New Perspectives on Precision Nucleon Tomography

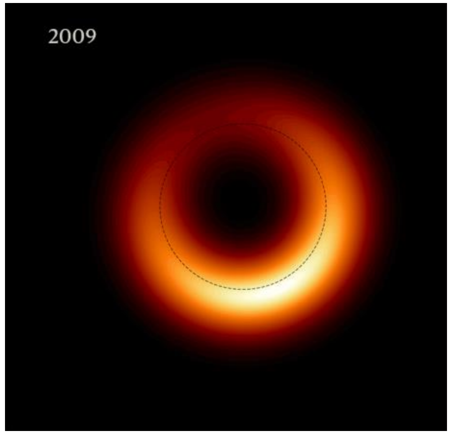
邵鼎煜

复旦大学

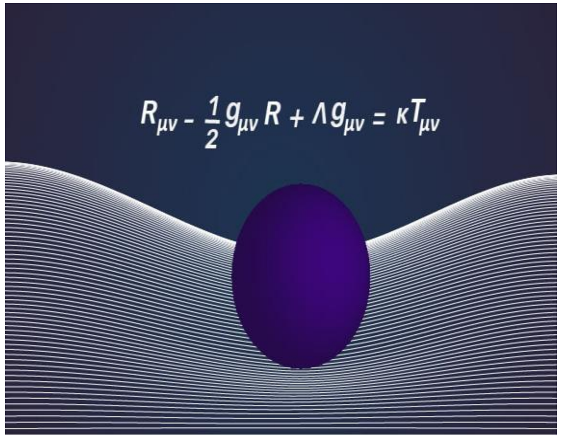
中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

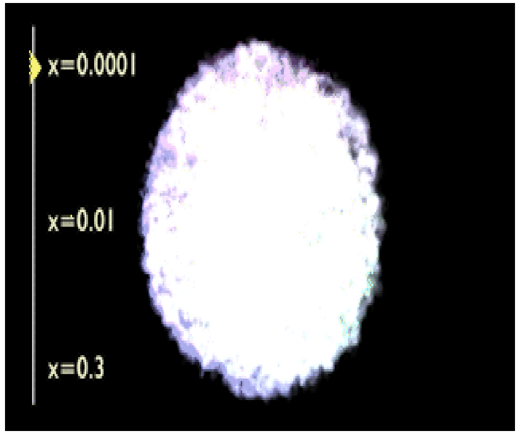
广州　　Jul 13 – 19, 2026

Nucleon tomograph



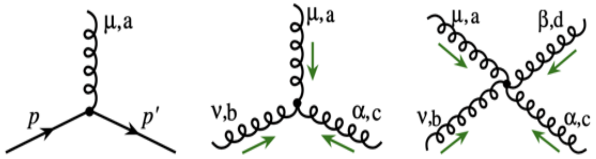
Black hole imaging will deepen our understanding of gravity





Nucleon imaging will deepen our understanding of the strong interaction

$$-\frac{1}{4}G^2_{\mu\nu,a}[A] + \sum_f \overline{\psi}_f \left(iD_\mu[A]\gamma^\mu - m_f\right)\psi_f$$



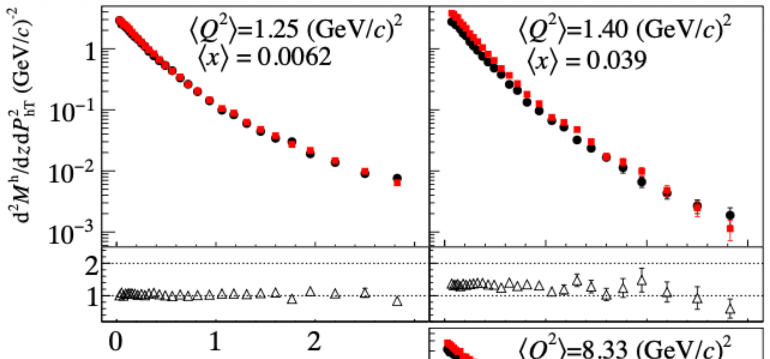
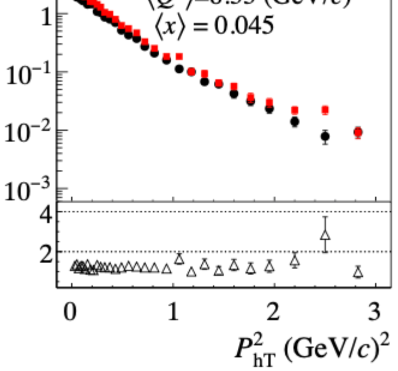
see X.D. Ji`s talk

New methods

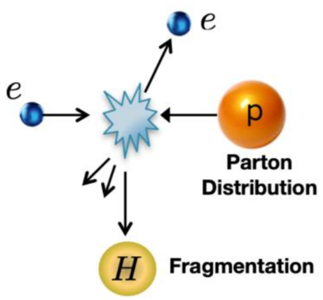
Quark TMDs in e-p collisions

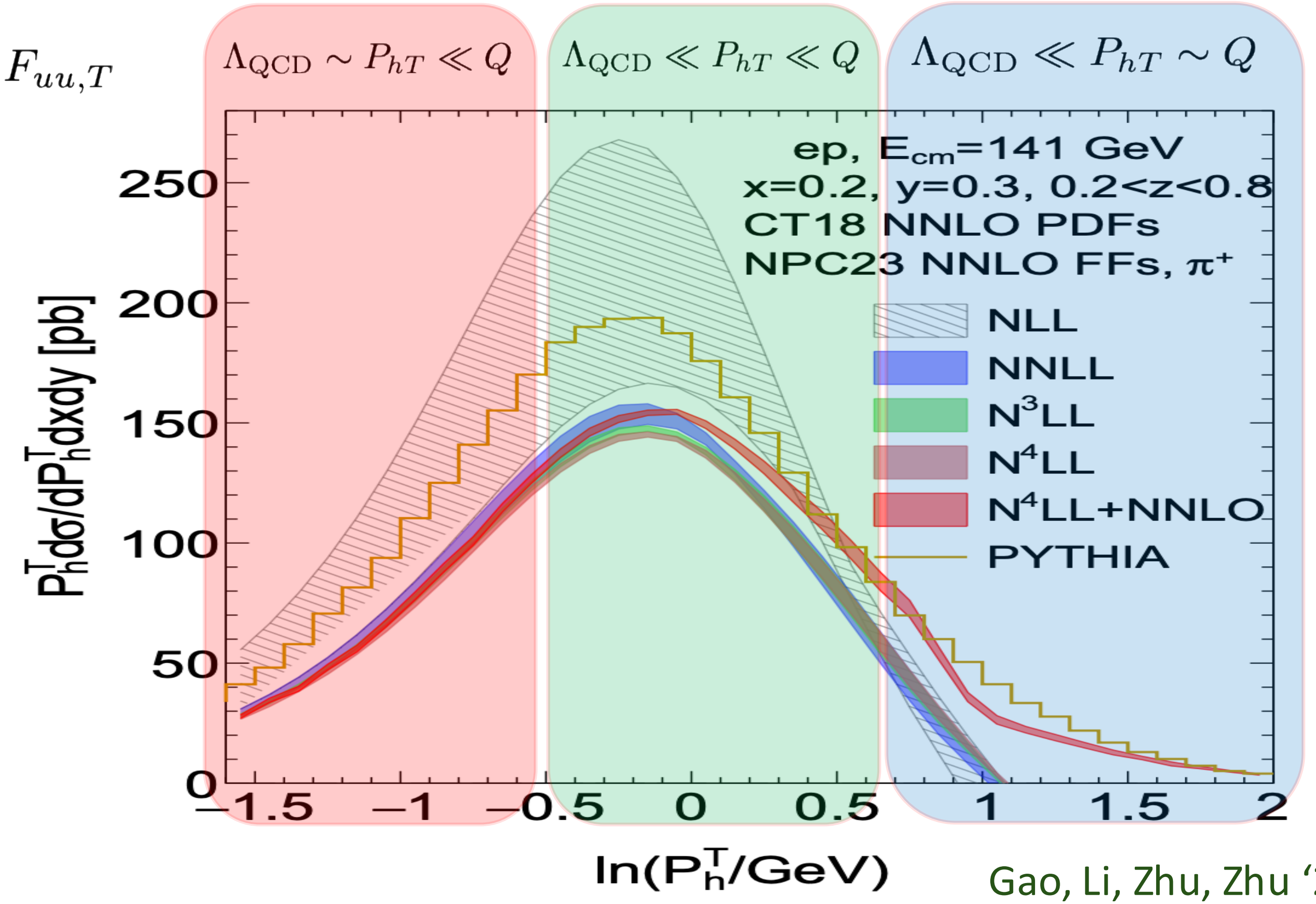
One of the most fundamental measurements in SIDIS related to quark transverse momentum distributions (TMDs) is the study of the unpolarized P_{hT} differential cross section

$$\frac{d^4\sigma_{\rm SIDIS}}{dx\,dy\,dz_h\,dP_{hT}} \propto P_{hT}\,\frac{\alpha_{em}^2}{x\,y\,Q^2}\left(1-y+\frac{1}{2}y^2\right)F_{uu,T}$$

Semi-Inclusive DIS

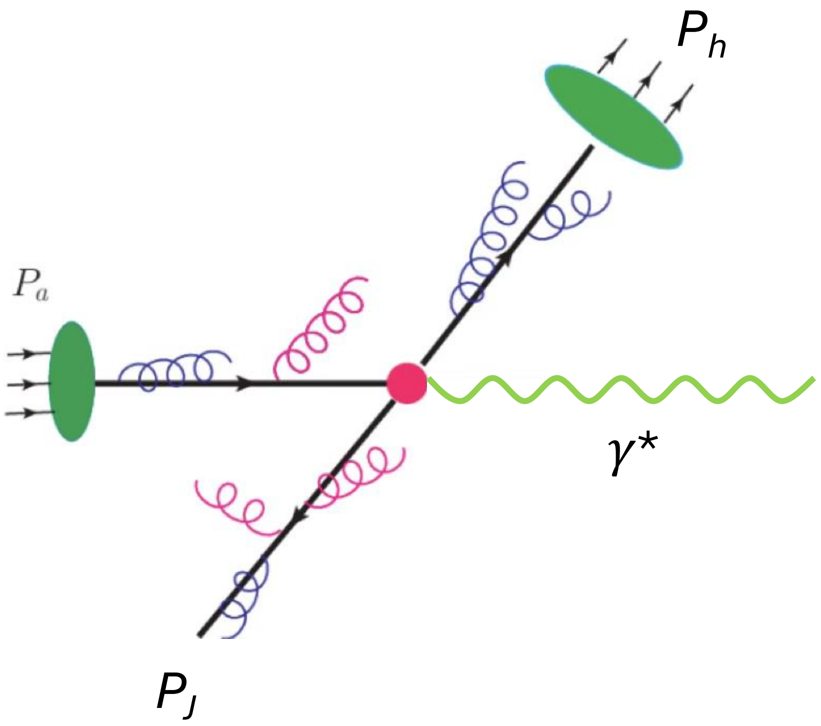




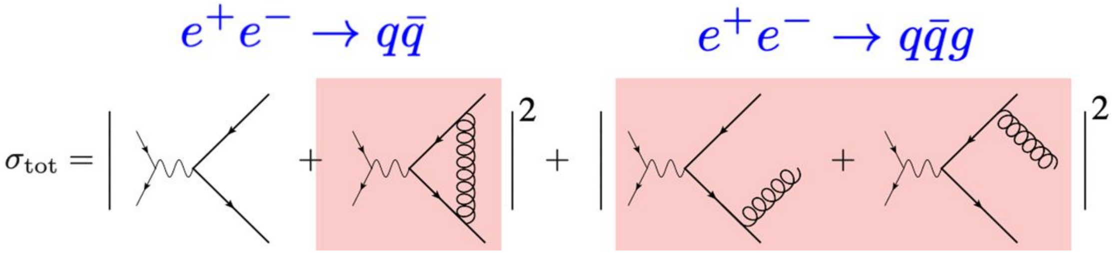
Gao, Li, Zhu, Zhu ‘26

NNLO QCD corrections for P_{hT} distribution

Hadron + jets @ NNLO



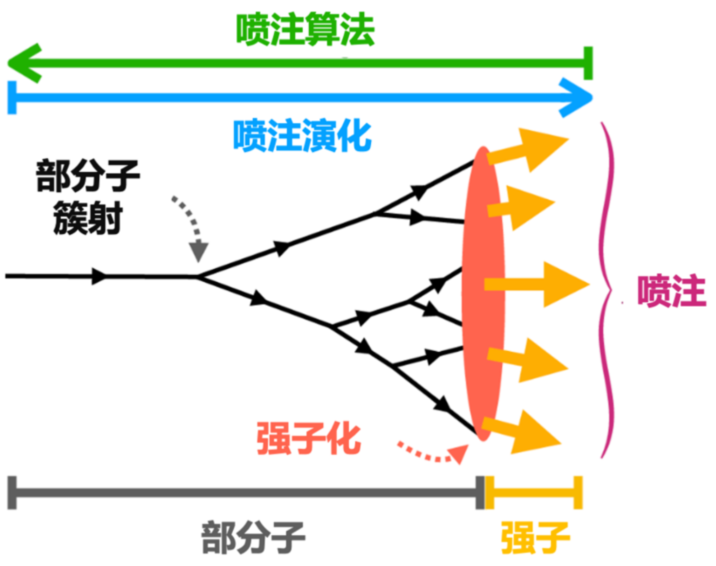
- **A key challenge is handling infrared (IR) divergences, which must cancel between real and virtual configurations.**



- **FMNLO framework for hadron production at NLO** Liu, Shen, Zhou, Gao '23
- **Transverse momentum (qT) subtraction for SIDIS at NNLO** Gao, Li, Zhu, Zhu '26
- **qT subtraction works well for colorless or colored (but massive) system**
  - **N3LO Drell-Yan** Chen, Gehrmann, Glover, Huss, Yang, Zhu '23
  - **N3LO di-Higgs** Chen, Dai, Li, Li, Shao, Wang '26
  - **N3LO di-photon** Czakon, Eschment, Generet, Poncelet '26
- **For processes with jets, qT is unsuitable because qT=0 for radiation emitted inside jets.**

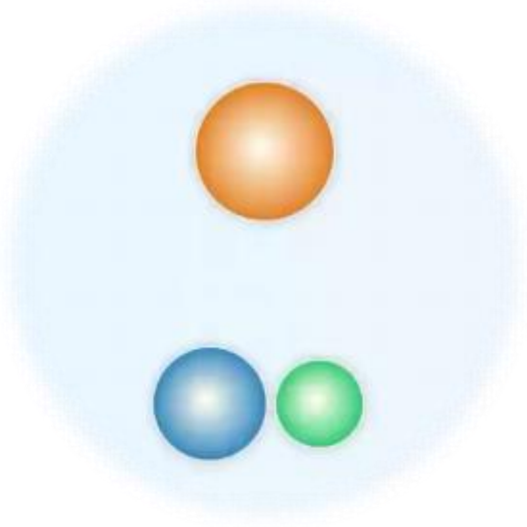
Winner-take-all qT subtraction for jets

- **Winner-take-all recombination scheme** Bertolini, Chan, Thaler '13



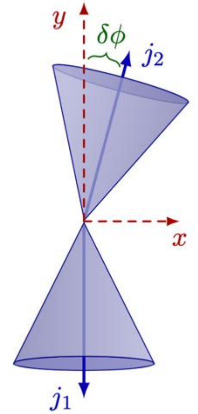
"赢者通吃"动量重组方案

$$p_{t,r} = p_{t,i} + p_{t,j}$$
$$\phi_r = (w_i\phi_i + w_j\phi_j)\,/\,(w_i + w_j)$$
$$y_r = (w_i y_i + w_j y_j)\,/\,(w_i + w_j)$$
$$\omega_i = (p_{t,i})^n \qquad n \to \infty$$



$$\alpha_s^m \log^n \frac{1}{\delta\phi}$$

- **Factorization theorem is significantly simplified** Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB
  - **NNLL resummation for $\delta\phi$ @ ep & eA** Fang(方申), Ke, DYS, Terry '24 JHEP
  - **N3LL + NNLO resummation for $\delta\phi$ @ ep** Fang(方申), Gao(高梅森), Li, DYS '25 JHEP
  - **WTA qT subtraction** Fu(符荣峻), Rahn, DYS, Waalewijn, Wu '25 PRL



Winner-take-all qT subtraction for jets

Fu(符荣峻), Rahn, DYS, Waalewijn, Wu PRL135 (2025) 171903

- **We propose two WTA qT subtraction methods to jets**

符荣峻 Jul 16, 2026, 5:28 PM 分会1

The key ingredient is the use of a recoil-free WTA jet axis!

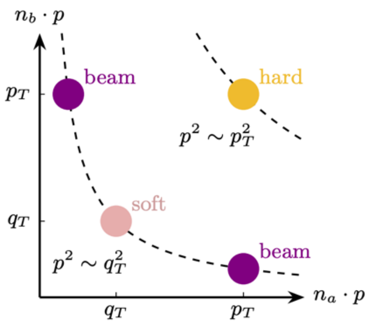
- **Azimuthal decorrelation: $\delta\phi$ or q_x**
  - **Suitable for processes that are planar at LO: pp → 2 jets, $\gamma^* p \to jj$, etc.;**
  - **Standard TMD PDFs and soft functions: known at N3LO** Luo, Yang, Zhu, Zhu, ’19; Ebert, Mistlberger, Vita ’20 …
  - **TMD jet functions: partially known at NNLO;** Reyes, Scimemi, Waalewijn, Zoppi ’19; Bell, Brune, Das, Wald ’23; Fang, Gao, Li, DYS ’24
- **Total transverse momentum q_T**
  - **Suitable for LO non-planar process, such as pp → V/H + 2 jets, pp → 3 jets, etc.**
  - **Soft function is new: Outside the jet (b_T), Inside the jet (b_x)**

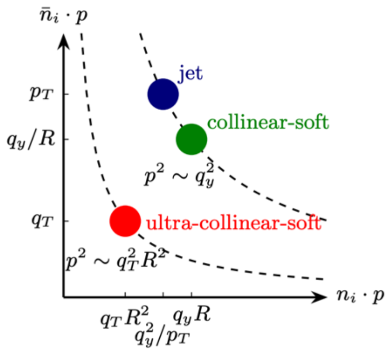
NNLO new soft functions

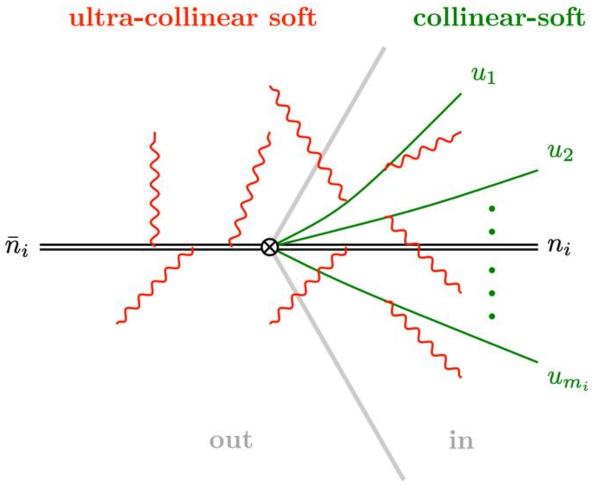
Fu(符荣峻), Rahn, DYS, Waalewijn, Wu 26 JHEP

➢ **In small R limit, soft function refactorizes into simpler global and (ultra)-collinear-soft contributions**

- **soft**: $p_s^\mu \sim q_T\,(1,1,1),$
- n_i**-collinear-soft**: $p_{cs}^\mu \sim |q_y|/R\,(R^2,1,R)_{n_i\bar{n}_i},$
- n_i**-ultra-collinear-soft**: $p_{ucs}^\mu \sim q_T\,(R^2,1,R)_{n_i\bar{n}_i}\ ,$



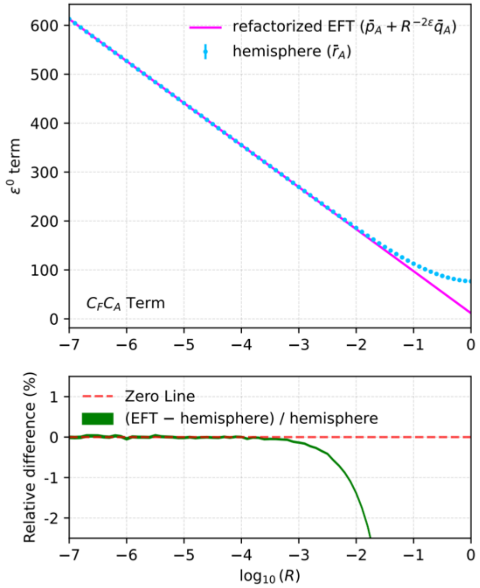




Multi-Wilson lines: Becher, Neubert, Rothen, DYS '16 PRL

Two-loop collinear-soft function

$$
\begin{aligned}
S_i^{\text{hemi},(2)}(b_\perp, b^+) = &\left(\frac{\mu|b_\perp|}{b_0}\right)^{4\epsilon}\left(\frac{\nu|b_\perp|R_i}{b_0}\right)^{\eta}\omega^2\left[\omega^2\left(\frac{\nu|b_\perp|R_i}{b_0}\right)^{\eta} C_i^2\frac{h_{\text{in}}^2}{2}\right.\\
&\left.+C_iC_A(h_A+v_A^{\text{in}})+C_in_fT_Fh_f\right]\\
&+\left(\frac{i\,b^+\mu}{b_0R_i}\right)^{4\epsilon}\left[C_i^2\frac{s_{\text{out}}^2}{2}+C_iC_A(g_A+v_A^{\text{out}})+C_in_fT_Fg_f\right]\\
&+\left(\frac{\mu|b_\perp|}{b_0}\right)^{2\epsilon}\left(\frac{ib^+\mu}{b_0R_i}\right)^{2\epsilon}\left(C_iC_Ar_A(r)+C_in_fT_Fr_f(r)\right)\\
&+\left(\frac{\mu|b_\perp|}{b_0}\right)^{2\epsilon}\left(\frac{ib^+\mu}{b_0R_i}\right)^{2\epsilon}\left(\frac{\nu|b_\perp|R_i}{b_0}\right)^{\eta}\omega^2C_i^2h_{\text{in}}s_{\text{out}}.
\end{aligned}
$$

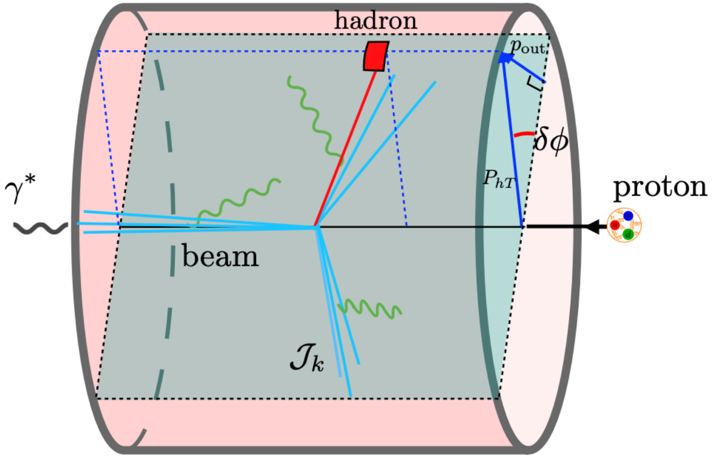


NNLO QCD corrections for P_{hT} distribution

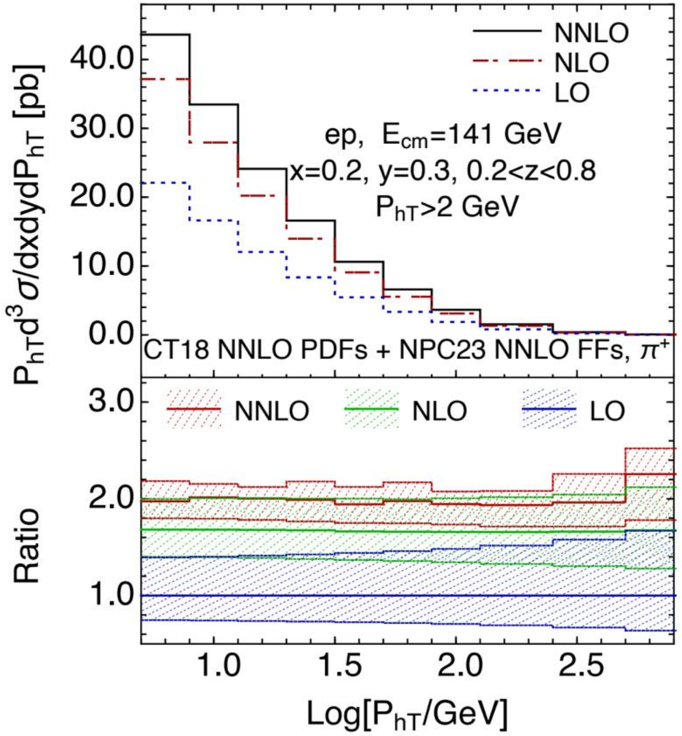
- **We present the first calculation of hadron production in DIS at finite transverse momentum to NNLO** Dong(董亮), Fang(方申), Gao, DYS, Li, Zhu (朱雨蛟) 2602.22972

董亮 Jul 16, 2026, 11:26 AM 分会1

$$\frac{d\sigma}{d\mathcal{O}} = \int_0^{\delta\phi^{\rm cut}} d\delta\phi \frac{d\sigma}{d\delta\phi\, d\mathcal{O}} + \int_{\delta\phi^{\rm cut}}^{\delta\phi^{\rm max}} d\delta\phi \frac{d\sigma}{d\delta\phi\, d\mathcal{O}}$$



$$\frac{d\sigma_{\rm LP}}{dx\, dy\, dz\, d^2\vec{P}_{hT}\, dp_{\rm out}} = \int \frac{db}{2\pi} e^{ip_{\rm out} b/\zeta} \times \sum_{ijk} \int d\xi\, H_{ei\to ejk}(Q,\xi,\zeta) \times \mathcal{B}_{i/p}(\xi,b)\, \mathcal{D}_{h/j}(\zeta,b)\, \mathcal{J}_k(b)\, S_{ijk}(b)$$

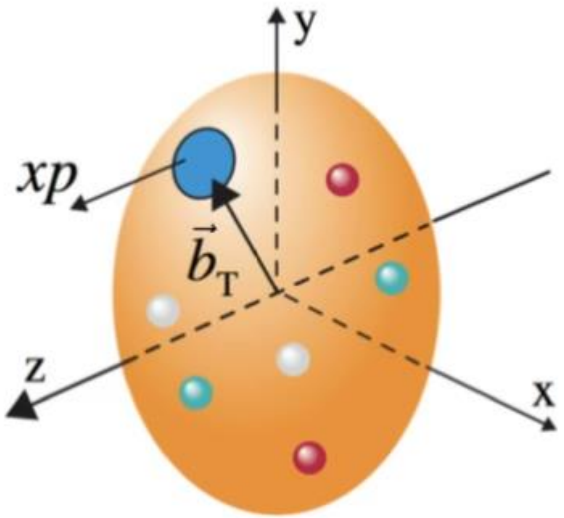


- **First N3LO SIDIS** Dong(董亮), Fang(方申), Gao, DYS, Li, Zhu (朱雨蛟), Zhu 2603.29673

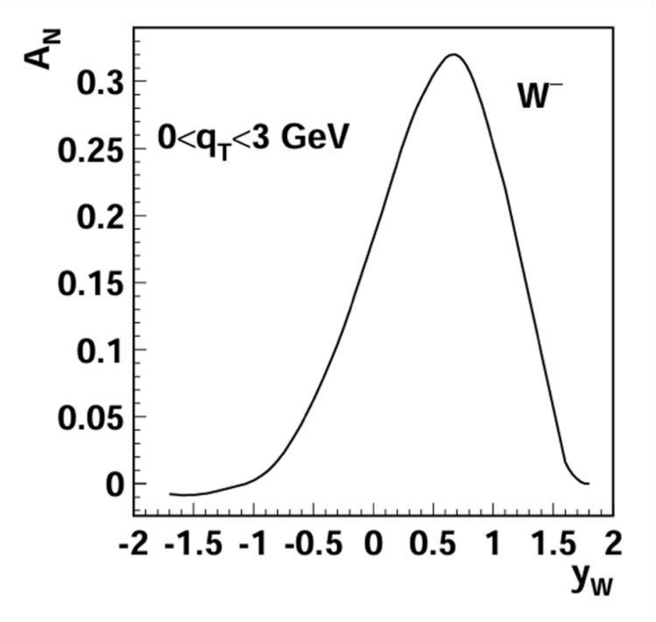
New probes

3D imaging and polarized TMDs

TMDs encode the quantum correlations between hadron polarization and the motion and polarization of quarks and gluons

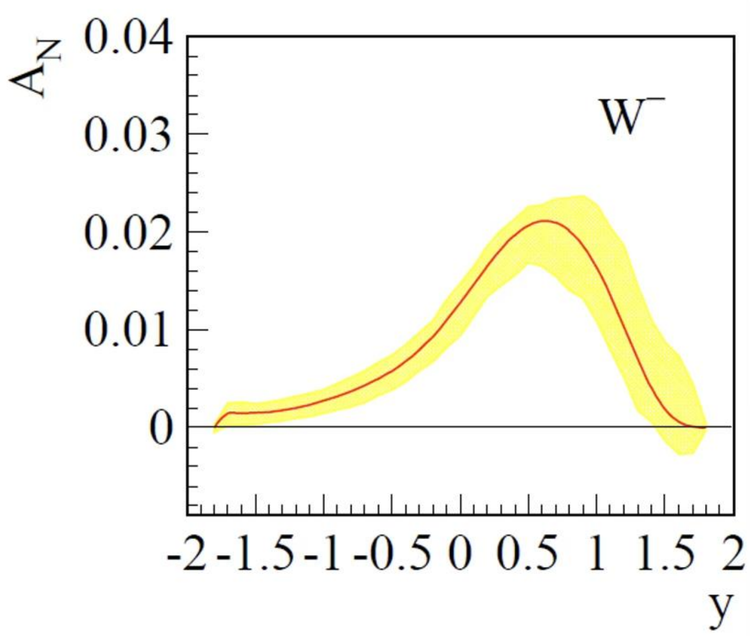


Without evolution



Kang & Qiu ‘09

With evolution



Echevarria, Idilbi, Kang, Vitev ’14

Evolution reduces the asymmetry

Nucleon tomography with zero-jettiness

- Sivers function can be probed via Drell-Yan process in polarized pp collision
- At high energies, initial state radiation acts as noise, reducing the asymmetry significantly.
- We introduce 0-jettiness $\boldsymbol{\tau = 2\sum_i \min\{p_a \cdot l_i\,, p_b \cdot l_i\}/Q^2}$ as a tunable resolution scale Fang(方申), Lin(林硕), DYS, Zhou PRL 136 (2026)021901

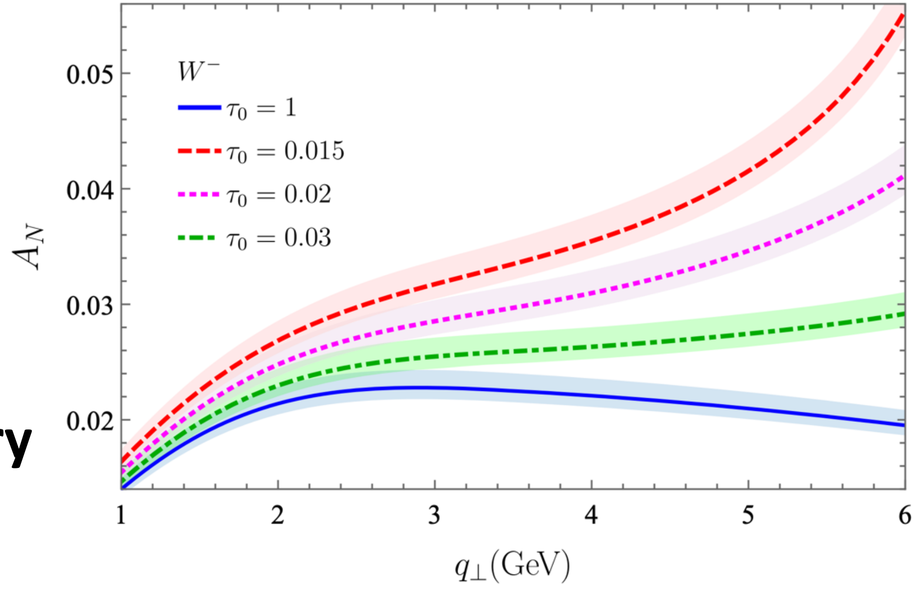
方申 海报 1-10

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

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

Modified Sukakov factor

$$S_{\mathrm{P}}(b) = \frac{C_F}{\pi}\left[\int_{\mu_b^2}^{t}\frac{\mathrm{d}\mu^2}{\mu^2}\left(2\ln\frac{t}{\mu^2} - \frac{3}{2}\right) - \int_{\mu_b^2}^{\tau_0 t}\frac{\mathrm{d}\mu^2}{\mu^2}\ln\frac{\tau_0 t}{\mu^2} + \int_{t}^{Q^2}\frac{\mathrm{d}\mu^2}{\mu^2}\left(\ln\frac{Q^2}{\mu^2} - \frac{3}{2}\right) + \int_{\tau_0 t}^{t}\frac{\mathrm{d}\mu^2}{\mu^2}\ln\frac{\mu^2}{\tau_0 t}\right]\alpha_s(\mu)$$



- We demonstrate a substantial enhancement of the asymmetry signal (e.g., by 83% for Z SSA at qT=5 GeV)

Accessing Nucleon Transversity via One-Point Energy Correlators

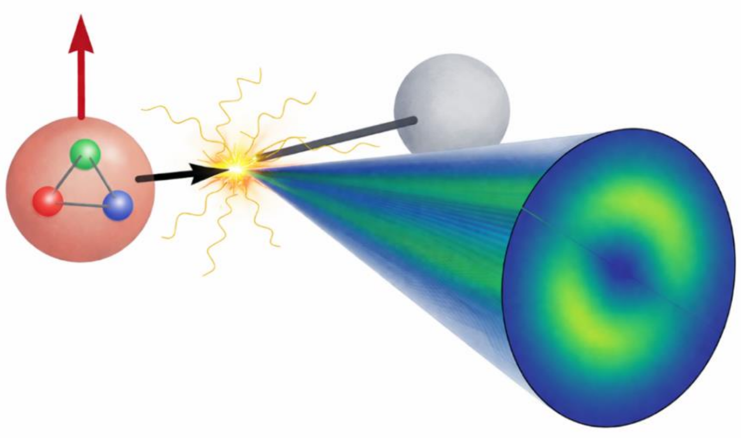
Gao(高梅森), Kang, Li(李婉辰), DYS PRL 136 (2026) 151902

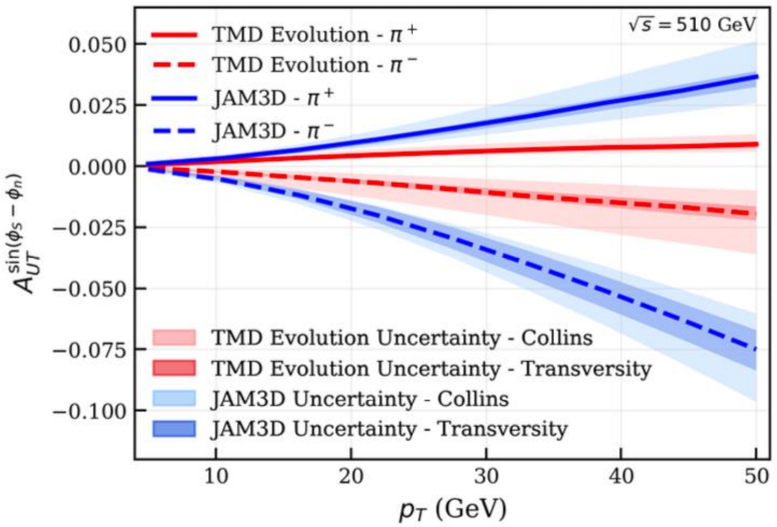
李婉辰 Jul 15, 2026, 5:16 PM 分会1

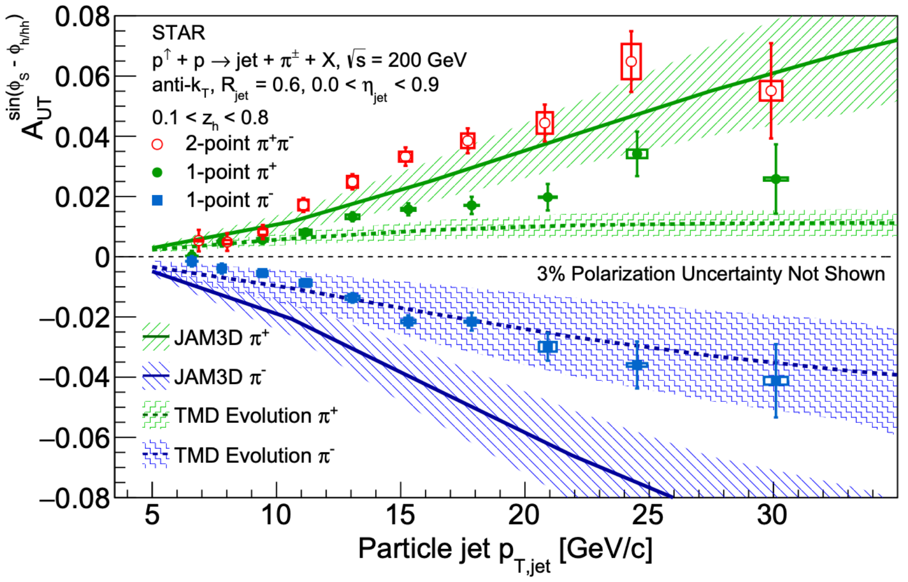
- **Transversity distribution h_1^q is a fundamental parton distribution.**
- **Its chiral-odd nature prevents access via inclusive DIS**
- **Nucleon tensor charge δq is essential for BSM search, Lattice QCD benchmarks**
- **We introduce the one-point energy correlator (OPEC) to probe the nucleon transversity**

$$\Delta^q(z,\hat{\boldsymbol{n}}) = \sum_X \sum_{i\in J} \langle\Omega|\bar{\chi}_n \delta_{Q,\mathcal{P}_n} \delta^{(2)}(\hat{\boldsymbol{n}}-\hat{\boldsymbol{n}}_i)|JX\rangle \frac{E_i}{E_J} \langle JX|\chi|\Omega\rangle$$

RHIC-STAR 2604.15543



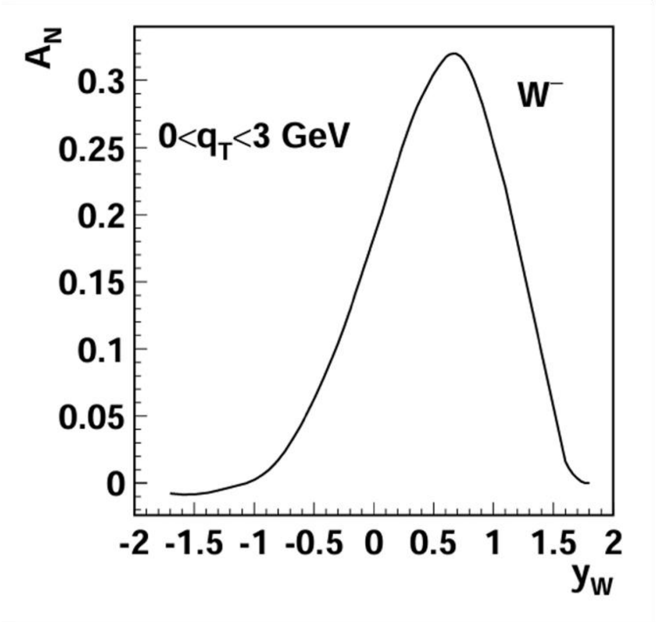




New insights

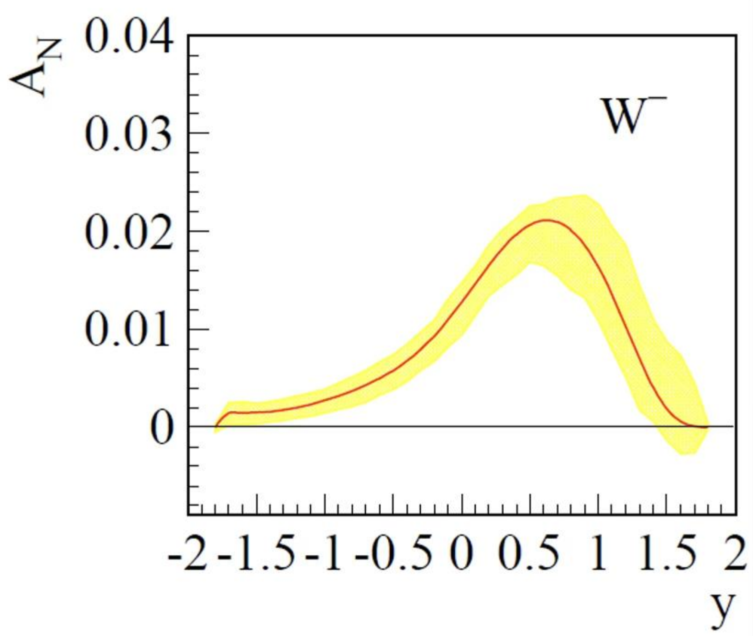
Spin asymmetry and QCD evolution

Without evolution



Kang & Qiu '09

With evolution



Echevarria, Idilbi, Kang, Vitev '14

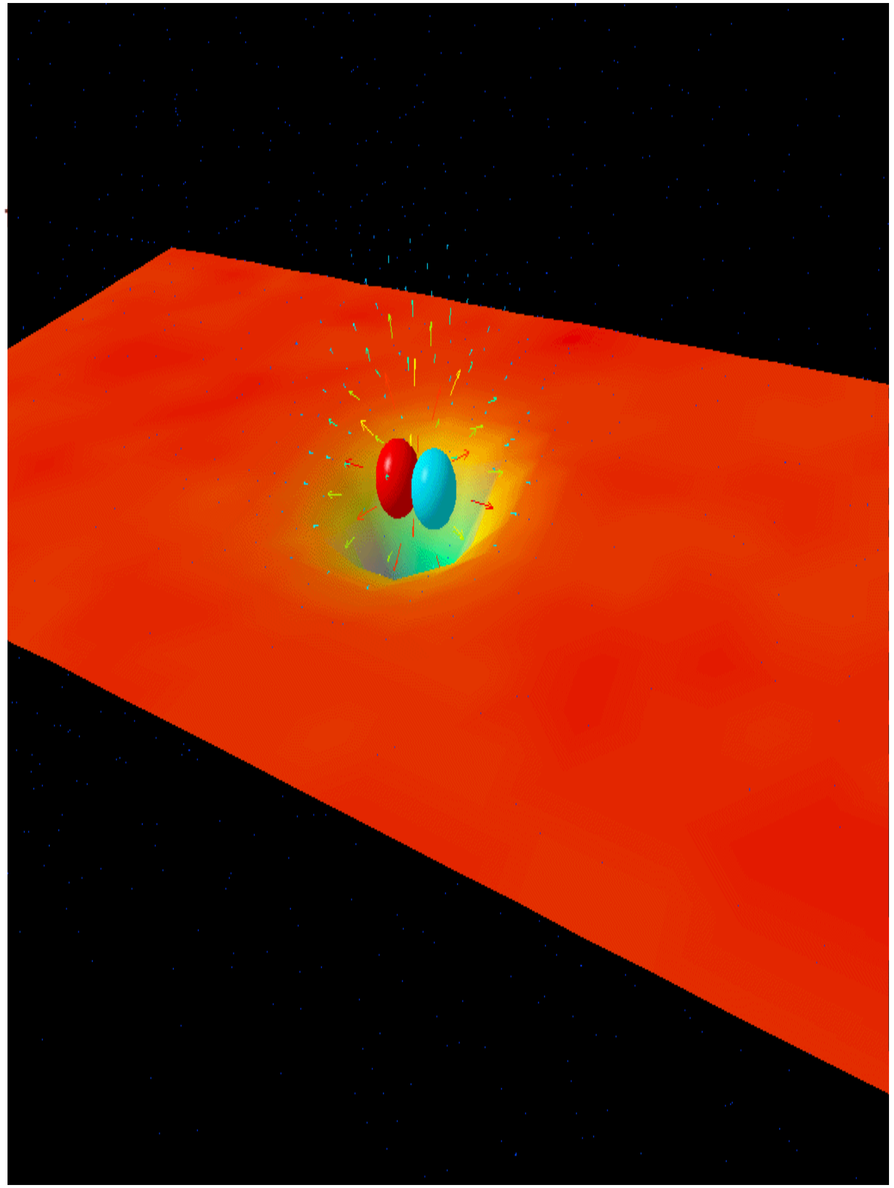
Evolution reduces the asymmetry $|+\rangle\langle-|$

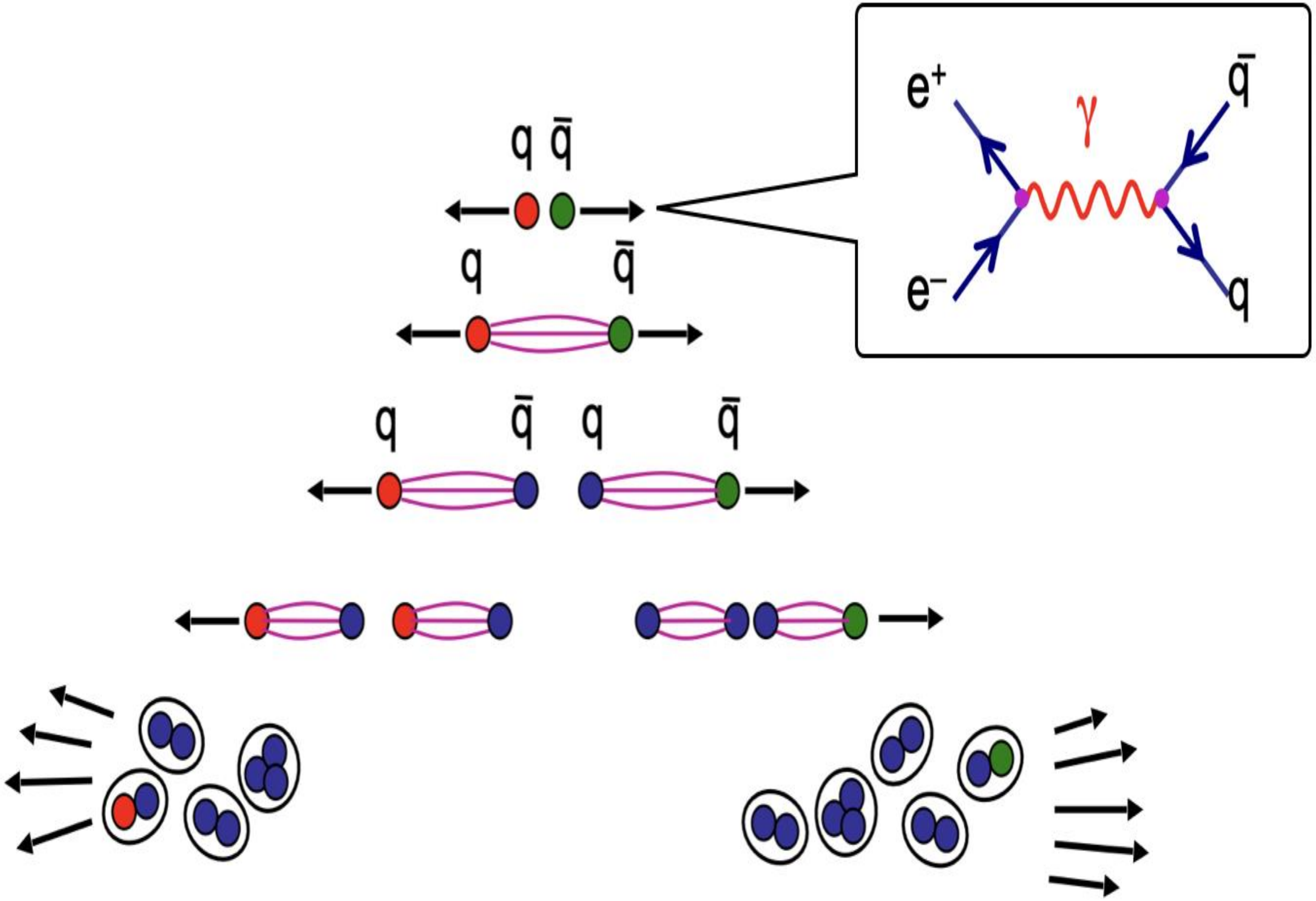
Quantum information interpretation

- Soft and collinear radiation destroy superposition
- Soft radiation decohere the directions of the momenta and the gauge representations of the particles
- Collinear radiation decohere the energies and the spin

Carney, Chaurette, Neuenfeld, Semenof '17
Neill, Waalewijn '19
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
… …

Decoherence by thermal emission of photons





Decoherence and quantum channel

Consider a bipartite system (assume no entanglement initially)

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

quantum map or quantum channel

Kraus representation theorem

$$\mathcal{E}[\rho] = \sum_j K_j \rho K_j^\dagger$$

K_i**: Kraus operators**

Completeness Relation

$$\sum_j K_j^\dagger K_j = \mathbb{1}$$

Effective field theory for decoherence

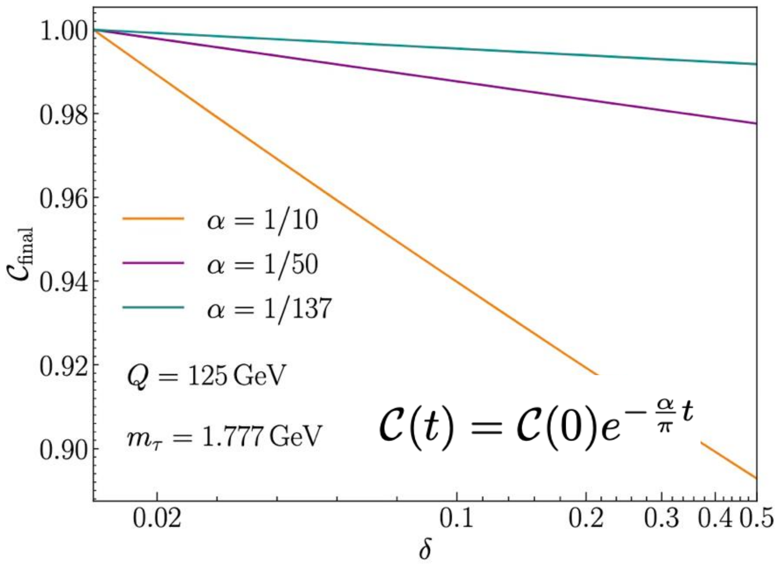
Lin, Liu, DYS, Wei 25 JHEP; Gu, Lin, DYS, Yang, Wang 25

- **A systematic framework calculating decoherence in high energy collisions by combing 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** $e^+e^- \to l^+l^- + n\gamma$ **IR states unresovled**
  - **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** $p = \sqrt{\frac{1}{2}\left[1 - \exp\left(-\frac{\alpha}{2\pi}t\right)\right]}$

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

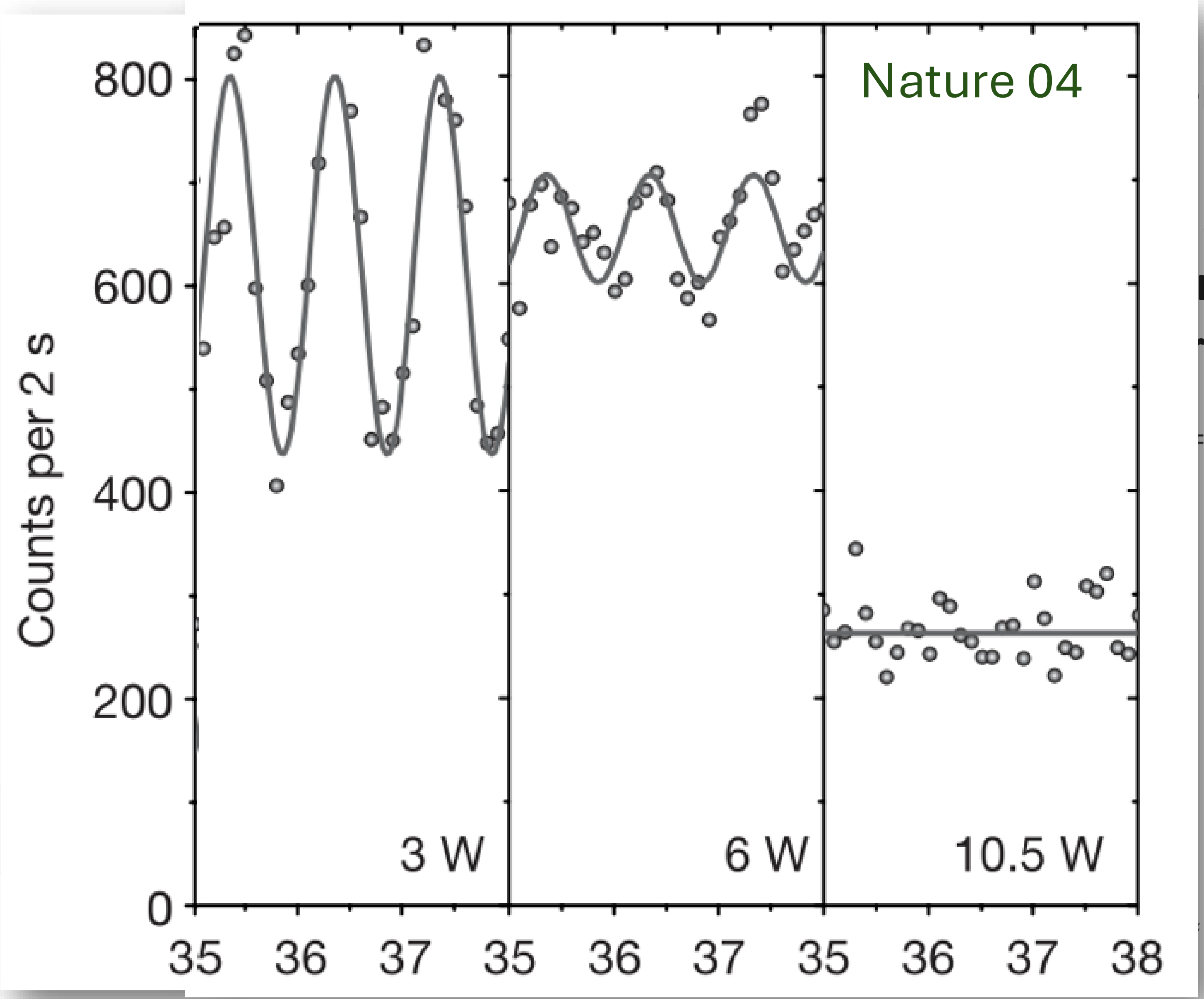
  - **Decay of all off-diagonal terms**

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



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

Beam energy scan for spin decoherence of hyperon pair



Liu, DYS, Wei 25 JHEP; Dai, Lin, DYS, Wei in progress

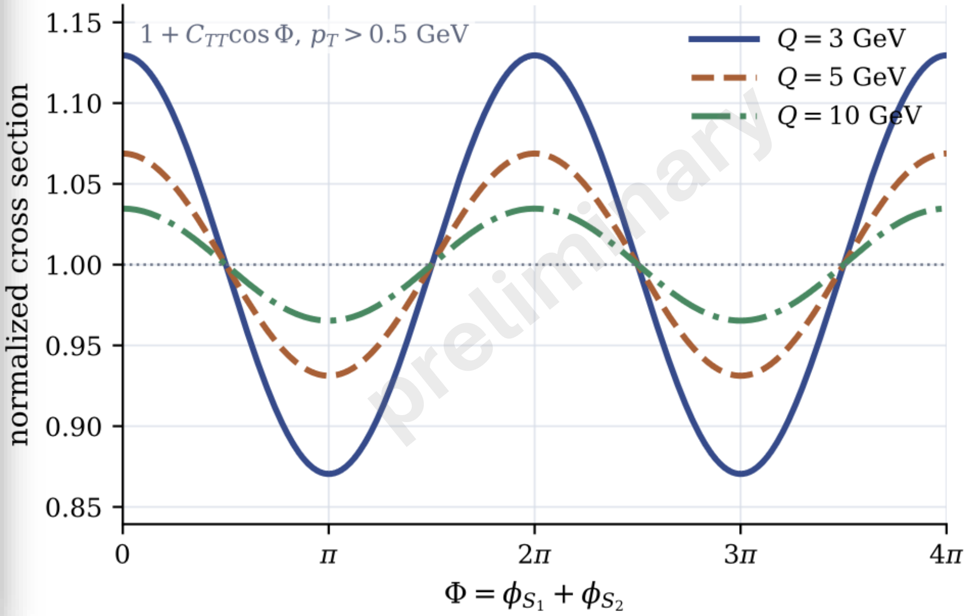
rmation is transmitted through QCD

and thus changes the unobserved

ns

raus operators are determined by FFs

$$\sqrt{\omega_q}\, K_{\alpha,\Lambda/q} \otimes \bar{K}_{\beta,\bar{\Lambda}/\bar{q}}$$



New paradigms

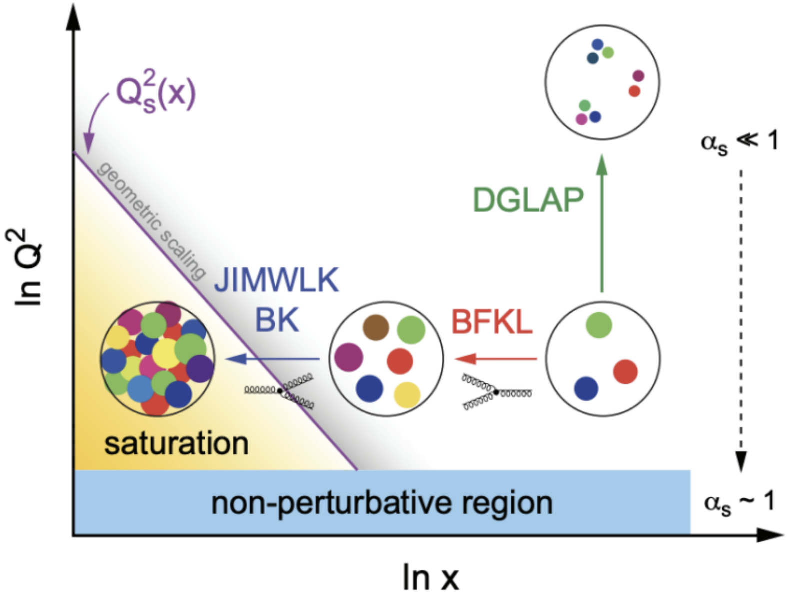
AI加速的 Balitsky–Kovchegov 演化方程模拟

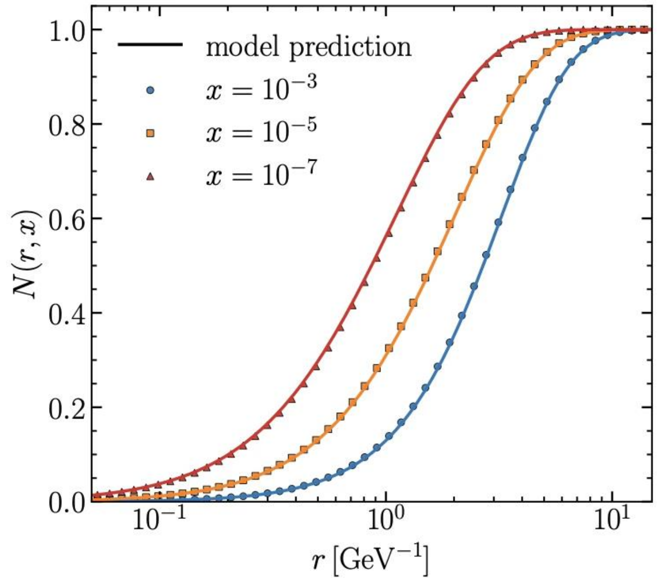
- **BK 方程（非线性）**

$$\partial_Y N(r,Y) = \mathcal{K}_{\rm BK} \otimes [N - NN]$$

  - **每组参数反复求解非线性演化方程**
  - **效率低、误差大**
- **训练Transformer直接学习BK演化算子的神经网络表示，从而实现跨能标映射的快速调用** Gao, Kang, Penttala, DYS '25 JHEP

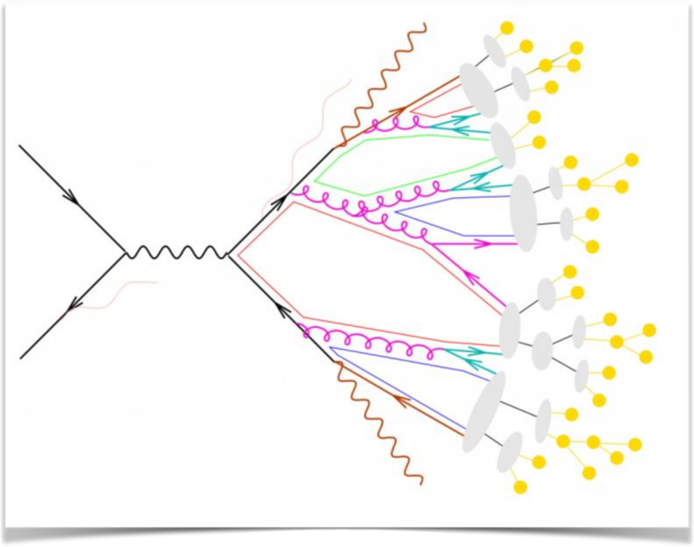
$$N_Y = \mathcal{U}(Y, Y_0) N_{Y_0}$$





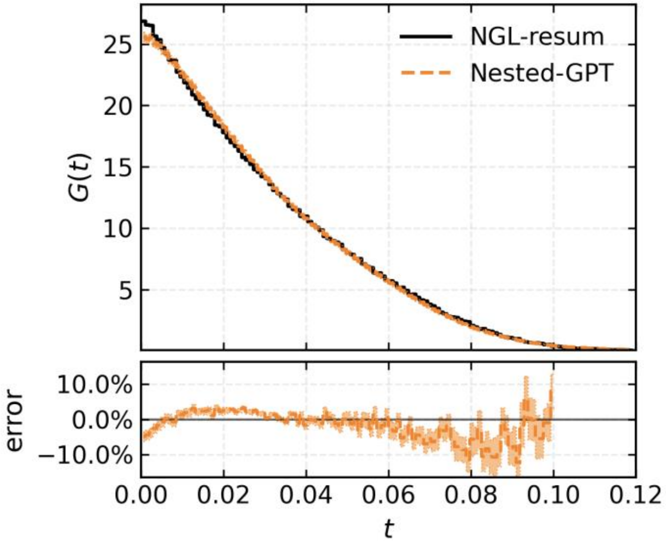
Nested-GPT for variable-multiplicity parton showers

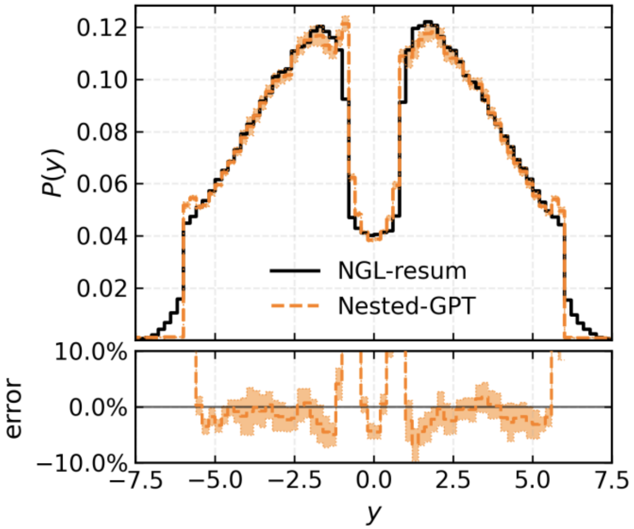
- **NGL resummation is governed by the non-linear BMS equation, physically interpreted as a dipole shower.** Dasgupta, Salam '01, Balsiger, Becher, DYS '18

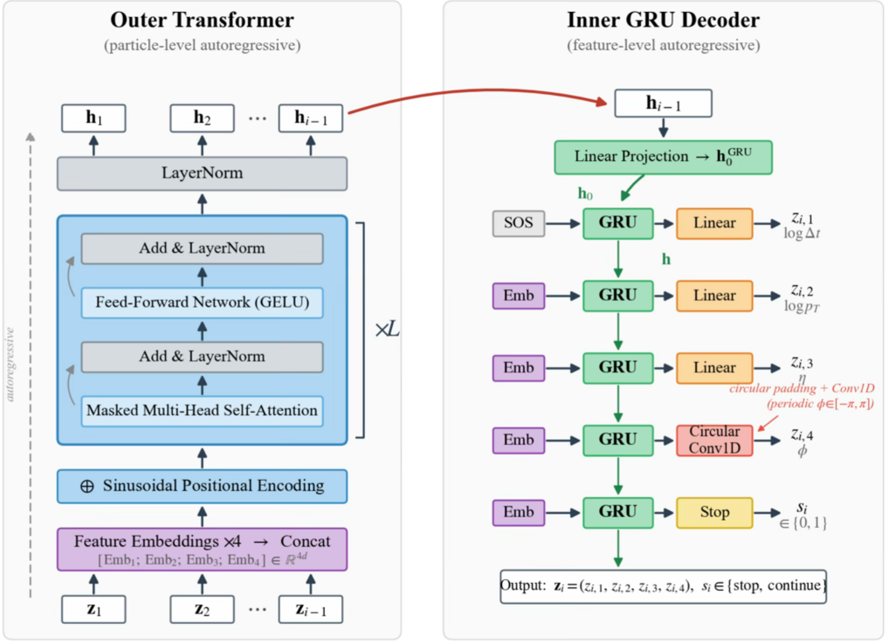


$$Q\frac{\partial}{\partial Q}G_{ab}(Q) = \int \frac{d^2\Omega_k}{4\pi}\bar{\alpha}_s W_{ab}(k)\left[u(k)G_{ak}(Q)G_{kb}(Q) - G_{ab}(Q)\right]$$

- **We introduce Nested-GPT, a hierarchical autoregressive Transformer architecture for simulating the variable-multiplicity parton shower histories.** Li, DYS, Shi, Sun '26







Summary and outlooks

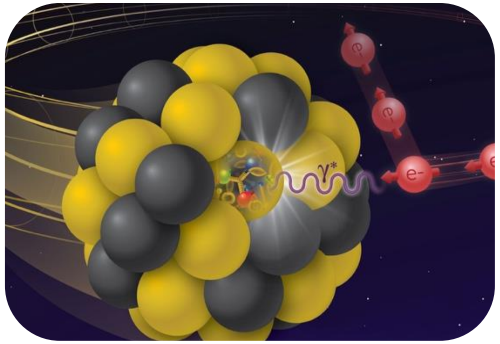
- **Precision frontier (new methods): new infrared subtraction schemes**
  - **obtained the first NNLO prediction for finite-Pt hadron production in DIS and the first NNNLO results for SIDIS**
- **Spin frontier (new probes): jets and jet substructure as powerful probes of nucleon structure**
  - **introduce 0-jettines to enhance signal of spin asymmetry**
  - **show that one-point energy correlators can access nucleon transversity and tensor charge**
- **Quantum frontier (new insights): decoherence is calculable, measurable and driven by RG evolution**
  - **unified SCET/RGE (HEP) + Open quantum systems (QIS)**
  - **RG flow = Quantum channel**
- **AI frontier (new paradigms): Applying generative AI to simulate RG evolution & parton shower**
  - **Fast fitting: BK equation**
  - **Fast simulation: BMS equation**

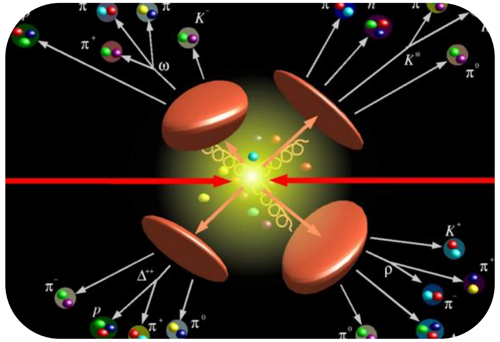
Summary and outlooks

Entanglement

Decoherence

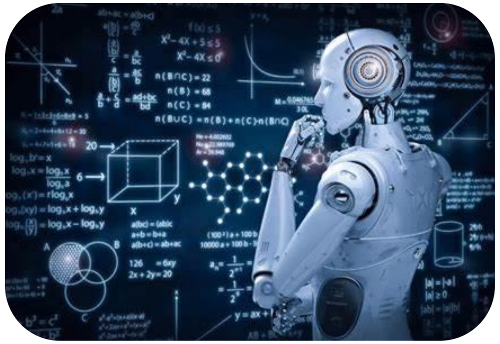
Quantum information





Spin physics, hadron structure

Jet physics, fragmentation



Fast fit

Fast simulation

Generative AI

Thank You