The 24th International Spin Symposium

Spin asymmetries in electron-jet production at the EIC

arXiv:2106.15624

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Overview

- Motivation
- $ep \to e + \text{jet}(h) + X$

  Theoretical framework

  Example 1: Unpolarized $\pi^{\pm}$ in jet

  Example 2: Transversely polarized Λ in jet
- Summary & Outlook

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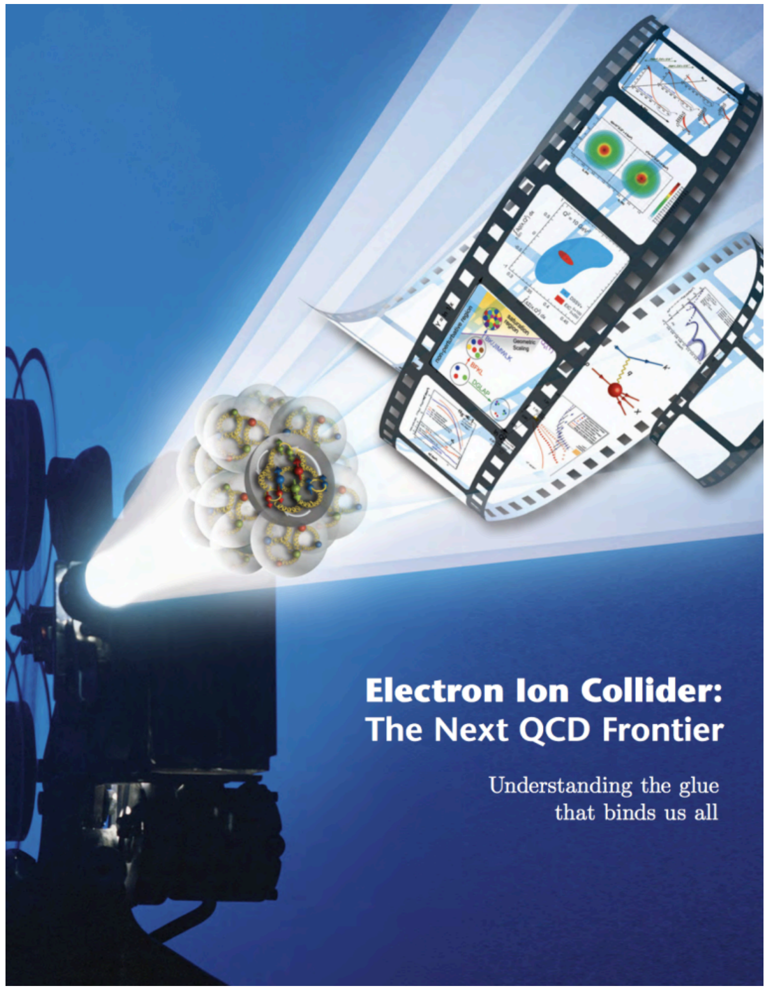
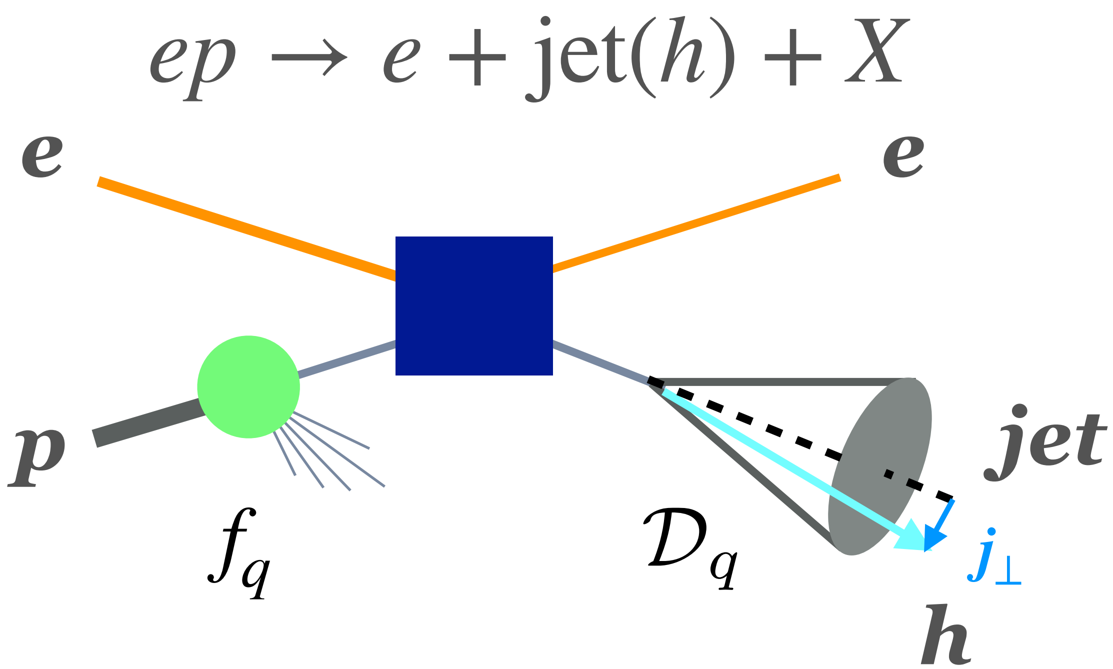
- Summary & Outlook

- Studies of jets have been used as an important probe to test the fundamental properties of hadrons.

- The advent of the Electron-Ion Collider (EIC) with polarized beams unlock the full potential of jets for probing 3D structure of the nucleon and nuclei (encoded in **TMDPDFs**).



- In the process of $ep \to e + \text{jet}(h) + X$, the hadron's distribution inside jet (**TMDJFFs**) correlate with the parton distribution functions (**TMDPDFs**) of the initial proton



$$\sigma \sim f_q \otimes \mathcal{D}_q$$

$\mathcal{D}_q$: Match to TMDFFs with a perturbative coefficient function

Factorization: $j_\perp \ll p_T R \ll Q$

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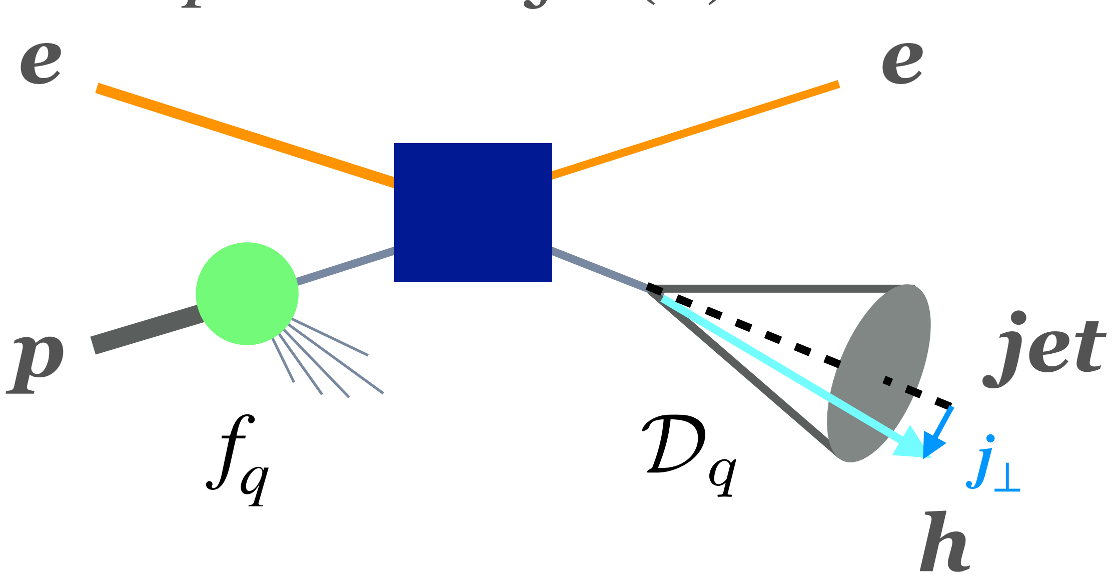
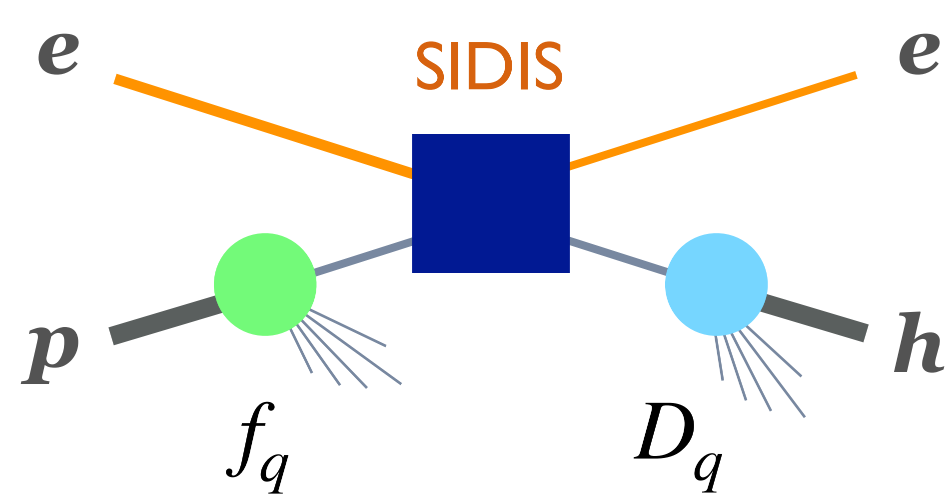


$$\sigma \sim f_q \otimes \mathcal{D}_q$$

$\mathcal{D}_q$: Match to TMDFFs with a perturbative coefficient function

Factorization: $j_\perp \ll p_T R \ll Q$

$$ep \to e + h + X$$



$$\sigma \sim f_q \otimes D_q$$

D_q: Non-perturbative

Factorization: $P_{hT} \ll Q$

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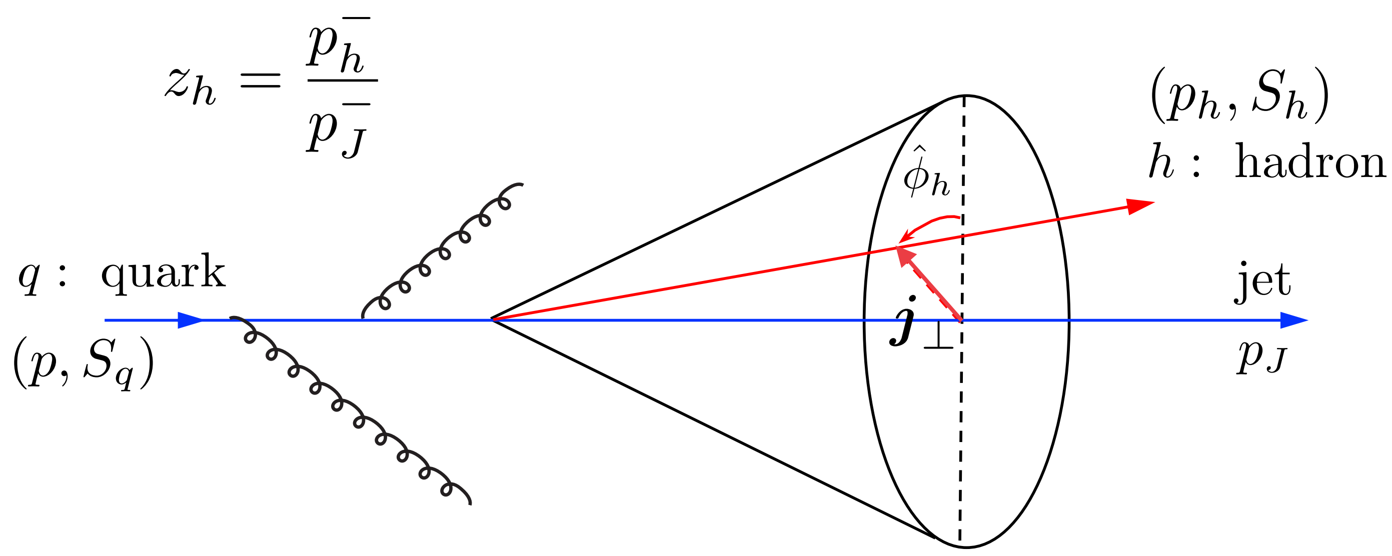
TMDJFFs

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



Leading TMDFFs

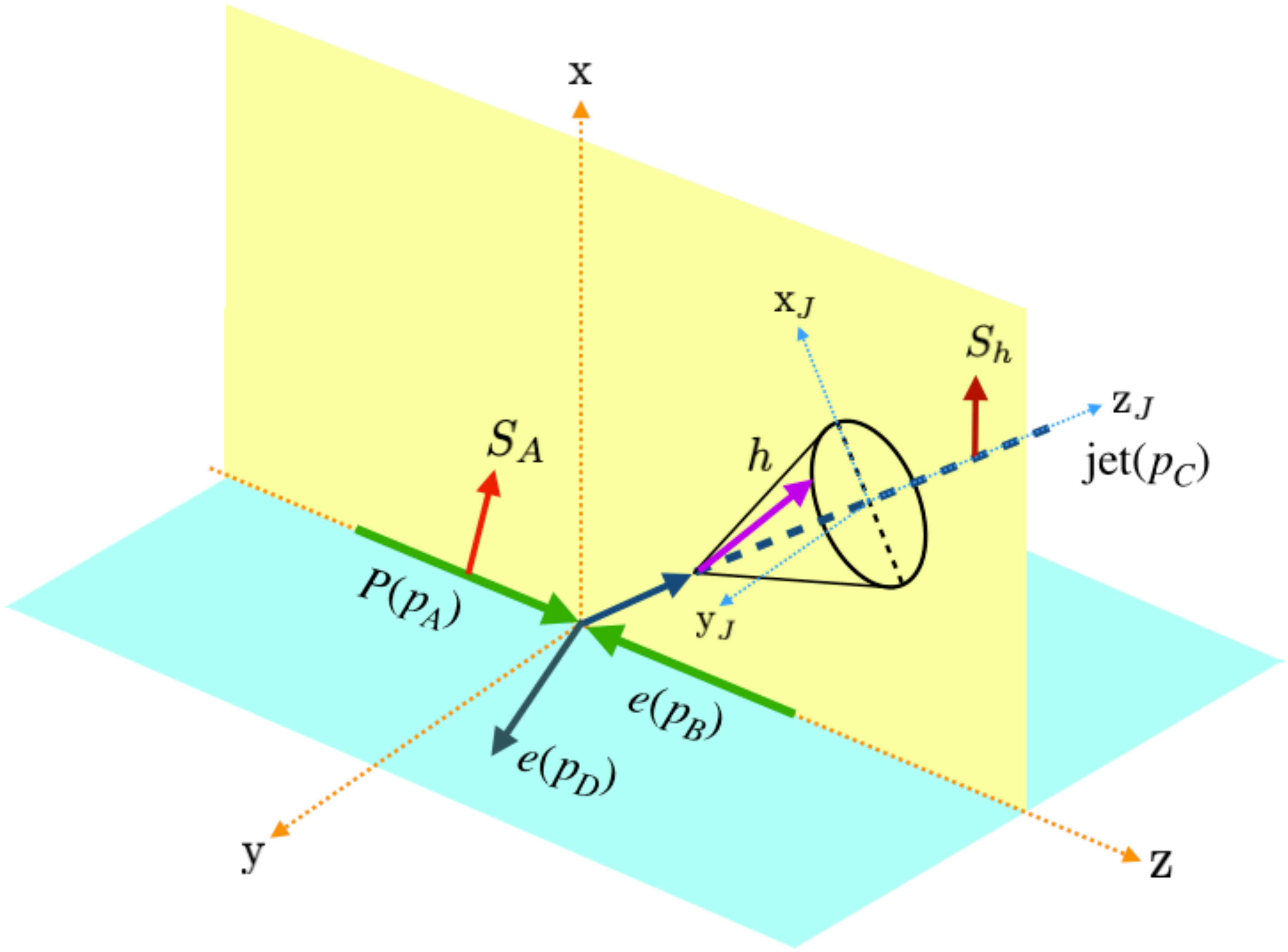
h/q	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_1, H_{1T}^\perp$

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

- All the possible spin asymmetries in back-to-back electron-jet production with jet fragmentation process, $ep \to e + \text{jet}(h) + X$, at the future electron ion collider (EIC)



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$$\boldsymbol{q}_T = \boldsymbol{p}_{C,T} + \boldsymbol{p}_{D,T}$$

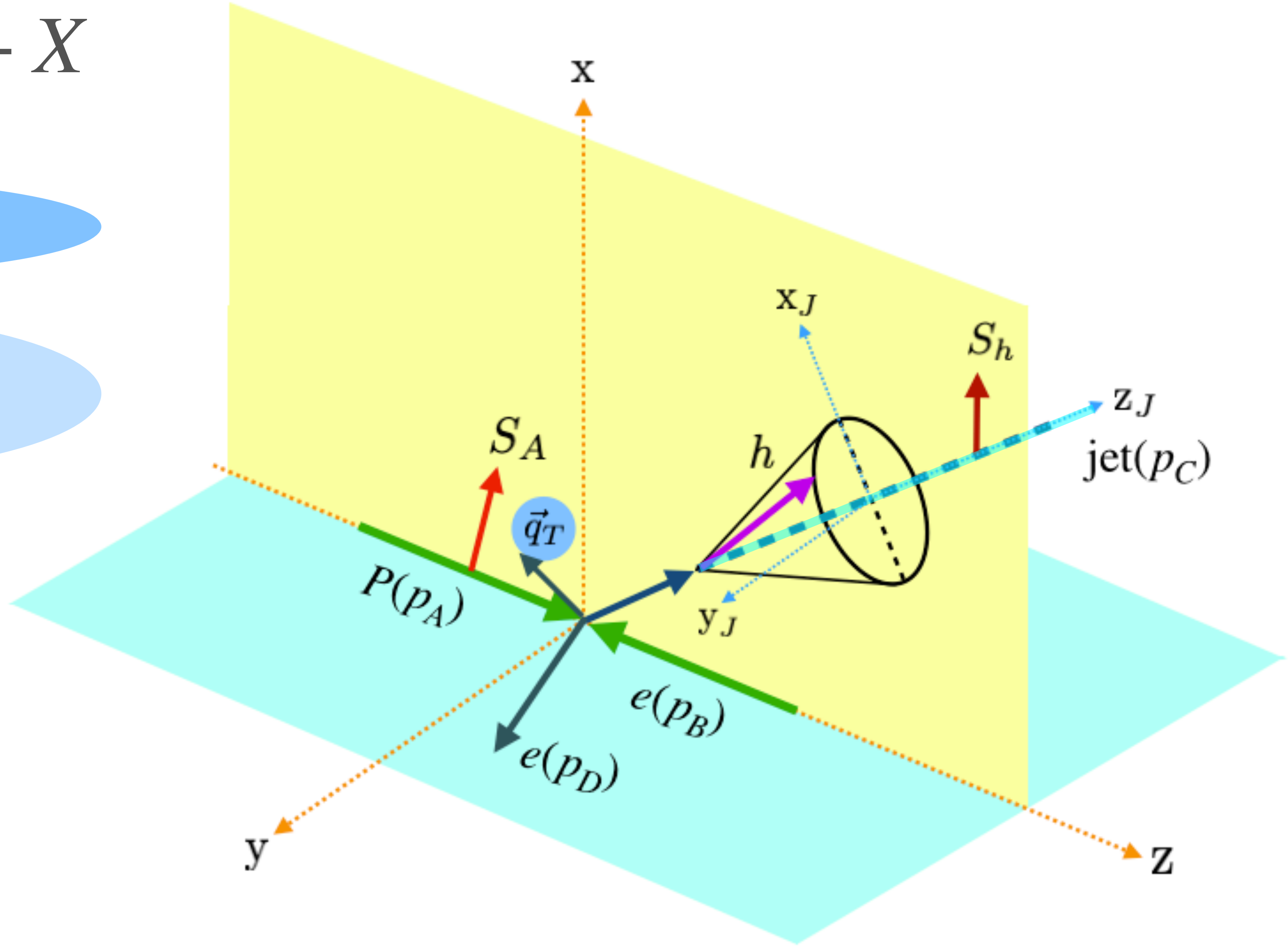
$$\boldsymbol{p}_T = \frac{\boldsymbol{p}_{C,T} - \boldsymbol{p}_{D,T}}{2}$$

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

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

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

$$\boldsymbol{S}_T$$



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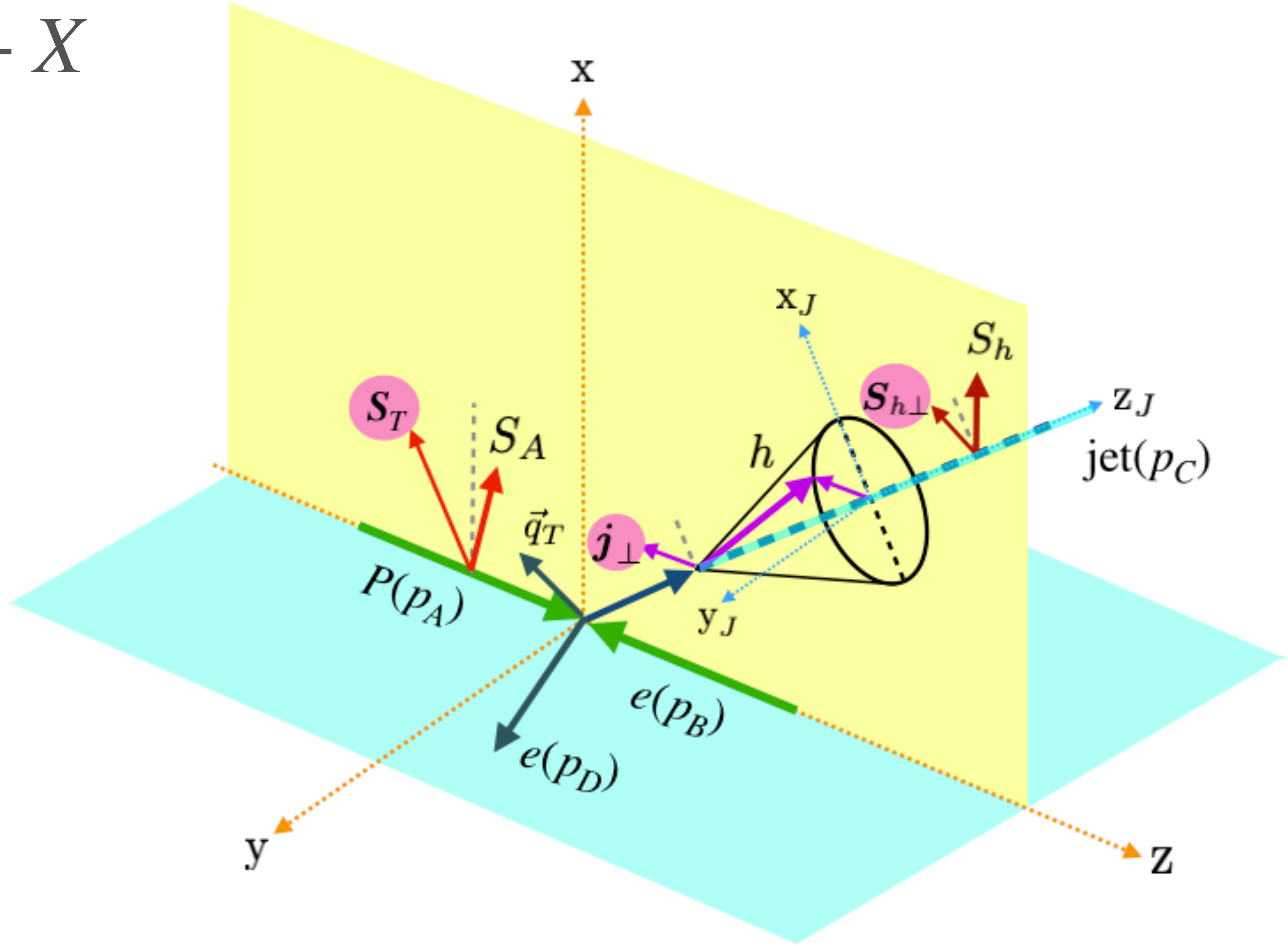

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$$\boldsymbol{q}_T = \boldsymbol{p}_{C,T} + \boldsymbol{p}_{D,T} \quad \phi_q$$

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$$\boldsymbol{S}_T \quad \phi_{S_A}$$

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

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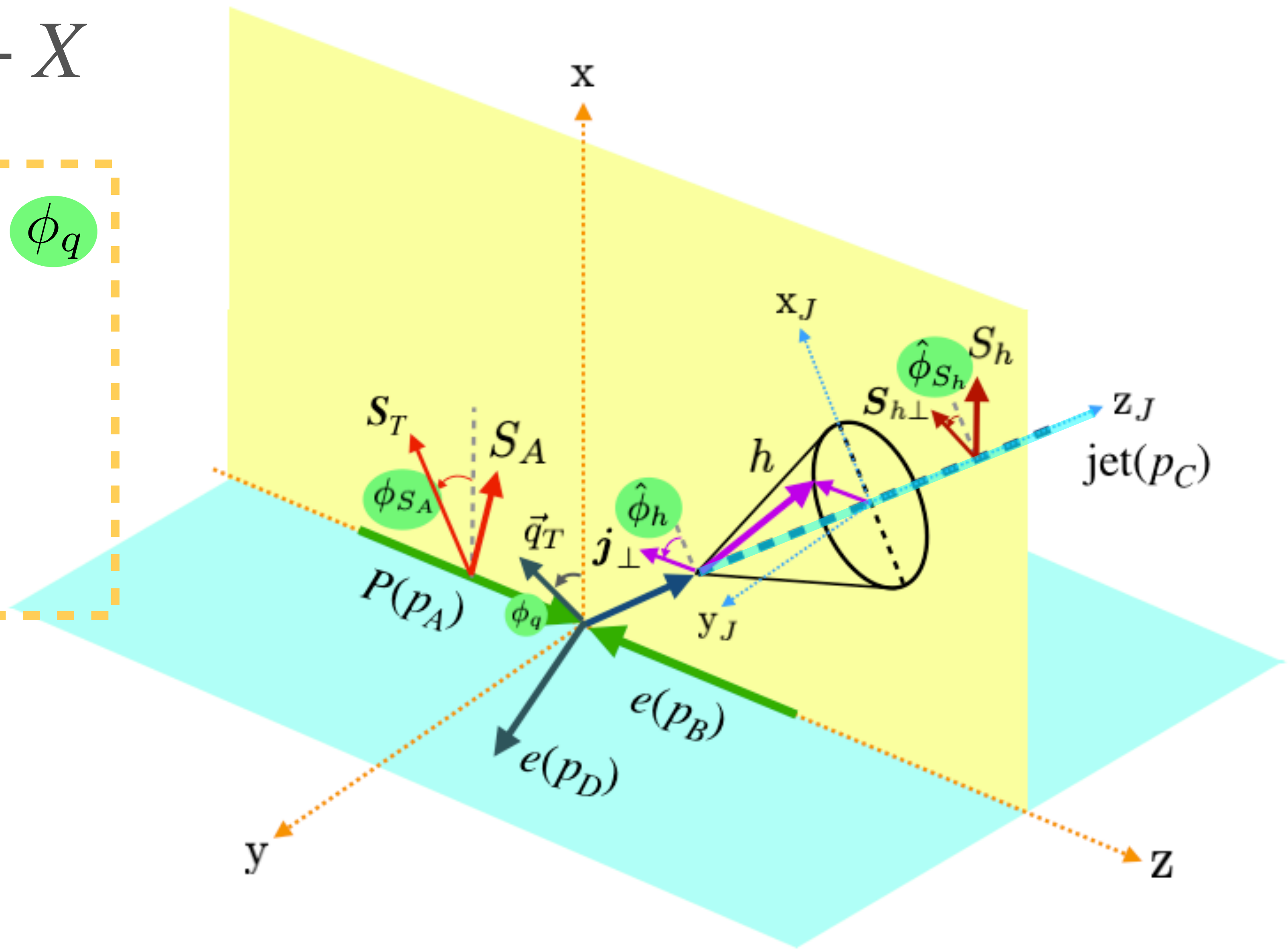

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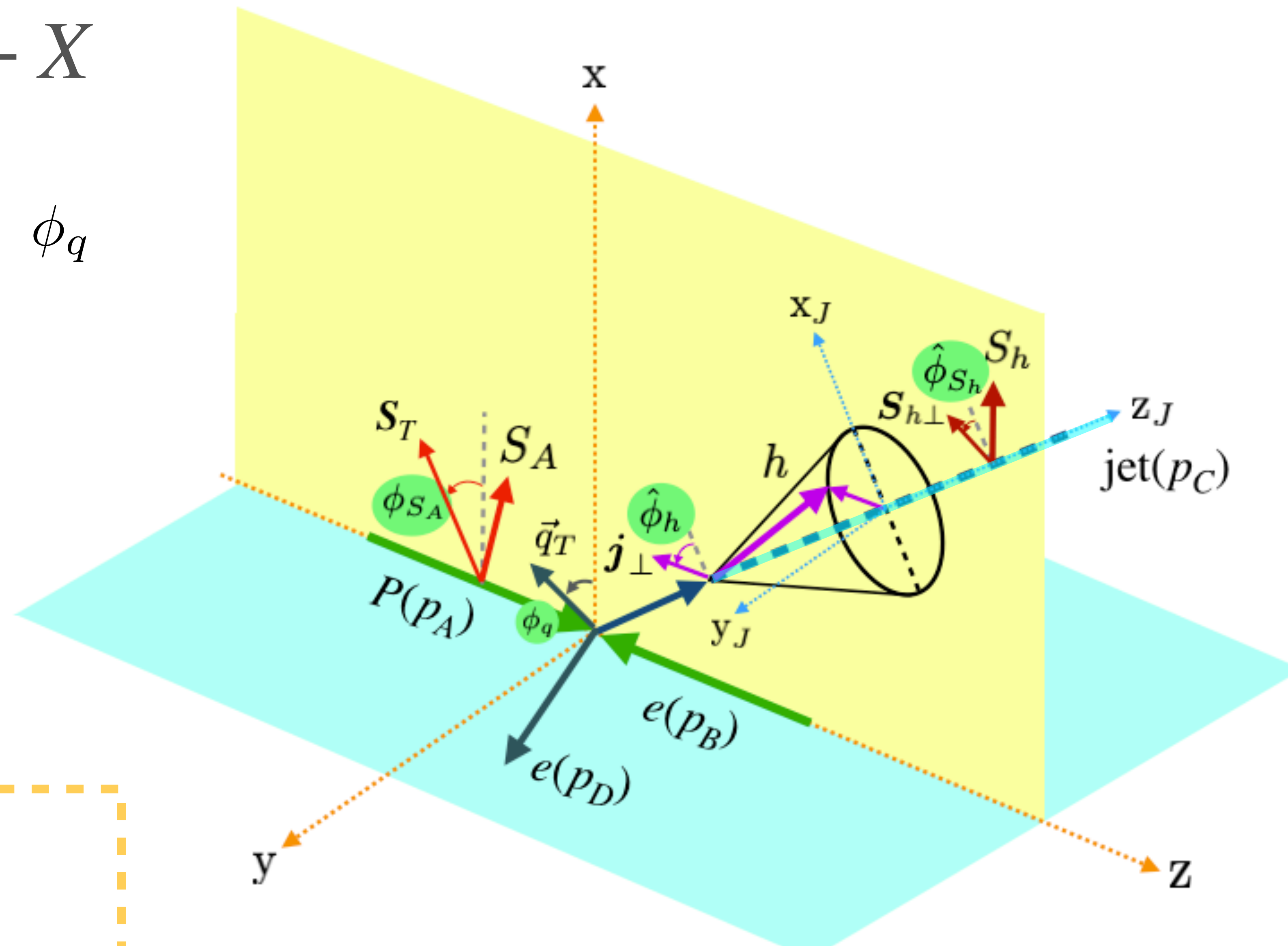

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TMDPDFs

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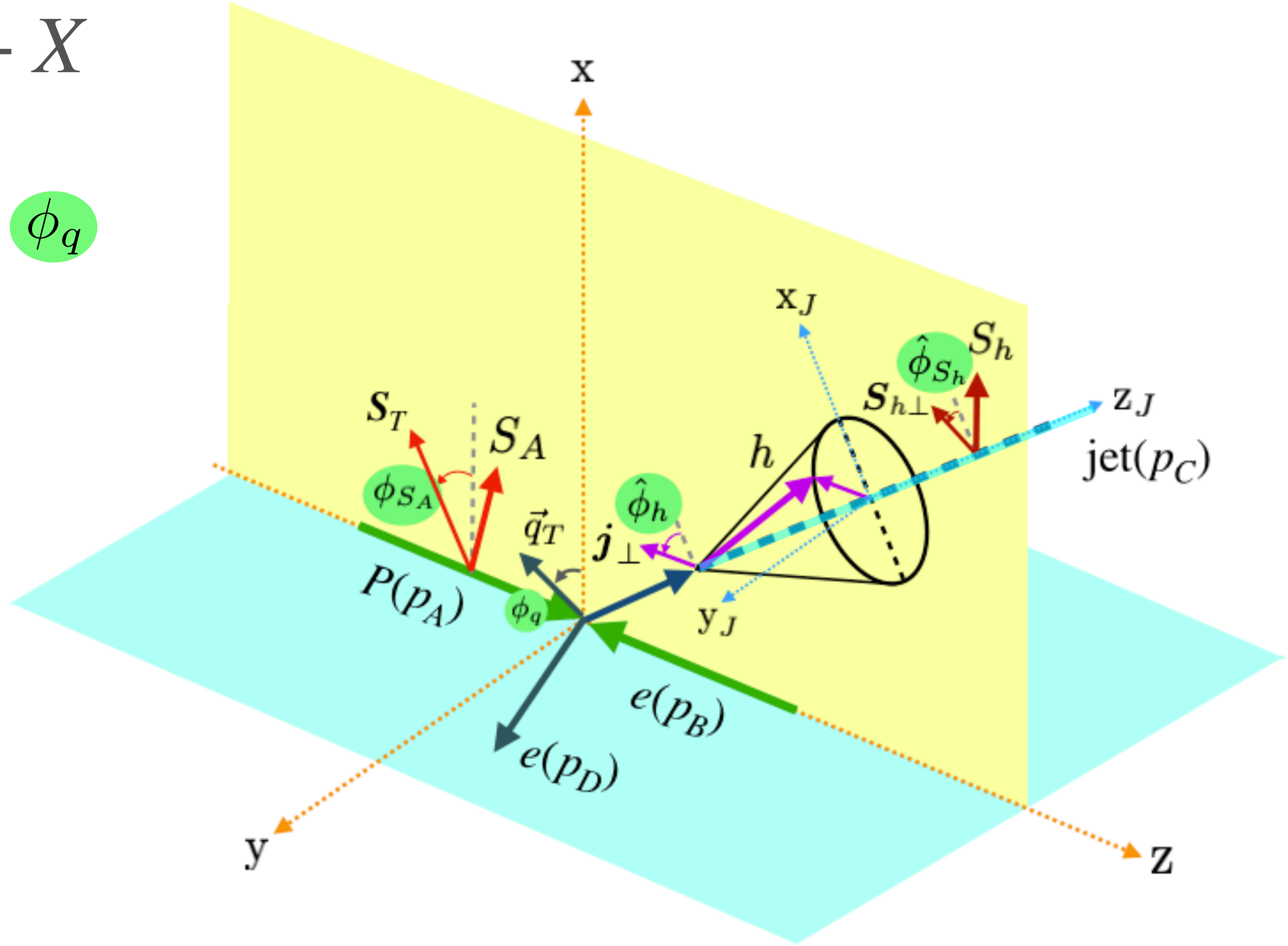
TMDJFFs $\boldsymbol{j}_\perp$ $\hat{\phi}_h$

$$\boldsymbol{S}_{h\perp} \quad \hat{\phi}_{S_h}$$



Different from SIDIS!

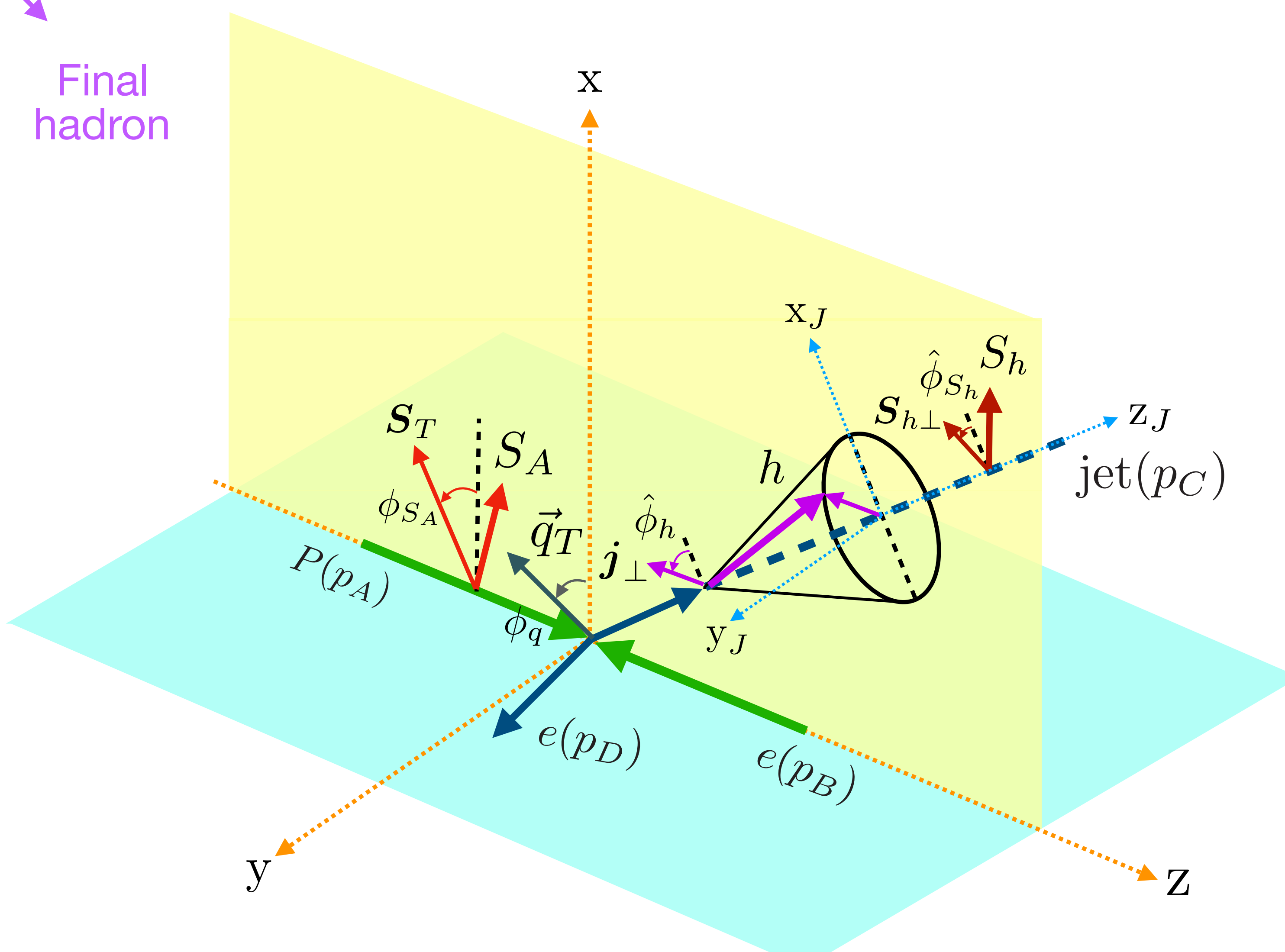
(Total 32 terms.)

$$\frac{d\sigma}{dp_T^2 dy_J d^2\boldsymbol{q}_T dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + \cos(\phi_q - \hat{\phi}_h) F_{UU,U}^{\cos(\phi_q - \hat{\phi}_h)} + \cdots$$

$$A_{UU,U}^{\cos(\phi_q - \hat{\phi}_h)} = \frac{F_{UU,U}^{\cos(\phi_q - \hat{\phi}_h)}}{F_{UU,U}}$$

$$ep \to e + \text{jet}(h) + X$$

incoming proton | incoming electron | Final hadron



Example 1

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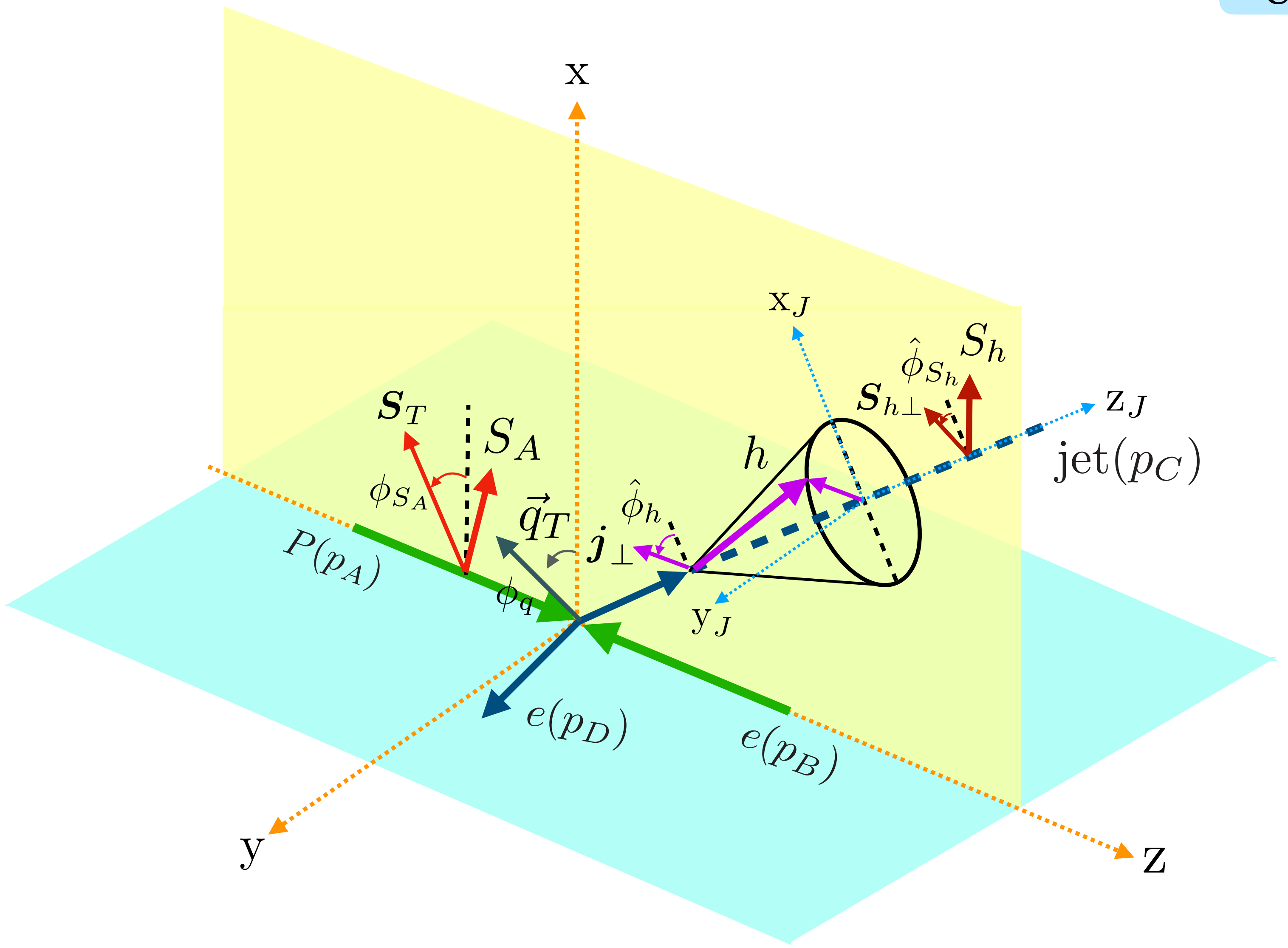
$$F_{UU,U} \sim f_1 \otimes \mathcal{D}_1^{h/q}$$

$$F_{UU,U}^{\cos(\phi_q-\hat{\phi}_h)} \sim h_1^\perp \otimes \mathcal{H}_1^{\perp\ h/q}$$

$h_1^\perp$ → Boer-Mulders function (arXiv: [0912.5194])

$\mathcal{H}_1^{\perp\ h/q}$ match to → Collins function (arXiv: [1505.05589])



$$ep \to e + \text{jet}(h) + X$$

h\ q	U	L	T
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TMDJFFs for quarks.

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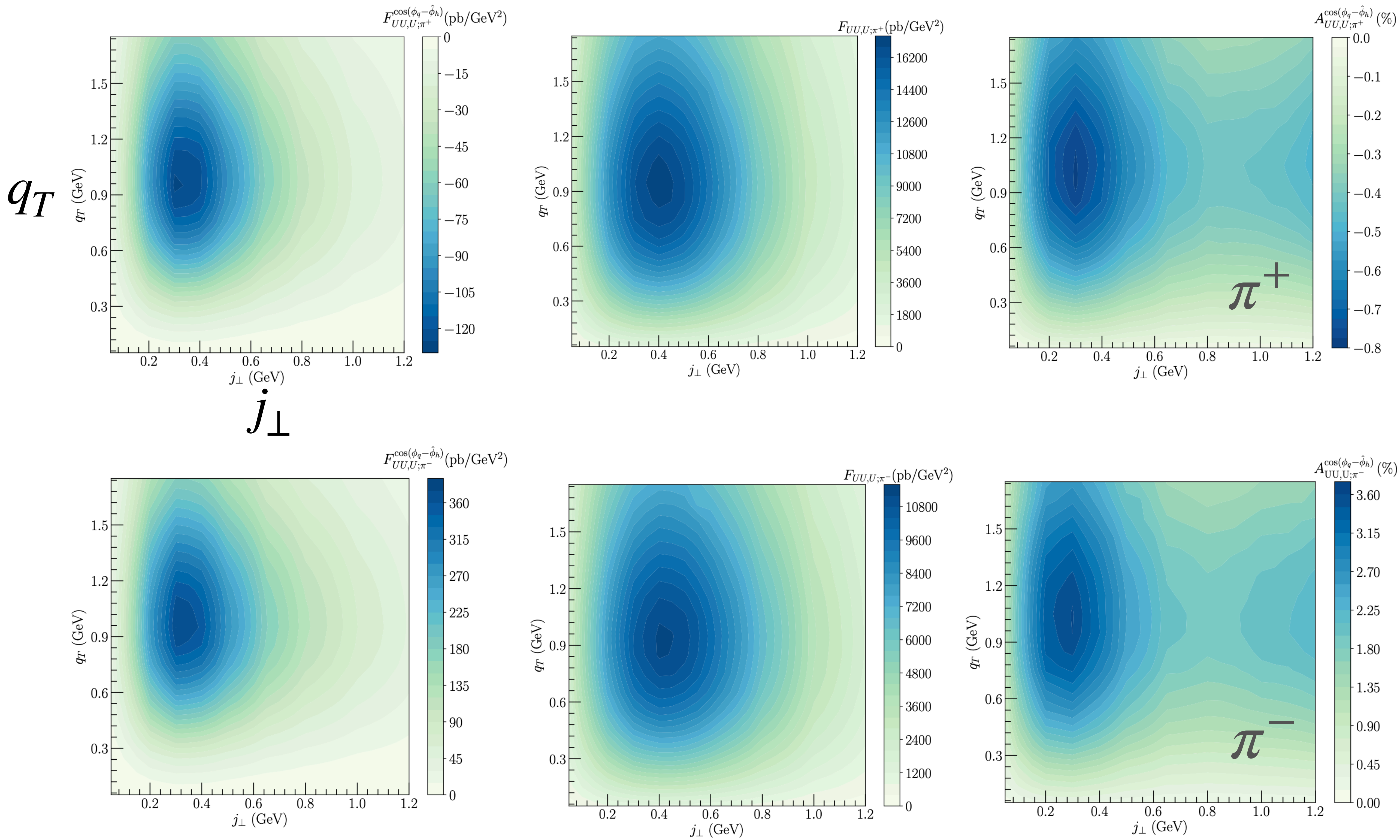

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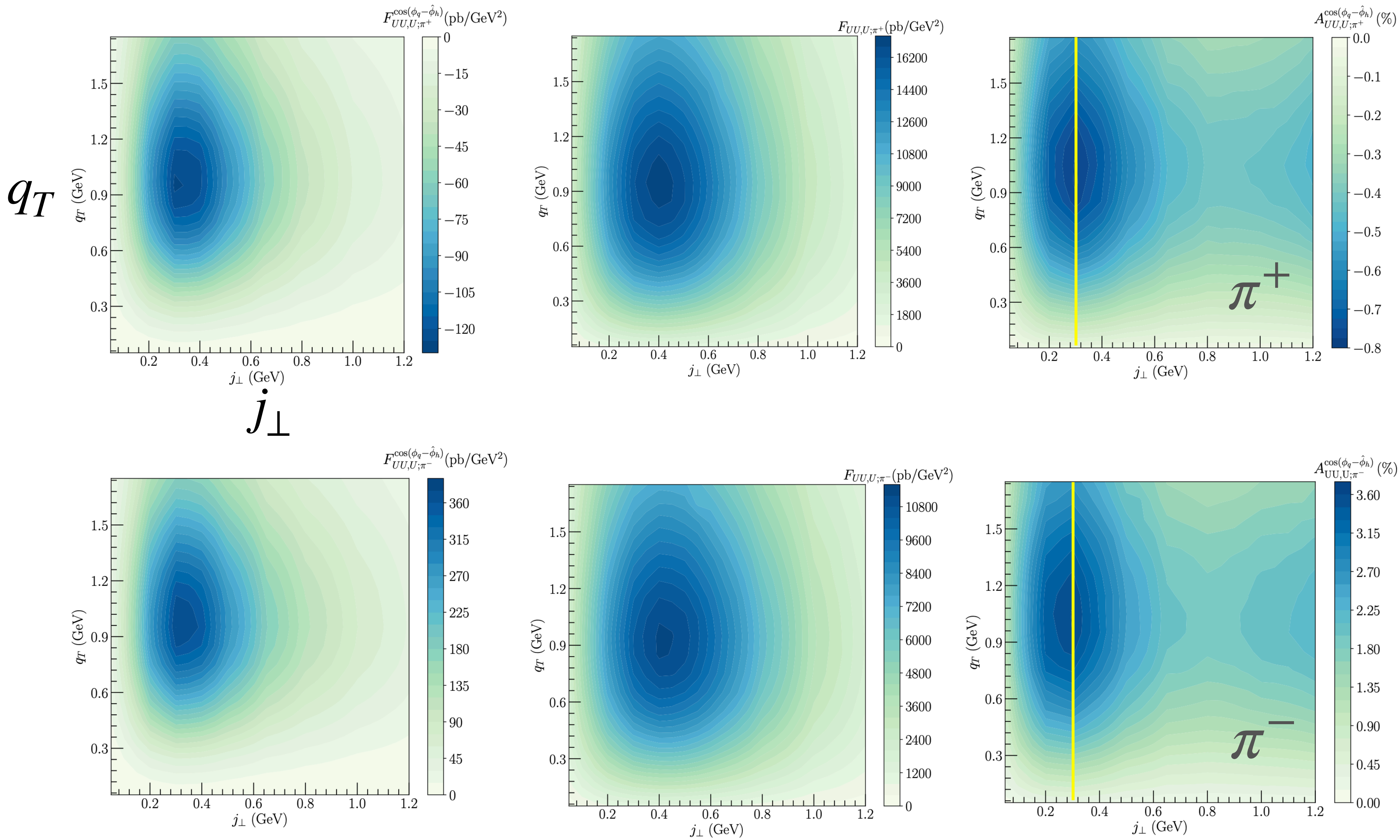

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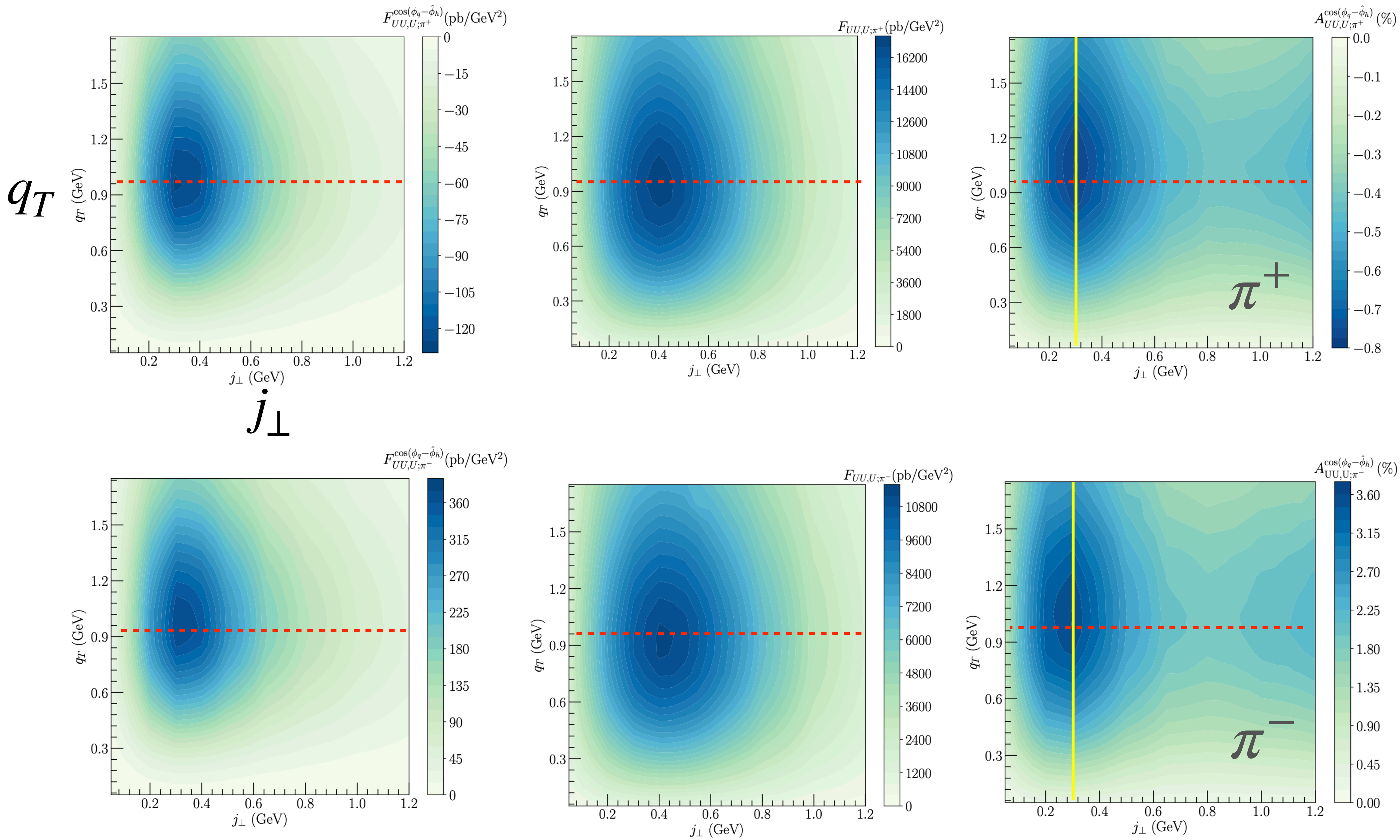

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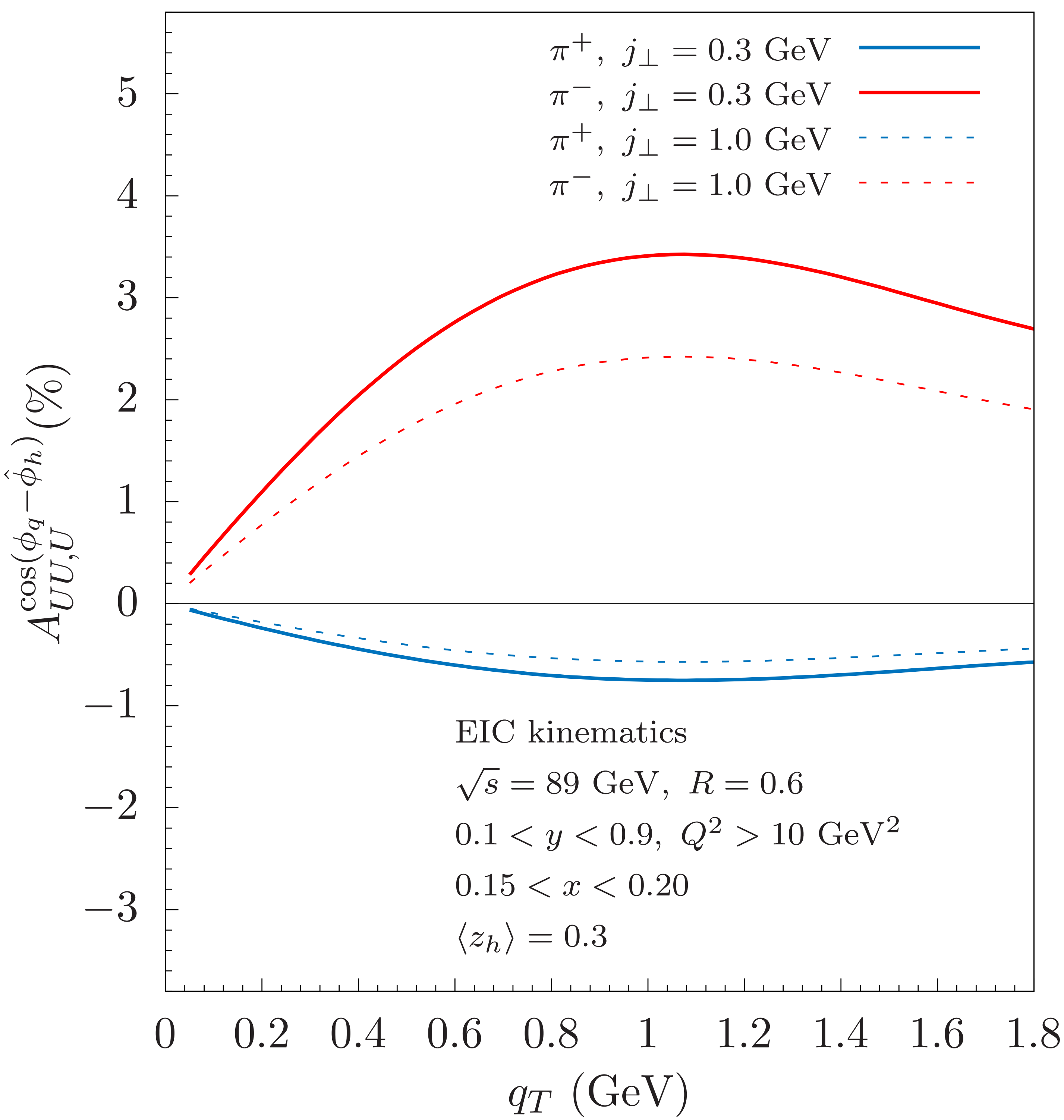

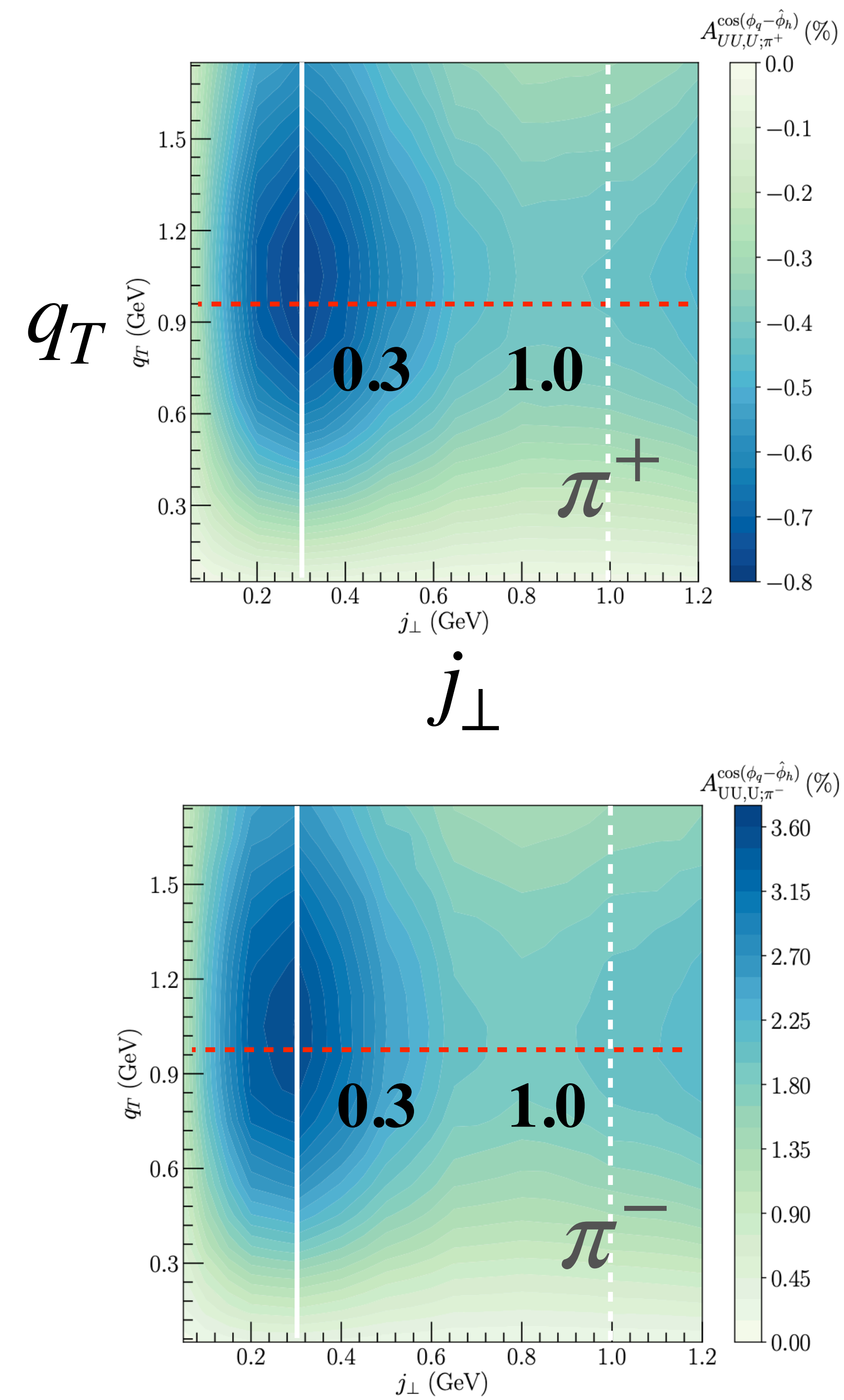

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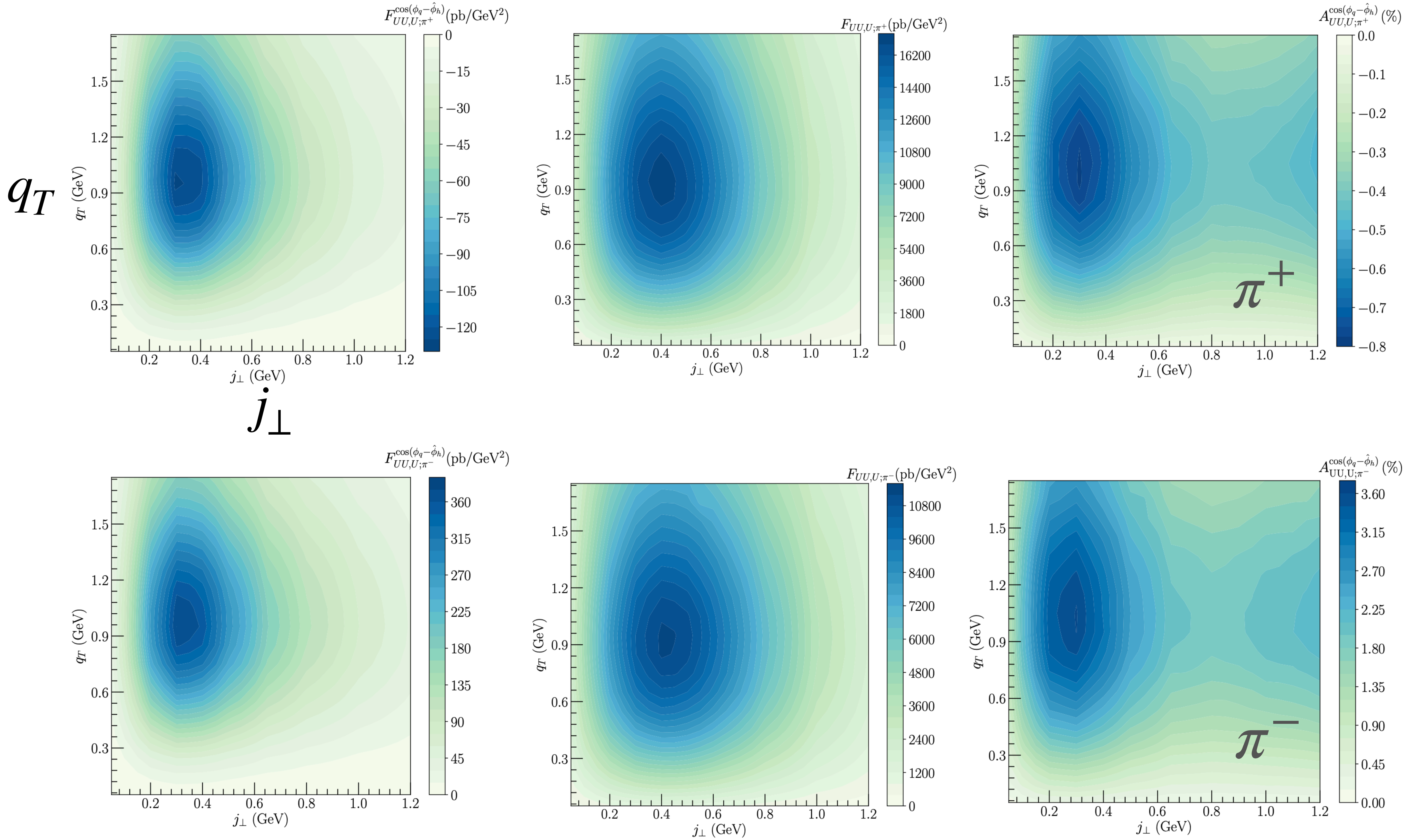

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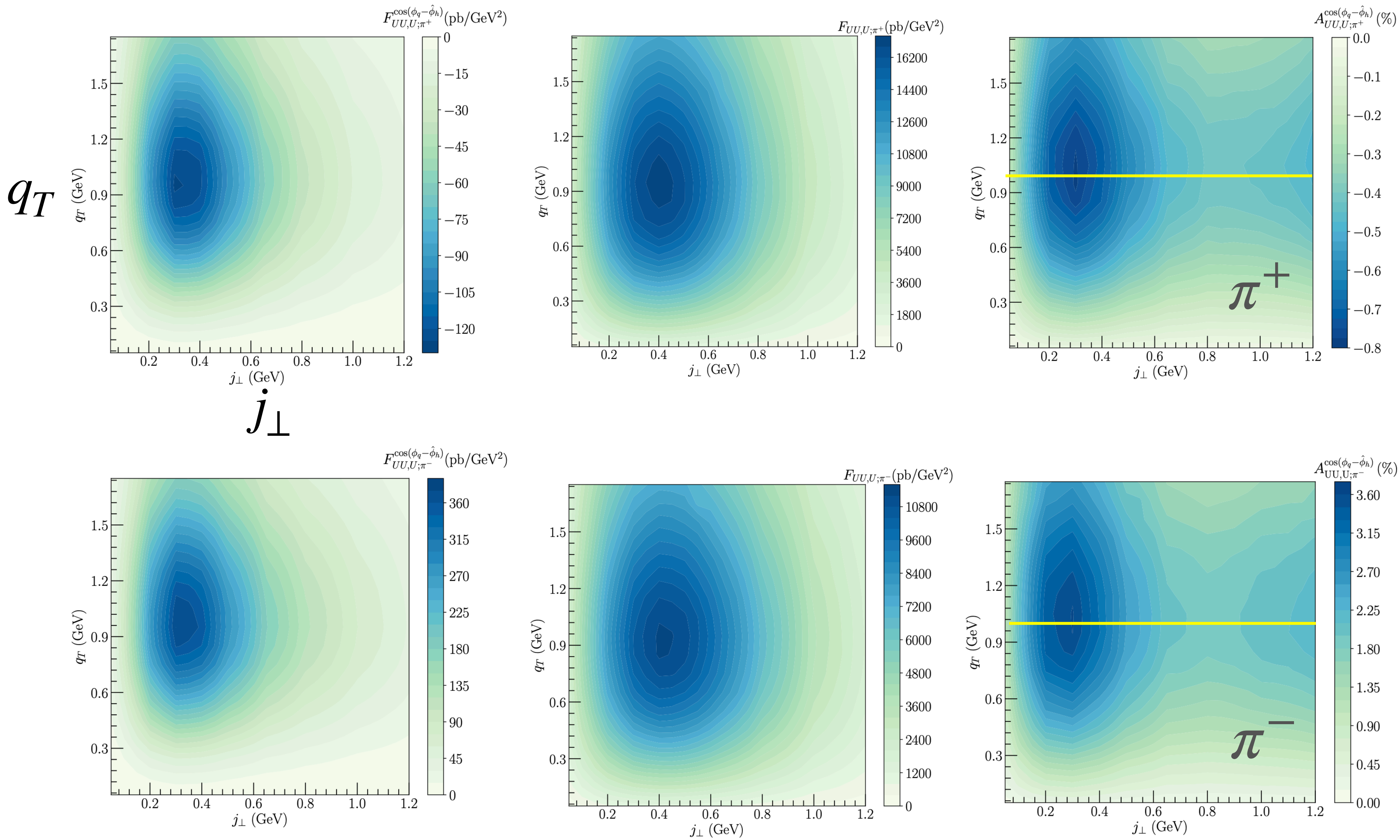

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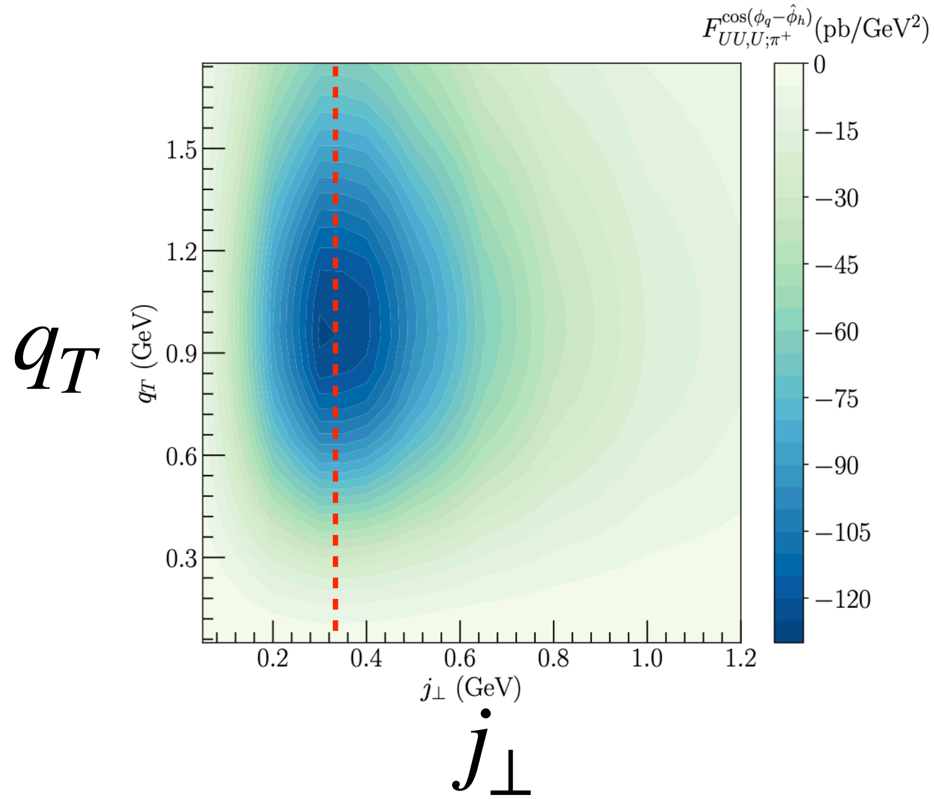

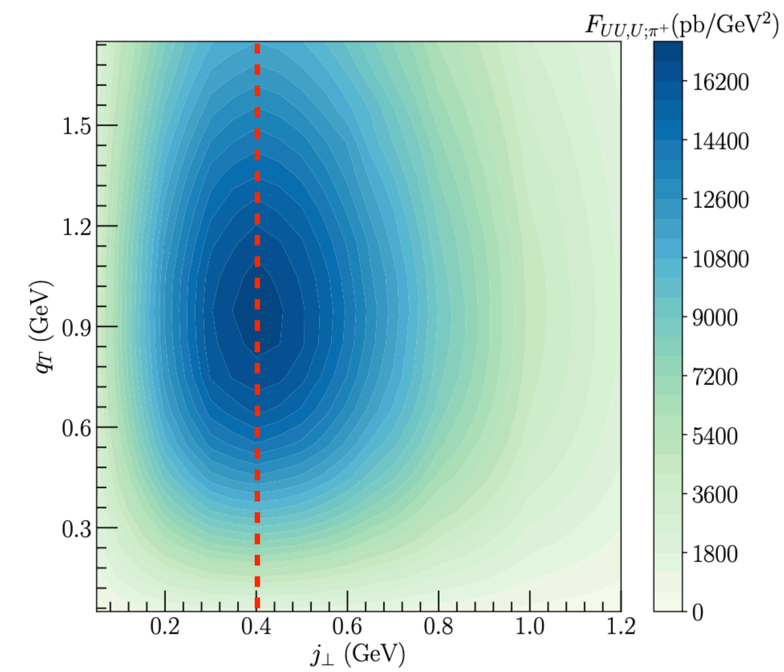

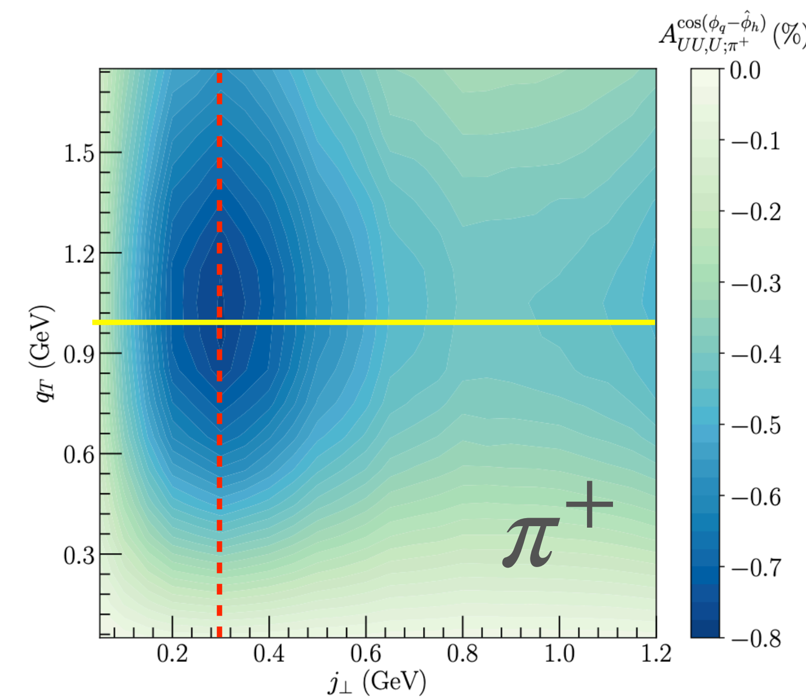

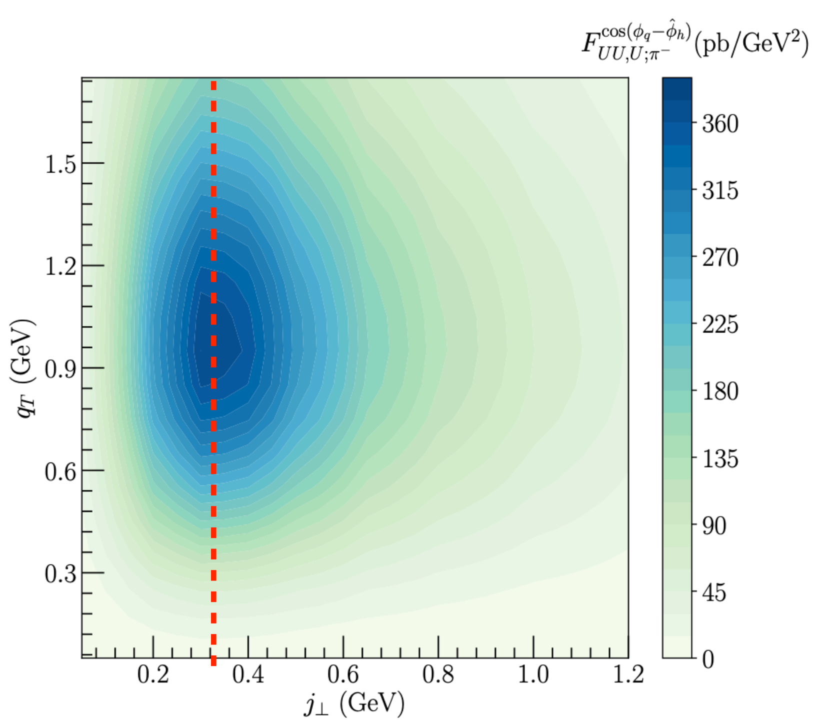

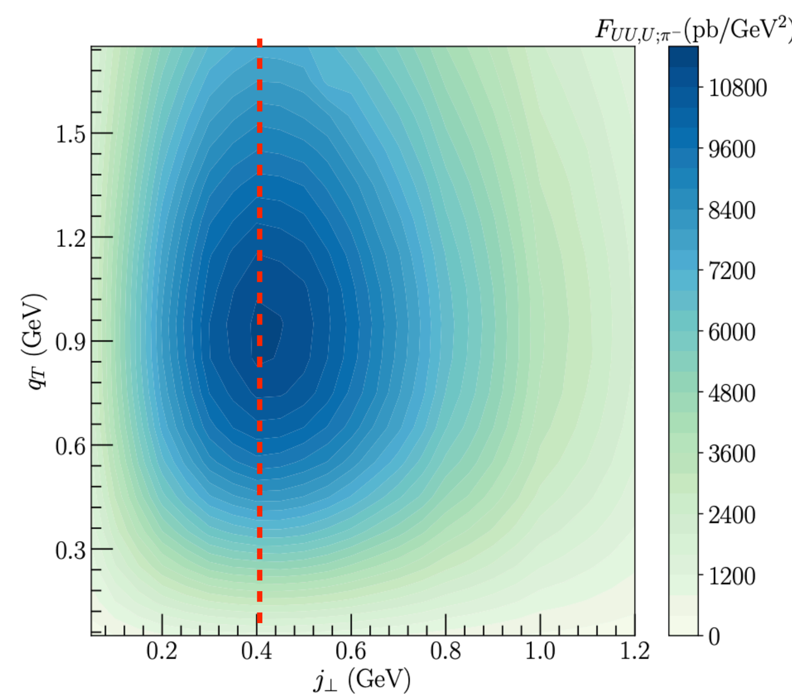

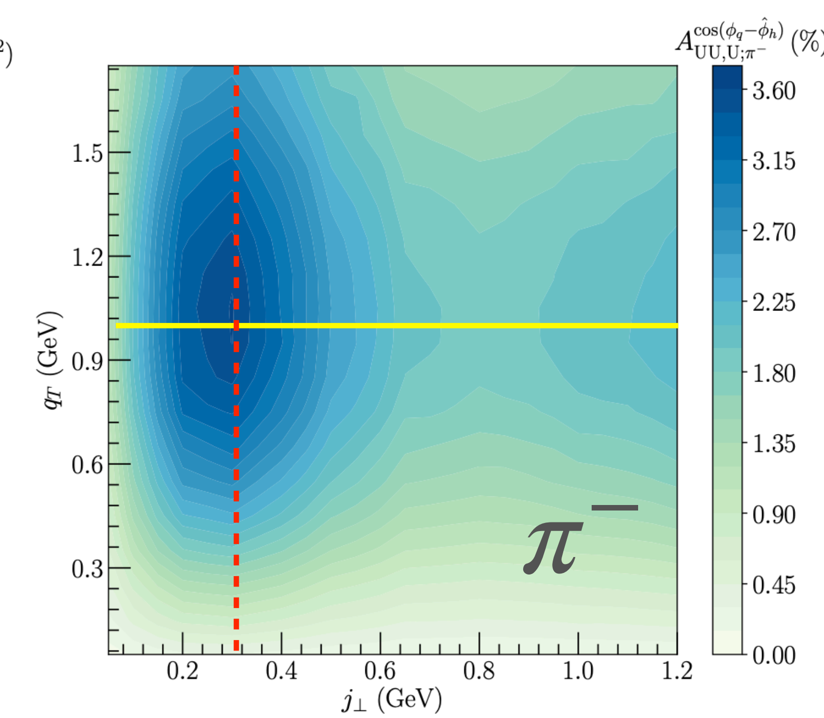

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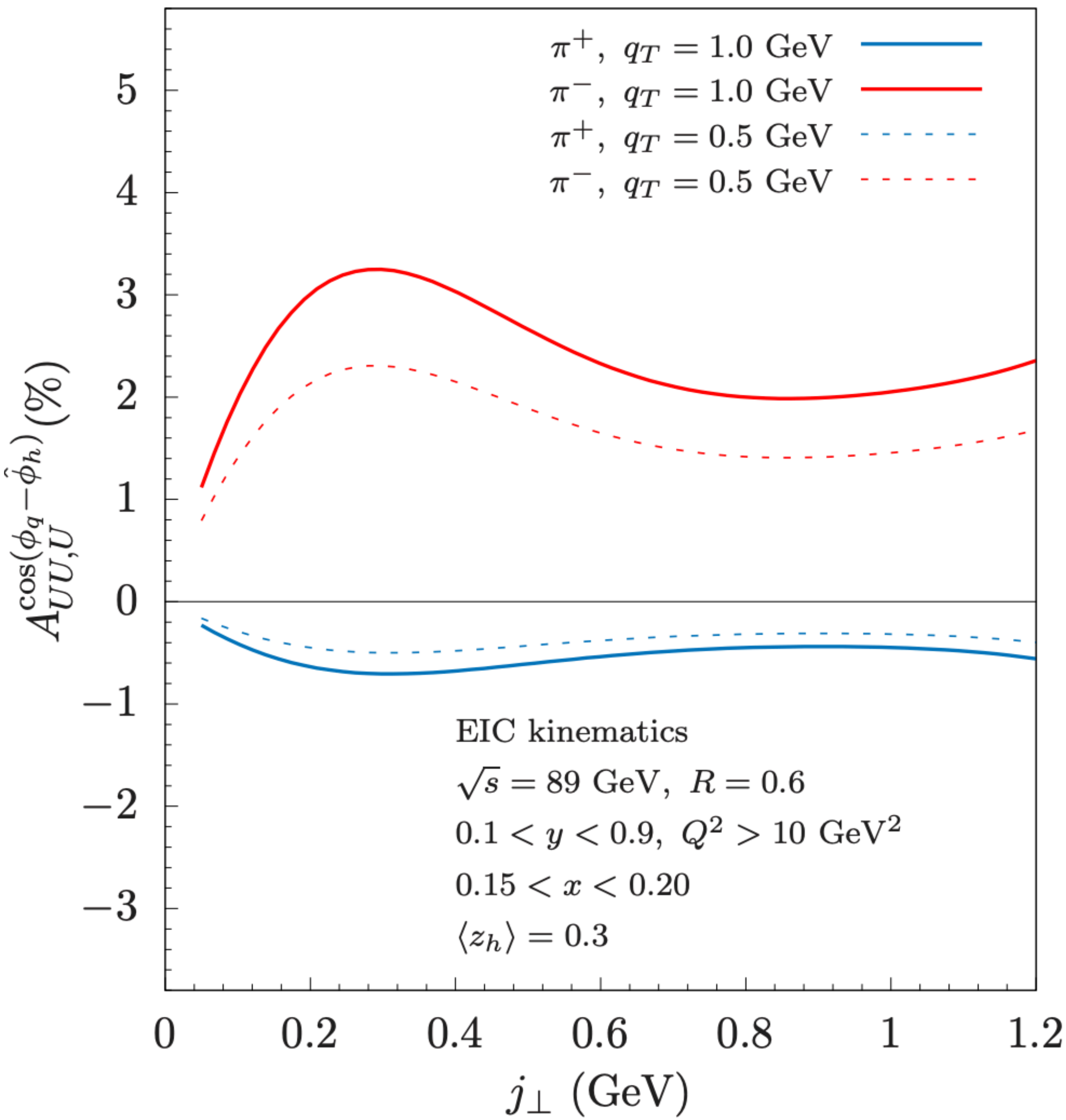

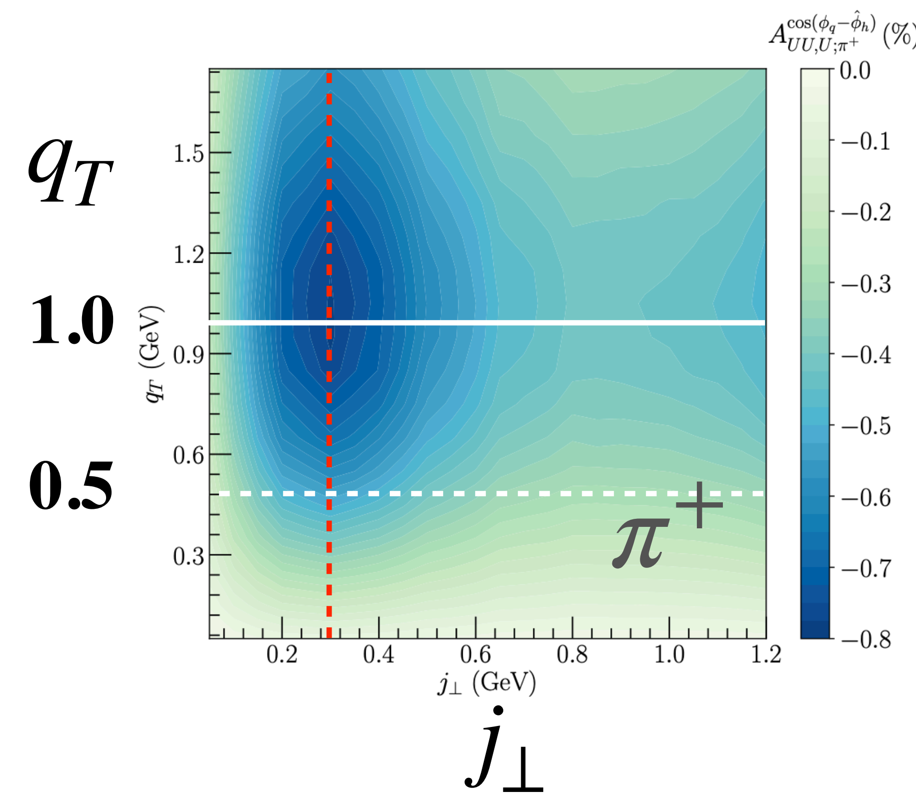

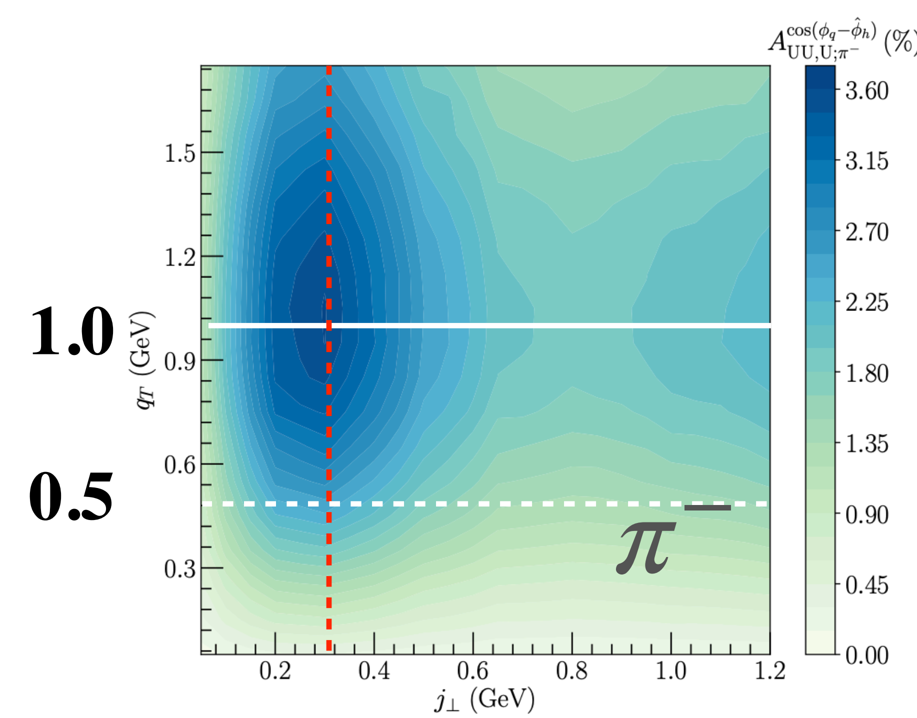

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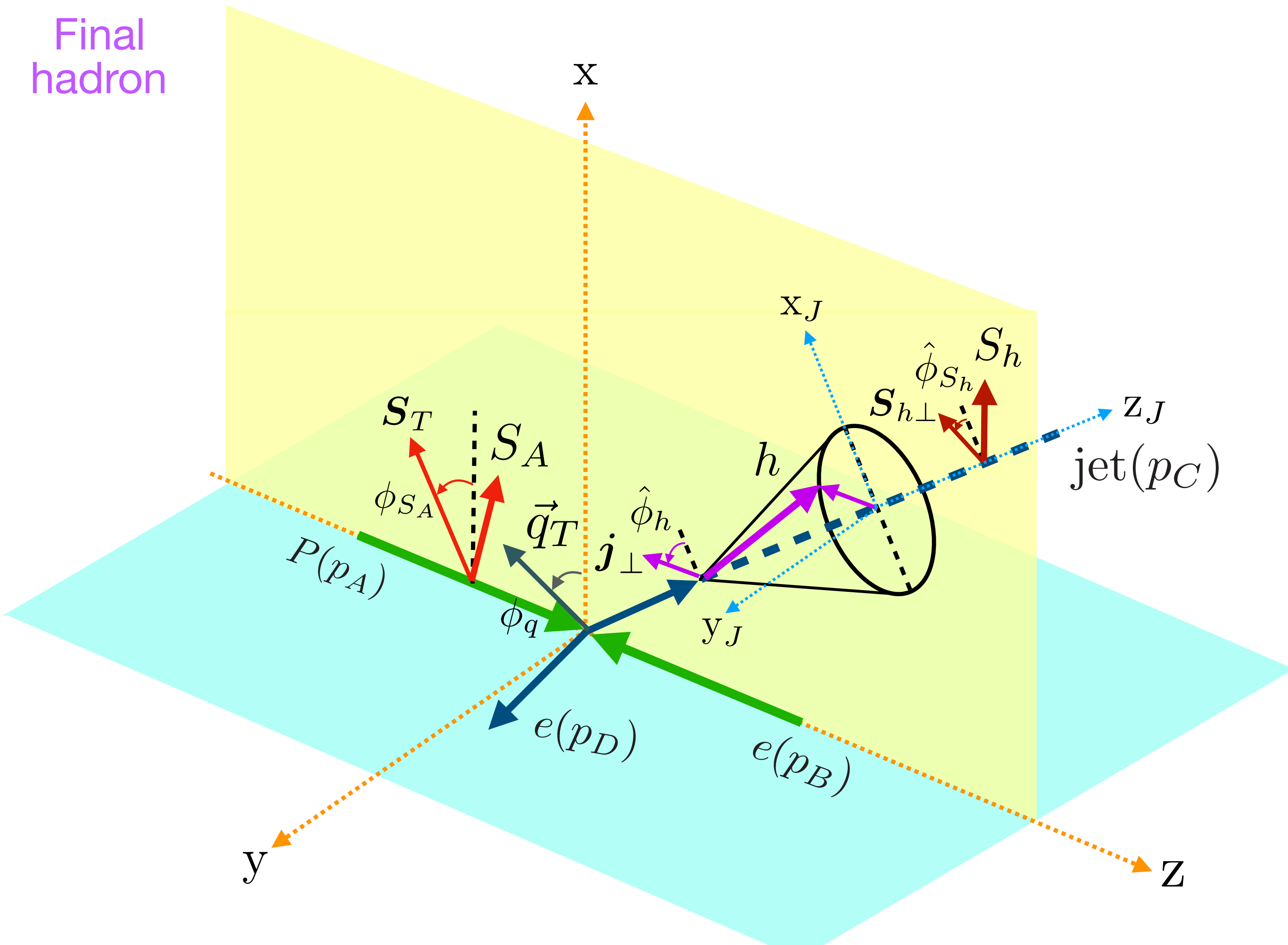
$$A_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})} = \frac{F_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})}}{F_{UU,U}}$$

$$ep \to e + \text{jet}(h^{\uparrow}) + X$$

incoming proton | incoming electron | Final hadron



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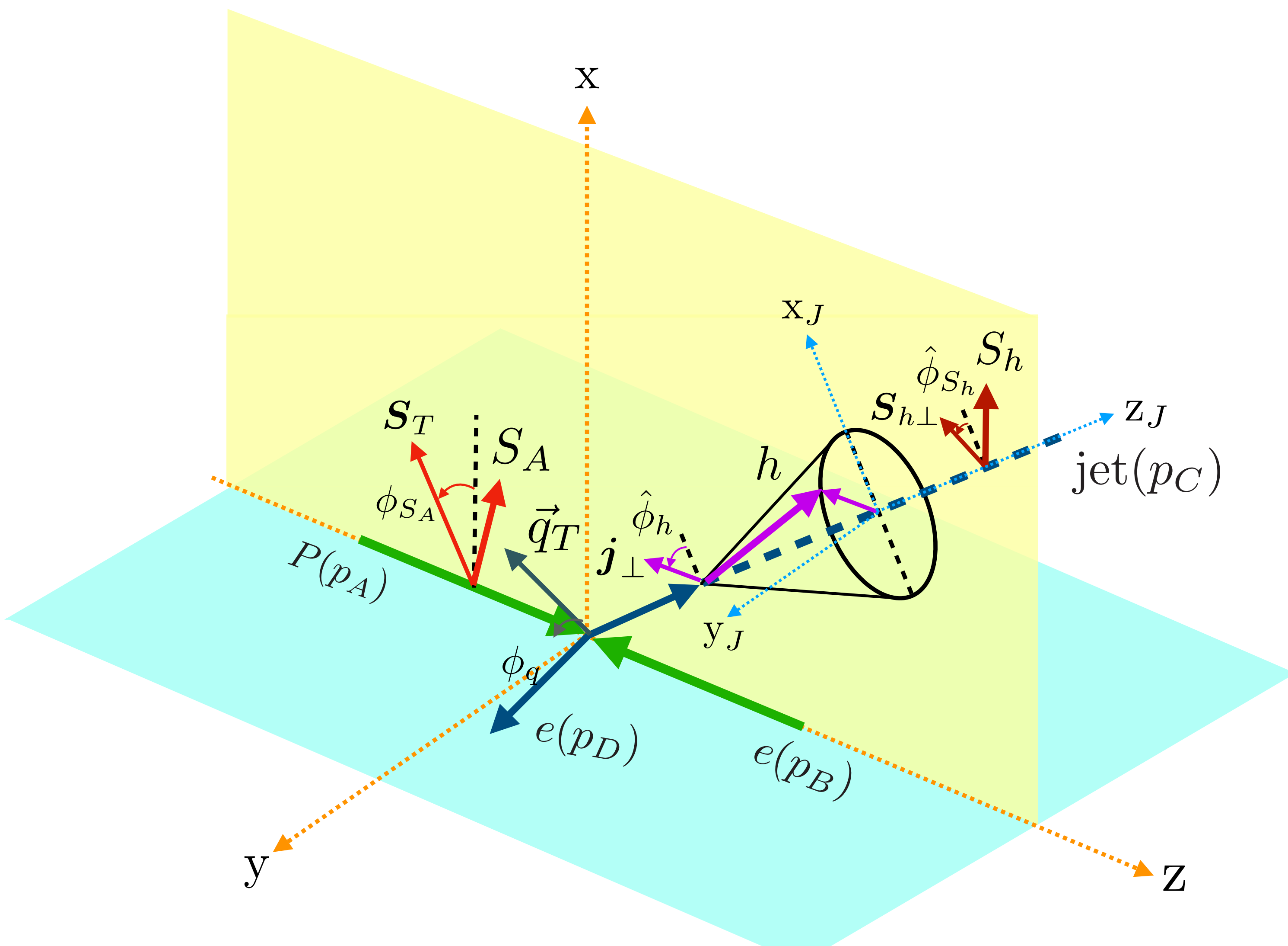
Unpolarized TMDPDF

match to

Polarizing TMDFF

arXiv: [2003.04828]



$$ep \to e + \text{jet}(\Lambda^\uparrow) + X$$

h\ q	U	L	T
U	$\mathcal{D}_1^{h/q}$		$\mathcal{H}_1^{\perp\, h/q}$
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TMDJFFs for quarks.

Example 2

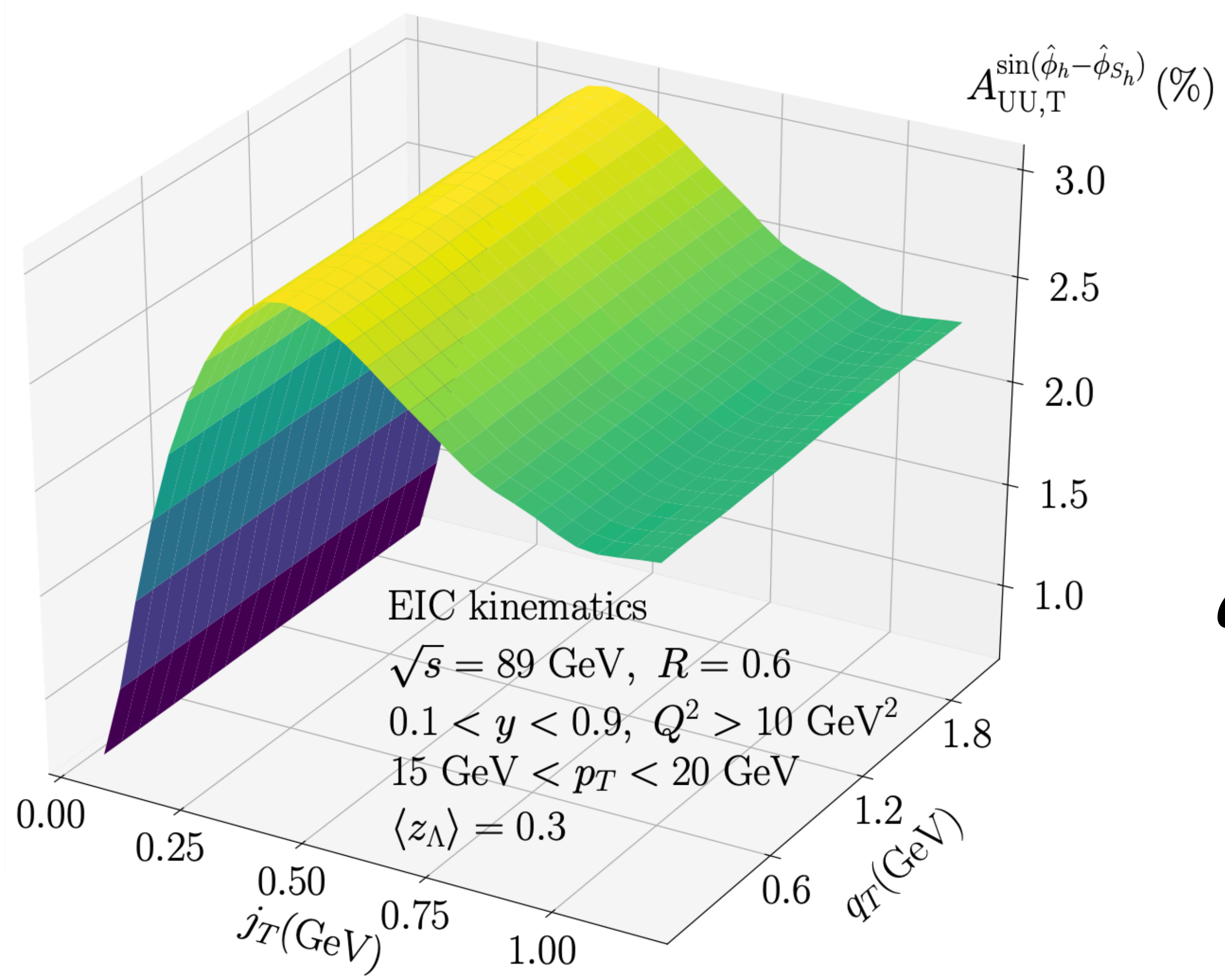
$$\frac{d\sigma}{dp_T^2 dy_J d^2\boldsymbol{q}_T dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + \cdots + S_{h\perp}\left\{\sin(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})} + \cdots\right.$$

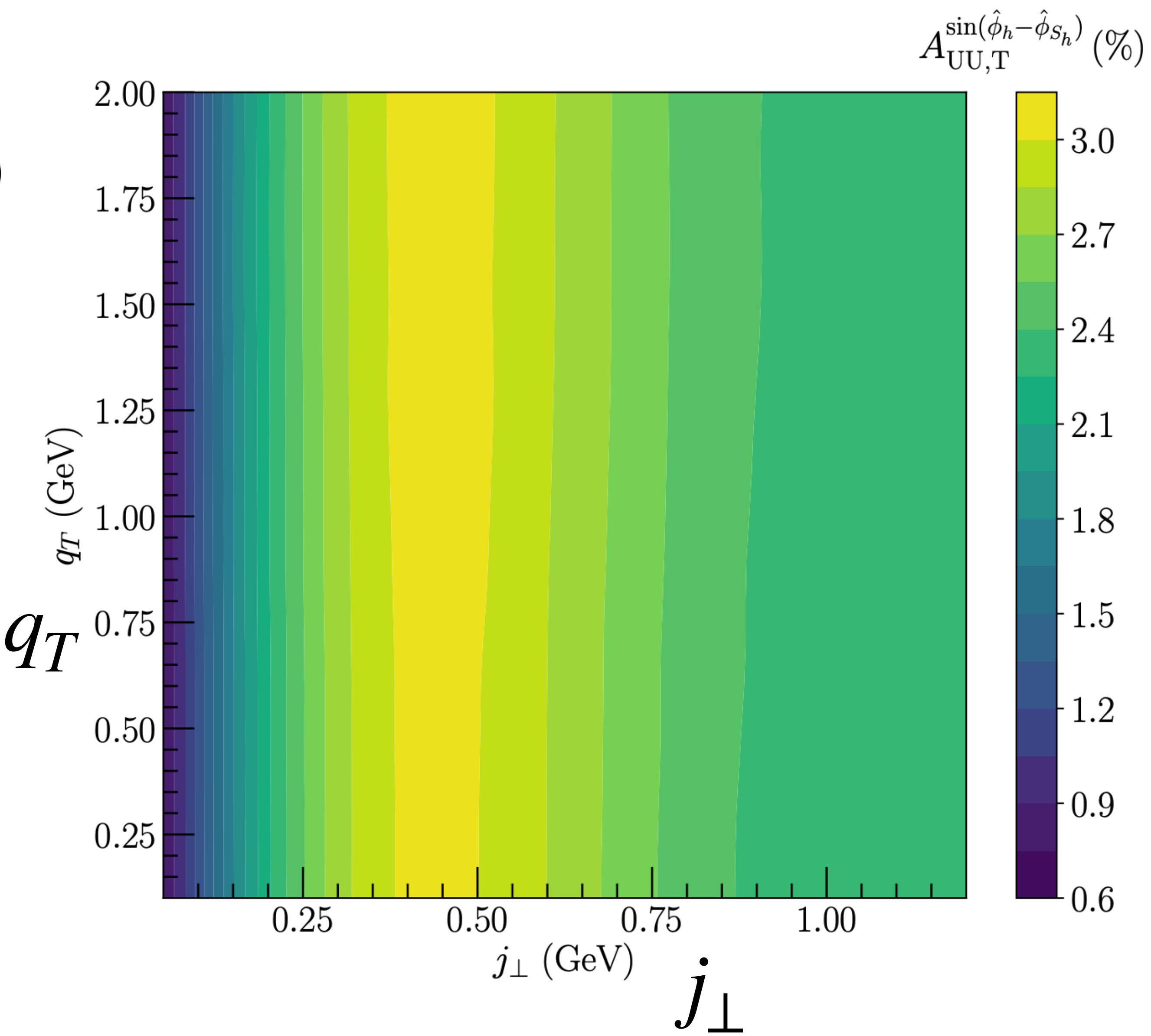
$$F_{UU,U} \sim f_1 \otimes \mathcal{D}_1^{h/q}$$

$$F_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})} \sim f_1 \otimes \mathcal{D}_{1T}^{\perp\, h/q}$$

q_T $j_\perp$

$$A_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})} = \frac{F_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})}}{F_{UU,U}}$$





Example 2

$$\frac{d\sigma}{dp_T^2 dy_J d^2\boldsymbol{q}_T dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + \cdots + S_{h\perp}\left\{\sin(\hat\phi_h - \hat\phi_{S_h}) F_{UU,T}^{\sin(\hat\phi_h - \hat\phi_{S_h})} + \cdots\right.$$

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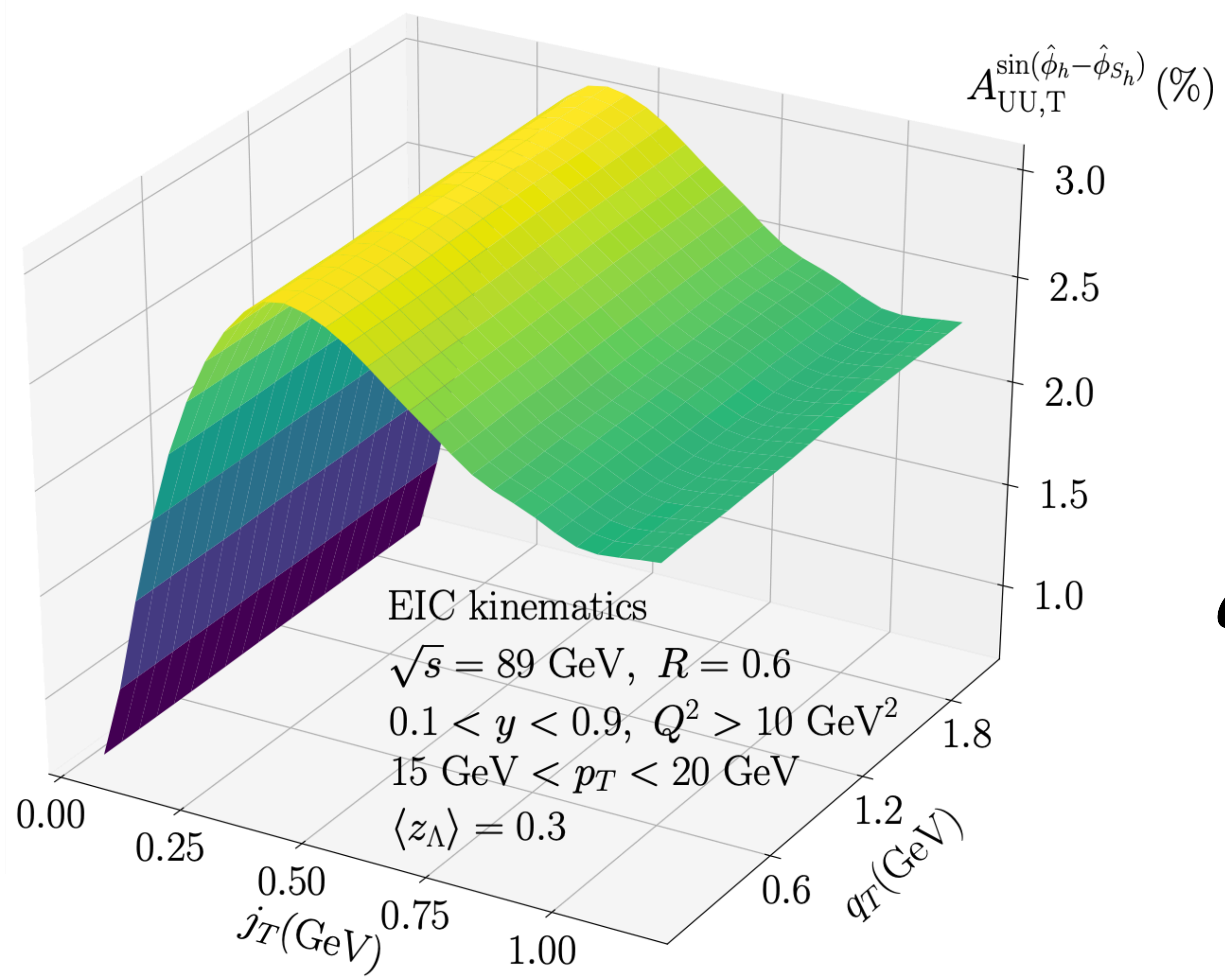

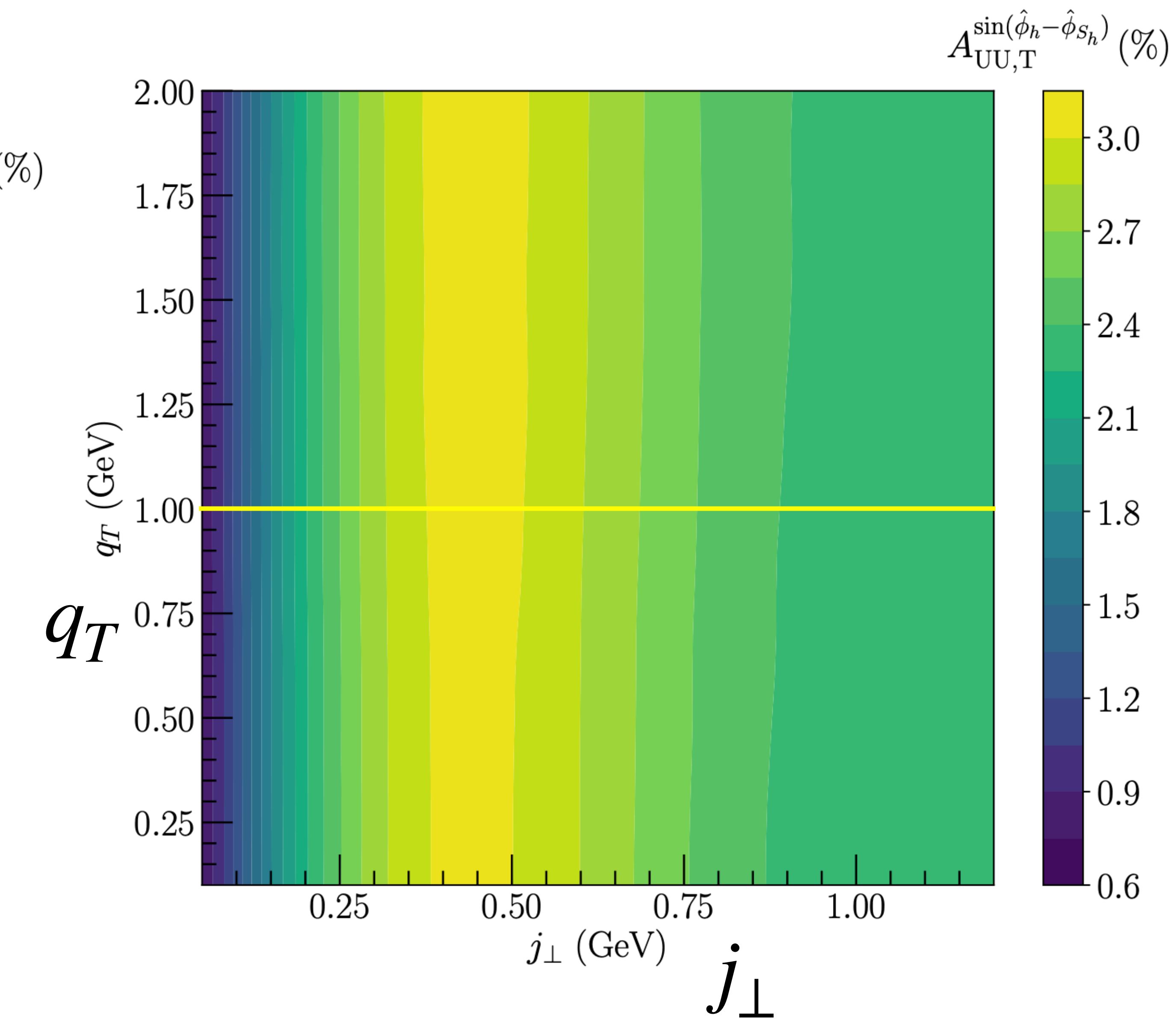

Example 2

$$\frac{d\sigma}{dp_T^2 dy_J d^2\boldsymbol{q}_T dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + \cdots + S_{h\perp}\left\{ \sin(\hat{\phi}_h - \hat{\phi}_{S_h}) F_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})} + \cdots \right.$$

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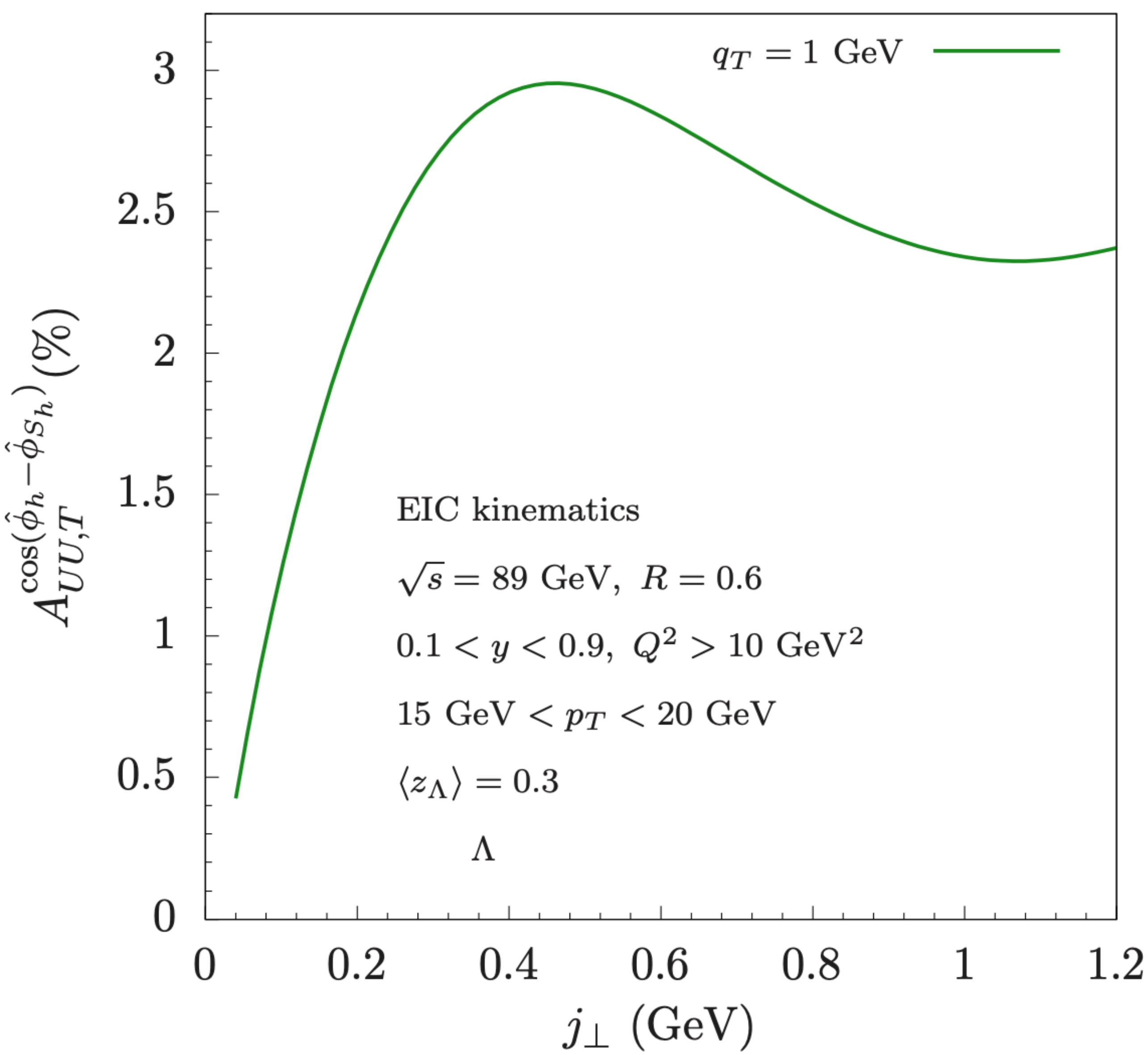
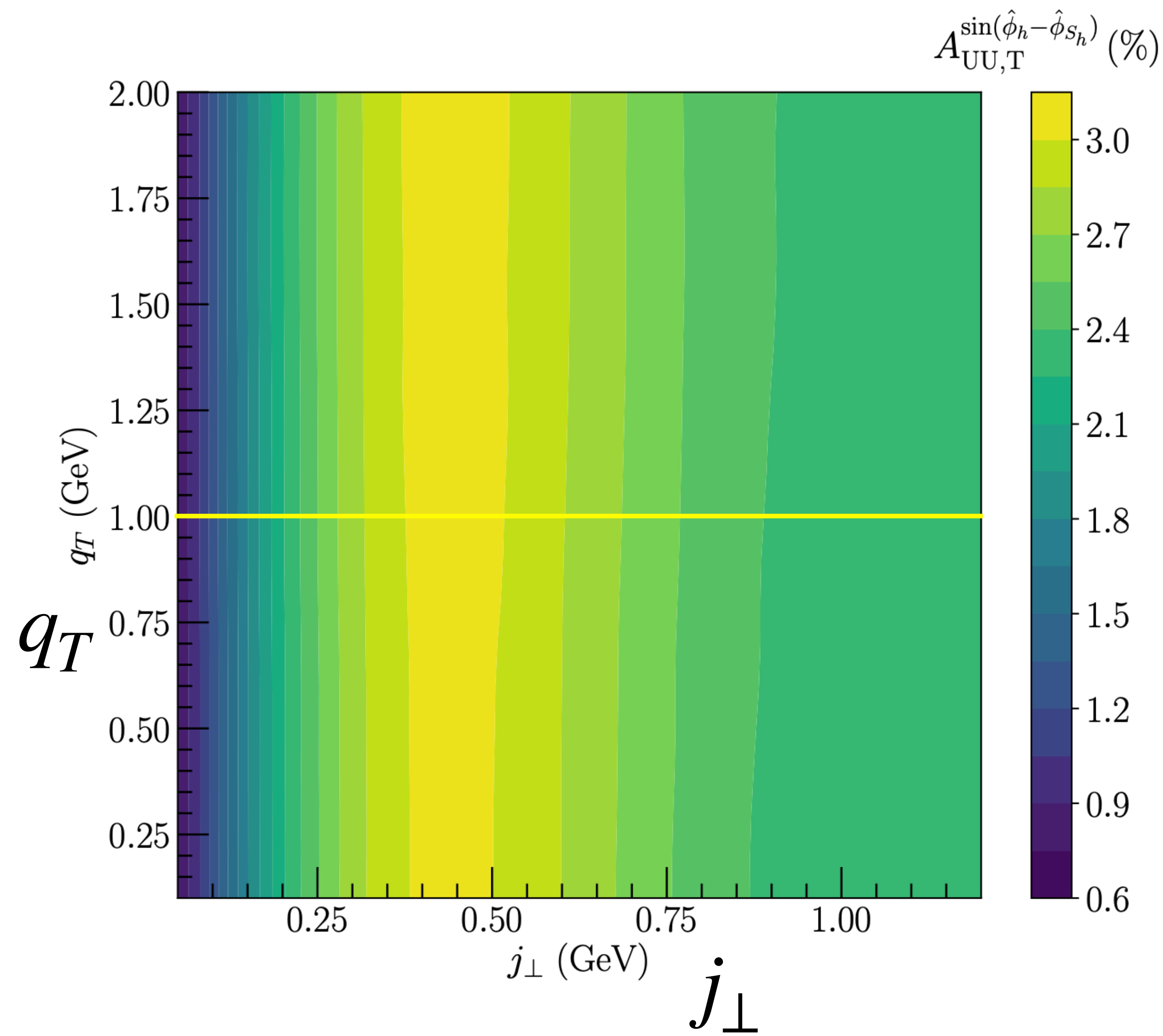
q_T $\quad j_\perp$

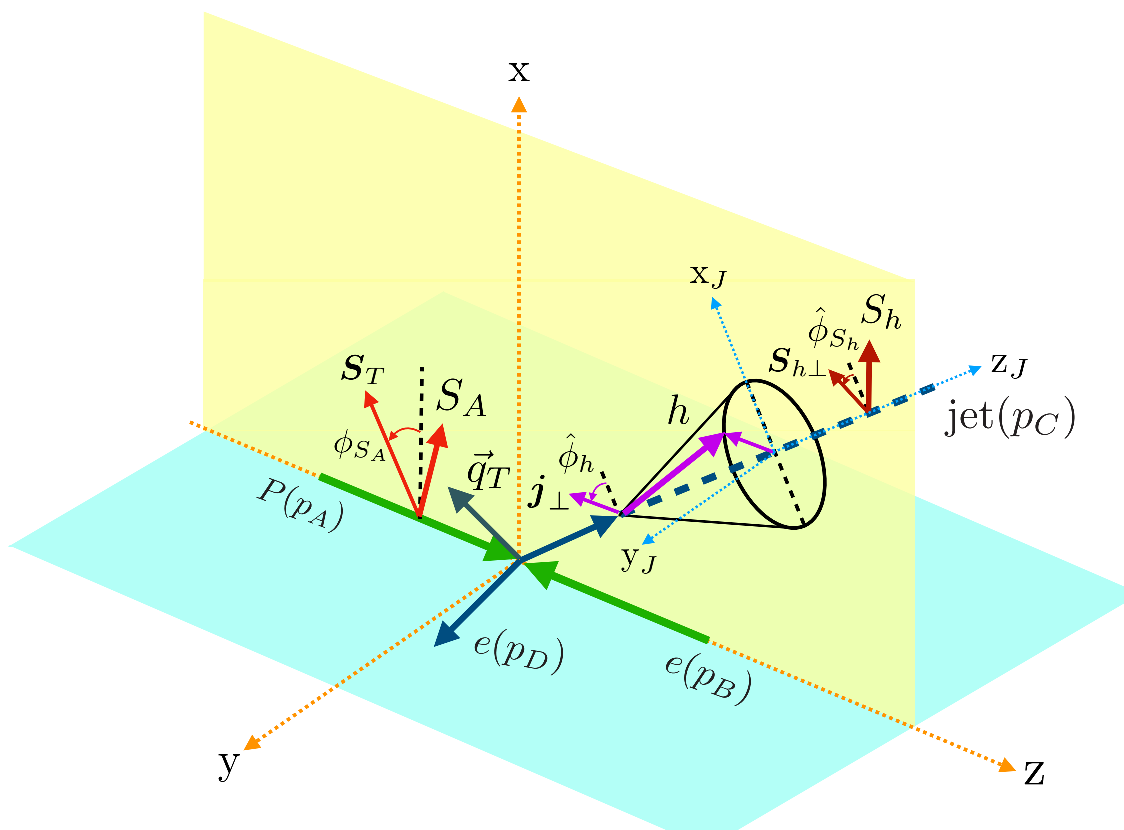
$$A_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})} = \frac{F_{UU,T}^{\sin(\hat{\phi}_h - \hat{\phi}_{S_h})}}{F_{UU,U}}$$





Summary & Outlook

- In summary, we have developed the theoretical framework for all spin asymmetries in back-to-back $e + \text{jet}(h)$ productions.
- Sizable asymmetry can be measured with EIC kinematics.
- Open new and exciting opportunities in the direction of studying spin-dependent hadron structures



$$\frac{d\sigma^{p(S_A)+e(\lambda_e)\to e+(\text{jet } h(S_h))+X}}{dp_T^2 dy_J d^2\boldsymbol{q}_T dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + \cos(\phi_q - \hat\phi_h) F_{UU,U}^{\cos(\phi_q-\hat\phi_h)}$$

$$+ \Lambda_p \Big\{ \lambda_e F_{LL,U} + \sin(\phi_q - \hat\phi_h) F_{LU,U}^{\sin(\phi_q-\hat\phi_h)} \Big\}$$

$$+ S_T \Big\{ \sin(\phi_q - \phi_{S_A}) F_{TU,U}^{\sin(\phi_q-\phi_{S_A})} + \lambda_e \cos(\phi_q - \phi_{S_A}) F_{TL,U}^{\cos(\phi_q-\phi_{S_A})}$$

$$+ \sin(\phi_{S_A} - \hat\phi_h) F_{TU,U}^{\sin(\phi_{S_A}-\hat\phi_h)} + \sin(2\phi_q - \hat\phi_h - \phi_{S_A}) F_{TU,U}^{\sin(2\phi_q-\hat\phi_h-\phi_{S_A})} \Big\}$$

$$+ \Lambda_h \Big\{ \lambda_e F_{UL,L} + \sin(\hat\phi_h - \phi_q) F_{UU,L}^{\sin(\hat\phi_h-\phi_q)} + \Lambda_p \Big[F_{LU,L} + \cos(\hat\phi_h - \phi_q) F_{LU,L}^{\cos(\hat\phi_h-\phi_q)} \Big]$$

$$+ S_T \Big[\cos(\phi_q - \phi_{S_A}) F_{TU,L}^{\cos(\phi_q-\phi_{S_A})} + \lambda_e \sin(\phi_q - \phi_{S_A}) F_{TL,L}^{\sin(\phi_q-\phi_{S_A})}$$

$$+ \cos(\phi_{S_A} - \hat\phi_h) F_{TU,L}^{\cos(\phi_{S_A}-\hat\phi_h)} + \cos(2\phi_q - \phi_{S_A} - \hat\phi_h) F_{TU,L}^{\cos(2\phi_q-\phi_{S_A}-\hat\phi_h)} \Big] \Big\}$$

$$+ S_{h\perp} \Big\{ \sin(\hat\phi_h - \hat\phi_{S_h}) F_{UU,T}^{\sin(\hat\phi_h-\hat\phi_{S_h})} + \lambda_e \cos(\hat\phi_h - \hat\phi_{S_h}) F_{UL,T}^{\cos(\hat\phi_h-\hat\phi_{S_h})}$$

$$+ \sin(\hat\phi_{S_h} - \phi_q) F_{UU,T}^{\sin(\hat\phi_{S_h}-\phi_q)} + \sin(2\hat\phi_h - \hat\phi_{S_h} - \phi_q) F_{UU,T}^{\sin(2\hat\phi_h-\hat\phi_{S_h}-\phi_q)}$$

$$+ \Lambda_p \Big[\cos(\hat\phi_h - \hat\phi_{S_h}) F_{LU,T}^{\cos(\hat\phi_h-\hat\phi_{S_h})} + \cos(\phi_q - \hat\phi_{S_h}) F_{LU,T}^{\cos(\phi_q-\hat\phi_{S_h})}$$

$$+ \cos(2\hat\phi_h - \hat\phi_{S_h} - \phi_q) F_{LU,T}^{\cos(2\hat\phi_h-\hat\phi_{S_h}-\phi_q)} + \lambda_e \sin(\hat\phi_h - \hat\phi_{S_h}) F_{LL,T}^{\sin(\hat\phi_h-\hat\phi_{S_h})} \Big]$$

$$+ S_T \Big[\cos(\phi_{S_A} - \hat\phi_{S_h}) F_{TU,T}^{\cos(\phi_{S_A}-\hat\phi_{S_h})} + \cos(2\hat\phi_h - \hat\phi_{S_h} - \phi_{S_A}) F_{TU,T}^{\cos(2\hat\phi_h-\hat\phi_{S_h}-\phi_{S_A})}$$

$$+ \sin(\hat\phi_h - \hat\phi_{S_h}) \sin(\phi_q - \phi_{S_A}) F_{TU,T}^{\sin(\hat\phi_h-\hat\phi_{S_h})\sin(\phi_q-\phi_{S_A})}$$

$$+ \cos(\hat\phi_h - \hat\phi_{S_h}) \cos(\phi_q - \phi_{S_A})) F_{TU,T}^{\cos(\hat\phi_h-\hat\phi_{S_h})\cos(\phi_q-\phi_{S_A})}$$

$$+ \cos(2\phi_q - \phi_{S_A} - \hat\phi_{S_h}) F_{TU,T}^{\cos(2\phi_q-\phi_{S_A}-\hat\phi_{S_h})}$$

$$+ \cos(2\hat\phi_h - \hat\phi_{S_h} + 2\phi_q - \phi_{S_A}) F_{TU,T}^{\cos(2\hat\phi_h-\hat\phi_{S_h}+2\phi_q-\phi_{S_A})}$$

$$+ \lambda_e \cos(\hat\phi_h - \hat\phi_{S_h}) \sin(\phi_{S_A} - \phi_q) F_{TL,T}^{\cos(\hat\phi_h-\hat\phi_{S_h})\sin(\phi_{S_A}-\phi_q)}$$

$$+ \lambda_e \sin(\hat\phi_h - \hat\phi_{S_h}) \cos(\phi_{S_A} - \phi_q)) F_{TL,T}^{\sin(\hat\phi_h-\hat\phi_{S_h})\cos(\phi_{S_A}-\phi_q)} \Big] \Big\}$$

Thank you

Back up

TMDJFFs

$$
\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})} \\
&\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(\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] \\
&\quad + 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})} \\
&\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(\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)} \\
&\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})} \\
&\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] \\
&\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_q - \phi_{S_A}) F_{TU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h}) \sin(\phi_q-\phi_{S_A})} \\
&\quad + \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})} \\
&\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})} \\
&\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})} \\
&\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}
$$

$$ep \to e + \text{jet}(h) + X$$

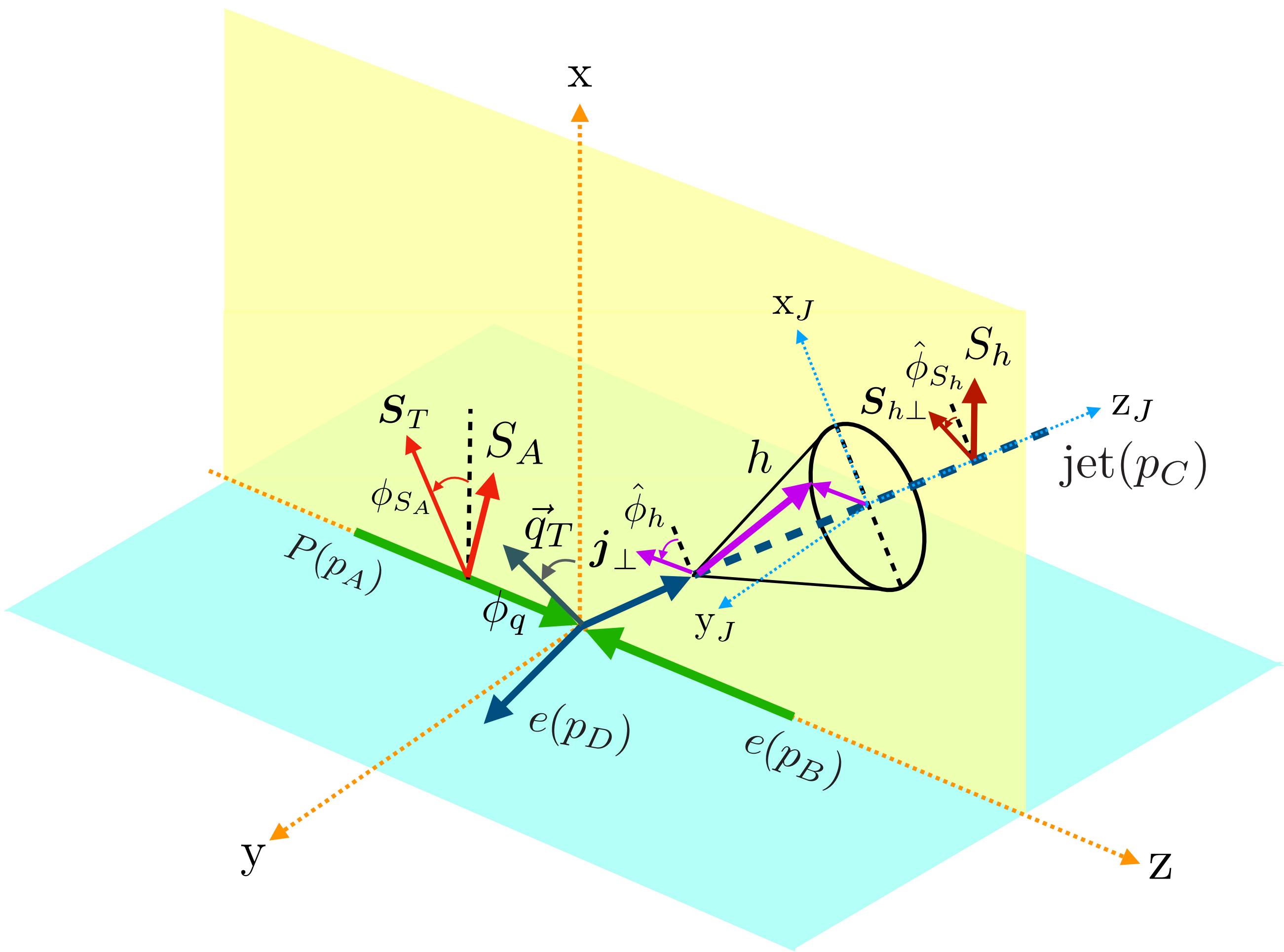


Illustration for the distribution of hadrons inside jets produced with an electron in the collisions of a polarized proton and en electron.