New Perspectives on Precision Nucleon Tomography

Ding-Yu Shao

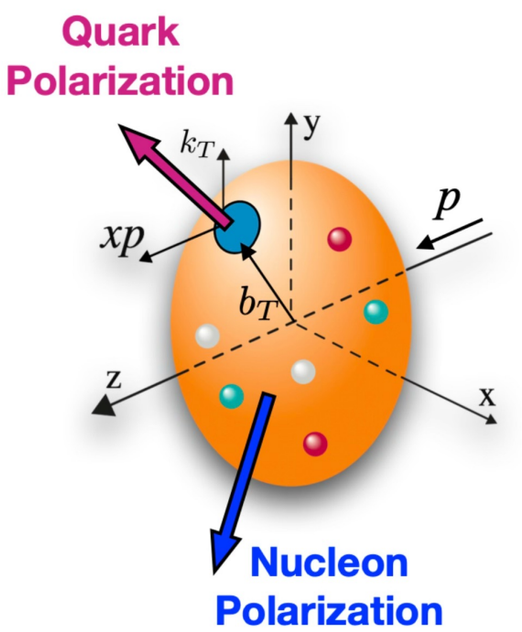
Fudan University

Resummation, Evolution & Factorization 2026 **IGFAE** **Oct 19 – 23, 2026**

Nucleon tomograph and TMDs

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

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

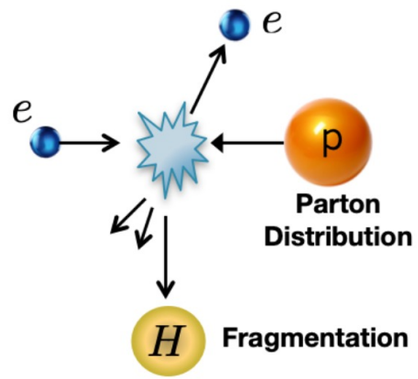


Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity; $h_{1T}^\perp$ = Pretzelosity

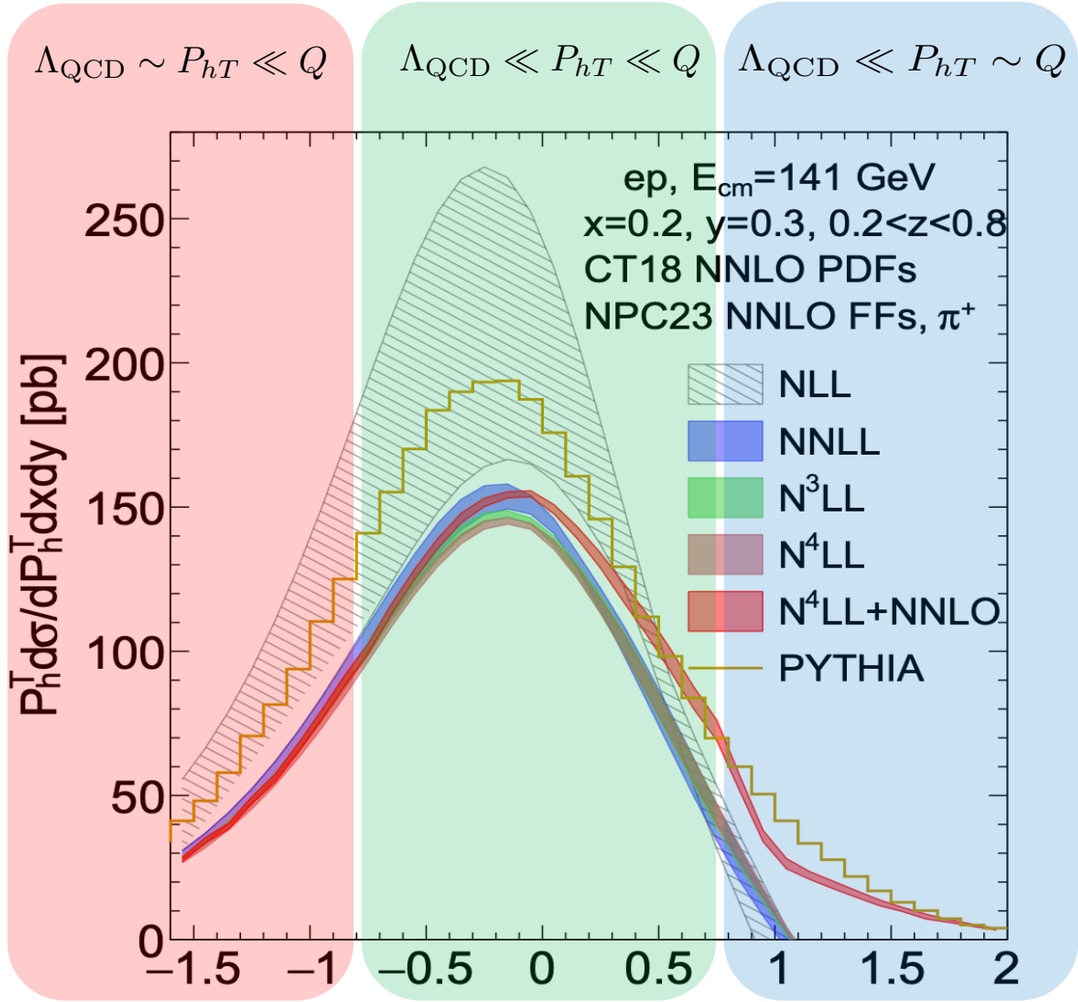
TMDs in e-p collisions

One of the most fundamental measurements in SIDIS related to TMDs is the study of the P_{hT} differential cross section

Semi-Inclusive DIS



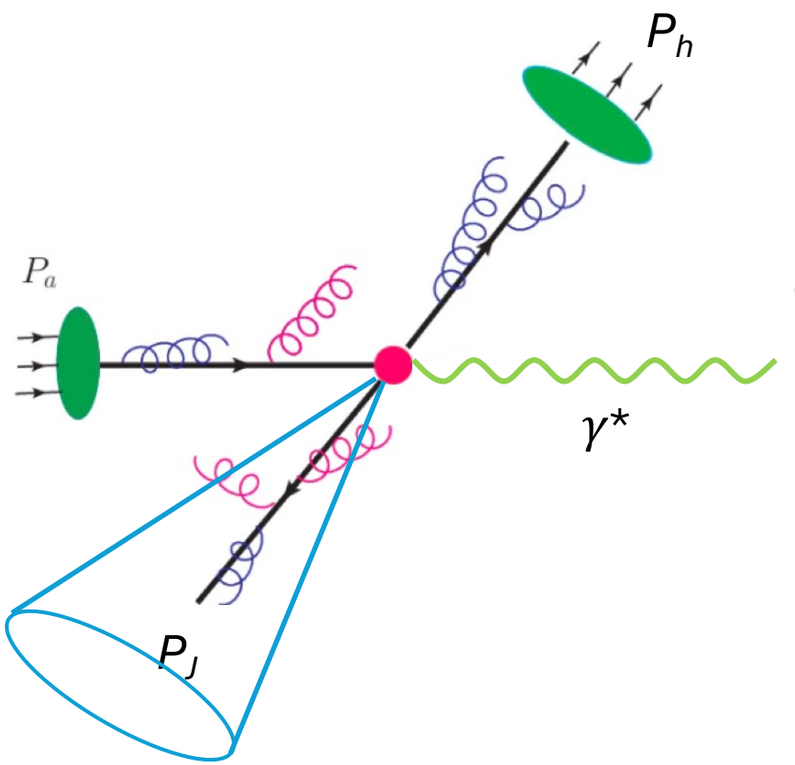
$$\frac{d^4\sigma_{\rm SIDIS}}{dx\,dy\,dz_h\,dP_{hT}} \propto P_{hT}\frac{\alpha_{em}^2}{x\,y\,Q^2}\left(1-y+\frac{1}{2}y^2\right)F_{uu,T}$$



Gao, Li, Zhu, Zhu '26

NNLO QCD corrections for P_{hT} distribution

Hadron + jets @ NNLO



- **One key challenge is handling infrared (IR) divergences**
- **Two main approaches for the cancellation of IR divergences**
  - **Slicing** (two-cutoff, qT & N-jettiness subtraction …)

$$\int |\mathcal{M}|^2 F_J \, \mathrm{d}\phi_d = \int_0^\delta \left[|\mathcal{M}|^2 F_J \, \mathrm{d}\phi_d\right]_{\mathrm{sing}} + \int_\delta^1 |\mathcal{M}|^2 F_J \, \mathrm{d}\phi_4 + \mathcal{O}(\delta)$$

  - **Subtraction** (Catani–Seymour dipole, FKS …)

$$\int |\mathcal{M}|^2 F_J \, \mathrm{d}\phi_d = \int \left[|\mathcal{M}|^2 F_J - S\right] \mathrm{d}\phi_4 + \int S \, \mathrm{d}\phi_d$$

- **qT slicing** (Catani & Grazzini ‘07) **works well for colorless or colored (but massive) system**
  - **N3LO Drell-Yan** Chen, Gehrmann, Glover, Huss, Yang, Zhu ’23
- **For processes with jets, conventional qT is unsuitable because qT=0 for radiation emitted inside jets.**
  - **kT-ness slicing** Buonocore, Grazzini, Haag, Rottoli, Savoini ’22
  - **Winner-take-all qT slicing** Fu, Rahn, DYS, Waalewijn, Wu ‘24

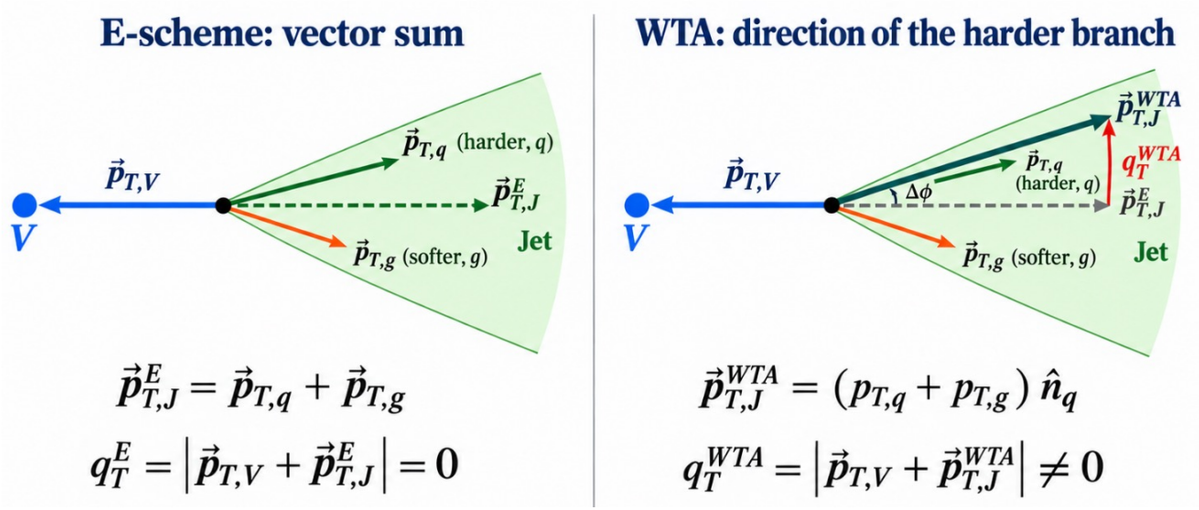
Winner-take-all qT slicing for jets

- **Winner-take-all recombination scheme** Salam E_t^{∞}-scheme; Bertolini, Chan, Thaler '13

WTA recombiniation scheme

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

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



- **Factorization theorem is significantly simplified** Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '18, Chien, Rahn, DYS, Waalewijn & Wu '22 + Schrignder '21
  - **NNNLL + $O(\alpha_s{}^2)$ resummation of $\delta\phi$ in $ep \to eJX$** Fang, Ke, DYS, Terry '24, Fang, Gao, Li, DYS '25
  - **Power corrections** Castillo, Jaarsma, Scimemi, Waalewijn '24, Jaarsma, Rio, Scimemi, Waalewijn '25

Winner-take-all qT slicing for jets

R. Fu, Rahn, DYS, Waalewijn, B. Wu PRL135(2025)17; JHEP08(2026)105

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

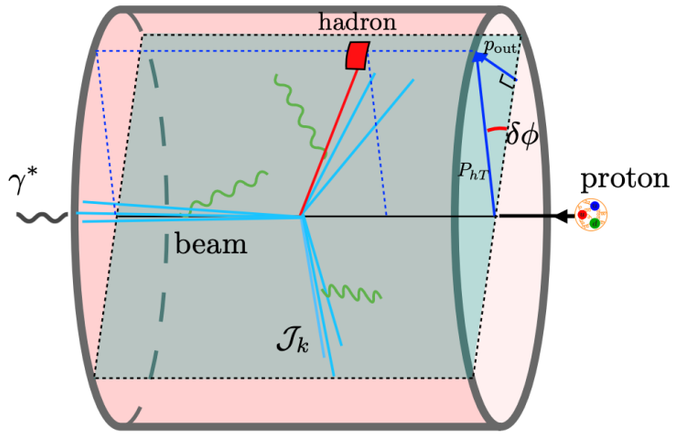
The key ingredient is the use of a recoil-free WTA jet axis!

- **Azimuthal decorrelation: $\delta\phi$ or q_y**
  - **Suitable for processes that are planar at LO: pp → 2 jets, etc.;**
  - **Standard TMD PDFs and soft functions (dipole): known at N3LO** Li, Zhu '16; 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, Dong, Fang, Gao, DYS, Li, Zhu '26
- **Total transverse momentum q_T**
  - **Suitable for LO non-planar process, such as pp → 3 jets, etc.**
  - **Soft function is new: Outside the jet (q_T), Inside the jet ($q_\perp$)**

NNLO QCD for P_{hT} distribution

L. Dong, S. Fang, J. Gao, DYS, H. Li, Y. Zhu PRL137(2026)8 + B. Zhou 2609.13743

- **We present the calculation of hadron production in DIS at finite transverse momentum to NNLO**

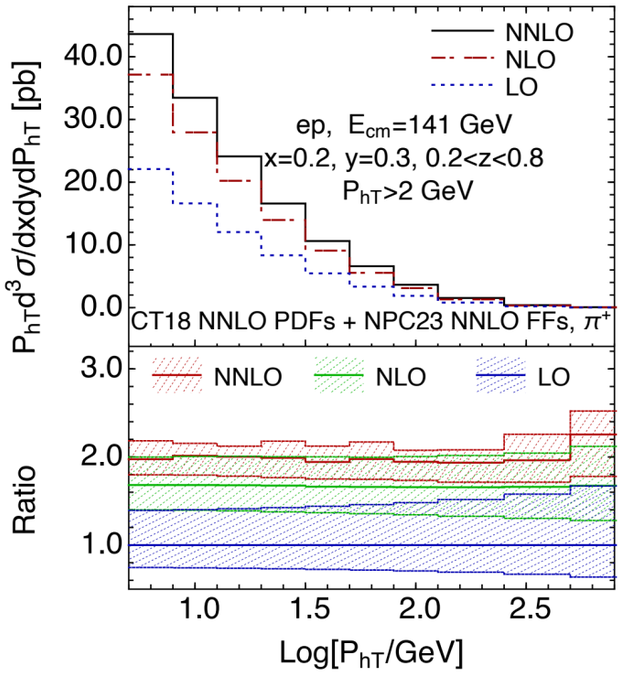


$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \int_0^{\delta\phi^{\rm cut}} \mathrm{d}\delta\phi \frac{\mathrm{d}\sigma}{\mathrm{d}\delta\phi\,\mathrm{d}\mathcal{O}} + \int_{\delta\phi^{\rm cut}}^{\delta\phi^{\rm max}} \mathrm{d}\delta\phi \frac{\mathrm{d}\sigma}{\mathrm{d}\delta\phi\,\mathrm{d}\mathcal{O}}$$

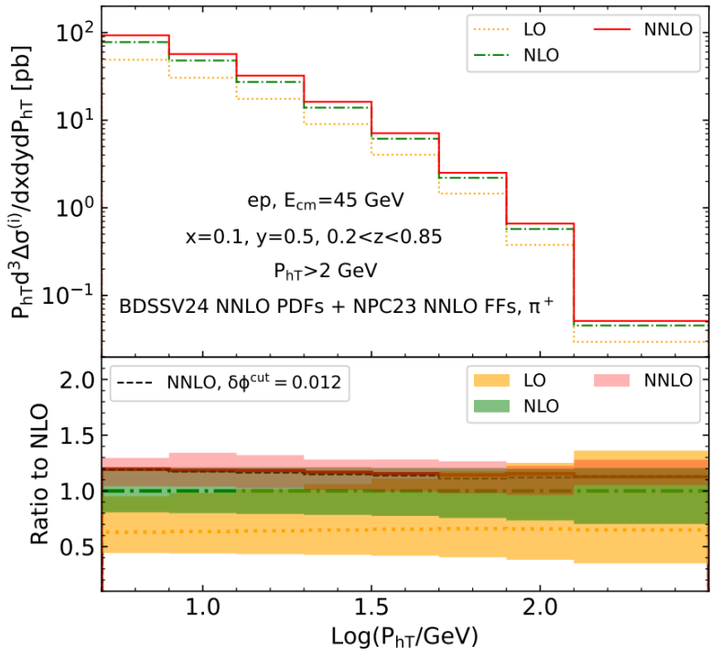
$$\frac{\mathrm{d}\sigma_{\rm LP}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}^2\vec{P}_{hT}\,\mathrm{d}p_{\rm out}} = \int \frac{\mathrm{d}b}{2\pi} e^{ip_{\rm out}b/\zeta} \times \sum_{ijk} \int \mathrm{d}\xi\, H_{ei\to ejk}(Q,\xi,\zeta) \times \mathcal{B}_{i/p}(\xi,b)\,\mathcal{D}_{h/j}(\zeta,b)\,\mathcal{J}_k(b)\,S_{ijk}(b)$$

Chien, Rahn, DYS, Waalewijn & Wu ’22 + Schrignder ’21

$e + p \to e + h + J + X$

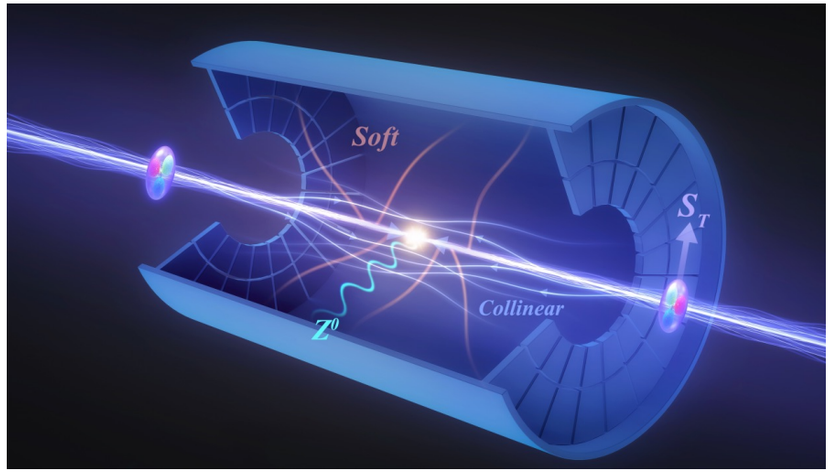


$e + \vec{p} \to e + h + J + X$



QCD evolution and spin asymmetry

Spin dependent cross section

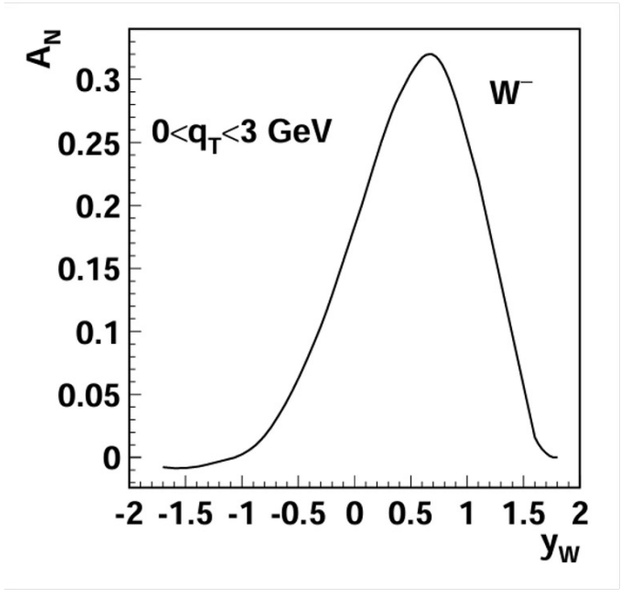


$$p + p^{\uparrow} \to V + X$$

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

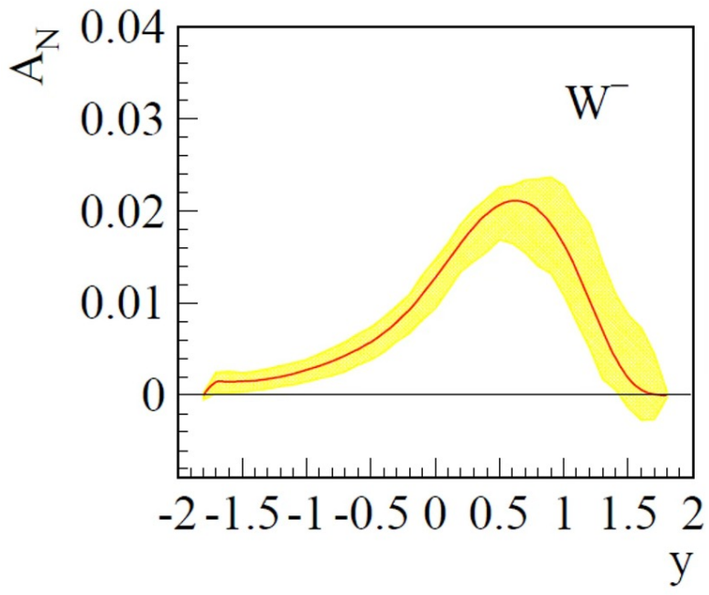
$$f_q(x, k_T) \qquad \frac{1}{M} \epsilon_{\alpha\beta}\, s_T^{\alpha}\, k_T^{\beta}\, f_{1T}^{\perp q}(x, k_T)$$

Without evolution



Kang & Qiu '09

With evolution



Echevarria, Idilbi, Kang, Vitev '14

Evolution reduces the asymmetry

Nucleon tomography with a jettiness veto

S. Fang, S. Lin, DYS, J. Zhou PRL136(2026)2

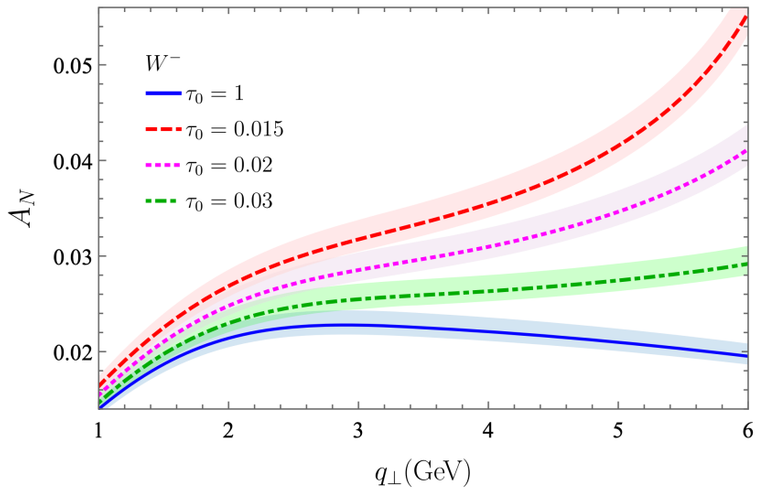
- **At high energies, QCD radiation acts as "noise", reducing the spin asymmetry significantly.**
- **Joint TMD and veto resummation** (Monni, Rottoli, Torrielli '19)
- **We apply *N*-jettiness $\tau = 2\sum_i \min\{p_a \cdot l_i, p_b \cdot l_i\}/Q^2$** (Stewart, Tackmann, & Waalewijn '10) **as a tunable resolution scale**
- **Joint qT and jettiness veto resummation for the polarized cross section**

Joint resummation formula in Drell-Yan

$$\frac{\mathrm{d}\sigma_{UT}(S_\perp)}{\mathrm{d}y\,\mathrm{d}^2\vec{q}_\perp} = \sin(\phi_q - \phi_S)\,\sigma_0 \int_0^\infty \frac{b^2\,\mathrm{d}b}{4\pi} J_1(bq_\perp) \sum_{q,q'} |V_{qq'}|^2 T_{F,q}(x_q, x_q, \mu_b) f_{q'}(x_{q'}, \mu_b)\, e^{-S_{\mathrm{P}}(b)}$$

Modified Sudakov factor

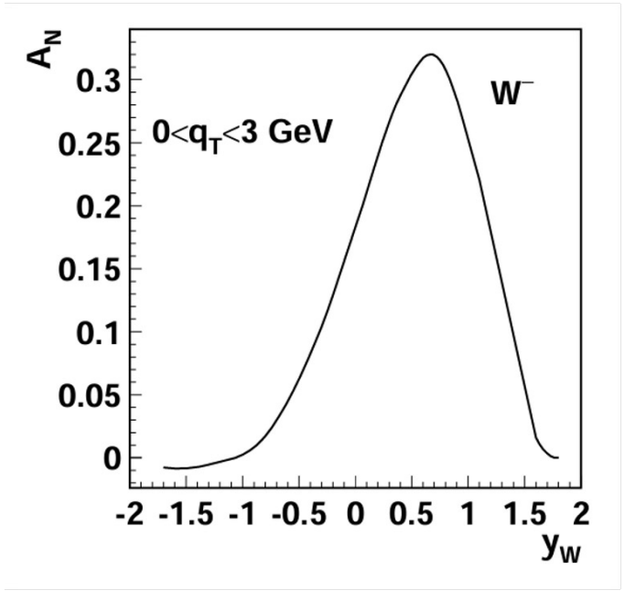
$$S_{\mathrm{P}}(b) = \frac{C_F}{\pi}\left[\int_{\mu_b^2}^{t}\frac{\mathrm{d}\mu^2}{\mu^2}\left(2\ln\frac{t}{\mu^2} - \frac{3}{2}\right) - \int_{\mu_b^2}^{\tau_0 t}\frac{\mathrm{d}\mu^2}{\mu^2}\ln\frac{\tau_0 t}{\mu^2} + \int_t^{Q^2}\frac{\mathrm{d}\mu^2}{\mu^2}\left(\ln\frac{Q^2}{\mu^2} - \frac{3}{2}\right)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



- **We demonstrate enhancement of the asymmetry (e.g., by 83% for Z SSA at qT=5 GeV)**
- **Recently, we propose the similar veto idea in $pA \to VX$ to enhance the signal of gluon saturation** Li, DYS, Wei, Zhou 2609.02356

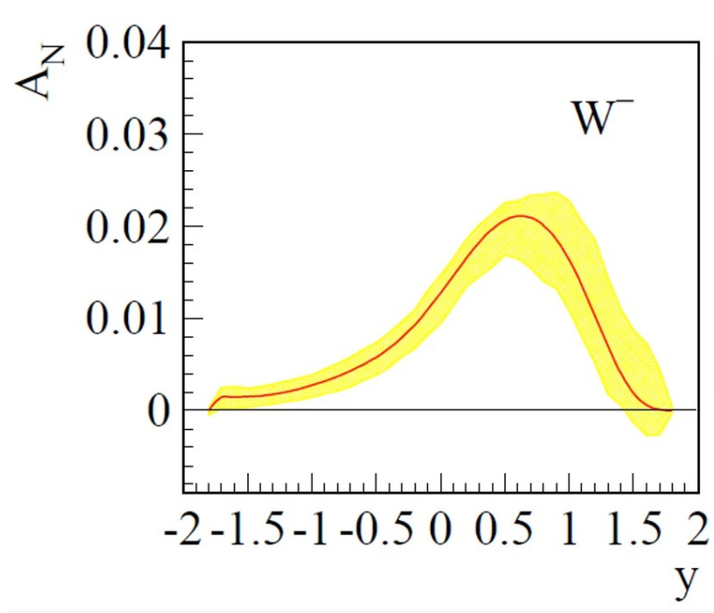
Spin asymmetry, evolution and decoherence

Without evolution



Kang & Qiu '09

With evolution



Echevarria, Idilbi, Kang, Vitev '14

Quantum information interpretation

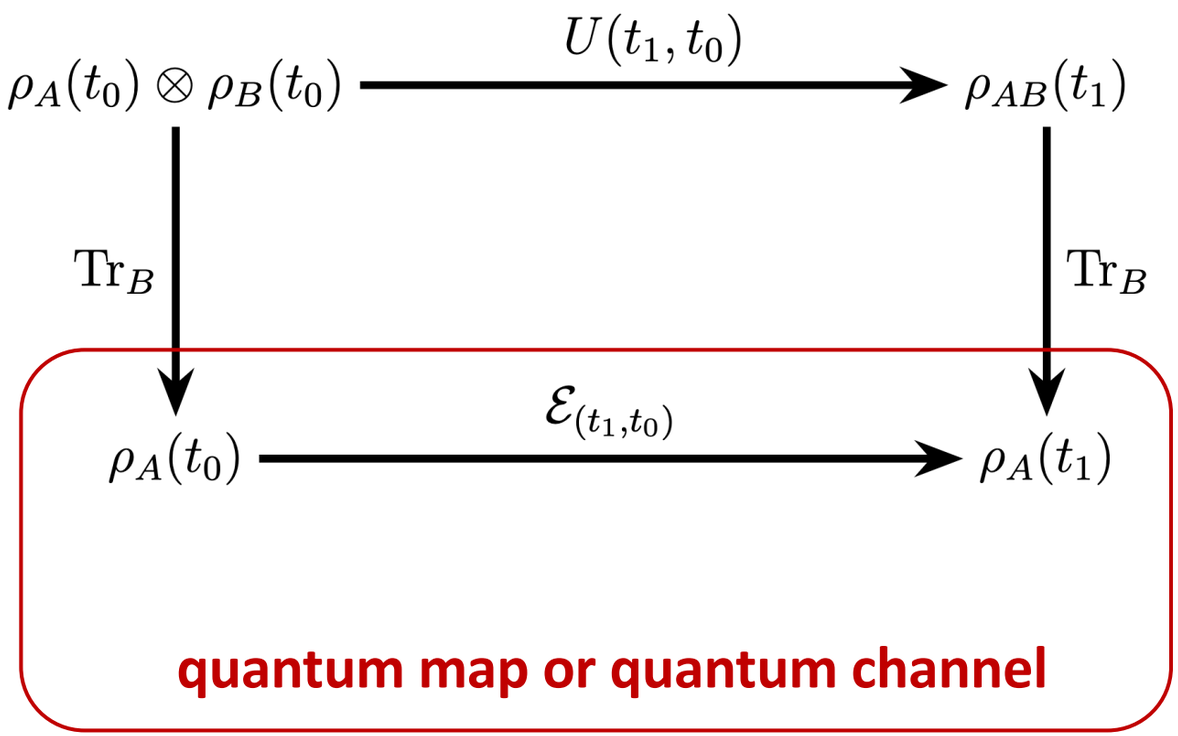
- Soft and collinear radiation suppress observable quantum interference
- At leading power, soft radiation suppresses interference between states with different momentum directions
- Collinear radiation suppresses interference between states with different energies or spins

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
... ...

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

Decoherence and quantum channel

Consider a bipartite system



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

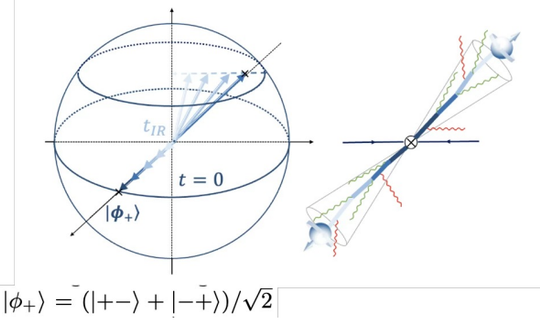
Gu, Lin, DYS, Wang, Yang 2510.13951

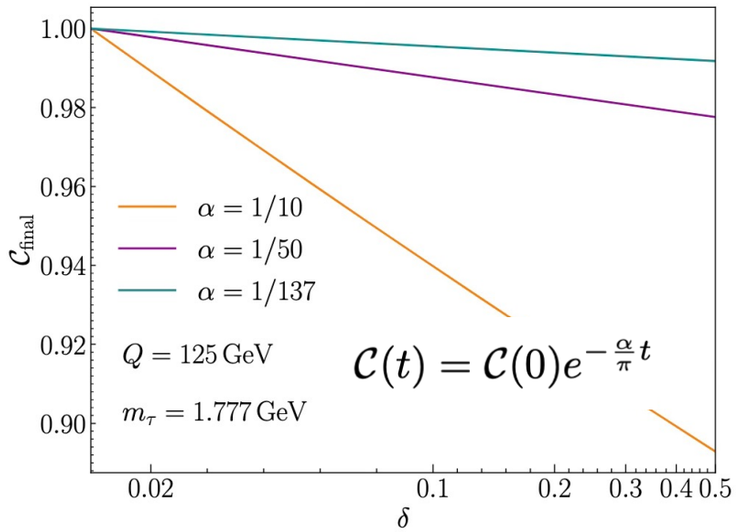
- **A framework calculating spin decoherence in high energy collisions by combing SCET and open-quantum-system methods**
- **The renormalization group evolution constitutes a quantum channel, where the RG flow parameter, rather than time, drives a Markovian loss of quantum coherence.**
- **E.g. Applications 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**

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

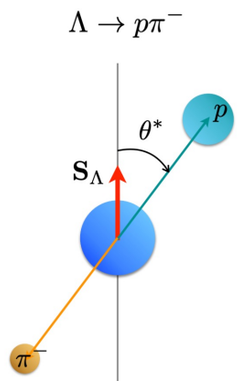




RGE drives decoherence
anomalous dimensions determine decoherence rate

Spin decoherence of hyperon pair in e^+e^-

Lin, Liu, DYS, Wei JHEP11(2025)082; Dai, Lin, DYS, Wei in progress



- **Hyperon-pair spin correlations probe how spin information is transmitted from quark to hadron**

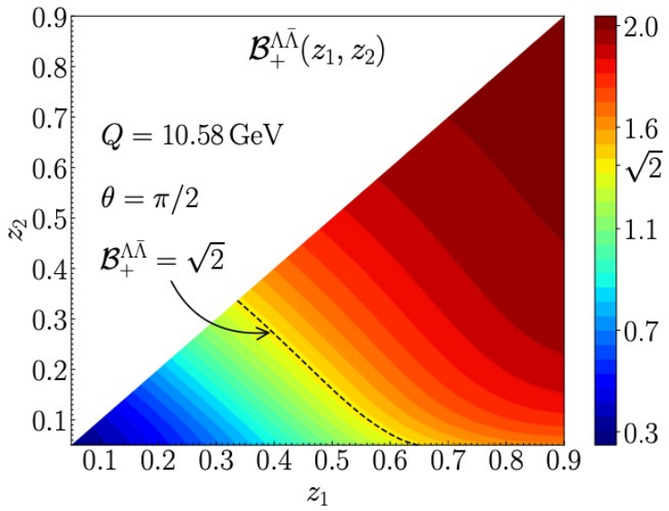
$$e^-(l) + e^+(l') \to \Lambda(z_1, \boldsymbol{S}_1) + \bar{\Lambda}(z_2, \boldsymbol{S}_2) + X$$

- **We develop a quantum channel description, and Kraus operators are determined by polarized fragmentation functions**

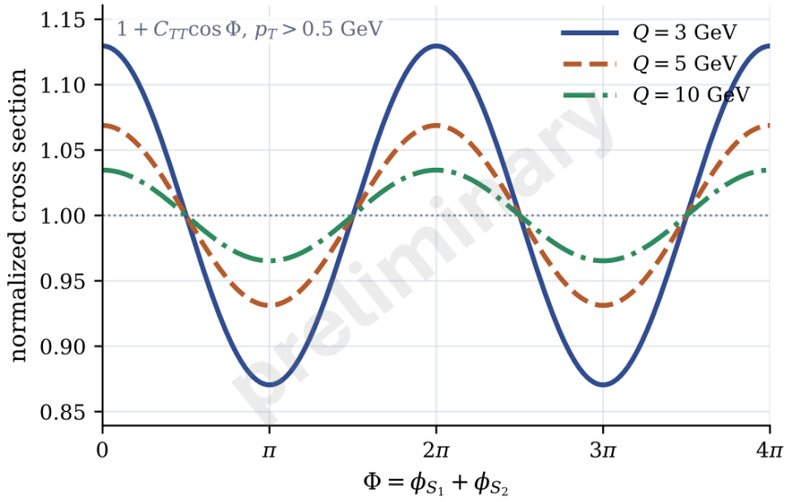
$$\hat{\rho}_{\Lambda\bar{\Lambda}} = \sum_q \sum_{\alpha,\beta=0}^{3} K_{q\alpha\beta}\, \hat{\rho}_0\, K_{q\alpha\beta}^\dagger, \qquad K_{q\alpha\beta} = \sqrt{\omega_q}\, K_{\alpha,\Lambda/q} \otimes \bar{K}_{\beta,\bar{\Lambda}/\bar{q}}$$

$$K_{0,\Lambda/q} = \left[\frac{D^U_{\Lambda/q} + D^L_{\Lambda/q} + 2D^T_{\Lambda/q}}{4D^U_{\Lambda/q}}\right]^{1/2} \mathbb{I}, \qquad K_{2,\Lambda/q} = \left[\frac{D^U_{\Lambda/q} - D^L_{\Lambda/q}}{4D^U_{\Lambda/q}}\right]^{1/2} \sigma_y,$$

$$K_{1,\Lambda/q} = \left[\frac{D^U_{\Lambda/q} - D^L_{\Lambda/q}}{4D^U_{\Lambda/q}}\right]^{1/2} \sigma_x, \qquad K_{3,\Lambda/q} = \left[\frac{D^U_{\Lambda/q} + D^L_{\Lambda/q} - 2D^T_{\Lambda/q}}{4D^U_{\Lambda/q}}\right]^{1/2}$$



Varying energy fraction and beam energy changes final state radiation, and thus changes the unobserved environment coupled to the measured hyperon spins



Summary

- Precision QCD with WTA qT slicing
  - We developed WTA qT slicing for processes involving jets
  - This enables NNLO predictions for hadron production in DIS at finite transverse momentum

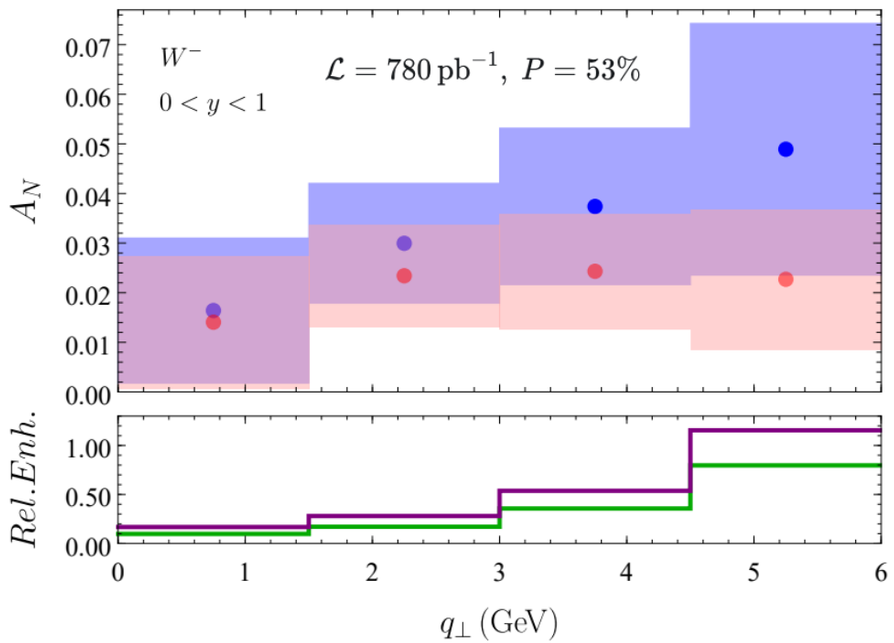
- New probes of nucleon spin structure
  - A 0-jettiness veto restricts QCD radiation and enhances single-spin asymmetries

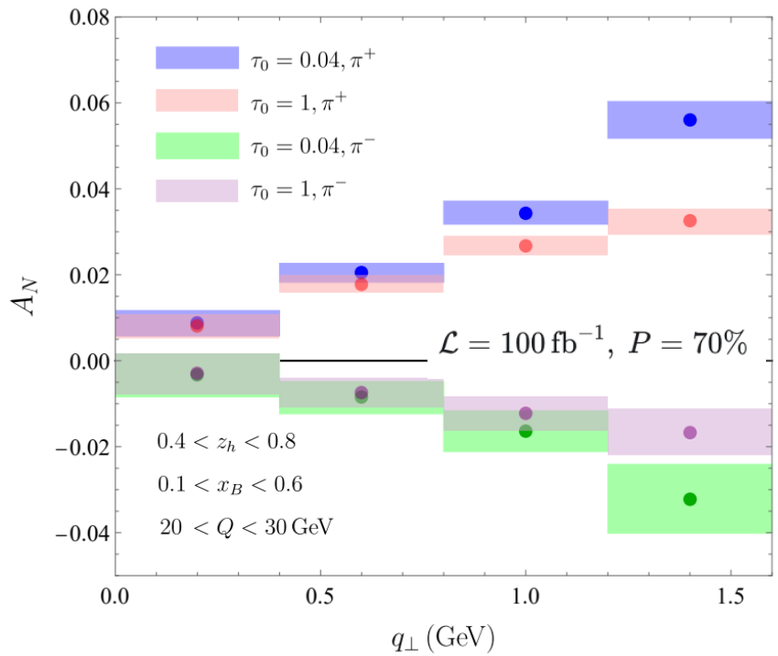
- Unresolved collinear radiation induces spin decoherence
  - We combine SCET and open-quantum-system methods to describe spin decoherence
  - RGE drives decoherence; anomalous dimensions determine decoherence rate

Thank You

Projected sensitivity with a jettiness veto

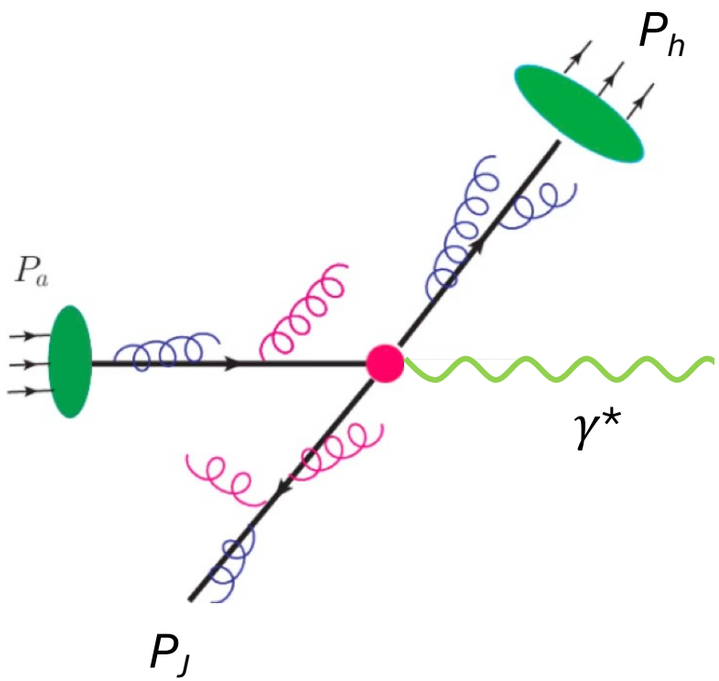
- Bands show projected statistical uncertainties (68% CL)
- The veto enhances the asymmetry but reduces the event yield
- The asymmetry gain outweighs the statistical cost in these projections
  - RHIC: 115% larger asymmetry versus 80% larger statistical uncertainty at qT ≃ 5 GeV

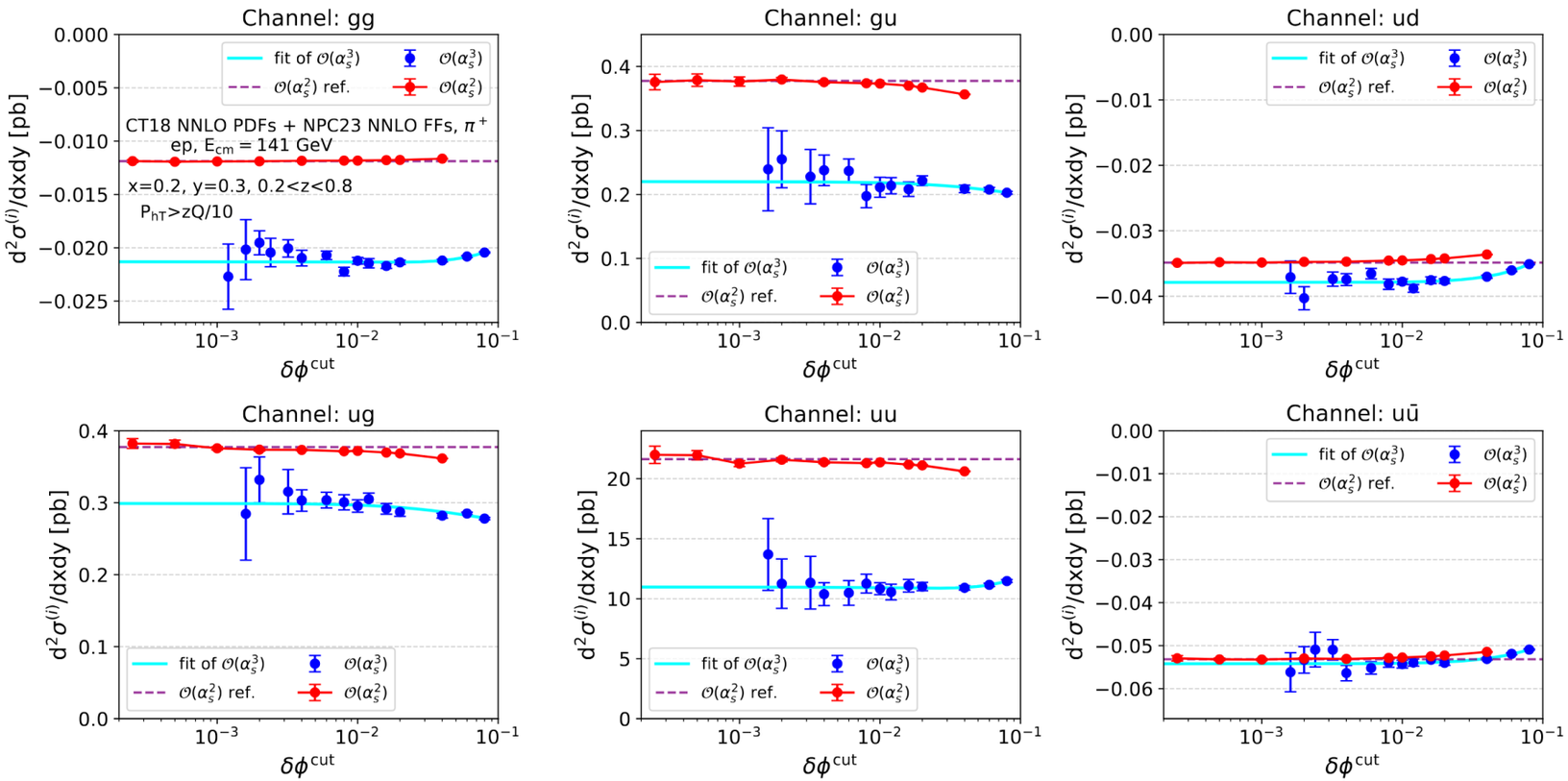




Numerical stability under slicing-parameter variation

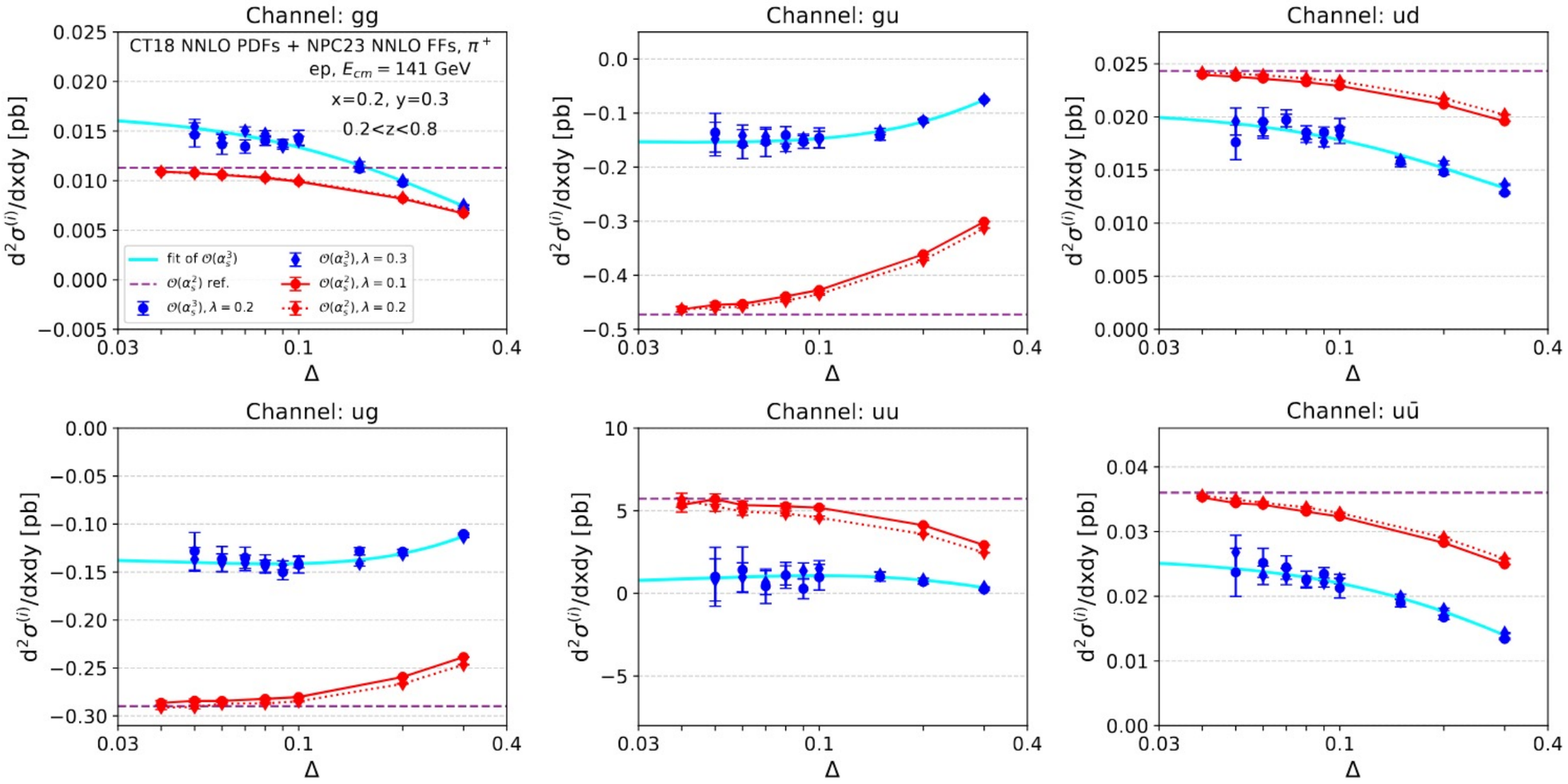
Hadron + jets @ NNLO





$$\sigma^{(2)}(\delta\phi^{\rm cut}) = (\delta\phi^{\rm cut})^2 \left(c_3 \ln^3 \delta\phi^{\rm cut} + c_2 \ln^2 \delta\phi^{\rm cut}\right) + d_0 \,.$$

Numerical stability under slicing-parameter variation



N3LO QCD corrections for SIDIS

Dong, Fang, Gao, DYS, Li, Zhu, Zhu PRL137(2026)15 + Zhou 2609.13743

