Tools and methods for quarkonium physics

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GDR Terascale,
LPNHE, Paris, November 24, 2016

* **Thanks a lot to Hua-Sheng Shao. Also based on slides by P. Artoisenet**

Part I

Introduction

Approaches to Quarkonium Production

See EPJC (2016) 76:107 for a recent review

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  2. Colour Singlet Model: hadronisation without gluon emission each emission costs $\alpha_s(m_Q)$ and occurs at short distances
  3. Colour Octet Mechanism (encapsulated in NRQCD): higher Fock states of the mesons taken into account; $Q\bar{Q}$ can be produced in octet states with different quantum # as the meson

CEM vs. CSM vs. COM

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1. Colour Evaporation Model
   - any $Q\bar{Q}$ state contributes to a specific quarkonium state
   - colourless final state via a simple 1/8 factor
   - one non-pertubative parameter per meson, supposedly universal

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   - this parameter is fixed by the decay width or potential models and by heavy-quark spin symmetry (HQSS)

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3. Colour Octet Mechanism
   - one non-perturbative parameter per Fock States
   - expansion in v^2; series can be truncated
   - the phenomenology partly depends on this
   - HQSS relates some non-perturbative parameters to each others and to a specific quarkonium polarisation

Public multi-process matrix-element/event Generators

without onia	*with onia*
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 *NLO* • MG5_aMC Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro • HELAC-NLO Bevilacqua, Czakon, Garzelli, Hameren, Kardos, Papadopoulos, Pittau, Worek • GoSam Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano • OpenLoops, Recola ...	*LO* • MadOnia Artoisenet, Maltoni, Stelzer • HELAC-Onia Shao • ... *NLO* • ??? *Single process; not automatised* • BcVEGPY (for B(c)) Chang, Wang (XG),... • FDC (NLO) Wang (JX),...

What for : new observables

Observables	Experiments	CSM	CEM	NRQCD	Interest
J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CS dominant) + DPS
J/ψ+D	LHCb	LO	LO ?	LO	Prod. Mechanism (c to J/psi fragmentation) + DPS
J/ψ+ϒ	D0	(N)LO	LO ?	LO	Prod. Mechanism (CO dominant) + DPS
J/ψ+hadron	STAR	LO	--	LO	B feed-down; Singlet vs Octet radiation
J/ψ+Z	ATLAS	NLO	NLO	Partial NLO	Prod. Mechanism + DPS
J/ψ+W	ATLAS	LO	LO ?	Partial NLO	Prod. Mechanism (CO dominant) + DPS
J/ψ vs mult.	ALICE,CMS (+UA1)	--	--	--	
J/ψ+b	-- (LHCb, D0, CMS ?)	--	--	LO	Prod. Mechanism (CO dominant) + DPS
ϒ+D	LHCb	LO	LO ?	LO	DPS
ϒ+γ	--	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CO LDME mix) + gluon TMD/PDF
ϒ vs mult.	CMS	--	--	--	
ϒ+Z	--	NLO	LO ?	LO	Prod. Mechanism + DPS
ϒ+ϒ	CMS	NLO ?	LO ?	LO ?	Prod. Mechanism (CS dominant ?) + DPS

Part II

MadOnia†

† Most slides from a presentation by P. Artoisenet

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Automatic generation of quarkonium amplitudes in NRQCD

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Abstract: We present a simple method to automatically evaluate arbitrary tree-level amplitudes involving the production or decay of a heavy quark pair $Q\bar{Q}$ in a generic ${}^{2S+1}L_J^{[1,8]}$, S- or P-wave state, i.e., the leading short distance coefficients appearing in the NRQCD factorization formalism. Our approach is based on extracting the relevant contributions from the open heavy quark-antiquark amplitudes through an expansion with respect to the quark-antiquark relative momentum and the application of suitable color and spin projectors. To illustrate the capabilities of the method and its implementation in MadGraph a few applications to quarkonium collider phenomenology are presented.

JHEP02(2008)102

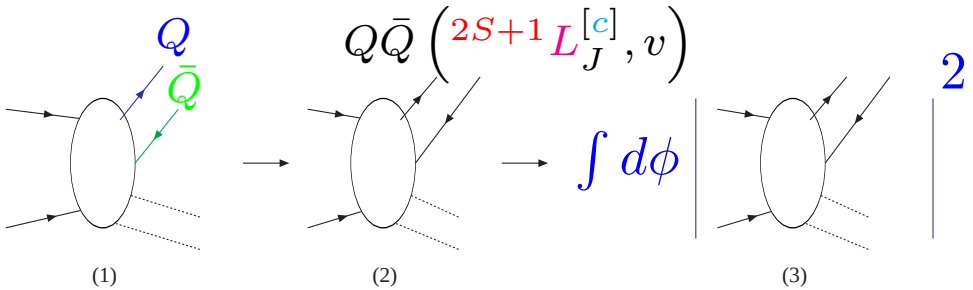
Introduction: the purpose of MadOnia

- expression of cross sections within NRQCD:

$$\sigma(ij \to \mathcal{Q} + X) \quad = \quad \sum_n \hat{\sigma}(ij \to Q\bar{Q}(n) + X)\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle_\Lambda$$

  - $\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle$ is the long distance matrix element
  - $\hat{\sigma}(i + j \to Q\bar{Q}(n) + X)$ is the short distance cross section

- MadOnia: automatic tree-level computation of $\hat{\sigma}(ij \to Q\bar{Q}(n) + X)$



(1) open quark amplitude (MadGraph)

(2) projected amplitude (MadOnia)

(3) phase-space integration (unweighting $\longrightarrow$ MC event generator)

Capabilities and Validation

- validation:
  - gauge invariance has been checked
  - charge conjugation conservation:

$$
\begin{aligned}
A({}^1S_0^{[1]} + (2k+1)\gamma) &= 0 \\
A({}^3S_1^{[1]} + (2k)\gamma) &= 0 \\
A({}^1P_1^{[1]} + (2k)\gamma) &= 0 \\
A({}^3P_1^{[1]} + (2k)\gamma) &= 0 \\
A({}^3P_{0,2}^{[1]} + (2k+1)\gamma) &= 0
\end{aligned}
$$

  - comparison with analytical amplitudes point by point in the phase space

$$ij \to \mathcal{Q}k$$

with i, j, k = quarks or gluons, for all S- and P-wave states, colour-singlet and colour-octet transitions

Illustration

- example: B_c production from e^+e^-
  - enter the process: fill the input file proc_card.dat

```
# Begin PROCESS # This is TAG. Do not modify this line

e+e->bc~cb~[3S11]   @0        # First Process
QCD=99              # Max QCD couplings
QED=2               # Max QED couplings
end_coup            # End the couplings input

e+e->bc~cb~[1S01]   @1        # Second Process
QCD=99              # Max QCD couplings
QED=2               # Max QED couplings
end_coup            # End the couplings input

done                # this tells MG there are no more procs

# End PROCESS  # This is TAG. Do not modify this line
#*************************************************************
# Model information
#*************************************************************
# Begin MODEL  # This is TAG. Do not modify this line
sm
# End   MODEL  # This is TAG. Do not modify this line
```

Illustration

- example: B_c production from e^+e^-
  - Output:
    MadOnia generates a fortran code that gives the squared matrix element summed/averaged over polarization degrees of freedom at an arbitrary phase-space point:

$$\frac{1}{4}\sum_{\lambda_1,\ldots,\lambda_5}|M(e^+(p_1)e^-(p_2)\to b(p_3)\bar{c}(p_4)B_c(p_5))|^2$$

Illustration

- interface with a phase-space generator to produce cross sections
  - B_c production via colour-singlet transitions (σ in fb)

	$^1S_0[1]$	$^3S_1[1]$	$^1P_1[1]$	$^3P_0[1]$	$^3P_1[1]$	$^3P_2[1]$
$e^+e^-@m_Z$	$1.58\,10^3$	$2.25\,10^3$	$1.72\,10^2$	$1.00\,10^2$	$2.09\,10^2$	$2.25\,10^2$
$\gamma\gamma$@LEP II	0.513	5.17	0.160	$2.66\,10^{-2}$	$5.74\,10^{-2}$	0.263
γp@HERA	356	$1.17\,10^3$	83.1	21.2	50.4	197
pp@LHC	$3.93\,10^7$	$9.82\,10^7$	$5.21\,10^6$	$1.79\,10^6$	$4.40\,10^6$	$1.06\,10^7$
$p\bar{p}$@Tev II	$2.54\,10^6$	$6.47\,10^6$	$3.29\,10^5$	$1.24\,10^5$	$2.87\,10^5$	$6.81\,10^5$

  - B_c production via colour-octet transitions (σ in fb)

	$^1S_0[8]$	$^3S_1[8]$	$^1P_1[8]$	$^3P_0[8]$	$^3P_1[8]$	$^3P_2[8]$
e^+e^-	1.64	2.31	0.162	0.105	0.217	0.235
$\gamma\gamma$	$5.38\,10^{-4}$	$5.42\,10^{-3}$	$1.69\,10^{-4}$	$2.83\,10^{-5}$	$6.04\,10^{-5}$	$2.77\,10^{-4}$
γp	1.15	8.25	0.494	$7.45\,10^{-2}$	0.238	1.57
pp	$4.20\,10^5$	$1.88\,10^6$	$1.19\,10^5$	$1.37\,10^4$	$6.20\,10^4$	$2.24\,10^5$
$p\bar{p}$	$2.86\,10^4$	$1.27\,10^5$	$8.13\,10^3$	$9.82\,10^2$	$4.24\,10^3$	$1.56\,10^4$

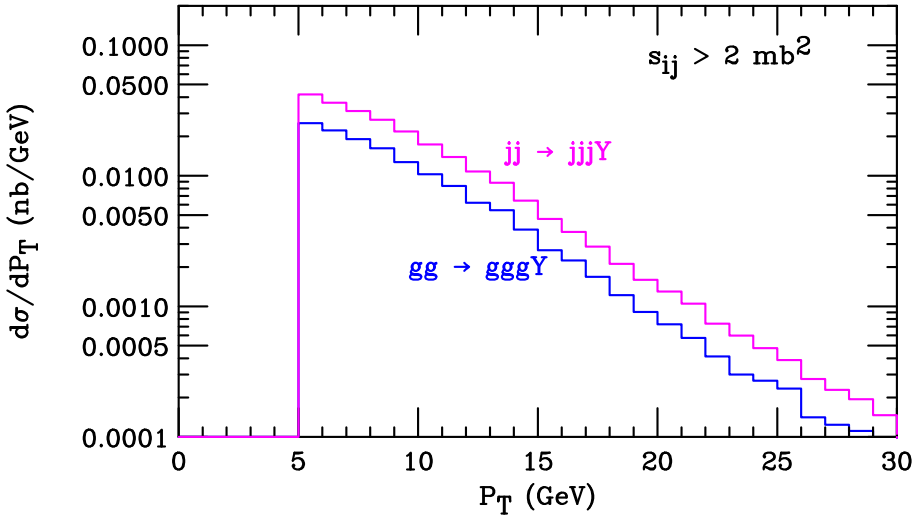
TIMING: 5' to enter all processes in the input card, 2 hours of run

- Υ + 3 jets production at the Tevatron

subprocesses:

dg_uuxdbbx3S11	gd_uuxdbbx3S11	gu_uuuxbbx3S11	ug_uddxbbx3S11	uux_uuxgbbx3S11
uxu_ddxgbbx3S11	du_udgbbx3S11	gdx_uuxdxbbx3S11	gux_uuxuxbbx3S11	ug_uggbbx3S11
uxd_uxdgbbx3S11	uxu_gggbbx3S11	dux_uxdgbbx3S11	gg_gggbbx3S11	gux_uxddxbbx3S11
ug_uuuxbbx3S11	uxdx_uxdxgbbx3S11	uxu_uuxgbbx3S11	dxg_uuxdxbbx3S11	gg_uuxgbbx3S11
gux_uxggbbx3S11	uu_uugbbx3S11	uxg_uuxuxbbx3S11	uxux_uxuxgbbx3S11	dxu_udxgbbx3S11
gu_uddxbbx3S11	ud_udgbbx3S11	uux_ddxgbbx3S11	uxg_uxddxbbx3S11	dxux_uxdxgbbx3S11
gu_uggbbx3S11	udx_udxgbbx3S11	uux_gggbbx3S11	uxg_uxggbbx3S11	

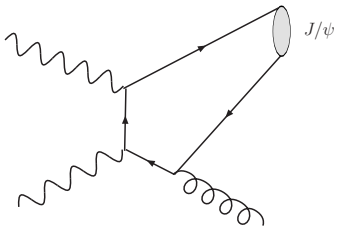
$\approx$ 2000 Feynman diagrams (reduced by a factor $\frac{1}{4}$ after the colour and spin projection are applied)

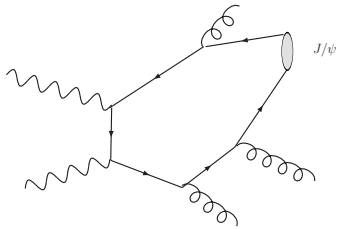


- J/ψ production from $\gamma\gamma$ collisions (Lep II, $\sqrt{s} = 196$ GeV)

$\gamma\gamma \to gJ/\psi(^3S_1[8])$ v.s. $\gamma\gamma \to gggJ/\psi(^3S_1[1])$

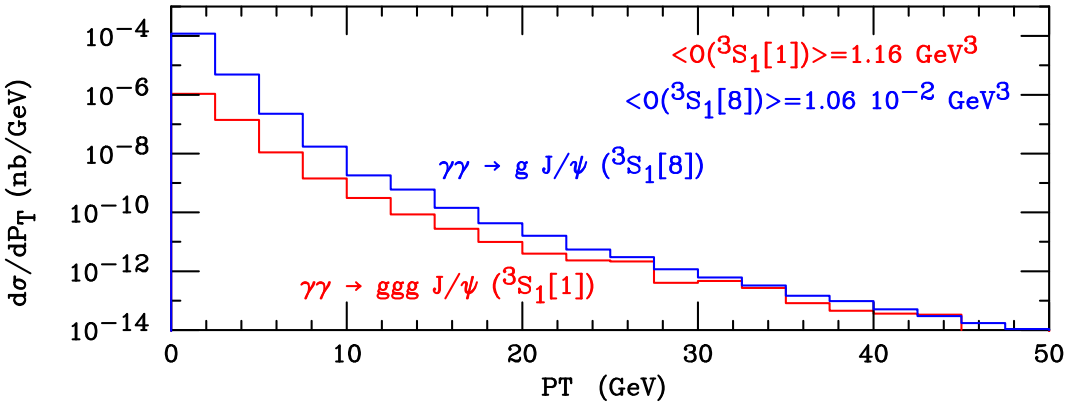
$\downarrow$ $\downarrow$





6 Feynman diagrams

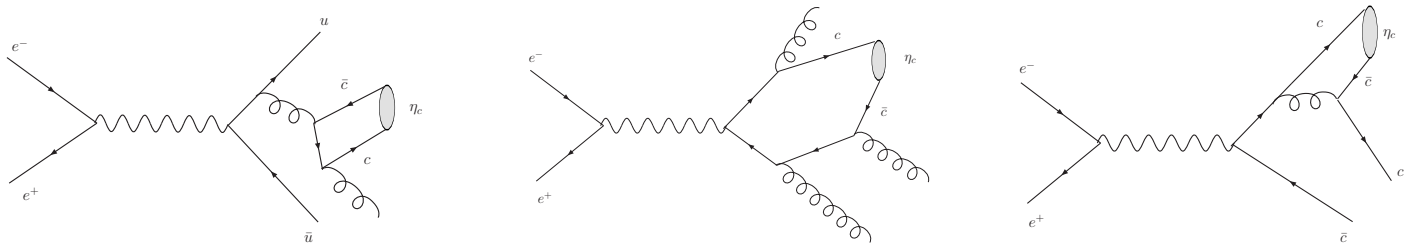
120 Feynman diagrams

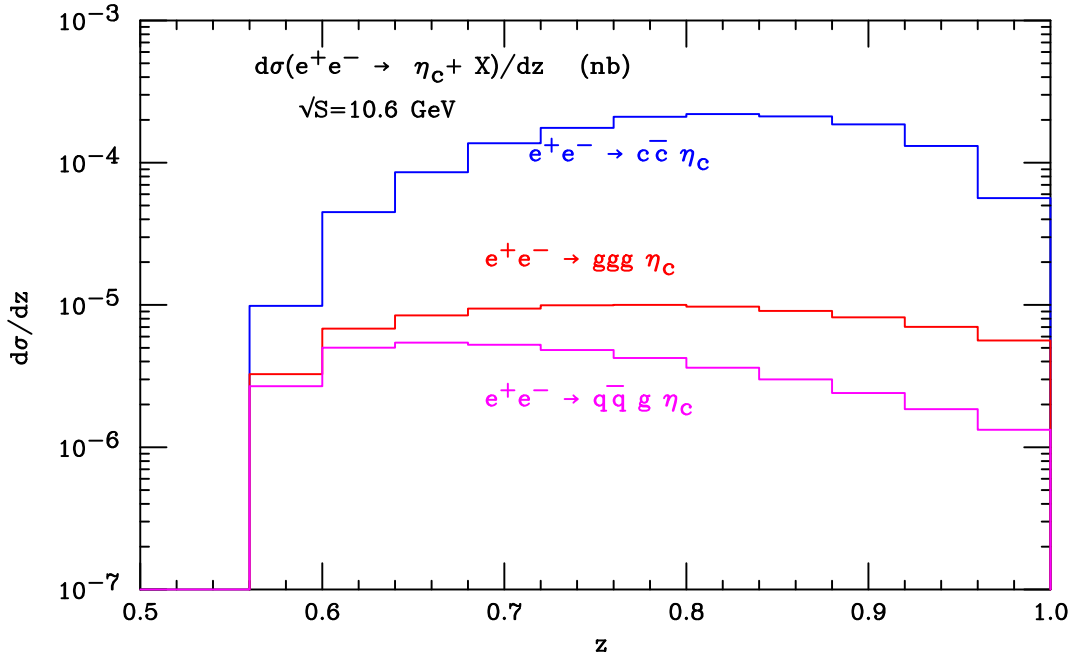


- $e^+e^- \to \eta_c + X$ @ 10.6 GeV

subprocesses:

$e^+e^- \to \eta_c q\bar{q}g$ $\quad$ $e^+e^- \to \eta_c ggg$ $\quad$ $e^+e^- \to \eta_c c\bar{c}$





$\sigma(\eta_c c\bar{c}) = 58.7$ fb

$\sigma(\eta_c ggg) = 3.72$ fb

$\sigma(\eta_c gq\bar{q}) = 1.63$ fb

Remarks:

$\sigma(J/\psi c\bar{c}) = 148$ fb

$\sigma(J/\psi gg) = 266$ fb

Summary about MadOnia

- Possibility to look at the quarkonium polarisation
- Possibility to generate LHE files (→ Pythia)
- Interfaced with LHAPDF
- Tuned version to compute NNLO* cross sections
- Possibility to include photon fluxes from ion collisions
- Available in MG4 (not anymore via the web interface, it seems)

Part III

HELAC-Onia

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journal homepage: www.elsevier.com/locate/cpc

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

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Phase space and event simulation
Quantum chromodynamics
Lattice gauge theory

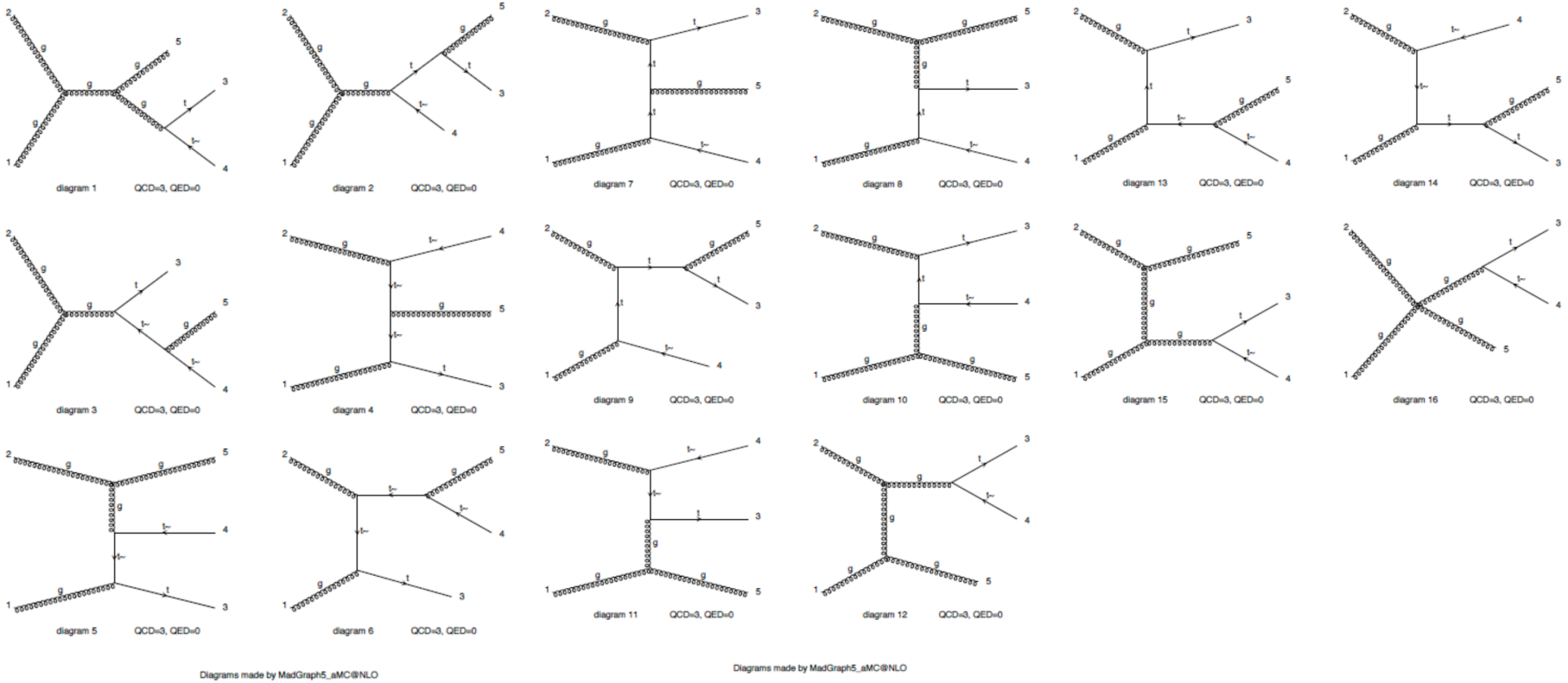
ABSTRACT

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 environment 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 further update is the possibility 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.

Generic method

off-shell recursion relations.

- Example : g g > t t~ g (16 Feynman diagrams)



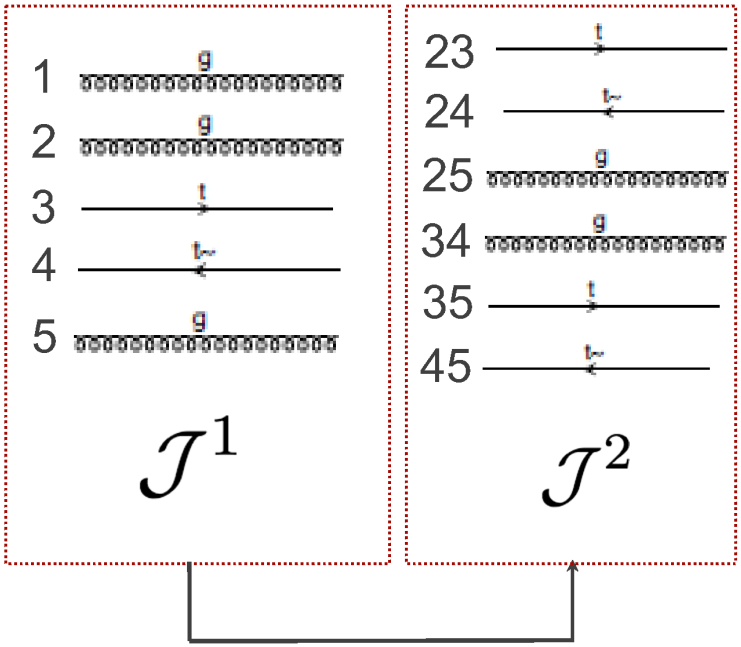
# of matrix calculations = 5 external WFs + (16*3-1) vertices = 52

Generic method

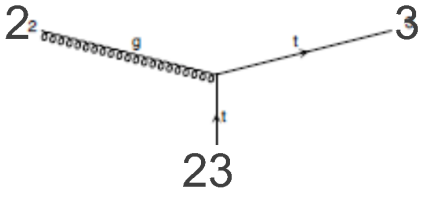
off-shell recursion relations.

- Example : g g > t t~ g (16 Feynman diagrams)

5 + 6



$\mathcal{J}^2 = \mathcal{J}^1 + \mathcal{J}^1$ e.g.

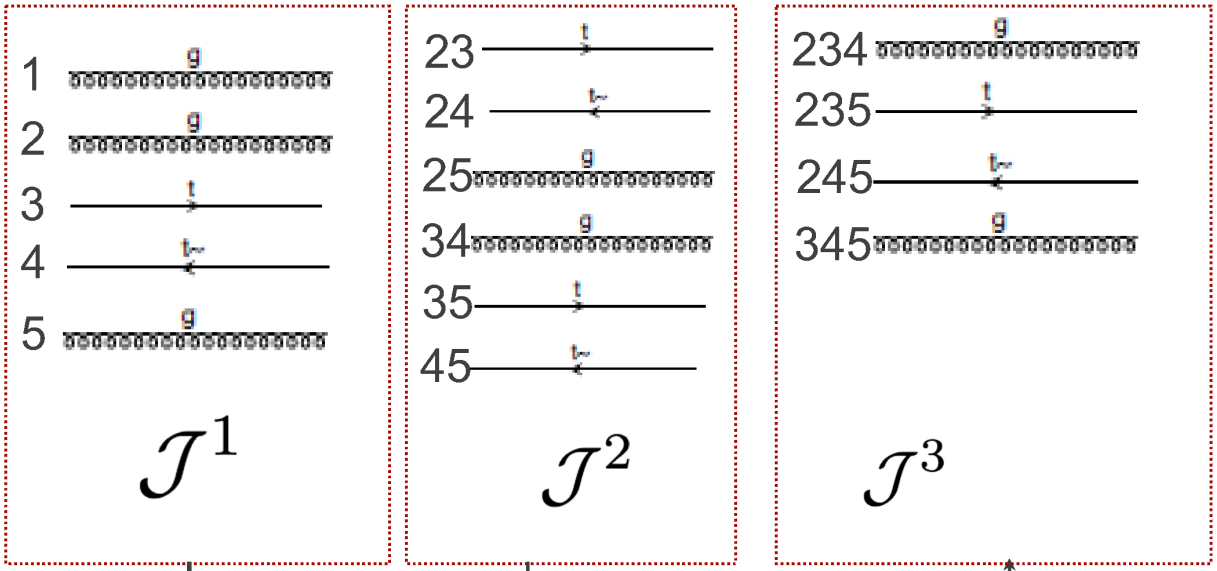


Generic method

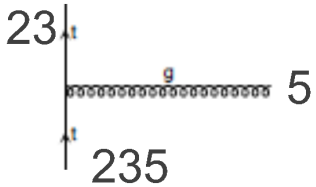
off-shell recursion relations.

- Example : g g > t t~ g (16 Feynman diagrams)

5 + 6 + 4 x 3



$\mathcal{J}^3 = \mathcal{J}^2 + \mathcal{J}^1$ e.g.



$\mathcal{J}^3 = \mathcal{J}^1 + \mathcal{J}^1 + \mathcal{J}^1$

no 4-pt vertex because there are only 2 gluons at level 1

Generic method

off-shell recursion relations.

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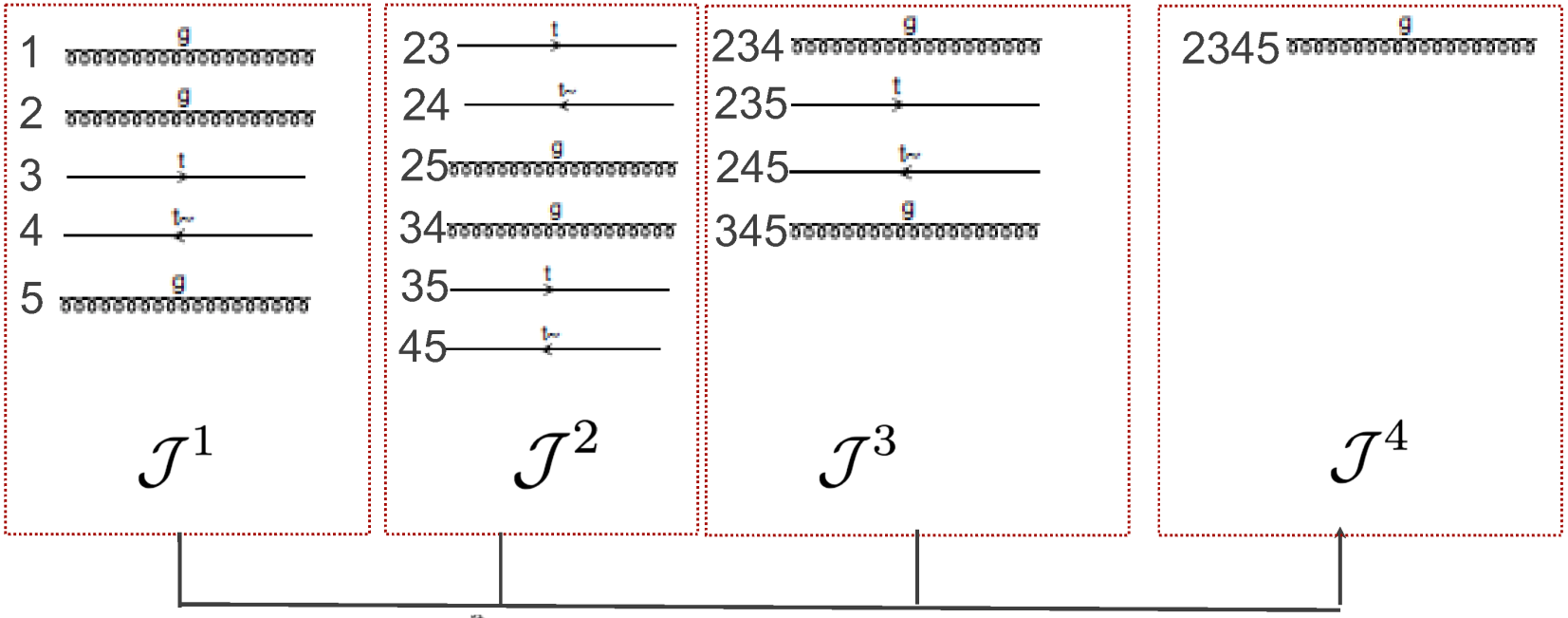
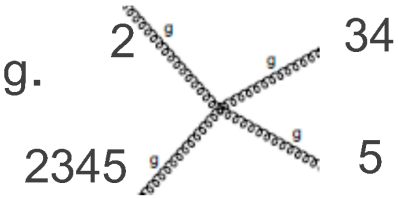
5 + 6 + 4*3 + (4+3+1)



$\mathcal{J}^4 = \mathcal{J}^2 + \mathcal{J}^1 + \mathcal{J}^1$ e.g.



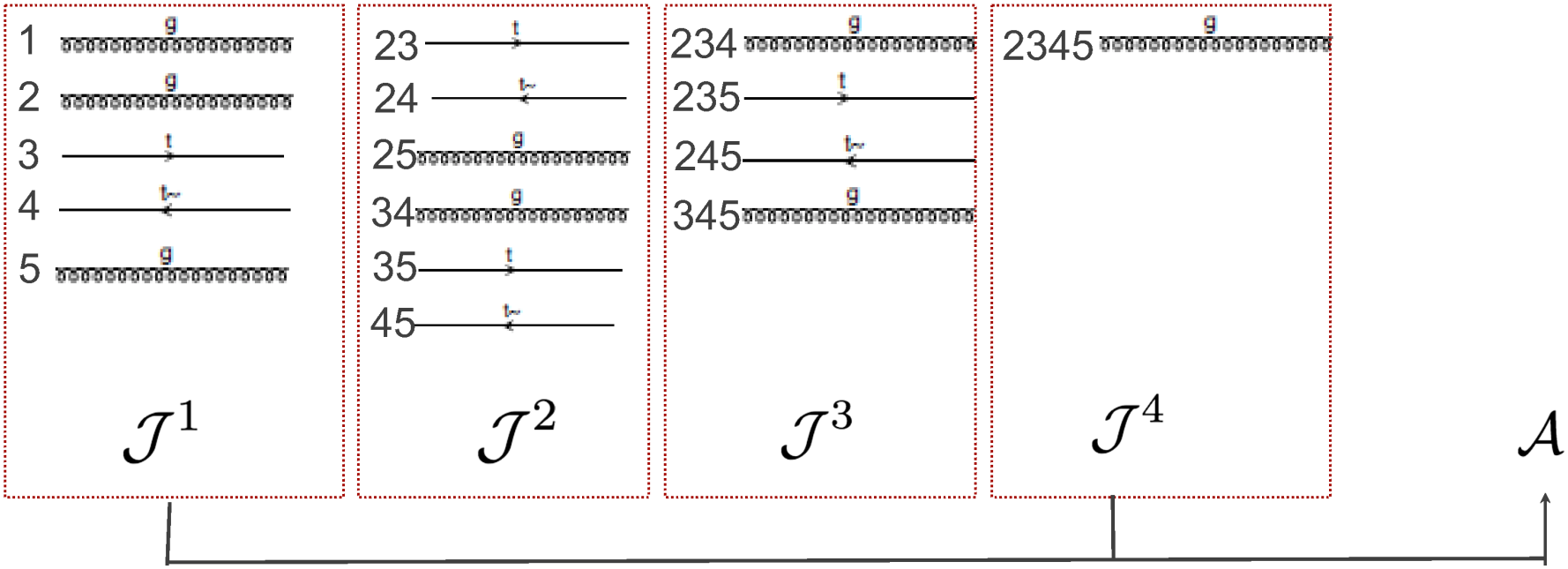
$\mathcal{J}^4 = \mathcal{J}^1 + \mathcal{J}^1 + \mathcal{J}^1 + \mathcal{J}^1$ no 5-pt vertex in QCD

Generic method

off-shell recursion relations.

- Example : g g > t t~ g (16 Feynman diagrams)

5 + 6 + 4*3 + (4+3+1) + 1 = 32



32 < 52 !!!

$$\mathcal{A} = \mathcal{J}^4 + leg\ 1$$

a^n < n! with large n=# of external legs

A few keywords

- One or more S- and P-wave onium tree-level helicity amplitude in NRQCD
- Color: octet and singlet
- Currently restricted to SM: possible for BSM extension
- Unique opportunity to produce multiple onia
- Event generation
- Yields and polarisations
- Spin-entangled decays
- Interface to parton shower Monte Carlo programs
- Automatically take into account multiple transitions
- Proton-nucleus collisions

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	./ho_cluster
> generate p p > t t~ [QCD]	> generate p p > psi psi
> output pp2ttx	> launch
> launch	

NEW DEVELOPMENTS IN VERSION 2.0

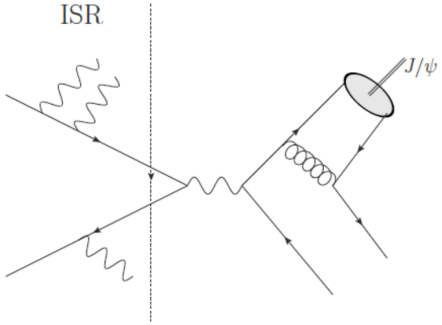
- Decay module

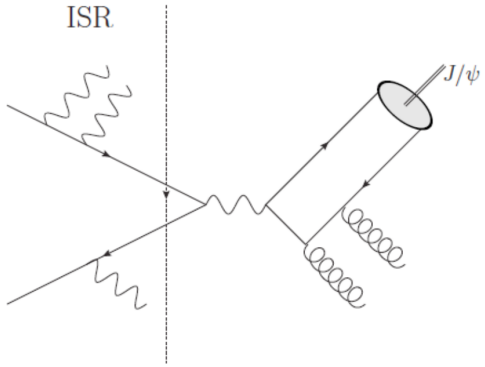
- Guarantee spin-correlations in heavy quarkonium decay chains.
- For instance, $\chi_c \to J/\psi + \gamma \to \ell^+\ell^- + \gamma$
  - Considering the helicity amplitude for the decay process is $\mathcal{A}(\mathbf{x})$, where $\mathbf{x}$ is the set of variables to characterize the kinematics.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

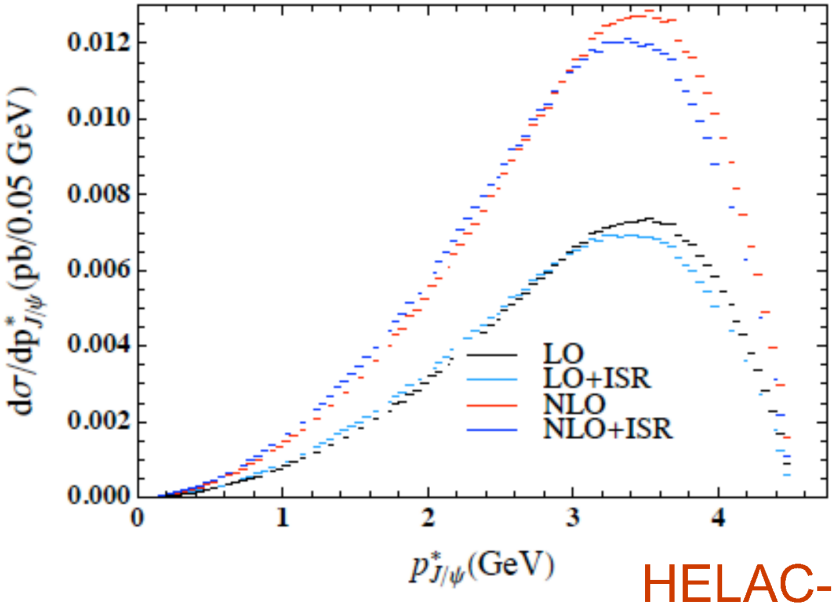
NEW DEVELOPMENTS IN VERSION 2.0

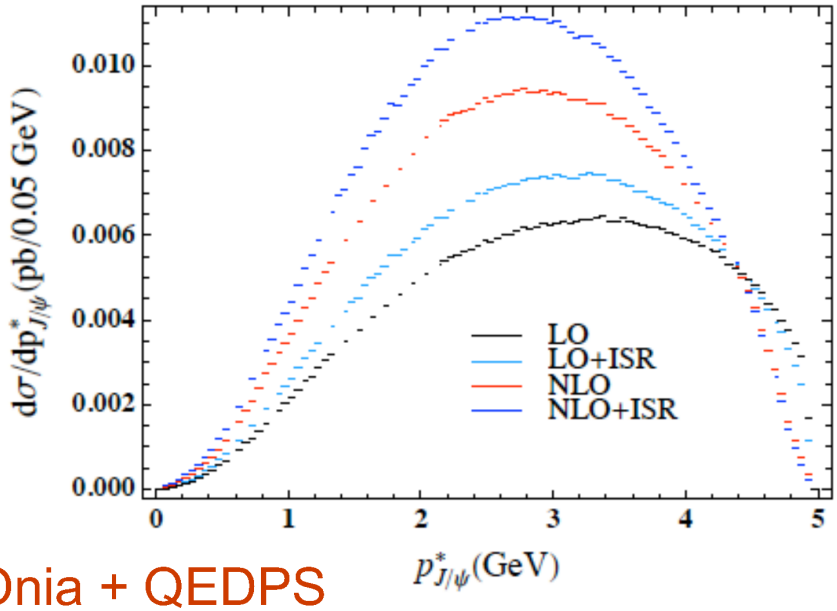
- Shower module
  - Interface to external parton shower Monte Carlo programs.

Shao (2014)









HELAC-Onia + QEDPS

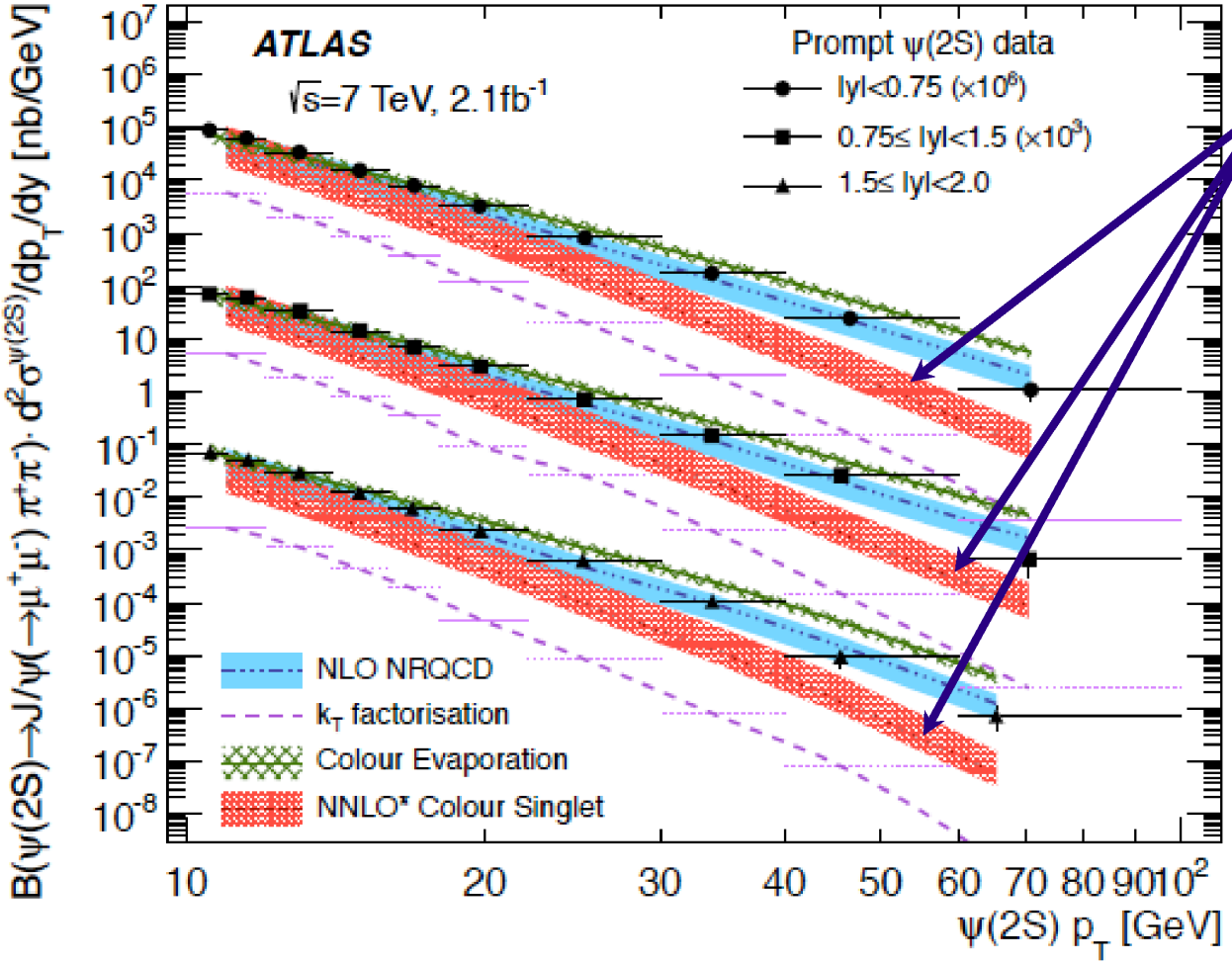
NEW DEVELOPMENTS IN VERSION 2.0

- 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
  - Double parton scattering for J/Ψ pair production:

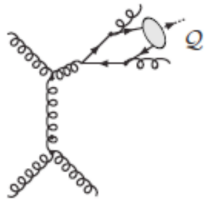
    2 scatterings at a time
- Planned :
  - Fragmentation function module
  - TMD module etc

Highest-Multiplicity processes: NNLO* QCD Corrections

ATLAS Collaboration (2014)



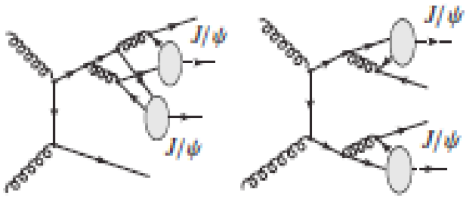
- NNLO* QCD correction.

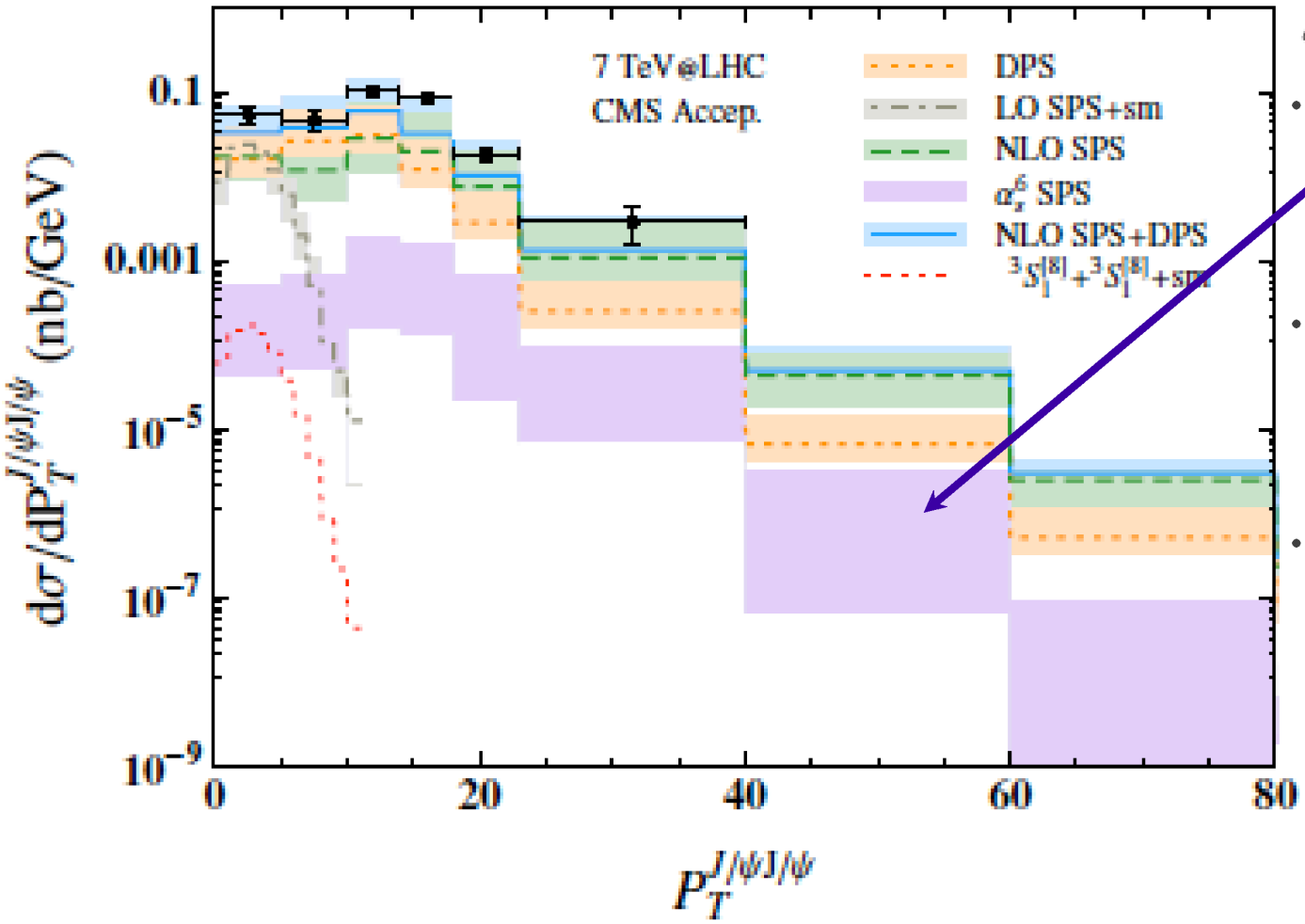


- First done by MadOnia [Artoisenet, JPL, Maltoni (2007)].
- The first 2 > 4 process with at least one quarkonium.
- HELAC-Onia reproduce the MadOnia result between 10-40 GeV.

Highest-Multiplicity processes: p p > Ψ+ Ψ +cc

JPL, Shao (2014)





- 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.

Summary about HELAC-Onia

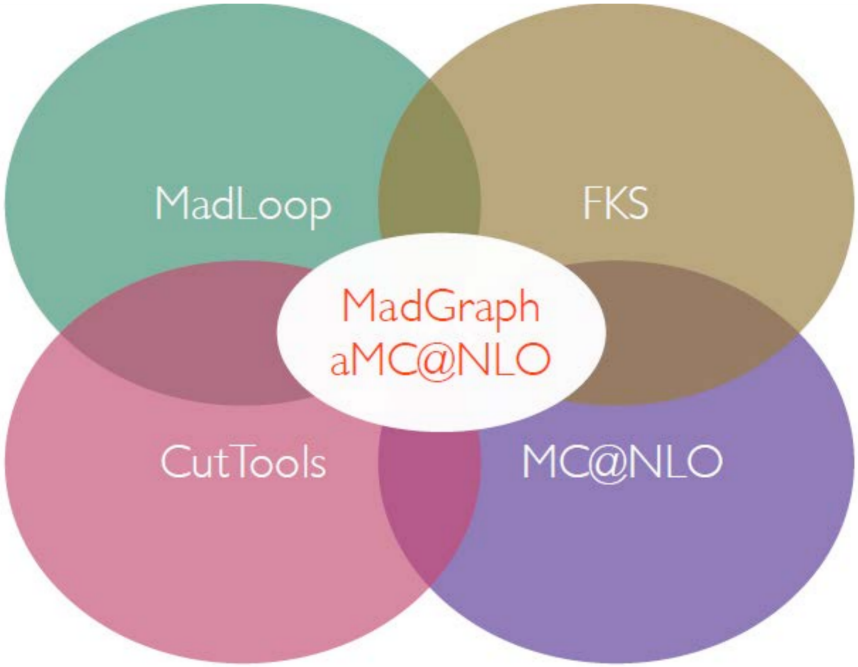
- HELAC-Onia is an user-friendly public tool to study heavy quarkonium physics in an automatic way.
- Based on recursion relations, it can be employed for high-multiplicity processes with a reduced computational cost.
- It provides a simulation tool for one or more S-wave and/or P-wave heavy quarkonia production based on tree-level helicity amplitudes.
- To do:
  - Ongoing developments to meet various application purposes.
  - Generalise to higher-order (e.g. NLO QCD correction).

Part IV

A trick to move to NLO accuracy

MadGraph5_aMC@NLO in A nutshell

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14



4 commands for a NLO calculation

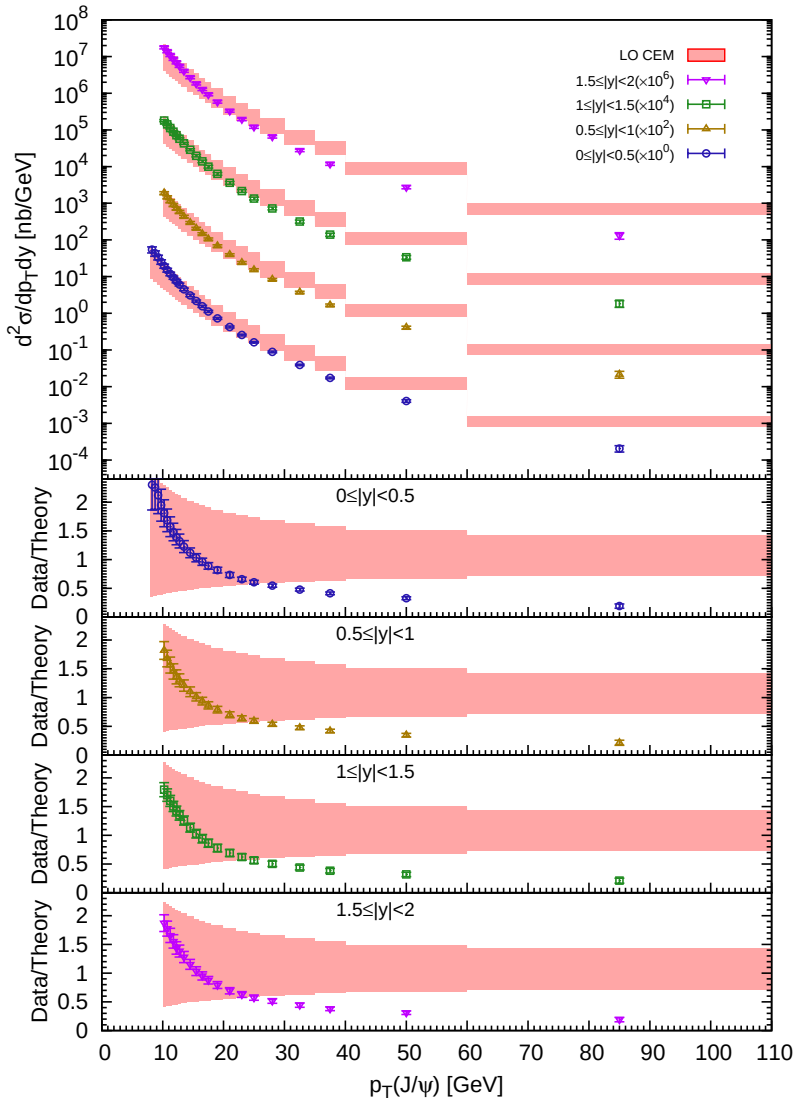
```
> ./bin/mg5_aMC
> generate process [QCD]
> output
> launch
```

Trick: In the CEM (quark-hadron duality), the quarkonium cross sections are proportional to those of **heavy-flavour-pair** production up to a **maximum invariant mass** $m_{Q\bar{Q}} = 2m_D$ (or m_B)

Nota: also works with some slight tunes of MCFM.

QCD corrections to the CEM P_T dependence

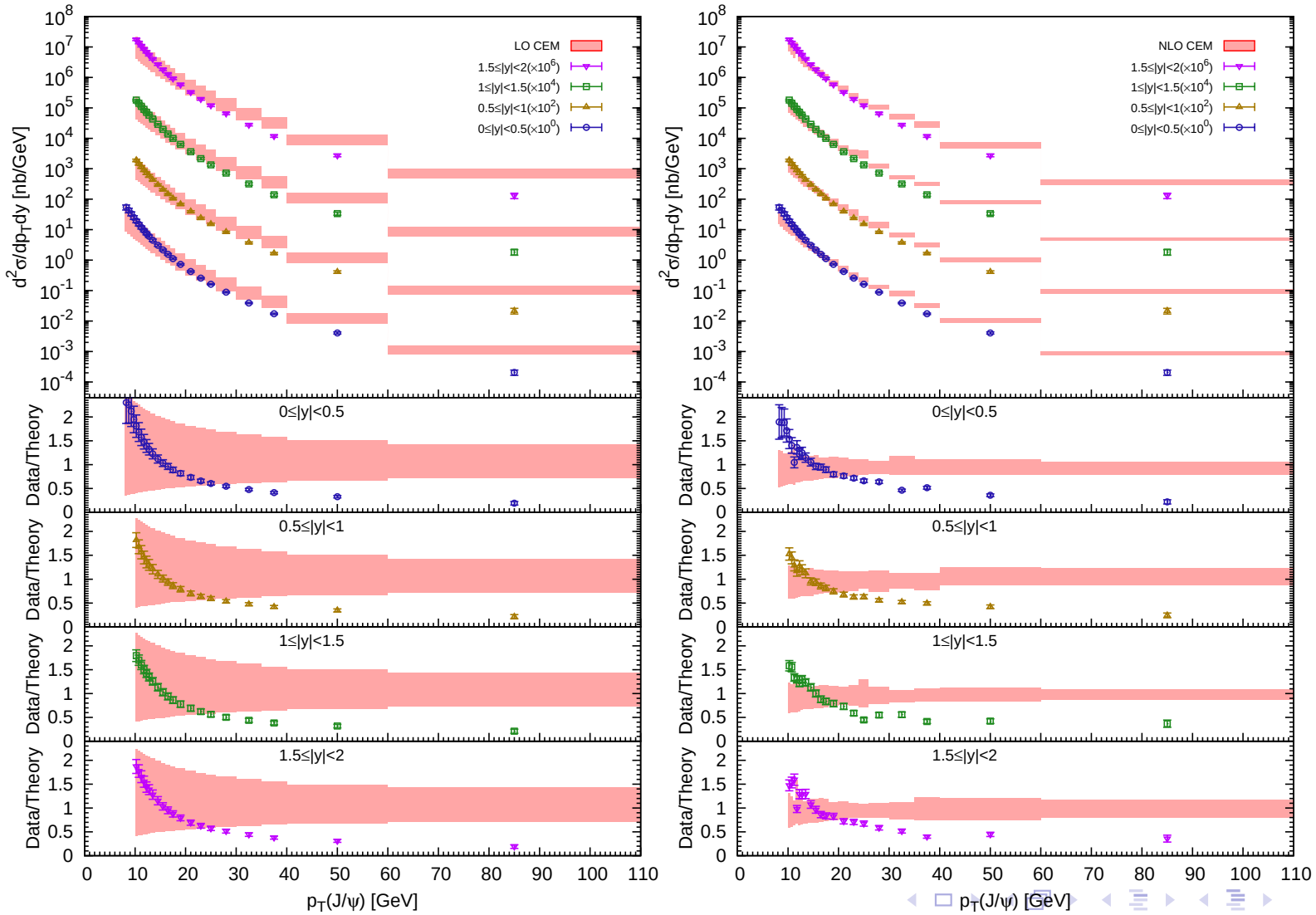
JPL, H.S. Shao JHEP 1610 (2016) 153



QCD corrections to the CEM P_T dependence

JPL, H.S. Shao JHEP 1610 (2016) 153

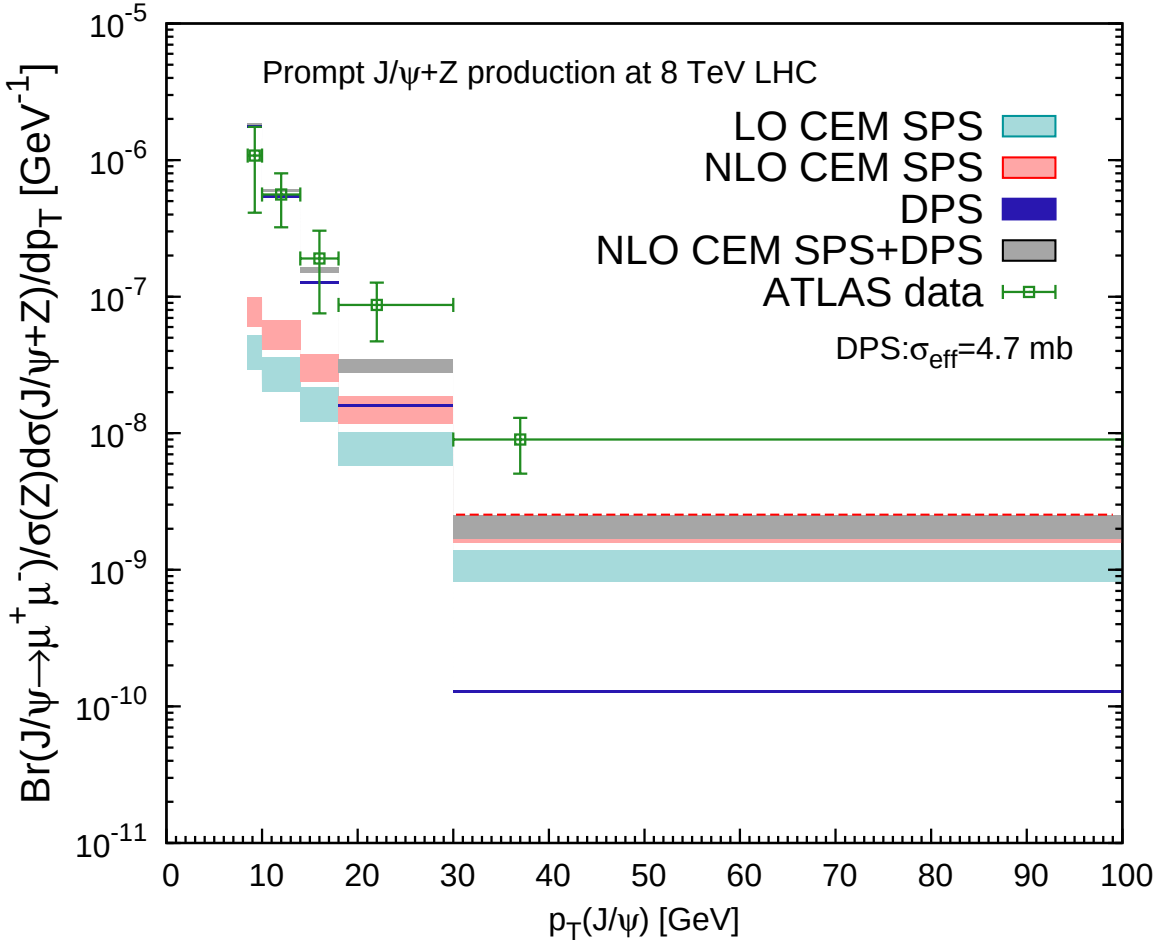
State of the art computation:



QCD corrections to the $Z + J/\psi$

JPL, H.S. Shao JHEP 1610 (2016) 153

LO was not even known:



Homework: Pick up you preferred (SM or BSM) particle and compute the associated production x-section with a J/ψ in the CEM.

Part V

Conclusion and outlooks

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- or with the CEM (but with caveats with regards the physics)

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- Need reinforced by numerous recent experimental studies at the LHC
- Two automated tools on the market: MadOnia and HELAC-Onia
- HELAC-Onia: maintained and developped
- First NLO evaluations with unautomatised tools
- or with the CEM (but with caveats with regards the physics)
- a NLO tool still to be devised (with octet + polarisation)