The J/ψ Production in Deeply Inelastic Scattering at HERA

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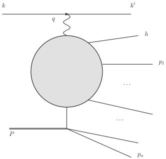
Based On

- HFZ and Zhan Sun, *The leptonic current structure and azimuthal asymmetry in deeply inelastic scattering*, arxiv:1701.08728
- Zhan Sun and HFZ, *QCD leading order study of the J/ψ leptoproduction at HERA within the nonrelativistic QCD framework*, arxiv:1702.02097
- Zhan Sun and HFZ, *QCD corrections to the color-singlet J/ψ production in deeply inelastic scattering at HERA*, arxiv:1705.05337
- Zhan Sun and HFZ, **Malt@FDC**

Cross Section



- Process: $ep \to h + X$

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

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

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

Inclusive DIS Analysis

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

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

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

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

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

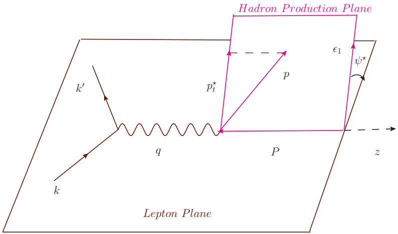
Independent Vectors and Tensors

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

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

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

- $\gamma^\star P$ rest frame



Hadronic Tensor in SIDIS

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

$$W_h^{\mu\nu} = W_g \epsilon^{\mu\nu} + W_L \epsilon_L^\mu \epsilon_L^\nu + W_{LT}(\epsilon_L^\mu \epsilon_1^\nu + \epsilon_1^\mu \epsilon_L^\nu) + W_T \epsilon_1^\mu \epsilon_1^\nu$$

$$L_{\mu\nu} W_h^{\mu\nu} = 8\pi\alpha Q^2 \{2W_g + \frac{4(1-y)}{y^2} W_L + \frac{4(2-y)}{y^2}\sqrt{1-y}\cos\psi^\star W_{LT} + [1 + \frac{2(1-y)}{y^2} + \frac{2(1-y)}{y^2}\cos(2\psi^\star)] W_T\}$$

Hadronic Tensor in SIDIS

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

Hadronic Tensor in SIDIS

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

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- Azimuthal dependent terms missing

Leptonic Tensor in SIDIS

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

$$A_1 = 1 + \frac{2(1-y)}{y^2} - \frac{2(1-y)}{y^2}\cos(2\psi^\star)$$
$$A_2 = 1 + \frac{6(1-y)}{y^2} - \frac{2(1-y)}{y^2}\cos(2\psi^\star)$$
$$A_3 = \frac{2(2-y)}{y^2}\sqrt{1-y}\cos(\psi^\star)$$
$$A_4 = \frac{4(1-y)}{y^2}\cos(2\psi^\star)$$

- Integrating over $\psi^\star$, one reproduces the reduced leptonic tensor

Leptonic Tensor in SIDIS

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

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

Cross Section Structure

- Define w_i

$$w_g = \epsilon_{\mu\nu} W_h^{\mu\nu}$$
$$w_L = \epsilon_{L\mu}\epsilon_{L\nu} W_h^{\mu\nu}$$
$$w_{LT} = (\epsilon_{L\mu}\epsilon_{1\nu} + \epsilon_{1\mu}\epsilon_{L\nu}) W_h^{\mu\nu}$$
$$w_T = \epsilon_{1\mu}\epsilon_{1\nu} W_h^{\mu\nu}$$

- Cross section

$$\mathrm{d}\sigma = \frac{\alpha}{256\pi^5 N_s N_c S Q^2 z} \sum_i A_i w_i \mathrm{d}Q^2 \mathrm{d}y \mathrm{d}p_t^{\star 2} \mathrm{d}z \mathrm{d}\psi^\star, \; i = g,\, L,\, LT,\, T$$

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

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

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

Laboratory Frame

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- Dependent on $\psi^\star$

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

Laboratory Frame

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

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

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

Wrong Results

- Catani, Ciafaloni and Hautmann, NPB 366, 135, 973 times: CASCADE?
- Graudenz, PRD 49, 3291, 77 times
- Harris and Smith, PRD 57, 2806, 202 times
- Klasen, Kramer and Potter, EPJC 1, 261, 72 times
- Potter, NPB 540, 382, 15 times
- Potter, NPB 559, 323, 5 times
- Kniehl and Zwirner, NPB 621, 337, 46 times
- Kniehl, Kramer and Maniatis, NPB 711, 345, 21 times
- Kniehl and Palisoc, EPJC 48, 451, 6 times
- Lipatov and Zotov, JHEP 0608, 043 8 times

Parameterization

- Momenta in $\gamma^\star p$ rest frame

$$p^\mu = (xE_p^\star,\ 0,\ 0,\ -xE_p^\star),\ q^\mu = (q_0^\star,\ 0,\ 0,\ E_p^\star)$$
$$p_\psi^\mu = (\tfrac{zW^2+m_t^{\star 2}/z}{2W},\ p_t^\star,\ 0,\ \tfrac{zW^2-m_t^{\star 2}/z}{2W}),$$
$$k^\mu = (E_k^\star,\ k_t^\star\cos\psi^\star,\ k_t^\star\sin\psi^\star,\ k_l^\star)$$

$$E_p^\star = \tfrac{W^2+Q^2}{2W},\ q_0^\star = \tfrac{W^2-Q^2}{2W},\ m_t^\star = \sqrt{p_t^{\star 2}+M^2},\ x = \tfrac{s}{W^2+Q^2}$$
$$E_k^\star = \tfrac{S-Q^2}{2W},\ k_l^\star = \tfrac{1}{2W}(Q^2 + \tfrac{W^2-Q^2}{W^2+Q^2}S),\ k_t^\star = \tfrac{Q}{y}\sqrt{1-y}$$

- Observables in the laboratory frame

$$p_t^2 = p_t^{\star 2} + z^2(1-y)Q^2 - 2z\sqrt{1-y}\,Qp_t^\star\cos\psi^\star$$
$$y_\psi = \tfrac{1}{2}\ln[\tfrac{m_t^{\star 2}+z^2(1-y)Q^2-2z\sqrt{1-y}\,Qp_t^\star\cos\psi^\star}{4y^2z^2E_l^2}]$$

Leptonic Tensor

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

$$l^{\mu\nu} = C_1(-g^{\mu\nu}) + C_2 p^\mu p^\nu + C_3 \frac{p^\mu p_\psi^\nu + p_\psi^\mu p^\nu}{2} + C_4 p_\psi^\mu p_\psi^\nu$$

$$C_1 = A_g, \qquad C_2 = \frac{4Q^2}{s^2}(A_L - 2\beta A_{LT} + \beta^2 A_T)$$
$$C_3 = \frac{4Q}{p_t^\star s}(A_{LT} - \beta A_T), \qquad C_4 = \frac{1}{p_t^{\star 2}} A_T$$

$$A_1 = 1 + \frac{2(1-y)}{y^2} - \frac{2(1-y)}{y^2}\cos(2\psi^\star)$$
$$A_2 = 1 + \frac{6(1-y)}{y^2} - \frac{2(1-y)}{y^2}\cos(2\psi^\star)$$
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Phase Space

- Phase space for the scattered lepton and the final-state hadrons

$$\mathrm{d}\Phi' \equiv \frac{\mathrm{d}^3 k'}{(2\pi)^3 2k'_0} = \frac{1}{32\pi^3 S}\mathrm{d}Q^2\mathrm{d}W^2\mathrm{d}\psi^\star$$

$$\mathrm{d}\Phi_H \equiv (2\pi)^4\delta^4(P+q-p_\psi-p_a)\frac{\mathrm{d}^3 p_\psi}{(2\pi)^3 2p_{\psi 0}}\frac{\mathrm{d}^3 p_a}{(2\pi)^3 2p_{a0}}$$

$$= \frac{1}{16\pi p_{a0}}\delta(p_0+q_0-p_{\psi 0}-p_{a0})\mathrm{d}p_t^{\star 2}\frac{\mathrm{d}z}{z}$$

$$f_{a/p}(x,\mu_f)\mathrm{d}x\mathrm{d}\Phi_H = \frac{1}{8\pi(W^2+Q^2)z(1-z)}f_{a/p}(x,\mu_f)\mathrm{d}p_t^{\star 2}\mathrm{d}z$$

- Final results

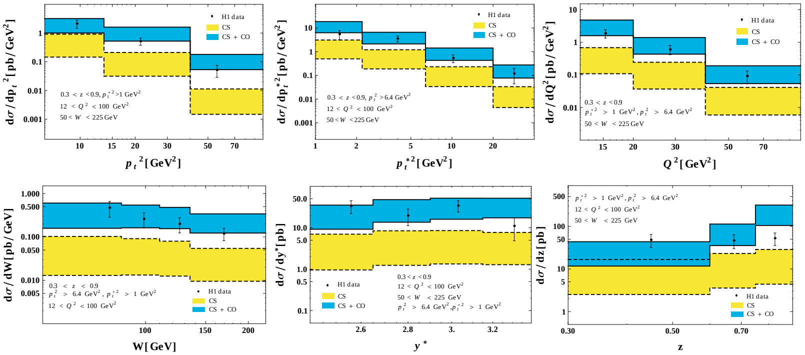
$$f_{a/p}(x,\mu_f)\mathrm{d}x\mathrm{d}\Phi =$$

$$\frac{1}{(4\pi)^4 S(W^2+Q^2)z(1-z)}f_{a/p}(x,\mu_f)\mathrm{d}Q^2\mathrm{d}W^2\mathrm{d}p_t^2\mathrm{d}z\mathrm{d}\psi^\star$$

$$= \frac{1}{(4\pi)^4 z(1-z)}f_{a/p}(x,\mu_f)\mathrm{d}x_B\mathrm{d}y\mathrm{d}p_t^{\star 2}\mathrm{d}z\mathrm{d}\psi^\star$$

DIS at LO[1]

- CS: below data
- NRQCD: good agreement



[1] Zhan Sun and HFZ, arxiv:1702.02097

Two Cutoff Phase Space Slicing Method

- Definitions of soft and collinear regions

$$s \equiv 2p \cdot q, \qquad E_g < \frac{\sqrt{s}}{2}\delta_s, \qquad p_i \cdot p_j < \frac{s}{2}\delta_c$$

- Initial-final state collinear

$$\mathrm{d}\sigma_{HC}^{1+B\to 3+4+5} = f_{2/B}(y)\mathrm{d}y\mathrm{d}\sigma_0^{1+2'\to 3+4}(\xi s)\left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu^2}{s}\right)^{\epsilon}\right]$$
$$\times\left(-\frac{1}{\epsilon}\right)\delta_c^{-\epsilon}P_{2'2}(\xi,\epsilon)\mathrm{d}\xi(1-\xi)^{\epsilon}\delta(y\xi - x)\mathrm{d}x$$

- Final state qg collinear (hard)

$$E_5 = (1-\xi)E_{45}, \quad E_{45} = \frac{s-Q^2-M^2}{2\sqrt{s-Q^2}}, \quad \frac{\sqrt{s}}{2}\delta_s < E_5 < E_{45},$$

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Two Cutoff Phase Space Slicing Method

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- Final state qg collinear (hard)

$$E_5 = (1-\xi)E_{45}, \quad E_{45} = \frac{s-Q^2-M^2}{2\sqrt{s-Q^2}}, \quad \frac{\sqrt{s}}{2}\delta_s < E_5 < E_{45}, \quad \frac{s\sqrt{s-Q^2}}{s-Q^2-M^2}\delta_s < \xi < 1$$

- Final state gg collinear (hard)

$$\frac{s\sqrt{s-Q^2}}{s-Q^2-M^2}\delta_s < \xi < 1 - \frac{s\sqrt{s-Q^2}}{s-Q^2-M^2}\delta_s$$

Two Cutoff Phase Space Slicing Method (Initial-final State Collinear)

$$E_5 = (1-\xi)E_2, \quad E_2 = \frac{s}{2\sqrt{s-Q^2}}$$

- p_5: light quark

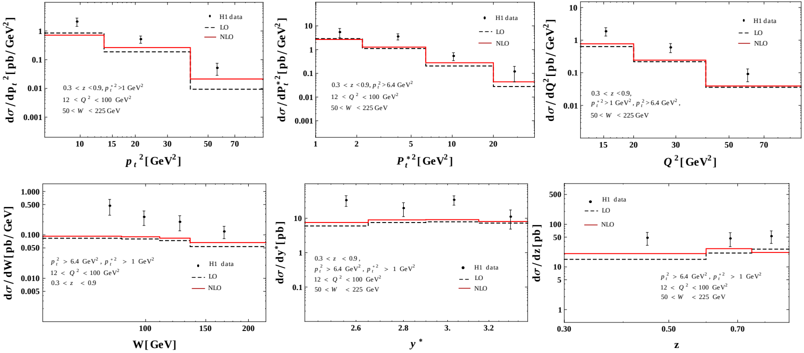
$$0 < E_5 < E_2, \quad x < \xi < 1$$

- p_5: gluon

$$\frac{\sqrt{s}}{2}\delta_s < E_5 < E_2, \quad x < \xi < 1 - \sqrt{\frac{s-Q^2}{s}}\delta_s$$

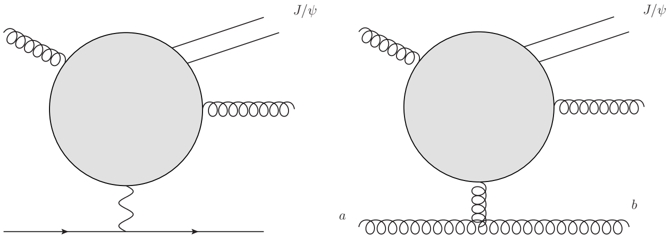
Color-singlet at NLO

- QCD corrections are minor, cannot describe data



Comparison between DIS and hadroproduction

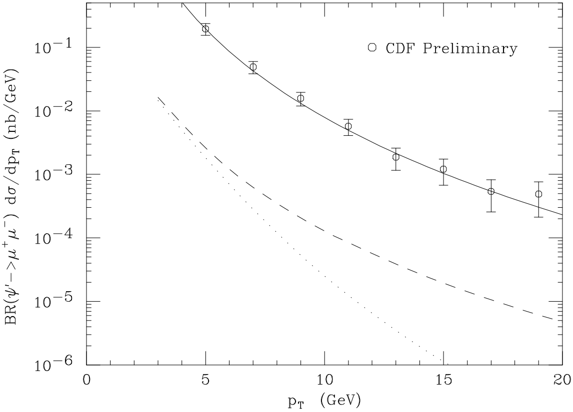
- Left: J/ψ production in deeply inelastic scattering (DIS) at LO
- Right: J/ψ hadroproduction at NLO



- Difference between J/ψ production in DIS at NLO and J/ψ hadroproduction at NNLO
  - Difference A: p_t^{-4} behaviour emerges in hadroproduction
  - Difference B: Gluons a and b can exchange gluons with c ($\bar{c}$) or other gluons

Analysis in the Differences

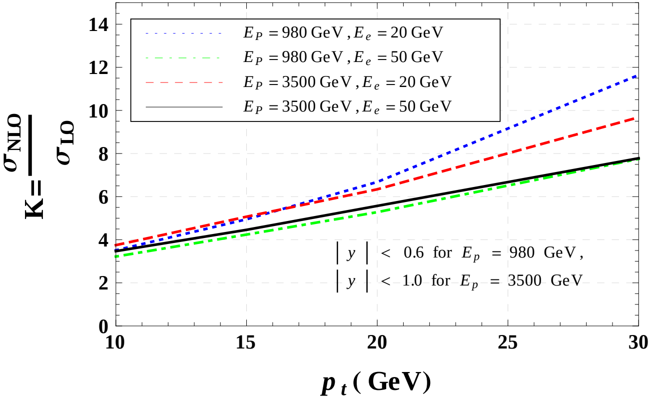
- p_t^{-4} terms are negligible (dashed line)



- $c\bar{c}$ fragmentation dominates NLP, contributions from a (b) exchanging gluons with c ($\bar{c}$) are suppressed

K-factor at High p_t

- K-factor ranges from 3 to 12
- Such K-factor cannot describe J/ψ hadroproduction data



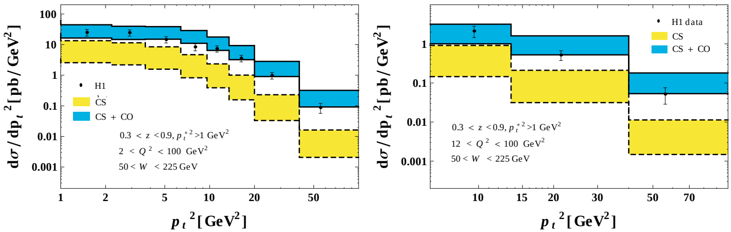
Conclusion

- 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.
- CS J/ψ hadroproduction at QCD NNLO cannot describe the Tevatron and LHC data unless Difference B provides large contributions.

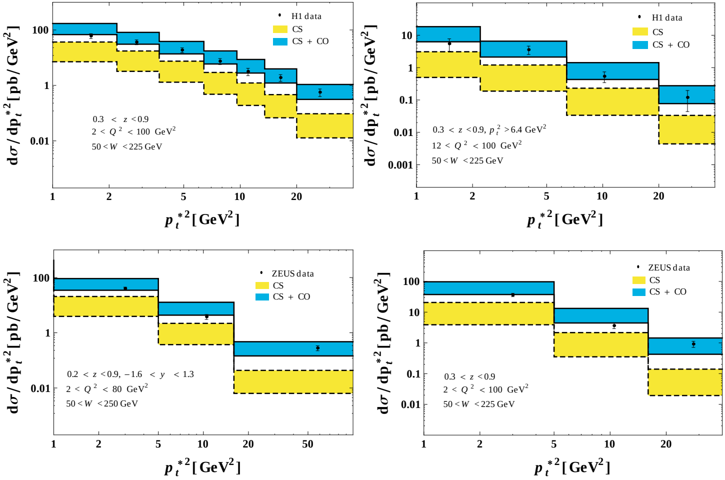
Thanks!

Backup

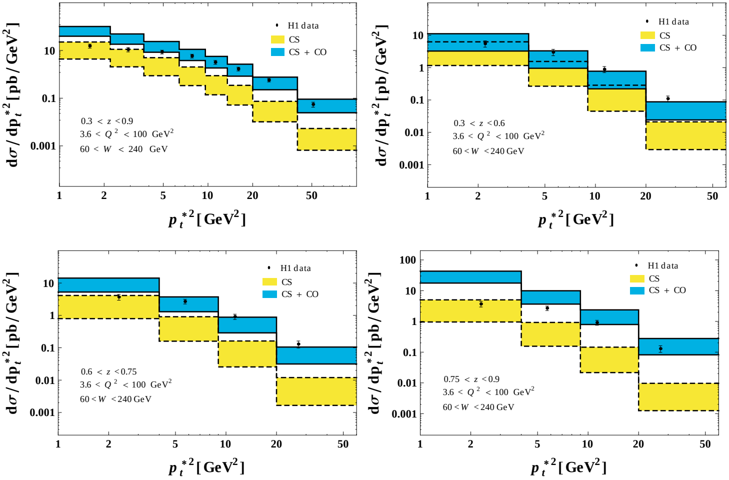
DIS at LO (p_t^2 Distributions)



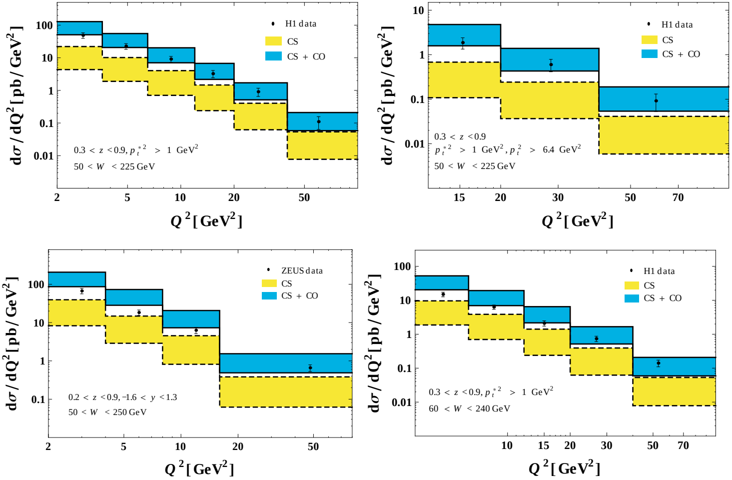
DIS at LO ($p_t^{\star 2}$ Distributions I)



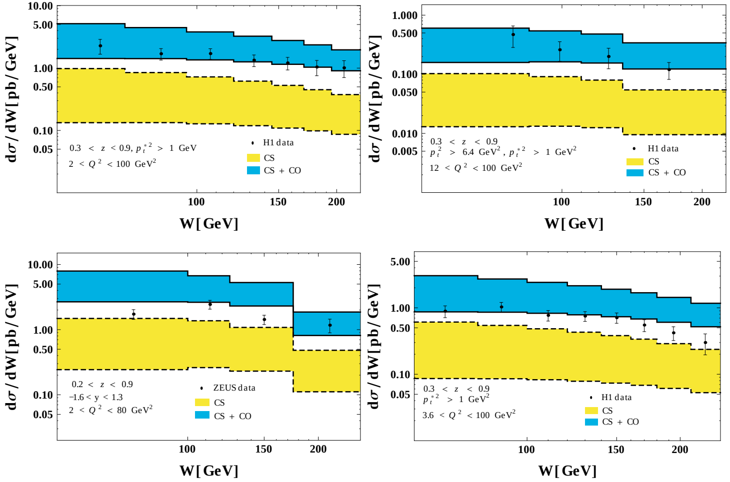
DIS at LO ($p_t^{\star 2}$ Distributions II)



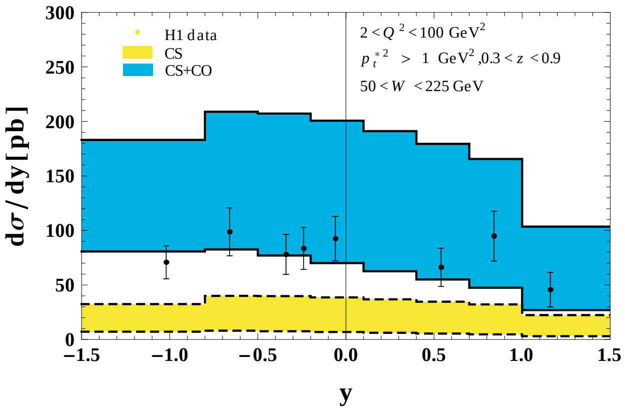
DIS at LO (Q^2 Distributions)



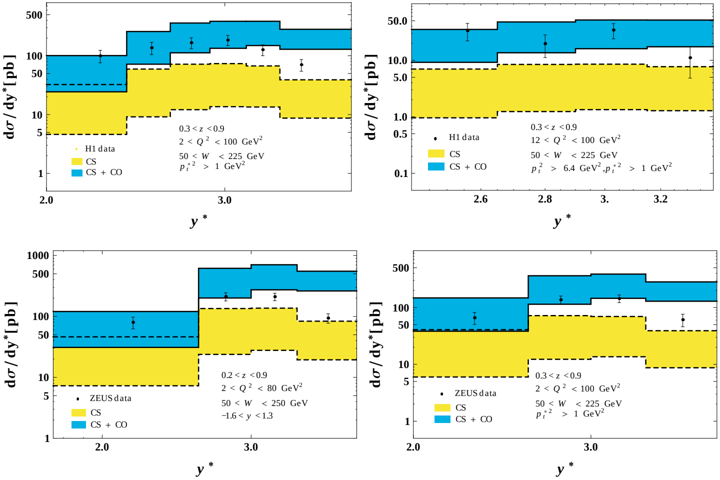
DIS at LO (W Distributions)



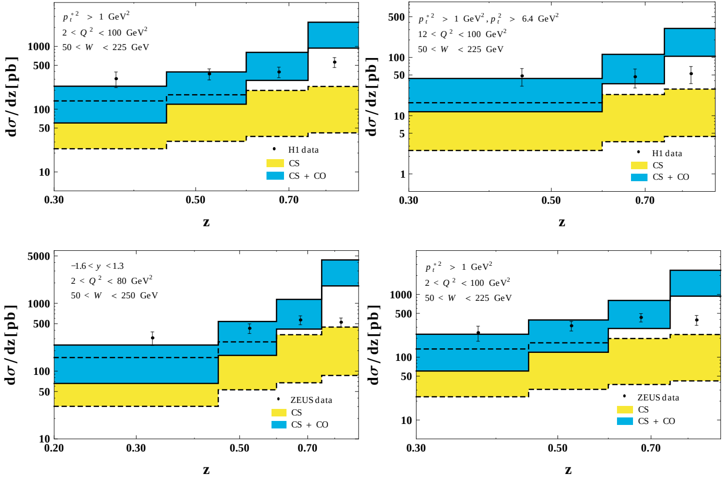
DIS at LO (y_ψ Distributions)



DIS at LO ($y^{\star}_{\psi}$ Distributions)



DIS at LO (z Distributions I)



DIS at LO (z Distributions II)