TMD dependent spin physics with jets at the EIC

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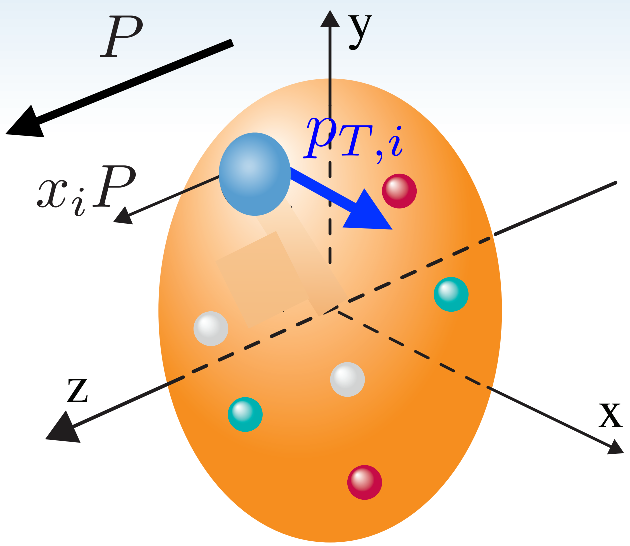
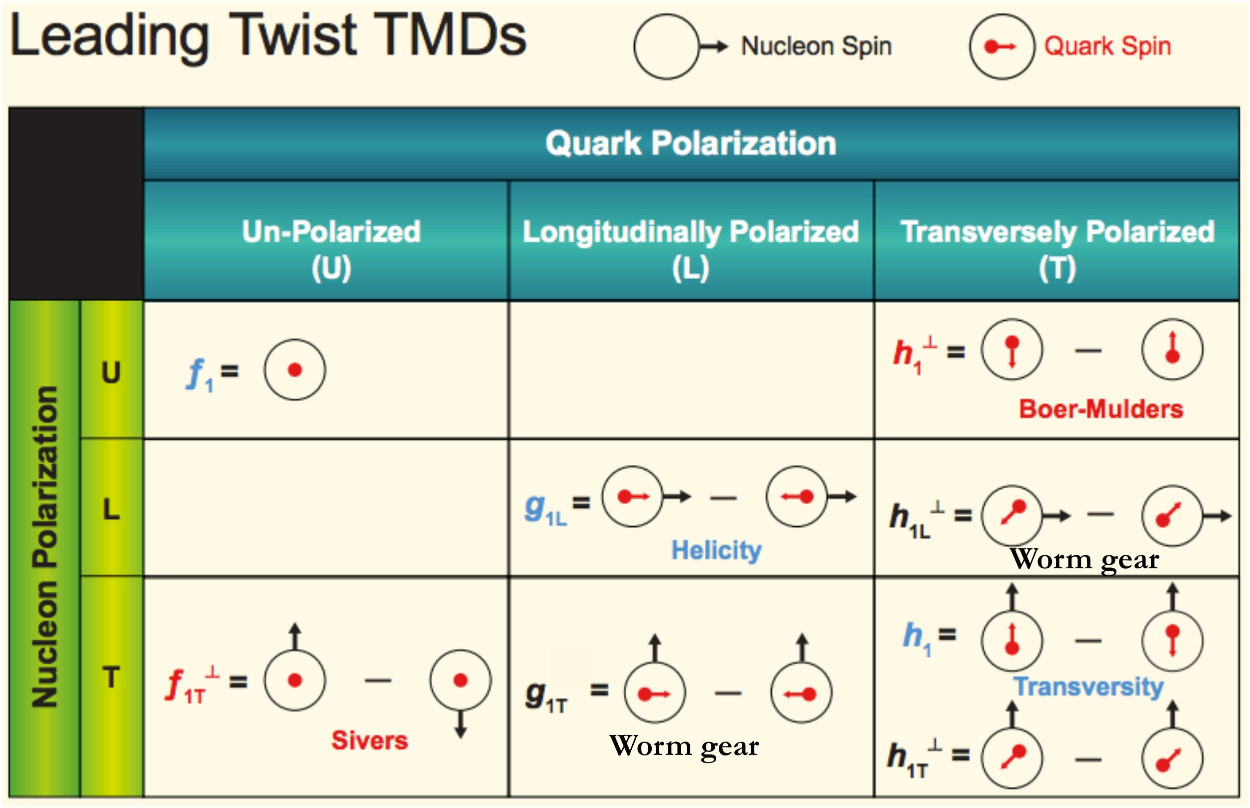
LBNL

Precision Studies on
QCD at EIC
19 - 23 July, 2021

TMD structure



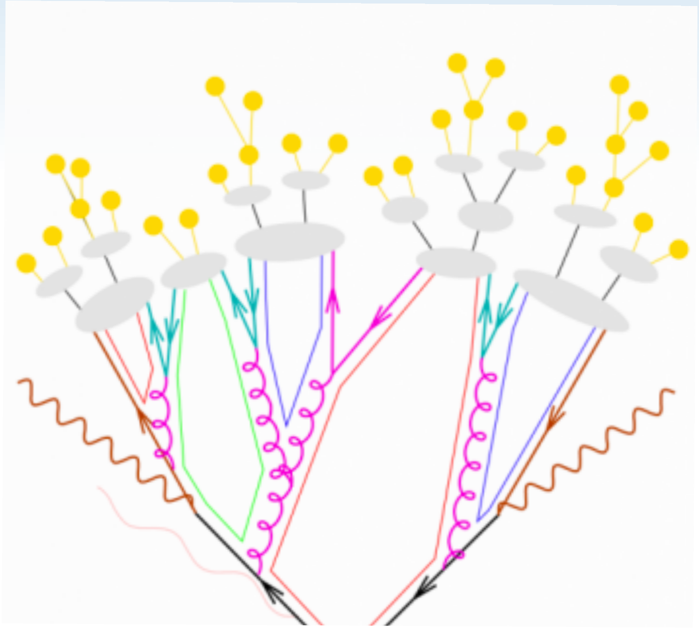


Leading Twist TMDs

Nucleon Spin   Quark Spin

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

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



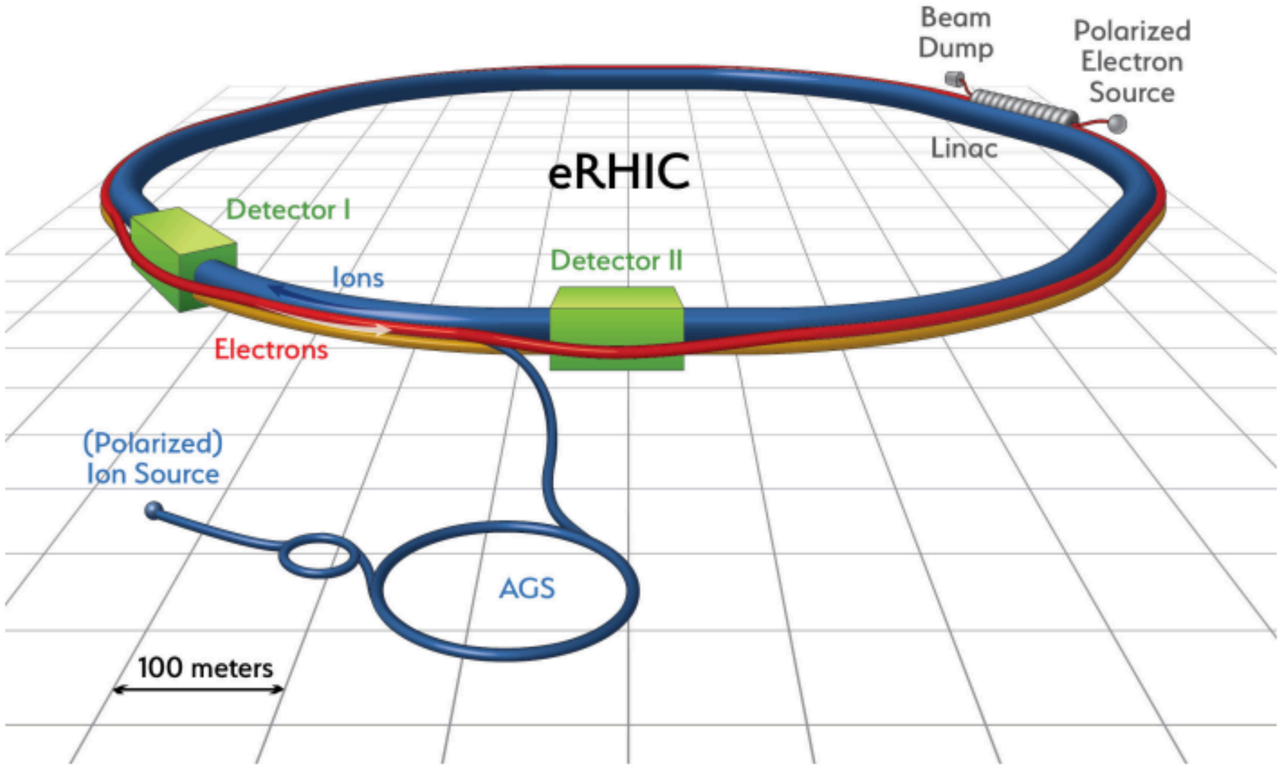
Quark polarization

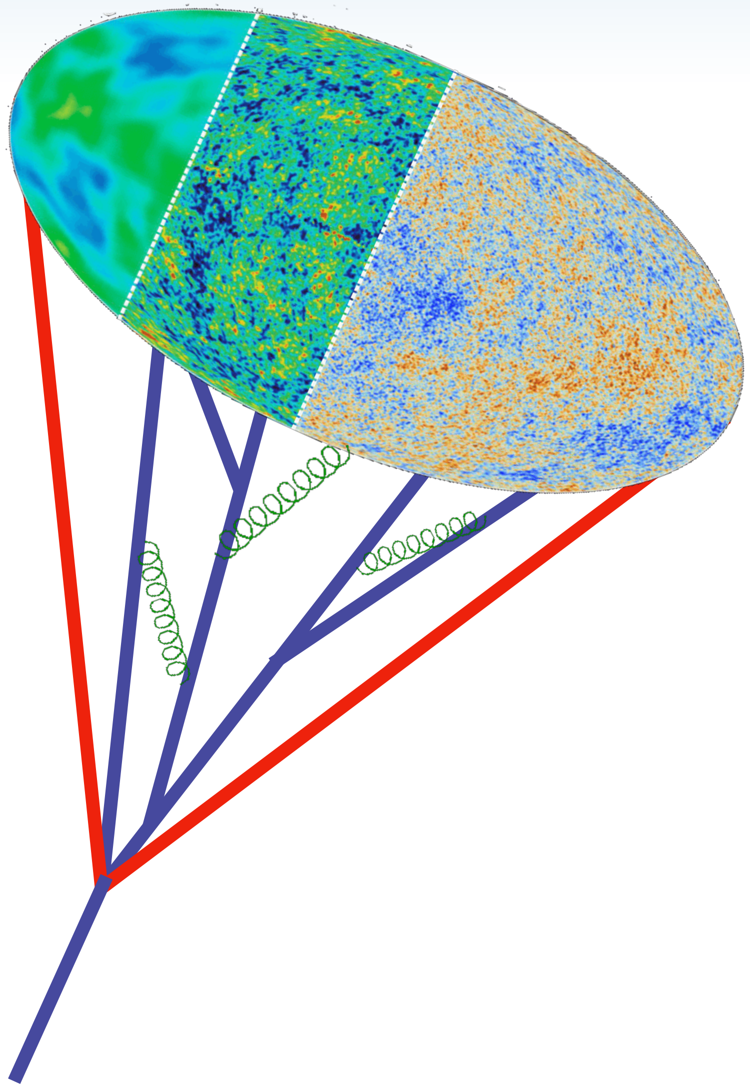
Hadron polarization

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

Study of hadron structures



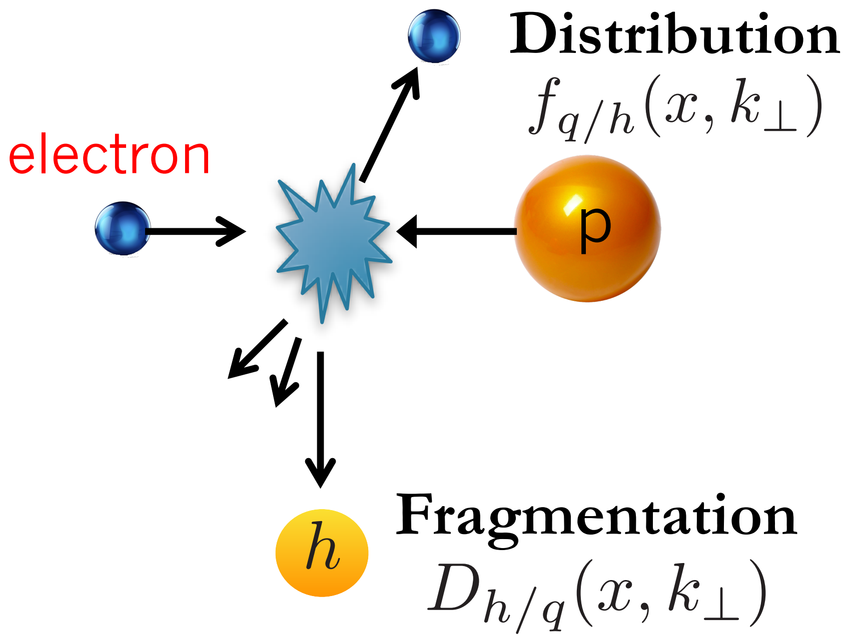


"Can we use jets at the EIC to probe TMD structure?"

Standard processes

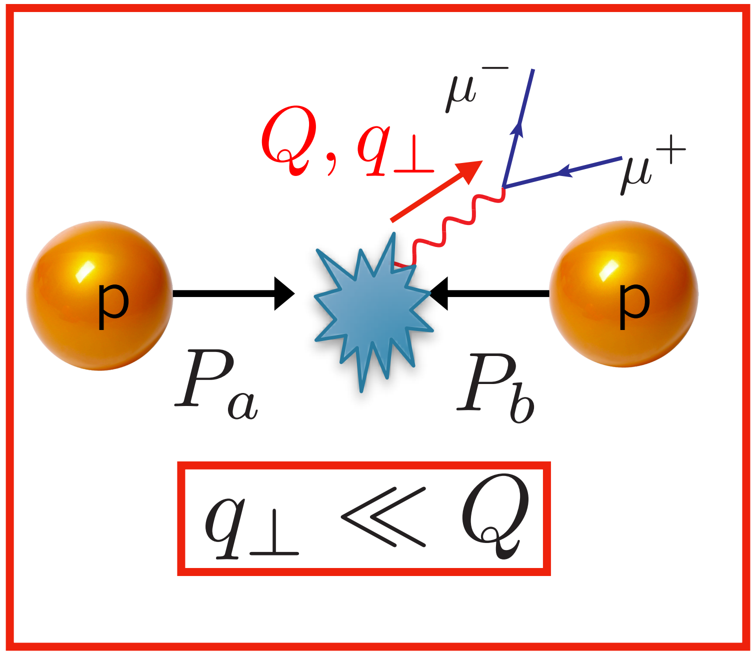
Semi-Inclusive DIS (SIDIS)

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



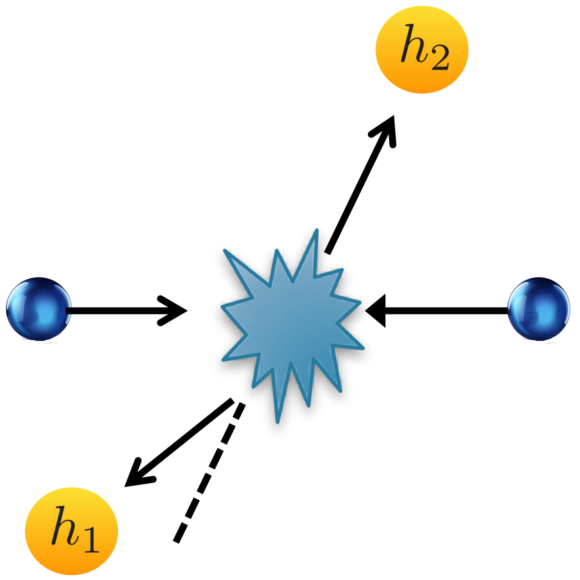
Drell-Yan

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



Dihadrons in e^+e^-

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



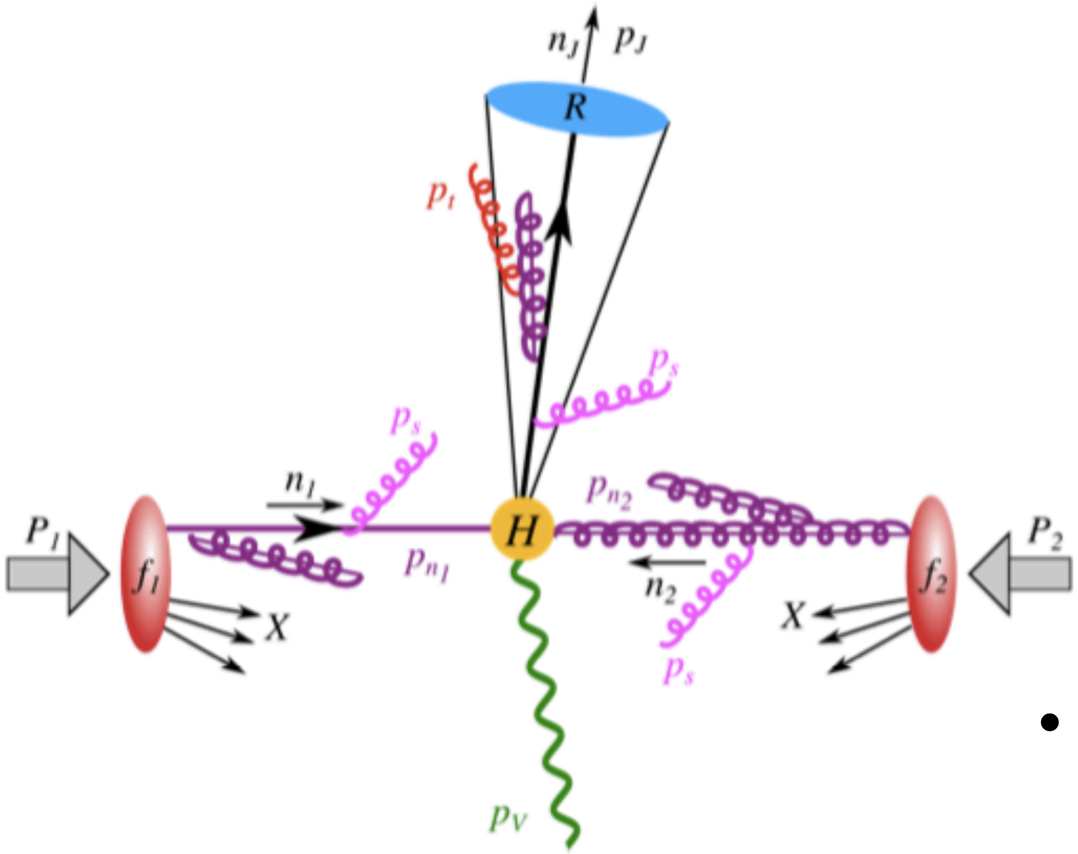
- They have a well-established factorization formalism

Well-established factorization using the traditional pQCD methods (CSS) and Soft-Collinear Effective Field Theory (SCET)

(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**



$$PP \to J_1 + J_2 + X, \quad PP \to J + V + X, \quad PP \to J(h) + X, \ldots$$

LHC / RHIC

$$e\,P \to e + J + X \quad e\,P \to Q + \bar{Q} + X, \quad e\,P \to J(h) + X, \ldots$$

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.**

Fig. from Chien, Shao, Wu `19

1) Inclusive jet production

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

2) Lepton + jet imbalance

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

3) Lepton + jet imbalance with hadron in jet

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

TMDFFs / TMDPDFs

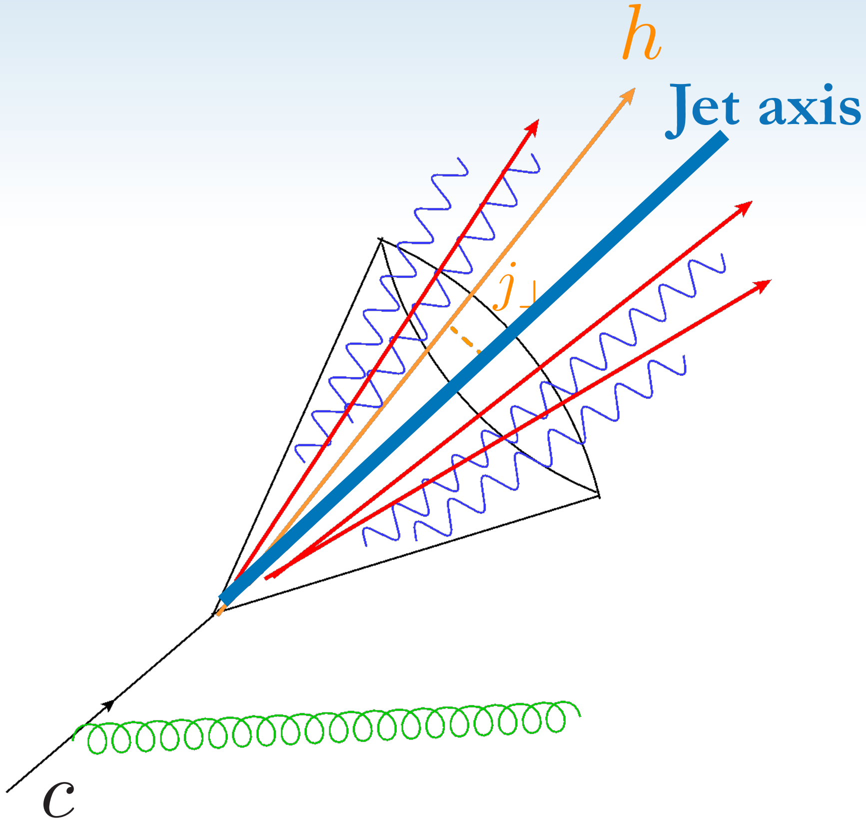
Hadron inside inclusive jet production

Unpolarized case:

(replace pp with ep for EIC)

$$\frac{d\sigma^{pp\to \text{jet}(h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} \underset{\Lambda_{\rm QCD}}{f_{a/A} \otimes f_{b/B}} \otimes \underset{p_T}{H_{ab}^c} \otimes \underset{\substack{p_T R\\ \Lambda_{\rm QCD}}}{\mathcal{G}_c^h(z_h, \boldsymbol{j}_\perp)}$$

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



1) Inclusive jet production

TMDFFs

$$\boxed{\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} \underset{\Lambda_{\rm QCD}}{f_{a/A} \otimes f_{b/B}} \otimes \underset{p_T}{H_{ab}^c} \otimes \underset{\Lambda_{\rm QCD}}{\boxed{D_c^h}}}$$

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

Procura, Stewart `10
Arleo, Fontannaz, Guillet, Nguyen `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16

Hadron inside inclusive jet production

Unpolarized case:

(replace pp with ep for EIC)

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

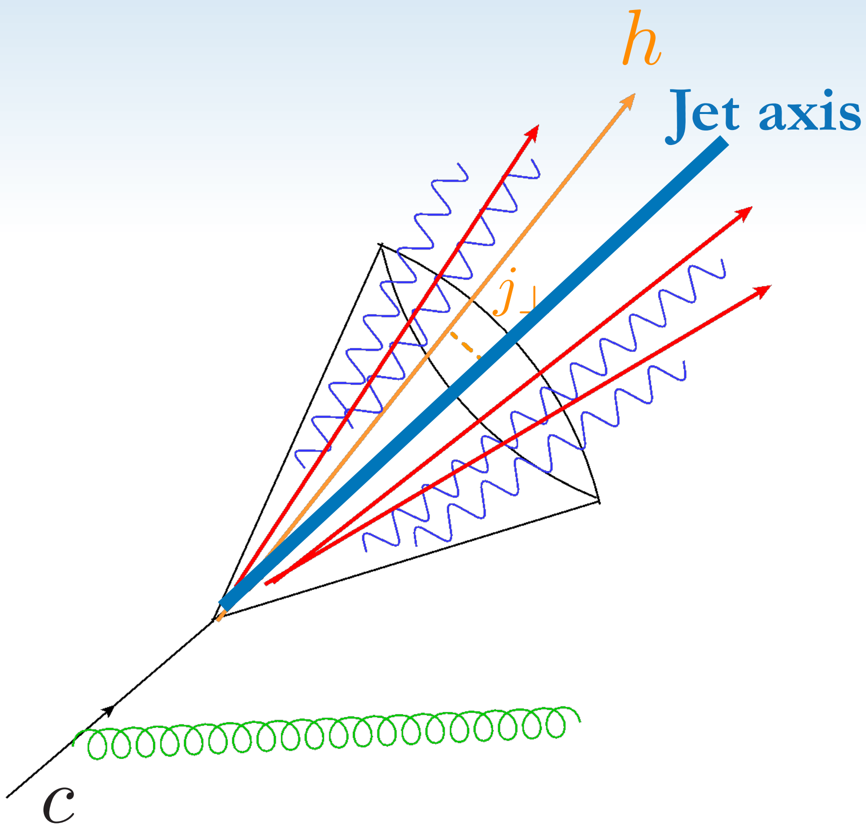
Λ_{QCD} p_T $p_T R$

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	$D_T^{\perp h/q}$	$G_T^{h/q}$	$H^{h/q}$ $H_T^{\perp h/q}$

(including polarized jet fragmentation functions)

TMD Jet Fragmentation Functions (TMDJFFs)

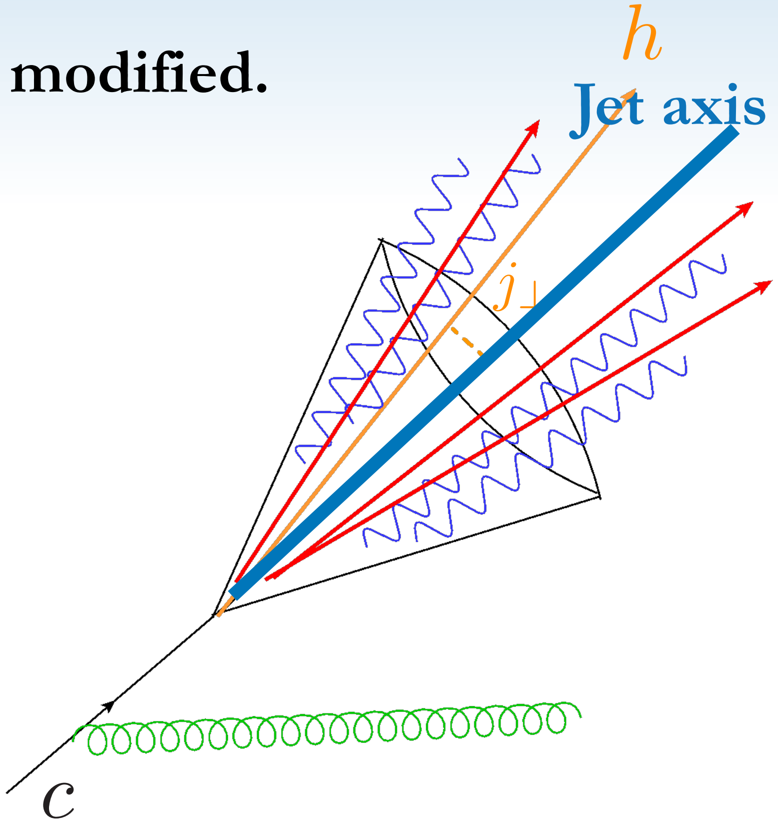
Quark polarization

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	$\mathcal{D}_T^{\perp h/q}$	$\mathcal{G}_T^{h/q}$	$\mathcal{H}^{h/q}$ $\mathcal{H}_T^{\perp h/q}$

TMD hadron in jet (TMDJFFs)

- **Still hard-collinear factorization structure other than jet function modified.**



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

When $\Lambda_{\rm QCD}\lesssim j_\perp \ll p_T R, \qquad \lambda\sim j_\perp/p_T$

collinear $k_c\sim p_T(\lambda^2,1,\lambda)$

soft $k_s\sim p_T(\lambda R,\lambda/R,\lambda)$

Unpolarized TMDJFF

$$\mathcal{D}_1^{h/q}(z,z_h,j_\perp^2,\mu,\zeta_J) = \mathcal{H}_{c\to i}(z,p_TR,\mu)\int_{\boldsymbol{k}_\perp,\,\boldsymbol{\lambda}_\perp} D_1^{h/q,\,\text{unsub}}(z_h,k_\perp^2,\mu,\zeta'/\nu^2)\,S_q(\lambda_\perp^2,\mu,\nu\mathcal{R})$$

$$= \mathcal{H}_{c\to i}(z,p_TR,\mu)\int \frac{b\,db}{2\pi} J_0\left(\frac{j_\perp b}{z_h}\right)\tilde{D}_1^{h/q,\,\text{unsub}}(z_h,b^2,\mu,\zeta'/\nu^2)\,S_q(b^2,\mu,\nu\mathcal{R})$$

$$= \mathcal{H}_{c\to i}(z,p_TR,\mu)\underbrace{D_1^{h/q}(z_h,j_\perp^2,\mu,\zeta_J)}$$

Standard subtracted TMDFFs, say in SIDIS

Relation also holds for other TMDJFFs.

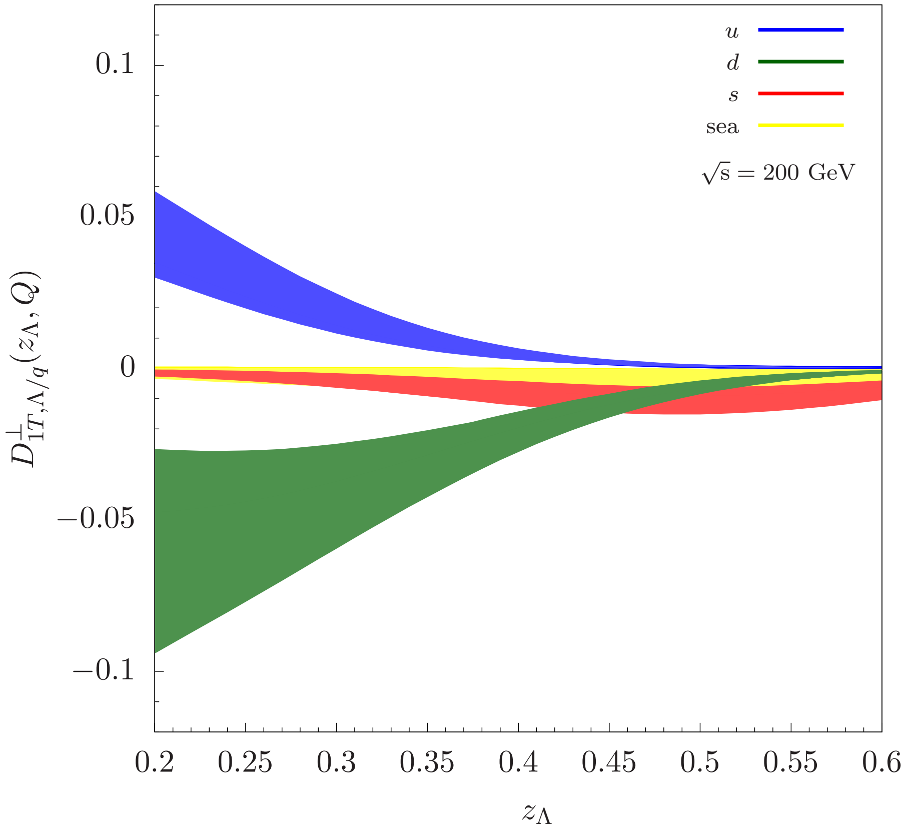
- **TMDJFFs can be related to TMDFFs**

Kang, Liu, Ringer, Xing, `17
Kang, KL, Shao, Zhao `21

Polarizing FF

TMD Fragmentation Functions

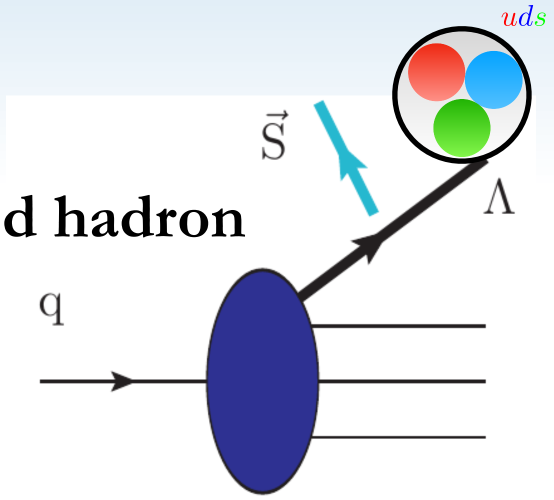
	Quark polarization		
Hadron polarization	U	L	T
U	$D^{h/q}$		$H^{\perp h/q}$
L		$G^{h/q}$	$H_L^{\perp h/q}$
T	$\boxed{D_T^{\perp h/q}}$	$G_T^{h/q}$	$H^{h/q}$ $H_T^{\perp h/q}$

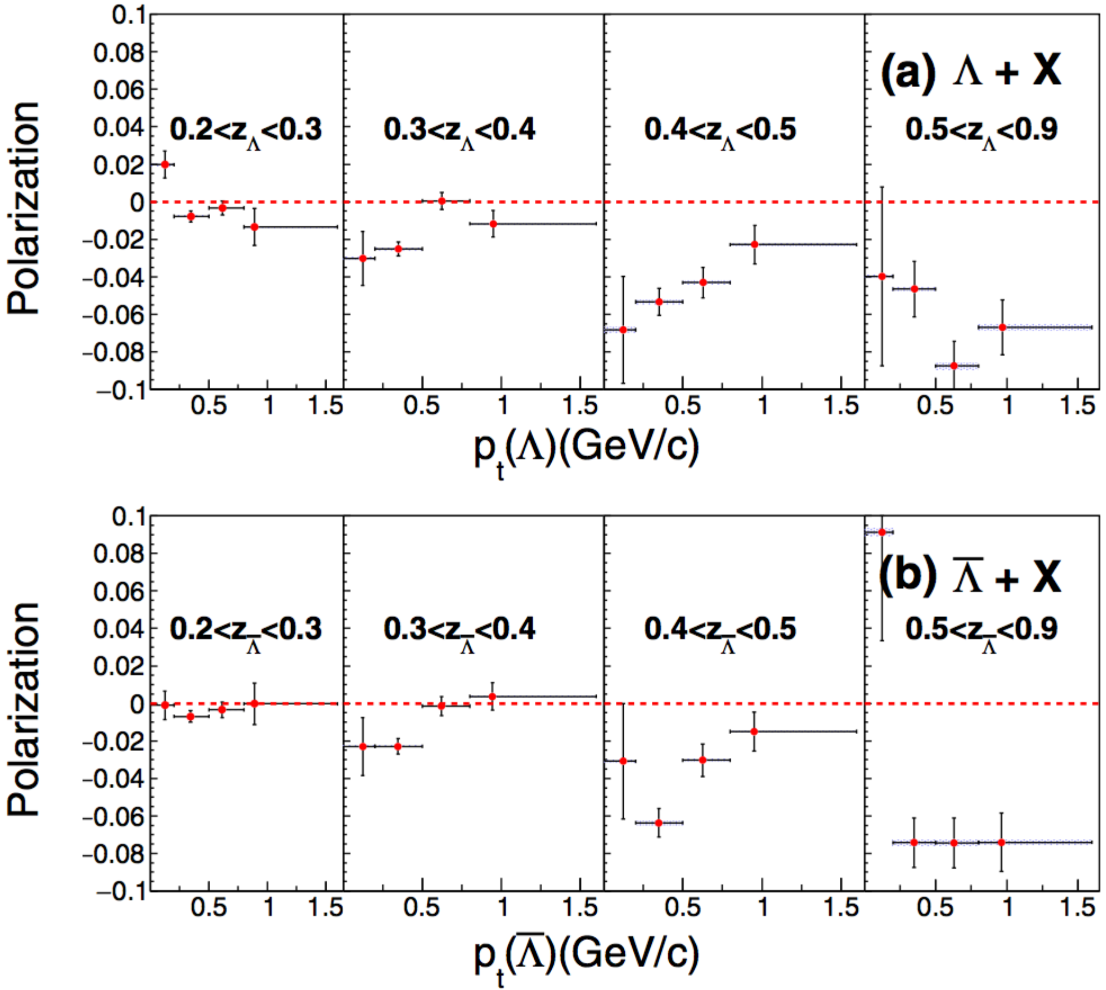


- Used PFF fits from Belle data

Callos, Kang, Terry, `20

- Describes transversely polarized hadron inside unpolarized parton.



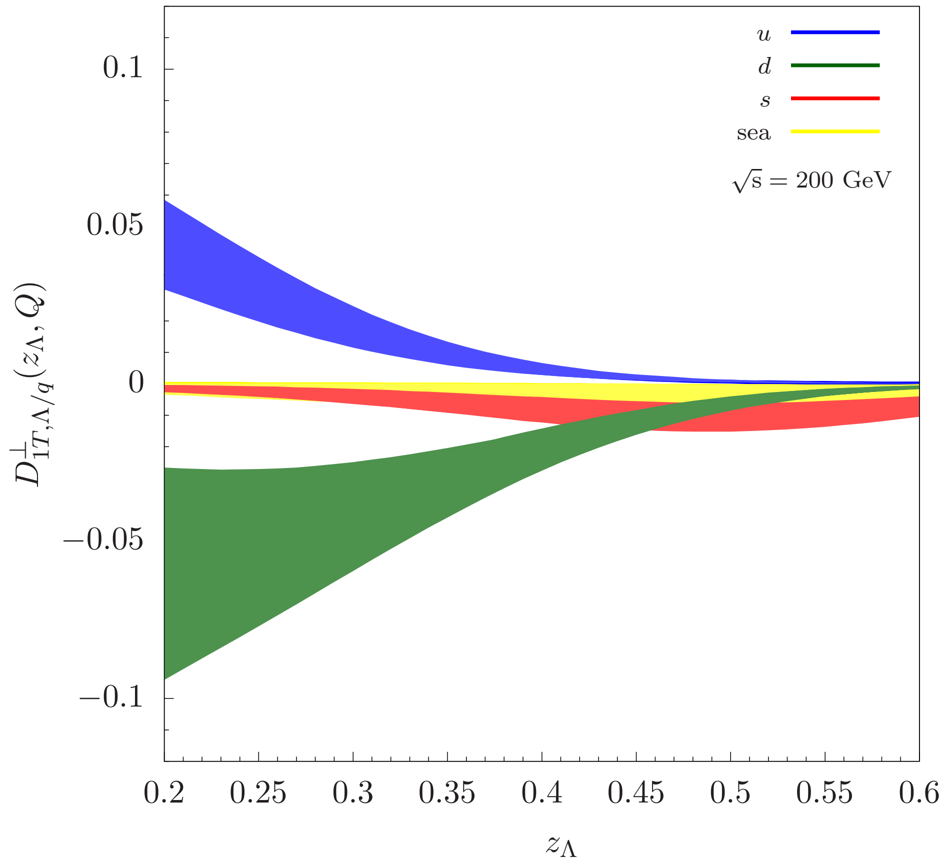


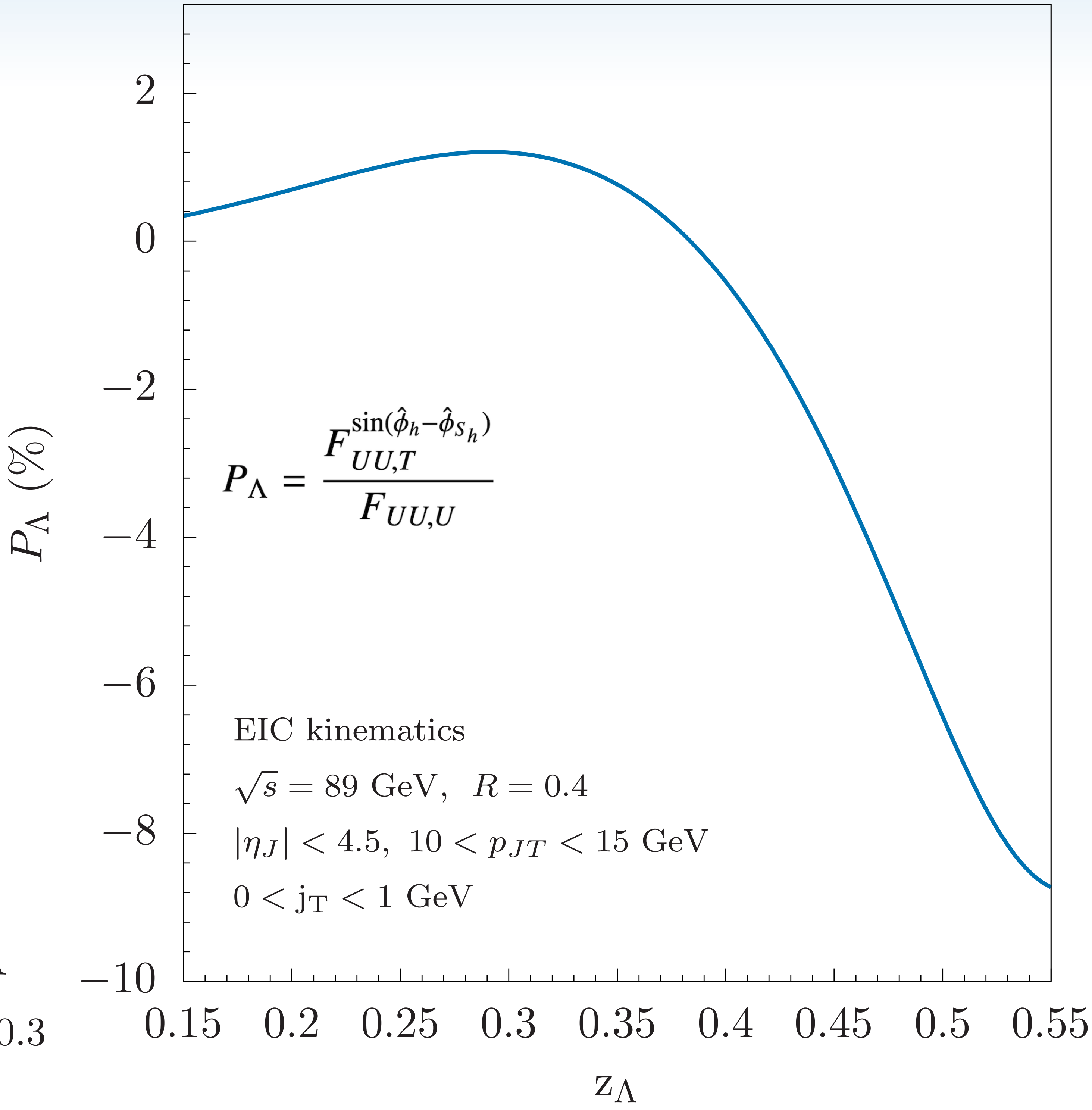
Belle Collaboration `19

Polarizing **JFF**

- **Used PFF fits from Belle data**

Callos, Kang, Terry, `20



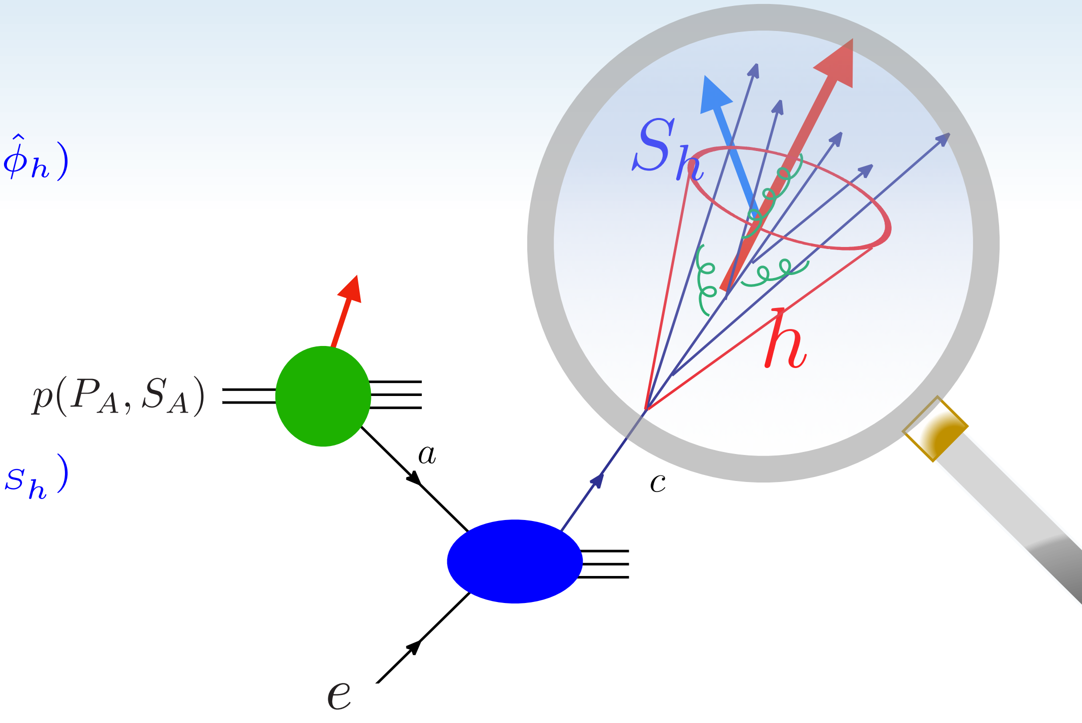


- **Predictions at the LHC kinematics**
- **Positive from up quark PFF at small z_Λ**
- **Negative from down quark PFF at $z_\Lambda \gtrsim 0.3$**

Kang, KL, Zhao, `20

Azimuthal angular dependence

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



$$\underset{\uparrow}{F_{S_A S_B,S_h}}$$

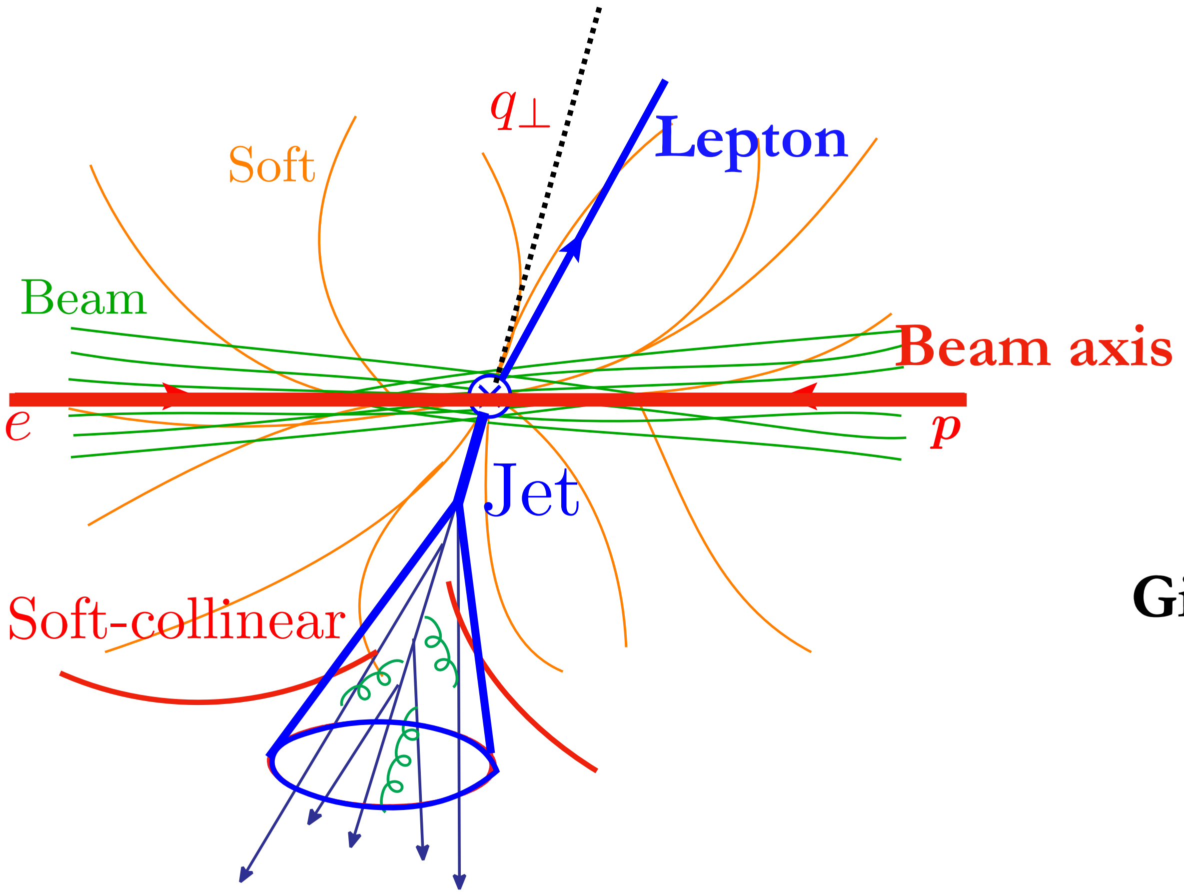
Polarization of A, B, h

- **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 $\qquad k_n \sim p_\perp(\lambda^2, 1, \lambda)_{n\bar{n}}$

global soft $\qquad k_{gs} \sim p_\perp(\lambda, \lambda, \lambda)$

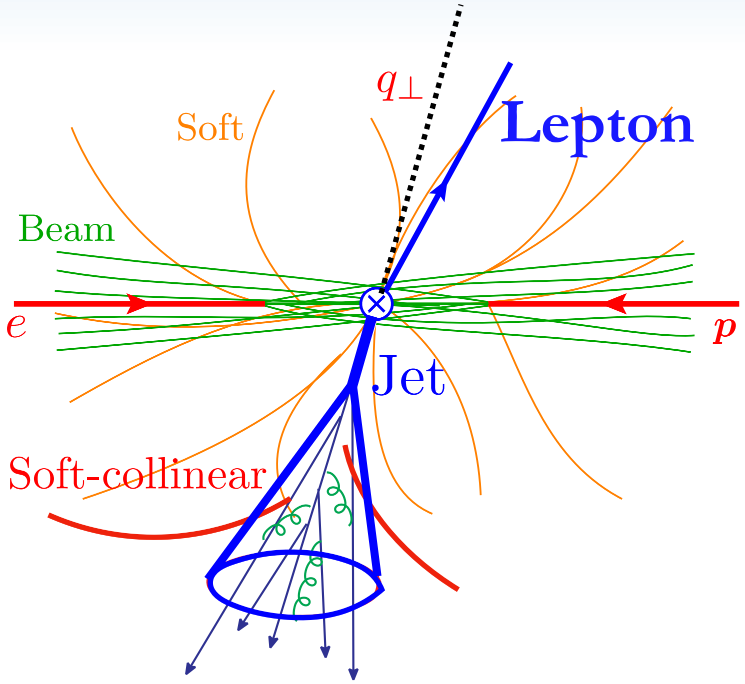
soft-collinear $\qquad k_{sc} \sim p_\perp R(\lambda R, \lambda/R, \lambda)_{n_J,\bar{n}_J}$

n_J-collinear $\qquad k_J \sim p_\perp(R^2, 1, R)_{n_J,\bar{n}_J}$

2) Lepton + jet imbalance
TMDPDFs

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

Lepton + Jet imbalance



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

We arrive at factorization using SCET

n-collinear $\quad k_n \sim p_\perp(\lambda^2,1,\lambda)_{n\bar{n}}$ **TMDPDFs**

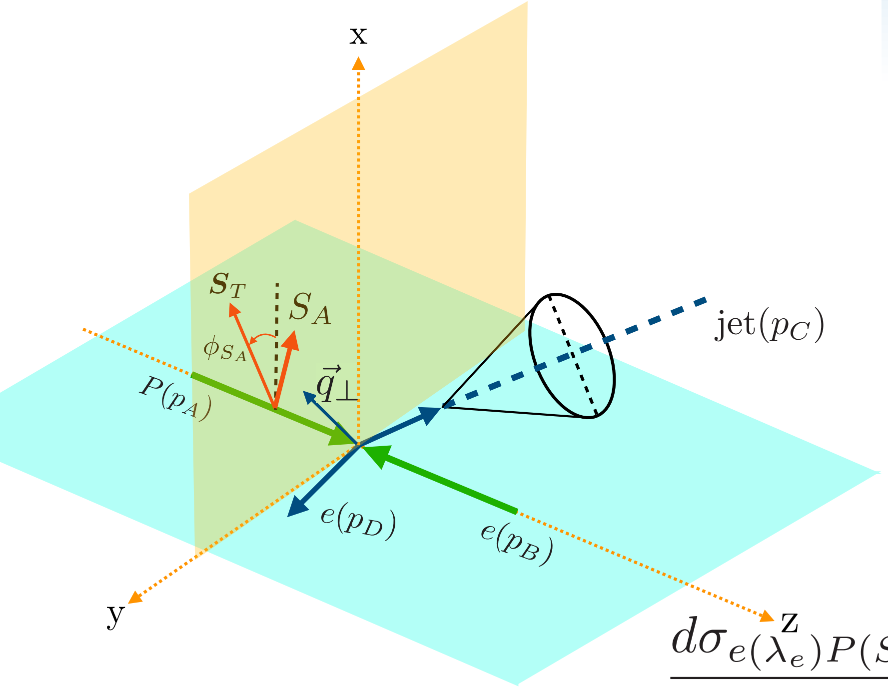
global soft $\quad k_{gs} \sim p_\perp(\lambda,\lambda,\lambda)$

soft-collinear $\quad k_{sc} \sim p_\perp R(\lambda R,\lambda/R,\lambda)_{n_J,\bar{n}_J}$ $\Big\}$ **Soft functions**

n_J-collinear $\quad k_J \sim p_\perp(R^2,1,R)_{n_J,\bar{n}_J}$ **Jet function**

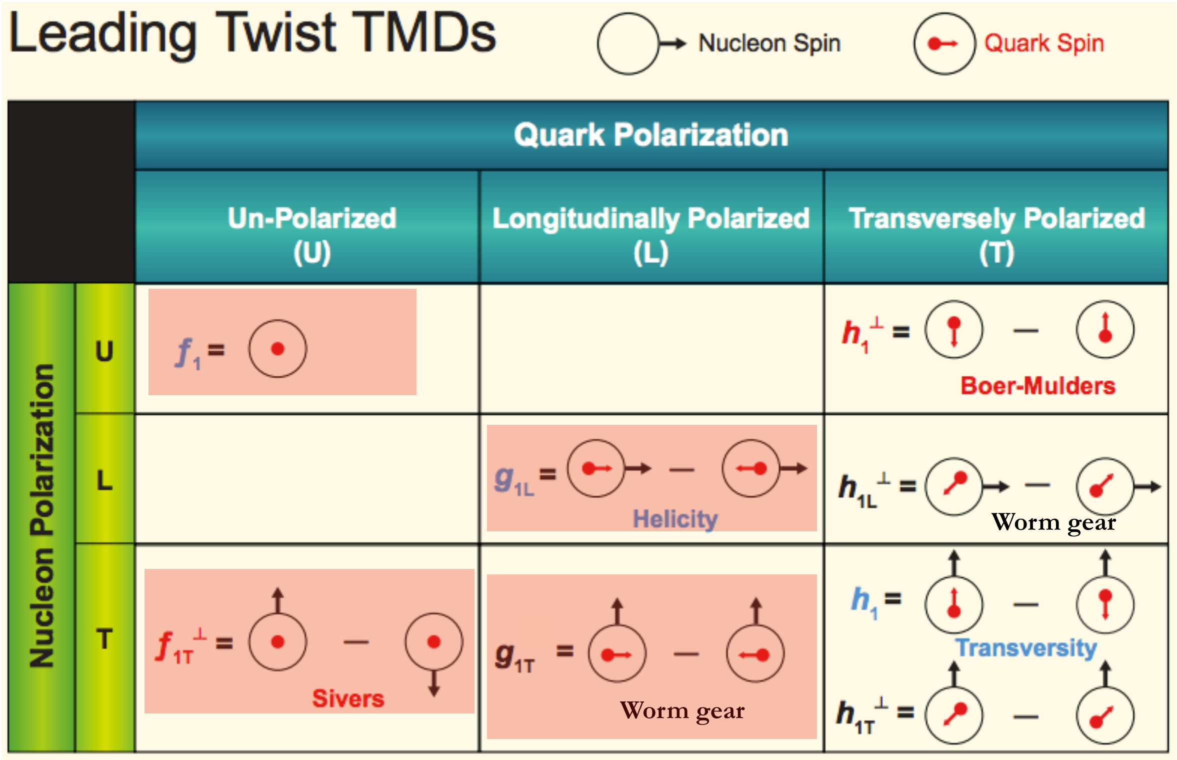
Liu, Ringer, Vogelsang, Yuan `18, `20
Arratia, Kang, Prokudin, Ringer `20
Also, Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `19, `20

Lepton + Jet imbalance



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

$$\begin{aligned}\frac{d\sigma_{e(\lambda_e)P(S)\to e+\text{jet}}}{dp_\perp dq_\perp} &= \overset{\sim f_1}{F_{UU}} + \lambda_p\lambda_e \overset{\sim g_{1L}}{F_{LL}}\\ &\quad + S_T\left\{ \sin(\phi_{S_A}-\phi_q)\underset{\sim f_{1T}^\perp}{F_{TU}^{\sin(\phi_{S_A}-\phi_q)}} + \lambda_e\cos(\phi_{S_A}-\phi_q)\underset{\sim g_{1T}}{F_{TL}^{\cos(\phi_{S_A}-\phi_q)}}\right\},\end{aligned}$$



Leading Twist TMDs — Nucleon Spin — Quark Spin

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

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

Liu, Ringer, Vogelsang, Yuan `18, `20
Arratia, Kang, Prokudin, Ringer `20
Kang, KL, Shao, Zhao `21

Sivers asymmetry

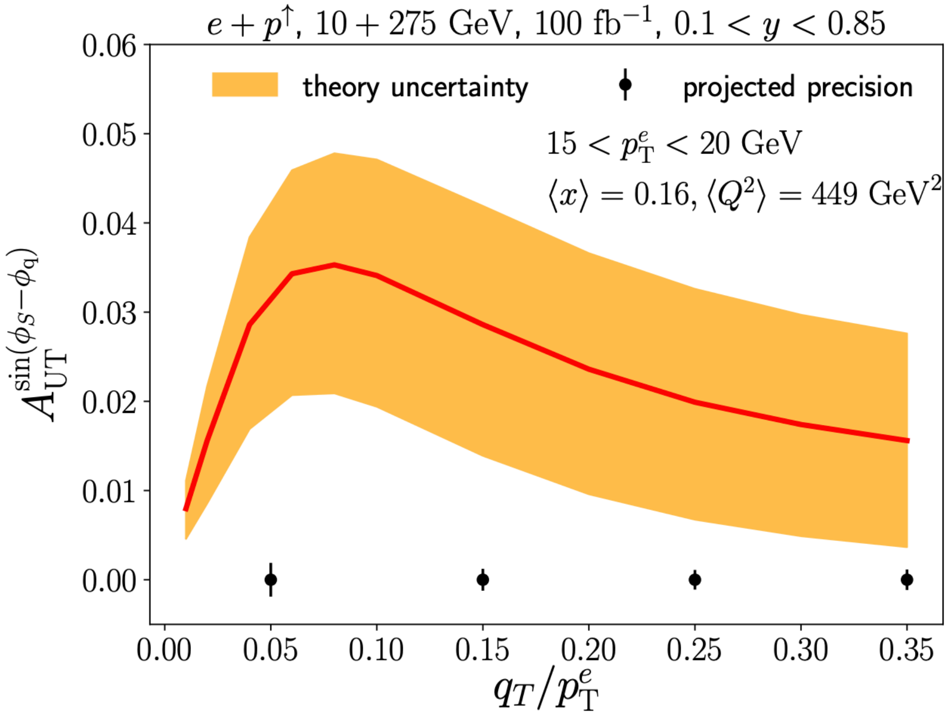
$$\frac{d\sigma_{e(\lambda_e)P(S)\to e+\text{jet}}}{dp_\perp dq_\perp} = \overset{\sim f_1}{F_{UU}} + \overset{\sim g_{1L}}{\lambda_p\lambda_e F_{LL}}$$

$$+S_T\left\{\sin(\phi_{S_A}-\phi_q)\underset{\sim f_{1T}^\perp}{\boxed{F_{TU}^{\sin(\phi_{S_A}-\phi_q)}}}+\lambda_e\cos(\phi_{S_A}-\phi_q)\underset{\sim g_{1T}}{F_{TL}^{\cos(\phi_{S_A}-\phi_q)}}\right\},$$

$$f_a(x_a,k_\perp)\to\frac{\epsilon_\perp^{\rho\sigma}S_{\perp\rho}k_{\perp\sigma}}{M}f_{aT}^\perp(x_a,k_\perp)$$

$$\boxed{\begin{aligned}\frac{d\Delta\sigma_{eP\to e+\text{jet}}}{dp_\perp dq_\perp}=\frac{\epsilon_\perp^{\rho\sigma}S_{\perp\rho}}{M}\int\prod_i^3 d^2k_{i\perp}H(Q)\delta^{(2)}(\vec{k}_{1\perp}+\vec{k}_{2\perp}+\vec{k}_{3\perp}-q_\perp)\\ \times k_{1\perp\sigma}\,f_{aT}^\perp(x_a,k_{1\perp})S^{\text{global}}(\vec{k}_{2\perp})S_{J_c}(\vec{k}_{3\perp})J_c(p_\perp R)\end{aligned}}$$

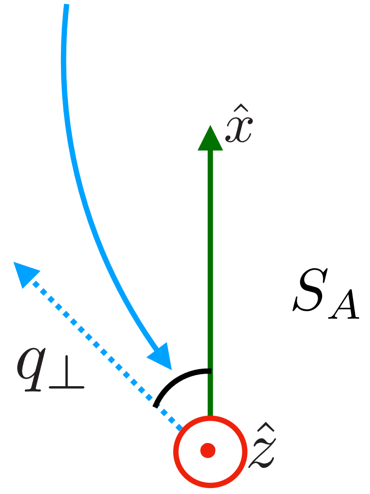
$$\propto\sin\boxed{(\phi_{S_A}-\phi_q)}$$



$$A_{UT}^{\sin(\phi_{S_A}-\phi_q)}=\frac{F_{UT}^{\sin(\phi_{S_A}-\phi_q)}}{F_{UU}}$$

- **Positive $\Delta\sigma \implies$ a preference of imbalance to be on left**

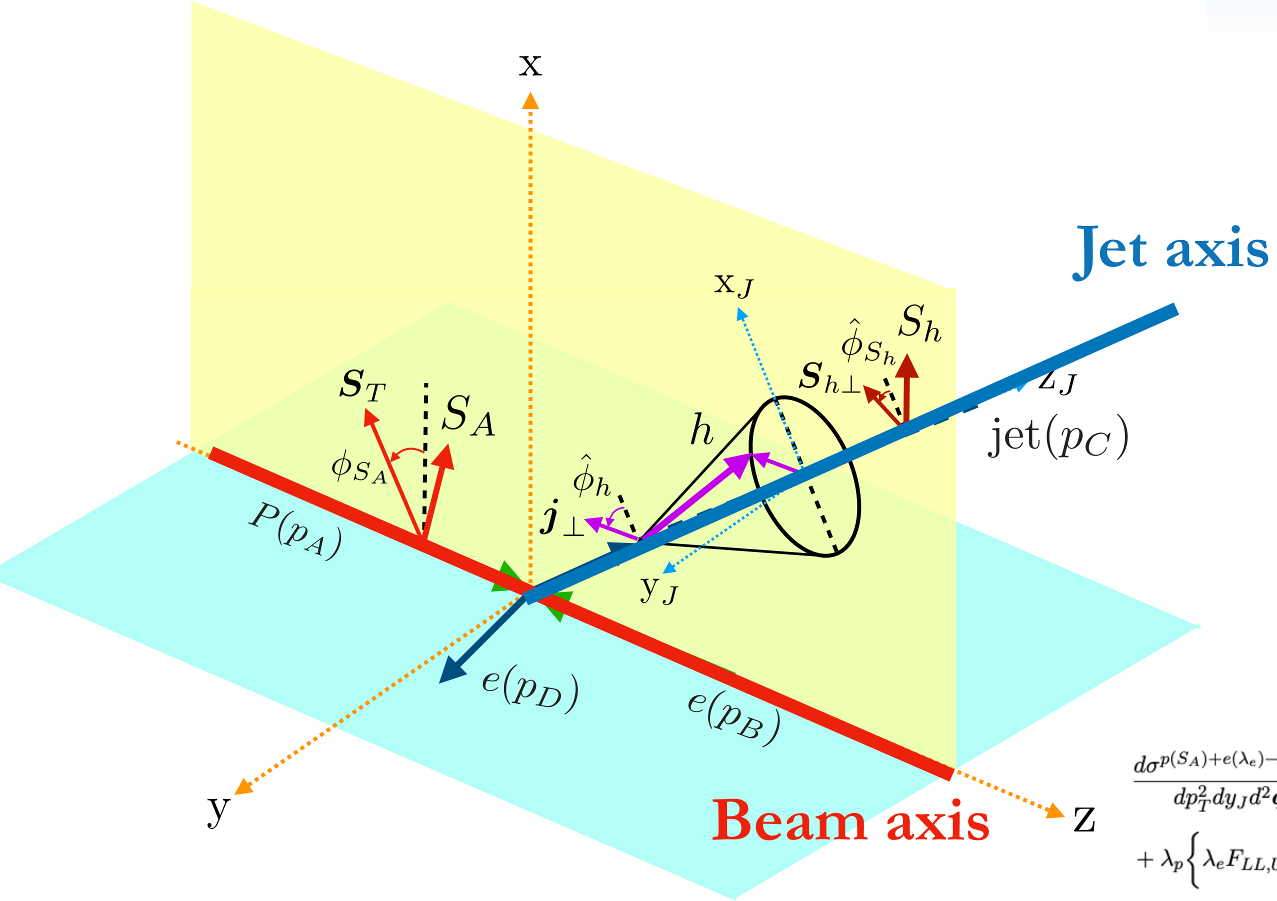
(When polarized proton moving towards us and transverse spin pointing up.)



Sivers from SIDIS extraction
Echevarria, Idilbi, Kang, Vitev, `14

Arratia, Kang, Prokudin, Ringer `20
Kang, KL, Shao, Zhao `21

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)

3) Lepton + jet imbalance with hadron in jet
TMDFFs / TMDPDFs

Many characteristic correlations

$$
\begin{aligned}
&\frac{d\sigma^{p(S_A)+e(\lambda_e)\to e+(\text{jet}\,h(S_h))+X}}{dp_T^2 dy_J 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_q-\phi_{S_A})F_{TU,U}^{\sin(\phi_q-\phi_{S_A})} + \lambda_e\cos(\phi_q-\phi_{S_A})F_{TL,U}^{\cos(\phi_q-\phi_{S_A})} \\
&\qquad + \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(\hat{\phi}_h-\phi_q)F_{UU,L}^{\sin(\hat{\phi}_h-\phi_q)} + \lambda_p\Big[F_{LU,L} + \cos(\hat{\phi}_h-\phi_q)F_{LU,L}^{\cos(\hat{\phi}_h-\phi_q)}\Big] \\
&\qquad + S_T\Big[\cos(\phi_q-\phi_{S_A})F_{TU,L}^{\cos(\phi_q-\phi_{S_A})} + \lambda_e\sin(\phi_q-\phi_{S_A})F_{TL,L}^{\sin(\phi_q-\phi_{S_A})} \\
&\qquad\qquad + \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})} \\
&+\sin(\hat{\phi}_{S_h}-\phi_q)F_{UU,T}^{\sin(\hat{\phi}_{S_h}-\phi_q)} + \sin(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_q)F_{UU,T}^{\sin(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_q)} \\
&+\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})} \\
&\qquad + \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] \\
&+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})} \\
&\qquad + \sin(\hat{\phi}_h-\hat{\phi}_{S_h})\sin(\phi_q-\phi_{S_A})F_{TU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})\sin(\phi_q-\phi_{S_A})} \\
&\qquad + \cos(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_q-\phi_{S_A}))F_{TU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})\cos(\phi_q-\phi_{S_A})} \\
&\qquad + \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})} \\
&\qquad + \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})} \\
&\qquad + \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)} \\
&\qquad + \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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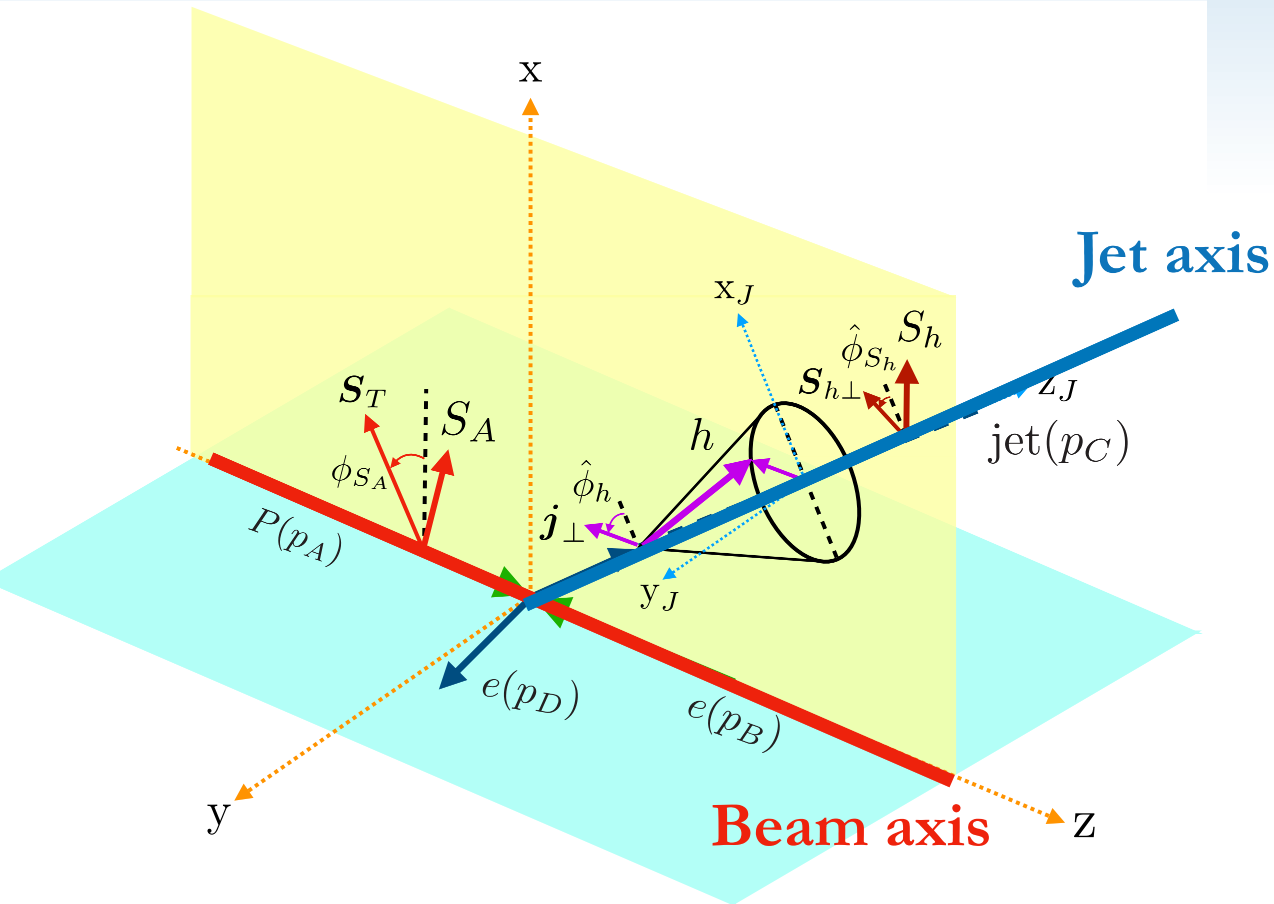
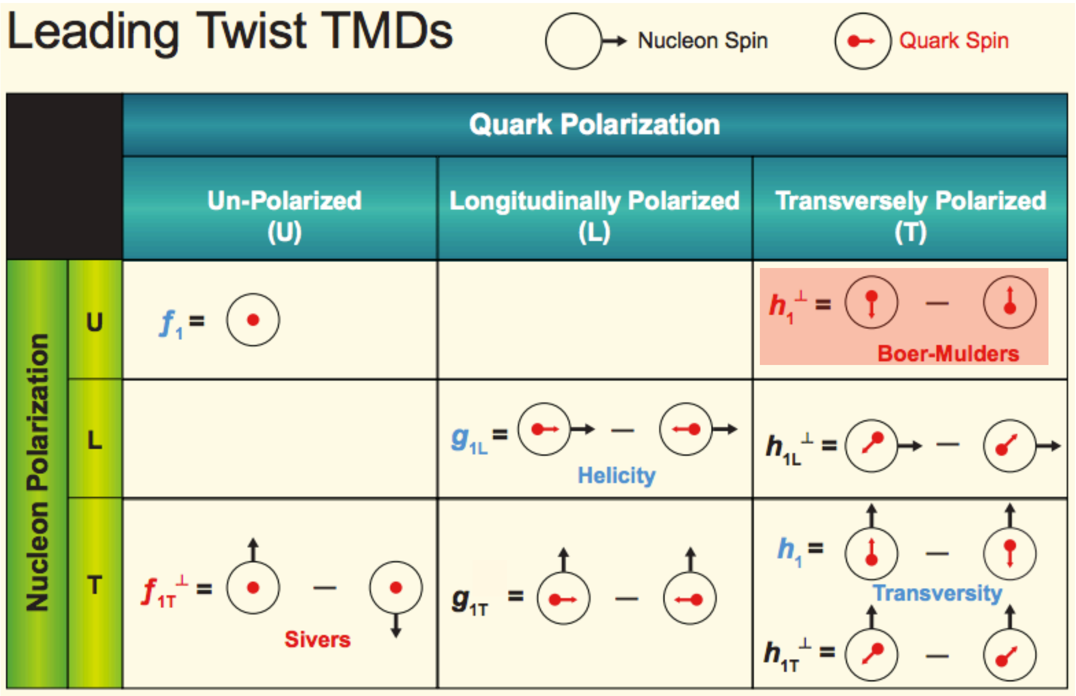
Phenomenology : $A^{\cos(\phi_q-\hat{\phi}_h)}$



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

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



Leading Twist TMDs ○→ Nucleon Spin ⊙ Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 = ⊙		$h_1^\perp$ = ⊙ − ⊙ Boer-Mulders
	L		g_{1L} = ⊙ − ⊙ Helicity	$h_{1L}^\perp$ = ⊙ − ⊙
	T	$f_{1T}^\perp$ = ⊙ − ⊙ Sivers	g_{1T} = ⊙ − ⊙	h_1 = ⊙ − ⊙ Transversity $h_{1T}^\perp$ = ⊙ − ⊙

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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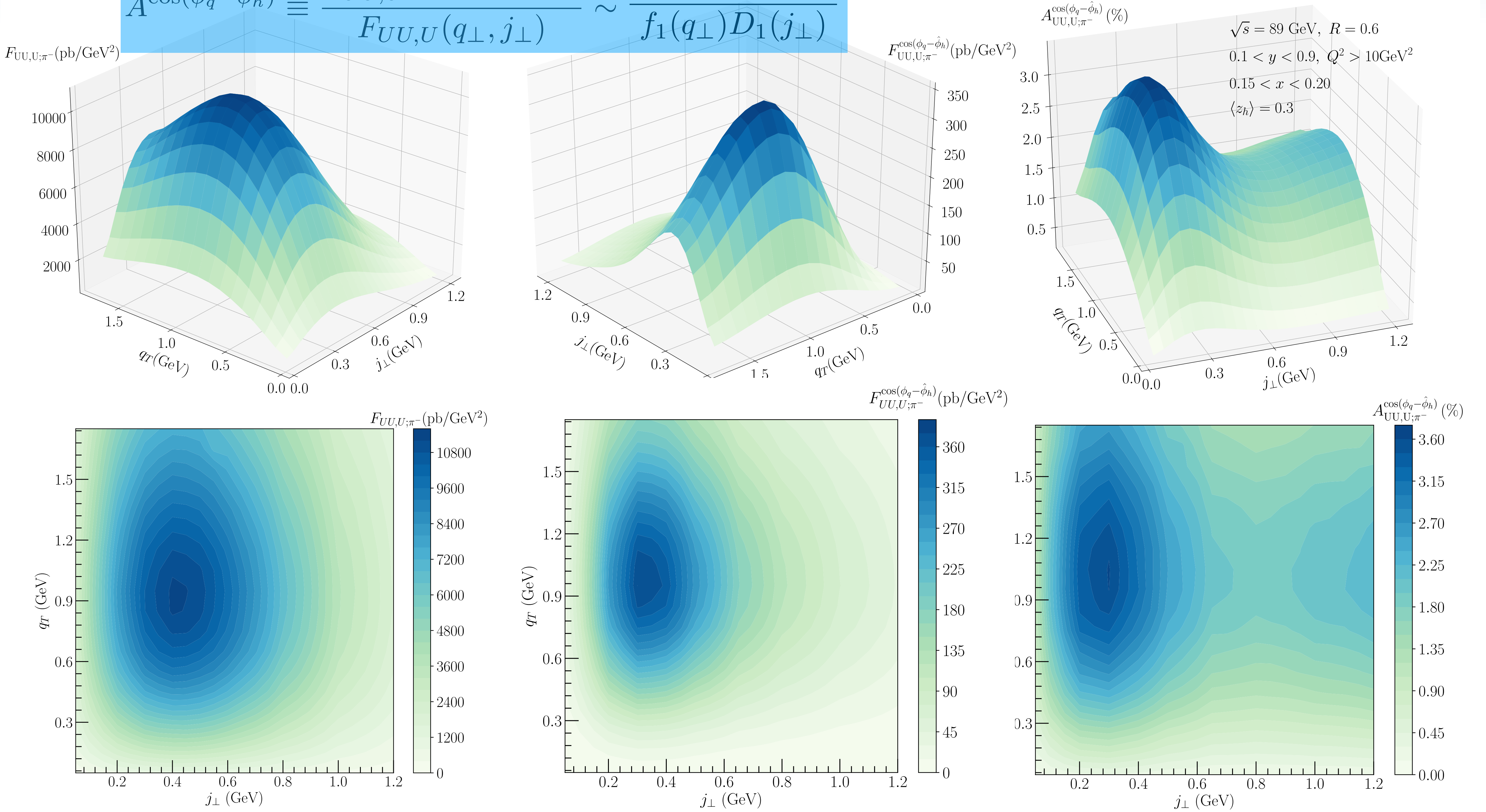
Unpolarized π in jet (Boer-Mulders, Collins)

π^- q_T [0,1.8], j_T [0,1.2]

Denominator Numerator Ratio

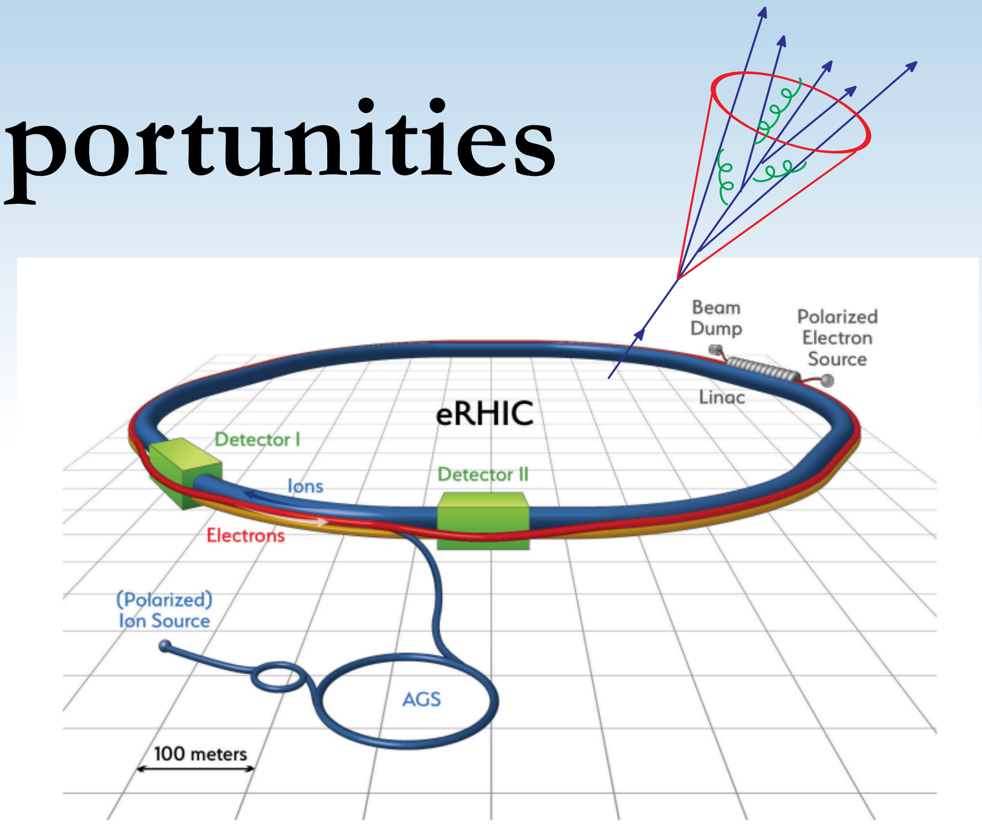
$$A^{\cos(\phi_q-\hat{\phi}_h)} \equiv \frac{F_{UU,U}^{\cos(\phi_q-\hat{\phi}_h)}(q_\perp, j_\perp)}{F_{UU,U}(q_\perp, j_\perp)} \sim \frac{h_1^\perp(q_\perp)H_1^\perp(j_\perp)}{f_1(q_\perp)D_1(j_\perp)}$$



Parametrization from *Barone, Melis, Prokudin `10* (Boer-Mulders)
Kang, Prokudin, Sun, Yuan `15 (Collins)

Kang, KL, Shao, Zhao `21

Opening new door of opportunities



- New processes involving jets to extract TMD structure

$$PP/eP \to J(h)+X, \quad eP \to e+J+X, \quad eP \to e+J(h)+X, \quad \cdots$$

- Jet substructure techniques can be used to access information about TMDFFs
  - Information differential in z_h allow more direct access to the FFs
- Jet processes at the EIC can deconvolve the dependence between the TMDPDF and TMDFF.
  - Its high luminosity, wide energy range, and polarized beams will illuminate our understanding of the hadron structure and process of hadronization.

- **Jets are great way to ‘isolate’ and obtain ‘differential information’ of the non-perturbative TMD of interest, and EIC will be a powerful collider where jets can be of great use to extract TMDs!**

Thank you!