Studying heavy quarks & quarkonia with NLOAccess

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Quarkonium production - the tools

- HELAC-Onia — H.-S. Shao, CPC 184 (2013) 2562-2570 & CPC 198 (2016) 238-259
  - LO(+PS) automated event generator for quarkonia in the SM
  - based on the NRQCD framework, relies on off-shell recursion relations
  - approximate NLO calculation (*e.g.* NLO*, aNLO) feasible

    C. Flore *et al.*, Phys. Lett. B 811 (2020) 135926; H.-S. Shao, JHEP 01 (2019) 112

- MG5_aMC@NLO — http://amcatnlo.web.cern.ch/amcatnlo/list_refs.htm
  - full NLO(+PS) matrix element and event generator in the SM and for BSM phenomenology
  - LO for any user-defined Lagrangian, and at the NLO for models supporting such a calculation
  - onium feasible within (I)CEM — J.-P. Lansberg *et al.*, Phys. Lett. B 807 (2020) 135559

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$\Rightarrow$ Les Houches Events available for both codes

NLO approximation of J/ψ production: NLO*

P. Artoisenet *et al.*, **PRL 101 (2008) 152001, J.-P. Lansberg, EPJC 61 (2009) 693 & PLB 679 (2009) 340**
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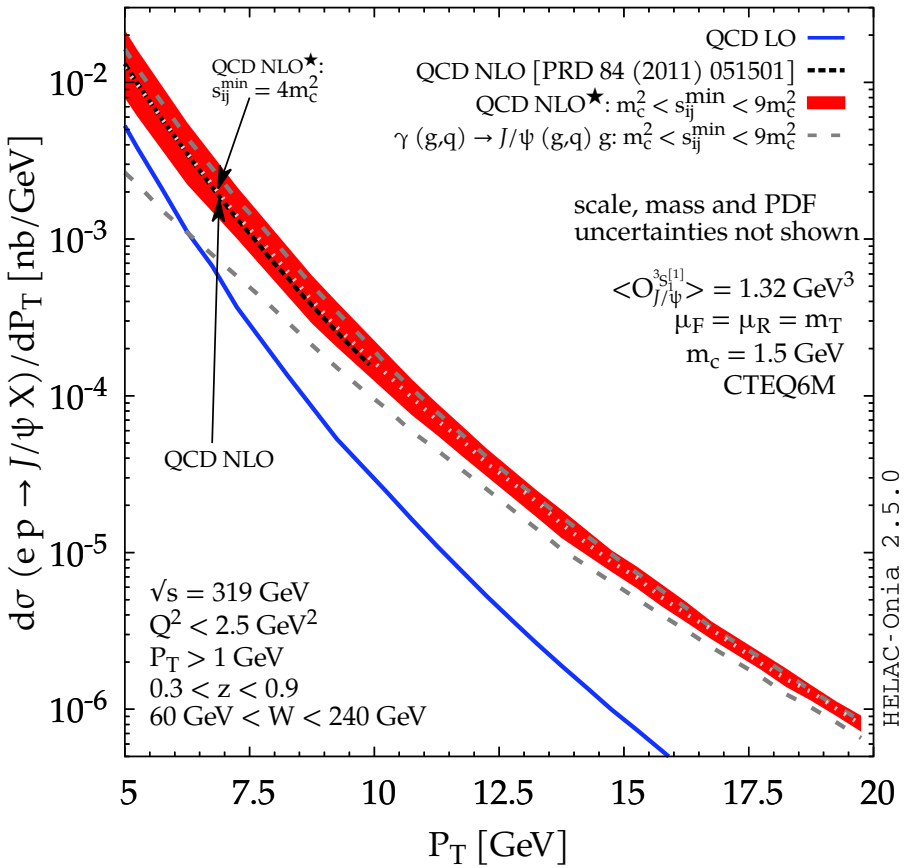

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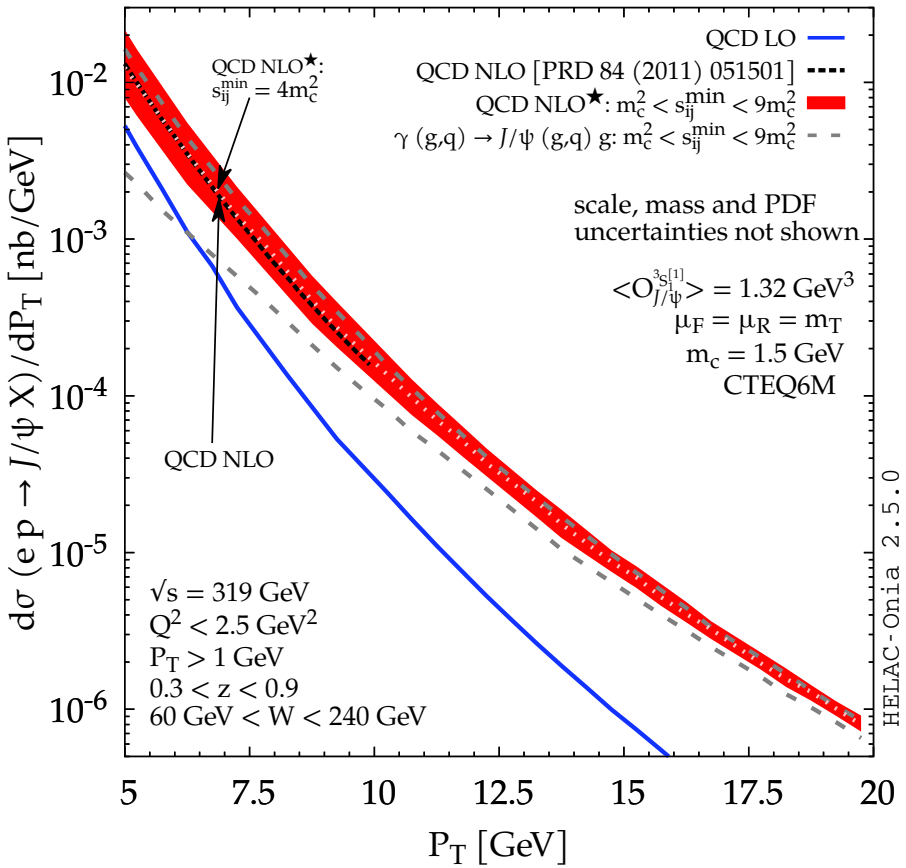

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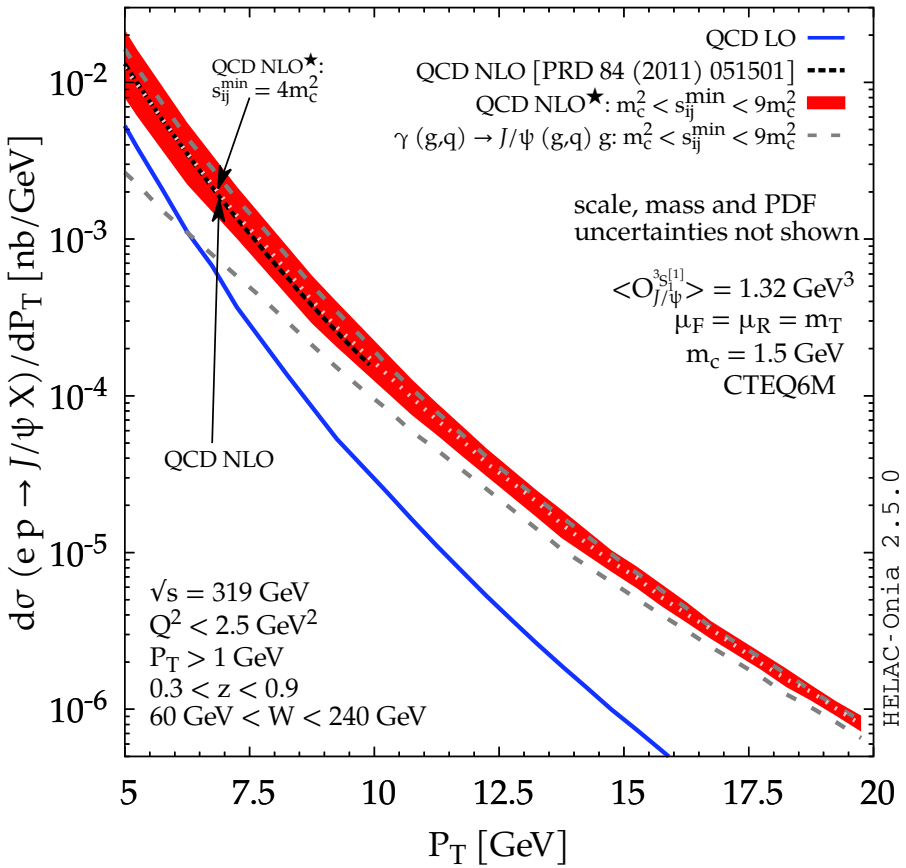

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Let's revisit HERA data!

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Revisiting HERA data

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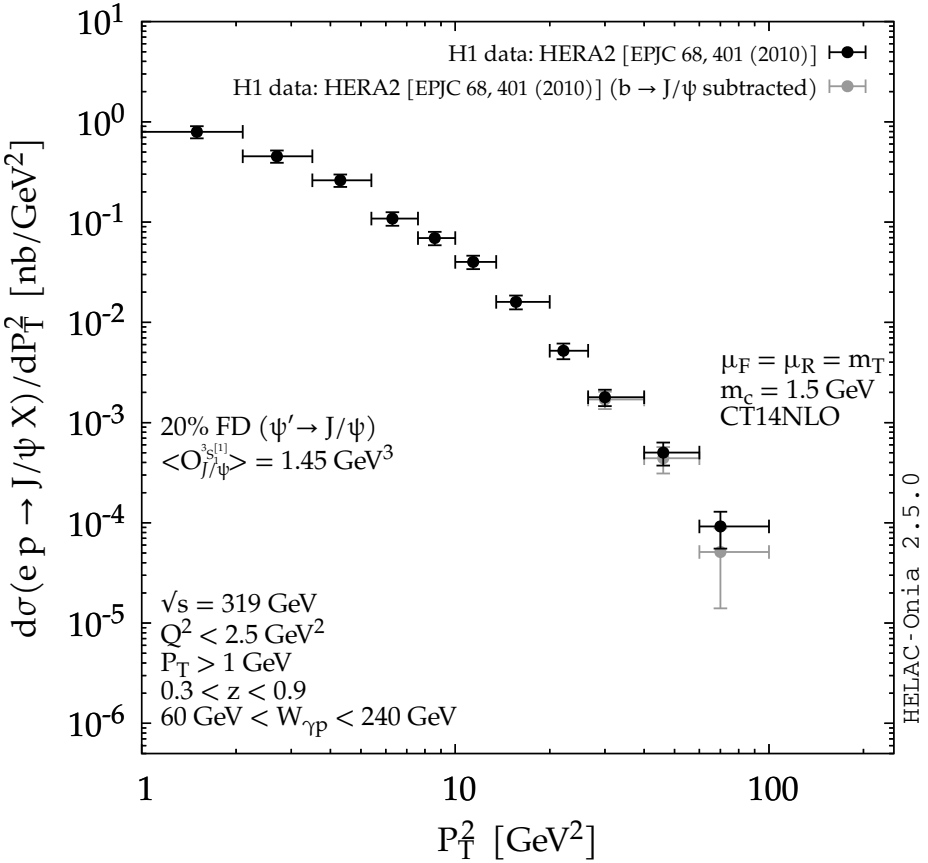

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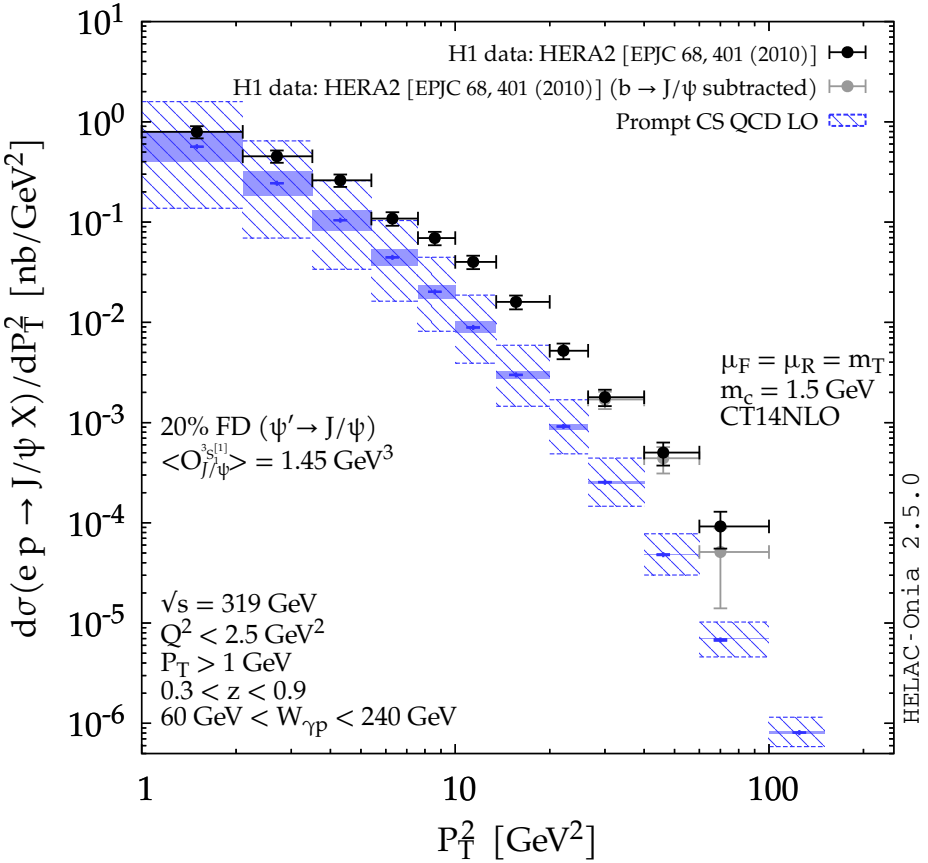

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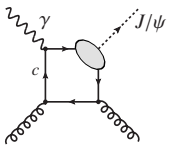

$$\gamma + g \to \psi + g \,@\, \alpha\alpha_s^2$$

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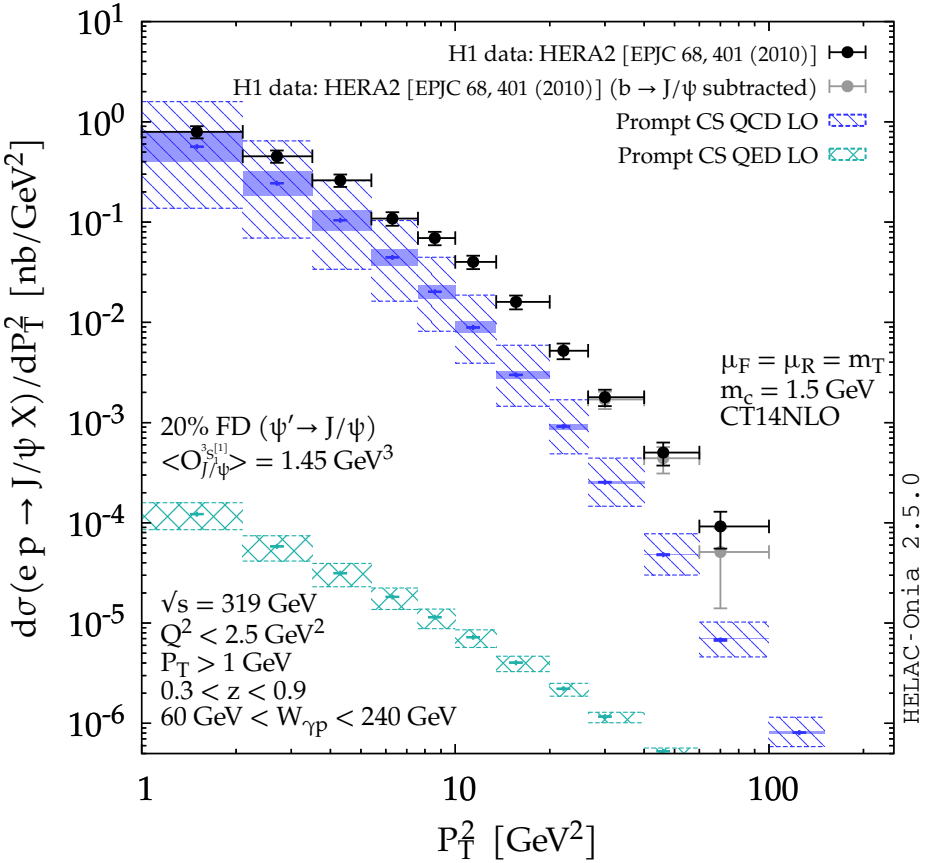

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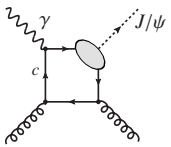

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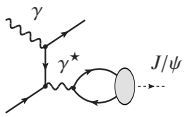

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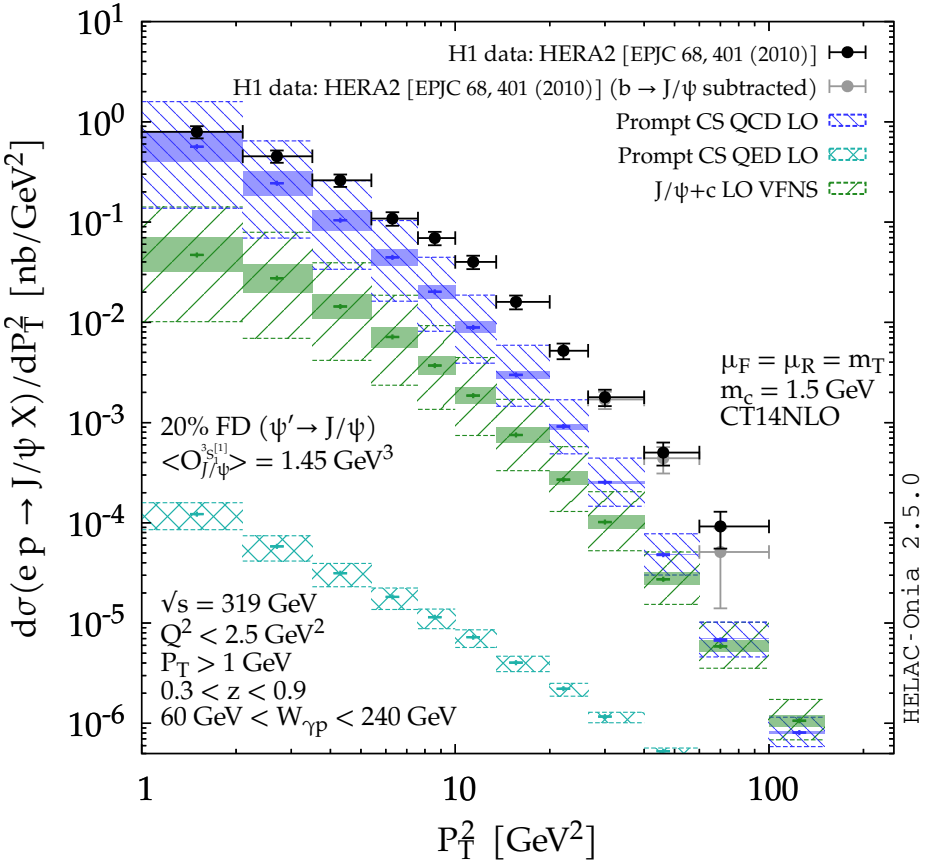

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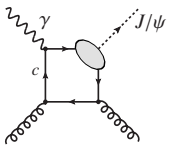

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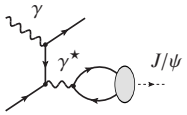

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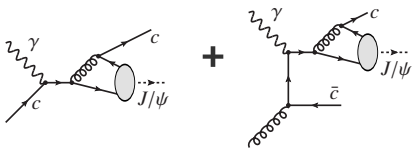

$\begin{cases} \gamma + c \to \psi + c \,@\, \alpha\alpha_s^2 & \text{(4FS)} \\ \gamma + g \to \psi + c + \bar{c} \,@\, \alpha\alpha_s^3 & \text{(3FS)} \end{cases}$ [also NEW!]

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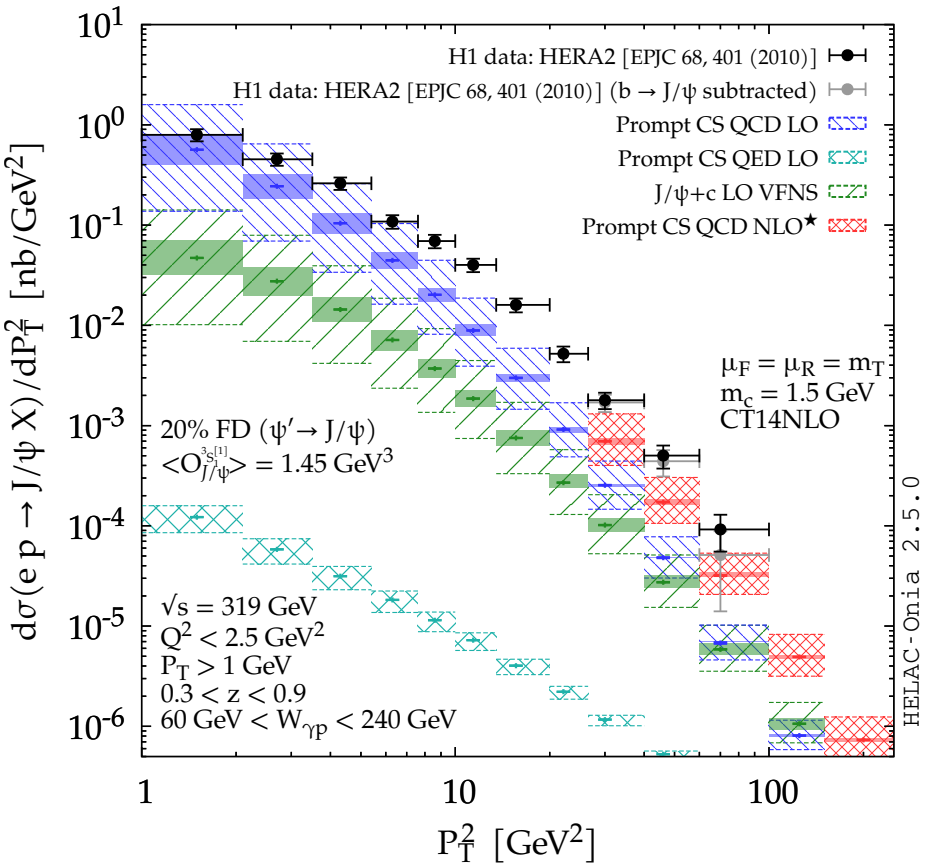

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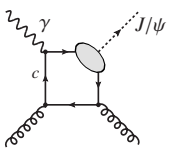

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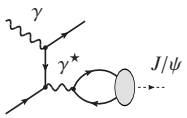

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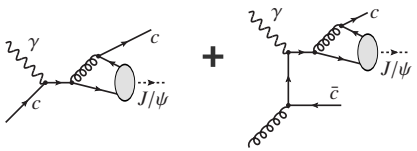

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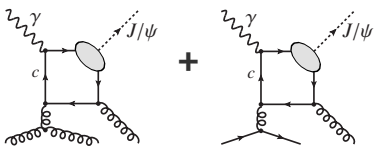

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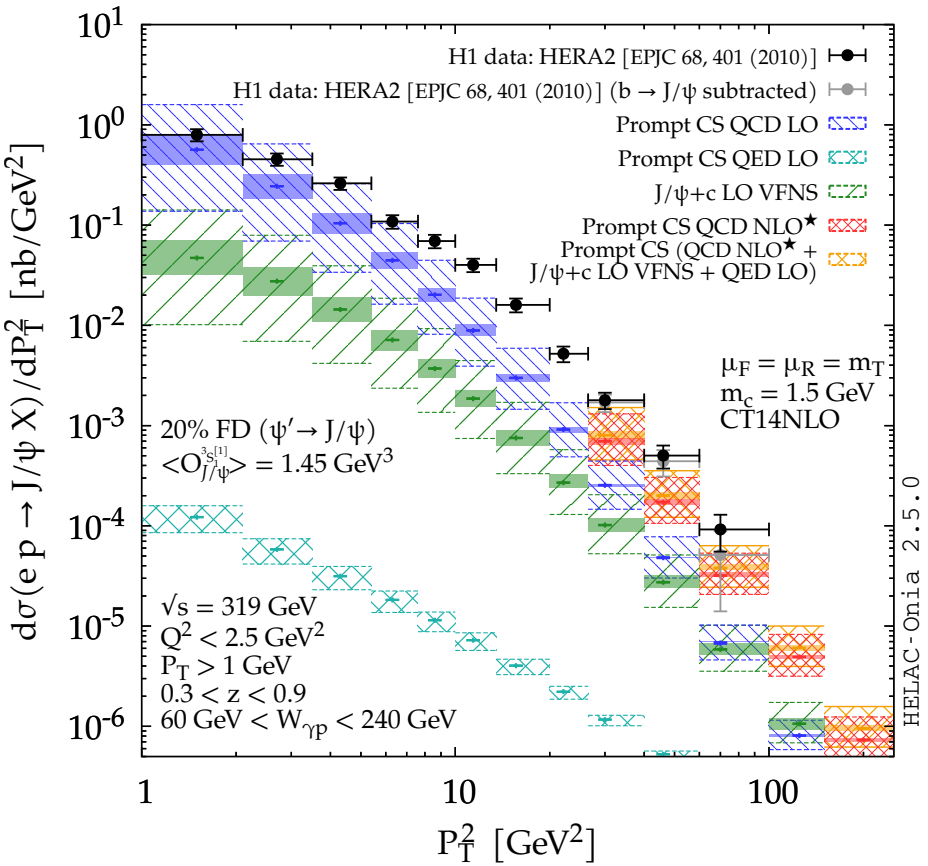

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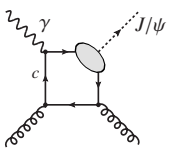

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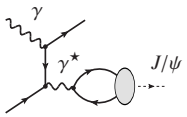

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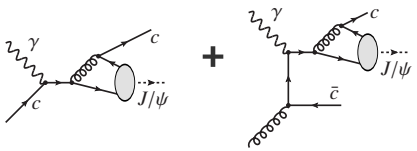

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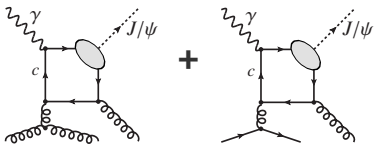

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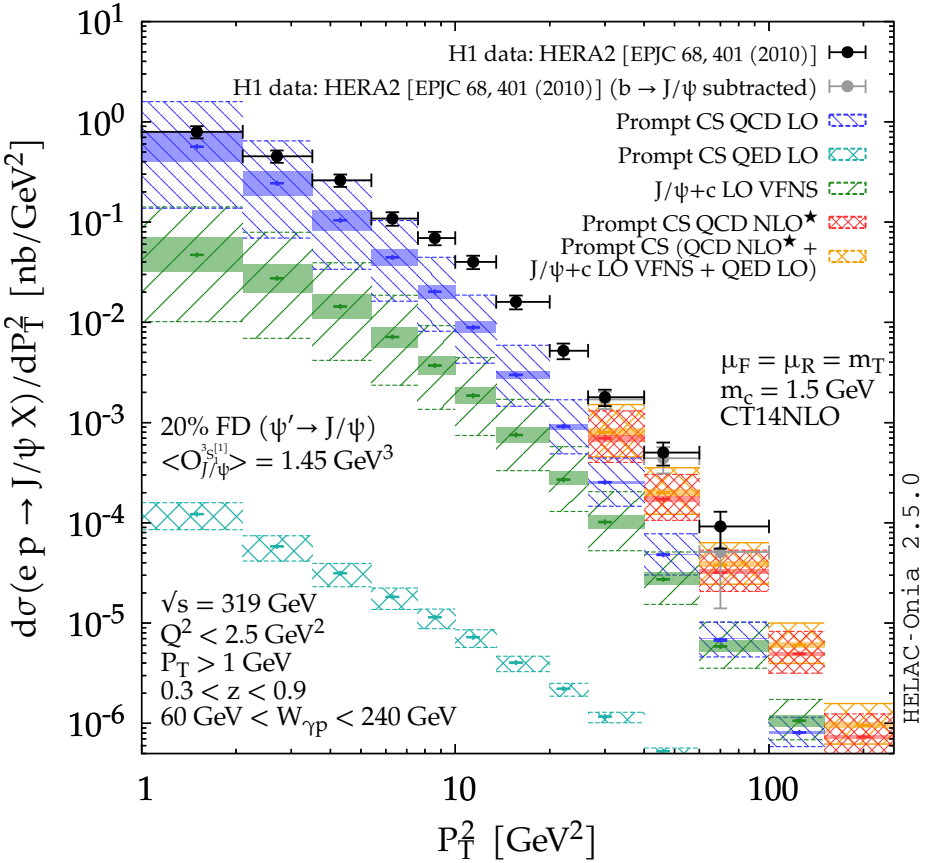

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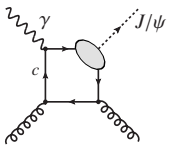

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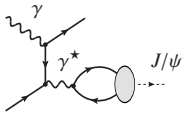

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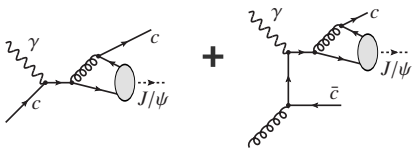

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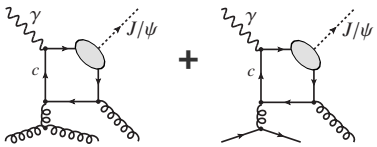

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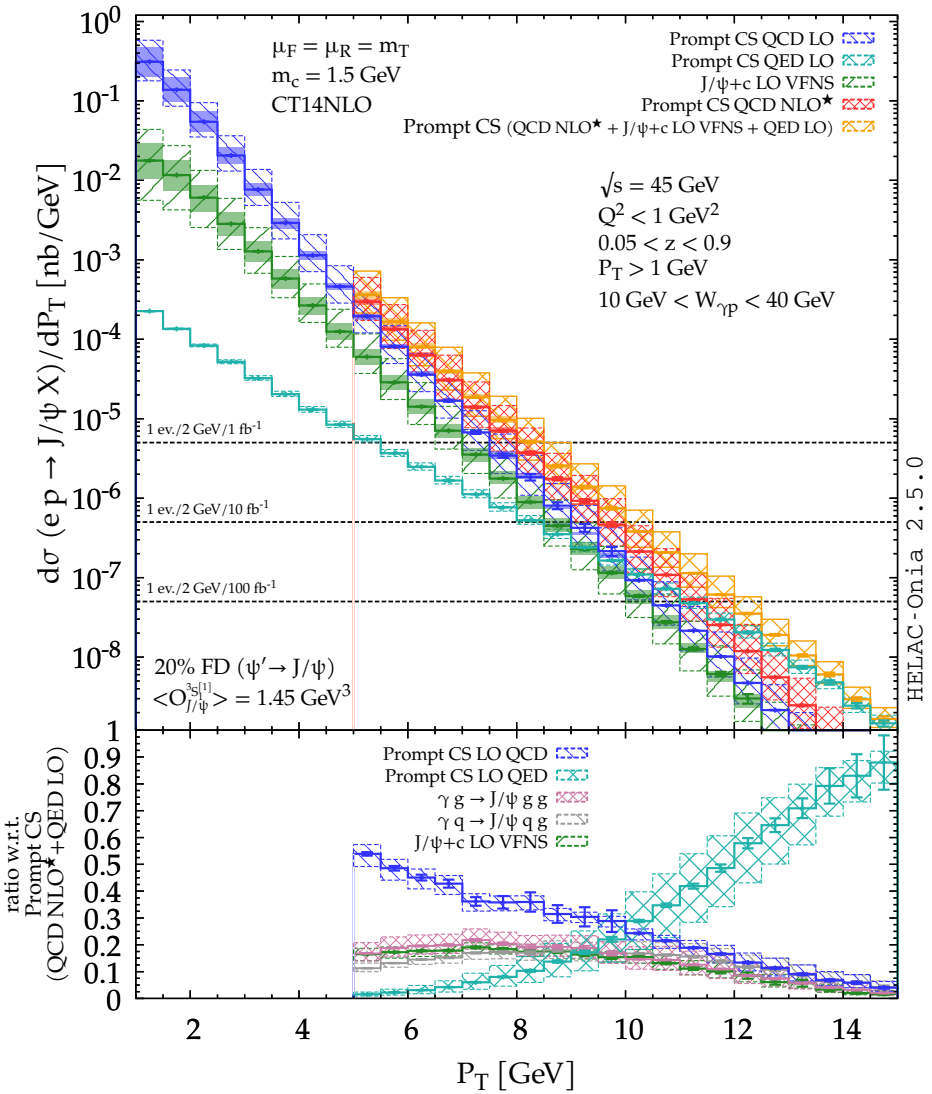
$[+\ \gamma + g \to \psi + g]$

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

$\to$ for the EIC, we have restricted our predictions to CSM

Predictions for $J/\psi + X$ at the EIC $\left[\sqrt{s_{ep}} = 45\ \text{GeV}\right]$



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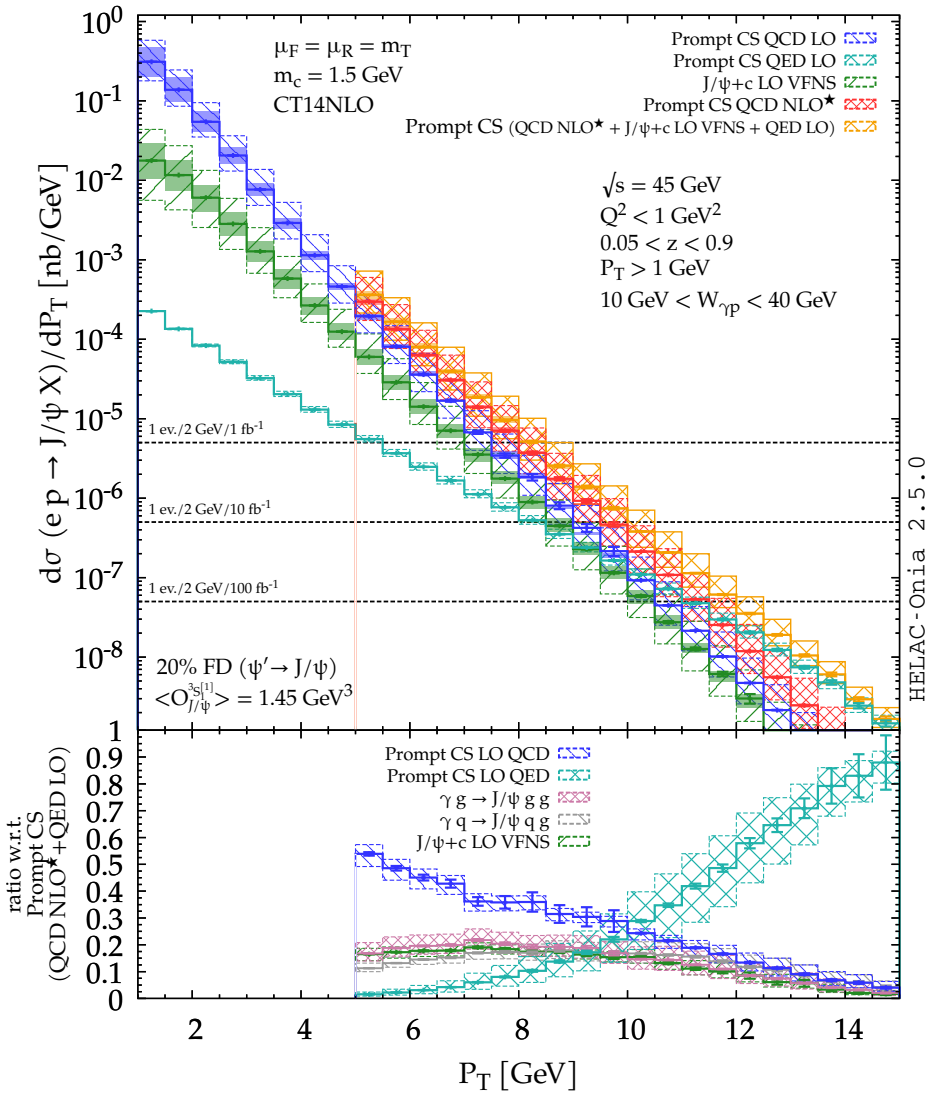

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- Yield can be measured up to $P_T \sim 11$ GeV with $\mathcal{L} = 100$ fb^{-1}

[using both *ee* and $\mu\mu$ decay channels and $\varepsilon_{J/\psi} \simeq 80\%$]

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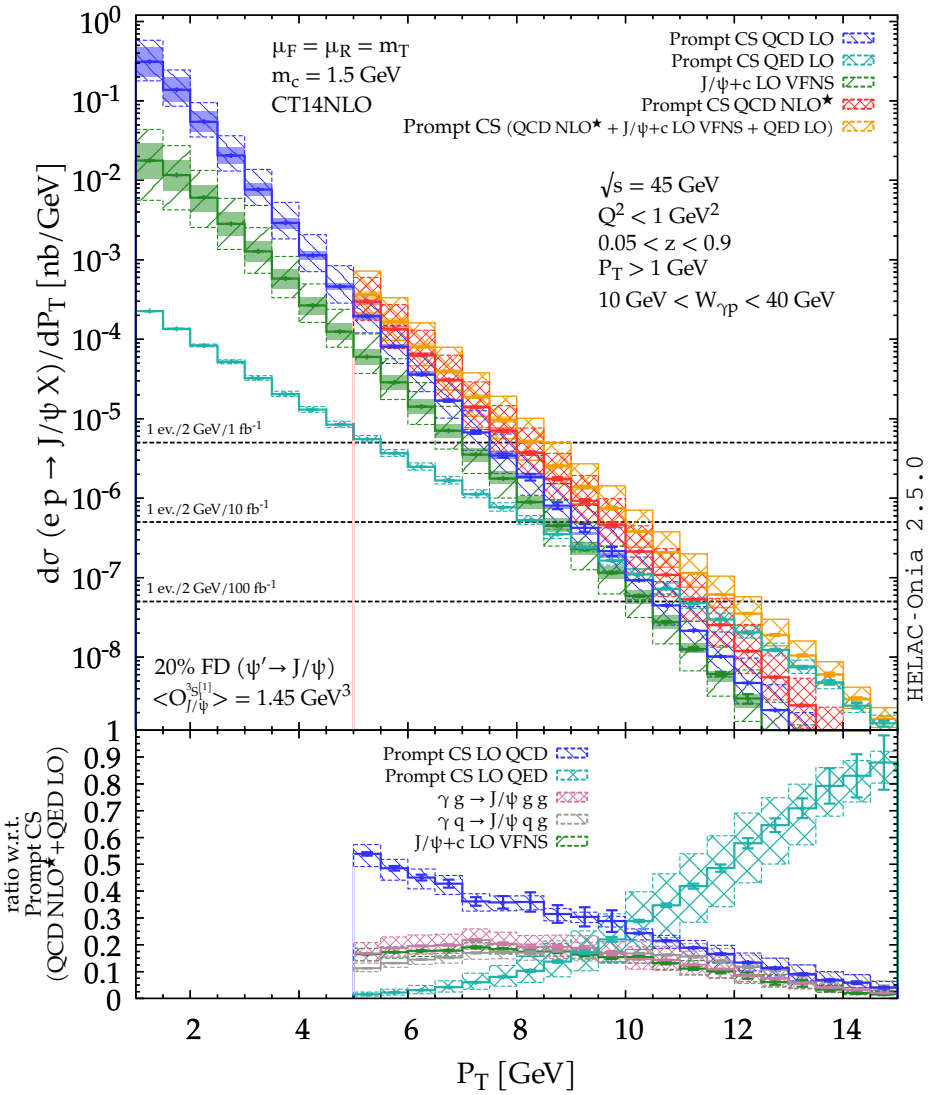

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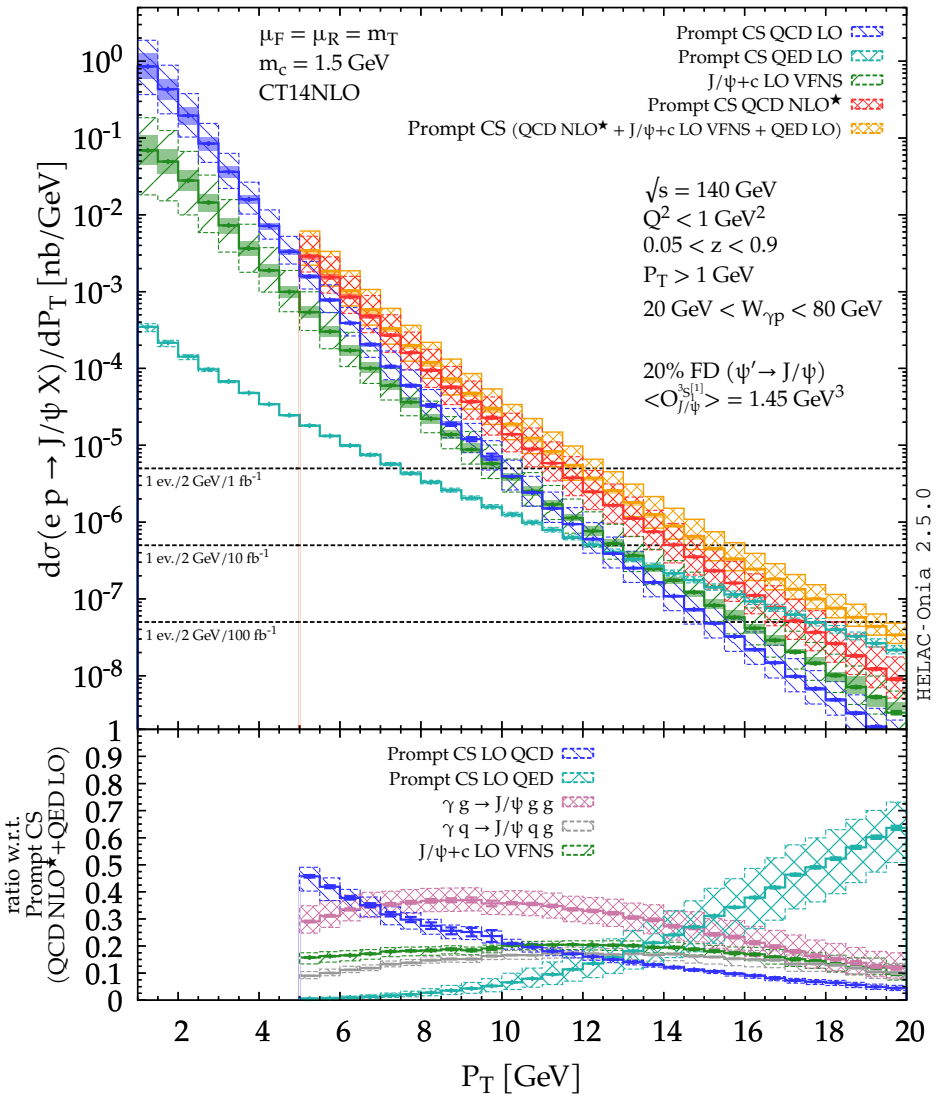
  [using both *ee* and $\mu\mu$ decay channels and $\varepsilon_{J/\psi} \simeq 80\%$]
- QED contribution leading at the largest reachable P_T
- $\gamma + q$ fusion contributes more than 30% for $P_T > 8$ GeV

Predictions for $J/\psi + X$ at the EIC $\left[\sqrt{s_{ep}} = 140\ \text{GeV}\right]$



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- At $\sqrt{s_{ep}} = 140$ GeV larger P_T range, up to ~ 18 GeV

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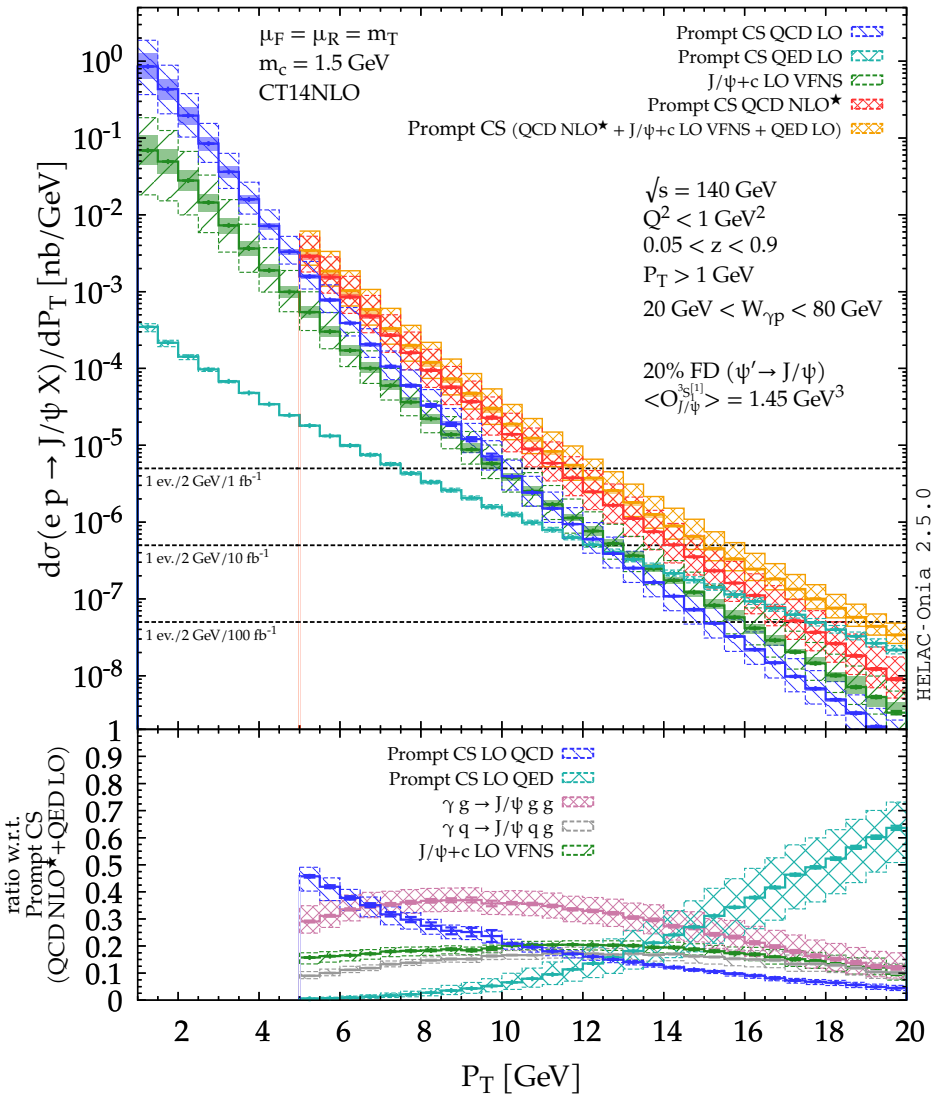

CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

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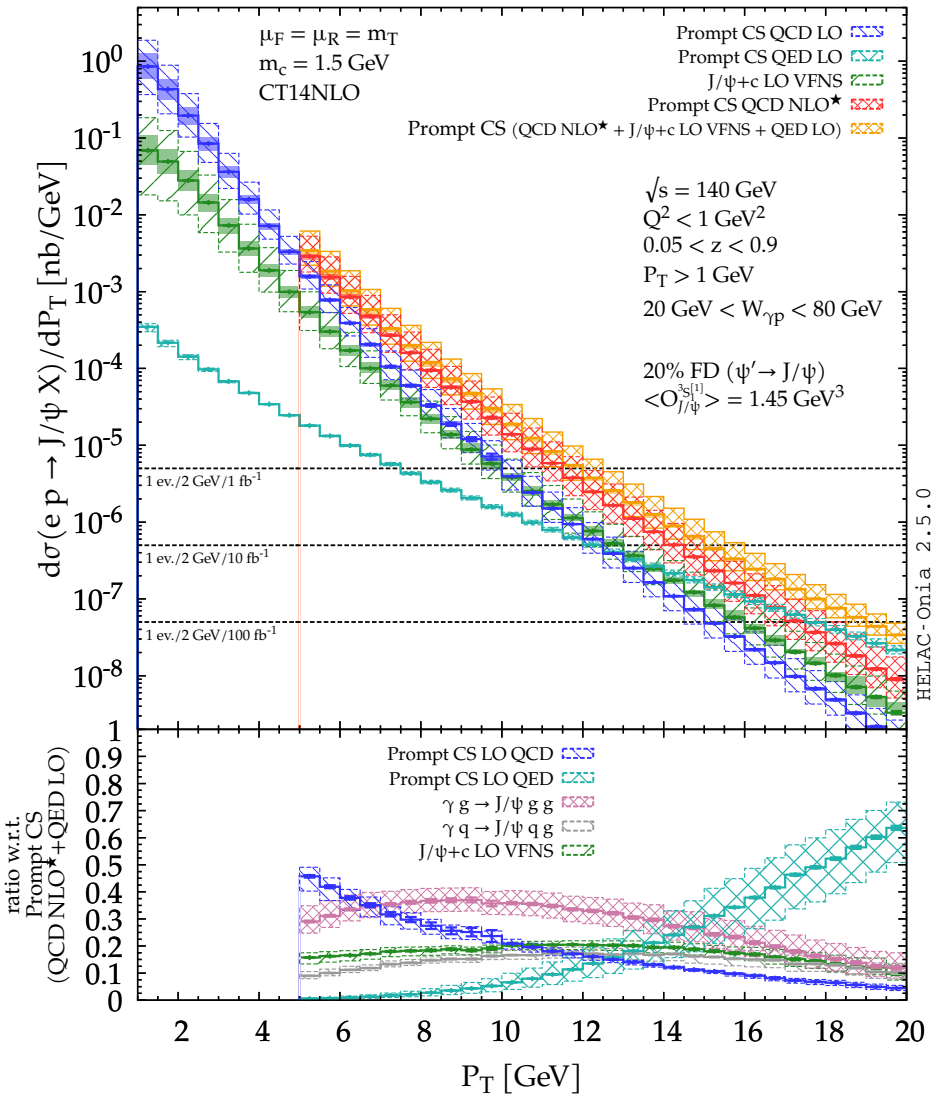

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Intrinsic charm at the EIC

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

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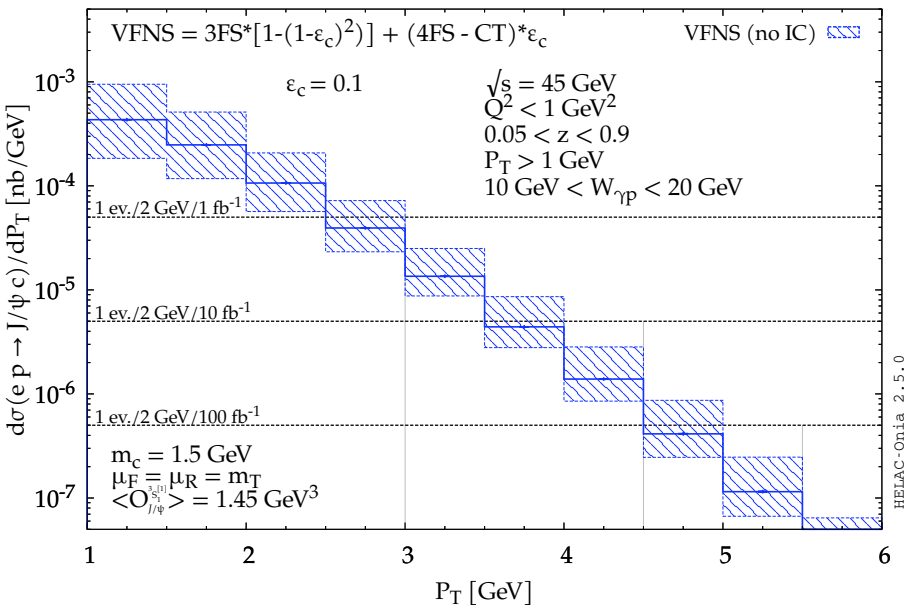

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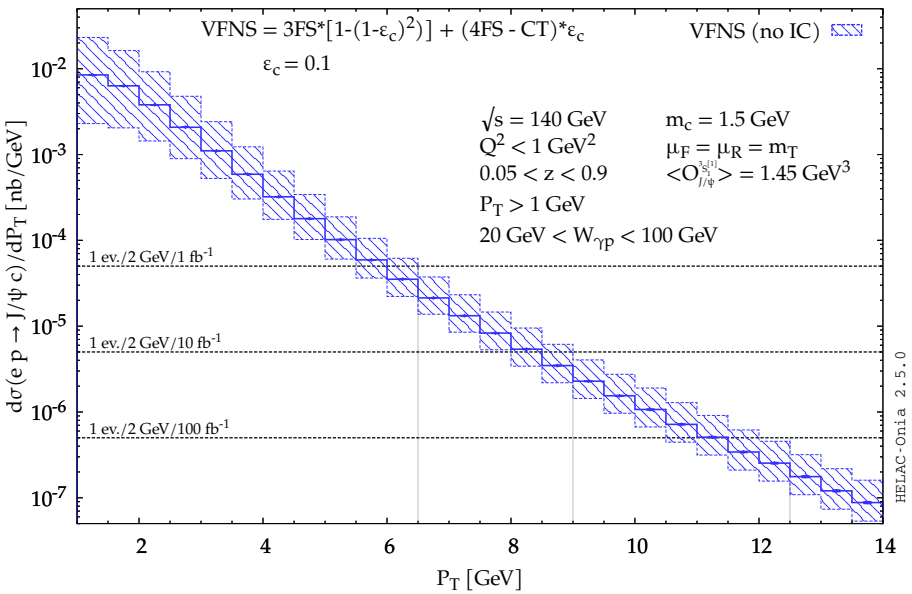

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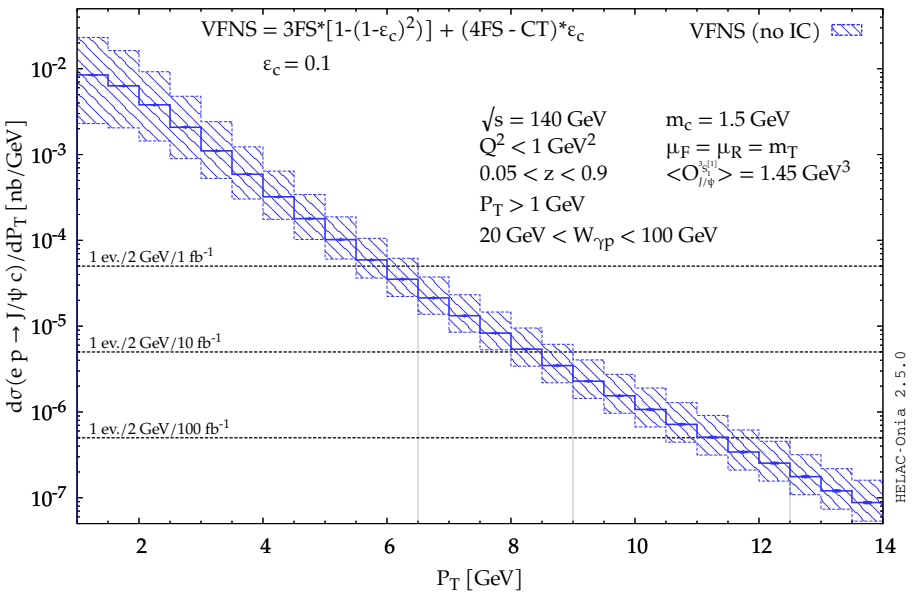

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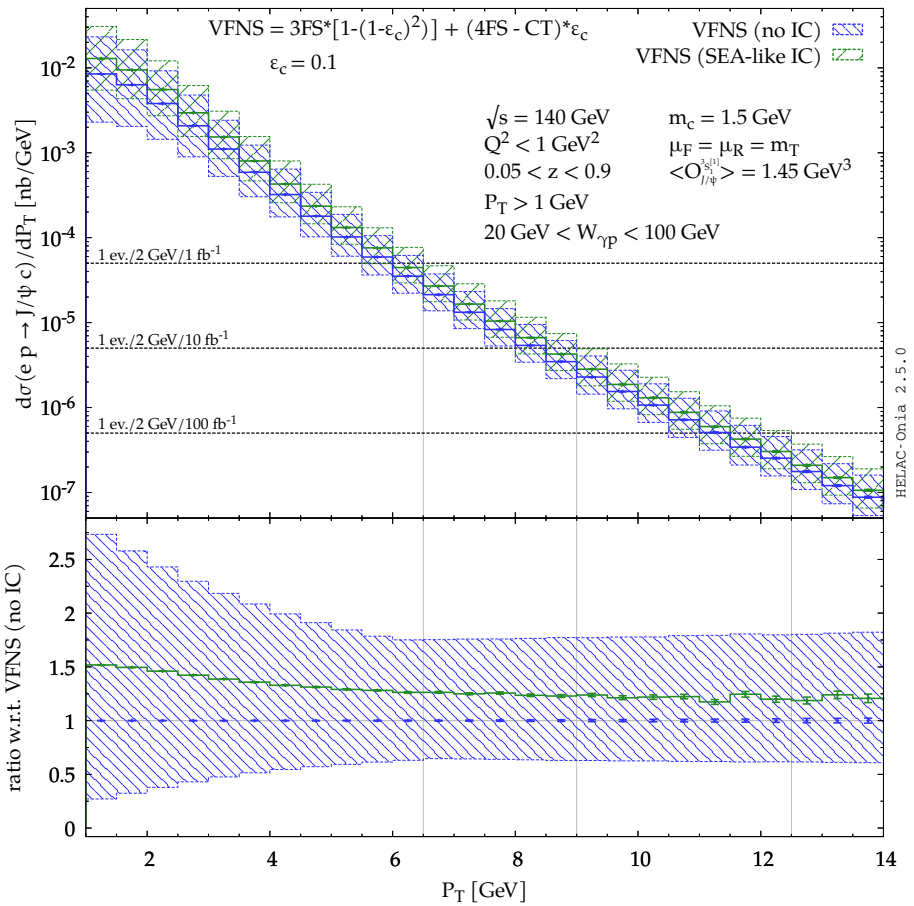

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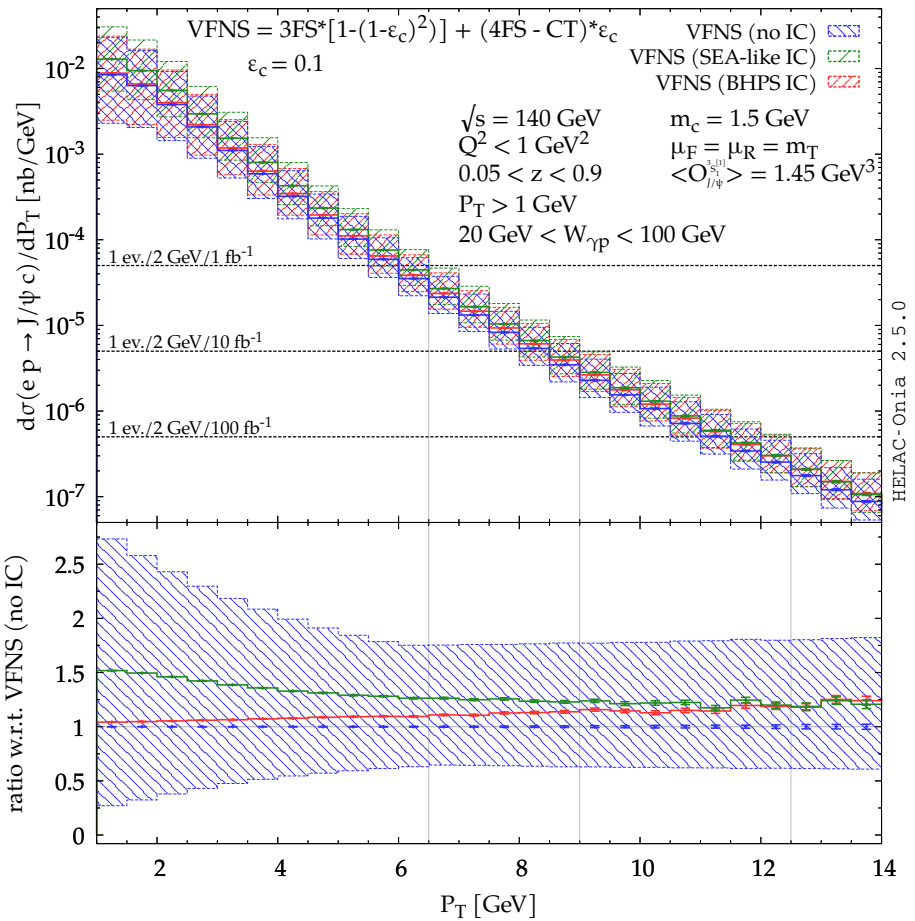

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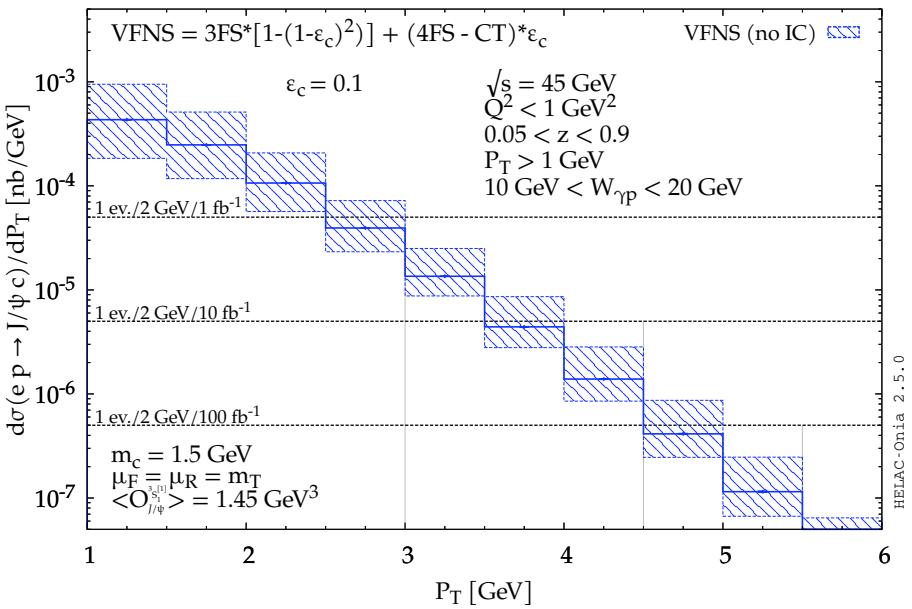

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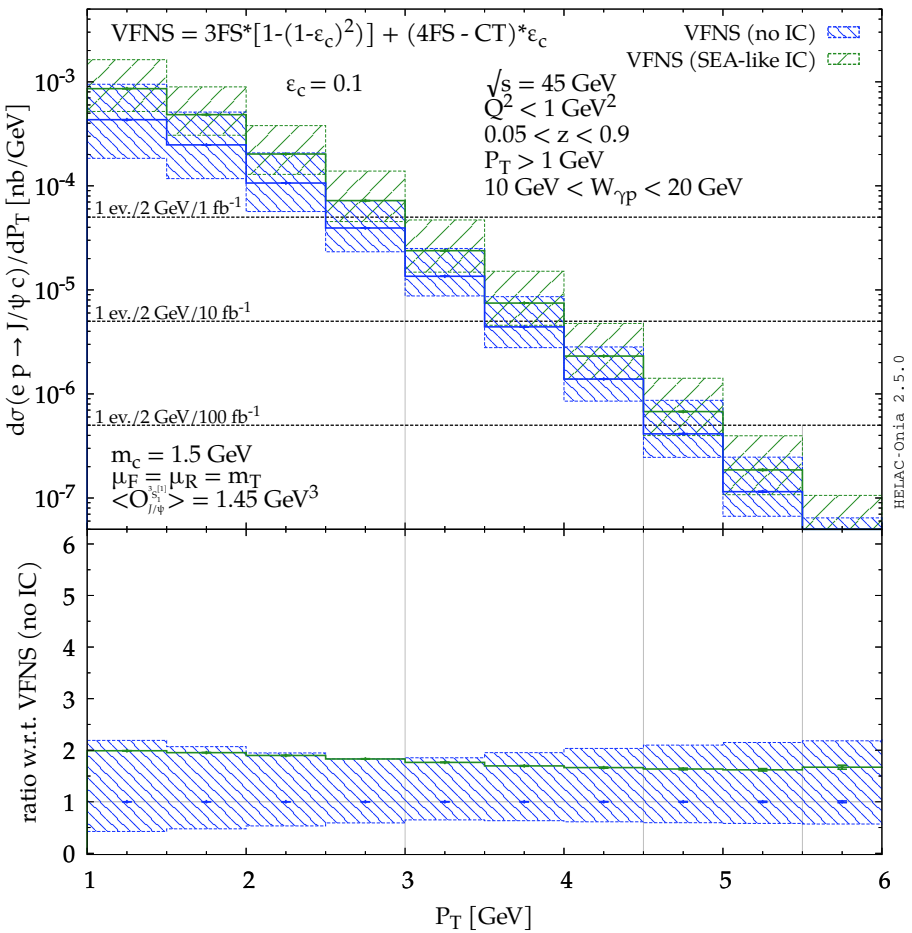

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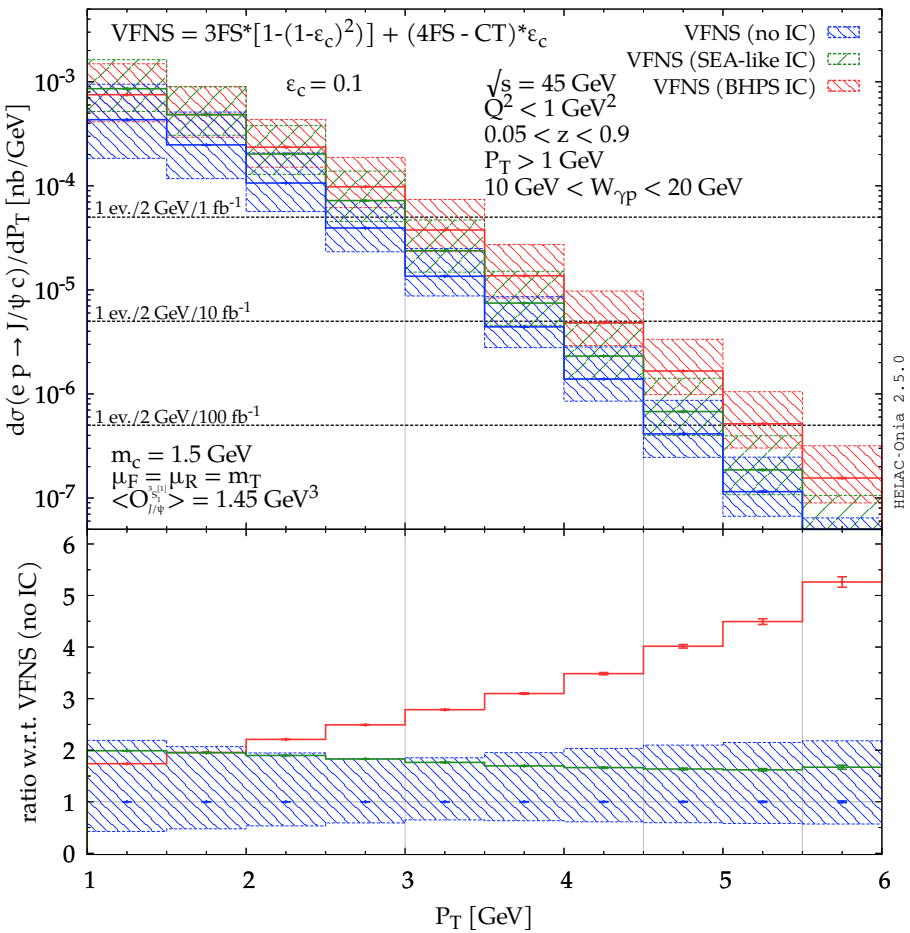

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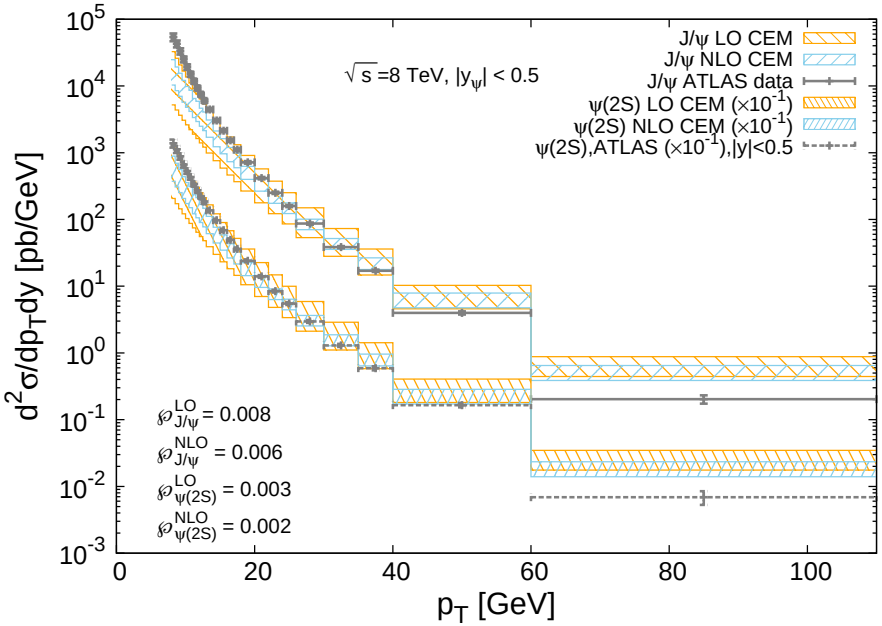
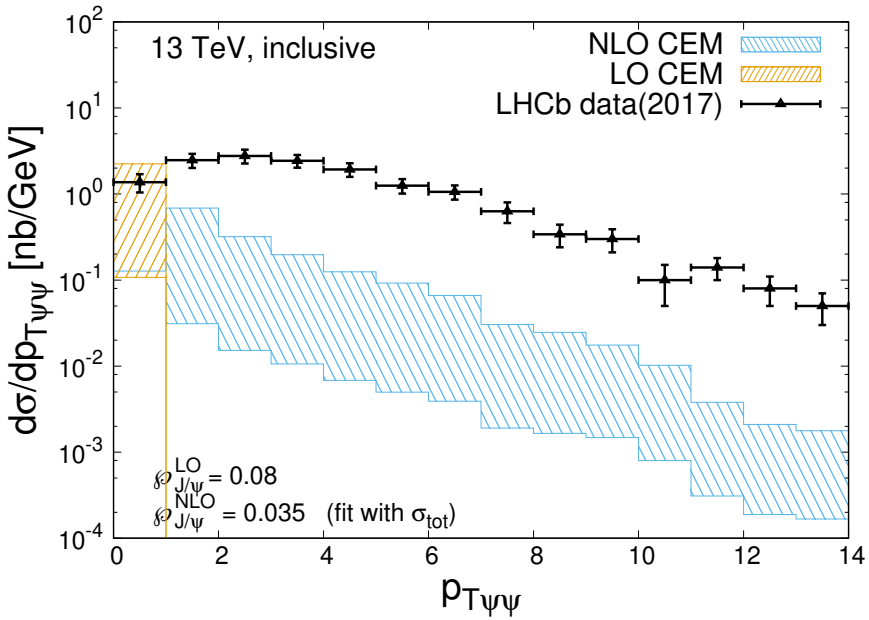
BHPS valence-like peak visible!

NLO (di-)onium production in the CEM

J.-P. Lansberg, H.-S. Shao, N. Yamanaka, Y.-J. Zhang, C. Noûs, PLB 807 (2020) 135559





All the computations were done with MG5_aMC@NLO **[J. Alwall *et al.*, JHEP 07 (2014) 079]**.

- Good description of the P_T spectrum for single J/ψ (still some issues at large P_T)
- di-J/ψ production cannot be described by NLO CEM

NLOAccess - the framework

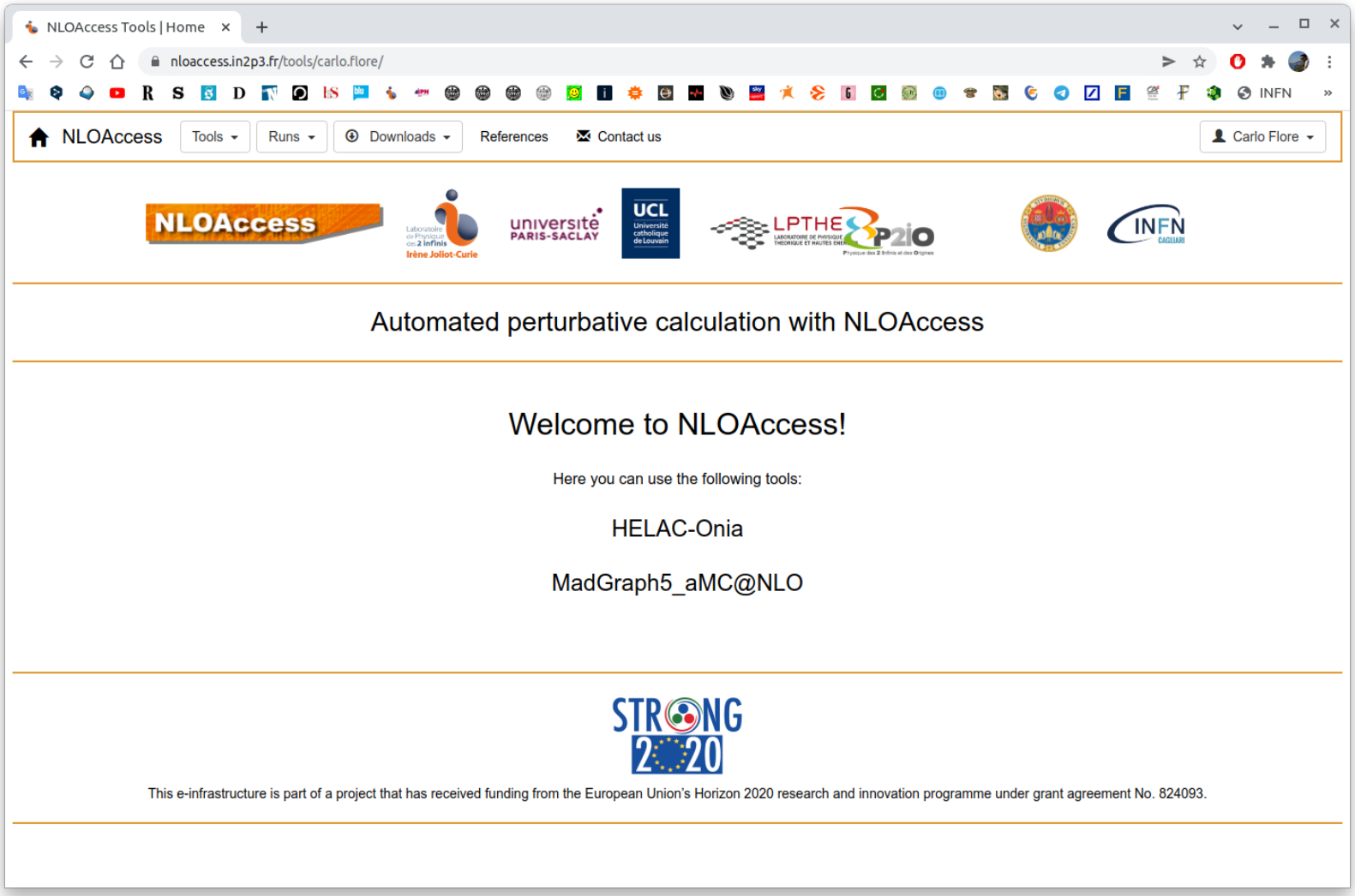
The STRONG-2020 WP **VA1-NLOAccess**:

- a virtual access for automated perturbative calculation for heavy ions and quarkonia
- an online code library
- any code that could be compiled and launched via bash could be added

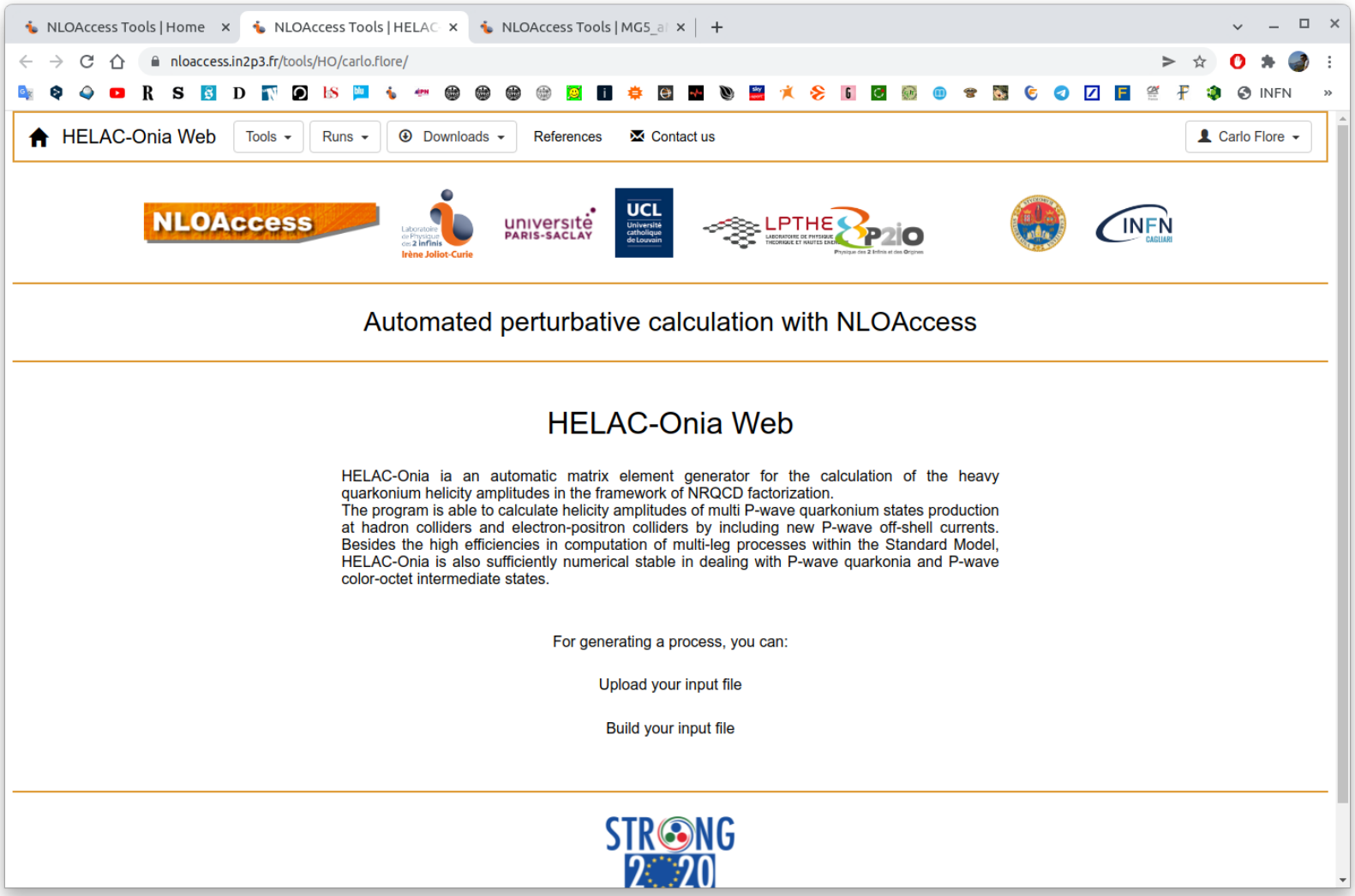
✓ HELAC-Onia and MadGraph5 (MG5_aMC@NLO) are included

NLOAccess Tools - homepage

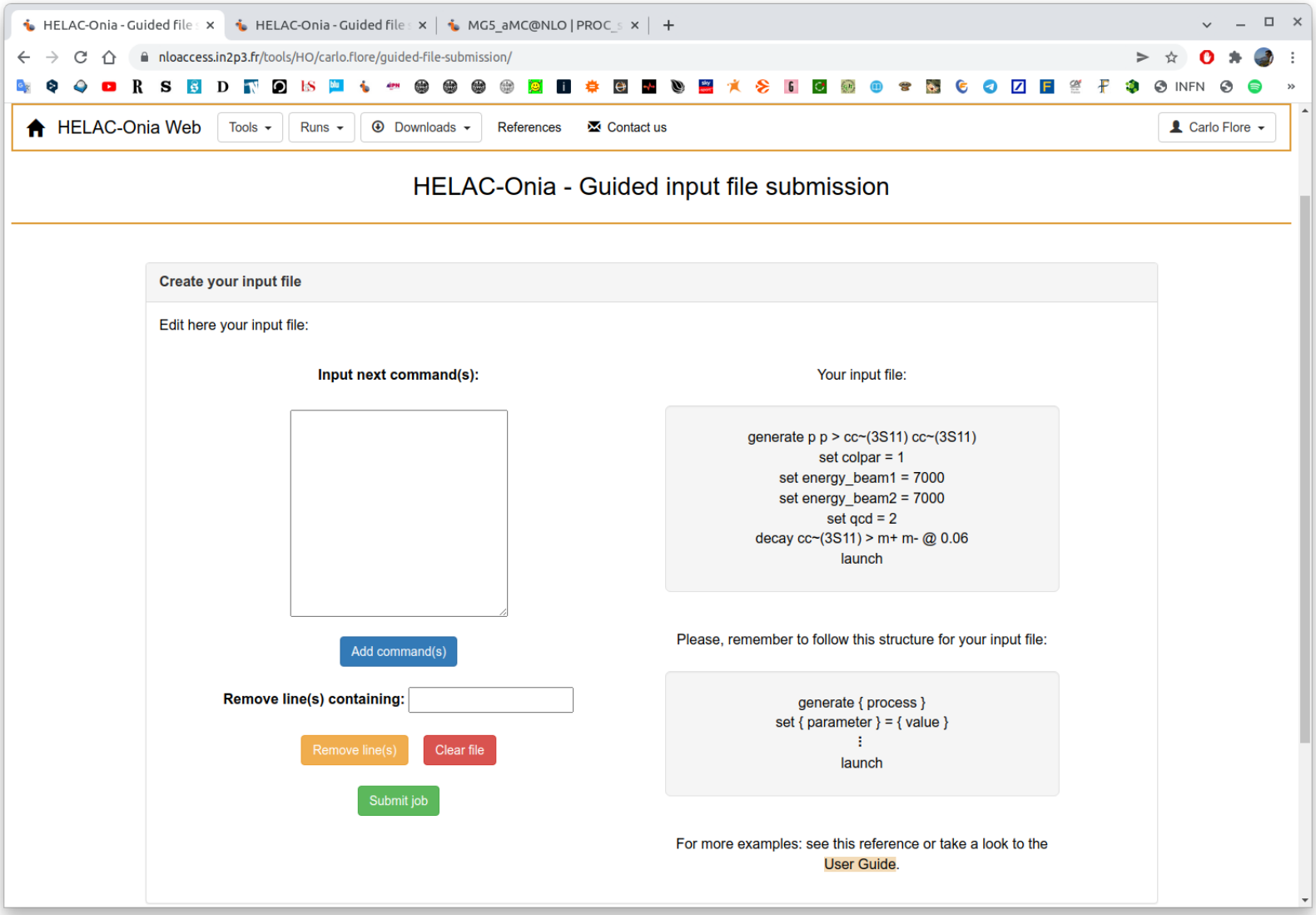
(https://nloaccess.in2p3.fr/tools/)



HELAC-Onia Web (https://nloaccess.in2p3.fr/HO/)



HELAC-Onia Web - run submission



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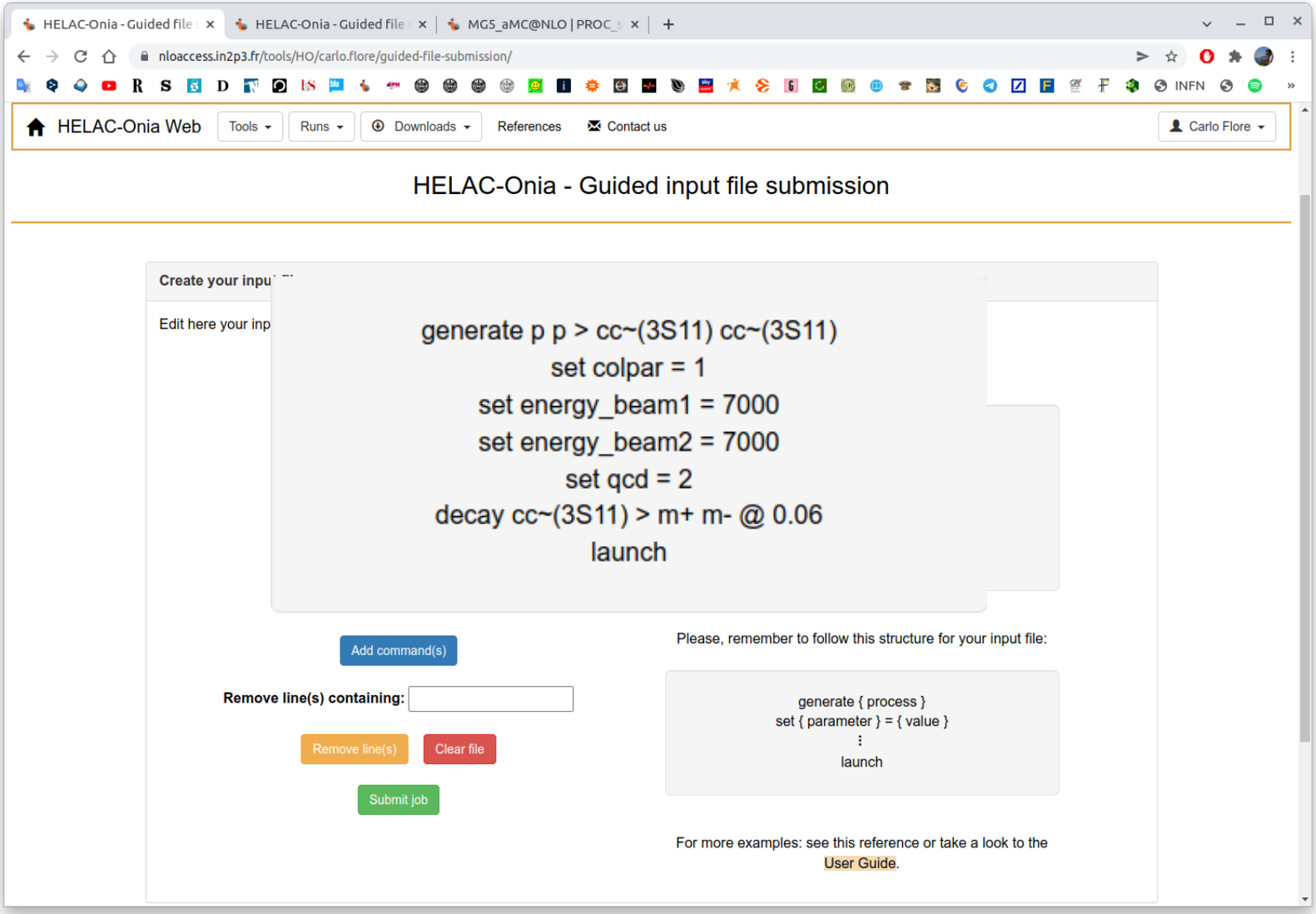


HELAC-Onia Web - input file

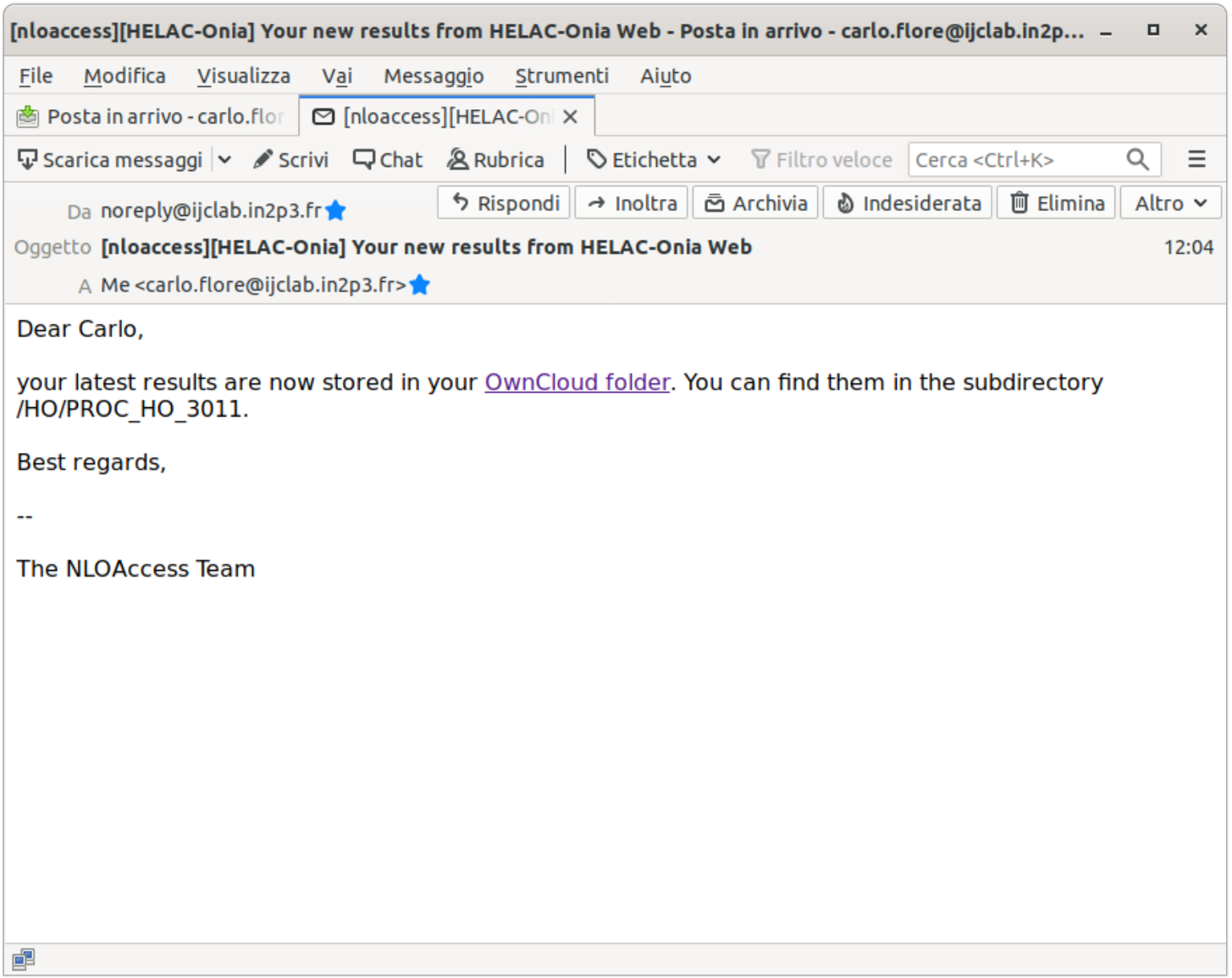
The input file should be in the following form:

```
generate { process }
set { parameter } = { value }
   ⋮
launch
```

Users can have control on several kind of parameters via the `set` command:

- collisions parameters;
- theory parameters;
- MC setup variables;
- PDFs parameters;
- kinematical cuts;
- quarkonium specific parameters (e.g. the values of different LDMEs);
- physical constants (both EW and QCD sectors, e.g. M_Z or M_W, or m_q, or couplings).
- kind of output (ROOT, Gnuplot, TopDrawer or LHE)

HELAC-Onia Web - results (I)



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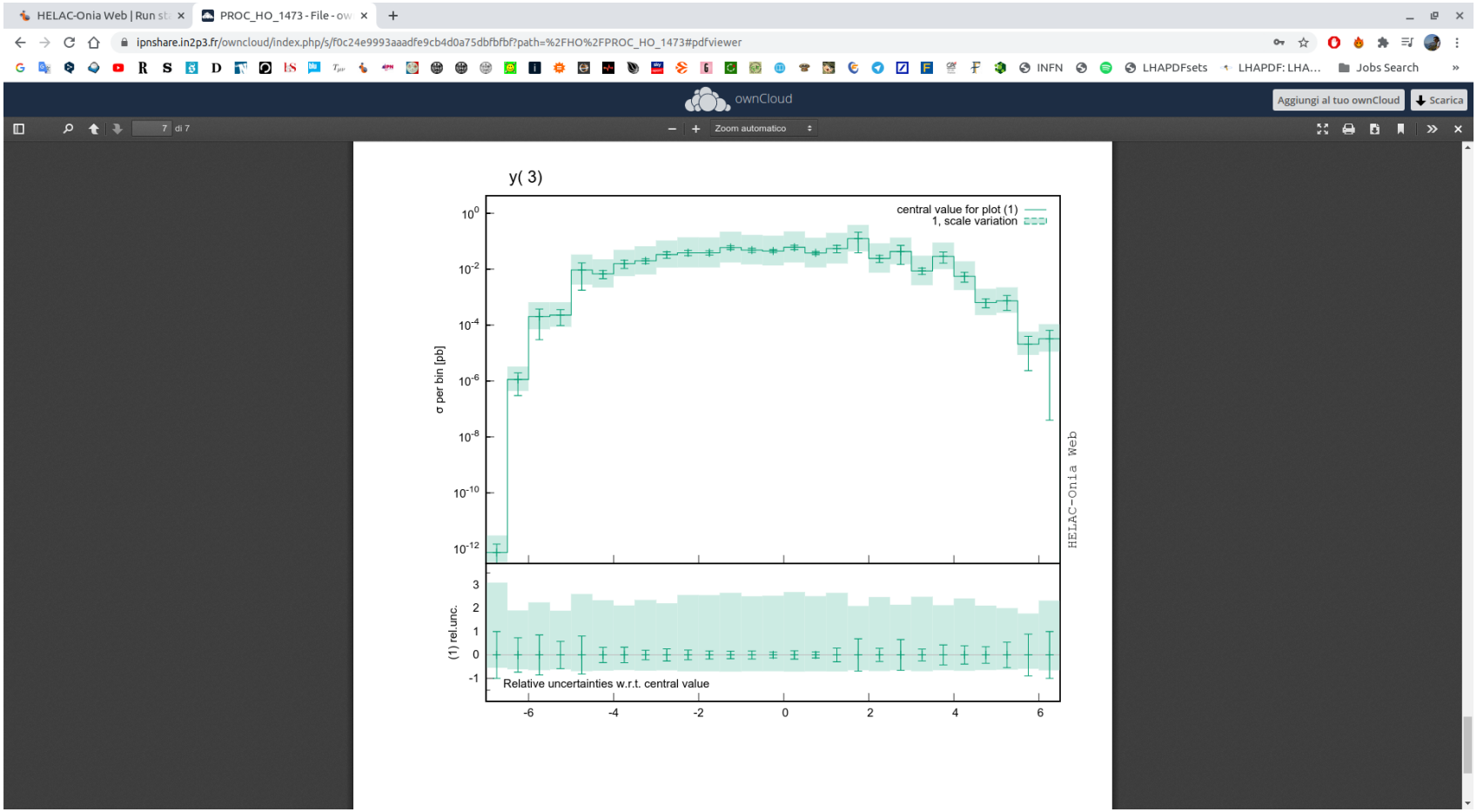
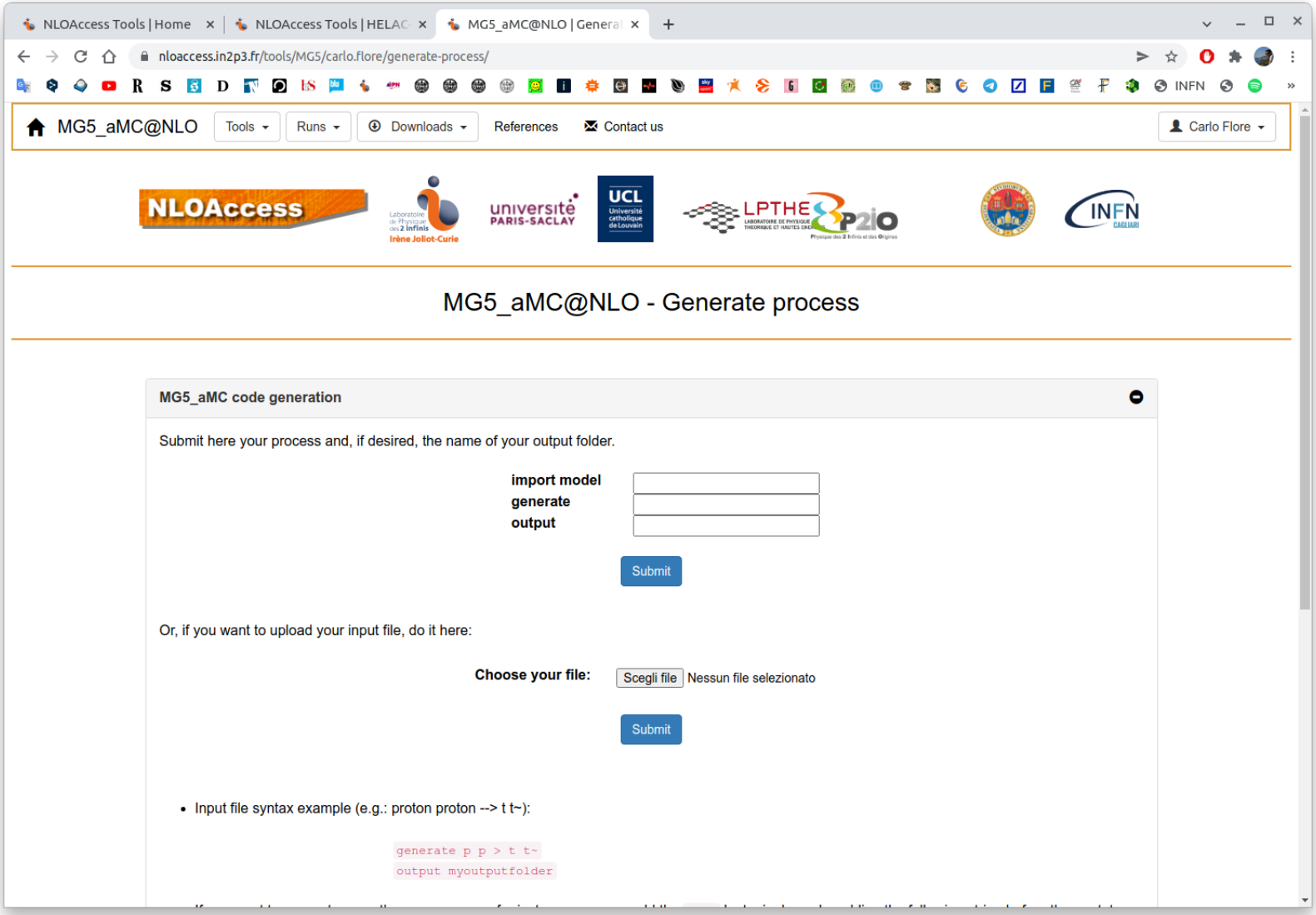


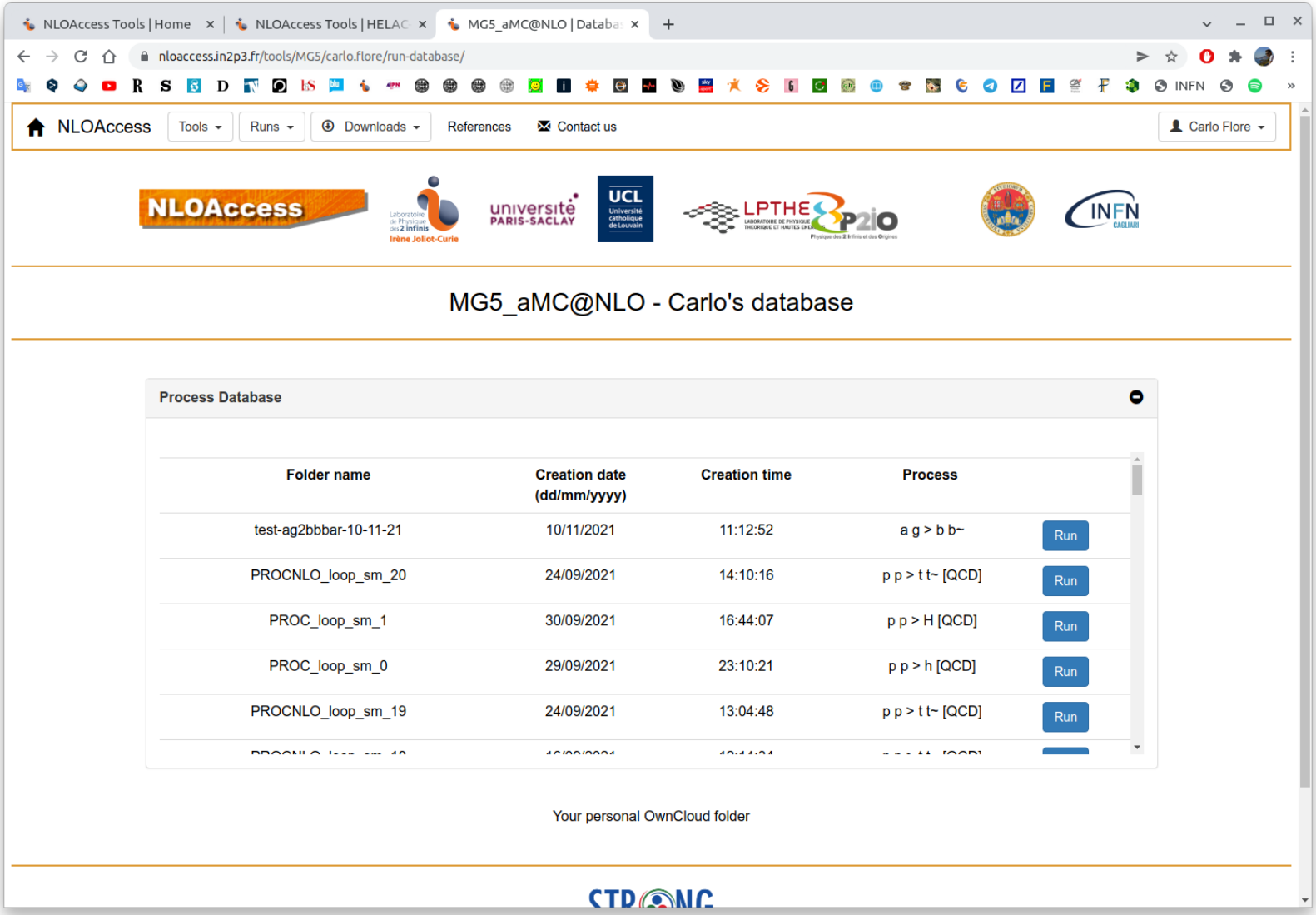
MG5_aMC@NLO (https://nloaccess.in2p3.fr/MG5/)

- MadGraph5 online version was only limited to LO calculation
- NLOAccess offers access for the first time to full NLO SM online calculation with MG5_aMC@NLO!

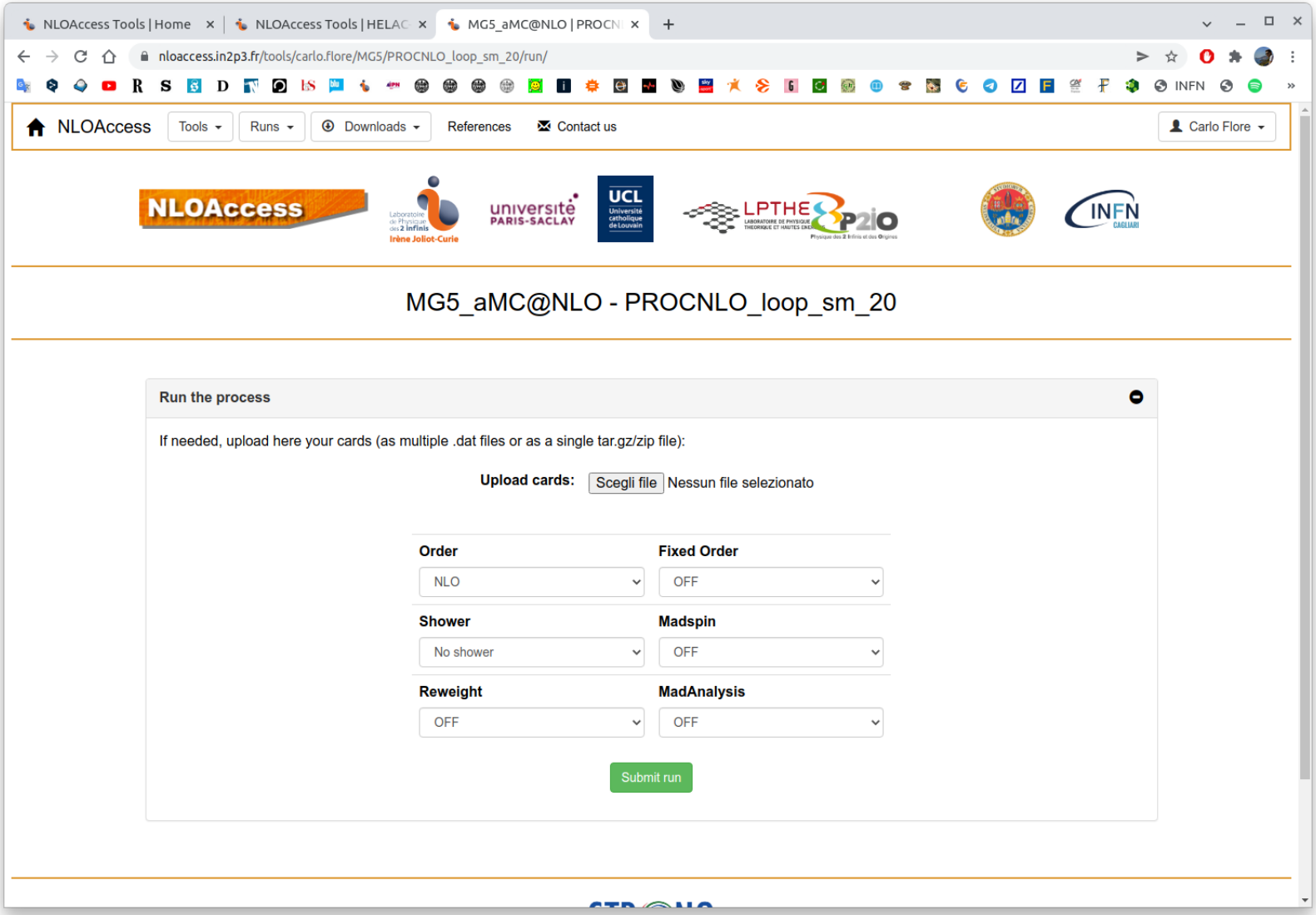
MG5_aMC@NLO - code generation



MG5_aMC@NLO - code database



MG5_aMC@NLO - code running



NLOAccess - what's next?

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- include asymmetric collisions in MG5 at NLO:

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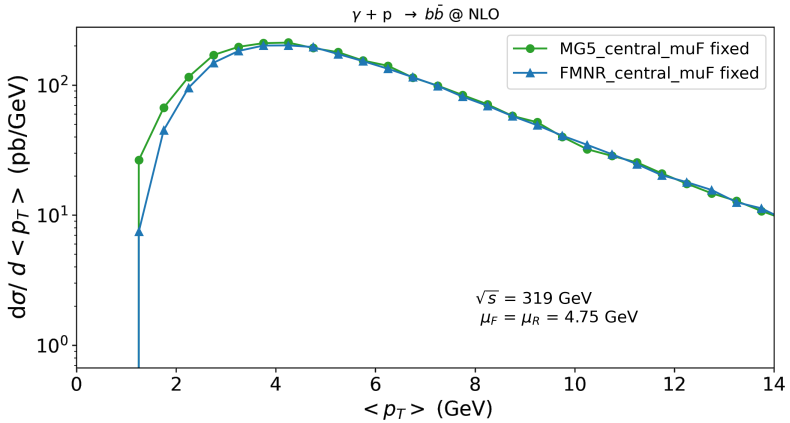
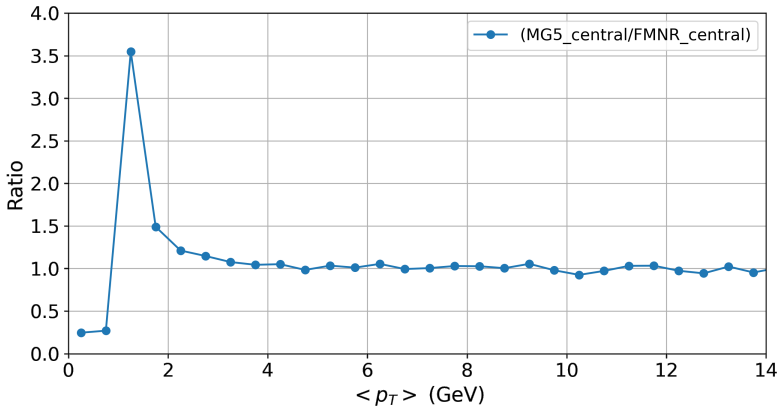
  extension to *eh* / *eA* collisions

[L. Manna, WUT Warsaw]





FMNR code from private communication w/ S. Frixione; courtesy of L. Manna

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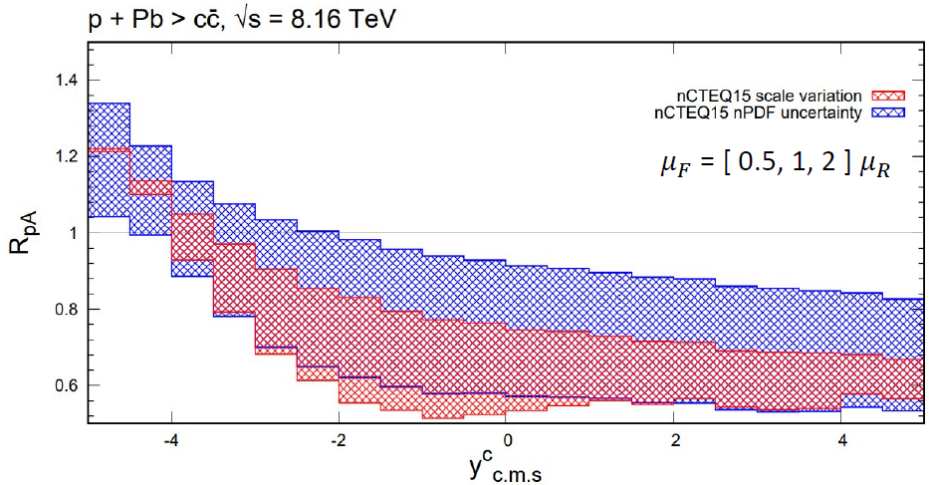
  [L. Manna, WUT Warsaw]

  extension to *pA*/*AB*/πp collisions and automated computation of nuclear modification factors (*e.g.* R_{pA})

  [A. Safronov, WUT Warsaw]



from A. Safronov's talk at ICHEP 2022

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- automation of onium production computations at NLO in MG5

  [A. Abdul-Hameed, LPTHE Paris]

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  [suggestions are welcome!]

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Thank you

Backup

Quarkonium Production Model

Phys.Rept. 889 (2020) 1-106 & EPJC (2016) 76:107 for reviews

- No agreement on which mechanism is dominant
- Differences in the treatment of the hadronization
- 3 common models:
  1. Color Singlet Model:
     hadronization w/o gluon emission; colour and spin are preserved during the hadronization
  2. NRQCD and Color Octet Mechanism:
     higher Fock states of the mesons taken into account; $Q\bar{Q}$ can be produced in octet states with different quantum number as the meson;
  3. Color Evaporation Model:
     based on quark-hadron duality;
     only the invariant mass matters; semi-soft gluons emissions;
     color-wise decorrelated $c\bar{c}$ prod. and hadr.

HELAC-Onia

H.-S. Shao, CPC 184 (2013) 2562-2570 & CPC 198 (2016) 238-259

HELAC-Onia is an automatic matrix element and event generator for quarkonium physics

- based on NRQCD framework
- based on off-shell recursion relations

NRQCD factorisation:

$$\sigma(pp \to \mathcal{Q} + X) = \sum_{i,j,n} \int dx_1 dx_2 \, f_{i/p}(x_1) \, f_{j/p}(x_2) \, \hat{\sigma}(ij \to Q\bar{Q}[n] + X) \, \langle \mathcal{O}_n^{\mathcal{Q}} \rangle$$

- $f_{i/p}(x_1), f_{j/p}(x_2)$ are the PDFs
- $\hat{\sigma}(ij \to Q\bar{Q}[n] + X)$ is the partonic cross section for producing a heavy quark pair in the Fock state n
- $n = {}^{2S+1}L_J^c$, with $c = 1, 8$ (color singlet or color octet)
- $\langle \mathcal{O}_n^{\mathcal{Q}} \rangle$ are the LDMEs

The Color Evaporation Model

- In the CEM, an onium production cross section is obtained from the one for $Q\bar{Q}$ production, with a cut on the invariant mass of the pair:

$$d\sigma_{\mathcal{Q}}^{(\mathrm{N})\mathrm{LO}} = \mathcal{P}_{\mathcal{Q}}^{(\mathrm{N})\mathrm{LO}} \int_{2m_Q}^{2m_H} dm_{Q\bar{Q}} \frac{d\sigma_{Q\bar{Q}}^{(\mathrm{N})\mathrm{LO}}}{dm_{Q\bar{Q}}}$$

- its Improved version (ICEM), momenta are rescaled:

$$d\sigma_{\mathcal{Q}}^{(\mathrm{N})\mathrm{LO}} = \mathcal{P}_{\mathcal{Q}}^{(\mathrm{N})\mathrm{LO}} \int_{2m_Q}^{2m_H} dm_{Q\bar{Q}} \frac{d\sigma_{Q\bar{Q}}^{(\mathrm{N})\mathrm{LO}}}{dm_{Q\bar{Q}}}\Big|_{p_{Q\bar{Q}}=\frac{m}{M_{\mathcal{Q}}}p_{\mathcal{Q}}}$$

Code vs metacode

What is the main difference between HELAC-Onia and MG5_aMC@NLO?

HELAC-Onia is a code

MG5_aMC@NLO is a metacode, *i.e.* a code generating another code

	HELAC-Onia	MG5_aMC@NLO
compilation	once	once for each `generate` command
running	run single executable each time	(re-)run the generated code for the requested process
code re-usage	✖	✓

NLOAccess - facts and figures

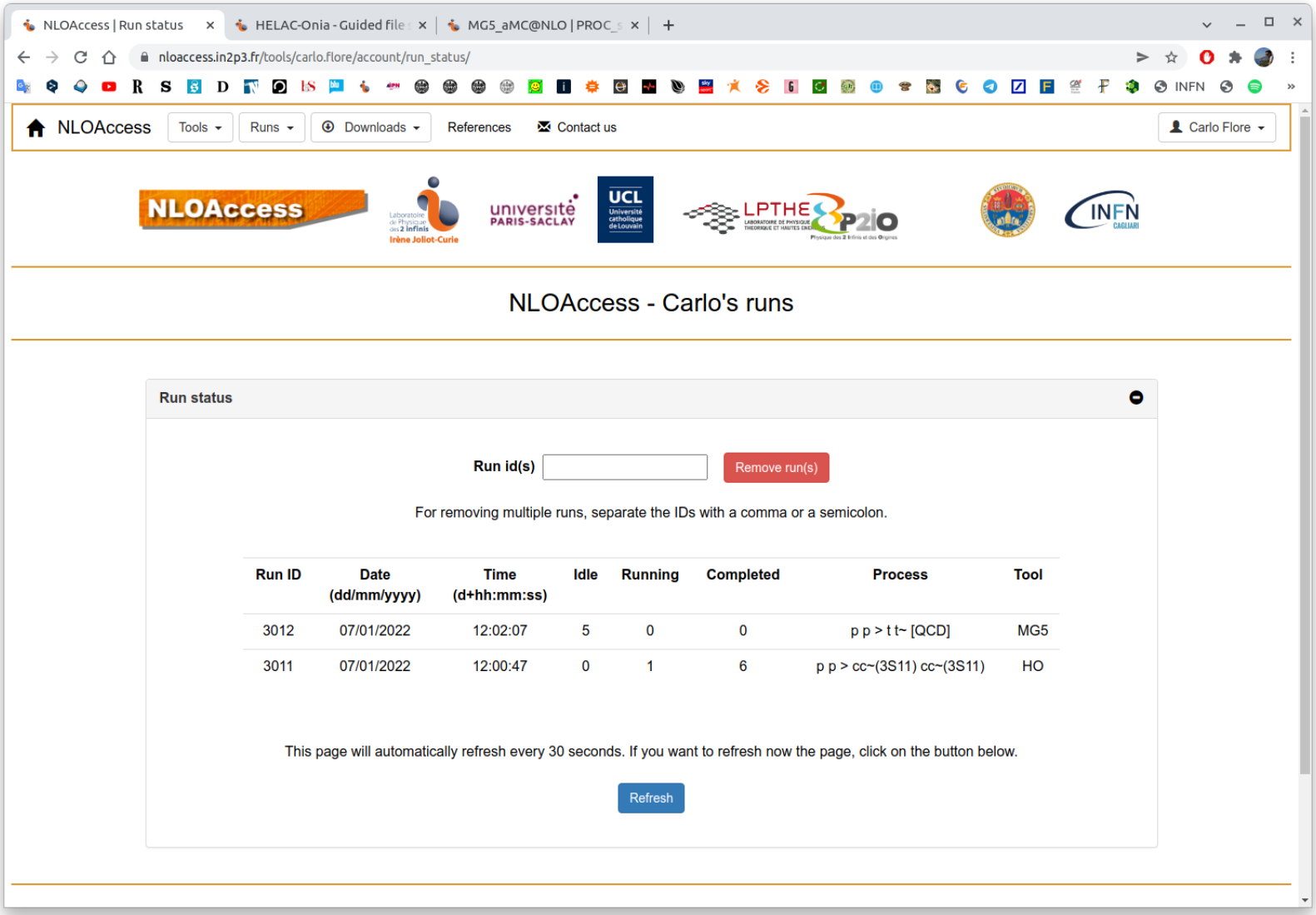
Some facts and figures about NLOAccess:

- general information at https://nloaccess.in2p3.fr
- HELAC-Onia Web: https://nloaccess.in2p3.fr/HO/
- MG5_aMC@NLO: https://nloaccess.in2p3.fr/MG5/
- 368 users from +30 countries all over the world; ∼ 3900 runs
- features:
  - secure two-step registration process
  - protected OwnCloud storage is given
  - file input as first way to submit a run
  - live user run status and run history
  - almost zero computational cost for the users
  - guided input file creation and submission for HO: https://nloaccess.in2p3.fr/HO/downloads/HO_online_guide_v01.pdf

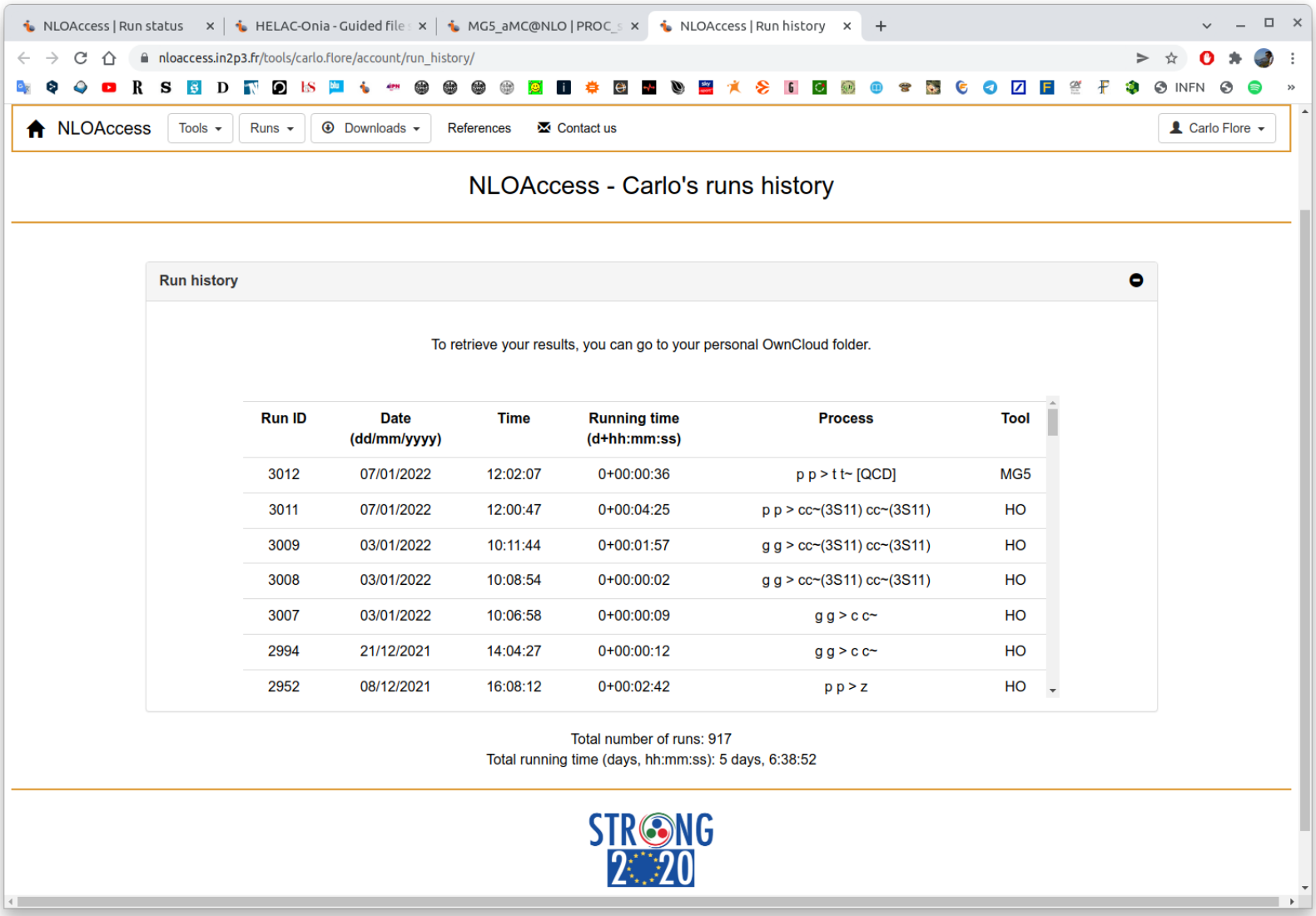
NLOAccess - homepage

(https://nloaccess.in2p3.fr)

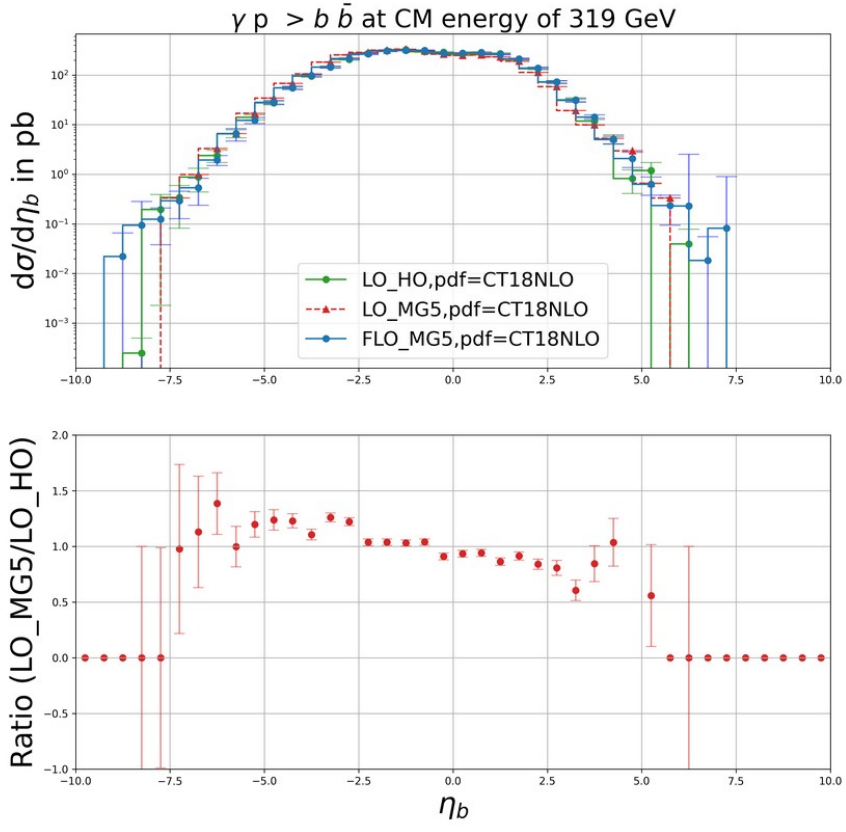
NLOAccess - run status



NLOAccess - run history



Result:



A comparison between pseudorapidity distribution of bottom quark production obtained from MG5 at LO (& FLO*) and with another LO event generator called Helac-onia (HO).

Cross section (nb)	MG5	HO
LO	$3.34 \pm 4.4*10^{-3}$	$3.34 +/- 10.08*10^{-3}$
FLO	$3.34 \pm 19*10^{-3}$	

*FLO (It's a specialty in MG5 that NLO code could be used for LO calculation as well)

courtesy of L. Manna