The J/ψ Production in Deeply Inelastic Scattering at HERA

Hong-Fei Zhang (in collaboration with Zhan Sun)

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Based On

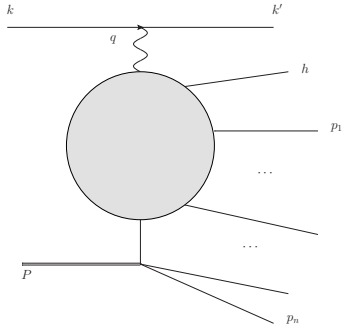
- HFZ and Zhan Sun, *The leptonic current structure and azimuthal asymmetry in deeply inelastic scattering*, Physical Review D96, 034002
- Zhan Sun and HFZ, *QCD leading order study of the J/ψ leptoproduction at HERA within the nonrelativistic QCD framework*, arxiv:1702.02097 (Accepted by European Physical Journal C)
- Zhan Sun and HFZ, *QCD corrections to the color-singlet J/ψ production in deeply inelastic scattering at HERA*, arxiv:1705.05337 (Accepted by Physical Review D (Rapid Communication))
- 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

- The leptonic tensor: wrong when some physical quantities are measured

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

Wrong Results

- Catani, Ciafaloni and Hautmann, NPB 366, 135, 973 times: CASCADE?
- Graudenz, PRD 49, 3291, 77 times
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- Lipatov and Zotov, JHEP 0608, 043 8 times

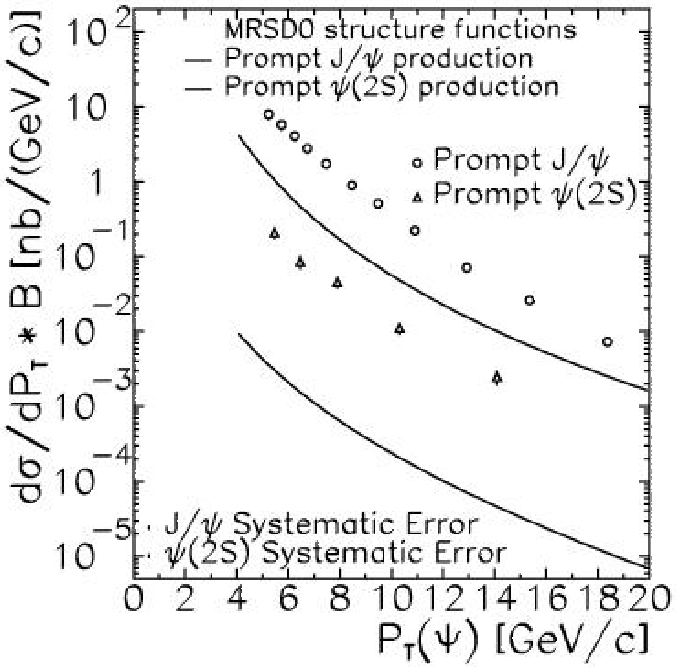
J/ψ production mechanism

- Color-singlet Model
- Color Evaporation Model
- Nonrelativistic QCD (NRQCD)[1]

[1] Bodwin, Braaten and Lepage, PRD 51, 1125 (1995)

Color-singlet Model

- Hard process: producing an on-shell **color-singlet** $c\bar{c}$ pair
- Long-distance process: the color-singlet $c\bar{c}$ pair evolve into a J/ψ
- ψ' (J/ψ) surplus[2]



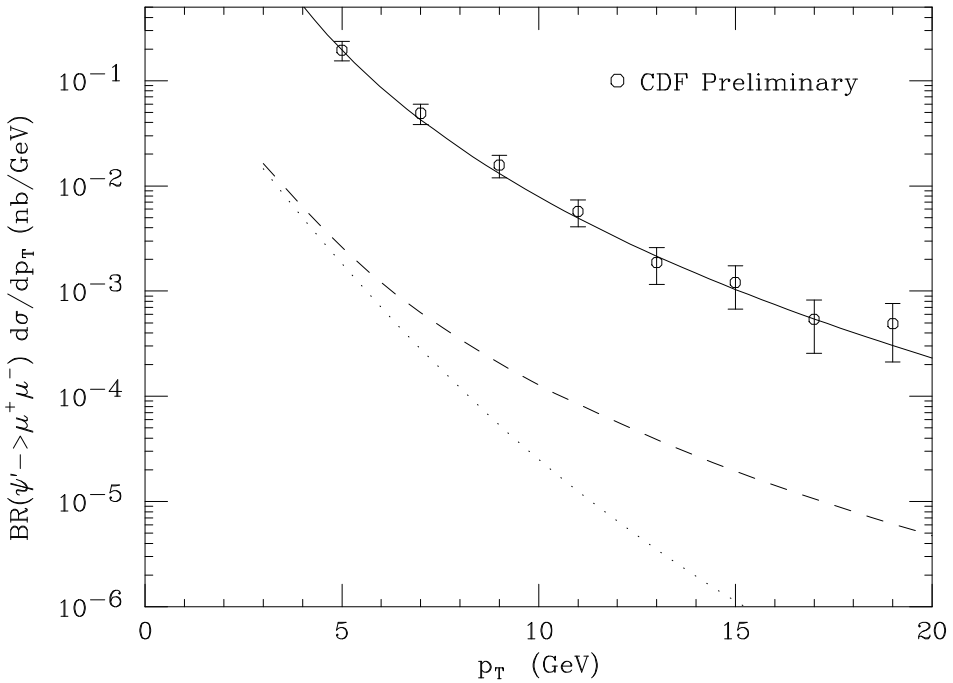
[2] CDF Collaboration, PRL 69, 3704 (1992)

Nonrelativistic QCD (NRQCD)

- A color-octet $c\bar{c}$ can also evolve into a J/ψ

$$d\sigma(H) = \sum_n df_n \langle \mathcal{O}^H(n) \rangle$$

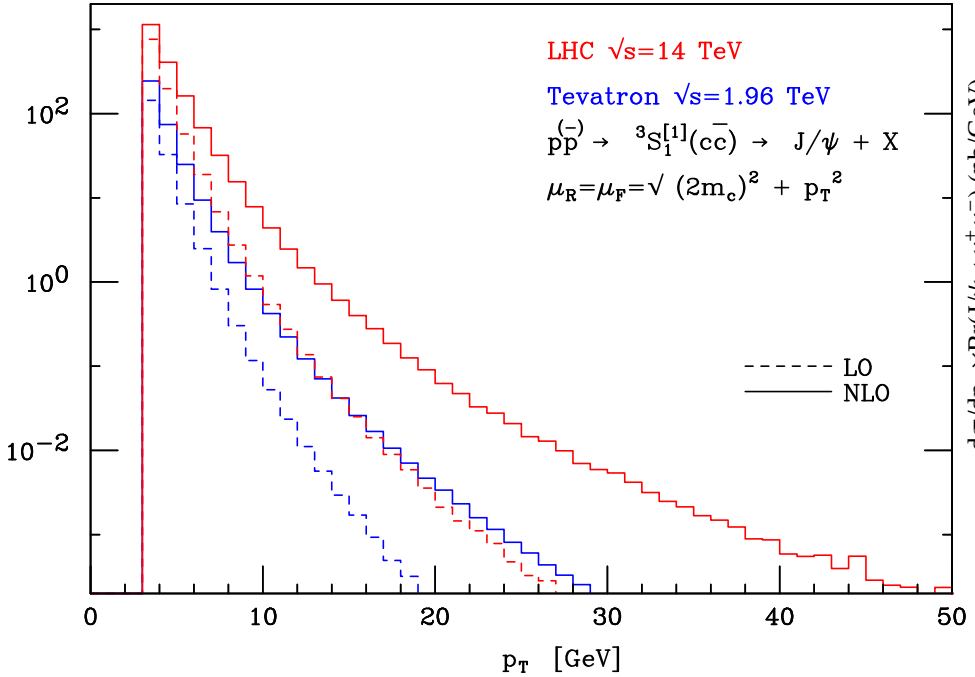
- NRQCD prediction for ψ' hadroproduction[3]

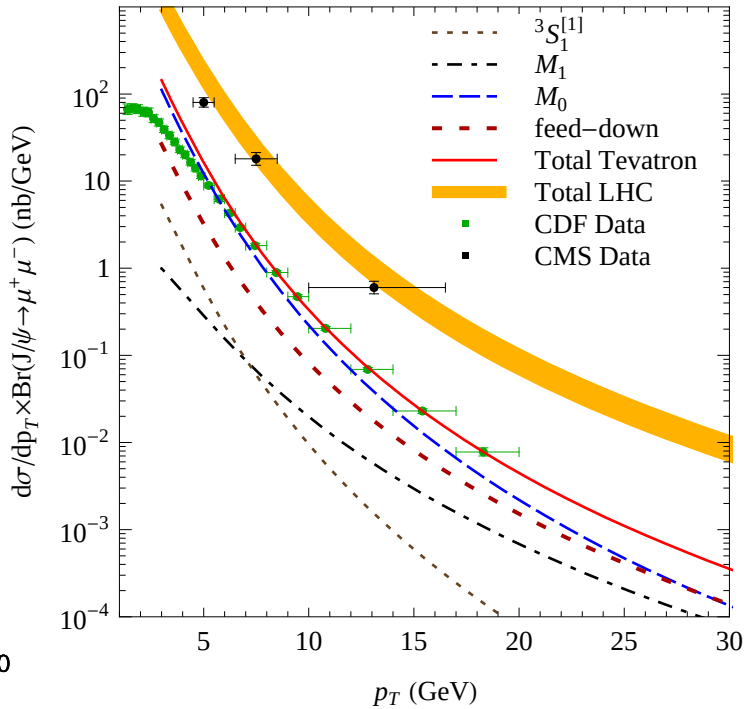


[3] Braaten and Fleming, PRL 74, 3327 (1995)

NRQCD at NLO

- Left: NLO corrections to CS J/ψ production[4]
- Right: NLO corrections to J/ψ production within the NRQCD framework[5]

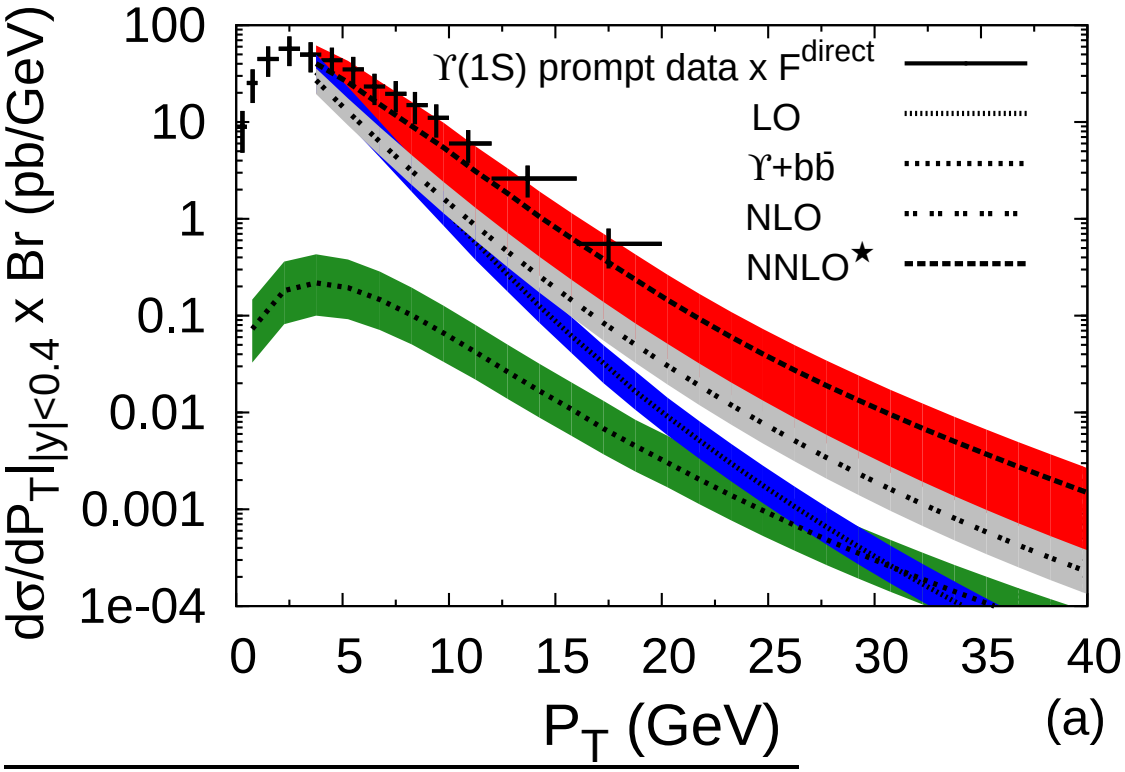




[4] Campbell, Maltoni and Tramontano, PRL 98, 252002 (2007)
[5] Ma, Wang and Chao, PRL 106, 042002 (2011)

NNLO$^{\star 6}$

- A tentative cut is applied on the tree diagrams at $\mathcal{O}(\alpha_s^5)$ to estimate the cross sections at NNLO
- Too large uncertainty, no severe constraint on J/ψ production mechanisms



[6] Artoisenet, Campbell, Lansberg, Maltoni and Tramontano, PRL 101, 152001 (2008)

Questions

- Higher-order corrections: larger?
- Is the color-octet mechanism necessary for the description of heavy quarkonium production?

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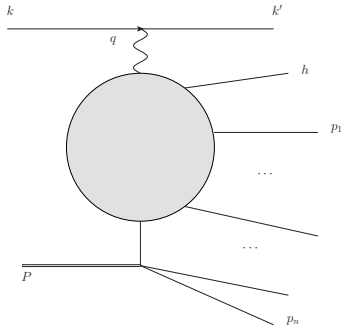
- Higher-order corrections: larger?
- Is the color-octet mechanism necessary for the description of heavy quarkonium production?
- J/ψ production in DIS—New opportunity

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.* Arxiv:1705.05337. **Accepted by Physical Review D (Rapid Communication)**

The Leptonic Tensor

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
- $Q^2 = -q^2$

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

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

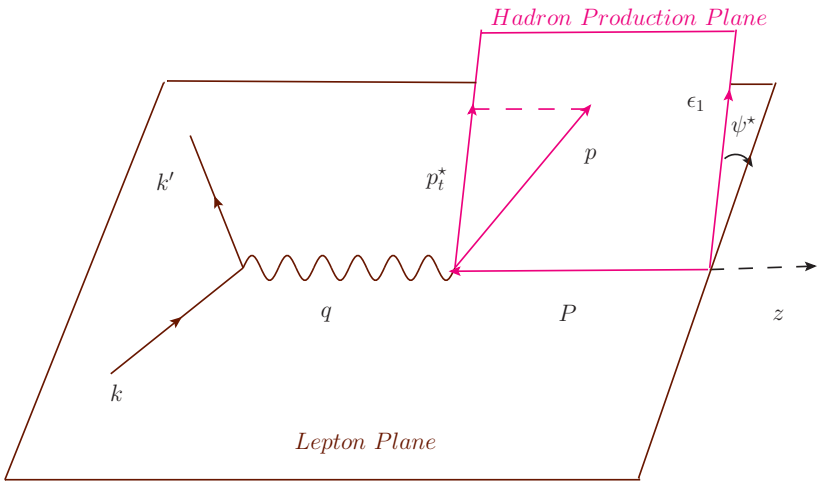
Independent Vectors and Tensors

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

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

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

- $\gamma^\star P$ 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

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

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

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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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- The cosine terms in A_i do not vanish after integration over $\psi^\star$

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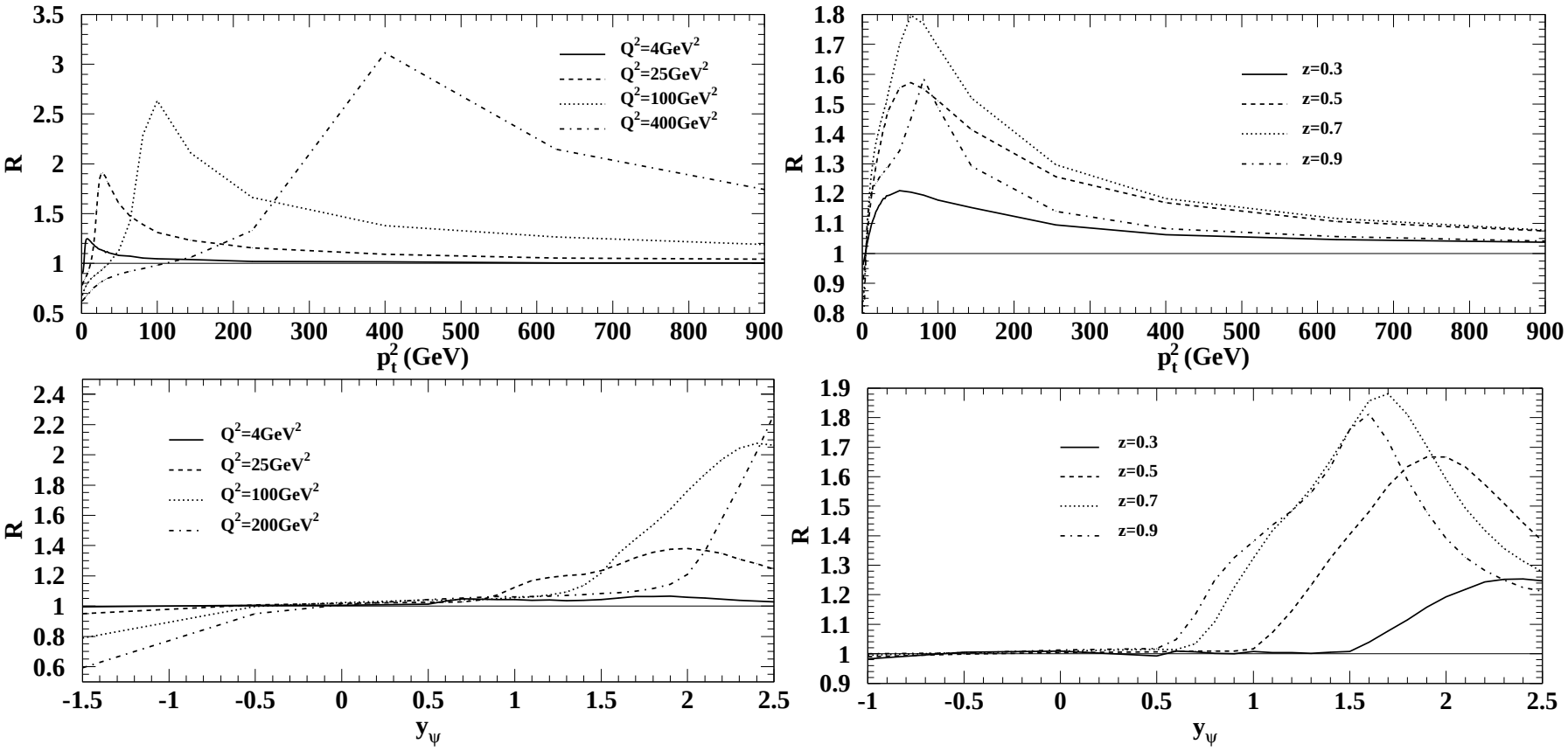
- Dependent on $\psi^\star$
- The cosine terms in A_i do not vanish after integration over $\psi^\star$
- The conventional leptonic tensor is WRONG

Comparison between the Right and the Wrong

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



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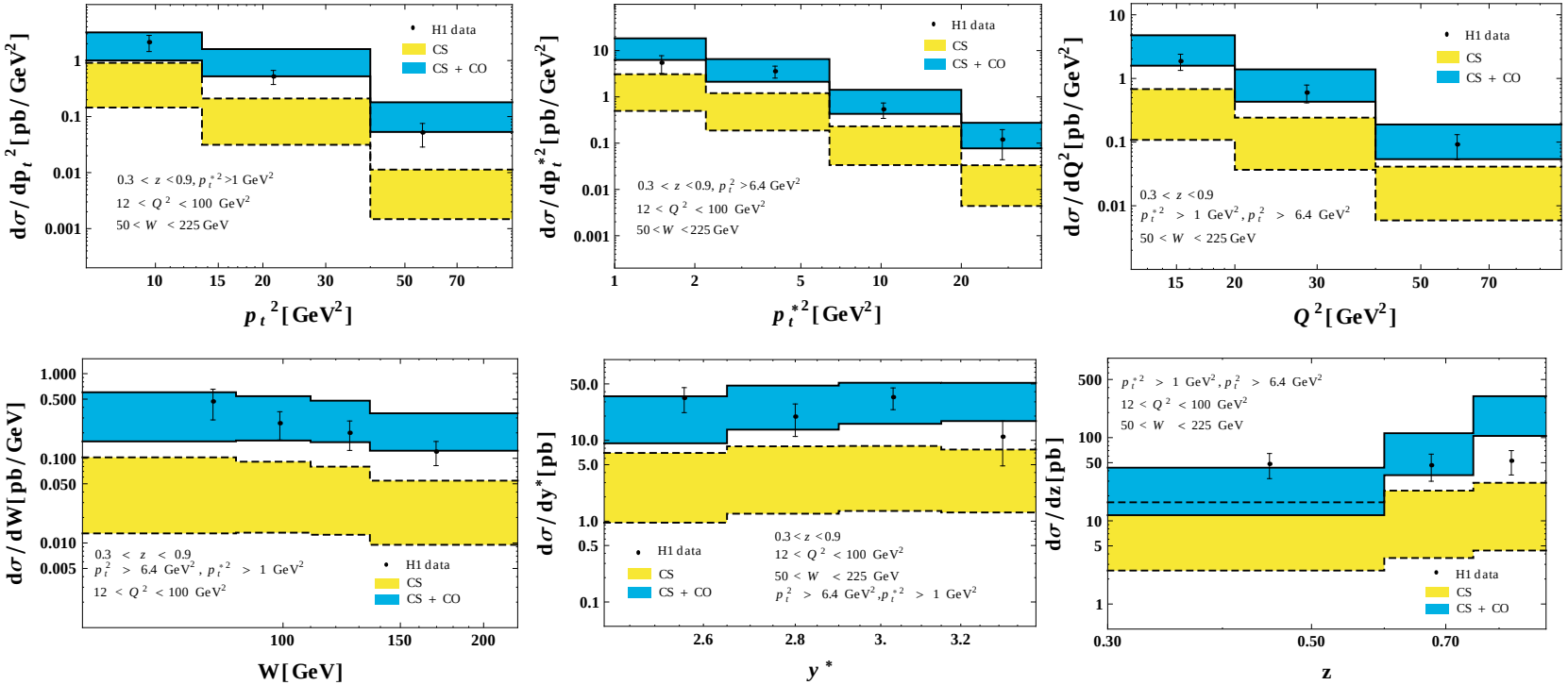
J/ψ Production in DIS

DIS at LO[7]

- CS: below data
- NRQCD: good agreement



[7] Zhan Sun and HFZ, arxiv:1702.02097

Referee's Comments

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Referee Report

This paper deals with some technical aspects concerning azimuthal phase integrations in inclusive and semi-inclusive deeply inelastic scattering. In particular, the authors claim that in many reference frames commonly adopted in the literature, not belonging to the class of so-called z-frames (in which the exchanged vector boson moves along the z direction) one can get wrong results for the cross sections and, in general, for azimuthally integrated observables. The authors pinpoint the origin of the problem in the adoption of a particular form for the leptonic tensor, Eqs. (7) and (18).

It is very difficult to believe that such a simple observation has escaped the attention of the large community working in the field of DIS and SIDIS. Honestly, I am very skeptical about this. In my opinion, a more in-depth and detailed treatment of the problem would be necessary in order to show unambiguously that the claim of the authors is correct and has been neglected in the previous literature.

Referee's Report

- First Round

  In fact, the authors claim that the lepton tensor in the form of Eq. (31) will lead to wrong results if the transverse momentum or the rapidity of the J/ψ meson in the laboratory frame are not taken to cover all their possible values.

  Unfortunately, this claim is wrong. The only assumption that goes into the derivation of Eq. (31) is that the azimuthal angle of the scattered lepton is integrated over. For a comprehensive discussion, see D. Graudenz, hep–ph/9307311. This was routinely done in most of the DIS experimental studies at HERA, and certainly in those related to heavy quarkonium production, which were used for comparisons in Refs. [58,59]. All the kinematic distributions considered in Refs. [57–59] are compatible with the integration over the azimuthal angle of the outgoing lepton.

  In conclusion, this paper is pointless and should not be published.

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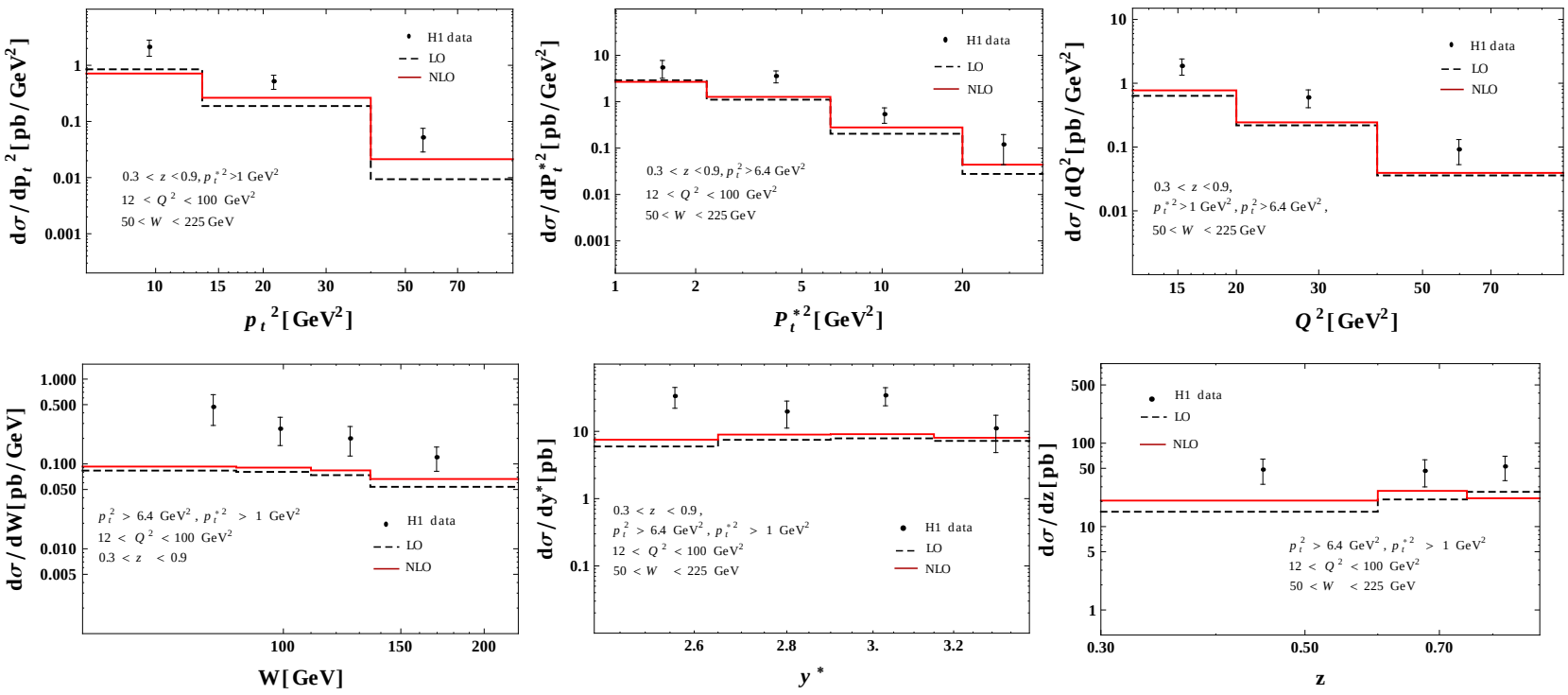
- **Second Round**

  Comments to the Author
  The article describes a calculation of differential direct J/psi production cross sections in deep-inelastic scattering within the factorization framework of nonrelativistic QCD. Although this leading order calculation is basically a repetition of the 15-year-old work [59] and in parts of even older works, it should nevertheless be published, because

  1. the predictions are compared to newer data not available at the time of [59],
  2. they use more modern color octet LDMEs determined from NLO fits as input, and
  3. they found a mistake in [59]: It seems that in Eq. (7) of [59], the leptonic tensor was integrated over the azimuthal angle of the outgoing lepton in the photon-incoming parton rest frame. This integration assumes that the rest of the integrand is independent of this angle, which is however not true in the case of J/psi transverse momentum, rapidity or derived distributions in the laboratory frame.

Color-singlet at NLO

- QCD corrections are minor, cannot describe data



Referee's Report

- Referee's Comments

2) In the calculations the authors use modified leptonic tensor and claim that in contrast to widely used traditional parametrization it gives correct result in all kinematical region. This statement is a little bit surprising since traditional form of the leptonic tensor requires only the gauge invariance, no assumptions on the final state is used. So, if the results of traditional and adopted by the authors approaches differ, there should be some errors in the latter one.

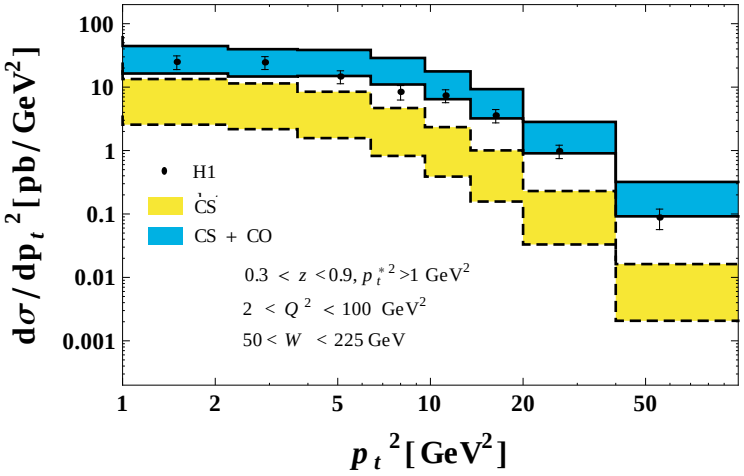
Conclusion

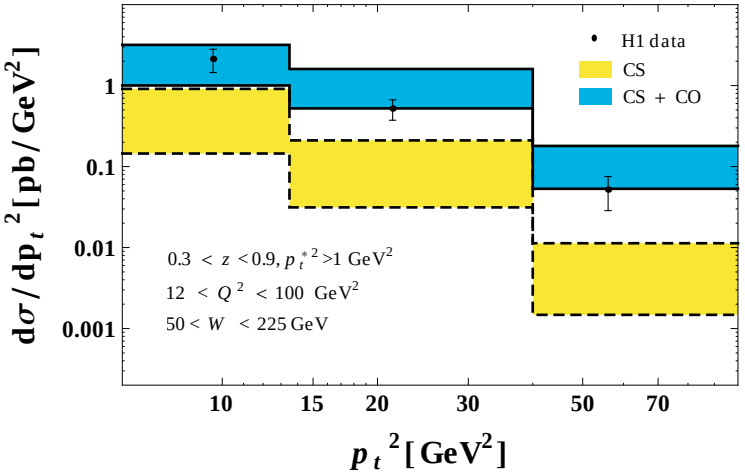
- Measuring p_t or rapidity in laboratory frame, structure functions, F_1, F_2 and F_3 are not sufficient to describe the cross sections.
- QCD corrections to CS J/ψ production in DIS in low p_t region is minor.

Thanks!

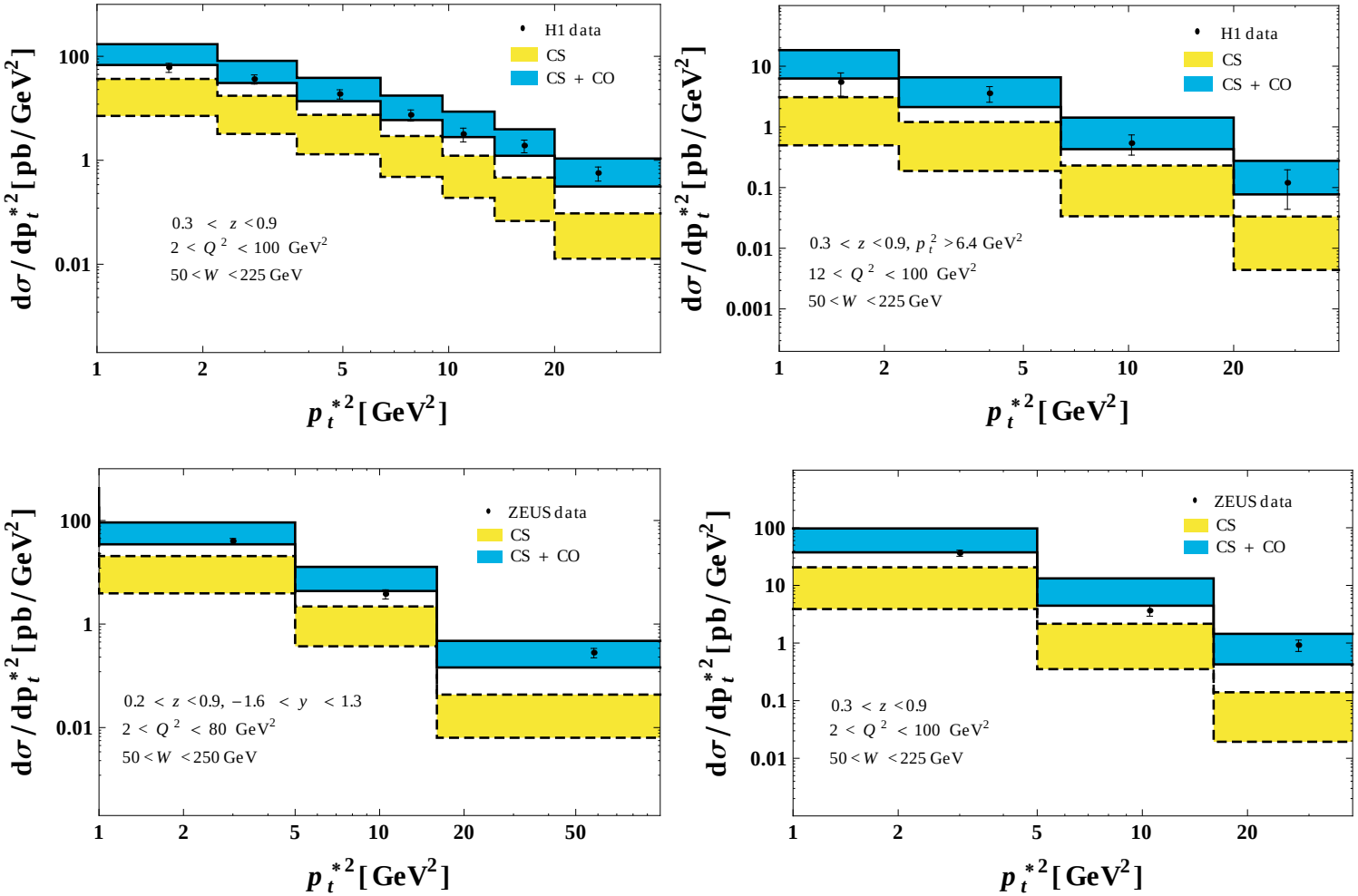
Backup

DIS at LO (p_t^2 Distributions)

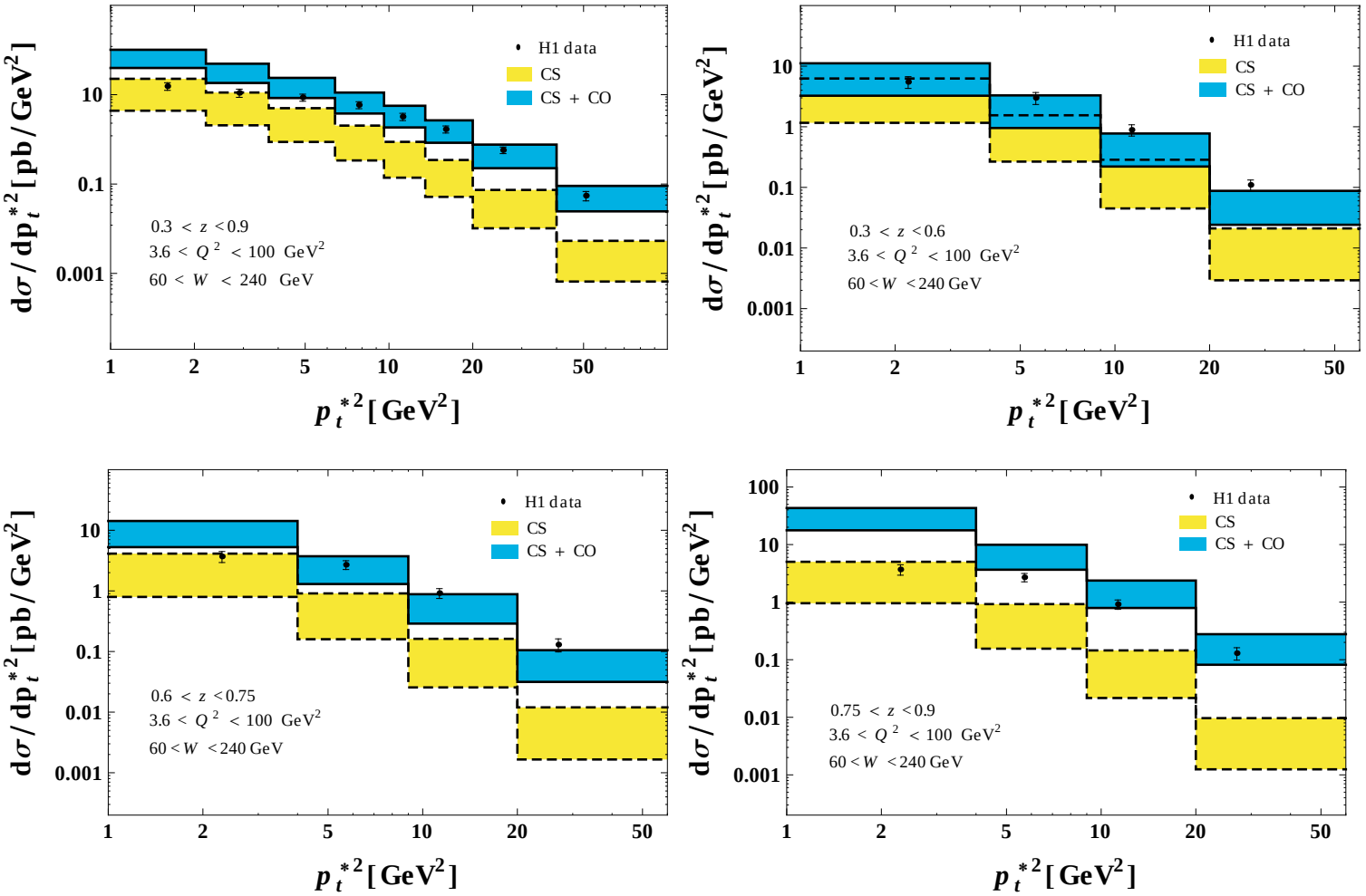




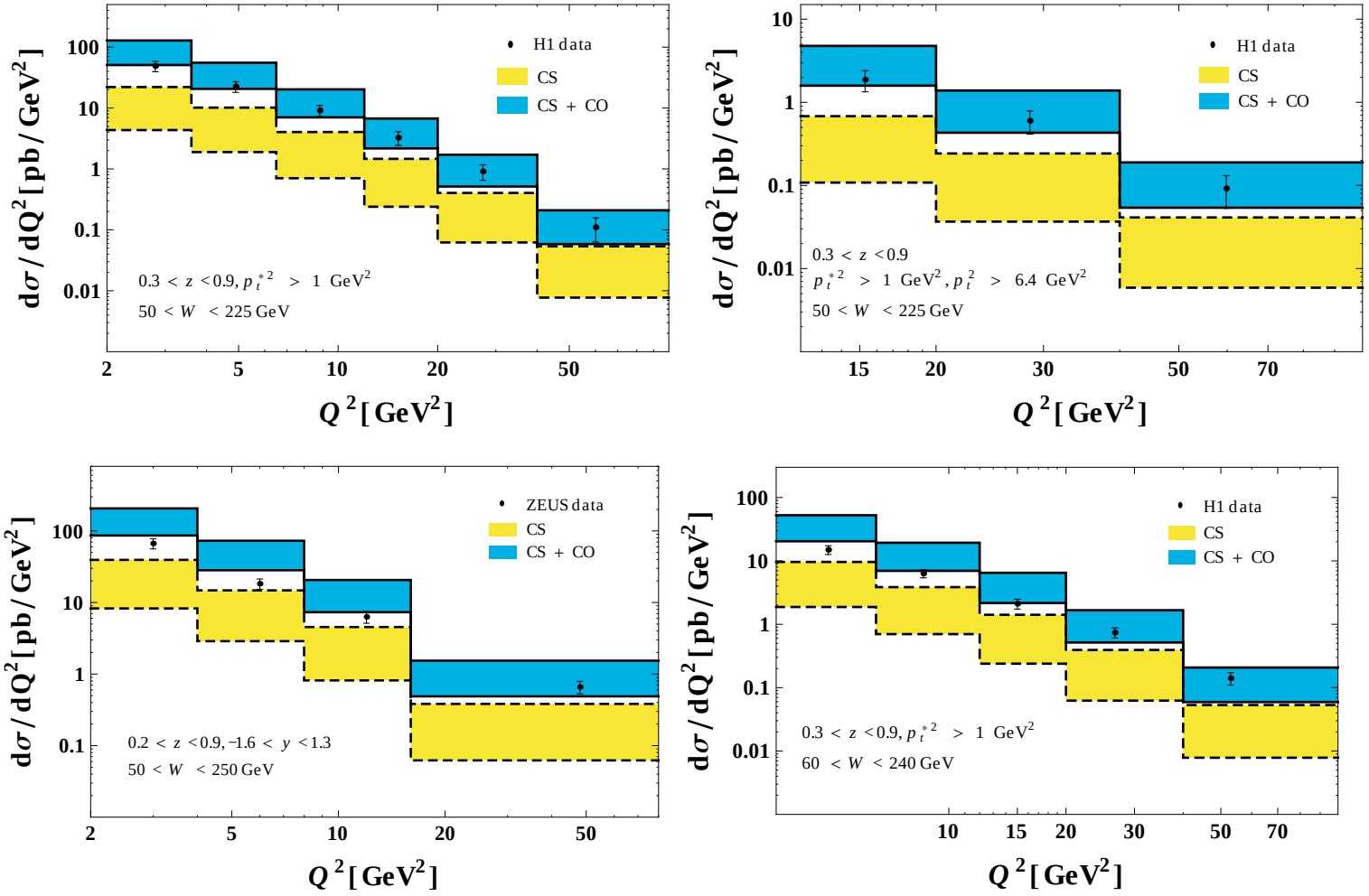
DIS at LO ($p_t^{\star 2}$ Distributions I)



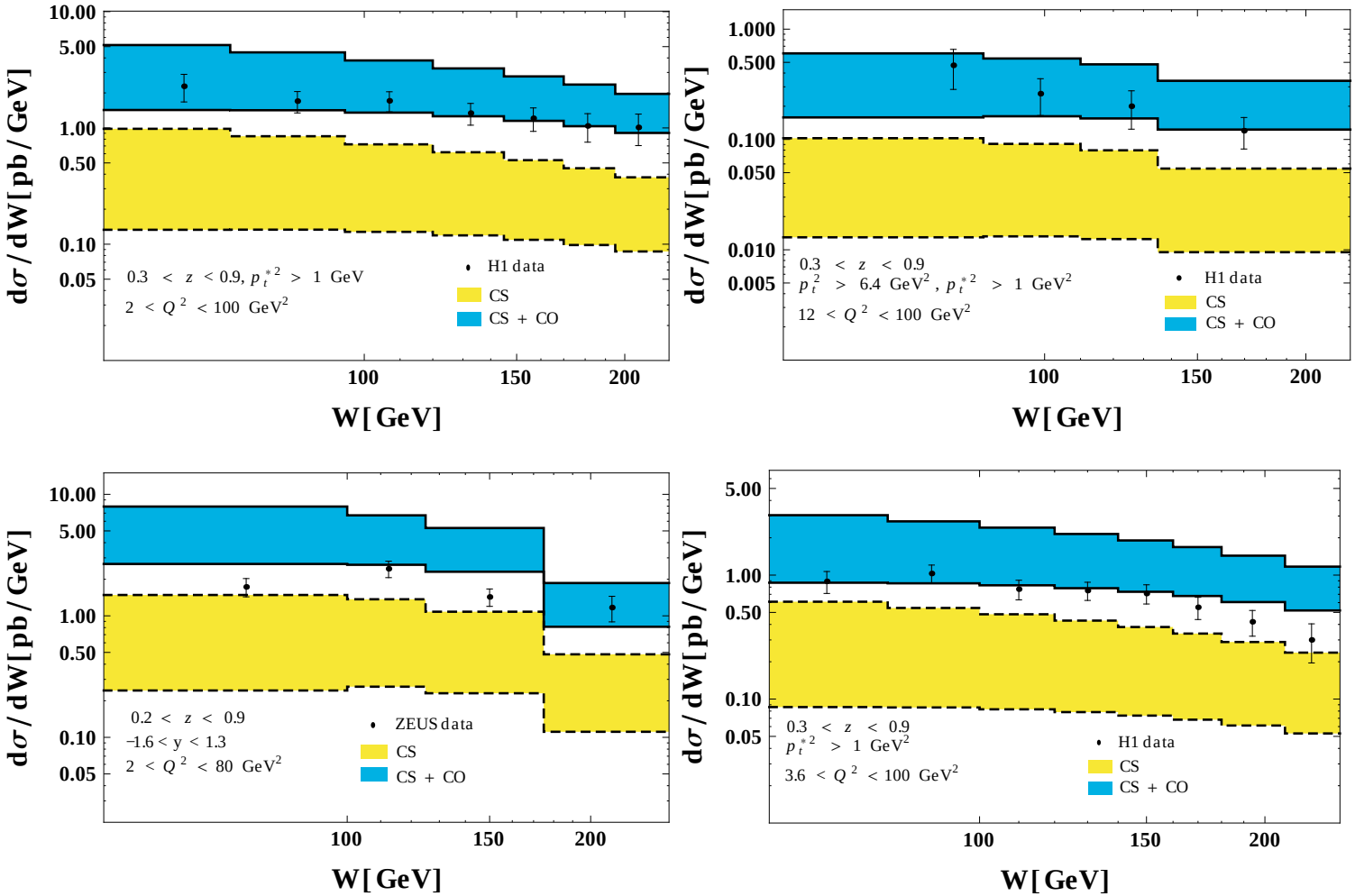
DIS at LO ($p_t^{\star 2}$ Distributions II)



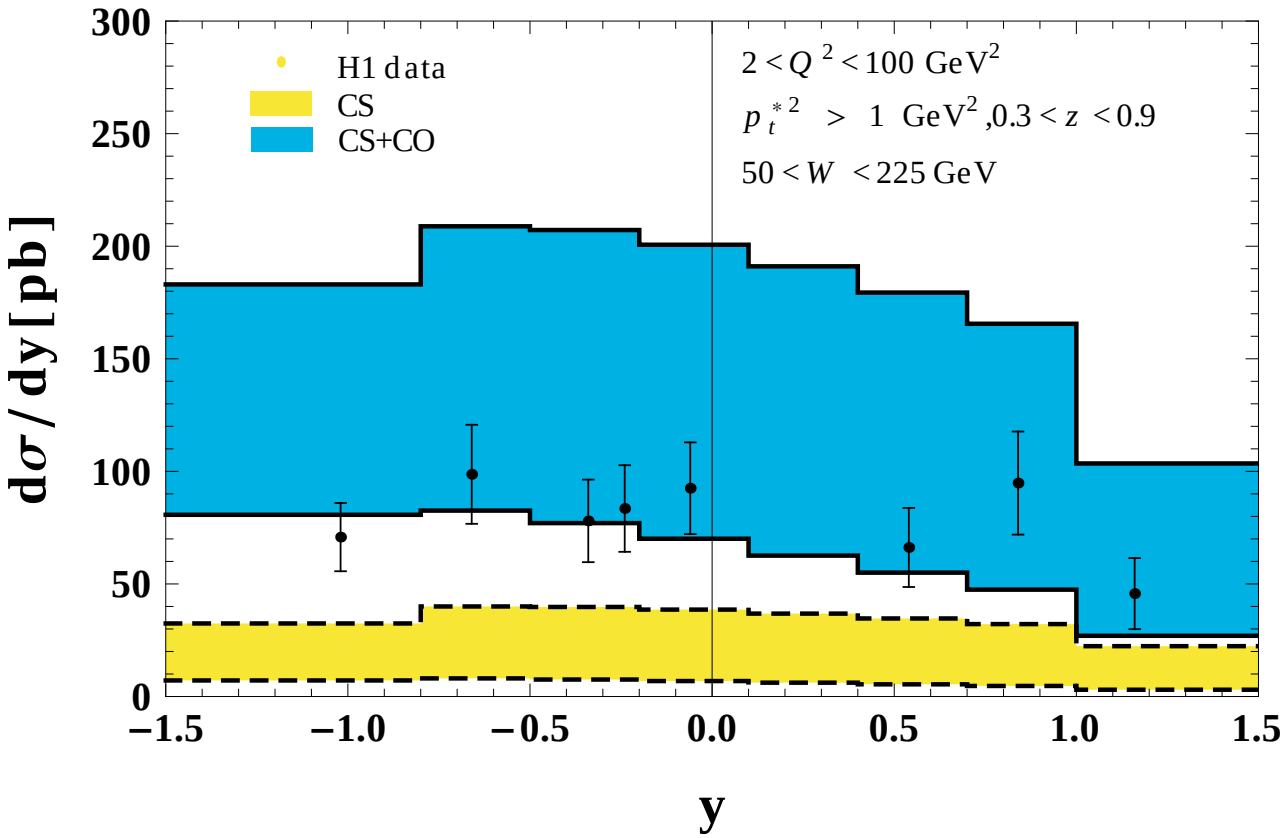
DIS at LO (Q^2 Distributions)



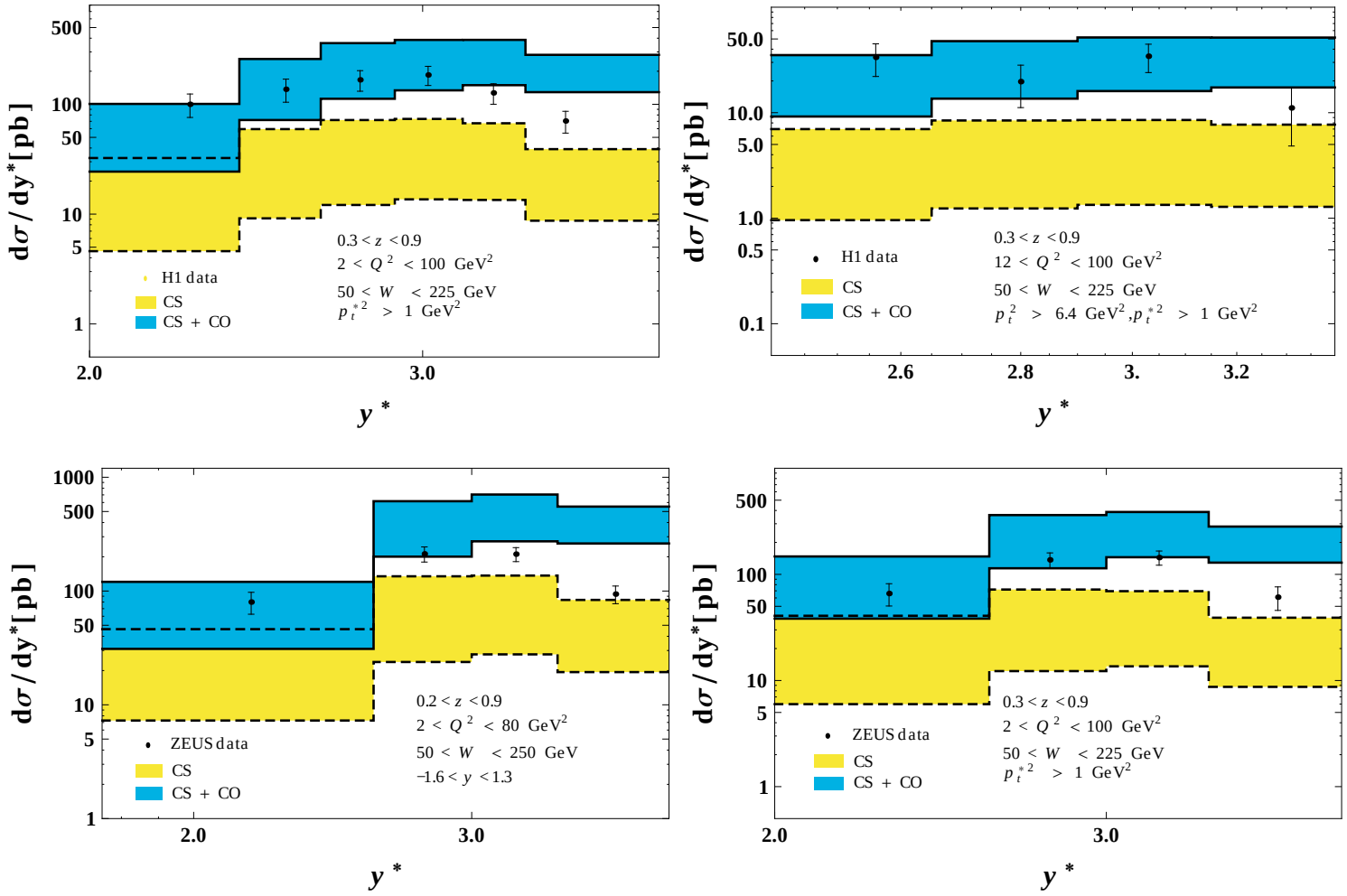
DIS at LO (W Distributions)



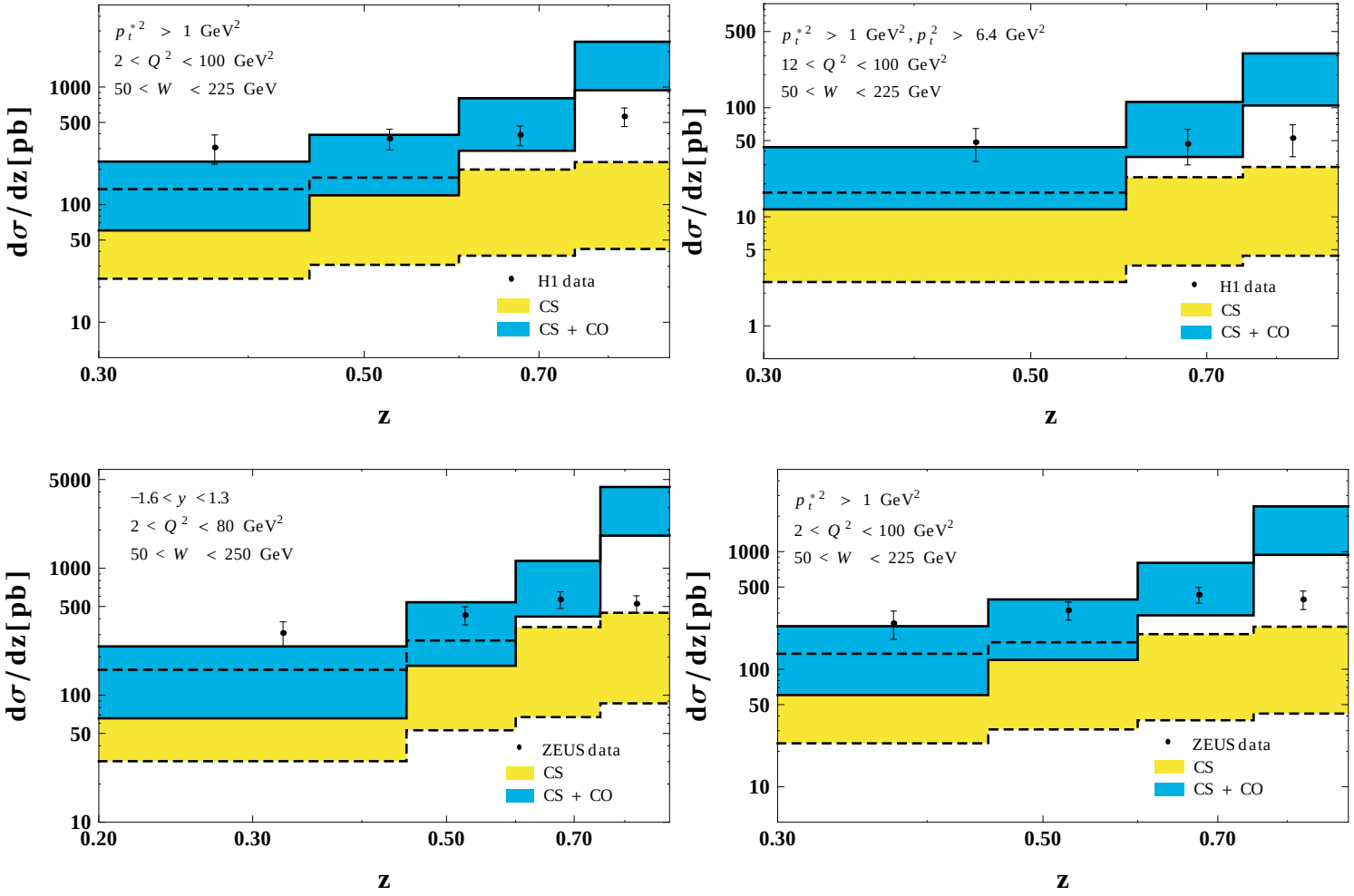
DIS at LO (y_ψ Distributions)



DIS at LO ($y^\star_\psi$ Distributions)



DIS at LO (z Distributions I)



DIS at LO (z Distributions II)