Curing the high-energy perturbative instability of quarkonium (photo)production cross sections

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Quarkonium Working Group 2024

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Work done in collaboration with M. Nefedov, M.A. Ozcelik
& A. Colpani Serri, Y. Feng, C. Flore, H.S. Shao, Y. Yedelkina

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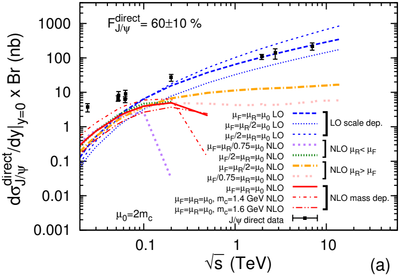

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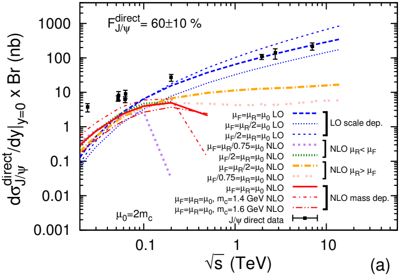

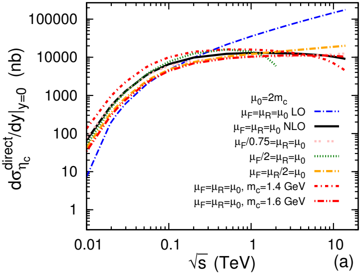

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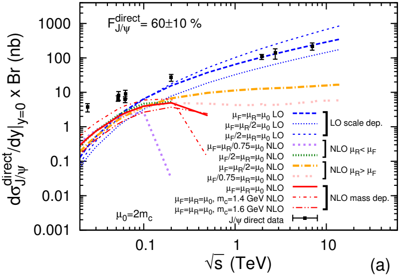

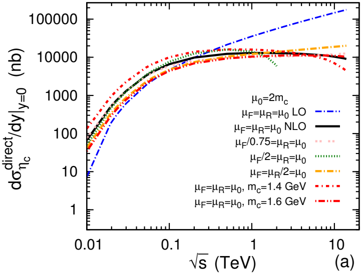

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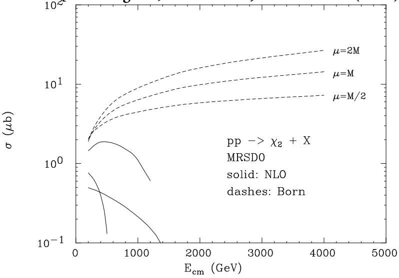

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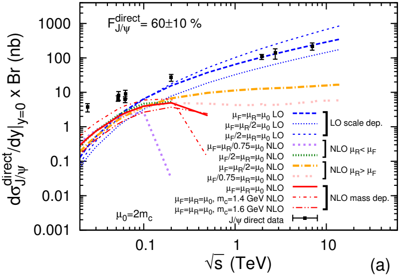

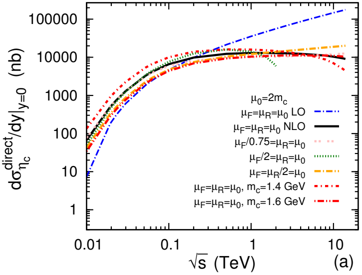

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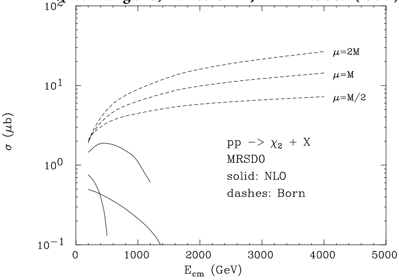
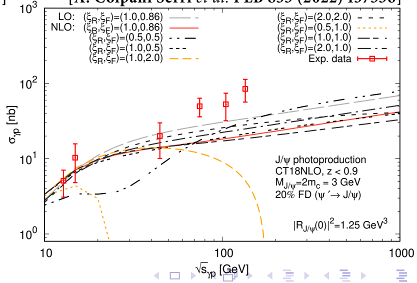


[A. Colpani Serri *et al.* PLB 835 (2022) 137556]



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- and, by digging out, same problem in $\gamma p \to \psi X$ found [A. Colpani Serri *et al.* PLB 835 (2022) 137556]

The NLO partonic cross section at large $\hat{s}$

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- If PDFs are not steep (evolved) enough, the large-$\hat{s}$ region dominates and the hadronic cross section becomes negative

Recap of NLO calculation & origin of negative numbers

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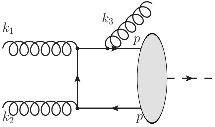

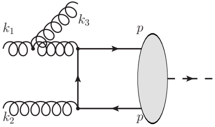

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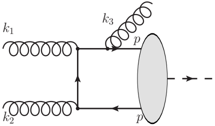

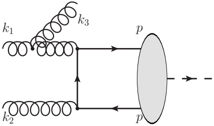

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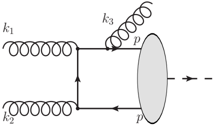

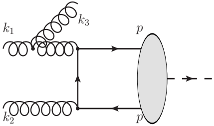

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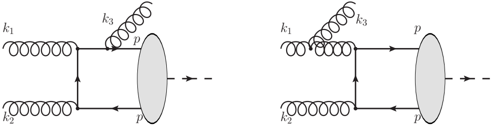

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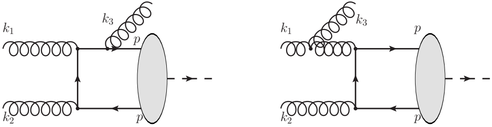

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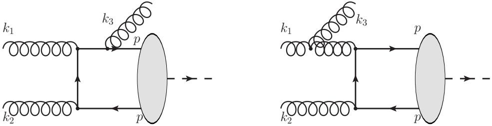

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A new scale-choice prescription

JPL, M.A. Ozcelik, EPJC 81 (2021) 6, 497

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A new scale-choice prescription

JPL, M.A. Ozcelik, EPJC 81 (2021) 6, 497

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Our results with the $\hat{\mu}_F$ prescription

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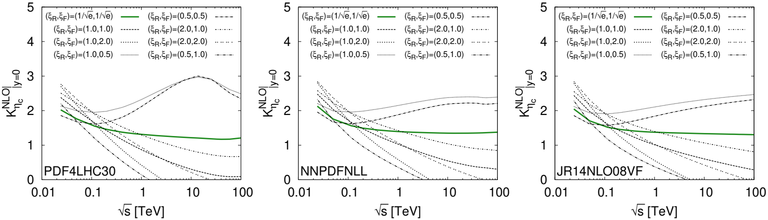

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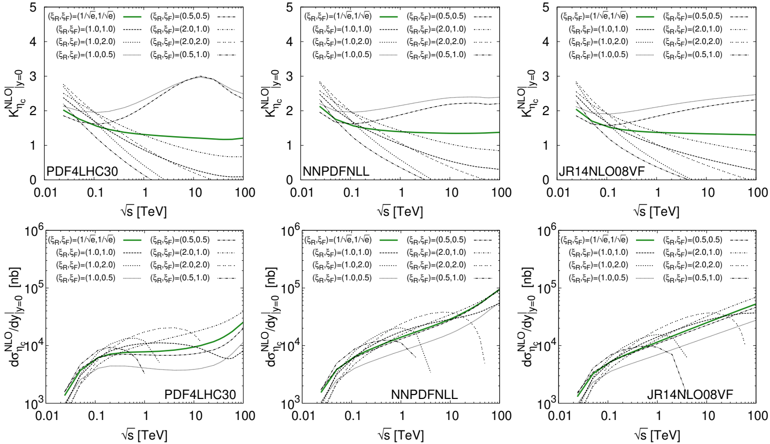

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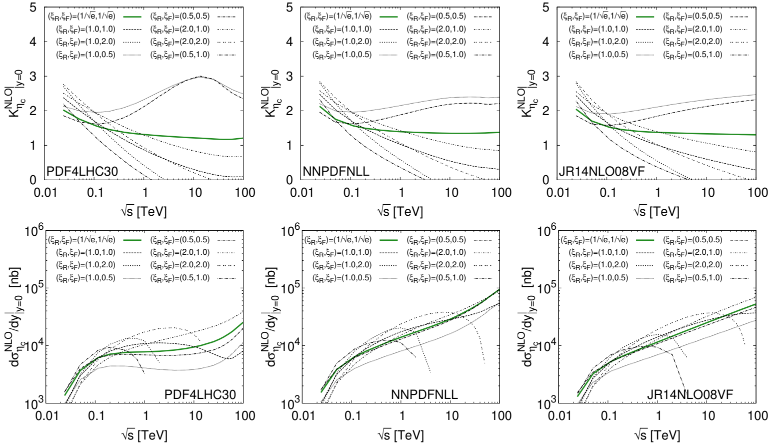

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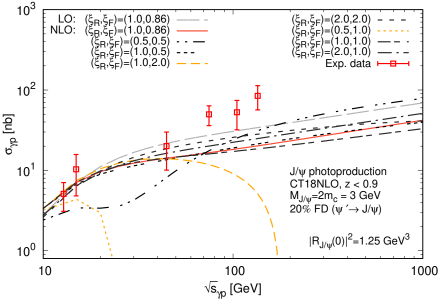
Measuring η_c total cross sections (at NICA, LHC-FT and LHC) : crucial constraints on gluon PDFs

The case of J/ψ photoproduction

A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao, Y. Yedelkina, PLB 835 (2022) 137556



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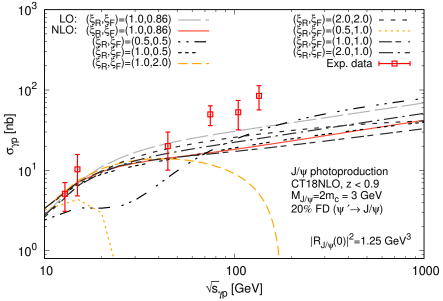

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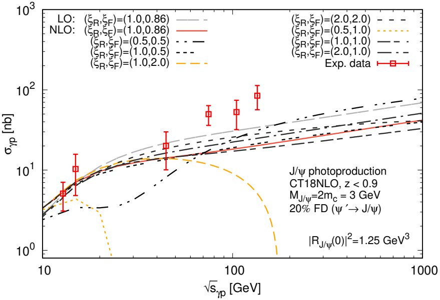

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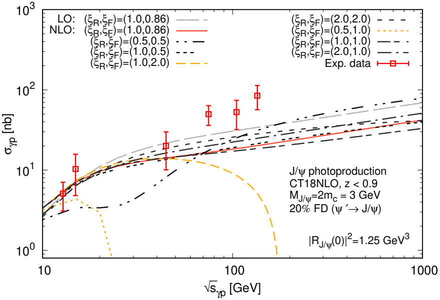

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- For J/ψ (Υ) photoproduction: $\hat{\mu}_F = 0.86 M_Q$ $(P_T \in [0, \infty],\ z < 0.9)$

Results with $\hat{\mu}_F = 0.86 M_Q$

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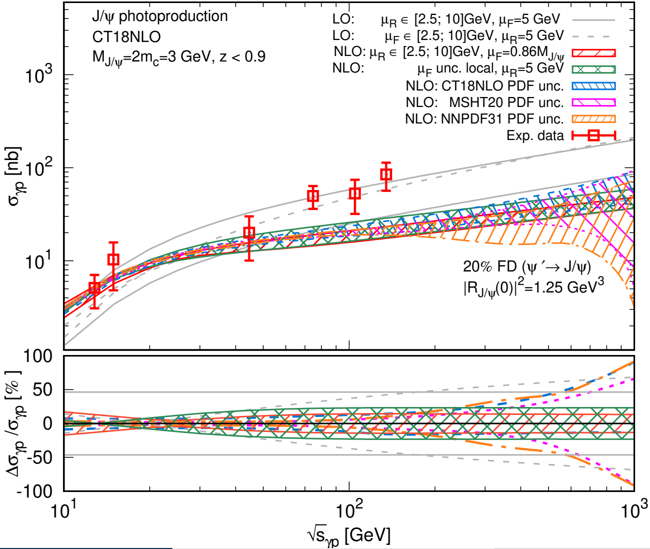

A word on the P_T-differential cross section

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- Contrary to a widespread belief, the CSM does a reasonnable job in describing the latest large-P_T H1 data **C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926**

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  - $\mu_F = 0.77 m_T$: compromise between $\hat{\mu}_F$ and conventional choices $(0.5; 1; 2) m_T$

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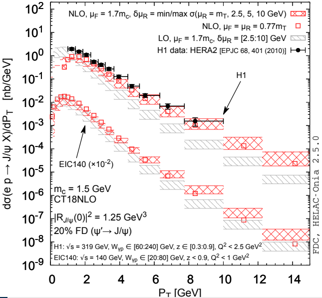

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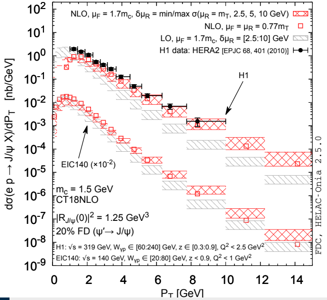
- Confirms the good agreement at large P_T and highlights the need for a more systematic solution at low $P_T \rightarrow$ resummation ?



High-energy factorisation: the example of photoproduction

$$\hat{\sigma}_{\mathrm{HEF}}(\eta) \propto \int_0^{1+\eta} \frac{dy}{y} \int_0^{\infty} d\mathbf{q}_{T1}^2 \, \mathcal{C}\left(\frac{y}{1+\eta}, \mathbf{q}_{T1}^2, \mu_F, \mu_R\right) \mathcal{H}(y, \mathbf{q}_{T1}^2) + \mathrm{NLLA} + O(1/\eta)$$

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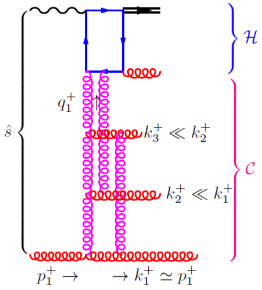

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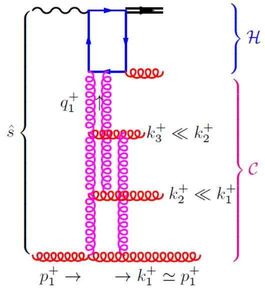

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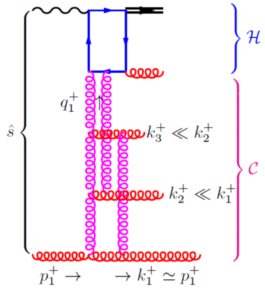

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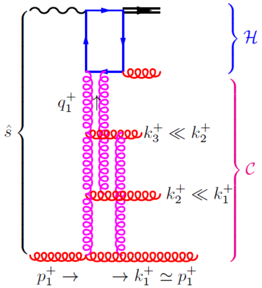

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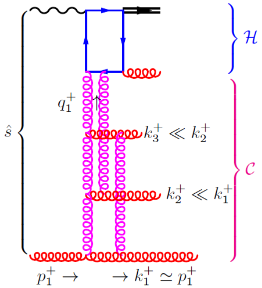

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- HEF can be used with the same collinear PDFs as CF and can be matched on to CF [better to use DLA for consistency]

Consistency check for $pp \to QX$

J.P. Lansberg, M. Nefedov, M.A.Ozcelik, JHEP 05 (2022) 083

HEF expanded up to NLO in α_s should reproduce the $A_1^{[m]}$ NLO coefficient

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$$\left. + \left(\frac{\alpha_s}{\pi}\right)^2 \ln \frac{1}{z} C_A^2 \left[2A_2^{[m]} + B_2^{[m]} + 4A_1^{[m]} \ln \frac{M^2}{\mu_F^2} + 2A_0^{[m]} \ln^2 \frac{M^2}{\mu_F^2} \right] + O(\alpha_s^3) \right\},$$

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From HEF, up to NNLO in α_s, one has

State	$A_0^{[m]}$	$A_1^{[m]}$	$A_2^{[m]}$	$B_2^{[m]}$
${}^1S_0$	1	$\mathbf{-1}$	$\frac{\pi^2}{6}$	$\frac{\pi^2}{6}$
${}^3S_1$	0	1	0	$\frac{\pi^2}{6}$
${}^3P_0$	1	$-\mathbf{\frac{43}{27}}$	$\frac{\pi^2}{6} + \frac{2}{3}$	$\frac{\pi^2}{6} + \frac{40}{27}$
${}^3P_1$	0	$\frac{5}{54}$	$-\frac{1}{9}$	$-\frac{2}{9}$
${}^3P_2$	1	$-\mathbf{\frac{53}{36}}$	$\frac{\pi^2}{6} + \frac{1}{2}$	$\frac{\pi^2}{6} + \frac{11}{9}$

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$$\hat{\sigma}_{gg}^{[m],\,\mathrm{HEF}}(z \to 0) = \sigma_{\mathrm{LO}}^{[m]} \left\{ A_0^{[m]} \delta(1-z) + \frac{\alpha_s}{\pi} 2C_A \left[A_1^{[m]} + A_0^{[m]} \ln \frac{M^2}{\mu_F^2} \right] + \left(\frac{\alpha_s}{\pi}\right)^2 \ln \frac{1}{z} C_A^2 \left[2A_2^{[m]} + B_2^{[m]} + 4A_1^{[m]} \ln \frac{M^2}{\mu_F^2} + 2A_0^{[m]} \ln^2 \frac{M^2}{\mu_F^2} \right] + O(\alpha_s^3) \right\},$$

From HEF, up to NNLO in α_s, one has

State	$A_0^{[m]}$	$A_1^{[m]}$	$A_2^{[m]}$	$B_2^{[m]}$
$^1S_0$	1	**-1**	$\frac{\pi^2}{6}$	$\frac{\pi^2}{6}$
$^3S_1$	0	1	0	$\frac{\pi^2}{6}$
$^3P_0$	1	**$-\frac{43}{27}$**	$\frac{\pi^2}{6}+\frac{2}{3}$	$\frac{\pi^2}{6}+\frac{40}{27}$
$^3P_1$	0	$\frac{5}{54}$	$-\frac{1}{9}$	$-\frac{2}{9}$
$^3P_2$	1	**$-\frac{53}{36}$**	$\frac{\pi^2}{6}+\frac{1}{2}$	$\frac{\pi^2}{6}+\frac{11}{9}$

Perfect match for NLO and prediction for NNLO !

NLO: JPL, M.A. Ozcelik, EPJC 81 (2021) 6, 497

Matching HEF and NLO CF (illustration for η_Q)

The HEF works only at $z \ll 1$ and does not include corrections $O(z)$, while NLO CF is exact in z but only NLO up to α_s. **We need to match them.**

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- Simplest prescription: just **subtract the overlap** at $z \ll 1$ where CF $\subset$ HEF:

$$\sigma^{[m]}_{\text{NLO+HEF}} = \sigma^{[m]}_{\text{LO CF}} + \int_{z_{\min}}^{1} \frac{dz}{z} \left[\check{\sigma}^{[m],ij}_{\text{HEF}}(z) + \hat{\sigma}^{[m],ij}_{\text{NLO CF}}(z) - \hat{\sigma}^{[m],ij}_{\text{NLO CF}}(0) \right] \mathcal{L}_{ij}(z)$$

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- Or introduce **smooth weights**:

$$\sigma^{[m]}_{\text{NLO+HEF}} = \sigma^{[m]}_{\text{LO CF}} + \int_{z_{\min}}^{1} dz \left\{ \left[\check{\sigma}^{[m],ij}_{\text{HEF}}(z) \frac{\mathcal{L}_{ij}(z)}{z} \right] w^{ij}_{\text{HEF}}(z) + \left[\hat{\sigma}^{[m],ij}_{\text{NLO CF}}(z) \frac{\mathcal{L}_{ij}(z)}{z} \right] \left(1 - w^{ij}_{\text{HEF}}(z)\right) \right\},$$

Inverse-error-weighting method

M.G. Echevarria, T. Kasemets, JPL, C. Pisano, A. Signori, PLB 781 (2018) 161

In the InEW method, the weights are calculated from the **parametric estimates of the error** of each contribution and combined as such:

$$w^{ij}_{\text{HEF}}(z) = \frac{[\Delta\sigma^{ij}_{\text{HEF}}(z)]^{-2}}{[\Delta\sigma^{ij}_{\text{HEF}}(z)]^{-2} + [\Delta\sigma^{ij}_{\text{CF}}(z)]^{-2}},$$

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$\sigma^{\rm LLA}_{\rm HEF}$ misses HO terms in $\frac{M_{\mathcal{Q}}^2}{\hat{s}}$. Our $\Delta\sigma_{\rm HEF}$ includes estimates of NLLA corrections as $\alpha_s^2\mathcal{O}(\frac{M_{\mathcal{Q}}^2}{\hat{s}}) \to \alpha_s \hat{\sigma}^{\rm NLO}_{\rm CF}$ $+(\frac{M_{\mathcal{Q}}^2}{\hat{s}})^{\alpha}(\hat{\sigma}^{\rm NLO}_{\rm CF}(\hat{s}) - \hat{\sigma}^{\rm NLO}_{\rm CF}(\infty))$ term

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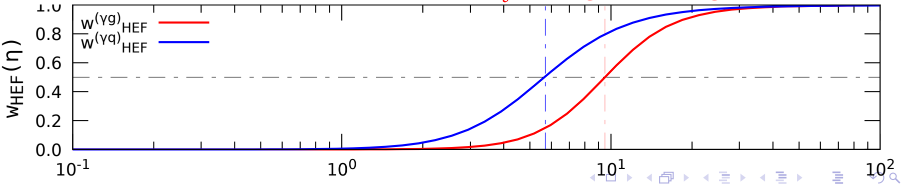
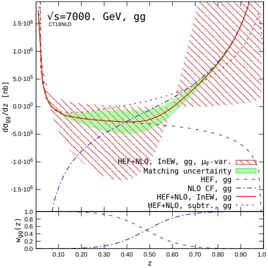
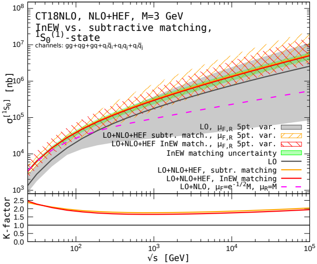


Matched results

η_c hadroproduction

JPL, M. Nefedov, M.A.Ozcelik, JHEP 05 (2022) 083 and 2306.02425(to appear in EPJC)





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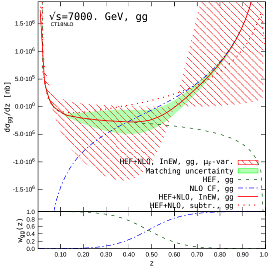
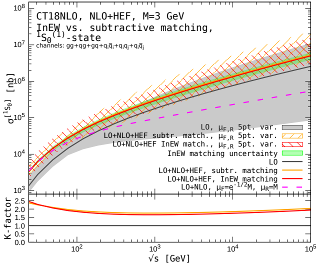
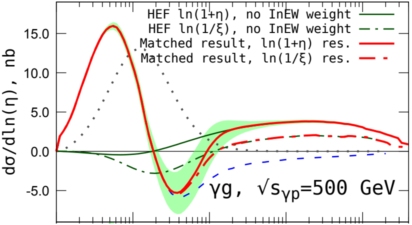
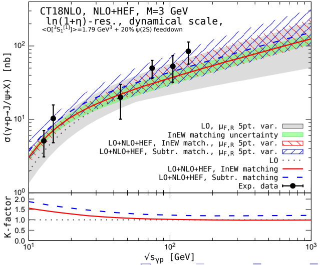




J/ψ photoproduction

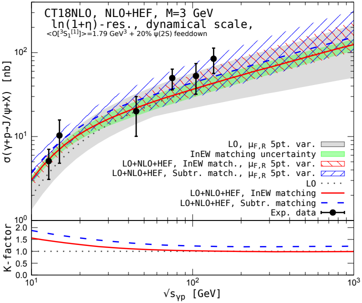




For this plot: dashed blue: CF NLO

Discussion

JPL, M. Nefedov, M.A.Ozcelik 2306.02425(to appear in EPJC)



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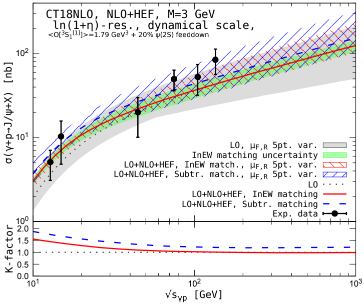

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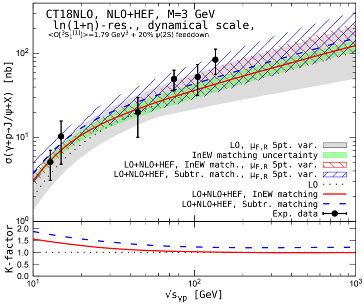

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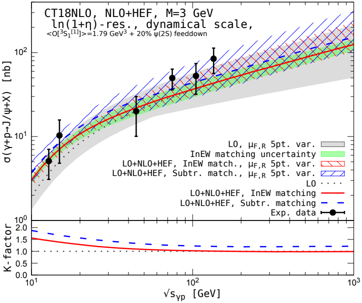

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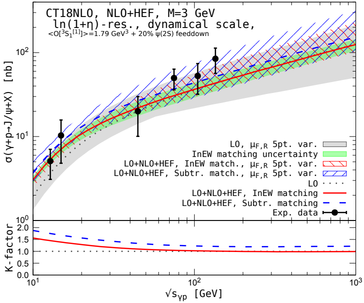

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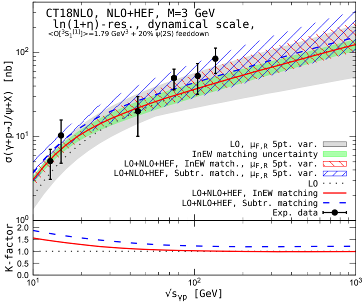

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Outlook I

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- Apply HEF @ LLA to $pp \to \chi_c X$ (worst case) and to $pp \to \psi X$

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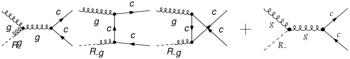
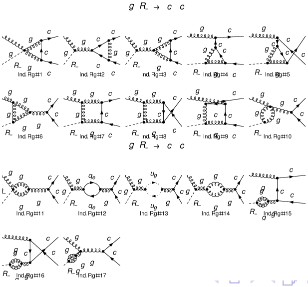
- Apply HEF @ LLA to $pp \to \chi_c X$ (worst case) and to $pp \to \psi X$
- Progress towards the first NLLA computation for quarkonia **M. Nefedov 2309.09608**

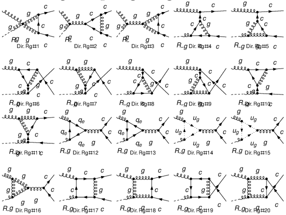
$Rg \to c\bar{c}\left[{}^1S_0^{[1]}\right]$ and $c\bar{c}\left[{}^3S_1^{[8]}\right]$ @ 1 loop

Interference with LO: 

Induced Rgg coupling diagrams:



Some Rg-coupling diagrams:



and so on...

Outlook I

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→ Virtual corr. done, with the expected IR and rapidity divergence structure

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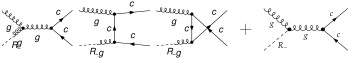
Interference with LO: 

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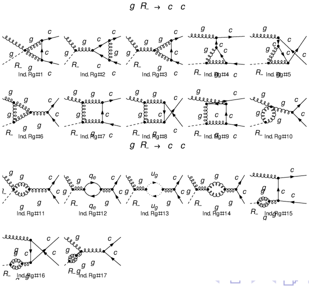

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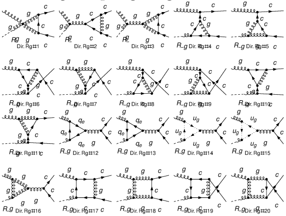

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Outlook II

Progress in Particle and Nuclear Physics 122 (2022) 103906

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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,*,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 [6], 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]

Check for updates

1. Introduction
2. Proton-proton collisions
3. Exclusive and diffractive production
4. Transverse-Momentum-Dependent effects in inclusive reactions
5. Proton-nucleus collisions
6. Nucleus-nucleus collisions
7. Double and triple parton scatterings
8. Summary

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. Generalities about quarkonium studies at the EIC
3. EIC tools for quarkonium studies
4. Quarkonia as tools to study the parton content of the nucleons
5. Quarkonia as tools to study the parton content of the nuclei

6. Summary

A EU Virtual Access to pQCD tools: NLOAccess

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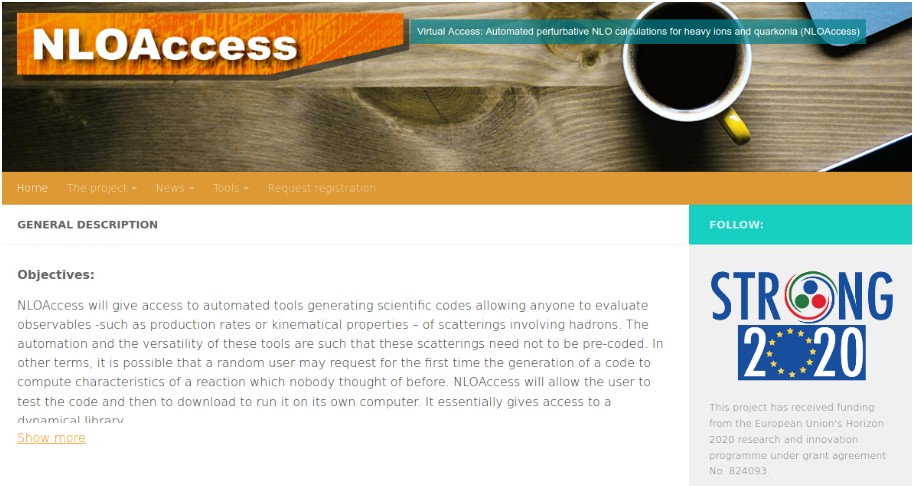

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Automated perturbative calculation with HELAC-Onia Web

Welcome to HELAC-Onia Web!

HELAC-Onia ia an automatic matrix element generator for the calculation of the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization.
The program is able to calculate helicity amplitudes of multi P-wave quarkonium states production at hadron colliders and electron-positron colliders by including new P-wave off-shell currents. Besides the high efficiencies in computation of multi-leg processes within the Standard Model, HELAC-Onia is also sufficiently numerical stable in dealing with P-wave quarkonia and P-wave color-octet intermediate states.

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Automated perturbative calculation with NLOAccess

MG5_aMC@NLO

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, an the NLO accuracy in the case of models that support this kind of calculations -- prominent among these are QCD and EW corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

Please login to use MG5_aMC@NLO.