Bound-state production in MadGraph5_aMC@NLO

33rd International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2026)

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May 5, 2026

Introduction: MadGraph5_aMC@NLO

MadGraph5_aMC@NLO = diagram/amplitude/event generator

★ compute matrix element in helicity-amplitude formalism

$$\sigma(h_A h_B \to k + X) = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_{i/h_A}(x_i) f_{j/h_B}(x_j) \hat{\sigma}(x_i, x_j, \mu_F, \mu_R)$$

- Lagrangian → Feynman rules → matrix element → parton events
- Hadronise events and detector events possible
- (Differential) cross-section computation
- LHE weighted-unweighted event generation

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NEW in MG5: **Bound states** and **Asymmetric collisions**

Quarkonia and Leptonia

JHEP 02 (2026) 159 Eur.Phys.J.A 61 (2025) 10, 239

Introduction: motivation (why quarkonia?)

Quarkonium = meson made of a heavy quark Q and its $\bar{Q}$

$\hookrightarrow$ *charmonium* ($c\bar{c}$): J/ψ, Ψ', η_c, χ_c...

$\hookrightarrow$ *bottomonium* ($b\bar{b}$): Υ, η_b, χ_b...

Many reasons why quarkonia are interesting: QCD studies, investigation of the internal structure of nucleons...

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Focus on inclusive processes → NRQCD formalism:

$$\sigma(\mathrm{pp} \to \mathcal{Q} + X) = \sum_{i,j,n} \int \mathrm{d}x_i \mathrm{d}x_j f_{i/\mathrm{p}}(x_i) f_{j/\mathrm{p}}(x_j) \times \hat{\sigma}(ij \to Q\bar{Q}[n] + X) \langle \mathcal{O}_n^{\mathcal{Q}} \rangle$$

$$n = {}^{2s+1}L_J^c$$

Spectroscopic notation

Why MadGraph5_aMC@NLO?

MadOnia: JHEP 02 (2008) 102

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Automation of S-wave LO quarkonium with P-waves and NLO in sight

JHEP 07 (2024), 050

Quarkonium implementation in MG5

→ based on JHEP 02 (2026) 159

Quarkonium amplitudes: colour and spin projectors

r: $a(k_1)b(k_2) \to Q(k_3)\bar{Q}(k_4) + \ldots$

$$\boxed{Q\bar{Q}[n] \quad n =^{2s+1} L_J^c}$$

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$$\downarrow \text{ colour projection } \downarrow$$

$$\boxed{\mathcal{A}_{\{[C]\}}(r) = \sum_{c_3, c_4} \mathbb{P}_C \mathcal{A}(r)}$$

Colour projectors

$\mathbb{P}_1 = \delta_{ij}/\sqrt{N_c}$ and $\mathbb{P}_8 = \sqrt{2}t^c_{ij}$

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Spin projectors

$$\mathbb{P}_S = \frac{\bar{v}_{\lambda_{\bar{Q}}}(k_4)\Gamma_S u_{\lambda_Q}(k_3)}{2\sqrt{2m_Q m_{\bar{Q}}}}$$

$\Gamma_0 = \gamma_5$ and $\Gamma_1 = \not{\epsilon}(K)$

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Now implemented in MadGraph5

Quarkonium: interface implementation

$$|J/\psi\rangle = J/\psi(1|3S11) + J/\psi(1|1S08) + J/\psi(1|3S18) + \ldots$$

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boundstates.py

```
77  # J/psi
78  jpsi_13s11 = Boundstate(pdg_code = 443,
79                          name = 'Jpsi(1|3S11)',
80                          particles = ['c','c~'],
81                          principal = 1,
82                          spin = 3,
83                          orbital = 0,
84                          J = 1,
85                          color = 1,
86                          charge = 0,
87                          texname = 'jpsi13S11')
88
89  jpsi_11s08 = Boundstate(pdg_code = 9941003,
90                          name = 'Jpsi(1|1S08)'
```

(`Boundstate` class similar to `Particle`)

Quarkonium: interface implementation

$$|J/\psi\rangle = J/\psi(1|3S11) + J/\psi(1|1S08) + J/\psi(1|3S18) + \ldots$$

A list of ALL available Fockstates can be shown with the prompt

`MG_aMC > display fockstates`

(after importing the onia model)

Quarkonium: interface implementation

$$|J/\psi\rangle = J/\psi(1|3S11) + J/\psi(1|1S08) + J/\psi(1|3S18) + \ldots$$

boundstates_default.txt

```
#
# Physical Boundstates (S-waves only)
#
# Syntax: label = Fock states (separated by spaces)
#
# Charmonium
etac = etac(1|1S01) etac(1|1S08) etac(1|3S18)
etac(2s) = etac(2|1S01) etac(2|1S08) etac(2|3S18)
Jpsi = Jpsi(1|3S11) Jpsi(1|1S08) Jpsi(1|3S18)
psi(2s) = psi(2|3S11) psi(2|1S08) psi(2|3S18)
# Charmed B mesons
```

boundstates_default.txt

(similar to multiparticle_default.txt)

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etac(2s) = etac(2|1S01) etac(2|1S08) etac(2|3S18)
Jpsi = Jpsi(1|3S11) Jpsi(1|1S08) Jpsi(1|3S18)
psi(2s) = psi(2|3S11) psi(2|1S08) psi(2|3S18)
Bc+ = Bc+(1|1S01) Bc+(1|1S08) Bc+(1|3S18)
B*c+ = B*c+(1|3S11) B*c+(1|1S08) B*c+(1|3S18)
Bc- = Bc-(1|1S01) Bc-(1|1S08) Bc-(1|3S18)
B*c- = B*c-(1|3S11) B*c-(1|1S08) B*c-(1|3S18)
etab = etab(1|1S01) etab(1|1S08) etab(1|3S18)
etab(2s) = etab(2|1S01) etab(2|1S08) etab(2|3S18)
Upsilon = Upsilon(1|3S11) Upsilon(1|1S08) Upsilon(1|3S18)
Upsilon(2s) = Upsilon(2|3S11) Upsilon(2|1S08) Upsilon(2|3S18)
etat = etat(1|1S01) etat(1|1S08) etat(1|3S18)
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From the mg5amcnlo folder: type `./bin/mg5_aMC`

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- ⋆ Example: $p + p \longrightarrow J/\psi + c + \bar{c}$

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MG_aMC > generate p p > jpsi c c~
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It will be equivalent to:

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MG_aMC > generate p p > jpsi(1|3S11) c c~
MG_aMC > add process p p > jpsi(1|1S08) c c~
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1. Benchmarked our matrix elements squared against `Helac-Onia`
2. Benchmarked cross section for quarkonium production processes

Cross-section benchmarking

Benchmarked cross sections against Helac-Onia

Process	MadGraph5 Helac-Onia	Process	MadGraph5 Helac-Onia
$u\bar{u} \to J/\psi\left[{}^3S_1^{[8]}\right] + H$	42.055(2) yb 42.056(3) yb	$gg \to J/\psi\left[{}^3S_1^{[8]}\right] + H$	1.8530(7) ab 1.8523(7) ab
$gg \to J/\psi\left[{}^3S_1^{[8]}\right] + HH$	15.927(3) yb 15.93(2) yb	$gg \to J/\psi\left[{}^3S_1^{[8]}\right] + HHH$	1.9802(5) rb 1.967(4) rb
$gg \to J/\psi\left[{}^3S_1^{[8]}\right] + g$	8.9215(7) µb 8.927(2) µb	$gg \to J/\psi\left[{}^3S_1^{[1]}\right] + J/\psi\left[{}^3S_1^{[1]}\right]$	8.921(2) nb 8.916(4) nb
$gg \to J/\psi\left[{}^3S_1^{[8]}\right] + J/\psi\left[{}^3S_1^{[8]}\right]$	86.240(7) pb 86.27(2) pb	$gg \to \eta_c\left[{}^1S_0^{[8]}\right] + \eta_b\left[{}^1S_0^{[8]}\right]$	195.984(9) fb 195.987(9) fb
$u\bar{u} \to \eta_c\left[{}^1S_0^{[1]}\right] + J/\psi\left[{}^3S_1^{[8]}\right]$	152.79(1) fb 152.73(6) fb	$u\bar{u} \to \eta_c\left[{}^1S_0^{[1]}\right] + \Upsilon\left[{}^3S_1^{[1]}\right]$	212.90(2) zb 212.9(1) zb
$u\bar{u} \to B_c^+\left[{}^1S_0^{[1]}\right] + B_c^{*-}\left[{}^3S_1^{[1]}\right]$	2.7920(5) pb 2.7925(7) pb	$e^+e^- \to J/\psi\left[{}^3S_1^{[1]}\right] + Z$	1.61586(9) fb 1.61584(8) fb

LDMEs for quarkonia

PRL 114 (2015) 092005, PRD 94 (2016) 014028

$\mathcal{Q}[n]$	$\langle \mathcal{O}_n^{\mathcal{Q}} \rangle$ [GeV^3]	$\mathcal{Q}[n]$	$\langle \mathcal{O}_n^{\mathcal{Q}} \rangle$ [GeV^3]
$\eta_c[^1S_0^{[1]}]$	0.386666666666667	$J/\psi[^3S_1^{[1]}]$	1.16
$\eta_c[^3S_1^{[8]}]$	0.0146	$J/\psi[^1S_0^{[8]}]$	0.0146
$\eta_c[^1S_0^{[8]}]$	0.003009743333333	$J/\psi[^3S_1^{[8]}]$	0.00902923
$\eta_c(2S)[^1S_0^{[1]}]$	0.253333333333333	$\psi(2S)[^3S_1^{[1]}]$	0.76
$\eta_c(2S)[^3S_1^{[8]}]$	0.02	$\psi(2S)[^1S_0^{[8]}]$	0.02
$\eta_c(2S)[^1S_0^{[8]}]$	0.0004	$\psi(2S)[^3S_1^{[8]}]$	0.0012
$\eta_b[^1S_0^{[1]}]$	3.093333333333333	$\Upsilon[^3S_1^{[1]}]$	9.28
$\eta_b[^3S_1^{[8]}]$	0.000170128	$\Upsilon[^1S_0^{[8]}]$	0.000170128
$\eta_b[^1S_0^{[8]}]$	0.0099142	$\Upsilon[^3S_1^{[8]}]$	0.0297426
$\eta_b(2S)[^1S_0^{[1]}]$	1.543333333333333	$\Upsilon(2S)[^3S_1^{[1]}]$	4.63
$\eta_b(2S)[^3S_1^{[8]}]$	0.0612263	$\Upsilon(2S)[^1S_0^{[8]}]$	0.0612263
$\eta_b(2S)[^1S_0^{[8]}]$	0.003197393333333	$\Upsilon(2S)[^3S_1^{[8]}]$	0.00959218
$B_c^{\pm}[^1S_0^{[1]}]$	0.736	$B_c^{*\pm}[^3S_1^{[1]}]$	2.208
$B_c^{\pm}[^3S_1^{[8]}]$	0.00736	$B_c^{*\pm}[^1S_0^{[8]}]$	0.02208
$B_c^{\pm}[^1S_0^{[8]}]$	0.00736	$B_c^{*\pm}[^3S_1^{[8]}]$	0.02208

Cross-section results

Cross-section results for quarkonia: some examples

Disclaimer! Cross sections only to show the flexibility of the code

+ hierarchy of the processes depend on LDMEs

Jet cuts: $p_{T,j} > 10$ GeV, $\eta_j < 5$

Single-quarkonium production

process	σ	**process**	σ
$pp \to \eta_c$	2.9366(5) µb	$pp \to \eta_b$	5.4935(7) µb
$pp \to J/\psi$	536.14(6) nb	$pp \to \Upsilon$	6.0655(4) nb

+

process	σ	**process**	σ
$pp \to \eta_c + j$	805.4(4) nb	$pp \to \eta_b + j$	315.4(2) nb
$pp \to J/\psi + j$	329.8(2) nb	$pp \to \Upsilon + j$	19.85(1) nb

Cross-section results for quarkonia: some examples

Photon cuts: $p_{T,\gamma} > 2$ GeV, $\eta_\gamma < 2.5$

Associated-quarkonium production

process	σ	**process**	σ
$pp \to J/\psi + \gamma$	19.13(1) nb	$pp \to \Upsilon + \gamma$	897.4(5) pb
$pp \to J/\psi + W^+$	1.9328(6) pb	$pp \to \Upsilon + W^+$	102.81(4) fb

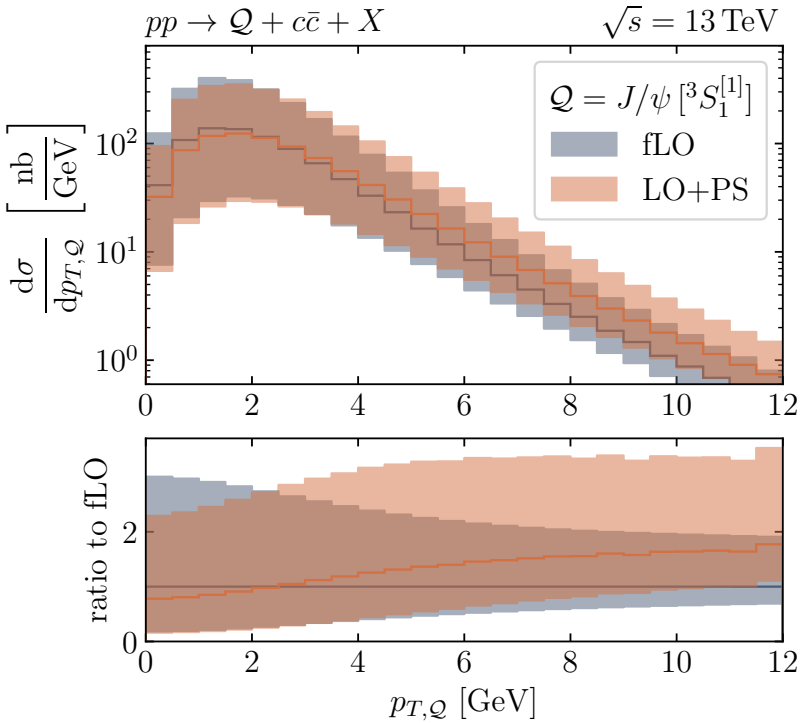
Quarkonium-pair production

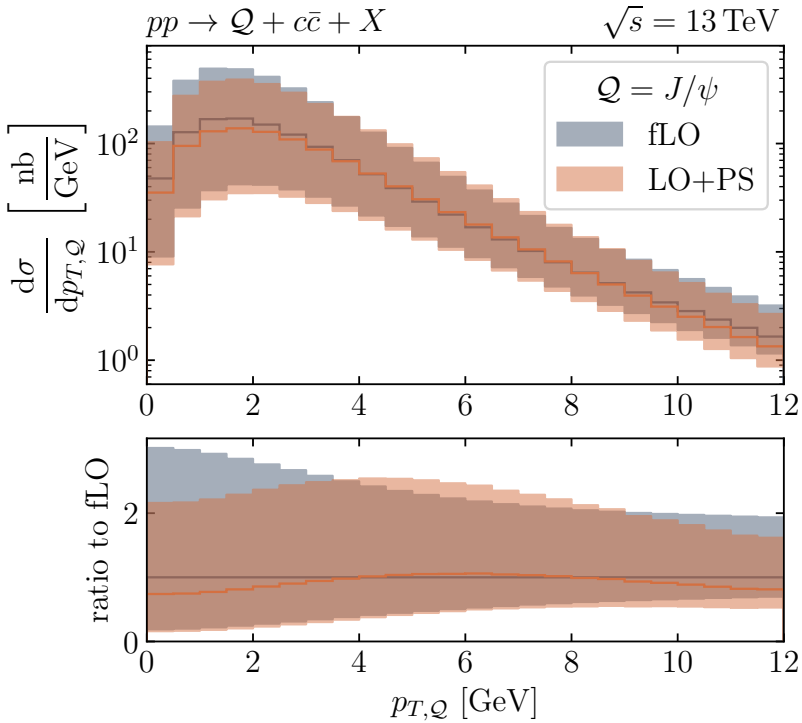
process	σ	**process**	σ
$pp \to \eta_c + \eta_c$	35.81(1) nb	$pp \to \eta_b + \eta_b$	75.64(3) pb
$pp \to \eta_c + J/\psi$	7.233(3) nb	$pp \to \eta_b + \Upsilon$	1.9244(6) pb
$pp \to J/\psi + J/\psi$	10.756(3) nb	$pp \to \Upsilon + \Upsilon$	44.63(1) pb

Cross-section results for quarkonia: parton showering

SPC 2022 (2022) 8

p_T distribution of J/ψ in $pp \to J/\psi\, c\, \bar{c}$ + Pythia8.3 showering





Quarkonium production in DIS

kinematic cuts: $p_{T,j} > 5$ GeV, $|\eta_j| < 5$, $p_{T,e} > 1$ GeV, $|\eta_e| < 3$

- ★ example process: $e^- p \to \eta_c e^- j$

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```
MG_aMC >
```

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MG_aMC >
MG_aMC > import model sm_onia-c_mass
MG_aMC > generate e- p > etac e- j
```

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MG_aMC > output; launch
```

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Do the same with J/ψ: etac → jpsi

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MG_aMC > output; launch
```

Do the same with J/ψ: etac → jpsi

$$\sigma(e^- p \to \eta_c + e^- j + X) = 394.8(1)\,\text{fb}$$
$$\sigma(e^- p \to J/\psi + e^- j + X) = 2.5651(8)\,\text{pb}$$

Individual partonic channels for η_c:

$$\sigma(e^- p \to e^- g \to \eta_c[{}^1S_0^{[1]}] + e^- g) = 17.9(5)\,\text{ab}$$

$$\sigma(e^- p \to e^- q \to \eta_c[{}^1S_0^{[1]}] + e^- q) = 0$$

$$\sigma(e^- p \to e^- g \to \eta_c[{}^3S_1^{[8]}] + e^- g) = 33.47(4)\,\text{fb}$$

$$\sigma(e^- p \to e^- q \to \eta_c[{}^3S_1^{[8]}] + e^- q) = 147.81(9)\,\text{fb}$$

$$\sigma(e^- p \to e^- g \to \eta_c[{}^1S_0^{[8]}] + e^- g) = 155.42(8)\,\text{fb}$$

$$\sigma(e^- p \to e^- q \to \eta_c[{}^1S_0^{[8]}] + e^- q) = 58.06(5)\,\text{fb}$$

Individual partonic channels for J/ψ:

$$\sigma(e^- p \to e^- g \to J/\psi\left[{}^3S_1^{[1]}\right] + e^- g) = 1.4171(6)\,\text{pb}$$

$$\sigma(e^- p \to e^- q \to J/\psi\left[{}^3S_1^{[1]}\right] + e^- q) = 0$$

$$\sigma(e^- p \to e^- g \to J/\psi\left[{}^1S_0^{[8]}\right] + e^- g) = 754.3(4)\,\text{fb}$$

$$\sigma(e^- p \to e^- q \to J/\psi\left[{}^1S_0^{[8]}\right] + e^- q) = 281.5(3)\,\text{fb}$$

$$\sigma(e^- p \to e^- g \to J/\psi\left[{}^3S_1^{[8]}\right] + e^- g) = 20.65(6)\,\text{fb}$$

$$\sigma(e^- p \to e^- q \to J/\psi\left[{}^3S_1^{[8]}\right] + e^- q) = 91.5(2)\,\text{fb}$$

HEFT: quarkonium in association to Higgs boson

PRD 66 (2002) 114002, PRD 104 (2021) 054006

- consider $p + p \rightarrow \mathcal{Q} + H$ with $\mathcal{Q} = J/\psi$ or Υ

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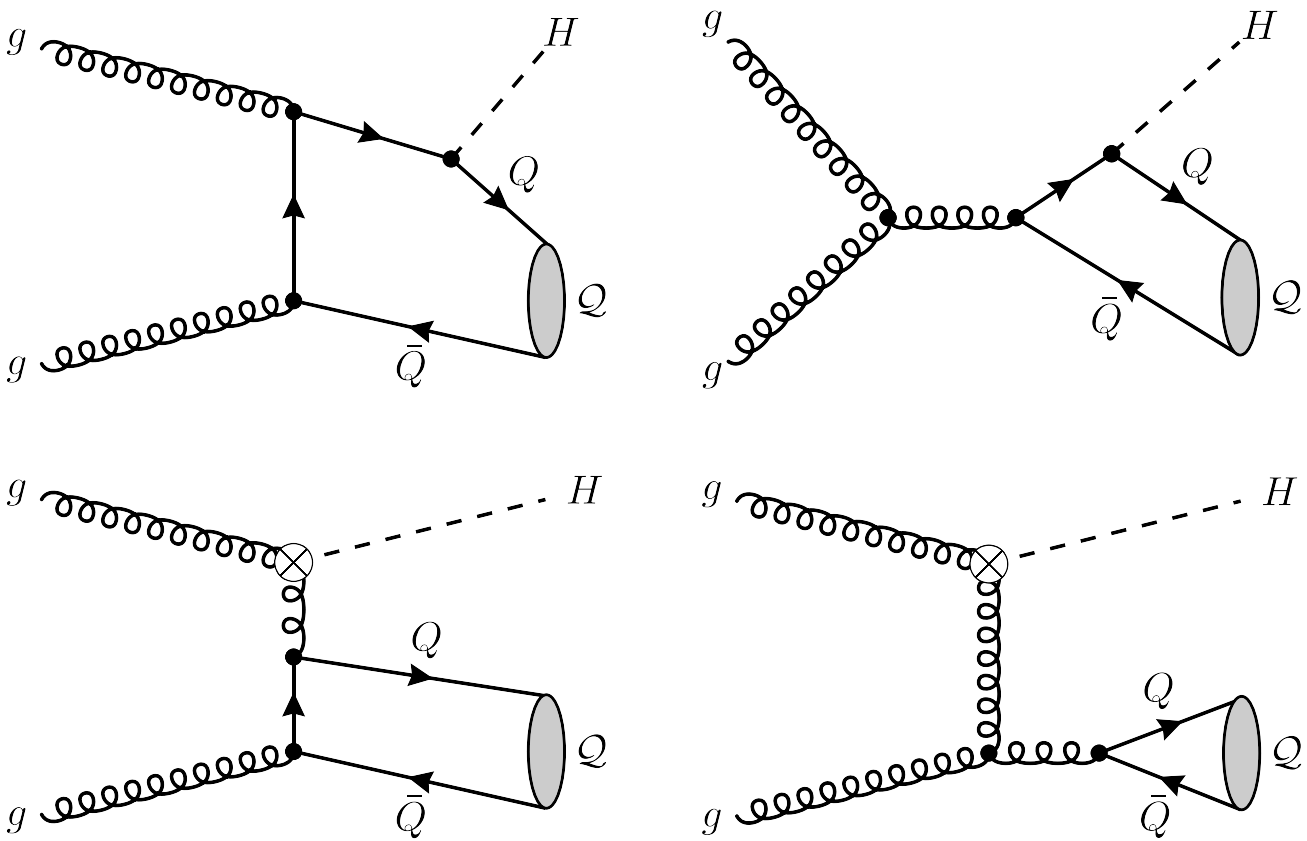

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PRD 66 (2002) 114002, PRD 104 (2021) 054006

★ consider $p + p \rightarrow \mathcal{Q} + H$ with $\mathcal{Q} = J/\psi$ or Υ

From the mg5amcnlo folder: type `./bin/mg5_aMC`

```
MG_aMC  >
```

HEFT: quarkonium in association to Higgs boson

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★ consider $p + p \rightarrow \mathcal{Q} + H$ with $\mathcal{Q} = J/\psi$ or Υ

From the mg5amcnlo folder: type `./bin/mg5_aMC`

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MG_aMC >
MG_aMC > import model heft_onia
```

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MG_aMC > import model heft_onia
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similar for J/ψ

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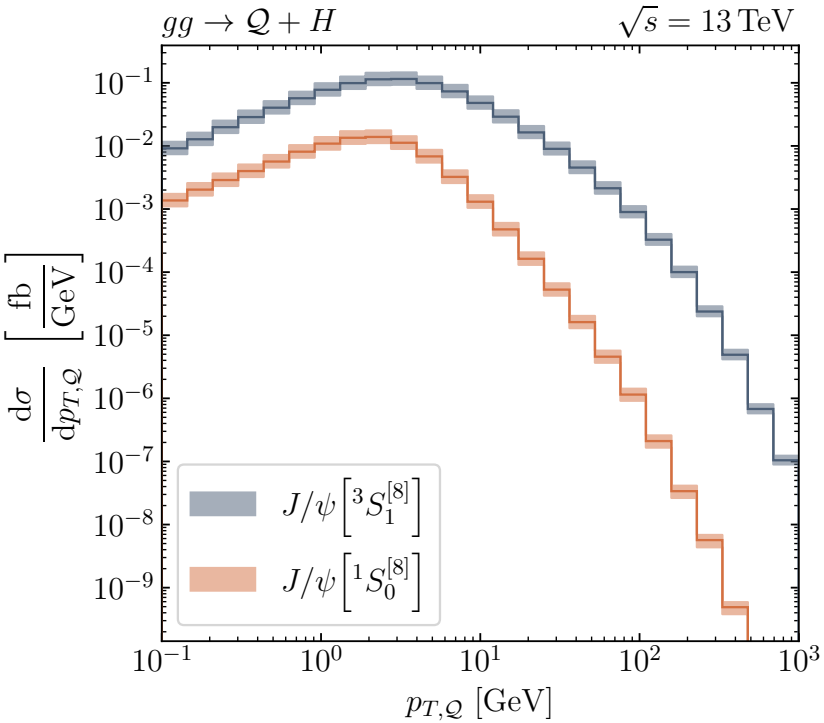
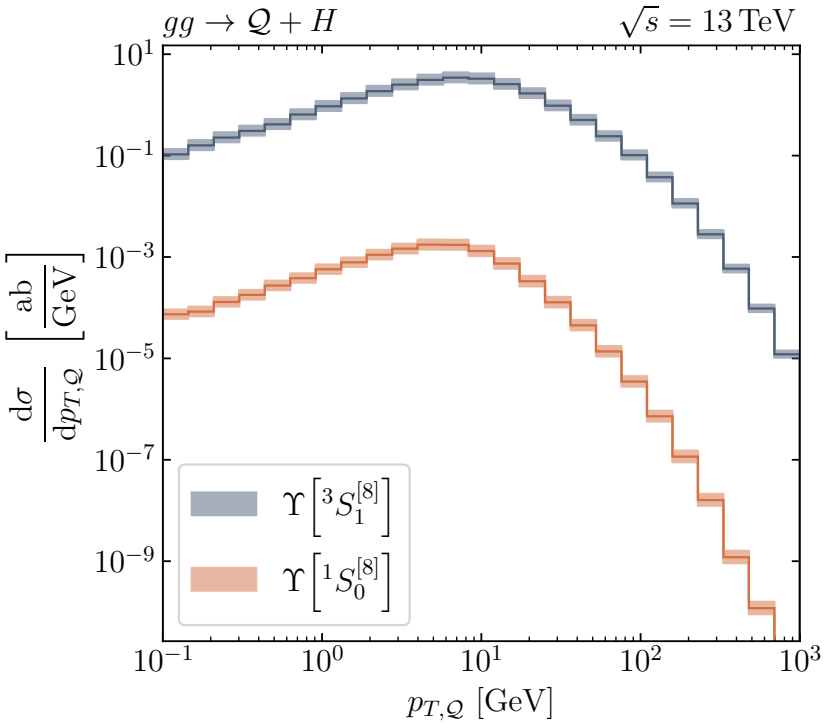
similar for J/ψ

$$\sigma(gg \rightarrow J/\psi + H) = 1.53^{+0.40}_{-0.29}\,\text{fb}$$
$$\sigma(gg \rightarrow \Upsilon + H) = 91^{+23}_{-17}\,\text{ab}$$

HEFT: quarkonium in association to Higgs boson

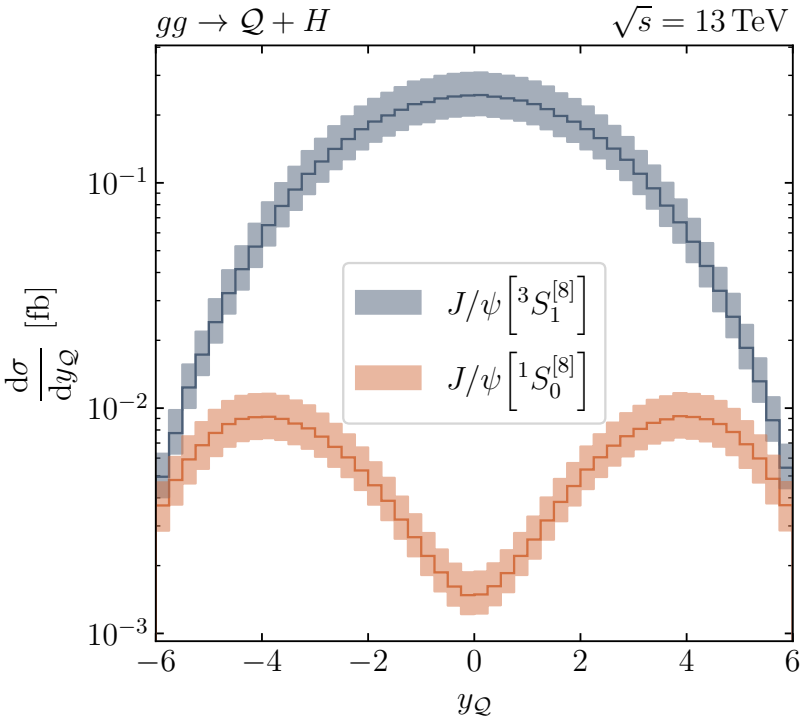
- ★ p_T distributions for J/ψ and Υ

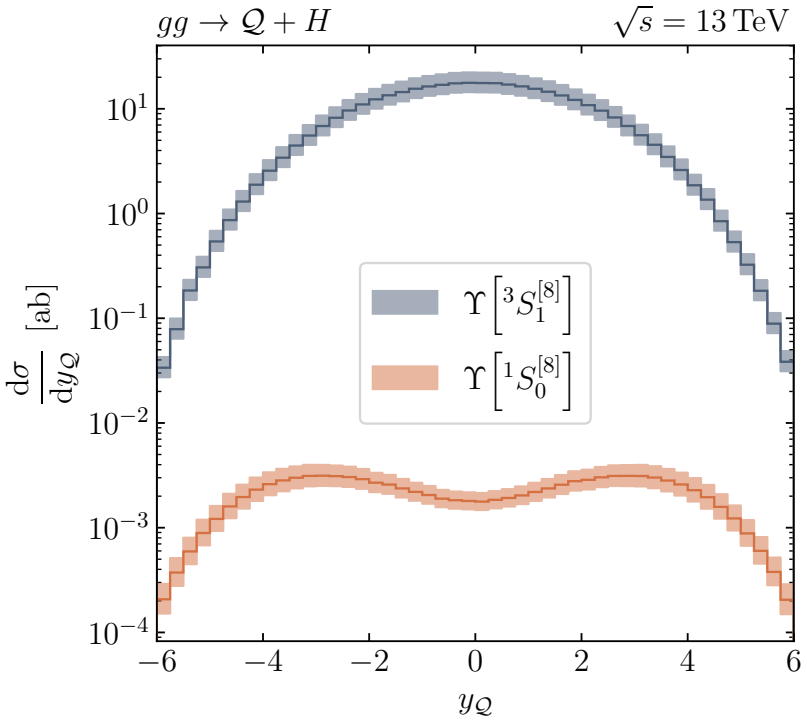




HEFT: quarkonium in association to Higgs boson

- ★ rapidity distributions for J/ψ and Υ





Conclusions

Summary and outlook

Implementation of LO S-wave quarkonia in MG5: done ✓

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- large amount of processes with single/multiple quarkonium in the final states
- leptonium states also included (lepton-antilepton states)
- paper published on JHEP! JHEP 02 (2026) 159
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- ⋆ include P-wave states (ongoing work)
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- ⋆ extension: DIS@NLO
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THANK YOU!

Backup slides

Motivation: why automation of quarkonium cross sections?

Many reasons, including:

- global data-theory comparisons
- physics cases for future experimental facilities
- global NRQCD fits

Matrix element/event generators publicly available
(↪ interfacing of e.g. HERWIG or PYTHIA with e.g. MG5_aMC)

↓

facilitates complete computation

✓ versatility and enhanced physics simulation capabilities

✗ integration complexity, computational overhead, code compatibility and increased learning requirements

Objectives and plan of the project

□ Implementation of quarkonia in `MadGraph5_aMC@NLO` at LO
↪ Single and multiple S-wave inclusive quarkonium production

- Colour projectors
- Spin projectors
- Interface
- Phase space adaptation

□ Extensions to states with leading P-wave Fock states
LO implementation ⟶ □ NLO in the easiest way possible!

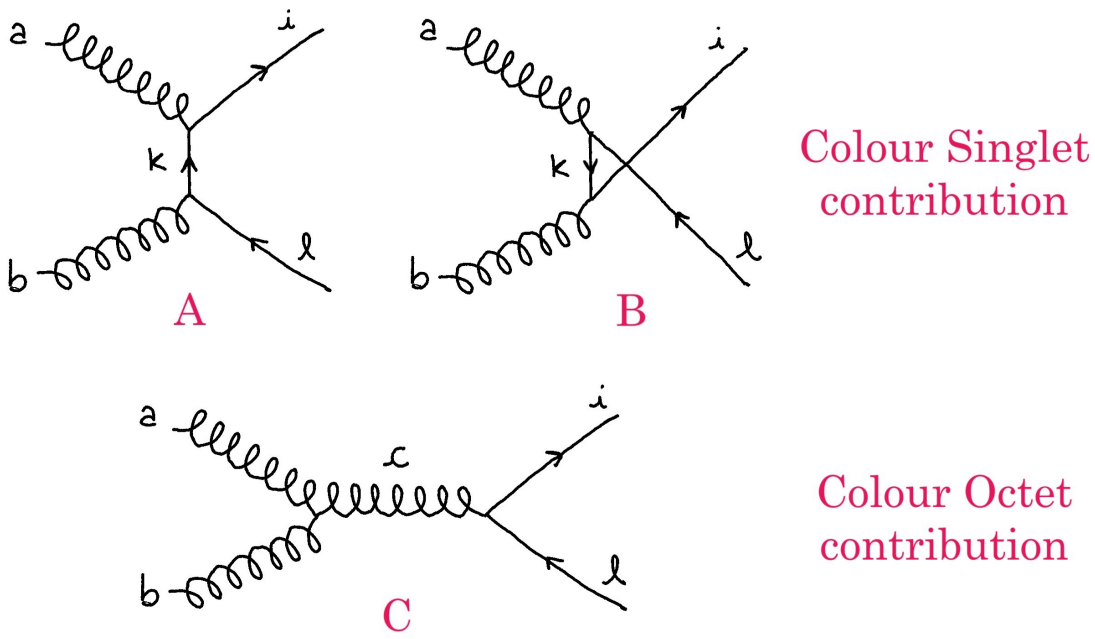
□ TMD factorisation also to be implemented
↪ for example gg → di-J/ψ (... not only for quarkonia)

Colour projectors $\mathbb{P}_C$ (1)

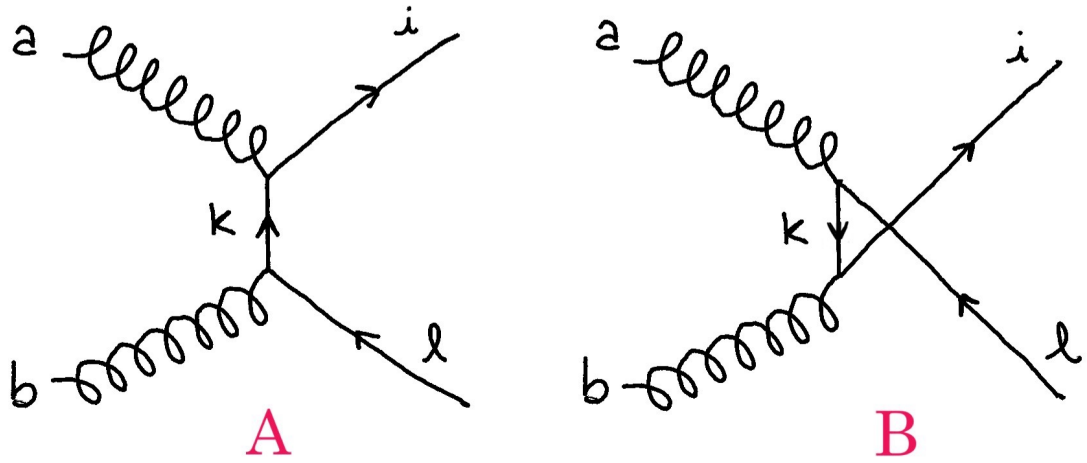
Quarkonium in the quantum state $n \longrightarrow$ colour singlet or octet?

$$\mathbb{P}_1 = \delta_{ij}/\sqrt{N_c}$$
$$\mathbb{P}_8 = \sqrt{2}t^c_{ij}$$

- Example: $gg \longrightarrow c\bar{c}$ **3 diagrams** at LO



Colour projectors $\mathbb{P}_C$ (2)

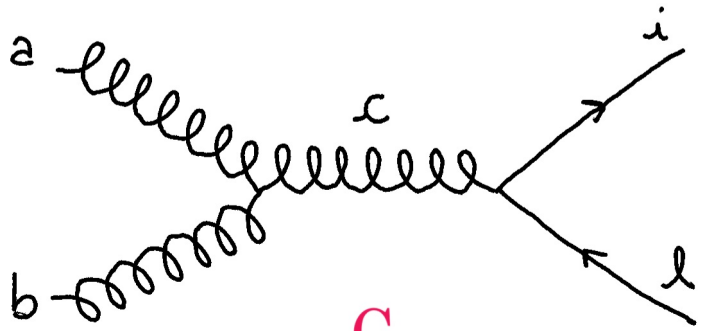


$$(\mathrm{A}) \sim (t^a_{ik} t^b_{kl}) = (t^a t^b)_{il} \quad \rightarrow \text{we set } (t^a t^b)_{il} = c1$$

$$(\mathrm{B}) \sim (t^b_{ik} t^a_{kl}) = (t^b t^a)_{il} \quad \rightarrow \text{we set } (t^b t^a)_{il} = c2$$

$$\hookrightarrow \text{open } c\bar{c} \text{ colour basis of dim} = 2$$

Colour projectors $\mathbb{P}_C$ (3)



C

$$(\mathrm{C}) \sim f^{abc}(t^c_{il}) = (t^a t^b)_{il} - (t^b t^a)_{il}$$

$$= \quad c1 \quad - \quad c2$$

$$c1c1^\dagger = (t^a t^b)_{il}(t^b t^a)_{il} = \mathrm{Tr}(t^a t^b t^b t^a) = \frac{16}{3}$$

$$\vdots$$

$$\longrightarrow \text{colour matrix:} \begin{pmatrix} c1c1^\dagger & c1c2^\dagger \\ c2c1^\dagger & c2c2^\dagger \end{pmatrix}$$

Colour projectors $\mathbb{P}_C$ (4)

Apply colour projectors: $\mathbb{P}_1 = \delta^{il}$ and $\mathbb{P}_8 = t^c_{il}$

- Colour singlet:

$$(t^a t^b)_{il}\delta^{il} = \mathrm{Tr}(t^a t^b) \qquad (\mathrm{A})$$
$$(t^b t^a)_{il}\delta^{il} = \mathrm{Tr}(t^b t^a) \qquad (\mathrm{B})$$

- Colour octet:

$$\left.\begin{aligned}(t^a t^b)_{il}\, t^c_{il} &= \mathrm{Tr}(t^a t^b t^c) = \tfrac{1}{4}(d^{abc} + i f^{abc}) \quad (1)\\ (t^b t^a)_{il}\, t^c_{il} &= \mathrm{Tr}(t^b t^a t^c) = \tfrac{1}{4}(d^{bac} + i f^{bac}) \quad (2)\end{aligned}\right\} \ (1) - (2): \quad (\mathrm{C})$$

The amplitude will be given by the sum of the three contributions

$$\mathcal{A} = A(\mathrm{A}) + A(\mathrm{B}) + A(\mathrm{C})$$

Code: implementation of Colour Projectors

Colour projectors for m colour singlet and colour octet quarkonia production and associated production implemented ✓

Metacode: quarkonium formalism implemented via extension of python files which produce fortran code → numerical manipulations

In `/mg5amcnlo/madgraph/core`

- `color_algebra.py`
- `color_amp.py`
- `helas_objects.py`

Spin projectors $\mathbb{P}_S$ implementation

Quarkonium in the quantum state $n \longrightarrow$ spin singlet or triplet?

- Considering $a(k_1)b(k_2) \longrightarrow Q(k_3)\bar{Q}(k_4)$: JHEP 07 (2024), 050

$$\mathcal{A}(r) = \bar{u}_{\lambda_Q}(k_3)\Gamma(r)v_{\lambda_{\bar{Q}}}(k_4)$$

- Apply colour projector: $\mathcal{A}_{\{C\}}(r) = \sum_{c_3,c_4} \mathbb{P}_C \mathcal{A}(r)$
- Apply spin projector: $\mathcal{A}_{\{C,S\}}(r) = \sum_{\lambda_Q,\lambda_{\bar{Q}}} \mathbb{P}_S \mathcal{A}_{\{C\}}(r)$

$$\mathbb{P}_S = \frac{\bar{v}_{\lambda_{\bar{Q}}}(k_4)\Gamma_S u_{\lambda_Q}(k_3)}{2\sqrt{2m_Q m_{\bar{Q}}}} \qquad S = 0, \Gamma_S = \gamma_5; 1, \Gamma_S = \not{\epsilon}(K)$$

Declaration of new effective spinors in:

- `/mg5amcnlo/aloha/template_files/aloha_functions.f`
- `/mg5amcnlo/madgraph/core/helas_objects.py`

Python: calls `template_files` $\longrightarrow$ `matrix_i.f` files

Amplitudes: **JAMP** decomposition

Amplitudes organised into colour basis **JAMPs**

$$\mathcal{A} = \sum_i A_i \overset{\text{example}}{=} A(\mathrm{A}) + A(\mathrm{B}) + A(\mathrm{C})$$

$$A(\mathrm{A}) = c1A_1 \qquad A(\mathrm{B}) = c2A_2 \qquad A(\mathrm{C}) = c1A_{31} - c2A_{32}$$

$$\underline{\text{JAMP decomposition}} \quad \begin{cases} \text{JAMP}_1 & = A_1 + A_{31} \propto c1 \\ \text{JAMP}_2 & = A_2 - A_{32} \propto c2 \end{cases}$$

$$|\mathcal{A}|^2 = \sum_{i,j=1,2} \text{JAMP}_i^* \langle c_i | c_j \rangle \text{JAMP}_j$$

(Depends on spin projectors - constructed from helas routines)
Efficiency: large number of Feynman diagrams possible...
...but colour basis much smaller!

Phase-space integration

MadGraph5 employs multichannelling for integration (VEGAS)

Quarkonium in the final state is a single particle, not two
⚠ $2 \to 1$ process interpreted as $2 \to 2$ ...

Default integration in MG5 works well for our purpose
Phase-space integration performed without multi-channeling

↓

Sufficient for all phenomenologically relevant cases

Benchmarked cross-sections predictions against Helac-Onia

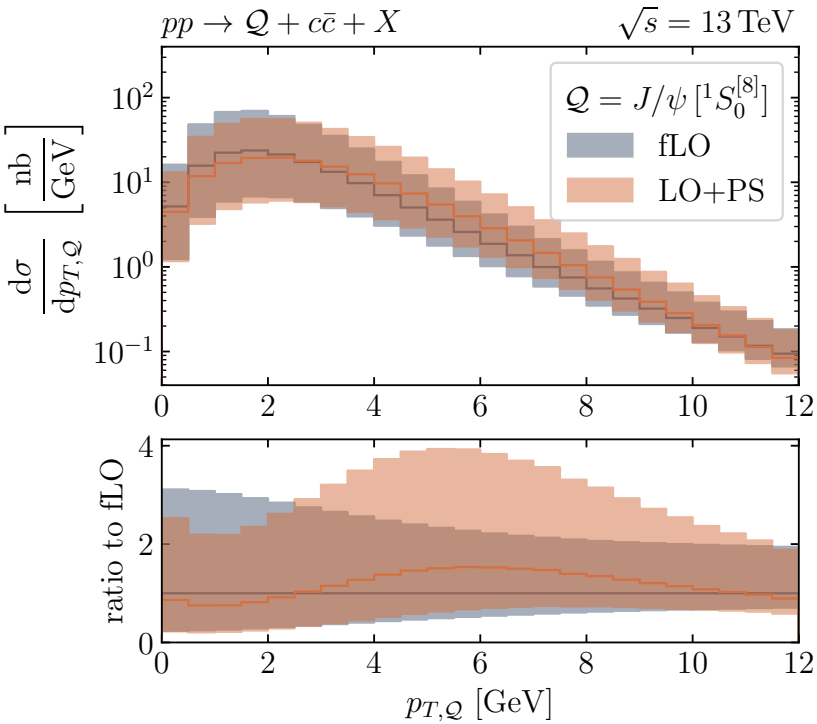
⇒

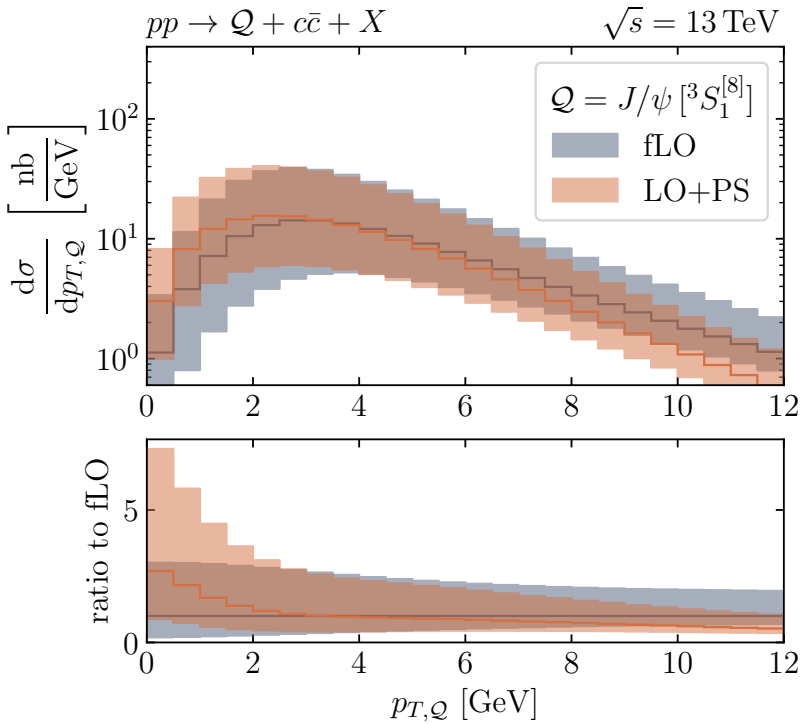
New parts in the code: search
ONIA

GitHub: release **onia** branch of MG5 version 3.x

Cross-section results for quarkonia: parton showering

p_T distribution of J/ψ in pp $\rightarrow J/\psi\, c\, \bar{c}$ + Pythia8 showering





MG5 + TMD factorisation

TMDs → quark and gluon ones

TMDs → 3D structure of the nucleon
Correlations between k_T and the polarisation of the nucleon/parton
2 components ▸ collinear (x)
▸ transversal ($\vec{k}_\perp$) → generate q_T (final-state)

Quark TMDs extracted from data
↪ SIDIS, DY processes
↪ Precision era!

Gluon TMDs → lack of data
↪ Extremely poorly know!
↪ How to measure them?
Inclusive **quarkonium** production

Prog.Part.Nucl.Phys. 122 (2022) 103906

		Quark		
		U	**L**	**T**
Nucleon	**U**	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

		Gluon		
		U	**C**	**L**
Nucleon	**U**	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

A. Bacchetta et al. (JHEP 08 (2008) 023)

TMD factorisation

Study of gluon TMDs → TMD factorisation ($q_T \ll Q$)

q_T: transverse momentum of the double-J/ψ; Q: scale of the process

P.J. Mulders, J. Rodrigues, PRD 63 094021

General factorised cross section

↪ partonic scattering amplitude $\hat{\mathcal{M}}$ (*perturbative*)

↪ k_T-dependent correlators Φ (*non-perturbative*)

$$d\sigma = \int dx_1 dx_2 d^2\vec{k}_{T1} d^2\vec{k}_{T2} \delta^{(2)}(\vec{k}_{T1} + \vec{k}_{T2} - \vec{q}_T)$$

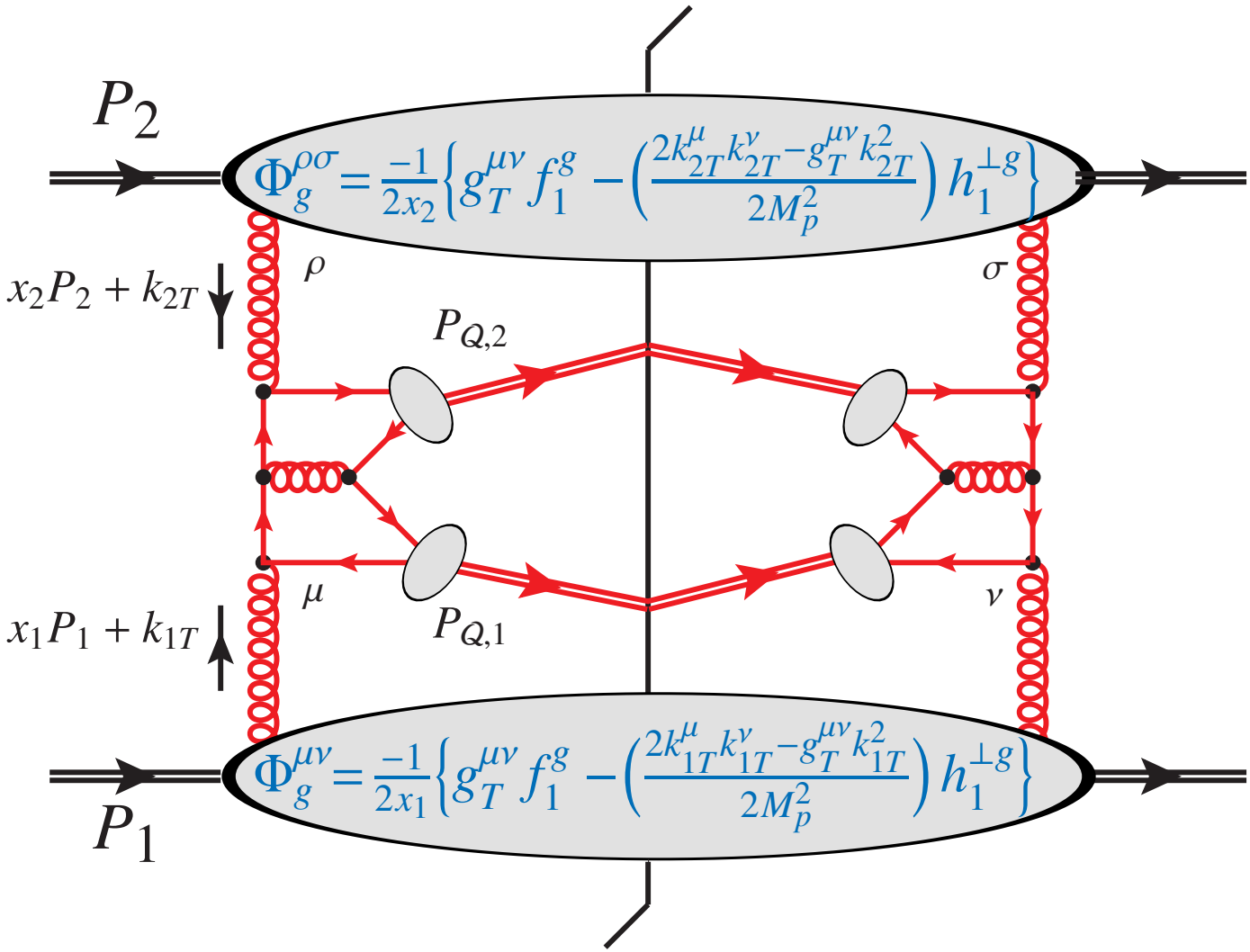
$$\times \Phi_g^{\mu\nu}(x_1, \vec{k}_{T1}) \Phi_g^{\rho\sigma}(x_2, \vec{k}_{T2}) \left[\hat{\mathcal{M}}_{\mu\rho} \hat{\mathcal{M}}^*_{\nu\sigma} \right]_{\substack{k_1 = x_1 P_1 \\ k_2 = x_2 P_2}} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

where:

$$\Phi_g^{\mu\nu}(x, \vec{k}_T) = \frac{1}{2x} \left[-g_T^{\mu\nu} f_1^g(x, \vec{k}_T^2) + \left(\frac{k_T^\mu k_T^\nu}{M_p^2} - g_T^{\mu\nu} \frac{\vec{k}_T^2}{2M_p^2} \right) h_1^{\perp g}(x, \vec{k}_T^2) \right]$$

LO Feynman diagram for $p(P_1) + p(P_2) \to \mathcal{Q}(P_{Q,1}) + \mathcal{Q}(P_{Q,1}) + X$

F. Scarpa, D. Boer, M.G. Echevarria, J.-P. Lansberg, M. Schlegel, EPJC (2020) 80:87



Hadronic cross section

The general formula for the cross section of gluon fusion is:

$$
\begin{aligned}
d\sigma^{gg} \propto & F_1 \times \mathcal{C}[f_1^g f_1^g] \\
& + F_2 \times \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}] \\
& + (F_3 \times \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3' \times \mathcal{C}[w_3' h_1^{\perp g} f_1^g]) \cos(2\Phi_{CS}) \\
& + (F_4 \times \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]) \cos(4\Phi_{CS})
\end{aligned}
$$

- first two members: azimuthally independent
- third member: $\cos(2\Phi_{CS})$-modulation
- fourth member: $\cos(4\Phi_{CS})$-modulation

$\mathcal{C}[f_1^g f_1^g]$ drives the q_T dependence

J.-P. Lansberg, C. Pisano, F. Scarpa, M. Schlegel, PLB 784(2018) 217

Computation of azimuthal modulations (average)

The corresponding expressions for $\cos(2\Phi_{CS})$ and $\cos(4\Phi_{CS})$:

$$\langle \cos 2\phi \rangle = \frac{1}{2} \frac{(F_3 \times \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3' \times \mathcal{C}[w_3' h_1^{\perp g} f_1^g])}{F_1 \times \mathcal{C}[f_1^g f_1^g] + F_2 \times \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}]}$$

$$\langle \cos 4\phi \rangle = \frac{1}{2} \frac{(F_4 \times \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}])}{F_1 \times \mathcal{C}[f_1^g f_1^g] + F_2 \times \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}]}$$

- Modulations due to $h_1^{\perp g}$
- First measurement by LHCb: JHEP 2403 (2024) 088

$$\langle \cos 2\phi \rangle = -0.029 \pm 0.050\,(\text{stat}) \pm 0.009\,(\text{syst})$$

$$\langle \cos 4\phi \rangle = -0.087 \pm 0.052\,(\text{stat}) \pm 0.013\,(\text{syst})$$

In MadGraph? Work in terms of helicities!

J.-P. Lansberg, C. Pisano, M. Schlegel, Nucl.Phys.B 920 (2017) 192-210

$$\rightarrow d\sigma = \frac{(2\pi)^4}{S^2}\, dPS_n \sum_{\lambda_a,\bar{\lambda}_a,\lambda_b,\bar{\lambda}_b=\pm 1} \frac{1}{(N_c^2-1)^2} \times$$
$$\sum_{a,b;I} \mathcal{A}^{ab}_{\lambda_a,\lambda_b;I}(\bar{k}_a,\bar{k}_b;\{P_i\})\mathcal{A}^{ab*}_{\bar{\lambda}_a,\bar{\lambda}_b;I}(\bar{k}_a,\bar{k}_b;\{P_i\}) \times$$
$$\int d^2k_{aT} \int d^2k_{bT}\delta^{(2)}(d^2k_{aT}+d^2k_{bT}-d^2q_T)\times$$
$$\Phi_{\bar{\lambda}_a,\lambda_a}(x_a,d^2k_{aT},\zeta_a,\mu)\Phi_{\bar{\lambda}_b,\lambda_b}(x_b,d^2k_{bT},\zeta_b,\mu)+\mathcal{O}(q_T/Q)$$

$$\Phi_{\lambda_a,\bar{\lambda}_a} = \frac{1}{2x_a}\left(\delta_{\lambda_a,\bar{\lambda}_a}\ f_1^g + \frac{k_{ax}^2-k_{ay}^2-2i\lambda_a k_{ax}k_{ay}}{2M^2}\delta_{\lambda_a,-\bar{\lambda}_a}\, h_1^{\perp g}\right)$$

gg fusion in arbitrary unpolarised process [colourless final state]

$$d\sigma^{gg} \propto \overbrace{\Big(\sum_{\lambda_a,\lambda_b} \hat{\mathcal{M}}_{\lambda_a,\lambda_b} \hat{\mathcal{M}}^*_{\lambda_a,\lambda_b}\Big)}^{F_1} \mathcal{C}[f_1^g f_1^g]$$

⇒ helicity non-flip, azimuthally independent

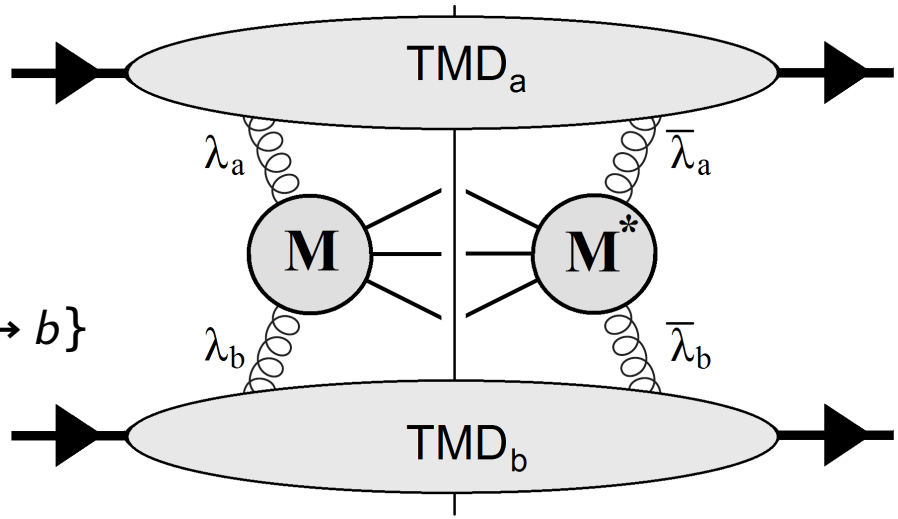
$$+\overbrace{\Big(\sum_{\lambda} \hat{\mathcal{M}}_{\lambda,\lambda} \hat{\mathcal{M}}^*_{-\lambda,-\lambda}\Big)}^{F_2} \mathcal{C}[w_2 \times h_1^{\perp g} h_1^{\perp g}]$$

⇒ double helicity flip, azimuthally independent

$$+\overbrace{\Big(\sum_{\lambda_a,\lambda_b} \hat{\mathcal{M}}_{\lambda_a,\lambda_b} \hat{\mathcal{M}}^*_{-\lambda_a,\lambda_b}\Big)}^{F_3} \mathcal{C}[w_3 \times f_1^g h_1^{\perp g}] + \{a \longleftrightarrow b\}$$

⇒ single helicity flip, $\cos(2\phi)$-modulation

$$+\overbrace{\Big(\sum_{\lambda} \hat{\mathcal{M}}_{\lambda,-\lambda} \hat{\mathcal{M}}^*_{-\lambda,\lambda}\Big)}^{F_4} \mathcal{C}[w_4 \times h_1^{\perp g} h_1^{\perp g}]$$

⇒ double helicity flip, $\cos(4\phi)$-modulation

[Slide courtesy of Jean-Philippe]