

NLO QCD CORRECTIONS TO INCLUSIVE J/ψ AND Υ PHOTOPRODUCTION CROSS SECTIONS AT LEPTON-HADRON COLLIDERS

Maxim Nefedov

on behalf of Y.Yedelkina C. Flore, J.P. Lansberg, H.S. Shao, A. Colpani Serri, Y. Feng,
M.A. Ozelik

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May 2-6, 2022



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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 $J/\psi(\Upsilon)$ photoproduction**:

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

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

- We will discuss the photoproduction at **NLO**;

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- **3 common models** (differences in the treatment of the hadronisation):
 - ▶ **Colour Singlet Model**;
 - ▶ NRQCD and Colour Octet Mechanism;
 - ▶ Colour Evaporation Model;

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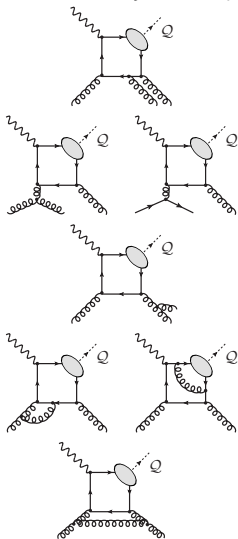
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 - ▶ **Colour Singlet Model**;
 - ▶ NRQCD and Colour Octet Mechanism;
 - ▶ Colour Evaporation Model;
- We do not discuss large z and exclusive reactions

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

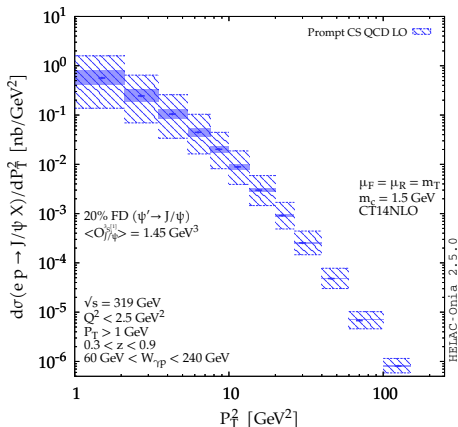
Photoproduction at mid and high P_T at HERA

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

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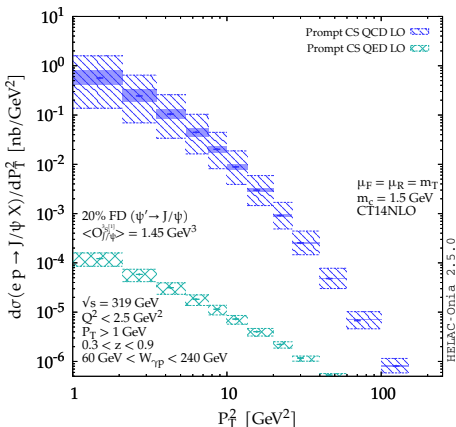
The computations were done with HELAC-Onia and FDC. The scale and mass uncertainties are shown by the hatched and solid bands.

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$$\gamma + q \rightarrow \psi + q @ \alpha^3 \text{ [NEW !]}$$

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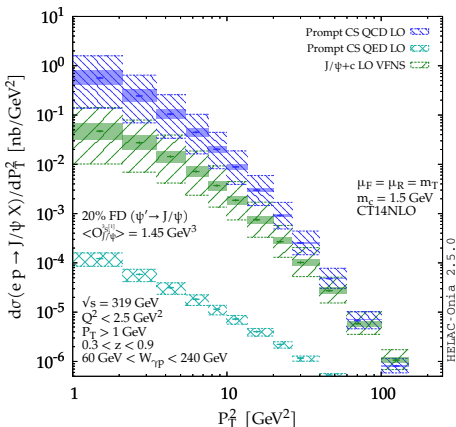
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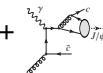
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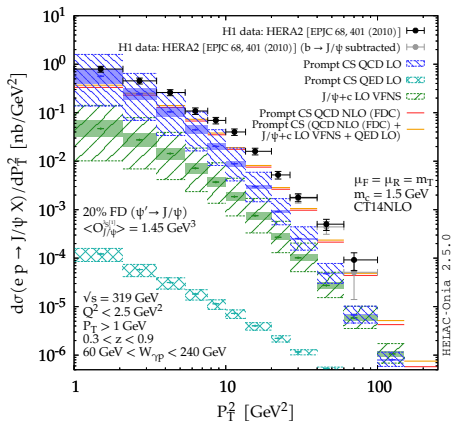
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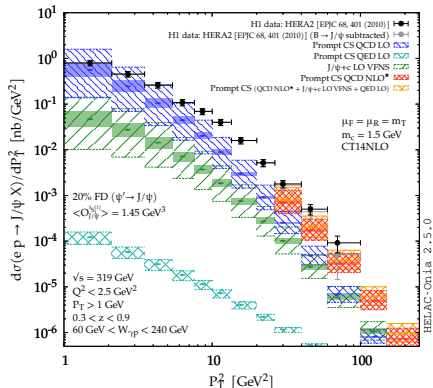


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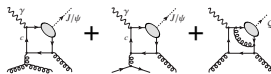
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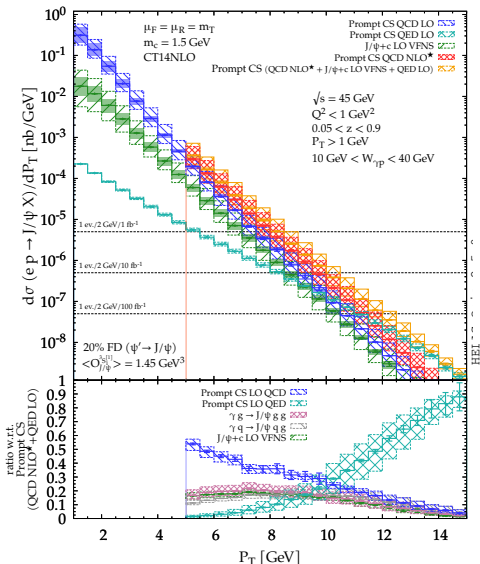
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Part II

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

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

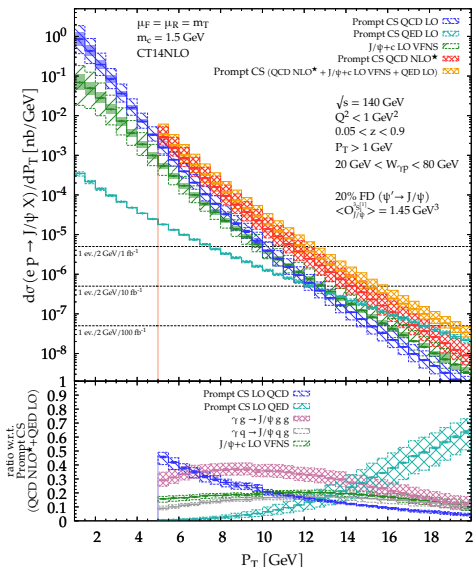
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- At $\sqrt{s_{ep}} = 45$ GeV, one gets into **valence region**
- Yield steeply falling with P_T
- Yield can be measured **up to** $P_T \sim 11$ GeV with $\mathcal{L} = 100 \text{ fb}^{-1}$
[using both ee and $\mu\mu$ decay channels and $\varepsilon_{J/\psi} \simeq 80\%$]
- 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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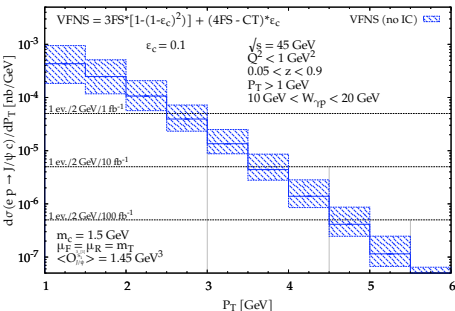
- At $\sqrt{s_{ep}} = 140$ GeV, larger P_T range up to approx. 18 GeV
- QED contribution also leading at the largest reachable P_T
- photon-gluon fusion contributions dominant up to approx. 15 GeV
- $J/\psi + 2$ hard partons [*i.e.* $J/\psi + \{gg, qg, c\bar{c}\}$] dominant for $P_T \sim 8 - 15$ GeV
- It could lead to the observation of $J/\psi + 2$ jets with moderate P_T^{jet}
- with a specific topology where the leading jet_1 recoils on the $J/\psi + \text{jet}_2$ pair
- We expect the $d\sigma$ to vanish when $E_{\text{jet}_2}^{J/\psi \text{ rest fr.}} \rightarrow 0$

Part III

J/ψ +charm associated production at the EIC

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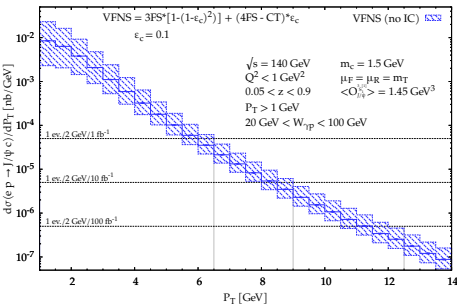
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- Same LO VFNS computation previously shown in green except for the **charm-detection efficiency**
 $\epsilon_c: \sigma^{VFNS} = \sigma^{3FS} \times (1 - (1 - \epsilon)^2) + (\sigma^{4FS} - \sigma^{CT}) \times \epsilon$
- At $\sqrt{s_{ep}} = 45 \text{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

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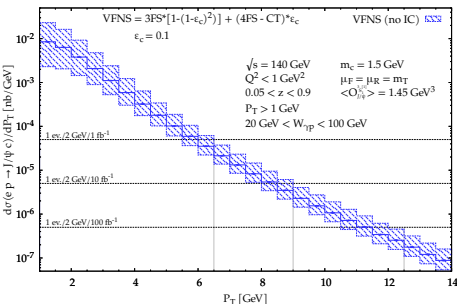
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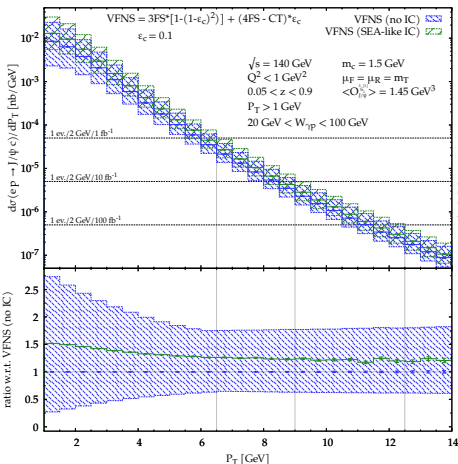


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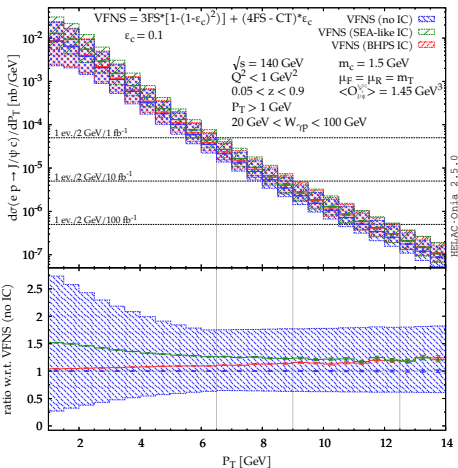


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- Small effect at $\sqrt{s_{ep}} = 140$ GeV [We used IC $c(x)$ encoded in CT14NNLO]

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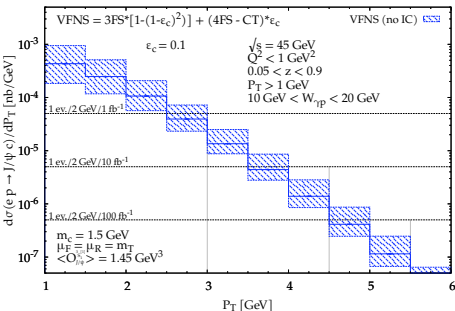


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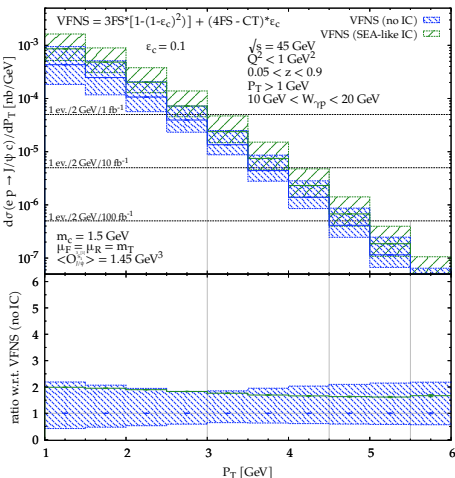


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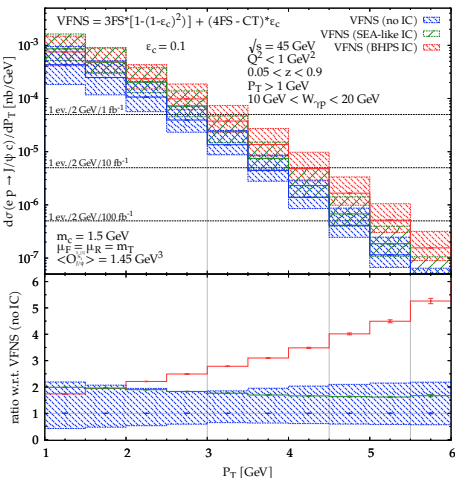


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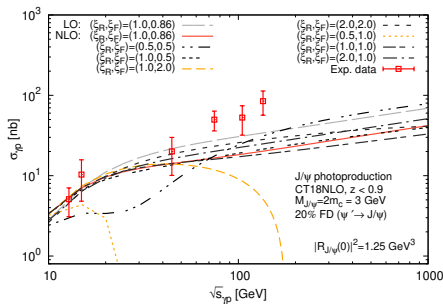
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Part IV

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

The negative cross-sections issue at high energies

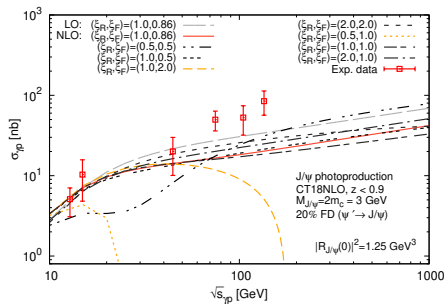
A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozelik, H.S. Shao, Y. Yedekina: arXiv:2112.05060 [hep-ph]



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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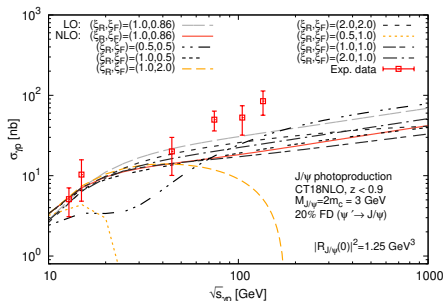


- **NLO** cross section for J/ψ photoproduction becomes negative for large μ_F when $\sqrt{s_{\gamma p}}$ increases

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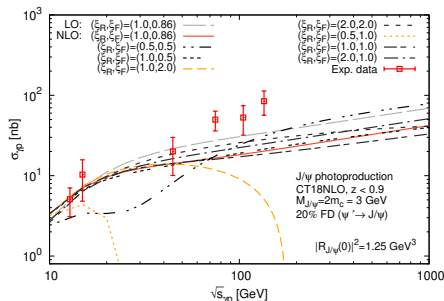
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J.P. Lansberg, M.A. Ozelik: Eur.Phys.J.C 81 (2021) 6, 497

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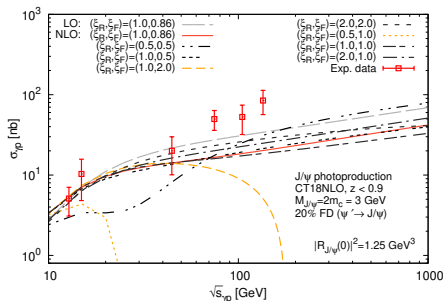
J.P. Lansberg, M.A. Ozelik: Eur.Phys.J.C 81 (2021) 6, 497

- 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

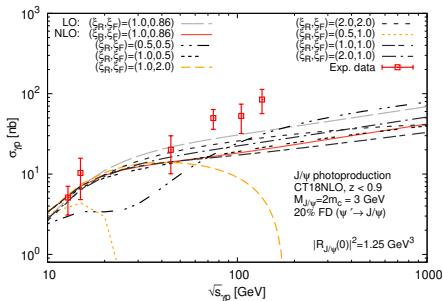
A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozelik, H.S. Shao, Y. Yedelkina: arXiv:2112.05060 [hep-ph]



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

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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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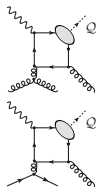
- $\hat{S} \rightarrow \infty : \hat{\sigma}_{\gamma i}^{NLO} \propto \alpha_s(\mu_R) \left(\bar{c}_1^{(\gamma i)} \log \frac{M_Q^2}{\mu_F^2} + c_1^{(\gamma i)} \right), A_{\gamma i} = \frac{c_1^{(\gamma i)}}{\bar{c}_1^{(\gamma i)}},$

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

A scale prescription for μ_F

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

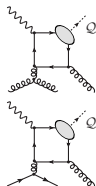
- In principle, such negative terms should be compensated by the **evolution** of the PDFs governed by the DGLAP equations;



A scale prescription for μ_F

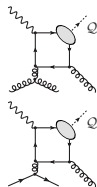
J.P. Lansberg, M.A. Ozelik: Eur.Phys.J.C 81 (2021) 6, 497

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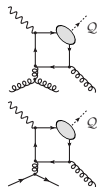
J.P. Lansberg, M.A. Ozelik: Eur.Phys.J.C 81 (2021) 6, 497



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A scale prescription for μ_F

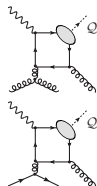
J.P. Lansberg, M.A. Ozelik: Eur.Phys.J.C 81 (2021) 6, 497



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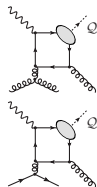
J.P. Lansberg, M.A. Ozelik: Eur.Phys.J.C 81 (2021) 6, 497



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 $\mu_F = \hat{\mu}_F = M e^{A_{\gamma i}/2};$

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



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 $\mu_F = \hat{\mu}_F = M e^{A_{\gamma i}/2}$;
- For J/ψ (Υ) photoproduction: $\hat{\mu}_F = 0.86M$
 $(P_T \in [0, \infty], z < 0.9)$

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

J.P. Lansberg, M.N., M.A. Ozelik: 2112.06789 [hep-ph]; [More info in my talk on Thursday!](#)

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

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

\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

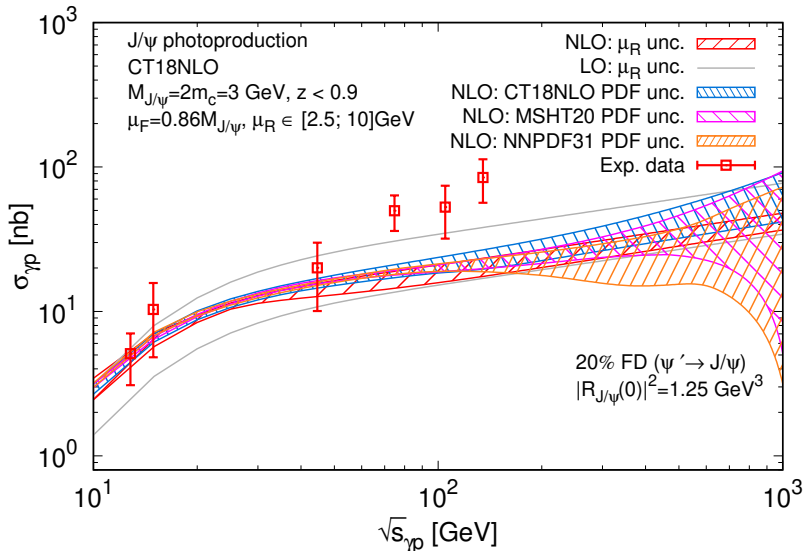
$\hat{\mu}_F = \mu_0 e^{A/2}$ is:

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

\Rightarrow the exponent resums $\ln 1/z$ -enhanced corrections.

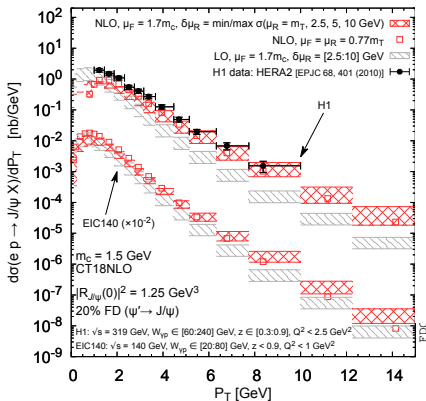
Results with $\hat{\mu}_F = 0.85M$

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



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

P_T -differential cross sections



- If p_T -dependence is taken into account, for $\hat{s} \rightarrow \infty$:

$$c_1^{(\gamma i)}(p_T)/\bar{c}_1^{(\gamma i)}(p_T) \propto (P_T/M_Q)^2$$
- $\Rightarrow \hat{\mu}_F = M e^{c_{\gamma i}^{(1)}/2\bar{c}_{\gamma i}^{(1)}} \propto M e^{P_T^2/M^2}$,
 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 $\langle P_T^2 \rangle = 2.5 \text{ GeV}^2$ (for J/ψ at HERA energies), we get $\alpha = 0.77$ and $\beta = 0.7$

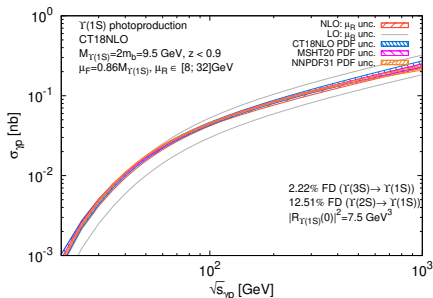
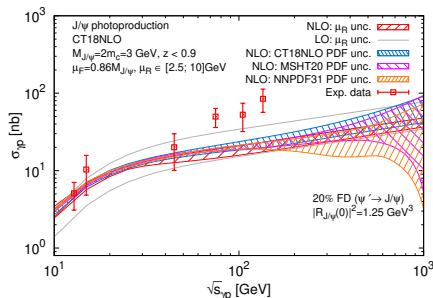
Part V

Can J/ψ & Y 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. Ozelik, 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

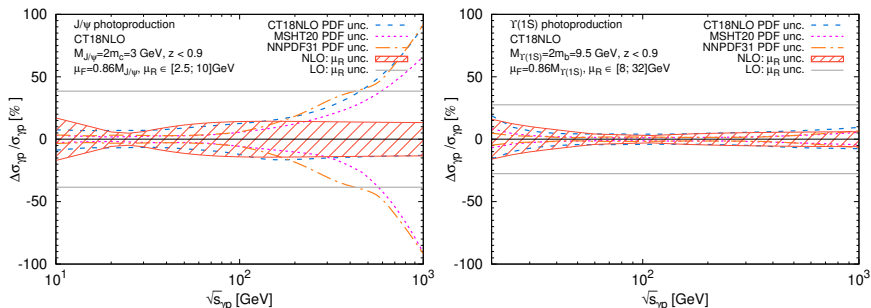


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J/ψ & Υ: PDF uncertainties of $\sigma(\sqrt{s_{\gamma p})}$

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozelik, 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



Exp. data: H1 - Nucl.Phys.B 472(1996)3-31, FTPS - B.H.Denby et al.: PRL 52(1984)795-798, NAI - NA14Collaboration, R.Barate et al.:Z.Phys.C 33(1987)505

Exp.	$\sqrt{s_{ep}}$	\mathcal{L} (fb $^{-1}$)	$N_{J/\psi}$	$N_{Y(1S)}$
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. $N_{\psi'} \simeq 0.08 \times N_{J/\psi}$, $N_{Y(2S)} \simeq 0.4 \times N_{Y(1S)}$, $N_{Y(3S)} \simeq 0.35 \times N_{Y(1S)}$

Part VI

Conclusions

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- The estimations for EIC can rely on CSM only

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- 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

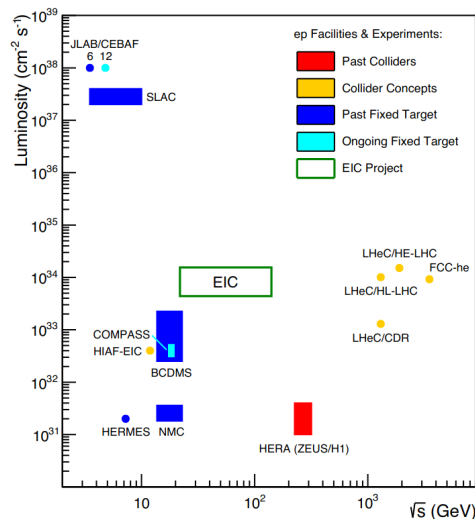
Resolved-photon contributions

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
 $L_{ep} \propto 10^{33-34} \text{ cm}^{-2} \text{ sec}^{-1}$
 (100-1000 times HERA)
- World's first:
 - collider with polarized (min 70%) lepton & proton/light-ion beams
 - electron-Nucleus collider

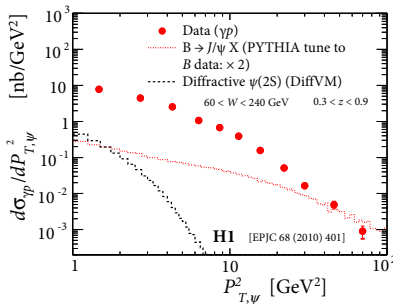
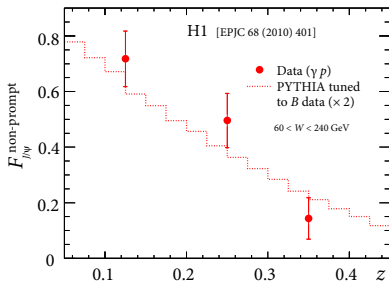
Feed down

C.Flore, J.-P. Lansberg, H.S. Shao, Y. Yedekina, 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 $b \rightarrow J/\psi$ cross section in the H1 kinematics.
 - ▶ Subtract this $b \rightarrow J/\psi$ 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 $\psi' \rightarrow J/\psi$ branching: $FD_{\psi' \rightarrow J/\psi} = |R_{\psi'}(0)|^2 / |R_{J/\psi}(0)|^2 Br(\psi' \rightarrow J/\psi)$

Feed down

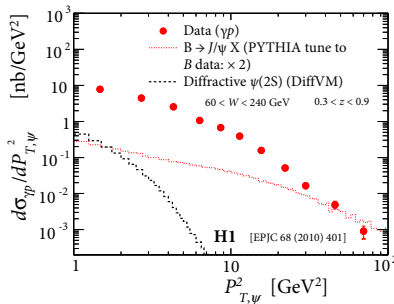
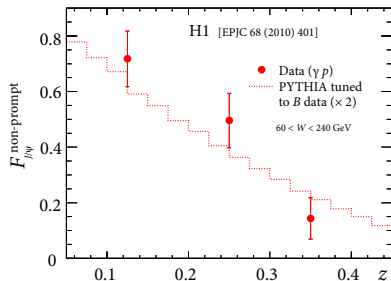
J.P. Lansberg, Phys.Rept. 889 (2020); C.Flore, J.-P. Lansberg, H.S. Shao, Y. Yedekina, PLB 811 (2020) 135926



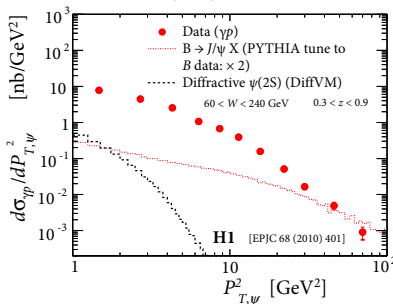
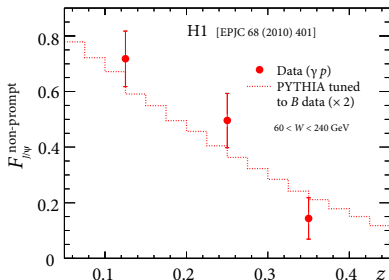
- **b FD** (5% on the P_T -integrated yields and can go up to $\approx 50\%$ at $P_T = 10 \text{ GeV}$): we do not include it as it can be experimentally removed.

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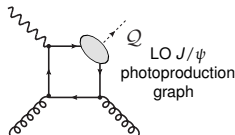
$$FD_{\psi' \rightarrow J/\psi} = |R_{\psi'}(0)|^2 / |R_{J/\psi}(0)|^2 \text{Br}(\psi' \rightarrow J/\psi)$$

Basic pQCD approach: the Colour Singlet Model (CSM)

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

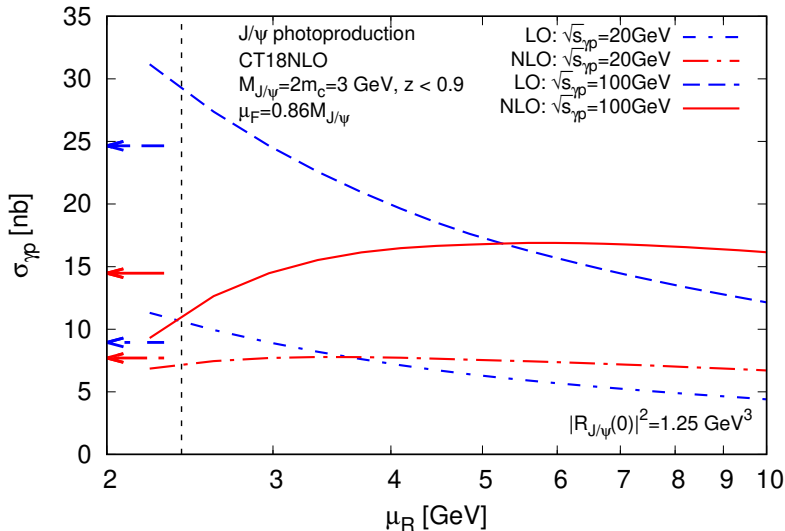
One supposes two **factorisations**:

- 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
→ Schrödinger wave function at $r = 0$

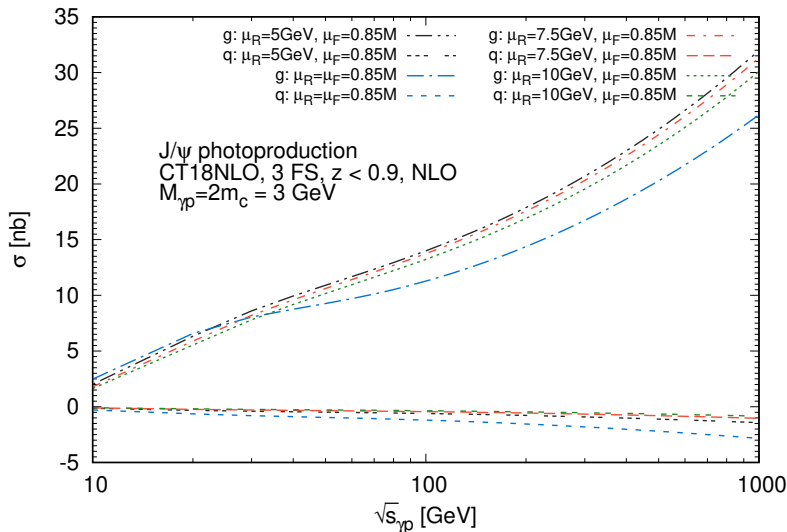


CSM: the Taylor series expansion of the amplitude in the $Q\bar{Q}$ relative momentum (v) to the first non-vanishing (Leading- v NRQCD) term.

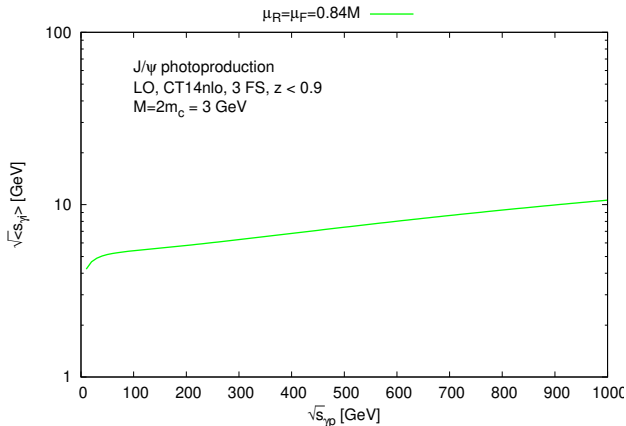
Dependence of $\sigma_{\gamma p}$ on the μ_R at an initial photon energy $s_{\gamma p}$



q& g contributions



μ_R choice



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