Some new observables in QCD spin physics

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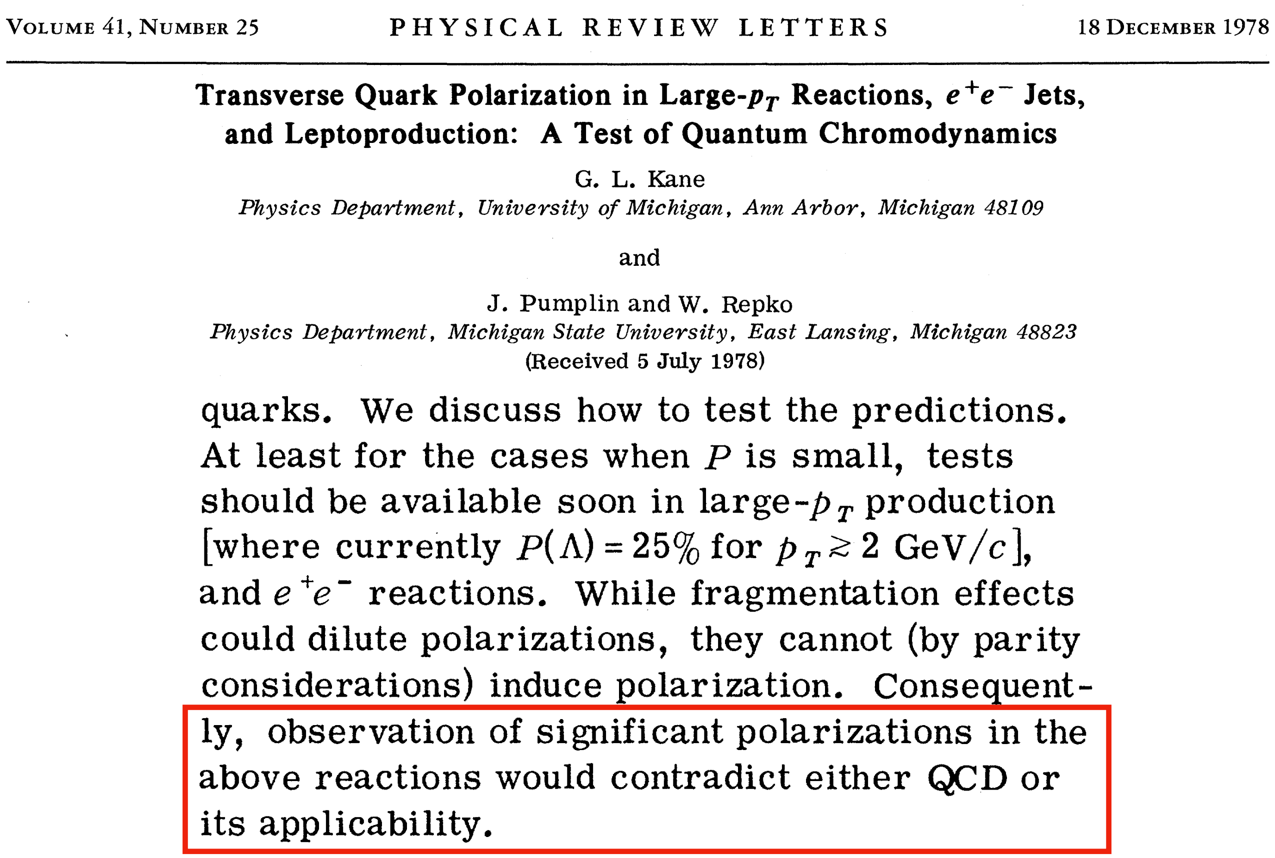
Introduction

One of the most important discoveries in hadron physics over the past decades is the measurements of large spin asymmetries



VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

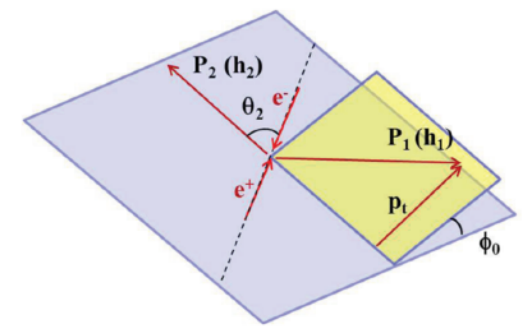
G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

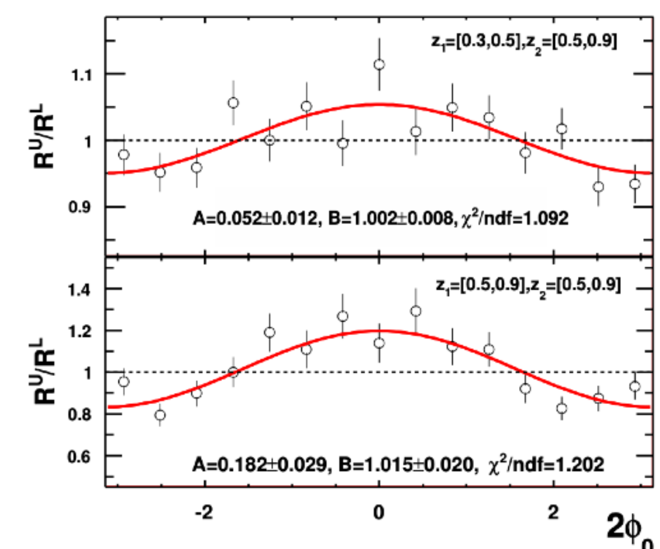
J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

(Received 5 July 1978)

quarks. We discuss how to test the predictions. At least for the cases when P is small, tests should be available soon in large-p_T production [where currently $P(\Lambda) = 25\%$ for $p_T \gtrsim 2$ GeV/c], and e^+e^- reactions. While fragmentation effects could dilute polarizations, they cannot (by parity considerations) induce polarization. Consequently, observation of significant polarizations in the above reactions would contradict either QCD or its applicability.



E.g. Collins asymmetry at BESIII

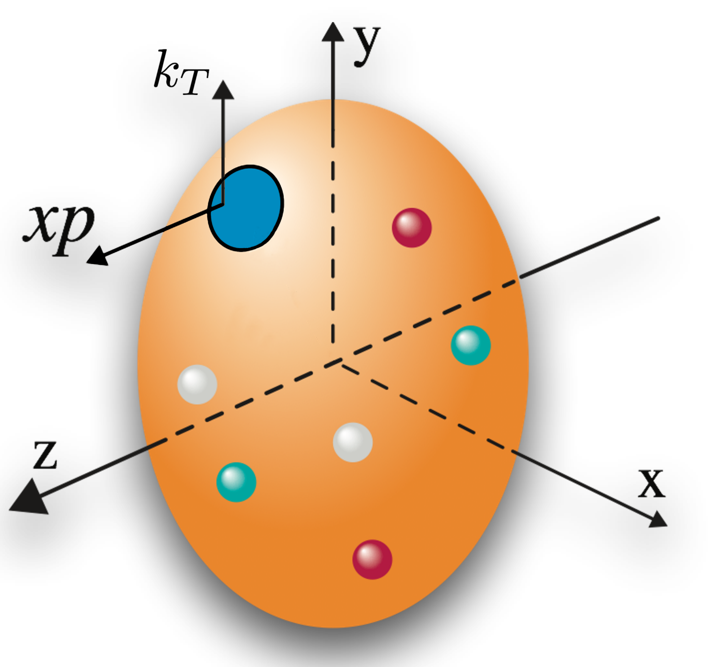


Also see Yixiong Zhou's talk

These experimental measurements can be used to probe the internal structure of hadrons

3D imaging of the hadron in the momentum space

- **Both longitudinal and transverse motion**
- **Large Lorentz boost in longitudinal direction (P_z), but not in transverse momentum (P_x, P_y), mapping out the small P_T is not easy**
- **Correlation between nucleon spin with parton(quark, gluon) orbital angular momentum**



EicC White paper '21

TMDs		Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally polarized (L)	Quark Polarization: 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

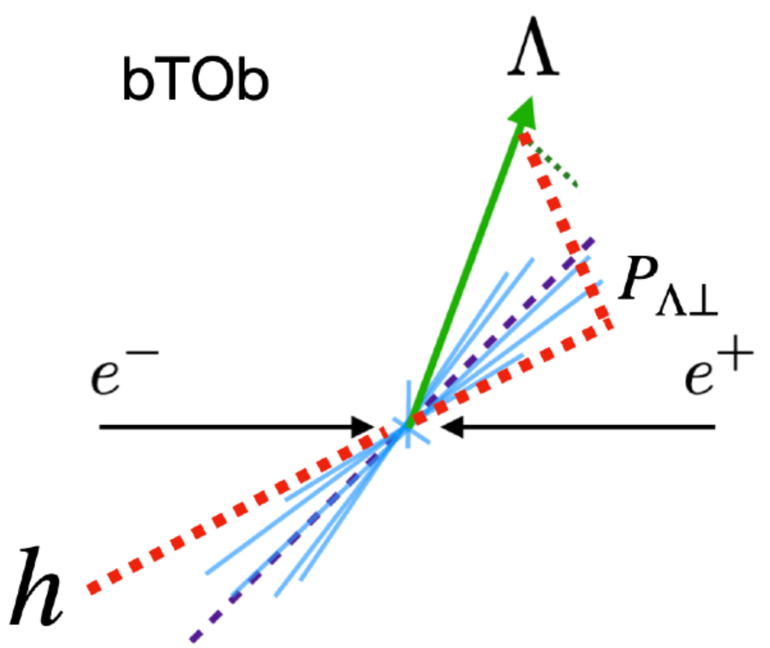
Nucleon spin   Quark spin

Figure 2.5: The leading-twist quark TMD distributions.

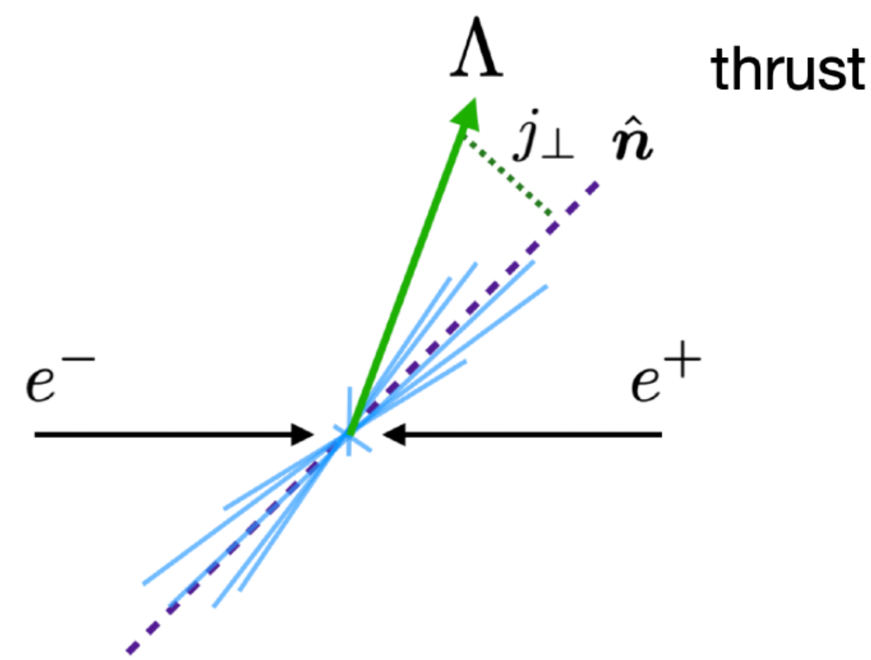
Transverse Λ polarization in electron positron collisions

The cleanest way to access fragmentation functions

$e^+e^- \to \Lambda^\uparrow h\, X$

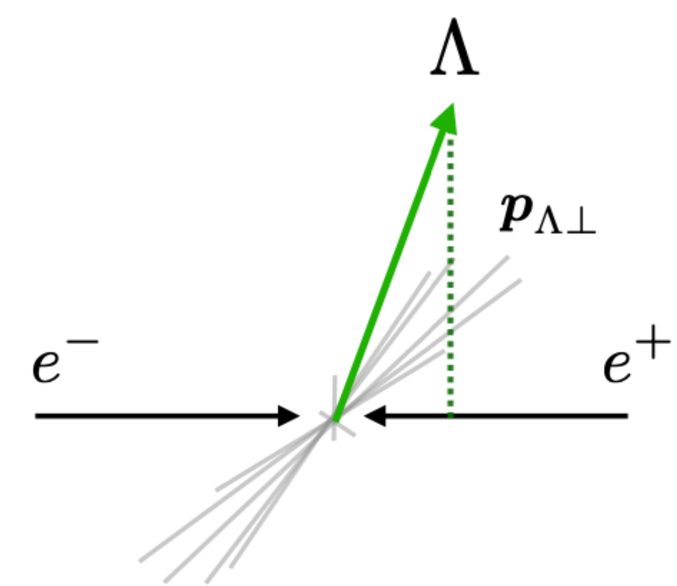


$e^+e^- \to \Lambda^\uparrow(\mathrm{Thrust})\, X$



$$T \equiv \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$$

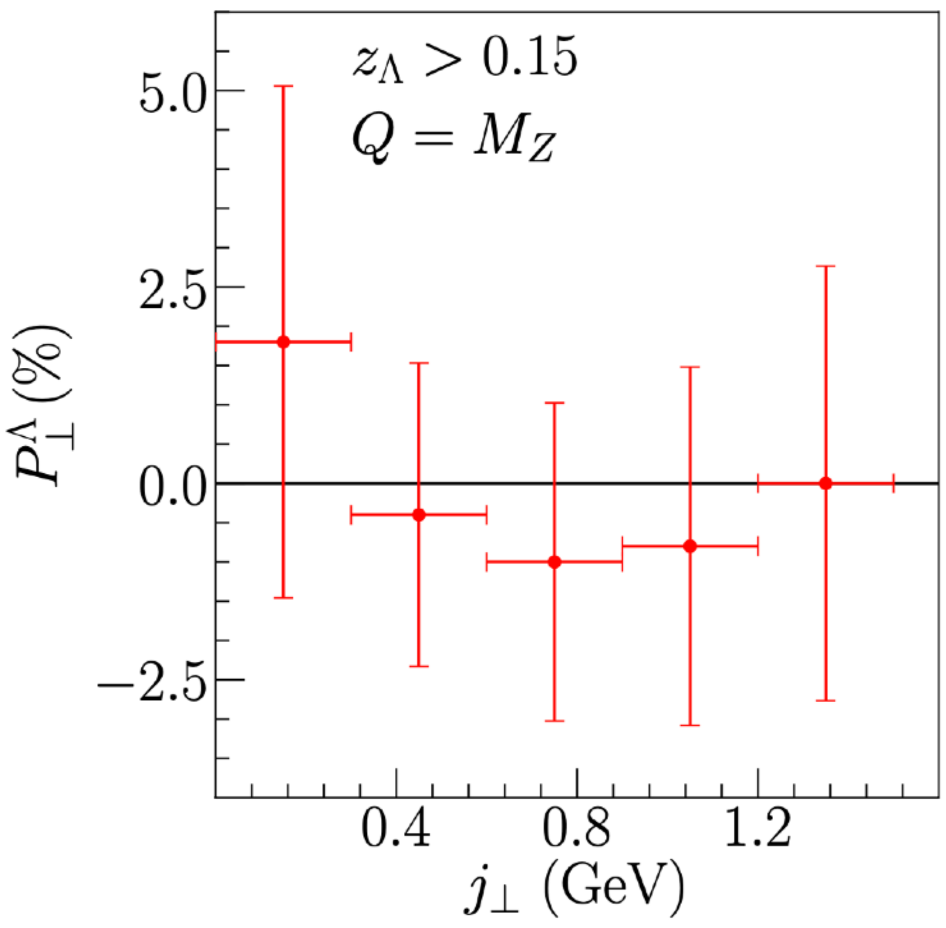
$e^+e^- \to \Lambda^\uparrow X$

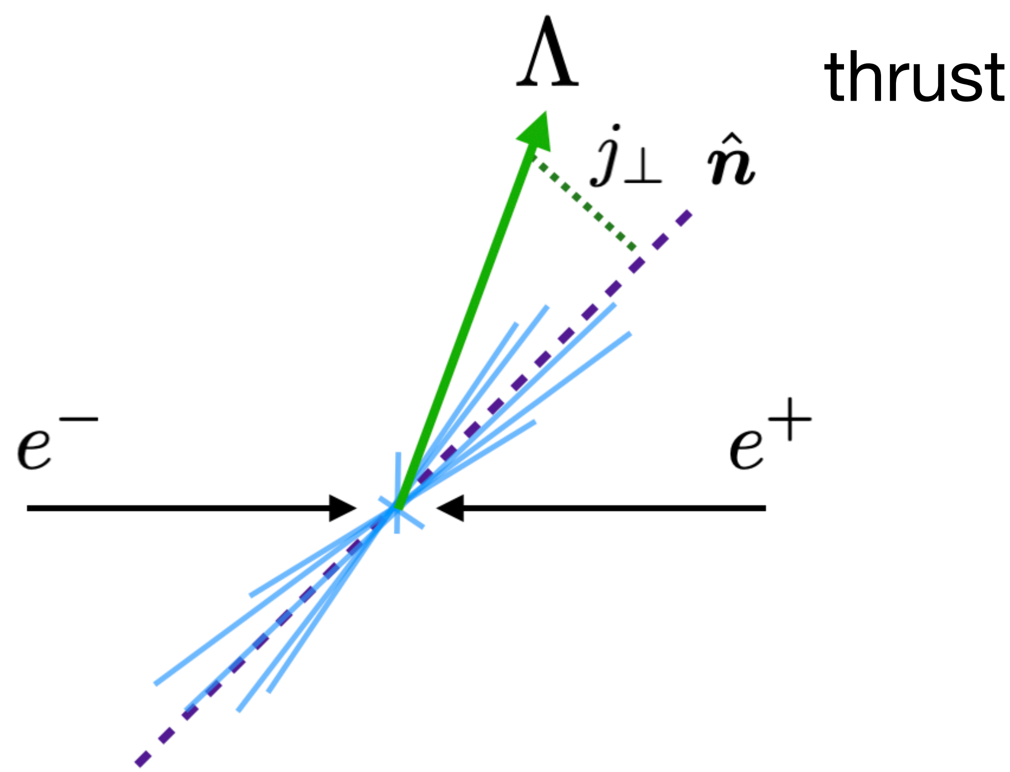


Also see Wenbiao Yan's talk

Transverse Λ polarization at the LEP

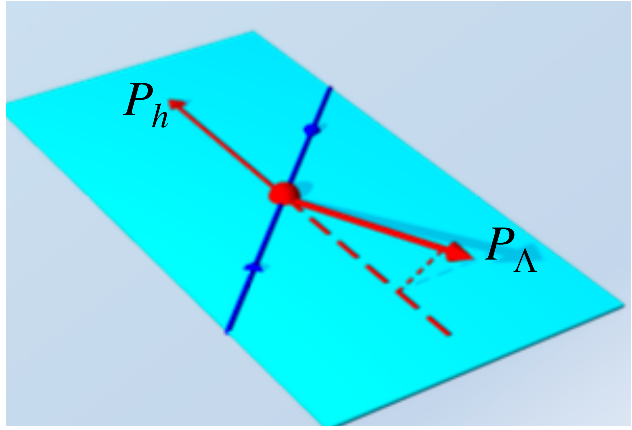
OPAL '97

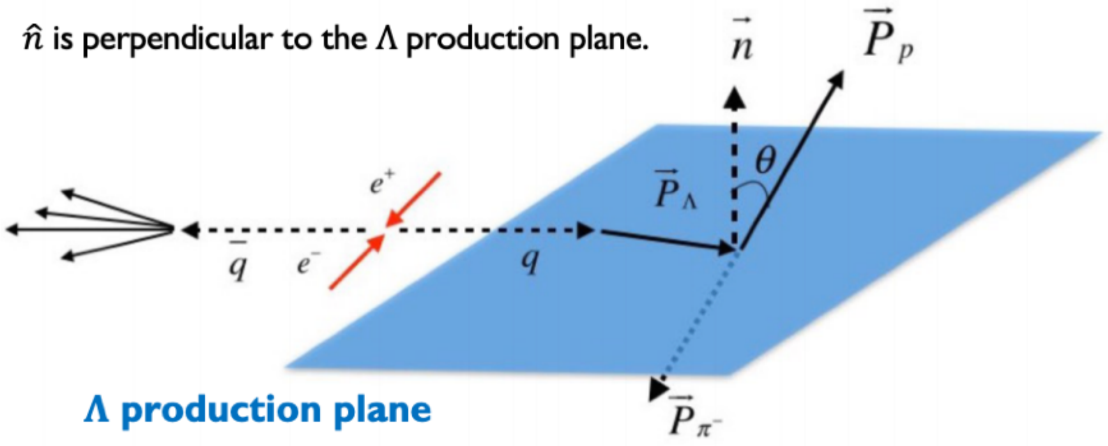




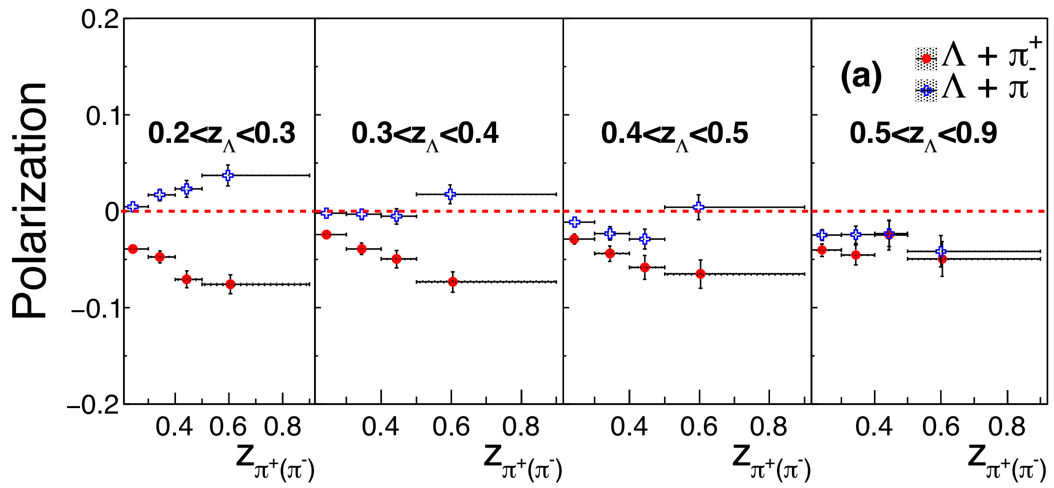
No significant transverse polarization is observed at the LEP

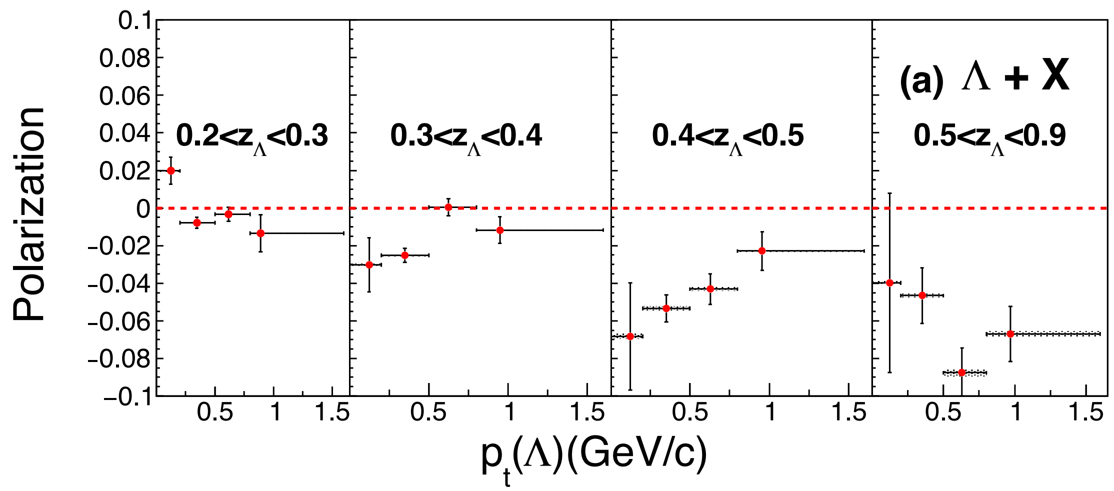
Transverse Λ polarization at the Belle





Belle '18 PRL



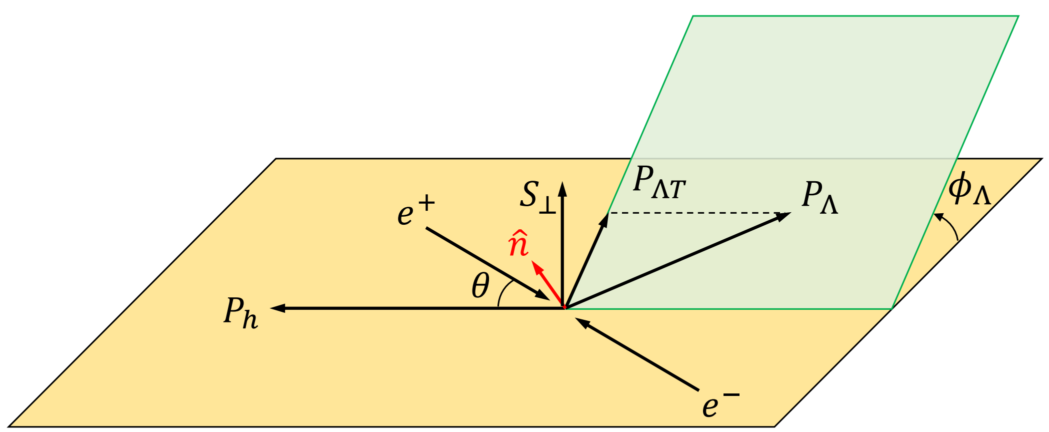


$$e^+e^- \to \Lambda^\uparrow h\, X$$

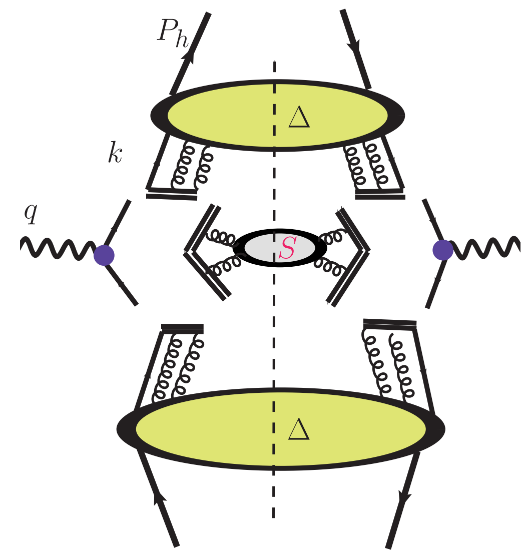
$$e^+e^- \to \Lambda^\uparrow(\text{Thrust})\, X$$

Back-to-back Λ+h

$$e^-(\ell) + e^+(\ell') \to \gamma^*(q) \to h(P_h) + \Lambda(P_\Lambda, \boldsymbol{S}_\perp) + X$$



TMD factorization theorem



$$W^{\mu\nu} \overset{\text{prelim}}{=} \frac{8\pi^3 z_A z_B}{Q^2} \sum_f \mathrm{Tr}\, k^+_{A,\gamma}\gamma^- H^\nu_f(Q)\, k^-_{B,\gamma}\gamma^+ \overline{H}^\mu_f(Q)$$
$$\times \int \frac{\mathrm{d}^{2-2\epsilon}\boldsymbol{b}_\mathrm{T}}{(2\pi)^{2-2\epsilon}} e^{-i\boldsymbol{q}_{h\mathrm{T}}\cdot\boldsymbol{b}_\mathrm{T}}\, \tilde{S}(b_\mathrm{T}) \tilde{D}_{1,\,H_A/f}(z_A, b_\mathrm{T})\, \tilde{D}_{1,\,H_B/\bar{f}}(z_B, b_\mathrm{T})$$
$$+ \text{ polarized terms.}$$

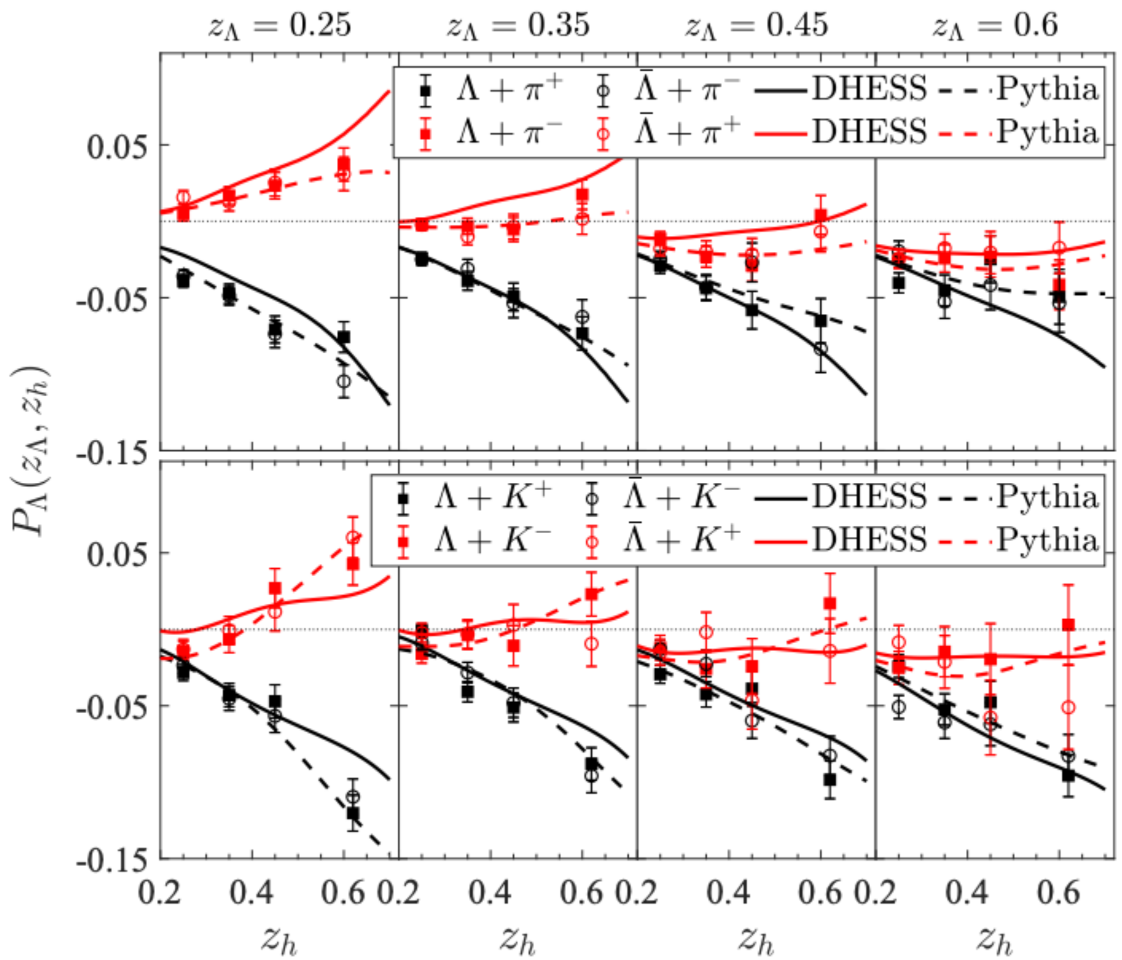
Spin-dependent cross section is factorized as:

$$\frac{d\sigma(\boldsymbol{S}_\perp)}{d\mathcal{PS}d^2\boldsymbol{q}_\perp} = \sigma_0 \left\{ \mathcal{F}\left[D_{\Lambda/q} D_{h/\bar{q}}\right] + |\boldsymbol{S}_\perp| \sin(\phi_S - \phi_\Lambda) \frac{1}{z_\Lambda M_\Lambda} \mathcal{F}\left[\hat{\boldsymbol{P}}_{\Lambda T} \cdot \boldsymbol{p}_{\Lambda\perp} D^\perp_{1T,\Lambda/q} D_{h/\bar{q}}\right] + \cdots \right\}$$

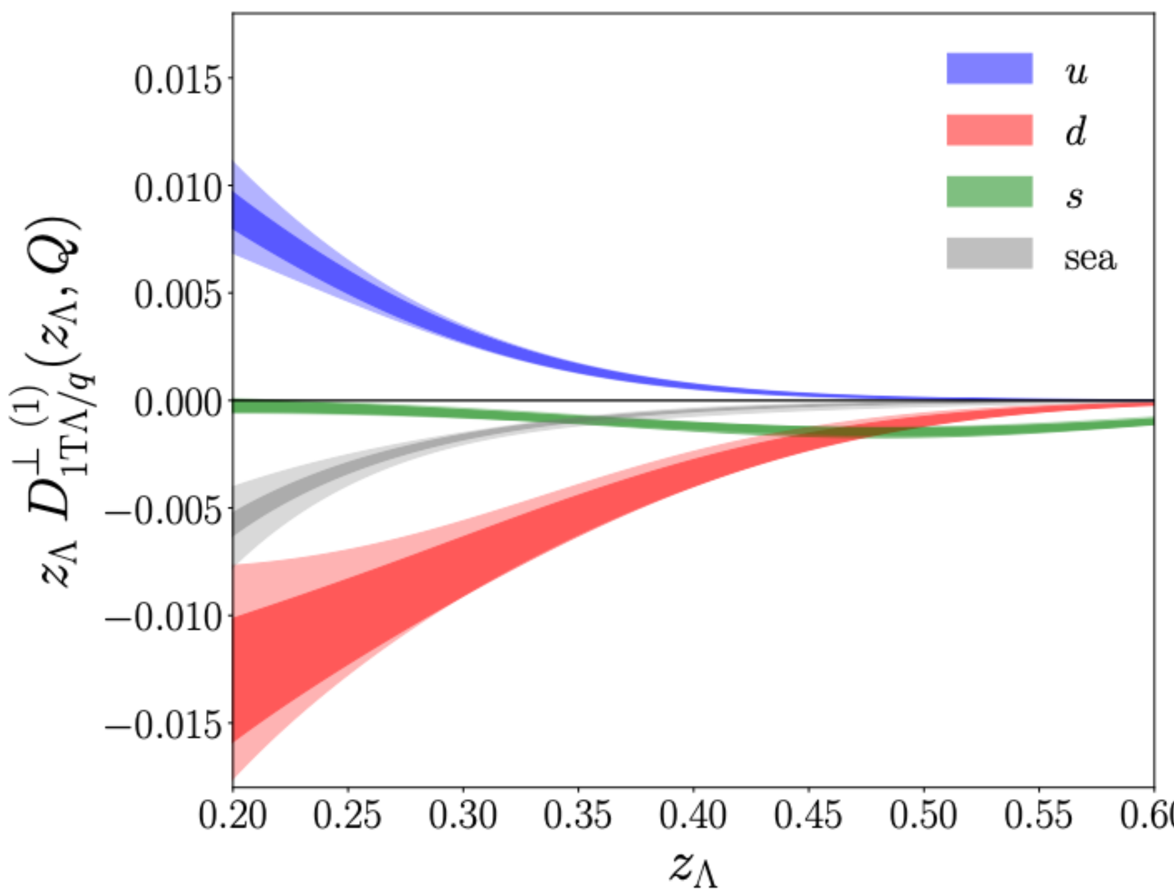
PFFs: Polarizing Fragmentation Functions

Fitting of PFFs from Λ+h data

Chen, Liang, Pan, Song, Wei '21



Kang, Terry, Vossen, Xu, Zhang '21



See also:
D' Alesio, Murgia, Zaccheddu '20
Callos, Kang, Terry '20
… …

Light bands: the uncertainty from the fit to Belle data

Dark bands: the simultaneous fit of the Belle data and the EIC pseudo-data

Theory framework on transverse Λ polarization

$$e^+e^- \to \Lambda^\uparrow h\, X$$

Collins-Soper-Sterman, Ji-Ma-Yuan,
Soft-Collinear Effective Theory… …

$$e^+e^- \to \Lambda^\uparrow(\mathrm{Thrust})\, X$$

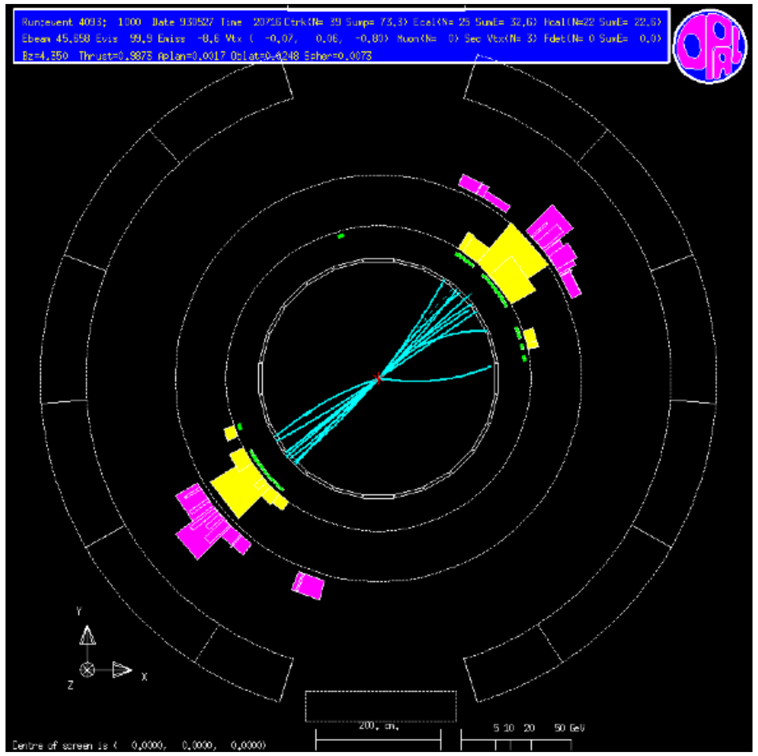
???

TMD factorization two scale problem

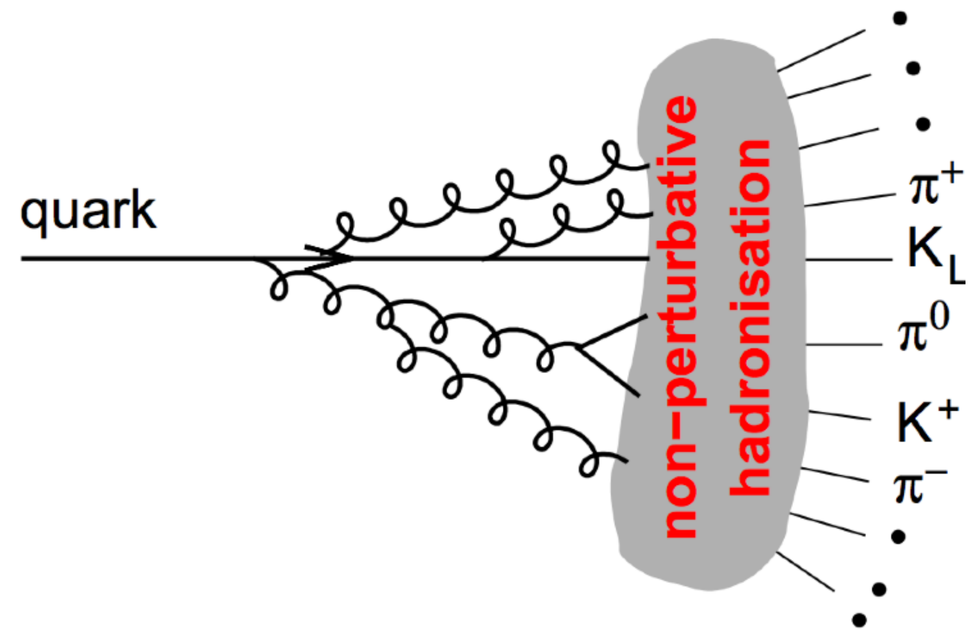
$$\Lambda_{QCD} \lesssim j_\perp \ll Q$$

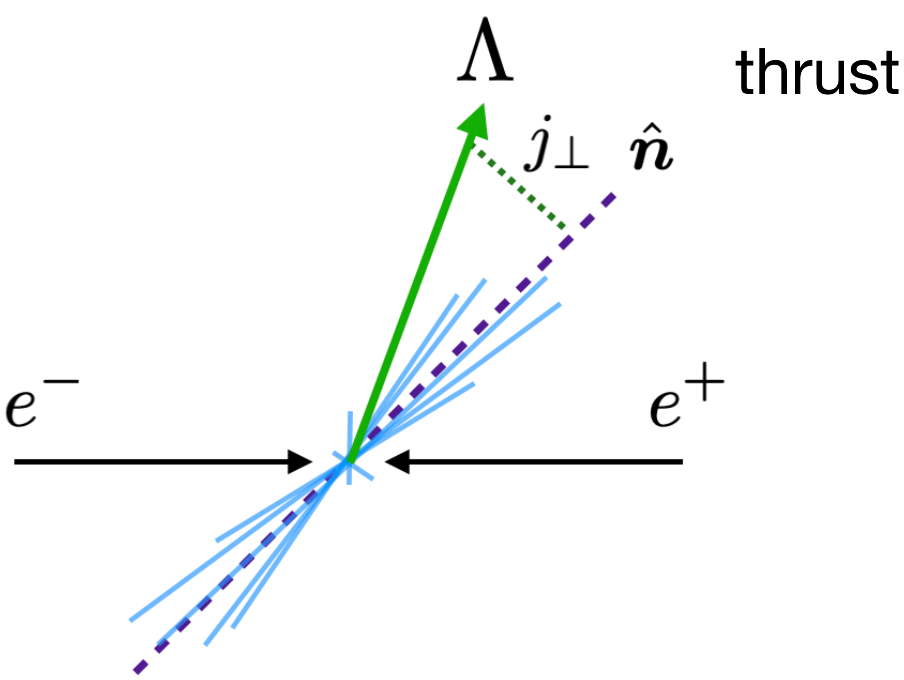
Is it the same (polarizing) fragmentation function in these two measurements ???

TMD factorization for Λ(thrust)



Parton fragmentation and hadronization





From short to long distances in quantum field theory

$$J\,(\text{ scale }\mu_2) \sim J\,(\text{scale}\,\mu_1)\exp\left[\int_{\mu_1}^{\mu_2}\frac{d\mu'}{\mu'}\int dx P\left(x,\alpha_s\left(\mu'\right)\right)\right]$$

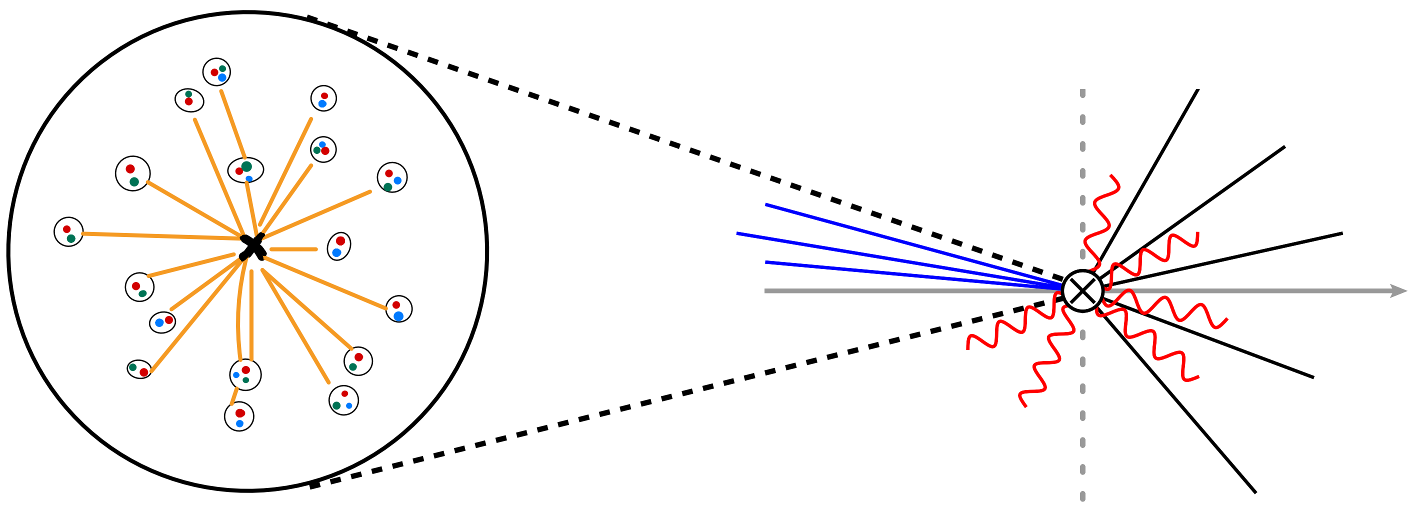
"Jets from Quantum Chromodynamics" Sterman & Weinberg '77

TMD factorization formula on the jet broadening

(Becher, Rahn, DYS '17 JHEP)

Definition of the broadening:

$$b_N = \sum_{i \in \text{jets}} \left| \vec{p}_i^{\perp} \right|$$



Construction of the theory formalism $b_N \ll Q$

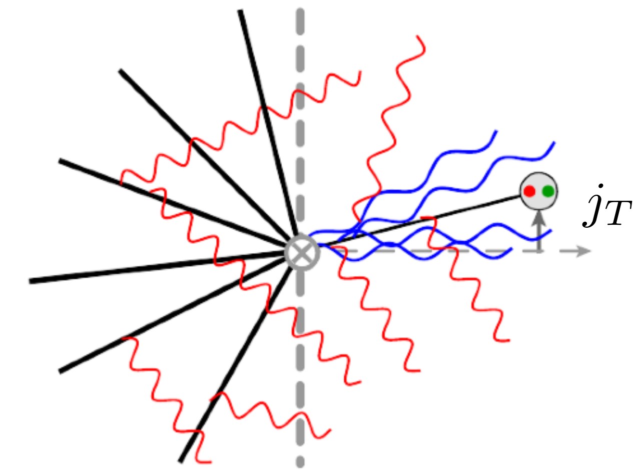
- **Two scales in the problem**
- **Rely on effective field theory: SCET + Jet Effective Theory** (Becher, Neubert, Rothen, DYS '16 PRL)

$$\frac{d\sigma}{db_N} = \sum_{f=q,\bar{q},g} \int db_N^s \int d^{d-2}p_N^{\perp} \mathcal{J}_f\left(b_N - b_N^s, p_N^{\perp}\right) \sum_{m=1}^{\infty} \langle \mathcal{H}_m^f(\{\underline{n}\}, Q) \otimes \mathcal{S}_m\left(\{\underline{n}\}, b_N^s, -p_N^{\perp}\right) \rangle$$

Rapidity divergence cancellation is verified at two-loop order !!!

All-order factorization formula

Kang, DYS, Zhao ’20 JHEP



Non-global observables Dasgupta & Salam ‘01

- **Do not exponentiate in a simple manner**
- **New hard partons acts as new source**
- **Non-linear evolution, BMS eq @ LL** Banfi, Marchesini, Smye ‘02
- **Multi-Wilson-line structure** Becher, Neubert, Rothen, DYS ’16 PRL
- **Super-leading logs resummation at hadron colliders** Becher, Neubert, DYS ’21 PRL

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} = \sum_{i=q,\bar{q},g} \int \frac{d^2\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{j}_T/z_h} \sum_{m=2}^{\infty} \frac{1}{N_c} \mathrm{Tr}_c\left[\boldsymbol{\mathcal{H}}^i_m(\{\underline{n}\},Q,\mu)\otimes\boldsymbol{\mathcal{S}}_m(\{\underline{n}\},b,\mu,\nu)\right] D_{h/i}(z_h,b,\mu,\zeta/\nu^2)$$

Color Trace

Hard scale

Soft scale

# of hard partons not fixed

Integrate the angles for hard partons

Factorization on single hadron unpolarized TMDs

Case-I: $e^-e^+ \to h_1 h_2 + X$

$$\frac{d\sigma}{d^2\boldsymbol{q}_T} \sim H \otimes D_{h_1} \otimes D_{h_2} \otimes S$$

Global observable, standard TMD factorization

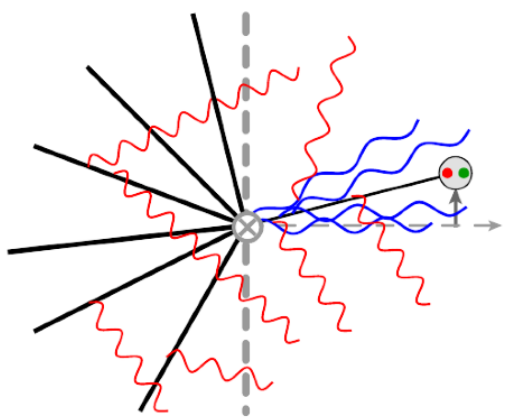
Collins, "*Foundations of perturbative QCD*"

Case-II: $e^-e^+ \to h + X$

$$\frac{d\sigma}{d^2\boldsymbol{q}_T} \sim D_h \otimes \sum_m \mathcal{H}_m \otimes \mathcal{S}_m$$

Non-global observable; new TMD factorization

Kang, DYS, Zhao '20 JHEP



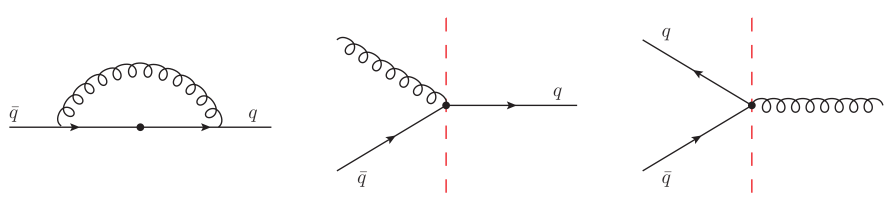
hard: $p_h \sim Q(1,1,1)$

collinear: $p_c \sim Q(\lambda^2,1,\lambda)$

soft: $p_s \sim Q(\lambda,\lambda,\lambda)$

$$\lambda = j_T/Q \ll 1$$

NLO hard function:



Divergences are half of the hard function in case-I

NLO soft function:

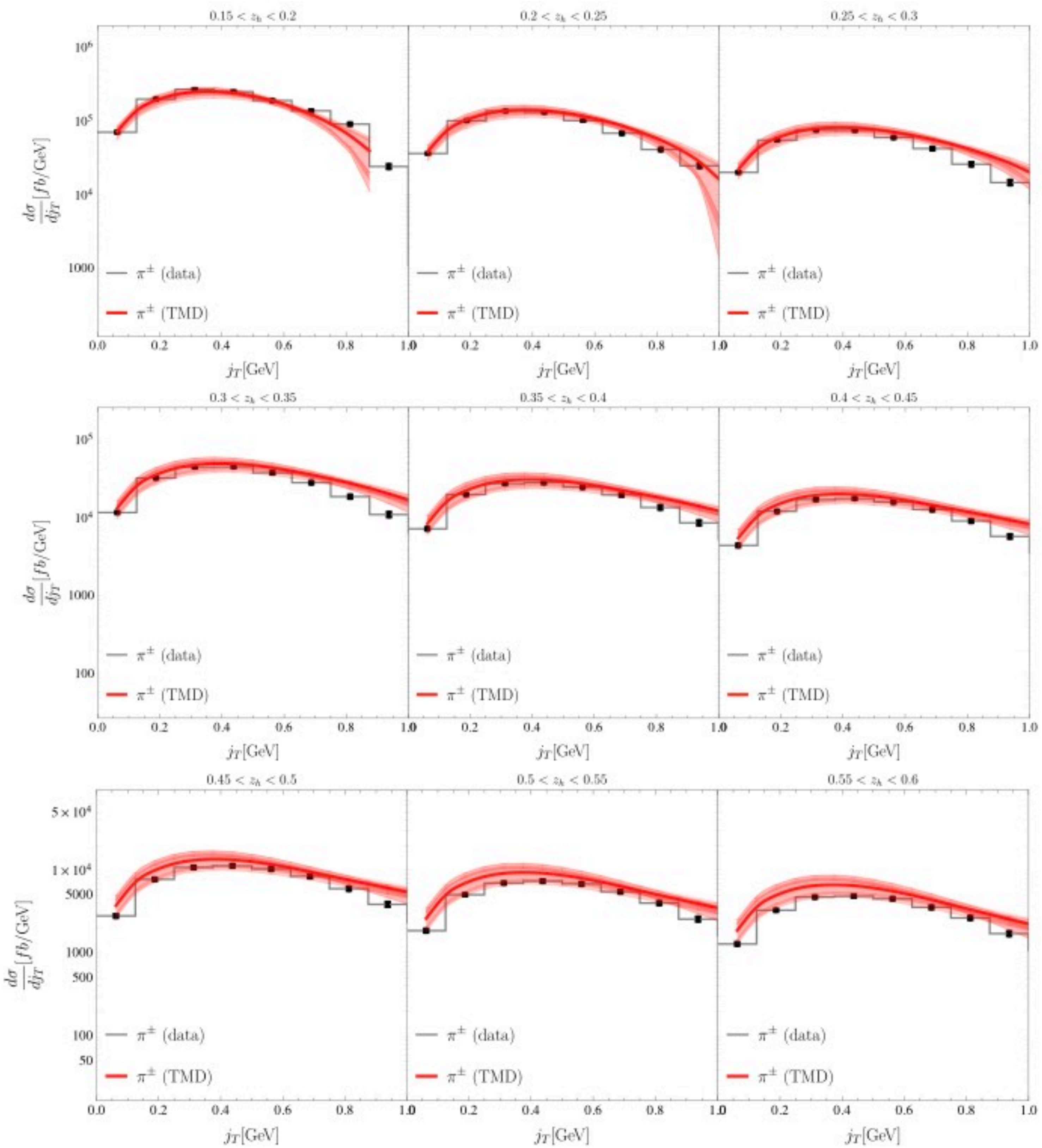
$$\frac{\alpha_s C_F}{2\pi^2}\frac{e^{\epsilon\gamma_E}}{\Gamma(1-\epsilon)}\int\frac{dk^+dk^-}{2}\left(\frac{\mu^2}{\vec{\lambda}_T^2}\right)^{\epsilon}\frac{2n\cdot\bar{n}}{k^+k^-}\delta^+(k^+k^- - \vec{\lambda}_T^2)\left|\frac{\nu}{2k_z}\right|^{\eta}\theta\left(1-\frac{k^+}{k^-}\right)$$

$$= \frac{\alpha_s}{2\pi}C_F\left[\frac{2}{\eta}\left(-\frac{1}{\epsilon}-\ln\left(\frac{\mu^2}{\mu_b^2}\right)\right)+\frac{1}{\epsilon^2}-\frac{1}{\epsilon}\ln\left(\frac{\nu^2}{\mu^2}\right)\right]$$

Divergences are half of the soft function in case-I

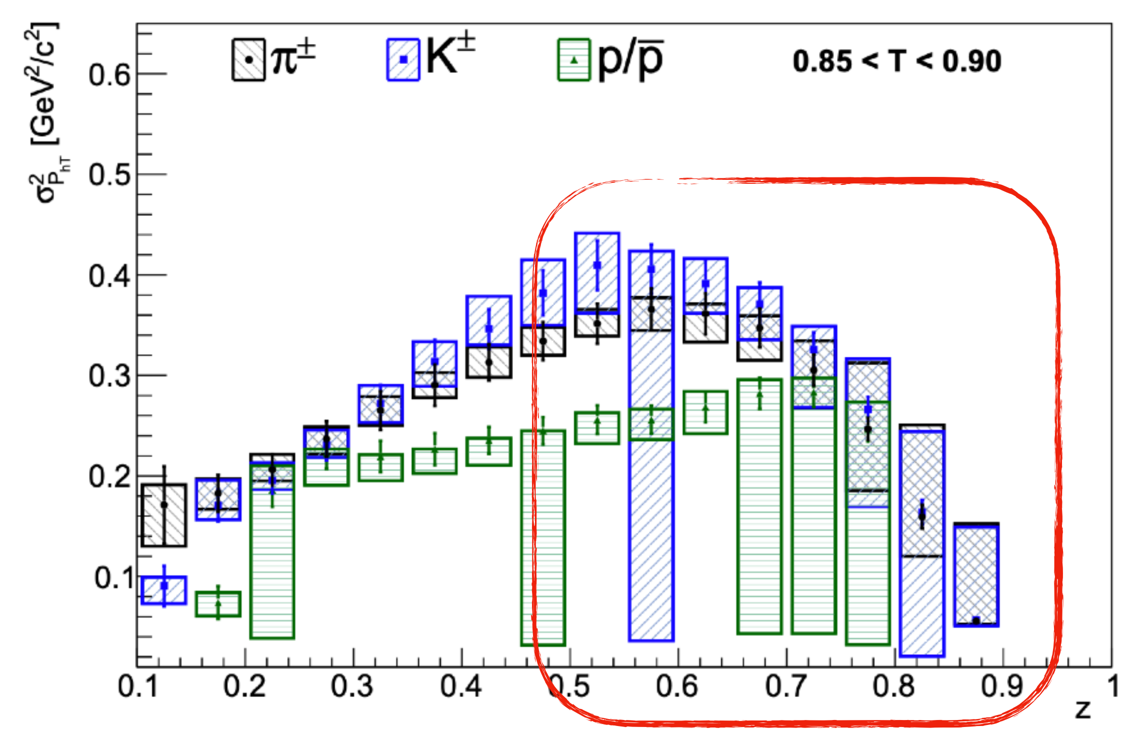
Numerical results

Kang, DYS, Zhao '20 JHEP



- **Our TMD resummation formula gives a good description of the shape of j_T distribution as $z_h < 0.65$**
- **As $z_h > 0.65$, one needs to also include threshold resummation effects**

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} \propto \frac{1}{\pi\sigma^2_{j_T}} \exp\left(-j_T^2/\sigma^2_{j_T}\right)$$



Joint threshold and TMD factorization

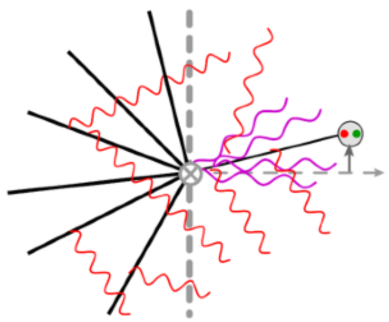
Kang, DYS, Zhao '20 JHEP

Joint factorization: $z_h \to 1$ **&** $j_T \ll Q$

Joint TMD and threshold resummation is first developed in Li '98 & Laenen, Sterman, Vogelsang '01

in the threshold region, a new mode: collinear-soft (c-soft) modes contribute

Li, Neill, Zhu '16 & Lustermans, Waalewijn, Zeune '16

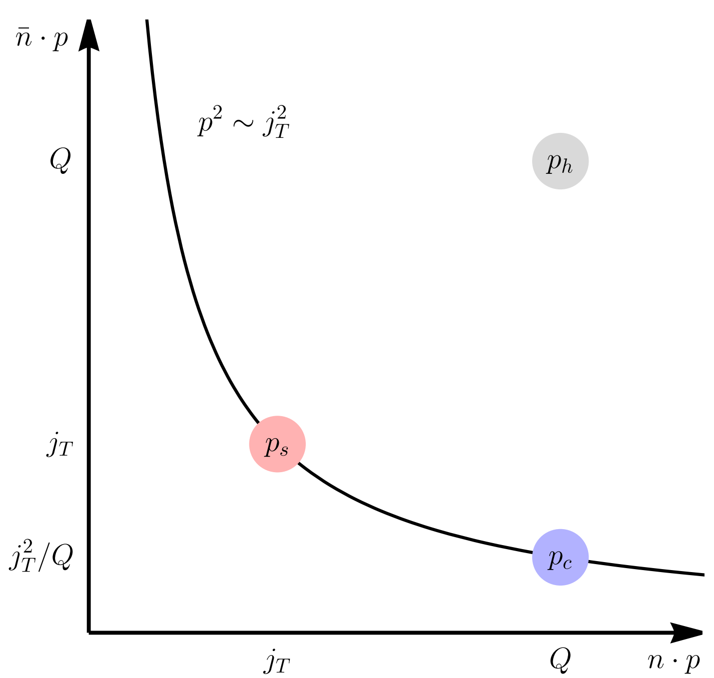


hard: $p_h \sim Q(1,1,1)$

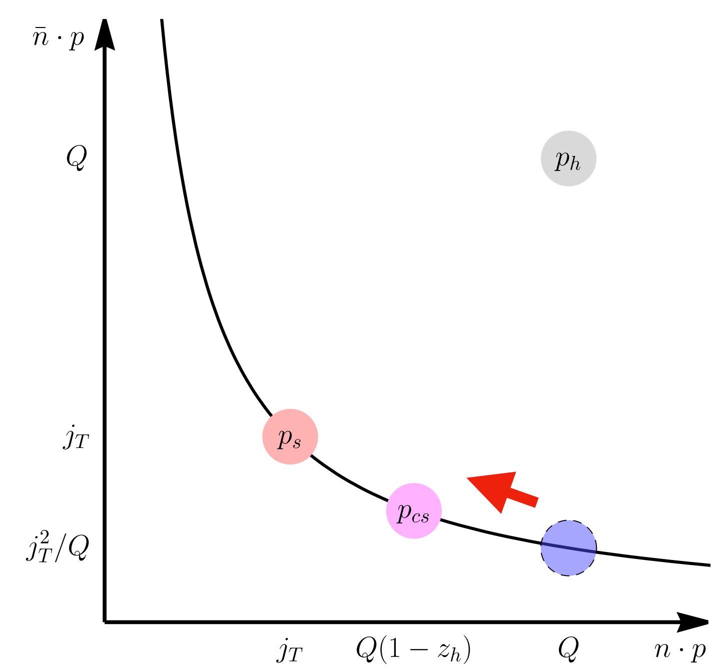
collinear: $p_c \sim Q(\lambda^2, 1, \lambda)$ $\xrightarrow{z_h \to 1}$ **c-soft**: $p_{\mathscr{S}} \sim (j_T^2/(Q(1-z_h)), Q(1-z_h), j_T)$

soft: $p_s \sim Q(\lambda, \lambda, \lambda)$

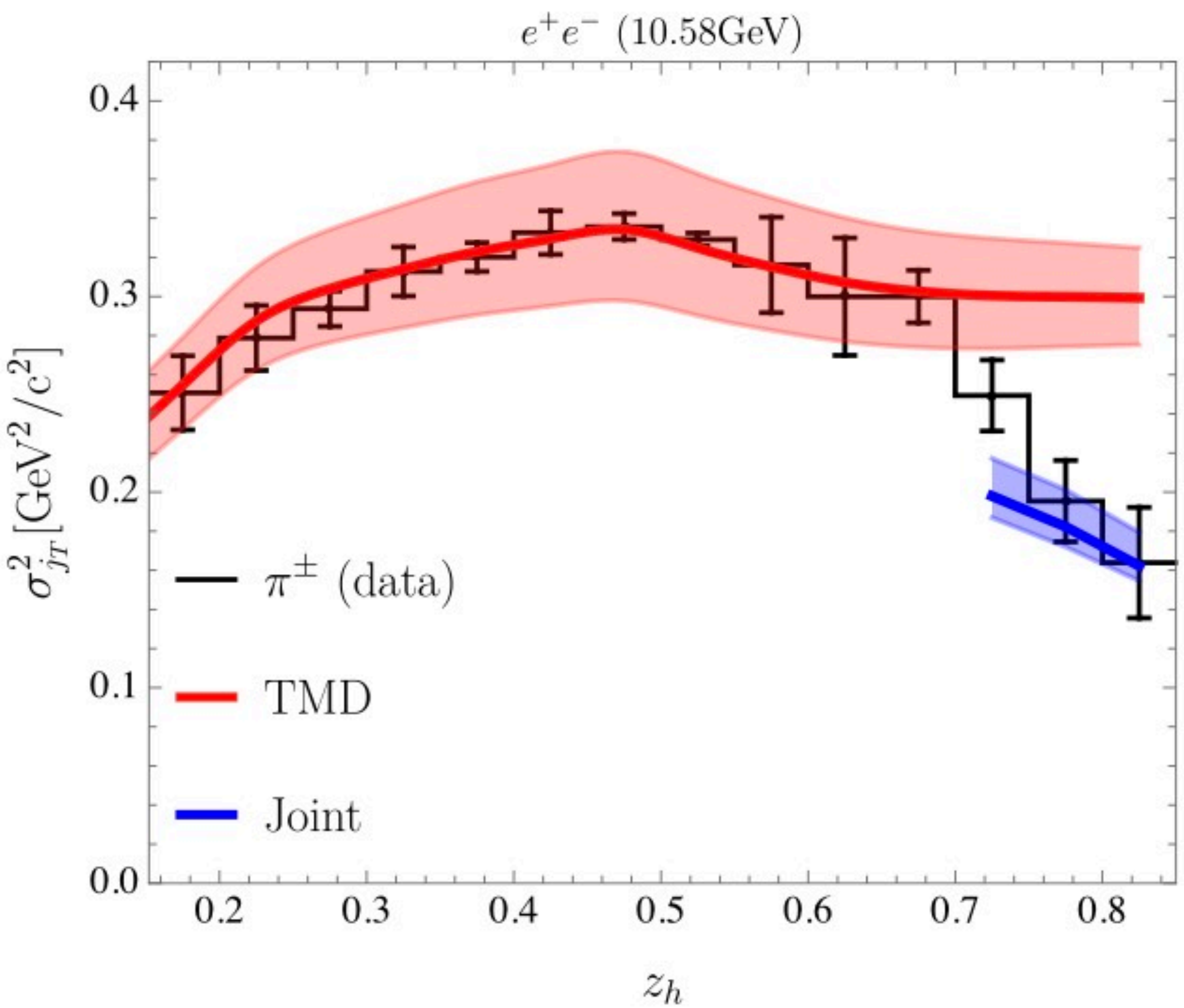
TMD FFs in the threshold limit



$z_h \to 1$



Numerical results

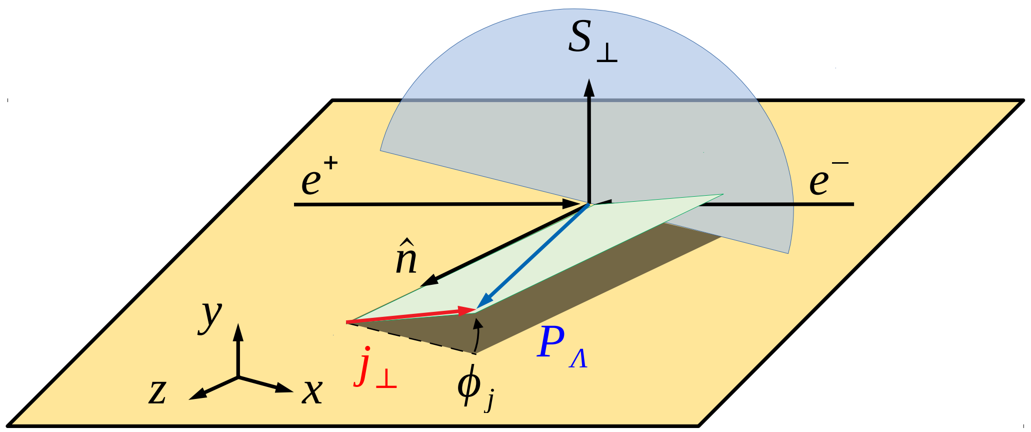


$$\frac{d\sigma}{dz_h d^2\vec{j}_T} \propto \frac{1}{\pi\sigma^2_{j_T}} \exp\left(-j_T^2/\sigma^2_{j_T}\right)$$

- **The Gaussian width of the j_T distribution given by the TMD formalism freeze to a certain value.**
- **After including joint threshold and TMD resummation effects, the theoretical predictions are consistent with the data**

Factorization on transverse polarized Λ hyperon production with the thrust axis

Gamberg, Kang, DYS, Terry, Zhao '21 PLB

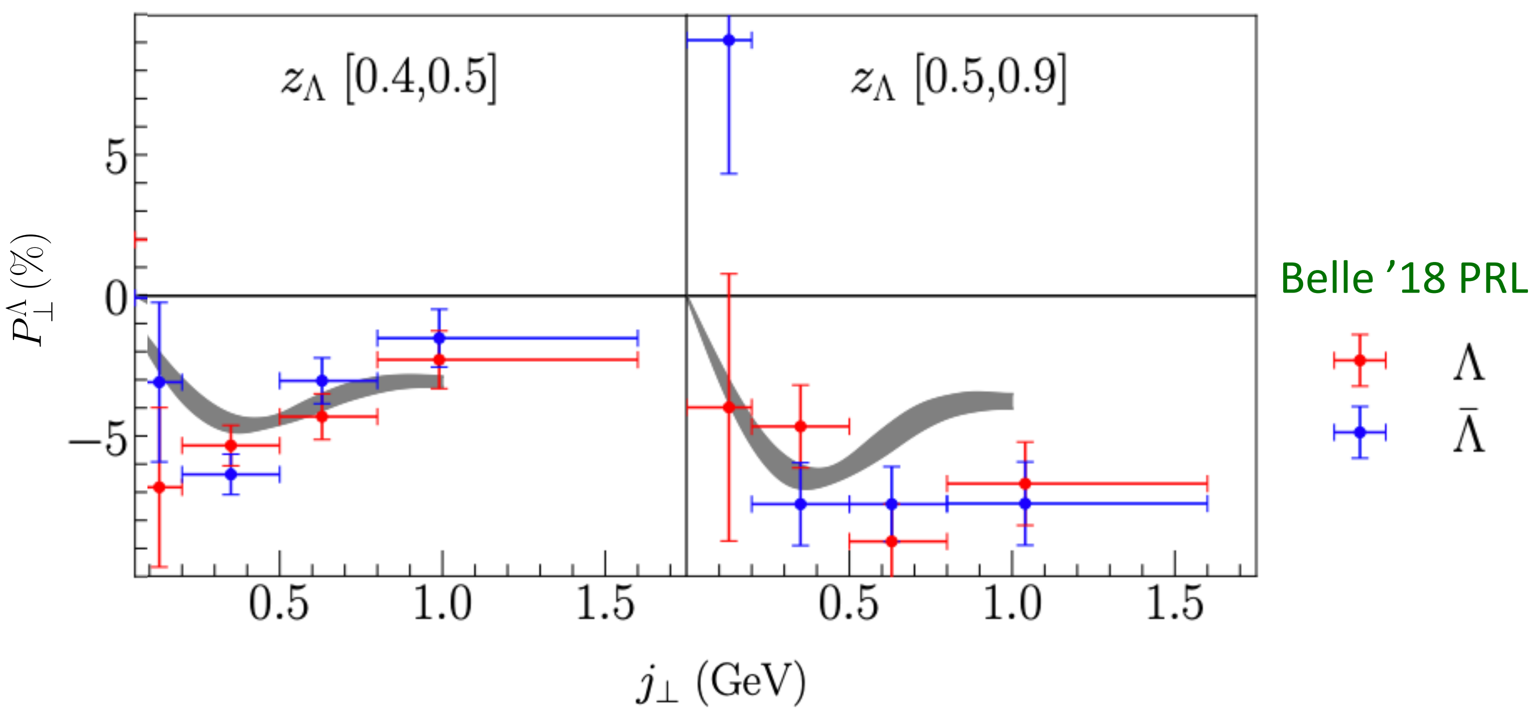


$$P_\perp^\Lambda(z_\Lambda, j_\perp) = \frac{d\Delta\sigma}{dz_\Lambda d^2\boldsymbol{j}_\perp} \Big/ \frac{d\sigma}{dz_\Lambda d^2\boldsymbol{j}_\perp}$$

Theory results are consistent with Belle data

Theory formula including QCD evolution

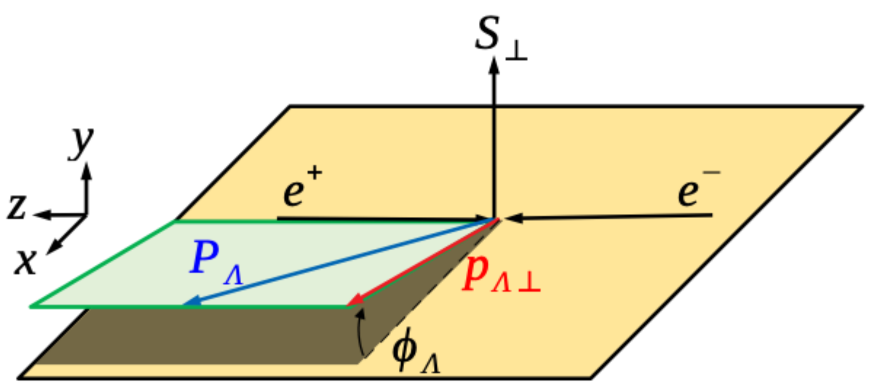
$$\begin{aligned}\frac{d\Delta\sigma}{dz_\Lambda d^2 j_\perp} &= \frac{d\sigma\,(\boldsymbol{S}_\perp)}{dz_\Lambda d^2\boldsymbol{j}_\perp} - \frac{d\sigma\,(-\boldsymbol{S}_\perp)}{dz_\Lambda d^2\boldsymbol{j}_\perp} \\ &= \sigma_0 \sin(\phi_s - \phi_j) \sum_q e_q^2 \int_0^\infty \frac{b^2 db}{2\pi} J_1\left(\frac{b j_\perp}{z_\Lambda}\right) \\ &\times \frac{M_\Lambda}{z_\Lambda^2} D_{1T,\Lambda/q}^{\perp(1)}(z_\Lambda, \mu_{b_*})\, e^{-S_{\rm NP}^\perp(b, z_\Lambda, Q_0', Q) - S_{\rm pert}(\mu_{b_*}, Q)} \\ &\times U_{\rm NG}(\mu_{b_*}, Q)\end{aligned}$$



This result provides proof of principle that the experimental data can be described using the factorization and resummation formalism that we have introduced.

Factorization on transverse polarized Λ hyperon production with the thrust axis

Gamberg, Kang, DYS, Terry, Zhao ’21 PLB



$$P^{\Lambda}_{\rm CM}(z_\Lambda, p_{\Lambda\perp}) = \frac{d\Delta\sigma}{dz_\Lambda\, d^2p_{\Lambda\perp}} \Big/ \frac{d\sigma}{dz_\Lambda\, d^2p_{\Lambda\perp}}$$

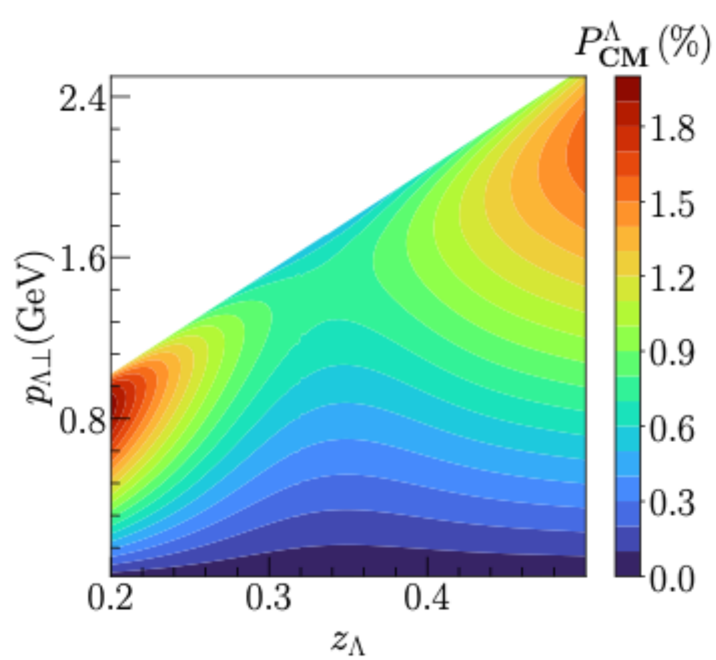
Twist-3 theory formula including QCD evolution

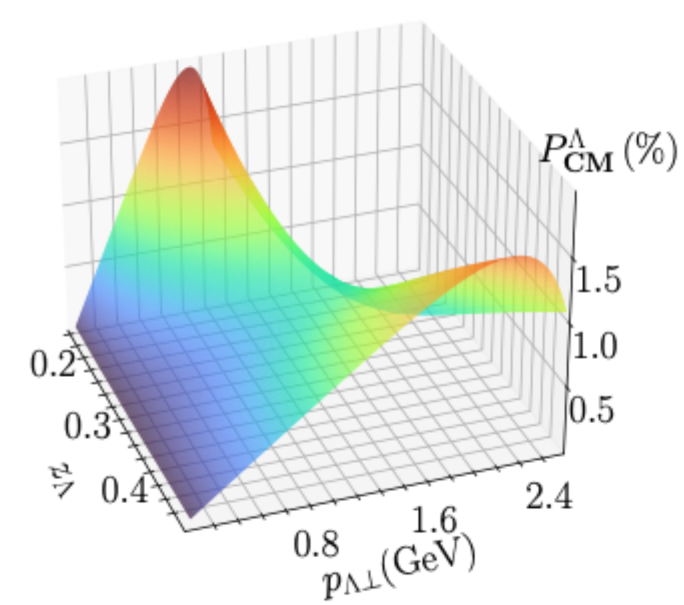
$$\frac{d\Delta\sigma}{dz_\Lambda\, d^2p_{\Lambda\perp}} = -\sin(\phi_s - \phi_\Lambda)\frac{2N_c\alpha_{\rm em}^2}{Q^4 z_\Lambda}\left(\frac{4M_\Lambda}{Q}\right)\frac{p_{\Lambda\perp}}{Q} \times \frac{1}{z_\Lambda^3}\sum_q e_q^2 \frac{D_{T,\Lambda/q}(z_\Lambda, Q)}{z_\Lambda}.$$

$$\frac{1}{z_\Lambda}D_{T,\Lambda/q}(z_\Lambda, Q) = -\left(1 - z_\Lambda\frac{d}{dz_\Lambda}\right)D^{\perp(1)}_{1T,\Lambda/q}(z_\Lambda, Q) - 2\int_0^1 d\beta\,\frac{\Im\left[\hat{D}^{qg}_{FT}(z_\Lambda, Q, \beta)\right]}{(1-\beta)^2}.$$

Also see Zhe Zhang’s talk

Theory predictions



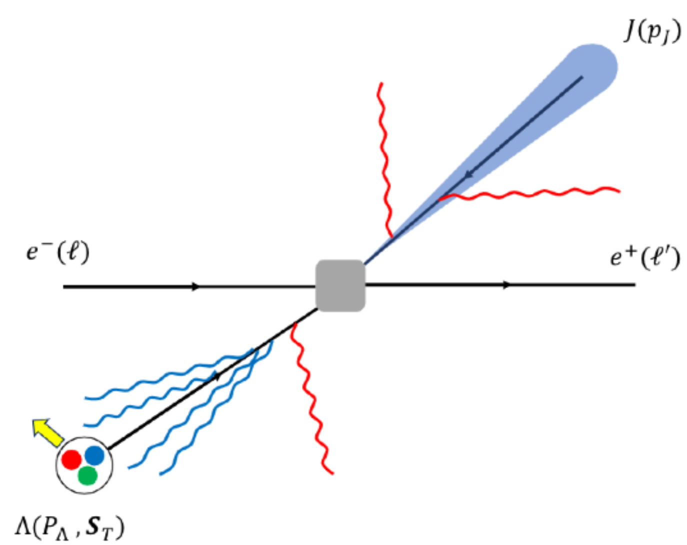


Transverse Lambda polarization and jet charge

(Gamberg, Kang, DYS, Terry, Zhao in progress)

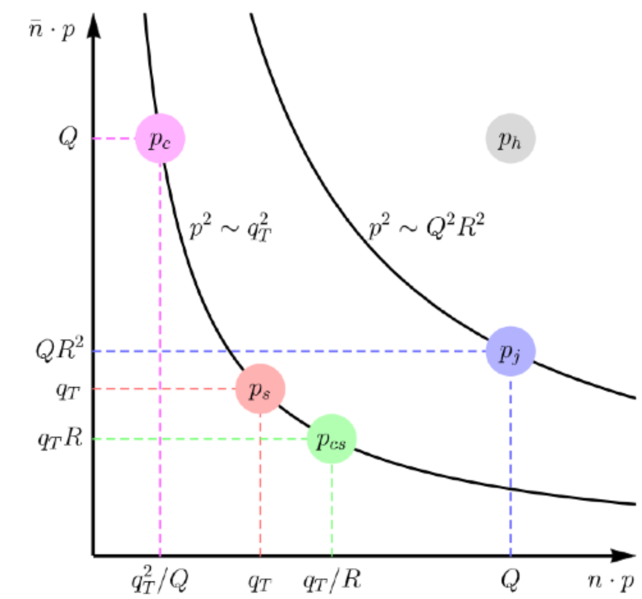
As shown in (Kang, Liu, Mantry, DYS '20 PRL)**, the jet charge observable is a novel probe of flavor structure for the hadron spin**

$$e^-(\ell) + e^+(\ell') \to J(p_J) + \Lambda(P_\Lambda, \boldsymbol{S}_T) + X$$



Dynamic modes:

- hard: $p_h \sim Q(1,1,1)$,
- soft: $p_s \sim q_T(1,1,1)$,
- collinear: $p_c \sim (q_T^2/Q, Q, q_T)$,
- jet: $p_j \sim Q(1, R^2, R)$,
- collinear-soft: $p_{cs} \sim q_T/R(1, R^2, R)$,

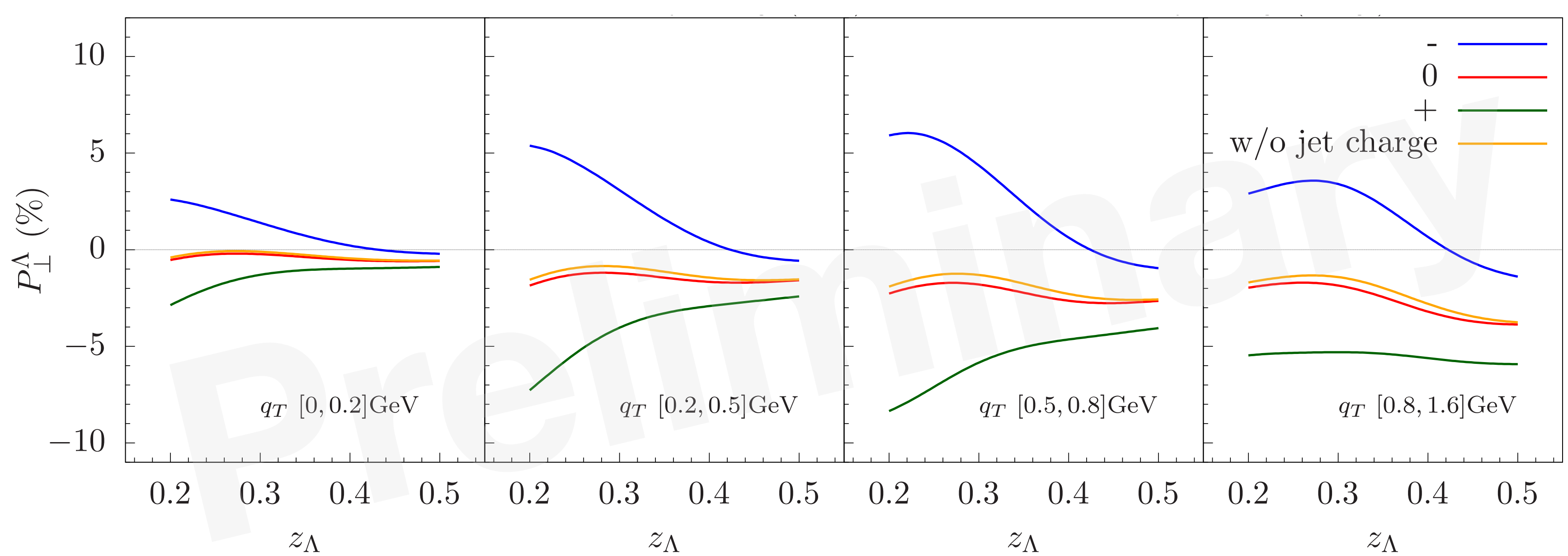


Jet charge definition: $Q_\kappa = \sum_i \left(\frac{p_{i,T}}{p_J}\right)^\kappa Q_i$

Charge tagged jet function:

$$\mathcal{G}_i(Q_\kappa, p_T R, \mu)$$

Polarization w/ jet charge

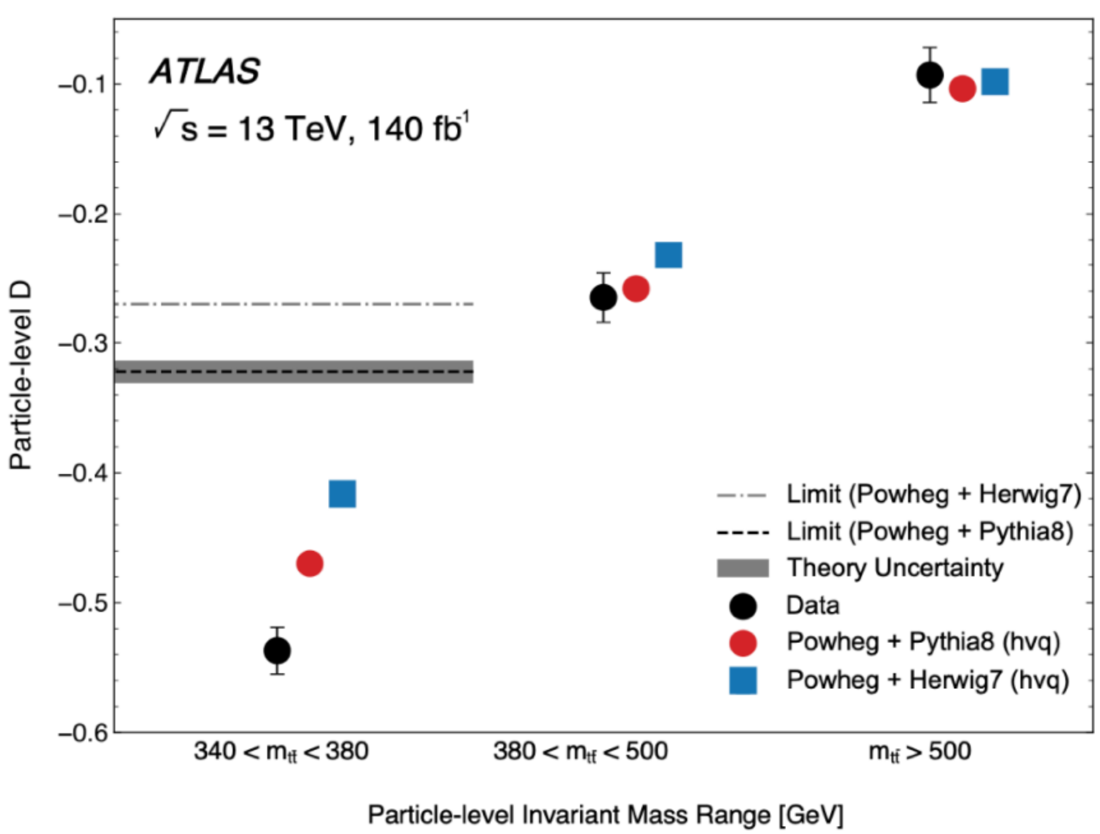


Quantum information science meets High energy physics

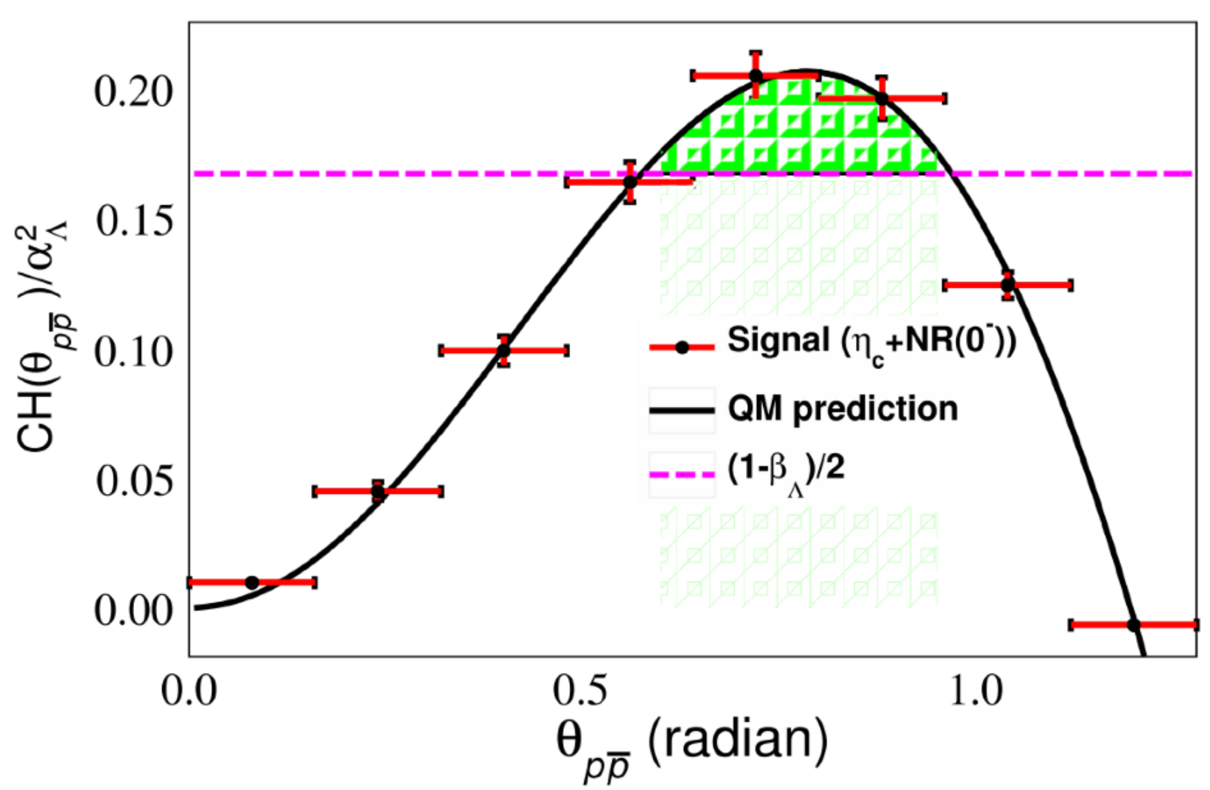
- **QIS 4 HEP**
  - **New experimental probes and fundamental tests**
  - **Enhanced simulations of quantum systems**
- **HEP 4 QIS**
  - **A novel testbed for fundamental QIS concepts in extreme regimes**

"Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics"

— A recent review 2504.00086



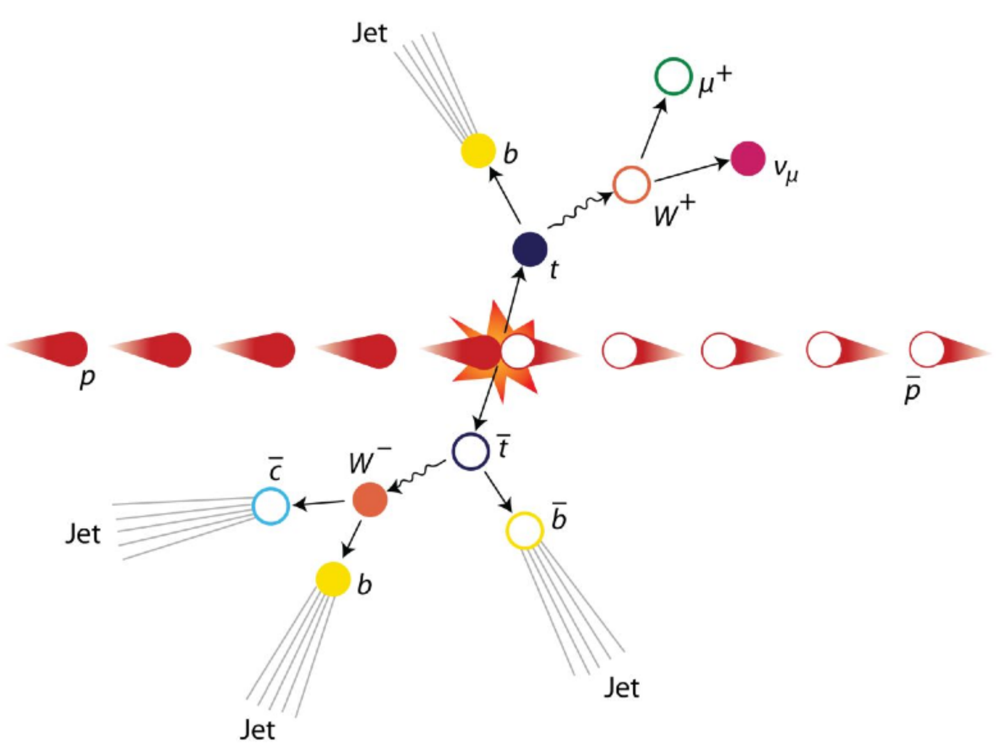
ATLAS Nature 2024

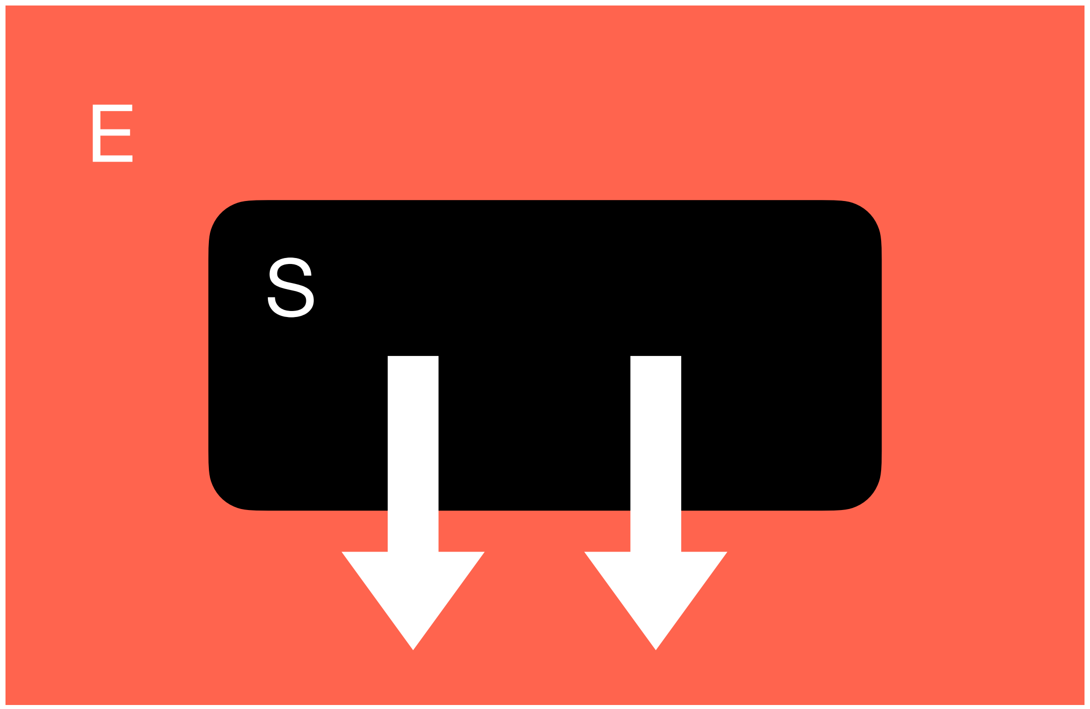


BESIII Nature Communications 2025

Decoherence in entangled fermion pairs

- In the above measurements at the LHC, entangled top quark pairs can not be treated as a closed system
- Top quarks may radiate gluons or photons in the short period of time before decaying, leading to a reduction in quantum spin information, i.e., decoherence.
- Decoherence can be studied by recognizing that realistic quantum systems are always embedded in some environment.
- This interaction with the system results in 'leakage of information' to the environment, decreasing the entanglement between the components of the system.





Some decoherence effects

- **“Infrared quantum information” Soft radiation decrease momentum entanglement** (Carney, Chaurette, Neuenfeld, Semenof ‘17)
- **K0 K0bar system** (Bertlmann ‘04) **Λ Λbar system** (Wu, Qian, Yang, Wang ‘24)
- **Inflation and effective field theory** (Burgess, Colas , Holman, Kaplanek ’25)
- **Black hole horizons decohere superpositions** (Biggs, Maldacena ’24)

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Open Quantum Systems: Dissipative Dynamics from Quarks to the Cosmos

December 1, 2025 - December 12, 2025

ORGANIZERS

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The application deadline for this event has passed.

Concurrence at LO (closed system)

- **We consider** $e^+e^- \to \tau^+\tau^-$
- **The spin state of a τ-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**

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

- **To probe entanglement, one can calculate the concurrence *C***

$$\mathcal{C}[\rho_{\rm LO}] = \frac{\sin^2\theta}{1+\cos^2\theta}$$

- **Maximum entanglement *cosϑ* = 0**

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

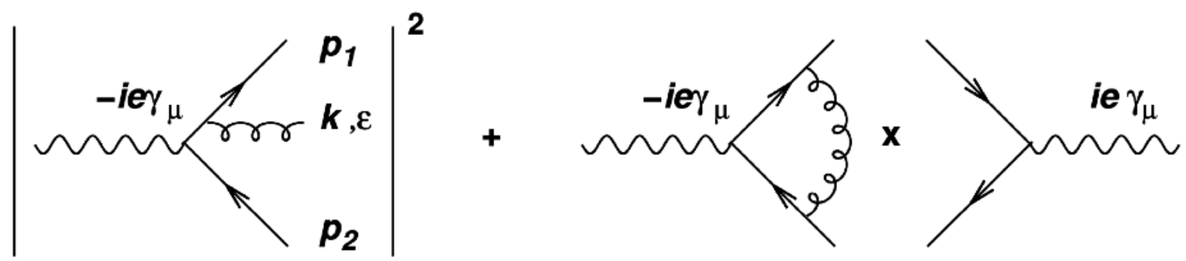
Quantum maps for open systems

Aoude, Barr, Maltoni, Satrioni ‘25

- **The evolution of an open system can represented by a quantum map**

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

Kraus operators



- **The virtual corrections lead to the same final state Hilbert space while the real emission leads to the extra Hilbert space of the environment.**
- **To obtain the reduced density matrix, we need to trace over the emitted radiation**

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

$$\bar{\mathcal{E}}_{\rm V}[\rho_{\rm LO}] = \mathsf{p}_{\rm V}\mathbb{1}\rho_{\rm LO}\mathbb{1}$$

$$\bar{\mathcal{E}}_{\rm R}[\rho_{\rm LO}] = \sum_j K_j \rho_{\rm LO} K_j^\dagger$$

Virtual: does not change LO structure (massless)

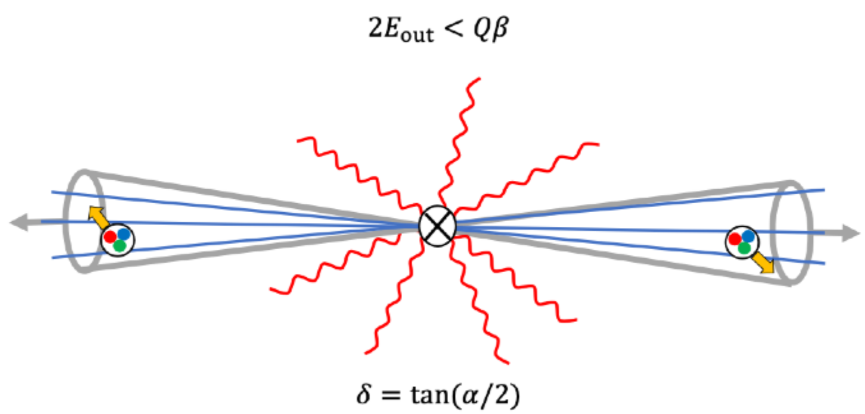
Real: ~~hard~~, collinear, ~~soft~~

Effective field theory for decoherence

J.Y. Gu, S.J. Lin (林士佳), DYS, L.T. Wang, S.X. Yang (杨斯翔) 2508.XXXXX

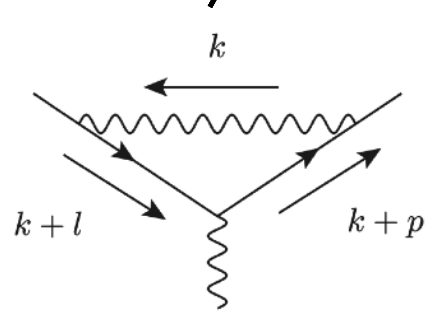
- **Radiation should be considered unresolvable if either soft of collinear**
- **We introduce the energy and angular resolution parameters, which is similar to Sterman-Weinberg cone jet definition** (Sterman, Weinberg ’77)

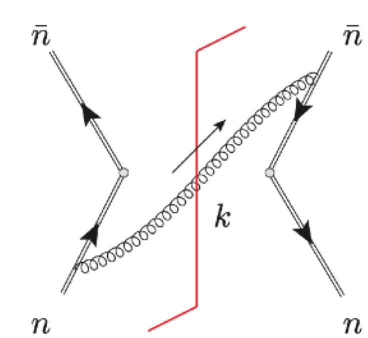
Two fermion events:



- **We apply soft collinear effective theory (SCET) + Jet Effective Theory (JET)** (Becher, Neubert, Rothen, DYS ’16 PRL)
- **The production matrix**

$$\hat{R} = H(Q,\mu) S(Q\beta,\delta,\mu) \hat{J}_f(Q\delta,\lambda,\mu) \hat{R}_{\rm LO} \hat{J}_{\bar{f}}(Q\delta,\lambda,\mu),$$





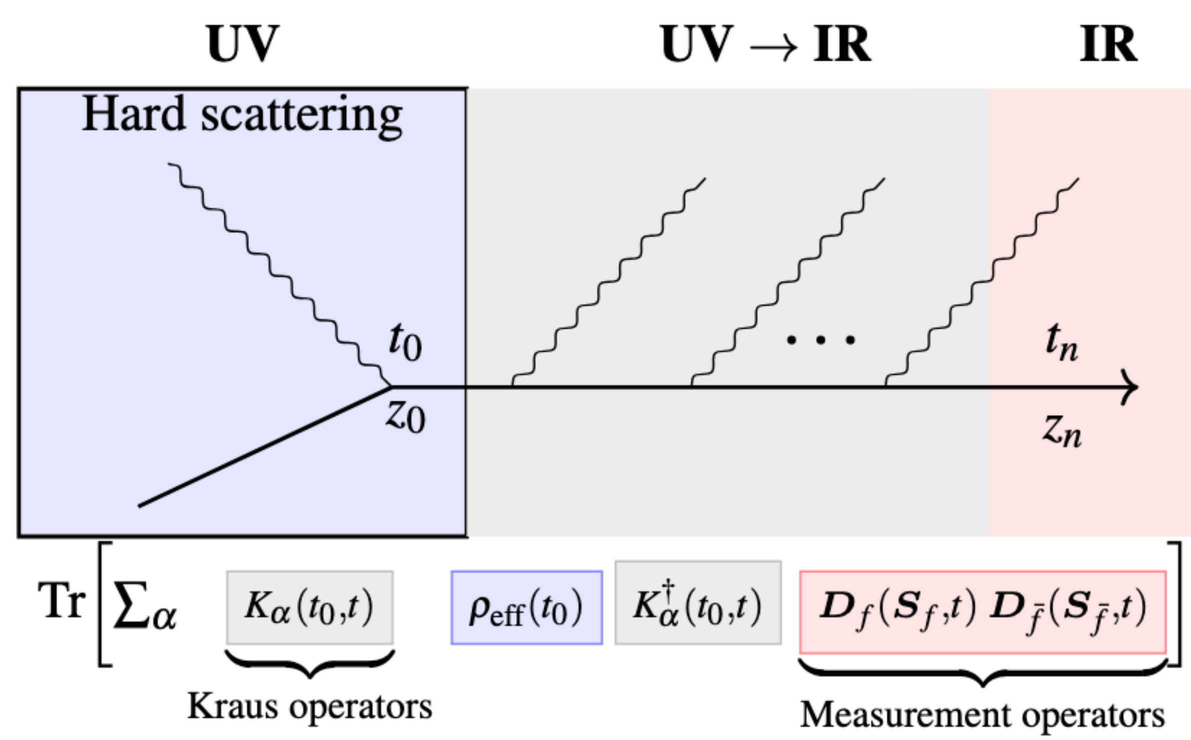
Fragmenting density matrix and measurement operator

J.Y. Gu, S.J. Lin (林士佳), DYS, L.T. Wang, S.X. Yang (杨斯翔) 2508.XXXXX

- **Fragmenting density matrix**

$$\hat{J}_f = \mathcal{J}_f^U\, \hat{I}\otimes\hat{I} + \mathcal{J}_f^L \hat{\sigma}_z\otimes\hat{\sigma}_z + \mathcal{J}_f^T (\hat{\sigma}_x\otimes\hat{\sigma}_x + \hat{\sigma}_y\otimes\hat{\sigma}_y)$$

  - **J^U : unpolarized FFs**
  - **J^L : longitudinal polarized-FFs**
  - **J^T : transverse polarized-FFs**



- **The Kraus operators in QED**

$$\hat{K}_{(i,j)} = \hat{K}_i^{\ell^-} \otimes \hat{K}_j^{\ell^+}$$

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

$$\hat{K}_1^{\ell^-} = \hat{K}_1^{\ell^+} = p\,\hat{\sigma}_3\,, \quad p = \sqrt{\frac{1}{2}\left[1-\exp\left(-\frac{\alpha}{2\pi}t\right)\right]}$$

Concurrence in QED

$$C(\rho) = \max\left\{0, \frac{\sin^2\theta}{1+\cos^2\theta}\left(\frac{Q\delta}{m}\right)^{-\frac{\alpha}{\pi}}\right\}$$

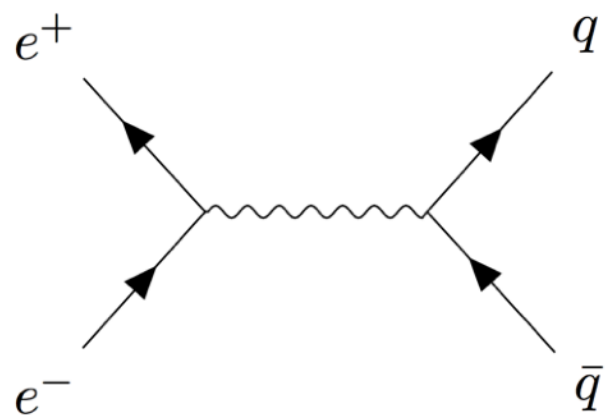
- **Lindblad operators in QED**

$$\mathcal{L}_t(\rho_{\mathrm{eff}}) = -\frac{\alpha}{2\pi}\rho_{\mathrm{eff}} + \frac{\alpha}{4\pi}\left[(\mathbb{I}\otimes\hat{\sigma}_3)\rho_{\mathrm{eff}}(\mathbb{I}\otimes\hat{\sigma}_3) + (\hat{\sigma}_3\otimes\mathbb{I})\rho_{\mathrm{eff}}(\hat{\sigma}_3\otimes\mathbb{I})\right]$$

phase-flip decoherence channe

Spin correlation in Λ pair production with a thrust cut

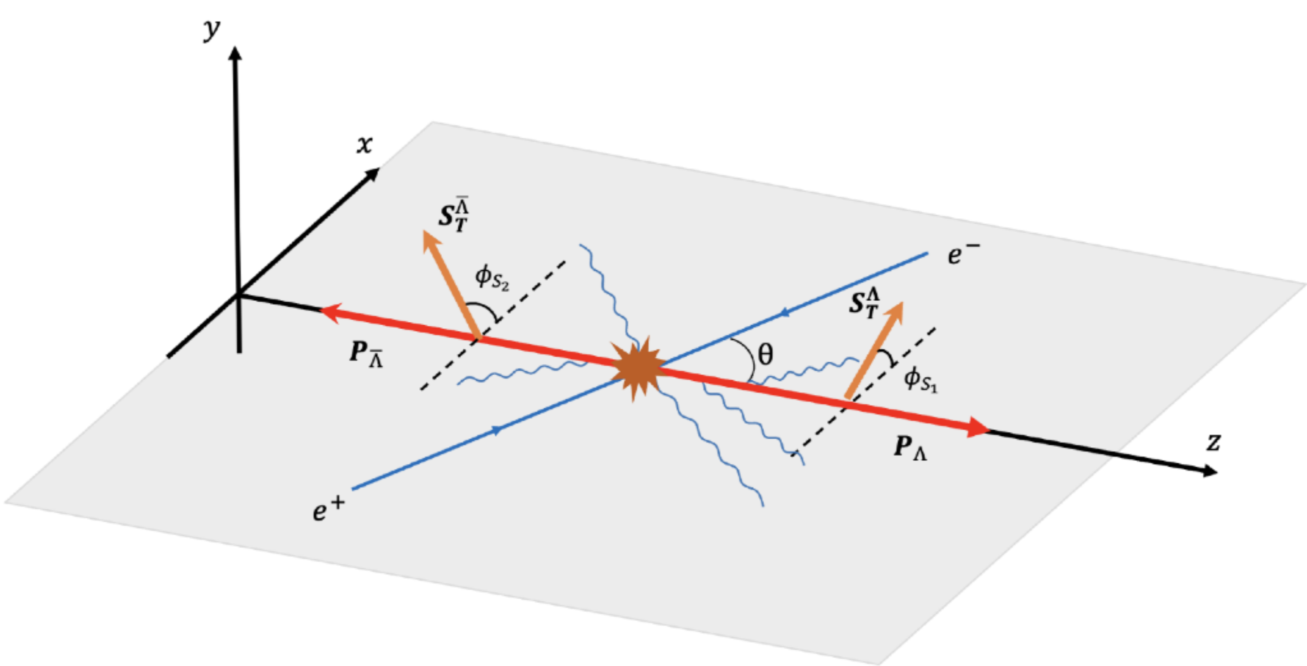
S.J. Lin (林士佳), M.J. Liu (刘铭钧), DYS, S.Y. Wei '25



Bell variable

Parton-level

$$\mathcal{B}_+^{q\bar{q}} = \frac{2\sin^2\theta}{1+\cos^2\theta}$$



Bell variable

Hadron-level

$$\mathcal{B}_+^{\Lambda\bar{\Lambda}} = \frac{2\,\mathrm{d}\sigma^T}{\mathrm{d}\sigma^U}$$

Parton model:

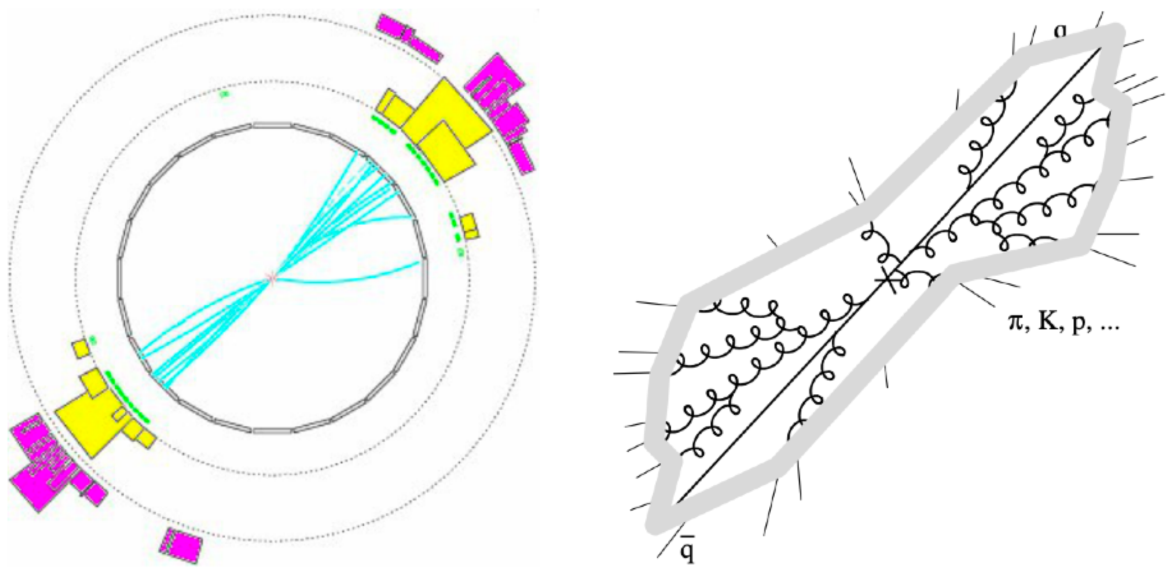
Boer, Jakob, Mulders '97

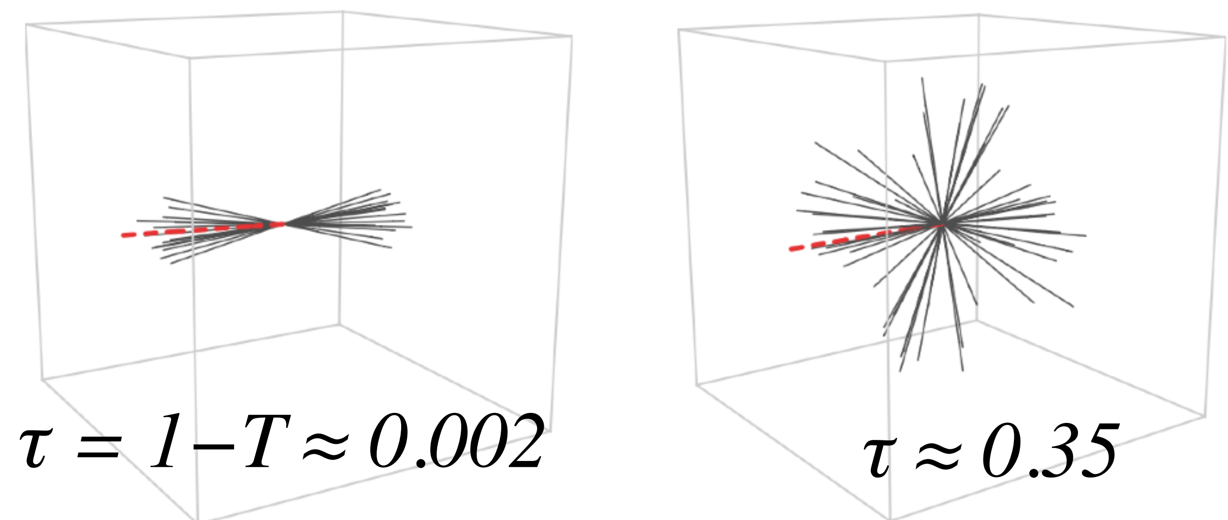
$$\frac{\mathrm{d}\sigma(\boldsymbol{S}^{\Lambda},\boldsymbol{S}^{\bar{\Lambda}})}{\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}\Omega} = \sum_q e_q^2 \Bigg[\frac{\mathrm{d}\sigma_0^U}{\mathrm{d}\Omega}\,\mathcal{D}^U_{\Lambda/q}(z_1,\mu)\,\mathcal{D}^U_{\bar{\Lambda}/\bar{q}}(z_2,\mu) + P_z^{\Lambda} P_z^{\bar{\Lambda}} \frac{\mathrm{d}\sigma_0^L}{\mathrm{d}\Omega}\,\mathcal{D}^L_{\Lambda/q}(z_1,\mu)\,\mathcal{D}^L_{\bar{\Lambda}/\bar{q}}(z_2,\mu)$$
$$+|\boldsymbol{S}_T^{\Lambda}||\boldsymbol{S}_T^{\bar{\Lambda}}|\cos(\phi_{S_1}+\phi_{S_2})\,\frac{\mathrm{d}\sigma_0^T}{\mathrm{d}\Omega}\,\mathcal{D}^T_{\Lambda/q}(z_1,\mu)\,\mathcal{D}^T_{\bar{\Lambda}/\bar{q}}(z_2,\mu)\Bigg]$$

Spin correlation in Λ pair production with a thrust cut

S.J. Lin (林士佳), M.J. Liu (刘铭钧), DYS, S.Y. Wei '25

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





- **The resummation predictions on the polarized cross section**

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

$$\frac{d\sigma^{\mathcal{P}}(\tau_{\rm cut})}{dz_1\, dz_2\, d\Omega} = \int_0^{\tau_{\rm cut}} d\tau \, \frac{d\sigma^{\mathcal{P}}}{d\tau\, dz_1\, dz_2\, d\Omega},$$

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

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

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

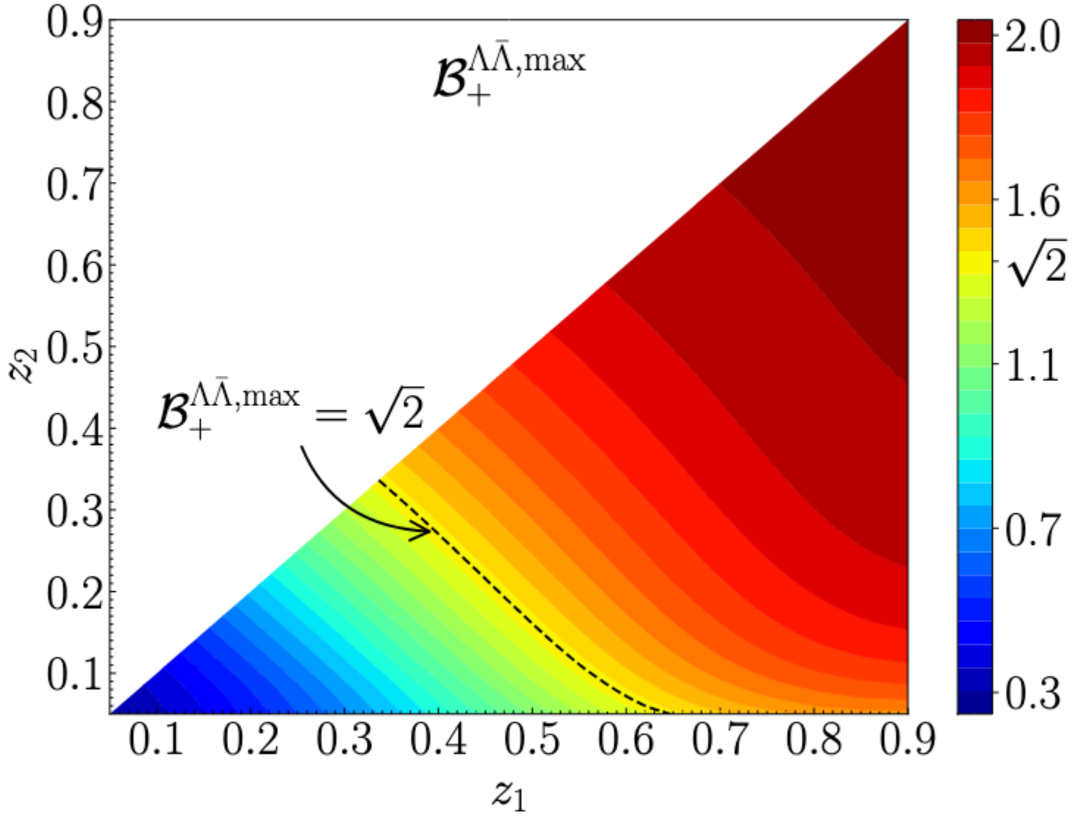
Bell nonlocality and decoherence

S.J. Lin (林士佳), M.J. Liu (刘铭钧), DYS, S.Y. Wei '25

- **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**

Energy correlators in e+e-

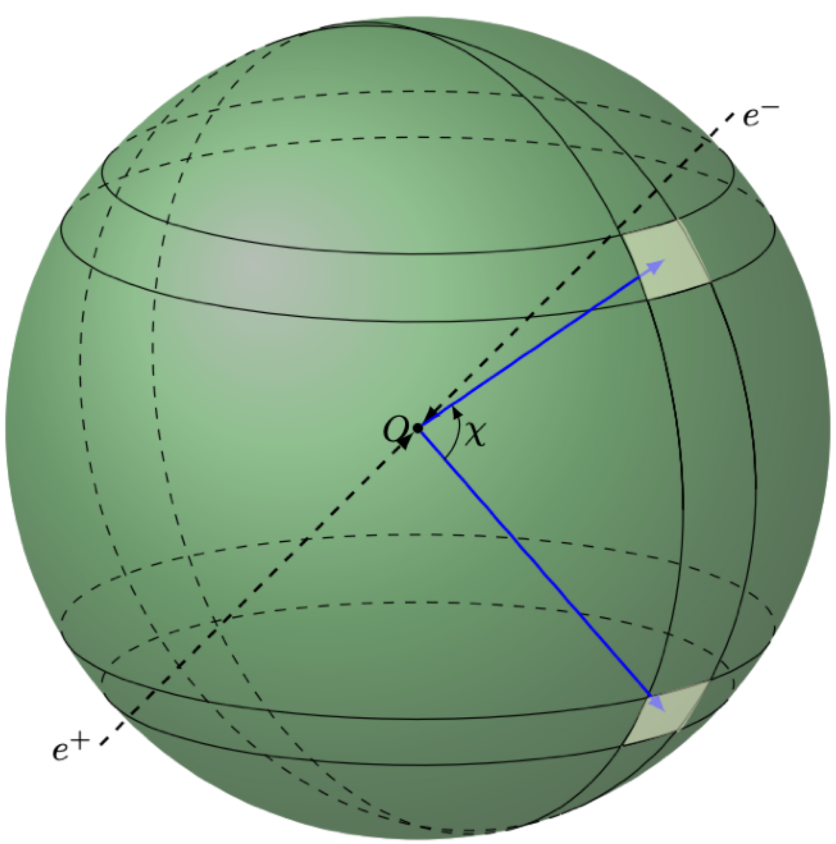
Louis Basham, Brown, Ellis, & Love '78; a recent review Moult, Zhu '25

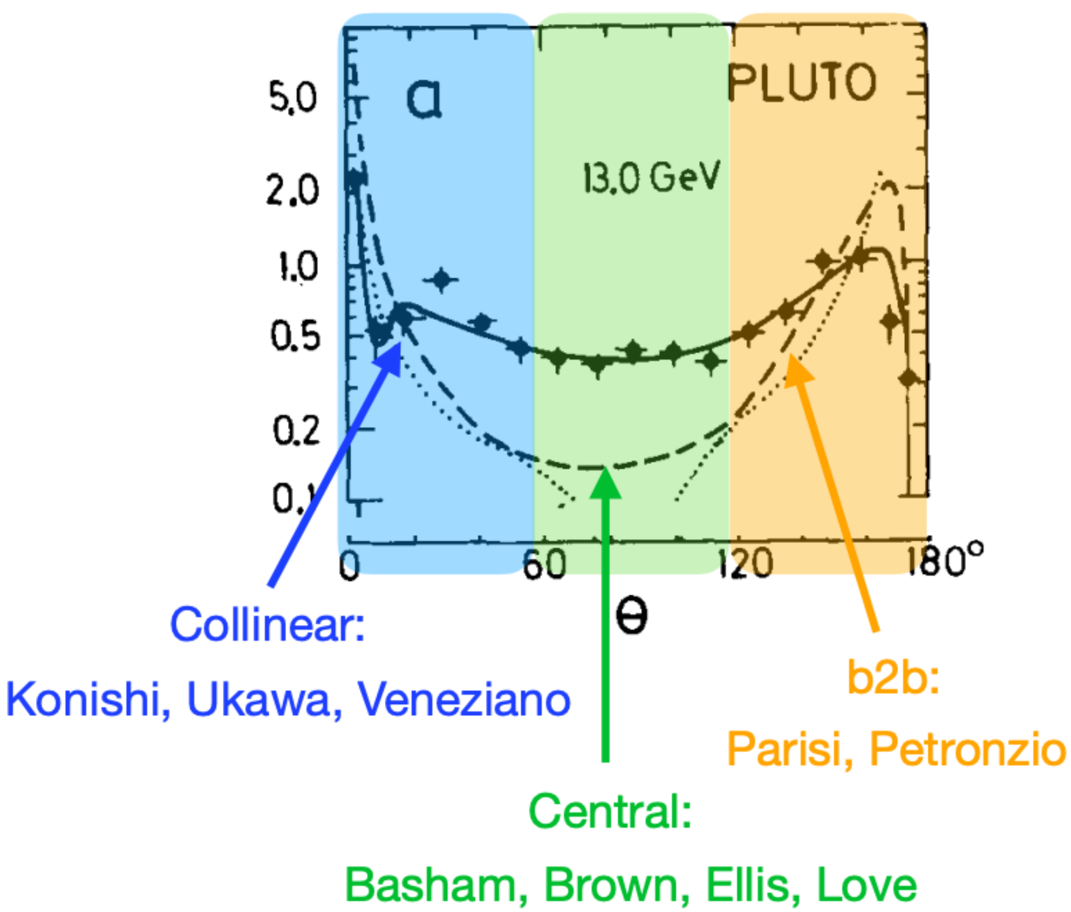
- **Correlators of energy flow operators** $\langle \mathcal{O}\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{O}^\dagger\rangle$ **characterize the final state in collider experiments**

Energy flow operators: $\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\; n^i T_{0i}(t, r\vec{n})$ Sterman '75

$$\mathrm{EEC}_{e^+e^-}(\tau) = \frac{1}{2}\sum_{i,j}\int d\theta_{ij}dz_i dz_j z_i z_j \frac{1}{\sigma}\frac{d\sigma}{d\theta_{ij}dz_i dz_j}\delta\left(\tau - \frac{1+\cos\theta_{ij}}{2}\right)$$

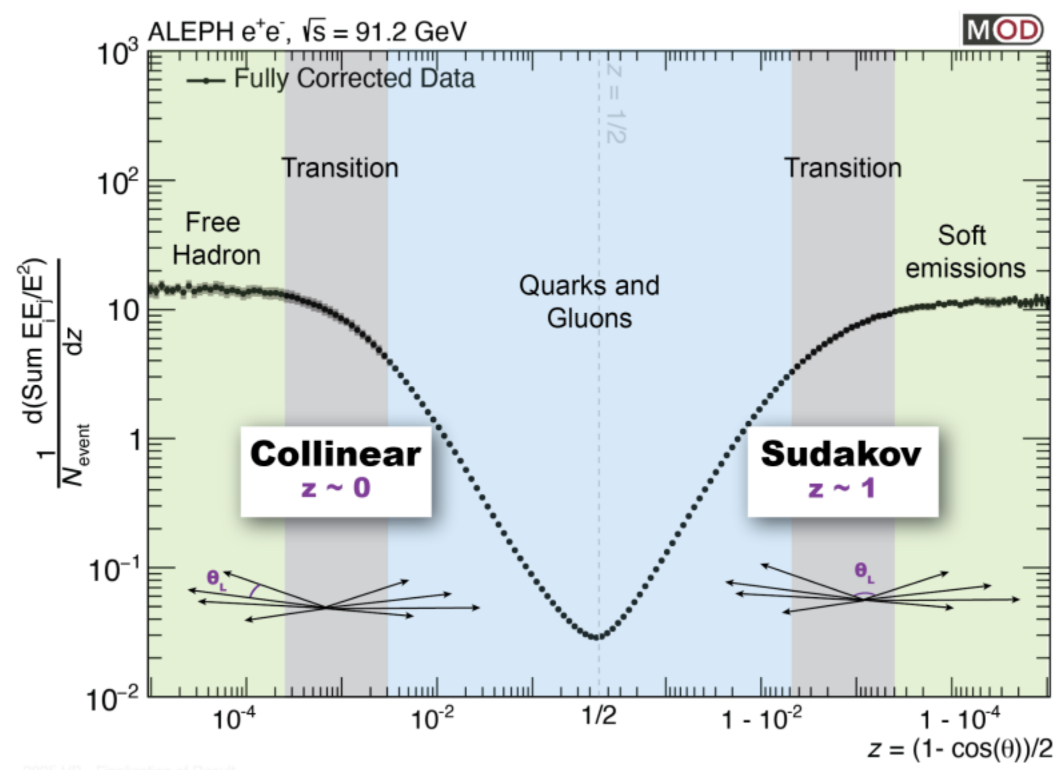
The first measurement at PLUTO 13 GeV

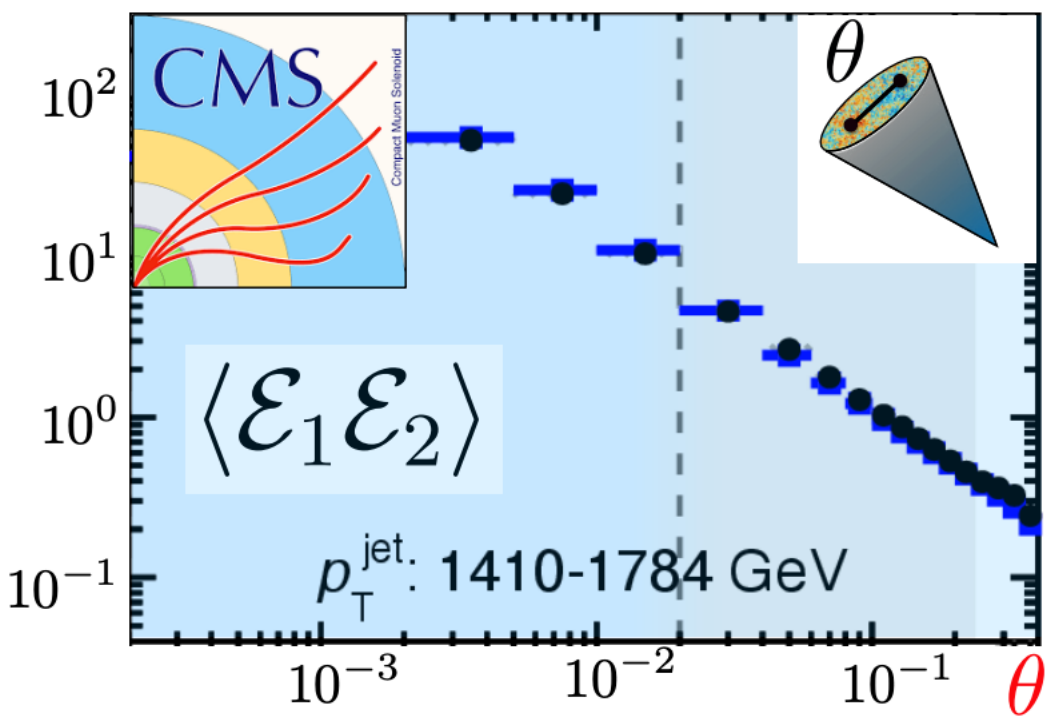




Energy correlators

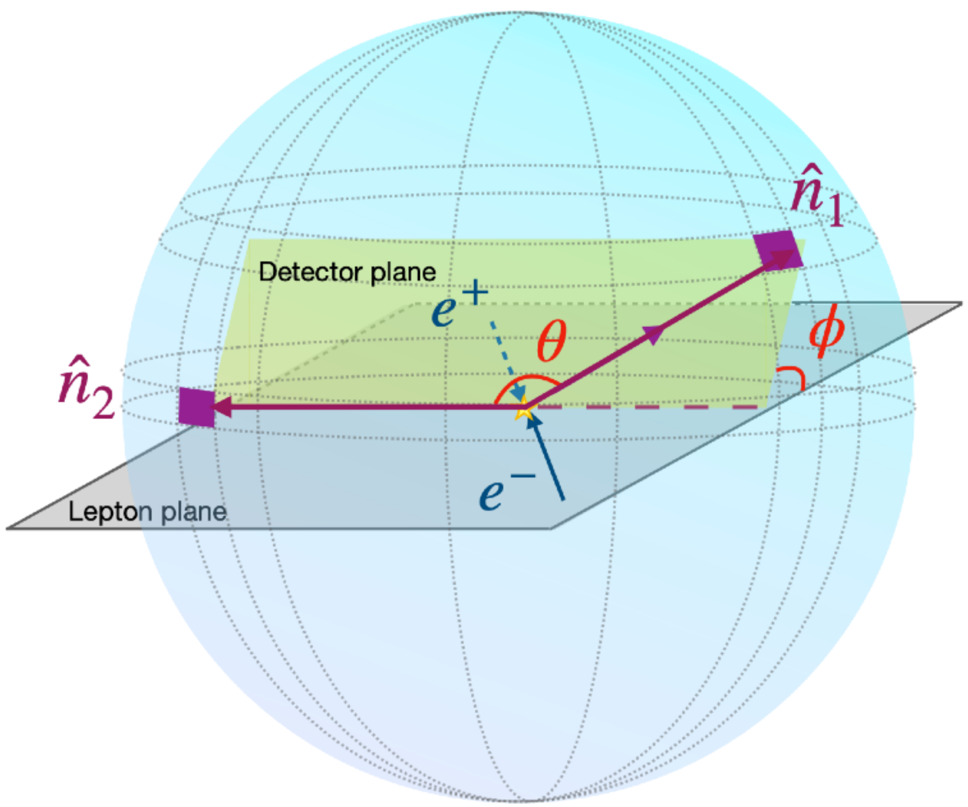
- **Energy Correlators are interesting observables for characterizing generic quantum theories** (Hofman, Maldacena, 2008)
- **Well defined at weak coupling, strong coupling, in a CFT, coupled to gravity**
- **Simpler in perturbation theory** Korchemsky, Sokatchev, Zhiboedov (2013)





Spin asymmetry of EEC in the large angle limit

- **Many spin asymmetries arise from the azimuthal correlations**
- **Azimuthal angle dependence in the small angle limit** Chen, Moult, & Zhu ’20; Li, Liu, Yuan, Zhu ‘23
- **We extend the EEC in the back-to-back by considering azimuthal asymmetries associated with the EEC** Kang, Lee, DYS, Zhao ’23



$$\frac{1}{\sigma_{\rm tot}}\frac{d\Sigma_{\rm e^+e^-}}{d\tau d\phi} = \frac{\langle \mathcal{O}\mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)\,\mathcal{O}^\dagger\rangle}{\langle \mathcal{O}\mathcal{O}^\dagger\rangle}$$

$$\mathrm{EEC}_{e^+e^-}(\tau,\phi) \equiv \frac{d\Sigma_{e^+e^-}}{d\tau d\phi} = \frac{1}{2}\sum_{1,2}\int d\sigma\, z_1 z_2\, \delta\left(\tau - \frac{1+\cos\theta_{12}}{2}\right)\delta(\phi-\phi_{12})$$

Azimuthal dependent EEC in e^+e^-

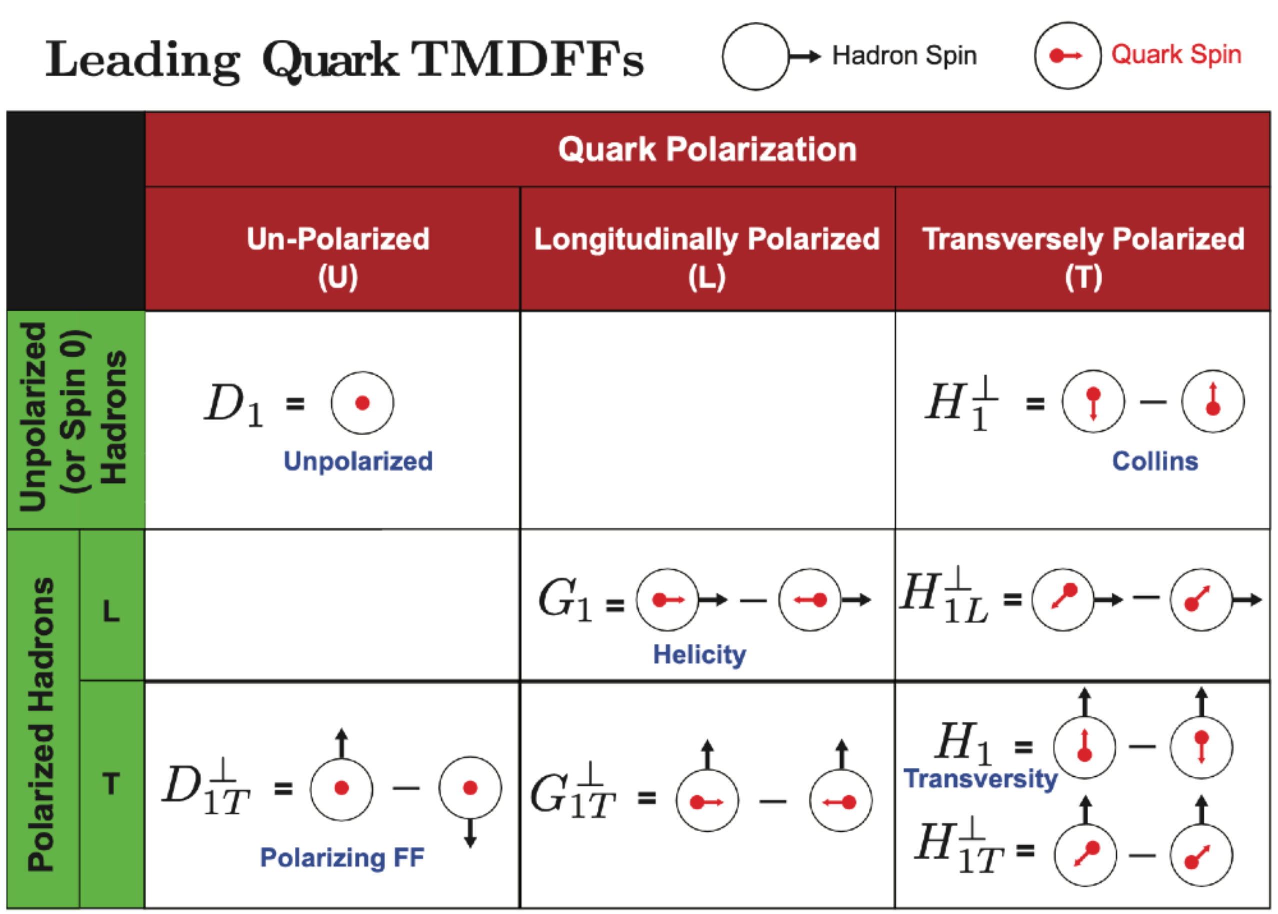
- **The standard TMD factorization for the back-to-back di-hadron process**

$$\frac{d\sigma}{dz_i dz_j d^2\boldsymbol{q}_T} = \sigma_0\, H(Q,\mu) \sum_q e_q^2 \int d^2\boldsymbol{p}_{1\perp} d^2\boldsymbol{p}_{2\perp} d^2\boldsymbol{\lambda}_\perp \delta^2\left(\frac{\boldsymbol{p}_{1\perp}}{z_1} + \frac{\boldsymbol{p}_{2\perp}}{z_2} - \boldsymbol{\lambda}_\perp + \boldsymbol{q}_T\right) S(\boldsymbol{\lambda}_\perp^2, \mu, \nu)$$
$$\times \left[D_{1,h_1/q}^{(u)}(z_1, \boldsymbol{p}_{1\perp}^2, \mu, \zeta/\nu^2) D_{1,h_2/\bar{q}}^{(u)}(z_2, \boldsymbol{p}_{2\perp}^2, \mu, \zeta/\nu^2) + \cos(2\phi_{12}) \left(\hat{\boldsymbol{q}}_{T,\alpha}\hat{\boldsymbol{q}}_{T,\beta} - \frac{1}{2} g_{\perp,\alpha\beta}\right) \right.$$
$$\left. \times \frac{\boldsymbol{p}_{1\perp}^\alpha}{z_1 M_1} H_{1,h_1/q}^{\perp(u)}(z_1, \boldsymbol{p}_{1\perp}^2, \mu, \zeta/\nu^2) \frac{\boldsymbol{p}_{2\perp}^\beta}{z_2 M_2} H_{1,h_2/\bar{q}}^{\perp(u)}(z_2, \boldsymbol{p}_{2\perp}^2, \mu, \zeta/\nu^2) \right].$$

$$z_i = \frac{2P_{hi} \cdot q}{Q^2} = \frac{2E_i}{Q}$$ **Energy fraction**

$D_{1,h/q}^{(u)}(z, \boldsymbol{p}_\perp^2, \mu, \zeta/\nu^2)$ **Unpolarized TMD FF**

$H_{1,h/q}^{\perp(u)}(z, \boldsymbol{p}_\perp^2, \mu, \zeta/\nu^2)$ **Collins TMD FF**



Azimuthal dependent EEC in e^+e^-

- **The TMD factorization for the azimuthal-dependent EEC in the back-to-back limit**

$$\mathrm{EEC}_{e^+e^-}(\tau,\phi)=\frac{1}{2}\sigma_0\,H(Q,\mu)\sum_q e_q^2\int\frac{b\,db}{2\pi}\Big[J_0(b\sqrt{\tau}Q)J_q(b,\mu,\zeta)J_{\bar{q}}(b,\mu,\zeta)+\cos(2\phi)\,\frac{b^2}{8}J_2(b\sqrt{\tau}Q)\;J_q^{\perp}(b,\mu,\zeta)J_{\bar{q}}^{\perp}(b,\mu,\zeta)\Big]$$

New term: azimuthal asymmetry

"Collins-type" EEC jet functions

A similar structure for Winner-take-All jet function was given in W. Lai, X. Liu, M Wang, H. Xing '21 '22

- **The unpolarized EEC jet function has a close relation to the unpolarized TMD FFs**

$$J_q(b,\mu,\zeta)\equiv\sum_h\int_0^1 dz\,z\,\tilde{D}_{1,h/q}(z,b,\mu,\zeta)$$

- **Collins-type EEC jet functions are closely connected with the Collins FFs**

$$J_q^{\perp}(b,\mu,\zeta)\equiv\sum_h\int_0^1 dz\,z\,\tilde{H}_{1,h/q}^{\perp}(z,b,\mu,\zeta)$$

Collins-type EEC jet function

- **We introduce Collins-type EEC jet function**

$$J_q(\boldsymbol{b},\mu,\zeta) \equiv \sum_h \int_0^1 dz z \tilde{D}_{1,h/q}(z,b,\mu_{b_*},\zeta_i)\, e^{-S_{\text{pert}}(\mu,\mu_{b_**})-S_{\text{NP}}^{D_1}(b,Q_0,\zeta)} \left(\sqrt{\frac{\zeta}{\zeta_i}}\right)^{\kappa(b,\mu_{b_*})}$$

$$J_q^{\perp}(\boldsymbol{b},\mu,\zeta) \equiv \sum_h \int_0^1 dz z \tilde{H}_{1,h/q}^{\perp}(z,b,\mu_{b_*},\zeta_i)\, e^{-S_{\text{pert}}(\mu,\mu_{b_*})-S_{\text{NP}}^{H_1^{\perp}}(b,Q_0,\zeta)} \left(\sqrt{\frac{\zeta}{\zeta_i}}\right)^{\kappa(b,\mu_{b_*})}$$

Collins function in *b*-space

- **The OPE of the subtracted unpolarized and Collins TMD FFs gives**

$$\tilde{D}_{1,h/q}(z,b,\mu,\zeta) = \left[C_{j\leftarrow q} \otimes D_{1,h/j}\right](z,b,\mu,\zeta) + \mathcal{O}(b^2\Lambda_{\text{QCD}}^2),$$

$$\tilde{H}_{1,h/q}^{\perp}(z,b,\mu,\zeta) = \left[\delta C_{j\leftarrow q}^{\text{Collins}} \otimes \hat{H}_{1,h/j}^{\perp(3)} + A_{j\leftarrow q}\tilde{\otimes}\hat{H}_{F,h/j}\right](z,b,\mu,\zeta) + \mathcal{O}(b^2\Lambda_{\text{QCD}}^2)\,,$$

twist-3 FFs (H_F is ignored)

$$\delta C_{q'\leftarrow q}^{\text{Collins}}(z,b,\mu,\zeta) = \delta_{qq'}\Bigg\{\delta(1-z) + \frac{\alpha_s}{\pi}\Bigg[C_F\delta(1-z)\left(-\frac{L_b^2}{4} + \frac{L_b}{2}\left(\frac{3}{2}+\ln\frac{\mu^2}{\zeta^2}\right) - \frac{\pi^2}{24}\right)$$
$$+\left(\ln z - \frac{L_b}{2}\right)\hat{P}_{q\leftarrow q}^{c}(z)\Bigg]\Bigg\} + \mathcal{O}(\alpha_s^2)\,,$$

The OPE of the Collins TMD FFs

- **The OPE of the subtracted unpolarized and Collins TMD FFs gives**

$$\tilde{H}^{\perp}_{1,h/q}(z,b,\mu,\zeta) = \left[\delta C^{\text{Collins}}_{j\leftarrow q} \otimes \hat{H}^{\perp(3)}_{1,h/j} + A_{j\leftarrow q}\tilde{\otimes}\hat{H}_{F,h/j}\right](z,b,\mu,\zeta) + \mathcal{O}(b^2\Lambda^2_{\text{QCD}})$$

- **Standard convolution** $\left[C_{j\leftarrow q}\otimes F_{h/j}\right](z,b,\mu,\zeta) = \int_z^1 \frac{dx}{x} C_{j\leftarrow q}\left(\frac{z}{x},b,\mu,\zeta\right) F_{h/j}(x,\mu)$

$$\delta C^{\text{Collins}}_{q'\leftarrow q}(z,b,\mu,\zeta) = \delta_{qq'}\Bigg\{\delta(1-z) + \frac{\alpha_s}{\pi}\Bigg[C_F\delta(1-z)\left(-\frac{L_b^2}{4} + \frac{L_b}{2}\left(\frac{3}{2} + \ln\frac{\mu^2}{\zeta^2}\right) - \frac{\pi^2}{24}\right) + \left(\ln z - \frac{L_b}{2}\right)\hat{P}^c_{q\leftarrow q}(z)\Bigg]\Bigg\} + \mathcal{O}(\alpha_s^2),$$

$\hat{H}^{\perp(3)}_{1,h/j}(z,\mu)$: twist-3 fragmentation function, related to the first $k_\perp$-moment of the Collins TMD FF

- **Double convolution**

$$\left[A_{j\leftarrow q}\tilde{\otimes}\hat{H}_{F,h/j}\right](z,b,\mu,\zeta) = \int_z^1 \frac{dx}{x}\int \frac{dz_1}{z_1^2}\,\text{PV}\left(\frac{1}{\frac{1}{x}-\frac{1}{z_1}}\right) A_{j\leftarrow q}\left(\frac{z}{x},z_1,b,\mu,\zeta\right)\hat{H}_{F,h/j}(x,z_1,\mu)$$

starts at the order $O(\alpha_S)$ and is ignored in our work

Sum rule

- **The collinear functions in the OPE matching obey the sum rules**

$$\sum_h \int_0^1 dz\, z\, D_{1,h/j}(z,\mu) = 1\,,$$

sum over longitudinal momentum fraction carried by the hadron is 1

$$\sum_h \int_0^1 dz\, \hat{H}^{\perp(3)}_{1,h/q}(z,\mu) = 0\,.$$

the transverse momentum carried by the final hadron sum to 0 (Schafer-Teryaev sum rule)

- **In the OPE region**

$$\begin{aligned} J_q^{\perp}(b,\mu,\zeta) &= \sum_h \int_0^1 dz\, z\, \tilde{H}^{\perp}_{1,h/q}(z,b,\mu,\zeta) \\ &= \sum_h \int_0^1 dz \int_z^1 \frac{dx}{x}\, \delta C^{\text{Collins}}_{q\leftarrow q}(\frac{z}{x}, b, \mu_{b_*}, \zeta) \hat{H}^{\perp(3)}_{1,h/q}(x,\mu_{b_*})\, e^{-S_{\text{pert}}(\mu,\mu_{b_*})} \\ &= \int_0^1 d\tau \delta C^{\text{Collins}}_{q\leftarrow q}(\tau, b, \mu_{b_*}, \zeta) \left[\sum_h \int_0^1 dx\, \hat{H}^{\perp(3)}_{1,h/q}(x,\mu_{b_*})\right] e^{-S_{\text{pert}}(\mu,\mu_{b_*})} \\ &= 0\,, \end{aligned}$$

= 0

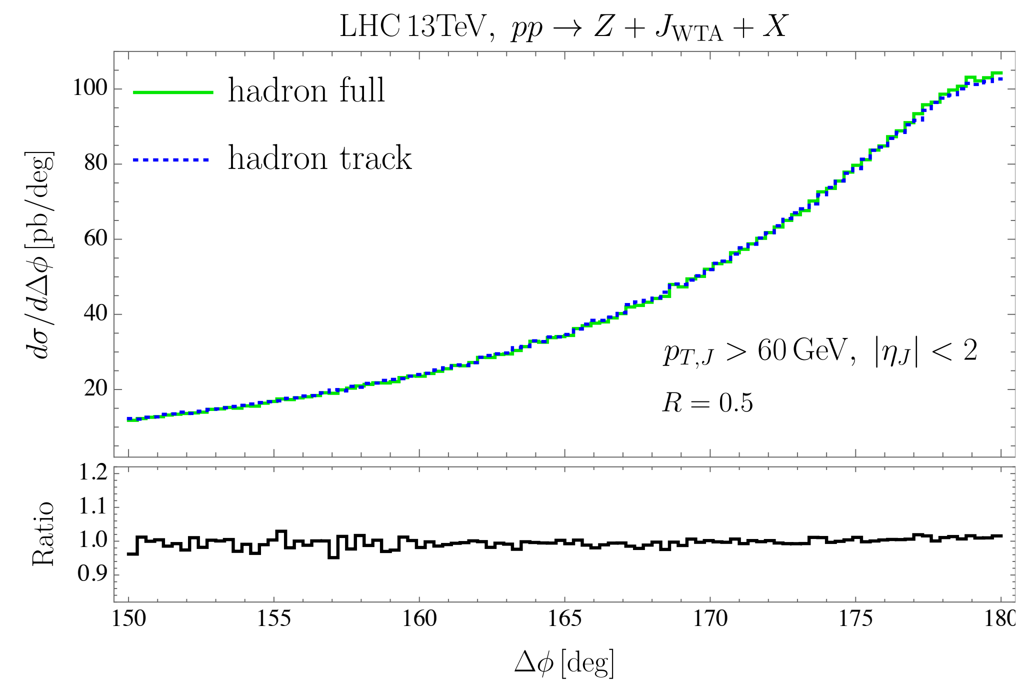
- **We find that the Collins-type EEC jet function becomes zero in the OPE region upon neglecting the off-diagonal matching terms.**

Collins-type EEC with subsets of hadrons

- **In the small angle limit, the track function formalism was used to study energy correlation between hadrons with specific quantum number** $\langle \mathcal{E}_{\mathbb{S}_1}(\hat{n}_1)\mathcal{E}_{\mathbb{S}_2}(\hat{n}_2)\rangle$ Chang, Procura, Thaler, & Waalewijn '13; Y, Li, Moult, Schrijnder, Waalewijn, H. X. Zhu '21; Jaarsma, Y. Li, Moult, Waalewijn, Z. X. Zhua '22, '23 + H. Chen '22 '23
- **In the large angle limit (TMD region), one can also use subset $\mathbb{S}$ of hadrons to define the jet function**
  - **Tacking jet function for the recoil free jets**

$$\bar{\mathscr{J}}_q^{(1)} = \mathscr{J}_q^{(1)} + 4C_F \int_0^1 \mathrm{d}x\, \frac{1+x^2}{1-x} \ln \frac{x}{1-x} \int_0^1 \mathrm{d}z_1\, T_q(z_1,\mu) \times \int_0^1 \mathrm{d}z_2\, T_g(z_2,\mu)[\theta(z_1 x - z_2(1-x)) - \theta(x - \tfrac{1}{2})]$$

Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB



  - **Charge-Charge correlation** Monni, Vita, Xu, Zhu '25
- **We explore a less inclusive version of EEC in the back-to-back limit that is only sensitive to the energy flow of subset $\mathbb{S}$ of hadrons**

$$\sum_h \Rightarrow \sum_{h\in\mathbb{S}}$$

E.g. $\mathbb{S}$ = charged particles — Better energy resolution and smaller experimental uncertainties

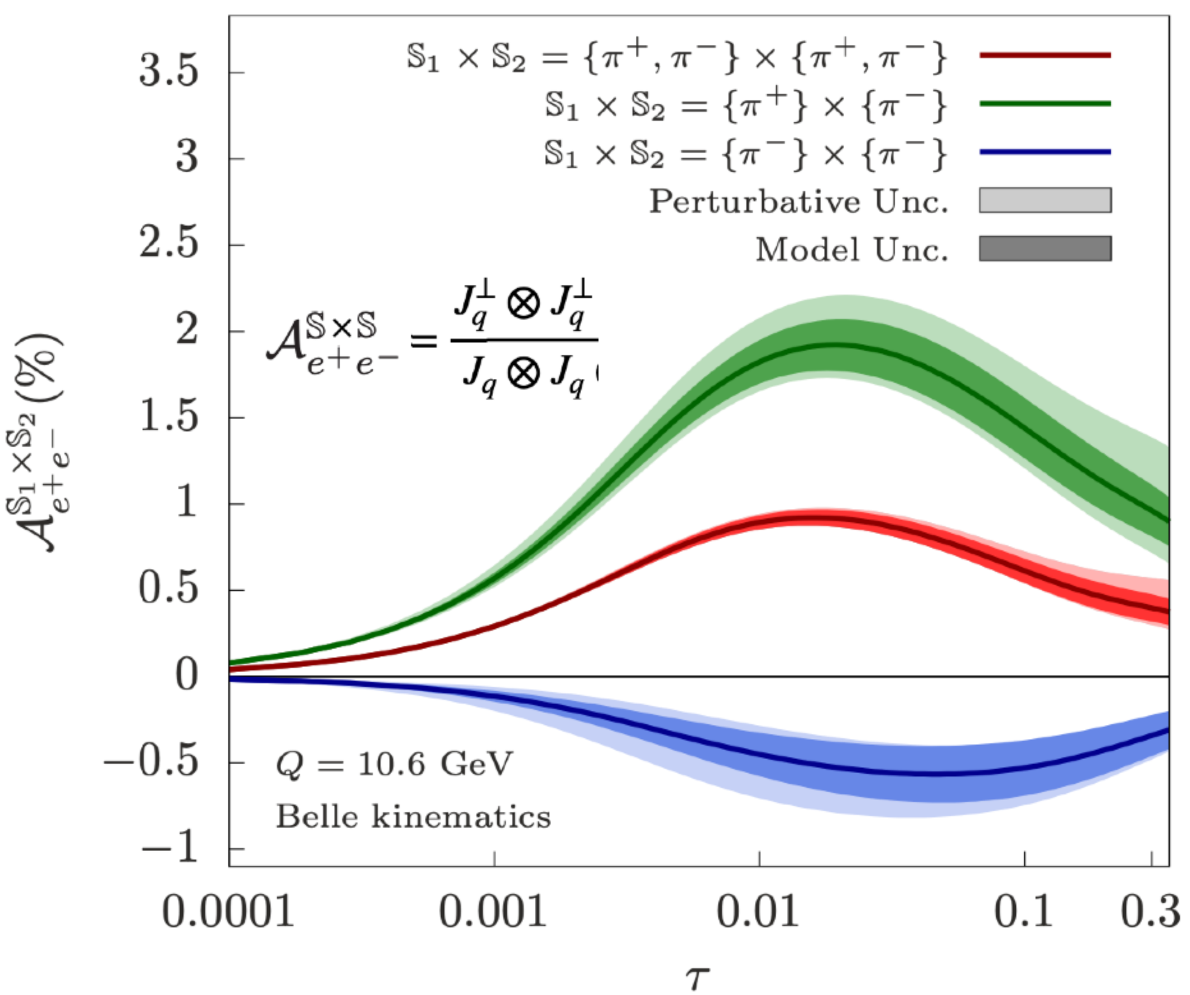
$\mathbb{S} = h$ — Probe fragmentation function

EEC in e^+e^- : Collins asymmetry

- **We provide a prediction for Collins asymmetry at Belle kinematics**

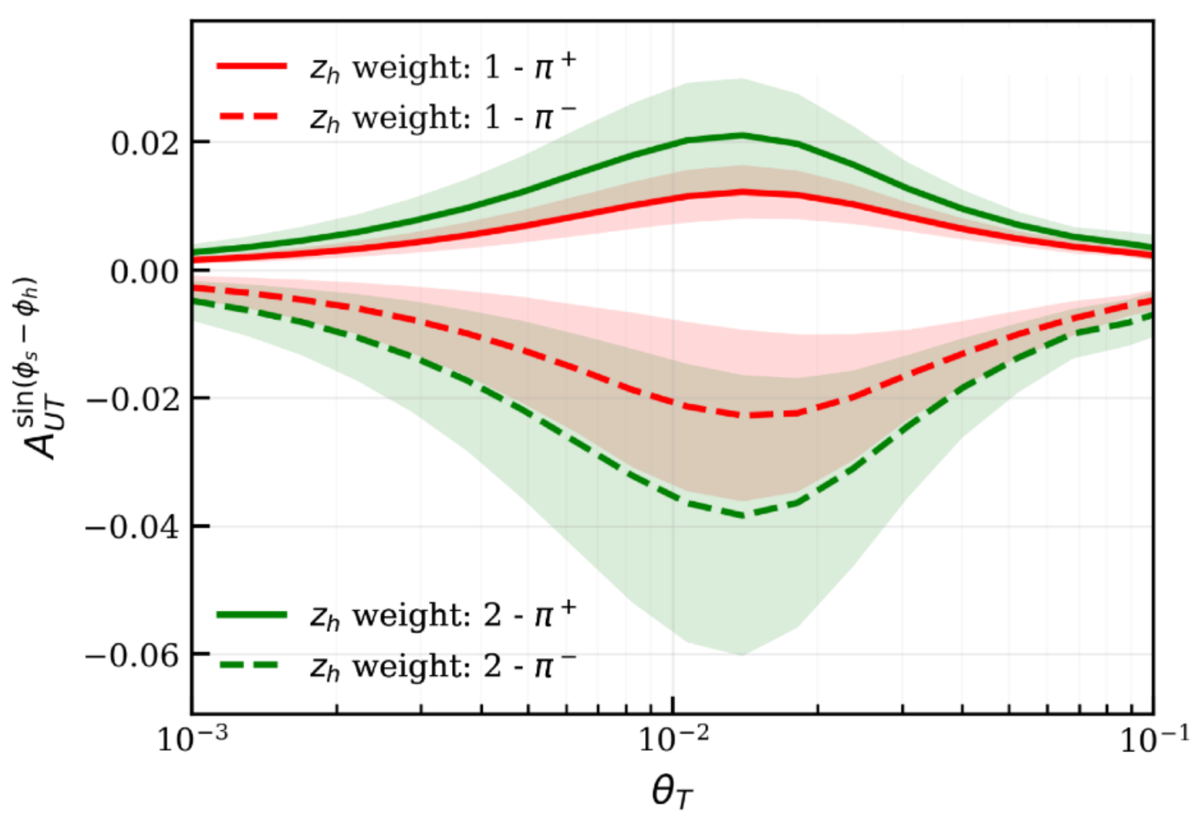
$$\mathrm{EEC}_{e^+e^-}(\tau,\phi) = \frac{d\Sigma_{e^+e^-}}{d\tau d\phi} = \frac{1}{2}\sigma_0 \sum_q e_q^2 \int d\boldsymbol{q}_T^2\, \delta\left(\tau - \frac{\boldsymbol{q}_T^2}{Q^2}\right) Z_{uu} \left[1 + \cos(2\phi)\, \frac{Z_{\text{Collins}}}{Z_{uu}}\right]$$

$$\equiv \frac{1}{2}\sigma_0 \sum_q e_q^2\, Z_{uu} \left[1 + \cos(2\phi)\, A_{e^+e^-}(\tau Q^2)\right],$$



$$Z_{uu} = \int \frac{bdb}{2\pi} J_0(bq_T) J_q(b,\mu,\zeta) J_{\bar{q}}(b,\mu,\zeta)\,,$$

$$Z_{\text{Collins}} = \int \frac{bdb}{2\pi}\frac{b^2}{8} J_2(bq_T) J_q^\perp(b,\mu,\zeta) J_{\bar{q}}^\perp(b,\mu,\zeta)\,.$$



Summary and Outlook

- **Jets and jet substructures offer new opportunity to understand hadron spin structures**
- **We develop the factorization framework to study transverse polarization effects for Λ(thrust) production in e^+e^- collisions**
  - **QCD effective field theory approach, model independent**
  - **Verify the universality of polarizing fragmentation function**
- **We apply fragmenting density matrix to investigate decoherence effects arising from soft and collinear radiation in spin entanglement**
- **Identify a correspondence between open quantum system and renormalization group**
- **Quantum information theory for hadronization**
- **We introduce the Collin-type EEC jet function for the first time**
- **By generalizing the EEC with azimuthal angle dependence, one gets access to spin dependent effects**

Thank you