HELAC-Onia: quarkonium-production predictions in NRQCD made easy

Hua-Sheng Shao

CERN, PH-TH

Based on work
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24 September 2015

ME/EVENT GENERATORS ON MARKET

w/o onia	**w/ onia**

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LO • Alpgen **Mangano, Moretti, Piccinini, Pittau, Polosa** • MG5/ME5 **Alwall, Herquet, Maltoni, Mattelaer, Stelzer** • HELAC-PHEGAS **Cafarella, Kanaki, Papadopoulos, Worek** • Sherpa ... **Gleisberg, Hoche, Krauss, Schaelicke, Schumann, Winter**	

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w/ onia

LO

- MadOnia
  Artoisenet, Maltoni, Stelzer
- HELAC-Onia
  HSS
- ...

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Institute of Nuclear Physics "Demokritos" Bergische Universitat Wuppertal Institute of Nuclear Physics PAN RWTH Aachen University

HELAC-Onia

Helac-Onia

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.

:: top ::

People

Hua-Sheng Shao

:: top ::

Compilers:

- gfortran

:: top ::

Software Download

NEW **HELAC-Onia Curent Version 1.1.2** (17 June 2013): HELAC-Onia-1.1.2.tar.gz

HELAC-Onia Version 1.0.0 (10 January 2013): HELAC-Onia-1.0.tgz

:: top ::

- **First version released on 10 Jan 2013.**
- **Download from** http://helac-phegas.web.cern.ch/helac-phegas/helac-onia.html
- **More and more functionalities are adding ...**

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HELAC-Onia: An automatic matrix element generator for heavy quarkonium physics☆

Hua-Sheng Shao *

Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
PH Department, TH Unit, CERN, CH-1211 Geneva 23, Switzerland

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ABSTRACT

By the virtues of the Dyson–Schwinger equations, we upgrade the published code HELAC to be capable to calculate the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization, which we dub HELAC-Onia. We rewrote the original HELAC to make the new program be 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. Therefore, 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 (e.g. $h_{c,b}$, $\chi_{c,b}$) and *P*-wave color-octet intermediate states. To the best of our knowledge, it is a first general-purpose automatic quarkonium matrix elements generator based on recursion relations on the market.

Program summary

Program title: HELAC-Onia.

Catalogue identifier: AEPR_v1_0

Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AEPR_v1_0.html

Program obtainable from: CPC Program Library, Queen's University, Belfast, N. Ireland

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CERN

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Hua-Sheng Shao *

Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Pek
PH Department, TH Unit, CERN, CH-1211 Geneva 23, Switzerland

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Catalogue identifier: AEPR_
Program summary URL: htt
Program obtainable from: C

HELAC-Onia 2.0: an upgraded matrix-element and event generator for heavy quarkonium physics

Hua-Sheng Shao

PH Department, TH Unit, CERN, CH-1211, Geneva 23, Switzerland
E-mail:huasheng.shao@cern.ch

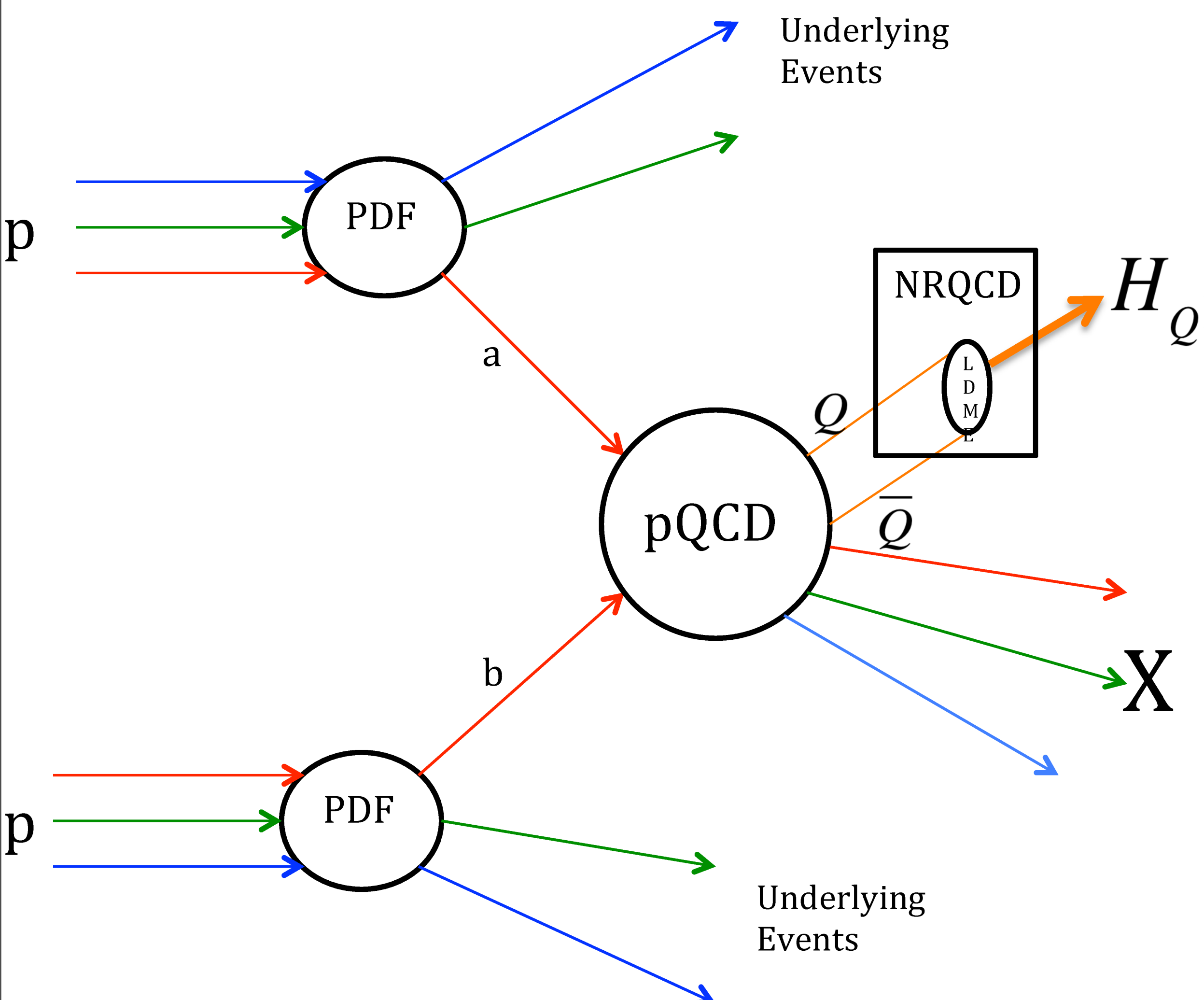
ABSTRACT

We present an upgraded version (denoted as version 2.0) of the program HELAC-ONIA for the automated computation of heavy-quarkonium helicity amplitudes within non-relativistic QCD framework. The new code has been designed to include many new and useful features for practical phenomenological simulations. It is designed for job submissions under cluster enviroment for parallel computations via PYTHON scripts. We have interfaced HELAC-ONIA to the parton shower Monte Carlo programs PYTHIA 8 and QEDPS to take into account the parton-shower effects. Moreover, the decay module guarantees that the program can perform the spin-entangled (cascade-)decay of heavy quarkonium after its generation. We have also implemented a reweighting method to automatically estimate the uncertainties from renormalization and/or factorization scales as well as parton-distribution functions to weighted or unweighted events. A futher update is the possiblity to generate one-dimensional or two-dimensional plots encoded in the analysis files on the fly. Some dedicated examples are given at the end of the writeup.

QCD MODELS FOR HEAVY QUARKONIUM

- **Color-Singlet Model** (CSM) [Einhor, Ellis (1975) ...]
  - $Q\bar{Q}$ are produced in the CS state at scale .
- **Color-Evaporation Model** (CEM) [Fritzsch (1977) ...]
  - Under quark-hadron duality, $Q\bar{Q}$ are produced with their invariant mass less than the threshold of open-flavor heavy meson pair.
- **Fragmentation Function Approach** (FF) [Braaten et al. (1996) ...]
  - Cross section can be factorized in terms of convolutions of parton production cross section with FFs in limit of .
- **Non-relativistic QCD** (NRQCD) [Bodwin et al. (1995)]
  - An effective field theory based on factorization conjecture. $Q\bar{Q}$ can be produced in both of CS and CO states at scale .

NRQCD FACTORIZATION



- NRQCD factorization

$$d\sigma(pp \to H_{Q\bar{Q}} + X)$$
$$= \sum_n d\sigma(pp \to Q\bar{Q}[n] + X) \times \langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$$

- pQCD factorization

$$d\sigma(pp \to Q\bar{Q}[n] + X)$$
$$= \sum_{a,b} f_{a/p}(x_1) f_{b/p}(x_2) |\mathcal{A}(ab \to Q\bar{Q}[n] + X)|^2$$

- LDME $\langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$ and PDF $f_{i/p}(x)$ are non-perturbative and (should be) universal.

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BASICS

- Based on NRQCD framework.
- Based on off-shell recursion relations, i.e. Dyson-Schwinger equation.
- Closed fermion chain between QQ is cutted again to form new effective wavefunctions.
- P-wave currents are introduced to avoid numerical instability issue in P-wave production helicity amplitudes.

4 Benchmark processes

4.1 B_c meson production at the LHC

OVERVIEW OF (EARLY) BENCHMARKS

4 Benchmark processes

4.1 B_c meson production at the LHC

process	HELAC-Onia(nb)	MADONIA(nb)
$gg \to B_c^+({}^1S_0^{[1]})b\bar{c}$	39.3994 ± 0.0958382	39.4
$gg \to B_c^+({}^3S_1^{[1]})b\bar{c}$	98.3109 ± 0.287252	98.3
$gg \to B_c^+({}^1P_1^{[1]})b\bar{c}$	5.21131 ± 0.0144431	5.20
$gg \to B_c^+({}^3P_J^{[1]})b\bar{c}$	16.7341 ± 0.0589108	16.72
$gg \to B_c^+({}^1S_0^{[8]})b\bar{c}$	0.411671 ± 0.00169734	0.411
$gg \to B_c^+({}^3S_1^{[8]})b\bar{c}$	1.78657 ± 0.00624756	1.79
$gg \to B_c^+({}^1P_1^{[8]})b\bar{c}$	0.11816 ± 0.000754526	0.117
$gg \to B_c^+({}^3P_J^{[8]})b\bar{c}$	0.305862 ± 0.0011841	0.3051
$q\bar{q} \to B_c^+({}^1S_0^{[1]})b\bar{c}$	0.137782 ± 0.000896985	0.137
$q\bar{q} \to B_c^+({}^3S_1^{[1]})b\bar{c}$	0.83905 ± 0.00524885	0.834
$q\bar{q} \to B_c^+({}^1P_1^{[1]})b\bar{c}$	$0.0296125 \pm 0.000154919$	0.0295
$q\bar{q} \to B_c^+({}^3P_J^{[1]})b\bar{c}$	0.111259 ± 0.000839535	0.1105
$q\bar{q} \to B_c^+({}^1S_0^{[8]})b\bar{c}$	$0.00103294 \pm 4.44716 \cdot 10^{-6}$	0.00103
$q\bar{q} \to B_c^+({}^3S_1^{[8]})b\bar{c}$	$0.00707624 \pm 0.0000459292$	0.00703
$q\bar{q} \to B_c^+({}^1P_1^{[8]})b\bar{c}$	$0.000253678 \pm 2.19206 \cdot 10^{-6}$	0.000251
$q\bar{q} \to B_c^+({}^3P_J^{[8]})b\bar{c}$	$0.000826534 \pm 5.16988 \cdot 10^{-6}$	0.0008207

OVERVIEW OF (EARLY) BENCHMARKS

4 Benchmark processes

4.1 B_c meson production at the LHC

4.2 Charmonia production at the B factory

process	HELAC-Onia(fb)	Refs.[32, 3](fb)
$e^+e^- \to \gamma^* \to \eta_c({}^1S_0^{[1]})c\bar{c}$	58.7938 ± 0.154193	58.7
$e^+e^- \to \gamma^* \to \eta_c({}^1S_0^{[1]})ggg$	3.72893 ± 0.0063512	3.72
$e^+e^- \to \gamma^* \to J/\psi({}^3S_1^{[1]})c\bar{c}$	147.864 ± 0.305001	148
$e^+e^- \to \gamma^* \to J/\psi({}^3S_1^{[1]})gg$	266.037 ± 0.247366	266

process	HELAC-Onia(fb)	Ref.[34](fb)
$e^+e^- \to \eta_c({}^1S_0^{[1]})c\bar{c}$	61.6802 ± 0.0854359	–
$e^+e^- \to J/\psi({}^3S_1^{[1]})c\bar{c}$	166.499 ± 0.175318	–
$e^+e^- \to J/\psi({}^3S_1^{[1]})J/\psi({}^3S_1^{[1]})$	6.64805 ± 0.0123474	6.65
$e^+e^- \to J/\psi({}^3S_1^{[1]})h_c({}^1P_1^{[1]})$	$0.00606923 \pm 6.84416 \cdot 10^{-6}$	0.0061

OVERVIEW OF (EARLY) BENCHMARKS

4 Benchmark processes

4.1 B_c meson production at the LHC

4.2 Charmonia production at the B factory

4.3 Double quarkonia production at the Tevatron and the LHC

Final States	HELAC-Onia(nb)	Ref.[35](nb)
$2\eta_c(^1S_0^{[1]})$	$3.316 \cdot 10^{-3} \pm 3.705 \cdot 10^{-6}$	$3.32 \cdot 10^{-3}$
$2J/\psi(^3S_1^{[1]})$	$0.05631 \pm 4.437 \cdot 10^{-5}$	0.0563
$2\eta_b(^1S_0^{[1]})$	$1.866 \cdot 10^{-5} \pm 2.385 \cdot 10^{-8}$	$1.87 \cdot 10^{-5}$
$2\Upsilon(^3S_1^{[1]})$	$1.226 \cdot 10^{-4} \pm 1.489 \cdot 10^{-7}$	$1.23 \cdot 10^{-4}$
$B_c(^1S_0^{[1]})\overline{B}_c(^1S_0^{[1]})$	$3.854 \cdot 10^{-3} \pm 9.529 \cdot 10^{-6}$	$3.86 \cdot 10^{-3}$
$B_c(^1S_0^{[1]})\overline{B}_c(^3S_1^{[1]})$	$1.001 \cdot 10^{-3} \pm 2.492 \cdot 10^{-6}$	$1.00 \cdot 10^{-3}$
$B_c(^3S_1^{[1]})\overline{B}_c(^3S_1^{[1]})$	$8.226 \cdot 10^{-3} \pm 9.531 \cdot 10^{-6}$	$8.23 \cdot 10^{-3}$

4 Benchmark processes

4.1 B_c meson production at the LHC

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4.3 Double quarkonia production at the Tevatron and the LHC

4.4 Hadroproduction of J/ψ and Υ in association with a heavy-quark pair

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4.5 Spin density matrix and polarization

OVERVIEW OF (EARLY) BENCHMARKS

4 Benchmark processes

4.1 B_c meson production at the LHC

4.2 Charmonia production at the B factory

One or more S-wave and P-wave quarkonium(a) tree-level helicity amplitudes in NRQCD

4.4 Hadroproduction of J/ψ and Υ in association with a heavy-quark pair

4.5 Spin density matrix and polarization

NEW DEVELOPMENTS IN VERSION 2.0

- More user-friendly interface

MadGraph5_aMC@NLO **Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (2014)**	**HELAC-Onia 2.0**
./bin/mg5 > generate p p > t t~ [QCD] > output pp2ttx > launch	./ho_cluster > generate g g > cc~(3S11) cc~(3S11) > launch

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./bin/mg5	./ho_cluster
> generate p p > t t~ [QCD]	> generate g g > cc~(3S11) cc~(3S11)
> output pp2ttx	> launch
> launch	

Computing a cross section from scratch only requires 2-3 commands !!

- Decay module
  - Guarantee spin-correlations in heavy quarkonium decay chains.
  - For example, $\chi_c \to J/\psi + \gamma \to \ell^+\ell^- + \gamma$
    - Considering the helicity amplitude for the decay process is $\mathcal{A}(\mathbf{x})$, where $\mathbf{x}$ is the set of variables to characterize the kinematics.
    - The maximal weight of $|\mathcal{A}(\mathbf{x})|^2$ is $W_{\rm max}$.
    - Randomly generate a phase space point $\mathbf{x}$.
    - Uniformly generate a random number $r \in [0,1]$. If $|\mathcal{A}(\mathbf{x})|^2 > r \times W_{\rm max}$, the event corresponding to $\mathbf{x}$ is retained. Otherwise, go to the former step.
  - Could be extended to $Z/H \to J/\psi + \gamma \to \mu^+\mu^- + \gamma$ (see next talk)

NEW DEVELOPMENTS IN VERSION 2.0

- Shower module
    - Interface to external parton shower Monte Carlo programs.

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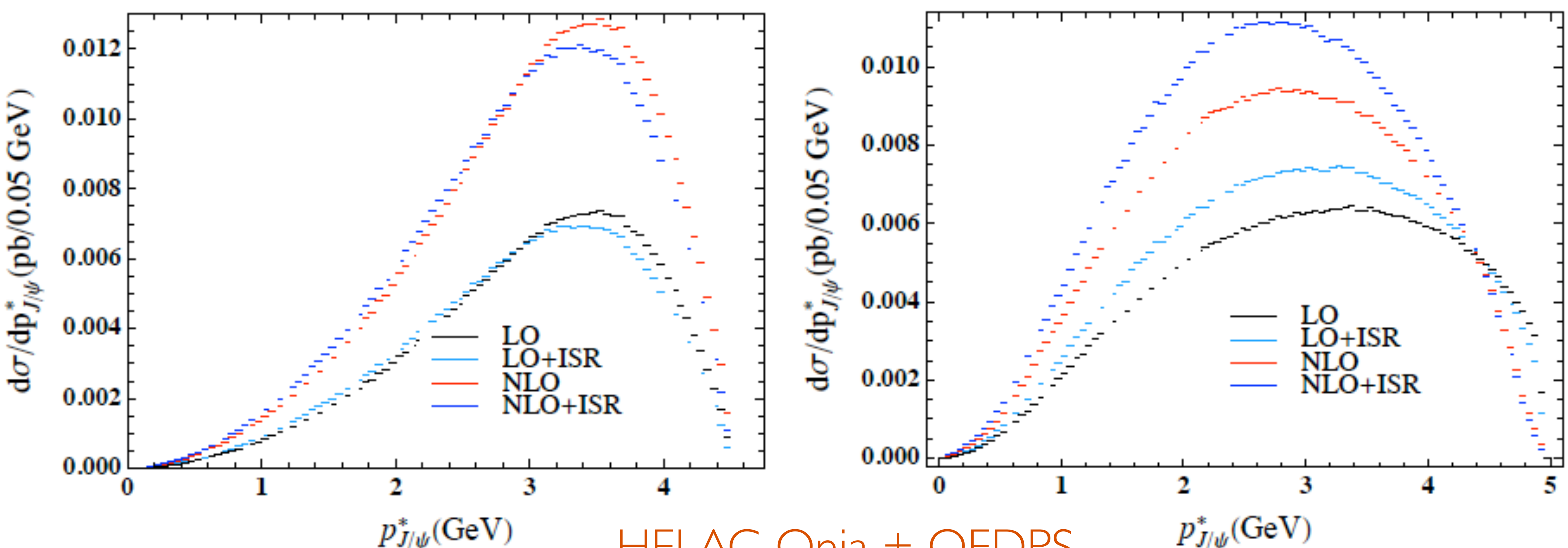
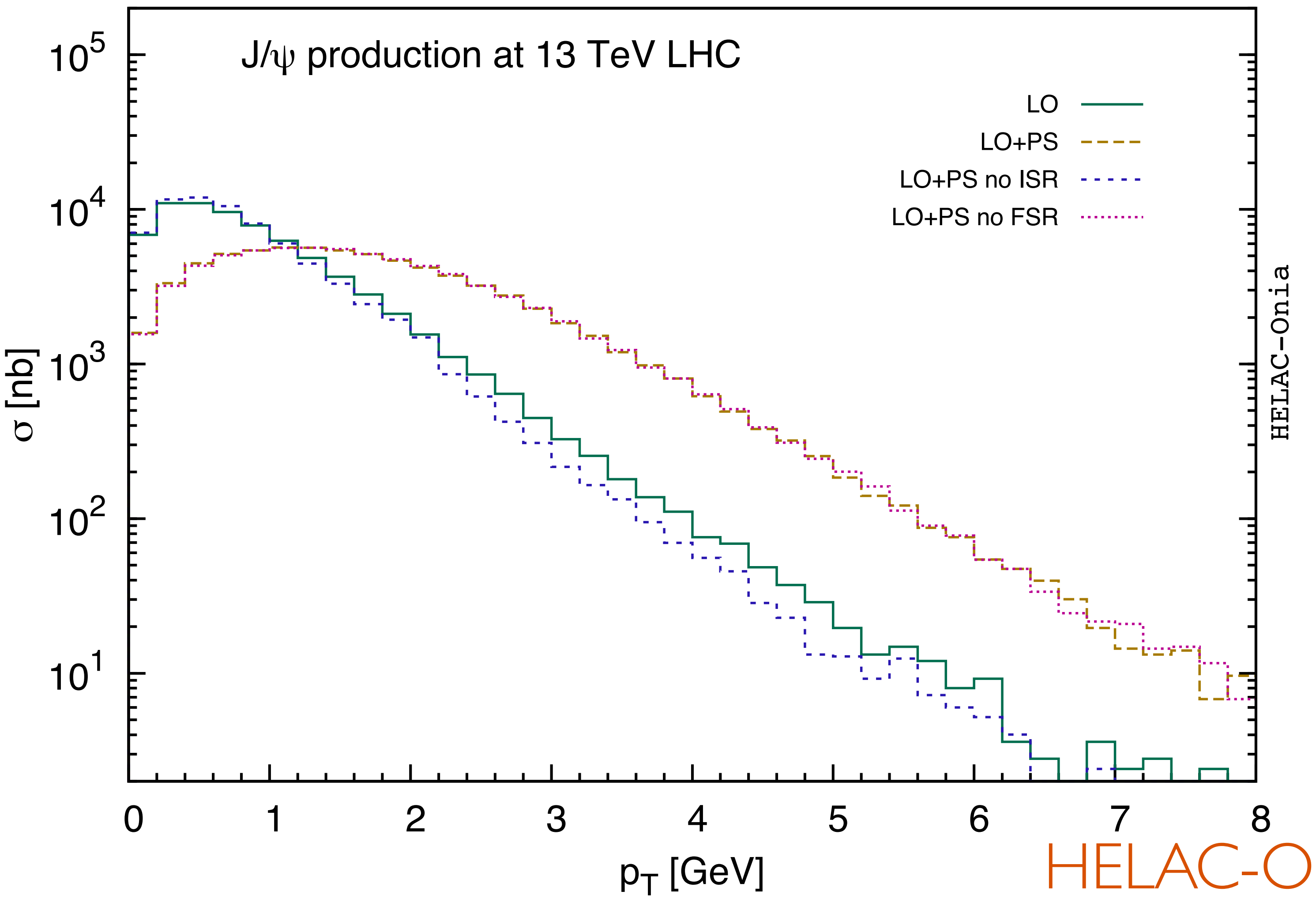
HSS (2014)

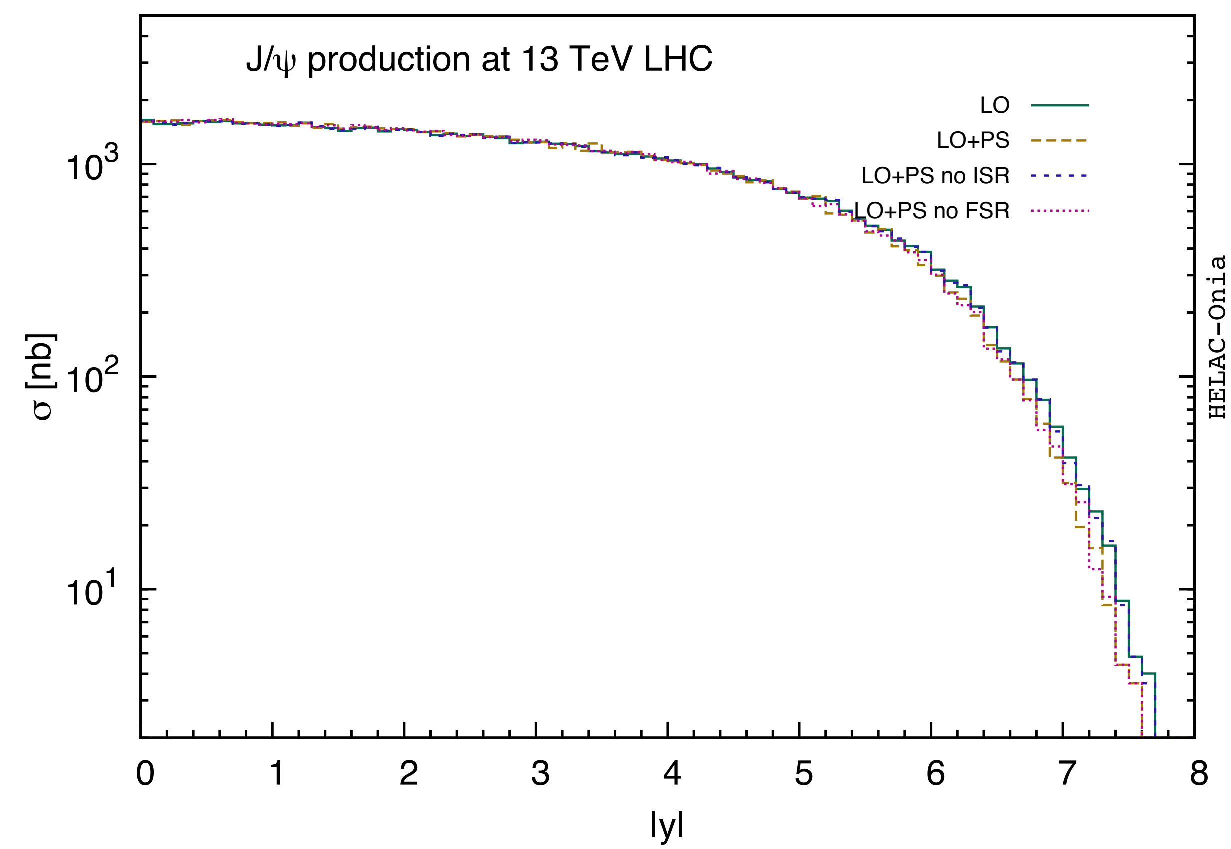


HELAC-Onia + QEDPS

NEW DEVELOPMENTS IN VERSION 2.0

- Shower module
  - Interface to external parton shower Monte Carlo programs.





HELAC-Onia + Pythia8

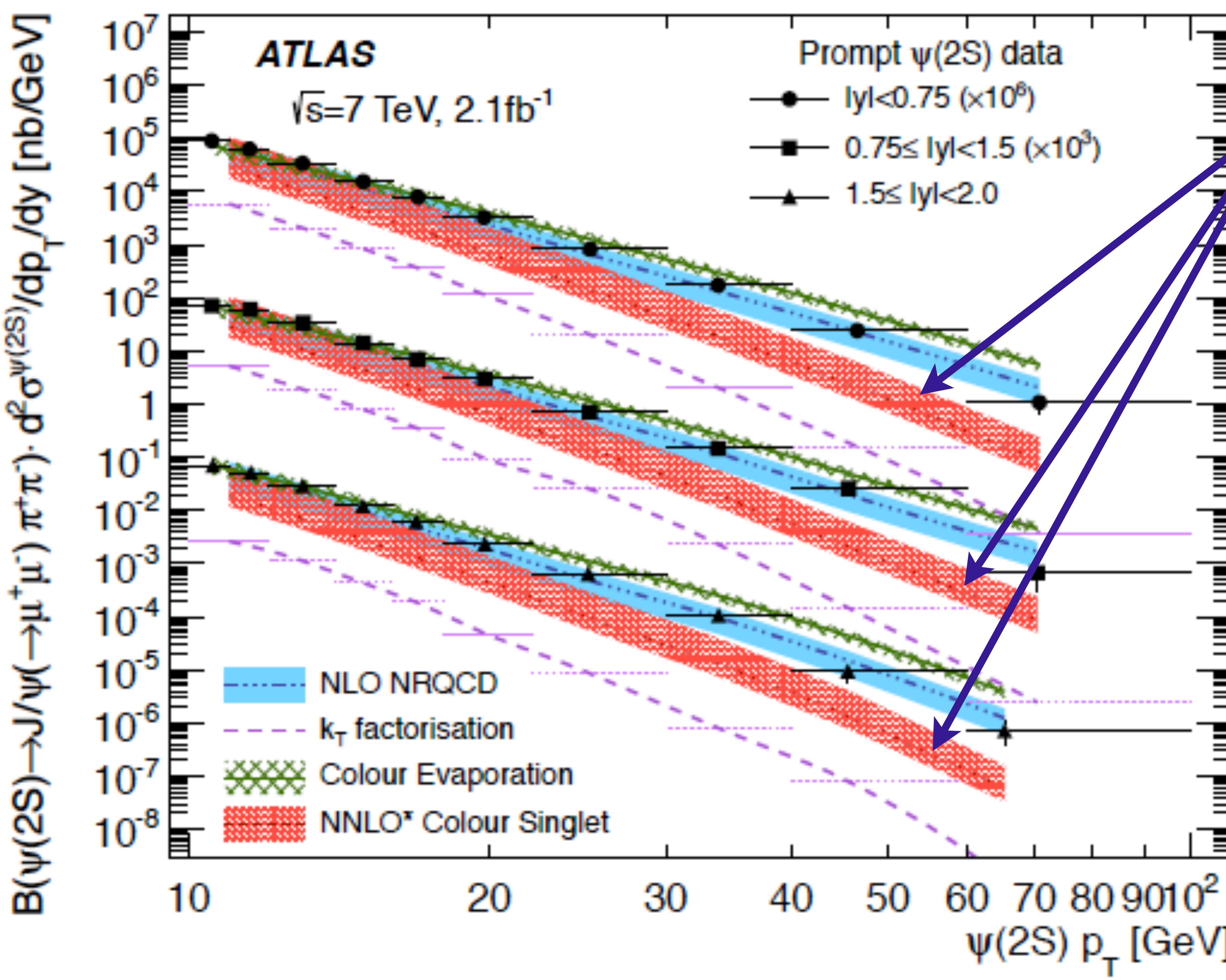
- Big ISR shower effect on transverse momentum distribution.
  - To do: comparison with TMD predictions (see Lansberg's talk tomorrow)
- Small effect on rapidity distribution.

NEW DEVELOPMENTS IN VERSION 2.0

- Analysis module
  - Generating topdrawer, gnuplot, root files on the fly. One-dimensional or two-dimensional distributions.
- Reweighting method is applied to estimate scale and PDF uncertainties on the fly.
- Addon codes
  - For example, double parton scattering for double psi production.
- In plan:
  - Fragmentation function module
  - TMD module etc

HIGHEST-MULTIPLICITY PROCESSES: NNLO* QCD CORRECTIONS

ATLAS Collaboration (2014)



- NNLO* QCD correction.

- First done by MadOnia [Artoisenet, Lansberg, Maltoni (2007)].
- The first 2 > 4 process with at least one quarkonium.
- HELAC-Onia reproduce the MadOnia result between 10-40 GeV.

HIGHEST-MULTIPLICITY PROCESSES: NNLO* QCD CORRECTIONS

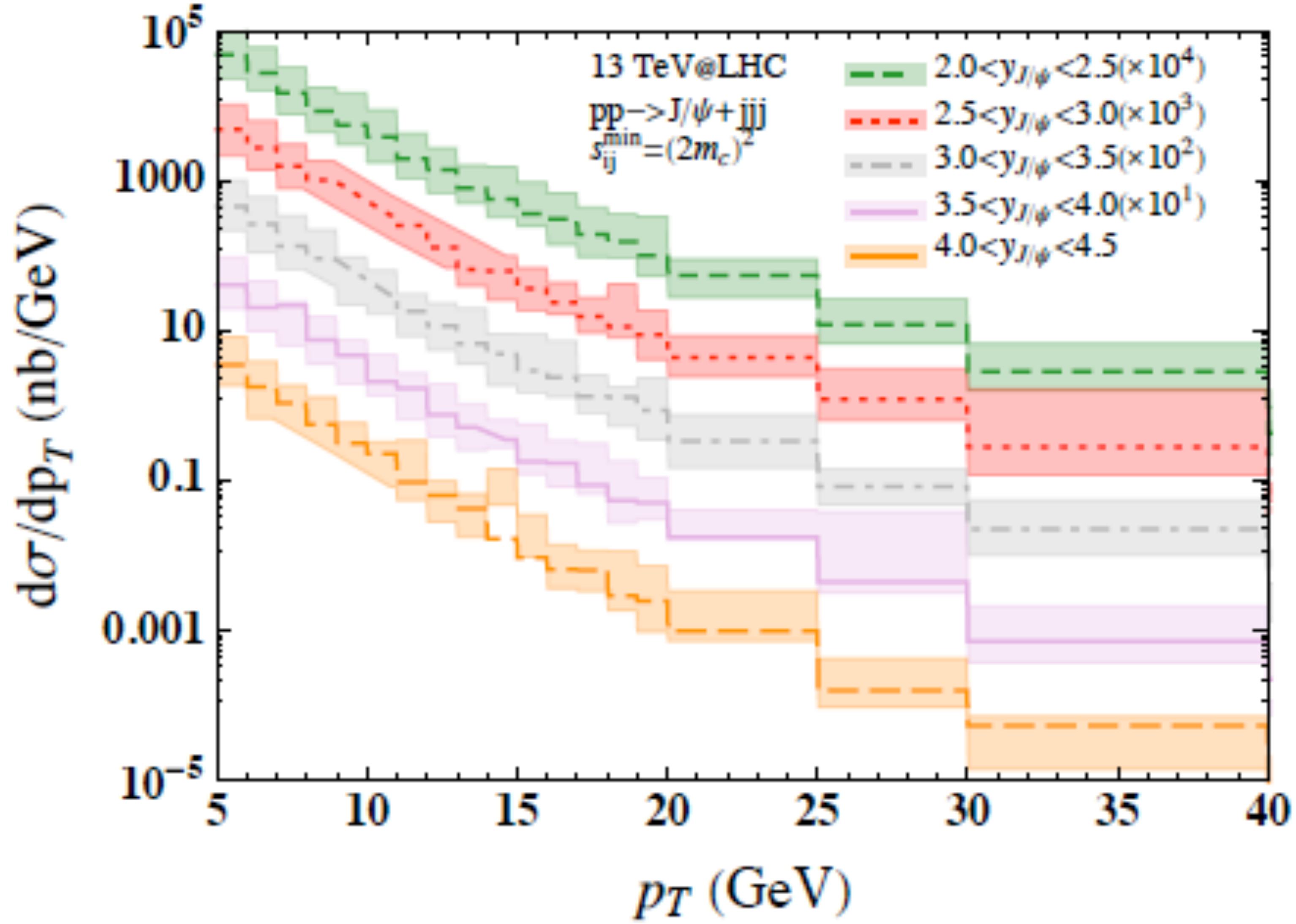


Figure 1: The transverse momentum distributions of J/ψ from $pp \to J/\psi + jjj$ in the LHCb acceptance at 13 TeV.

HELAC–Onia

```
HO> generate g g > cc~(3S11) g g g
HO> generate g g > cc~(3S11) u u~ g
HO> generate u g > cc~(3S11) g g u
HO> generate g u > cc~(3S11) g g u
HO> generate u g > cc~(3S11) u u~ u
HO> generate g u > cc~(3S11) u u~ u
HO> generate u g > cc~(3S11) d d~ u
HO> generate g u > cc~(3S11) d d~ u
HO> generate u u~ > cc~(3S11) g g g
HO> generate u u~ > cc~(3S11) u u~ g
HO> generate u u~ > cc~(3S11) d d~ g
HO> generate u u > cc~(3S11) u u g
HO> generate u d > cc~(3S11) u d g
```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HIGHEST-MULTIPLICITY PROCESSES: P P > PSI+PSI+CC

Lansberg, HSS (2014)

```
HO> generate g g > cc~(3S11) cc~(3S11) c c~
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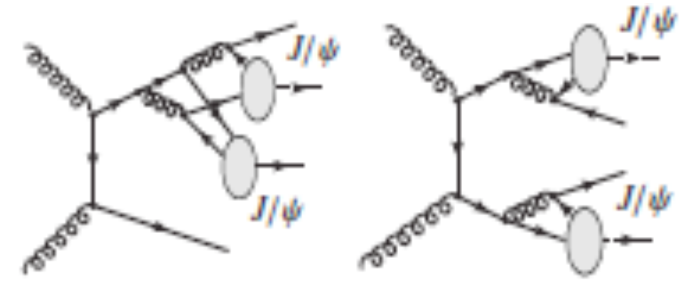

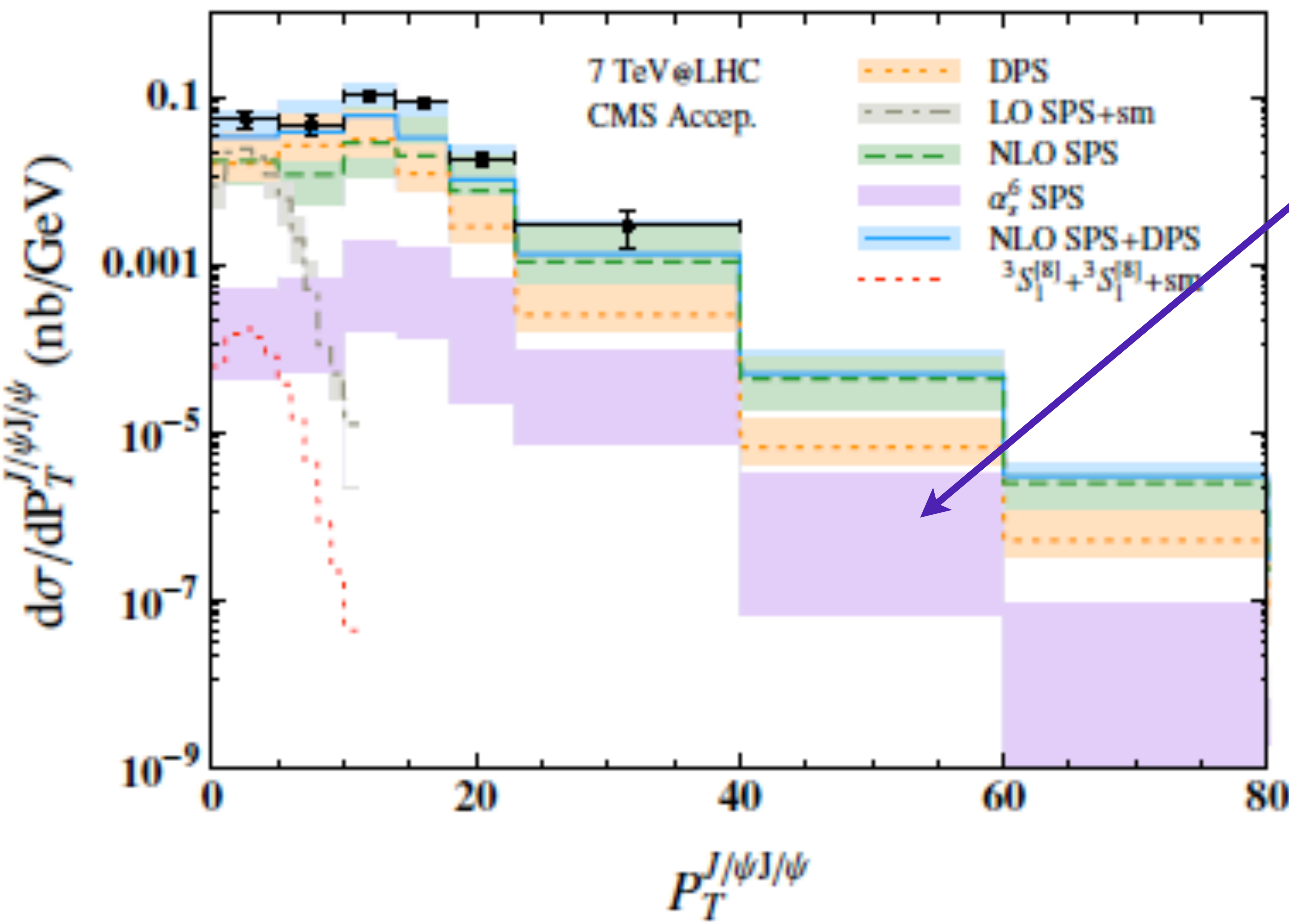

- NNLO level process for double psi production.
- The first 2 > 4 process with at least two quarkonia.
- Satisfactory accuracy achieved for all plots within one week on single core.

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CONCLUSION & OUTLOOK

- HELAC-Onia is an user-friendly public tool to study heavy quarkonium physics in an automatic way.
- Based on recursion relation, it can be applied to high-multiplicity processes with relatively lower computational cost.
- It provides a simulation tool for one or more S-wave and/or P-wave heavy quarkonia production based on tree-level helicity amplitudes.
- To do:
  - Ongoing developments to meet various application purposes.
    - e.g. TMD, exclusive process ? (See L. Szymanowski's talk tomorrow)
  - Generalize to higher-order (e.g. NLO QCD correction).
  - Is there a specific motivation to extend to BSM ? for B-physics ? for Baryon production ?