Large transverse momentum in semi-inclusive deeply inelastic scattering beyond the lowest order

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QCD Evolution
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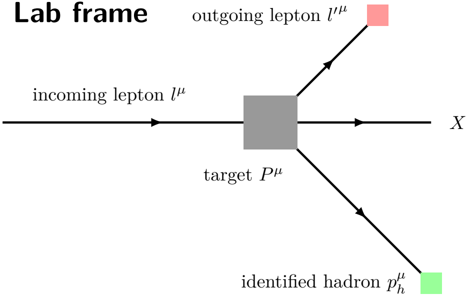
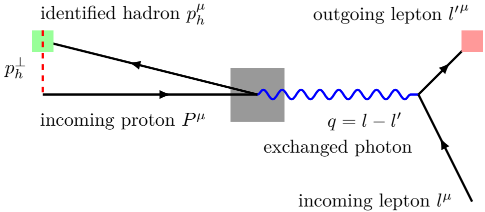
Jefferson Lab
EXPLORING THE NATURE OF MATTER

Semi inclusive deep inelastic scattering (SIDIS)

Lab frame

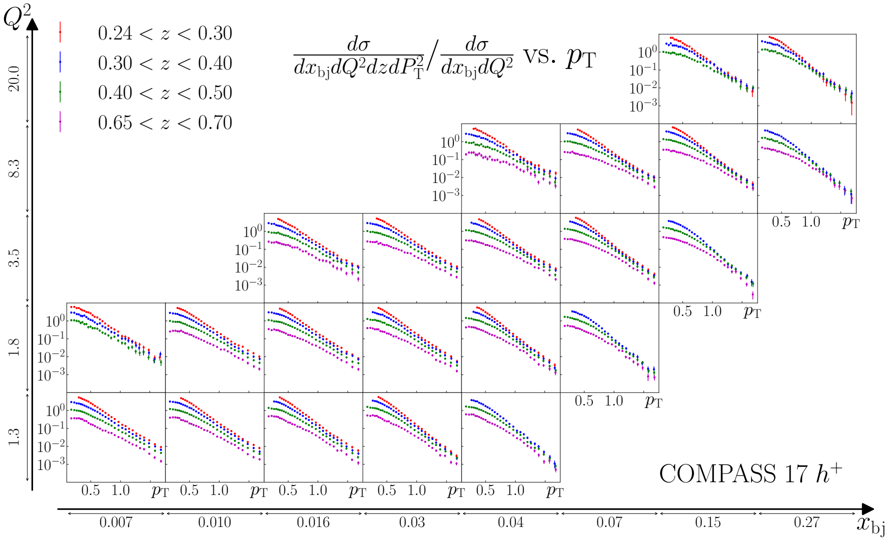


Breit frame



- Process is dominated by one photon exchange with large virtuality $Q^2 \gg \lambda_{\mathrm{QCD}}$
- In the Breit frame the proton and the photon has zero transverse momentum.
- The detected hadron has $p_h^{\perp}$ relative to proton-photon axis
- **Key question** :
  How is $p_h^{\perp}$ generated at short distances?

SIDIS data: $l + d \to l' + h^+ + X$

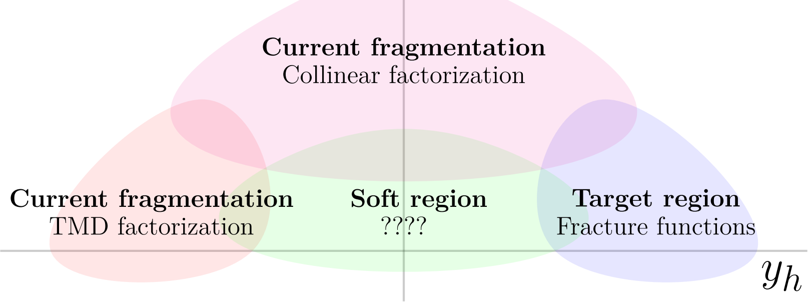


- JLab 12 data have measurements up to $p_T \sim 1.4$

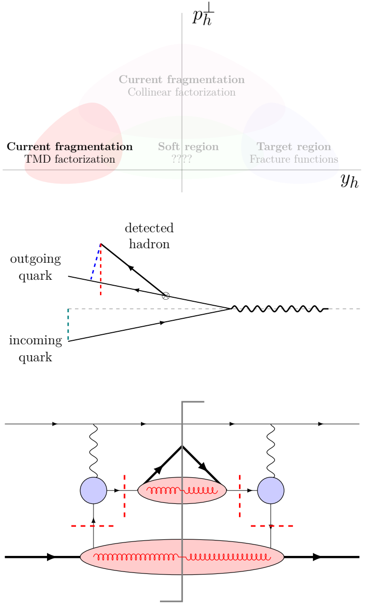
Kinematic regions

- Detected hadron's rapidity $y_h = \frac{1}{2} \ln \left(\frac{p_h^+}{p_h^-} \right)$
- Current region $p_h^- \gg p_h^+$
- Target region $p_h^- \ll p_h^+$
- Different regions are described by different theoretical approximations

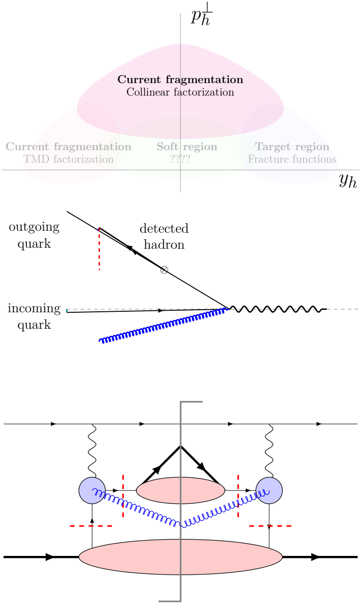
- The higher the c.o.m energy, the larger the separation among the regions
- In this talk I will focus on the large p_T current region



Small transverse momentum



Large transverse momentum



Combining large and small $p_h^\perp$ approximation

- SIDIS reaction

$$l + P \to l' + p_h + X$$

- SIDIS invariants

$$q = l - l' \qquad Q^2 = -q^2$$

$$x = \frac{Q^2}{2P \cdot q} \qquad z = \frac{P \cdot p_h}{P \cdot q}$$

$$q_T = p_h^\perp / z$$

- SIDIS cross section

$$\Gamma \equiv \frac{d\sigma}{dx dQ^2 dz dq_T}$$

- The W+Y construction

$$\begin{aligned}\Gamma =& \Gamma \\ =& \mathbf{T}_{\rm TMD}\Gamma + [\Gamma - \mathbf{T}_{\rm TMD}\Gamma] \\ =& \underbrace{\mathbf{T}_{\rm TMD}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\rm coll}\left[\Gamma - \mathbf{T}_{\rm TMD}\Gamma\right]}_{\mathbf{Y}} \\ &+ \mathcal{O}(m^2/Q^2)\Gamma\end{aligned}$$

- Nomenclature

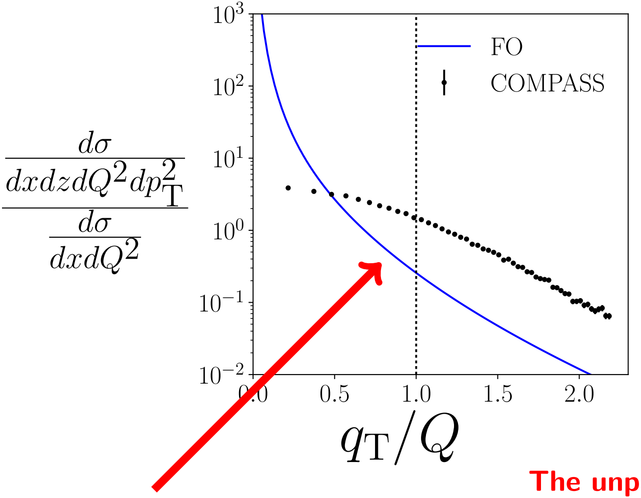
$$\mathrm{W} \equiv \mathbf{T}_{\rm TMD}\Gamma$$

$$\mathrm{FO} \equiv \mathbf{T}_{\rm coll}\Gamma$$

$$\mathrm{ASY} \equiv \mathbf{T}_{\rm coll}\mathbf{T}_{\rm TMD}\Gamma$$

$$\mathrm{Y} \equiv \mathrm{FO} - \mathrm{ASY}$$

Does it work?



- Kinematics

  $Q^2 = 1.92\ \text{GeV}^2$

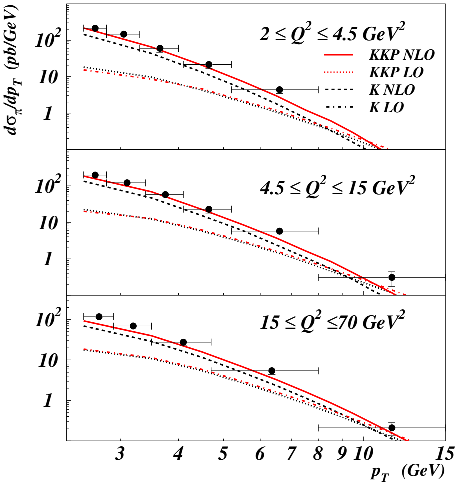
  $x = 0.0318$

  $z = 0.375$

- Need order α_S^2 or beyond?
- Issues with fragmentation functions?
- Subleading power corrections?

The unpolarized SIDIS cross sections needs to be ready to interpret upcoming TMD data from JLab 12

order α_S^2 corrections to FO



Daleo,et al. (2005)
PRD.71.034013

- There are strong indications that order α_S^2 corrections are very important
- An order of magnitude of corrections at small p_T.
- As a sanity check, we need to have an independent calculation

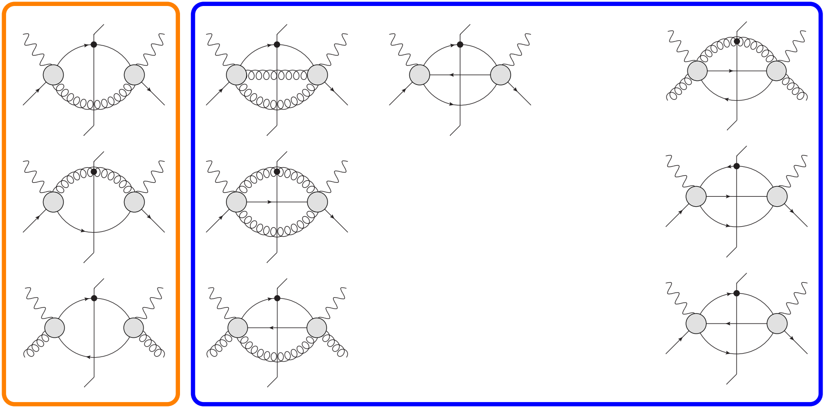
Our setup for $O(\alpha_S^2)$ contribution

$$W^{\mu\nu}(P,q,P_H) = \int_{x-}^{1+} \frac{d\xi}{\xi} \int_{z-}^{1+} \frac{d\zeta}{\zeta^2} \hat{W}_{ij}^{\mu\nu}(q, x/\xi, z/\zeta) f_{i/P}(\xi) d_{H/j}(\zeta)$$

$$\begin{aligned}\{\mathrm{P}_g^{\mu\nu}\hat{W}_{\mu\nu}^{(N)};\mathrm{P}_{PP}^{\mu\nu}\hat{W}_{\mu\nu}^{(N)}\} &\equiv \frac{1}{(2\pi)^4}\int \{|M_g^{2\to N}|^2;|M_{pp}^{2\to N}|^2\}\,\mathrm{d}\Pi^{(N)} - \text{Subtractions} \\ &\equiv \{\mathrm{P}_g^{\mu\nu}\hat{W}_{\mu\nu}^{(N)};\mathrm{P}_{PP}^{\mu\nu}\hat{W}_{\mu\nu}^{(N)}\}_{\text{unsub}} - \text{Subtractions}\end{aligned}$$

- ✓ Compute $2 \to 2$ virtual graphs (Passarino-Veltman)
- ✓ Compute $2 \to 3$ real graphs
- ✓ Integrate 3-body PS analytically using dim reg
- ✓ Cancel double and single IR poles

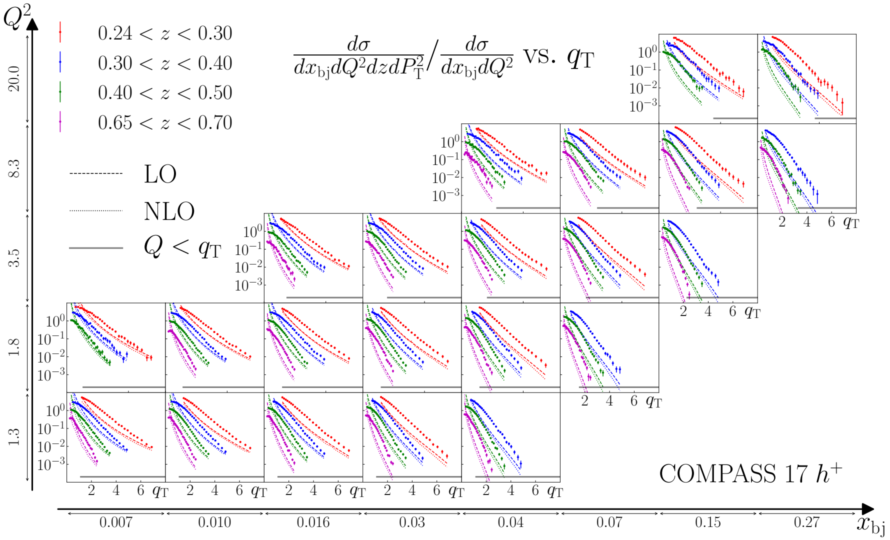
Our setup for $O(\alpha_S^2)$ contribution



Born/Virtual   Real

- Dots indicates the fragmenting parton

Preliminary results



- The $O(\alpha_S^2)$ seems to not improve the theory prediction

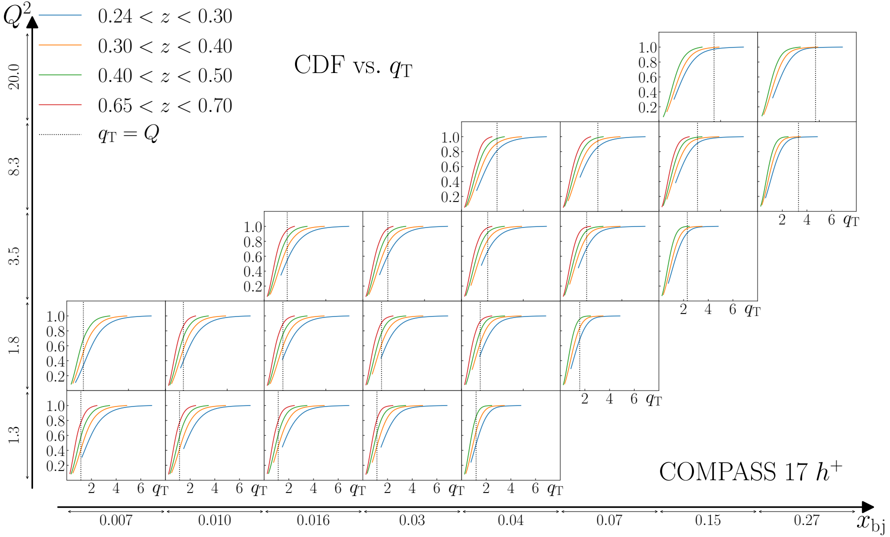
Question

- How important is the P_{T} tail for the integrated SIDIS multiplicities?

- Consider the cumulative distribution function (CDF)

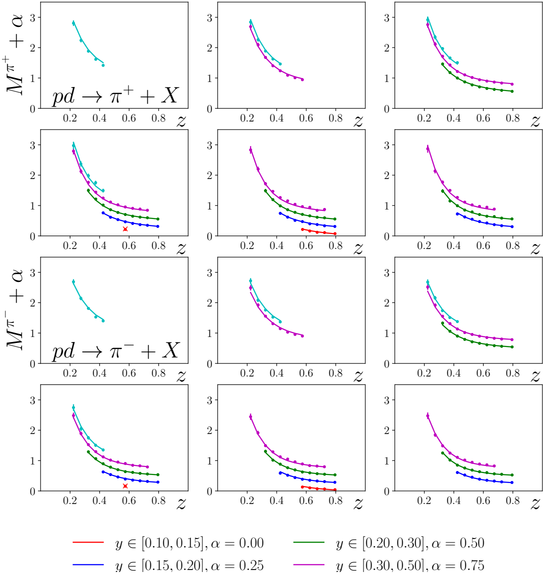
$$\mathrm{CDF} = \int_0^{P_{\mathrm{T}}^2} dP_{\mathrm{T}}^2 \frac{1}{M(x,z)} \frac{dM}{dP_{\mathrm{T}}^2}(x,z,P_{\mathrm{T}}^2)$$

From q_T differential to q_T integrated

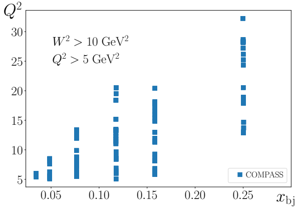


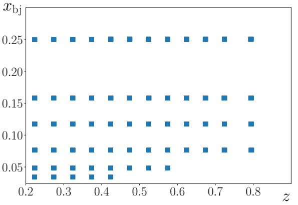
- q_T integrated multiplicity at small x and small z is dominated by the perturbative tail → good news for JLab12

q_T integrated SIDIS data



- α is use to offset the data
- The q_T integrated spectrum is successfully described in collinear factorization at NLO



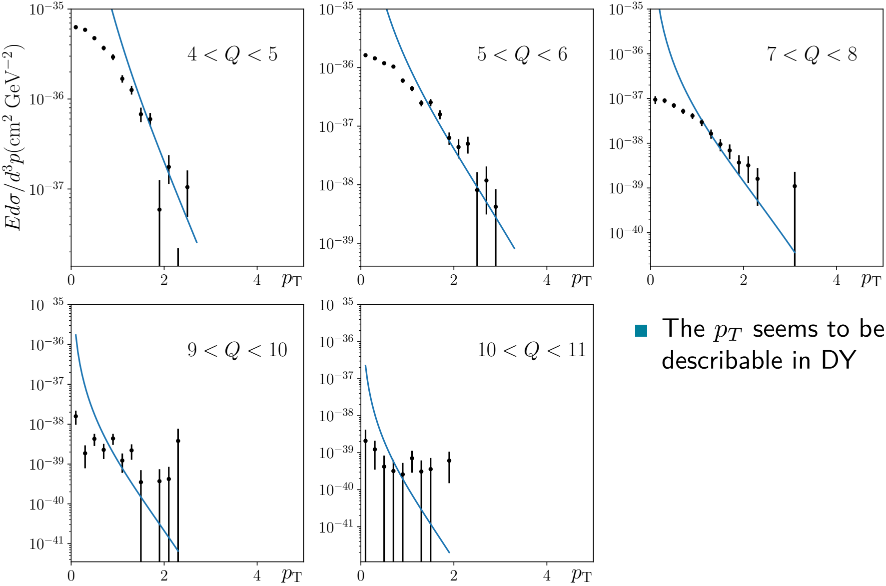


Question

- How does the p_T tail described by FO in DY?

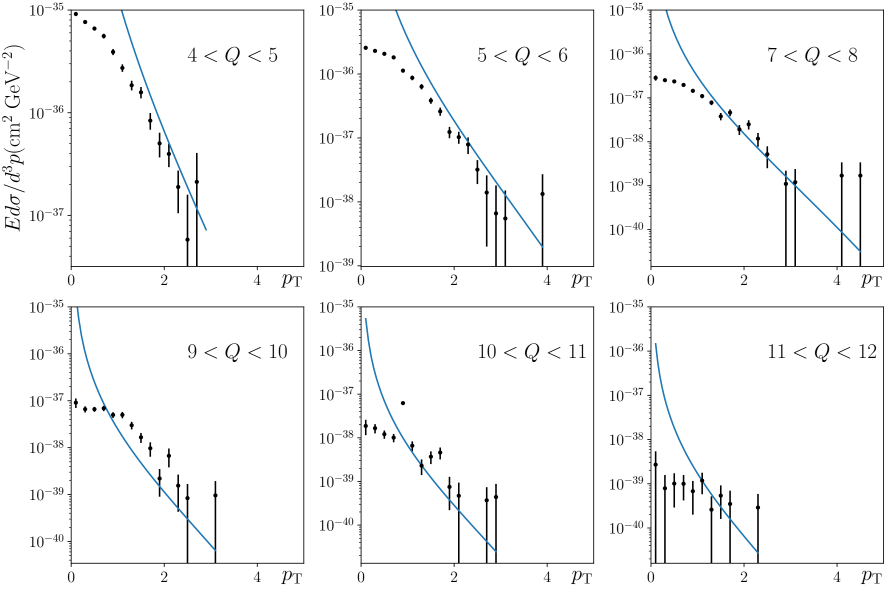
- Consider low energy DY data from FNAL E288 experiment

$p + \text{nucleon} \to l + l' \ \sqrt{s} = 20\text{GeV}$

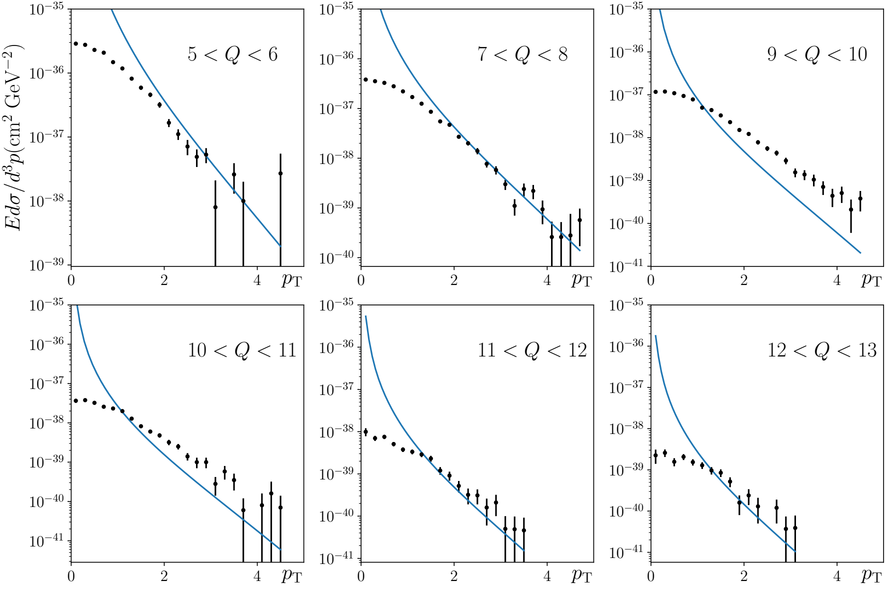


- The p_T seems to be describable in DY

$p + \text{nucleon} \to l + l' \ \sqrt{s} = 24\text{GeV}$



$p + \text{nucleon} \to l + l' \;\; \sqrt{s} = 28\text{GeV}$



Summary and outlook

$$\frac{d\sigma}{dx\ dy\ d\Psi\ dz\ d\phi_h\ dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sum_{i=1}^{18} F_i(x,z,Q^2,P_{hT}^2)\beta_i$$

F_i	Standard label	β_i
F_1	$F_{UU,T}$	1
F_2	$F_{UU,L}$	ε
F_3	F_{LL}	$S_{\|\|}\lambda_e\sqrt{1-\varepsilon^2}$
F_4	$F_{UT}^{\sin(\phi_h+\phi_S)}$	$\|\vec{S}_\perp\|\varepsilon\sin(\phi_h+\phi_S)$
F_5	$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\sin(\phi_h-\phi_S)$
F_6	$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\varepsilon\sin(\phi_h-\phi_S)$
F_7	$F_{UU}^{\cos 2\phi_h}$	$\varepsilon\ \cos(2\phi_h)$
F_8	$F_{UT}^{\sin(3\phi_h-\psi_S)}$	$\|\vec{S}_\perp\|\varepsilon\sin(3\phi_h-\phi_S)$
F_9	$F_{LT}^{\cos(\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\lambda_e\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)$
F_{10}	$F_{UL}^{\sin\ 2\phi_h}$	$S_{\|\|}\varepsilon\sin(2\phi_h)$
F_{11}	$F_{LT}^{\cos\phi_S}$	$\|\vec{S}_\perp\|\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S$
F_{12}	$F_{LL}^{\cos\phi_h}$	$S_{\|\|}\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h$
F_{13}	$F_{LT}^{\cos(2\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)$
F_{14}	$F_{UL}^{\sin\phi_h}$	$S_{\|\|}\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h$
F_{15}	$F_{LU}^{\sin\phi_h}$	$\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h$
F_{16}	$F_{UU}^{\cos\phi_h}$	$\sqrt{2\varepsilon(1+\varepsilon)}\ \cos\phi_h$
F_{17}	$F_{UT}^{\sin\phi_S}$	$\|\vec{S}_\perp\|\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S$
F_{18}	$F_{UT}^{\sin(2\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)$

- I discussed the current status of F_{UU}
- At present, there is no successful description of data using W+Y
- There are many results where the success is shown by restricting the q_T range and avoiding the inclusion of Y
- For low energies DY the FO seems to work
- The key question: how p_T is generated at low energies is still a challenging question