



Studying heavy quarks & quarkonia with NLOAccess

Carlo Flore

Université Paris-Saclay, CNRS, IJCLab Orsay

**Joint STRONG-2020 Annual Meeting/HF2022 session
Institut Pascal
17 Oct 2022**

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

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

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

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

- NLO* only contains the real-emission contributions with an IR cut-off, $\sqrt{s_{ij}^{\min}}$, and is expected to account for the leading P_T contributions at NLO (P_T^{-6})

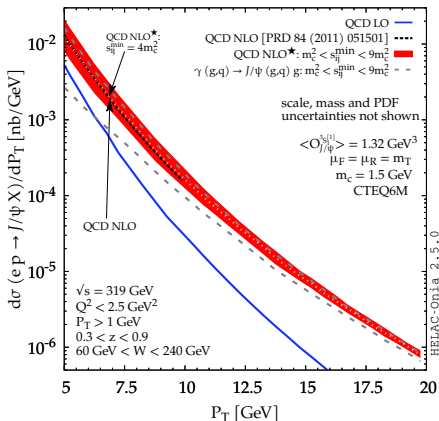
NLO approximation of J/ψ production: NLO*

P. Artoisenet *et al.*, PRL 101 (2008) 152001, J.-P. Lansberg, EPJC 61 (2009) 693 & PLB 679 (2009) 340
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

- NLO* only contains the real-emission contributions with an IR cut-off, $\sqrt{s_{ij}^{\min}}$, and is expected to account for the leading P_T contributions at NLO (P_T^{-6})
- It has been successfully checked against full NLO computations for $P_T > 3$ GeV

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



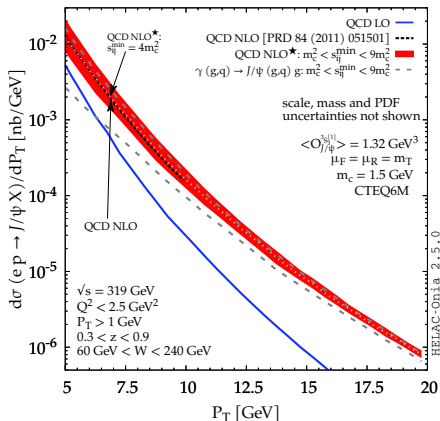
- NLO* only contains the real-emission contributions with an IR cut-off, $\sqrt{s_{ij}^{\text{min}}}$, and is expected to account for the leading P_T contributions at NLO (P_T^{-6})
- It has been successfully checked against full NLO computations for $P_T > 3 \text{ GeV}$

CSM QCD NLO from PRD 84 (2011) 051501

All the computations are done with HELAC-Onia [H.-S. Shao, CPC198 (2016) 238].

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



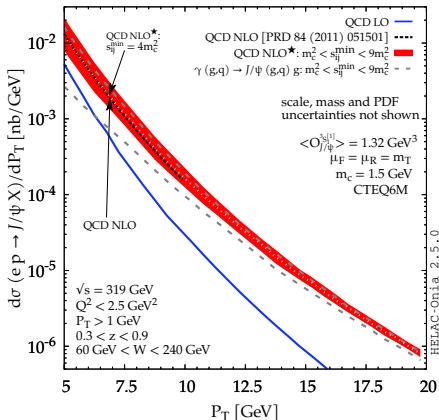
- NLO* only contains the real-emission contributions with an IR cut-off, $\sqrt{s_{ij}^{\min}}$, and is expected to account for the leading P_T contributions at NLO (P_T^{-6})
- It has been successfully checked against full NLO computations for $P_T > 3$ GeV
- $\sqrt{s_{ij}^{\min}} / m_c \in [1:3]$ suitable for our study; $\sqrt{s_{ij}^{\min}} = 2m_c$ remarkably reproduces NLO results

CSM QCD NLO from PRD 84 (2011) 051501

All the computations are done with HELAC-Onia [H.-S. Shao, CPC198 (2016) 238].

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



- NLO* only contains the real-emission contributions with an IR cut-off, $\sqrt{s_{ij}^{\min}}$, and is expected to account for the leading P_T contributions at NLO (P_T^{-6})
- It has been successfully checked against full NLO computations for $P_T > 3 \text{ GeV}$
- $\sqrt{s_{ij}^{\min}} / m_c \in [1:3]$ suitable for our study; $\sqrt{s_{ij}^{\min}} = 2m_c$ remarkably reproduces NLO results

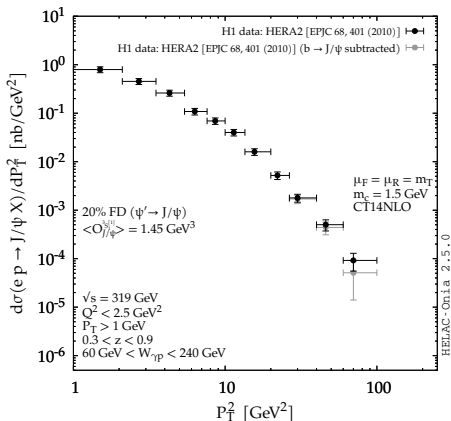
Let's revisit HERA data!

CSM QCD NLO from PRD 84 (2011) 051501

All the computations are done with HELAC-Onia [H.-S. Shao, CPC198 (2016) 238].

Revisiting HERA data

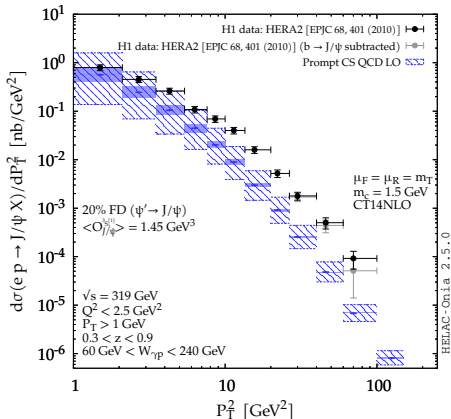
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



All the computations are done with [HELAC-ONIA \[H.-S. Shao, CPC198 \(2016\) 238\]](#).

Revisiting HERA data

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



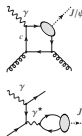
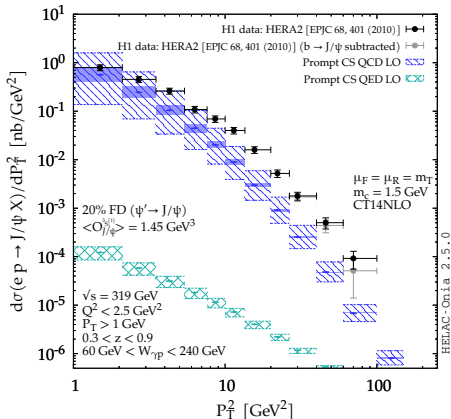
$$\gamma + g \rightarrow \psi + g @ \alpha\alpha_s^2$$

All the computations are done with **HELAC-Onia** [H.-S. Shao, CPC198 (2016) 238].
Scale and mass uncertainties are shown by the hatched and solid bands respectively.

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

Revisiting HERA data

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



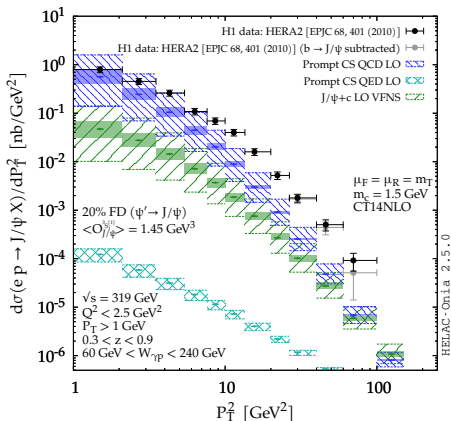
$$\gamma + g \rightarrow \psi + g @ \alpha\alpha_s^2$$

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

All the computations are done with **HELAC-Onia** [H.-S. Shao, CPC198 (2016) 238].
Scale and mass uncertainties are shown by the hatched and solid bands respectively.

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

Revisiting HERA data



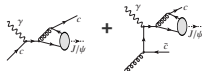
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



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



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



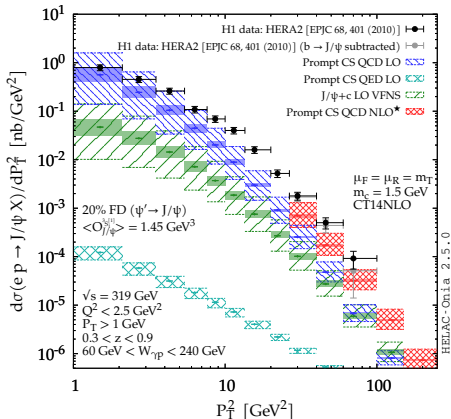
$$\left\{ \begin{array}{l} \gamma + c \rightarrow \psi + c @ \alpha\alpha_s^2 \quad (4\text{FS}) \\ \gamma + g \rightarrow \psi + c + \bar{c} @ \alpha\alpha_s^3 \quad (3\text{FS}) \end{array} \right. \text{ [also NEW!]}$$

All the computations are done with **HELAC-Onia** [H.-S. Shao, CPC198 (2016) 238].
 Scale and mass uncertainties are shown by the hatched and solid bands respectively.

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

Revisiting HERA data

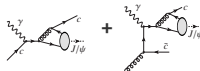
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



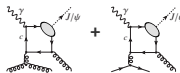
$$\gamma + g \rightarrow \psi + g @ \alpha\alpha_s^2$$



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



$$\left\{ \begin{array}{l} \gamma + c \rightarrow \psi + c @ \alpha\alpha_s^2 \quad (4\text{FS}) \\ \gamma + g \rightarrow \psi + c + \bar{c} @ \alpha\alpha_s^3 \quad (3\text{FS}) \end{array} \right. \text{ [also NEW!]}$$



$$\left\{ \begin{array}{l} \gamma + g \rightarrow \psi + g + g @ \alpha\alpha_s^3 \\ \gamma + q \rightarrow \psi + g + q @ \alpha\alpha_s^3 \end{array} \right.$$

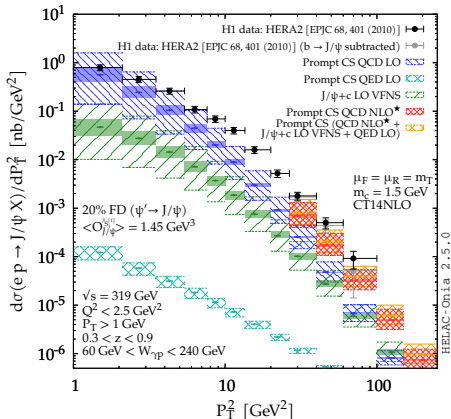
$$[+ \gamma + g \rightarrow \psi + g]$$

All the computations are done with **HELAC-Onia** [H.-S. Shao, CPC198 (2016) 238].

Scale and mass uncertainties are shown by the hatched and solid bands respectively.

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

Revisiting HERA data



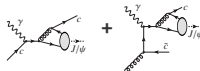
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



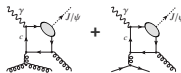
$$\gamma + g \rightarrow \psi + g @ \alpha\alpha_s^2$$



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



$$\left\{ \begin{array}{l} \gamma + c \rightarrow \psi + c @ \alpha\alpha_s^2 \quad (4\text{FS}) \\ \gamma + g \rightarrow \psi + c + \bar{c} @ \alpha\alpha_s^3 \quad (3\text{FS}) \end{array} \right. \text{ [also NEW!]}$$



$$\left\{ \begin{array}{l} \gamma + g \rightarrow \psi + g + g @ \alpha\alpha_s^3 \\ \gamma + q \rightarrow \psi + g + q @ \alpha\alpha_s^3 \end{array} \right.$$

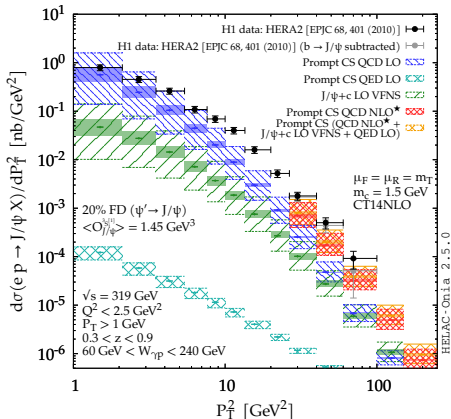
$$[+ \gamma + g \rightarrow \psi + g]$$

All the computations are done with **HELAC-Onia** [H.-S. Shao, CPC198 (2016) 238].
Scale and mass uncertainties are shown by the hatched and solid bands respectively.

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

Revisiting HERA data

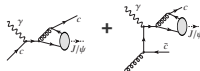
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



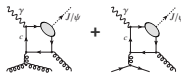
$$\gamma + g \rightarrow \psi + g @ \alpha\alpha_s^2$$



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



$$\left\{ \begin{array}{l} \gamma + c \rightarrow \psi + c @ \alpha\alpha_s^2 \quad (4\text{FS}) \\ \gamma + g \rightarrow \psi + c + \bar{c} @ \alpha\alpha_s^3 \quad (3\text{FS}) \end{array} \right. \text{ [also NEW!]}$$



$$\left\{ \begin{array}{l} \gamma + g \rightarrow \psi + g + g @ \alpha\alpha_s^3 \\ \gamma + q \rightarrow \psi + g + q @ \alpha\alpha_s^3 \end{array} \right.$$

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

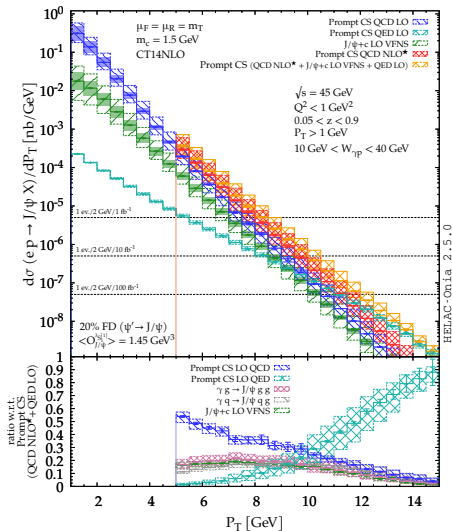
The CSM up to $\alpha\alpha_s^3$ reproduces J/ψ photoproduction at HERA

→ for the EIC, we have restricted our predictions to CSM

Predictions for $J/\psi + X$ at the EIC

$[\sqrt{s_{ep}} = 45 \text{ GeV}]$

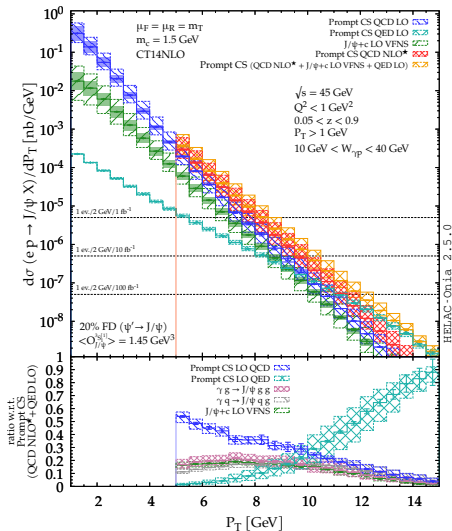
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



- At $\sqrt{s_{ep}} = 45 \text{ GeV}$, one gets into valence region

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

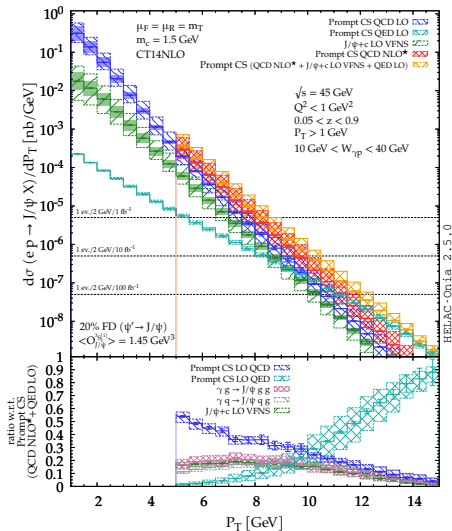
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



- At $\sqrt{s_{ep}} = 45 \text{ GeV}$, one gets into **valence region**
- Yield steeply falling with P_T
- Yield can be measured **up to**
 $P_T \sim 11 \text{ GeV}$ with $\mathcal{L} = 100 \text{ fb}^{-1}$
 [using both ee and $\mu\mu$ decay channels and $\epsilon_{J/\psi} \simeq 80\%$]

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

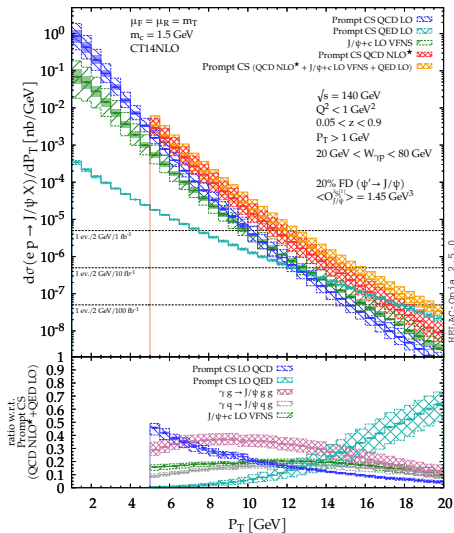
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



- At $\sqrt{s_{ep}} = 45 \text{ GeV}$, one gets into **valence region**
- Yield steeply falling with P_T
- Yield can be measured **up to** $P_T \sim 11 \text{ GeV}$ with $\mathcal{L} = 100 \text{ fb}^{-1}$
 [using both ee and $\mu\mu$ decay channels and $\epsilon_{J/\psi} \simeq 80\%$]
- **QED** contribution **leading** at the largest reachable P_T
- $\gamma + q$ fusion contributes more than 30% for $P_T > 8 \text{ GeV}$

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

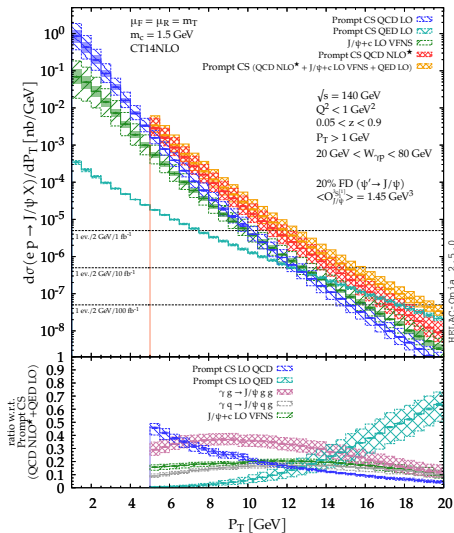
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



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

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

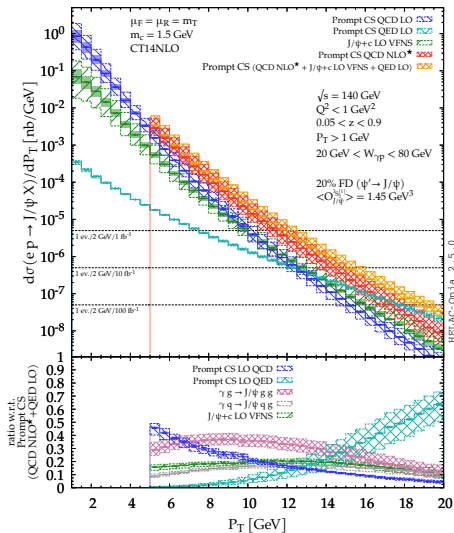
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



- At $\sqrt{s_{ep}} = 140 \text{ GeV}$ larger P_T range, up to $\sim 18 \text{ GeV}$
- QED contribution also leading at the largest reachable P_T
- $\gamma + g$ fusion contributions dominant up to $P_T \sim 15 \text{ GeV}$

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

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



- At $\sqrt{s_{ep}} = 140 \text{ GeV}$ larger P_T range, up to $\sim 18 \text{ GeV}$
- QED contribution also leading at the largest reachable P_T
- $\gamma + g$ fusion contributions dominant up to $P_T \sim 15 \text{ GeV}$
- large- P_T J/ψ photoproduction induced also by quark initiated processes

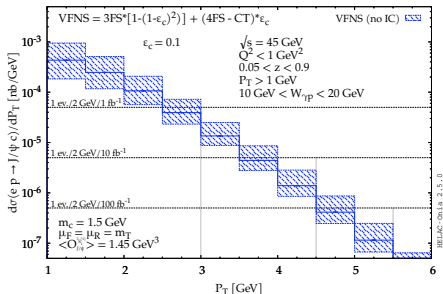
Intrinsic charm at the EIC

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

- Recent studies: measurement by LHCb in $Z+\text{charmed jets}$ and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

Intrinsic charm at the EIC



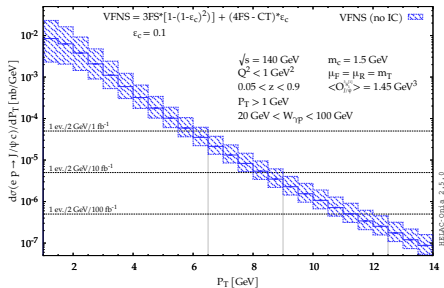
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

- Recent studies: measurement by LHCb in Z+charmed jets and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

- At $\sqrt{s_{ep}} = 45$ 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 $\mathcal{L} = (100, 10, 1) \text{ fb}^{-1}$

Intrinsic charm at the EIC



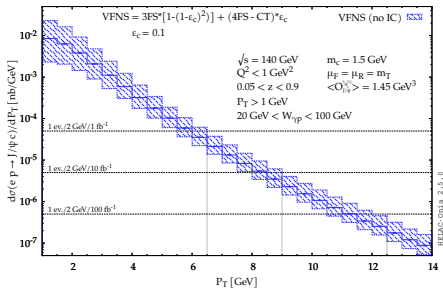
CF, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

- Recent studies: measurement by LHCb in Z+charmed jets and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

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

Intrinsic charm at the EIC



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

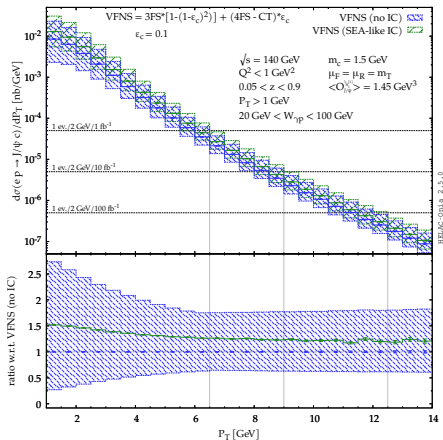
- Recent studies: measurement by LHCb in Z +charmed jets and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

- At $\sqrt{s_{ep}} = 45$ GeV, yield limited to **low** P_T even with $\mathcal{L} = 100$ fb $^{-1}$
- But it is clearly observable if $\epsilon_c = 0.1$ with $\mathcal{O}(500, 50, 5)$ events for $\mathcal{L} = (100, 10, 1)$ fb $^{-1}$
- At $\sqrt{s_{ep}} = 140$ GeV, P_T range up to 10 GeV with **up to thousands of events** with $\mathcal{L} = 100$ fb $^{-1}$
- Could be observed via **charm jet**

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

Intrinsic charm at the EIC



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

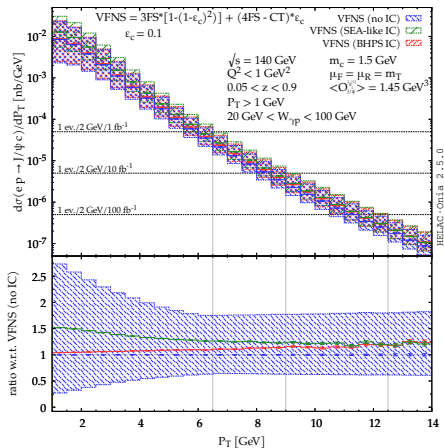
- Recent studies: measurement by LHCb in Z+charmed jets and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

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

- 4FS $\gamma c \rightarrow J/\psi c$ depends on $c(x)$ and could be enhanced by **intrinsic charm**
- Small effect at $\sqrt{s_{ep}} = 140$ GeV [We used IC $c(x)$ encoded in CT14NNLO]

Intrinsic charm at the EIC



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

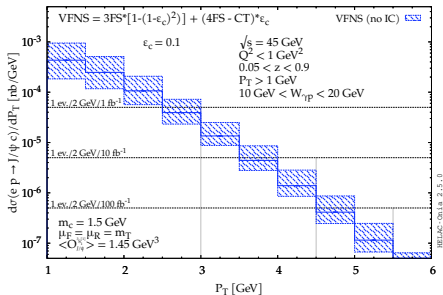
- Recent studies: measurement by LHCb in Z+charmed jets and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

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

- 4FS $\gamma c \rightarrow J/\psi c$ depends on $c(x)$ and could be enhanced by **intrinsic charm**
- Small effect at $\sqrt{s_{ep}} = 140 \text{ GeV}$ [We used IC $c(x)$ encoded in CT14NNLO]

Intrinsic charm at the EIC



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

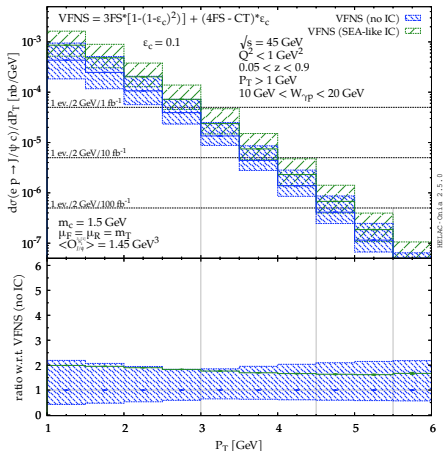
- Recent studies: measurement by LHCb in Z +charmed jets and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

- At $\sqrt{s_{ep}} = 45$ GeV, yield limited to **low** P_T even with $\mathcal{L} = 100 \text{ fb}^{-1}$
- But it is clearly observable if $\varepsilon_c = 0.1$ with $\mathcal{O}(500, 50, 5)$ events for $\mathcal{L} = (100, 10, 1) \text{ fb}^{-1}$
- At $\sqrt{s_{ep}} = 140$ GeV, P_T range up to 10 GeV with **up to thousands of events** with $\mathcal{L} = 100 \text{ fb}^{-1}$
- Could be observed via **charm jet**

- 4FS $\gamma c \rightarrow J/\psi c$ depends on $c(x)$ and could be enhanced by **intrinsic charm**
- Small effect at $\sqrt{s_{ep}} = 140$ GeV [We used IC $c(x)$ encoded in CT14NNLO]
- Measurable effect** at $\sqrt{s_{ep}} = 45$ GeV

Intrinsic charm at the EIC



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

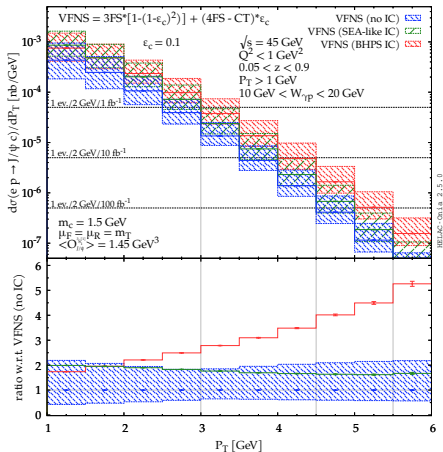
- Recent studies: measurement by LHCb in Z+charmed jets and NNPDF phenomenological analysis

R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

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

- 4FS $\gamma c \rightarrow J/\psi c$ depends on $c(x)$ and could be enhanced by **intrinsic charm**
- Small effect at $\sqrt{s_{ep}} = 140 \text{ GeV}$ [We used IC $c(x)$ encoded in CT14NNLO]
- Measurable effect** at $\sqrt{s_{ep}} = 45 \text{ GeV}$

Intrinsic charm at the EIC



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

- Recent studies: measurement by LHCb in Z+charmed jets and NNPDF phenomenological analysis

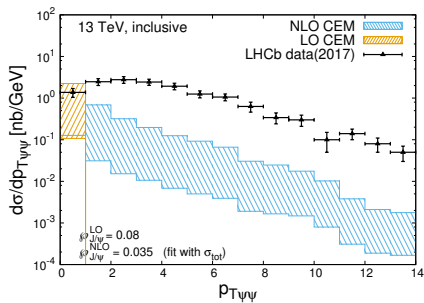
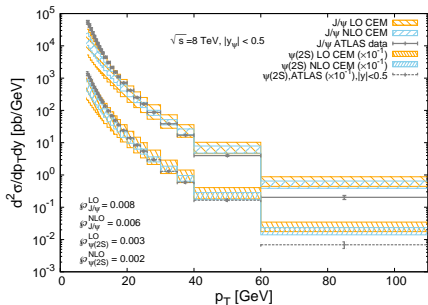
R. Aaij *et al.*, PRL 128(8) 2022; R.D. Ball *et al.*, Nature 608 (7923)(2022) 483

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

- 4FS $\gamma c \rightarrow J/\psi c$ depends on $c(x)$ and could be enhanced by **intrinsic charm**
- Small effect at $\sqrt{s_{ep}} = 140 \text{ GeV}$ [We used IC $c(x)$ encoded in CT14NNLO]
- Measurable effect** at $\sqrt{s_{ep}} = 45 \text{ GeV}$: **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

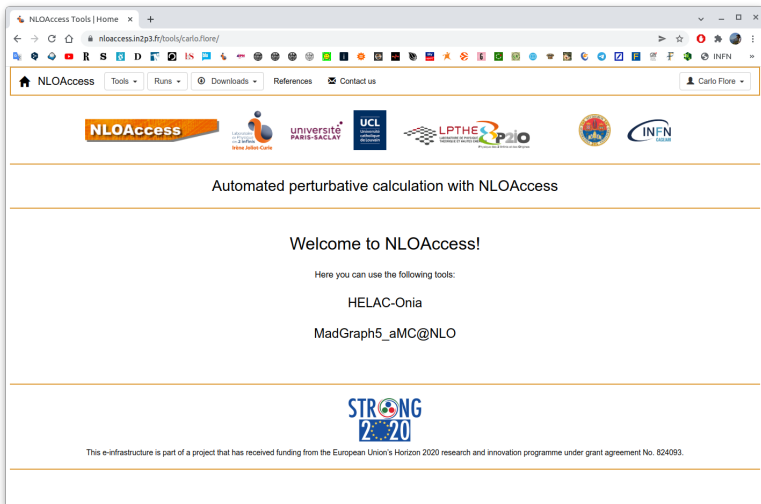
NLOAccess - the framework

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/>)



The screenshot shows a web browser window with the URL `nloaccess.in2p3.fr/tools/carlo.flore/`. The page features a navigation bar with 'NLOAccess', 'Tools', 'Runs', 'Downloads', 'References', and 'Contact us'. Below the navigation bar are logos for NLOAccess, Université Paris-Saclay, UCL, LPTHE, and INFN. The main content area includes the text 'Automated perturbative calculation with NLOAccess', 'Welcome to NLOAccess!', and a list of tools: 'HELAC-Onia' and 'MadGraph5_aMC@NLO'. At the bottom, there is a 'STRONG 2020' logo and a note about funding from the European Union's Horizon 2020 programme.

NLOAccess Tools | Home x +

nloaccess.in2p3.fr/tools/carlo.flore/

NLOAccess Tools Runs Downloads References Contact us

Carlo Flore

NLOAccess Université Paris-Saclay UCL LPTHE INFN

Automated perturbative calculation with NLOAccess

Welcome to NLOAccess!

Here you can use the following tools:

HELAC-Onia

MadGraph5_aMC@NLO

STRONG 2020

This e-infrastructure is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 824093.

The screenshot shows a web browser window with the URL `nloaccess.in2p3.fr/tools/H0/carlo.flore/`. The browser's address bar and tabs are visible at the top. Below the browser window, the website's header features the NLOAccess logo and logos for partner institutions: Université Paris-Saclay, UCL, LPTHE, and INFN. The main content area is titled "Automated perturbative calculation with NLOAccess" and "HELAC-Onia Web". A paragraph describes the tool's capabilities: "HELAC-Onia is 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." Below this text, there are two buttons: "Upload your input file" and "Build your input file". At the bottom of the page, the STRONG-2020 logo is displayed.

HELAC-Onia Web - run submission

The screenshot shows a web browser window with the URL `nioaccess.in2p3.fr/tools/HO/carlo.flore/guided-file-submission/`. The page title is "HELAC-Onia - Guided input file submission". The interface includes a navigation bar with "Tools", "Runs", "Downloads", "References", and "Contact us" links, and a user profile for "Carlo Flore".

The main content area is titled "Create your input file" and contains the following elements:

- A text input field labeled "Input next command(s):" with a blue "Add command(s)" button below it.
- A "Remove line(s) containing:" label followed by a text input field, with "Remove line(s)" and "Clear file" buttons below it.
- A green "Submit job" button.
- A "Your input file:" section displaying a pre-filled code block:

```
generate p p > cc-(3S11) cc-(3S11)
set colpar = 1
set energy_beam1 = 7000
set energy_beam2 = 7000
set qcd = 2
decay cc-(3S11) > m+ m- @ 0.06
launch
```
- A note: "Please, remember to follow this structure for your input file:" followed by a code block:

```
generate { process }
set { parameter } = { value }
:
launch
```
- A reference: "For more examples: see this reference or take a look to the [User Guide](#)."

HELAC-Onia Web - run submission

The screenshot shows a web browser window with the URL `nioaccess.in2p3.fr/tools/HO/carlo.flore/guided-file-submission/`. The page title is "HELAC-Onia - Guided input file submission". The main content area is titled "Create your input" and contains a text editor with the following code:

```
generate p p > cc~(3S11) cc~(3S11)
      set colpar = 1
      set energy_beam1 = 7000
      set energy_beam2 = 7000
      set qcd = 2
decay cc~(3S11) > m+ m- @ 0.06
launch
```

Below the text editor, there is a blue button labeled "Add command(s)", a text input field for "Remove line(s) containing:", and two buttons: "Remove line(s)" and "Clear file". At the bottom of the editor area is a green "Submit job" button.

To the right of the editor, there is a note: "Please, remember to follow this structure for your input file:" followed by a code block:

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

Below this note, it says: "For more examples: see this reference or take a look to the [User Guide](#)."

HELAC-Onia Web - input file

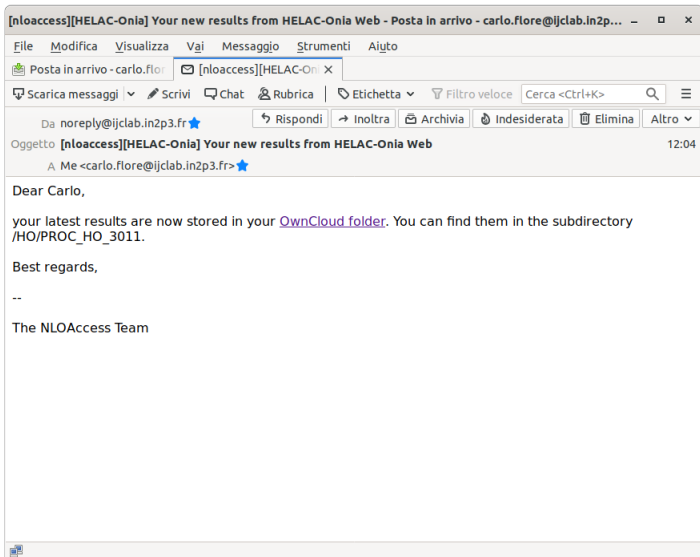
The input file should be in the following form:

```
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)



The screenshot shows an email client window with the following details:

- Subject:** [nloaccess][HELAC-Onia] Your new results from HELAC-Onia Web - Posta in arrivo - carlo.flore@ijclab.in2p3...
- Sender:** noreply@ijclab.in2p3.fr
- Recipient:** Me <carlo.flore@ijclab.in2p3.fr>
- Time:** 12:04
- Body:**

Dear Carlo,

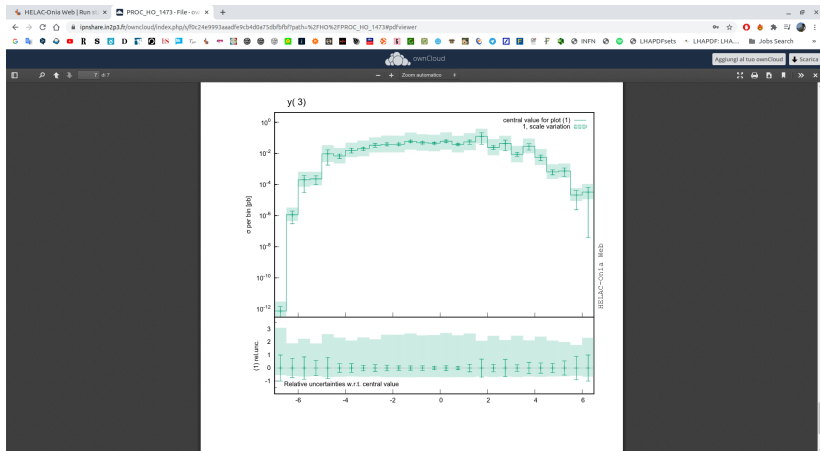
your latest results are now stored in your [OwnCloud folder](#). You can find them in the subdirectory /HO/PROC_HO_3011.

Best regards,

--

The NLOAccess Team

HELAC-Onia Web - results (II)

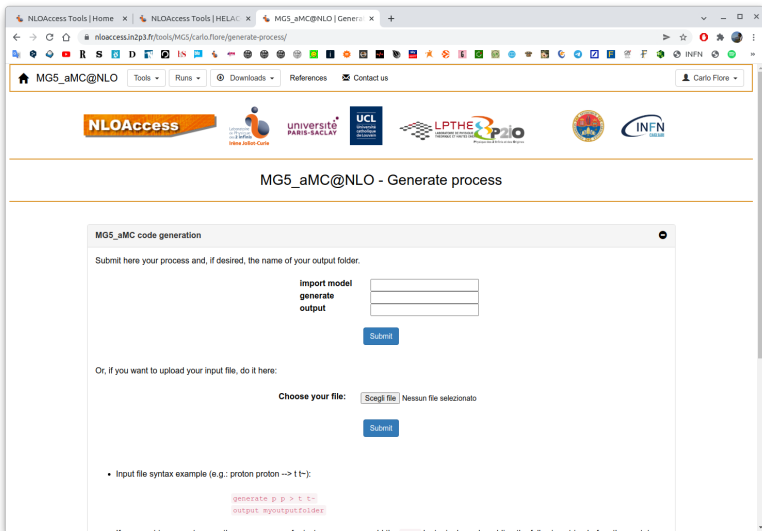


- MadGraph5 online version was only limited to LO calculation
- NLOAccess offers access **for the first time to full NLO SM online calculation** with **MG5_aMC@NLO!**



The screenshot shows a web browser window with the URL `nloaccess.in2p3.fr/tools/MG5/carlo.flore/`. The page features a navigation bar with the text "MG5_aMC@NLO" and a user profile "Carlo Flore". Below the navigation bar is a row of logos for NLOAccess, Université Paris-Saclay, UCL, LPTHE, P2IO, and INFN. The main content area is titled "Automated perturbative calculation with NLOAccess" and "MG5_aMC@NLO". A paragraph of text describes the framework's capabilities, including LO accuracy simulations and tree- and one-loop-level calculations. Below the text, there are two links: "Generate a new code" and "Check your code database". At the bottom of the page is the "STRONG 2020" logo.

MG5_aMC@NLO - code generation



The screenshot shows a web browser window with the URL `nloaccess.in2p3.fr/tools/MG5/carlo.flore/generate-process/`. The page header includes the NLOAccess logo and logos for partner institutions: universit  PARIS-SACLAY, UCL, LPTHE, and INFN. The main heading is "MG5_aMC@NLO - Generate process".

The central form is titled "MG5_aMC code generation" and contains the following elements:

- Text: "Submit here your process and, if desired, the name of your output folder."
- Form fields: Three stacked input boxes for "import model", "generate", and "output".
- Button: A blue "Submit" button.
- Text: "Or, if you want to upload your input file, do it here:"
- Text: "Choose your file:"
- Form: A file selection button labeled "Scegli file" and the text "Nessun file selezionato".
- Button: A blue "Submit" button.
- List item: "Input file syntax example (e.g.: proton proton --> t t-):"
- Code block:

```
generate p p > t t-
output _myoutputfolder
```

MG5_aMC@NLO - code database

The screenshot shows a web browser window with the URL `nloaccess.in2p3.fr/tools/MG5/carlo.flore/run-database/`. The page features a navigation bar with 'NLOAccess', 'Tools', 'Runs', 'Downloads', 'References', and 'Contact us'. Below the navigation bar are logos for NLOAccess, Université Paris-Saclay, UCL, LPTHE, and INFN. The main heading is 'MG5_aMC@NLO - Carlo's database'. A 'Process Database' table is displayed with the following data:

Folder name	Creation date (dd/mm/yyyy)	Creation time	Process	
lest-ag2bbbar-10-11-21	10/11/2021	11:12:52	$ag > b b^-$	Run
PROCNLO_loop_sm_20	24/09/2021	14:10:16	$pp > t\bar{t} [QCD]$	Run
PROC_loop_sm_1	30/09/2021	16:44:07	$pp > H [QCD]$	Run
PROC_loop_sm_0	29/09/2021	23:10:21	$pp > h [QCD]$	Run
PROCNLO_loop_sm_19	24/09/2021	13:04:48	$pp > t\bar{t} [QCD]$	Run

Below the table, it says 'Your personal OwnCloud folder'. At the bottom of the page is the CTP-ONC logo.

MG5_aMC@NLO - code running

The screenshot shows a web browser window with the URL `nloaccess.in2p3.fr/tools/carlo.flore/MG5/PROCNLO_loop_sm_20/run/`. The page header includes the NLOAccess logo and navigation menus. Below the header are logos for partner institutions: NLOAccess, Université Paris-Saclay, UCL, LPTHE, and INFN. The main content area is titled "MG5_aMC@NLO - PROCNLO_loop_sm_20". A "Run the process" panel is open, displaying instructions to upload cards and a configuration form with the following settings:

Upload cards: <input type="button" value="Scegli file"/> Nessun file selezionato	
Order	Fixed Order
<input type="text" value="NLO"/>	<input type="text" value="OFF"/>
Shower	Madspin
<input type="text" value="No shower"/>	<input type="text" value="OFF"/>
Reweight	MadAnalysis
<input type="text" value="OFF"/>	<input type="text" value="OFF"/>

A green "Submit run" button is located at the bottom of the configuration panel.

NLOAccess - what's next?

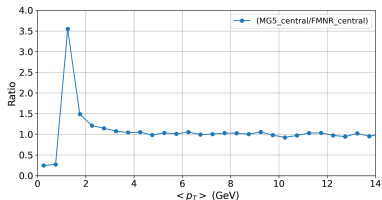
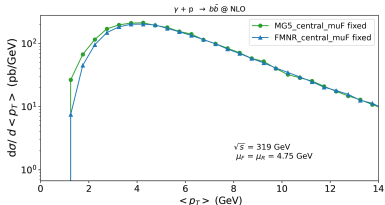
NLOAccess - what's next?

- include **asymmetric collisions** in MG5 at NLO:

NLOAccess - what's next?

- include **asymmetric collisions** in MG5 at NLO:
extension to eh/eA collisions

[L. Manna, WUT Warsaw]



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

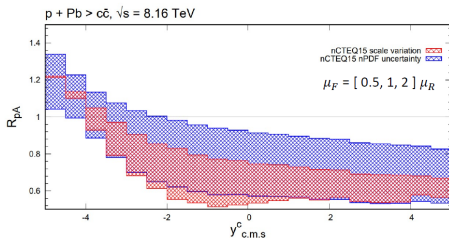
NLOAccess - what's next?

- include **asymmetric collisions** in MG5 at NLO:
extension to eh/eA collisions

[L. Manna, WUT Warsaw]

extension to $pA/AB/\pi p$ collisions and automated computation of nuclear modification factors (e.g. R_{pA})

[A. Safronov, WUT Warsaw]



from A. Safronov's talk at ICHEP 2022

NLOAccess - what's next?

- automation of onium production computations at NLO in MG5
[A. Abdul-Hameed, LPTHE Paris]
- automation of spin and transverse momentum effects for quarkonium production
[C. Flett, Jyvaskyla U. & IJCLab Orsay]

NLOAccess - what's next?

- automation of onium production computations at NLO in MG5
[A. Abdul-Hameed, LPTHE Paris]
- automation of spin and transverse momentum effects for quarkonium production
[C. Flett, Jyvaskyla U. & IJCLab Orsay]
- inclusion of other codes
[suggestions are welcome!]

NLOAccess - what's next?

- automation of onium production computations at NLO in MG5
[A. Abdul-Hameed, LPTHE Paris]
- automation of spin and transverse momentum effects for quarkonium production
[C. Flett, Jyvaskyla U. & IJCLab Orsay]
- inclusion of other codes
[suggestions are welcome!]

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 is an automatic matrix element and event generator for quarkonium physics

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

NRQCD factorisation:

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

- $f_{i/p}(x_1), f_{j/p}(x_2)$ are the **PDFs**
- $\hat{\sigma}(ij \rightarrow Q\bar{Q}[n] + X)$ 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)
- $\langle \mathcal{O}_n^Q \rangle$ 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:

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

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

$$d\sigma_Q^{(N)\text{LO}} = \mathcal{P}_Q^{(N)\text{LO}} \int_{2m_Q}^{2m_H} dm_{Q\bar{Q}} \frac{d\sigma_{Q\bar{Q}}^{(N)\text{LO}}}{dm_{Q\bar{Q}}} \Big|_{p_{Q\bar{Q}} = \frac{m}{M_Q} p_Q}$$

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/H0/>
- 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 H0:
https://nloaccess.in2p3.fr/H0/downloads/H0_online_guide_v01.pdf

NLOAccess - homepage

(<https://nloaccess.in2p3.fr>)

NLOAccess
Virtual Access: Automated perturbative NLO calculations for heavy ions and quarkonia (NLOAccess)

Home - The project - Communication - Tools - Account - Downloads - Request registration

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.

The automated tools on which NLOAccess is based are (i) the MADGRAPH ensemble heavily used by the high-energy physics (HEP) community, but extended to deal with meson and heavy-ion beams and (ii) the HELAC-ONIA code allowing the computation of cross section for heavy-quark bound states, the quarkonia.

The portal NLOAccess will allow one to access additional automated tools. I will extend the portal of MADGRAPH@UCLouvain with the necessary additions to deal with heavy-ion collisions and quarkonium production.

As of today, in contrast to HEP, no such place exists for hadronic physics where interested colleagues can go test their ideas and turn them into concrete realisation with automated Monte Carlo tools. In addition, the available tools are limited to a reduced class of applications. For each, one needs to install them one by one, sometimes along with dedicated libraries and one needs to get familiar with their syntax. A single portal for hadron physics will not only ease the task of the

FOLLOW:

STRONG 2020

This e-infrastructure is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 624093.

Search

RECENT POSTS

© Jean-Philippe Lansberg gives a talk at

NLOAccess - run status

NLOAccess | Run status

HELAC-Onia - Guided File | MGS_aMC@NLO | PROC_ |

nloaccess.in2p3.fr/tools/carlo.fiore/account/run_status/

NLOAccess Tools Runs Downloads References Contact us

Carlo Fiore

NLOAccess Université Paris-Saclay UCL LPTHE INFN

NLOAccess - Carlo's runs

Run status

Run id(s) Remove run(s)

For removing multiple runs, separate the IDs with a comma or a semicolon.

Run ID	Date (dd/mm/yyyy)	Time (d+hh:mm:ss)	Idle	Running	Completed	Process	Tool
3012	07/01/2022	12:02:07	5	0	0	p p > t t~ [QCD]	MGS
3011	07/01/2022	12:00:47	0	1	6	p p > cc~(3S11) cc~(3S11)	HO

This page will automatically refresh every 30 seconds. If you want to refresh now the page, click on the button below.

Refresh

NLOAccess - run history

NLOAccess - Carlo's runs history

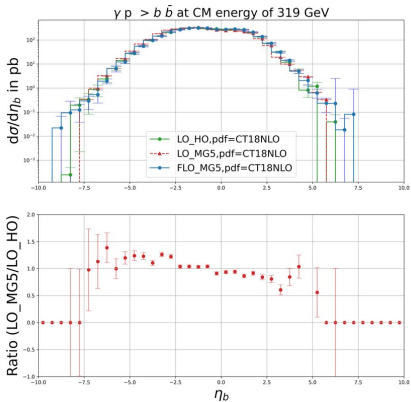
Run history

To retrieve your results, you can go to your personal OwnCloud folder.

Run ID	Date (dd/mm/yyyy)	Time	Running time (d+hh:mm:ss)	Process	Tool
3012	07/01/2022	12:02:07	0+00:00:36	p p > t1- [QCD]	MG5
3011	07/01/2022	12:00:47	0+00:04:25	p p > cc-(3S11) cc-(3S11)	HO
3009	03/01/2022	10:11:44	0+00:01:57	g g > cc-(3S11) cc-(3S11)	HO
3008	03/01/2022	10:08:54	0+00:00:02	g g > cc-(3S11) cc-(3S11)	HO
3007	03/01/2022	10:06:58	0+00:00:09	g g > c c~	HO
2994	21/12/2021	14:04:27	0+00:00:12	g g > c c~	HO
2952	08/12/2021	16:08:12	0+00:02:42	p p > z	HO

Total number of runs: 917
Total running time (days, hh:mm:ss): 5 days, 6:38:52

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	$3.34 \pm 4.4 \cdot 10^{-3}$	$3.34 \pm 10.08 \cdot 10^{-3}$
FLO	$3.34 \pm 19 \cdot 10^{-3}$	

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

courtesy of L. Manna