Extensions of MadGraph5_aMC@NLO for QCD studies

Implementation of quarkonium production

EPS-HEP 2025

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in collaboration with C. Flett, J.-P. Lansberg, O. Mattelaer, H.-S. Shao, L. Simon

July 11, 2025

MadGraph5_aMC@NLO = diagram/amplitude/event generator

⋆ compute matrix element in helicity-amplitude formalism

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

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- 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: **Quarkonium states** and **Asymmetric collisions**

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

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

↪ *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:

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

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

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

Quarkonium amplitudes: colour and spin projectors

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

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

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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

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

boundstates.py

```
# J/psi
jpsi_13s11 = Boundstate(pdg_code = 443,
                        name = 'Jpsi(1|3S11)',
                        particle = 'c',
                        antiparticle = 'c~',
                        principal = 1,
                        spin = 3,
                        orbital = 0,
                        J = 1,
                        color = 1,
                        charge = 0,
                        texname = 'jpsi13S11')

jpsi_11s08 = Boundstate(pdg_code = 9941003,
                        name = 'Jpsi(1|1S08)',
                        particle = 'c',
```

(Boundstate class similar to Particle)

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

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

```
MG_aMC > display fockstates
```

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

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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Generate process: single, associated and multiple production

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

```
MG_aMC >
```

Quarkonium : interface implementation

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MG_aMC >
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(or `sm_onia-c_mass`)

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It will be equivalent to:

```
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1. Benchmarked our matrix elements squared against `Helac-Onia`

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1. Benchmarked our matrix elements squared against `Helac-Onia`
2. Benchmarked cross section for quarkonium production processes

Matrix-element benchmarking

Using the standalone mode within MadGraph5:

- g g > $J/\psi(1|3S18)$ g

Phase-space point (input)			
E	px	py	pz
0.5000000E+03	0.0000000E+00	0.0000000E+00	0.5000000E+03
0.5000000E+03	0.0000000E+00	0.0000000E+00	-0.5000000E+03
0.5000048E+03	0.1109232E+03	0.4448265E+03	-0.1995510E+03
0.4999952E+03	-0.1109232E+03	-0.4448265E+03	0.1995510E+03

↓

Matrix-element results:

MadGraph5	0.004119538625333256 GeV^0
Helac-Onia	0.004119538625384255 GeV^0

- g g > $J/\psi(1|3S18)$ $J/\psi(1|3S18)$ g

MadGraph5	$7.834108245259083 \cdot 10^{-11}$ GeV^0
Helac-Onia	$7.834108245162441 \cdot 10^{-11}$ GeV^0

- g g > $J/\psi(1|3S11)$ $\Upsilon(1|3S18)$ g

MadGraph5	$1.1567670809229112 \cdot 10^{-15}$ GeV^0
Helac-Onia	$1.1567669436267628 \cdot 10^{-15}$ GeV^0

- g g > $J/\psi(1|3S11)$ $e^{+}e^{-}$ g

MadGraph5	$1.1045368093659422 \cdot 10^{-15}$ GeV^0
Helac-Onia	$1.1045244940481948 \cdot 10^{-15}$ GeV^0

Cross-section benchmarking

Phase-space integration

MadGraph5 employs multichannelling for integration (VEGAS)

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

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

$\downarrow$

Sufficient for all phenomenologically relevant cases

Benchmarked cross-sections predictions against Helac-Onia

$\Rightarrow$

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

Cross-section results

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

HEFT: quarkonium in association to Higgs boson

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

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

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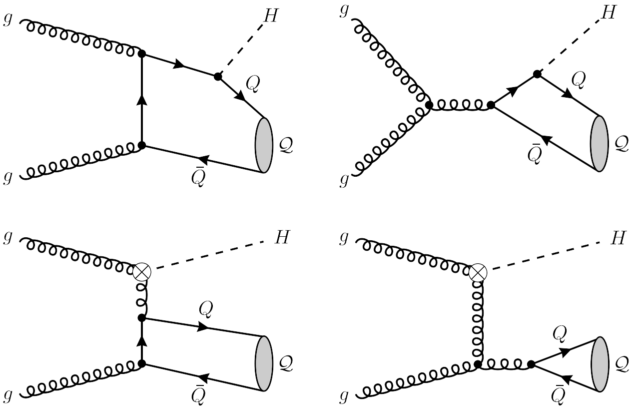

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From the mg5amcnlo folder: type `./bin/mg5_aMC`

```
MG_aMC >
```

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```
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```
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MG_aMC > generate g g > Upsilon H
```

similar for J/ψ

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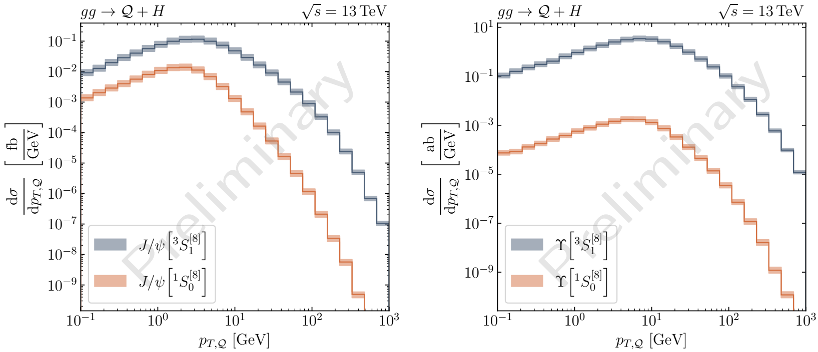
similar for J/ψ

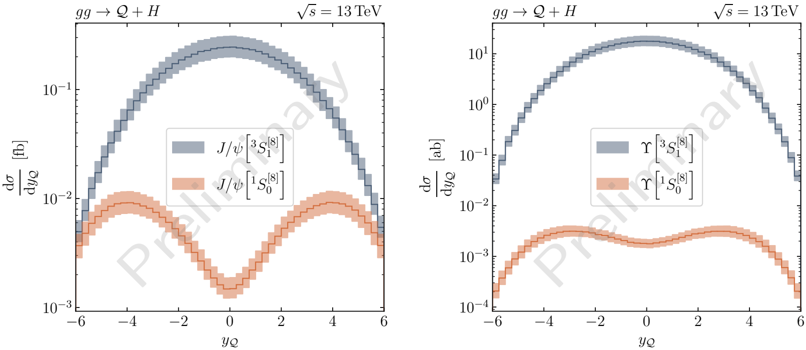
$$\sigma(gg \to J/\psi + H) = 1.53^{+0.40}_{-0.29}\,\text{fb}$$
$$\sigma(gg \to \Upsilon + H) = 91^{+23}_{-17}\,\text{ab}$$

★ p_T distributions for J/ψ and Υ



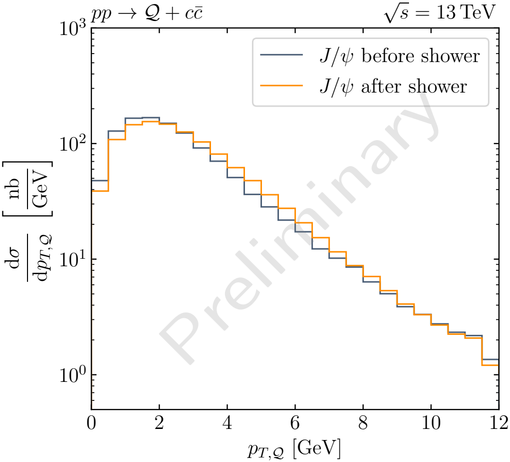
HEFT: quarkonium in association to Higgs boson

★ rapidity distributions for J/ψ and Υ



Cross-section results for quarkonia: parton showering

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



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

- leptonium states also included (lepton-antilepton)
- final testing, cross-section results, parton showering
- *Automating S-wave NRQCD and NRQED bound-state calculations within the MadGraph5_aMC@NLO framework* in preparation 2508.XXXXX

Next steps: include ⋆ P-wave states ⋆ NLO extension JHEP 07 (2024), 050

Implementation of asymmetric collisions in `MG5`: done ✓

- hadron-hadron (AB) results PLB 866 (2025) 139554, 2501.14487
- photoproduction (eA) results + publication soon 2410.17061

Next: ⋆ All codes on online platform: https://nloaccess.in2p3.fr

Summary and outlook

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

- leptonium states also included (lepton-antilepton)
- final testing, cross-section results, parton showering
- *Automating S-wave NRQCD and NRQED bound-state calculations within the MadGraph5_aMC@NLO framework* in preparation 2508.XXXXX

Next steps: include ⋆ P-wave states ⋆ NLO extension JHEP 07 (2024), 050

Implementation of asymmetric collisions in MG5: done ✓

- hadron-hadron (AB) results PLB 866 (2025) 139554, 2501.14487
- photoproduction (eA) results + publication soon 2410.17061

Next: ⋆ All codes on online platform: https://nloaccess.in2p3.fr

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

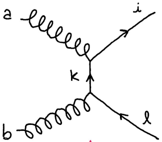
☐ Extensions to states with leading P-wave Fock states
LO implementation ⟶ ☐ NLO in the easiest way possible!

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

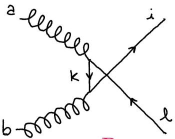
Quarkonium in the quantum state n → colour singlet or octet?

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

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

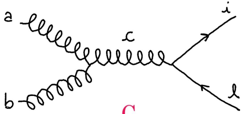


A



B

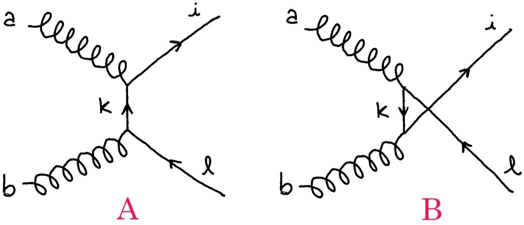
Colour Singlet contribution



C

Colour Octet contribution

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

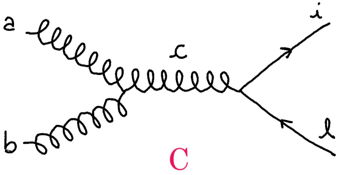


(A) $\sim (t^a_{ik} t^b_{kl}) = (t^a t^b)_{il}$ $\longrightarrow$ we set $(t^a t^b)_{il} = c1$

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

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

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



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

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

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

$$\vdots$$

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

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

- Colour singlet:

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

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

- Colour octet:

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

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

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

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`

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 organised into colour basis **JAMPs**

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

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

JAMP decomposition

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

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

(Depends on spin projectors - constructed from helas routines)
Efficiency: large number of Feynman diagrams possible...

...but colour basis much smaller!

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Warsaw University of Technology

New parts in the code: search
ONIA

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

Master integral for asymmetric collisions

Currently in `MadGraph5` (symmetric AA collisions):

$$\sigma(\mathrm{AA} \to X) = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i^{\mathrm{A}}(x_i, \mu_F; \mathrm{LHAID}) f_j^{\mathrm{A}}(x_j, \mu_F; \mathrm{LHAID}) \hat{\sigma}_{(ij \to X)}$$

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For asymmetric collisions (hadron-hadron AB):

$$\sigma(\mathrm{AB} \to X) = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i^{\mathrm{A}}(x_i, \mu_F; \mathrm{LHAID1}) f_j^{\mathrm{B}}(x_j, \mu_F; \mathrm{LHAID2}) \hat{\sigma}_{(ij \to X)}$$

↪ work done by C. Flore, D. Kikoła, A. Kusina, J-P. Lansberg, O. Mattelaer and A. Safronov

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For asymmetric collisions (hadron-hadron AB):

$$\sigma(\mathrm{AB} \to X) = \sum_{i,j} \int \mathrm{d}x_i \mathrm{d}x_j f_i^{\mathrm{A}}(x_i, \mu_F; \mathrm{LHAID1}) f_j^{\mathrm{B}}(x_j, \mu_F; \mathrm{LHAID2}) \hat{\sigma}_{(ij \to X)}$$

↪ work done by C. Flore, D. Kikoła, A. Kusina, J-P. Lansberg, O. Mattelaer and A. Safronov

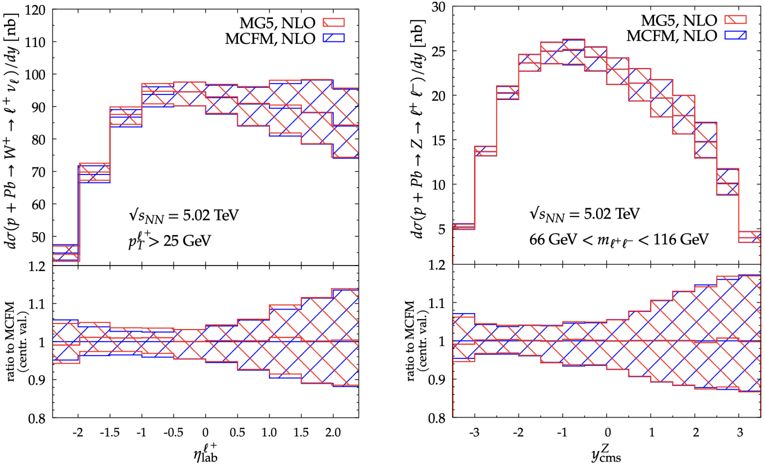
For asymmetric collisions (photoproduction eA):

$$\sigma(\mathrm{eA} \to X) = \sum_{j} \int \mathrm{d}x_\gamma \mathrm{d}x_j f_\gamma^{\mathrm{e}}(x_\gamma, Q^2_{\mathrm{max}}) f_j^{\mathrm{A}}(x_j, \mu_F; \mathrm{LHAID}) \hat{\sigma}_{(\gamma j \to X)}$$

↪ work done by C. Flore, D. Kikoła, J-P. Lansberg, O. Mattelaer and L. Manna

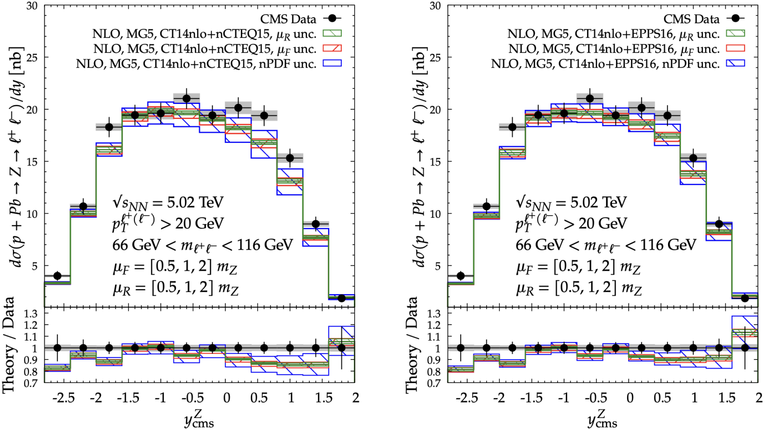
Automated NLO calculations for asymmetric hadron-hadron collisions in MadGraph5_aMC@NLO
2501.14487

Validation with MCFM for ⋆W^+ and ⋆Z production in pPb



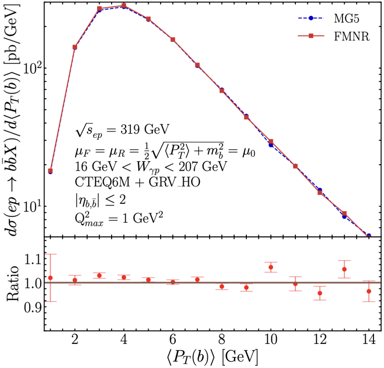
Automated NLO calculations for asymmetric hadron-hadron collisions in MadGraph5_aMC@NLO
2501.14487

NLO computation of Z production in pPb and CMS data

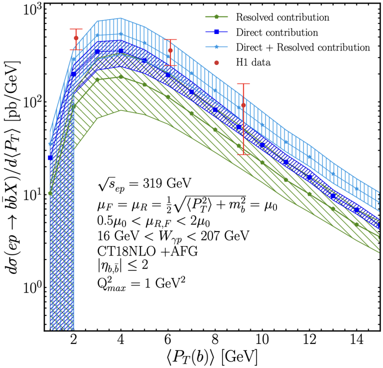


Resolved photoproduction in MadGraph5_aMC@NLO
2410.17061

★ validation with FMNR



★ comparison to HERA H1 data



Asymmetric collisions (photoproduction eA)

Resolved photoproduction in MadGraph5_aMC@NLO
2410.17061

b quark direct and resolved photoproduction at ⋆ 45 GeV ⋆ 140 GeV