Leptonic Current Structure and Azimuthal Asymmetry in Deeply Inelastic Scattering

Hong-Fei Zhang

@ QWG2017

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Based On

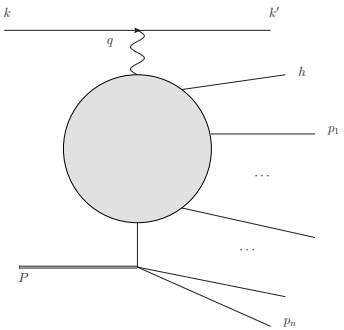
- HFZ and Zhan Sun, *The leptonic current structure and azimuthal asymmetry in deeply inelastic scattering*, **Physical Review D96, 034002**
- Zhan Sun and HFZ, *QCD leading order study of the J/ψ leptoproduction at HERA within the nonrelativistic QCD framework*, **European Physical Journal C77, 744**
- Zhan Sun and HFZ, *QCD corrections to the color-singlet J/ψ production in deeply inelastic scattering at HERA*, **Physical Review D96, 091502**
- Zhan Sun and HFZ, **Malt@FDC**

Background

Deeply Inelastic Scattering (DIS)

- 1990 Nobel Prize: Jerome Friedman, Henry Kendall and Richard Edward Taylor
- Probe to the structure of hadrons and photons
- Parton model
- Parton distribution functions
- Q^2 scaling
- Multiple distributions

Cross Section



- Process: $ep \to h + X$

$$\mathrm{d}\sigma = \frac{1}{4P\cdot k}\frac{1}{N_c N_s} L_{\mu\nu}\frac{1}{Q^4} H^{\mu\nu}\mathrm{d}\Phi'\mathrm{d}\Phi_H$$

- $L_{\mu\nu}$: Leptonic tensor, $H^{\mu\nu}$: Hadronic tensor

$$L_{\mu\nu} = 8\pi Q^2[(-g_{\mu\nu} - \frac{q_\mu q_\nu}{Q^2}) + \frac{(2k-q)_\mu (2k-q)_\nu}{Q^2}]$$

- The conventional leptonic tensor

$$L_{\mu\nu} = 8\pi\alpha Q^2[\frac{2-2y+y^2}{y^2}(-g_{\mu\nu} - \frac{q_\mu q_\nu}{Q^2}) + \frac{6-6y+y^2}{y^2}\frac{1}{Q^2}(q_\mu + \frac{Q^2}{P\cdot q}p_\mu)(q_\nu + \frac{Q^2}{P\cdot q}p_\nu)]$$

The Conventional Leptonic Tensor

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The Conventional Leptonic Tensor

- The leptonic tensor: wrong when some physical quantities are measured
- Wrong results
  - Highly cited papers
  - Event generators!!!

Partial List of Papers using the Conventional Leptonic Tensor

- Catani, Ciafaloni and Hautmann. *HIGH ENERGY FACTORIZATION AND SMALL-x HEAVY FLAVOUR PRODUCTION*. Nucl.Phys.B.366.135, 1004 times
- Jung and Salam. *Hadronic final state predictions from CCFM: The hadron level Monte Carlo generator CASCADE*. Eur.Phys.J.C.19.351, 254 times
- Jung. *The CCFM Monte Carlo Generator CASCADE*. Comput.Phys.Commun.143.100, 225 times
- Jung and *etc.* *The CCFM Monte Carlo generator CASCADE Version 2.2.03*. Eur.Phys.J.C.70.1237, 139
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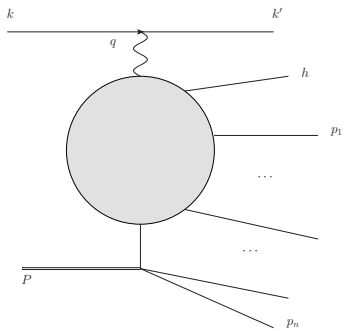
The Leptonic Tensor

Cross Section



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$$\mathrm{d}\sigma = \frac{1}{4P\cdot k}\frac{1}{N_c N_s} L_{\mu\nu}\frac{1}{Q^4} H^{\mu\nu}\mathrm{d}\Phi'\mathrm{d}\Phi_H$$

- $L_{\mu\nu}$: Leptonic tensor, $H^{\mu\nu}$: Hadronic tensor
- $Q^2 = -q^2$

$$\mathrm{d}\Phi' = \frac{\mathrm{d}^3k'}{(2\pi)^3 2k'_0}$$
$$\mathrm{d}\Phi_H = \frac{\mathrm{d}^3h}{(2\pi)^3 2h_0}(2\pi)^4\delta^4\left(P+q-h-\sum_i p_i\right)\prod_i \frac{\mathrm{d}^3p_i}{(2\pi)^3 2p_{i0}} \equiv \mathrm{d}\Phi_h \mathrm{d}\Phi_X$$

Inclusive DIS Analysis

$$W^{\mu\nu}(P,q) \equiv \int H^{\mu\nu}(P,q,h,p_1,\ldots,p_n)\mathrm{d}\Phi_H = (-g^{\mu\nu} - \frac{q^\mu q^\nu}{Q^2})F_1(x,Q^2) + \frac{1}{Q^2}(q^\mu + \frac{Q^2}{P\cdot q}P^\mu)(q^\nu + \frac{Q^2}{P\cdot q}P^\nu)\frac{1}{2x}F_2(x,Q^2)$$

$$L_{\mu\nu} = 8\pi Q^2[(-g_{\mu\nu} - \frac{q_\mu q_\nu}{Q^2}) + \frac{(2k-q)_\mu(2k-q)_\nu}{Q^2}]$$

$$L_{\mu\nu}W^{\mu\nu} = 16\pi Q^2[F_1(x,Q^2) + \frac{1-y}{xy^2}F_2(x,Q^2)]$$

$$L_{\mu\nu} = 8\pi\alpha Q^2[\frac{2-2y+y^2}{y^2}(-g_{\mu\nu} - \frac{q_\mu q_\nu}{Q^2}) + \frac{6-6y+y^2}{y^2}\frac{1}{Q^2}(q_\mu + \frac{Q^2}{P\cdot q}p_\mu)(q_\nu + \frac{Q^2}{P\cdot q}p_\nu)]$$

Semiinclusive DIS (SIDIS)

- When the final state h is observed

$$W_h^{\mu\nu}(P,q,h) \equiv \int H^{\mu\nu}(P,q,h,p_1,\ldots,p_n)\mathrm{d}\Phi_X$$

- It depends on P, q and h

$$W_h^{\mu\nu} \sim -g^{\mu\nu} - \frac{q^\mu q^\nu}{Q^2},\ P^\mu,\ q^\mu,\ h^\mu,\ P^\nu,\ q^\nu,\ h^\nu$$

- The current conservation

$$q_\mu W_h^{\mu\nu} = q_\nu L^{\mu\nu} = 0$$

- We need to build current-conserving vectors and tensors

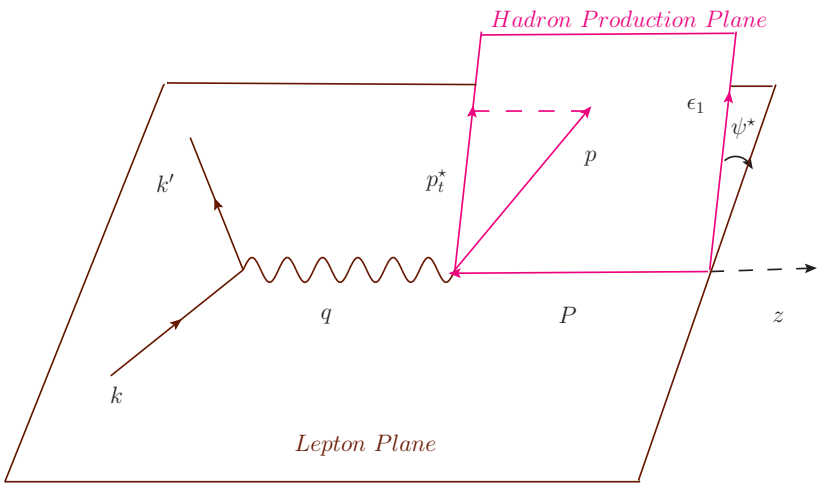
Independent Vectors and Tensors

$$\epsilon^{\mu\nu} = -g^{\mu\nu} - \frac{q^\mu q^\nu}{Q^2},\ \epsilon_L = \frac{1}{Q}(q + \frac{Q^2}{P\cdot q}P),\ \epsilon_1 = \frac{1}{p_t^\star}(h - \rho P - zq)$$

$$z = \frac{P\cdot h}{P\cdot q},\ \rho = \frac{h\cdot q + zQ^2}{P\cdot q}$$

$$q\cdot\epsilon_L = q\cdot\epsilon_1 = \epsilon_L\cdot\epsilon_1 = 0,\ \epsilon_L^2 = 1,\ \epsilon_1^2 = -1$$

- $\gamma^\star P$ rest frame



Hadronic Tensor in SIDIS

$$W_h^{\mu\nu} \sim \epsilon^{\mu\nu},\ \epsilon_L^\mu \epsilon_L^\nu,\ \epsilon_1^\mu \epsilon_1^\nu,\ \epsilon_L^\mu \epsilon_1^\nu + \epsilon_1^\mu \epsilon_L^\nu$$

$$W_h^{\mu\nu} = W_1 \epsilon^{\mu\nu} + W_2 \epsilon_L^\mu \epsilon_L^\nu + W_3(\epsilon_L^\mu \epsilon_1^\nu + \epsilon_1^\mu \epsilon_L^\nu) + W_4 \epsilon_1^\mu \epsilon_1^\nu$$

$$L_{\mu\nu} W_h^{\mu\nu} = 8\pi\alpha Q^2 \{2W_1 + \frac{4(1-y)}{y^2} W_2 + \frac{4(2-y)}{y^2}\sqrt{1-y}\cos\psi^\star W_3 + [1 + \frac{2(1-y)}{y^2} + \frac{2(1-y)}{y^2}\cos(2\psi^\star)] W_4\}$$

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- Is the conventional leptonic tensor correct?

$$L_{\mu\nu} = 8\pi\alpha Q^2[\frac{2-2y+y^2}{y^2}(-g_{\mu\nu} - \frac{q_\mu q_\nu}{Q^2}) + \frac{6-6y+y^2}{y^2}\frac{1}{Q^2}(q_\mu + \frac{Q^2}{P\cdot q}p_\mu)(q_\nu + \frac{Q^2}{P\cdot q}p_\nu)]???$$

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- Azimuthal dependent terms missing!!!

Leptonic Tensor in SIDIS

$$L^{\mu\nu} = 8\pi Q^2[A_1\epsilon^{\mu\nu} + A_2\epsilon_L^\mu\epsilon_L^\nu + A_3(\epsilon_L^\mu\epsilon_1^\nu + \epsilon_1^\mu\epsilon_L^\nu) + A_4\epsilon_1^\mu\epsilon_1^\nu]$$

$$A_1 = 1 + \frac{2(1-y)}{y^2} - \frac{2(1-y)}{y^2}\cos(2\psi^\star)$$
$$A_2 = 1 + \frac{6(1-y)}{y^2} - \frac{2(1-y)}{y^2}\cos(2\psi^\star)$$
$$A_3 = \frac{2(2-y)}{y^2}\sqrt{1-y}\cos(\psi^\star)$$
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- Integrating over $\psi^\star$, one reproduces the conventional leptonic tensor

Leptonic Tensor in SIDIS

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- Integrating over $\psi^\star$, one reproduces the conventional leptonic tensor
- Only when W_i are independent of $\psi^\star$

Cross Section Structure

- Define w_i

$$
\begin{aligned}
w_1 &= \epsilon_{\mu\nu} W_h^{\mu\nu} \\
w_2 &= \epsilon_{L\mu} \epsilon_{L\nu} W_h^{\mu\nu} \\
w_3 &= (\epsilon_{L\mu} \epsilon_{1\nu} + \epsilon_{1\mu} \epsilon_{L\nu}) W_h^{\mu\nu} \\
w_4 &= \epsilon_{1\mu} \epsilon_{1\nu} W_h^{\mu\nu}
\end{aligned}
$$

- Cross section

$$
\mathrm{d}\sigma = \frac{\alpha}{256\pi^5 N_s N_c S Q^2 z} \sum_{i=1}^{4} A_i w_i \mathrm{d}Q^2 \mathrm{d}y \mathrm{d}p_t^{\star 2} \mathrm{d}z \mathrm{d}\psi^\star
$$

$$
A_i = A_i(y, \psi^\star),\ w_i = w_i(Q^2, y, z, p_t^\star)
$$

Laboratory Frame

$$p_t^2 = p_t^{\star 2} + z^2 Q^2 (1-y) - 2zQp_t^\star \sqrt{1-y}\cos(\psi^\star)$$

- When p_t is specified, $p_t^\star$ and $\psi^\star$ are constrained in a curved surface
- Replace $\mathrm{d}p_t^{\star 2}$ by $\mathrm{d}p_t^2$, multiplying the Jacobian

$$J = \left|\frac{\partial p_t^{\star 2}}{\partial p_t^2}\right| = \frac{p_t^\star}{\sqrt{p_t^2 - (1-y)z^2 Q^2 \sin^2\psi^\star}}$$

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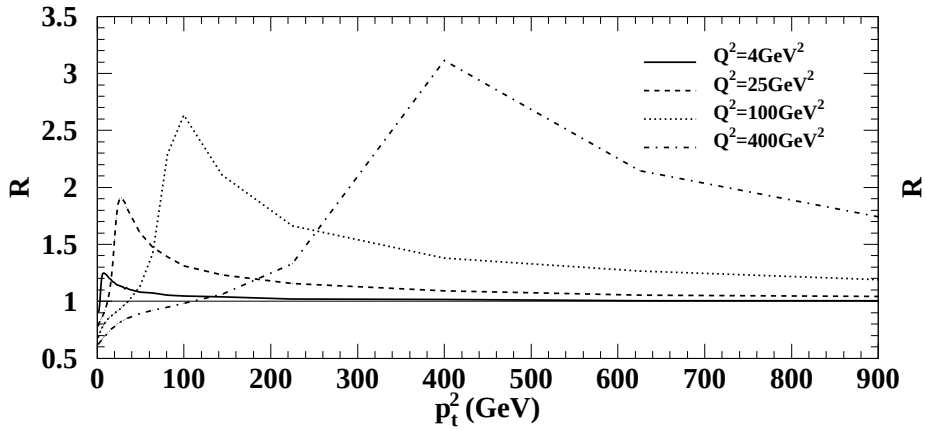
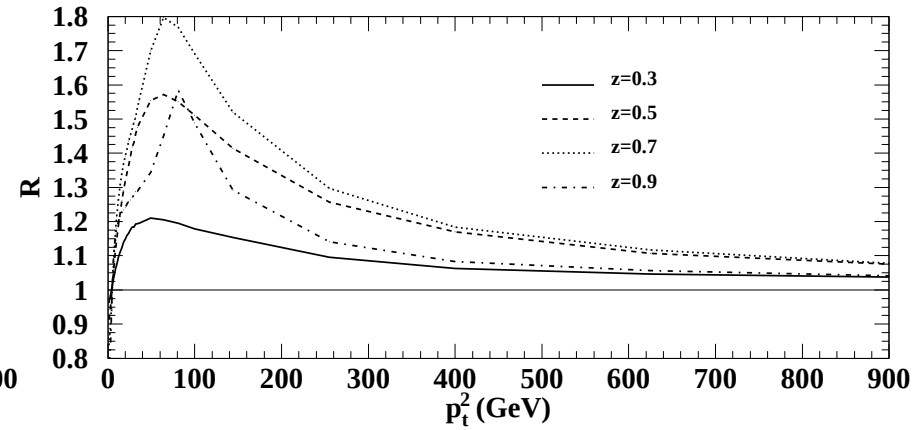
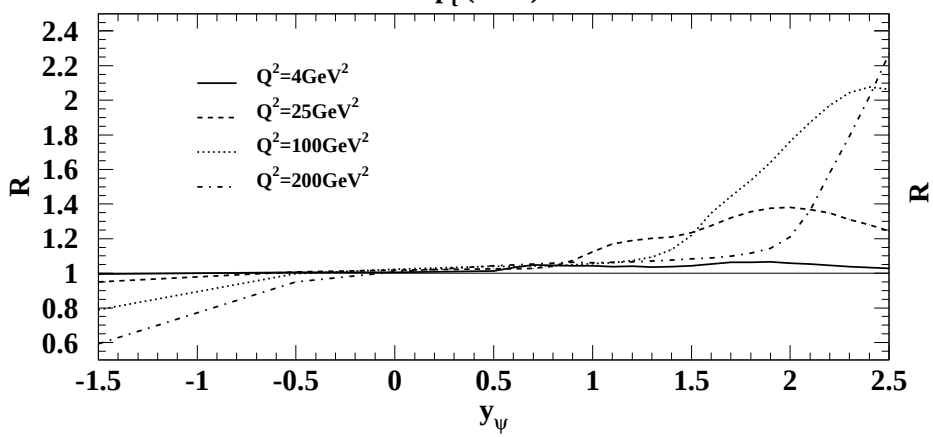
- Dependent on $\psi^\star$
- The cosine terms in A_i do not vanish after integration over $\psi^\star$
- The conventional leptonic tensor is WRONG

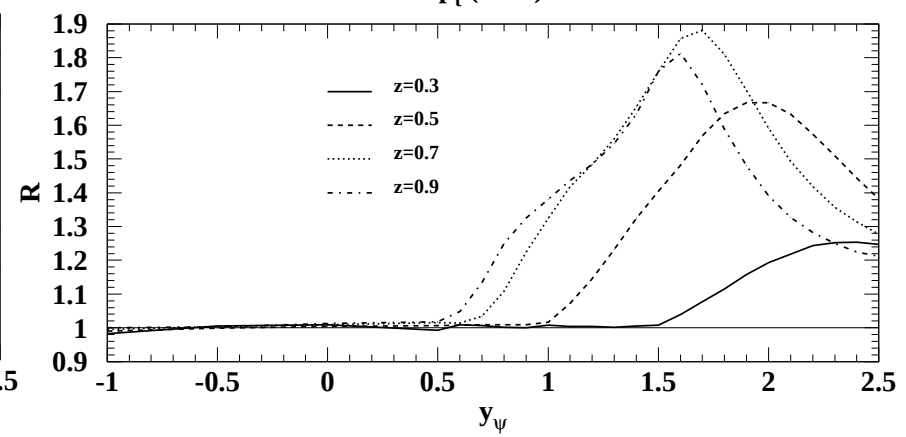
Comparison between the Right and the Wrong

- R is the ratio of the wrong results to the correct ones









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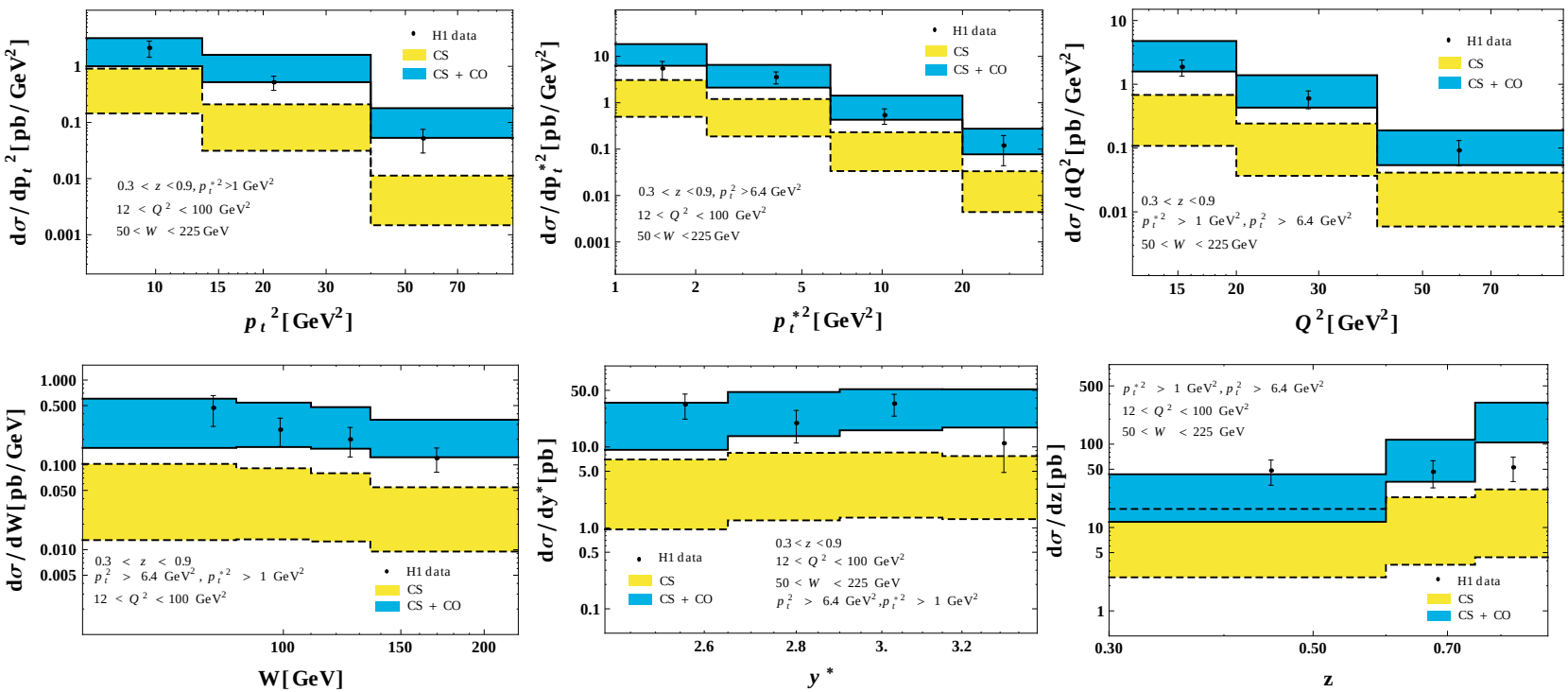
Impact

- Many phenomenological studies should be redone!
- Many event generators should be revisited!
- Experimental data should be reanalyzed!
- $F_2^{c\bar{c}}$ puzzle should be revisited!
- Many PDFs should be renewed!

J/ψ Production in DIS

DIS at LO[1]

- CS: below data
- NRQCD: good agreement



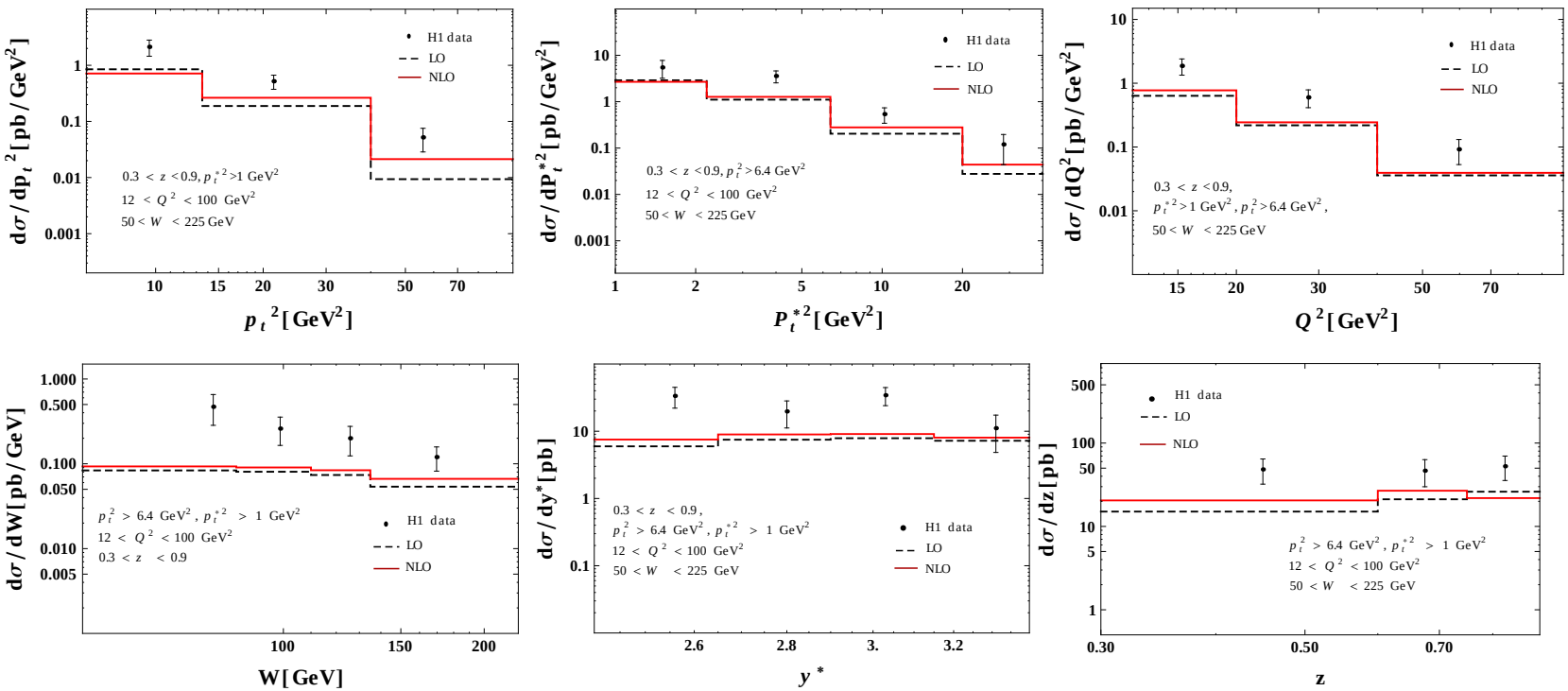
[1] Zhan Sun and HFZ, arxiv:1702.02097

Progress

- 10 years ago
  - J. Campbell, F. Maltoni, F. Tramontano. *QCD Corrections to J/ψ and Υ Production at Hadron Colliders.* **Physical Review Letters 98, 252002** (2007)
  - P. Artoisenet, J. Campbell, F. Maltoni, F. Tramontano. *J/ψ Production at HERA.* **Physical Review Letters 102, 142001** (2009)
- 2017
  - Zhan Sun and Hong-Fei Zhang. *QCD corrections to the color-singlet J/ψ production in deeply inelastic scattering at HERA.* **Physical Review D96, 091502 (Rapid Communication)**

Color-singlet at NLO

- QCD corrections are minor, cannot describe data



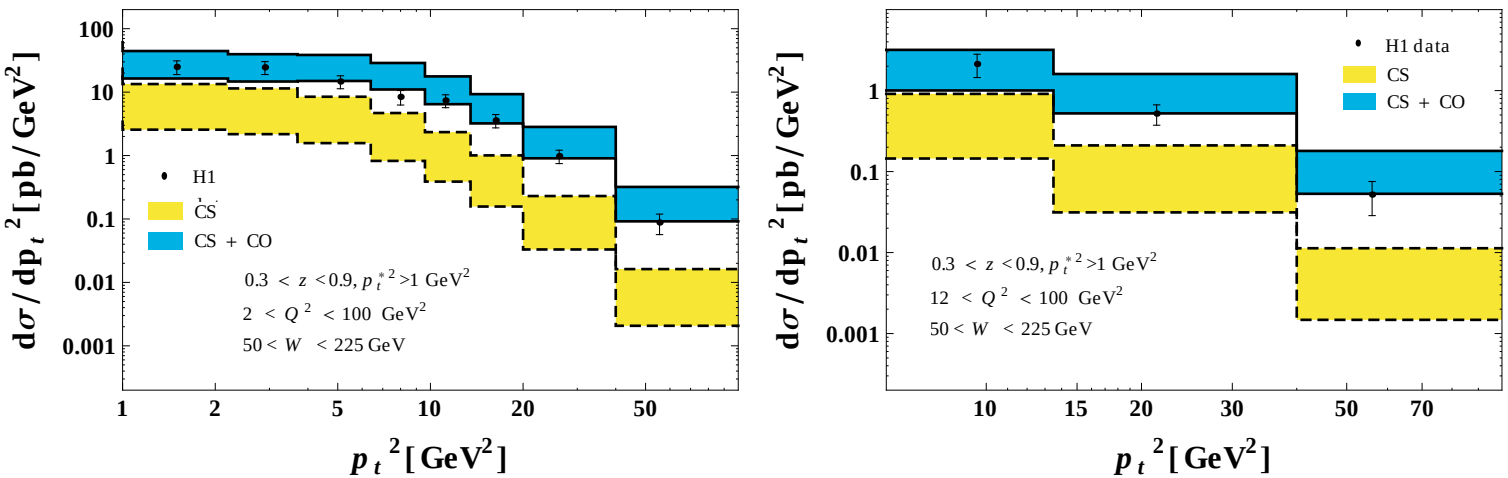
Conclusion

- Measuring p_t or rapidity in laboratory frame, structure functions, F_1, F_2 and F_3 are not sufficient to describe the cross sections.
- QCD corrections to CS J/ψ production in DIS in low p_t region is minor.

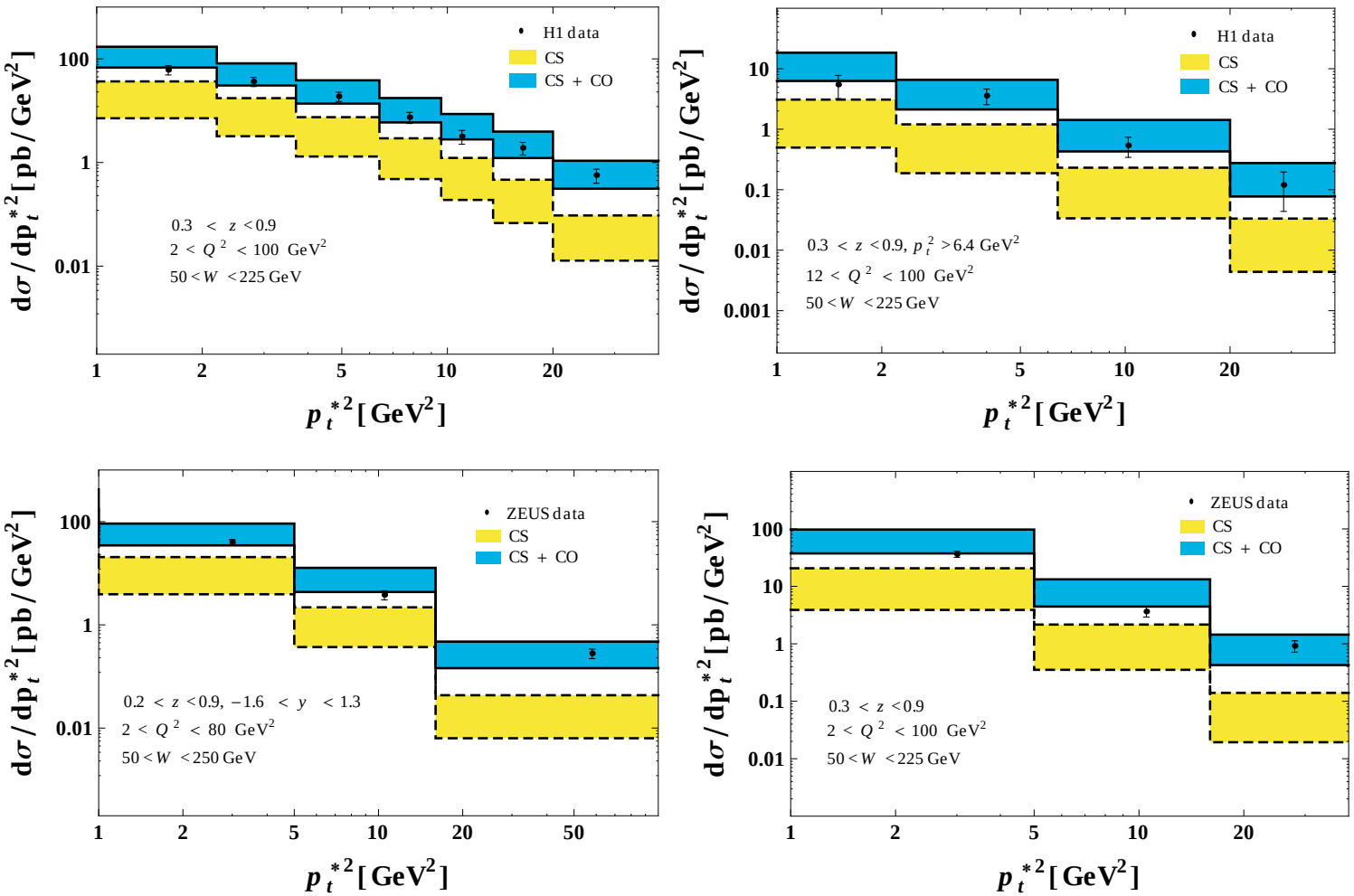
Thanks!

Backup

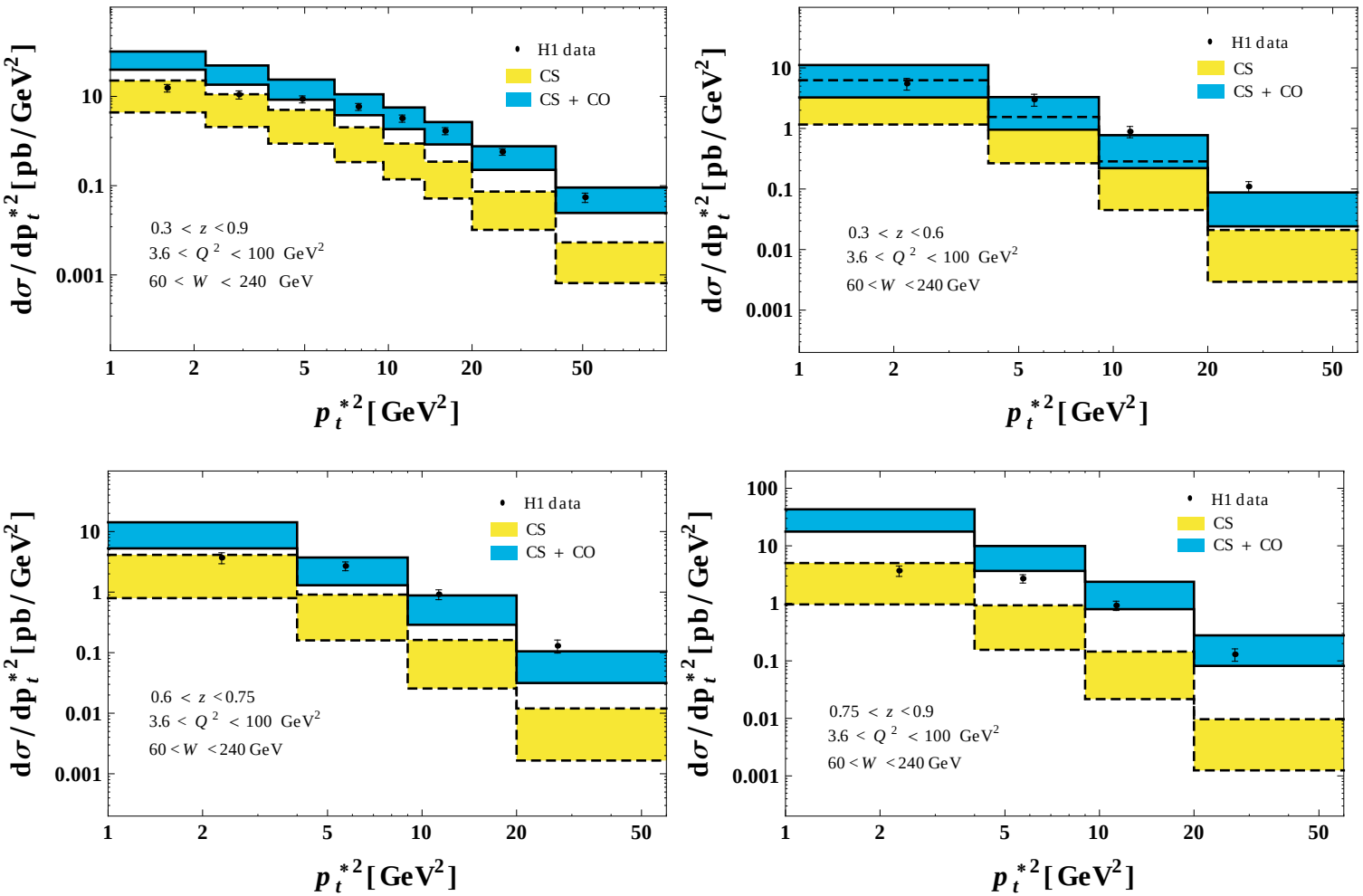
DIS at LO (p_t^2 Distributions)



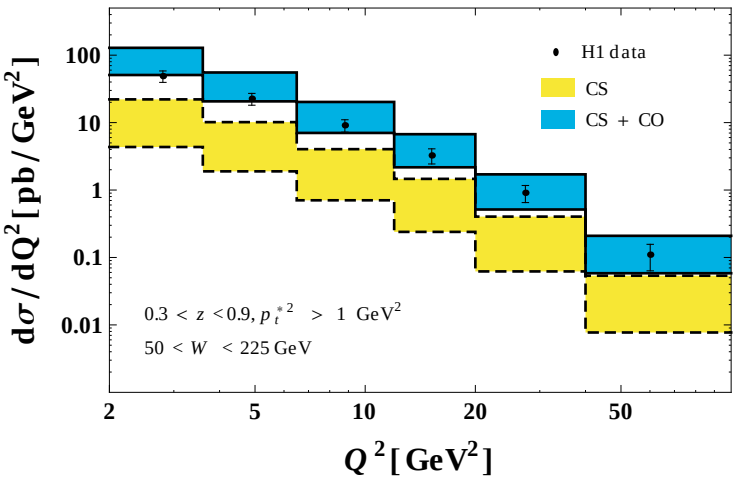
DIS at LO ($p_t^{\star 2}$ Distributions I)

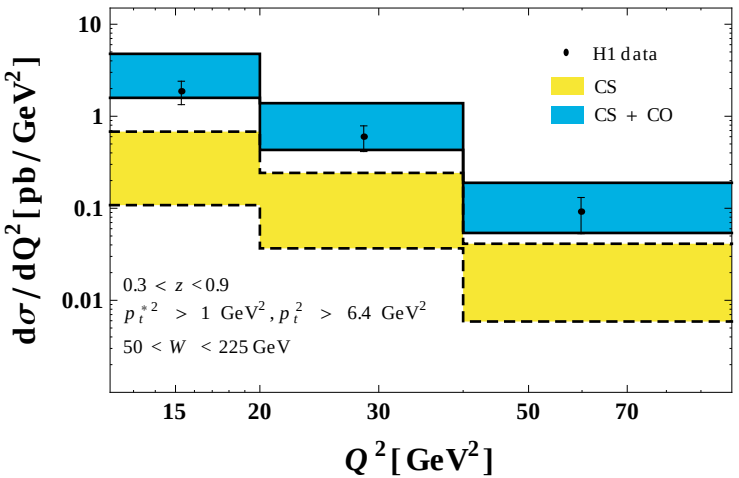


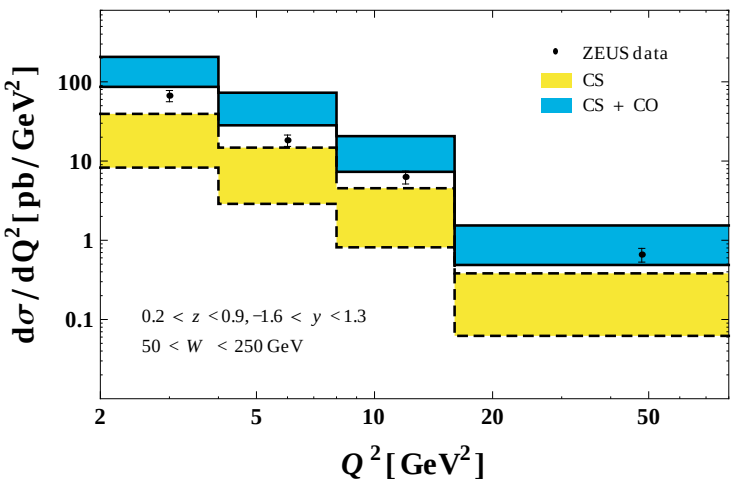
DIS at LO ($p_t^{\star 2}$ Distributions II)

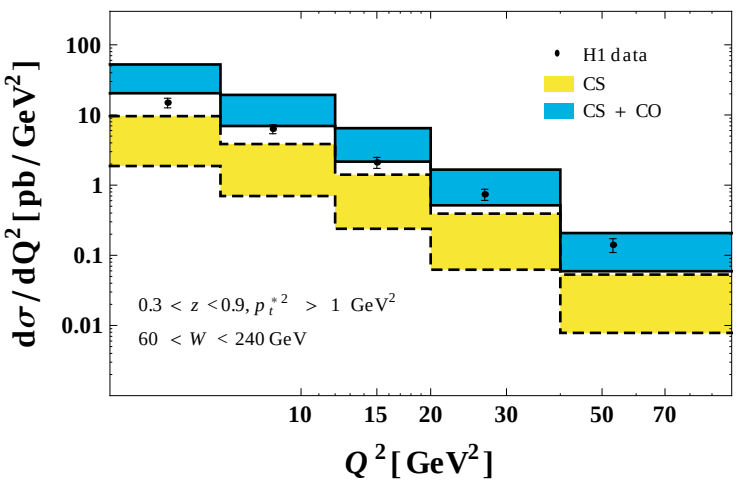


DIS at LO (Q^2 Distributions)

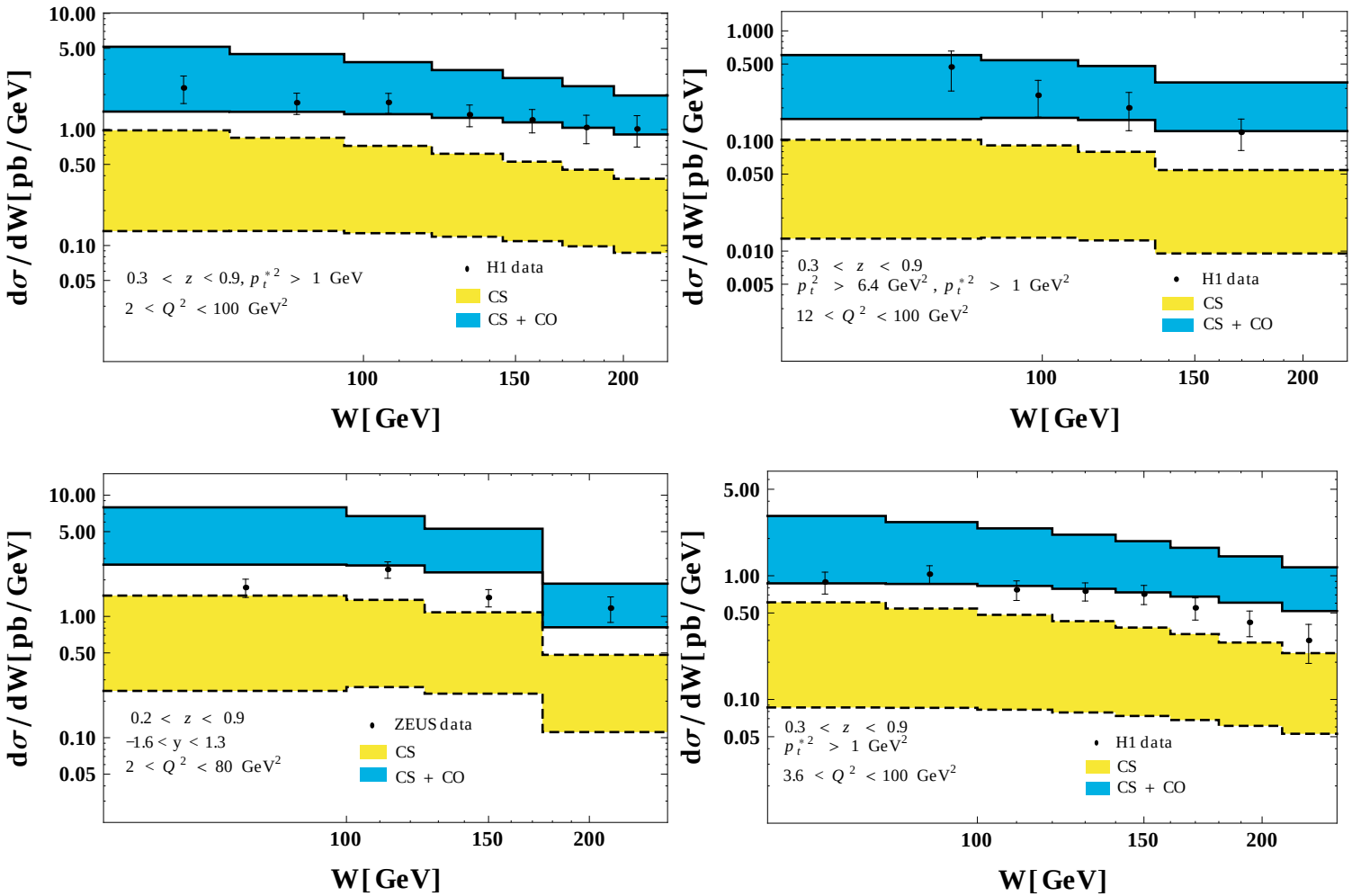




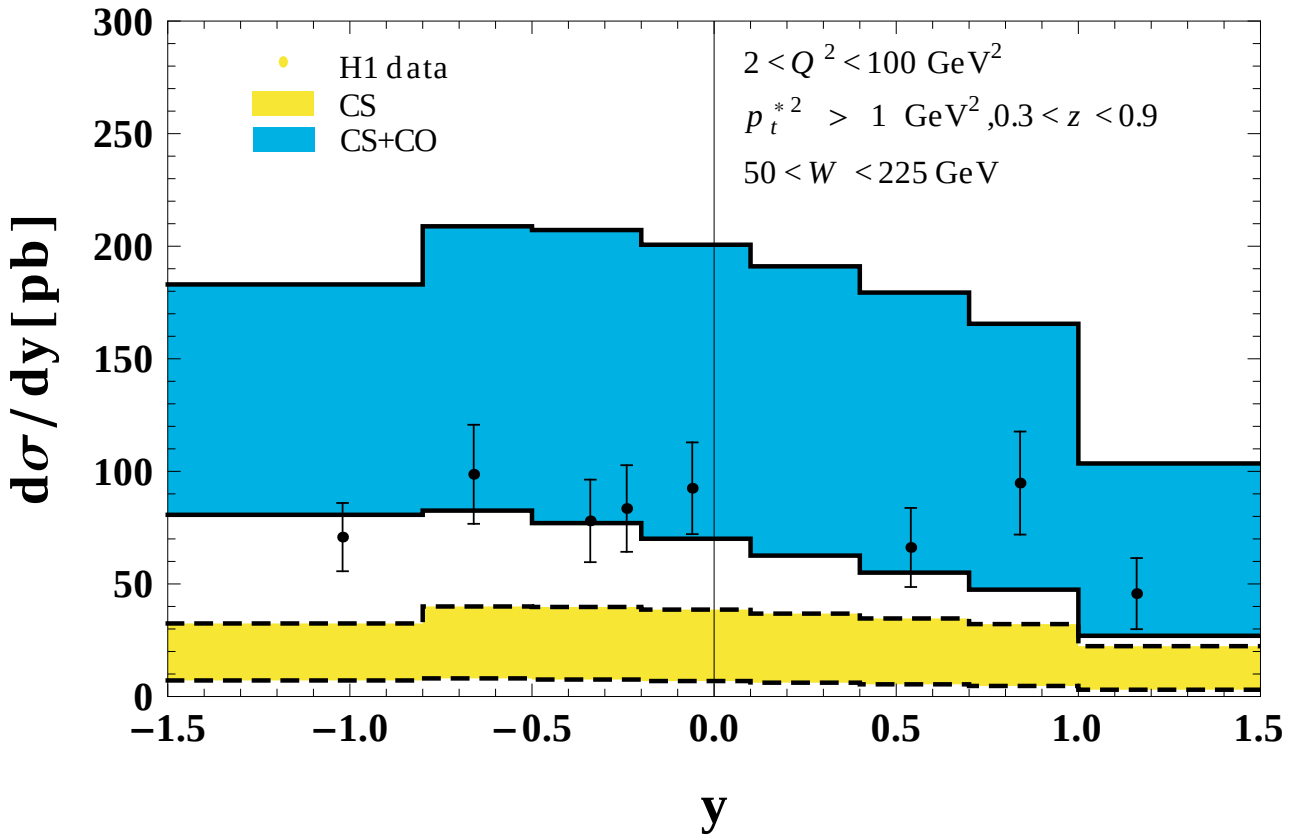




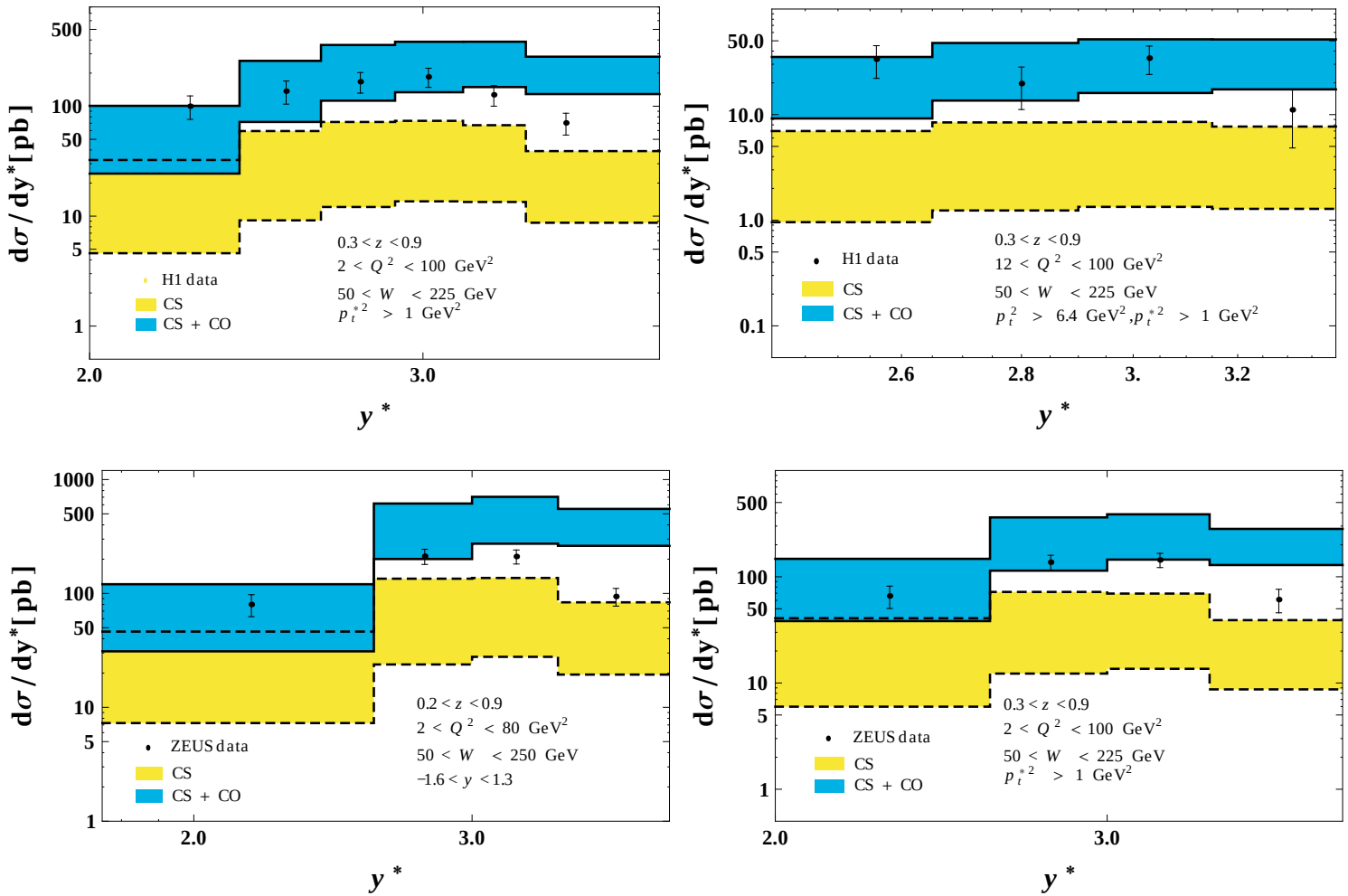
DIS at LO (W Distributions)



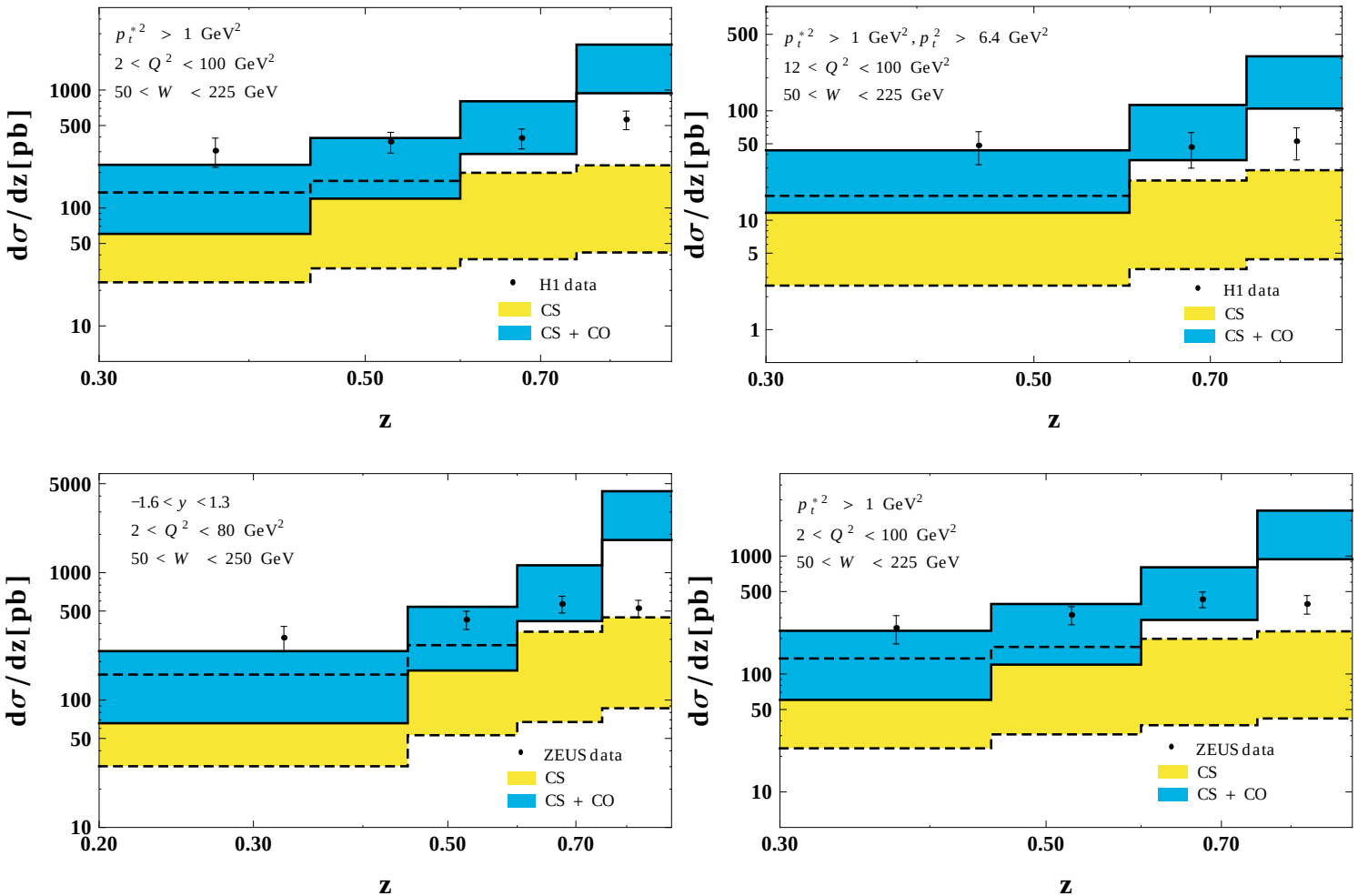
DIS at LO (y_ψ Distributions)



DIS at LO ($y_\psi^\star$ Distributions)



DIS at LO (z Distributions I)



DIS at LO (z Distributions II)