Jets and Transverse Momentum Dependent Functions (TMDs)

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Z.-B. Kang, K. Lee, and F. Zhao,
Polarized jet fragmentation functions,
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- We generalize the unpolarized Fragmentation Functions to hadron distribution in jets with polarization

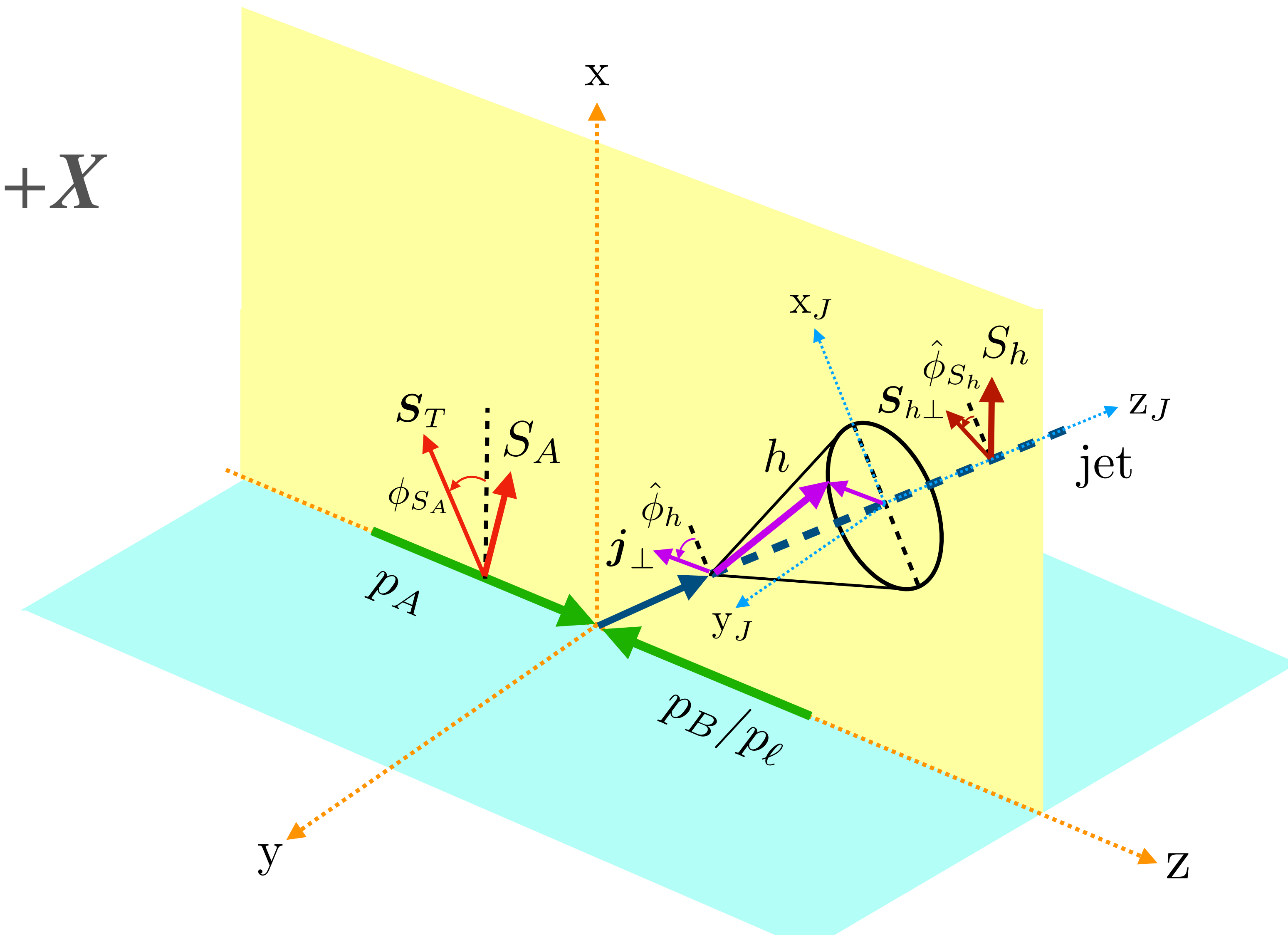
- Both collinear and TMD Jet Fragmenting Functions are derived

$$\boldsymbol{p}+\boldsymbol{e}/\boldsymbol{p} \rightarrow (\mathrm{jet}\boldsymbol{h})+\boldsymbol{X}$$

$$z_h = \frac{p_h^-}{p_J^-},$$

$$\boldsymbol{j}_\perp$$

$$\boldsymbol{S}_{h\perp}$$



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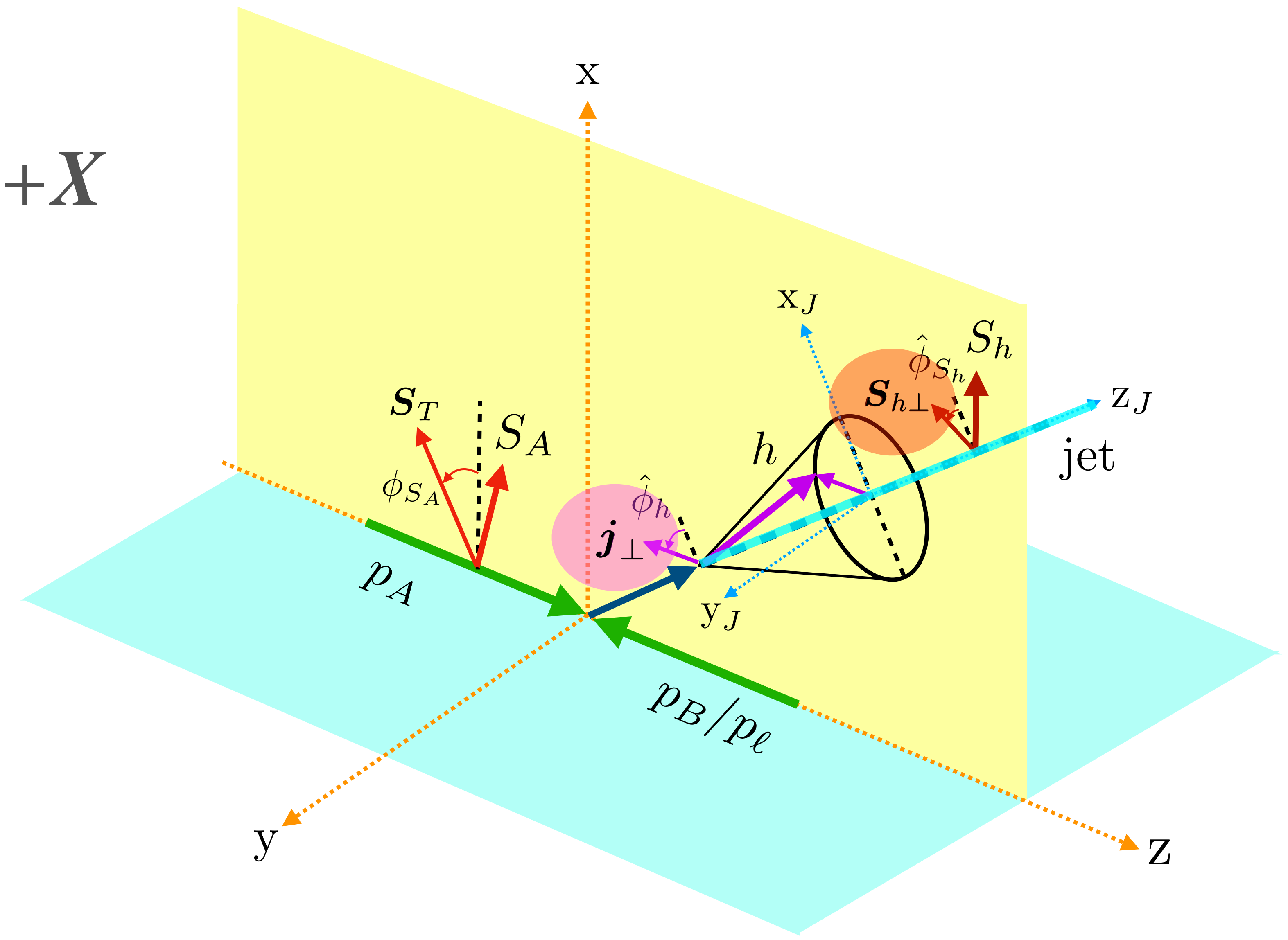

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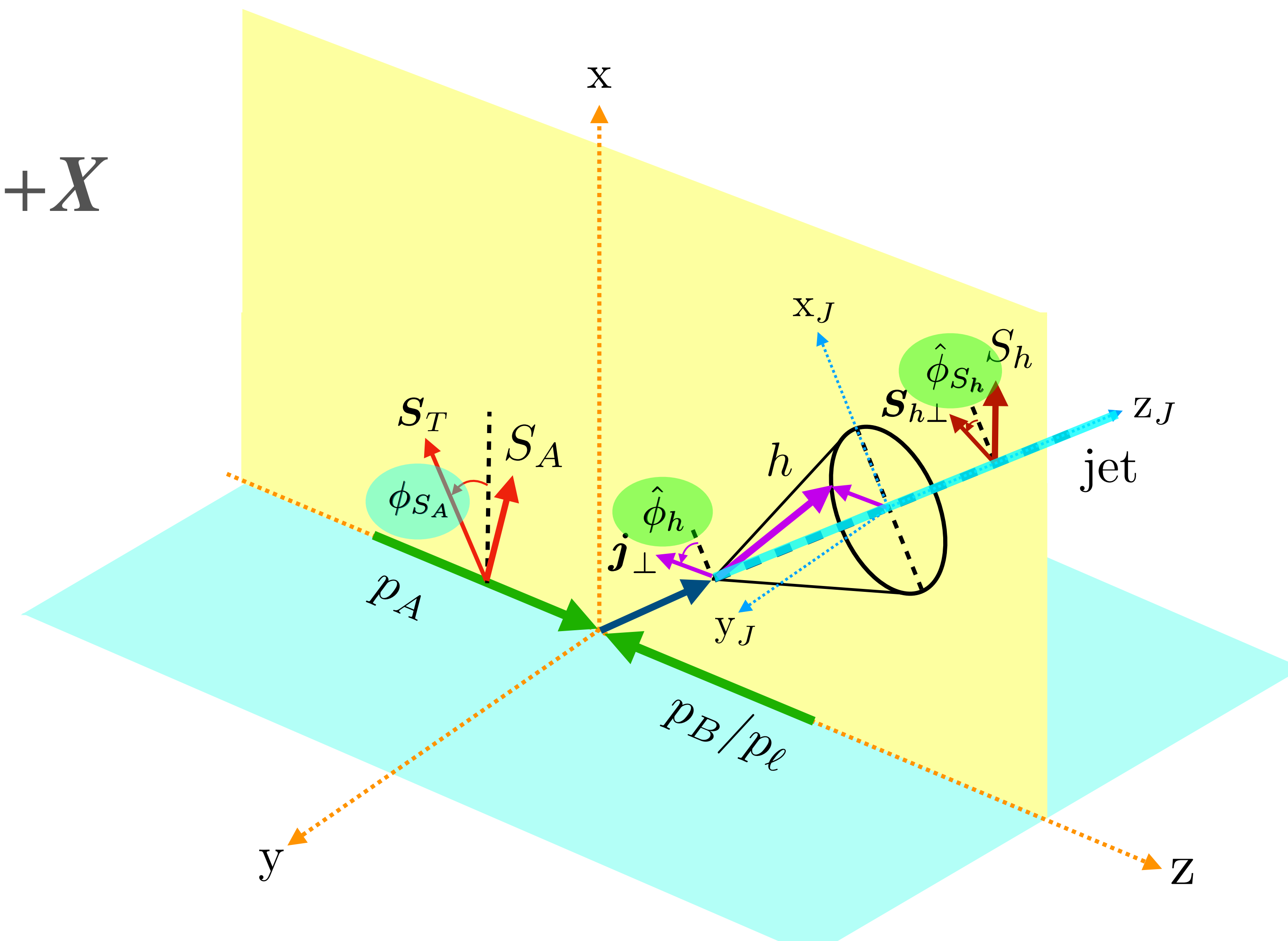


Collinear JFFs

light-cone coordinates $v = (v^+, v^-, v_T)$

$$p_h = \left(\frac{M_h^2}{p_h^-}, p_h^-, 0\right)$$

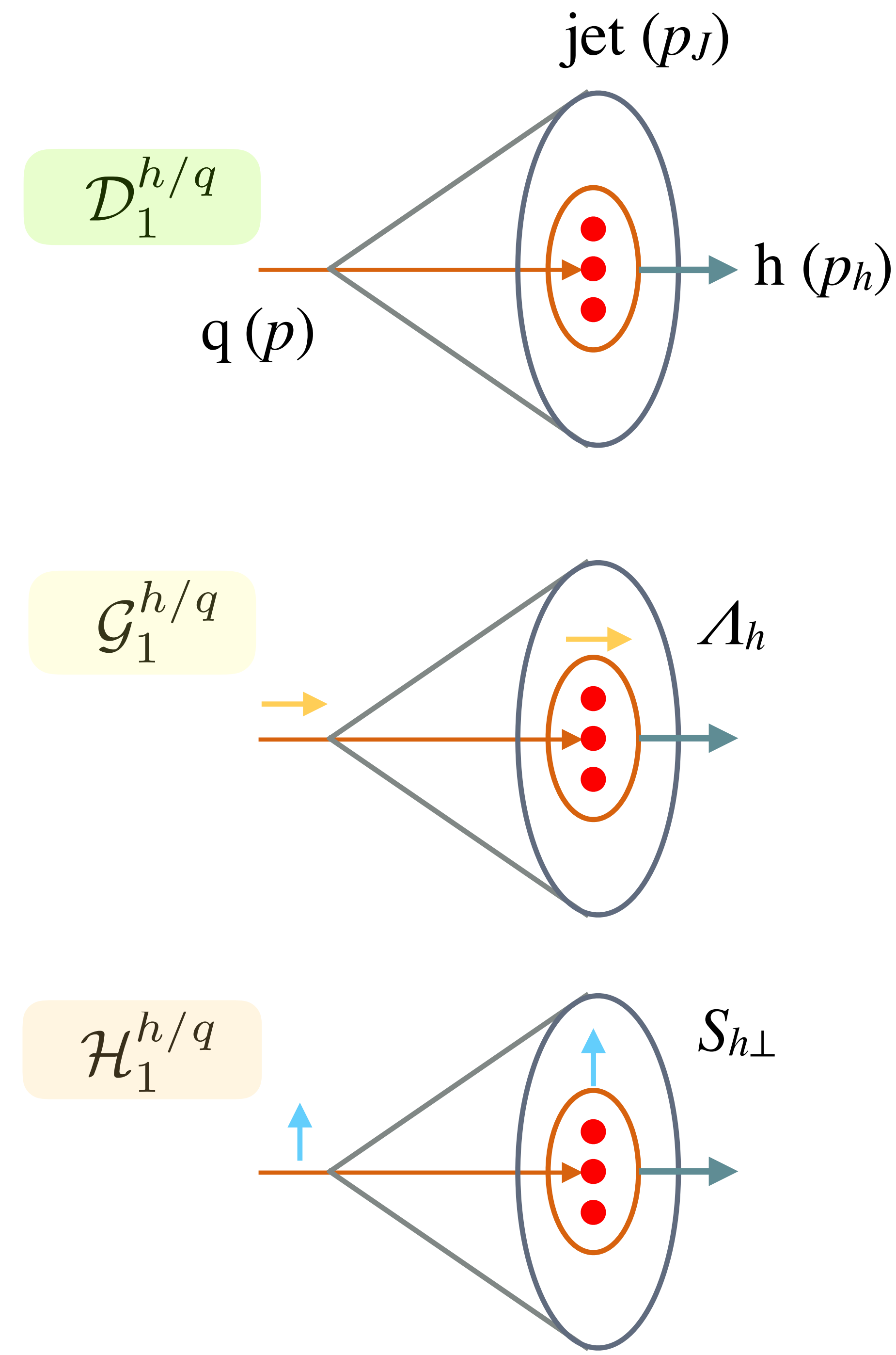
$$S_h = \left(-\Lambda_h \frac{M_h}{p_h^-}, \Lambda_h \frac{p_h^-}{M_h}, \boldsymbol{S}_{h\perp}\right)$$

$$z = \frac{p_J^-}{p^-}, \qquad z_h = \frac{p_h^-}{p_J^-}$$

Collinear JFFs

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		
L		$\mathcal{G}_1^{h/q}$	
T			$\mathcal{H}_1^{h/q}$

Collinear JFFs for quarks. Here U, L, and T represent unpolarized, longitudinally, and transversely polarized state



$$p(p_A, S_A) + \Big(p(p_B)/e(p_\ell)\Big) \to (\text{jet}(\eta_J, p_{JT}, R)\ h(z_h, j_\perp, S_h)) + X$$

$$d\sigma \sim F_{AB,C}$$

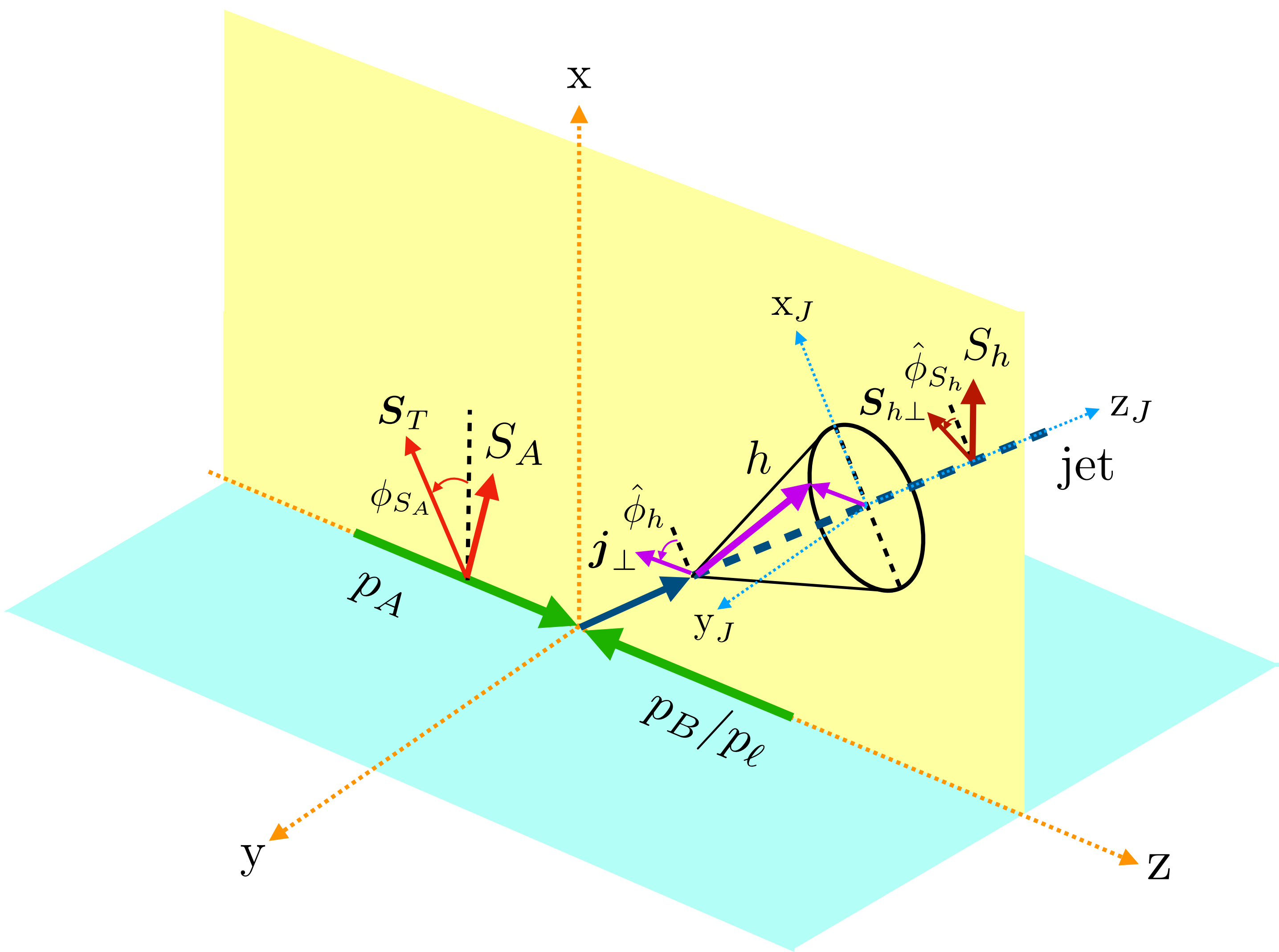


Illustration for the distribution of hadrons inside jets in the collisions of a polarized proton and an unpolarized proton or lepton.

$$F_{UU,C} \sim f_{a/A}(x_a, \mu)\,,$$

$$F_{LU,C} \sim g_{a/A}(x_a, \mu)\,,$$

A/a	U	L	T
U	$f^{a/A}$		
L		$g^{a/A}$	
T			$h^{a/A}$

Collinear PDFs for quarks.

Collinear JFFs

$$p(p_A, S_A) + \Big(p(p_B)/e(p_\ell)\Big) \to (\text{jet}(\eta_J, p_{JT}, R)\ h(z_h, j_\perp, S_h)) + X$$

Measure z_h distribution,

$$d\sigma \sim F_{UU,U} + \Lambda_h\, \lambda F_{LU,L} + |S_{h\perp}||S_T| \cos(\phi_{S_A} - \hat{\phi}_{S_h}) F_{TU,T}^{\cos(\phi_{S_A} - \hat{\phi}_{S_h})}$$

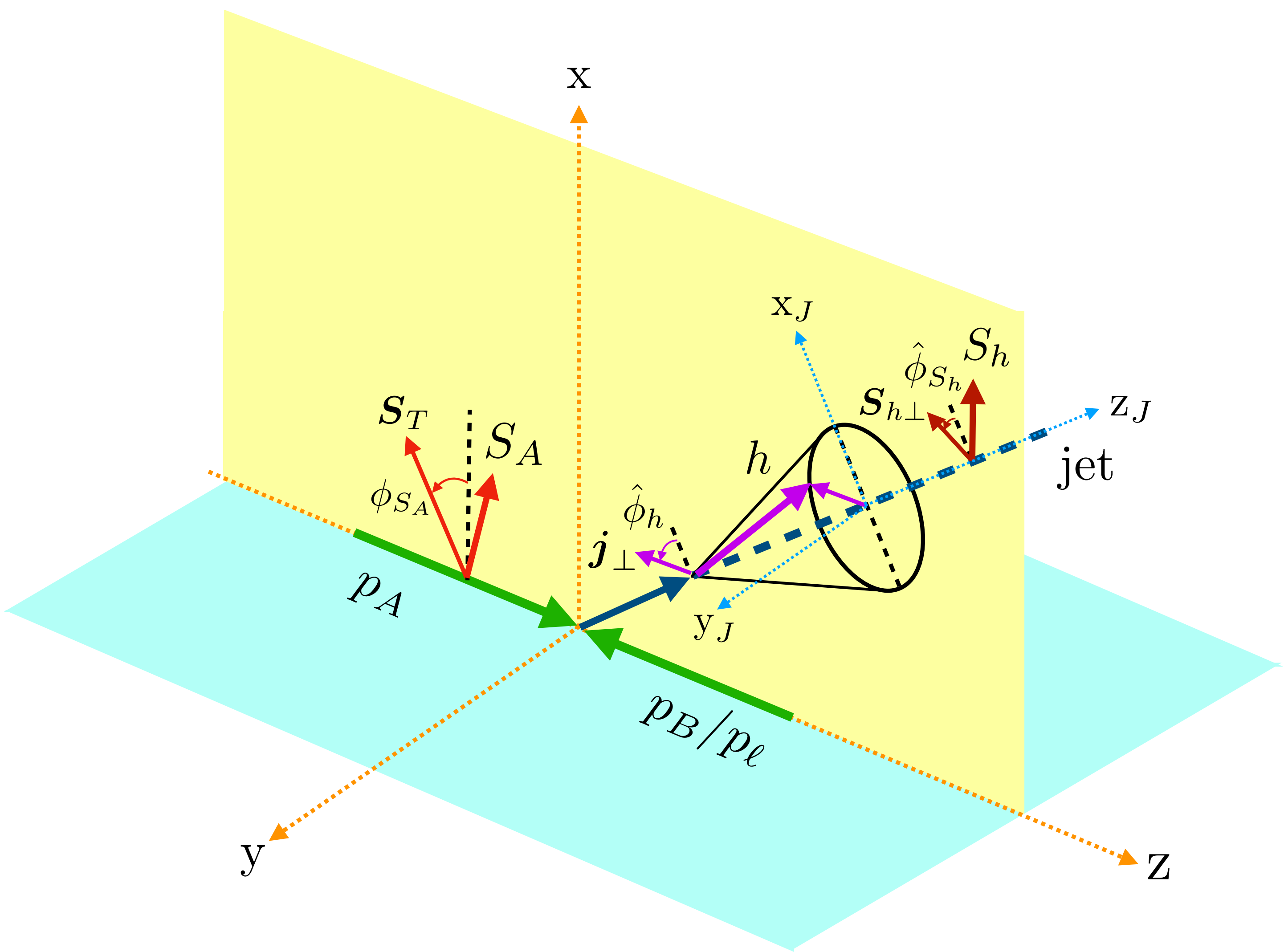


Illustration for the distribution of hadrons inside jets in the collisions of a polarized proton and an unpolarized proton or lepton.

$F_{UU,U} \sim \mathcal{D}_1^{h/c}$

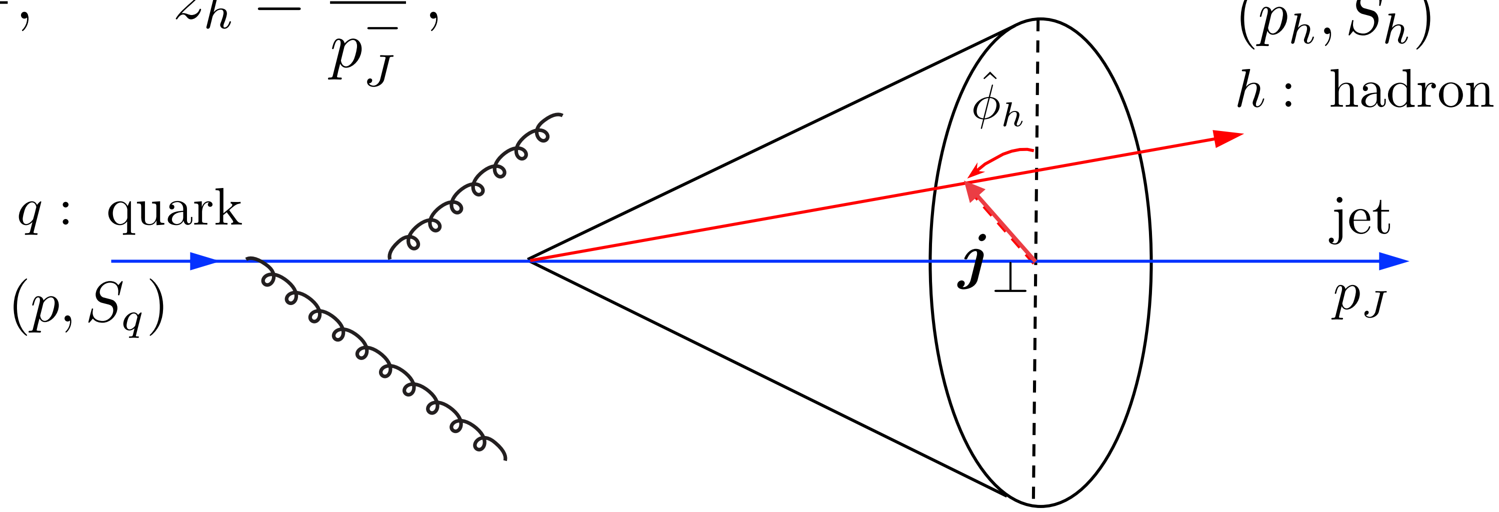
$F_{LU,L} \sim \mathcal{G}_1^{h/c}$

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		
L		$\mathcal{G}_1^{h/q}$	
T			$\mathcal{H}_1^{h/q}$

Collinear JFFs for quarks.

$$p(p_A, S_A) + \Big(p(p_B)/e(p_\ell)\Big) \to (\text{jet}(\eta_J, p_{JT}, R)\ h(z_h, j_\perp, S_h)) + X$$

$$z = \frac{p_J^-}{p^-}, \qquad z_h = \frac{p_h^-}{p_J^-},$$



Leading TMDFFs

h/q	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_1, H_{1T}^\perp$

Leading TMDJFFs

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		$\mathcal{H}_1^{\perp\ h/q}$
L		$\mathcal{G}_{1L}^{h/q}$	$\mathcal{H}_{1L}^{h/q}$
T	$\mathcal{D}_{1T}^{\perp\ h/q}$	$\mathcal{G}_{1T}^{h/q}$	$\mathcal{H}_1^{h/q}$, $\mathcal{H}_{1T}^{\perp\ h/q}$

Transverse momentum dependent FFs/JFFs for quarks. Here U, L, and T represent unpolarized, longitudinally, and transversely polarized state

$$\frac{d\sigma}{dp_{JT}d\eta_J dz_h d^2 j_\perp} = F_{UU,U} + |S_T|\sin(\phi_{S_A} - \hat{\phi}_h)F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)} + \Lambda_h \left[\lambda F_{LU,L} + |S_T|\cos(\phi_{S_A} - \hat{\phi}_h)F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)}\right]$$
$$+ |S_{h\perp}|\Big\{ \sin(\hat{\phi}_h - \hat{\phi}_{S_h})F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda\cos(\hat{\phi}_h - \hat{\phi}_{S_h})F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})}$$
$$+ |S_T|\big(\cos(\phi_{S_A} - \hat{\phi}_{S_h})F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})} + \cos(2\hat{\phi}_h - \hat{\phi}_{S_h} - \phi_{S_A})F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})}\big)\Big\},$$

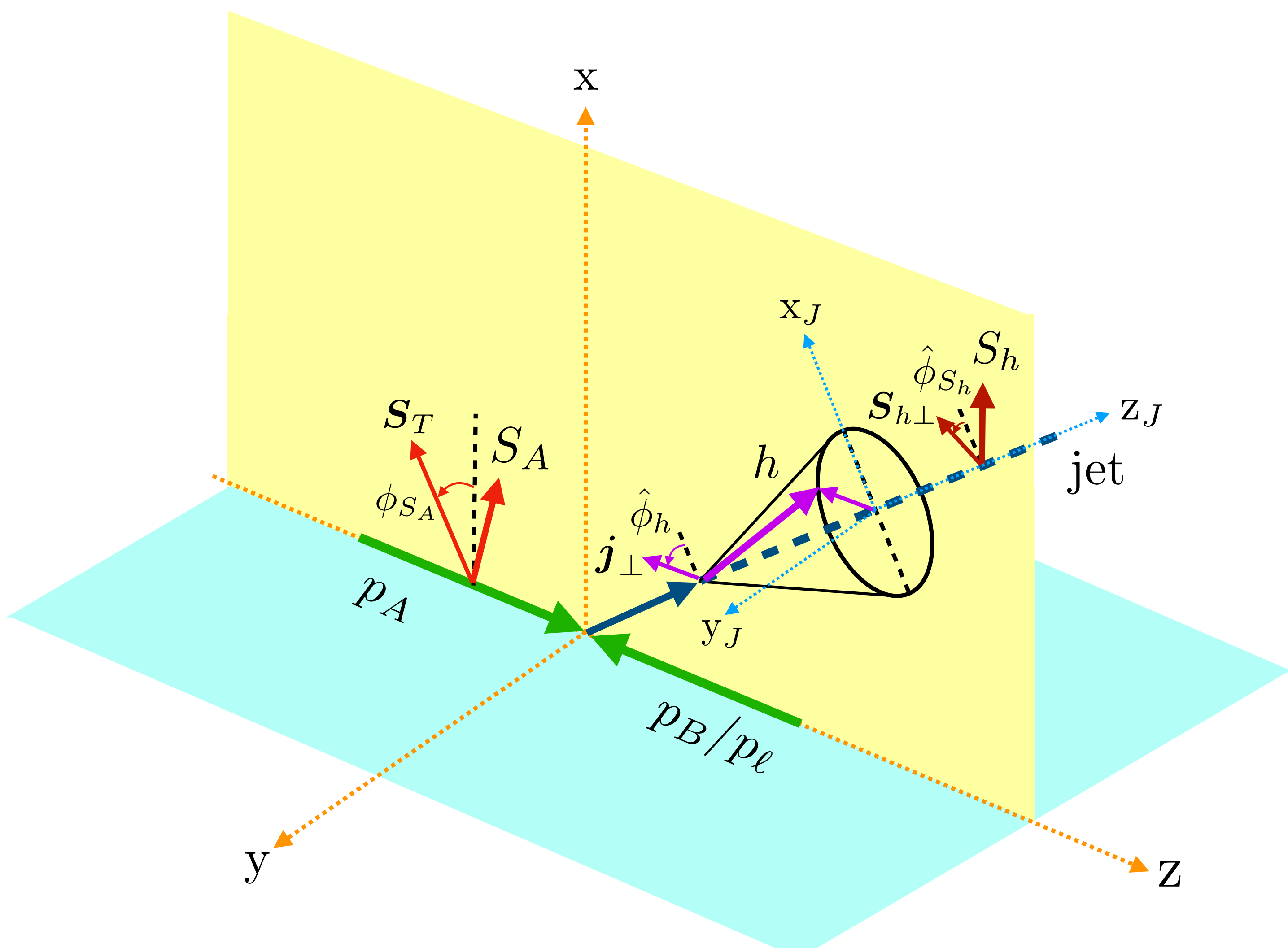


Illustration for the distribution of hadrons inside jets in the collisions of a polarized proton and an unpolarized proton or lepton.

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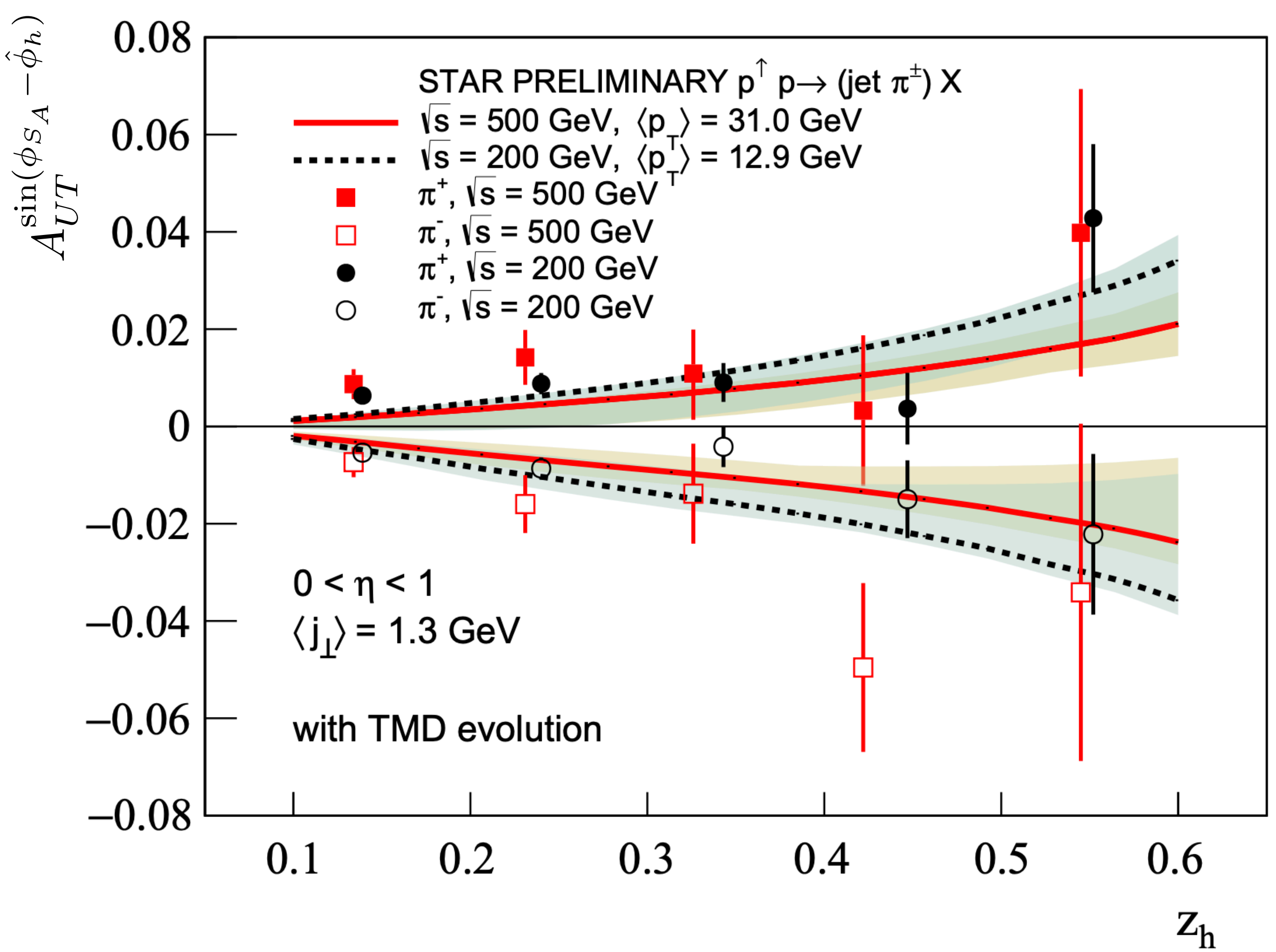
$$+ |S_{h\perp}| \Big\{ \sin(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda \cos(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})}$$
$$+ |S_T| \big(\cos(\phi_{S_A} - \hat{\phi}_{S_h}) F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})} + \cos(2\hat{\phi}_h - \hat{\phi}_{S_h} - \phi_{S_A}) F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})} \big) \Big\},$$

$$p^\uparrow(p_A, S_T) + p(p_B) \to (\text{jet}(\eta_J, p_{JT}, R)\, h(z_h, j_\perp, S_h)) + X$$

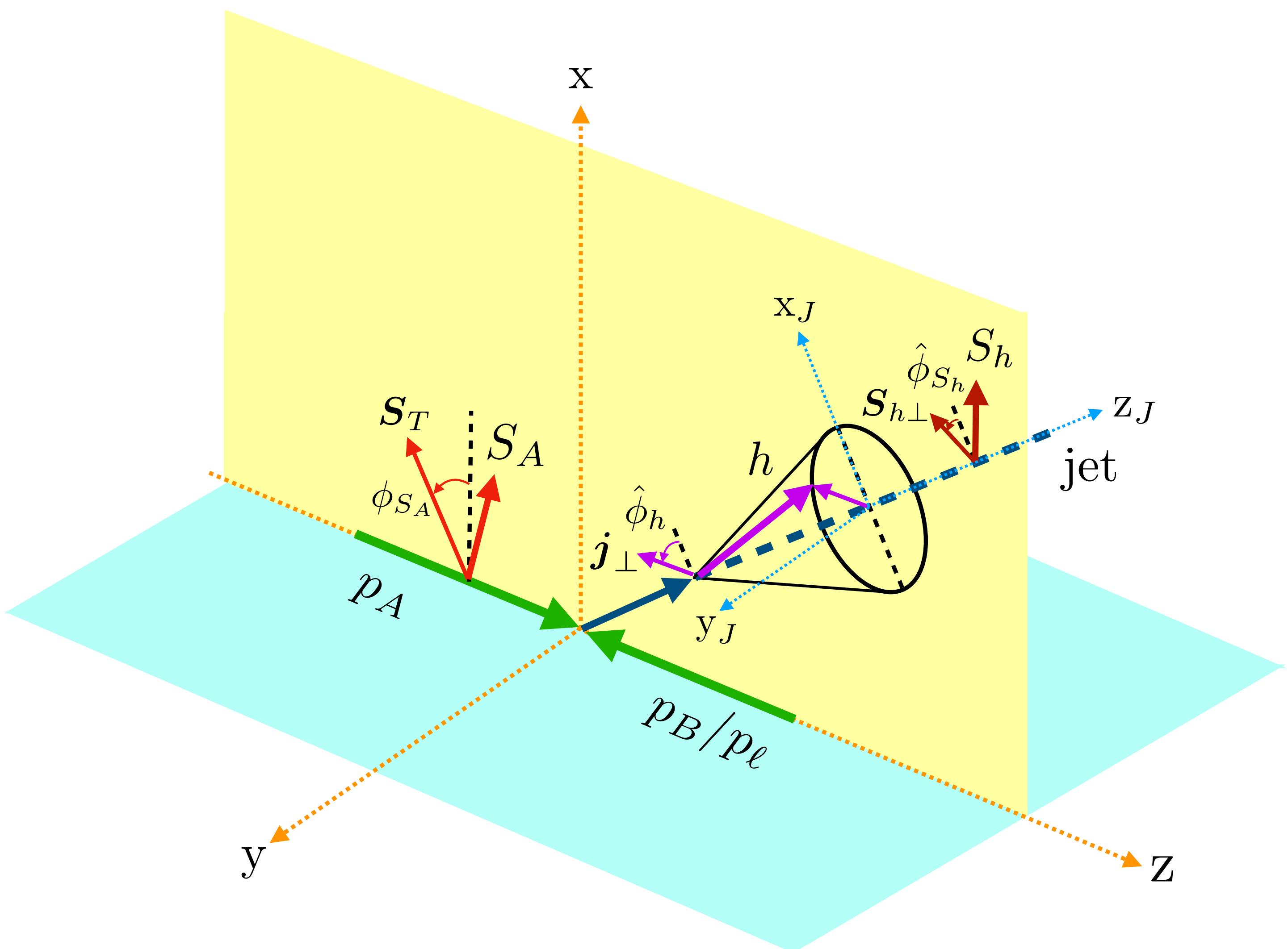
$$A_{UT}^{\sin(\phi_{S_A}-\hat{\phi}_h)} = \frac{F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)}}{F_{UU,U}}$$

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		$\mathcal{H}_1^{\perp\, h/q}$
L		$\mathcal{G}_{1L}^{h/q}$	$\mathcal{H}_{1L}^{h/q}$
T	$\mathcal{D}_{1T}^{\perp\, h/q}$	$\mathcal{G}_{1T}^{h/q}$	$\mathcal{H}_1^{h/q}$, $\mathcal{H}_{1T}^{\perp\, h/q}$



Kang, Prokudin, Ringer, Yuan `17

$$\frac{d\sigma}{dp_{JT}d\eta_J dz_h d^2 j_\perp} = F_{UU,U} + |S_T|\sin(\phi_{S_A}-\hat{\phi}_h)F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)} + \Lambda_h\left[\lambda F_{LU,L} + |S_T|\cos(\phi_{S_A}-\hat{\phi}_h)F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)}\right]$$
$$+ |S_{h\perp}|\Big\{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda\cos(\hat{\phi}_h-\hat{\phi}_{S_h})F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})}$$
$$+ |S_T|\big(\cos(\phi_{S_A}-\hat{\phi}_{S_h})F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})} + \cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})}\big)\Big\},$$



$$F_{UU,U} \sim \mathcal{D}_1^{h/q}$$
$$F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} \sim \mathcal{D}_{1T}^{\perp\ h/q}$$

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		$\mathcal{H}_1^{\perp\ h/q}$
L		$\mathcal{G}_{1L}^{h/q}$	$\mathcal{H}_{1L}^{h/q}$
T	$\mathcal{D}_{1T}^{\perp\ h/q}$	$\mathcal{G}_{1T}^{h/q}$	$\mathcal{H}_1^{h/q},\ \mathcal{H}_{1T}^{\perp\ h/q}$

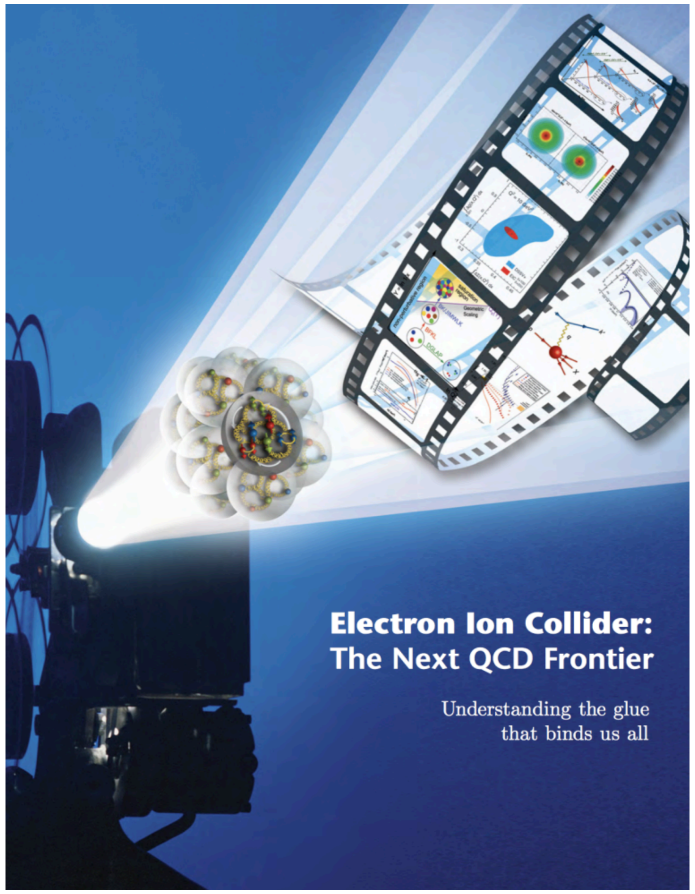
TMDJFFs for quarks.

Phenomenology

- The asymmetry $D_{LL}^{\text{jet}\Lambda}$ and P_{Λ} of an inclusive jet sample

$$e+p \rightarrow (\text{jet}\Lambda)+X$$

for helicity and transverse polarization are studied for EIC.



$$p\left(p_A, S_A\right) + e\left(p_\ell\right) \rightarrow \left(\text{jet}\left(\eta_J, p_{JT}, R\right) \vec{\Lambda}\left(z_\Lambda, S_\Lambda\right)\right) + X$$

$$F_{LU,L} \sim g \otimes \mathcal{G}_1^{\Lambda/c}$$

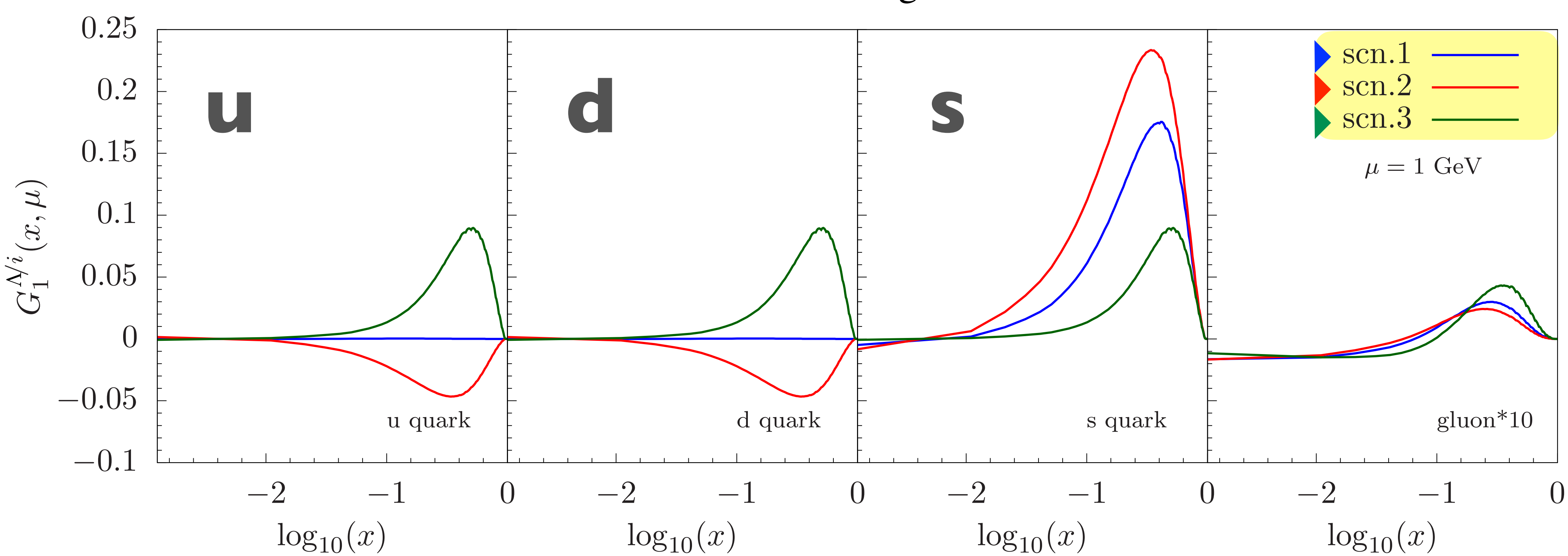
$$D_{LL}^{\text{jet}\Lambda} = \frac{F_{LU,L}}{F_{UU,U}}$$

g : longitudinally polarized collinear PDFs

$\mathcal{G}_1$: longitudinally polarized JFFs

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		
L		$\mathcal{G}_1^{h/q}$	
T			$\mathcal{H}_1^{h/q}$

Polarized Lambda Fragmentation Functions



Florian, Stratmann, Vogelsang `97

Collinear JFFs

$$p\,(p_A, S_A) + e\,(p_\ell) \to (\text{jet}\,(\eta_J, p_{JT}, R)\,\vec{\Lambda}\,(z_\Lambda, S_\Lambda)) + X$$

$$F_{LU,L} \sim g \otimes \mathcal{G}_1^{\Lambda/c}$$

$$D_{LL}^{\text{jet}\Lambda} = \frac{F_{LU,L}}{F_{UU,U}}$$

g : longitudinally polarized collinear PDFs

$\mathcal{G}_1$: longitudinally polarized JFFs

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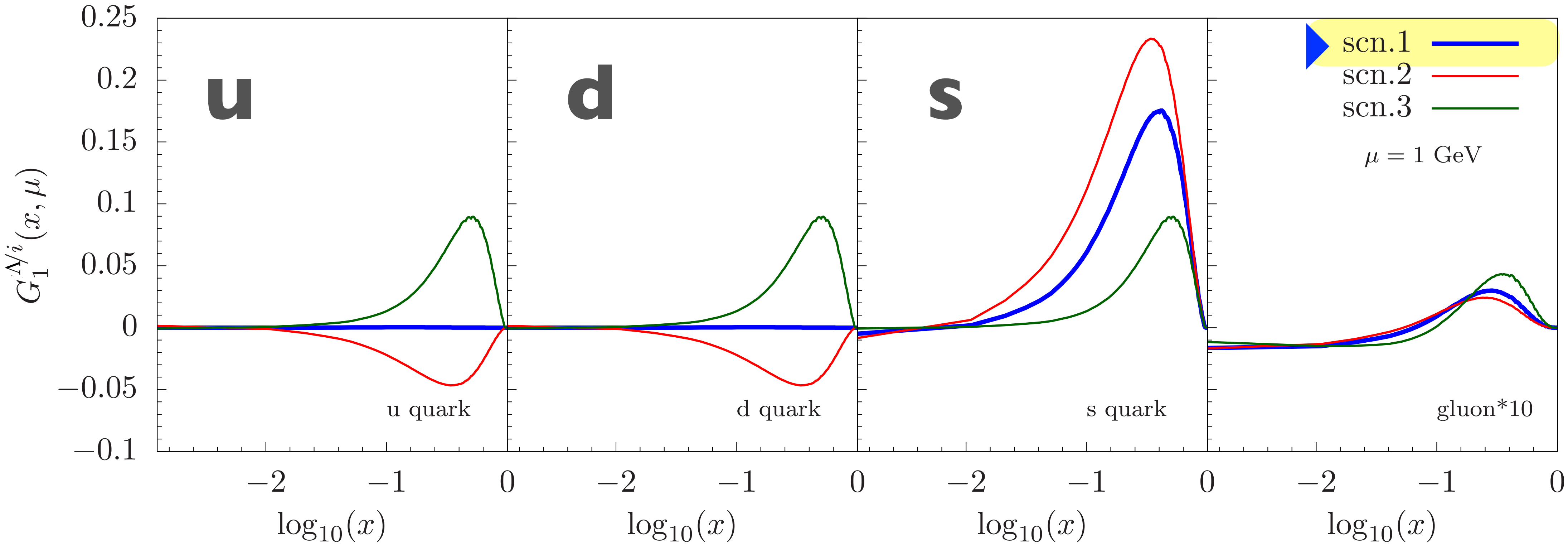
L		$\mathcal{G}_1^{h/q}$	
T			$\mathcal{H}_1^{h/q}$

Polarized Lambda Fragmentation Functions



Florian, Stratmann, Vogelsang `97

Collinear JFFs

$$p\,(p_A, S_A) + e\,(p_\ell) \to (\text{jet}\,(\eta_J, p_{JT}, R)\,\vec{\Lambda}\,(z_\Lambda, S_\Lambda)) + X$$

$$F_{LU,L} \sim g \otimes \mathcal{G}_1^{\Lambda/c}$$

$$D_{LL}^{\text{jet}\Lambda} = \frac{F_{LU,L}}{F_{UU,U}}$$

g : longitudinally polarized collinear PDFs

$\mathcal{G}_1$: longitudinally polarized JFFs

h\ q	U	L	T
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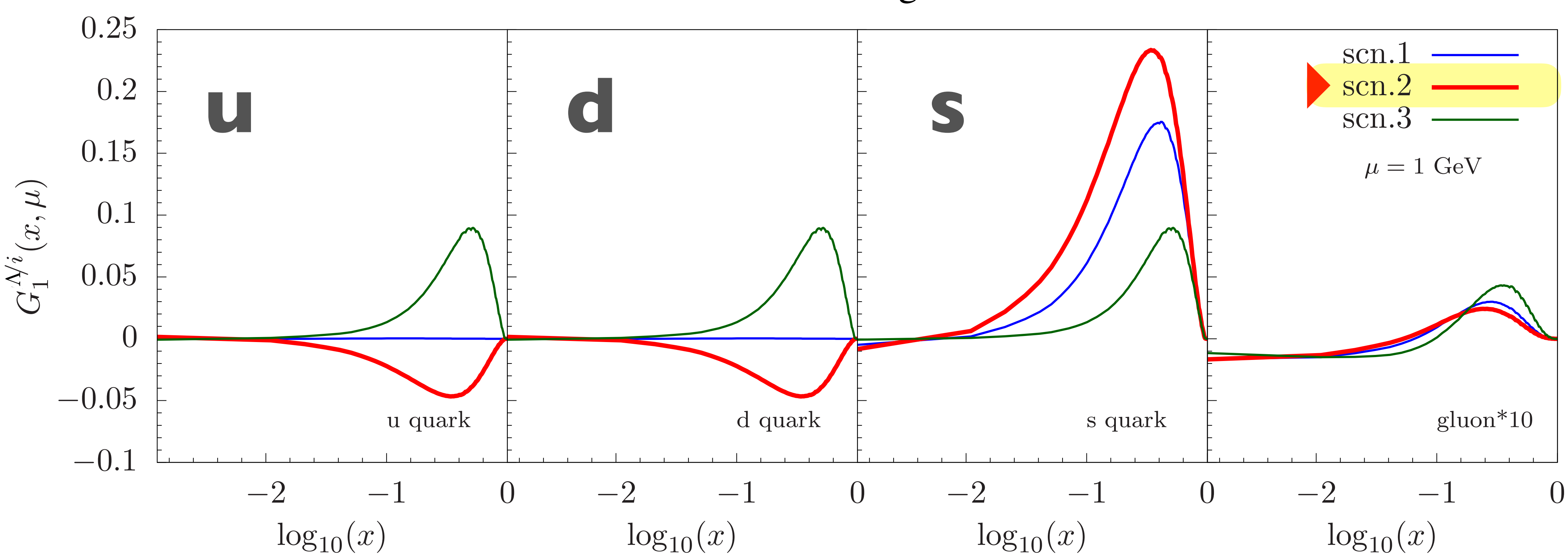
L		$\mathcal{G}_1^{h/q}$	
T			$\mathcal{H}_1^{h/q}$

Polarized Lambda Fragmentation Functions



Florian, Stratmann, Vogelsang `97

$$p\,(p_A, S_A) + e\,(p_\ell) \to (\text{jet}\,(\eta_J, p_{JT}, R)\,\vec{\Lambda}\,(z_\Lambda, S_\Lambda)) + X$$

$$F_{LU,L} \sim g \otimes \mathcal{G}_1^{\Lambda/c}$$

$$D_{LL}^{\text{jet}\Lambda} = \frac{F_{LU,L}}{F_{UU,U}}$$

g : longitudinally polarized collinear PDFs

$\mathcal{G}_1$: longitudinally polarized JFFs

h\ q	U	L	T
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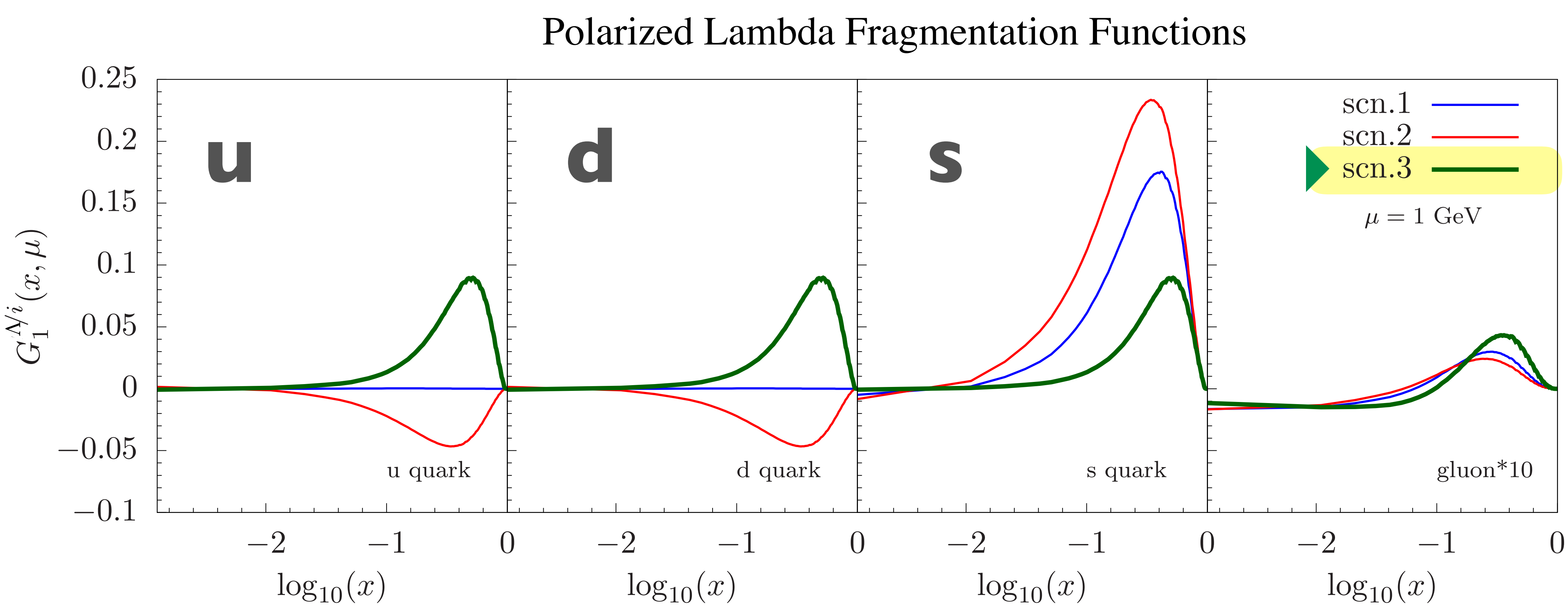
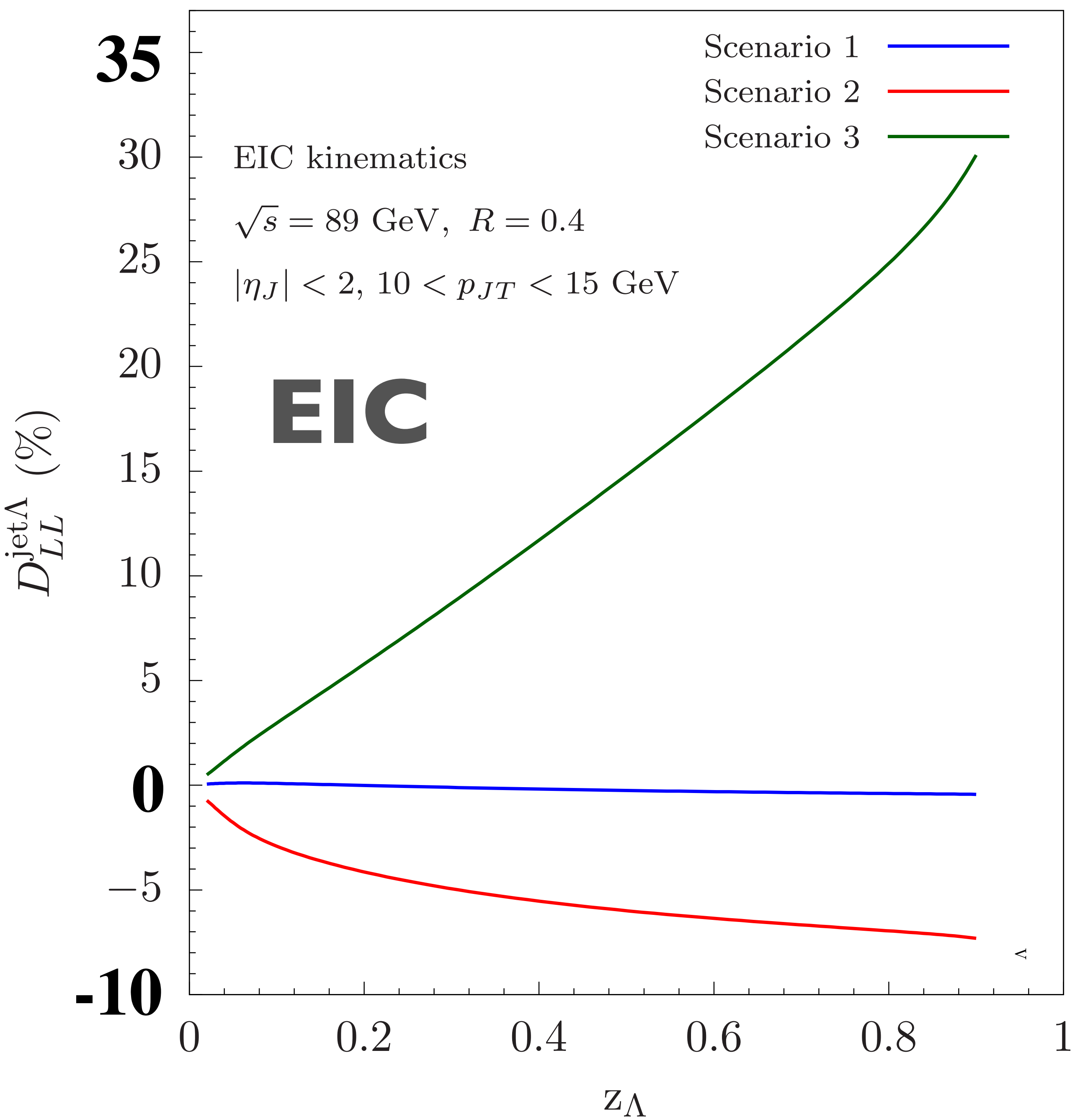


Florian, Stratmann, Vogelsang `97

$$p\,(p_A, S_A) + e\,(p_\ell) \to (\text{jet}\,(\eta_J, p_{JT}, R)\,\vec{\Lambda}\,(z_\Lambda, S_\Lambda)) + X$$

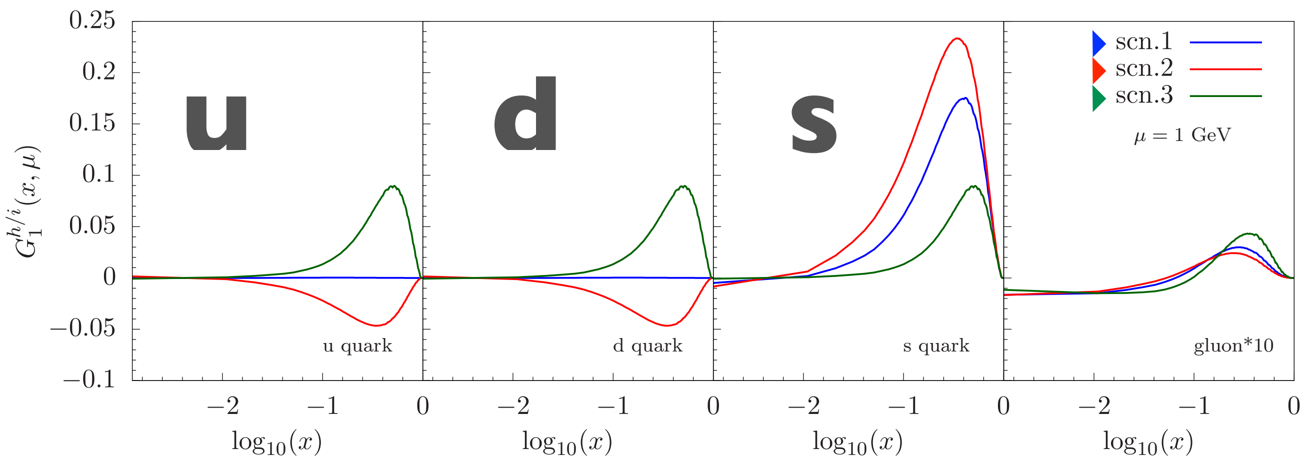


$$D_{LL}^{\text{jet}\Lambda} = \frac{F_{LU,L}}{F_{UU,U}}$$

$$F_{UU,U} \sim f_a \otimes \mathcal{D}_1^{\Lambda/c}$$

$$F_{LU,L} \sim g_a \otimes \mathcal{G}_1^{\Lambda/c}$$

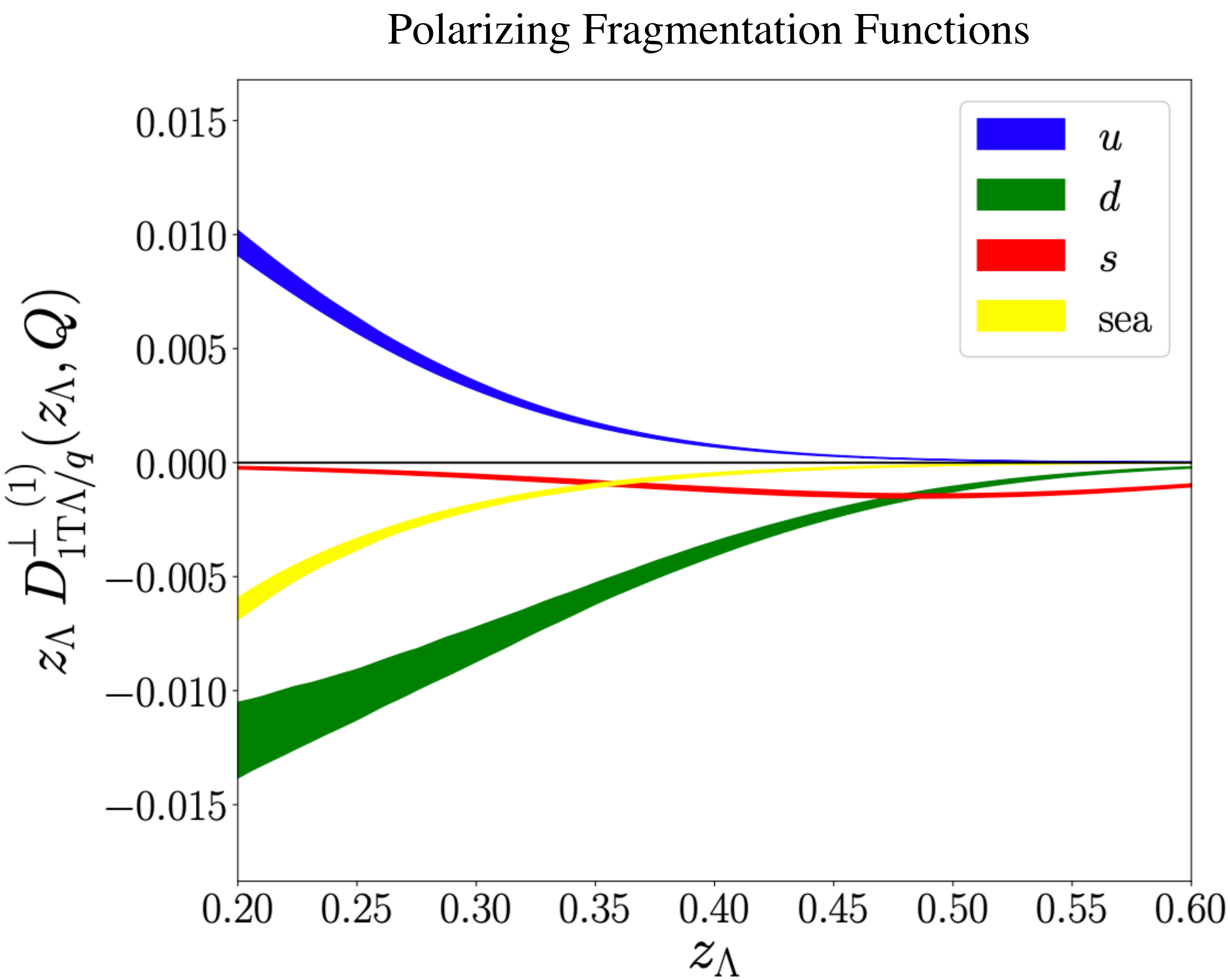
h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		
L		$\mathcal{G}_1^{h/q}$	
T			$\mathcal{H}_1^{h/q}$

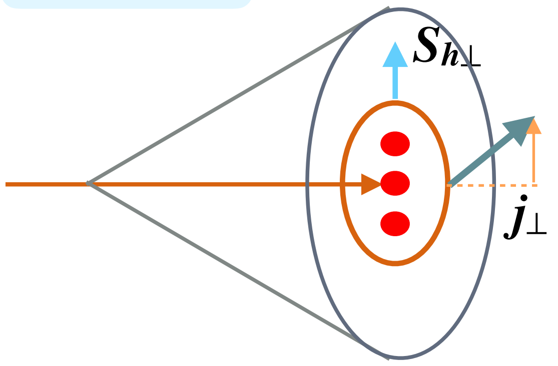


$$p\,(p_A) + e\,(p_\ell) \to (\text{jet}\,(\eta_J, p_{JT}, R)\,\Lambda^{\uparrow}(z_\Lambda, \boldsymbol{j}_\perp S_\Lambda)) + X$$

$$P_\Lambda = \frac{F_{UU,T}^{\sin(\hat\phi_h - \hat\phi_{S_h})}}{F_{UU,U}}$$

$$F_{UU,T}^{\sin(\hat\phi_h - \hat\phi_{S_h})} \sim f_a \otimes \mathcal{D}_{1T}^{\perp\ \Lambda/c}$$

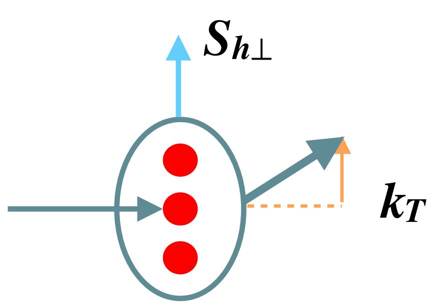




matching

$D_{1T}^{\perp\ \Lambda/c}$

TMDFFs



Callos, Kang, Terry `20

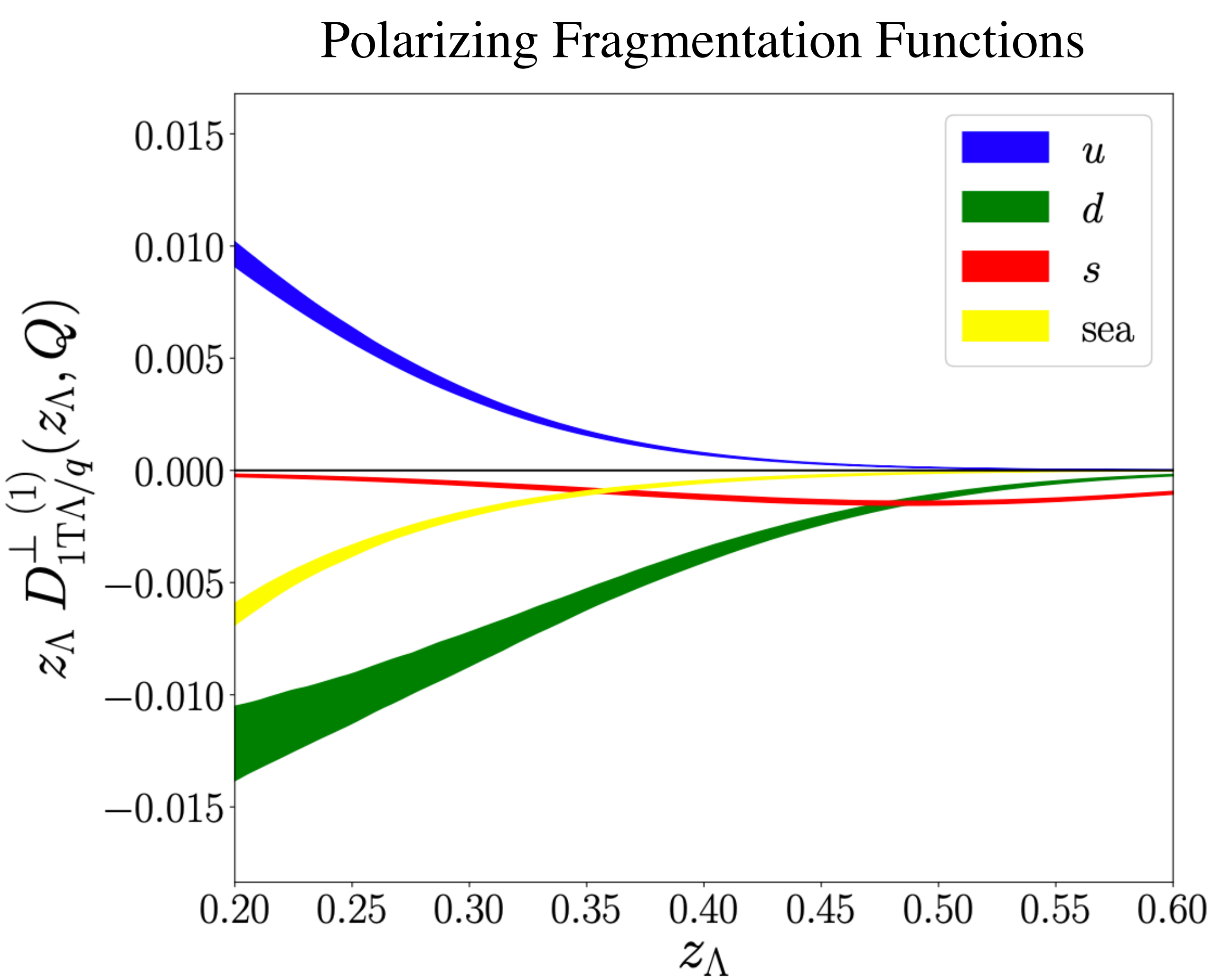
$$p\,(p_A) + e\,(p_\ell) \to (\text{jet}\,(\eta_J, p_{JT}, R)\,\Lambda^{\uparrow}(z_\Lambda, \boldsymbol{j}_\perp S_\Lambda)) + X$$

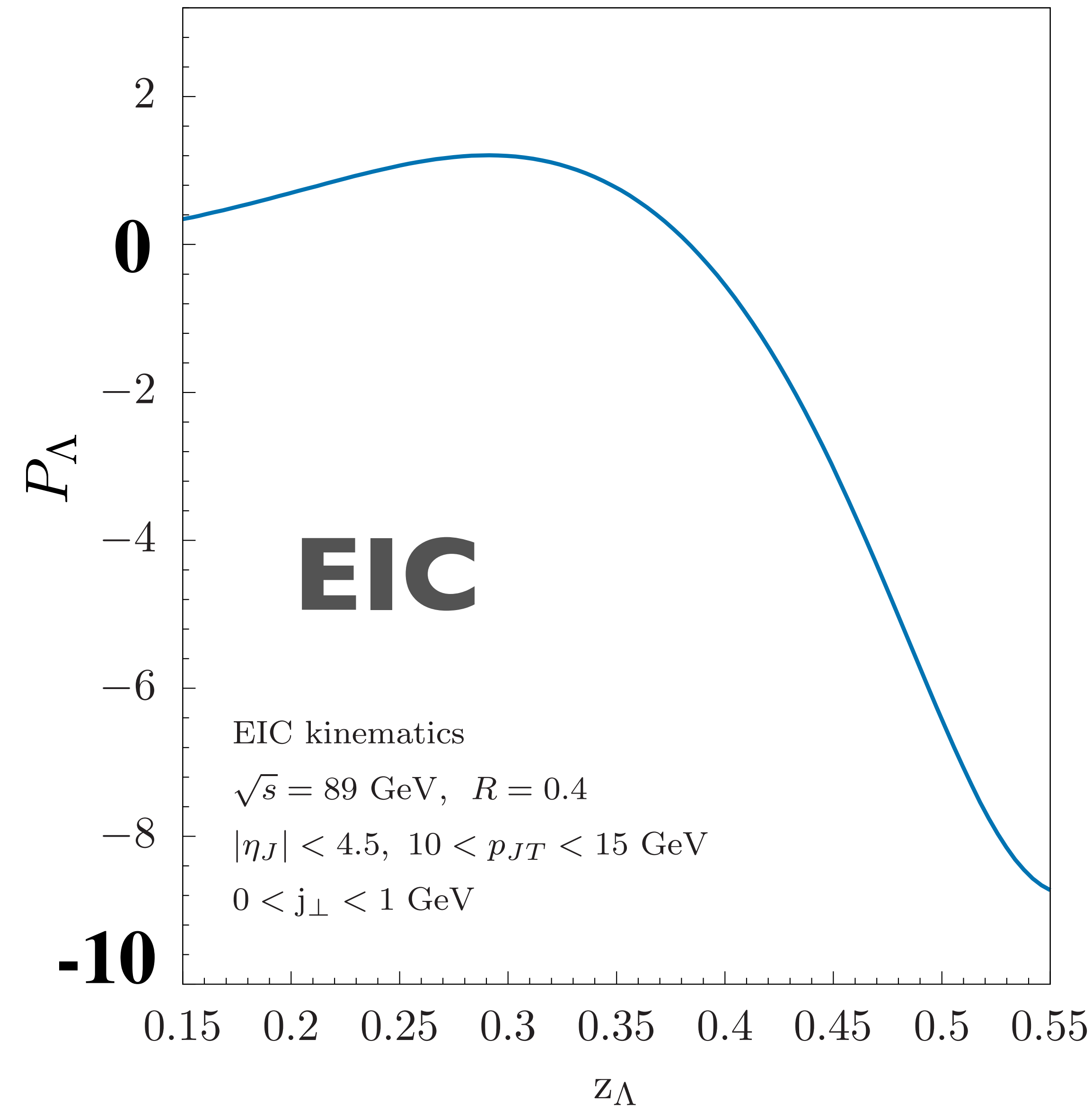
$$P_\Lambda = \frac{F_{UU,T}^{\sin(\hat\phi_h - \hat\phi_{S_h})}}{F_{UU,U}}$$

$$F_{UU,U} \sim f_a \otimes \mathcal{D}_1^{\Lambda/c}$$

$$F_{UU,T}^{\sin(\hat\phi_h - \hat\phi_{S_h})} \sim f_a \otimes \mathcal{D}_{1T}^{\perp\,\Lambda/c}$$

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		$\mathcal{H}_1^{\perp\,h/q}$
L		$\mathcal{G}_{1L}^{h/q}$	$\mathcal{H}_{1L}^{h/q}$
T	$\mathcal{D}_{1T}^{\perp\,h/q}$	$\mathcal{G}_{1T}^{h/q}$	$\mathcal{H}_1^{h/q}$, $\mathcal{H}_{1T}^{\perp\,h/q}$

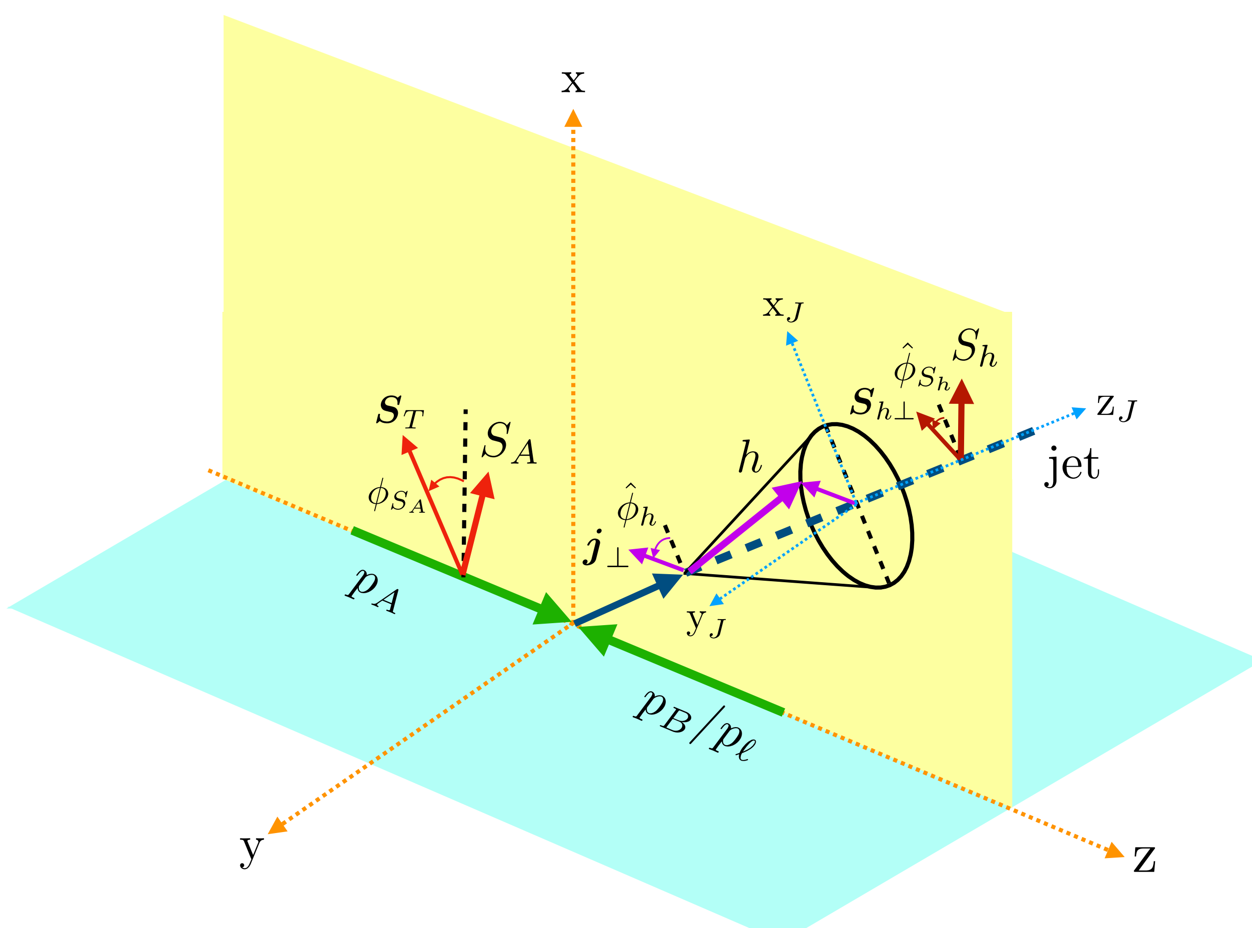


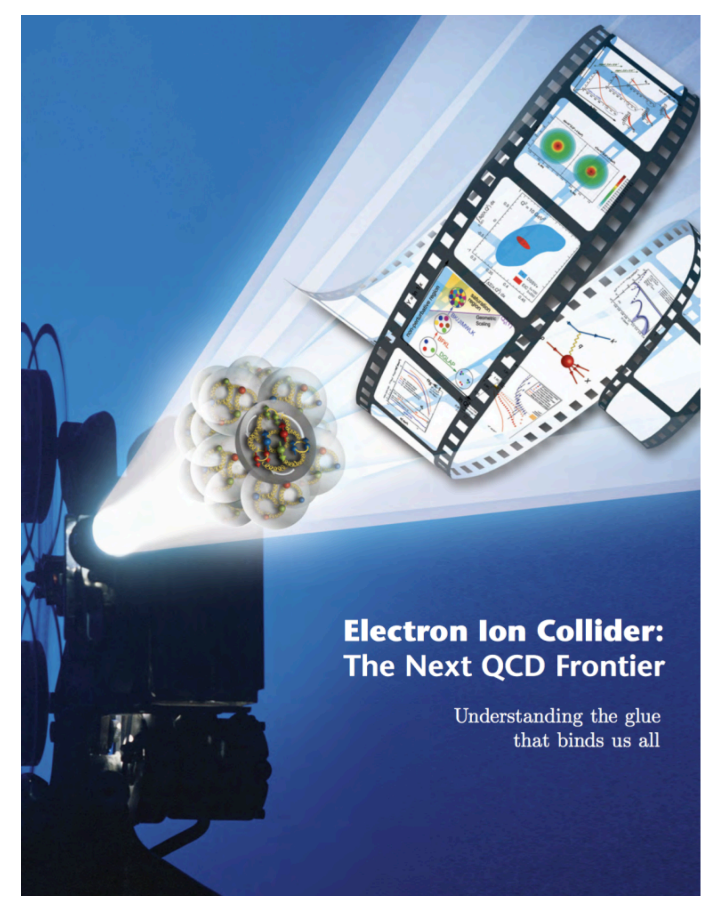


Summary & Outlook

- We have developed the theoretical framework of the unpolarized/ polarized hadron distribution inside jets
- Study the general angular dependence for the process

$$p\left(p_A, S_A\right) + e\left(p_\ell, S_l\right) \to e\left(p_\ell'\right) + \left(\text{jet}\left(\eta_J, p_{JT}, R\right) h\left(z_h, \boldsymbol{j}_\perp S_h\right)\right) + X$$

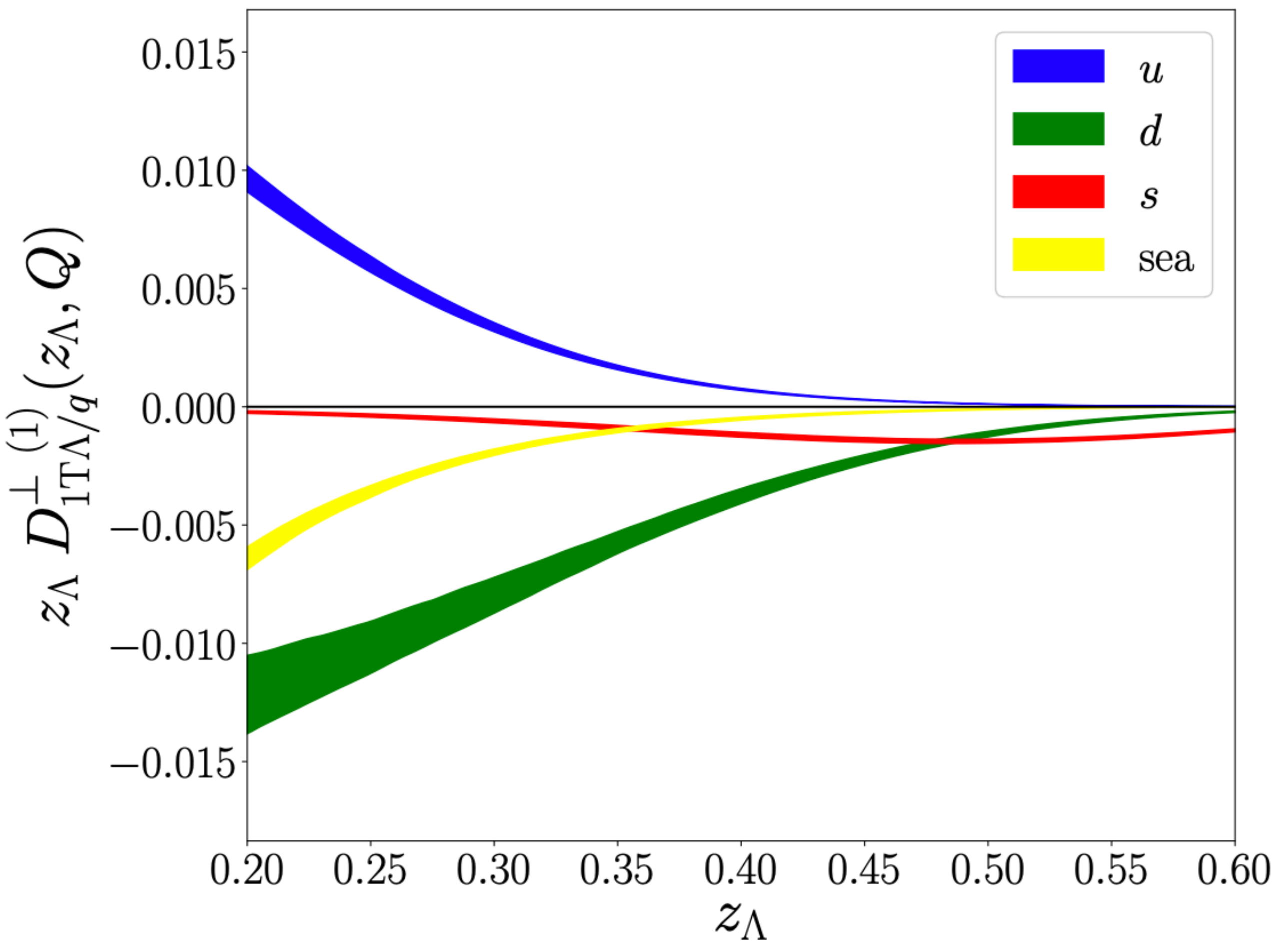




Thank you

Backup

Polarizing Fragmentation Functions



$$D_{1T,\Lambda/q}^{(1)\perp}(z_\Lambda, Q) = \frac{\langle M_D^2 \rangle}{2 z_\Lambda^2 M_\Lambda^2} D_{1T,\Lambda/q}^{\perp}(z_\Lambda, Q)$$

$$\Delta^{h/q\left[in_\nu \sigma^{iv}\gamma_5\right]} = S^i_{h\perp} \mathcal{H}_{1T}^{h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) + \frac{\epsilon_T^{ij} j_\perp^j}{z_h M_h} \mathcal{H}_1^{\perp h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) - \frac{j_\perp^i}{z_h M_h} \Lambda_h \mathcal{H}_{1L}^{\perp h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) + \frac{j_\perp^i \boldsymbol{j}_\perp \cdot S_{h\perp}}{z_h^2 M_h^2} \mathcal{H}_{1T}^{\perp h/q}\left(z, z_h, \boldsymbol{j}_\perp\right)$$

$$\mathcal{H}_1^{h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) = \mathcal{H}_{1T}^{h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) + \frac{-\frac{1}{2}\boldsymbol{j}_\perp^2}{z_h^2 M_h^2} \mathcal{H}_{1T}^{\perp h/q}\left(z, z_h, \boldsymbol{j}_\perp\right)$$

$$\Delta^{h/q\left[in_\nu \sigma^{iv}\gamma_5\right]} = S^i_{h\perp} \mathcal{H}_1^{h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) + \frac{\epsilon_T^{ij} j_\perp^j}{z_h M_h} \mathcal{H}_1^{\perp h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) - \frac{j_\perp^i}{z_h M_h} \Lambda_h \mathcal{H}_{1L}^{\perp h/q}\left(z, z_h, \boldsymbol{j}_\perp\right) + \frac{j_\perp^i \boldsymbol{j}_\perp \cdot S_{h\perp} - \frac{1}{2}\boldsymbol{j}_\perp^2 S^i_{h\perp}}{z_h^2 M_h^2} \mathcal{H}_{1T}^{\perp h/q}\left(z, z_h, \boldsymbol{j}_\perp\right)$$