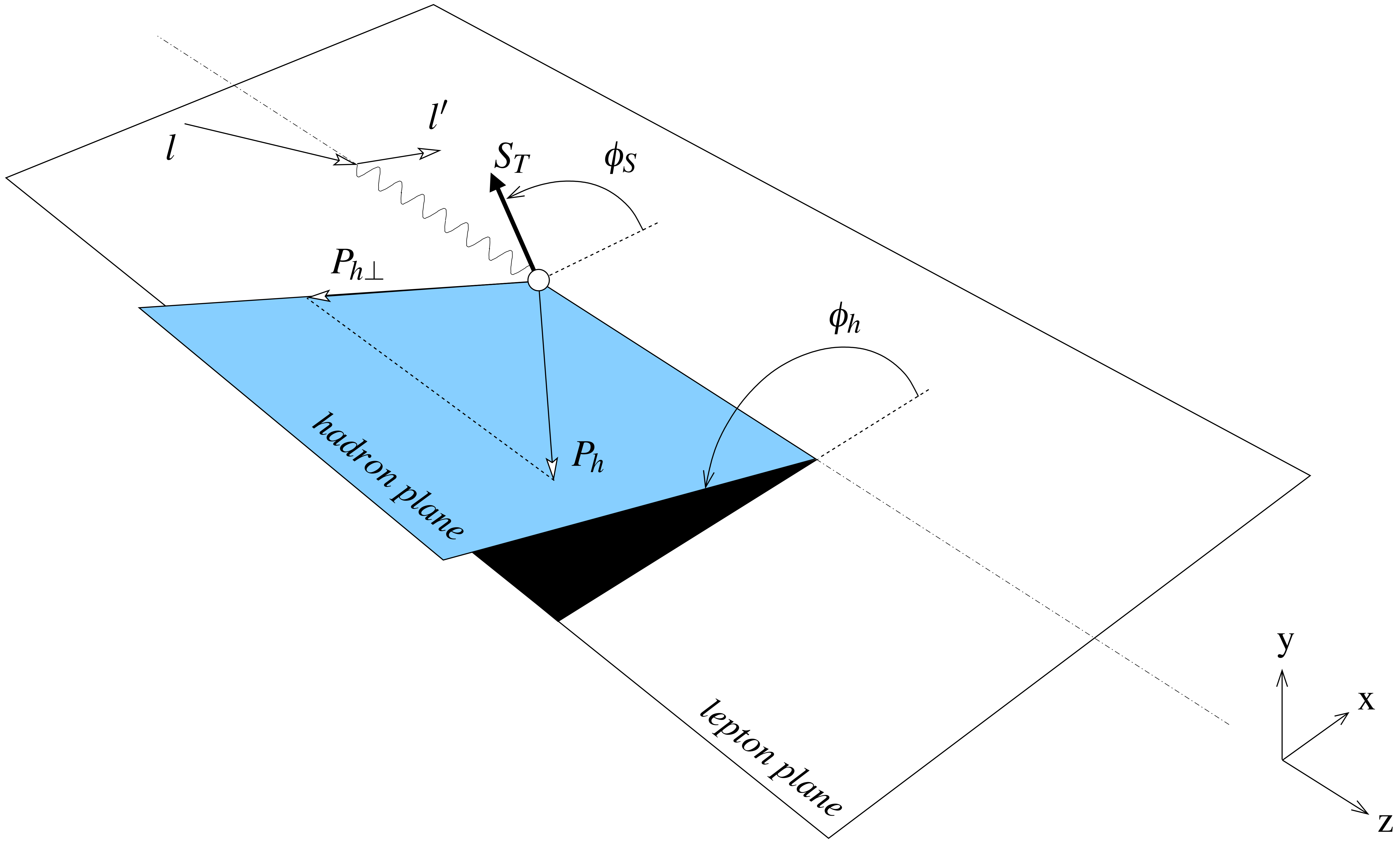
ALESSANDRO BACCHETTA, PAVIA U. AND INFN

SIDIS STRUCTURE FUNCTIONS AND EXCLUSIVE CONTRIBUTIONS

SIDIS KINEMATICS

Bacchetta, Diehl, Goeke, Metz, Mulders, Schlegel, [hep-ph/0611265](hep-ph/0611265)



Q = photon virtuality

M = hadron mass

$P_{h\perp}$ = hadron transverse momentum = P_T

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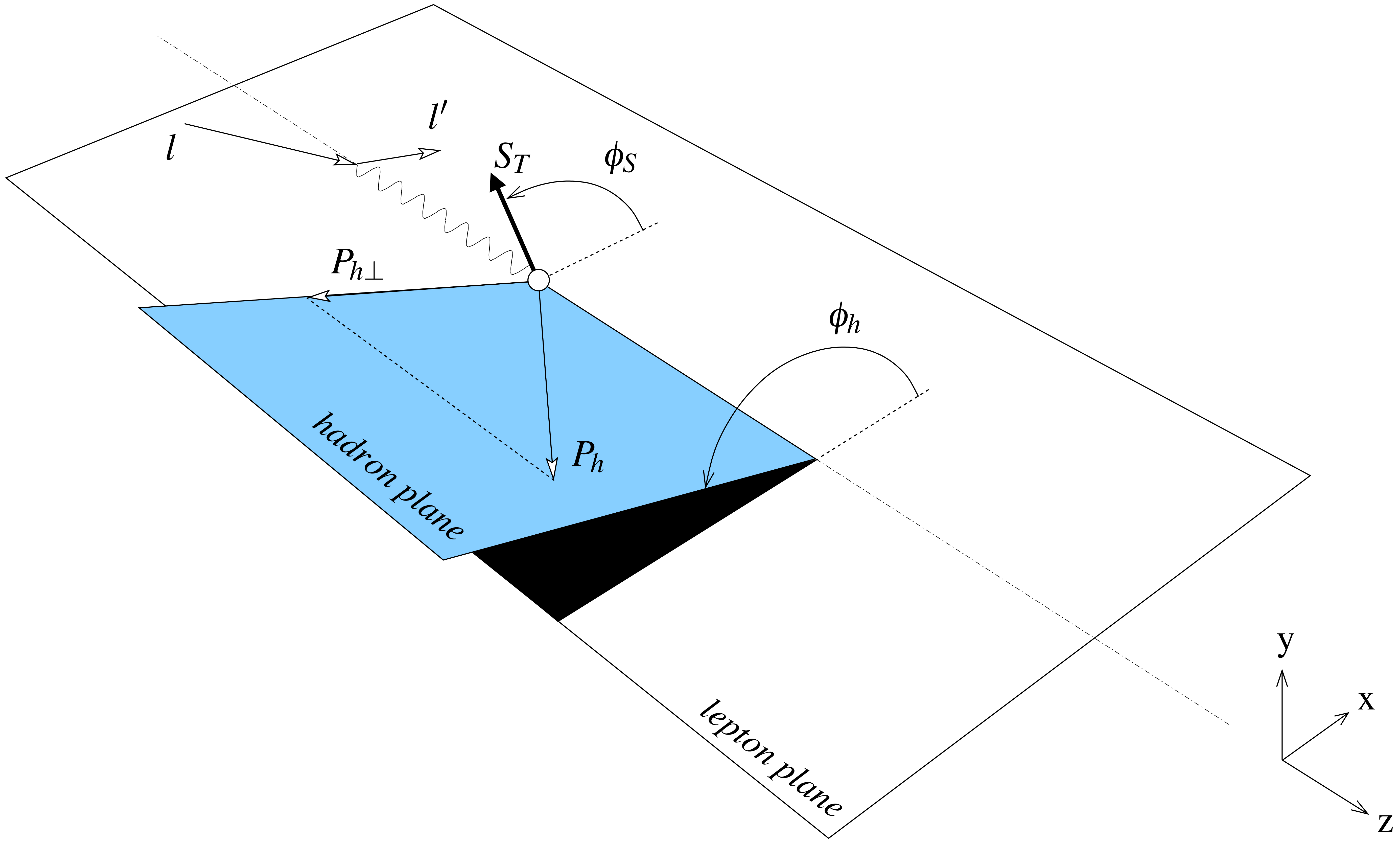


Q = photon virtuality

M = hadron mass

$P_{h\perp}$ = hadron transverse momentum = P_T $\qquad q_T^2 \approx P_{h\perp}^2/z^2$

SIDIS STRUCTURE FUNCTIONS

Bacchetta, Diehl, Goeke, Metz, Mulders, Schlegel, hep-ph/0611265

$$
\begin{aligned}
&\frac{d\sigma}{dx\, dy\, d\phi_S\, dz\, d\phi_h\, dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\, y\, Q^2}\, \frac{y^2}{2\,(1-\varepsilon)} \Bigg\{ F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\, \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} + S_L \Bigg[\sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \Bigg] \\
&\quad + S_L\, \lambda_e \Bigg[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_h\, F_{LL}^{\cos\phi_h} \Bigg] \\
&\quad + S_T \Bigg[\sin(\phi_h - \phi_S) \Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \Big) + \varepsilon\, \sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\, \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Bigg] + S_T \lambda_e \Bigg[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Bigg] \Bigg\}
\end{aligned}
$$

UNPOLARIZED SIDIS

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$

$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\Bigg\}$$

UNPOLARIZED SIDIS

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\right\}$$

Note: this expression can be applied to any process $l + P \to l' + h + X$, including DVMP and even DVCS, if h is replaced by a photon.

UNPOLARIZED SIDIS

$$
\frac{d\sigma}{dx\, dy\, d\phi_S\, dz\, d\phi_h\, dP_{h\perp}^2}
= \frac{\alpha^2}{x\, y\, Q^2} \frac{y^2}{2\,(1-\varepsilon)} \Big\{ F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h}
+ \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} \Big\}
$$

Note: this expression can be applied to any process $l + P \to l' + h + X$, including DVMP and even DVCS, if *h* is replaced by a photon.
Usually, the exclusive expressions are given in terms of t instead of $P_{h\perp}$

$$
t = -\frac{P_{h\perp}^2}{z} - z\left(M_h^2 + \frac{1-z}{z} Q^2\right) + \cdots, \qquad dt = -\frac{dP_{h\perp}^2}{z}
$$

Harut Avakian, private communication

INCLUSIVE DIS

$$\frac{d\sigma}{dx\,dy} = \frac{4\pi\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left\{F_{UU,T} + \varepsilon\,F_{UU,L}\right\}$$

INCLUSIVE DIS

$$\frac{d\sigma}{dx\,dy} = \frac{4\pi\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left\{ F_{UU,T} + \varepsilon\, F_{UU,L} \right\}$$

$$F_{UU,T} = 2x_B F_1,$$

$$F_{UU,L} = (1+\gamma^2)F_2 - 2x_B F_1$$

INCLUSIVE DIS

$$\frac{d\sigma}{dx\,dy} = \frac{4\pi\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left\{F_{UU,T} + \varepsilon\,F_{UU,L}\right\}$$

$$F_{UU,T} = 2x_B F_1,$$

$$F_{UU,L} = (1+\gamma^2)F_2 - 2x_B F_1$$

Note: this expression can be applied to any process $l + P \to l' + X$, including elastic scattering.

HELICITY STRUCTURE FUNCTIONS

Bacchetta, Diehl, Goeke, Metz, Mulders, Schlegel, [hep-ph/0611265](hep-ph/0611265)

see also Diehl, Sapeta, [hep-ph/0503023](hep-ph/0503023)

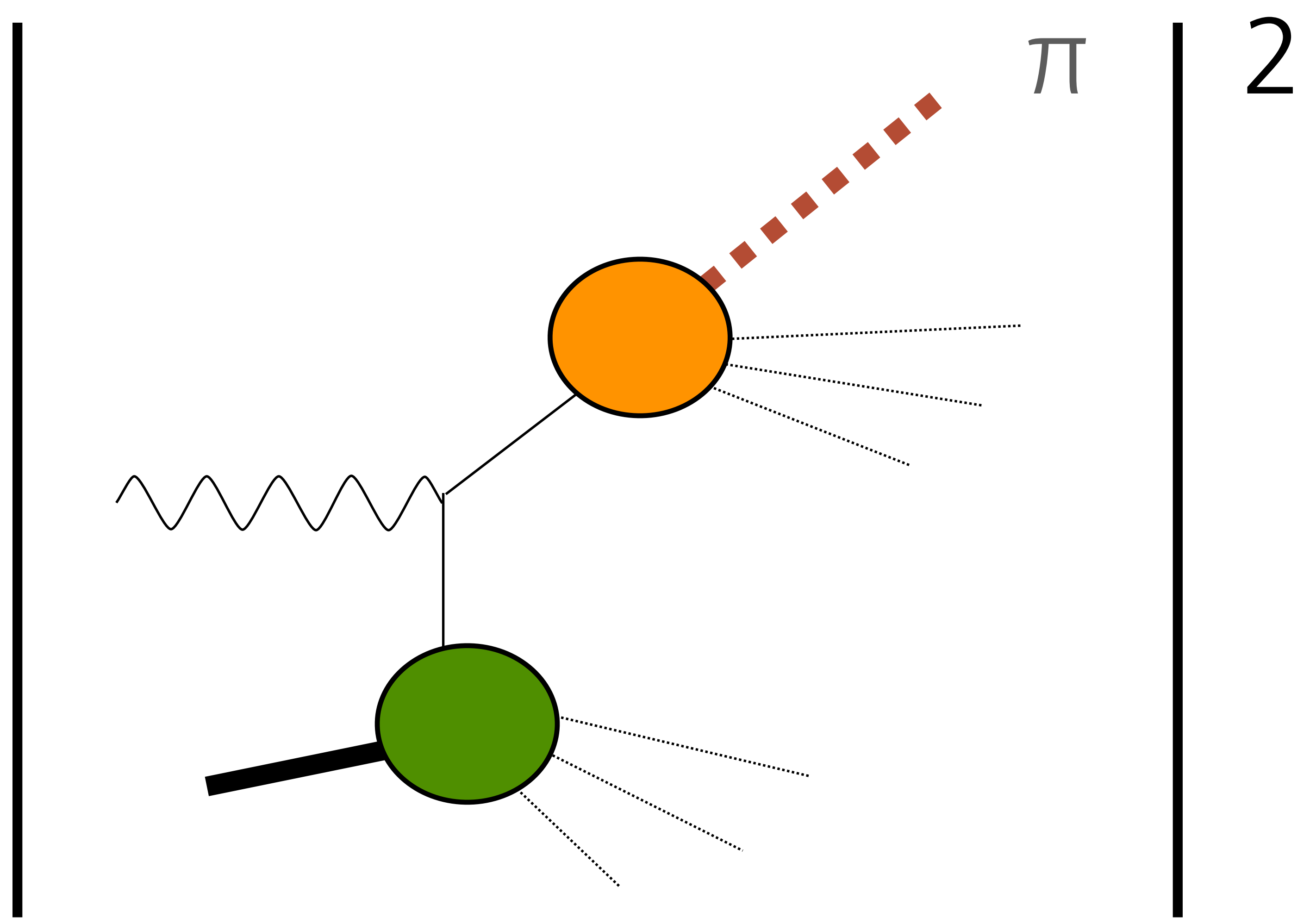
Helicity structure functions are often used instead of the previously defined ones

$$F_{UU,T} = \frac{1}{2}\left(F^{++}_{++} + F^{--}_{++}\right), \qquad F_{UU,L} = F^{++}_{00},$$

$$F^{\cos\phi_h}_{UU} = -\frac{1}{\sqrt{2}}\,\mathrm{Re}\left(F^{++}_{+0} + F^{--}_{+0}\right), \qquad F^{\cos 2\phi_h}_{UU} = -\mathrm{Re}\,F^{++}_{+-}, \tag{A.2}$$

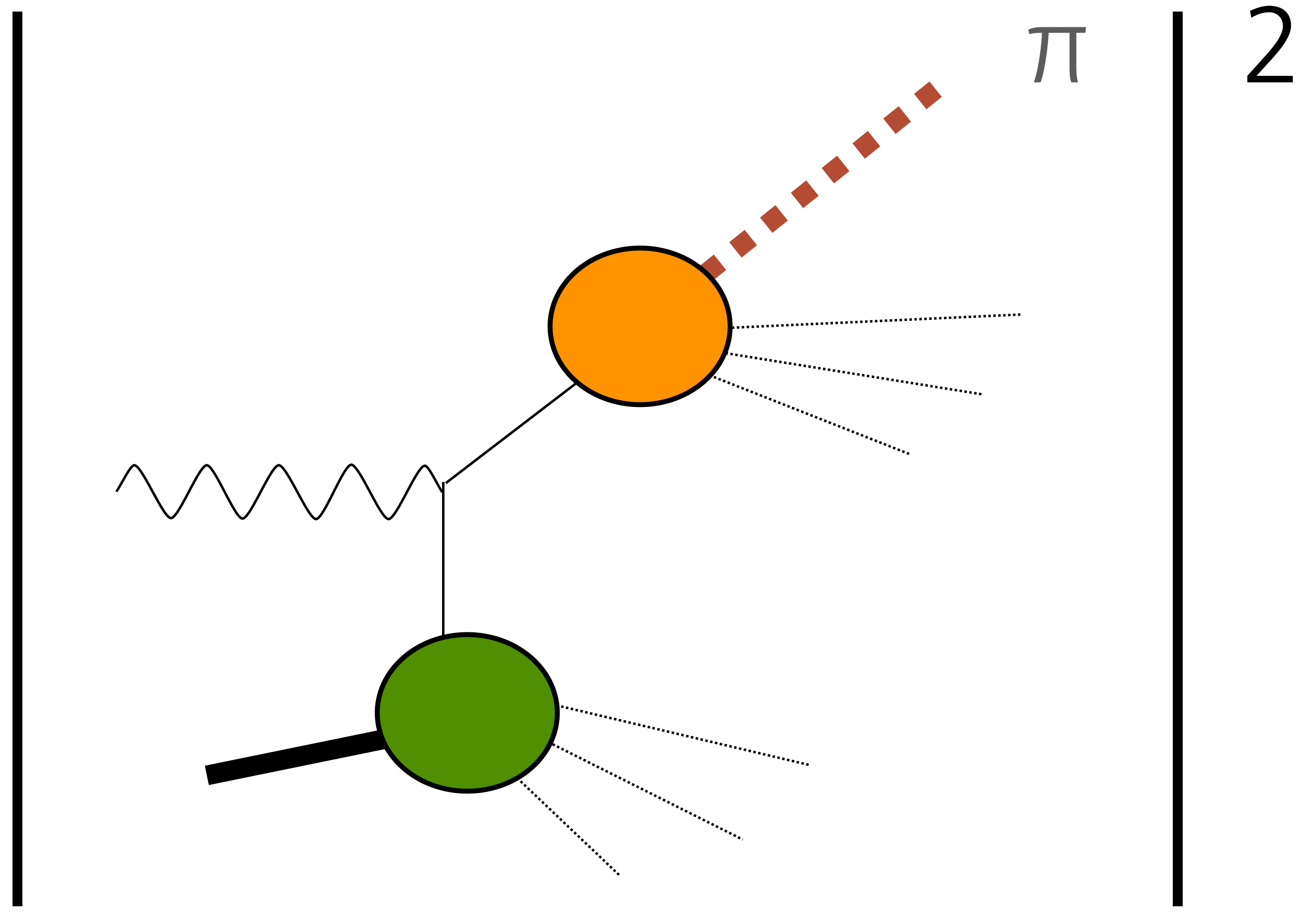
$$F^{\sin\phi_h}_{LU} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}\left(F^{++}_{+0} + F^{--}_{+0}\right), \tag{A.3}$$

FROM SEMI-INCLUSIVE TO INCLUSIVE



leading-order and leading-twist contribution to SIDIS

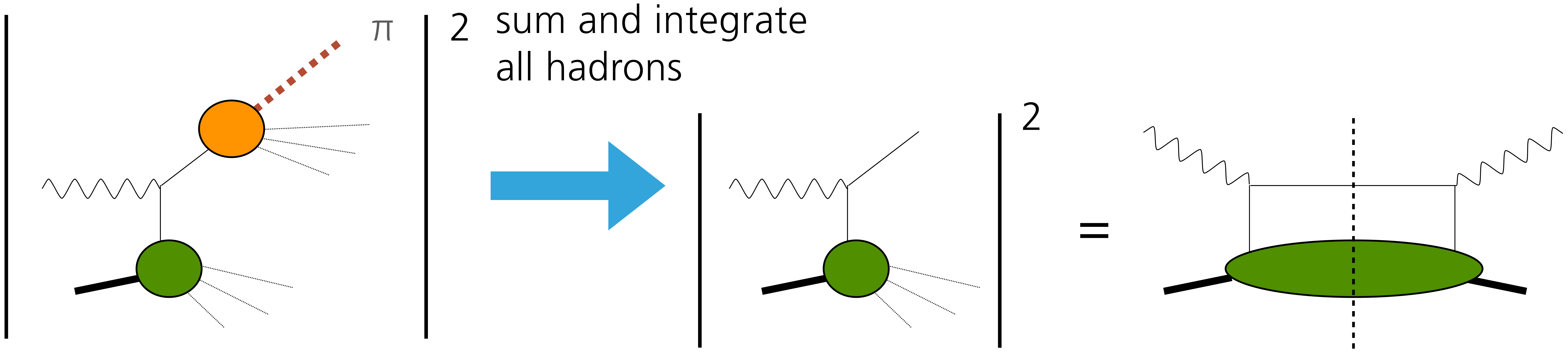
FROM SEMI-INCLUSIVE TO INCLUSIVE



sum and integrate
all hadrons

leading-order and leading-twist
contribution to SIDIS

FROM SEMI-INCLUSIVE TO INCLUSIVE



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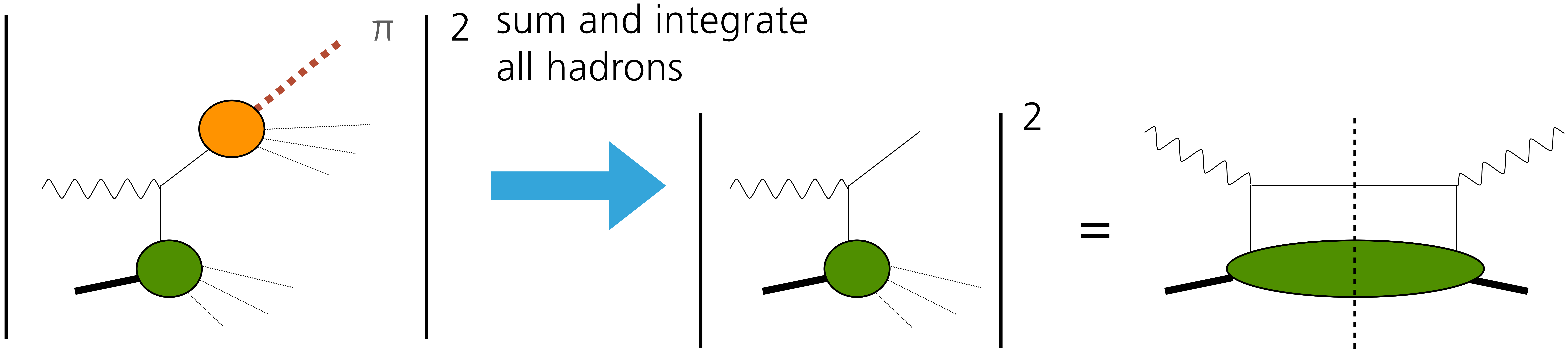
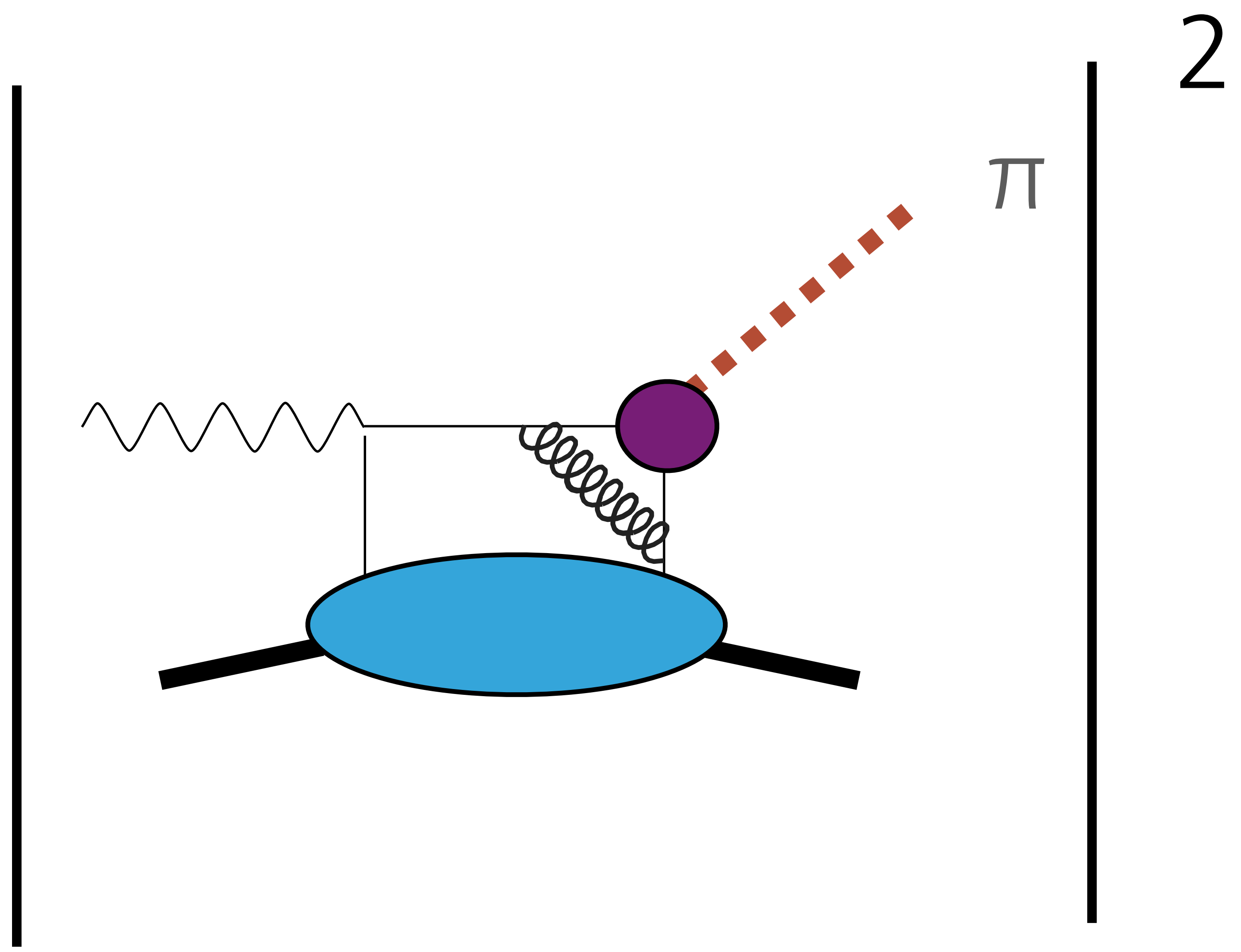


leading-order and leading-twist
contribution to SIDIS

we should recover
the leading-order, leading-twist part of
INCLUSIVE DIS

EXCLUSIVE "CONTAMINATIONS"



leading-order and leading-twist
contribution to DVMP

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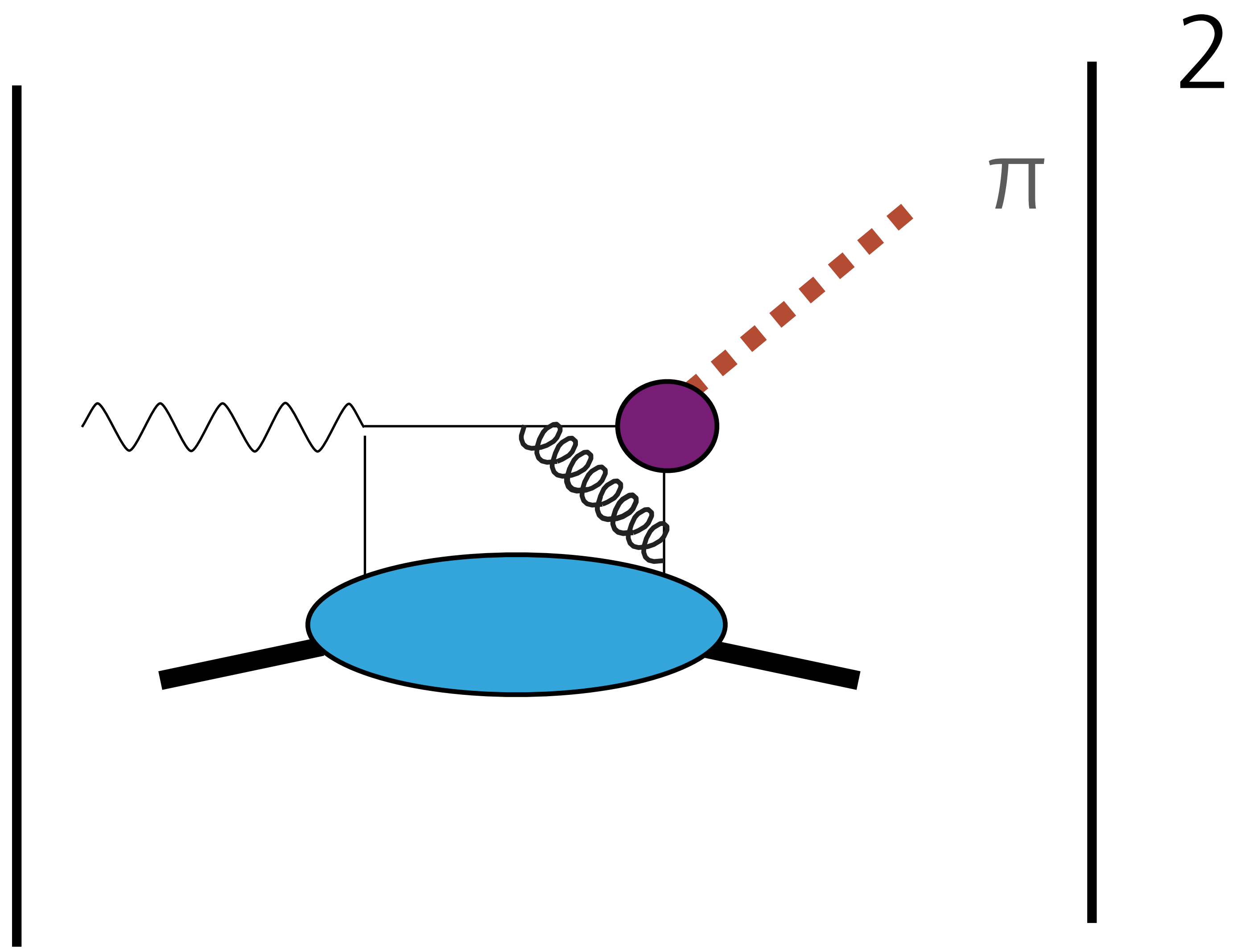

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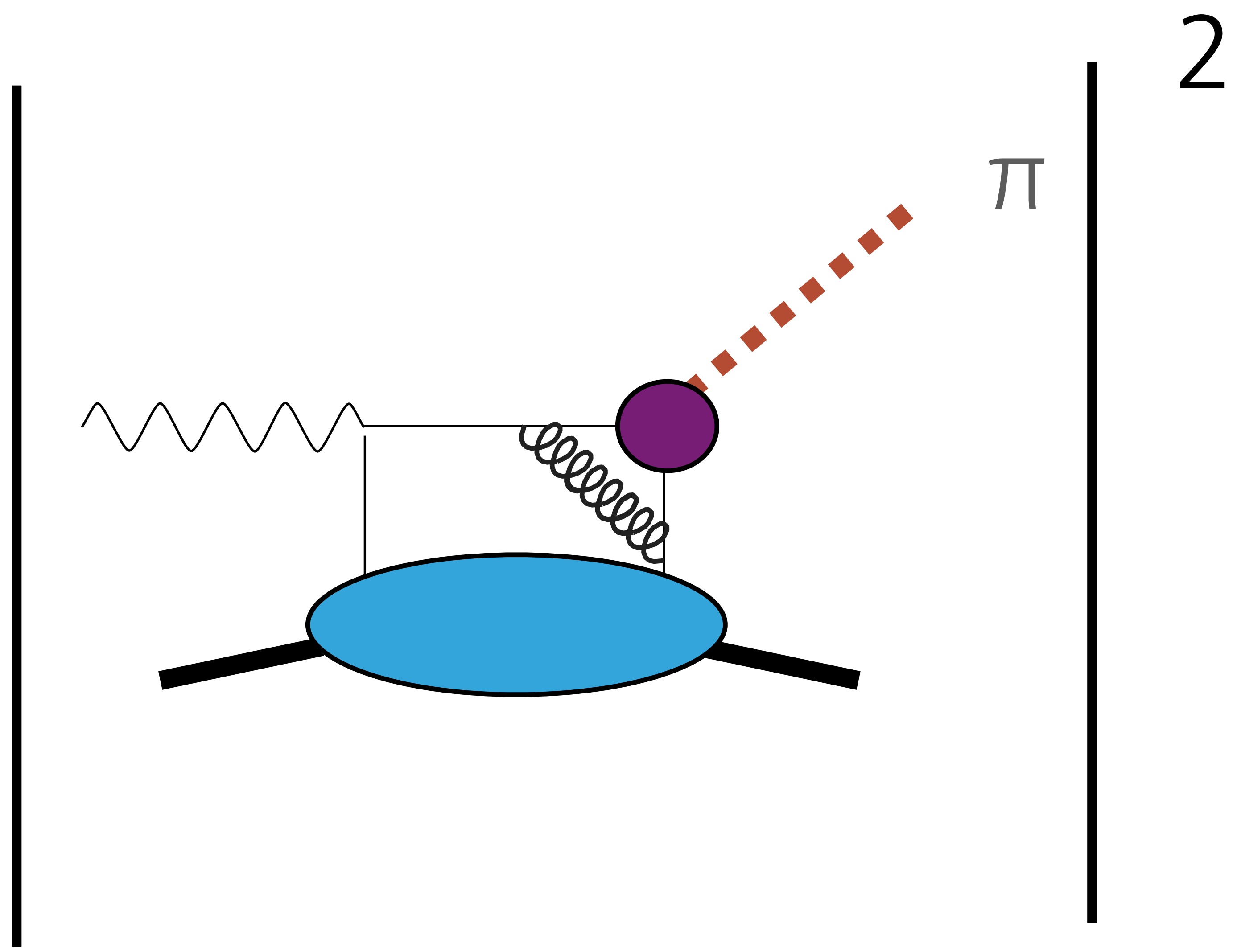

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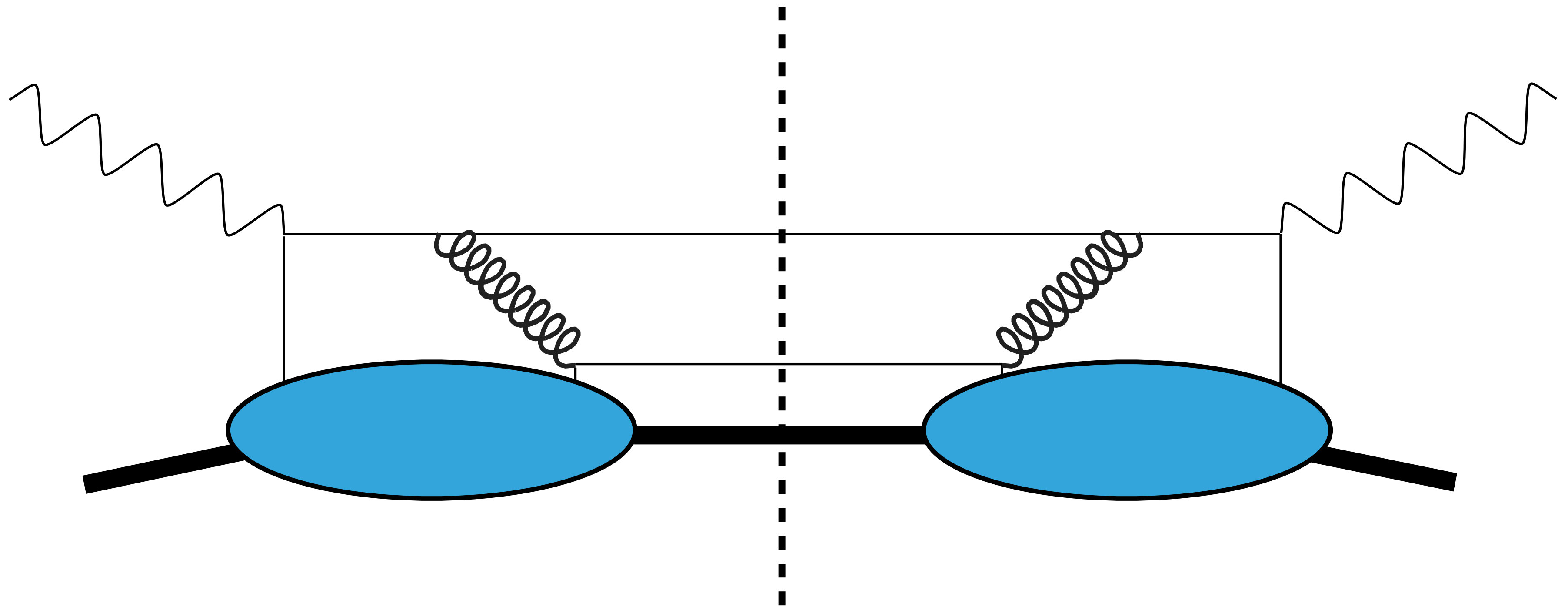

leading-order and leading-twist
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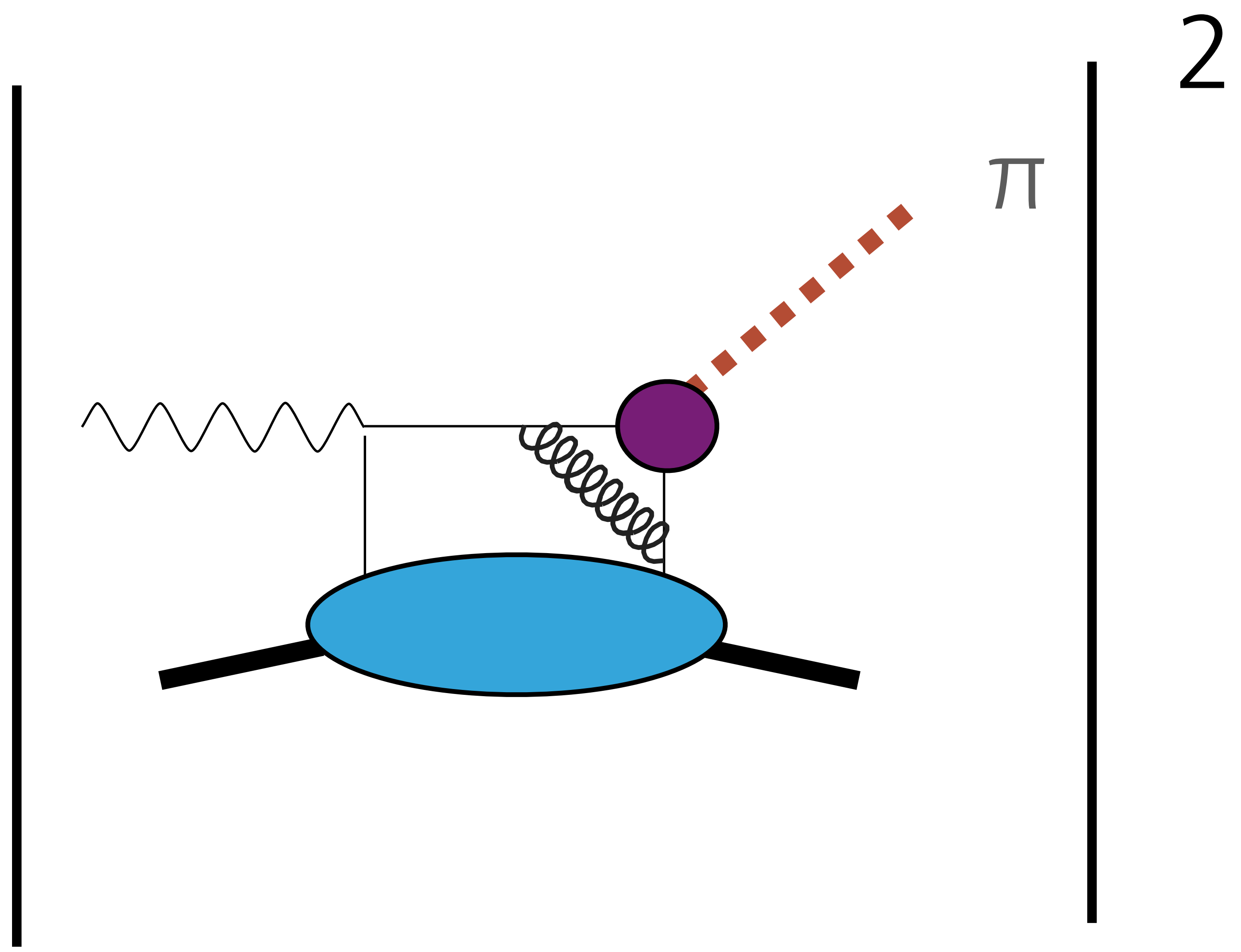

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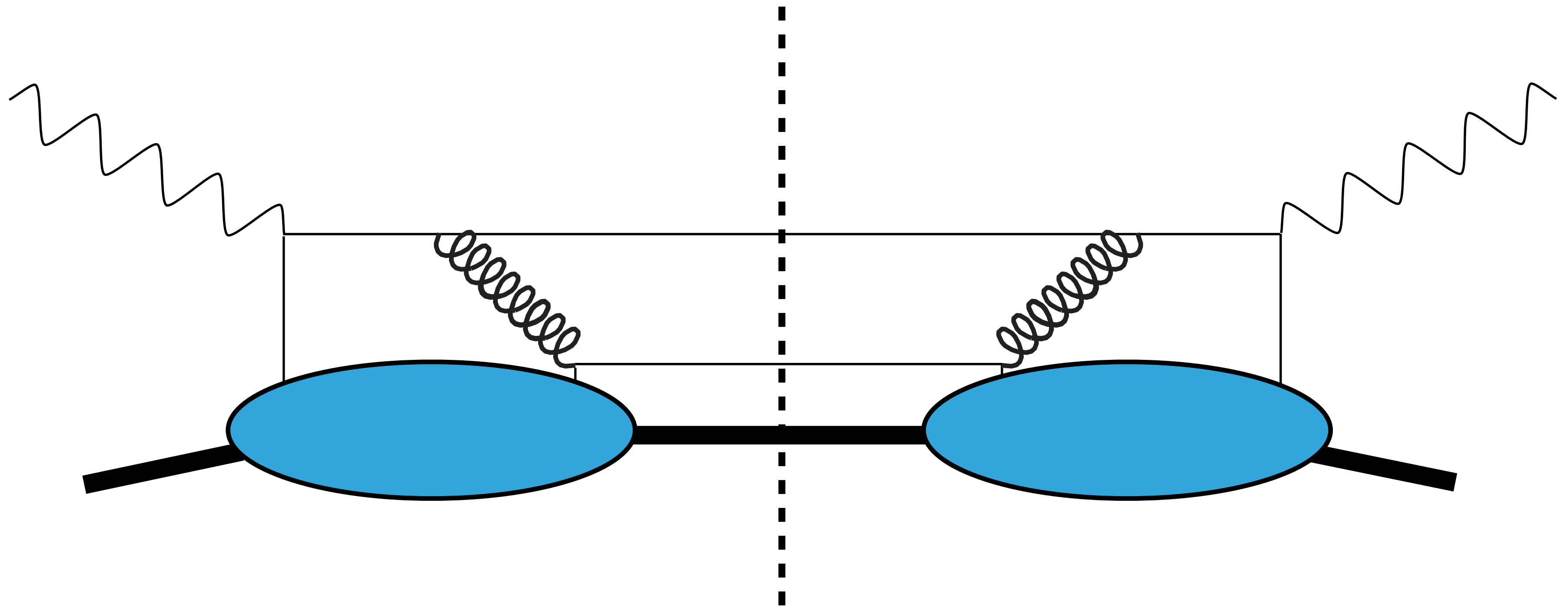
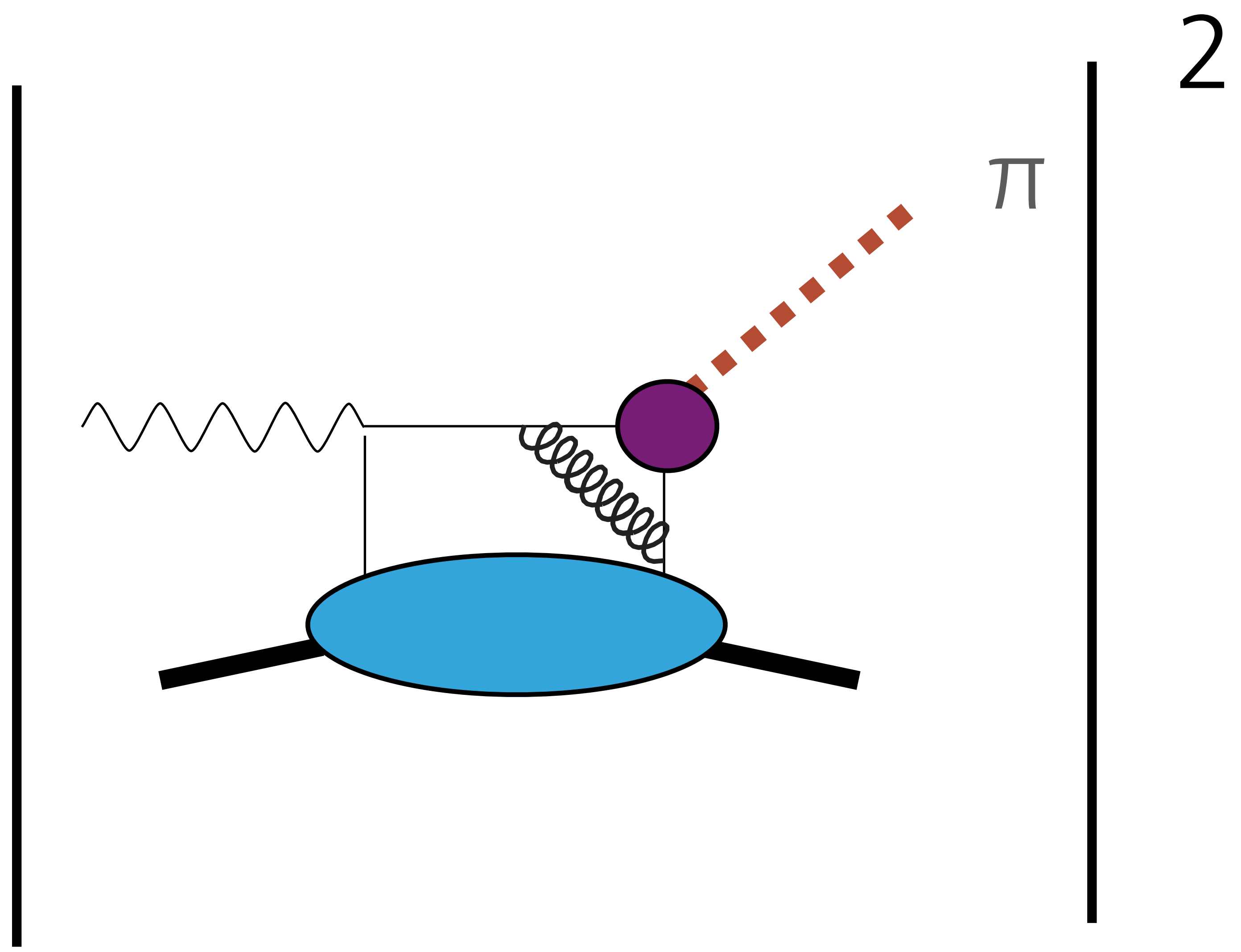


leading-order and leading-twist contribution to DVMP

This is a suppressed contribution to INCLUSIVE DIS

EXCLUSIVE "CONTAMINATIONS"



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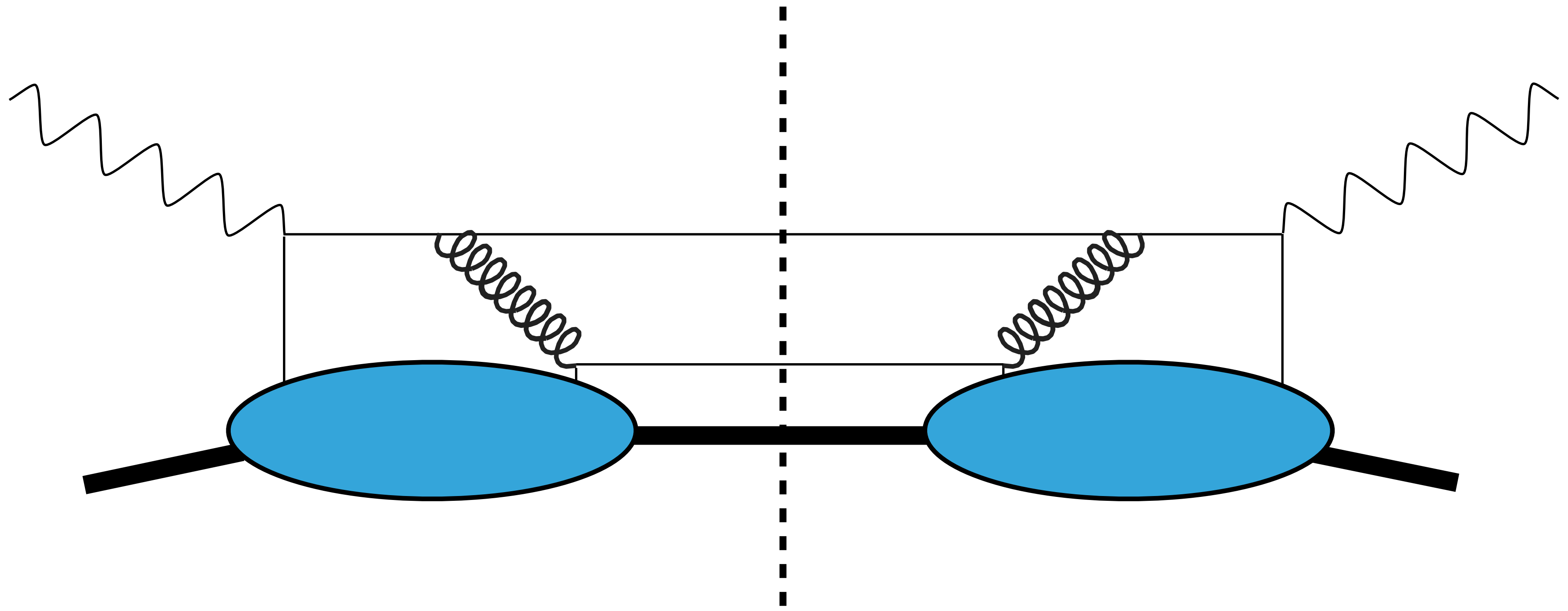

leading-order and leading-twist
contribution to DVMP

This is a suppressed contribution to
INCLUSIVE DIS

There are other contributions,
most of them not from exclusive processes

CONTRIBUTIONS TO INCLUSIVE DIS

$$F_{UU,T} = x f_1 + \alpha_s \Big[C_T \otimes f_1 \Big]$$

$$F_{UU,L} = \alpha_s \Big[C_L \otimes f_1 \Big]$$

CONTRIBUTIONS TO INCLUSIVE DIS

$$F_{UU,T} = xf_1 + \alpha_s \Big[C_T \otimes f_1 \Big]$$

$$F^{\text{excl}}_{UU,T} = \mathcal{O}\left(\frac{M^6}{Q^6} \right)$$

$$F_{UU,L} = \alpha_s \Big[C_L \otimes f_1 \Big]$$

$$F^{\text{excl}}_{UU,L} \propto \frac{\alpha_s}{Q^4} \Big[C \otimes \tilde{H} \Big]$$

CONTRIBUTIONS TO INCLUSIVE DIS

$$F_{UU,T} = x f_1 + \alpha_s \Big[C_T \otimes f_1 \Big]$$

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GPDs

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There are other contributions,
most of them not from exclusive processes

CONTRIBUTIONS TO INCLUSIVE DIS

Even if this is in principle highly suppressed,
it has been found to be large in experiments

$$F_{UU,T} = x f_1 + \alpha_s \Big[C_T \otimes f_1 \Big]$$

$$F_{UU,T}^{\text{excl}} = \mathcal{O}\left(\frac{M^6}{Q^6}\right)$$

GPDs

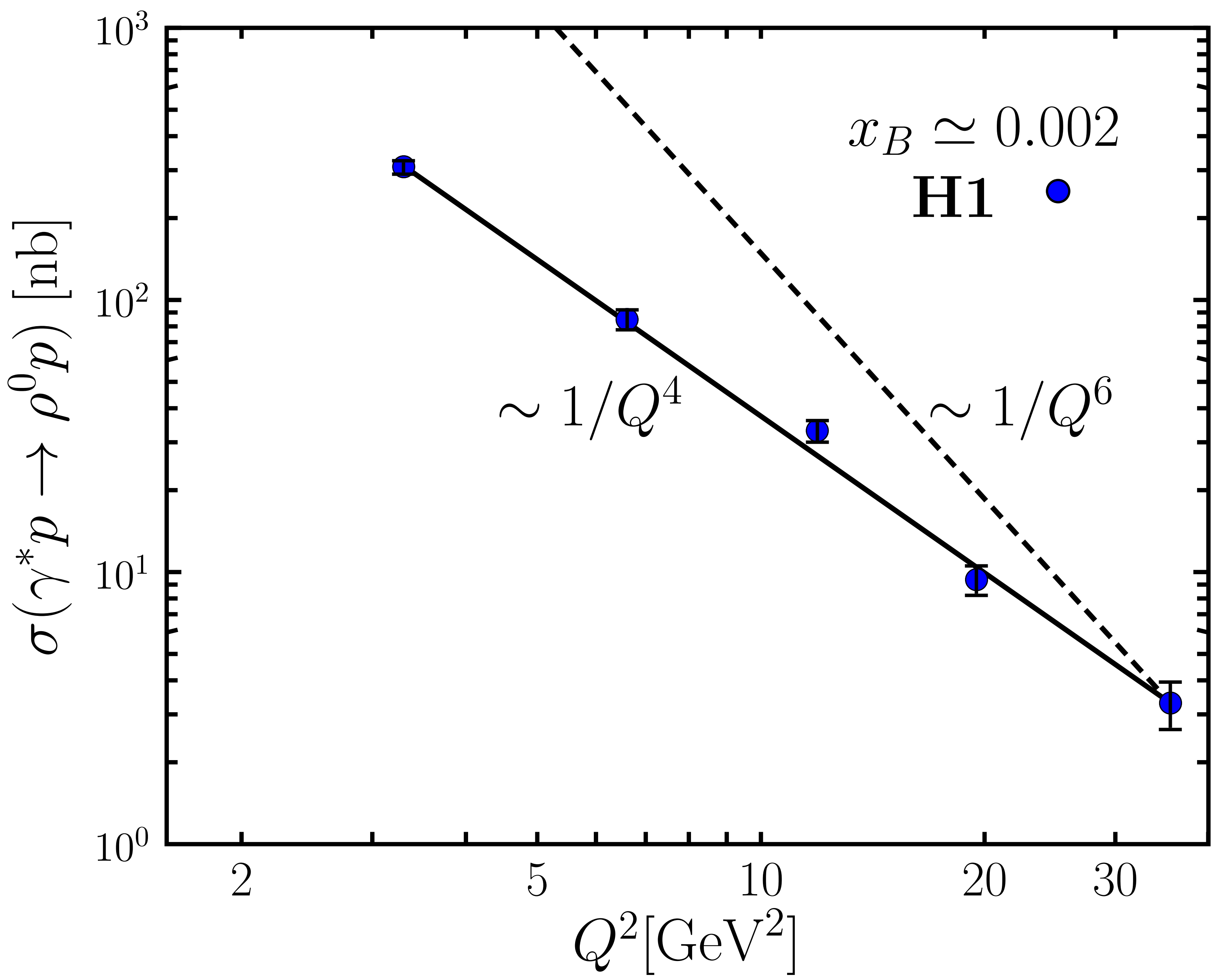
$$F_{UU,L} = \alpha_s \Big[C_L \otimes f_1 \Big]$$

$$F_{UU,L}^{\text{excl}} \propto \frac{\alpha_s}{Q^4} \Big[C \otimes \tilde{H} \Big]$$

There are other contributions,
most of them not from exclusive processes

EXPERIMENTAL MEASUREMENTS FOR EXCLUSIVE ρ^0

from L. Favart, M. Guidal, T. Horn, P. Kroll, arXiv:511.04535



SIDIS STRUCTURE FUNCTIONS IN DIFFERENT REGIMES

Bacchetta, Boer, Diehl, Mulders, arXiv:0803.0227

(schematically only)

Low transverse momentum

High transverse momentum

Integrated

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High transverse momentum

Integrated

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right]$$

Twist 2

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Twist 2

High transverse momentum

$$F_{UU,T} = \frac{\alpha_s}{P_{h\perp}^2}\left[f_1 \otimes D_1\right]_A$$

Twist 2

Integrated

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High transverse momentum

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Twist 2

Integrated

$$F_{UU,T} = x f_1 D_1 + \alpha_s \Big[f_1 \otimes D_1\Big]_C$$

Twist 2

SIDIS STRUCTURE FUNCTIONS IN DIFFERENT REGIMES

(schematically only)

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$$F_{UU,T} = \mathcal{C}\Big[f_1 D_1\Big]$$

Twist 2

$$F_{UU,L} = \mathcal{O}\left(\frac{M^2}{Q^2}, \frac{P_{h\perp}^2}{Q^2}\right)$$

Twist 4

see talk by L. Gamberg

High transverse momentum

$$F_{UU,T} = \frac{\alpha_s}{P_{h\perp}^2}\Big[f_1 \otimes D_1\Big]_A$$

Twist 2

Integrated

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Twist 4

see talk by L. Gamberg

High transverse momentum

$$F_{UU,T} = \frac{\alpha_s}{P_{h\perp}^2}\Big[f_1 \otimes D_1\Big]_A$$

Twist 2

$$F_{UU,L} = \frac{\alpha_s}{P_{h\perp}^2}\frac{P_{h\perp}^2}{Q^2}\Big[f_1 \otimes D_1\Big]_B = 2\, F_{UU}^{\cos 2\phi_h}$$

Twist 2

Integrated

$$F_{UU,T} = x f_1 D_1 + \alpha_s \Big[f_1 \otimes D_1\Big]_C$$

Twist 2

SIDIS STRUCTURE FUNCTIONS IN DIFFERENT REGIMES

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Low transverse momentum

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$$F_{UU,L} = \mathcal{O}\left(\frac{M^2}{Q^2}, \frac{P_{h\perp}^2}{Q^2}\right)$$

Twist 4

see talk by L. Gamberg

High transverse momentum

$$F_{UU,T} = \frac{\alpha_s}{P_{h\perp}^2}\Big[f_1 \otimes D_1\Big]_A$$

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$$F_{UU,L} = \frac{\alpha_s}{P_{h\perp}^2}\,\frac{P_{h\perp}^2}{Q^2}\Big[f_1 \otimes D_1\Big]_B$$

$$= 2\,F_{UU}^{\cos 2\phi_h}$$

Twist 2

Integrated

$$F_{UU,T} = x f_1 D_1 + \alpha_s\Big[f_1 \otimes D_1\Big]_C$$

Twist 2

$$F_{UU,L} = \alpha_s\Big[f_1 \otimes D_1\Big]_D$$

Twist 2

SIDIS STRUCTURE FUNCTIONS IN DIFFERENT REGIMES

(schematically only)

Bacchetta, Boer, Diehl, Mulders, arXiv:0803.0227

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Twist 2

$$F_{UU,L} = \mathcal{O}\left(\frac{M^2}{Q^2}, \frac{P_{h\perp}^2}{Q^2}\right)$$

Twist 4

see talk by L. Gamberg

High transverse momentum

$$F_{UU,T} = \frac{\alpha_s}{P_{h\perp}^2}\Big[f_1 \otimes D_1\Big]_A$$

Twist 2

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Twist 2

Integrated

$$F_{UU,T} = x f_1 D_1 + \alpha_s\Big[f_1 \otimes D_1\Big]_C$$

Twist 2

$$F_{UU,L} = \alpha_s\Big[f_1 \otimes D_1\Big]_D$$

Twist 2

All of them can contain corrections $\mathcal{O}\left(\frac{M^2}{Q^2}, \frac{P_{h\perp}^2}{Q^2}\right)$

SIDIS STRUCTURE FUNCTIONS IN DIFFERENT REGIMES

Bacchetta, Boer, Diehl, Mulders, arXiv:0803.0227

(schematically only)

Low transverse momentum	High transverse momentum	Integrated
$F_{UU,T} = \mathcal{C}\Big[f_1 D_1\Big]$	$F_{UU,T} = \dfrac{\alpha_s}{P_{h\perp}^2}\Big[f_1 \otimes D_1\Big]_A$	$F_{UU,T} = x f_1 D_1 + \alpha_s \Big[f_1 \otimes D_1\Big]_C$
Twist 2	Twist 2	Twist 2
$F_{UU,L} = \mathcal{O}\left(\dfrac{M^2}{Q^2}, \dfrac{P_{h\perp}^2}{Q^2}\right)$	$F_{UU,L} = \dfrac{\alpha_s}{P_{h\perp}^2}\dfrac{P_{h\perp}^2}{Q^2}\Big[f_1 \otimes D_1\Big]_B = 2\,F_{UU}^{\cos 2\phi_h}$	$F_{UU,L} = \alpha_s \Big[f_1 \otimes D_1\Big]_D$
Twist 4 *see talk by L. Gamberg*	Twist 2	Twist 2

All of them can contain corrections $\mathcal{O}\left(\dfrac{M^2}{Q^2}, \dfrac{P_{h\perp}^2}{Q^2}\right)$

Nice property of F_{UUL}:
at low transverse momentum
is a clean twist-4 signal

LOW AND HIGH P_T

	observable	twist (low $P_{h\perp}$)	twist (high $P_{h\perp}$)
"SIDIS F_T"	$F_{UU,T}$	2	2
"SIDIS F_L"	$F_{UU,L}$	4	2
"Cahn" - $f^{\perp}$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
$e,\ g^{\perp}$ and friends	$F_{LU}^{\sin\phi_h}$	3	2

LOW AND HIGH P_T

		low $P_{h\perp}$	high $P_{h\perp}$
	observable	twist	twist
"SIDIS F_T"	$F_{UU,T}$	2	2
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"Cahn" - $f^{\perp}$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
$e,\ g^{\perp}$ and friends	$F_{LU}^{\sin\phi_h}$	3	2

There are several possibilities:

LOW AND HIGH P_T

	observable	low $P_{h\perp}$ twist	high $P_{h\perp}$ twist
"SIDIS F_T"	$F_{UU,T}$	2	2
"SIDIS F_L"	$F_{UU,L}$	4	2
"Cahn" - $f^{\perp}$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
$e,\ g^{\perp}$ and friends	$F_{LU}^{\sin\phi_h}$	3	2

There are several possibilities:

- Twist 2 TMD matching twist 2 PDF

LOW AND HIGH P_T

	observable	low $P_{h\perp}$ twist	high $P_{h\perp}$ twist
"SIDIS F_T"	$F_{UU,T}$	2	2
"SIDIS F_L"	$F_{UU,L}$	4	2
"Cahn" - $f^\perp$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
$e,\ g^\perp$ and friends	$F_{LU}^{\sin\phi_h}$	3	2

There are several possibilities:

- Twist 2 TMD matching twist 2 PDF
- Twist 3 TMD matching twist 2 PDF

LOW AND HIGH P_T

		low $P_{h\perp}$	high $P_{h\perp}$
	observable	twist	twist
"SIDIS F_T"	$F_{UU,T}$	2	2
"SIDIS F_L"	$F_{UU,L}$	4	2
"Cahn" - $f^\perp$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
$e,\ g^\perp$ *and friends*	$F_{LU}^{\sin\phi_h}$	3	2

There are several possibilities:

- Twist 2 TMD matching twist 2 PDF
- Twist 3 TMD matching twist 2 PDF
- Twist 2 TMD matching twist 3 PDF

LOW AND HIGH P_T

	observable	low $P_{h\perp}$ twist	high $P_{h\perp}$ twist
"SIDIS F_T"	$F_{UU,T}$	2	2
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"Cahn" - $f^\perp$	$F_{UU}^{\cos\phi_h}$	3	2
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e, $g^\perp$ *and friends*	$F_{LU}^{\sin\phi_h}$	3	2

There are several possibilities:

- Twist 2 TMD matching twist 2 PDF
- Twist 3 TMD matching twist 2 PDF
- Twist 2 TMD matching twist 3 PDF
- Expected mismatch

LOW AND HIGH P_T

	observable	low $P_{h\perp}$ twist	high $P_{h\perp}$ twist
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- Twist 4 TMD matching twist 2 PDF?

POSSIBLE TERMS AT LOW TRANSVERSE MOMENTUM

see, e.g., Wei, Song, Chen, Liang, arxiv:1611.08688

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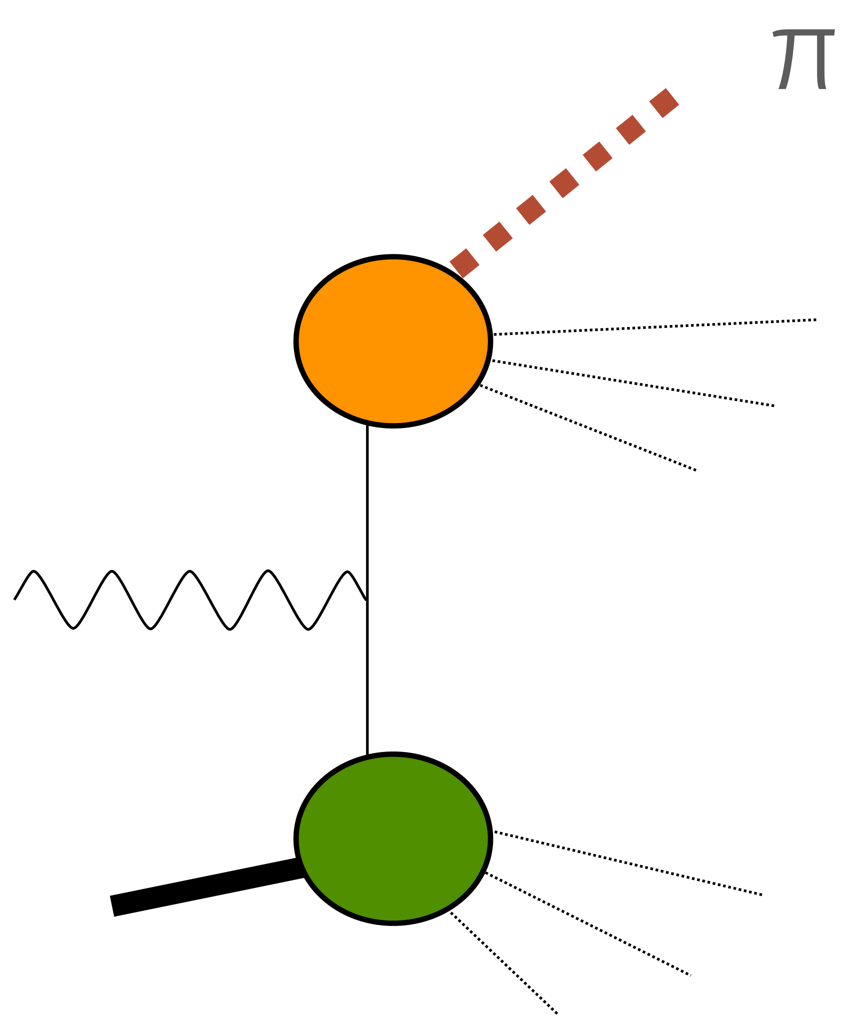
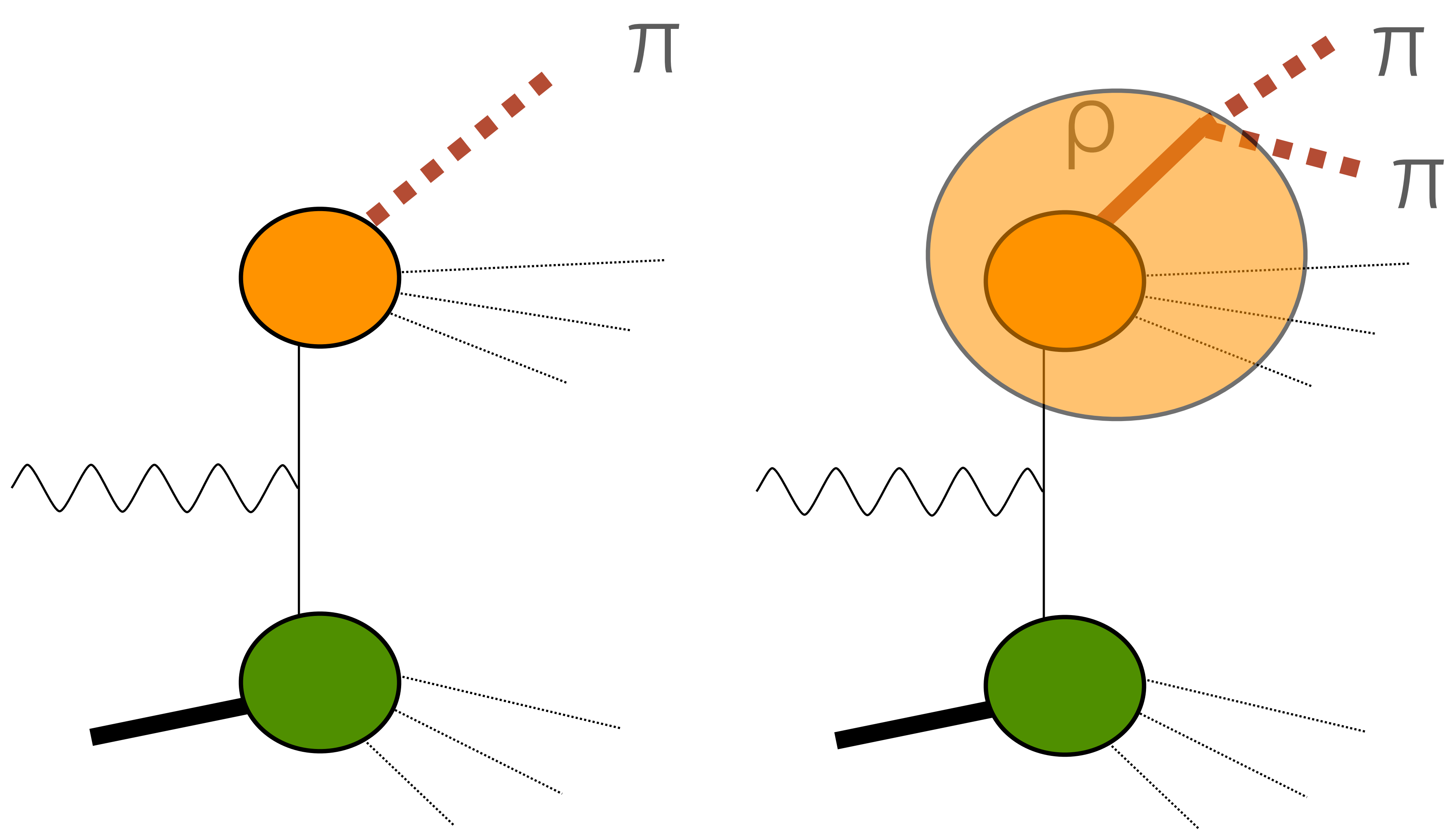
factorization breaking terms?

EXCLUSIVE "CONTAMINATIONS" IN SEMI-INCLUSIVE DIS



Semi-inclusive

EXCLUSIVE "CONTAMINATIONS" IN SEMI-INCLUSIVE DIS



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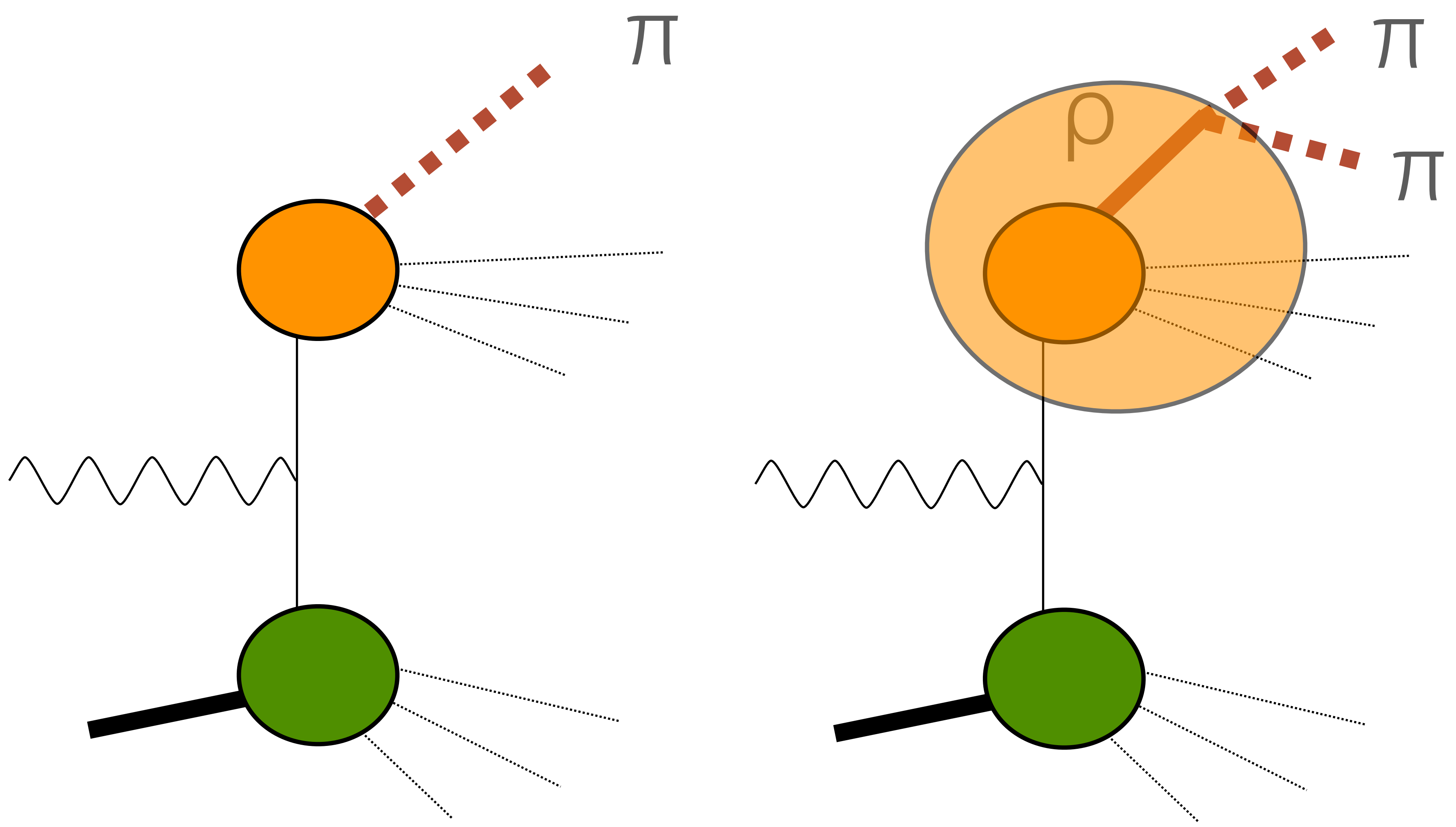

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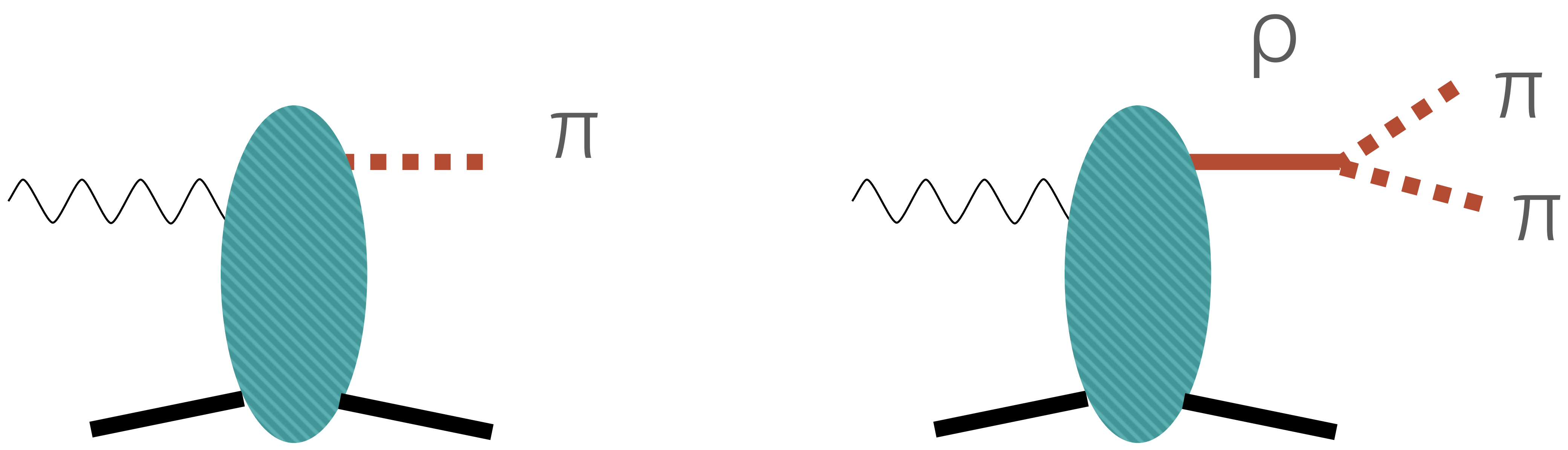

Exclusive

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Diehl, Kugler, Schäfer, Weiss, hep-ph/0506171

Integrated over transverse momentum

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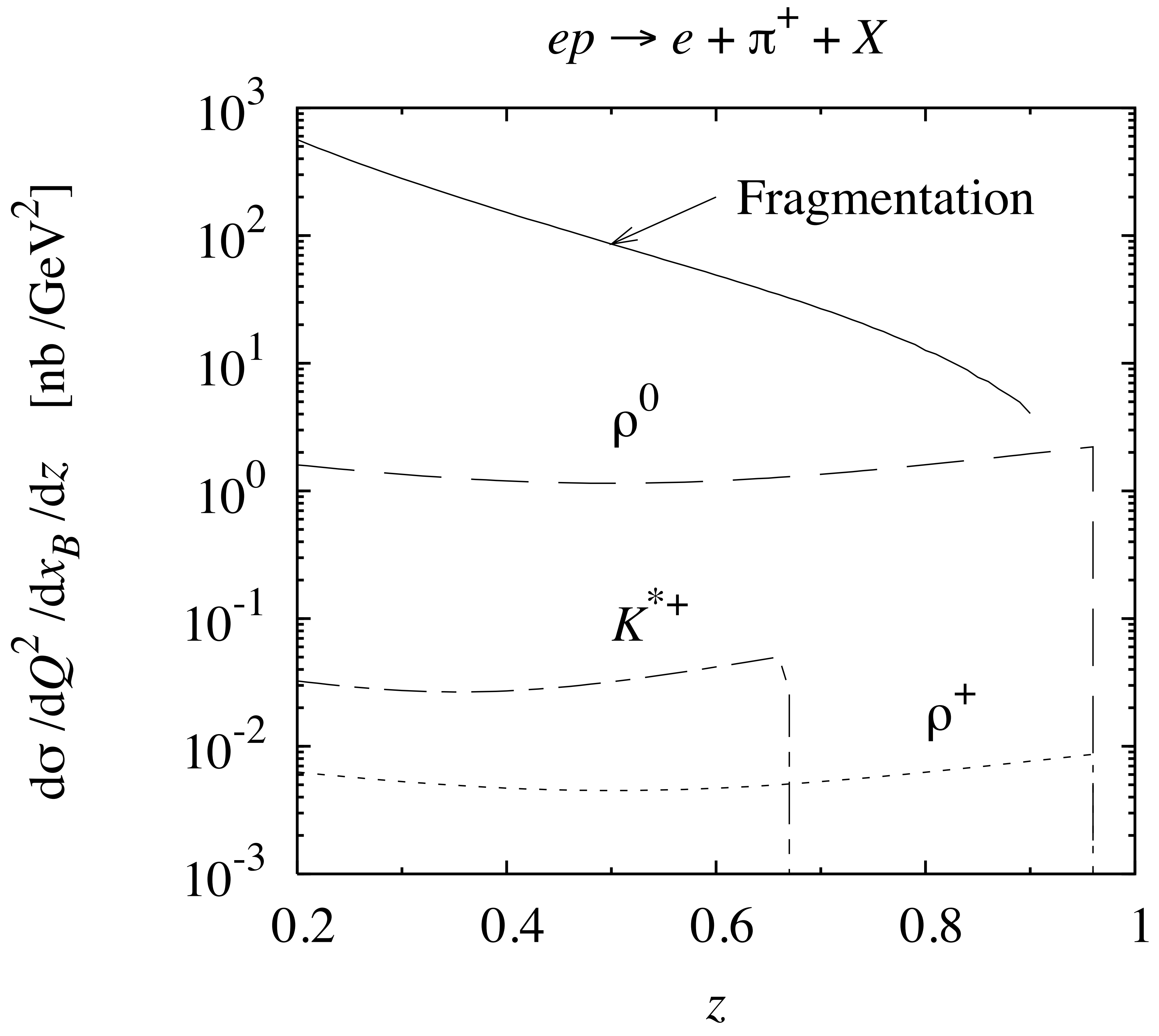
GPDs

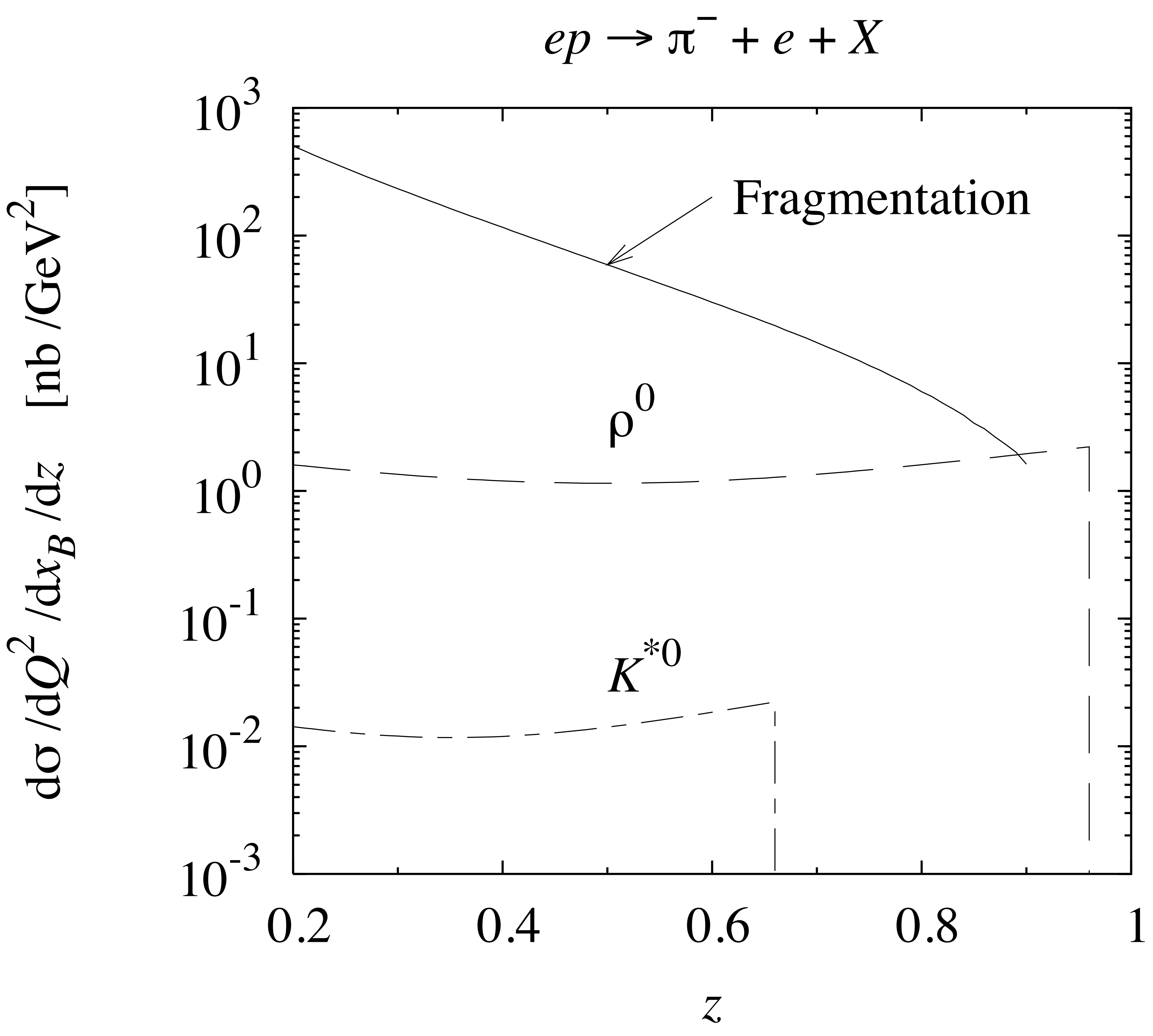
$$F_{UU,L}^{\mathrm{excl}} \propto \frac{\alpha_s}{Q^4}\Big[\phi_\pi \otimes \tilde{H} + D_{\rho\to\pi^+\pi^-}\,\phi_\rho \otimes H\Big]$$

meson distribution amplitudes

EXAMPLE OF THEORY ESTIMATES

Diehl, Kugler, Schäfer, Weiss, hep-ph/0506171





I am not aware of similar calculations for $P_{h\perp}$ dependence

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- There are no good estimates of these contributions as functions of $P_{h\perp}$