QUARKONIUM PRODUCTION AT THE EIC: UNPOLARISED-NUCLEON PDF FROM J/ψ & Υ PRODUCTION

Yelyzaveta Yedelkina

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Part I

Introducing inclusive J/ψ & Υ photoproduction

Introduction: inclusive $J/\psi(\Upsilon)$ photoproduction

C.-H. Chang, NPB172, 425 (1980); R. Baier & R. Rückl Z. Phys. C 19, 251(1983);

Let's us first discuss **inclusive** J/ψ **(Υ) photoproduction**:

- as a reminder, J/ψ (Υ) is a $c\bar{c}$ ($b\bar{b}$) bound state with $J = 1,\ L = 0,\ S = 1$; vector particle
- inclusive photoproduction:

$$\gamma(Q^2 \simeq 0) + p \to J/\psi + X;$$

- We will discuss the photoproduction at NLO;

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  - NRQCD and Colour Octet Mechanism;
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- We do not discuss large z and exclusive reactions

$\rightarrow$ see the exclusive sessions

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J.P. Lansberg, Phys.Rept. 889 (2020)

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- It will be needed to re-evaluate its impact $\rightarrow$ as M. Rinaldi will discuss

General structure of NLO corrections

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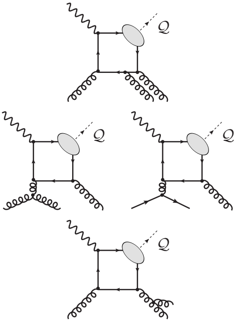

Singularities at NLO [and how they are removed]:

- Real emission
  - Infrared divergences: Soft [cancelled by loop IR contr. after phase-space integration (the KLN theorem)]
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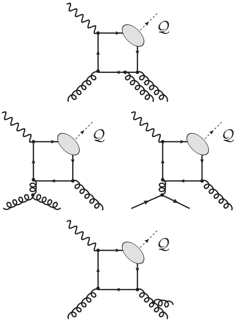

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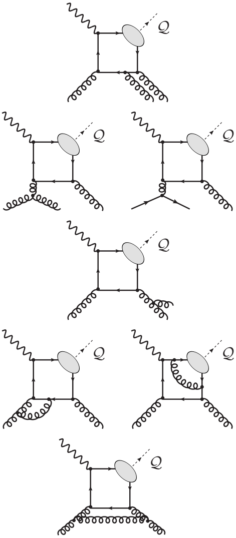

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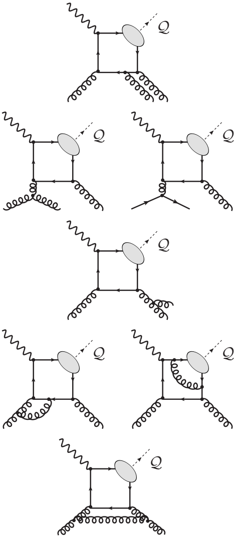

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- Virtual (loop) contribution
  - Ultraviolet divergences: [removed by renormalisation]
  - Infrared divergences: [cancelled by real Infrared contribution]

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Part II

Photoproduction at mid and high P_T at HERA

Different contributions in the CSM up to NLO

C.Flore, JP Lansberg, H.S. Shao, YY, PLB 811 (2020) 135926

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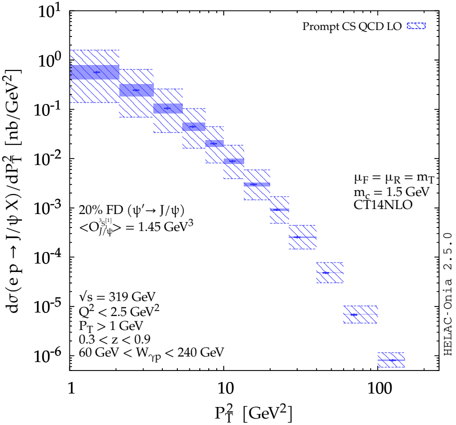

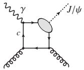

$\gamma + g \to \psi + g$ @ $\alpha\alpha_s^2$

Notes:
All the computations were done with HELAC-ONIA. The scale and mass uncertainties are shown by the hatched and solid bands. **H.S. Shao, CPC198 (2016) 238**; See also `https://nloaccess.in2p3.fr`

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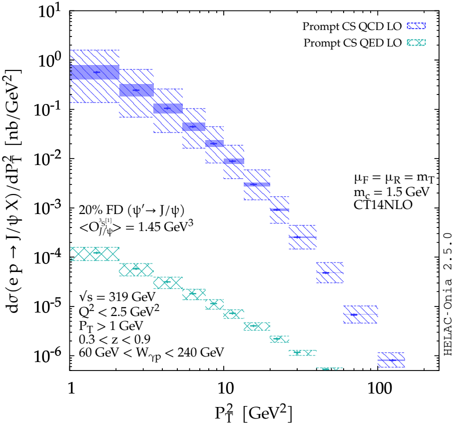
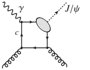
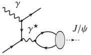




$$\gamma + g \to \psi + g \,@\, \alpha\alpha_s^2$$



$$\gamma + q \to \psi + q \,@\, \alpha^3$$ [NEW !]

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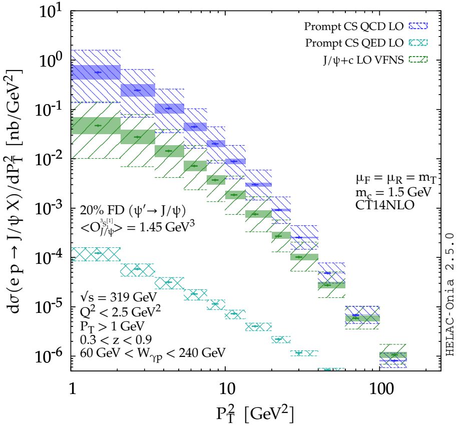

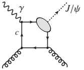

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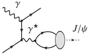

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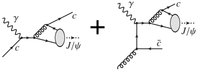

$\gamma + c \to \psi + c$ @ $\alpha\alpha_s^2$ w. 4 Flavour Scheme

$\gamma + g \to \psi + c + \bar{c}$ @ $\alpha\alpha_s^3$ w. 3 Flavour Scheme

VFNS [also NEW !]

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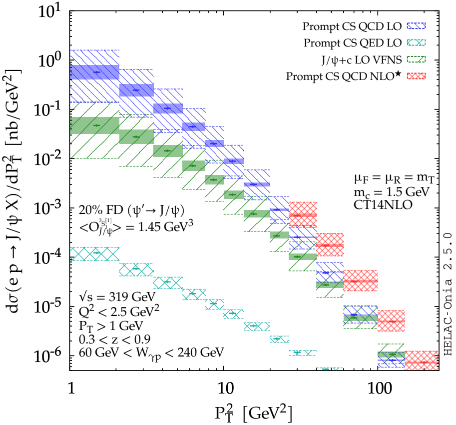

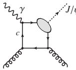

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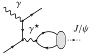

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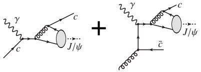

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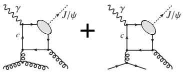

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NLO⋆ only contains the real-emission contributions with an IR cut-off and is expected to account for the leading P_T contributions at NLO (P_T^{-6}). It has been succesfully checked against full NLO computations for $P_T > 3$ GeV.

Comparison to the latest HERA data by H1

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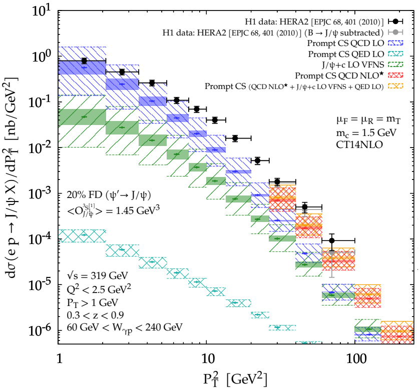

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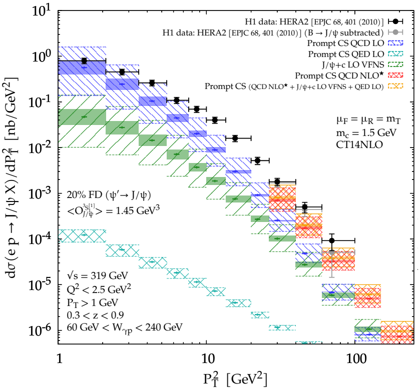

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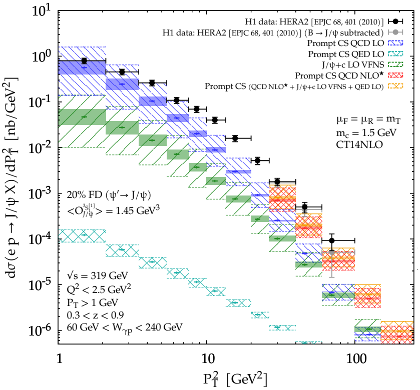

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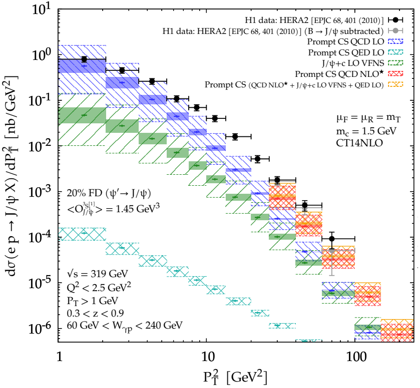

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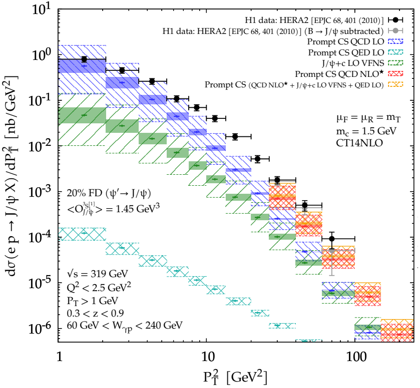

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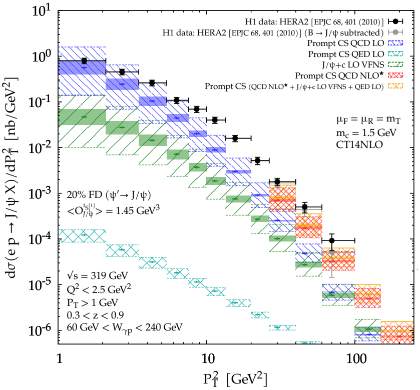

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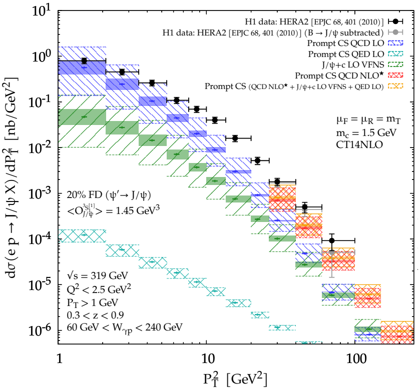

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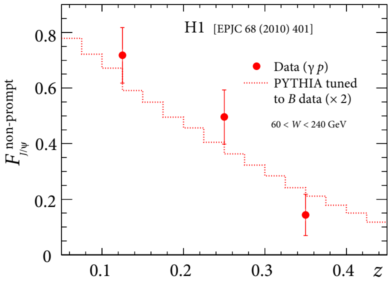
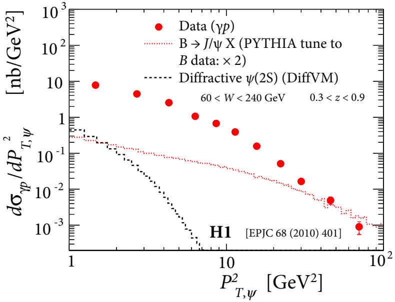
The CSM up to $\alpha\alpha_s^3$ reproduces photoproduction at HERA

$\rightarrow$ the EIC predictions can rely on CSM only

Feed down

J.P. Lansberg, Phys.Rept. 889 (2020); C.Flore, JP Lansberg, H.S. Shao, YY, PLB 811 (2020) 135926





- b FD (5% on the P_T-integrated yields and can go up to $\approx$ 50% at $P_T = 10$ GeV): we do not include it as it can be experimentally removed.

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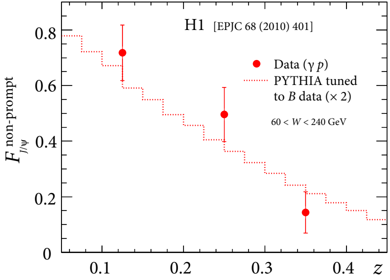

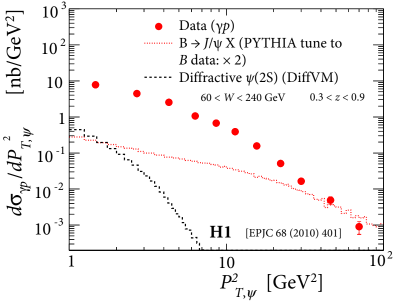

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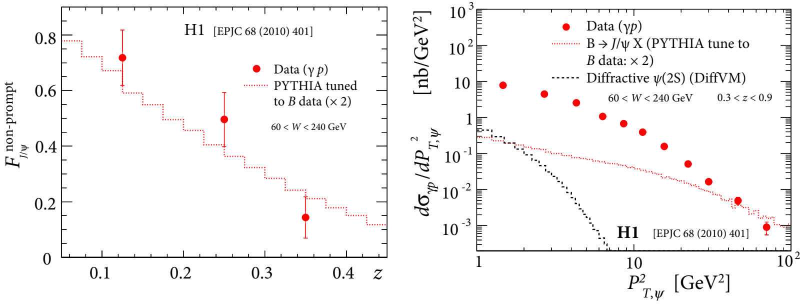

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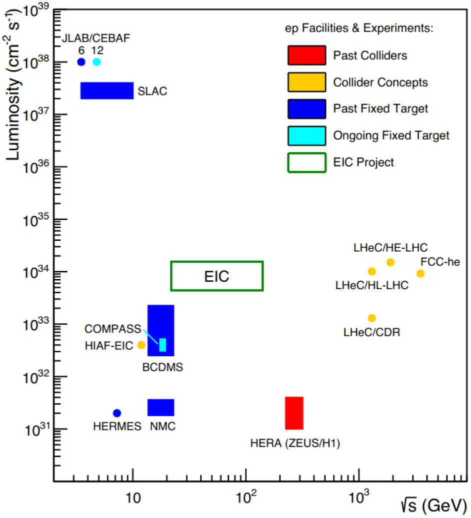
- 20% ψ' FD: follows from the ratio of the wave functions at the origin and from the $\psi' \to J/\psi$ branching: $FD_{\psi'\to J/\psi} = |R_{\psi'}(0)|^2/|R_{J/\psi}(0)|^2\ Br(\psi' \to J/\psi)$

Part III

Photoproduction at mid and high P_T at the Electron-Ion Collider

The Electron Ion Collider at BNL

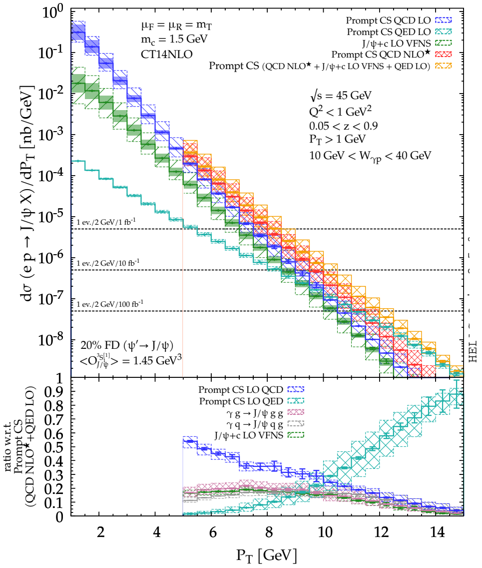
Abhay Deshpande EIC @ BNL, HiX at Kolympari



- Hadrons up to 275 GeV
- Electrons up to 5-10(20) GeV
- CoM $\sqrt{s}$: 20-100 (140) GeV
- High luminosity $L_{ep} \propto 10^{33-34} cm^{-2} sec^{-1}$ (100-1000 times HERA)
- World's first:
  - collider with polarized (min 70%) lepton & proton/light-ion beams
  - electron-Nucleus collider

Predictions for the EIC : $J/\psi + X$ ($\sqrt{s_{ep}} = 45$ GeV)

C.Flore, JP Lansberg, H.S. Shao, YY, PLB 811 (2020) 135926



- At $\sqrt{s_{ep}} = 45$ GeV, one gets into valence region
- Yield steeply falling with P_T
- Yield can be measured up to $P_T \sim 11$ GeV with $\mathcal{L} = 100$ fb^{-1}

  [using both *ee* and $\mu\mu$ decay channels and $\varepsilon_{J/\psi} \simeq 80\%$]
- QED contribution leading at the largest reachable P_T
- photon-quark fusion contributes more than 30 % for $P_T > 8$ GeV

Predictions for the EIC : $J/\psi + X$ ($\sqrt{s_{ep}} = 140$ GeV)

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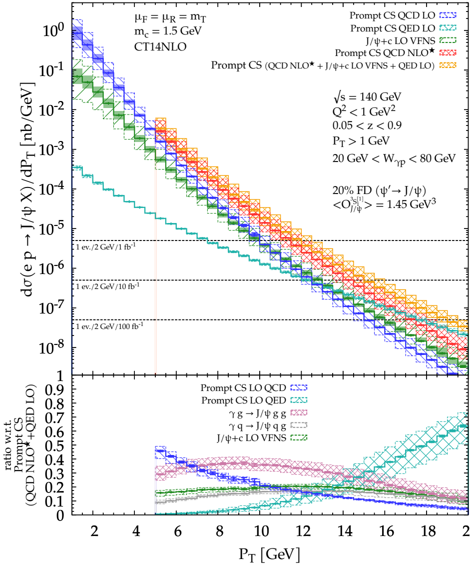

- At $\sqrt{s_{ep}} = 140$ GeV, larger P_T range up to approx. 18 GeV
- QED contribution also leading at the largest reachable P_T
- photon-gluon fusion contributions dominant up to approx. 15 GeV
- $J/\psi + 2$ hard partons [*i.e.* $J/\psi + \{gg, qg, c\bar{c}\}$] dominant for $P_T \sim 8 - 15$ GeV
- It could lead to the observation of $J/\psi + 2$ jets with moderate $P_T^{\rm jet}$
- with a specific topology where the leading jet$_1$ recoils on the $J/\psi+$ jet$_2$ pair
- We expect the $d\sigma$ to vanish when $E_{\rm jet_2}^{J/\psi \text{ rest fr.}} \to 0$

Part IV

J/ψ+charm associated production at the EIC

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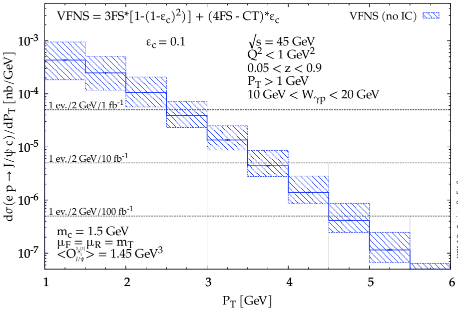

- Same LO VFNS computation previously shown in green except for the charm-detection efficiency ϵ_c: $\sigma^{VFNS} = \sigma^{3FS} \times (1-(1-\epsilon)^2) + (\sigma^{4FS} - \sigma^{CT}) \times \epsilon$
- At $\sqrt{s_{ep}} = 45$ GeV, yield limited to low P_T even with $\mathcal{L} = 100$ fb^{-1}
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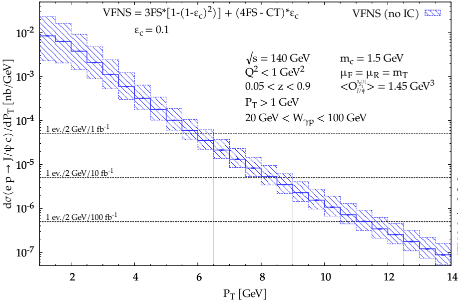
J/ψ+charm associated production at the EIC

C.Flore, JP Lansberg, H.S. Shao, YY, PLB 811 (2020) 135926



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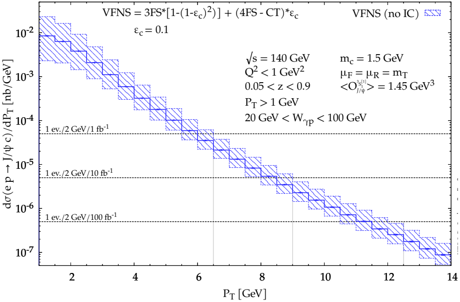

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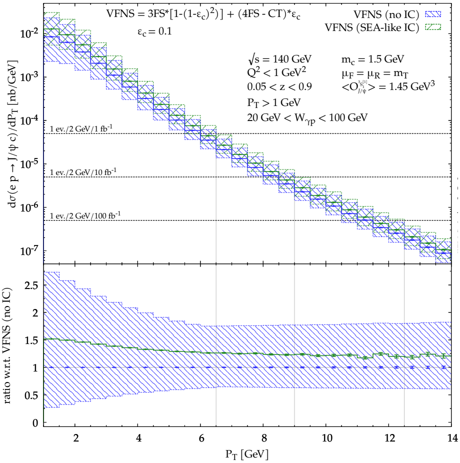

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- Small effect at $\sqrt{s_{ep}} = 140$ GeV [We used IC $c(x)$ encoded in CT14NNLO]

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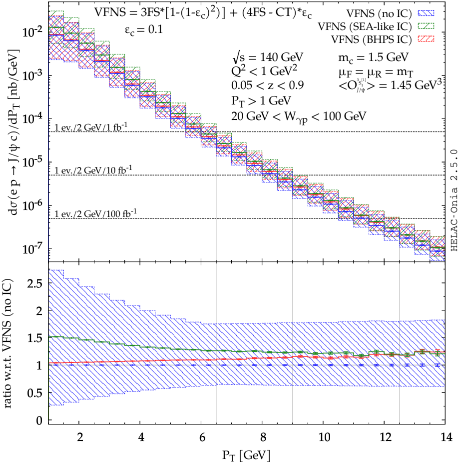

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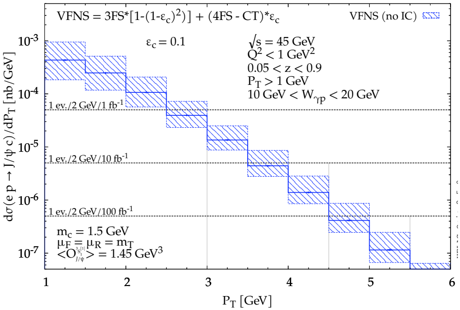

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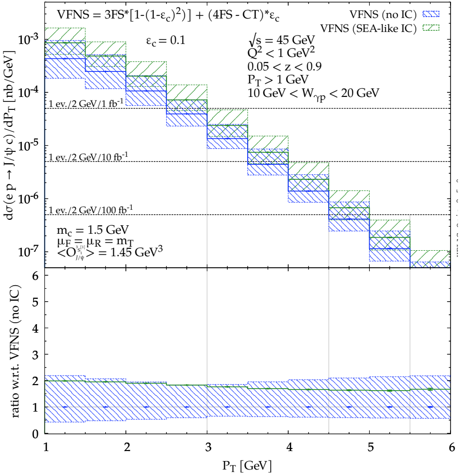

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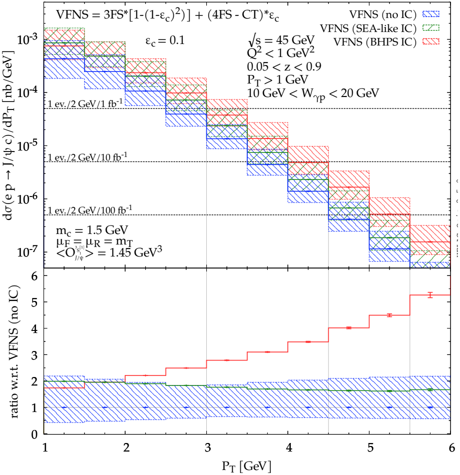

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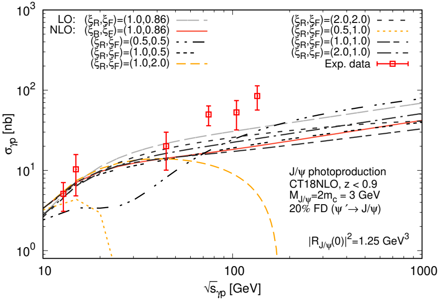
- Measurable effect at $\sqrt{s_{ep}} = 45$ GeV: BHPS valence-like peak visible !

Part V

Study of the impact of the NLO corrections to P_T-integrated photoproduction cross section

The negative cross-sections issue at high energies

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, YY: arXiv:2112.05060 [hep-ph]



Exp. data: H1 - M.Kraemer: NPB 459(1996)3-50, FTPS - B.H.Denby et al.: PRL 52(1984)795-798, NAI - NA14Collaboration, R.Barate et al.:Z.Phys.C 33(1987)505

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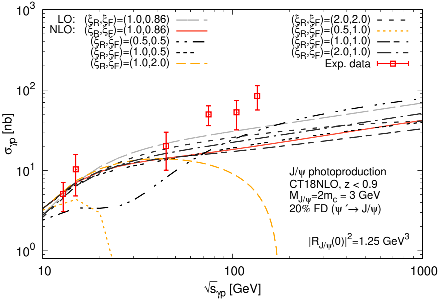

- NLO cross section for J/ψ photoproduction becomes negative for large μ_F when $\sqrt{s_{\gamma p}}$ increases

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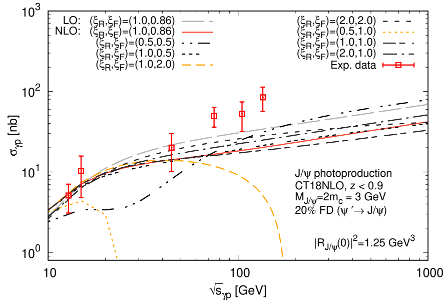

- NLO cross section for J/ψ photoproduction becomes negative for large μ_F when $\sqrt{s_{\gamma p}}$ increases
- For $\mu_F = 2M$, $\sigma < 0$ as in case of η_c hadroproduction

J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497

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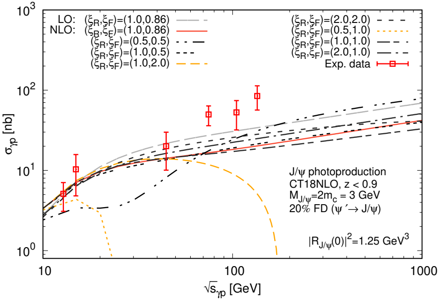

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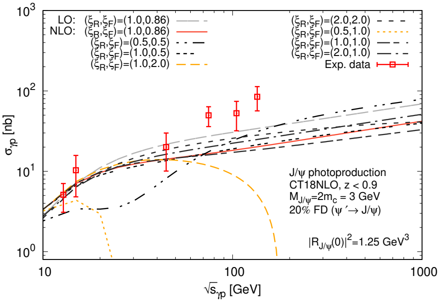
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497

- 2 possible sources of negative partonic cross sections: loop corrections (interference) and from real emission (subtraction of IR poles)

Exp. data: H1 - M.Kraemer: NPB 459(1996)3-50, FTPS - B.H.Denby et al.: PRL 52(1984)795-798, NAI - NA14Collaboration, R.Barate et al.:Z.Phys.C 33(1987)505

Negative cross-section values

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, YY: arXiv:2112.05060 [hep-ph]



- Initial state collinear divergences are removed via the subtraction into the PDFs via AP-CT

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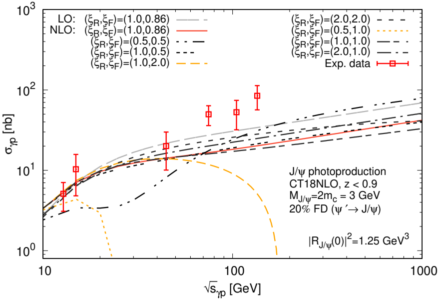

- Initial state collinear divergences are removed via the subtraction into the PDFs via AP-CT
- $\lim_{\hat{s}\to\infty} \hat{\sigma}^{NLO}_{\gamma i} \propto \left(\log \frac{M_{\mathcal{Q}}^2}{\mu_F{}^2} + A_{\gamma i}\right)$, $A_{\gamma g} = A_{\gamma q}$

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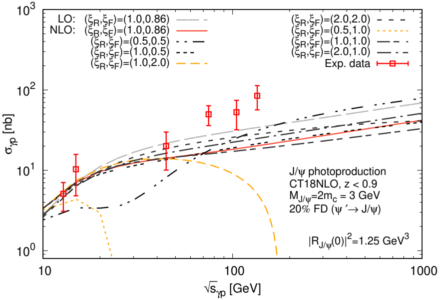

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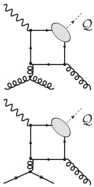
- If large $\mu_F \to \hat{\sigma} < 0 \to \sigma < 0$: over-subtraction from AP-CT into the PDFs

A scale prescription for μ_F

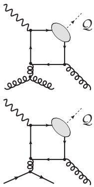
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497



- In principle, such negative terms should be compensated by the evolution of the PDFs governed by the DGLAP equations;

A scale prescription for μ_F

J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497



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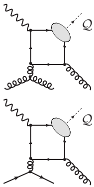
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497



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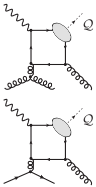
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497



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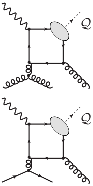
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497



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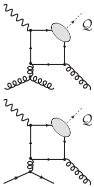
- The choice of factorisation scale to avoid possible negative hadronic cross-section: (for $\eta_Q: \ A_{gi} = -1$) $\mu_F = \hat{\mu}_F = Me^{A_{\gamma i}/2}$;

A scale prescription for μ_F

J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497



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- The choice of factorisation scale to avoid possible negative hadronic cross-section: (for $\eta_Q:\ A_{gi} = -1$) $\mu_F = \hat{\mu}_F = Me^{A_{\gamma i}/2}$;
- For J/ψ (Υ) photoproduction: $\hat{\mu}_F = 0.86M$ ($P_T \in [0,\infty],\ z < 0.9$)

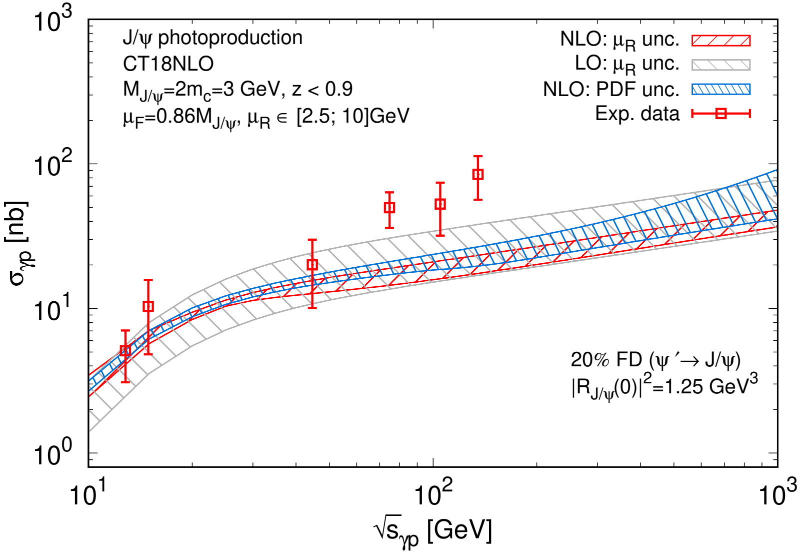
HEF: resummation of collinear emission contributions

J.P. Lansberg, M.Nefedov, M.A. Ozcelik: 2112.06789 [hep-ph]

- Mellin transformation: $f(N) = \int_0^1 dx\, x^{N-1} f(x)$, we can rewrite $\hat{\sigma}$ from x to N space
- From the DGLAP equations we know that: $f(N, \hat{\mu}_F) \approx f(N, \mu_0) exp(\frac{2A\alpha_s(\mu_0)C_A}{\pi N})$, where we used $\gamma_{gg}(N) \approx \frac{2C_A}{N}$; $\alpha_s \neq \alpha_s(\mu)$, μ_0 is the default scale choice.
- In the exponent we did some approximate resummation of collinear emission contributions for $\hat{s} \to \infty$: $\alpha_s^n \ln^{n-1} \frac{1}{\hat{z}} \to \frac{\alpha_s^n}{N^n}$ for $n = 0$, where $\hat{z} = \frac{M^2}{\hat{s}}$

Results with $\hat{\mu}_F = 0.85M$

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, YY: arXiv:2112.05060 [hep-ph]



Exp. data: H1 - M.Kraemer: Nucl.Phys.B 459(1996)3-50, FTPS - B.H.Denbyet al.: Phys.Rev.Lett. 52(1984)795-798, NAI - NA14Collaboration, R.Barateet al.:Z.Phys.C 33(1987)505

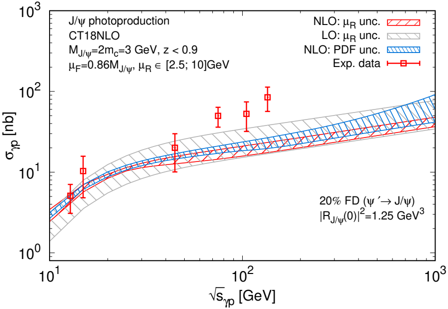
Part VI

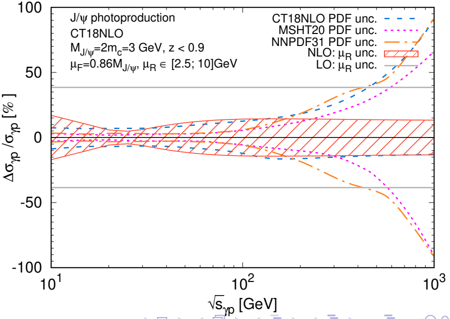
Can J/ψ & Υ allow us to probe PDFs? : PDF vs scale uncertainties

J/ψ: PDF uncertainties of $\sigma(\sqrt{s_{\gamma p}})$

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, YY: arXiv:2112.05060 [hep-ph]

- PDF uncertainties increase at large $\sqrt{s}$ (i.e. small x)
- The μ_R unc. are reduced at NLO in comparison with LO;

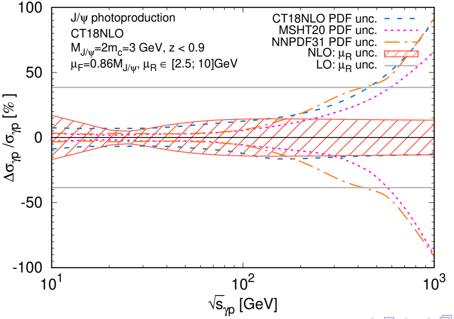




J/ψ: PDF uncertainties of $\sigma(\sqrt{s_{\gamma p}})$

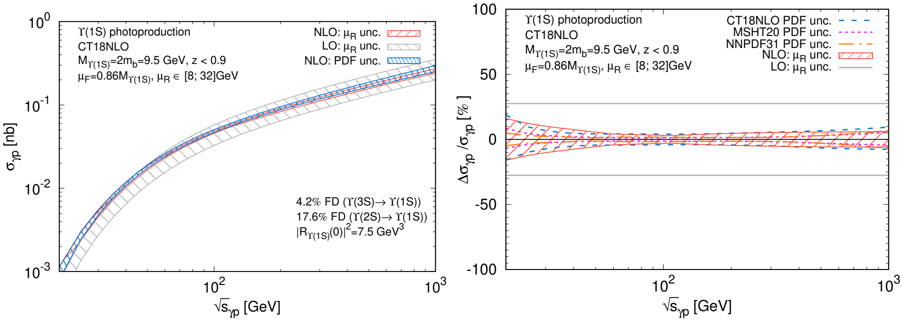
A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, YY: arXiv:2112.05060 [hep-ph]

- PDF uncertainties increase at large $\sqrt{s}$ (i.e. small x)
- The μ_R unc. are reduced at NLO in comparison with LO;
- An increase of μ_R unc. from $\sqrt{s_{\gamma p}} \gtrsim 50$ GeV comes from the loop corrections.
- At NNLO we will have such contributions squared; we expect rather positive NNLO corrections, which will reduce μ_R unc.



Υ photoproduction

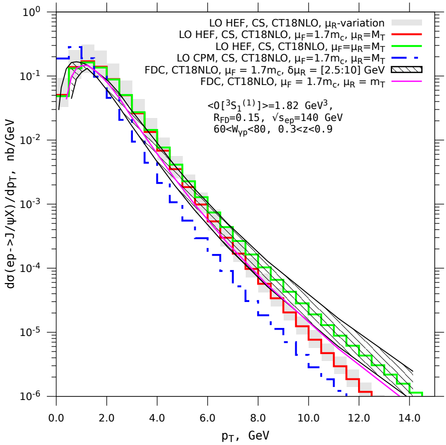
A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, YY: arXiv:2112.05060 [hep-ph]



- We see further reduction of scale uncertainties at NLO comparably to LO
- PDF uncertainties are larger at high $\sqrt{s_{\gamma p}}$: a potential to probe PDFs

Predictions of the high-energy factorization

a private communication with M.Nefedov;

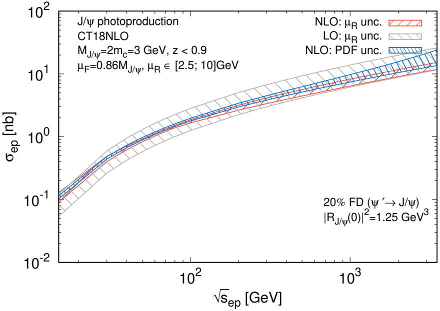


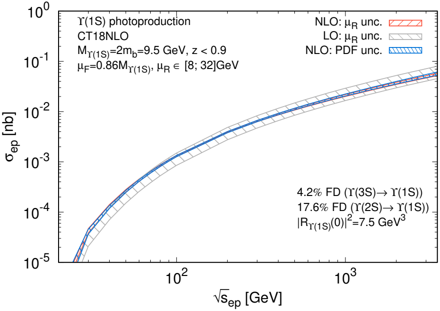
- The Leading-Twist High-Energy factorization (HEF) is the formalism to resum large logarithms $\ln(1/z_+)$ in higher-order corrections to the CF description of inclusive $l-h$ & $h-h$ reactions
- No significant difference with NLO at low p_T
- However, at large P_T HEF may be not applicable
- We need a consistent matching with NLO CF calculation

NB: $z_+ = p^+_{J/\psi}/(x_1 P^+)$: LC $k^\pm = k^0 \pm k^3$, x_1 is the momentum fraction of the parton initiating the hard process, $P^+ = 2E_p$ - (+)-comp. of p moment.

$\sigma_{ep}(\sqrt{s})$

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, YY: arXiv:2112.05060 [hep-ph]





Exp.	$\sqrt{s_{ep}}$	$\mathcal{L}$ (fb^{-1})	$N_{J/\psi}$	$N_{\Upsilon(1S)}$
EIC	45	100	$8.5^{+0.5}_{-1.0} \cdot 10^6$	$7.8^{+0.9}_{-1.1} \cdot 10^2$
EIC	140	100	$2.5^{+0.1}_{-0.4} \cdot 10^7$	$9.7^{+0.3}_{-0.9} \cdot 10^3$

$$N_{\psi'} \simeq 0.08 \times N_{J/\psi},$$
$$N_{\Upsilon(2S)} \simeq 0.5 \times N_{\Upsilon(1S)},$$
$$N_{\Upsilon(3S)} \simeq 0.4 \times N_{\Upsilon(1S)}$$

We expect μ_R unc. to shrink at NNLO: possibility to constrain PDF

Part VII

Electroproduction of J/ψ and Υ

Inclusive electroproduction

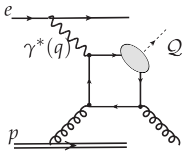
J.P. Lansberg, Phys.Rept. 889 (2020); Z. Sun, H.F. Zhang, Phys.Rev.D 96 (2017) 9, 091502; J.W. Qiu, X.P. Wang, H. Xing, Chin.Phys.Lett. 38 (2021) 4, 041201

- In inclusive $J/\psi(\Upsilon)$ production:

$$\gamma(Q^2 > Q_0^2) + p \to J/\psi + X;$$

for $Q_0^2 \approx (1, 1.5)\text{GeV}^2$

- Small resolved contributions
- Larger Q^2 (higher resolution) suppress the gluon saturation effects and also improve the perturbative expansion in α_s
- The computation more complicated
- σ is suppressed $1/Q^4$; only 4 exp. studies: H1 (Eur.Phys.J.C 10 (1999), 373-393);Eur.Phys.J.C 25 (2002), 41-53;Eur.Phys.J.C 68 (2010), 401-420), ZEUS (Eur.Phys.J.C 44 (2005), 13-25)

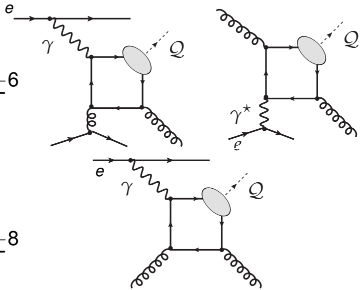


Photoproduction vs electroproduction of J/ψ

J.W. Qiu, X.P. Wang, H. Xing, Chin.Phys.Lett. 38 (2021) 4, 041201

$\propto p_T^{-6}$

$\propto p_T^{-8}$



- The electroproduction could scale as $\propto p_T^{-6}$ and the photoproduction as $\propto p_T^{-8}$

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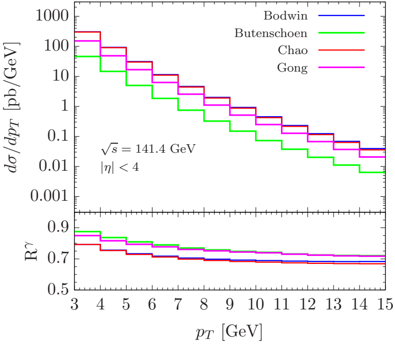
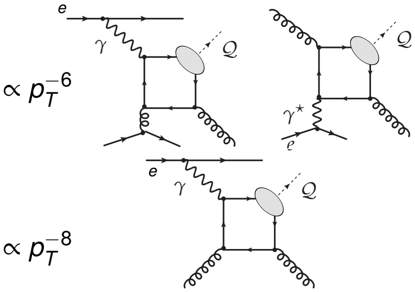
J.W. Qiu, X.P. Wang, H. Xing, Chin.Phys.Lett. 38 (2021) 4, 041201



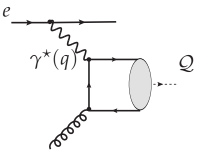


- The electroproduction could scale as $\propto p_T^{-6}$ and the photoproduction as $\propto p_T^{-8}$
- $R^\gamma = 1$: only photoproduction; $R^\gamma = 0$: only electroproduction
- So, at higher p_T the effect for electroproduction will be larger

LDME study with electroproduction of J/ψ

J.W. Qiu, X.P. Wang, H. Xing, Chin.Phys.Lett.38 (2021) 4, 041201

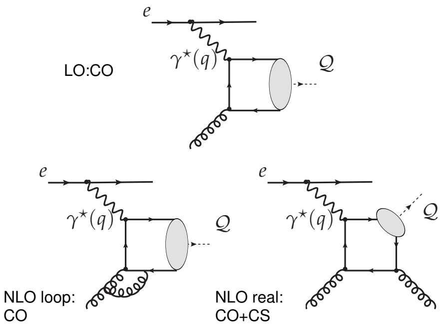
LO:CO



- At LO only color octet ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ $c\bar{c}$ pair can contribute to high p_T J/ψ production in ep collisions

LDME study with electroproduction of J/ψ

J.W. Qiu, X.P. Wang, H. Xing, Chin.Phys.Lett.38 (2021) 4, 041201



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- For NLO real contribution, all four leading $c\bar{c}$ states (${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$) contribute

LDME study with electroproduction of J/ψ

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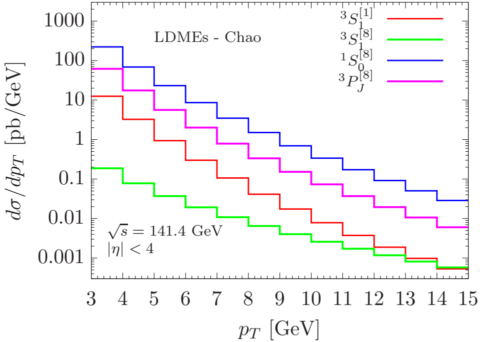
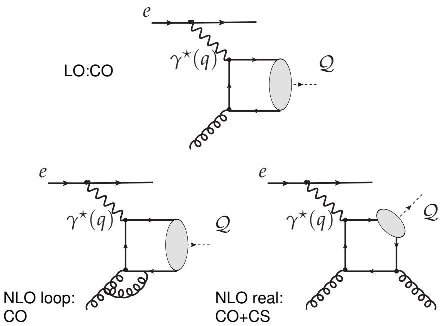
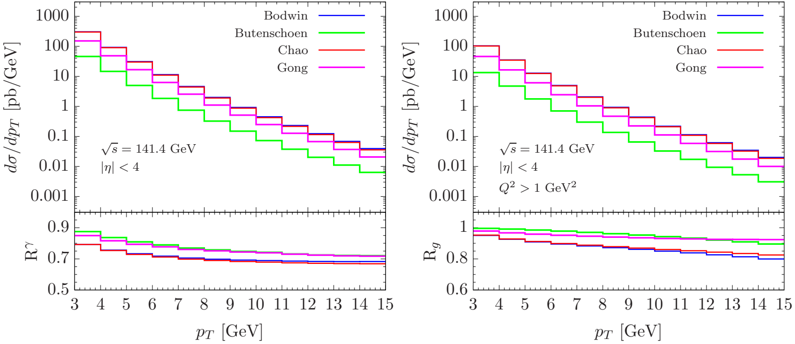




- At LO only color octet $^1S_0^{[8]}$ and $^3P_J^{[8]}$ $c\bar{c}$ pair can contribute to high p_T J/ψ production in *ep* collisions
- For NLO real contribution, all four leading $c\bar{c}$ states ($^3S_1^{[1]}$, $^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$) contribute
- If $^1S_0^{[8]}$ dominates, since it is unpolarised, high-p_T J/ψ produced in inclusive *ep* collisions are expected to be unpolarized.

Introducing inclusive electroproduction of J/ψ

J.W. Qiu, X.P. Wang, H. Xing, Chin.Phys.Lett.38 (2021) 4, 041201



- Different sets of LDMEs lead to very different production rate $\rightarrow$ could provide new insights into the J/ψ production mechanism
- $R_g \rightarrow 1$ (the gluon initiated fraction of total $d\sigma$): the production is dominated by initial gluon channel (as for photoproduction: s.12) $\rightarrow$ a good observable to probe the initial gluon PDF

Part VIII

Conclusions

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- The EIC predictions can rely on CSM only
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- A specific μ_F choice can be employed to avoid a possible over subtraction of collinear divergences which lead to NLO negative σ values at large $\sqrt{s_{\gamma p}}$
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- This would likely allow one to better probe gluon PDFs
- Inclusive electroproduction of J/ψ measured at the EIC could allow for new constraints of the gluon PDF over a wide range of scales
- The EIC could provide the 1st measurement of Υ electroproduction

Backup

Feed down

C.Flore, JP Lansberg, H.S. Shao, YY, PLB 811 (2020) 135926

- b FD (5% on the P_T-integrated yields and is significant around $P_T = 10$ GeV): we do not include it as it can be experimentally removed.
- Tune Pythia 8.2 using a b analysis by H1 using di-electrons events which extends to large P_T
  - Compute the corresponding LO+PS cross section using Pythia 8.2
  - Perform a χ^2-minimisation to compute a tuning factor (absorbs the theory uncertainties), such that the obtained LO+PS Pythia spectrum reproduces best the H1 b data
  - Again use Pythia 8.2 to compute the $b \to J/\psi$ cross section in the H1 kinematics.
  - Subtract this $b \to J/\psi$ yield from the inclusive one
- χ_c FD: no theory or experimental indication that it could be relevant
- 20% ψ' FD: follows from the ratio of the wave functions at the origin and from the $\psi' \to J/\psi$ branching: $FD_{\psi' \to J/\psi} = |R_{\psi'}(0)|^2 / |R_{J/\psi}(0)|^2 \; Br(\psi' \to J/\psi)$

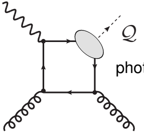
Basic pQCD approach: the Colour Singlet Model (CSM)

C.-H. Chang, NPB172, 425 (1980); R. Baier & R. Rückl Z. Phys. C 19, 251(1983);

One supposes two **factorisations**:

1. **collinear**, in which the hadronic cross section can be written as the convolution of the **PDFs** with the **partonic cross section**;
2. between the hard part (a perturbative amplitude, which describes the $Q\bar{Q}$ **pair production**) and the soft part (a non-perturbative matrix element, which describes **hadronisation**):

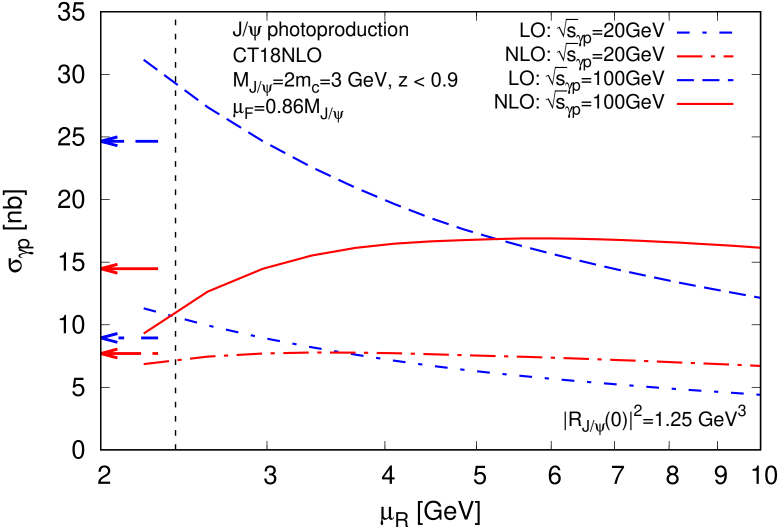
- Perturbative creation of 2 quarks, Q and $\bar{Q}$
  - on-shell
  - in a colour singlet state
  - with a vanishing relative momentum
  - in a $^3S_1$ state (for J/ψ, ψ' and Υ)
- Non-perturbative binding of quarks
  $\rightarrow$ Schrödinger wave function at $r = 0$



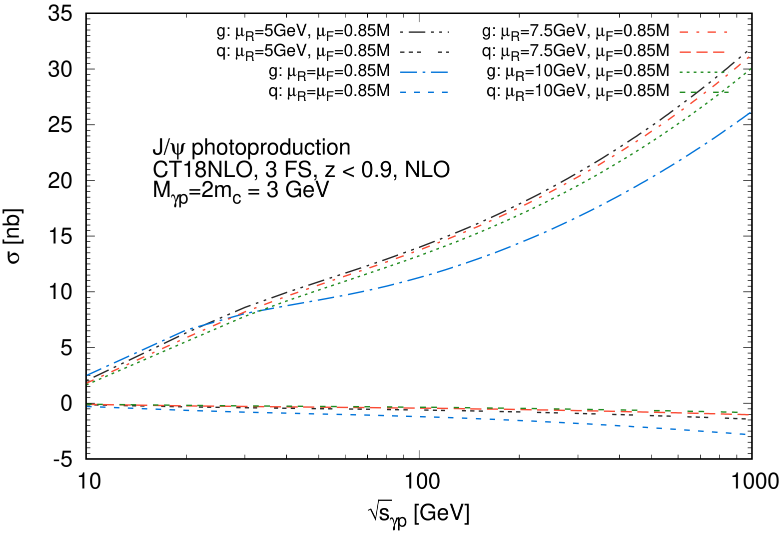
LO J/ψ photoproduction graph

CSM: the Taylor series expansion of the amplitude in the $Q\overline{Q}$ relative momentum (v) to the first non-vanishing (Leading-v NRQCD) term.

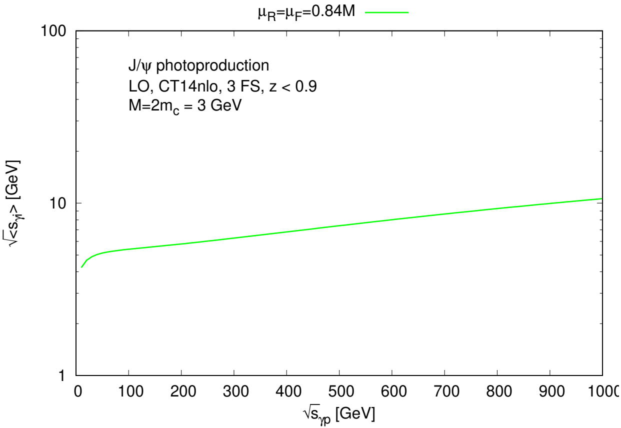
Dependence of $\sigma_{\gamma p}$ on the μ_R at an initial photon energy $s_{\gamma p}$



q& g contributions

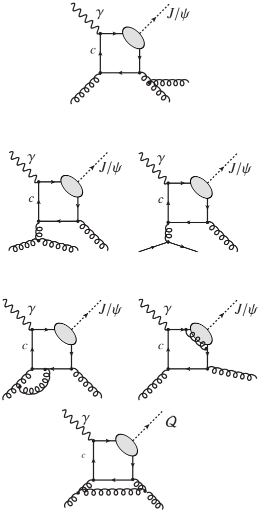


μ_R choice



1. the natural scale choice in case of J/ψ photoproduction is not a mass of c-quark, becase of some loop corrections.
2. For J/ψ: $\mu_{Rmin} = 1.6 m_c$ ($\sqrt{s_{\gamma p}} = 10\text{GeV}$)

NLO*: P_T-discussion



IR cut-off - a lower cut on the invariant mass of each pair of massless partons, s_{ij}.

$\ln(s_{ij}^{min})(1/p_T)^N$, $N \geq 8$

If the initial gluon/quark emits a large-p_T gluon/quark and if the final gluon is semi-hard, the increase of p_T results in the growth of all the possible $s_{ij} -> (1/p_T)^6$

We do not consider loop corrections in NLO*: $(1/p_T)^8$