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NLO QCD corrections to inclusive J/ψ and Υ photoproduction cross sections at the EIC

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anr STRONG 2020 INVESTIR L'AVENIR

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

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

We will discuss **inclusive J/ψ (Υ) photoproduction**:

- 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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- inclusive photoproduction:

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

- We will discuss the photoproduction at NLO;
- 3 common models (differences in the treatment of the hadronisation):
  - Colour Singlet Model;
  - NRQCD and Colour Octet Mechanism;
  - Colour Evaporation Model;

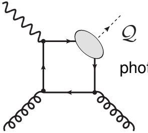
Basic pQCD approach: the Colour Singlet Model (CSM)

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 $r = 0$

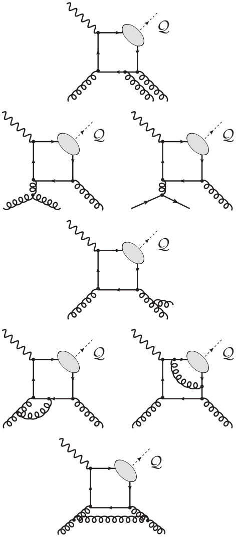


LO J/ψ photoproduction graph

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

General structure of NLO corrections

M. Krämer, Nucl.Phys., B459, 3 (96')



Singularities at NLO [and how they are removed]:

- Real emission
  - Infrared divergences: Soft [cancelled by loop IR contr.]
  - Infrared divergences: Collinear
    - ★ initial state [subtracted via "renormalisation" of collinear PDFs (Altarelli-Parisi counter-terms)]
    - ★ final state [cancelled by loop IR contr.]
- Virtual (loop) contribution
  - Ultraviolet divergences: [removed by renormalisation]
  - Infrared divergences: [cancelled by real Infrared contribution]
- We use the **FDC** code [J.-X. Wang Nucl.Instrum.Meth. A534(2004)241-245] to produce NLO results

[The quark and antiquark attached to the blob are taken as on-shell and their relative velocity v is set to zero.]

Part I

Photoproduction at mid and high P_T at HERA

Different contributions in the CSM up to NLO

NLO*: C.Flore, J.-P. Lansberg, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

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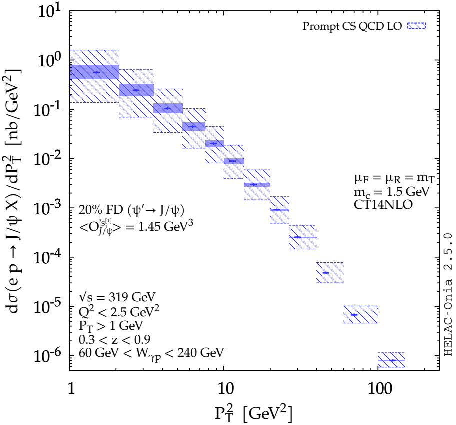

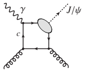

$\gamma + g \to \psi + g$ @ $\alpha\alpha_s^2$

Notes:
The computations were done with HELAC-Onia and FDC. The scale and mass uncertainties are shown by the hatched and solid bands. HELAC-Onia: **H.S. Shao, CPC198 (2016) 238; FDC: J.-X. Wang Nucl.Instrum.Meth. A534(2004)241-245**; See also https://nloaccess.in2p3.fr

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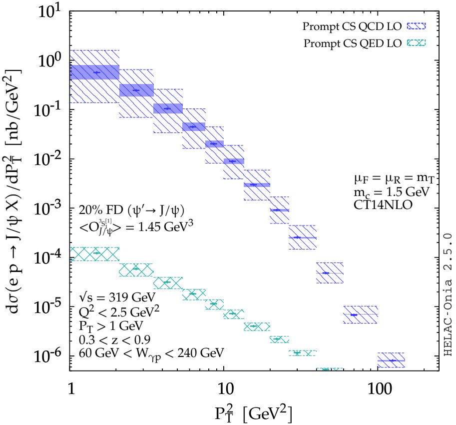

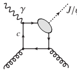

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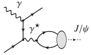

$\gamma + q \to \psi + q$ @ α^3 [NEW !]

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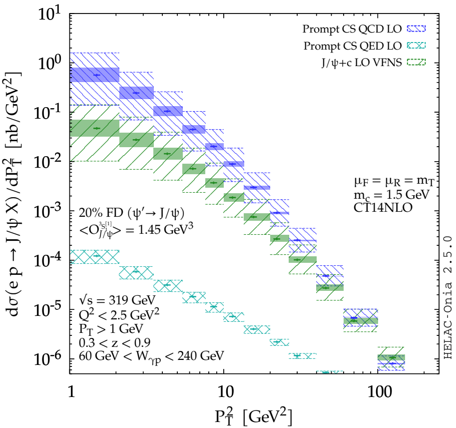

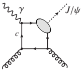

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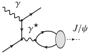
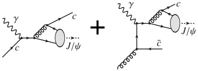


$\gamma + q \to \psi + q \,@\, \alpha^3$ [NEW !]



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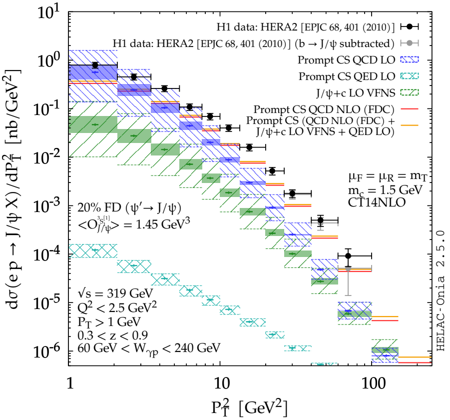

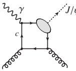

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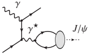
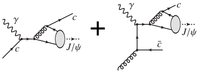


$\gamma + q \to \psi + q$ @ α^3 [NEW !]



$\gamma + c \to \psi + c$ @ $\alpha\alpha_s^2$ w. 4 Flavour Scheme
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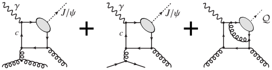
VFNS [also NEW !]



$\gamma + g \to \psi + g + g$ @ $\alpha\alpha_s^3$
$\gamma + q \to \psi + g + q$ @ $\alpha\alpha_s^3$
[+ $\gamma g \to \psi g$ @ 1L]

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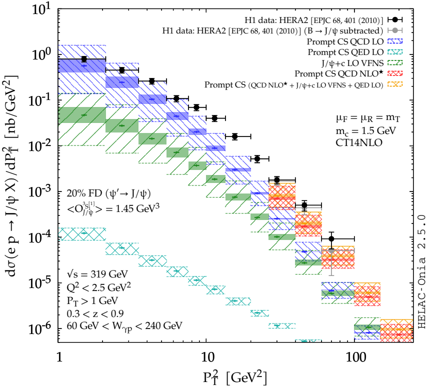

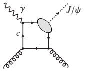

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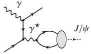

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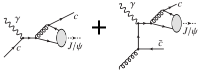

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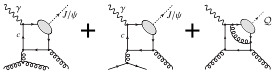


$\gamma + g \to \psi + g + g$ @ $\alpha\alpha_s^3$
$\gamma + q \to \psi + g + q$ @ $\alpha\alpha_s^3$ [+ $\gamma g \to \psi g$ @ 1L]

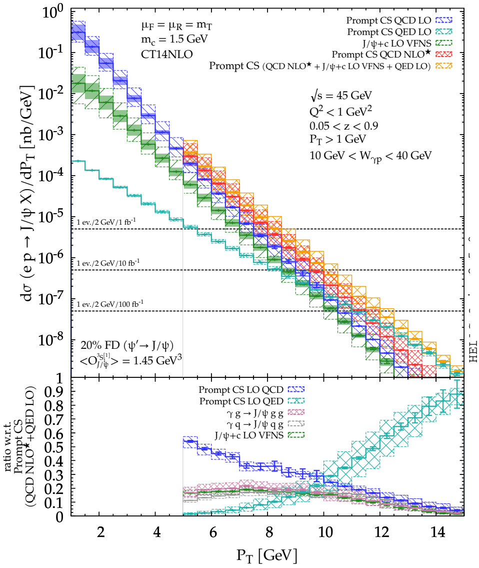
The CSM up to $\alpha\alpha_s^3$ reproduces photoproduction at HERA

Part II

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

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

C.Flore, J.-P. Lansberg, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

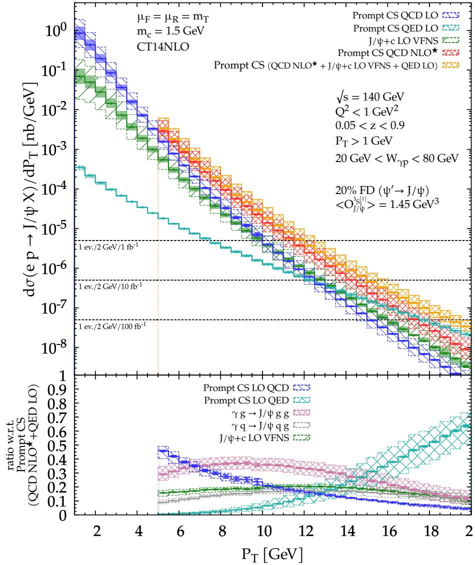


- At $\sqrt{s_{ep}} = 45$ GeV, one gets into valence region
- Yield steeply falling with P_T
- Yield can be measured up to $P_T \sim 11$ GeV with $\mathcal{L} = 100$ fb^{-1}

  [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)

C.Flore, J.-P. Lansberg, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



- 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^{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 $E_{\text{jet}_2}^{J/\psi \text{ rest fr.}} \to 0$

Part III

J/ψ+charm associated production at the EIC

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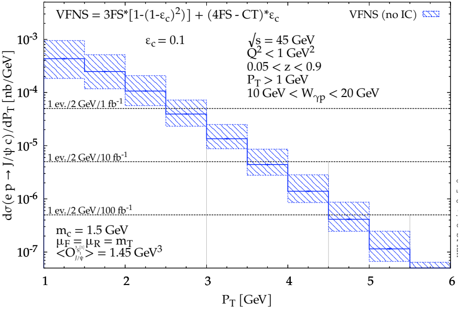

- Same LO VFNS computation previously shown in green except for the charm-detection efficiency ϵ_c: $\sigma^{VFNS} = \sigma^{3FS} \times (1 - (1-\epsilon)^2) + (\sigma^{4FS} - \sigma^{CT}) \times \epsilon$
- At $\sqrt{s_{ep}} = 45$ GeV, yield limited to low P_T even with $\mathcal{L} = 100$ fb^{-1}
- But it is clearly observable if $\epsilon_c = 0.1$ with $\mathcal{O}(500, 50, 5)$ events for $\mathcal{L} = (100, 10, 1)$ fb^{-1}

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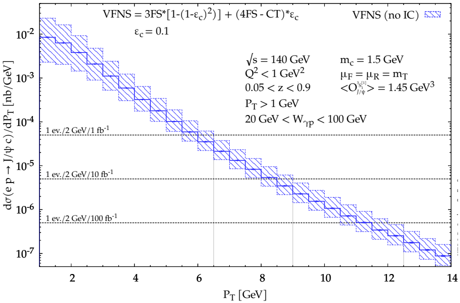

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- At $\sqrt{s_{ep}} = 140$ GeV, P_T range up to 10 GeV with up to thousands of events with $\mathcal{L} = 100$ fb^{-1}
- Could be observed via charm jet

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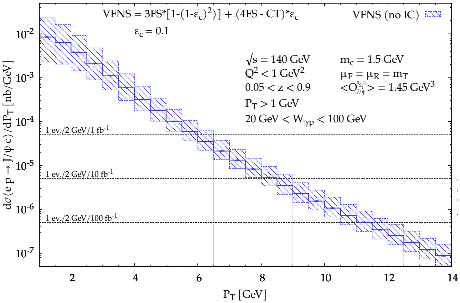

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- 4FS $\gamma c \to J/\psi c$ depend on $c(x)$ and could be enhanced by intrinsic charm

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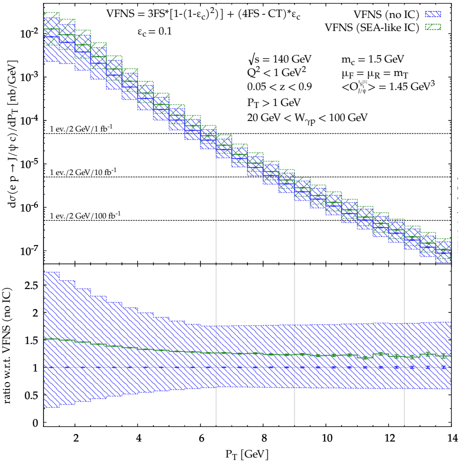

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- Small effect at $\sqrt{s_{ep}} = 140$ GeV [We used IC $c(x)$ encoded in CT14NNLO]

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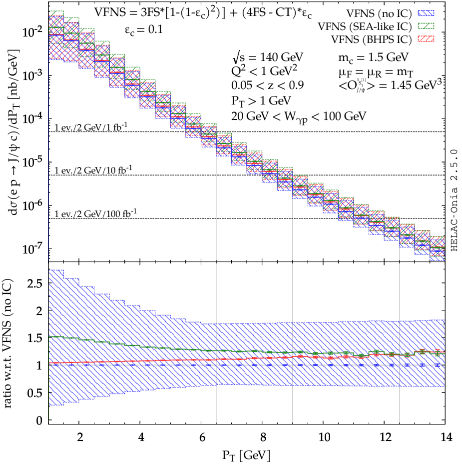

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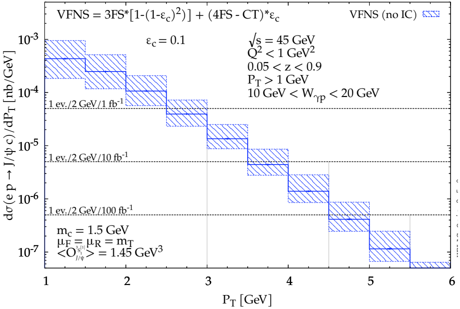

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- Measurable effect at $\sqrt{s_{ep}} = 45$ GeV

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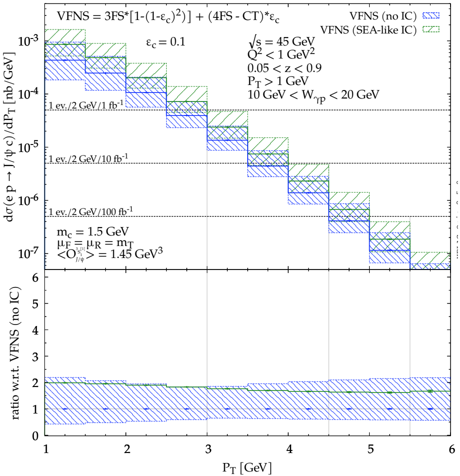

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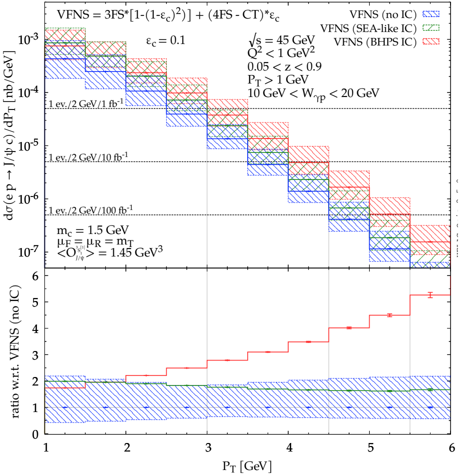
J/ψ+charm associated production at the EIC

C.Flore, J.-P. Lansberg, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



- 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}
- But it is clearly observable if $\epsilon_c = 0.1$ with $\mathcal{O}(500, 50, 5)$ events for $\mathcal{L} = (100, 10, 1)$ fb^{-1}
- At $\sqrt{s_{ep}} = 140$ GeV, P_T range up to 10 GeV with up to thousands of events with $\mathcal{L} = 100$ fb^{-1}
- Could be observed via charm jet

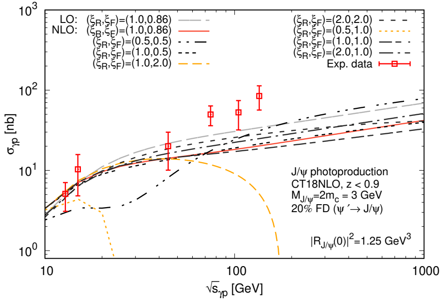
- 4FS $\gamma c \to J/\psi c$ depend on $c(x)$ and could be enhanced by intrinsic charm
- Small effect at $\sqrt{s_{ep}} = 140$ GeV [We used IC $c(x)$ encoded in CT14NNLO]
- Measurable effect at $\sqrt{s_{ep}} = 45$ GeV: BHPS valence-like peak visible !

Part IV

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, Y. Yedelkina: 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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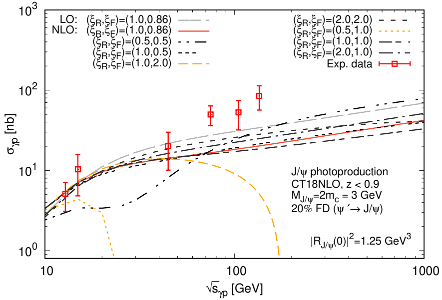

- NLO cross section for J/ψ photoproduction becomes negative for large μ_F when $\sqrt{s_{\gamma p}}$ increases

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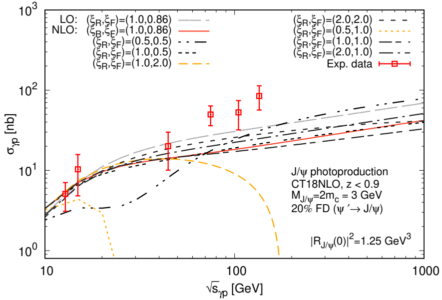

- NLO cross section for J/ψ photoproduction becomes negative for large μ_F when $\sqrt{s_{\gamma p}}$ increases
- For $\mu_F = 2M$, $\sigma < 0$ as in case of η_c hadroproduction

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

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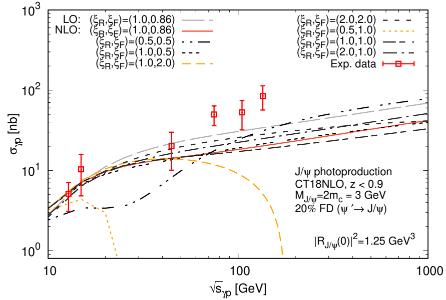

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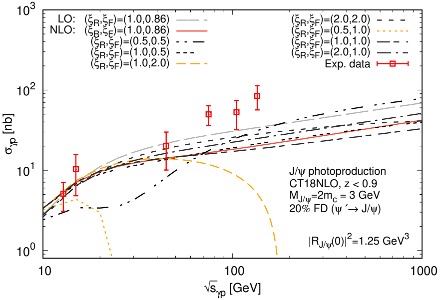
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497

- 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, Y. Yedelkina: arXiv:2112.05060 [hep-ph]



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

Negative cross-section values

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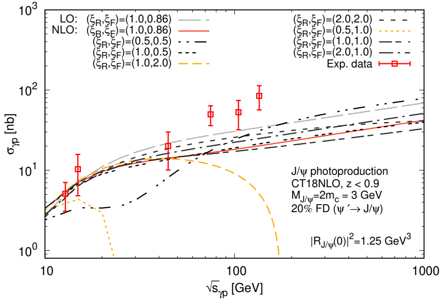
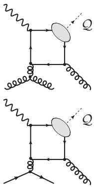


- Initial state collinear divergences are removed via the subtraction into the PDFs via AP-CT
- $\hat{s} \to \infty : \ \hat{\sigma}^{NLO}_{\gamma i} \propto \alpha_s(\mu_R) \left(\bar{c}_1^{(\gamma i)} \log \frac{M_{\mathcal{Q}}^2}{{\mu_F}^2} + c_1^{(\gamma i)} \right), \ A_{\gamma i} = \frac{c_1^{(\gamma i)}}{\bar{c}_1^{(\gamma i)}},$

$$\boxed{A_{\gamma g} = A_{\gamma q}}$$

A scale prescription for μ_F

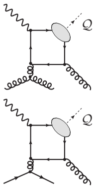
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497



- 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



- In principle, such negative terms should be compensated by the evolution of the PDFs governed by the DGLAP equations;
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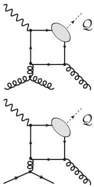
A scale prescription for μ_F

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



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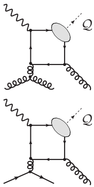
- But as $A_{\gamma g} = A_{\gamma q}$, we can choose μ_F such that $lim_{\hat{s}\to\infty}\hat{\sigma}^{NLO}_{\gamma i} = 0$

A scale prescription for μ_F

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



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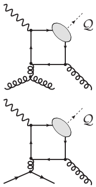
A scale prescription for μ_F

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



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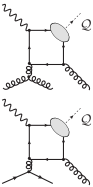
- The choice of factorisation scale to avoid possible negative hadronic cross-section: (for η_Q : $A_{gi} = -1$) $\mu_F = \hat{\mu}_F = Me^{A_{\gamma i}/2}$;

A scale prescription for μ_F

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



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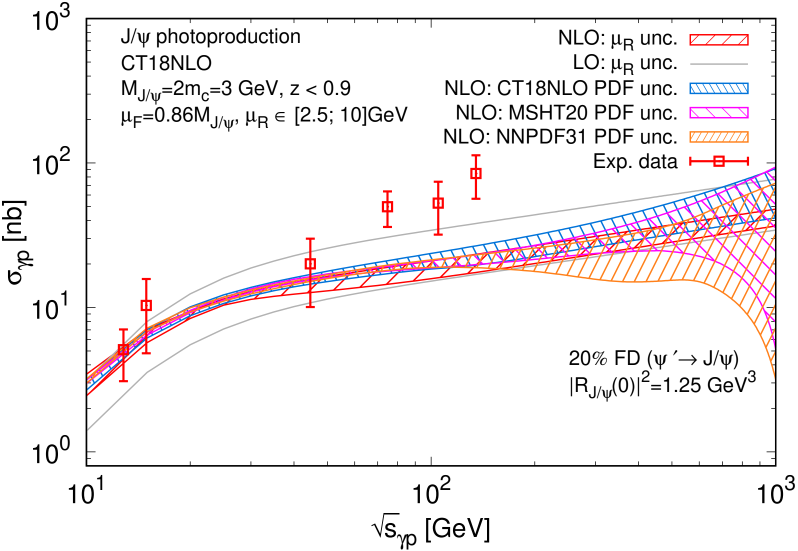
- For J/ψ (Υ) photoproduction: $\hat{\mu}_F = 0.86M$ $(P_T \in [0, \infty],\ z < 0.9)$

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

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



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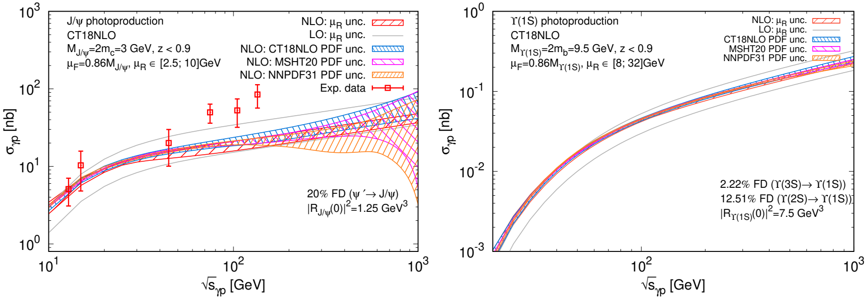
Part V

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

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

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, Y. Yedelkina: 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



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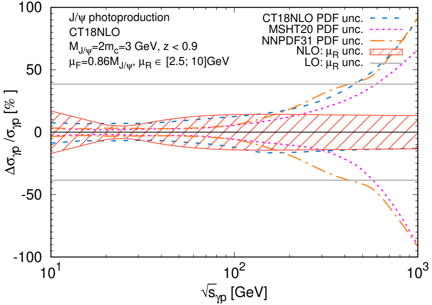
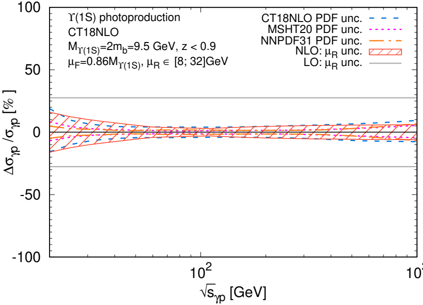
J/ψ&Υ: PDF uncertainties of $\sigma(\sqrt{s_{\gamma p}})$

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, Y. Yedelkina: 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
- Increase of μ_R unc. from $\sqrt{s_{\gamma p}} \gtrsim$ 50 GeV from the loop corr.
- At NNLO we expect a further reduction of μ_R uncertainties





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

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

Exp.	$\sqrt{s_{ep}}$	$\mathcal{L}$ (fb^{-1})	$N_{J/\psi}$	$N_{\Upsilon(1S)}$
EicC	16.7	100	$1.5^{+0.3}_{-0.2}\cdot 10^6$	$2.3^{+1.1}_{-1.4}\cdot 10^0$
AMBER	17.3	1	$1.6^{+0.3}_{-0.3}\cdot 10^4$	< 1
EIC	45	100	$8.5^{+0.5}_{-1.0}\cdot 10^6$	$6.1^{+0.7}_{-0.8}\cdot 10^2$
EIC	140	100	$2.5^{+0.1}_{-0.4}\cdot 10^7$	$7.6^{+0.3}_{-0.7}\cdot 10^3$
LheC	1183	100	$9.3^{+2.9}_{-2.9}\cdot 10^7$	$8.1^{+0.4}_{-0.7}\cdot 10^4$
FCC-eh	3464	100	$1.6^{+0.2}_{-1.0}\cdot 10^8$	$1.8^{+0.1}_{-0.2}\cdot 10^5$

We expect μ_R unc. to shrink at NNLO:
Possibility to constrain PDF with differential measurements

Rem. $N_{\psi'} \simeq 0.08 \times N_{J/\psi}$, $N_{\Upsilon(2S)} \simeq 0.4 \times N_{\Upsilon(1S)}$, $N_{\Upsilon(3S)} \simeq 0.35 \times N_{\Upsilon(1S)}$

Part VI

Conclusions

Conclusions

- The CSM up to $\alpha\alpha_s^3$ reproduces photoproduction at HERA up to scale-uncertainty
- The estimations for EIC can rely on CSM only

Conclusions

- The CSM up to $\alpha\alpha_s^3$ reproduces photoproduction at HERA up to scale-uncertainty
- The estimations for EIC can rely on CSM only
- NLO QCD corrections are important for P_T-integrated σ
- A specific μ_F choice can be employed to avoid a possible over subtraction of collinear divergences which lead to negative NLO σ values at large $\sqrt{s_{\gamma p}}$
- Loop correction matter and significant NNLO corrections (likely positive) are expected as well as a further reduction of the μ_R unc., esp. around 100 GeV
- This would likely allow one to better probe gluon PDFs at small-x and $\mu_F \sim M$.

Backup

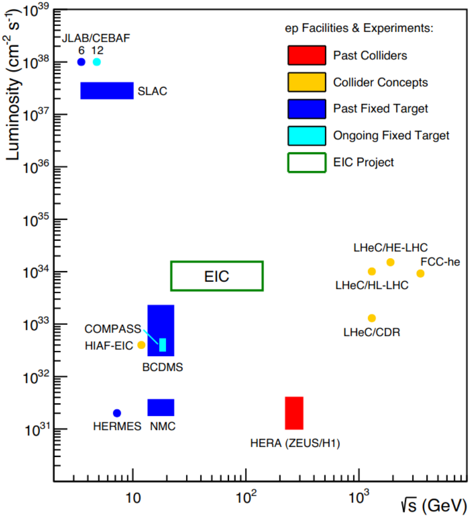
Resolved-photon contributions

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

- At high energies, the hadronic content of the photon can be 'resolved' during the collisions
- Are very similar to those for hadroproduction
- At low z they can appear as important where only a small fraction of the photon energy is involved in the quarkonium production (limited impact at HERA)
- At lower energies, like at the EIC, their impact should be further reduced
- Can be avoided by a simple kinematical cut on low elasticity values, z
- It will be needed to re-evaluate its impact

The Electron Ion Collider at BNL

Abhay Deshpande EIC @ BNL, HiX at Kolympari



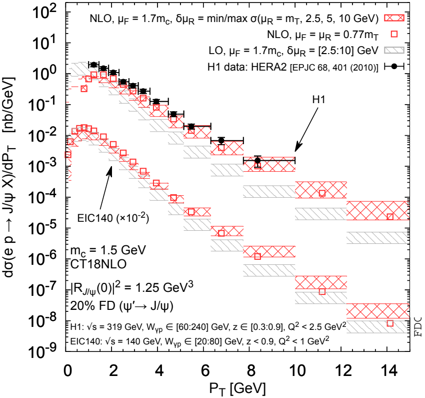
- Hadrons up to 275 GeV
- Electrons up to 5-10(20) GeV
- CoM $\sqrt{s}$: 20-100 (140) GeV
- High luminosity $L_{ep} \propto 10^{33-34} cm^{-2} sec^{-1}$ (100-1000 times HERA)
- World's first:
  - collider with polarized (min 70%) lepton & proton/light-ion beams
  - electron-Nucleus collider

Feed down

C.Flore, J.-P. Lansberg, H.S. Shao, Y. Yedelkina, 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: $FD_{\psi' \to J/\psi} = |R_{\psi'}(0)|^2 / |R_{J/\psi}(0)|^2 \; Br(\psi' \to J/\psi)$

P_T-differential cross sections

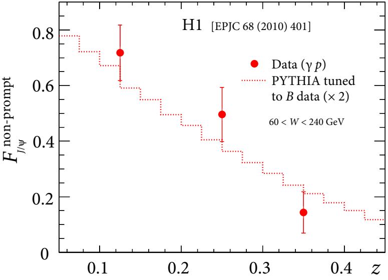


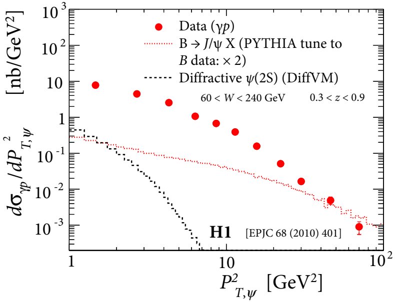
- If p_T-dependence is taken into account, for $\hat{s} \to \infty$: $c_1^{(\gamma i)}(p_T)/\overline{c}_1^{(\gamma i)}(p_T) \propto (P_T/M_{\mathcal{Q}})^2$
- $\Rightarrow \hat{\mu}_F = M e^{c^{(1)}_{\gamma i}/2\overline{c}^{(1)}_{\gamma i}} \propto M e^{P_T^2/M^2}$, which is weird
- Full matched calculation between NLO and $\ln \hat{s}/M^2$-resummation is needed
- Common dynamical scale choice: $\mu_F = (0.5, 1, 2) m_T$

- one can use $\mu_F = \alpha\sqrt{M^2 + P_T^2}$ or $\mu_F = \sqrt{(\beta M)^2 + P_T^2}$
- if P_T is large, then $\mu_F \propto P_T$
- For $\mu_F = \hat{\mu}_F$ with $< P_T^2 >= 2.5\text{GeV}^2$ (for J/ψ at HERA energies), we get $\alpha = 0.77$ and $\beta = 0.7$

Feed down

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





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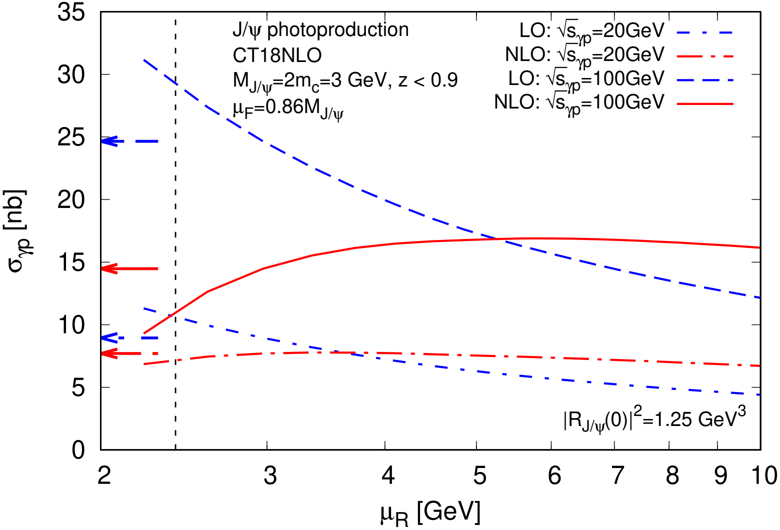
$FD_{\psi' \to J/\psi} = |R_{\psi'}(0)|^2 / |R_{J/\psi}(0)|^2 \; Br(\psi' \to J/\psi)$

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



$\hat{\mu}_F$-prescription as $\ln 1/\hat{z}$ resummation

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

- Mellin transform: $f(N) = \int_0^1 dx\, x^{N-1} f(x)$ maps $\ln 1/x$ to the $1/N$ poles: $\alpha_s^n \ln^{n-1} \frac{1}{\hat{z}} \to \frac{\alpha_s^n}{N^n}$, where $\hat{z} = \frac{M^2}{\hat{s}}$
- LO DGLAP splitting at $z \to 0$:

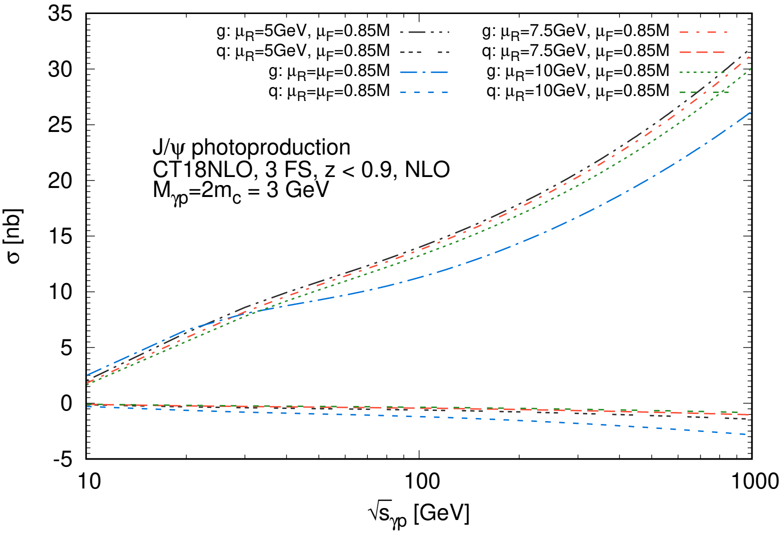
$$\frac{\alpha_s}{2\pi} z P_{gg}(z) \simeq \frac{\alpha_s C_A}{\pi} \to \gamma_{gg}(N) \simeq \frac{\alpha_s C_A}{\pi N}$$

$\Rightarrow$ solution of DGLAP equation in N-space ($\frac{\partial f_g(N,\mu_F)}{\partial \ln \mu_F^2} = \gamma_{gg}(N) f_g(N, \mu_F^2)$) in the DLA ($[\alpha_s / N \ln \mu_F]^n$) with $\hat{\mu}_F = \mu_0 e^{A/2}$ is:

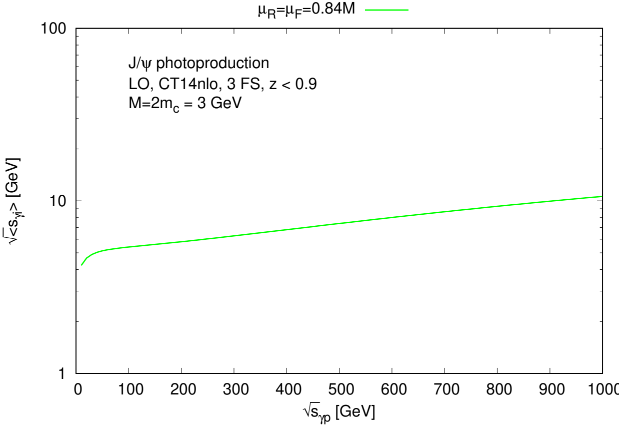
$$f(N, \hat{\mu}_F) \approx f(N, \mu_0) exp\left(\frac{2A\alpha_s(\mu_0) C_A}{\pi N}\right),$$

$\Rightarrow$ In the exponent we did some approximate resummation of collinear emission contributions for $\hat{s} \to \infty$.

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: $\mu_{Rmin} = 1.6 m_c$ ($\sqrt{s_{\gamma p}} = 10\text{GeV}$)