Transverse Lambda hyperon polarization at lepton colliders

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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

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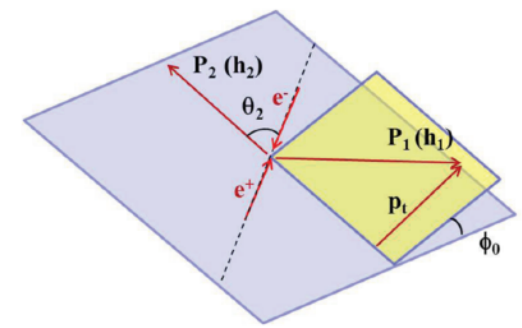
Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

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

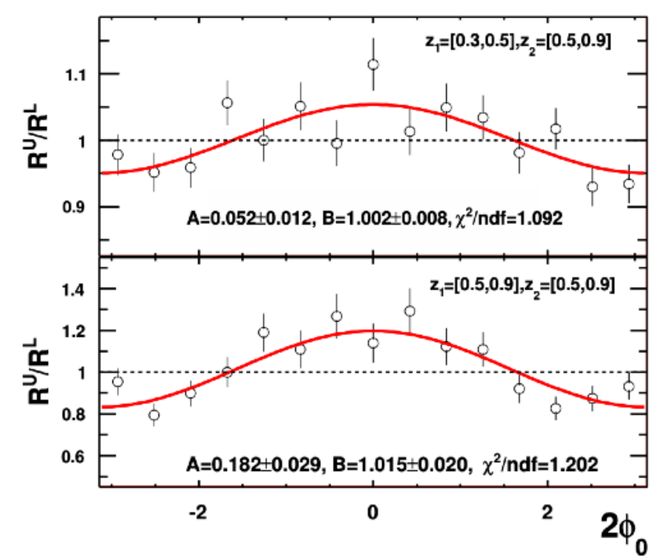
and

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

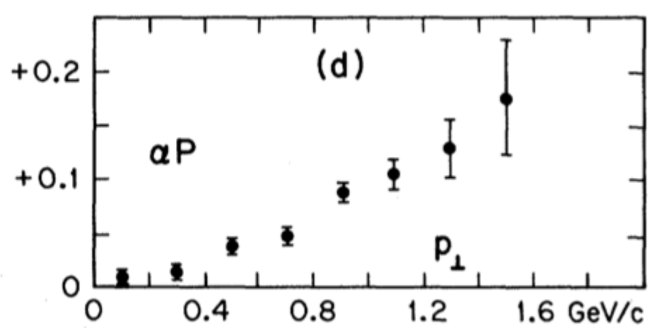


These experimental measurements can be used to probe the internal structure of hadrons

EXP on transverse Λ polarization

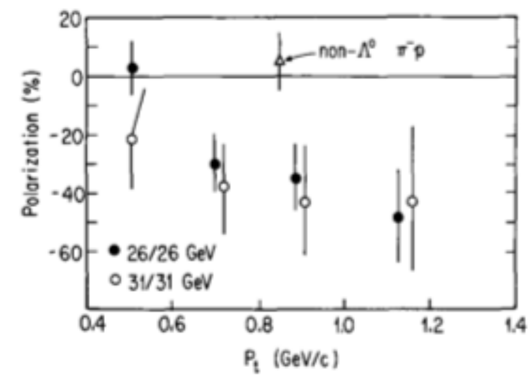
Bunce et.al. '76

$p + Be \to \Lambda^{\uparrow} + X$



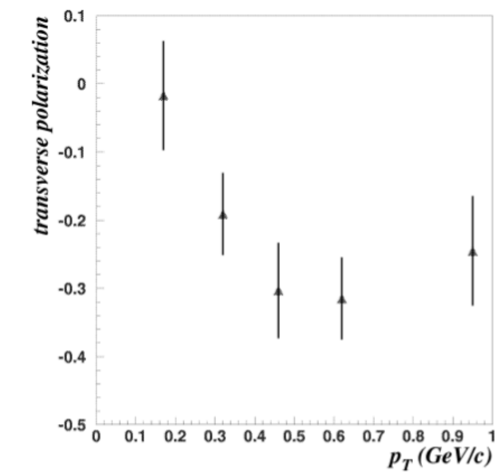
Erhan et.al. '79

$pp \to \Lambda^{\uparrow} X$

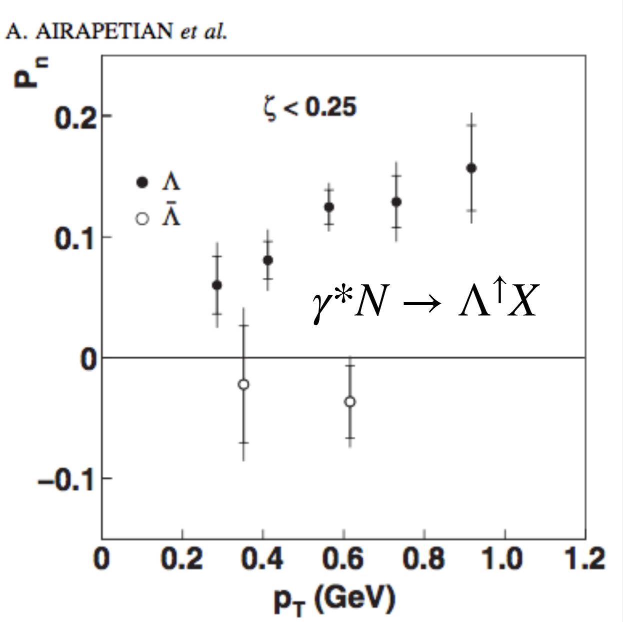


NOMAD '20

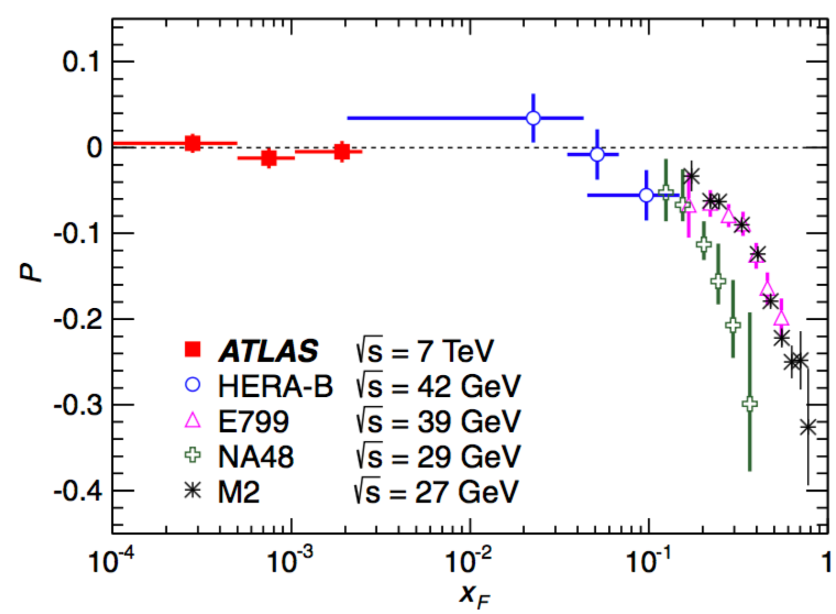
$\nu N \to \Lambda^{\uparrow} X$



HERMES '76



Atlas '15

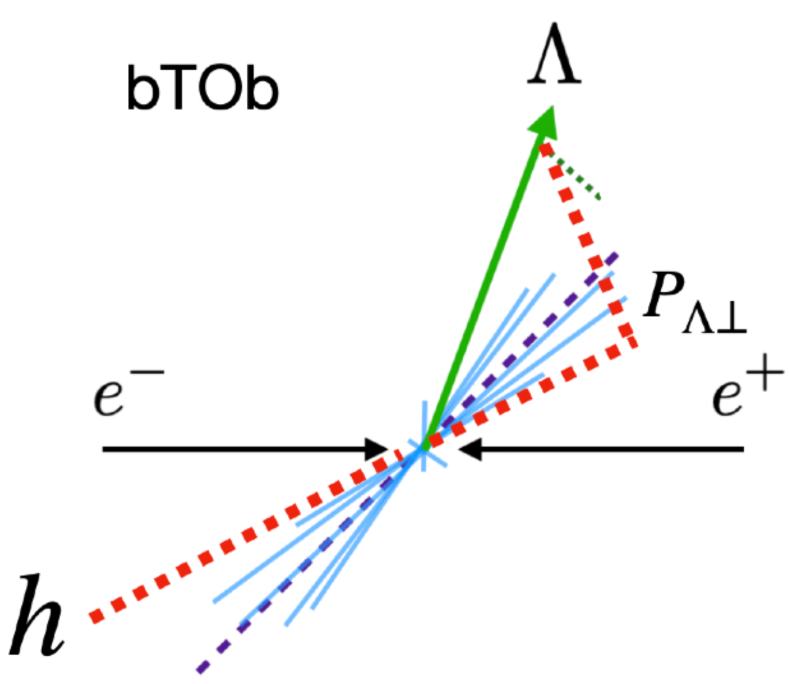


Ma, Schmidt, Soffer, Yang '01
Liang, Wang '06
… …

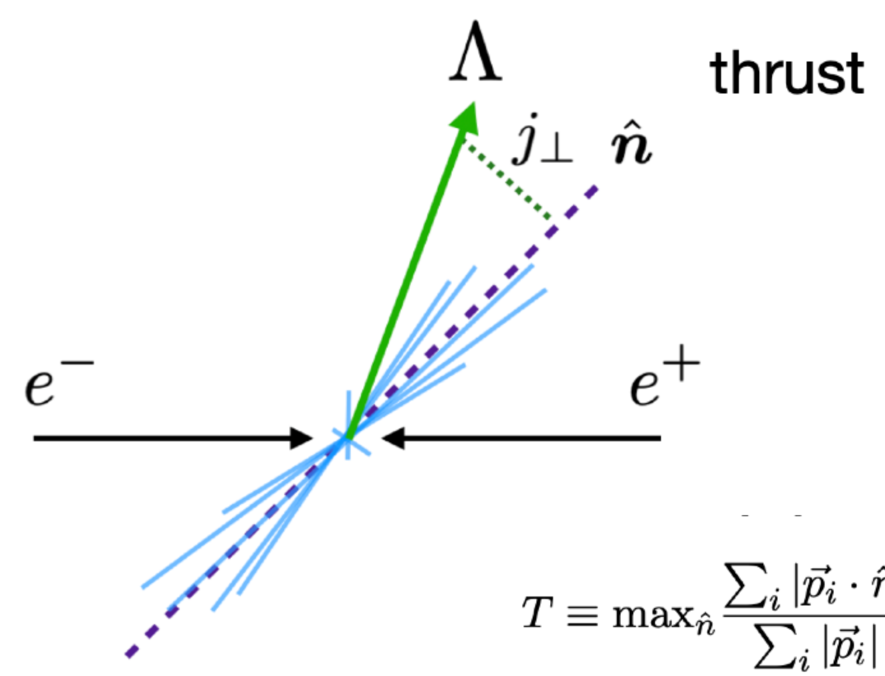
Transverse Λ polarization in electron positron collisions

In N+N or l+N collisions, it is not possible to disentangle initial-state effects, related to dynamics inside the colliding hadrons, and final-state effects, related to the fragmentation of the partons.

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



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

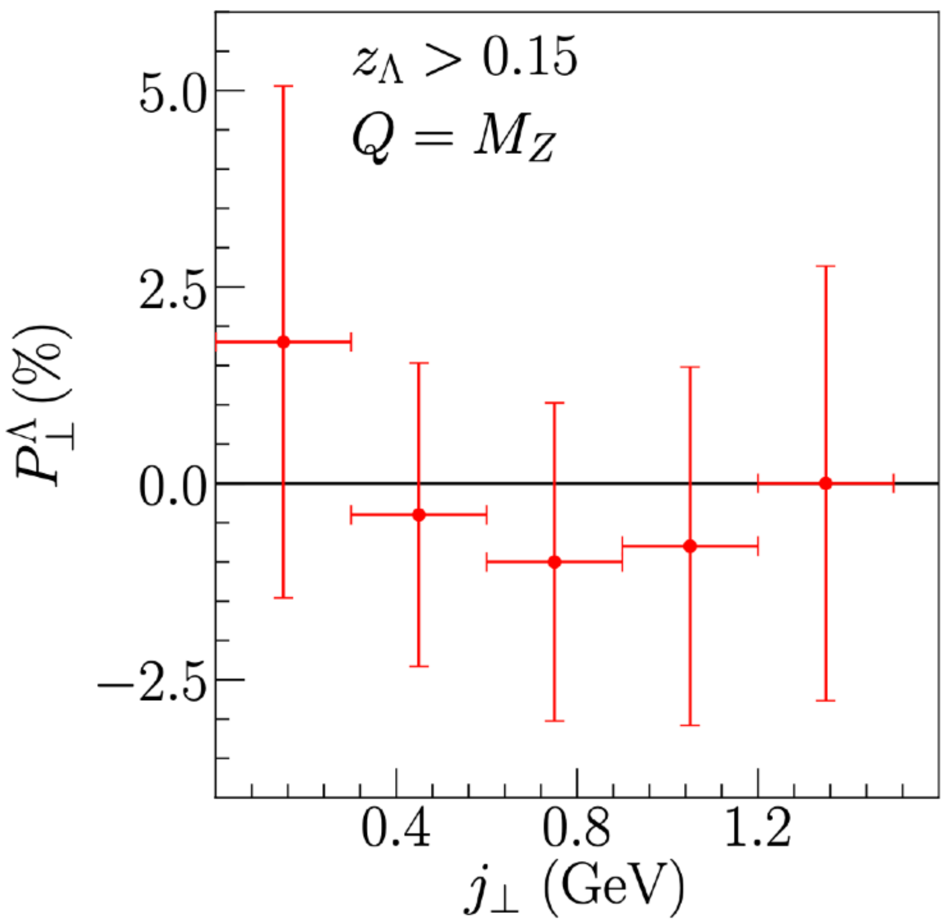


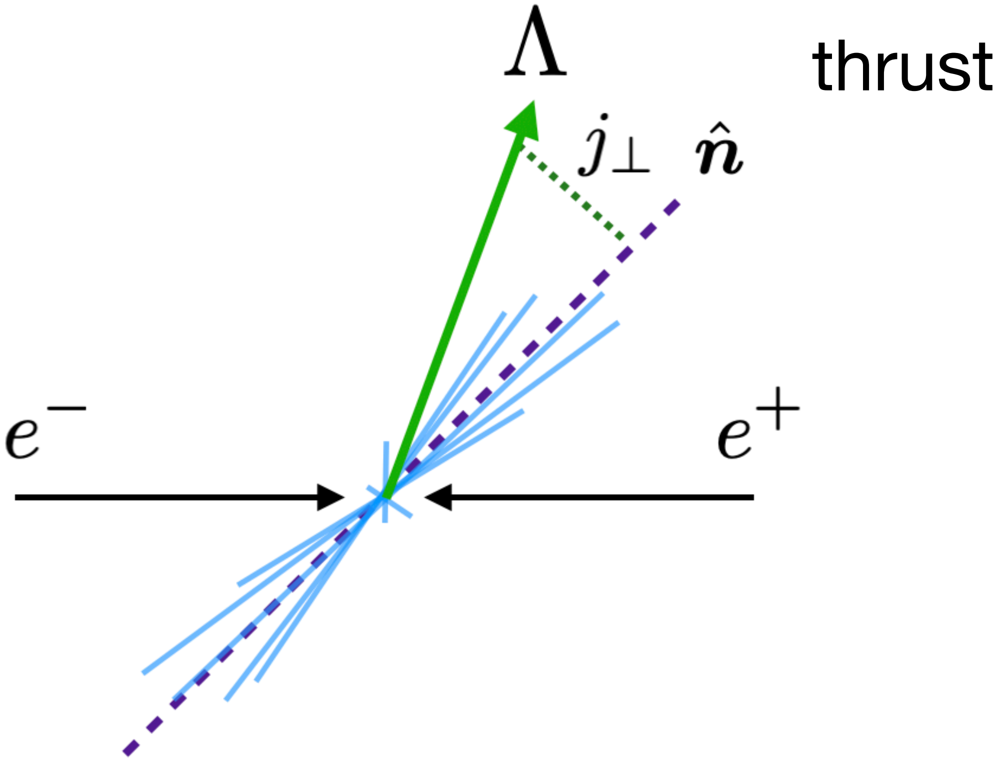
$$T \equiv \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$$

e$^+$e$^-$ cleanest way to access fragmentation functions

Transverse Λ polarization at the LEP

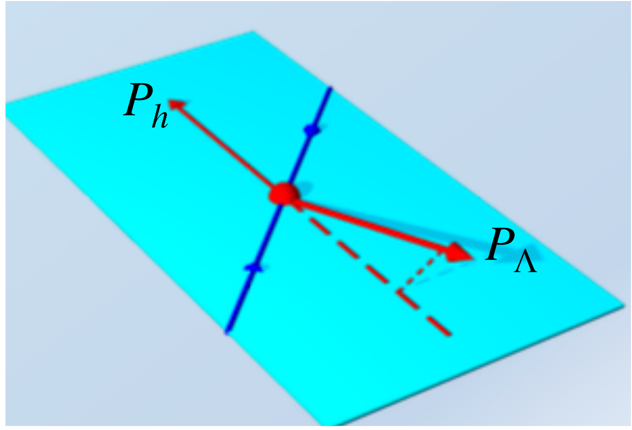
OPAL '97

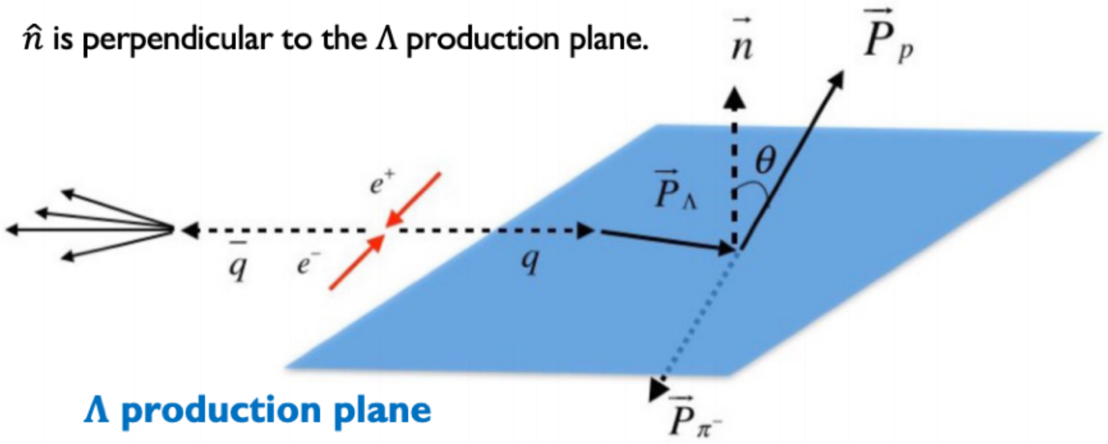




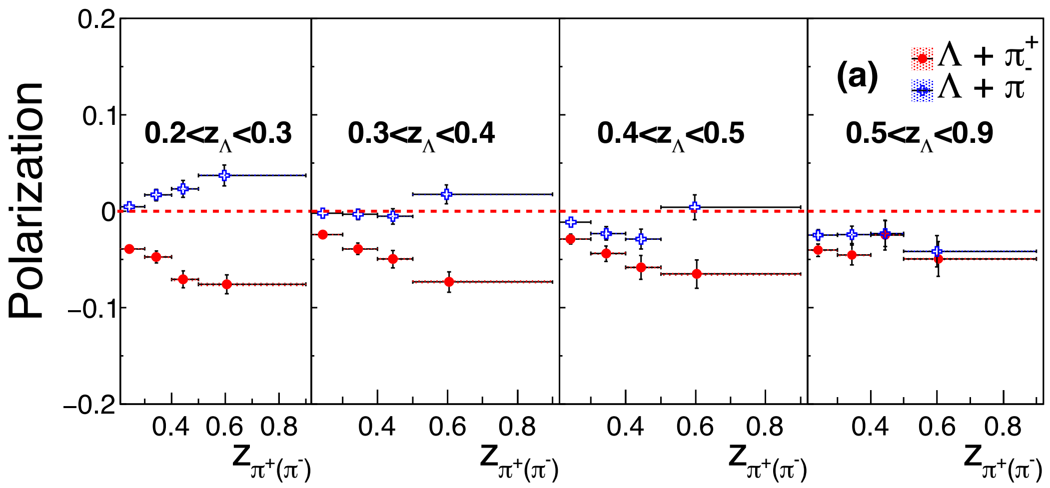
No significant transverse polarization is observed at the LEP

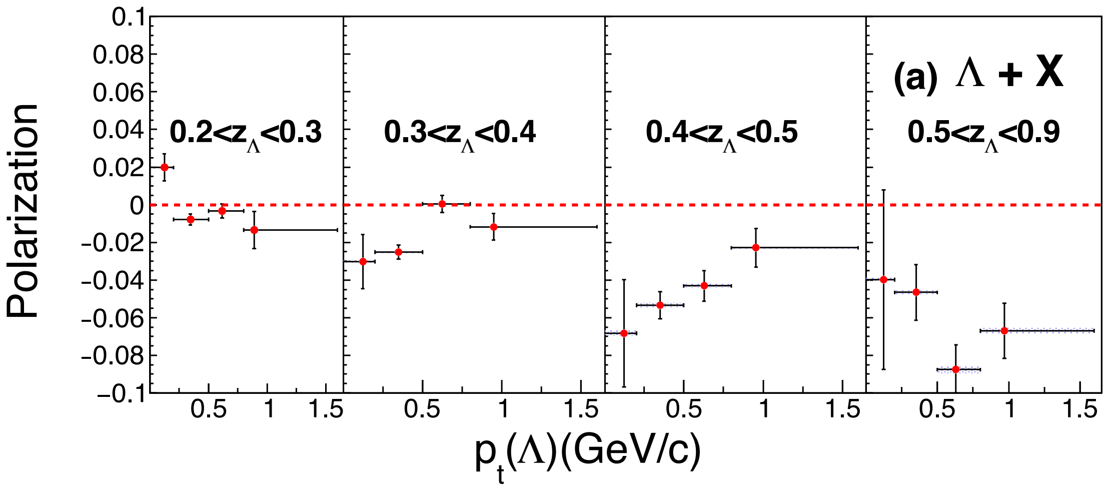
Transverse Λ polarization at the Belle





Belle '18 PRL





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

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

Theory framework on transverse Λ polarization

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

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

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

???

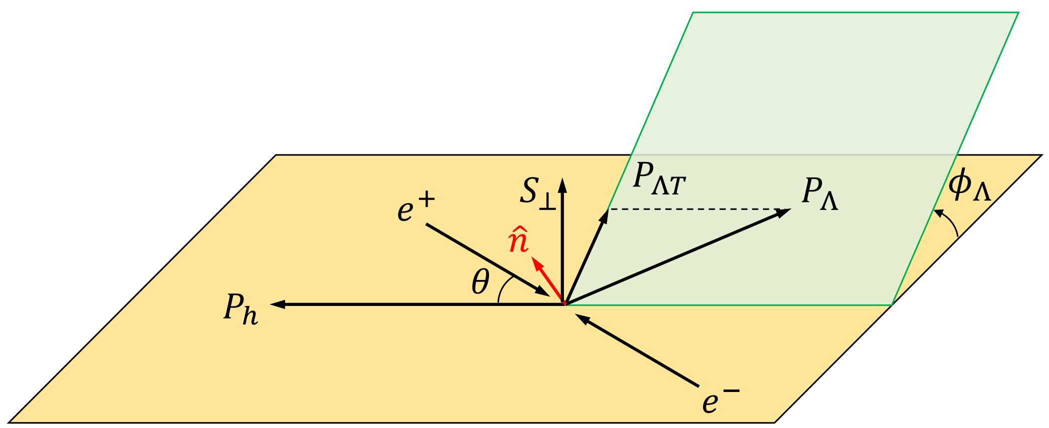
TMD factorization two scale problem

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

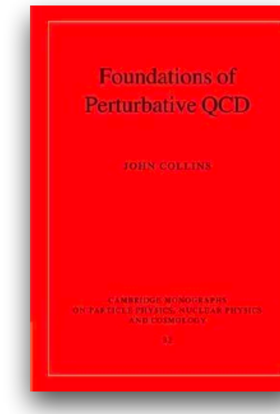
Is it the same (polarizing) fragmentation function in these two measurements ???

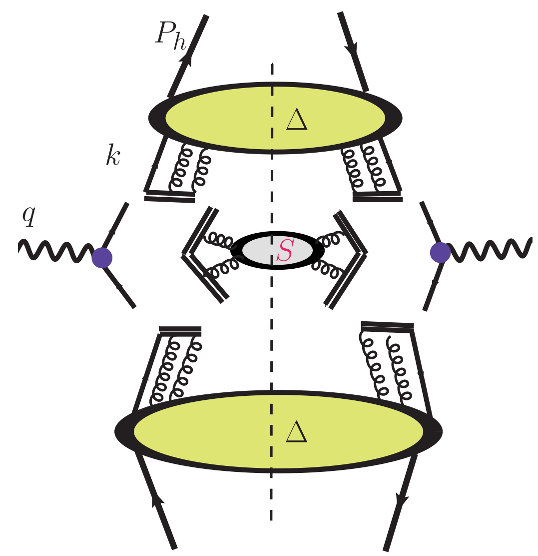
Back-to-back Λ+h

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



TMD factorization theorems have been established for back-to-back Λ+h





$$W^{\mu\nu} \overset{\text{prelim}}{=} \frac{8\pi^3 z_A z_B}{Q^2} \sum_f \mathrm{Tr}\, k^+_{A,\gamma} \gamma^- H^\nu_f(Q)\, k^-_{B,\gamma} \gamma^+ \overline{H}^\mu_f(Q)$$

$$\times \int \frac{\mathrm{d}^{2-2\epsilon} \boldsymbol{b}_\mathrm{T}}{(2\pi)^{2-2\epsilon}} e^{-i \boldsymbol{q}_{h\mathrm{T}} \cdot \boldsymbol{b}_\mathrm{T}}\, \tilde{S}(b_\mathrm{T}) \tilde{D}_{1,\, H_A/f}(z_A, b_\mathrm{T})\, \tilde{D}_{1,\, H_B/\bar{f}}(z_B, b_\mathrm{T})$$

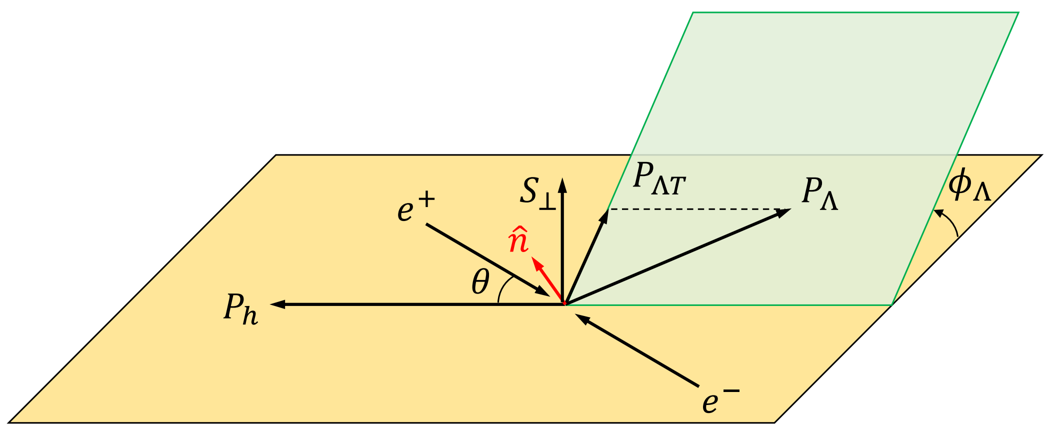
$+$ polarized terms.

Spin-dependent cross section is factorized as:

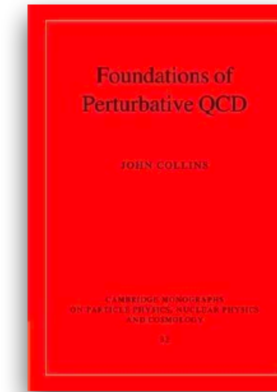
$$\frac{d\sigma\left(\boldsymbol{S}_\perp\right)}{d\mathcal{PS}d^2\boldsymbol{q}_\perp} = \sigma_0 \left\{ \mathcal{F}\left[D_{\Lambda/q} D_{h/\bar{q}}\right] + |\boldsymbol{S}_\perp| \sin\left(\phi_S - \phi_\Lambda\right) \frac{1}{z_\Lambda M_\Lambda} \mathcal{F}\left[\hat{\boldsymbol{P}}_{\Lambda T}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

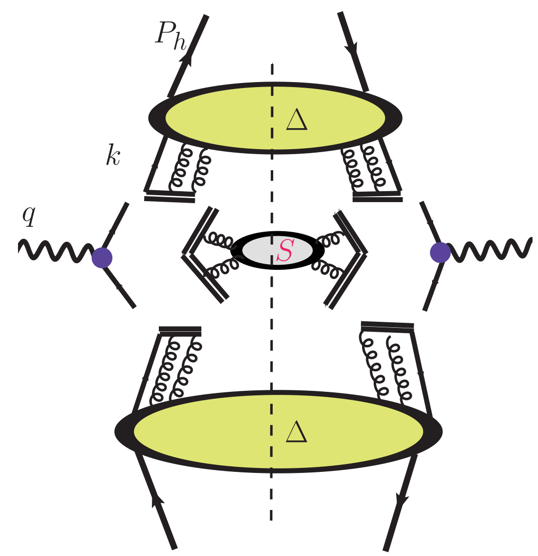
Back-to-back Λ+h

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



TMD factorization theorems have been established for back-to-back Λ+h





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

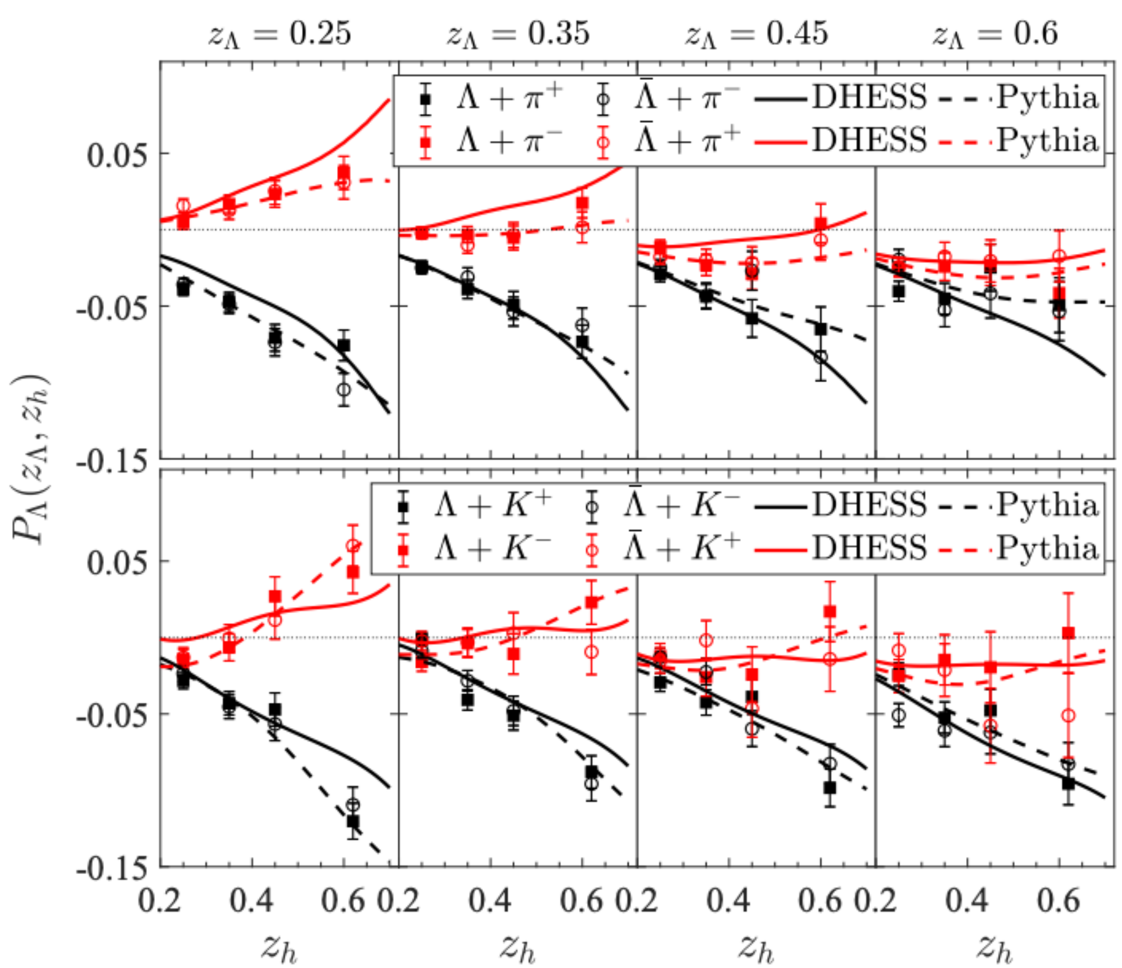
Spin-dependent cross section is factorized as:

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

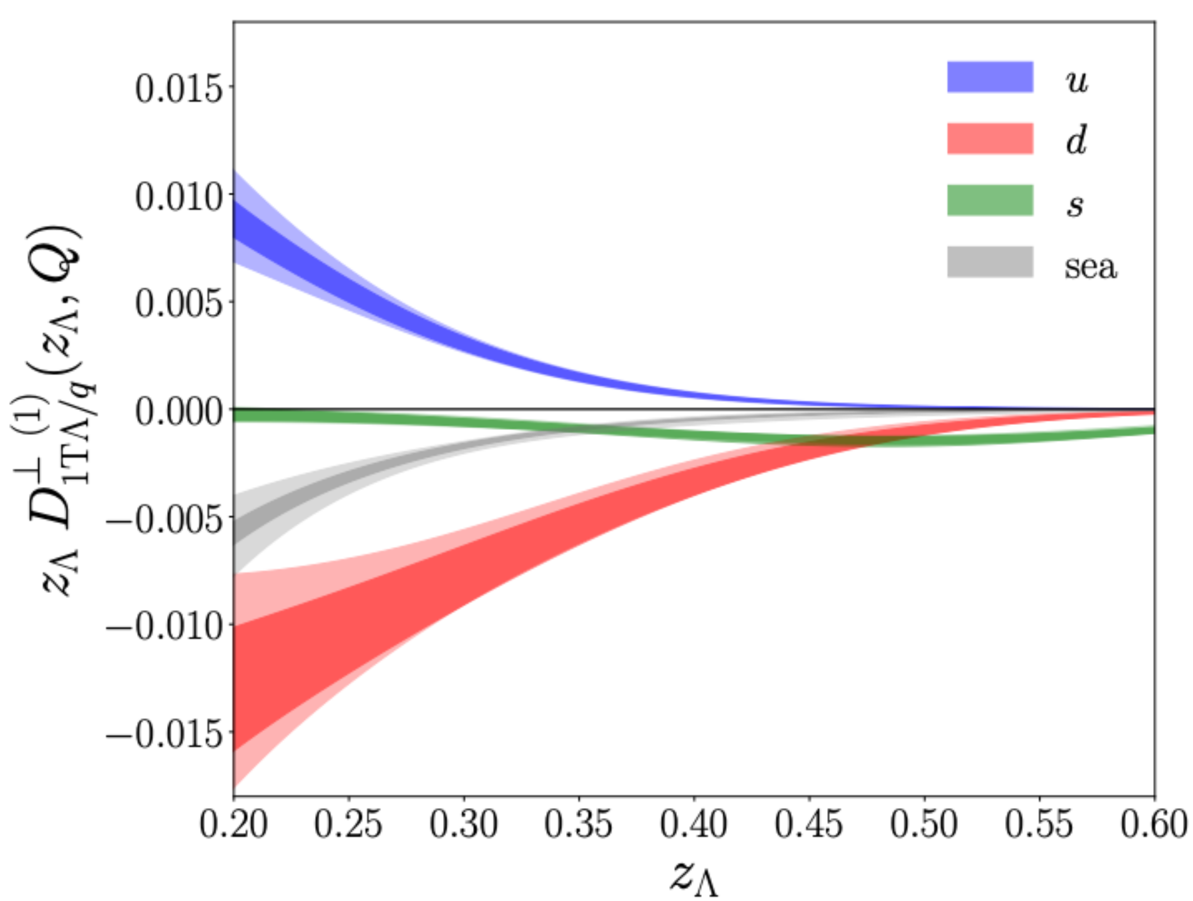
Polarizing fragmentation function

Fitting of PFFs from Λ+h data

Chen, Liang, Pan, Song, Wei '21



Kang, Terry, Vossen, Xu, Zhang '21

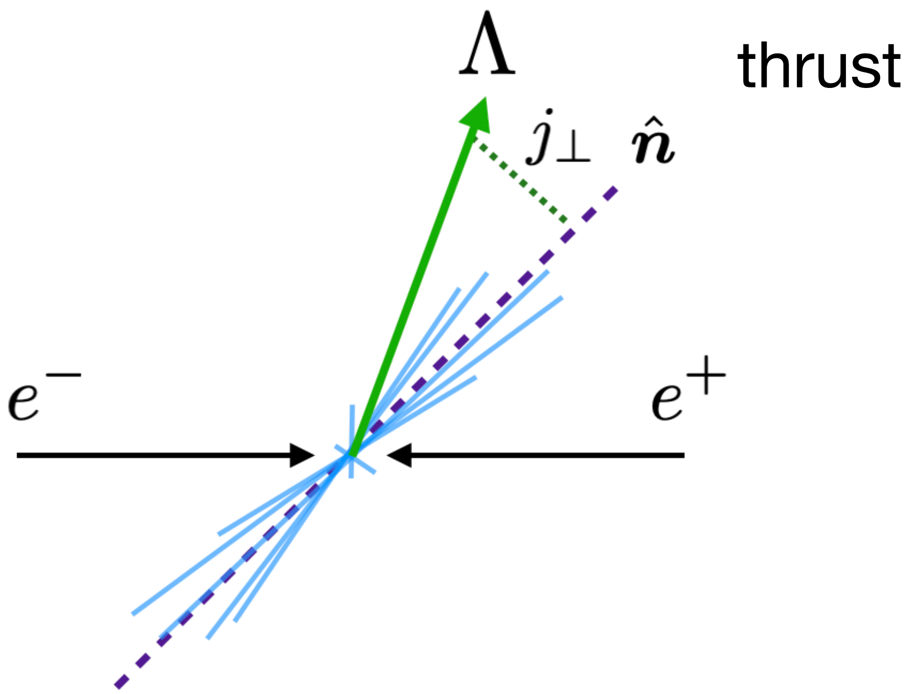


See also:
Yang, Lu, Schmidt '17
D' Alesio, Murgia, Zaccheddu '20
Callos, Kang, Terry '20
Li, Wang, Yang, Lu '20
… …

Light bands: the uncertainty from the fit to Belle data

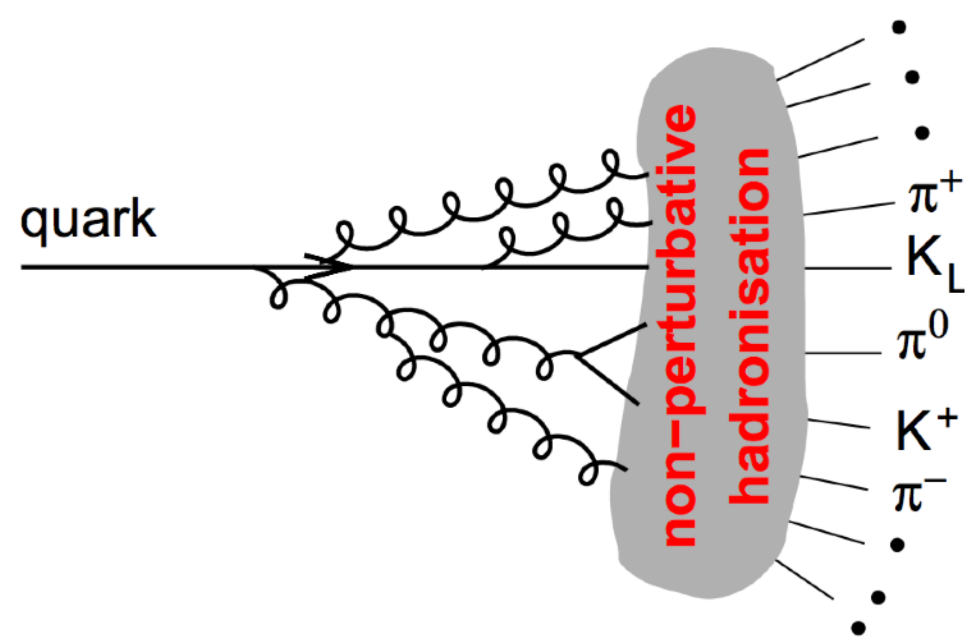
Dark bands: the simultaneous fit of the Belle data and the EIC pseudo-data

TMD factorization for Λ(thrust)



Wei, Chen, Song, Liang ’14; Yang, Chen, Liang ’17,……(Twist-4 FF, parton model on the jet)

Parton fragmentation and hadronization



From short to long distances in quantum field theory

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

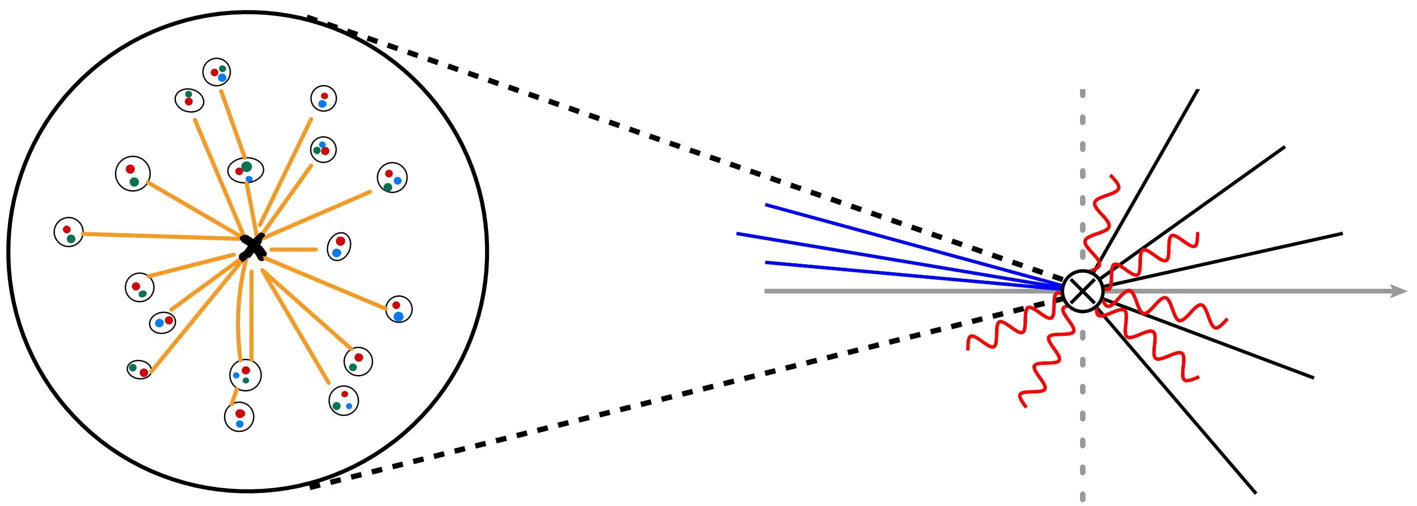
“Jets from Quantum Chromodynamics” Sterman & Weinberg ‘77

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)

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

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

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

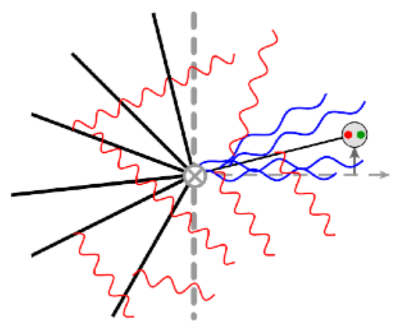
Collins, "*Foundations of perturbative QCD*"

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

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

Non-global observable; new TMD factorization

Kang, DYS, Zhao '20 JHEP



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

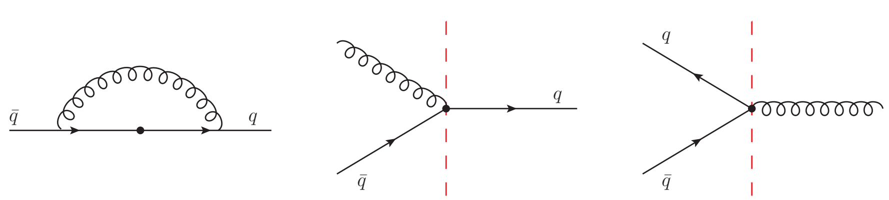
collinear: $p_c \sim Q(\lambda^2, 1, \lambda)$ $\qquad \lambda = j_T/Q \ll 1$

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

Factorization formula: (neglecting NGLs)

$$\frac{d\sigma}{dz_h d^2\vec{j}_T} = \sigma_0 \sum_{i=q,\bar{q},g} e_q^2 \int d^2\vec{k}_T\, d^2\vec{\lambda}_T\, \delta^{(2)}\left(\vec{j}_T - \vec{k}_T - z_h\vec{\lambda}_T\right) \mathcal{H}^i(Q,\mu) D_{h/i}(z_h, k_T, \mu, \zeta^2/\nu) \mathcal{S}_i(\lambda_T, \mu, \nu)$$

NLO hard function:



Divergences are half of the hard function in case-I

NLO soft function:

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

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

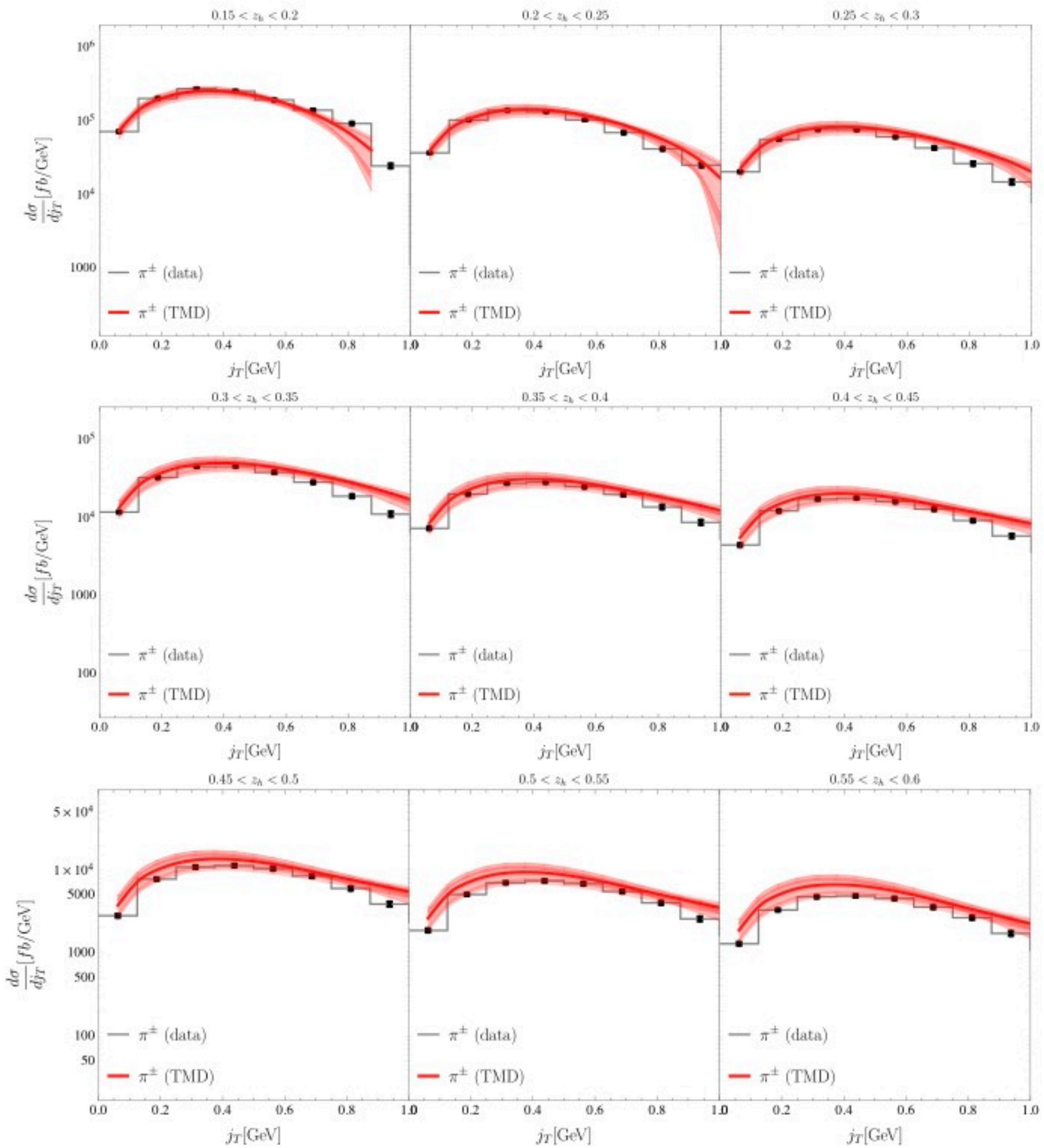
Divergences are half of the soft function in case-I

Factorization formula (full story)

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

"Multi-Wilson-line structure" (Caron-Hout '15; Becher, Neubert, Rothen & DYS '16 PRL; ……)

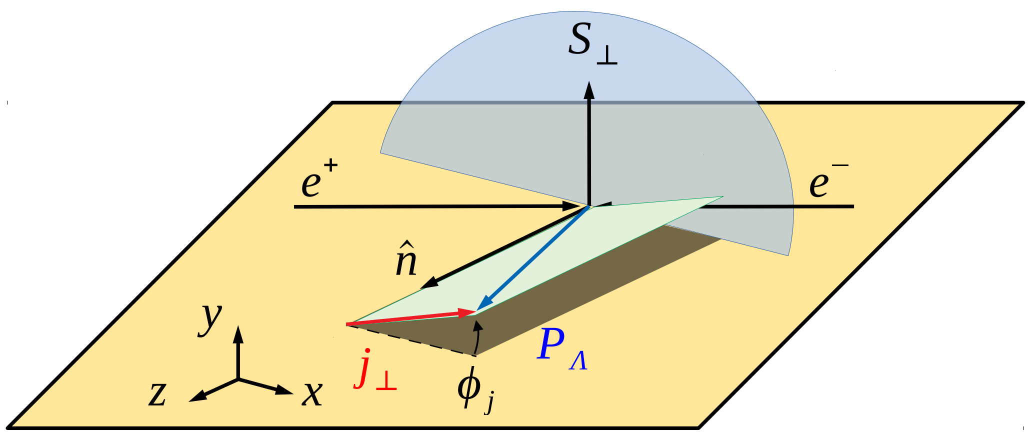
Numerical results



Our TMD resummation formula gives a good description of the shape of j_T distribution

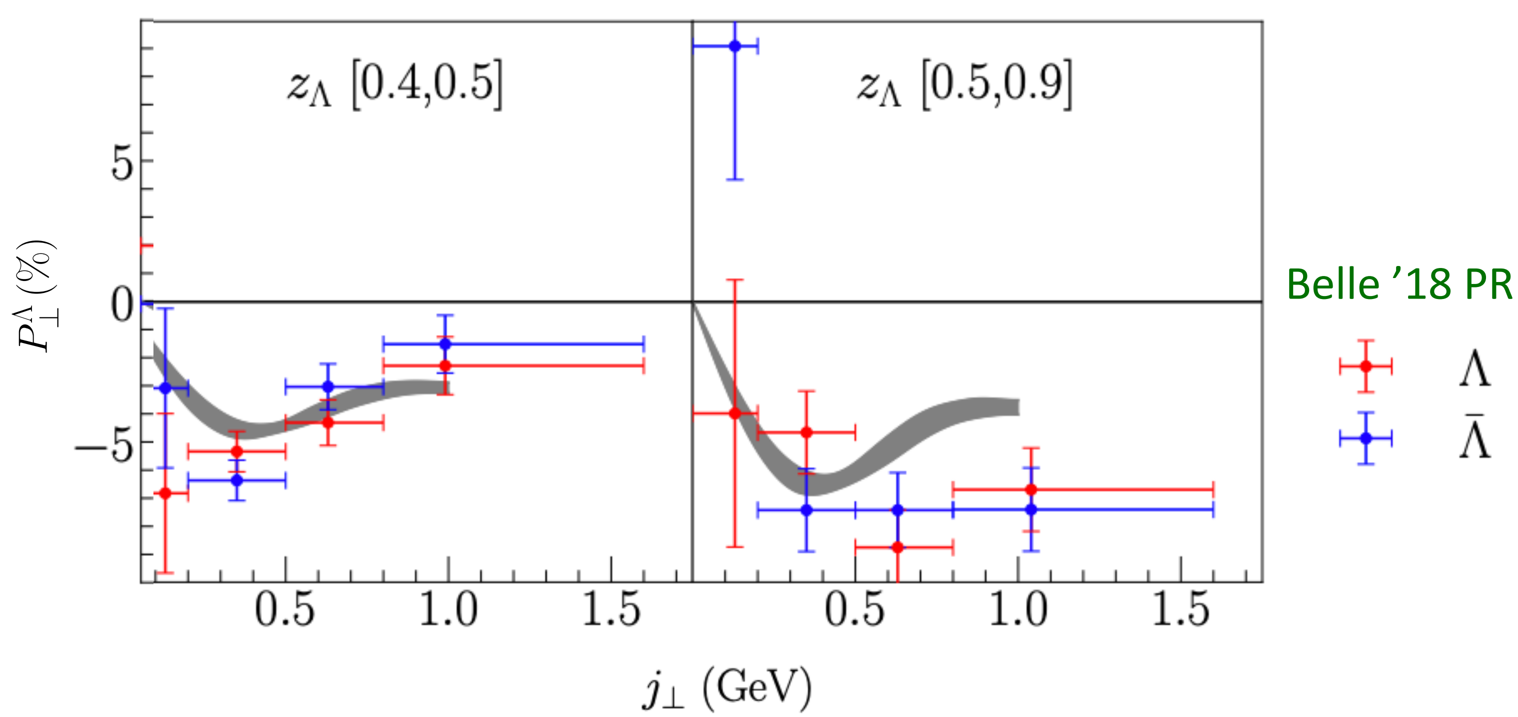
Factorization on transverse polarized Λ hyperon production with the thrust axis

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 predictions are consistent with Belle data



Theory formula including QCD evolution

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

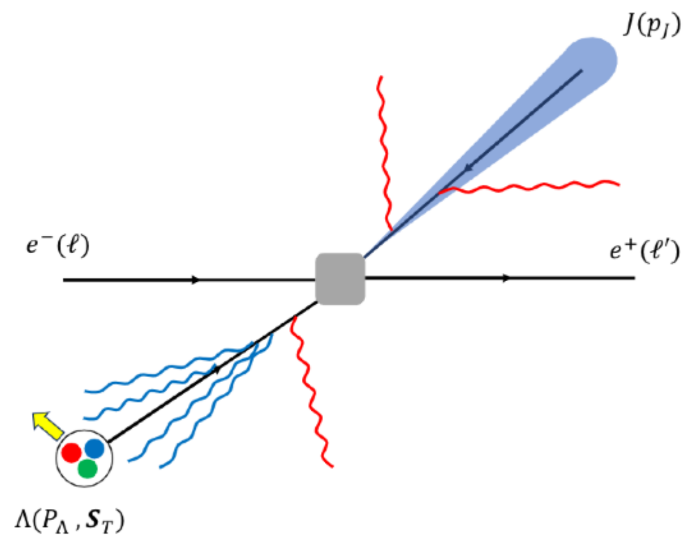
This result provides proof of principle that the experimental data can be described using the factorization and resummation formalism that we have introduced.

Transverse Lambda polarization and jet charge

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

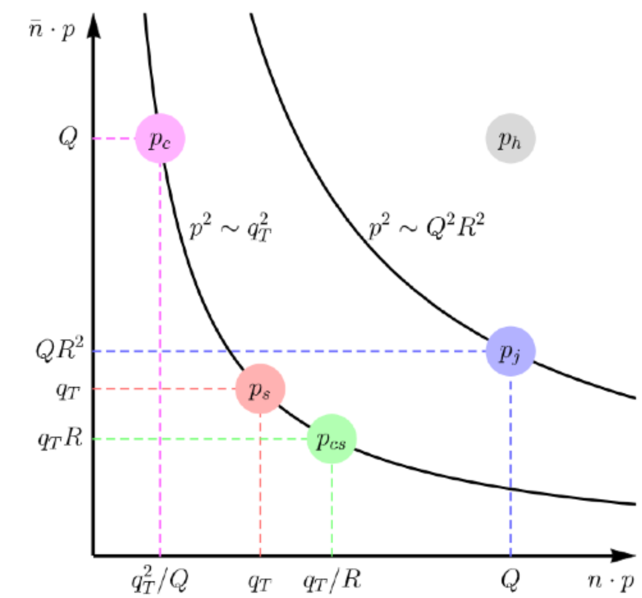
As shown in (Kang, Liu, Mantry, DYS '20 PRL), the jet charge observable is a novel probe of flavor structure for the hadron spin

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



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: $p_{cs} \sim q_T/R(1, R^2, R)$,

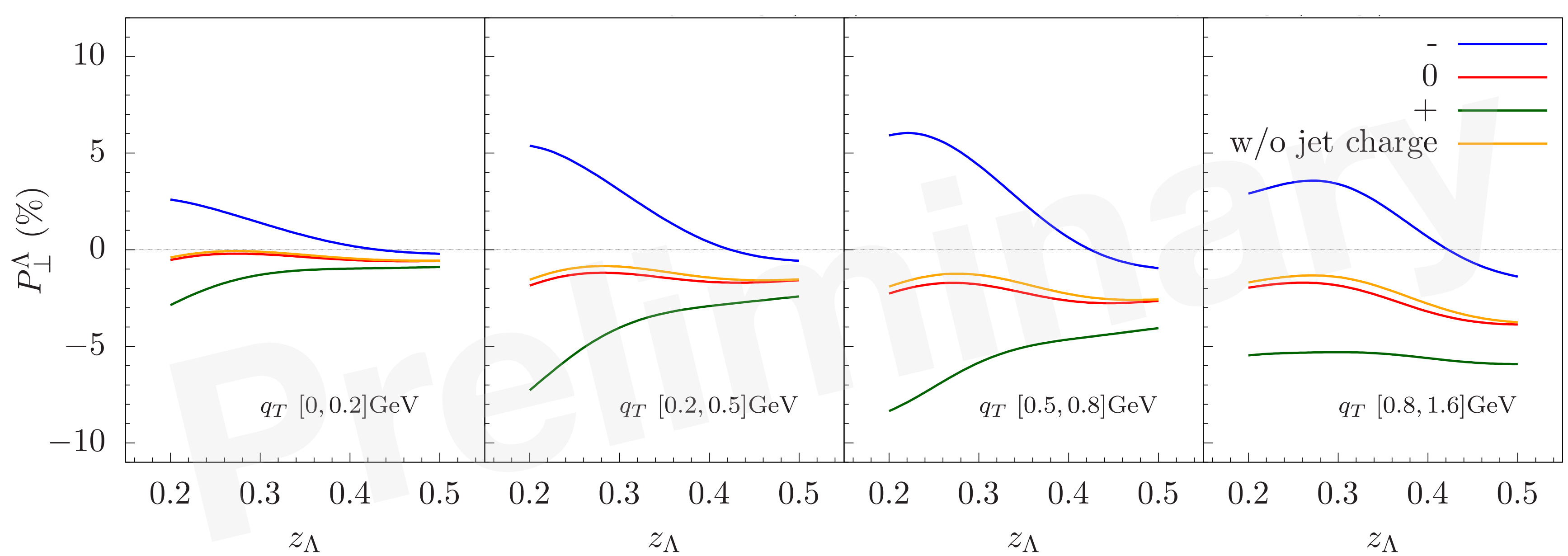


Jet charge definition: $Q_\kappa = \sum_i \left(\frac{p_{i,T}}{p_J}\right)^\kappa Q_i$

Charge tagged jet function:

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

Polarization w/ jet charge



Summary and Outlook

- We develop the theory framework to study transverse polarization effects for Λ(thrust) production in e^+e^- collisions
  - QCD effective field theory approach, model independent
  - TMD factorization formula, rapidity divergence is cancelled at two loop
  - Include QCD evolution (both linear and non-linear) from Q to $j_T \gtrsim \Lambda_{QCD}$
  - Our predictions are consistent with Belle data
  - Verify the universality of polarizing fragmentation function
  - We propose to use jet charge to separate different flavors of PFFs
- Jets and jet substructures can be calculated in pQCD, which offer new opportunity to understand hadron structures

Thank you