New Perspectives on Precision Nucleon Tomography

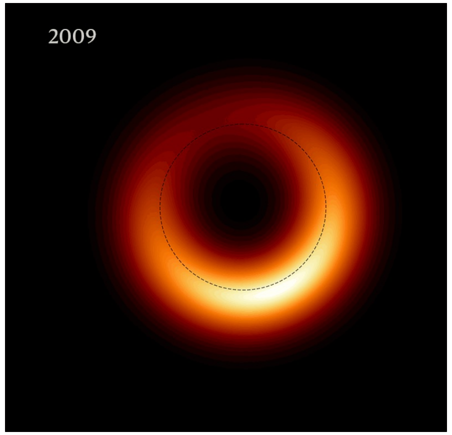
Ding-Yu Shao

Fudan University

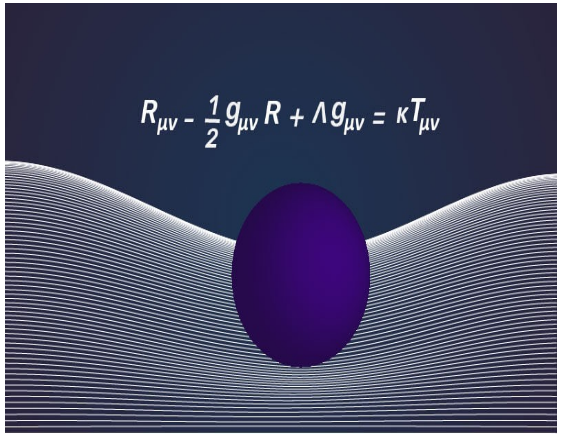
International Workshop on New Opportunities for Particle Physics 2026

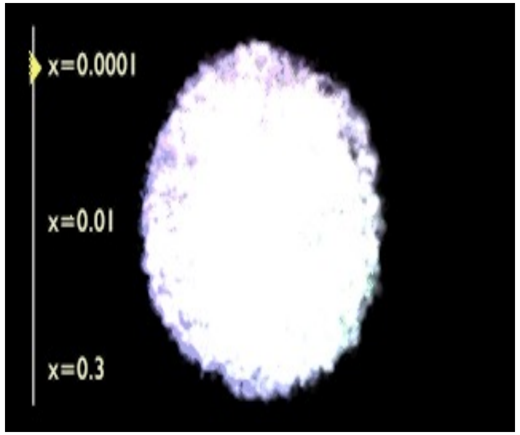
Beijing Aug 14 – 16, 2026

Nucleon tomograph and QCD



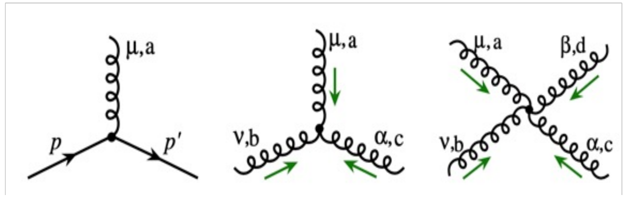
Black hole imaging will deepen our understanding of gravity





Nucleon imaging will deepen our understanding of the strong interaction

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



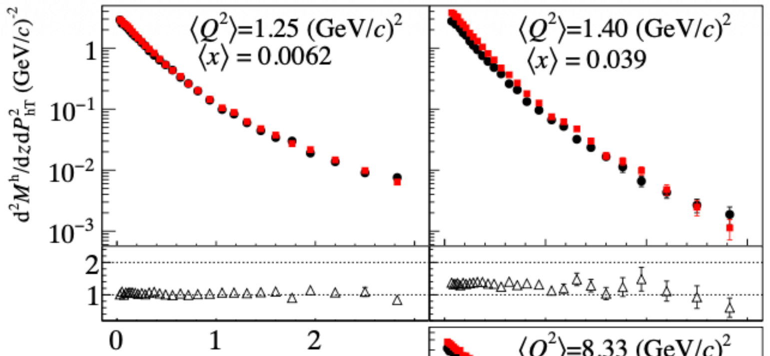
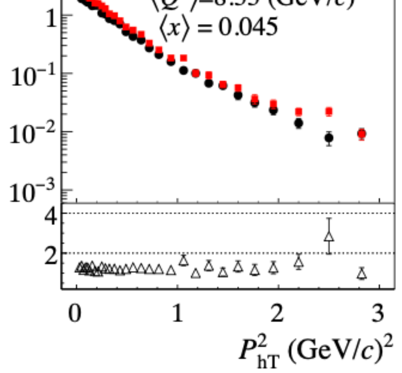
1. New methods

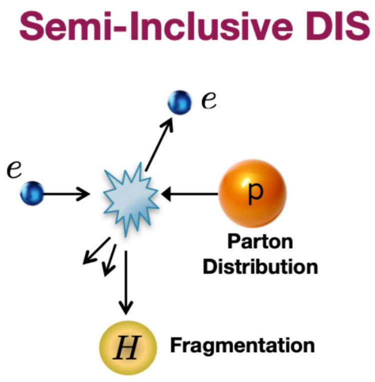
Winner-take-all qT subtraction for high-order QCD

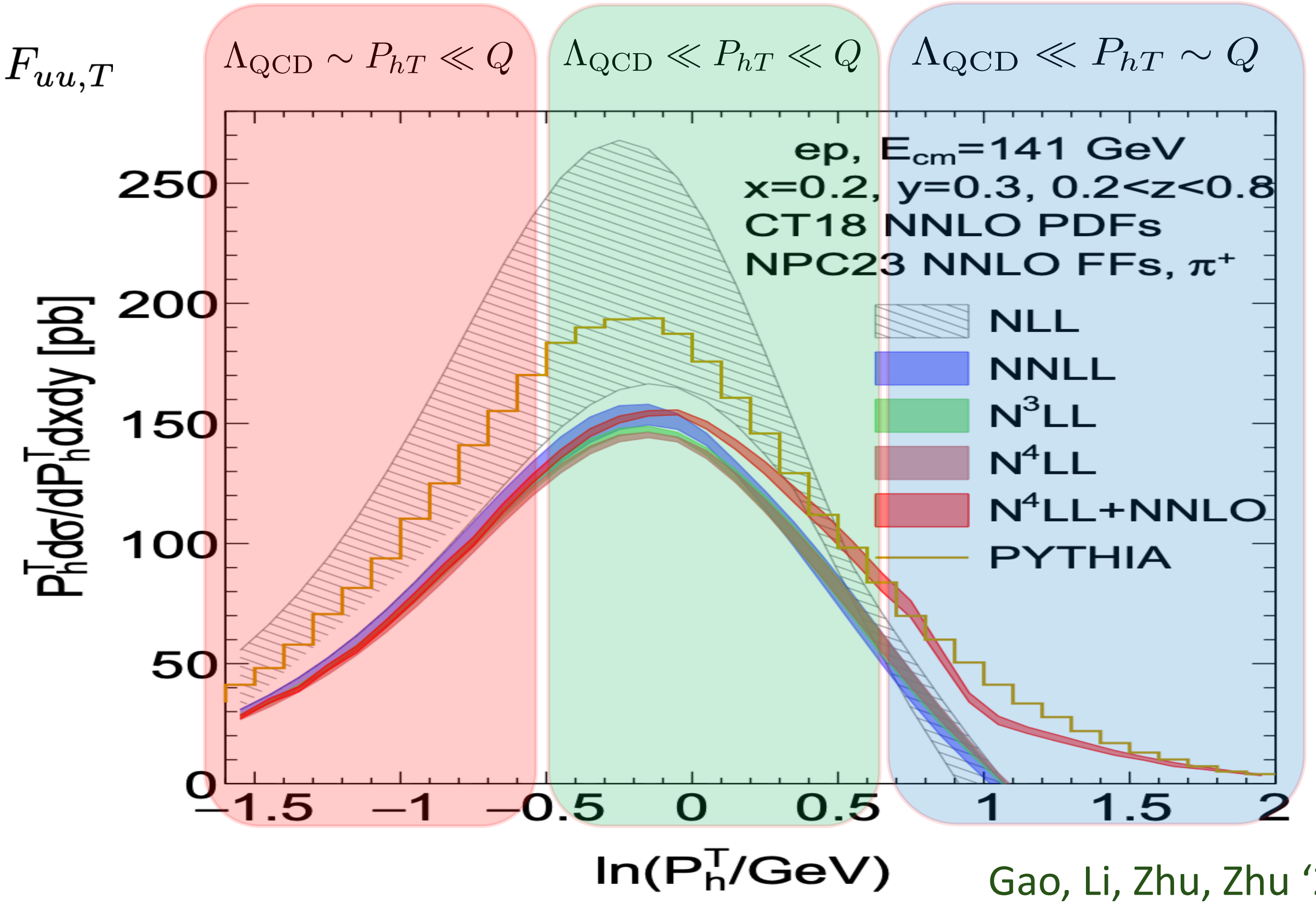
TMDs in e-p collisions

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

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

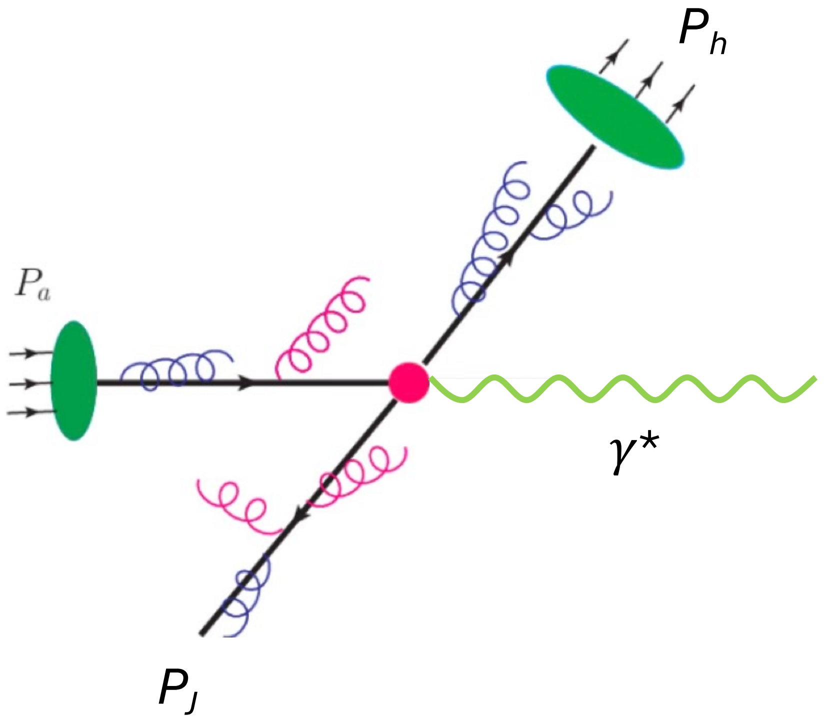




Gao, Li, Zhu, Zhu '26

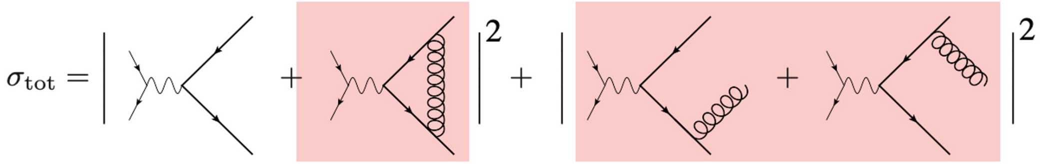
NNLO QCD corrections for P_{hT} distribution

Hadron + jets @ NNLO



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

$e^+e^- \to q\bar{q}$ $\qquad$ $e^+e^- \to q\bar{q}g$



$$\delta\sigma_{real} = \sigma_0 \frac{\alpha_s}{2\pi} C_F \left(\frac{Q^2}{\mu^2}\right)^{-\epsilon} \left[\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} - \frac{2\pi^2}{3}\right]$$

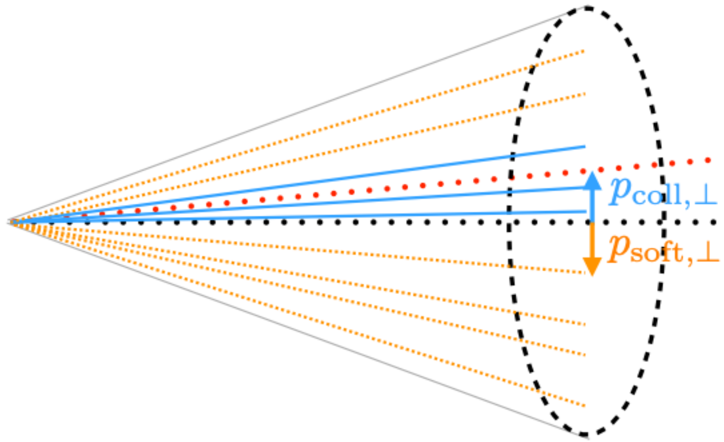
$$\delta\sigma_{virtual} = \sigma_0 \frac{\alpha_s}{2\pi} C_F \left(\frac{Q^2}{\mu^2}\right)^{-\epsilon} \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \frac{2\pi^2}{3}\right]$$

- **qT subtraction** (Catani & Grazzini '07) **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, conventional qT is unsuitable because qT=0 for radiation emitted inside jets.**

Winner-take-all qT subtraction for jets

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

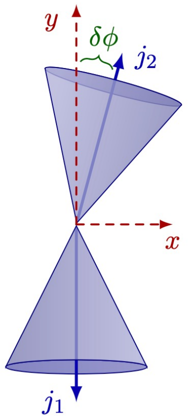


WTA scheme

$$p_{t,r} = p_{t,i} + p_{t,j}$$
$$\phi_r = (w_i \phi_i + w_j \phi_j) \,/\, (w_i + w_j)$$
$$y_r = (w_i y_i + w_j y_j) \,/\, (w_i + w_j)$$

$$\omega_i = (p_{t,i})^n \qquad n \to \infty$$

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



- **Factorization theorem is significantly simplified** Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '18, Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB
  - **NNLL resummation for $\delta\phi$ @ ep & eA** Fang, Ke, DYS, Terry '24 JHEP
  - **N3LL + NNLO resummation for $\delta\phi$ @ ep** Fang, Gao, Li, DYS '25 JHEP
  - **WTA qT subtraction** Fu, Rahn, DYS, Waalewijn, Wu '24 PRL

Winner-take-all qT subtraction for jets

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

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

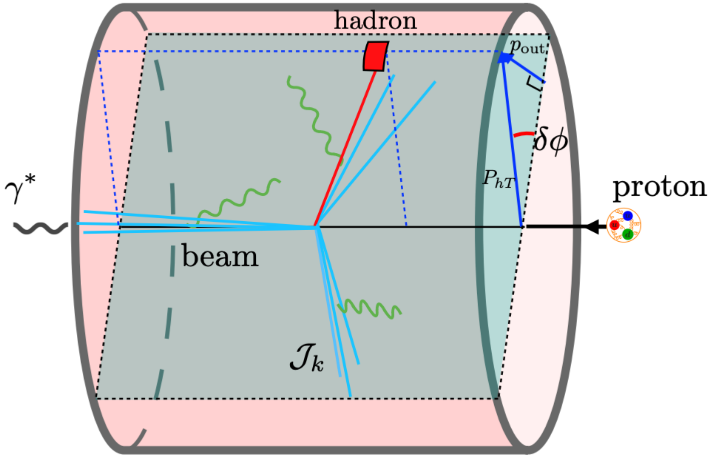
The key ingredient is the use of a recoil-free WTA jet axis!

- **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 (dipole): known at NNLO** 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)** Fu, Rahn, DYS, Waalewijn, Wu '26

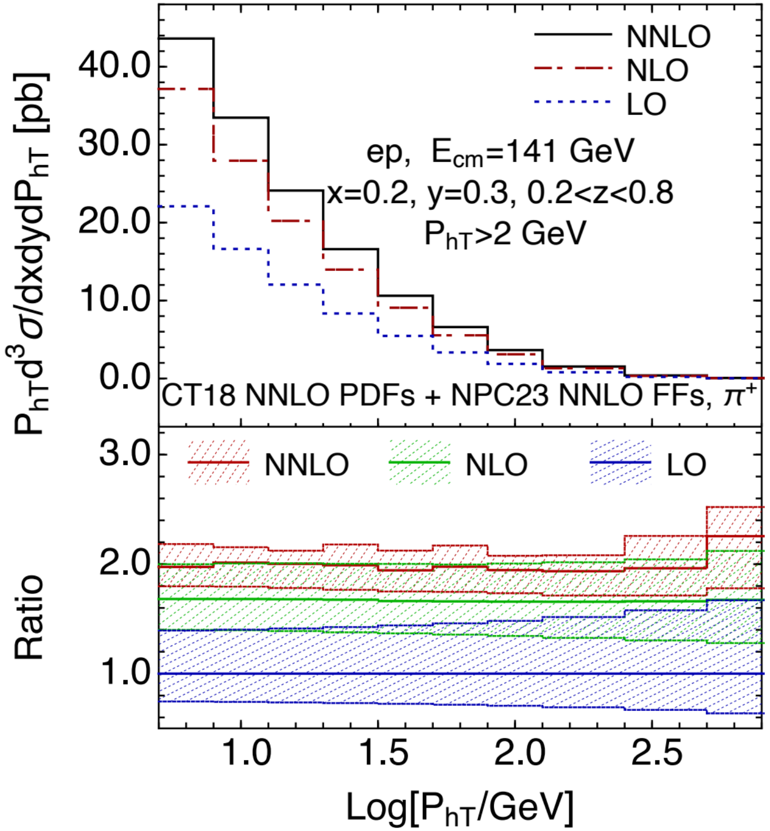
NNLO QCD corrections for P_{hT} distribution

- **We present the first calculation of hadron production in DIS at finite transverse momentum to NNLO** Dong, Fang, Gao, DYS, Li, Zhu 2602.22972 PRL

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



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



- **First N3LO SIDIS** Dong, Fang, Gao, DYS, Li, Zhu , Zhu 2603.29673

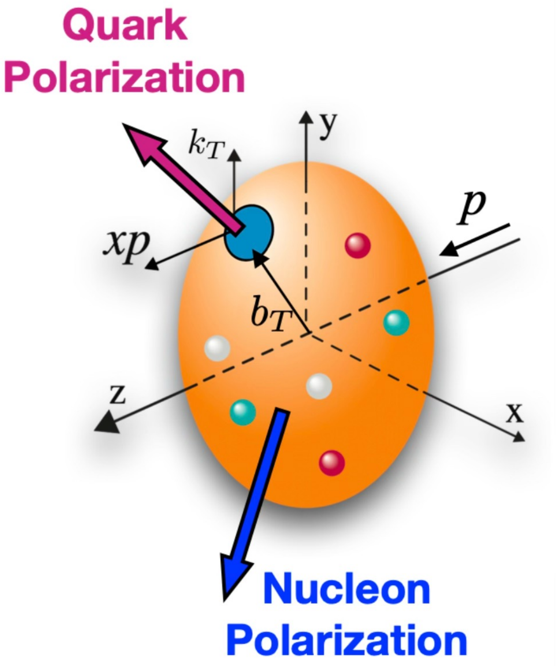
2. New probes

Event shapes and correlators for proton spin

3D imaging and polarized TMDs

- Polarized transverse momentum distributions (TMDs) encode the quantum correlations between hadron polarization and the motion and polarization of partons

$$\tilde{f}_{i/ps}^{[\Gamma]0(u)}(x, \mathbf{b}_T, \epsilon, \tau, xP^+) = \int \frac{db^-}{2\pi} e^{-ib^-(xP^+)} \left\langle p(P,S) \middle| \left[\bar{\psi}^i(b^\mu) W_\sqsubset(b^\mu, 0) \frac{\Gamma}{2} \psi^i(0) \right]_\tau \middle| p(P,S) \right\rangle$$



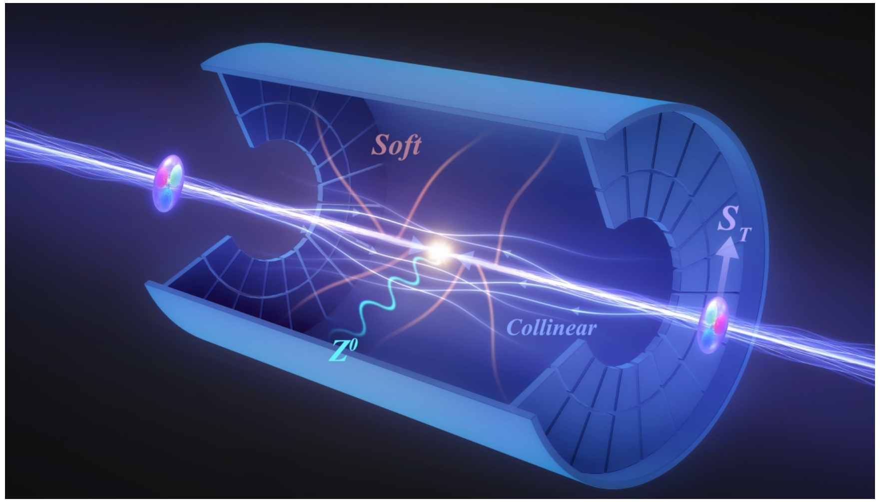
TMDs		Quark Polarization		
		Unpolarized (U)	Longitudinally polarized (L)	Transversely polarized (T)
Nucleon Polarization	U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
	L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity
	T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity	h_1 transversity $h_{1T}^\perp$ pretzelosity

Nucleon spin   Quark spin

Figure 2.5: The leading-twist quark TMD distributions.

QCD evolution and spin asymmetry

Spin dependent cross section

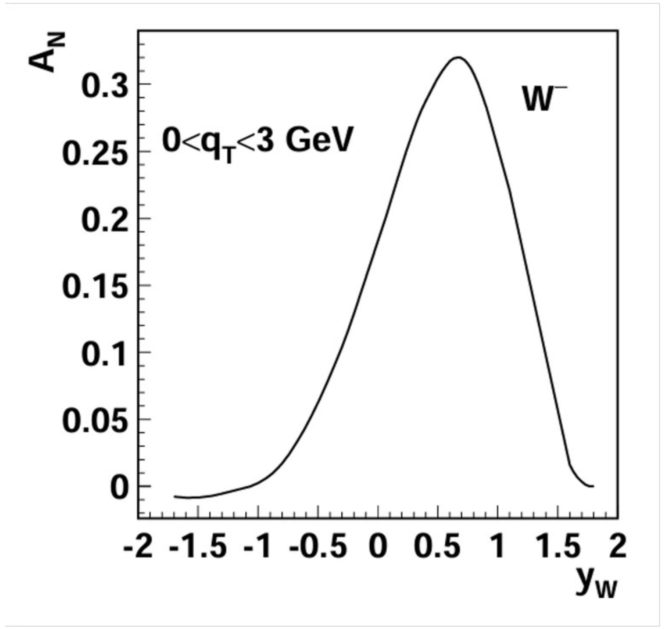


$$p + p^{\uparrow} \rightarrow V + X$$

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

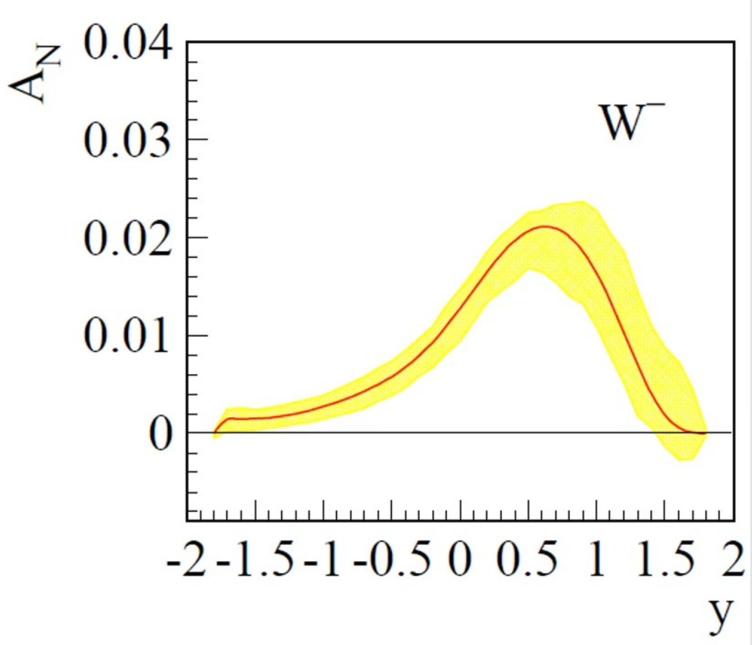
$$f_q(x, k_T) \qquad \frac{1}{M}\epsilon_{\alpha\beta}\, s_T^{\alpha}\, k_T^{\beta}\, f_{1T}^{\perp q}(x, k_T)$$

Without evolution



Kang & Qiu '09

With evolution



Echevarria, Idilbi, Kang, Vitev '14

Evolution reduces the asymmetry

Nucleon tomography with 0-jettiness

- **At high energies, QCD radiation acts as "noise", reducing the asymmetry significantly.**

Fang, Lin, DYS, Zhou PRL 136 (2026)021901

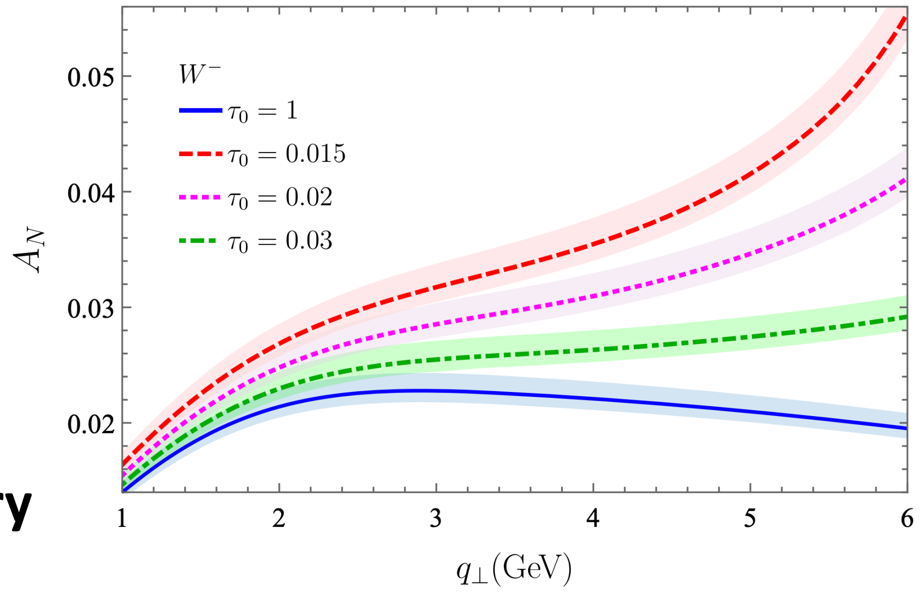
- **We apply 0-jettiness $\boldsymbol{\tau = 2\sum_i \min\{p_a \cdot l_i\,, p_b \cdot l_i\}/Q^2}$** (Stewart, Tackmann, & Waalewijn '10) **as a tunable resolution scale**
- **Joint qT and 0-jettiness resummation** (Procura, Waalewijn & Zeune '14) **for transversely polarized Drell-Yan cross section**

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

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

Modified Sudakov factor

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

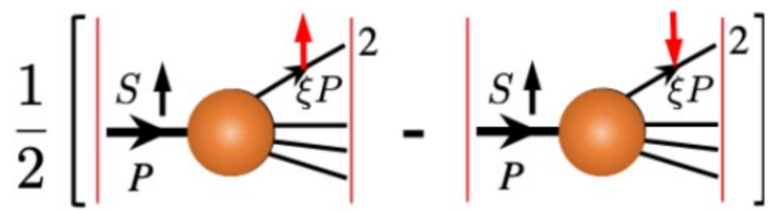


- **We demonstrate a substantial enhancement of the asymmetry signal (e.g., by 83% for Z SSA at qT=5 GeV)**

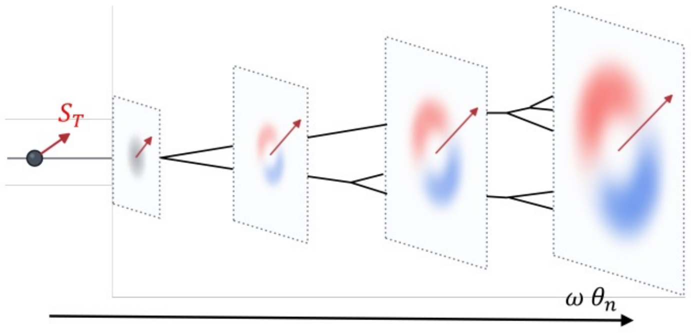
Accessing Nucleon Transversity via One-Point Energy/Charge Correlators

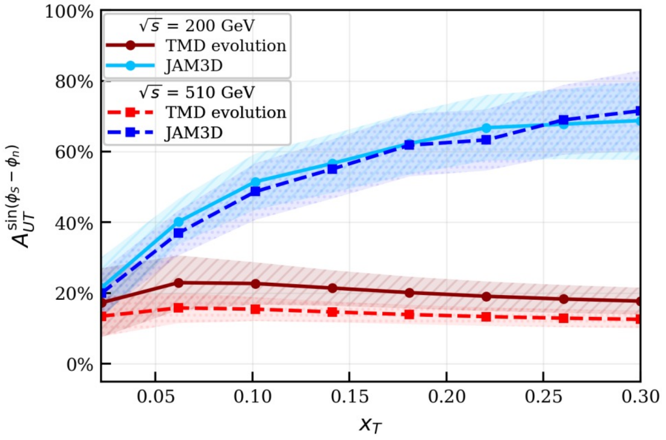
Gao, Kang, Li, DYS PRL 136 (2026) 151902
Li, Liu, DYS 2607.16392

- **Transversity distribution $h_1^q(x)$ measures transverse-spin asymmetry of quarks in a transversely polarized nucleon**
- **Its chiral-odd nature prevents access via inclusive DIS**
- **Nucleon tensor charge $\delta q \equiv \int dx\, h_1^q(x) - h_1^{\bar{q}}(x)$ is essential for BSM search, Lattice QCD benchmarks**
- **We propose the one-point energy/charge correlator to probe the nucleon transversity**

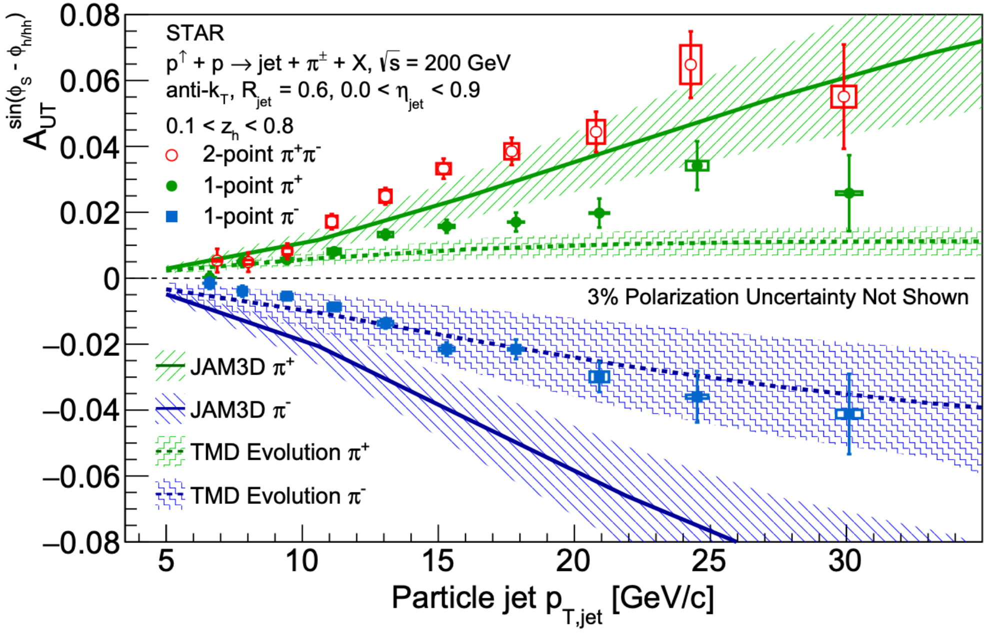


$$\mathcal{J}^q_{\Gamma,\omega}(\vec{n}_T) = \int \mathrm{d}\xi\ \mathrm{d}^2 x_T e^{i\omega\xi}\ \mathrm{Tr}\left[\frac{\Gamma}{2}\langle 0|\chi_n(\xi, x_T)\,\widehat{\mathcal{G}}(\hat{n})\bar{\chi}_n(0)|0\rangle\right]$$





RHIC-STAR 2604.15543 PRL



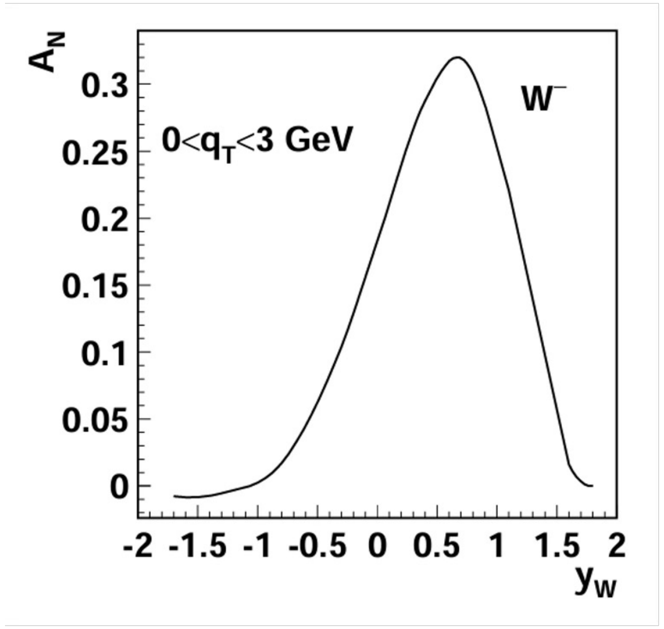
EEC review see: 2506.09119 Moult & Zhu

3. New insights

Decoherence from unresolved radiation

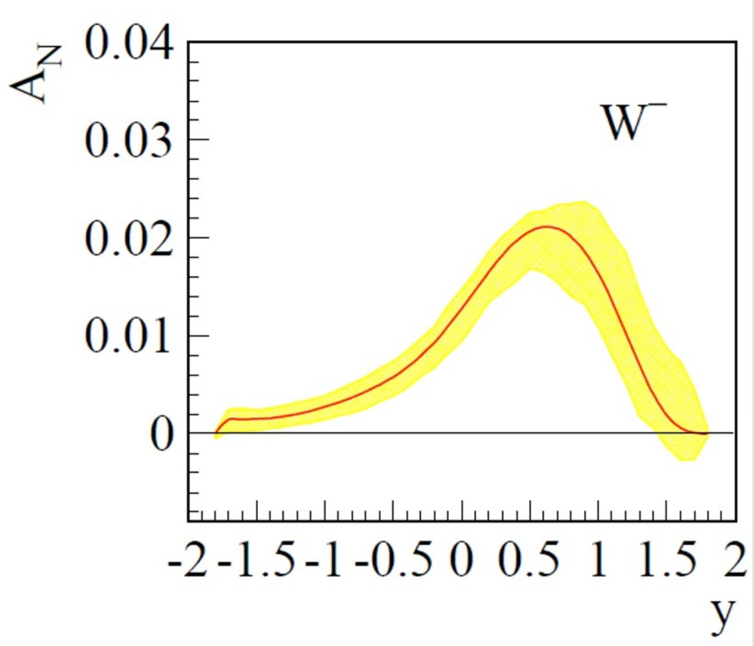
Spin asymmetry, evolution and decoherence

Without evolution



Kang & Qiu '09

With evolution



Echevarria, Idilbi, Kang, Vitev '14

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

Quantum information interpretation

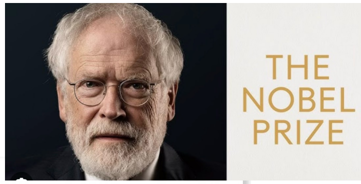
- Soft and collinear radiation wash out observable quantum interference.
- Soft radiation decohere the directions of the momenta and the gauge representations of the particles
- Collinear radiation decohere the energies and the spin

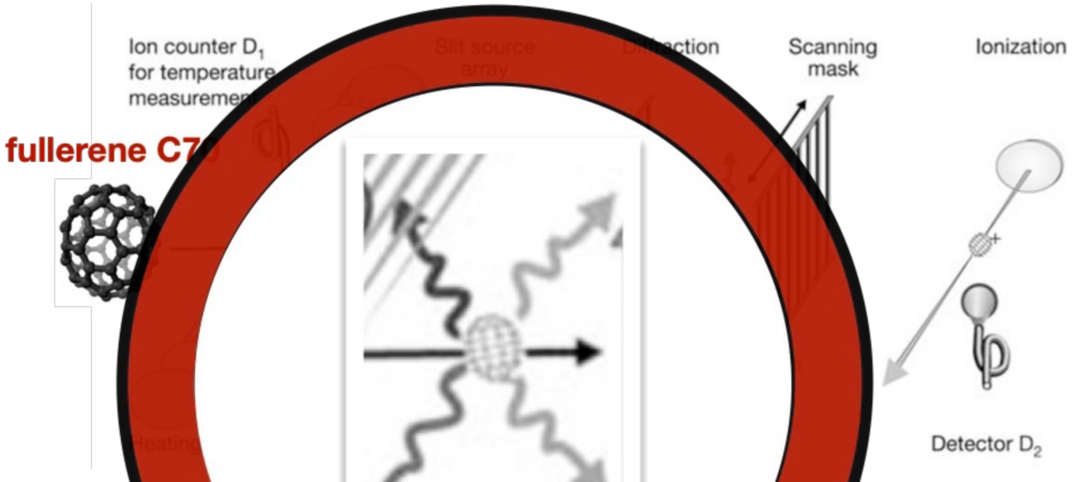
Carney, Chaurette, Neuenfeld, Semenof '17
Neill, Waalewijn '19
Aoude, Barr, Maltoni, Satrioni '25
S.J. Lin, M.J. Liu, DYS, S.Y. Wei '25
J.Y. Gu, S.J. Lin, DYS, S.X. Yang, L.T Wang '25
… …

See also Aoude's talk

Decoherence by thermal emission of photons

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





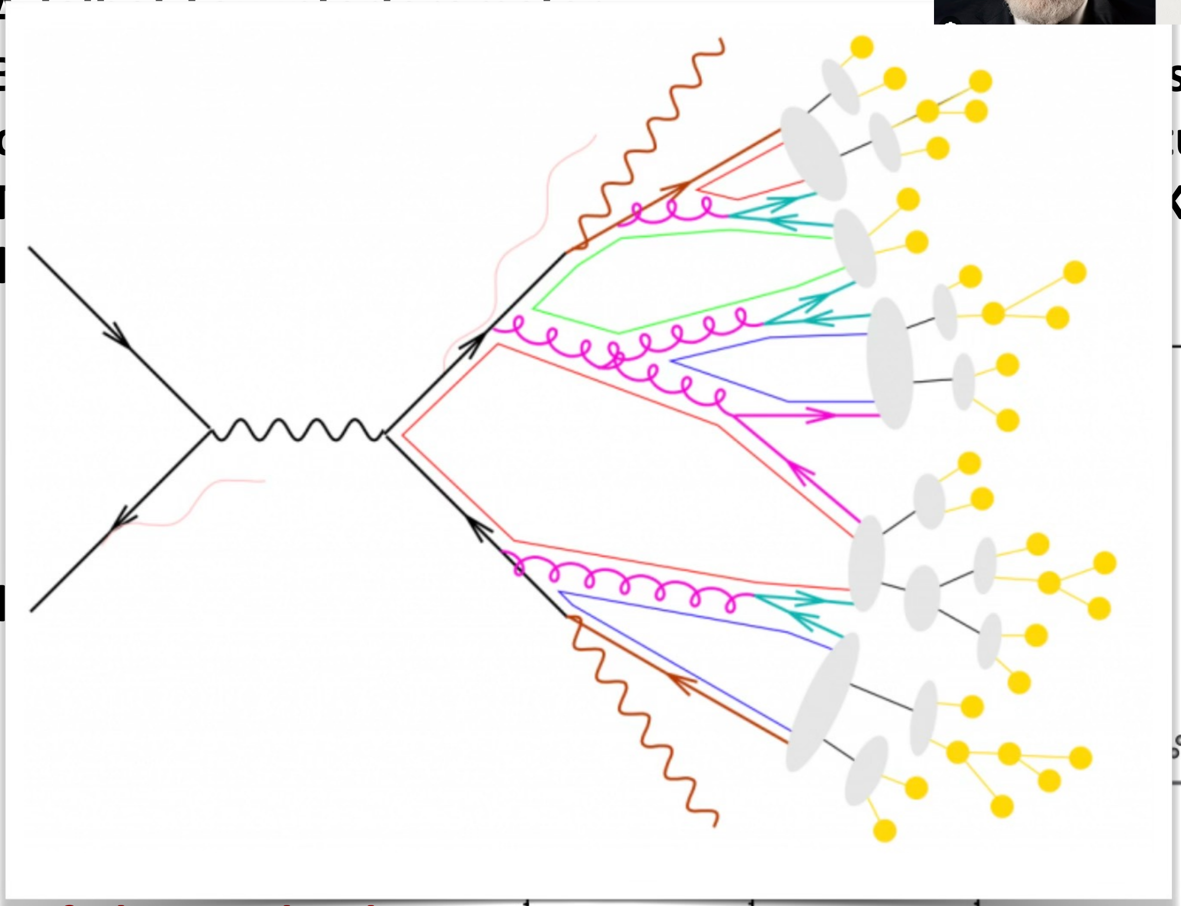
➢ A

➢ E … ss

thr … ure

➢ T … X

(col



- ➢ Cold Mo
  - ➢ M… radiation.
  - ➢ Result: Strong quantum interference is observed … visibility.
- ➢ Hot Molecules:
  - ➢ Molecules emit thermal photons that carry path
  - ➢ Result: The interference fringe visibility drops to
- ➢ The decoherence mechanism is the thermal emission of photons by the molecule itself

Effective field theory for decoherence

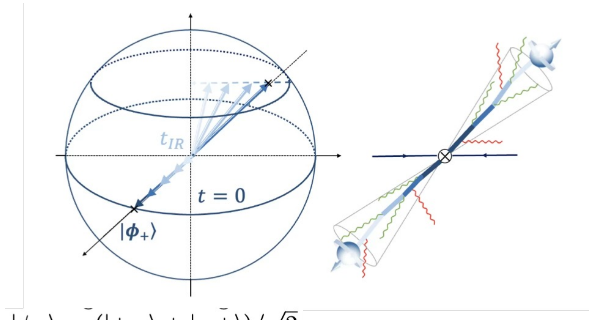
Gu, Lin, DYS, Wang, Yang '25

- A systematic framework calculating spin decoherence in high energy collisions by combing SCET and open-quantum-system methods
- 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 $p = \sqrt{\frac{1}{2}\left[1 - \exp\left(-\frac{\alpha}{2\pi}t\right)\right]}$

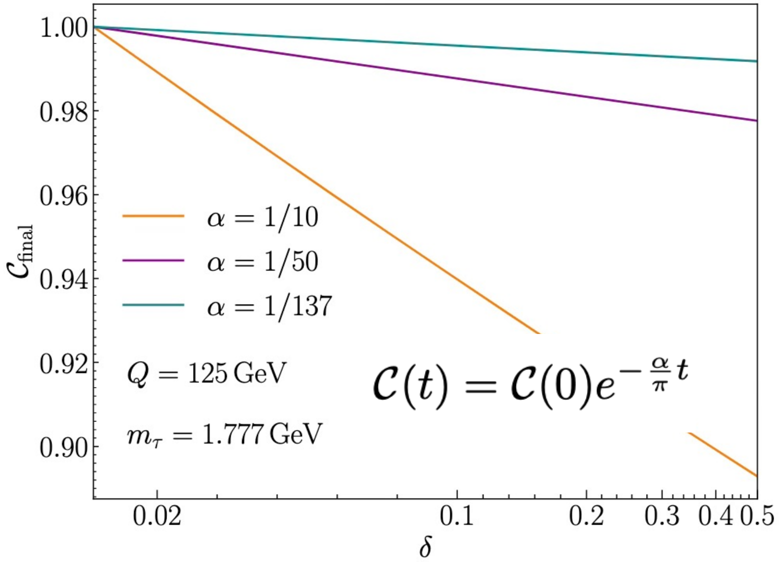
$$\hat{K}_0^{\ell^-} = \hat{K}_0^{\ell^+} = \sqrt{1-p^2}\,\mathbb{I} \qquad \hat{K}_1^{\ell^-} = \hat{K}_1^{\ell^+} = p\,\hat{\sigma}_3$$

  - Decay of all off-diagonal terms

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



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



RGE drives decoherence

anomalous dimensions determine decoherence rate

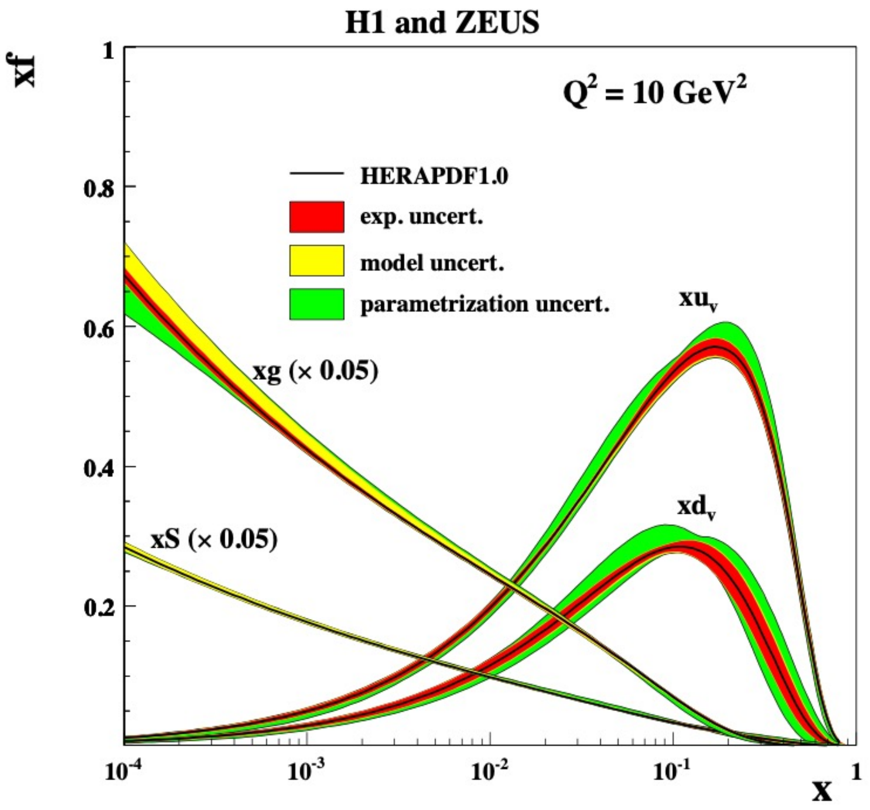
4. New paradigms

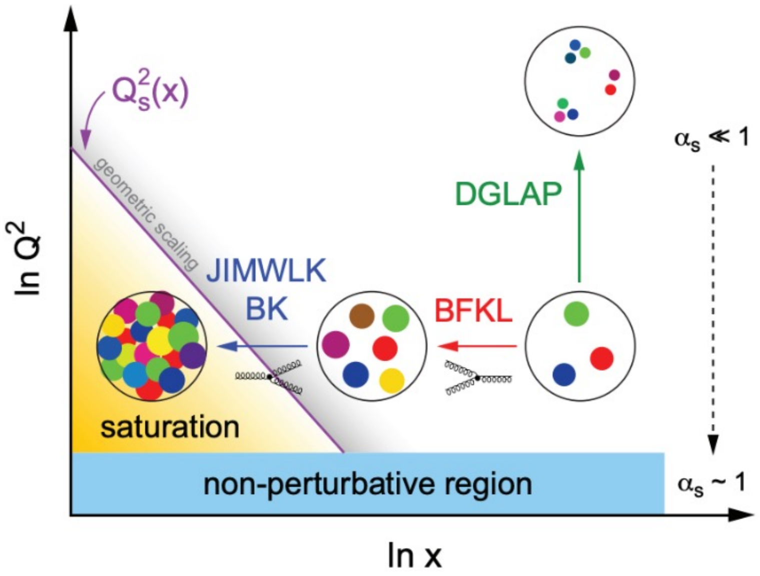
Physics-informed AI for nonlinear RGE

Gluon saturation and small x physics

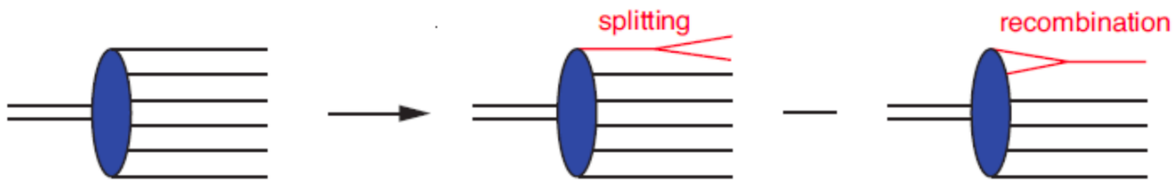
DGLAP kernel: $P_{gg}(x) \to \frac{1}{x}$ for $x \to 0$

Gluon density rapidly increases at small-x





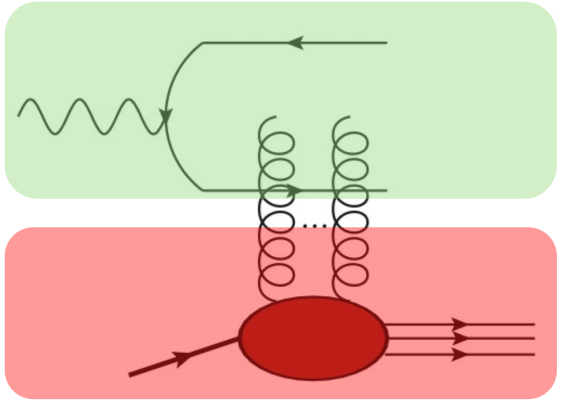
Non-linear evolution effect becomes important



BFKL (linear) → BK / JIMWLK (nonlinear)

Deep inelastic scattering at small x

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


Dipole frame

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

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

Balitsky-Kovchegov equation

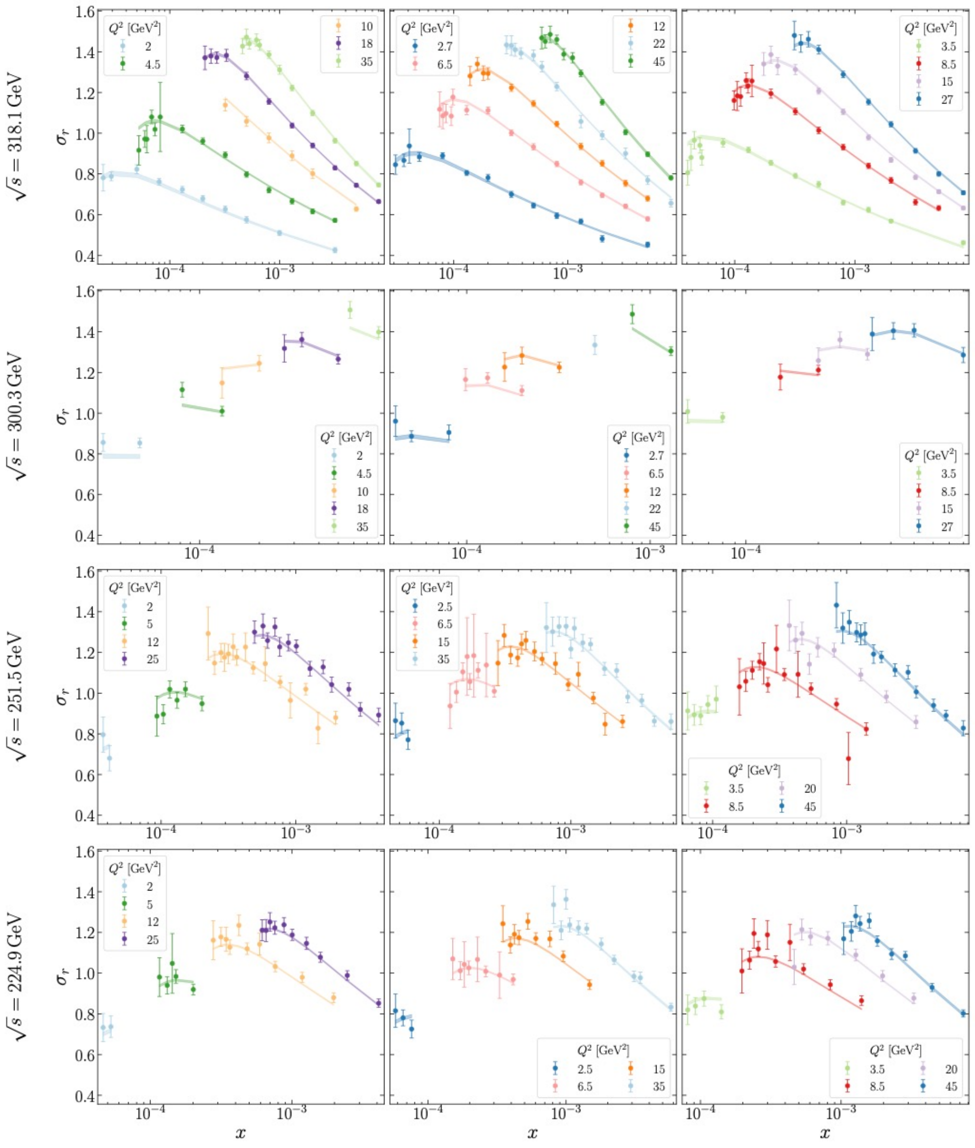
- The small-x, or rapidity, dependence of the dipole amplitude is governed by BK evolution

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

Non-linear gluon recombinition

- 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

Global-fit results



Gao, Kang, Penttala, DYS '25 JHEP

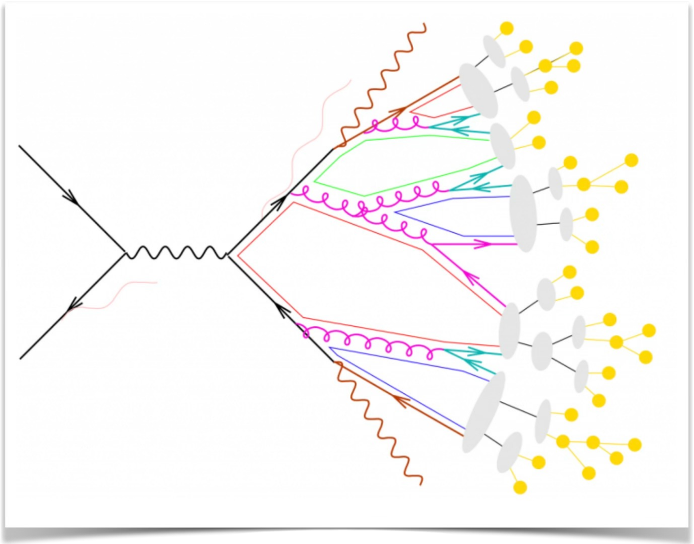
		$x_0 = 0.01$	
Parameter	**Prior Range**	**4-param ($\gamma = 1$)**	**5-param (γ free)**
Q^2_{s0} [GeV^2]	[0.01, 0.11]	$0.063^{+0.001}_{-0.004}$	$0.068^{+0.024}_{-0.015}$
e_c	[0.5, 70.0]	$29.0^{+8.7}_{-3.1}$	$18.7^{+20.1}_{-9.6}$
C^2	[2.0, 20.0]	$4.45^{+0.99}_{-0.59}$	$4.82^{+1.56}_{-2.63}$
$\sigma_0/2$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

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

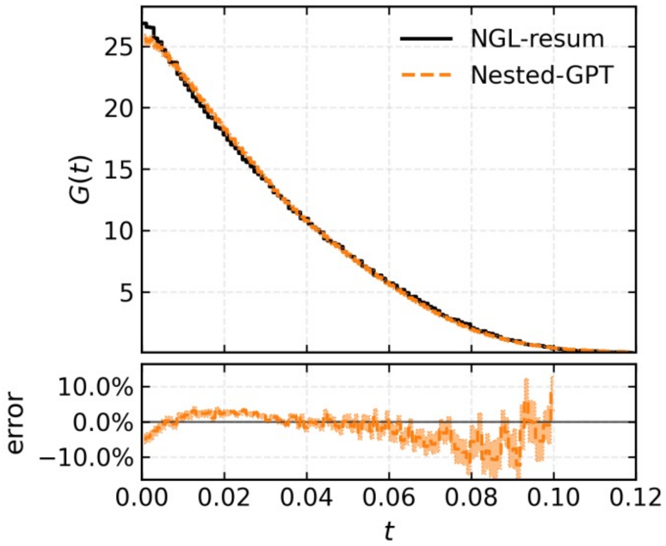
Nested-GPT for variable-multiplicity parton showers

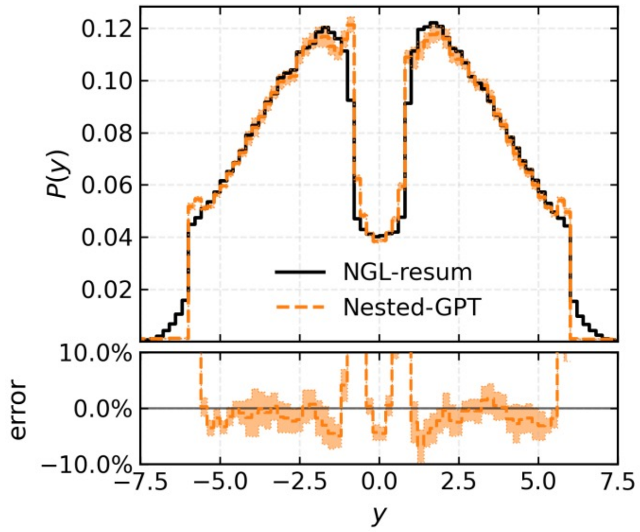
- **Non-global logs resummation is governed by the non-linear BMS equation, physically interpreted as a dipole shower.** Dasgupta, Salam ’01, Banfi, Marchesini, Smye ‘02

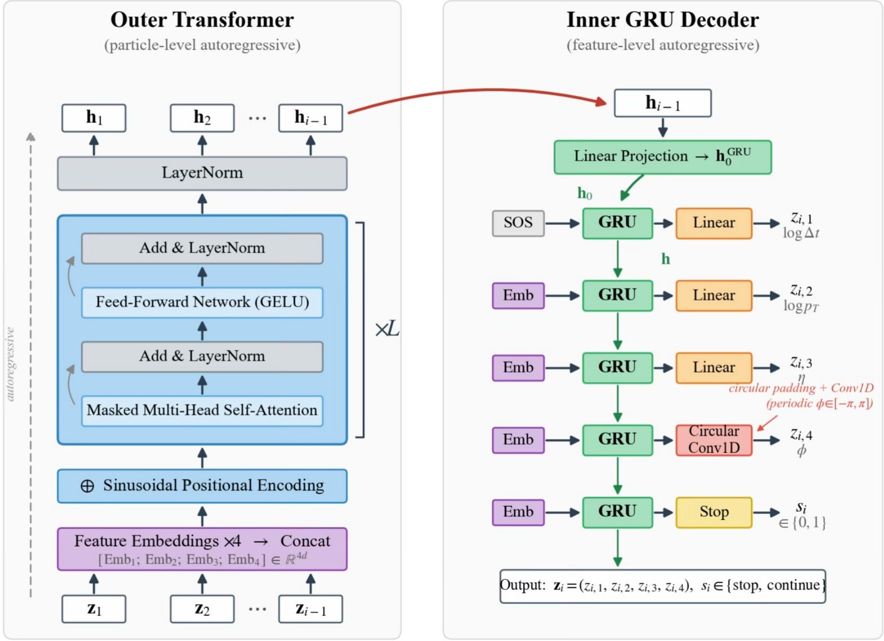
$$Q\frac{\partial}{\partial Q}G_{ab}(Q) = \int \frac{d^2\Omega_k}{4\pi}\bar{\alpha}_s W_{ab}(k)\left[u(k)G_{ak}(Q)G_{kb}(Q) - G_{ab}(Q)\right]$$



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







Summary and outlook

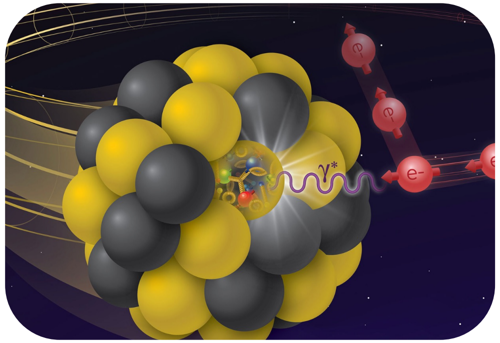
- **Precision frontier (new methods): new infrared subtraction schemes**
  - **obtained the first NNLO prediction for finite-Pt hadron production in DIS and the first NNNLO results for SIDIS**
- **Spin frontier (new probes): jets and jet substructure as powerful probes of nucleon structure**
  - **introduce 0-jettines to enhance signal of spin asymmetry**
  - **show that one-point energy/charge correlators can access transversity and tensor charge**
- **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**

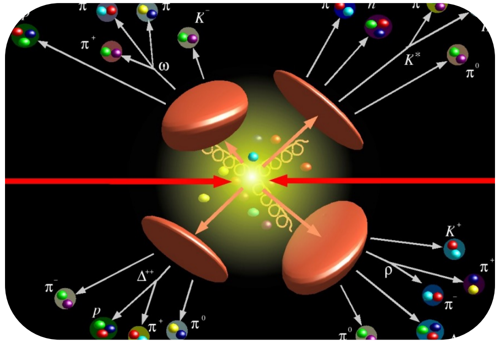
Summary and outlook

Entanglement

Decoherence

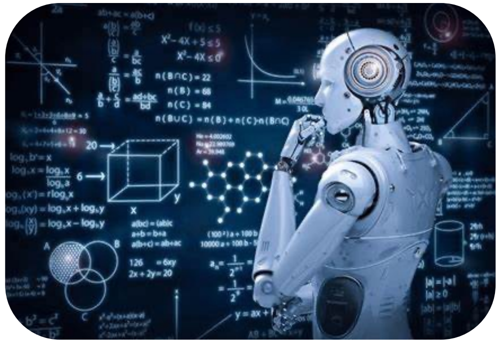
Quantum information





Spin physics, hadron structure

Jet physics, fragmentation



Fast fit

Fast simulation

Generative AI

Thank You