Implementation of Quarkonium Production cross sections within Madgraph

International Workshop on Heavy Quarkonium

17-20 October 2007, DESY Hamburg

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PLAN

- Introduction: the purpose of MadOnia
- Capabilities and Validation
- Illustration and Ongoing Studies
- Conclusion and Perspectives

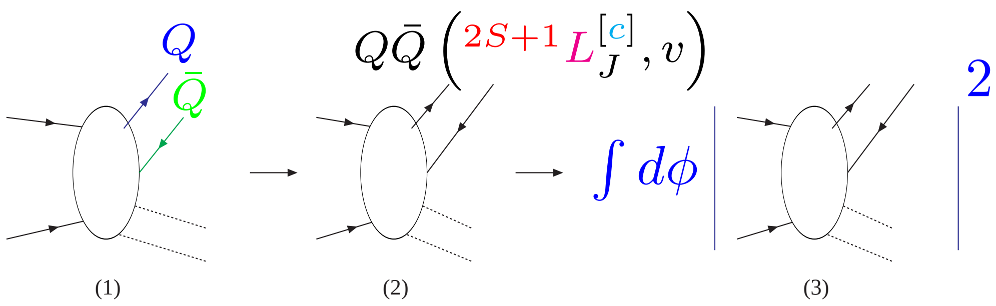
Introduction: the purpose of MadOnia

- 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

- capabilities:
  - universality: MadOnia generates any helicity amplitude

$$\mathcal{M}\left(ij \to Q\bar{Q}\left({}^{2S+1}L_J^{[c]}\right) + X\right)$$

    at tree-level, for any model that can be implemented in MadGraph
  - it keeps track of quantum numbers on event-by-event basis $\longrightarrow$ events ready for showering and hadronization (in particular, calculation in terms of color-ordered amplitudes).
  - $Q\bar{Q}'$ production: the quark and the anti-quark can be of different flavour (such as B_c)
  - double quarkonium production (ex: $e^+e^- \longrightarrow J/\psi\eta_c$)
  - relativistic corrections for S-wave state production can be computed

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^-

Illustration

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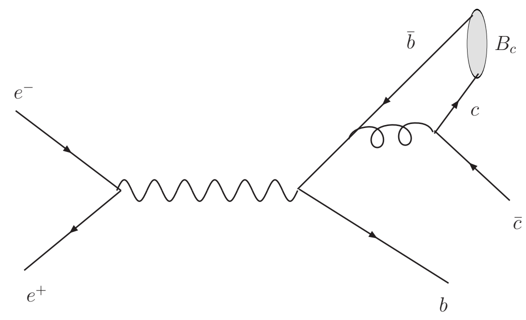
$$e^+e^- \to b\bar{c}B_c(^3S_1^{[1]})$$



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
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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)

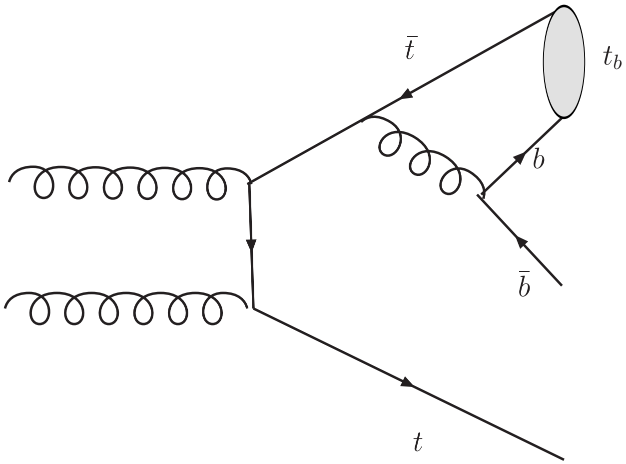
	$^1S_0[8]$	$^3S_1[8]$	$^1P_1[8]$	$^3P_0[8]$	$^3P_1[8]$	$^3P_2[8]$
e^+e^-	1.64	2.31	0.162	0.105	0.217	0.235
$\gamma\gamma$	$5.38\,10^{-4}$	$5.42\,10^{-3}$	$1.69\,10^{-4}$	$2.83\,10^{-5}$	$6.04\,10^{-5}$	$2.77\,10^{-4}$
γp	1.15	8.25	0.494	$7.45\,10^{-2}$	0.238	1.57
pp	$4.20\,10^5$	$1.88\,10^6$	$1.19\,10^5$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

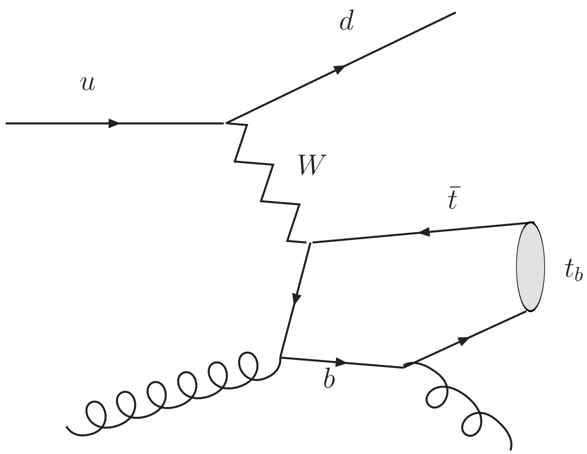
TIMING: 5' to enter all processes in the input card, 2 hours of run

Illustration

- Testing new ideas: t_b production at the LHC

$$V_{tb} = 0.3, \quad |R_{tb}|^2 = 8.13\,\text{GeV}^3$$



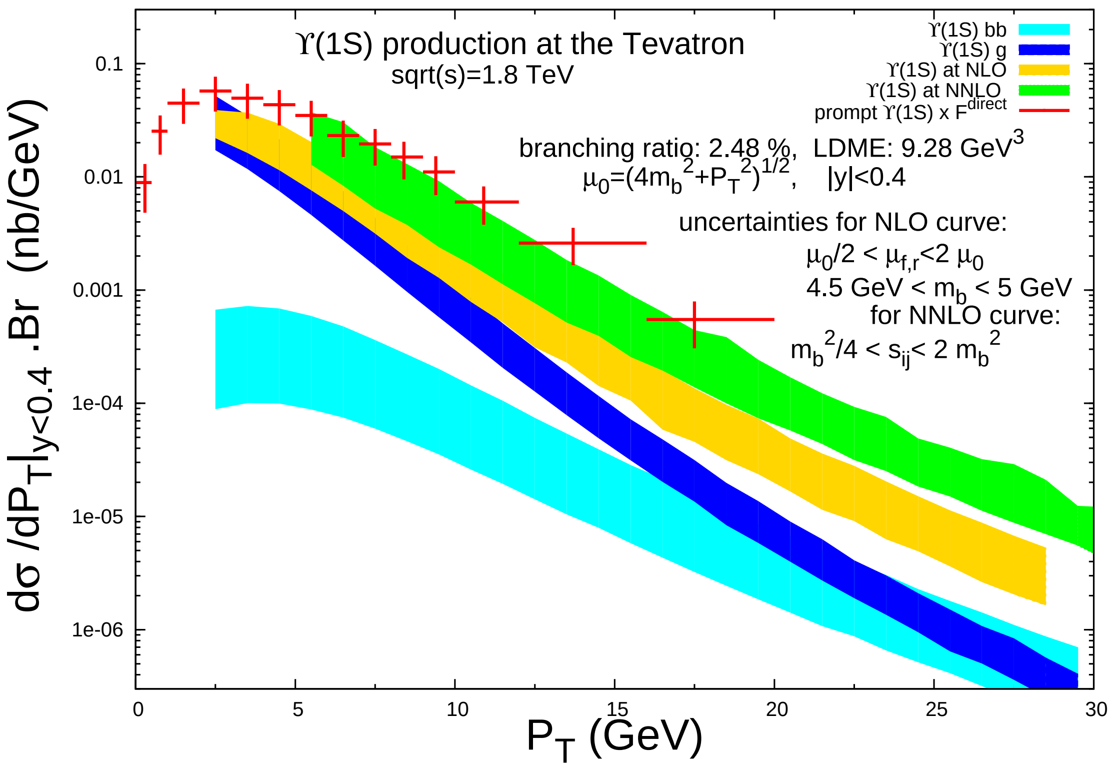


$\sigma = 9.95$ fb

$\sigma = 2.52$ fb

Current studies:

- $\Upsilon + 3$ jets production at the Tevatron



Current studies:

- 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	

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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 projections are applied)

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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
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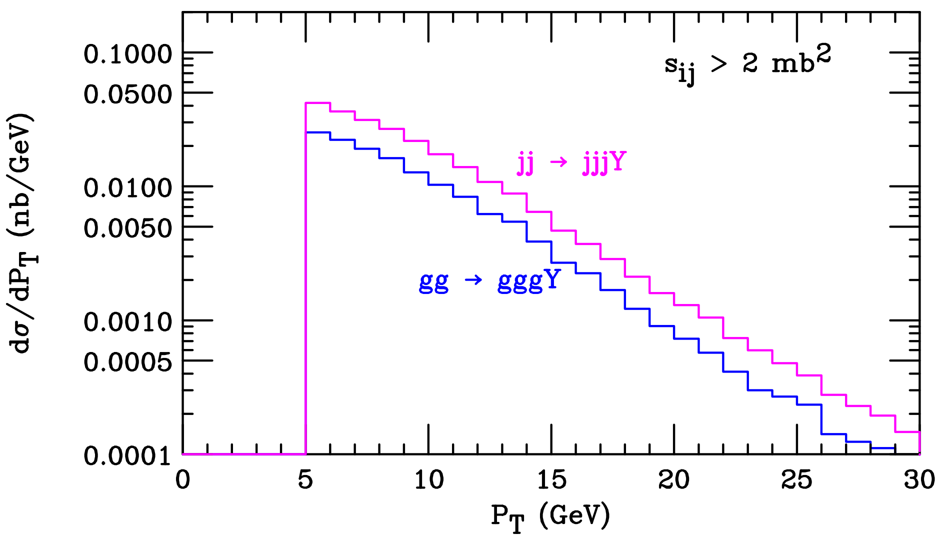

Current studies:

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

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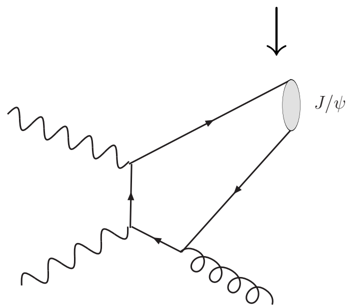
$\gamma\gamma \to gJ/\psi(^3S_1[8])$



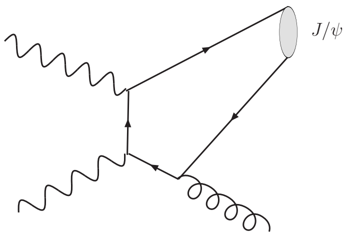
6 Feynman diagrams

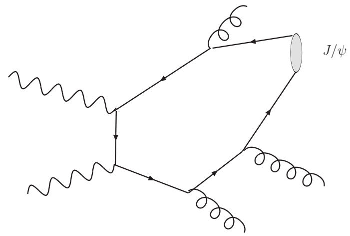
Current studies:

- 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

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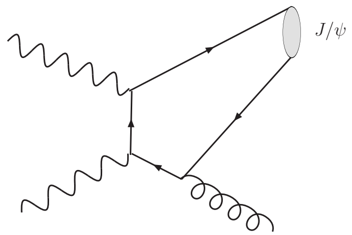
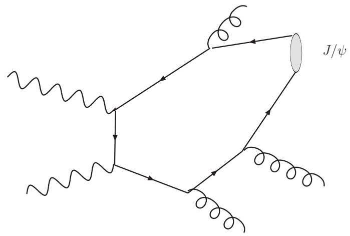
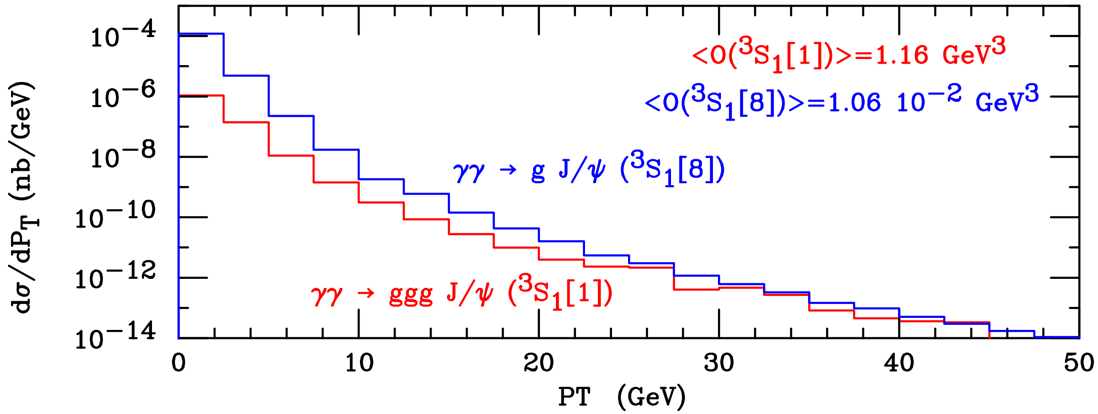


6 Feynman diagrams



120 Feynman diagrams

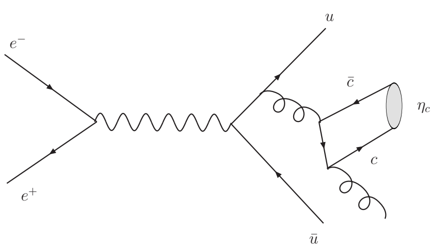


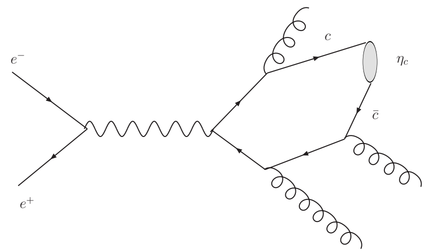
Current studies:

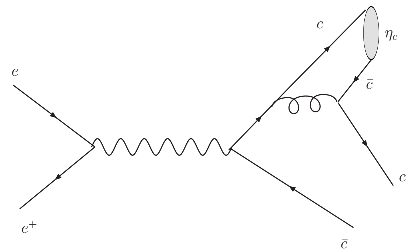
- $e^+e^- \to \eta_c + X$ @ 10.6 GeV

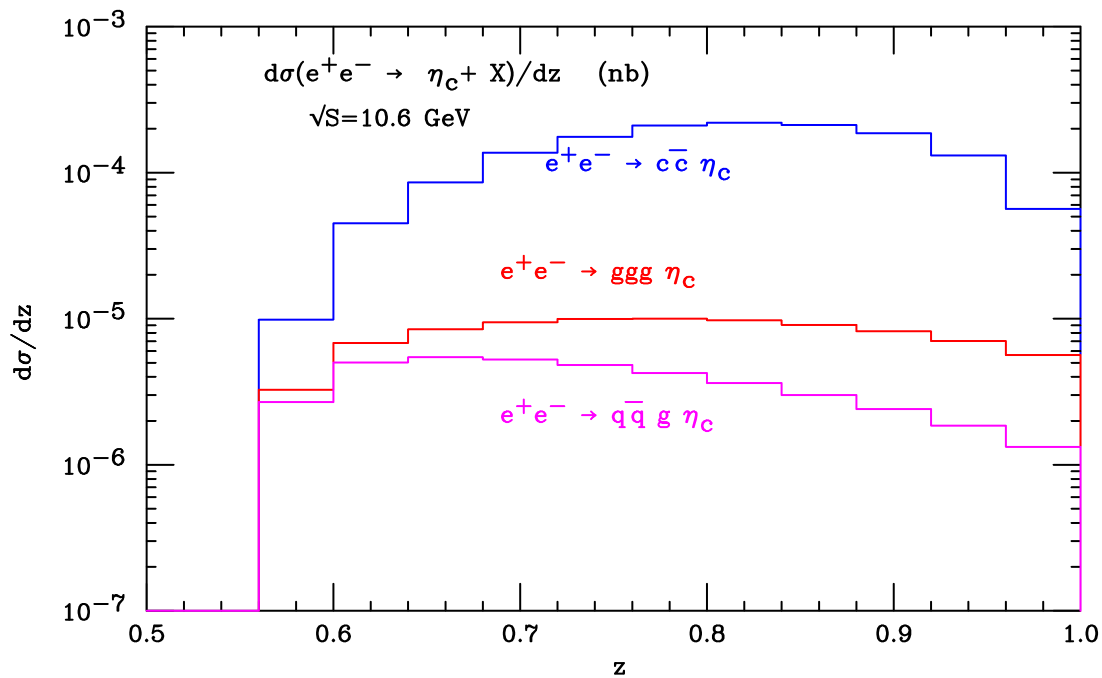
  subprocesses:

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









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

Conclusion & Perspectives

- MadOnia is an amplitude generator for quarkonium production within NRQCD which is:
  - universal (new model can be defined)
  - user-friendly
  - flexible
- Examples of application:
  - $p\bar{p} \to \Upsilon + 3$ jets at the Tevatron
  - $e^+e^- \to \eta_c + X$ at B factories
- work in progress: event generator with interfaces to Pythia and Herwig