Quarkonium production: where do we stand and where to go with the EIC ?

J.P. Lansberg

IJCLab Orsay – Paris Saclay U. – CNRS

Physics Opportunities with Heavy Quarkonia at the EIC
CFNS workshop, October 25-28, 2021

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Part I

Quarkonium production mechanisms

Approaches to Quarkonium Production

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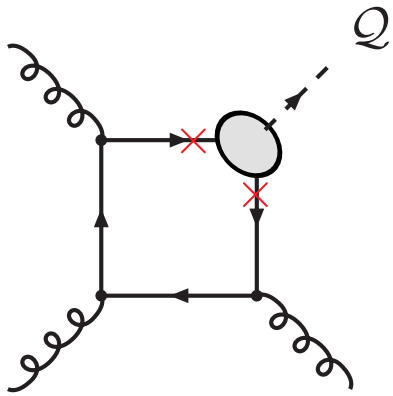
  3. Colour Octet Mechanism (encapsulated in NRQCD): higher Fock states of the mesons taken into account; $Q\bar{Q}$ can be produced in octet states with different quantum # as the meson; bleaching with semi-soft gluons ?

Basic pQCD approach: the Colour Singlet Model (CSM)

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



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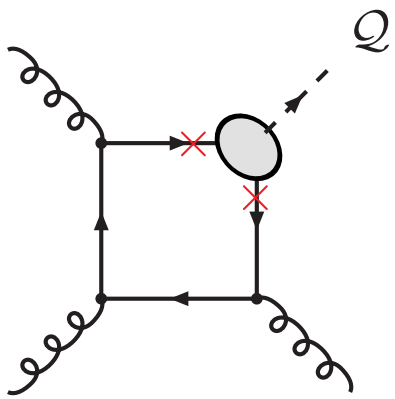

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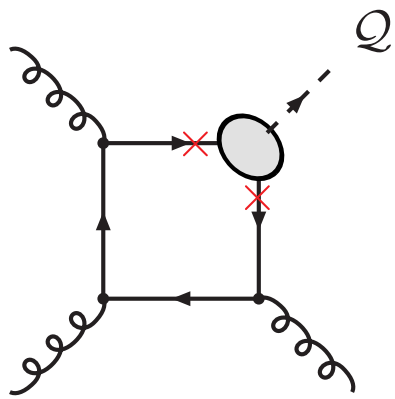

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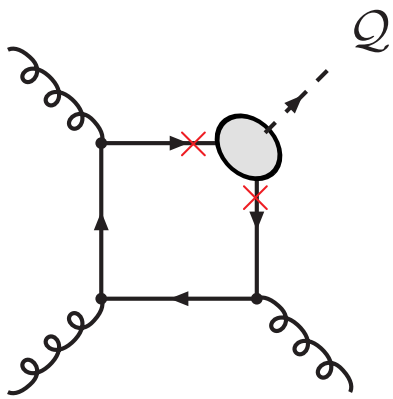

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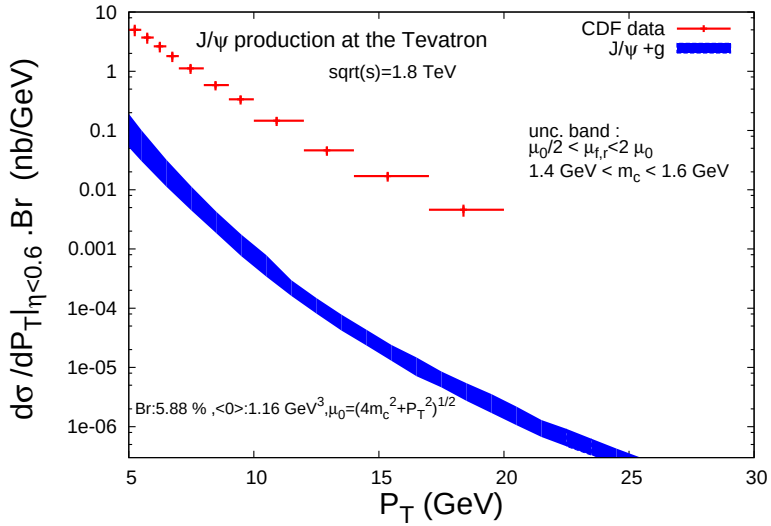

CDF, PRL 79:572 & 578,1997

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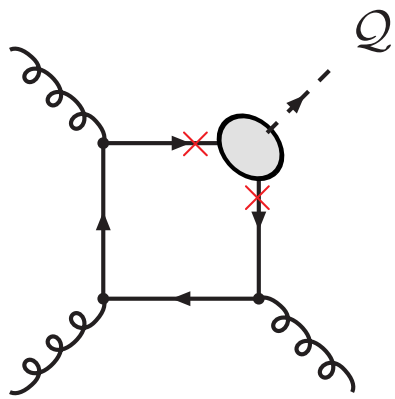

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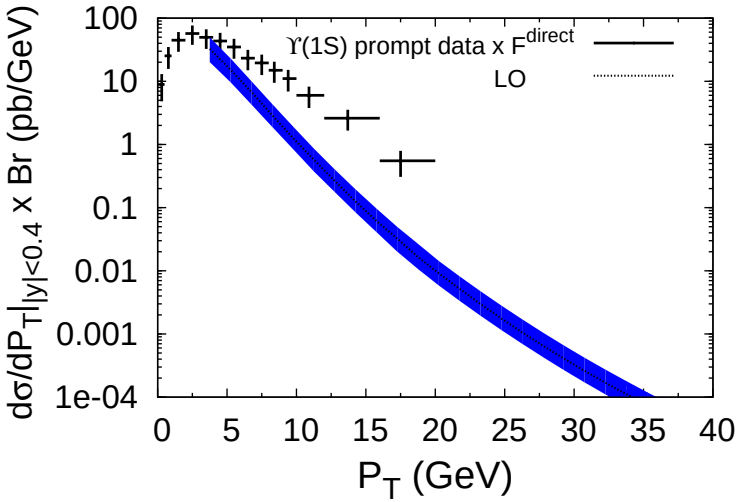

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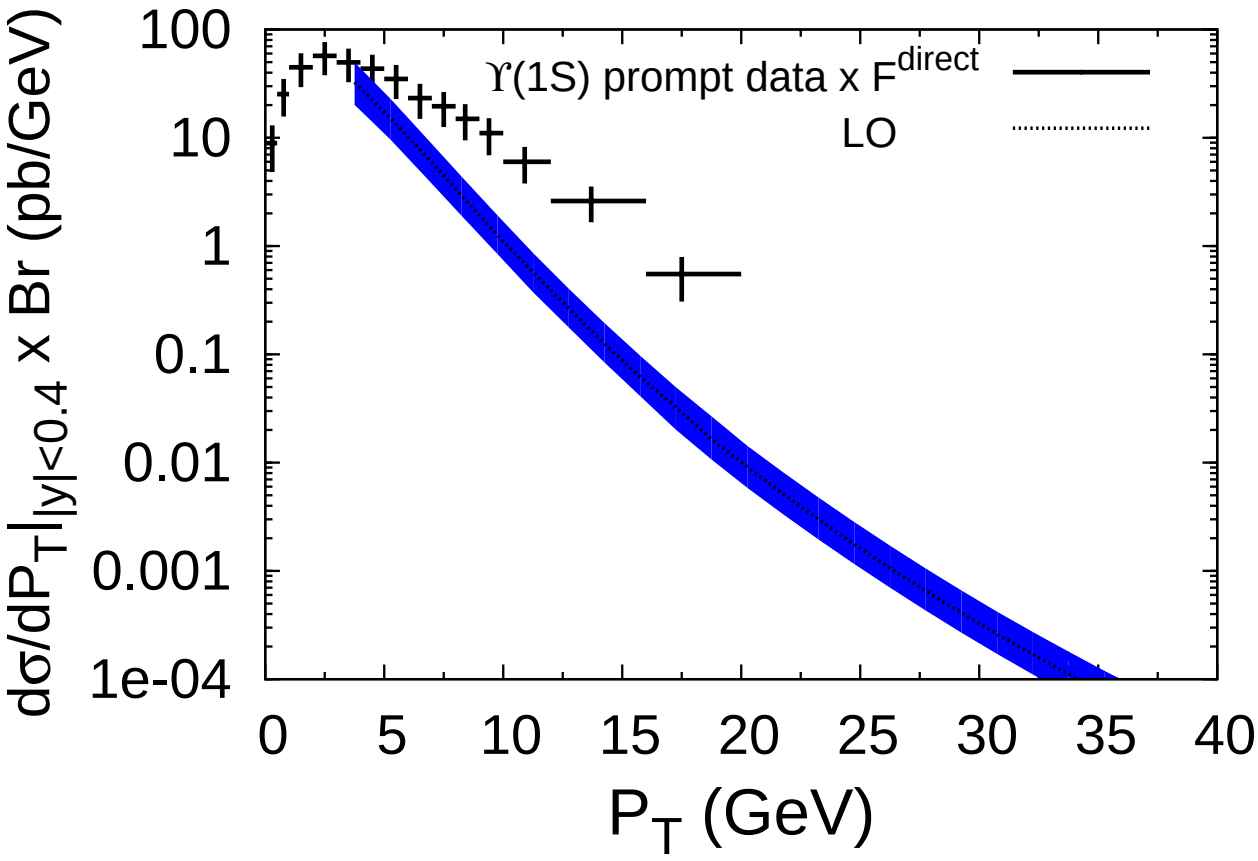

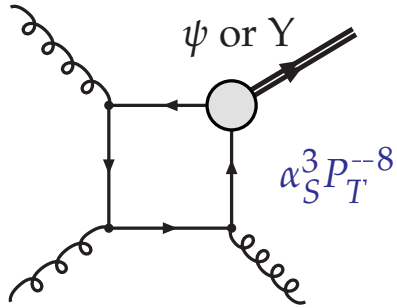

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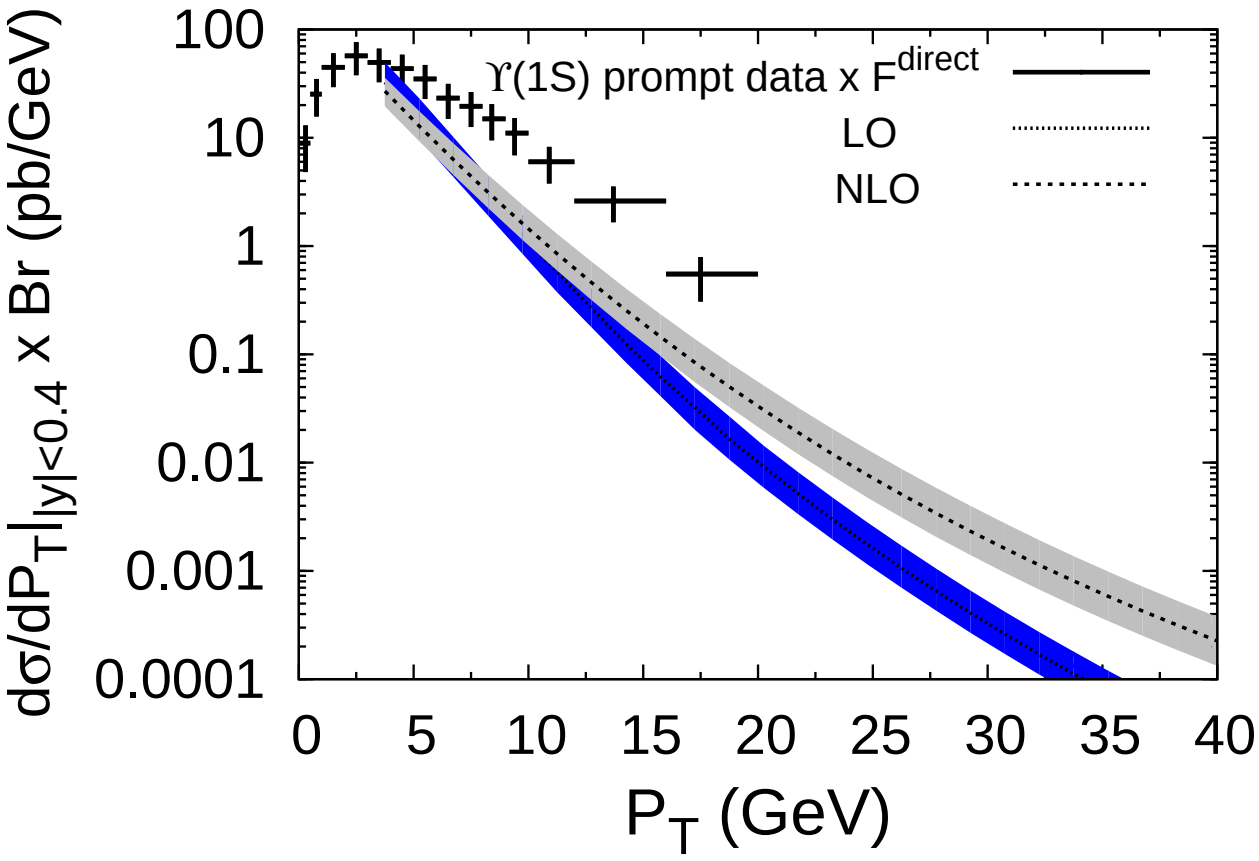

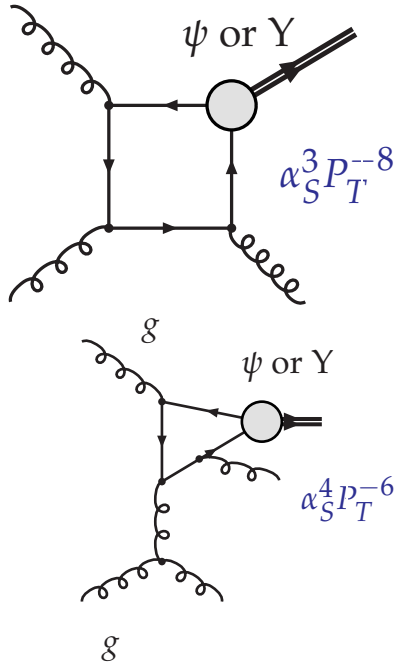

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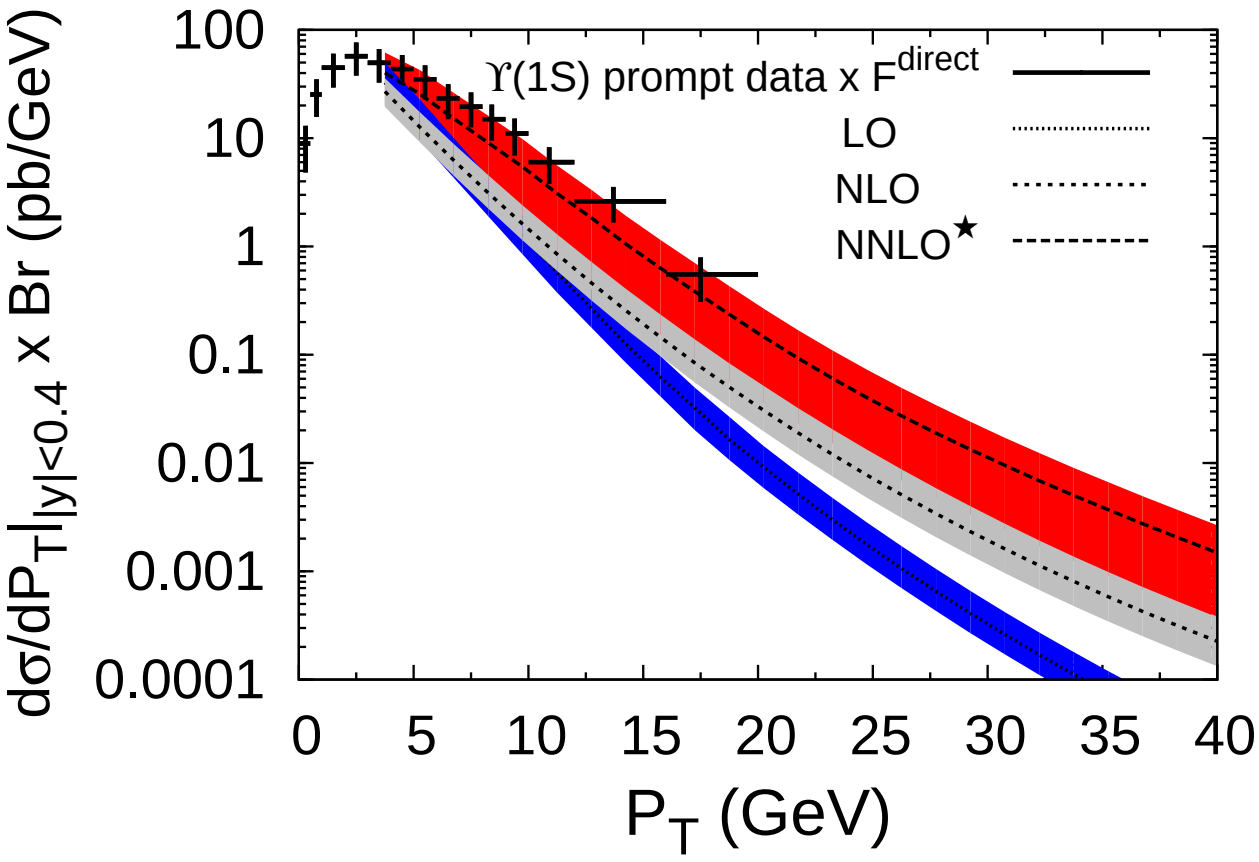

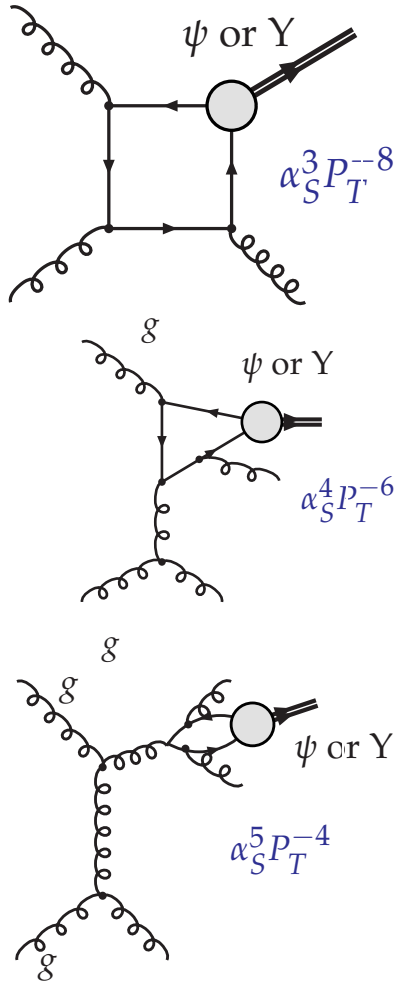

Attention: the NNLO* is not a complete NNLO

See a recent study by H.S. Shao JHEP 1901 (2019) 112

Colour Octet Mechanism Dominance : not so simple

Color Octet Mechanism: physical states can be produced by coloured pairs

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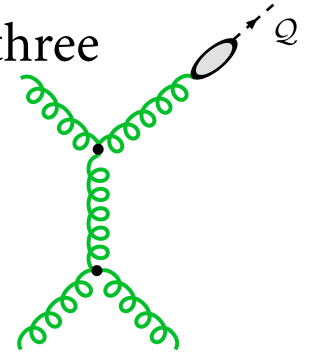

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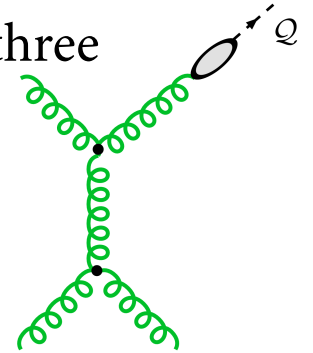

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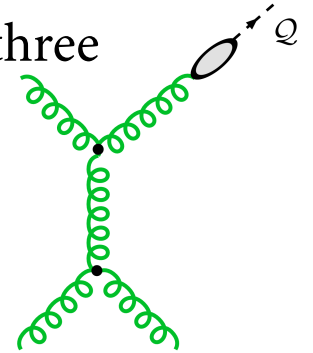

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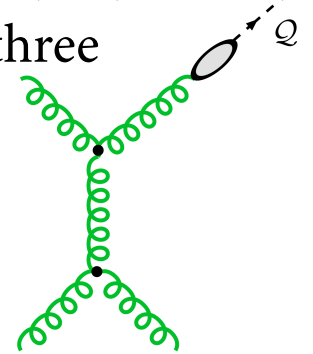

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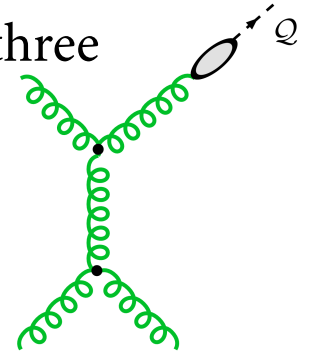

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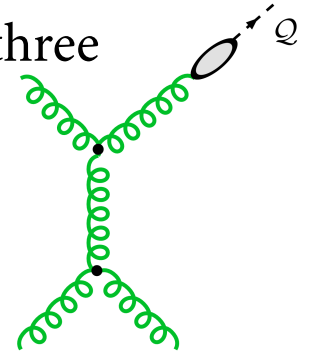

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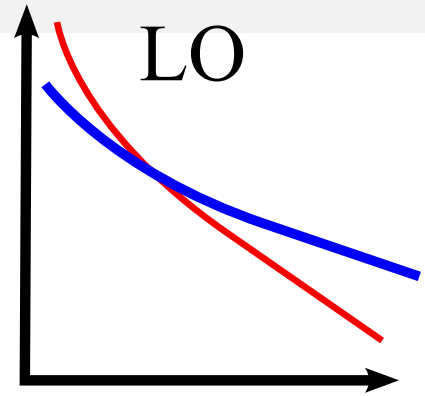

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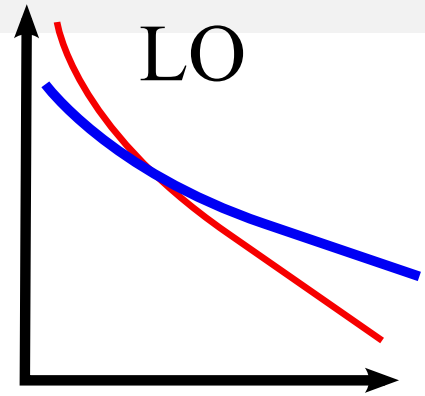

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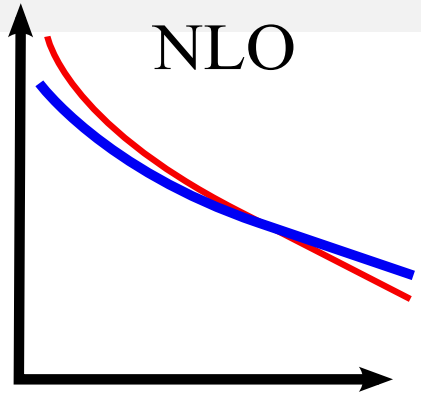

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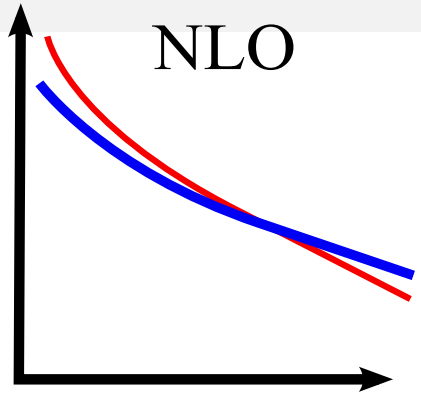

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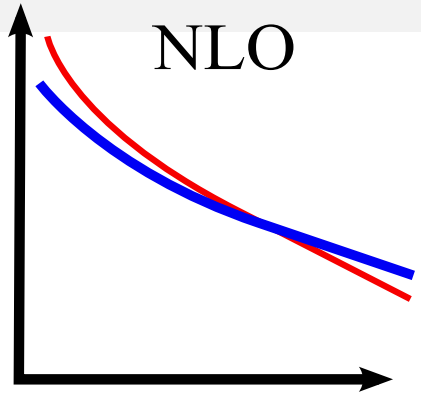

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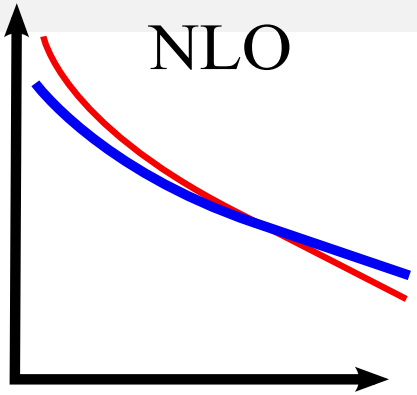

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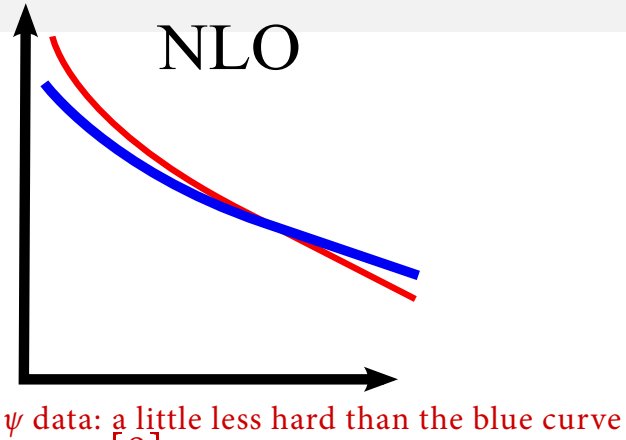

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- As such, it is hazardous to use NLO LDMEs for other processes at LO !

As an illustration, some NLO LDMEs are negative $\Rightarrow \sigma^{\rm LO} \times \langle \mathcal{O} \rangle < 0$

QCD corrections to the CEM P_T dependence

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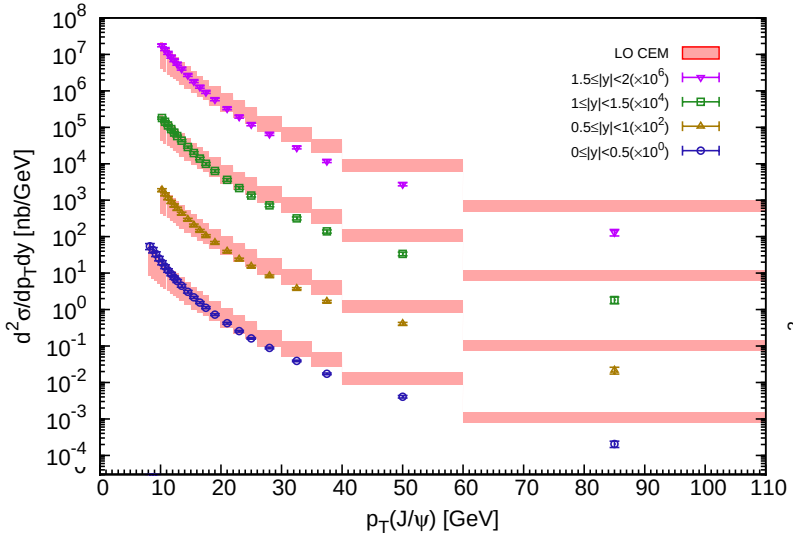
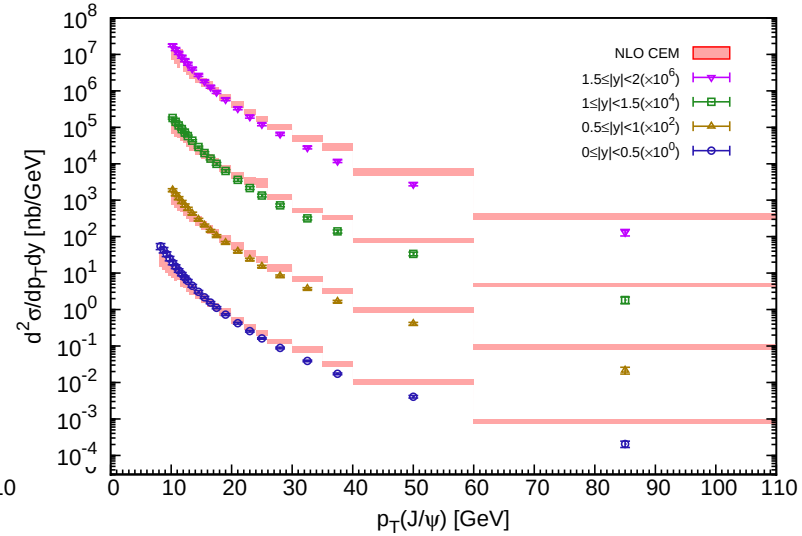
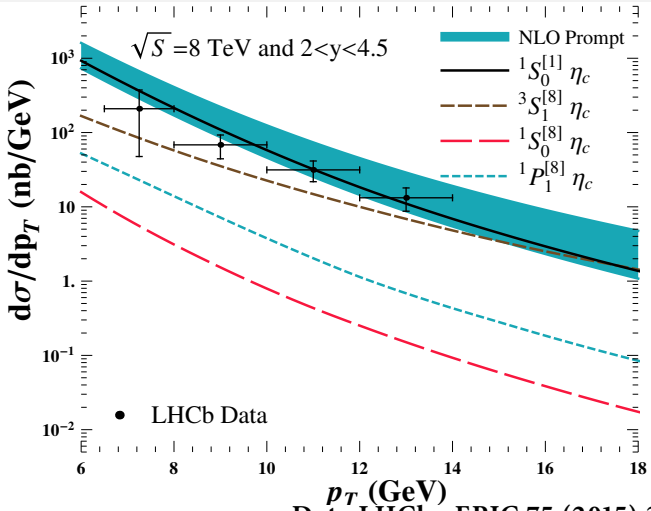




The last piece in the puzzle: the η_c



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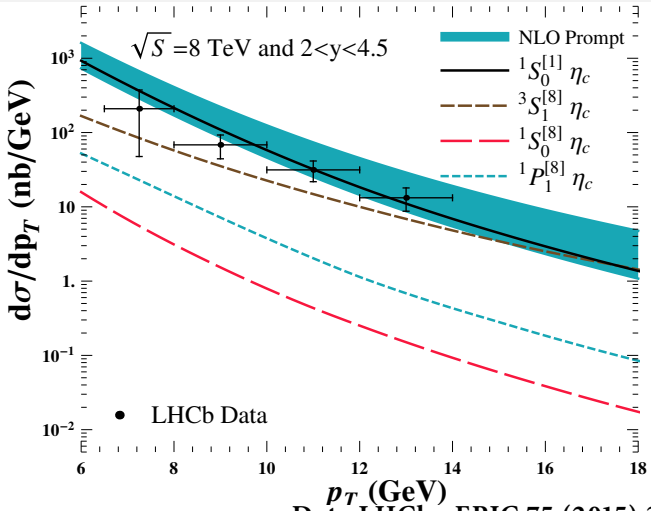

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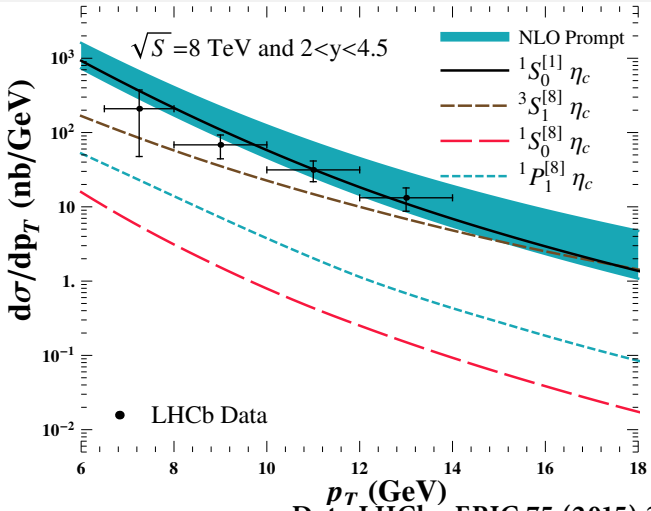

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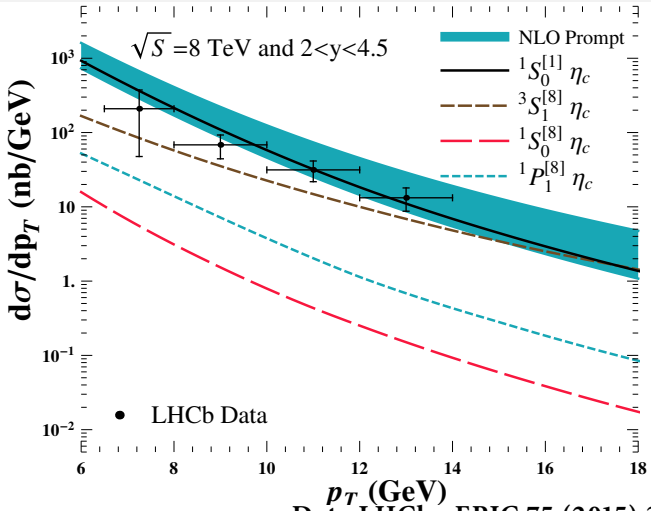

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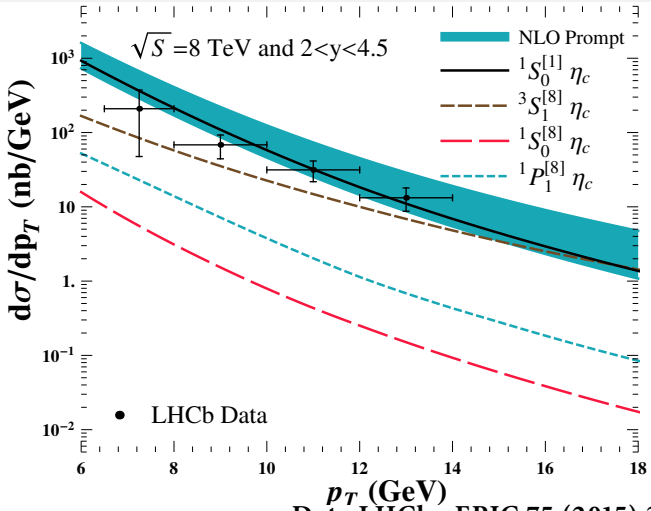

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- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out **(Hamburg) M. Butenschoen *et al.* PRL 114 (2015) 092004; (PKU) H. Han *et al.* 114 (2015) 092005; (IHEP) H.F. Zhang *et al.* 114 (2015) 092006**

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Part III

Photoproduction at mid and high P_T: on the importance of QCD and QED corrections

Photoproduction at mid and high P_T

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LO CSM also fails in photoproduction at HERA

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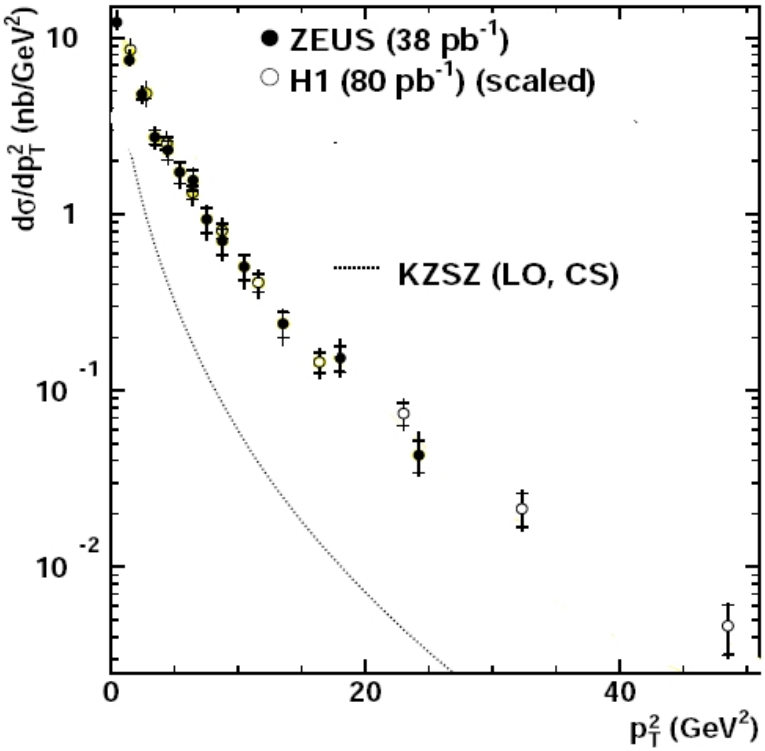

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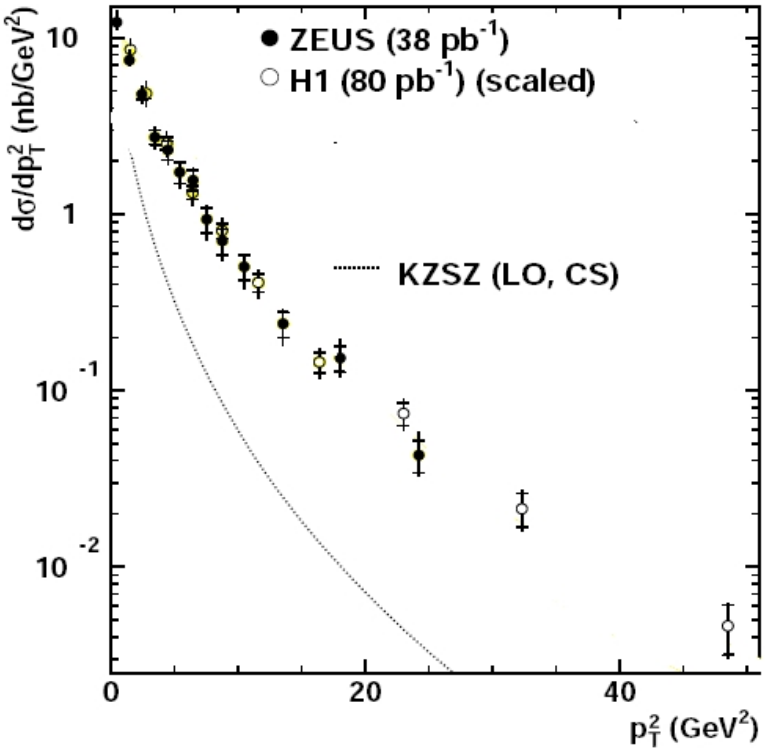

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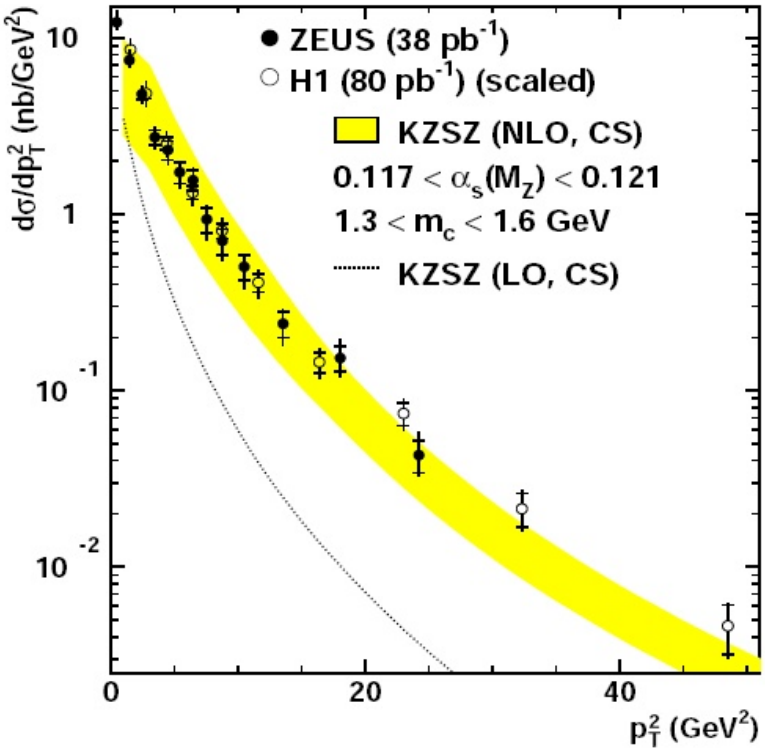

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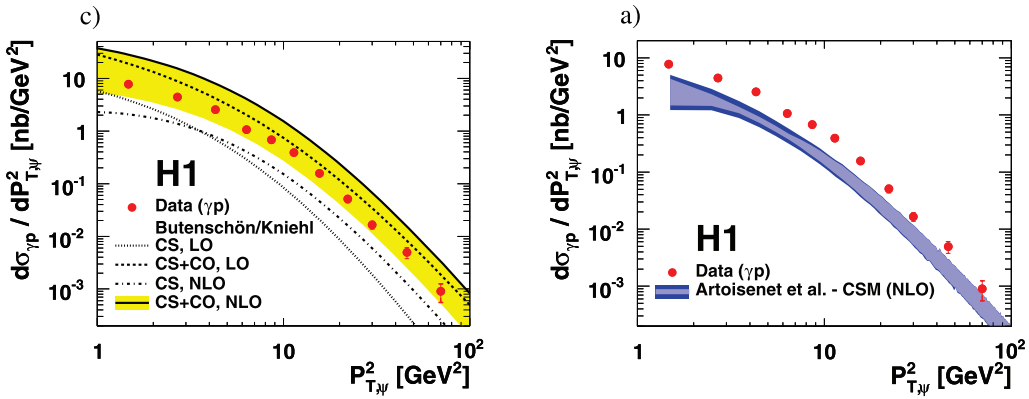

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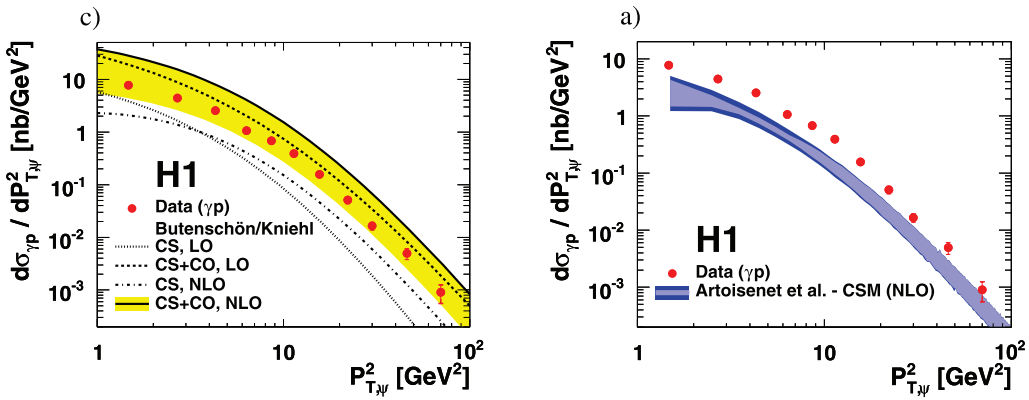
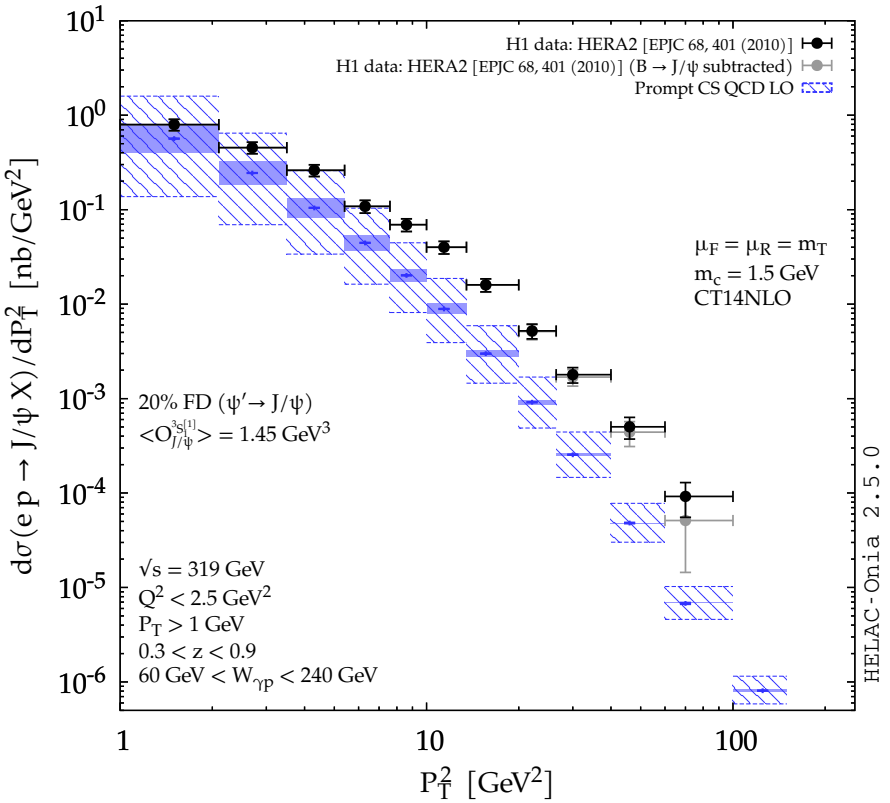
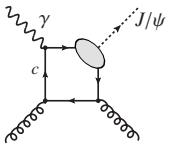


→ Let us revisit this in view of the EIC prospects

Is the CSM after all a good baseline ?

C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926





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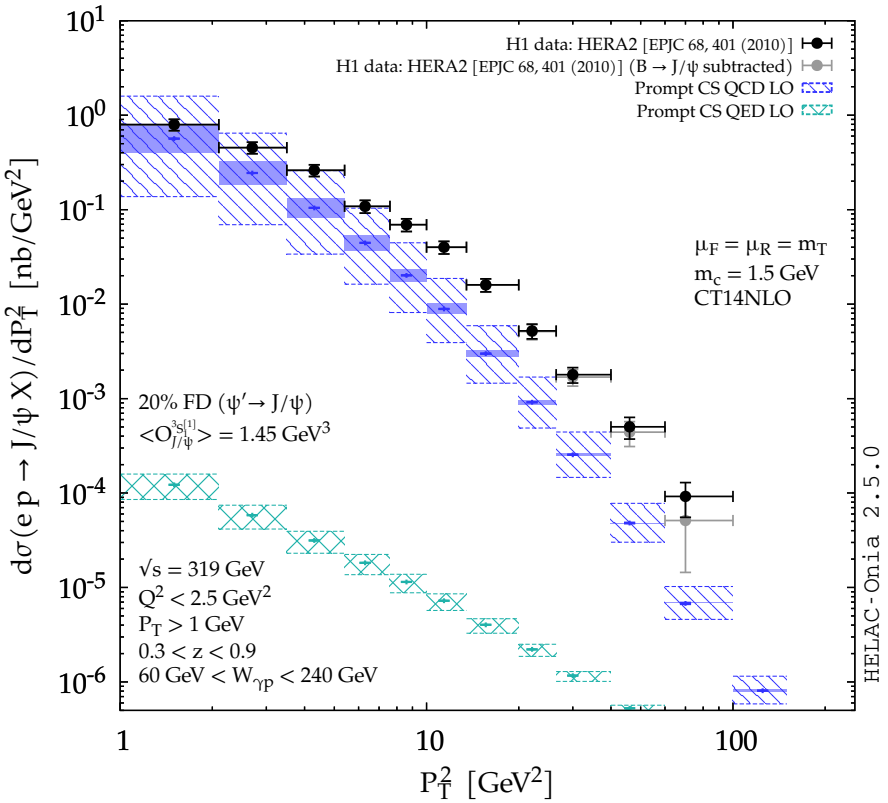

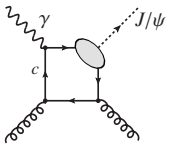

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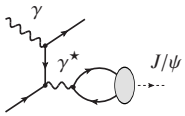

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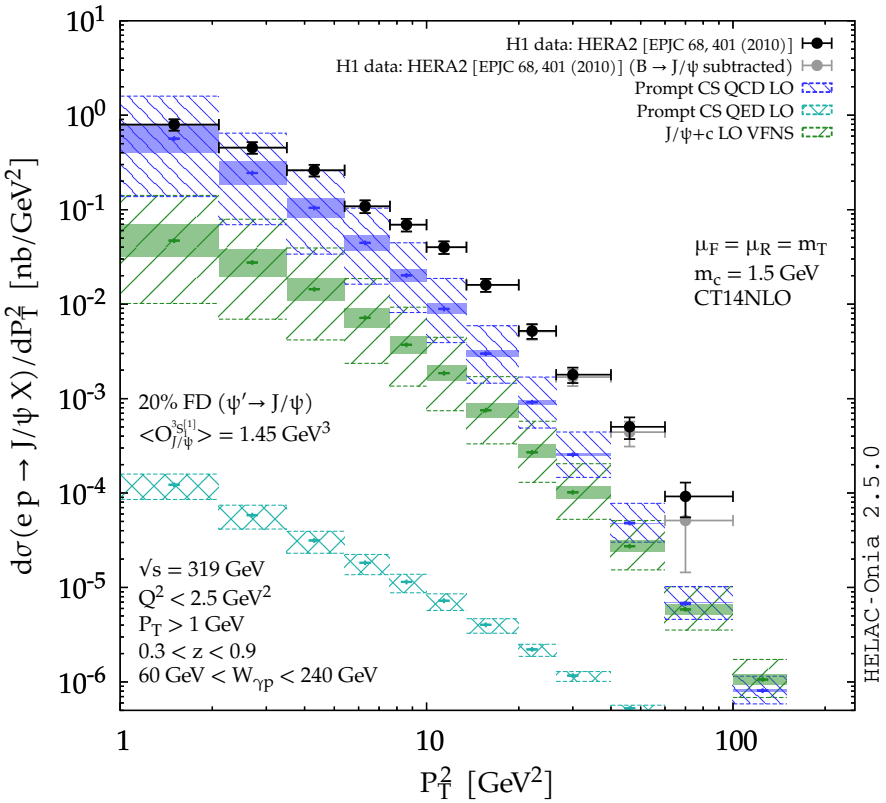

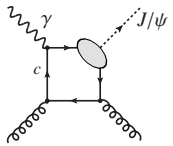

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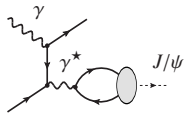

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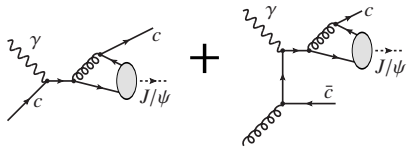

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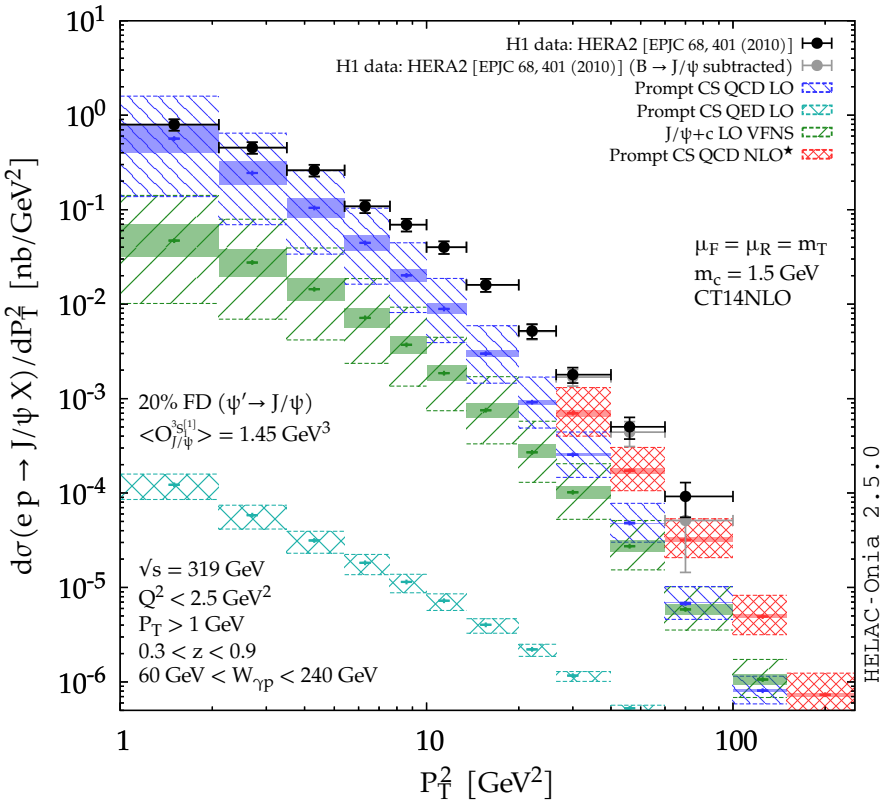

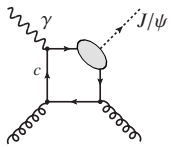

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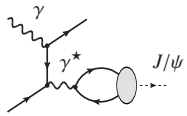

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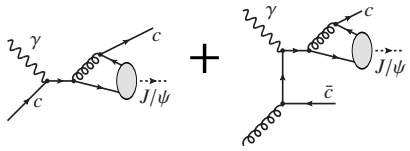

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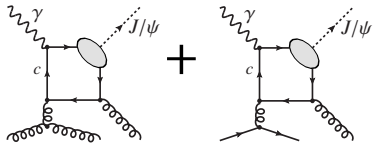

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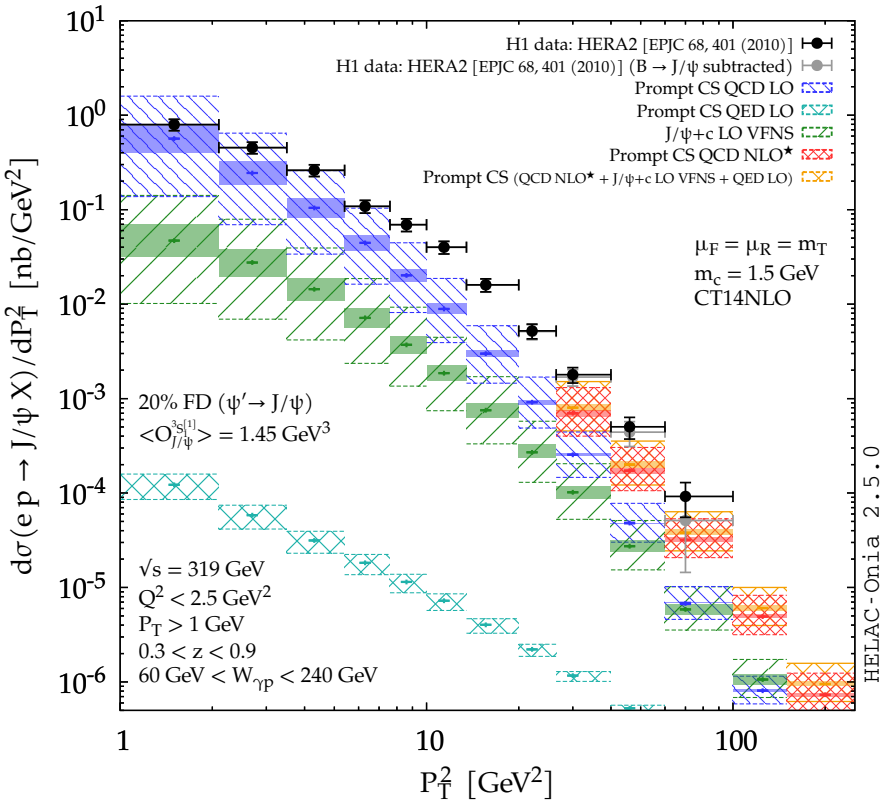

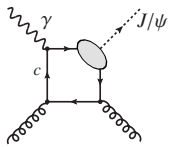

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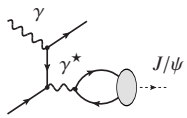

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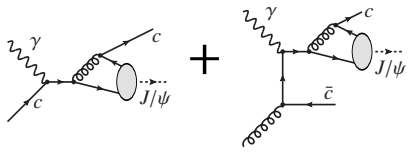

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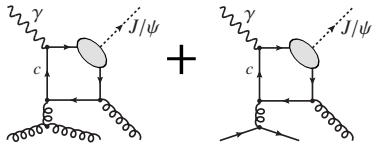

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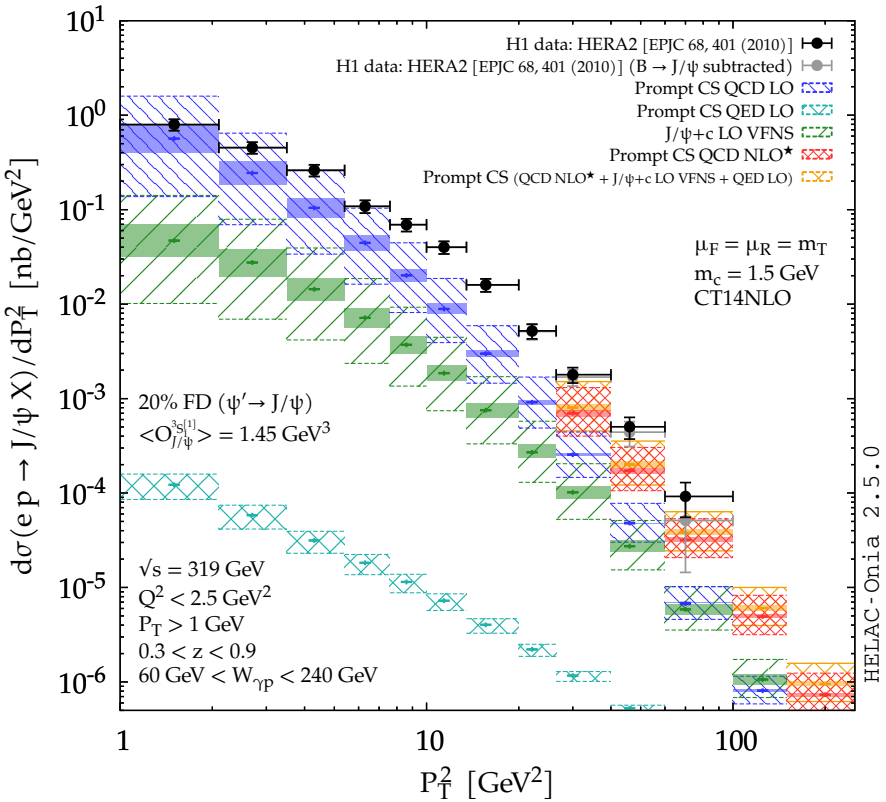
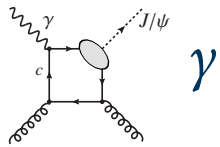
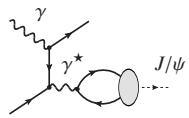
Is the CSM after all a good baseline ?

C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

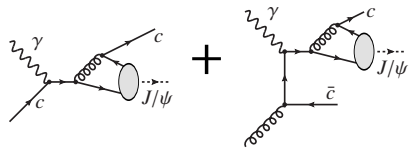




$\gamma + g \to \psi + g \,@\, \alpha\alpha_s^2$ [LO]

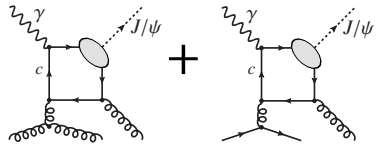


$\gamma + q \to \psi + q \,@\, \alpha^3$ [NEW !]



$\begin{cases} \gamma+c\to\psi+c \,@\, \alpha\alpha_s^2 \text{ w. 4 Flav.} \\ \gamma+g\to\psi+c+\bar{c} \,@\, \alpha\alpha_s^3 \text{ w. 3 Flav.} \end{cases}$

[also NEW !]



$\begin{cases} \gamma+g\to\psi+g+g \,@\, \alpha\alpha_s^3 \\ \gamma+q\to\psi+g+q \,@\, \alpha\alpha_s^3 \end{cases}$ + LO

- LO QCD does a good job at low P_T
- LO QED much harder but small normalisation [will matter at EIC]
- J/ψ+charm: starts to matter at high P_T [will also matter at EIC]
- NLO$^{(\star)}$ close the data, the overall sum nearly agrees with them
- Agreement when the expected $B \to J/\psi$ feed down (always overlooked) is subtracted

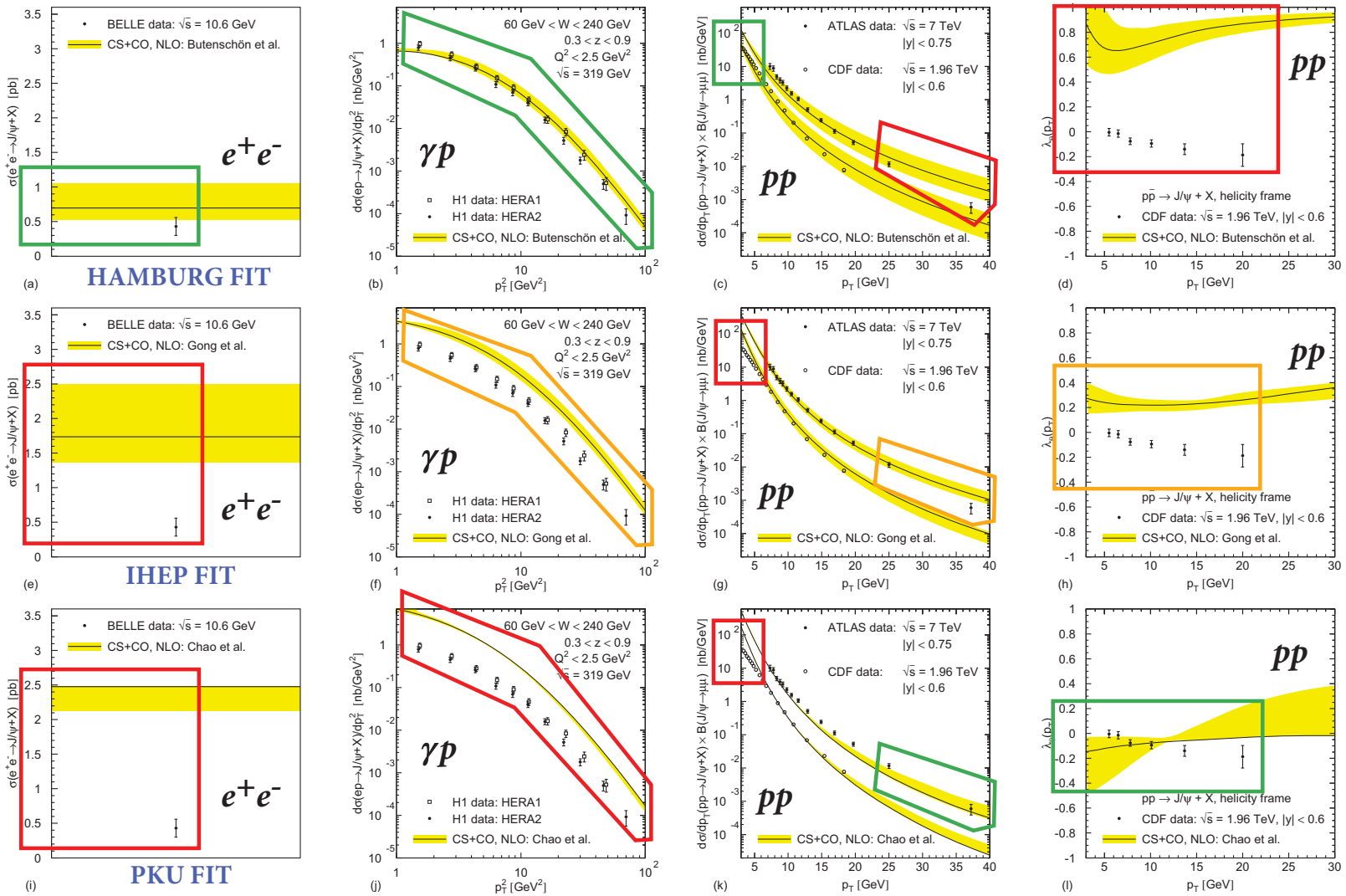
→ CSM accounts for the data and can be used for EIC predictions

Part IV

Overall

Universality of NLO NRQCD fits ?

Plot from M. Butenschön (ICHEP 2012); Discussion in JPL, Phys.Rept. 889 (2020) 1



Further caveats: LDME upper limit from η_c data clearly violated by the 3 fits !

The current situation in one slide ...

See JPL. arXiv:1903.09185 [hep-ph] (Phys.Rept. 889 (2020) 1)

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...not as clear now

[large NLO and NNLO correction to the P_T spectrum ; but not perfect → need a full NNLO]

P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, PRL 101, 152001 (2008); JPL EPJC 61 (2009) 693; H.S. Shao JHEP 1901 (2019) 112

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- CSM is doing well for the P_T integrated yield

S.J. Brodsky, JPL PRD 81 (2010) 051502; Y. Feng, JPL. J.X.Wang Eur.Phys.J. C75 (2015) 313

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- All approaches have troubles with ep, ee or pp polarisation and/or the η_c data
- Clear need for data beyond pp inclusive data

→ sensitive to different linear combination of LDMEs

[e.g. photoproduction, associated production, ...]

Part V

Predictions for the EIC : inclusive production

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C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

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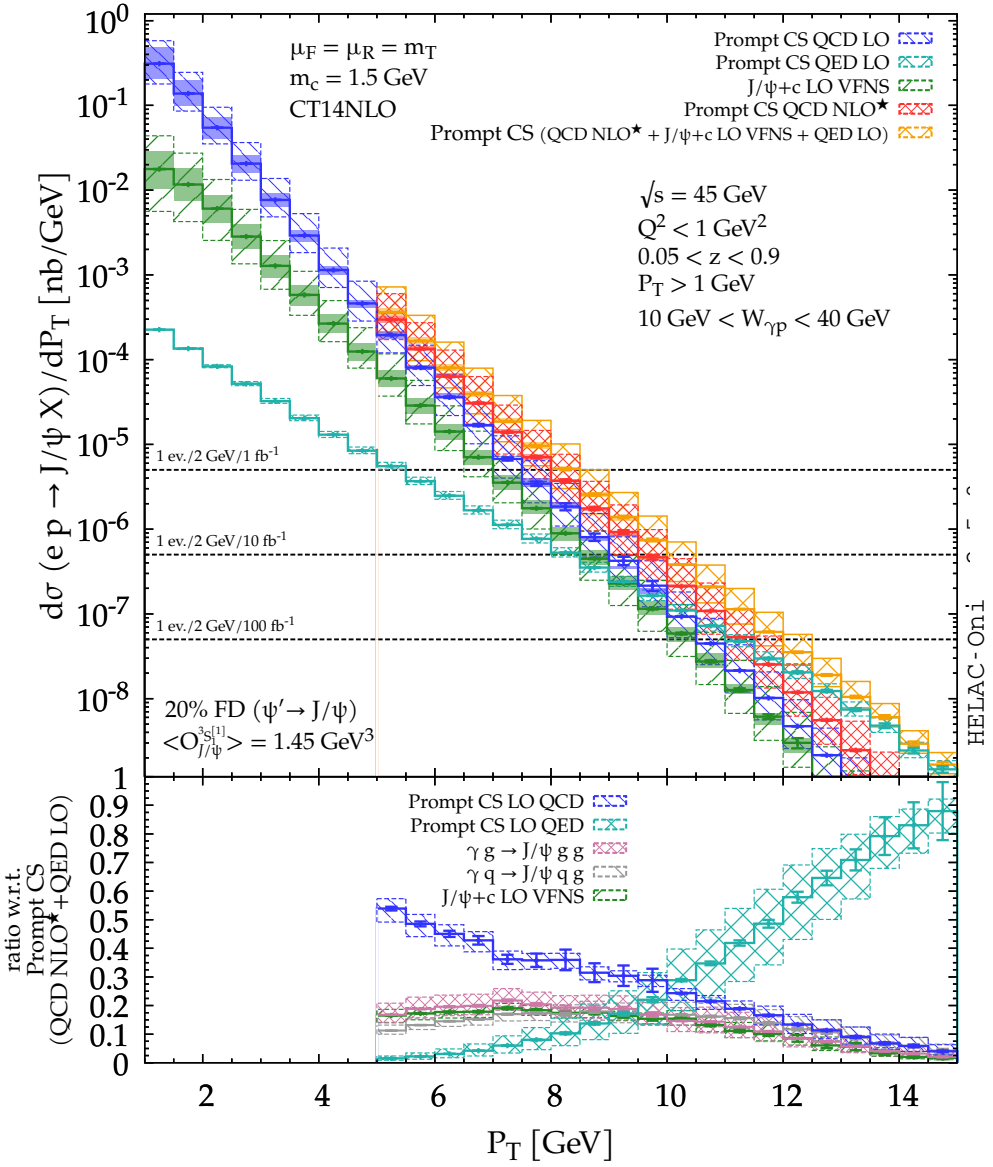

- At $\sqrt{s_{ep}}$ = 45 GeV, one enters the valence region
- Yield measurable up to P_T = 10 GeV with $\mathcal{L}$ = 100 fb^{-1}

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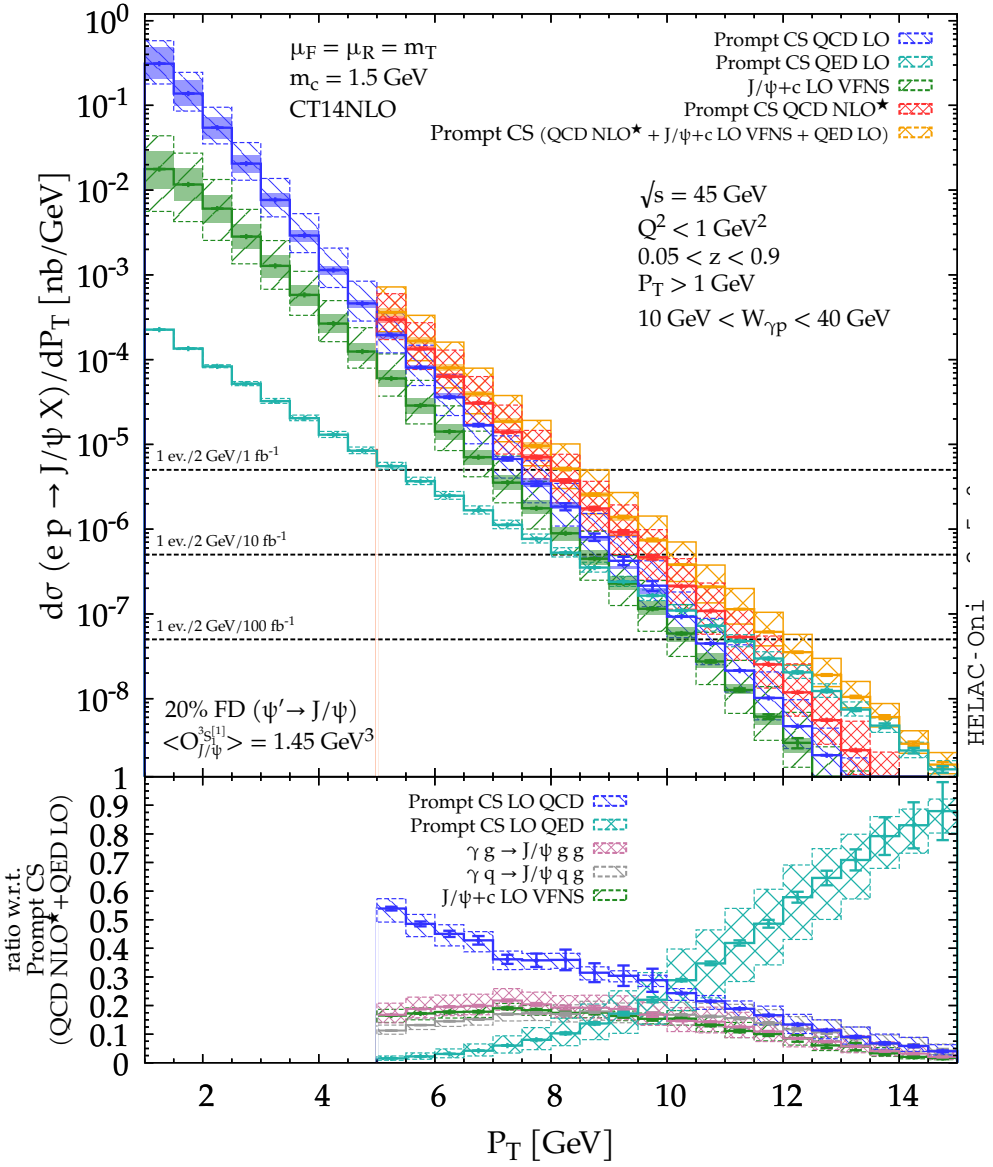

- At $\sqrt{s_{ep}}$ = 45 GeV, one enters the valence region
- Yield measurable up to P_T = 10 GeV with $\mathcal{L}$ = 100 fb^{-1}
- QED contribution leading at the largest measurable P_T

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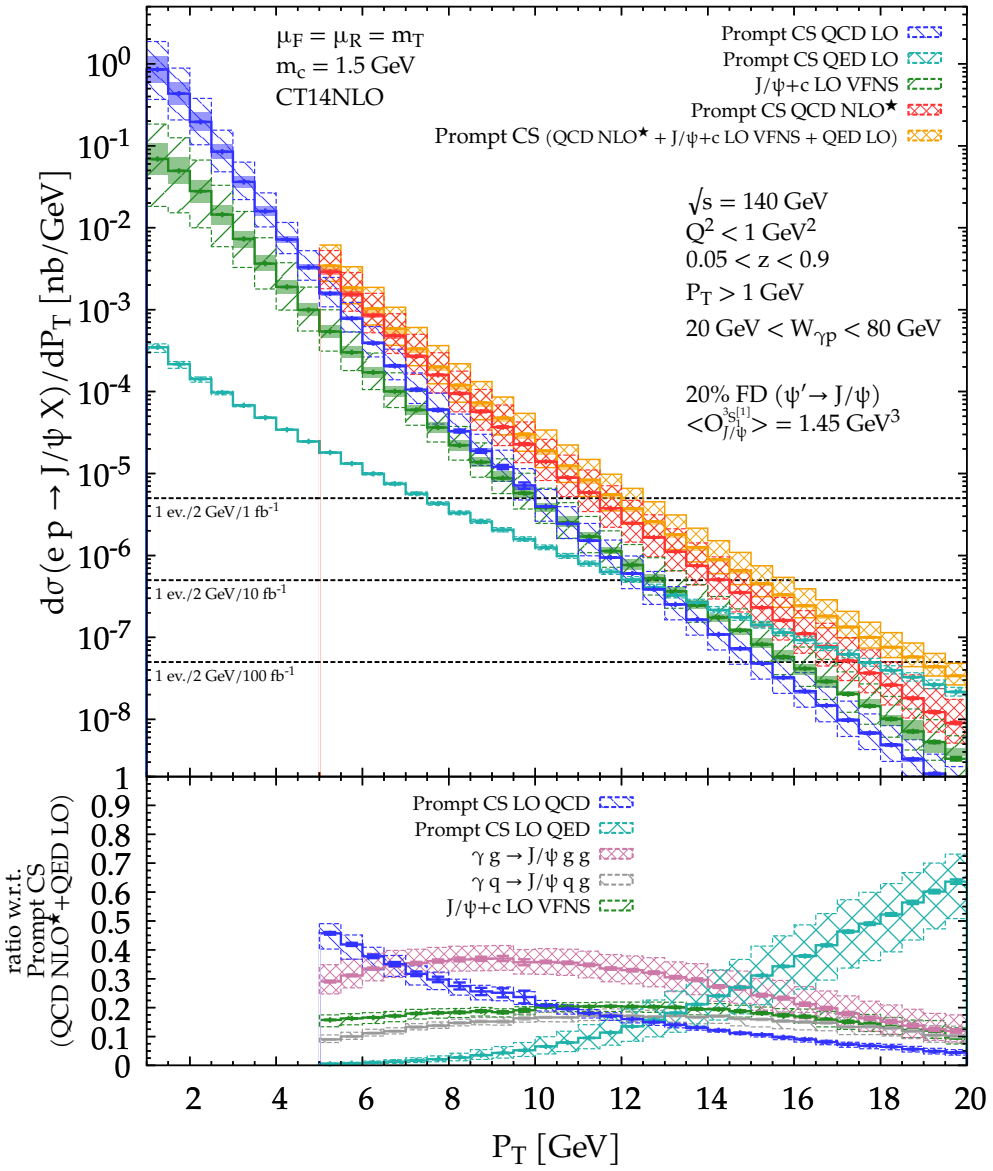

- At $\sqrt{s_{ep}}$ = 140 GeV, P_T range up to 15-20 GeV
- photon-gluon fusion remains dominant

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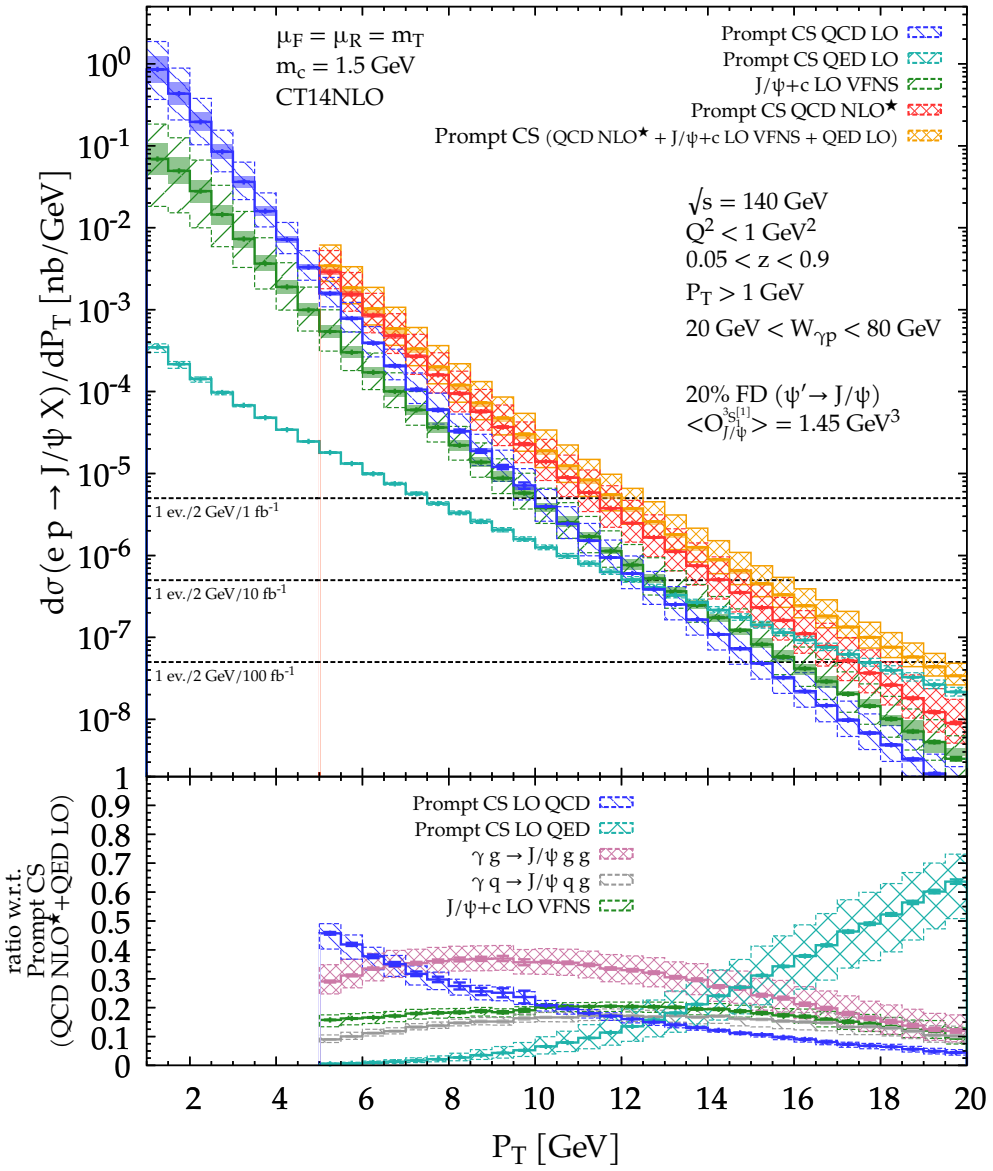

- At $\sqrt{s_{ep}}$ = 140 GeV, P_T range up to 15-20 GeV
- photon-gluon fusion remains dominant
- J/ψ + 2 hard partons dominant for $P_T \sim 10 - 15$ GeV
- Could lead to J/ψ + 2 jets with moderate P_T
- A priori the leading jet$_1$ recoils on the J/ψ+ jet$_2$ pair
- $d\sigma$ should scale with $M_{J/\psi+\text{jet}_2} - M_{J/\psi}$

J/ψ+charm associated production at the EIC

C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

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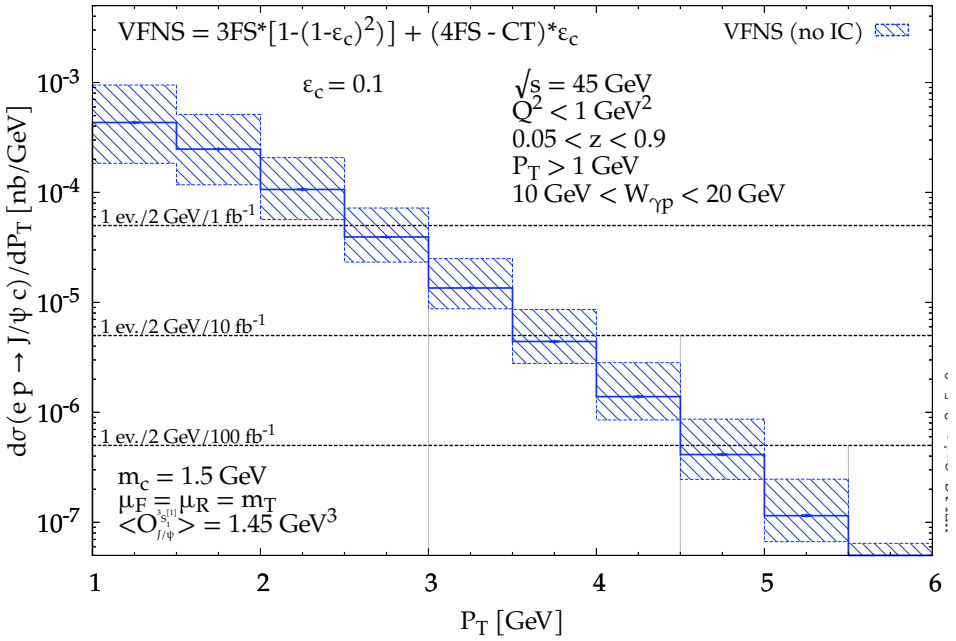

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- Same LO VFNS computation as for J/ψ+charm contributing to $J/\psi + X$ except for the detection efficiency ϵ:
  $VFNS =$
  $3FS \times \left(1 - (1-\epsilon)^2\right) + (4FS - CT) \times \epsilon$
- At $\sqrt{s_{ep}} = 45$ GeV, yield limited to low P_T even with $\mathcal{L} = 100$ fb^{-1}
- But it is clearly observable if $\epsilon_c = 0.1$
- Azimuthal distribution could be studied

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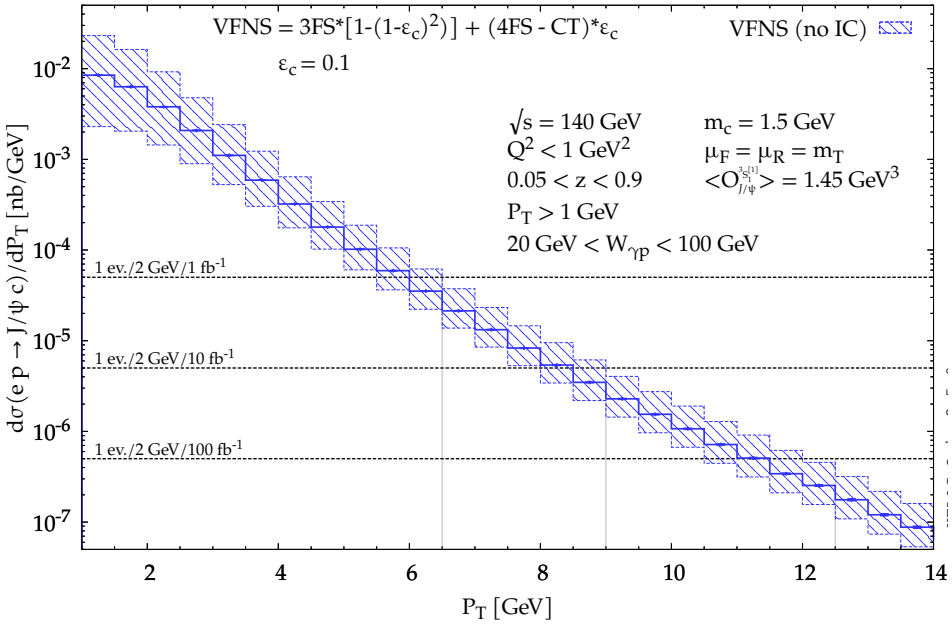

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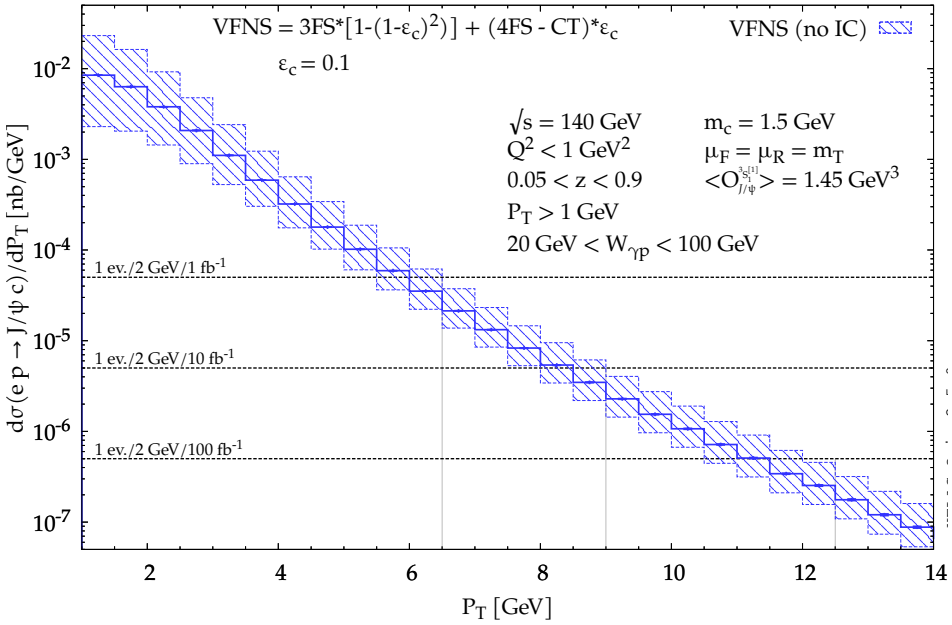

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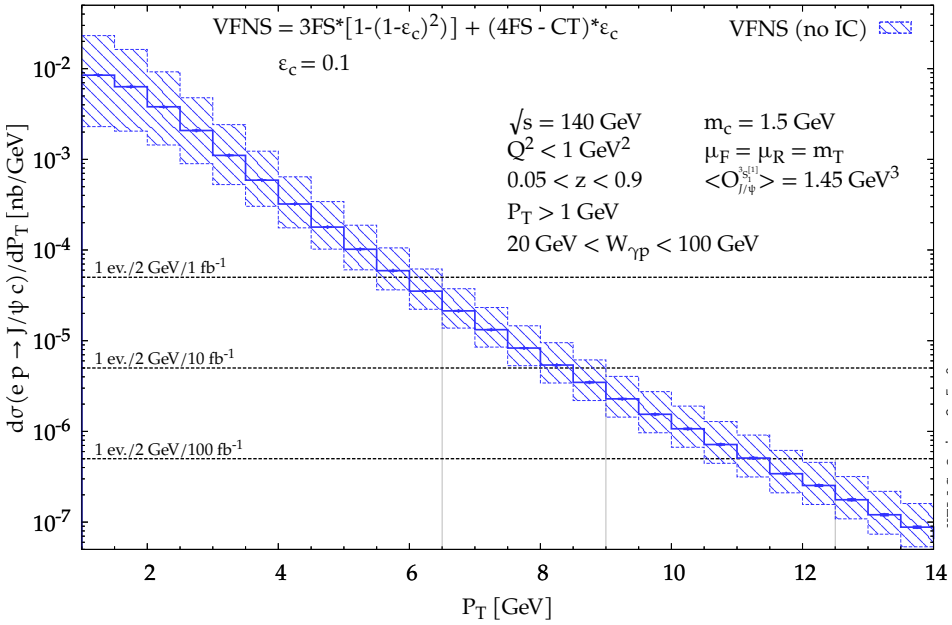

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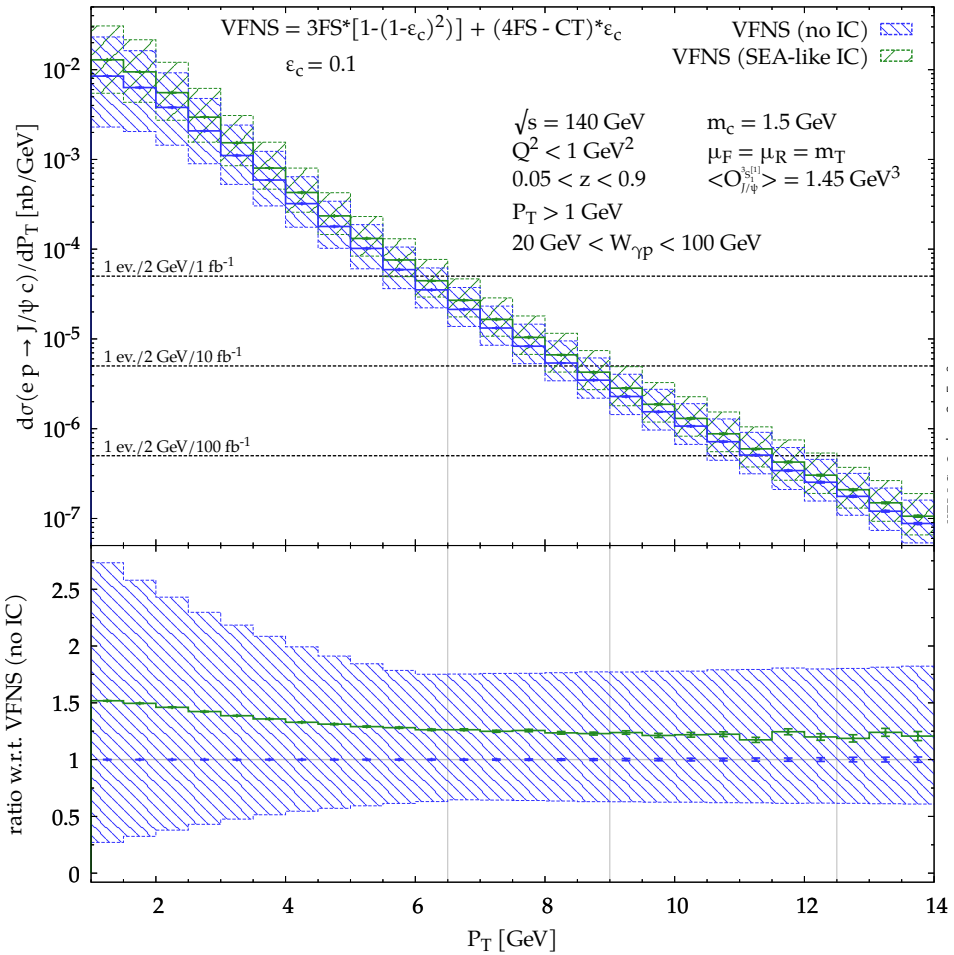

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- Small effect at $\sqrt{s_{ep}}$ = 140 GeV

[We used IC $c(x)$ encoded in CT14NNLO]

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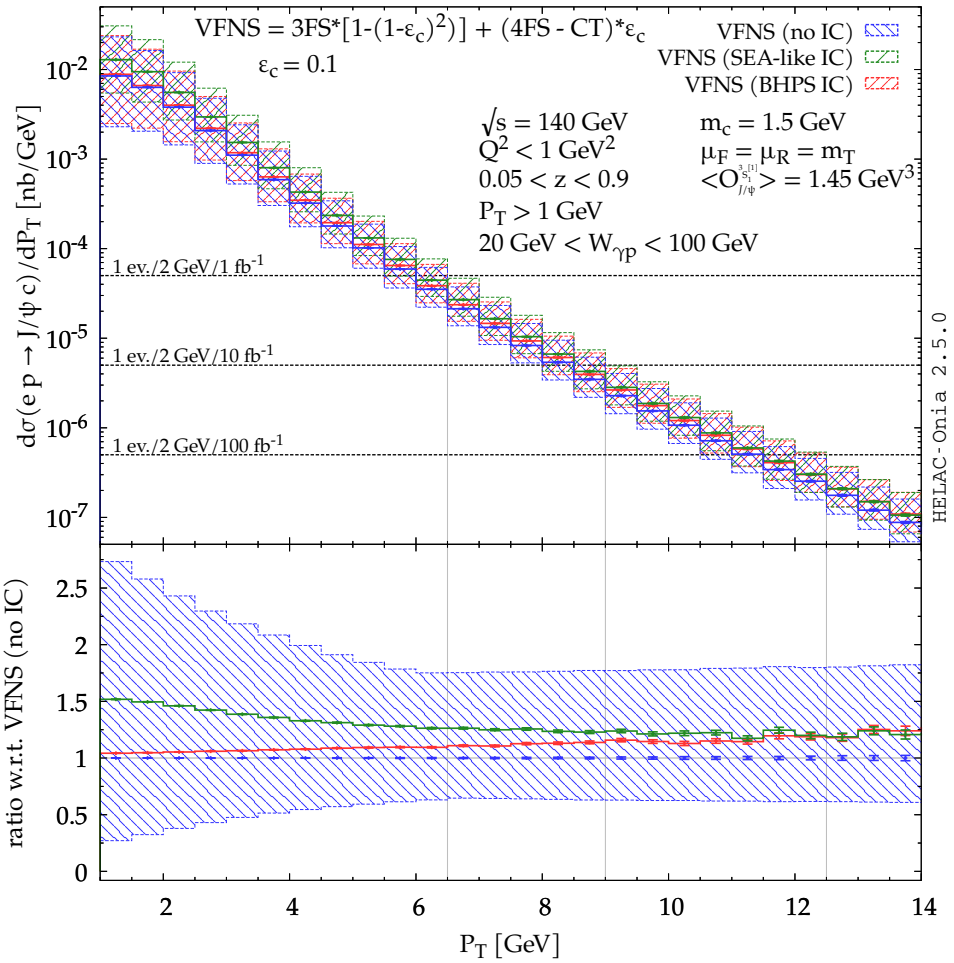

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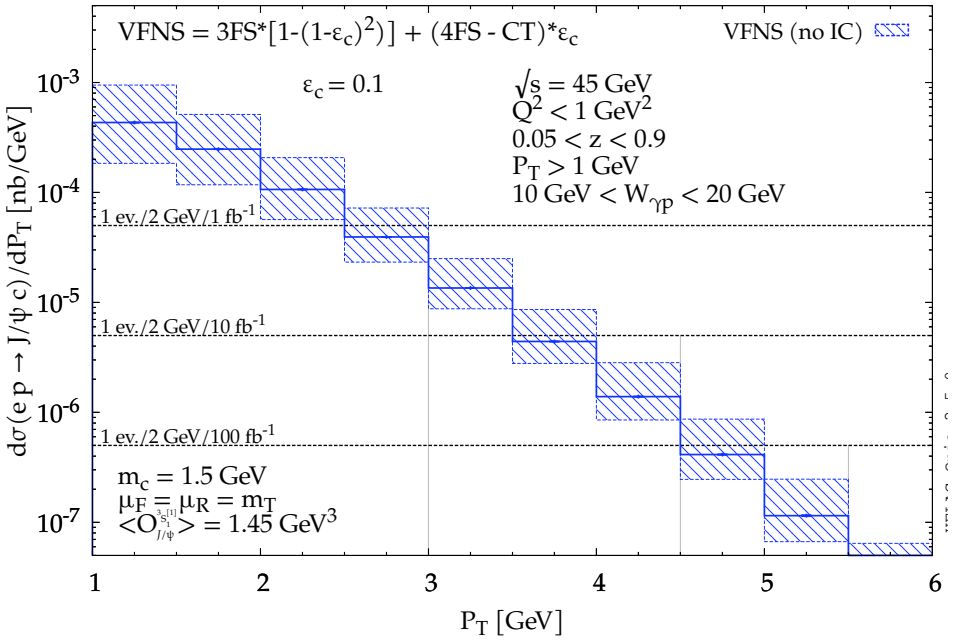

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- Small effect at $\sqrt{s_{ep}}$ = 140 GeV
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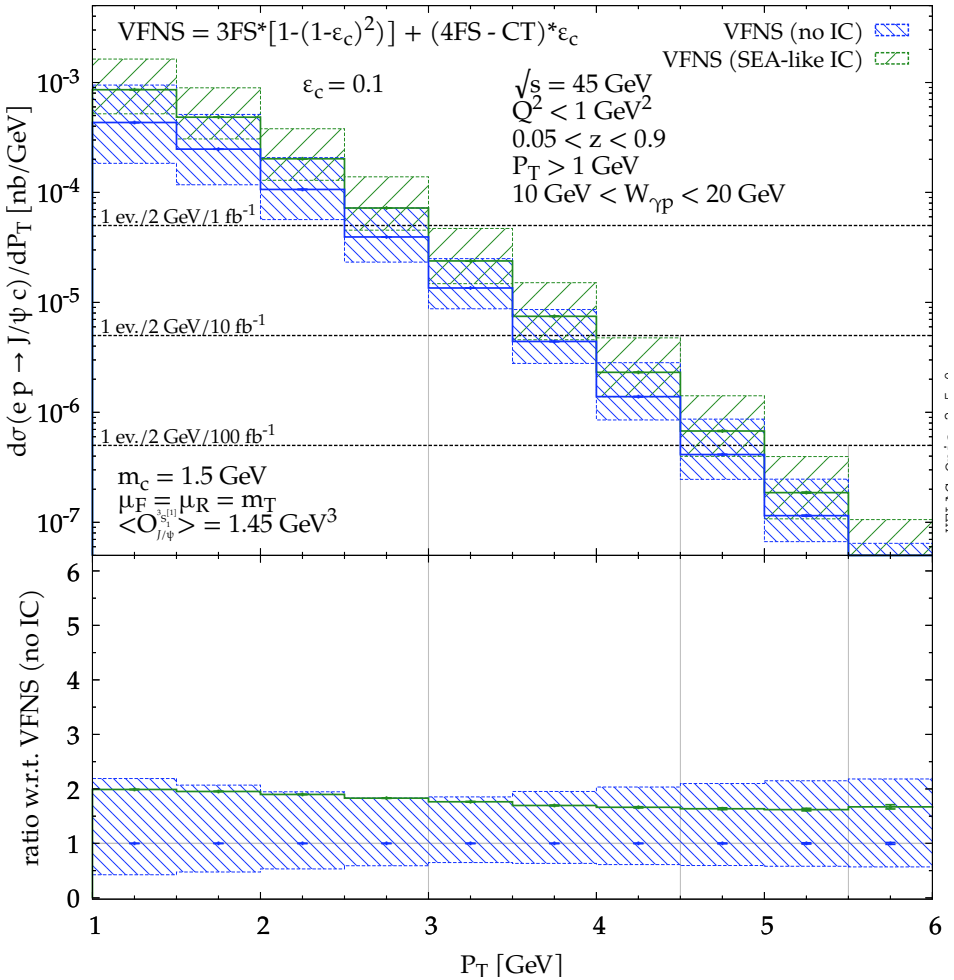

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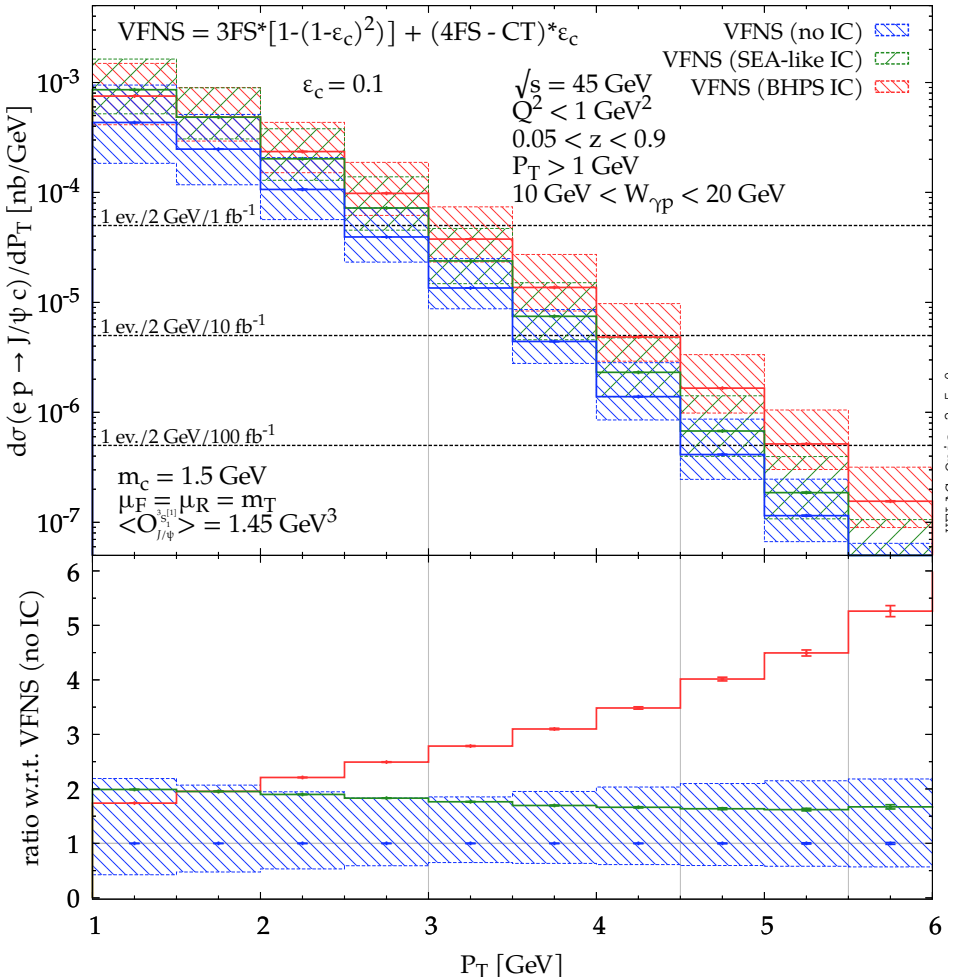

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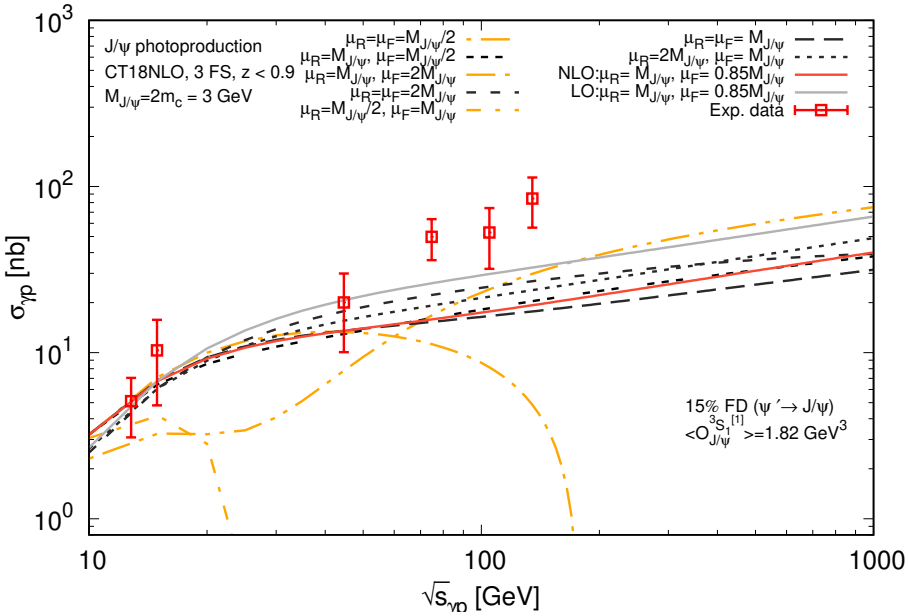
- Small effect at $\sqrt{s_{ep}}$ = 140 GeV [We used IC $c(x)$ encoded in CT14NNLO]
- Measurable effect at $\sqrt{s_{ep}}$ = 45 GeV: BHPS valence-like peak visible !

Part VI

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

The negative cross-sections issue at "high" energies



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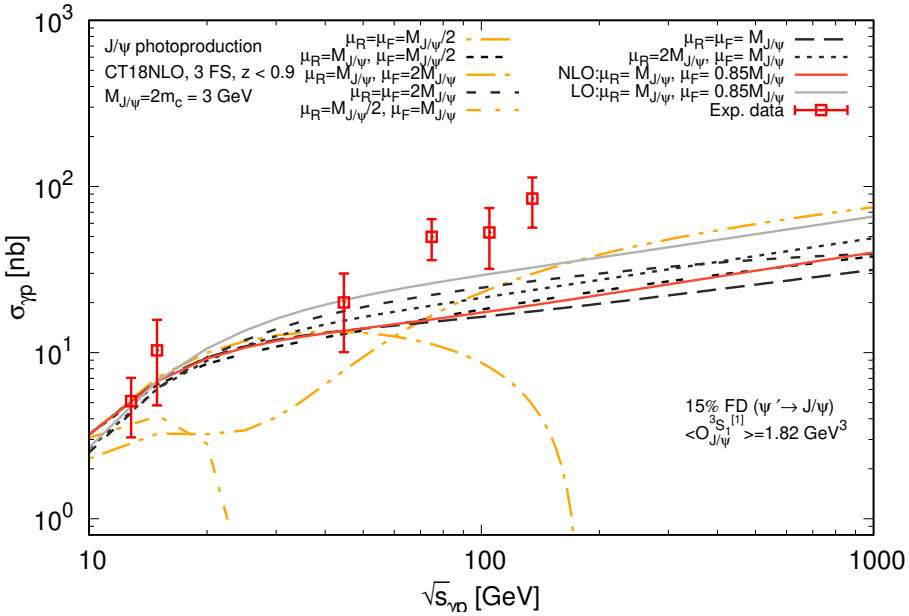

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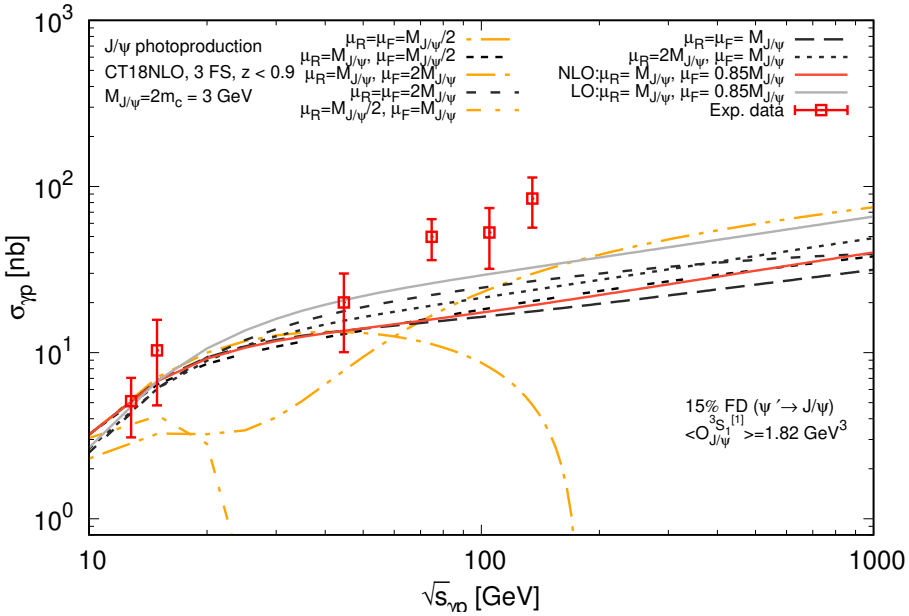

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J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497

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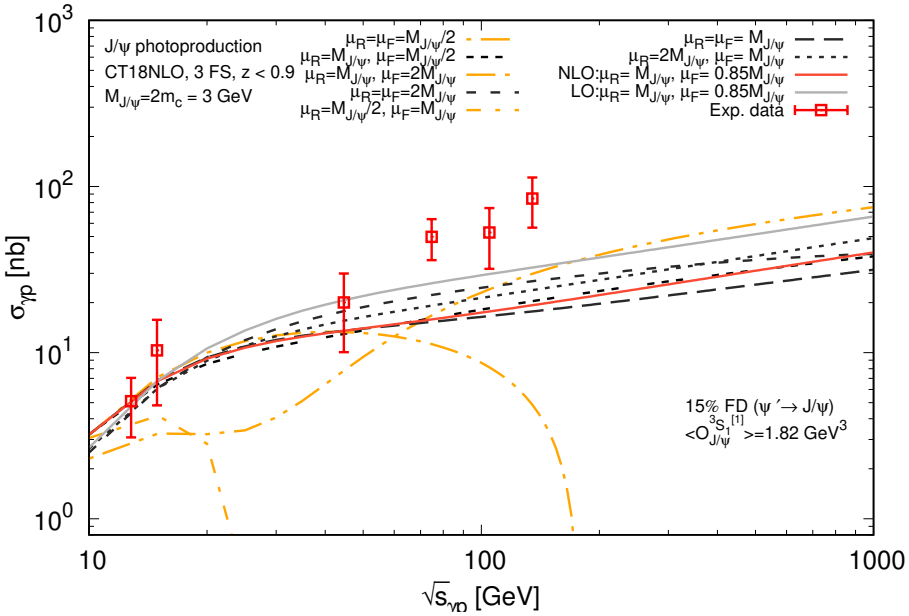

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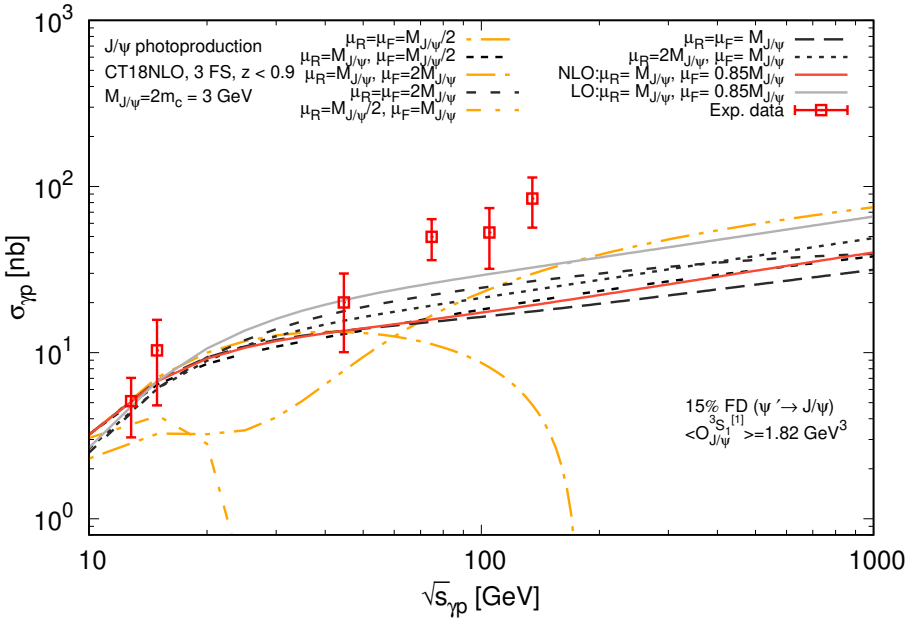
J.P. Lansberg, M.A. Ozcelik: Eur.Phys.J.C 81 (2021) 6, 497

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

Negative cross-section values



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

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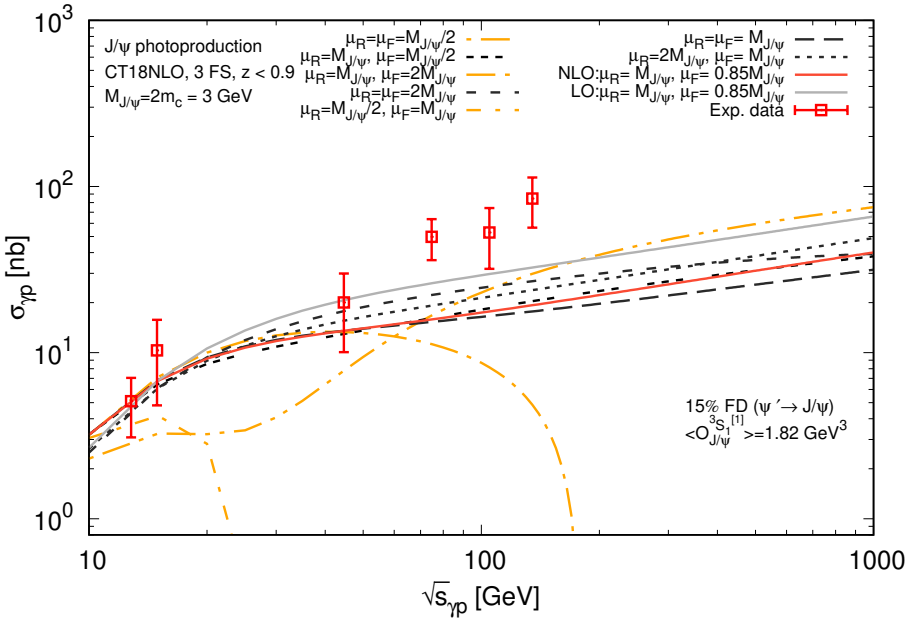

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- $\lim_{\hat{s}\to\infty} \hat{\sigma}_{\gamma i}^{NLO} \propto \left(\log \frac{m_Q^2}{{\mu_F}^2} + A_{\gamma i}\right), A_{\gamma g} = A_{\gamma q}$

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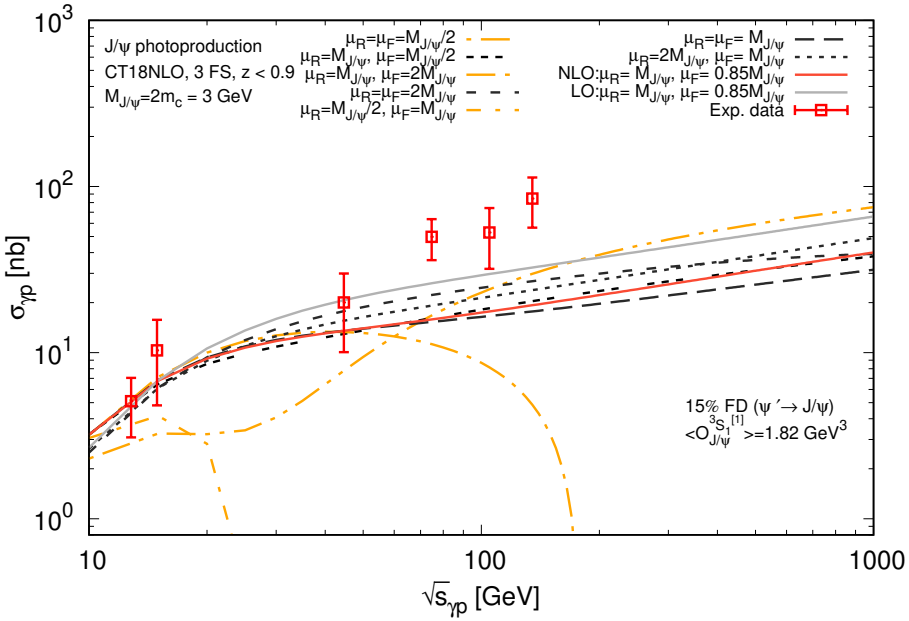

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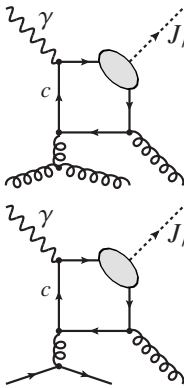
- $\lim_{\hat{s}\to\infty} \hat{\sigma}^{NLO}_{\gamma i} \propto \left(\log \frac{m_Q^2}{\mu_F{}^2} + A_{\gamma i}\right), A_{\gamma g} = A_{\gamma q}$
- If large $\mu_F \to \hat{\sigma} < 0 \to \sigma < 0$: over-subtraction from AP-CT into the PDFs

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;

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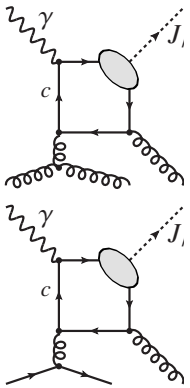

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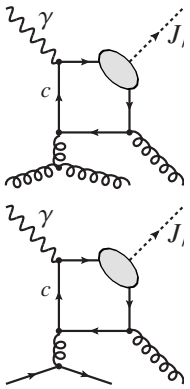

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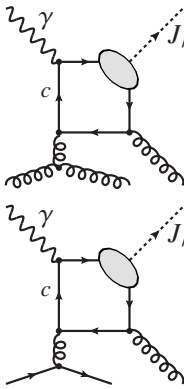

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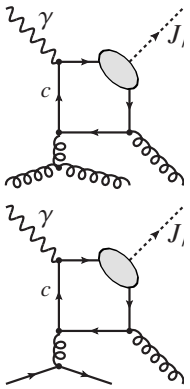

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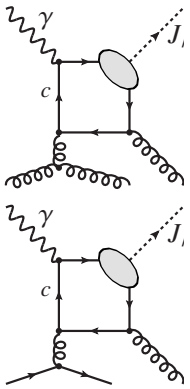

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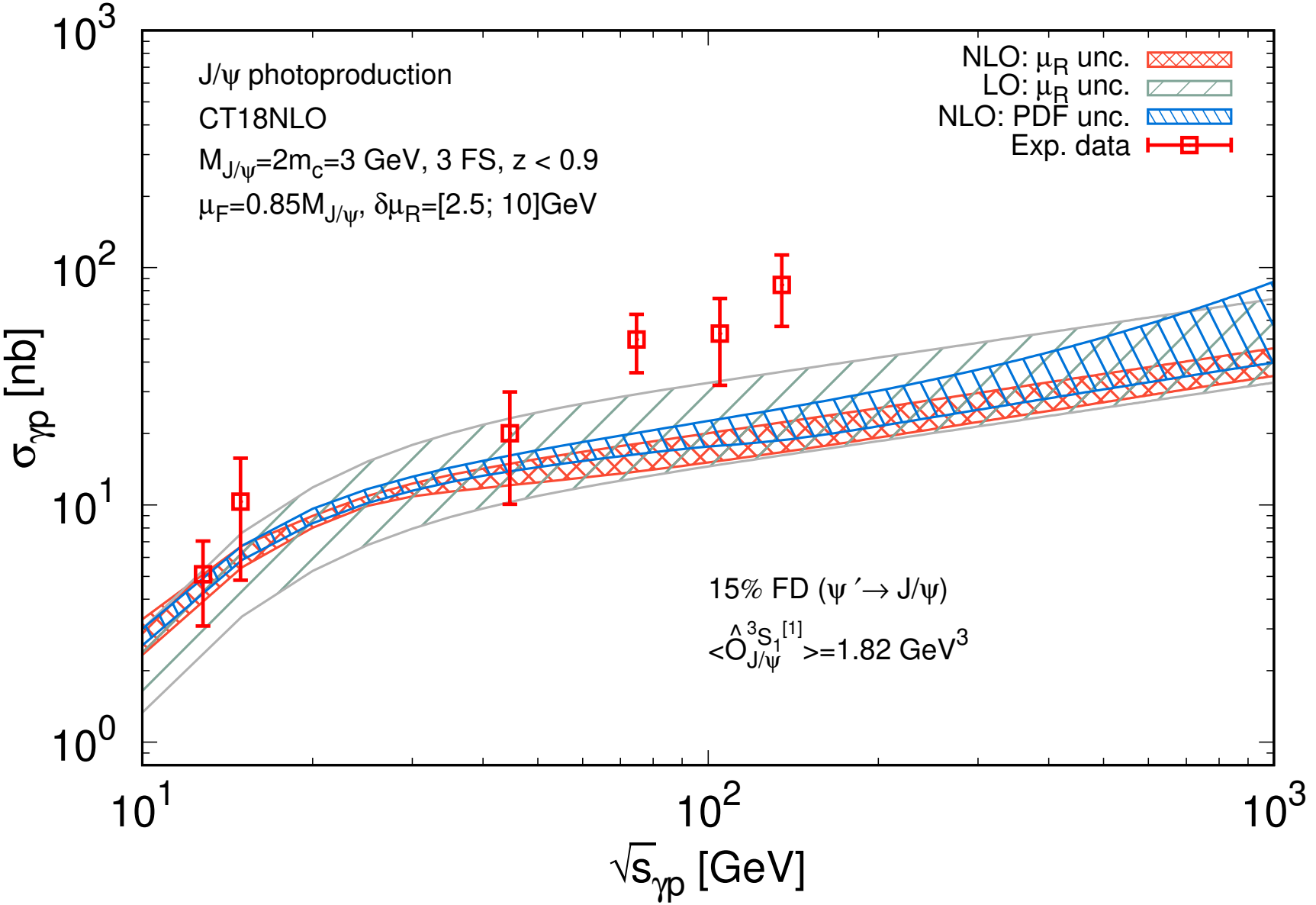
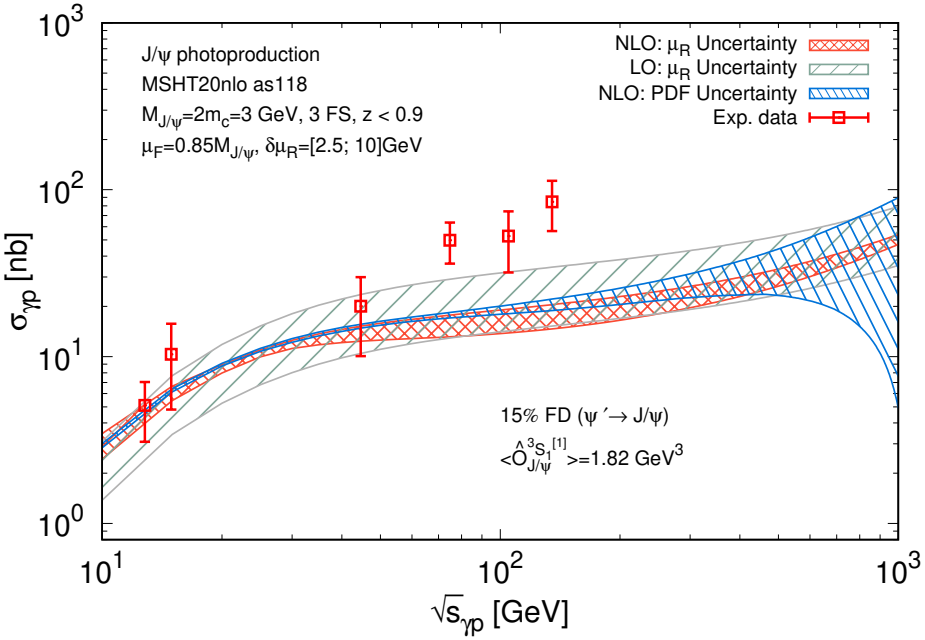
- For J/ψ (Υ) photoproduction: $\hat{\mu}_F = 0.85M$
  ($P_T \in [0, \infty]$, $z < 0.9$)

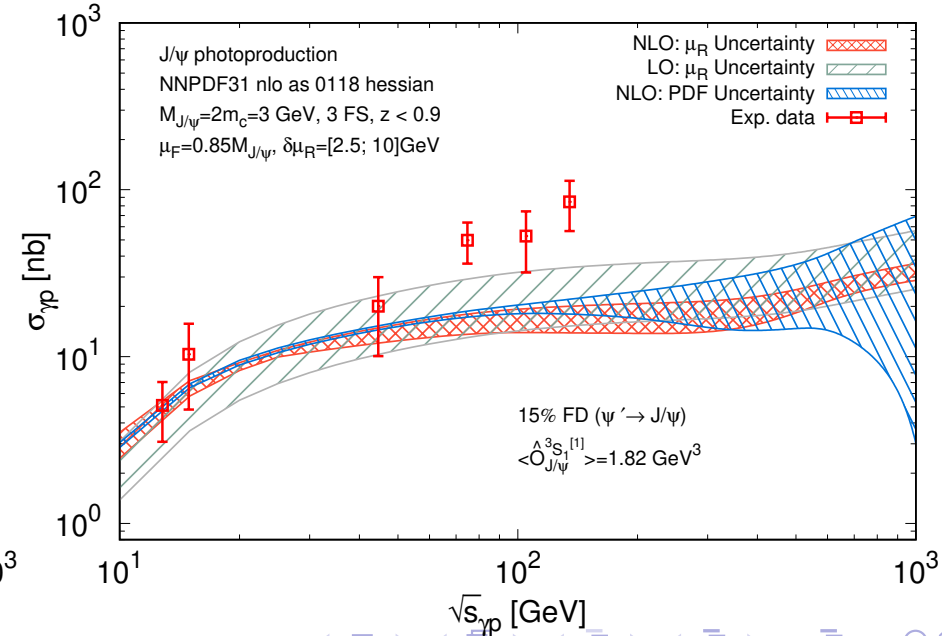
Results with $\hat{\mu}_F = 0.85M$



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

- PDF uncertainties increase at large $\sqrt{s}$ (i.e. small x)





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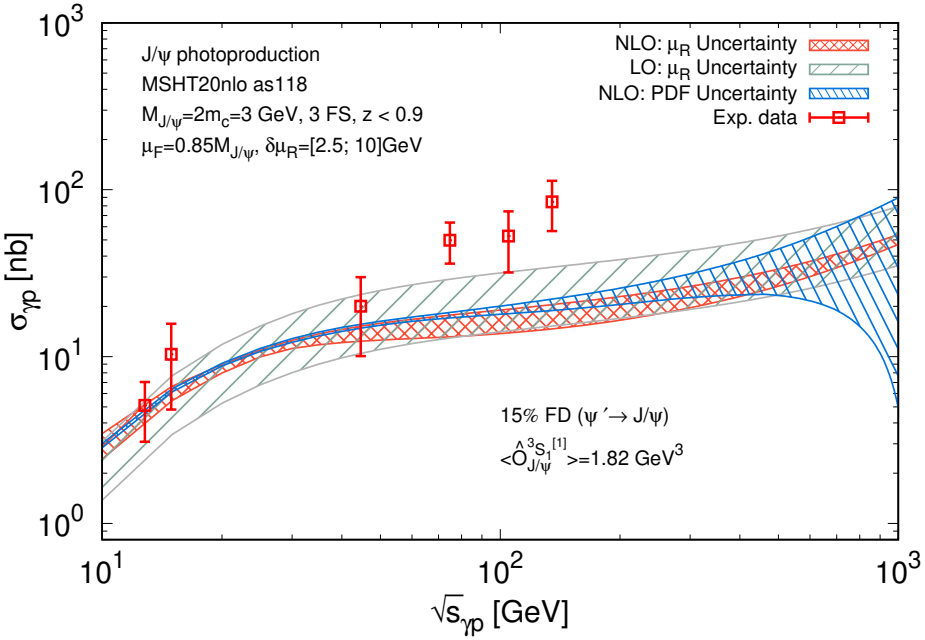

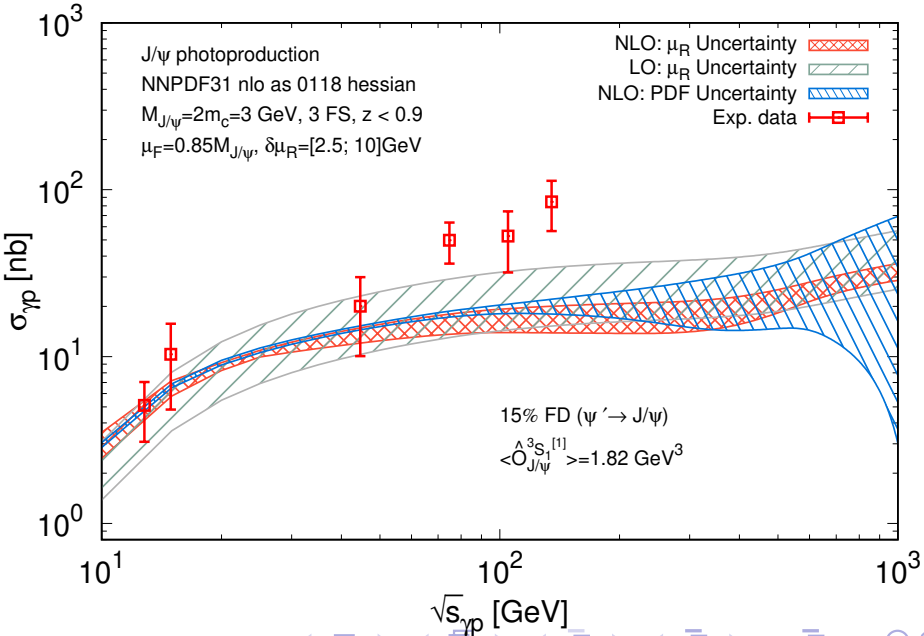

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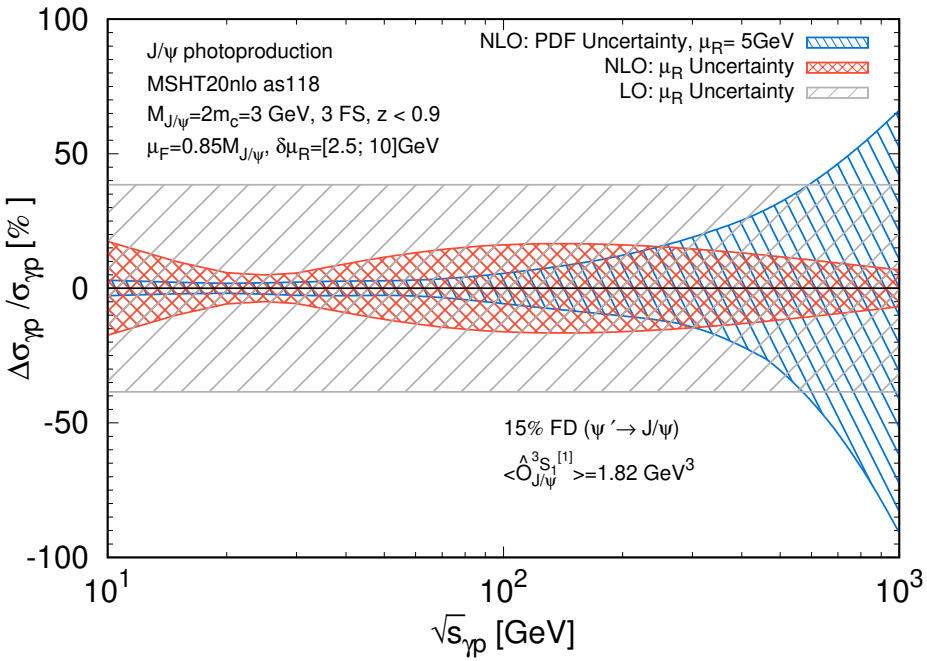

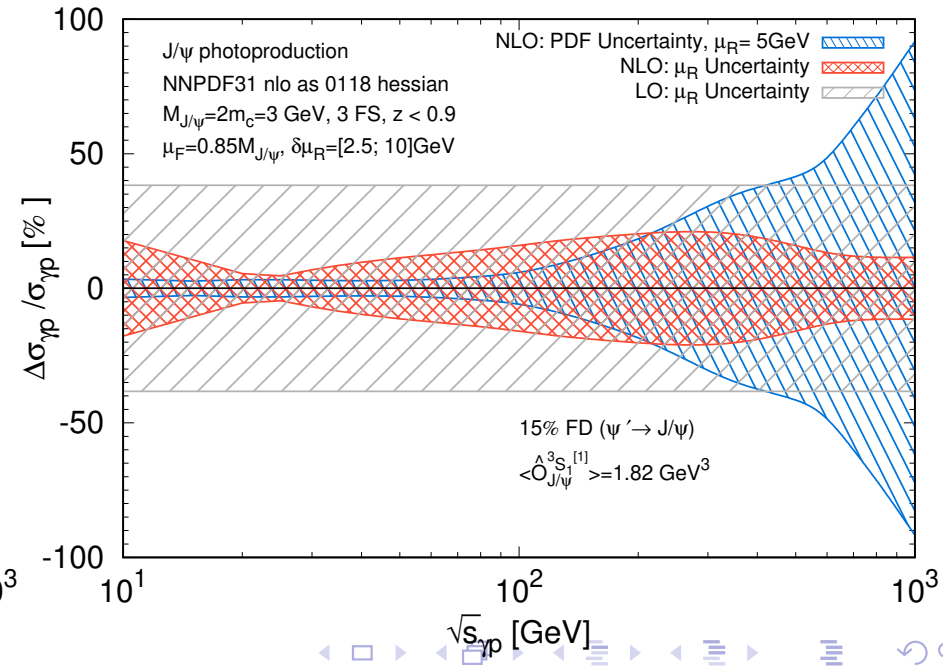

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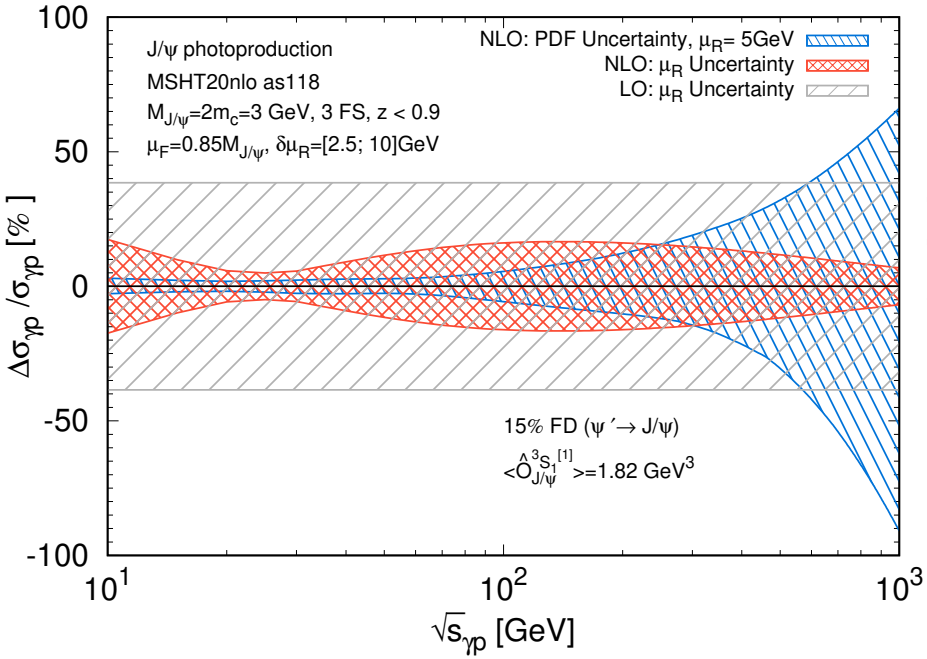

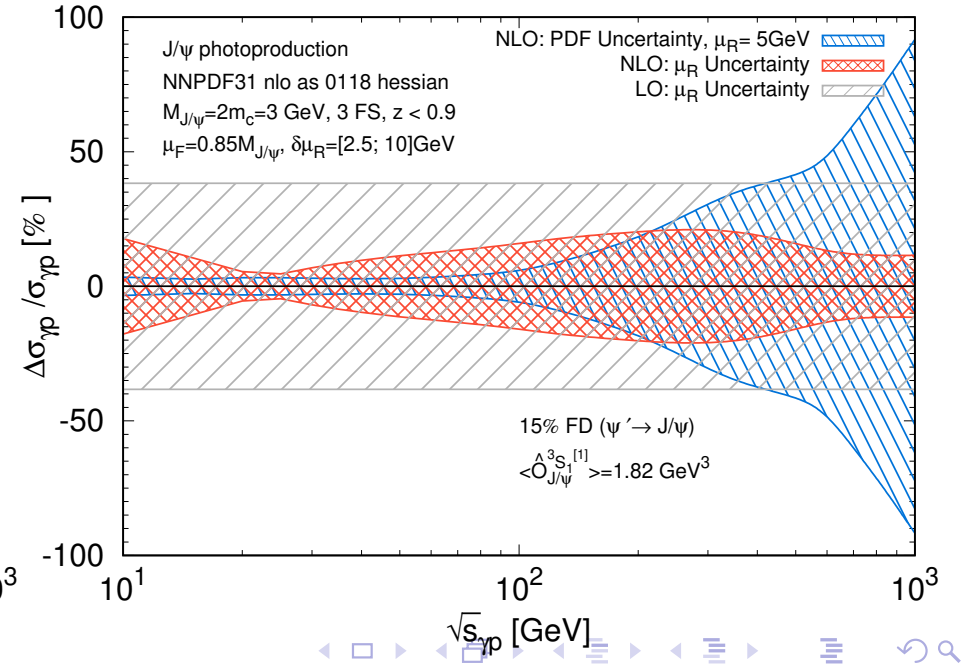

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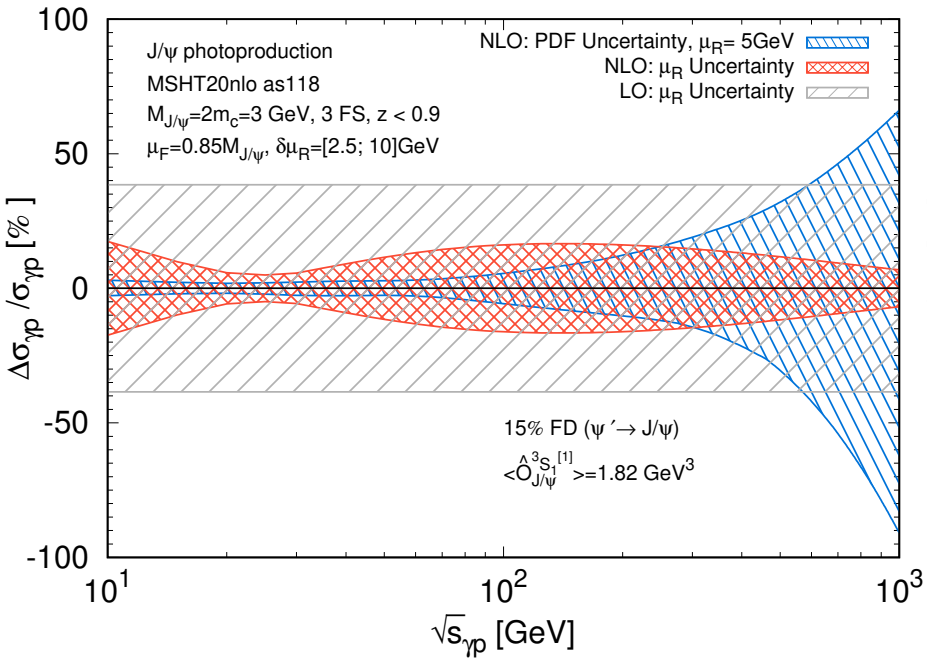
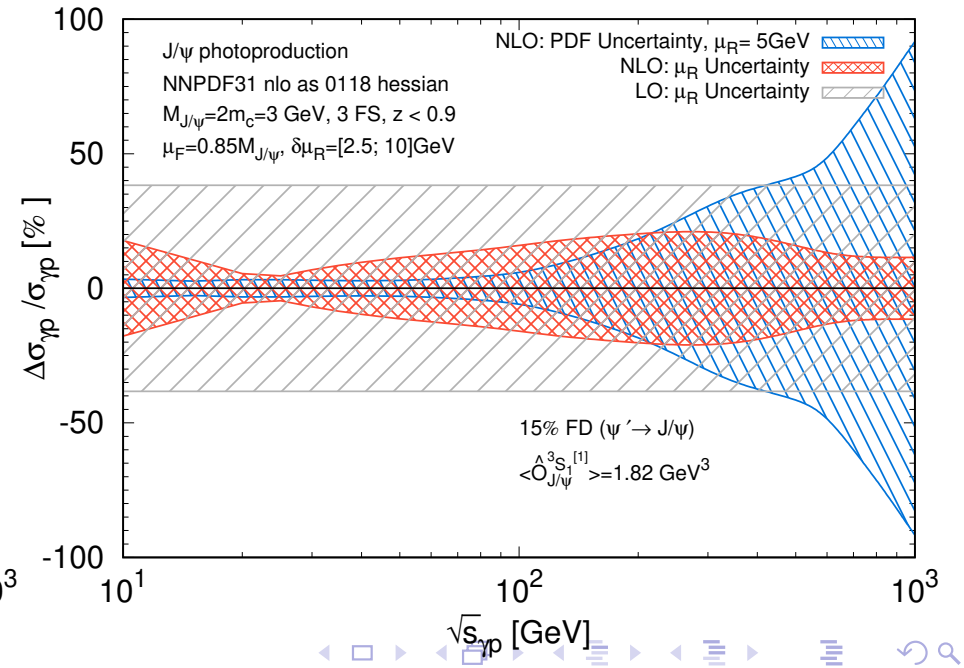
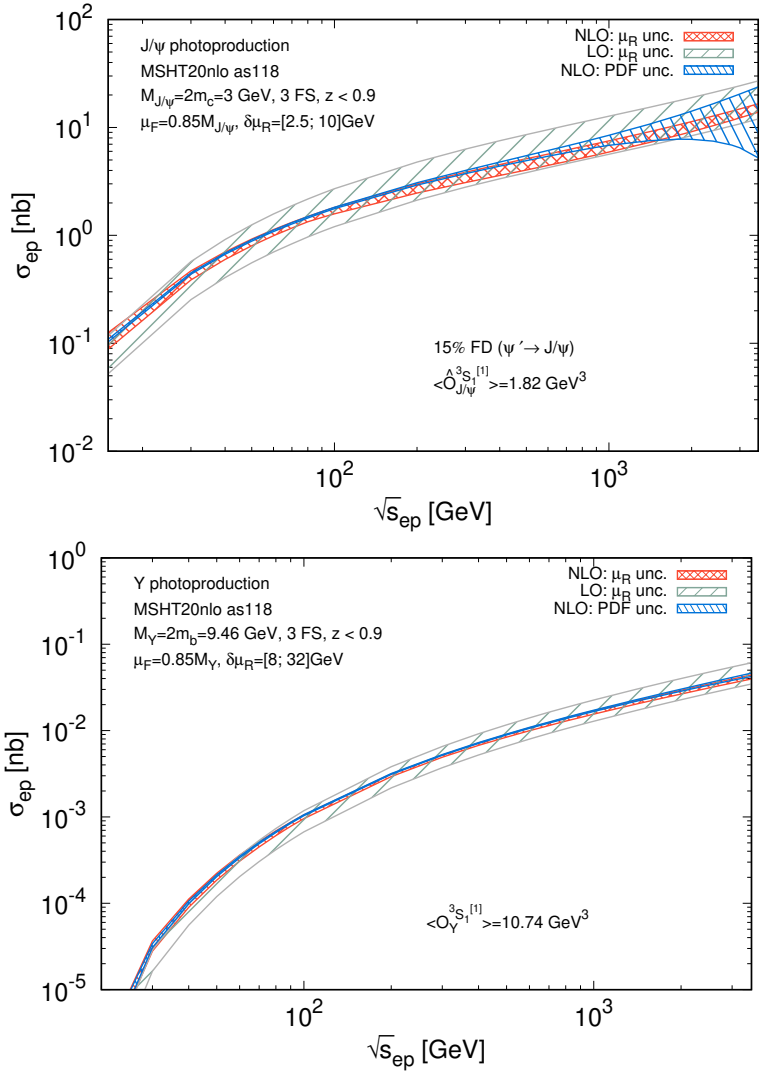
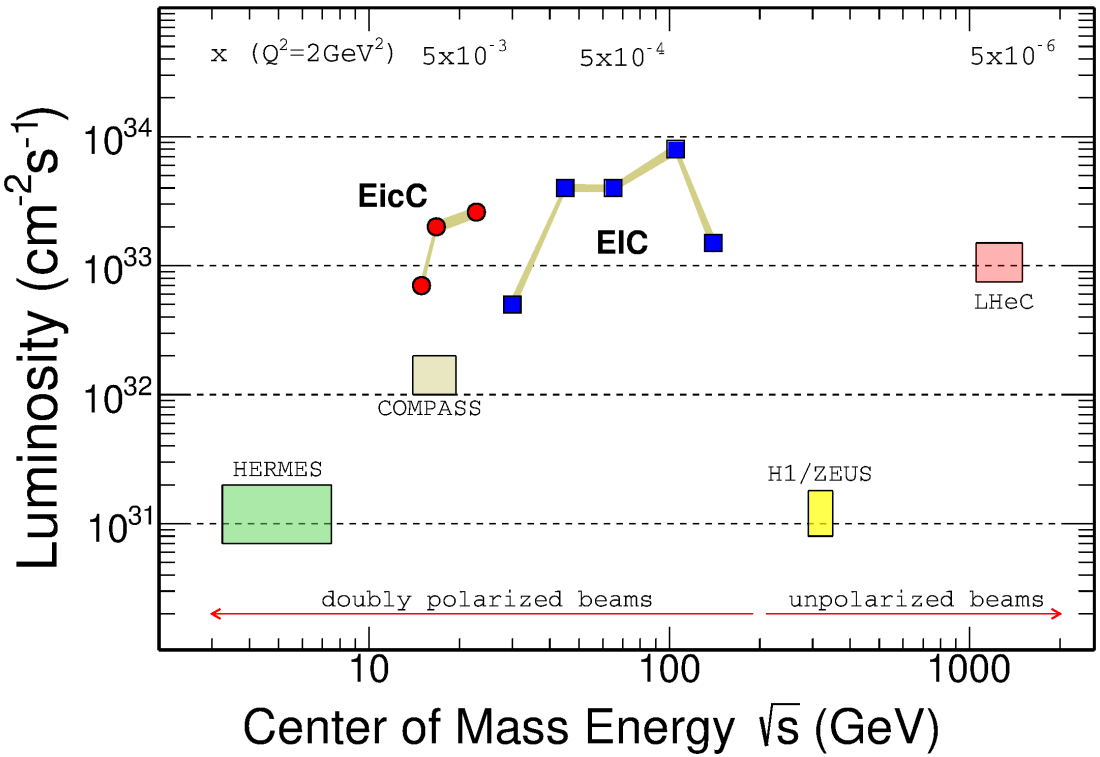
- At NNLO these loop contributions will be squared
- Likely positive NNLO corrections beside a further reduction of the μ_R unc.





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





Possibility to constrain PDF at NNLO if μ_R unc. are further reduced

Part VII

Shaping the EIC quarkonium physics case

EIC quarkonium physics case

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Progress in Particle and Nuclear Physics xxx (xxxx) xxx

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Review

Prospects for quarkonium studies at the high-luminosity LHC

Émilien Chapon [1,a], David d'Enterria [2,a], Bertrand Ducloué [3,a], Miguel G. Echevarria [4,a], Pol-Bernard Gossiaux [5,a], Vato Kartvelishvili [6,a], Tomas Kasemets [7,a], Jean-Philippe Lansberg [8,a,b], Ronan McNulty [9,a], Darren D. Price [10,a], Hua-Sheng Shao [11,a], Charlotte Van Hulse [9,a], Michael Winn [12,a], Jaroslav Adam [13], Liupan An [14], Denys Yen Arrebato Villar [5], Shohini Bhattacharya [15], Francesco G. Celiberto [16,17,18,19], Cvetan Cheshkov [20], Umberto D'Alesio [21], Cesar da Silva [22], Elena G. Ferreiro [23], Chris A. Flett [24,25], Carlo Flore [8], Maria Vittoria Garzelli [26,14,27], Jonathan Gaunt [28,10], Jibo He [29], Yiannis Makris [17], Cyrille Marquet [30], Laure Massacrier [8], Thomas Mehen [31], Cédric Mezrag [12], Luca Micheletti [32], Riccardo Nagar [33], Maxim A. Nefedov [34], Melih A. Ozcelik [8], Biswarup Paul [21], Cristian Pisano [21], Jian-Wei Qiu [35], Sangem Rajesh [21], Matteo Rinaldi [36], Florent Scarpa [8,37], Maddie Smith [5], Pieter Taels [30], Amy Tee [6], Oleg Teryaev [38], Ivan Vitev [22], Kazuhiro Watanabe [35], Nodoka Yamanaka [39,40], Xiaojun Yao [41], Yanxi Zhang [2,42]

arxiv: 2012.14161 [hep-ph]

Physics case for quarkonium studies at the Electron Ion Collider

Editors: Daniël Boer[a,1], Carlo Flore[b,1], Daniel Kikoła[c,1], Jean-Philippe Lansberg[b,1], Charlotte Van Hulse[b,1]

[a] *Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, 9747 AG Groningen, The Netherlands*
[b] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[c] *Faculty of Physics, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland*

Abstract

The physics case for quarkonium-production studies accessible at the future US Electron Ion Collider is described.

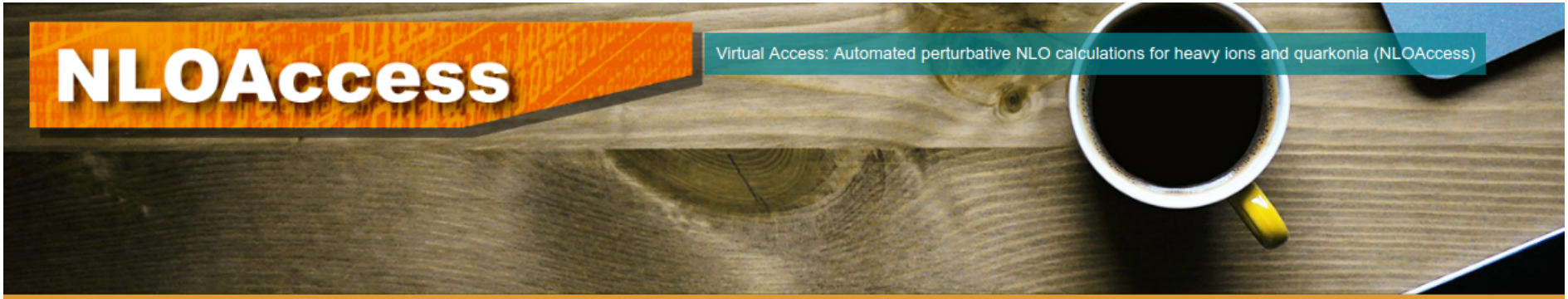
1. Introduction
2. The EIC complex
3. Why Quarkonia ?
4. Parton content of the nucleon
5. Parton content of the nuclei

Part VIII

Online tools for future prospects

A EU Virtual Access to pQCD tools: NLOAccess

[in2p3.fr/nloaccess]



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GENERAL DESCRIPTION

Objectives:

NLOAccess will give access to automated tools generating scientific codes allowing anyone to evaluate observables -such as production rates or kinematical properties – of scatterings involving hadrons. The automation and the versatility of these tools are such that these scatterings need not to be pre-coded. In other terms, it is possible that a random user may request for the first time the generation of a code to compute characteristics of a reaction which nobody thought of before. NLOAccess will allow the user to test the code and then to download to run it on its own computer. It essentially gives access to a dynamical library

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