}{16128},$$

$$c_8 = \frac{846901}{928972800} \zeta(8) - \frac{683}{645120} \zeta(3) \zeta(5) - \frac{17}{645120} \zeta(2) \zeta(3)^2 - \frac{1}{3225600} \zeta(5, 3),$$

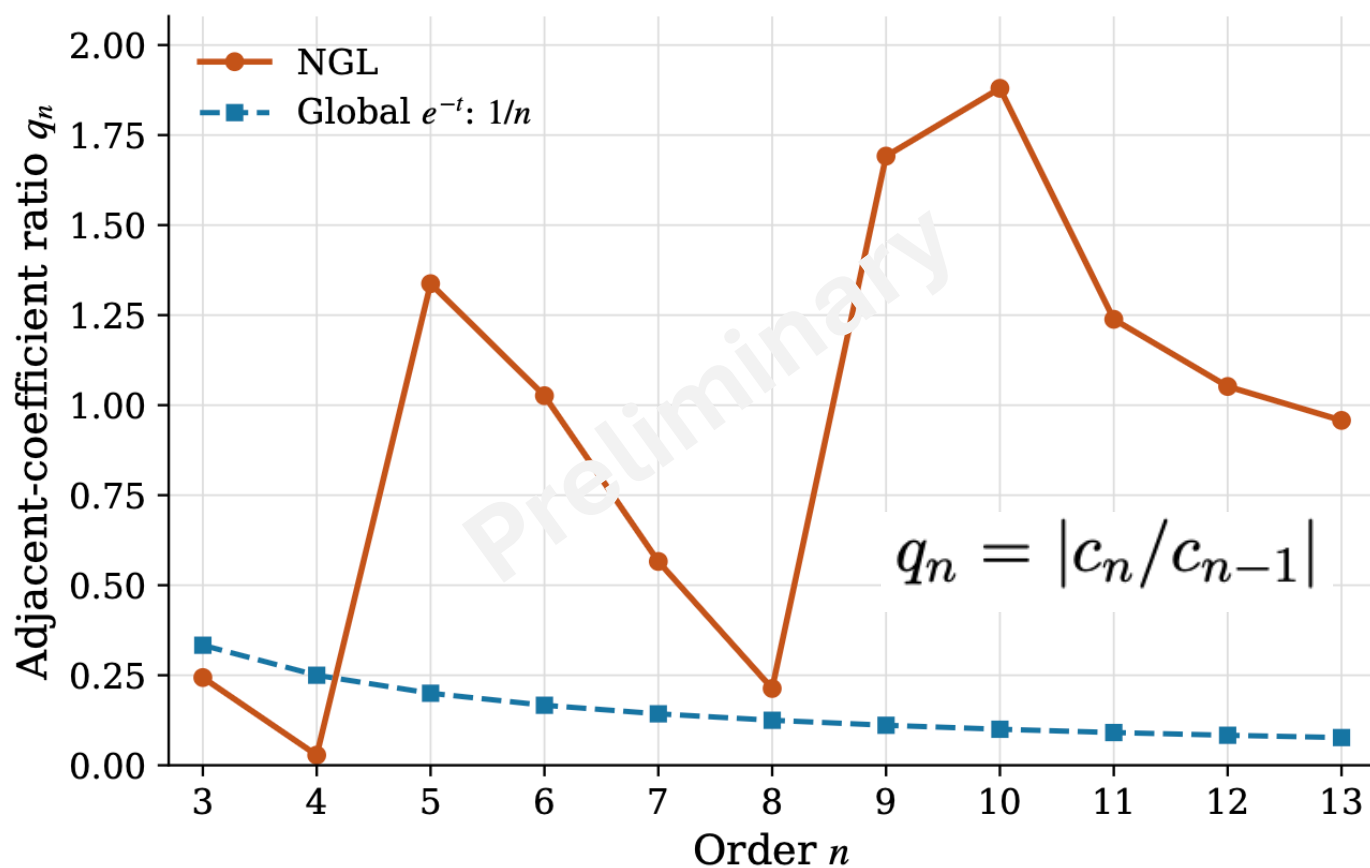
# Global logs v. s. Non-global logs



GL and NGL differ  
by  $10^7$  !



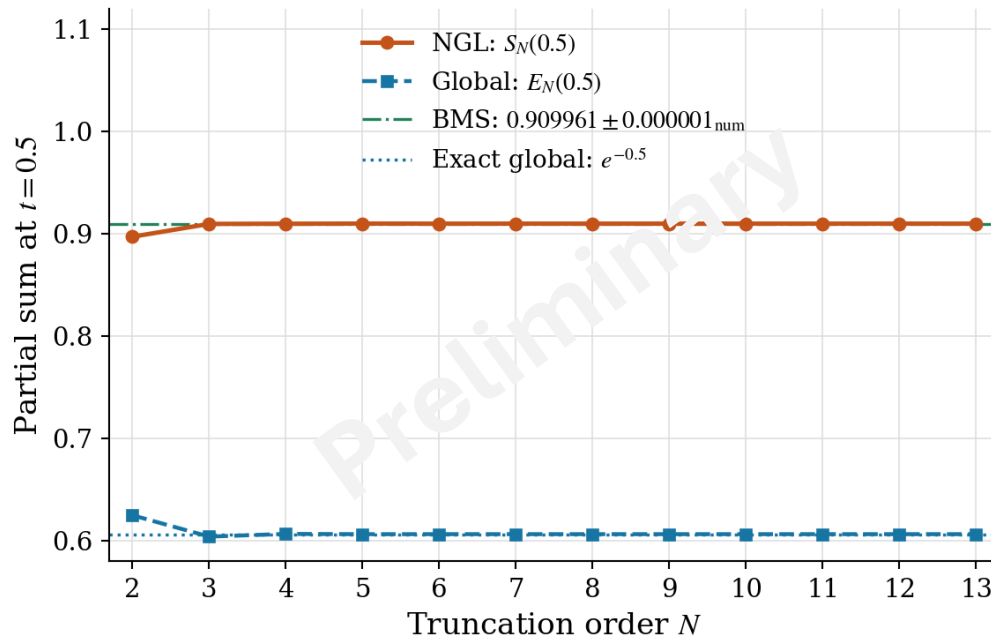
# Global logs v. s. Non-global logs



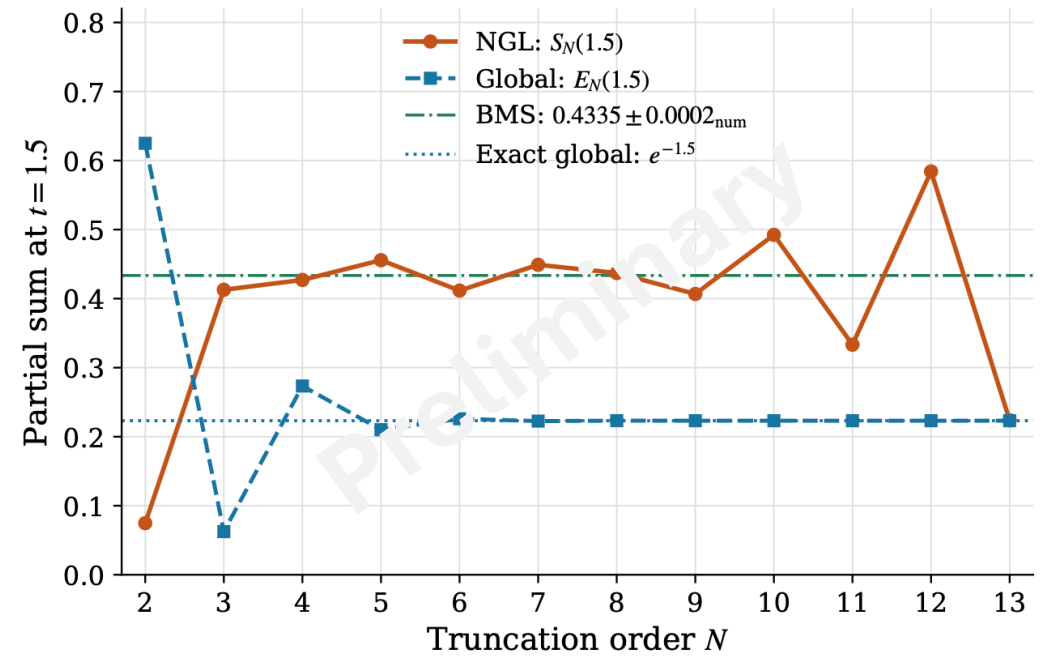


# Global logs v. s. Non-global logs

**t = 0.5**



**t = 1.5**



$$t = \int_{\mu_R}^{\mu_L} \frac{d\mu}{\mu} \frac{N_c \alpha_s(\mu)}{\pi} \xrightarrow{\text{fixed coupling}} \frac{N_c \alpha_s}{\pi} \ln \frac{m_L^2}{m_R^2}$$



# Summary

- **Quantum frontier (new insights):** spin decoherence is **calculable, measurable and driven by RG evolution**
  - unified SCET/RGE (HEP) + Open quantum systems (QIS)
  - RGE drives decoherence through unresolved radiation.
- **AI frontier (new paradigms):** Applying **generative AI to simulate RGE & parton shower**
  - Fast fitting: BK equation
  - Fast simulation: BMS equation

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# **Thank You**

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