Quarkonium Production with MG5aMC

MadGraph5_aMC@NLO meeting 2025

Lukas Simon

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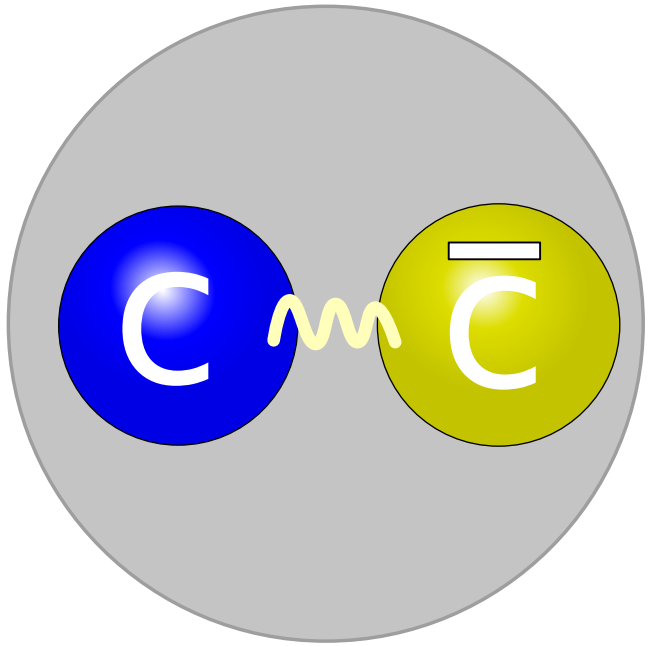
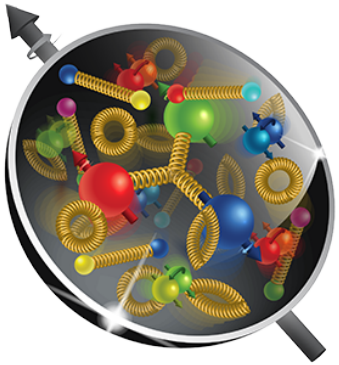
February 3, 2025

Quarkonium Production

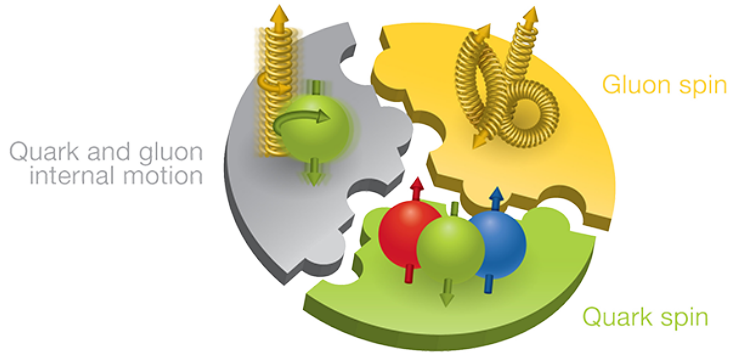


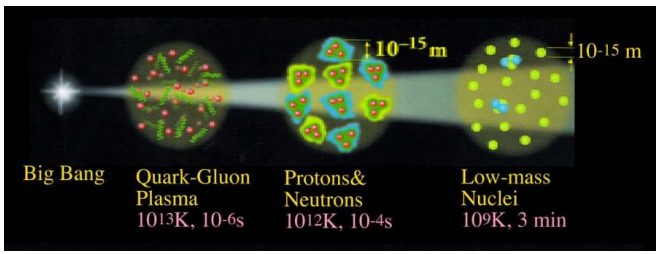
Phenomenological relevance



gluon PDFs
quarkonia are dominantly produced via gluon fusion and give direct access to the momentum distributions of gluons in nuclei and parton correlations in protons

spin puzzle
quarkonia can help to unravel the role of the gluon spin and angular momentum in the nucleon spin





quark-gluon plasma
quarkonia are sensitive to probe the properties of the quark-gluon plasma in nucleus-nucleus collisions

Quarkonium production in NRQCD factorisation

$$\mathrm{d}\sigma(AB \to H + X) = \sum_n \Big(\sum_{a,b,X} \int \mathrm{d}x_a \mathrm{d}x_b \; f_{a/A}(x_a) f_{b/B}(x_b) \;\; \mathrm{d}\hat{\sigma}(ab \to Q\bar{Q}'[n] + X) \Big) \; \langle \mathcal{O}_n^H \rangle$$

Quarkonium production in NRQCD factorisation

$$\mathrm{d}\sigma(AB \to H + X) = \sum_n \Big(\sum_{a,b,X} \int \mathrm{d}x_a \mathrm{d}x_b \underbrace{f_{a/A}(x_a) f_{b/B}(x_b)}_{\text{PDF}} \, \mathrm{d}\hat{\sigma}(ab \to Q\bar{Q}'[n] + X) \Big) \langle \mathcal{O}_n^H \rangle$$

Parton Distribution Function (PDF)

- parton distribution functions of partons a and b in the initial hadrons A and B

Quarkonium production in NRQCD factorisation

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Parton Distribution Function (PDF)

- parton distribution functions of partons a and b in the initial hadrons A and B

Partonic cross section

- short distance production of a $Q\bar{Q}'$ pair in a colour representation C, with spin S and orbital angular momentum state L
- spectroscopic notation of Fock states: $n = {}^{2S+1}L_J^{[C]}$

Quarkonium production in NRQCD factorisation

$$\mathrm{d}\sigma(AB \to H + X) = \sum_n \Big(\sum_{a,b,X} \int \mathrm{d}x_a \mathrm{d}x_b \, f_{a/A}(x_a) f_{b/B}(x_b) \, \mathrm{d}\hat{\sigma}(ab \to Q\bar{Q}'[n] + X) \Big) \langle \mathcal{O}_n^H \rangle$$

PDF — partonic cross section — LDME

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Long Distance Matrix Element (LDME)

- hadronisation of the heavy quark pair into the physical quarkonium state H

Amplitudes with quarkonia

Projection to Fock states

$$a(k_1)b(k_2) \to Q(k_3)\bar{Q}'(k_4) + \dots$$

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

Amplitudes with quarkonia

Projection to Fock states

$$a(k_1)b(k_2) \to Q(k_3)\bar{Q}'(k_4) + \dots$$

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

colour projection

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

Colour projector

$$\mathbb{P}_{C=1} = \frac{\delta^{c_3 c_4}}{\sqrt{N_c}}$$

$$\mathbb{P}_{C=8} = \sqrt{2}\, T^{c_3 4}_{c_4 c_3}$$

Amplitudes with quarkonia

Projection to Fock states

$$a(k_1)b(k_2) \to Q(k_3)\bar{Q}'(k_4) + \dots$$

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

colour projection

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

spin projection

$$\mathcal{A}_{\{[C],S\}}(r) = \sum_{\lambda_Q,\lambda_{\bar{Q}'}} \mathbb{P}_S \mathcal{A}_{\{[C]\}}(r)$$

Spin projector

$$\mathbb{P}_{S=0} = \frac{\bar{v}_{\lambda_{\bar{Q}'}}(k_4)\gamma_5 u_{\lambda_Q}(k_3)}{2\sqrt{2m_Q m_{\bar{Q}'}}}$$

$$\mathbb{P}_{S=1} = \frac{\bar{v}_{\lambda_{\bar{Q}'}}(k_4)\not{\epsilon}^*_{\lambda_s}(K) u_{\lambda_Q}(k_3)}{2\sqrt{2m_Q m_{\bar{Q}'}}}$$

with

$$K^\mu = k_3^\mu + k_4^\mu$$

Amplitudes with quarkonia

Projection to Fock states

$$a(k_1)b(k_2) \to Q(k_3)\bar{Q}'(k_4) + \dots$$

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spin projection

$$\mathcal{A}_{\{[C],S\}}(r) = \sum_{\lambda_Q,\lambda_{\bar{Q}'}} \mathbb{P}_S \mathcal{A}_{\{[C]\}}(r)$$

orbital angular momentum projection

$$\mathcal{A}_{\{[C],S,L\}}(r) = \left[\left(\varepsilon^{\mu,*}_{\lambda_l}(K)\frac{d}{dq^\mu}\right)^L \mathcal{A}_{\{[C],S\}}(r)\right]_{q=0}$$

Orbital angular momentum

$$k_3^\mu = \frac{m_Q}{m_Q + m_{\bar{Q}'}}K^\mu + q^\mu$$

$$k_4^\mu = \frac{m_{\bar{Q}'}}{m_Q + m_{\bar{Q}'}}K^\mu - q^\mu$$

Amplitudes with quarkonia

Projection to Fock states

$$a(k_1)b(k_2) \to Q(k_3)\bar{Q}'(k_4) + \dots$$

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

colour projection

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

spin projection

$$\mathcal{A}_{\{[C],S\}}(r) = \sum_{\lambda_Q,\lambda_{\bar{Q}'}} \mathbb{P}_S \mathcal{A}_{\{[C]\}}(r)$$

orbital angular momentum projection

$$\mathcal{A}_{\{[C],S,L\}}(r) = \left[\left(\varepsilon^{\mu,*}_{\lambda_l}(K)\frac{d}{dq^\mu}\right)^L \mathcal{A}_{\{[C],S\}}(r)\right]_{q=0}$$

total angular momentum projection

$$\mathcal{A}_{\{[C],S,L,J\}}(r) = \sum_{\lambda_s,\lambda_l} \mathbb{P}_J \mathcal{A}_{\{[C],S,L\}}(r)$$

Total angular momentum

Clebsch–Gordan coefficient:

$$\mathbb{P}_J = \langle J, \lambda_j | L, \lambda_l; S, \lambda_s \rangle$$

Quarkonia in MG5aMC

MadGraph5_aMC@NLO[Alwall *et al.* (2014)]

Another tool for automated quarkonium production?

There are already automated tools for cross-section computations with NRQCD quarkonia

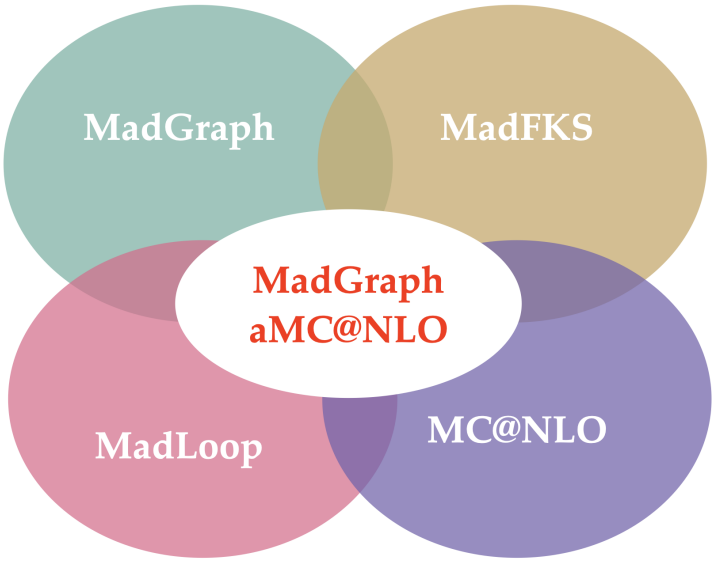
- MadOnia[Artoisenet, Maltoni, Stelzer (2008)]
  - based on MadGraph4
  - restricted to one quarkonium
- HELAC-Onia[Shao (2016)]
  - heavy-ion collisions are not supported
  - diagram selection not possible

Why MG5aMC now?

- well-established in the HEP community
- **flexible** (variety of models: HEFT, MSSM, ...)
- **all-in-one solution** (link to parton shower and analysis tools)
- NRQCD bound states **beyond quarkonia** (positronium etc.)
- automation of **NLO** is feasible[Ajjath, Shao, LS (2024)]

MadGraph5_aMC@NLO[Alwall *et al.* (2014)]

Automatic
tree-level matrix
element generator



Automation of real
corrections using
FKS subtraction

Automation of
virtual corrections

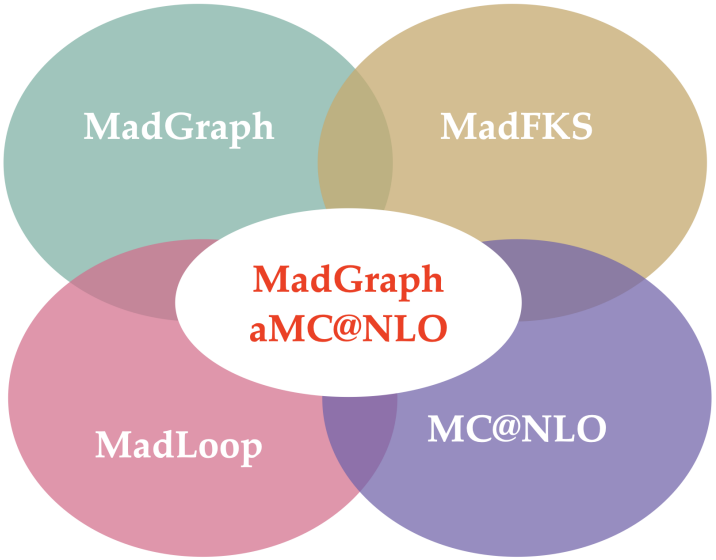
Matching
& Merging

$$\sigma^{\mathrm{NLO}} = \int \mathrm{d}\phi_n \, \mathcal{B} + \int \mathrm{d}\phi_n \, \mathcal{V} + \int \mathrm{d}\phi_{n+1} \, \mathcal{R}$$

MadGraph5_aMC@NLO[Alwall *et al.* (2014)]

Born-level contributions

Automatic
tree-level matrix
element generator



$$\sigma^{\mathrm{NLO}} = \int \mathrm{d}\phi_n \, \mathcal{B} + \int \mathrm{d}\phi_n \, \mathcal{V} + \int \mathrm{d}\phi_{n+1} \, \mathcal{R}$$

Quarkonia in MG5aMC

Physical states vs. Fock states

$$|J/\psi\rangle = \underbrace{\left|c\bar{c}[^3S_1^{[1]}]\right\rangle}_{\mathcal{O}(1)} + \underbrace{\left|c\bar{c}[^3P_J^{[8]}] + g\right\rangle}_{\mathcal{O}(v)} + \underbrace{\left|c\bar{c}[^1S_0^{[8]}] + g\right\rangle}_{\mathcal{O}(v^{3/2})} + \underbrace{\left|c\bar{c}[^3S_1^{[8]}] + gg\right\rangle}_{\mathcal{O}(v^2)} + \dots$$

↳ **Fock states** are treated as elementary particles

↳ **Physical states** are a collection of Fock states, similar to defnitions of `multiparticle`

$$\begin{aligned}\mathrm{d}\hat{\sigma}(ab \to J/\psi + X) = {} & \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^3S_1^{[1]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^3S_1^{[1]}]}\rangle + \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^3P_J^{[8]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^3P_J^{[8]}]}\rangle \\ & + \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^1S_0^{[8]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^1S_0^{[8]}]}\rangle + \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^3S_1^{[8]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^3S_1^{[8]}]}\rangle\end{aligned}$$

Quarkonia in MG5aMC

Interface: Syntax

$$\mathrm{d}\hat{\sigma}(ab \to J/\psi + X) = \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^3S_1^{[1]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^3S_1^{[1]}]} \rangle + \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^3P_J^{[8]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^3P_J^{[8]}]} \rangle$$
$$+ \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^1S_0^{[8]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^1S_0^{[8]}]} \rangle + \mathrm{d}\hat{\sigma}(ab \to c\bar{c}[^3S_1^{[8]}] + X)\langle \mathcal{O}^{J/\psi}_{c\bar{c}[^3S_1^{[8]}]} \rangle$$

The input

```
MG_aMC>generate p p > Jpsi
```

is equivalent to

```
MG_aMC>generate p p > Jpsi(1|3S11)
MG_aMC>add process p p > Jpsi(1|3PJ8)
MG_aMC>add process p p > Jpsi(1|1S08)
MG_aMC>add process p p > Jpsi(1|3S18)
```

Quarkonia in MG5aMC

Interface: Defining bound states

fockstates_default.txt
~/Software/mg5amcnlo/input

```
################################################################################
#
# Copyright (c) 2025 The MadGraph5_aMC@NLO Development team and Contributors
#
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#
# For more information, visit madgraph.phys.ucl.ac.be and amcatnlo.web.cern.ch
#
################################################################################

# N: principal quantum number
# S: spin type
# L: orbital angular momentum quantum number
# J: total angular momentum quantum number
# C: color type

pid         pythia  name            particle    anti-particle   N   S   L   J   C   charge  mass    width

####################
# Charmonia        #
####################

# etac
44111001    441     etac(1|1S01)    c           c~              1   1   0   0   1   0       2.98100 0.02970
44111008    9940001 etac(1|1S08)    c           c~              1   1   0   0   8   0       3.18100 0.0
44113018    9999999 etac(1|3S18)    c           c~              1   3   0   1   8   0       0.0     0.0
44121001    100441  etac(2|1S01)    c           c~              2   1   0   0   1   0       0.0     0.0
44121008    9999999 etac(2|1S08)    c           c~              2   1   0   0   8   0       0.0     0.0
44123018    9999999 etac(2|3S18)    c           c~              2   3   0   1   8   0       0.0     0.0

# J/psi
44313011    443     Jpsi(1|3S11)    c           c~              1   3   0   1   1   0       3.09692 0.00009
44311008    9999999 Jpsi(1|1S08)    c           c~              1   1   0   0   8   0       0.0     0.0
44313018    9940003 Jpsi(1|3S18)    c           c~              1   3   0   1   8   0       3.29692 0.0
44323011    100443  psi(2|3S11)     c           c~              2   3   0   1   1   0       3.68611 0.00030
44321008    9999999 psi(2|1S08)     c           c~              2   1   0   0   8   0       0.0     0.0
```

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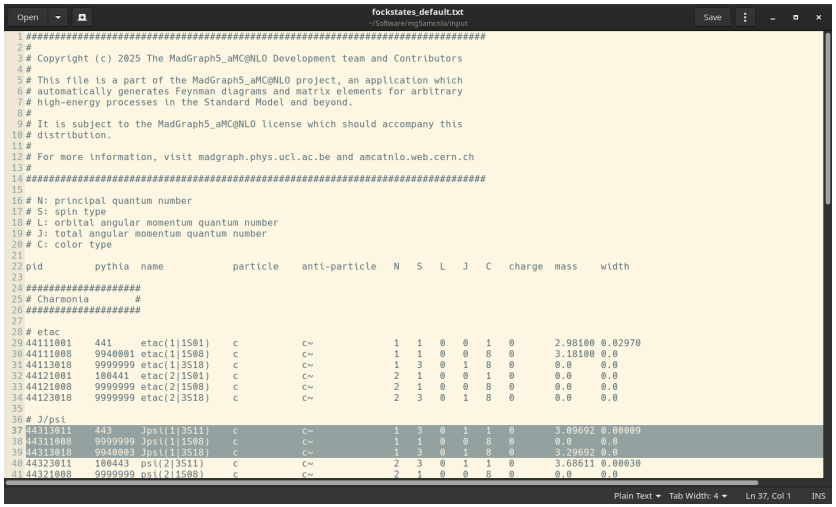
Quarkonia in MG5aMC

Interface: Defining bound states




```
1  ##########################################################################################
2  #
3  # Copyright (c) 2025 The MadGraph5_aMC@NLO Development team and Contributors
4  #
5  # This file is a part of the MadGraph5_aMC@NLO project, an application which
6  # automatically generates Feynman diagrams and matrix elements for arbitrary
7  # high-energy processes in the Standard Model and beyond.
8  #
9  # It is subject to the MadGraph5_aMC@NLO license which should accompany this
10 # distribution.
11 #
12 # For more information, visit madgraph.phys.ucl.ac.be and amcatnlo.web.cern.ch
13 #
14 ##########################################################################################
15
16 # N: principal quantum number
17 # S: spin type
18 # L: orbital angular momentum quantum number
19 # J: total angular momentum quantum number
20 # C: color type
21
22 pid         pythia  name            particle    anti-particle   N   S   L   J   C   charge  mass    width
23
24 ####################
25 # Charmonia        #
26 ####################
27
28 # etac
29 44111001    441     etac(1|1S01)    c           c~              1   1   0   0   1   0       2.98100 0.02970
30 44111008    9940001 etac(1|1S08)    c           c~              1   1   0   0   8   0       3.18100 0.0
31 44113018    9999999 etac(1|3S18)    c           c~              1   3   0   1   8   0       0.0     0.0
32 44121001    100441  etac(2|1S01)    c           c~              2   1   0   0   1   0       0.0     0.0
33 44121008    9999999 etac(2|1S08)    c           c~              2   1   0   0   8   0       0.0     0.0
34 44123018    9999999 etac(2|3S18)    c           c~              2   3   0   1   8   0       0.0     0.0
35
36 # J/psi
37 44313011    443     Jpsi(1|3S11)    c           c~              1   3   0   1   1   0       3.09692 0.00009
38 44311008    9999999 Jpsi(1|1S08)    c           c~              1   1   0   0   8   0       0.0     0.0
39 44313018    9940003 Jpsi(1|3S18)    c           c~              1   3   0   1   8   0       3.29692 0.0
40 44323011    100443  psi(2|3S11)     c           c~              2   3   0   1   1   0       3.68611 0.00030
41 44321008    9999999 psi(2|1S08)     c           c~              2   1   0   0   8   0       0.0     0.0
```

Quarkonia in MG5aMC

Interface: Defining bound states

boundstates_default.txt
~/Software/mg5amcnlo/input

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#
################################################################################
#
# Quarkonium 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
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)
# Bottomonium
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)
# Toponium
etat = etat(1|1S01) etat(1|1S08) etat(1|3S18)
etat(2s) = etat(2|1S01) etat(2|1S08) etat(2|3S18)
```

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Quarkonia in MG5aMC

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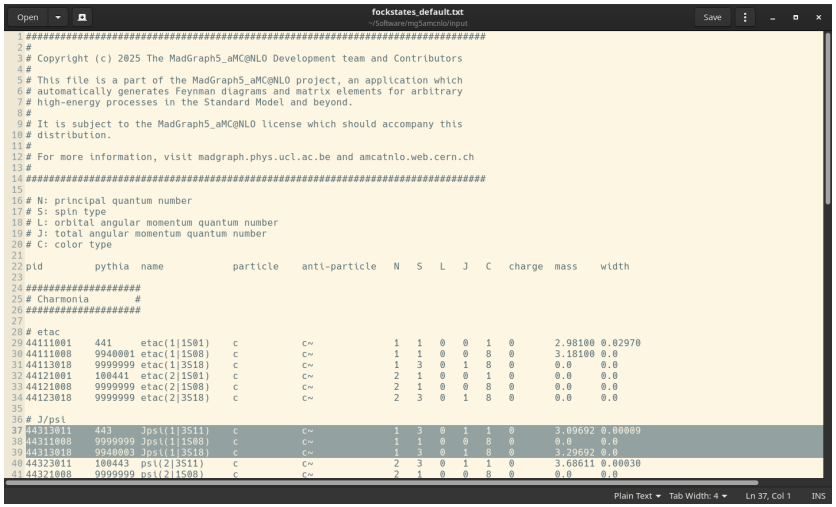


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44121001    100441  etac(2|1S01)    c           c~              2   1   0   0   1   0       0.0     0.0
44121008    9999999 etac(2|1S08)    c           c~              2   1   0   0   8   0       0.0     0.0
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# J/psi
44313011    443     Jpsi(1|3S11)    c           c~              1   3   0   1   1   0       3.09692 0.00009
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44323011    100443  psi(2|3S11)     c           c~              2   3   0   1   1   0       3.68611 0.00030
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# 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
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)
# Bottomonium
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)
# Toponium
etat = etat(1|1S01) etat(1|1S08) etat(1|3S18)
etat(2s) = etat(2|1S01) etat(2|1S08) etat(2|3S18)
```
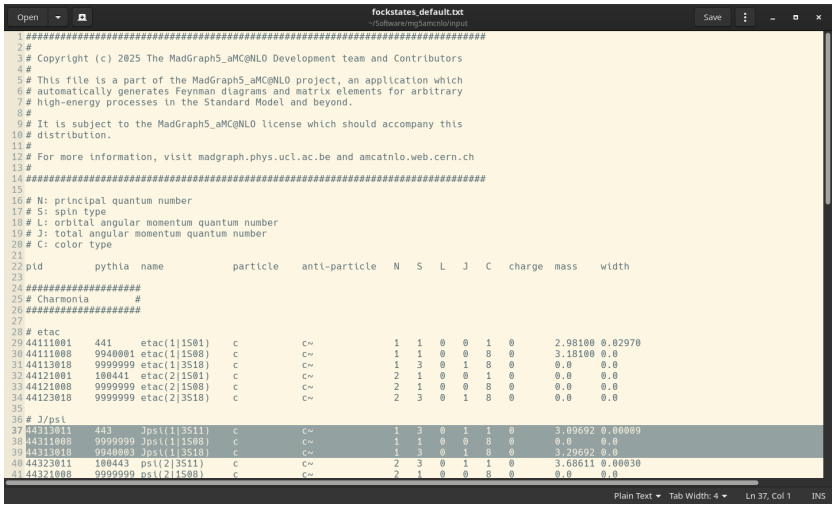

Quarkonia in MG5aMC

Interface: Defining bound states




```
INFO: Change particles name to pass to MG5 convention
Pass the definition of 'j' and 'p' to 3 flavour scheme.
Kept definitions of multiparticles l+ / l- / vl / vl~ unchanged
Defined multiparticle all = g u d s u~ d~ s~ a ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ 
Defined boundstate etac = etac(1|1S01) etac(1|1S08) etac(1|3S18)
Defined boundstate etac(2s) = etac(2|1S01) etac(2|1S08) etac(2|3S18)
Defined boundstate Jpsi = Jpsi(1|3S11) Jpsi(1|1S08) Jpsi(1|3S18)
Defined boundstate psi(2s) = psi(2|3S11) psi(2|1S08) psi(2|3S18)
Defined boundstate Bc+ = Bc+(1|1S01) Bc+(1|1S08) Bc+(1|3S18)
Defined boundstate B*c+ = B*c+(1|3S11) B*c+(1|1S08) B*c+(1|3S18)
Defined boundstate Bc- = Bc-(1|1S01) Bc-(1|1S08) Bc-(1|3S18)
Defined boundstate B*c- = B*c-(1|3S11) B*c-(1|1S08) B*c-(1|3S18)
Defined boundstate etab = etab(1|1S01) etab(1|1S08) etab(1|3S18)
Defined boundstate etab(2s) = etab(2|1S01) etab(2|1S08) etab(2|3S18)
Defined boundstate Upsilon = Upsilon(1|3S11) Upsilon(1|1S08) Upsilon(1|3S18)
Defined boundstate Upsilon(2s) = Upsilon(2|3S11) Upsilon(2|1S08) Upsilon(2|3S18)
Defined boundstate etat = etat(1|1S01) etat(1|1S08) etat(1|3S18)
Defined boundstate etat(2s) = etat(2|1S01) etat(2|1S08) etat(2|3S18)
MG5_aMC>generate g g > Jpsi
INFO: Trying to generate process g g > Jpsi(1|3S11)
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=2: WEIGTHED IS QCD+2*QED
INFO: Trying process: g g > c c~ WEIGHTED<=2 @1
INFO: Process has 3 diagrams
1 processes with 3 diagrams generated in 0.004 s
Total: 1 processes with 3 diagrams
INFO: Trying to generate process g g > Jpsi(1|1S08)
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=2: WEIGTHED IS QCD+2*QED
INFO: Trying process: g g > c c~ WEIGHTED<=2 @1
INFO: Process has 3 diagrams
1 processes with 3 diagrams generated in 0.003 s
Total: 2 processes with 6 diagrams
INFO: Trying to generate process g g > Jpsi(1|3S18)
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=2: WEIGTHED IS QCD+2*QED
INFO: Trying process: g g > c c~ WEIGHTED<=2 @1
INFO: Process has 3 diagrams
1 processes with 3 diagrams generated in 0.003 s
Total: 3 processes with 9 diagrams
MG5_aMC>output gg2jpsi
INFO: initialize a new directory: gg2jpsi
INFO: remove old information in gg2jpsi
INFO: Organizing processes into subprocess groups
INFO: Generating Helas calls for process: g g > c c~ WEIGHTED<=2 @1
INFO: Processing color information for process: g g > c c~ @1
INFO: Generating Helas calls for process: g g > c c~ WEIGHTED<=2 @1
INFO: Processing color information for process: g g > c c~ @1
INFO: Generating Helas calls for process: g g > c c~ WEIGHTED<=2 @1
```

Quarkonia in MG5aMC

Born-level contributions

Status:

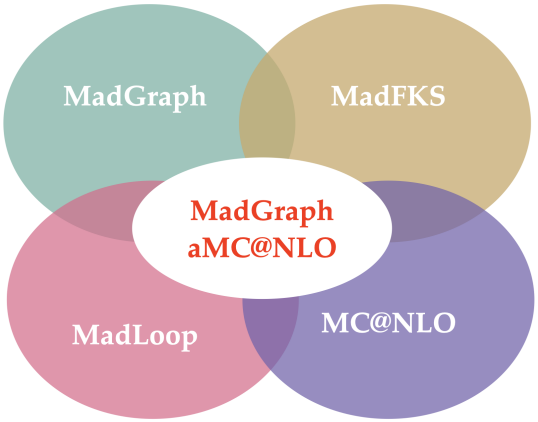
Automated tree-level amplitude generation:

$\mathcal{A}(ab \to Q\bar{Q}'[n] + X) = \mathbb{P}_J \mathbb{P}_L \mathbb{P}_S \mathbb{P}_C \mathcal{A}(ab \to Q\bar{Q}' + X)$

- colour projectors $\mathbb{P}_C$ for colour singlets ✓ and colour octets ✓
- spin projectors $\mathbb{P}_S$ for spin 0 ✓ and spin 1 ✓ states
- orbital $\mathbb{P}_L$ and total angular momentum projectors $\mathbb{P}_J$ for P-wave states ✗

Quarkonia in MG5aMC

Running modes



Standalone mode:

- self-contained `Fortran77` library
- computes $|\mathcal{A}|^2$ for given phase-space points

Standalone matrix elements for S-wave quarkonium production are **validated** against `HELAC-Onia` [Shao (2016)].

Quarkonia in MG5aMC

Born-level contributions

Status:

Automated tree-level amplitude generation:

$\mathcal{A}(ab \to Q\bar{Q}'[n] + X) = \mathbb{P}_J \mathbb{P}_L \mathbb{P}_S \mathbb{P}_C \mathcal{A}(ab \to Q\bar{Q}' + X)$

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Quarkonia in MG5aMC

Born-level contributions

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$\mathcal{A}(ab \to Q\bar{Q}'[n] + X) = \mathbb{P}_J \mathbb{P}_L \mathbb{P}_S \mathbb{P}_C \mathcal{A}(ab \to Q\bar{Q}' + X)$

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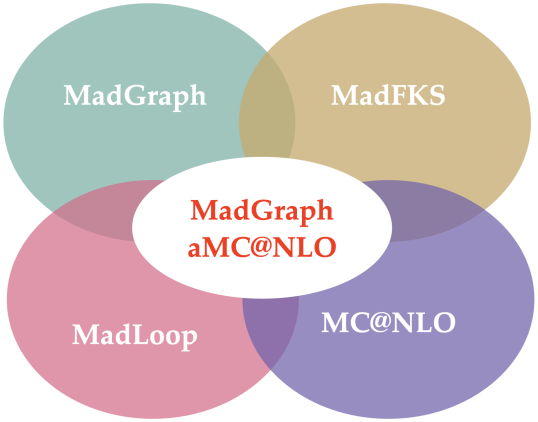
- spin projectors $\mathbb{P}_S$ for spin 0 ✓ and spin 1 ✓ states
- orbital $\mathbb{P}_L$ and total angular momentum projectors $\mathbb{P}_J$ for P-wave states ✗

Automated event generation:

- brut force phase-space integration works ✓

Quarkonia in MG5aMC

Running modes



Standalone mode:

- self-contained `Fortran77` library
- computes $|\mathcal{A}|^2$ for given phase-space points

Tree-level mode:

- paralellised integration over phase space
- fixed order cross sections

Tree-level cross sections for a few S-wave quarkonium production processes are **validated** against `HELAC-Onia` [Shao (2016)].

$\Rightarrow$(e.g. $gg \to c\bar{c}[^3S_1^{[8]}] + HHH$)

Quarkonia in MG5aMC

Born-level contributions

Status:

Automated tree-level amplitude generation:

$\mathcal{A}(ab \to Q\bar{Q}'[n] + X) = \mathbb{P}_J \mathbb{P}_L \mathbb{P}_S \mathbb{P}_C \mathcal{A}(ab \to Q\bar{Q}' + X)$

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Quarkonia in MG5aMC

Born-level contributions

Status:

Automated tree-level amplitude generation:

$\mathcal{A}(ab \to Q\bar{Q}'[n] + X) = \mathbb{P}_J \mathbb{P}_L \mathbb{P}_S \mathbb{P}_C \mathcal{A}(ab \to Q\bar{Q}' + X)$

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- spin projectors $\mathbb{P}_S$ for spin 0 ✓ and spin 1 ✓ states
- orbital $\mathbb{P}_L$ and total angular momentum projectors $\mathbb{P}_J$ for P-wave states ✗

Automated event generation:

- brut force phase-space integration works ✓

LO cross sections with an arbitrary number of S-wave quarkonia and an arbitrary number of elementary particles can be computed.

Quarkonia in MG5aMC

Born-level contributions

Status:

Automated tree-level amplitude generation:

$\mathcal{A}(ab \to Q\bar{Q}'[n] + X) = \mathbb{P}_J \mathbb{P}_L \mathbb{P}_S \mathbb{P}_C \mathcal{A}(ab \to Q\bar{Q}' + X)$

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Automated event generation:

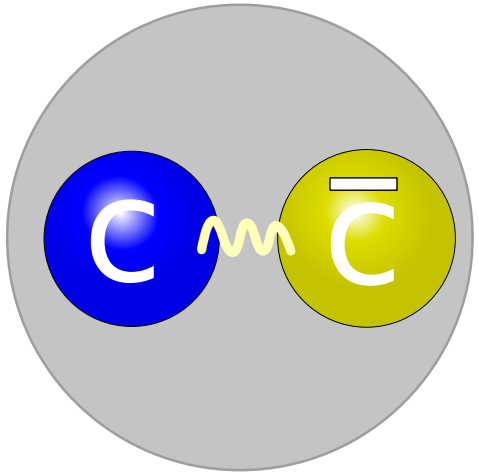
- brut force phase-space integration works ✓

LO cross sections with an arbitrary number of S-wave quarkonia and an arbitrary number of elementary particles can be computed.

Next:

Extension to **P-wave** (technical challenges) quarkonia, improve phase-space integration by adoption of **single-diagram-enhanced multi-channeling** (conceptual challenges), and **NLO** (conceptual challenges)

Summary



Summary

- **automated cross section** computations for processes with **NRQCD bound states** in a future `MadGraph5_aMC@NLO` release
  - user-friendly interface
  - easily extensible framework (arbitrary bound states, application to BSM, etc.)

Summary

- **automated cross section** computations for processes with **NRQCD bound states** in a future `MadGraph5_aMC@NLO` release
  - user-friendly interface
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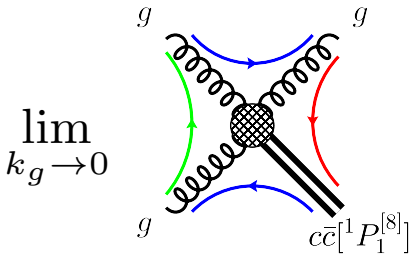
- Cross sections with **S-wave quarkonia can already be computed**

Summary

- **automated cross section** computations for processes with **NRQCD bound states** in a future `MadGraph5_aMC@NLO` release
  - user-friendly interface
  - easily extensible framework (arbitrary bound states, application to BSM, etc.)
- Cross sections with **S-wave quarkonia can already be computed**
- **P-wave in sight** – only technical challenges remaining
- first steps towards automation of fully differential **NLO cross section** in the FKS scheme made[Ajjath, Shao, LS (2024)]

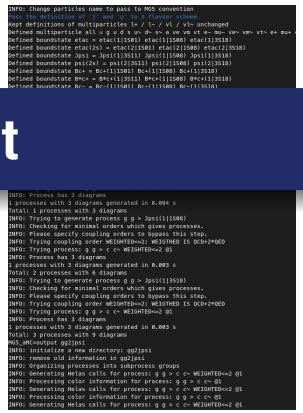


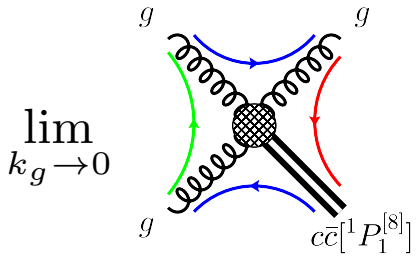
Summary

- **automated cross section** computations for processes with **NRQCD bound states** in a future `MadGraph5_aMC@NLO` release
  - user-friendly interface
  - easily extensible framework (arbitrary

check out the `onia` branch on git

- Cross sections with **S-wave quarkonia can already be computed**
- **P-wave in sight** – only technical challenges remaining
- first steps towards automation of fully differential **NLO cross section** in the FKS scheme made[Ajjath, Shao, LS (2024)]





Backup

Colour-octet spin-singlet P-wave

Soft limit of the amplitude

$$\lim_{k_g \to 0} \left(\quad + \quad \right) = \mathrm{Eik} \left(\quad \right) \otimes \quad c\bar{c}[^1P_1^{[8]}]$$

$$+ \quad c\bar{c}[^1P_1^{[8]}] \otimes \mathrm{Eik} \left(\quad c\bar{c}[^1P_1^{[8]}] \right)$$

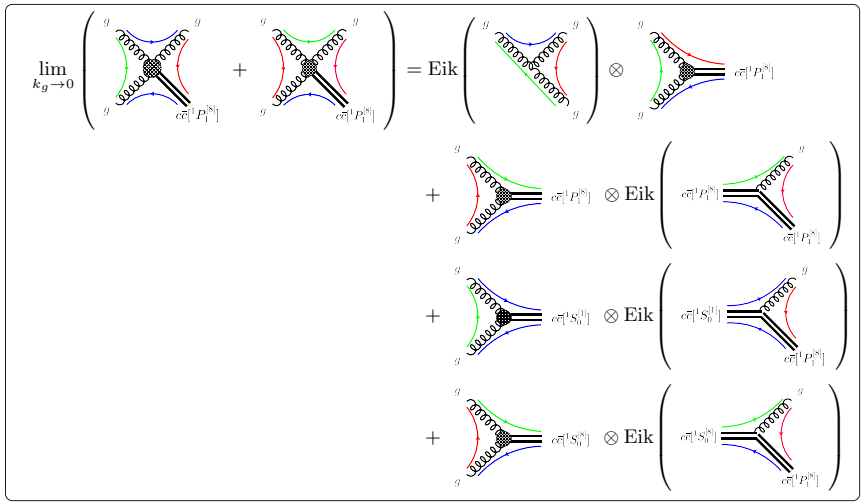
$$+ \quad c\bar{c}[^1S_0^{[1]}] \otimes \mathrm{Eik} \left(\quad c\bar{c}[^1S_0^{[1]}] \right)$$

$$+ \quad c\bar{c}[^1S_0^{[8]}] \otimes \mathrm{Eik} \left(\quad c\bar{c}[^1S_0^{[8]}] \right)$$

BACKUP

Colour-octet spin-singlet P-wave

Soft limit of the amplitude



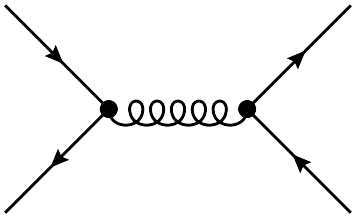
$$\lim_{k_i \to 0} \mathcal{A}_{\{[8],0,1,1\}}(r) = \sum_{\substack{j=n_I \\ j\neq i}}^{n_L^{(R)}+n_H} g_s \frac{k_j \cdot \varepsilon^*_{\lambda_i}(k_i)}{k_j \cdot k_i} \vec{Q}(\mathcal{I}) \mathcal{A}_{\{[8],0,1,1\}}(r^{\not i})$$
$$+ g_s \frac{K \cdot \varepsilon^*_{\lambda_i}(k_i)}{K \cdot k_i} \vec{Q}(Q\bar{Q}'[{}^1P_1^{[8]}]) \mathcal{A}_{\{[8],0,1,1\}}(r^{\not i})$$
$$+ g_s \left[\frac{\varepsilon^*_{\lambda_l}(K) \cdot \varepsilon^*_{\lambda_i}(k_i)}{K \cdot k_i} - \frac{K \cdot \varepsilon^*_{\lambda_i}(k_i) k_i \cdot \varepsilon^*_{\lambda_l}(K)}{(K \cdot k_i)^2} \right]$$
$$\times \left[\vec{Q}_{\text{eff}}(Q\bar{Q}'_{[81]}) \mathcal{A}_{\{[1],0,0,0\}}(r^{\not i}) + \vec{Q}_{\text{eff}}(Q\bar{Q}'_{[88]}) \mathcal{A}_{\{[8],0,0,0\}}(r^{\not i}) \right]$$

BACKUP

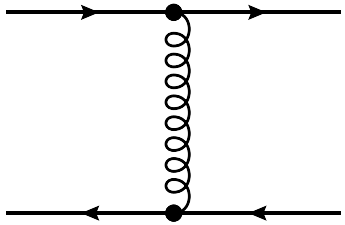
Phase-space integration in a nutshell

Single-diagram-enhanced multi-channel integration

Example: $q\bar{q} \to q\bar{q}$



peak in s



peak in t

Single-diagram-enhanced multi-channel integration[Maltoni, Stelzer (2003)]:

$$\int \mathrm{d}\Pi_2 \left|\mathcal{A}_1 + \mathcal{A}_2\right|^2 = \int \mathrm{d}\Pi_2 \left(\underbrace{\left|\mathcal{A}_1\right|^2 \frac{\left|\mathcal{A}_1 + \mathcal{A}_2\right|^2}{\left|\mathcal{A}_1\right|^2 + \left|\mathcal{A}_2\right|^2}}_{\text{peak in } s} + \underbrace{\left|\mathcal{A}_2\right|^2 \frac{\left|\mathcal{A}_1 + \mathcal{A}_2\right|^2}{\left|\mathcal{A}_1\right|^2 + \left|\mathcal{A}_2\right|^2}}_{\text{peak in } t} \right)$$

Phase-space parametrisation[Byckling, Kajantie (1971)]:

$$\int \mathrm{d}\Pi_n \sim \int \mathrm{d}M_{n-1} \int \mathrm{d}\Omega_n \cdots \int \mathrm{d}M_2 \int \mathrm{d}\Omega_3 \int \mathrm{d}\Omega_2$$

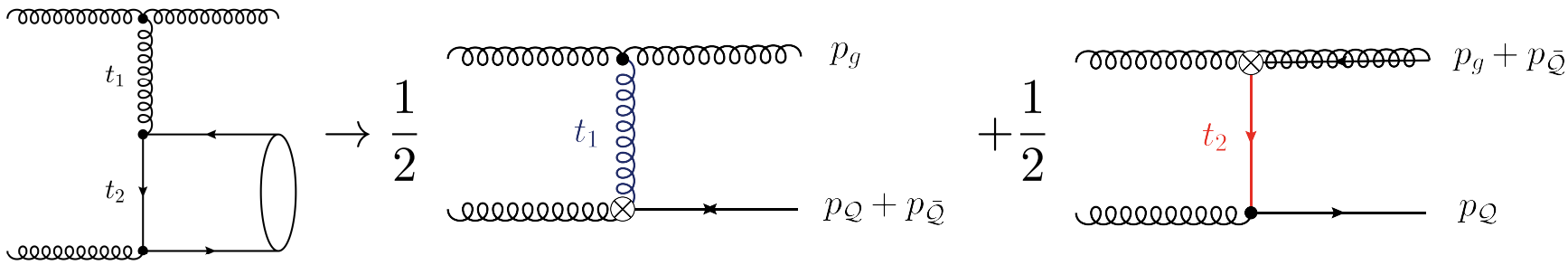
$$\int \mathrm{d}\Pi_n \sim \int \mathrm{d}M_{n-1} \int \mathrm{d}\phi_n \int \mathrm{d}t_{n-1} \cdots \int \mathrm{d}M_2 \int \mathrm{d}\phi_3 \int \mathrm{d}t_2 \int \mathrm{d}\phi_2 \int \mathrm{d}t_1$$

BACKUP

Quarkonia in MG5aMC

Phase-space integration: Single-diagram-enhanced multi-channel integration

Example: $gg \to \mathcal{Q}\bar{\mathcal{Q}}[n]g$



Issue: Two t-channel peaks, but only one can be integration parameter

$$\text{either} \quad \int \mathrm{d}\Pi_2 \sim \int \mathrm{d}t_1 \quad \text{or} \quad \int \mathrm{d}\Pi_2 \sim \int \mathrm{d}t_2$$

Solution:

$$\int \mathrm{d}\Pi_2 = \frac{1}{2} \int \underbrace{\mathrm{d}\Pi_2}_{\sim \mathrm{d}t_1} + \frac{1}{2} \int \underbrace{\mathrm{d}\Pi_2}_{\sim \mathrm{d}t_2}$$

- Momentum $p_{\mathcal{Q}} + p_{\bar{\mathcal{Q}}}$ of bound state is integration parameter
- Momentum $p_{\mathcal{Q}}$ of bound state's parton is integration parameter
  $\to$ new parametrisation is required

BACKUP

Quarkonia in MG5aMC

Interface: Input cards

Open | param_card.dat | ~/MadGraph/gg2Jpsi/Cards | Save

```
#####################################################################
## PARAM_CARD AUTOMATICALLY GENERATED BY MG5 FOLLOWING UFO MODEL   ####
#####################################################################
##                                                                  ##
##  Width set on Auto will be computed following the information    ##
##        present in the decay.py files of the model.               ##
##        See  arXiv:1402.1178 for more details.                    ##
##                                                                  ##
#####################################################################

###################################
## INFORMATION FOR MASS
###################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.250000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000e+00 # d : 0.0
  2 0.000000e+00 # u : 0.0
  3 0.000000e+00 # s : 0.0
  4 0.000000e+00 # c : 0.0
```

Plain Text | Tab Width: 4 | Ln 38, Col 1 | INS

BACKUP

Quarkonia in MG5aMC

Interface: Input cards

```
###################################################################
## PARAM_CARD AUTOMATICALLY GENERATED BY MG5 FOLLOWING UFO MODEL   ####
###################################################################
##                                                                ##
##  Width set on Auto will be computed following the information    ##
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##        See  arXiv:1402.1178 for more details.                  ##
##                                                                ##
###################################################################

#####################################
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#####################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
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  1 0.000000e+00 # d : 0.0
  2 0.000000e+00 # u : 0.0
  3 0.000000e+00 # s : 0.0
  4 0.000000e+00 # c : 0.0
```

BACKUP

Quarkonia in MG5aMC

Interface: Input cards

Open | onia_card.dat | ~/MadGraph/gg2Jpsi/Cards | Save

```
##########################################################################
##
## Copyright (c) 2025 The MadGraph5_aMC@NLO Development team and Contributors
##
## This file is a part of the MadGraph5_aMC@NLO project, an application which
## automatically generates Feynman diagrams and matrix elements for arbitrary
## high-energy processes in the Standard Model and beyond.
##
## It is subject to the MadGraph5_aMC@NLO license which should accompany this
## distribution.
##
## For more information, visit madgraph.phys.ucl.ac.be and amcatnlo.web.cern.ch
##
##########################################################################
#
#*********************************************************************
# Long distance matrix elements (LDME)                               *
#*********************************************************************
Block ldme
   44311008  0.0150000000000000   # LDME for jpsi(1|1s08)
   44313011  1.1599999999999999   # LDME for jpsi(1|3s11)
   44313018  0.0090000000000000   # LDME for jpsi(1|3s18)
```

Plain Text | Tab Width: 4 | Ln 31, Col 4 | INS

BACKUP

Quarkonia in MG5aMC

Interface: Input cards

param_card.dat
~/MadGraph/gg2Jpsi/Cards

```
#####################################################################
## PARAM_CARD AUTOMATICALLY GENERATED BY MG5 FOLLOWING UFO MODEL    ####
#####################################################################
##                                                                  ##
##  Width set on Auto will be computed following the information    ##
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##                                                                  ##
#####################################################################

###################################
## INFORMATION FOR MASS
###################################
Block mass
     5 4.700000e+00 # MB
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   1 0.000000e+00 # d : 0.0
   2 0.000000e+00 # u : 0.0
   3 0.000000e+00 # s : 0.0
   4 0.000000e+00 # c : 0.0
```

Plain Text | Tab Width: 4 | Ln 38, Col 1 | INS

onia_card.dat
~/MadGraph/gg2Jpsi/Cards

```
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##
#*******************************************************************************
#
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# Long distance matrix elements (LDME)                               *
#*********************************************************************
Block ldme
    44311008  0.0150000000000000   # LDME for jpsi(1|1s08)
    44313011  1.1599999999999999   # LDME for jpsi(1|3s11)
    44313018  0.0090000000000000   # LDME for jpsi(1|3s18)
```

Plain Text | Tab Width: 4 | Ln 31, Col 4 | INS

BACKUP