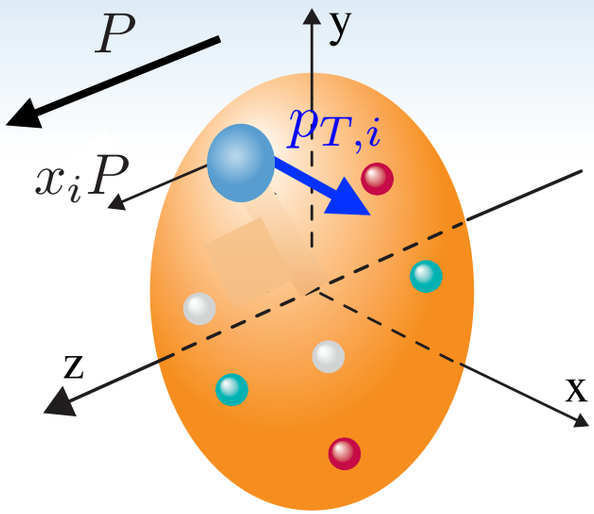
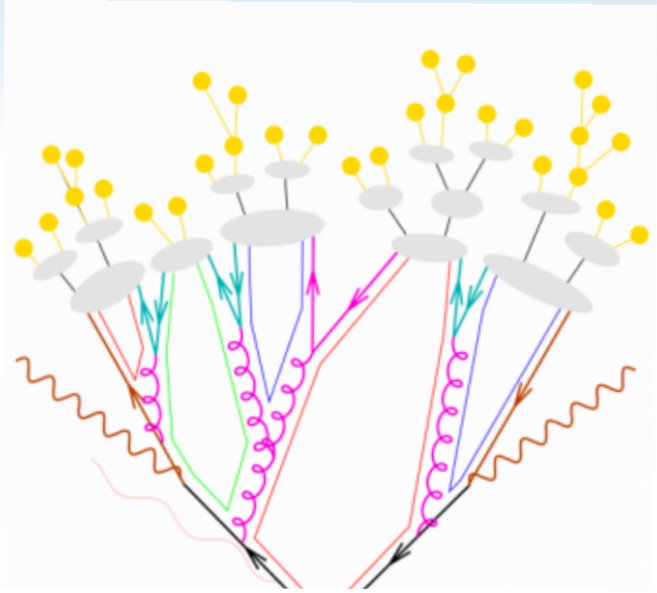
TMD structure at the EIC using jets

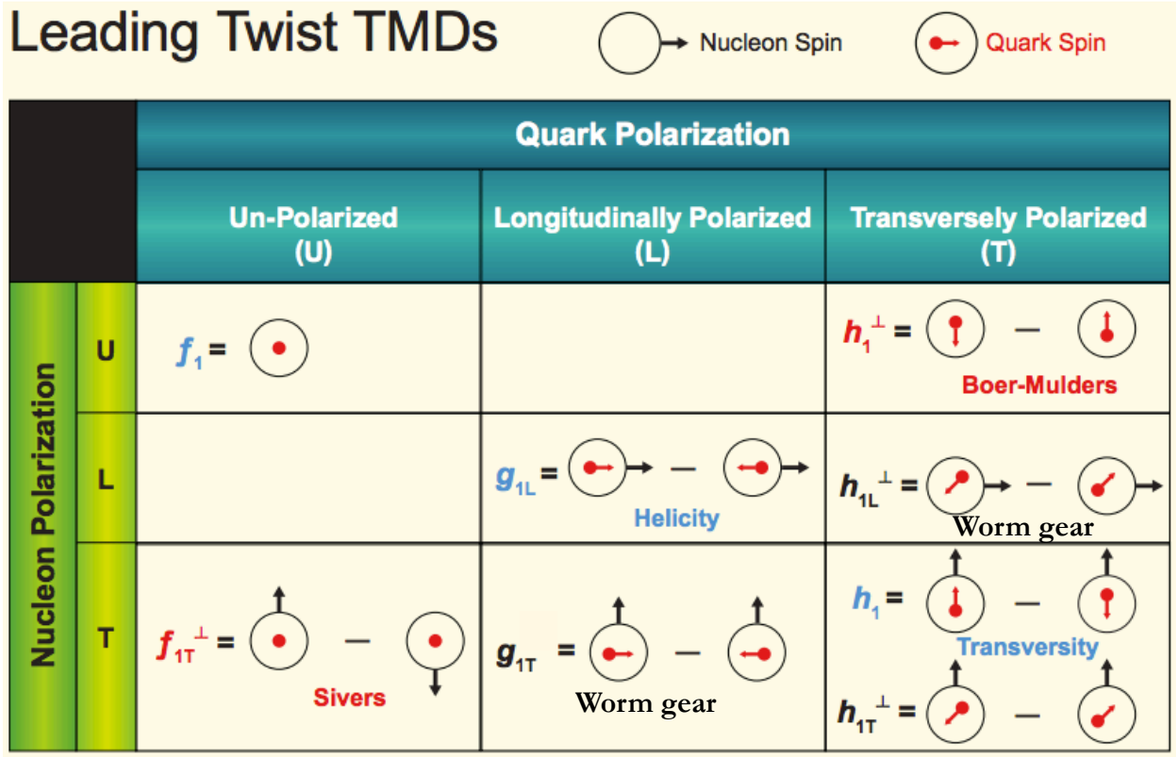
Kyle Lee
LBNL

EIC opportunities for Snowmass,
01/25/2021 - 01/29/2021

TMD structure







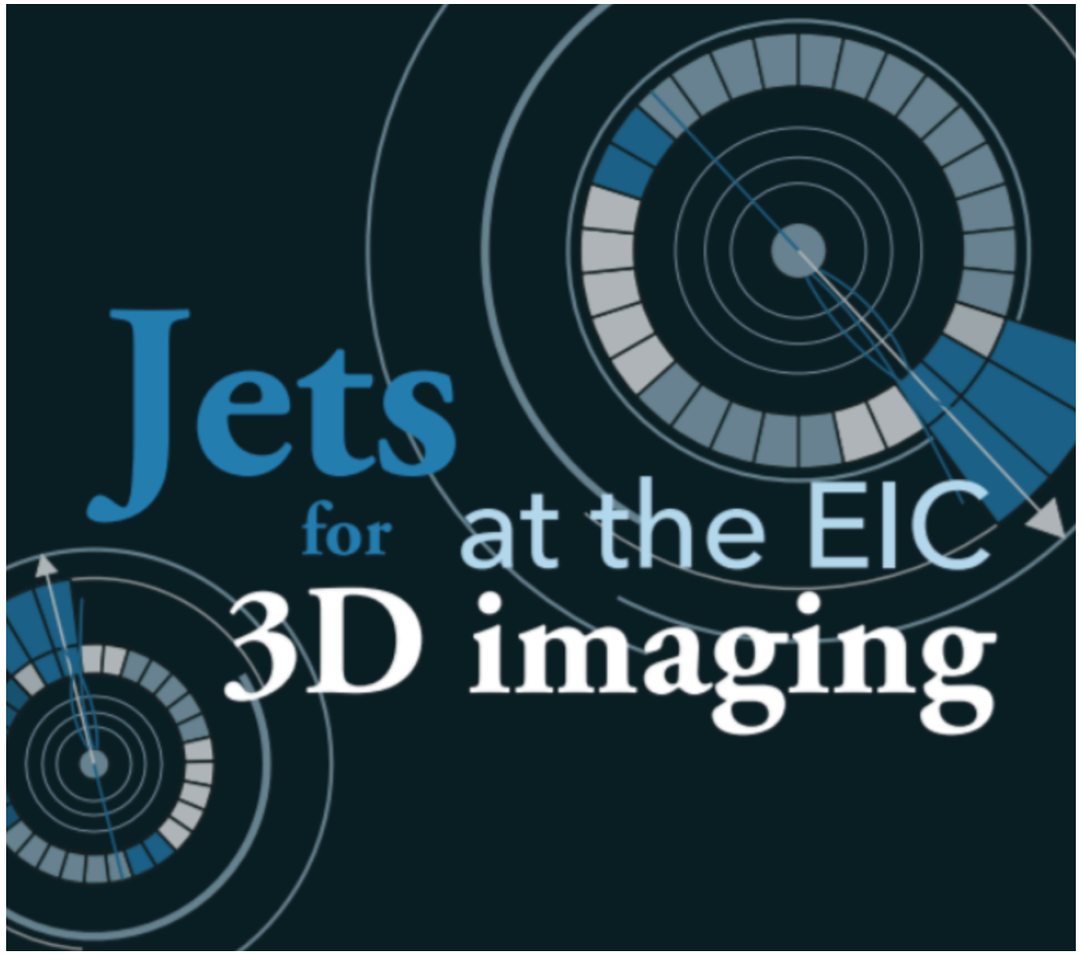
Quark polarization

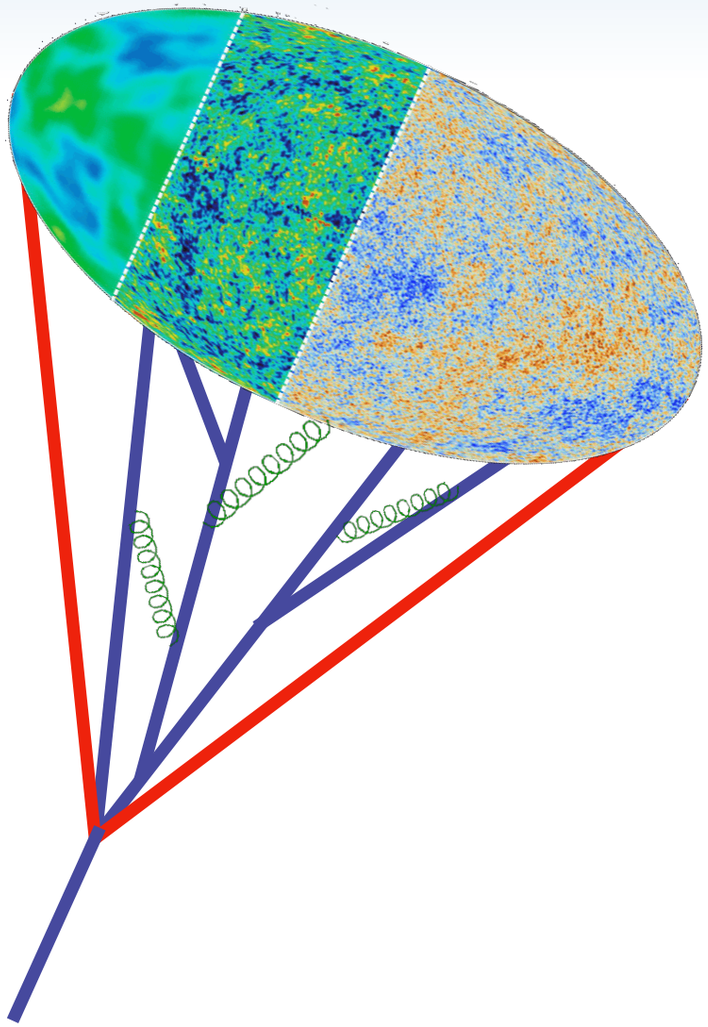
Hadron polarization	U	L	T
U	$D^{h/q}$		$H^{\perp h/q}$
L		$G^{h/q}$	$H_L^{\perp h/q}$
T	$D_T^{\perp h/q}$	$G_T^{h/q}$	$H^{h/q}$ $H_T^{\perp h/q}$

Quark TMDPDF inside spin- $\frac{1}{2}$ hadron

Quark TMDFF inside spin- $\frac{1}{2}$ hadron

Study of hadron structures



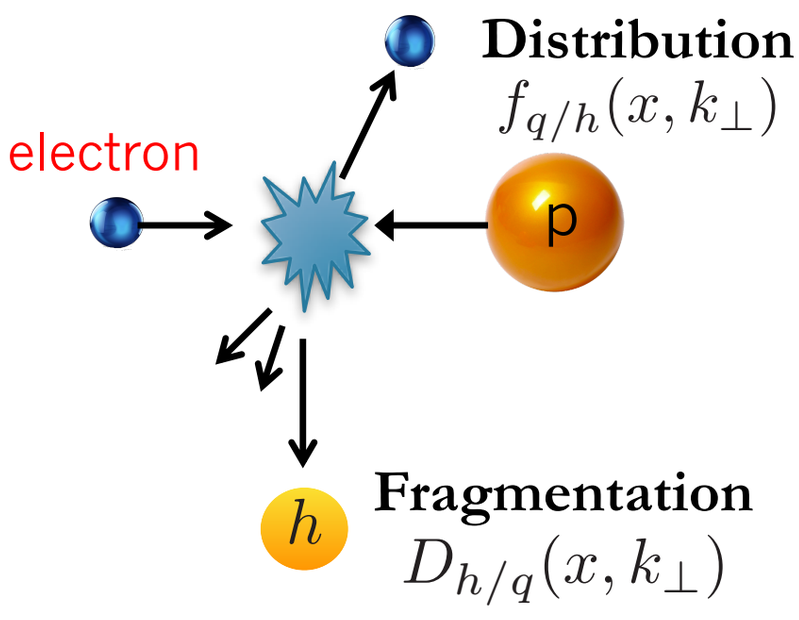


"Can we use jets at the EIC to probe TMD structure?"

Standard processes

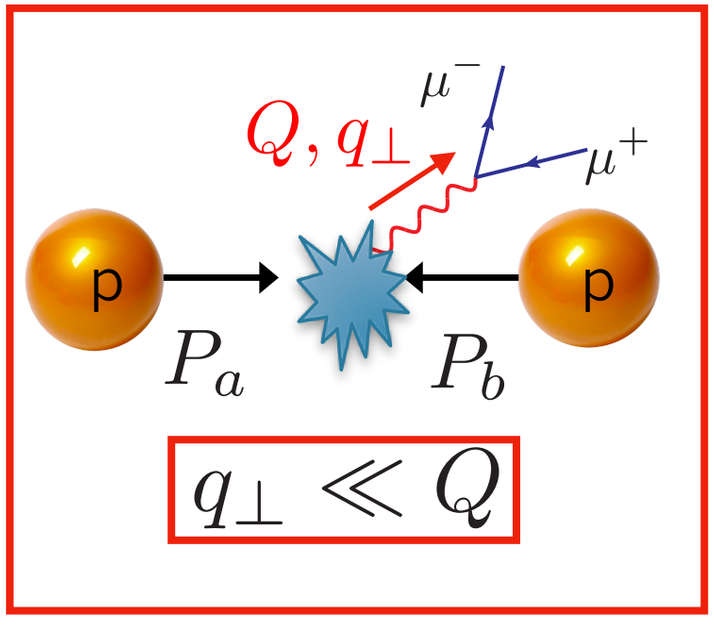
Semi-Inclusive DIS (SIDIS)

$$\sigma \sim f_{q/P}(x, k_\perp) D_{h/q}(x, k_\perp)$$



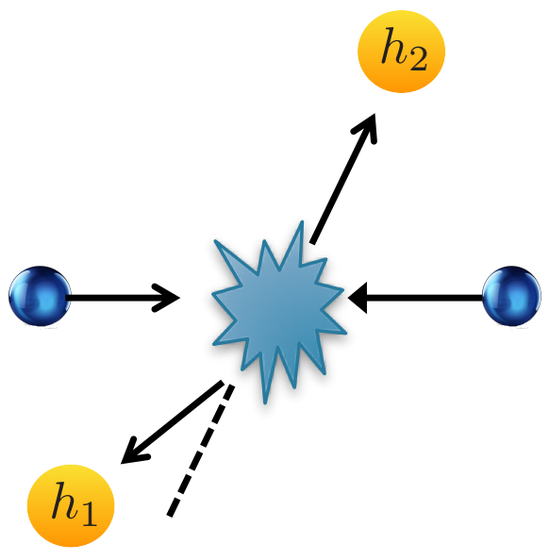
Drell-Yan

$$\sigma \sim f_{q/P}(x, k_\perp) f_{\bar{q}/P}(x, k_\perp)$$



Dihadrons in e^+e^-

$$\sigma \sim D_{h_1/q}(x, k_\perp) D_{h_2/q}(x, k_\perp)$$



(CSS) Collin, Soper, Sterman `81-`85
Ji, Ma, Yuan ` 04
Becher, Neubert, Wilhelm `11-`13
Echevarria, Idilbi, Scimemi `11-`14
...

Beyond the standard processes

- Many other imaginable processes with sensitivity to the TMD structure

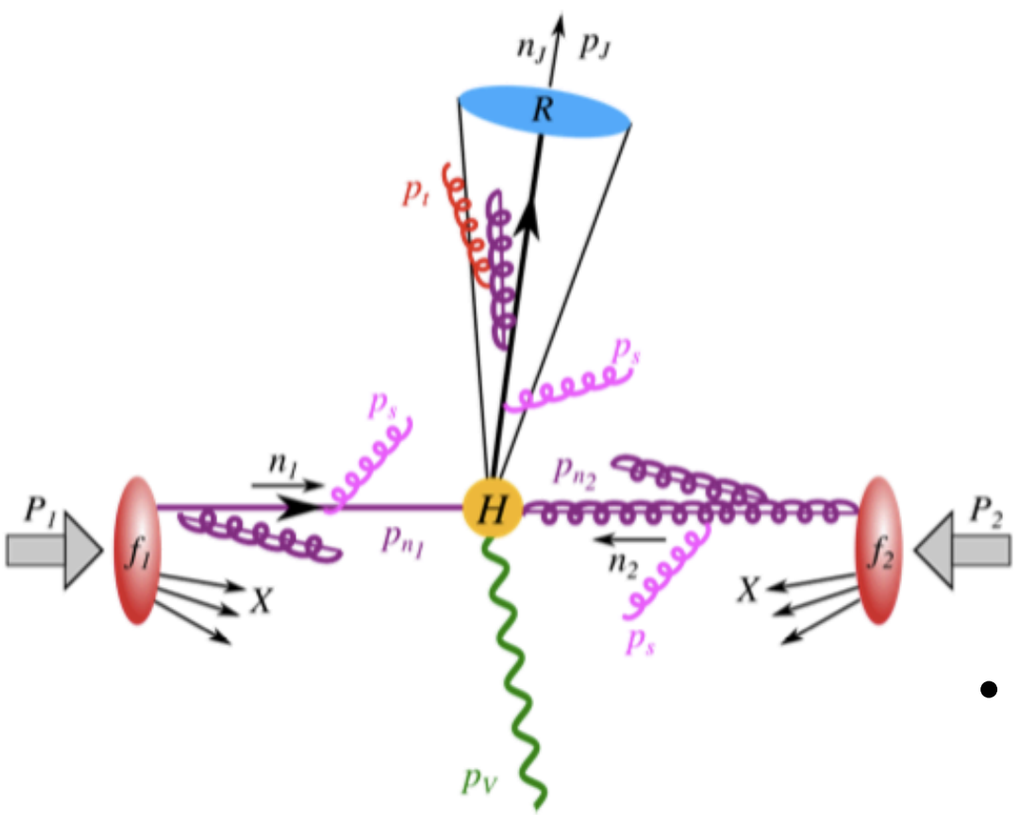


Fig. from Chien, Shao, Wu `19

$PP \to J_1 + J_2 + X,$	$e\,P \to e + J + X$
$PP \to J + V + X,$	$e\,P \to Q + \bar{Q} + X,$
$PP \to J(h) + X, \ldots$	$e\,P \to J(h) + X, \ldots$
LHC / RHIC	**EIC**

- Many experiments sensitive to such processes
- Standard processes have low sensitivity to gluon TMDs.
- Standard processes sensitive to two TMDs simultaneously; many involving jets will only be sensitive to a single TMD.

1) Inclusive jet production

$$e\,P \to J(h) + X$$

2) Lepton + jet imbalance

$$e\,P \to e + J + X$$

3) Lepton + jet imbalance with hadron in jet

$$e\,P \to e + J(h) + X$$

Hadron inside inclusive jet production

Unpolarized case:

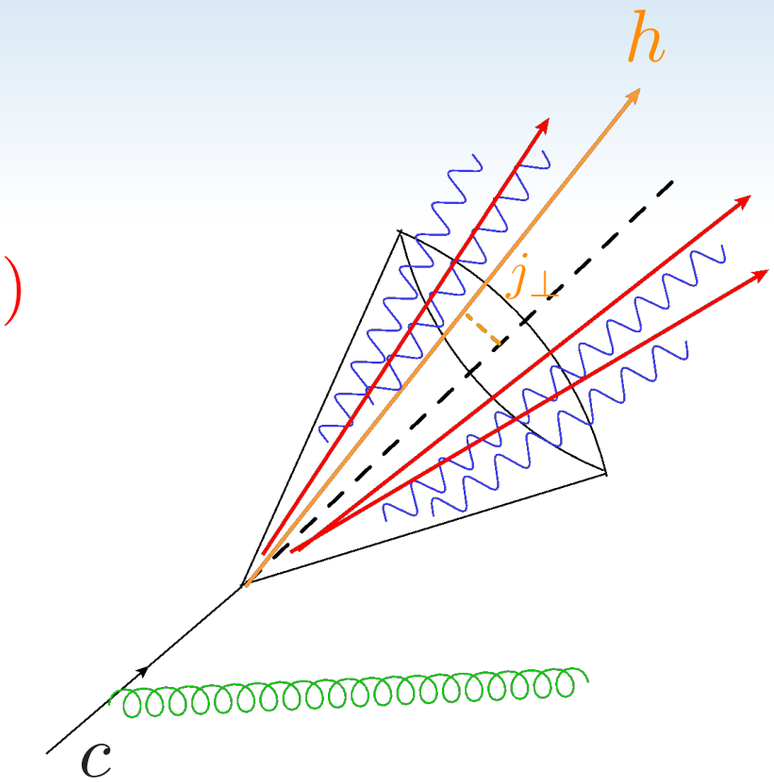
(replace pp with ep for EIC)

$$\frac{d\sigma^{pp\to \mathrm{jet}(h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes H^c_{ab} \otimes \mathcal{G}^h_c(z_h, \boldsymbol{j}_\perp)$$

Λ_{QCD} $\quad p_T \quad$ $p_T R$, Λ_{QCD}

where $z = p_T^J / p_T^c$

$z_h = p_T^h / p_T^J$



TMD Fragmentation Functions (TMDFFs)

Quark polarization

Hadron polarization	U	L	T
U	$D^{h/q}$		$H^{\perp h/q}$
L		$G^{h/q}$	$H_L^{\perp h/q}$
T	$D_T^{\perp h/q}$	$G_T^{h/q}$	$H^{h/q}$ $H_T^{\perp h/q}$

TMD Jet Fragmentation Functions (TMDJFFs)

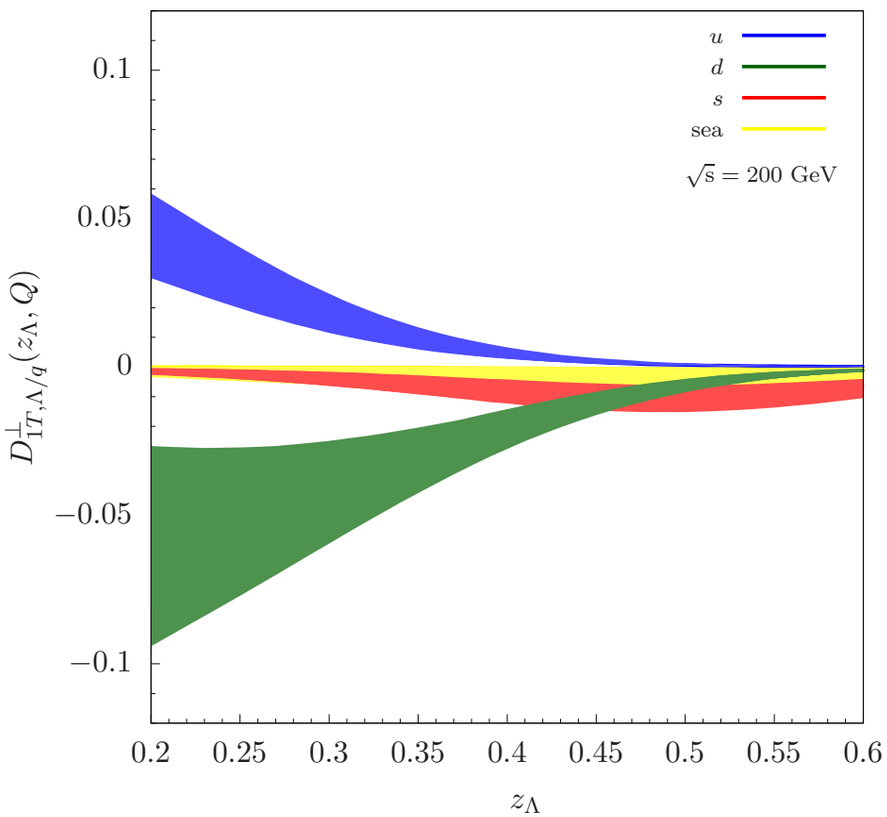
Quark polarization

Hadron polarization	U	L	T
U	$\mathcal{D}^{h/q}$		$\mathcal{H}^{\perp h/q}$
L		$\mathcal{G}^{h/q}$	$\mathcal{H}_L^{\perp h/q}$
T	$\mathcal{D}_T^{\perp h/q}$	$\mathcal{G}_T^{h/q}$	$\mathcal{H}^{h/q}$ $\mathcal{H}_T^{\perp h/q}$

Polarizing JFF

- **Polarizing FF fits from Belle data**

Callos, Kang, Terry, `20



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Polarizing FF

TMD Jet Fragmentation Functions (TMDJFFs)

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Polarizing JFF

Kang, KL, Zhao, `20

Polarizing JFF

- **Polarizing FF fits from Belle data**

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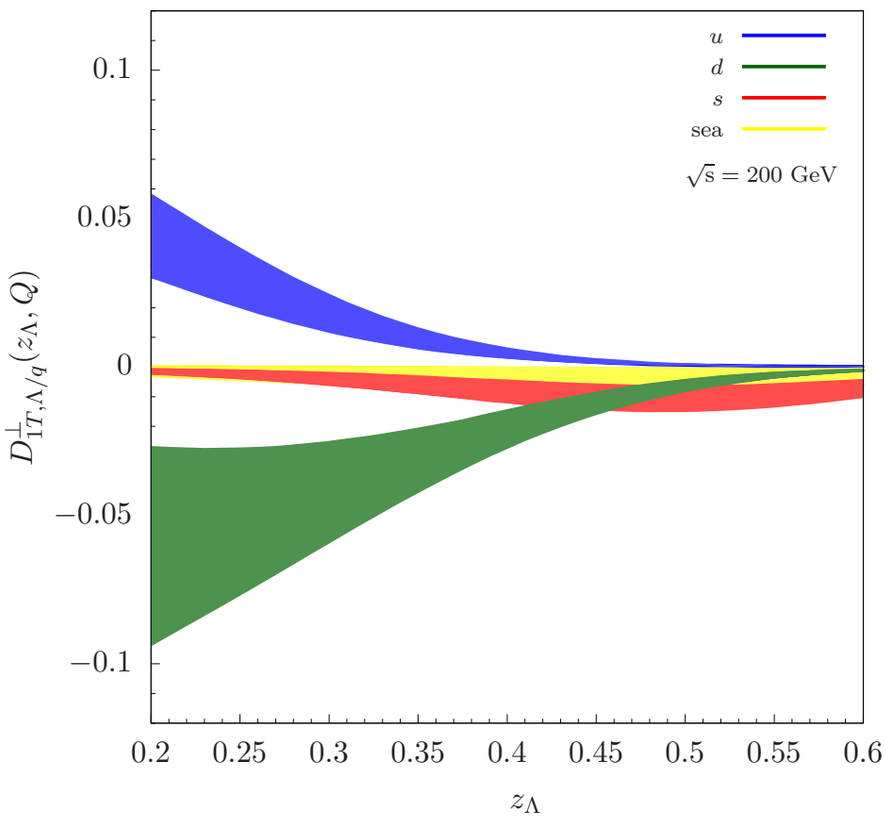

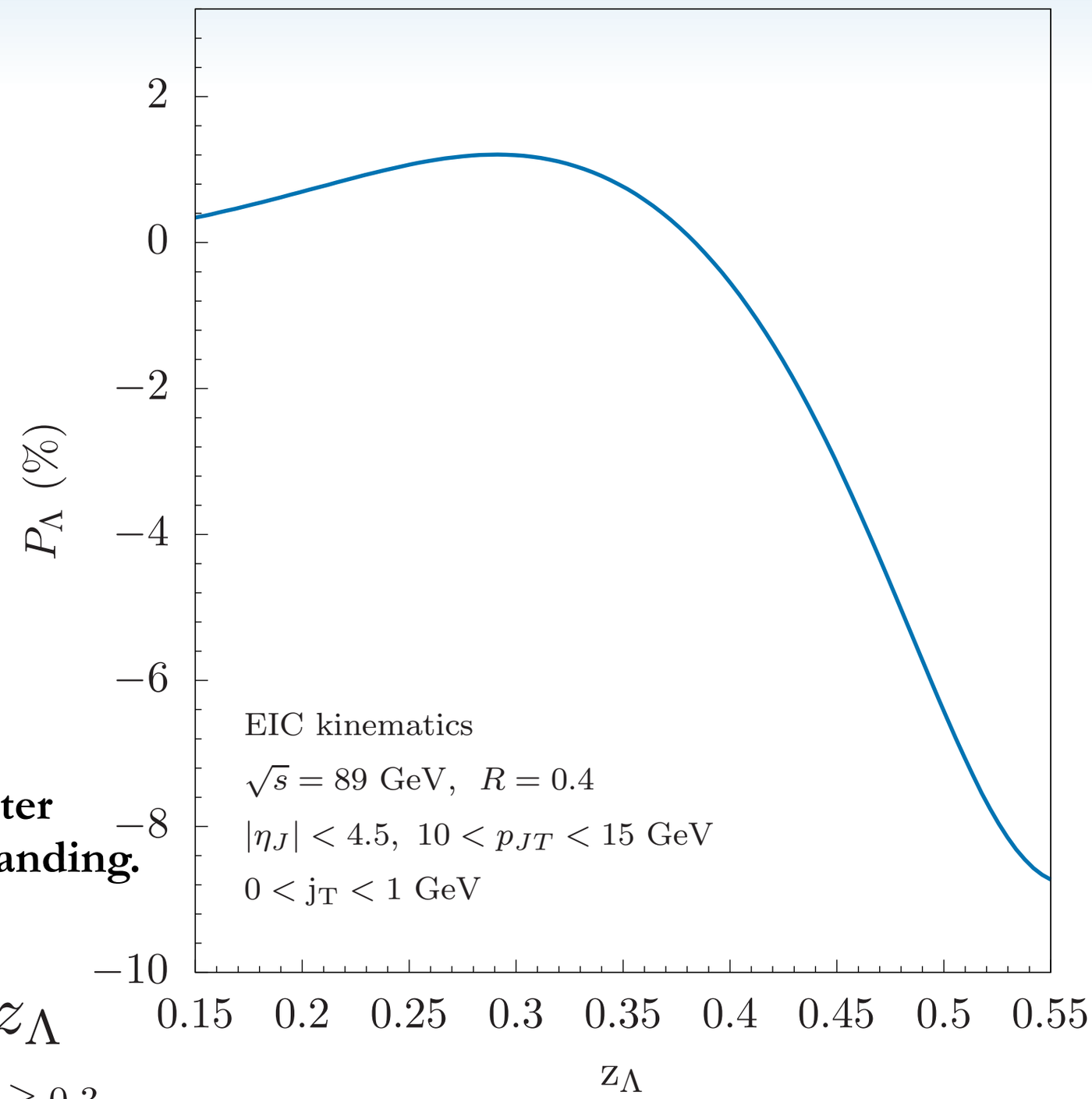

- **Differential information in z_Λ gives better constraint on data / qualitative understanding.**
- **Predictions at the EIC kinematics**
  - **Positive from up quark PFF at small z_Λ**
  - **Negative from down quark PFF at $z_\Lambda \gtrsim 0.3$**

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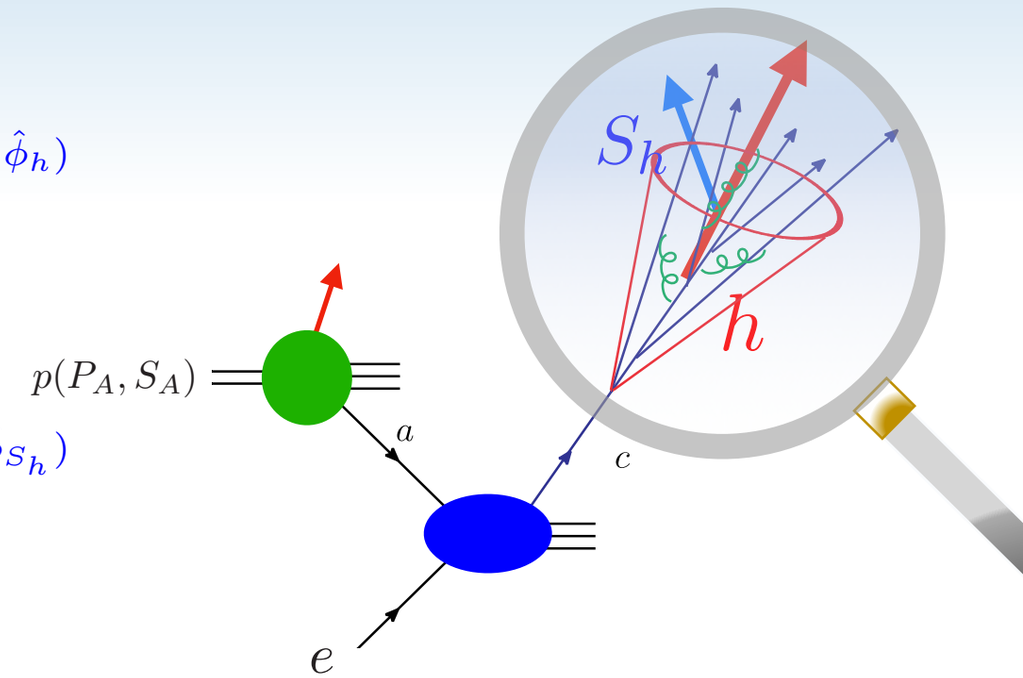
Azimuthal angular dependence

$$\frac{d\sigma^{p(S_A)+p/e\to(\text{jet } h(S_h))X}}{dp_{JT}d\eta_J dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + |\boldsymbol{S}_T|\sin(\phi_{S_A}-\hat{\phi}_h)F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)}$$
$$+\Lambda_h\left[\lambda F_{LU,L} + |\boldsymbol{S}_T|\cos(\phi_{S_A}-\hat{\phi}_h)F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)}\right]$$
$$+|\boldsymbol{S}_{h\perp}|\Big\{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda\cos(\hat{\phi}_h-\hat{\phi}_{S_h})F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})}$$
$$+|\boldsymbol{S}_T|\big(\cos(\phi_{S_A}-\hat{\phi}_{S_h})F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})}$$
$$+\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})}\big)\Big\},$$



$$F_{S_A S_B, S_h}$$

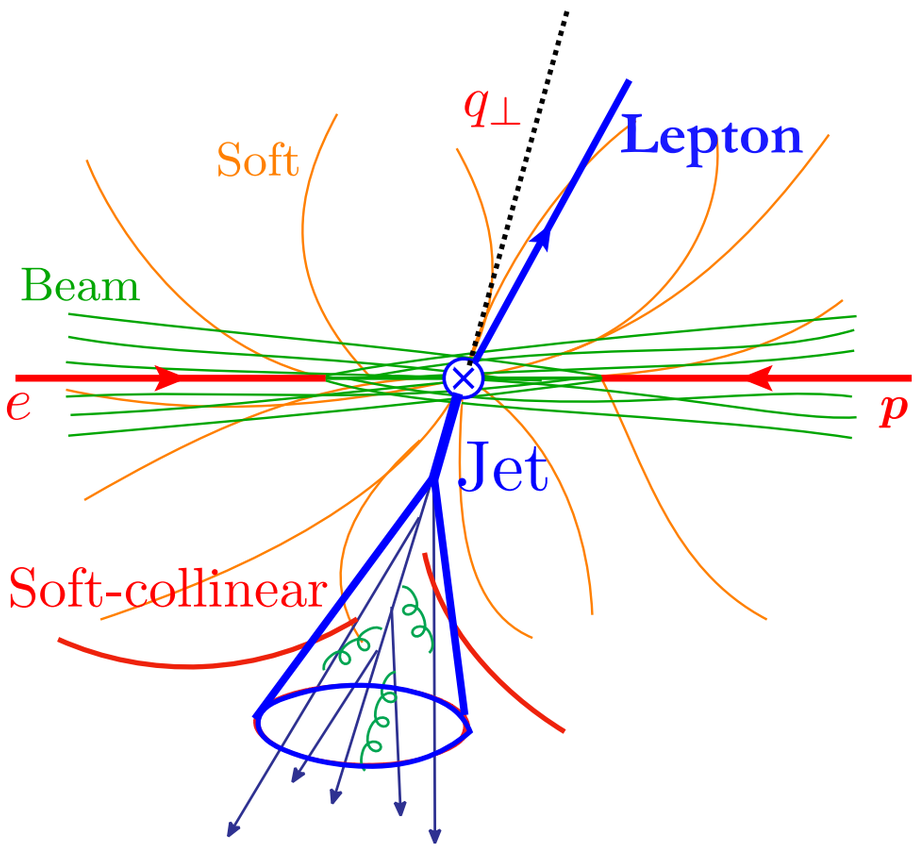
Polarization of A, B, h

- **Different structures come with different characteristic angular dependence.**

Kang, KL, Zhao, `20

Lepton + Jet imbalance

- **One of the simplest process** $e + P \to e + \text{Jet} + X$



$$q_\perp \equiv |\vec{p}_{e\perp} + \vec{p}_{J\perp}|, \qquad p_\perp \equiv |\vec{p}_{e\perp} - \vec{p}_{J\perp}|/2$$

$q_\perp \ll p_\perp$, **sensitive to the large logs of** $\ln(q_\perp/p_\perp)$ **and TMD structures of the hadrons.**

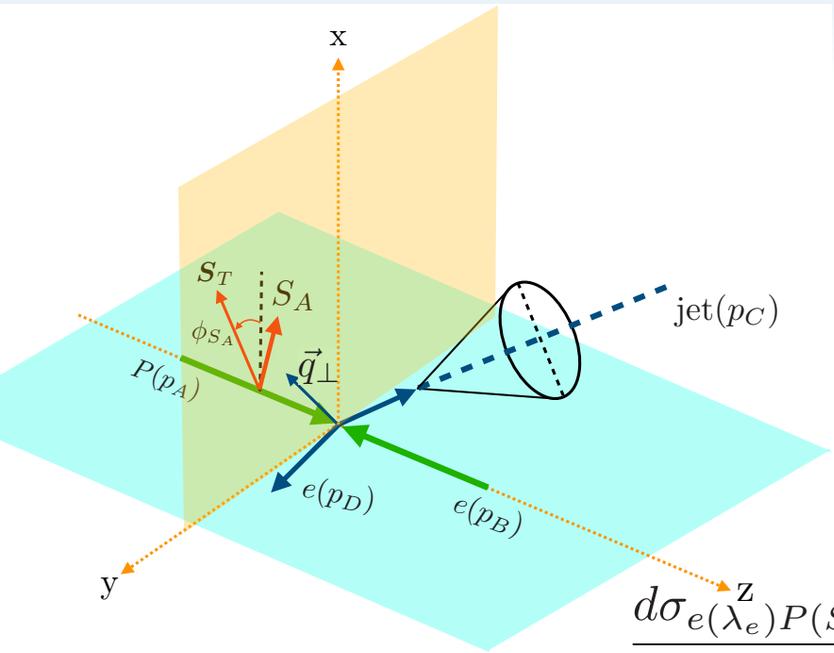
$$q_\perp = p_{X,\perp} = |\vec{k}_{c,\perp} + \vec{k}_{gs,\perp} + \vec{k}_{sc,\perp}|$$

Giving relevant modes : $(+,-,\perp)$ $\qquad \lambda = q_\perp/p_\perp$

n-collinear	$k_n \sim p_\perp(\lambda^2, 1, \lambda)_{n\bar{n}}$
global soft	$k_{gs} \sim p_\perp(\lambda, \lambda, \lambda)$
soft-collinear	$k_{sc} \sim p_\perp R(\lambda R, \lambda/R, \lambda)_{n_J,\bar{n}_J}$
n_J-collinear	$k_J \sim p_\perp(R^2, 1, R)_{n_J,\bar{n}_J}$

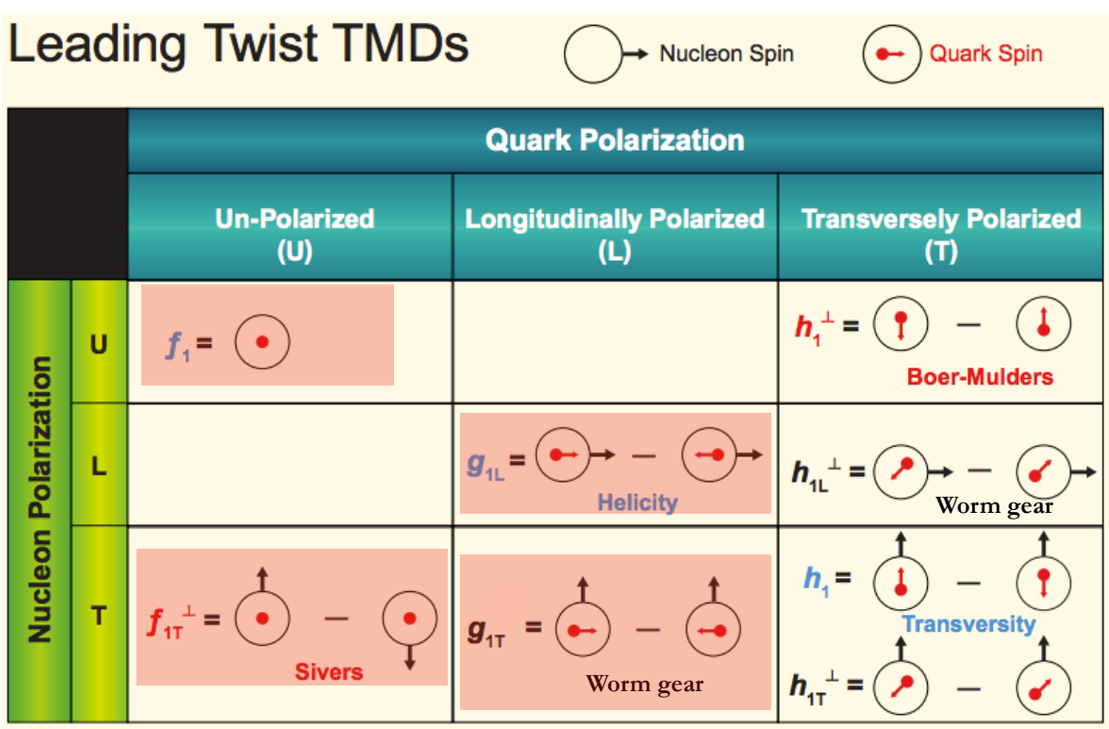
Liu, Ringer, Vogelsang, Yuan `18, `20
Arratia, Kang, Prokudin, Ringer `20

Lepton + Jet imbalance



$$\frac{d\sigma_{eP\to e+\text{jet}}}{dp_\perp dq_\perp} = \int \prod_i^3 d^2k_{i\perp} H(Q)\delta^{(2)}(\vec{k}_{1\perp}+\vec{k}_{2\perp}+\vec{k}_{3\perp}-q_\perp) \times f_a(x,\vec{k}_{1\perp}) S^{\text{global}}(\vec{k}_{2\perp}) S_{J_c}(\vec{k}_{3\perp}) J_c(p_\perp R)$$

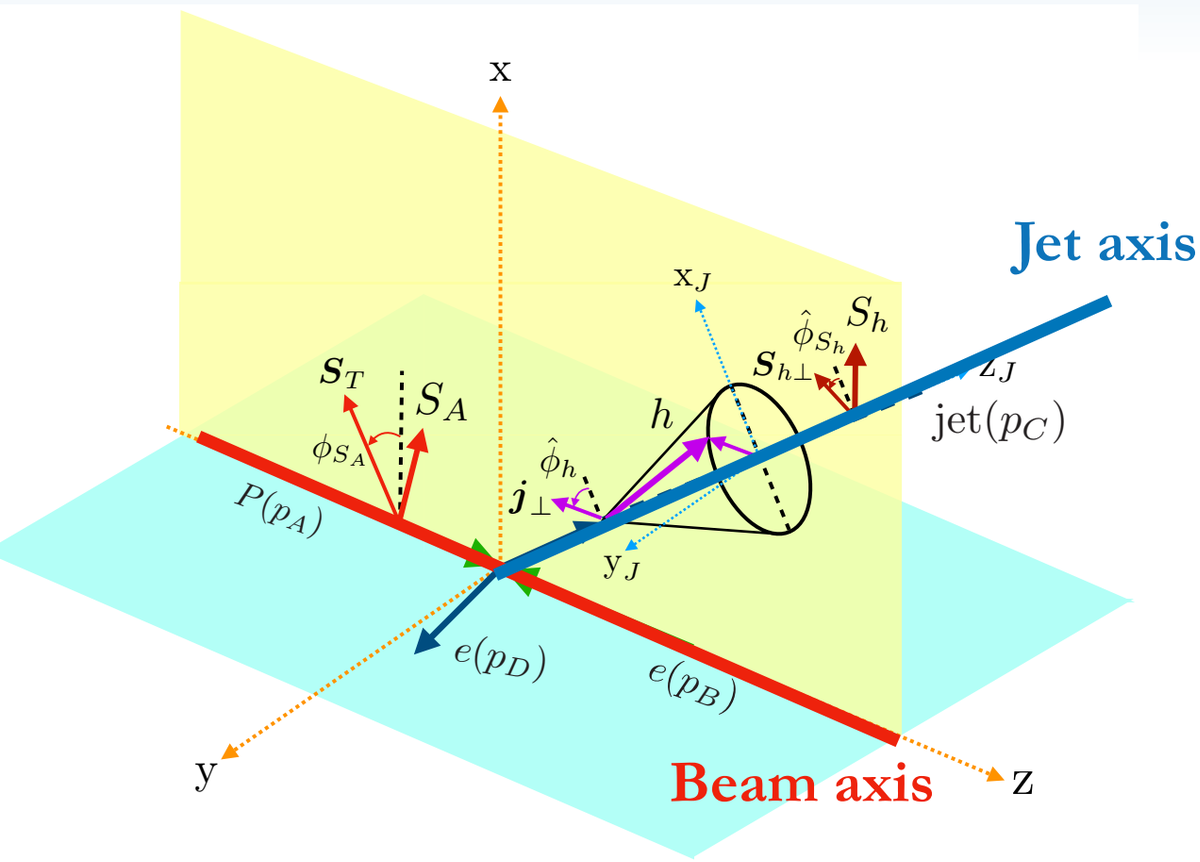
$$\frac{d\sigma_{e(\lambda_e)P(S)\to e+\text{jet}}}{dp_\perp dq_\perp} = \underbrace{F_{UU}}_{\sim f_1} + \lambda_p\lambda_e \underbrace{F_{LL}}_{\sim g_{1L}} + S_T\Big\{\sin(\phi_{S_A}-\phi_q)\underbrace{F_{TU}^{\sin(\phi_{S_A}-\phi_q)}}_{\sim f_{1T}^\perp} + \lambda_e\cos(\phi_{S_A}-\phi_q)\underbrace{F_{TL}^{\cos(\phi_{S_A}-\phi_q)}}_{\sim g_{1T}}\Big\},$$



- **With jet, only sensitive to single TMDs (compared to standard processes)**
- **We do not get sensitivity to all TMDPDFs**

Liu, Ringer, Vogelsang, Yuan `18, `20
Arratia, Kang, Prokudin, Ringer `20
Kang, KL, Shao, Zhao; In progress

Polarized Jet Fragmentation Functions and lepton + jet imbalance



- Observation of polarized hadron inside jet gives sensitivity to all TMDPDFs and TMDFFs. (analogous correlations to standard SIDIS)
- Sensitivity to two TMDs, but sensitive to $\vec{q}_\perp$ and $\vec{j}_\perp$ separately (advantage of two axes)

Many characteristic correlations

$$
\begin{aligned}
\frac{d\sigma^{p(S_A)+e(\lambda_e)\to e+(\mathrm{jet}\,h(S_h))+X}}{dy_l d^2\boldsymbol{l}_T d^2\boldsymbol{q}_T dz_h d^2\boldsymbol{j}_\perp} &= F_{UU,U} + \cos(\phi_q-\hat{\phi}_h)F_{UU,U}^{\cos(\phi_q-\hat{\phi}_h)} \\
&+ \lambda_p\Big\{\lambda_e F_{LL,U} + \sin(\phi_q-\hat{\phi}_h)F_{LU,U}^{\sin(\phi_q-\hat{\phi}_h)}\Big\} \\
&+ S_T\Big\{\sin(\phi_{S_A}-\phi_q)F_{TU,U}^{\sin(\phi_{S_A}-\phi_q)} + \lambda_e\cos(\phi_{S_A}-\phi_q)F_{TL,U}^{\cos(\phi_{S_A}-\phi_q)} \\
&\quad + \sin(\phi_{S_A}-\hat{\phi}_h)F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)} + \sin(2\phi_q-\hat{\phi}_h-\phi_{S_A})F_{TU,U}^{\sin(2\phi_q-\hat{\phi}_h-\phi_{S_A})}\Big\} \\
&+ \Lambda_h\Big\{\lambda_e F_{UL,L} + \sin(\phi_q-\hat{\phi}_h)F_{UU,L}^{\sin(\phi_q-\hat{\phi}_h)} + \lambda_p\Big[F_{LU,L} + \cos(\phi_q-\hat{\phi}_h)F_{LU,L}^{\cos(\phi_q-\hat{\phi}_h)} \\
&\quad + S_T\Big[\cos(\phi_{S_A}-\phi_q)F_{TU,L}^{\cos(\phi_{S_A}-\phi_q)} + \lambda_e\sin(\phi_{S_A}-\phi_q)F_{TL,L}^{\sin(\phi_{S_A}-\phi_q)} \\
&\quad + \cos(\phi_{S_A}-\hat{\phi}_h)F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)} + \cos(2\phi_q-\phi_{S_A}-\hat{\phi}_h)F_{TU,L}^{\cos(2\phi_q-\phi_{S_A}-\hat{\phi}_h)}\Big]\Big\} \\
&+ S_{h\perp}\Big\{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda_e\cos(\hat{\phi}_h-\hat{\phi}_{S_h})F_{UL,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})} \\
&\quad + \sin(\phi_q-\hat{\phi}_{S_h})F_{UU,T}^{\sin(\phi_q-\hat{\phi}_{S_h})} + \sin(\hat{\phi}_{S_h}+\phi_q-2\hat{\phi}_h)F_{UU,T}^{\sin(\hat{\phi}_{S_h}+\phi_q-2\hat{\phi}_h)} \\
&\quad + \lambda_p\Big[\cos(\hat{\phi}_h-\hat{\phi}_{S_h})F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})} + \cos(\phi_q-\hat{\phi}_{S_h})F_{LU,T}^{\cos(\phi_q-\hat{\phi}_{S_h})} \\
&\quad + \cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_q)F_{LU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_q)} + \lambda_e\sin(\hat{\phi}_h-\hat{\phi}_{S_h})F_{LL,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})}\Big] \\
&\quad + S_T\Big[\cos(\phi_{S_A}-\hat{\phi}_{S_h})F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})} + \cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})} \\
&\quad + \sin(\hat{\phi}_h-\hat{\phi}_{S_h})\sin(\phi_{S_A}-\phi_q)F_{TU,T}^{\sin(\phi_{S_A}-\hat{\phi}_h)\sin(\phi_q-\phi_{S_A})} \\
&\quad + \cos(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_{S_A}-\phi_q))F_{TU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_{S_A}-\phi_q)} \\
&\quad + \cos(2\phi_q-\phi_{S_A}-\hat{\phi}_{S_h})F_{TU,T}^{\cos(2\phi_q-\phi_{S_A}-\hat{\phi}_{S_h})} \\
&\quad + \cos(2\hat{\phi}_h-\hat{\phi}_{S_h}+2\phi_q-\phi_{S_A})F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}+2\phi_q-\phi_{S_A})} \\
&\quad + \lambda_e\cos(\hat{\phi}_h-\hat{\phi}_{S_h})\sin(\phi_{S_A}-\phi_q)F_{TL,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})\sin(\phi_{S_A}-\phi_q)} \\
&\quad + \lambda_e\sin(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_{S_A}-\phi_q))F_{TL,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_{S_A}-\phi_q)}\Big]\Big\},
\end{aligned}
$$

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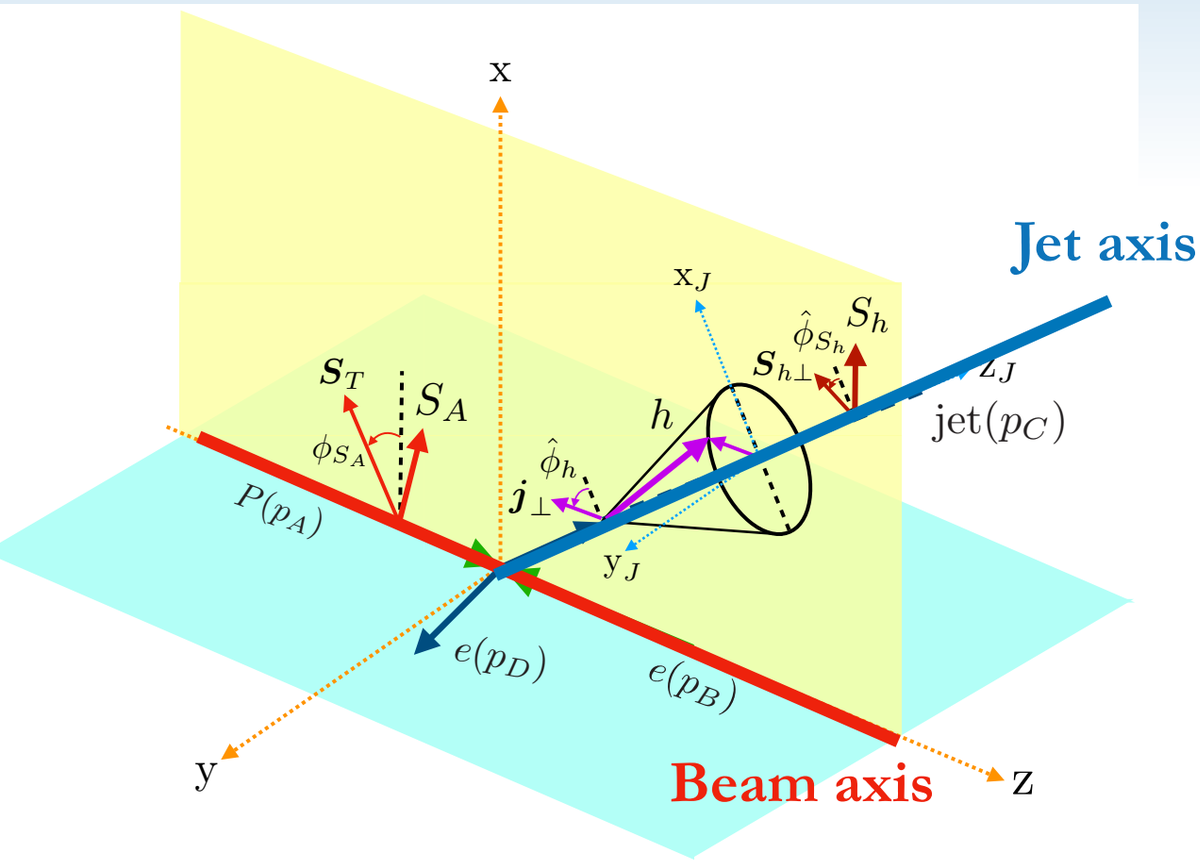
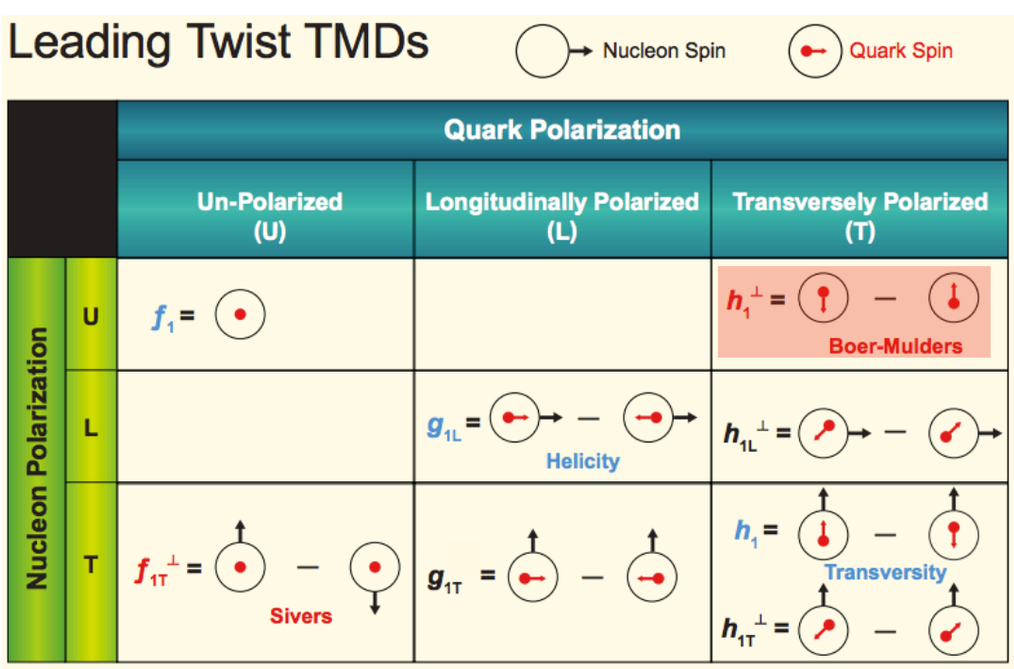
Kang, KL, Shao, Zhao; In progress

Phenomenology : $A^{\cos(\phi_q - \hat{\phi}_h)}$



$$A^{\cos(\phi_q - \hat{\phi}_h)} \equiv \frac{F_{UU,U}^{\cos(\phi_q - \hat{\phi}_h)}(q_\perp, j_\perp)}{F_{UU,U}(q_\perp, j_\perp)} \sim \frac{h_1^\perp(q_\perp) H_1^\perp(j_\perp)}{f_1(q_\perp) D_1(j_\perp)}$$

- **Boer-Mulders and Collins functions sensitive to transverse momentum measured with respect to different axes.**
- **"Separation" of the incoming and outgoing dynamics.**



Quark polarization

Hadron polarization	U	L	T
U	$D^{h/q}$		$H^{\perp h/q}$ Collins
L		$G^{h/q}$	$H_L^{\perp h/q}$
T	$D_T^{\perp h/q}$	$G_T^{h/q}$	$H^{h/q}$ $H_T^{\perp h/q}$

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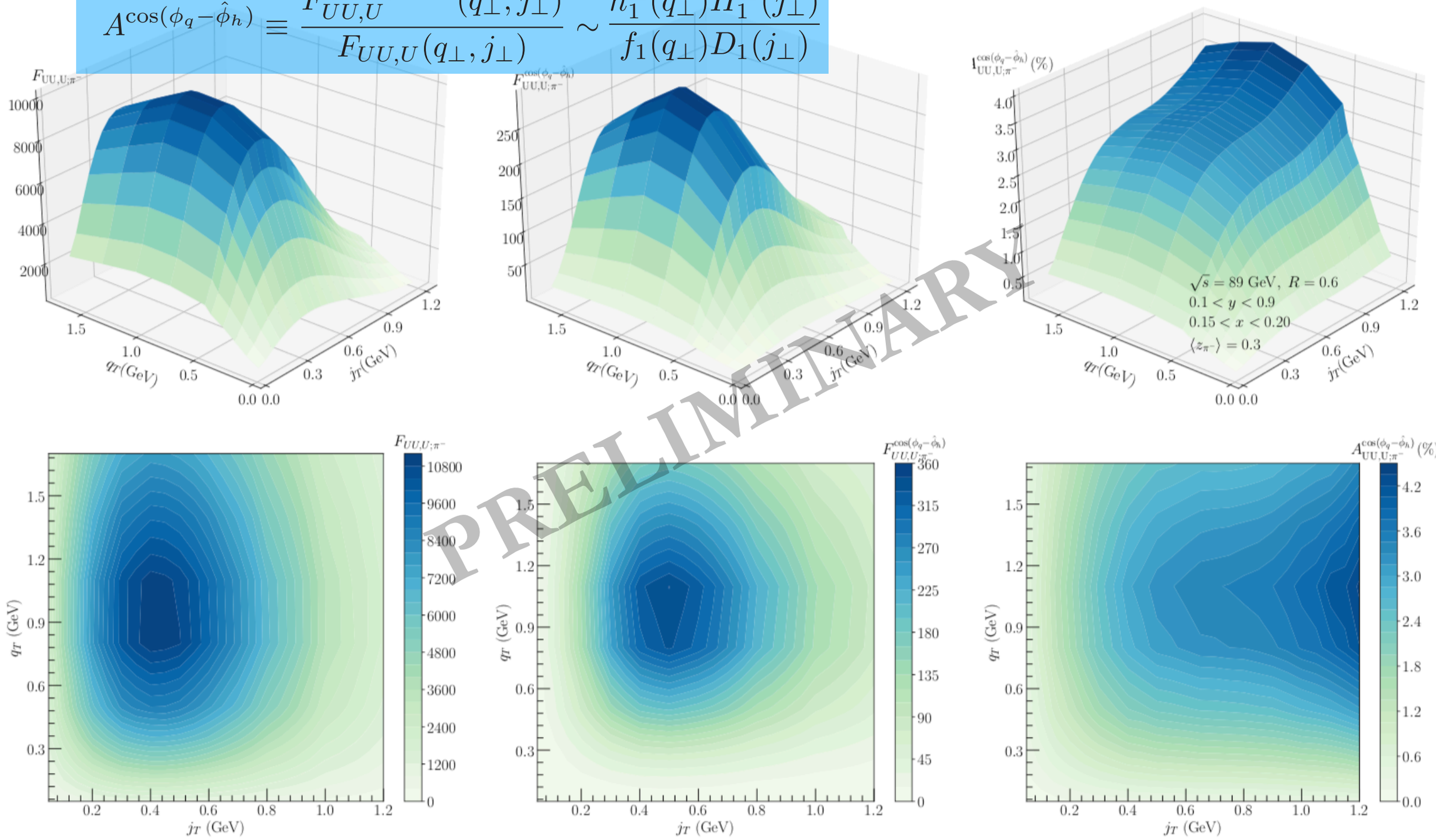
Kang, KL, Shao, Zhao; In progress

Unpolarized π in jet (Boer-Mulders, Collins)

π⁻ q_T [0,**1.8**], j_T [0,1.2]

$$A^{\cos(\phi_q-\hat{\phi}_h)} \equiv \frac{F_{UU,U}^{\cos(\phi_q-\hat{\phi}_h)}(q_\perp, j_\perp)}{F_{UU,U}(q_\perp, j_\perp)} \sim \frac{h_1^\perp(q_\perp)H_1^\perp(j_\perp)}{f_1(q_\perp)D_1(j_\perp)}$$

Denominator | Numerator | Ratio



Parametrization from *Barone, Melis, Prokudin `10*

Kang, KL, Shao, Zhao; In progress

Thank you!