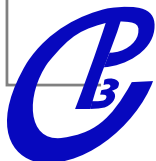


# Automatic Generation of Quarkonium Amplitudes in NRQCD

*Lunch seminar*  
*14 November 2007*

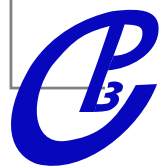
Pierre Artoisenet

Center of Particle Physics and Phenomenology  
Université Catholique de Louvain

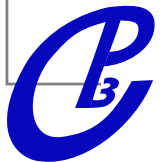


# PLAN

- Introduction: the heavy quarkonium system
- MadOnia: a new code for quarkonium production
- Illustration
- Ongoing studies:  $J/\psi$  and  $\Upsilon$  hadroproduction
- Conclusion and Perspectives

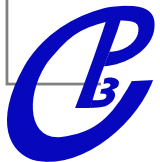
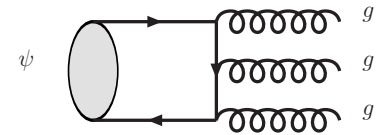
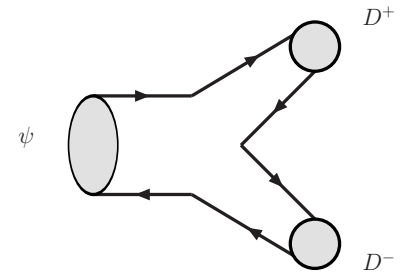
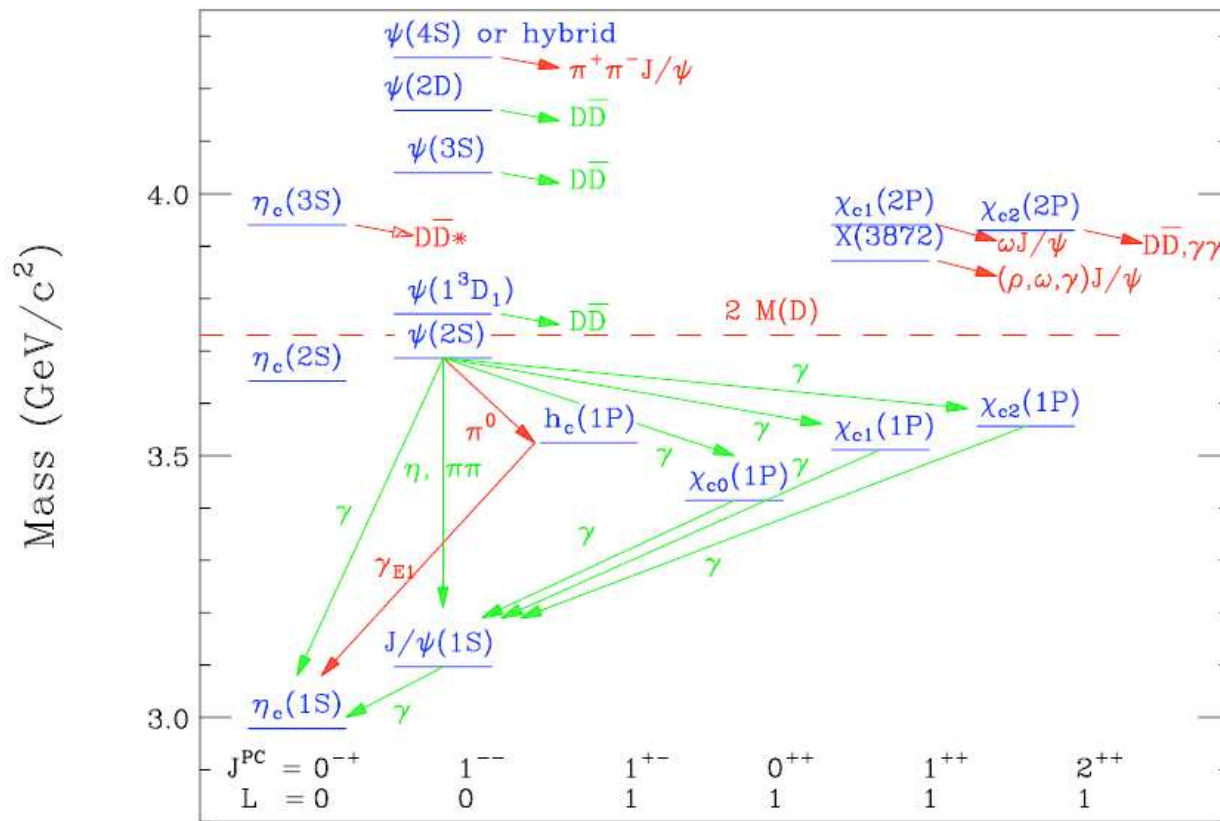


# Introduction: the heavy quarkonium system



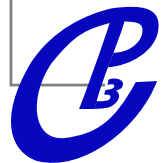
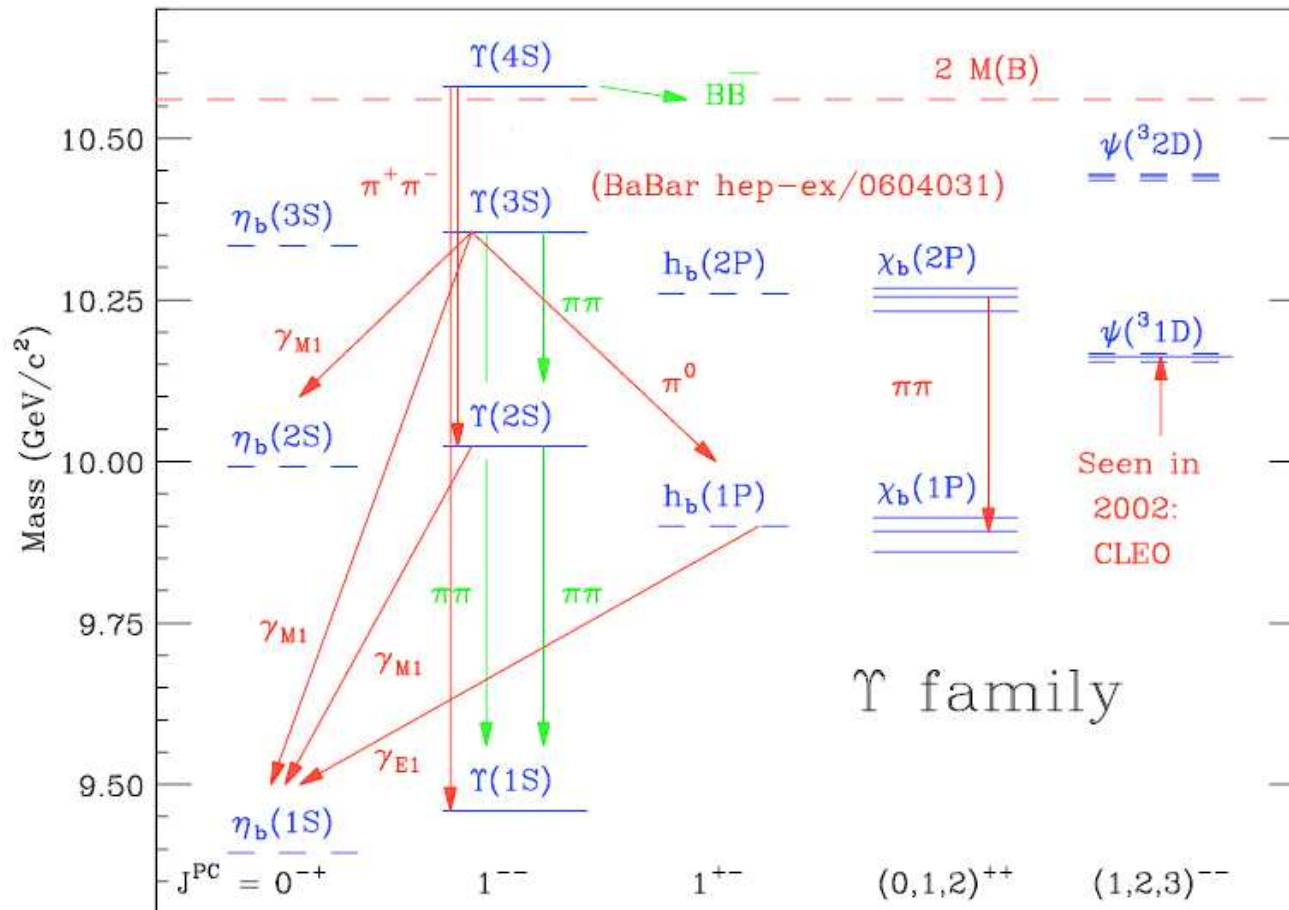
# Heavy quarkonium system

- charmonium:  $c\bar{c}$  bound state ( $\frac{v^2}{c^2} \approx 0.3$ )



# Heavy quarkonium system

- bottomonium:  $b\bar{b}$  bound state ( $\frac{v^2}{c^2} \approx 0.1$ )



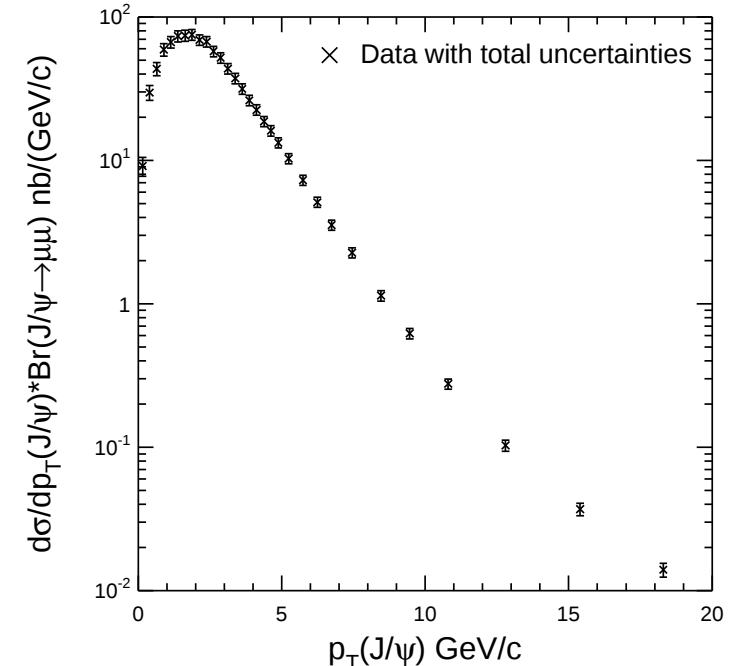
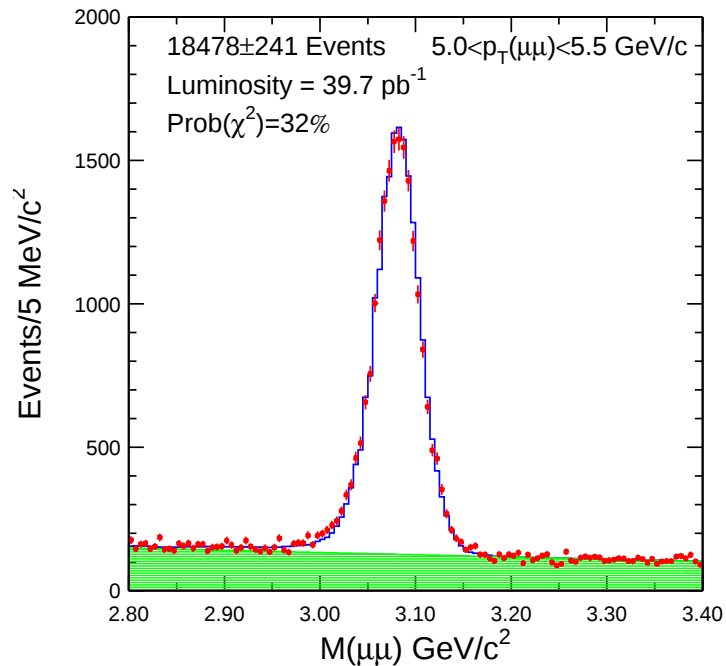
# Heavy quarkonium system

● experimental observation

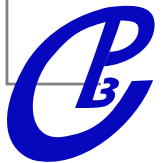
●  $Q(1^{--}) \rightarrow l^+ l^-$

● very clean signature in hadron colliders

example:  $J/\psi$  production at the Tevatron II ( $\sqrt{s} = 1.96$  TeV)

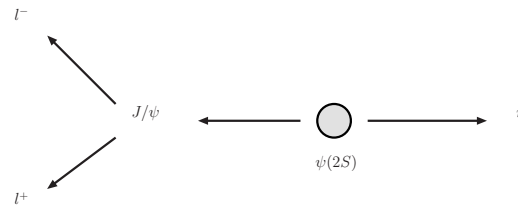


Phys. Rev. D 71 032001 (2005)



# Heavy quarkonium system

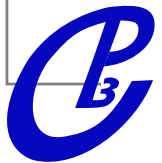
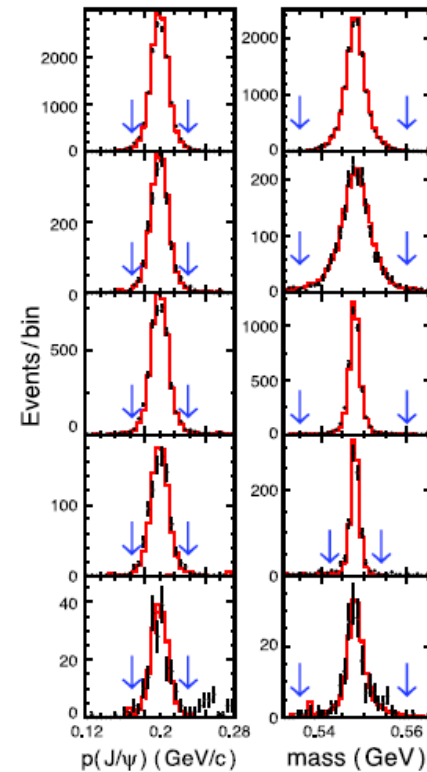
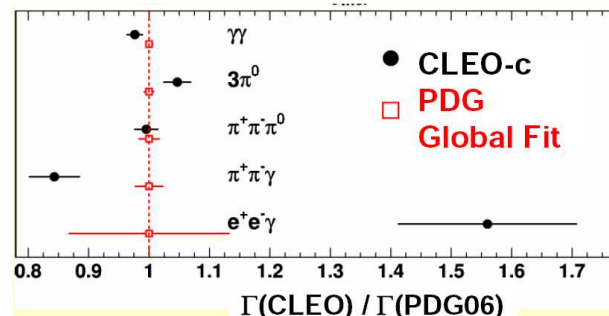
- experimental observation
- $Q(1^{--}) \rightarrow l^+ l^-$
- can be used as a probe for exclusive measurement  
example:  $e^+ e^- \rightarrow \psi(2S) \rightarrow J/\psi \eta$  (A. Lopez eta al, PRL 99 122001 (2007))



27M  $\psi(2S)$

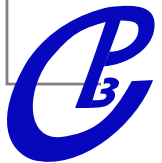
$$Br(\psi(2S) \rightarrow J/\psi \eta) = 3.1\%$$

$$Br(J/\psi \rightarrow l^+ l^-) = 12\%$$



# Heavy quarkonium system

- experimental observation
  - $Q(1^{--}) \rightarrow l^+ l^-$
  - $\chi_{c,b}$  states can be observed through radiative decays (E transitions)



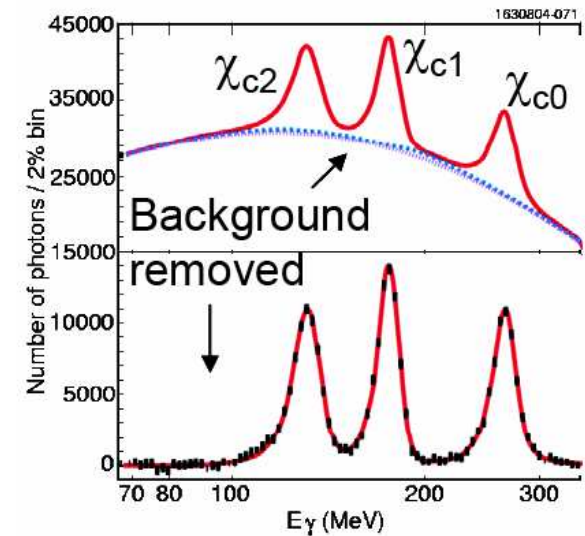
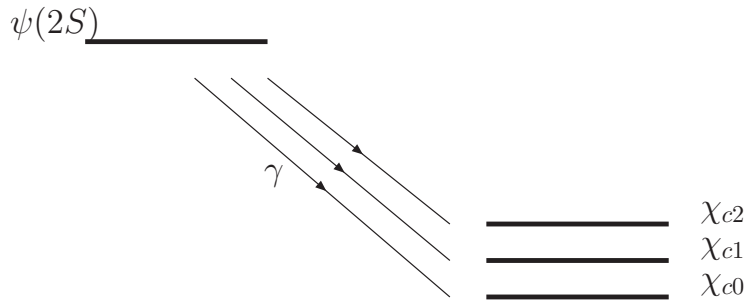
# Heavy quarkonium system

● experimental observation

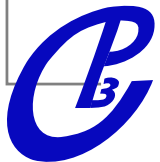
●  $Q(1^{--}) \rightarrow l^+ l^-$

●  $\chi_{c,b}$  states can be observed through radiative decays (E transitions)

Example 1: measurement of  $\chi_c$  decays at Cleo



$\chi_{cj}$  decays to  $\gamma\gamma$ ,  $\pi\pi$ ,  $KK$ ,  $\eta^{(\prime)}\eta^{(\prime)}$ , baryon/anti-baryon, multibody final states (H. Mahlke, Charmonium results from Cleo)



# Heavy quarkonium system

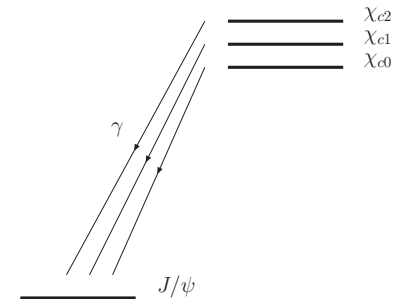
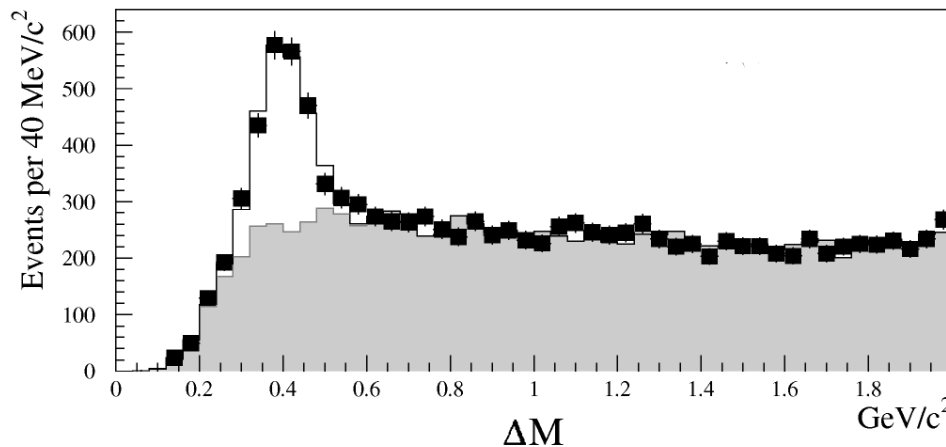
● experimental observation

●  $Q(1^{--}) \rightarrow l^+ l^-$

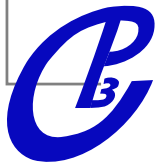
●  $\chi_{c,b}$  states can be observed through radiative decays (E transitions)

Example 2:  $p\bar{p} \rightarrow \chi_c + X, \quad \chi_c \rightarrow J/\psi \gamma$

$$\Delta M = m(\mu^+ \mu^- \gamma) - m(\mu^+ \mu^-)$$

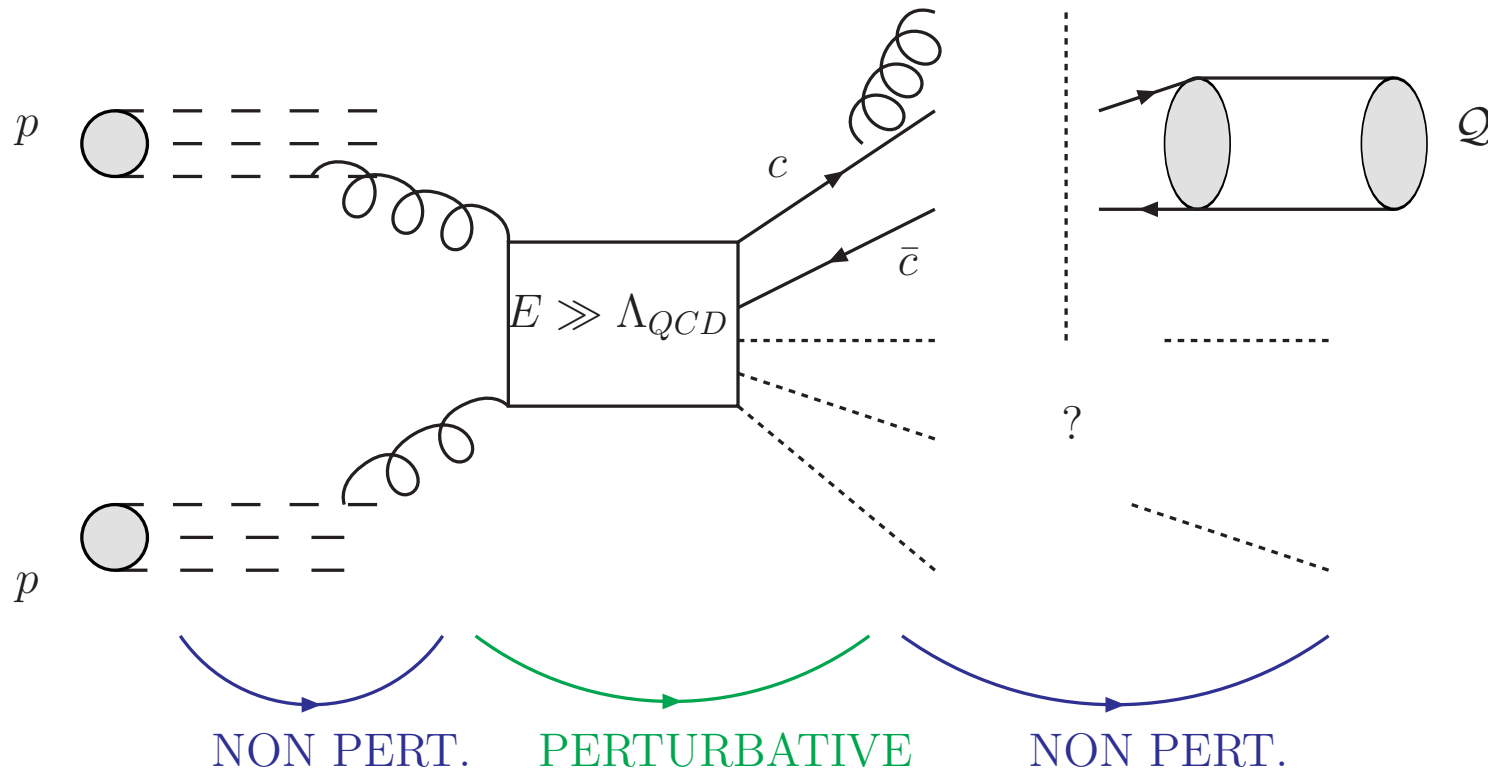


F. Abe et al., Phys. Rev. Lett. 79, 578



# Theoretical aspects

aim: factorize the non perturbative effects in a process-independent way



# Theoretical aspects

## ● Color Singlet Model

$$\sigma_Q = \sigma(c\bar{c}(^{2S+1}L_J^{[1]})) |\psi(0)|^2$$

the perturbative  $c\bar{c}$  pair has the same quantum numbers "as in the bound state".

## ● Color Evaporation Model

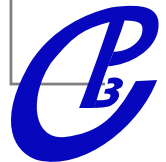
$$\sigma_{onium} = \frac{1}{9} \int_{2m_c}^{2m_D} \frac{\sigma_{c\bar{c}}}{dm} dm, \quad \sigma_Q = \rho_Q \sigma_{onium}$$

the perturbative  $c\bar{c}$  pair is created without any constrain.

## ● Non relativistic QCD

$$\sigma(Q) = \sum_n \hat{\sigma}(c\bar{c}(n)) \langle \mathcal{O}^Q(n) \rangle_\Lambda$$

the perturbative  $c\bar{c}$  pair is *a priori* in an arbitrary state  $n$ , but  $c\bar{c}(n) \rightarrow Q \sim v^f(n, Q)$

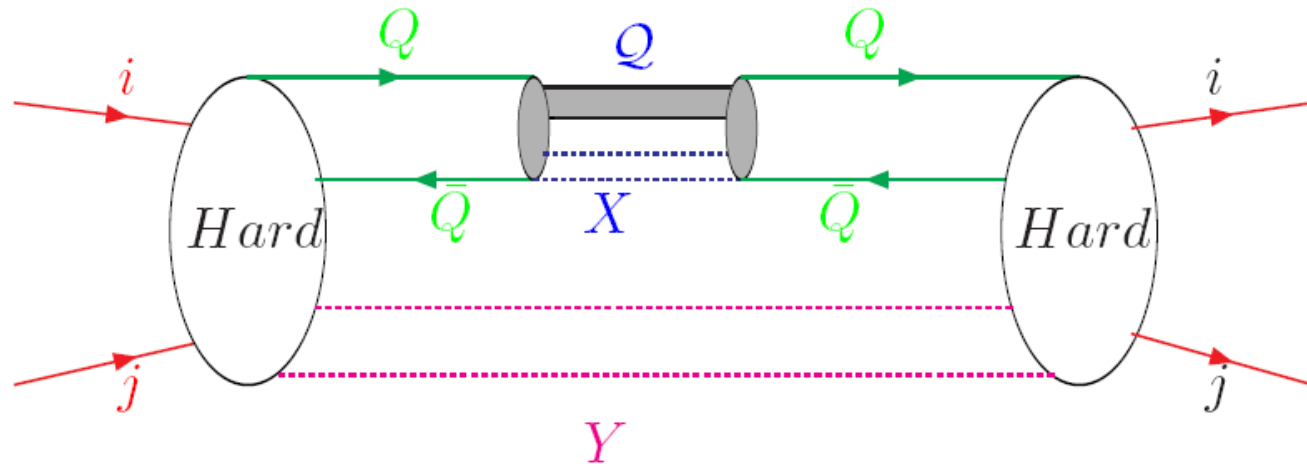


# NRQCD factorization

- Factorization at the level of the squared amplitude:

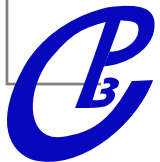
$$\mathcal{A}^*(ij \rightarrow Y Q \bar{Q}_n) \quad \langle 0 | \mathcal{O}^Q(n) | 0 \rangle \quad \mathcal{A}(ij \rightarrow Y Q \bar{Q}_n)$$

$$\sum_n \overbrace{\langle i, j | T | Y Q \bar{Q}_n \rangle} \overbrace{\langle Q \bar{Q}_n | Q X \rangle \langle Q X | Q \bar{Q}_n \rangle} \overbrace{\langle Q \bar{Q}_n Y | T | i, j \rangle}$$

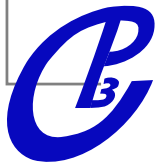


soft partons (X) are included in the long distance part

→ the intermediate  $Q\bar{Q}$  pair can be in a color-octet state



# MadOnia: a new code for quarkonium production



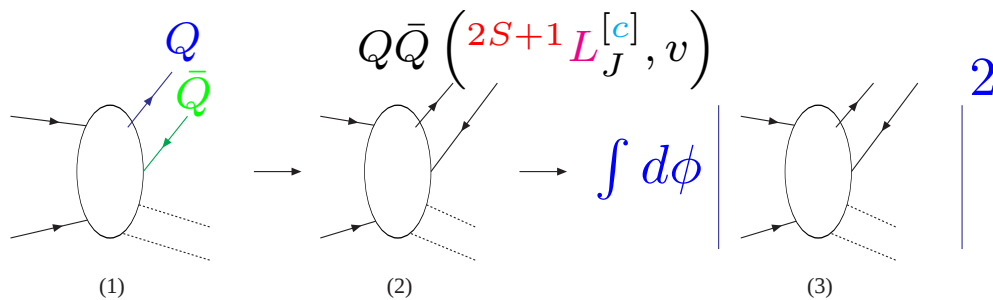
# The purpose of MadOnia

- expression of cross sections within NRQCD:

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

- $\langle \mathcal{O}^{\mathcal{Q}}(n) \rangle$  are the long distance matrix elements
- $\hat{\sigma}(i + j \rightarrow Q\bar{Q}(n) + X)$  are the short distance cross sections

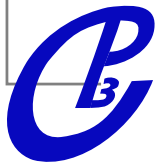
- **MadOnia**: automatic tree-level computation of  $\hat{\sigma}(ij \rightarrow Q\bar{Q}(n) + X)$



(1) open quark amplitude  
(MadGraph)

(2) projected amplitude  
(**MadOnia**)

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



# Capabilities and Validation

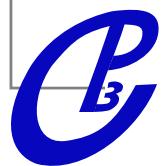
● capabilities:

- **universality**: MadOnia generates any helicity amplitude

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

at tree-level, for any model that can be implemented in MadGraph

- it keeps track of **quantum numbers** on event-by-event basis → 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:  $e^+e^- \rightarrow J/\psi\eta_c$ )
- **relativistic corrections** for  $S$ -wave state production can be computed



# Capabilities and Validation

validation:

- gauge invariance has been checked
- charge conjugation conservation:

$$A(^1S_0^{[1]} + (2k + 1)\gamma) = 0$$

$$A(^3S_1^{[1]} + (2k)\gamma) = 0$$

$$A(^1P_1^{[1]} + (2k)\gamma) = 0$$

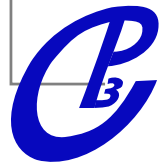
$$A(^3P_1^{[1]} + (2k)\gamma) = 0$$

$$A(^3P_{0,2}^{[1]} + (2k + 1)\gamma) = 0$$

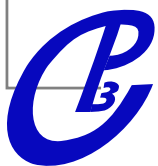
- comparison with analytical amplitudes point by point in the phase space

$$ij \rightarrow Qk$$

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

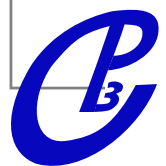


# Illustration



# Illustration

 example:  $B_c$  production from  $e^+e^-$

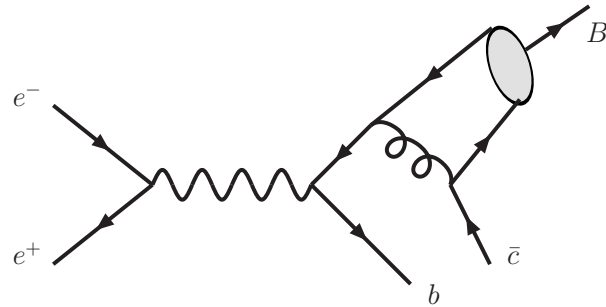


# Illustration

● example:  $B_c$  production from  $e^+e^-$

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

$$e^+e^- \rightarrow b\bar{c}B_c(^1S_0^{[1]})$$



# Illustration



example:  $B_c$  production from  $e^+e^-$



enter the process: fill the input file proc\_card.dat

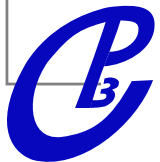
```
# Begin PROCESS # This is TAG. Do not modify this line

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
```



# 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
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e+e->bc~cb~[1S01]  @1      # Second Process
QCD=99             # Max QCD couplings
QED=2              # Max QED couplings
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```
*****
```

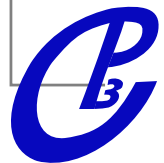
```
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```

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# Illustration

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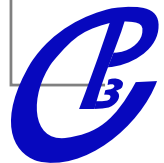
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# Illustration

- example:  $B_c$  production from  $e^+e^-$
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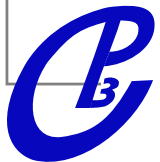
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# Illustration

- example:  $B_c$  production from  $e^+e^-$
- enter the process: fill the input file proc\_card.dat

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e+e->bc~cb~[3S11]  @0      # First Process
QCD=99             # Max QCD couplings
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# Illustration

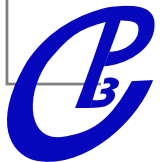
● example:  $B_c$  production from  $e^+e^-$

● 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:

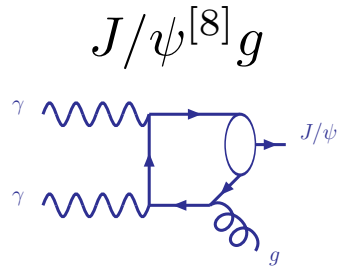
$$\frac{1}{4} \sum_{\lambda_1, \dots, \lambda_5} |M(e^+(p_1)e^-(p_2) \rightarrow b(p_3)\bar{c}(p_4)B_c(p_5))|^2$$

● interface with a **phase-space generator**  $\rightarrow$  cross sections



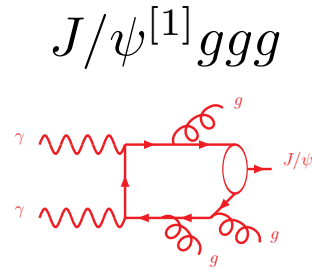
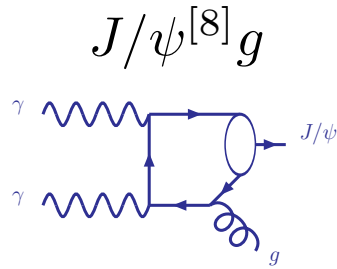
# Illustration

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



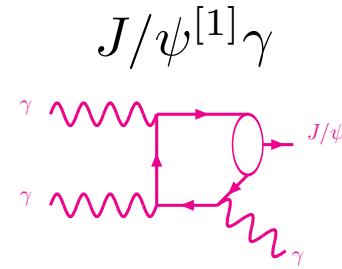
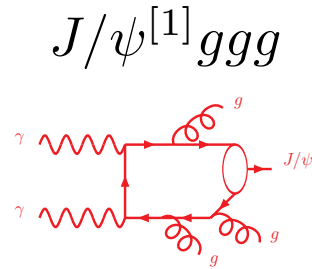
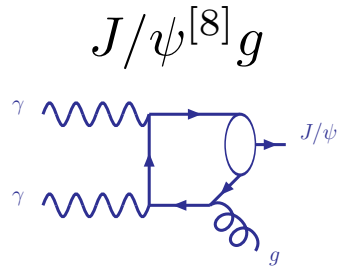
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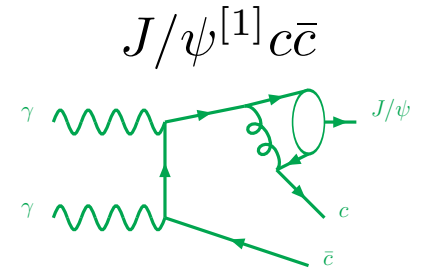
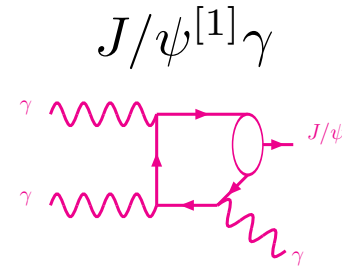
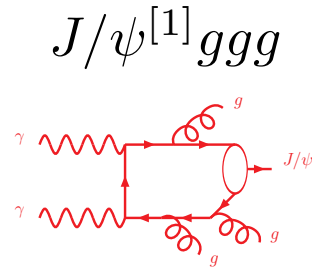
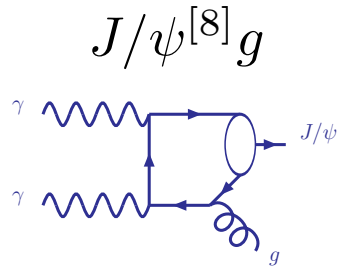
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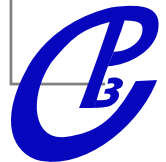
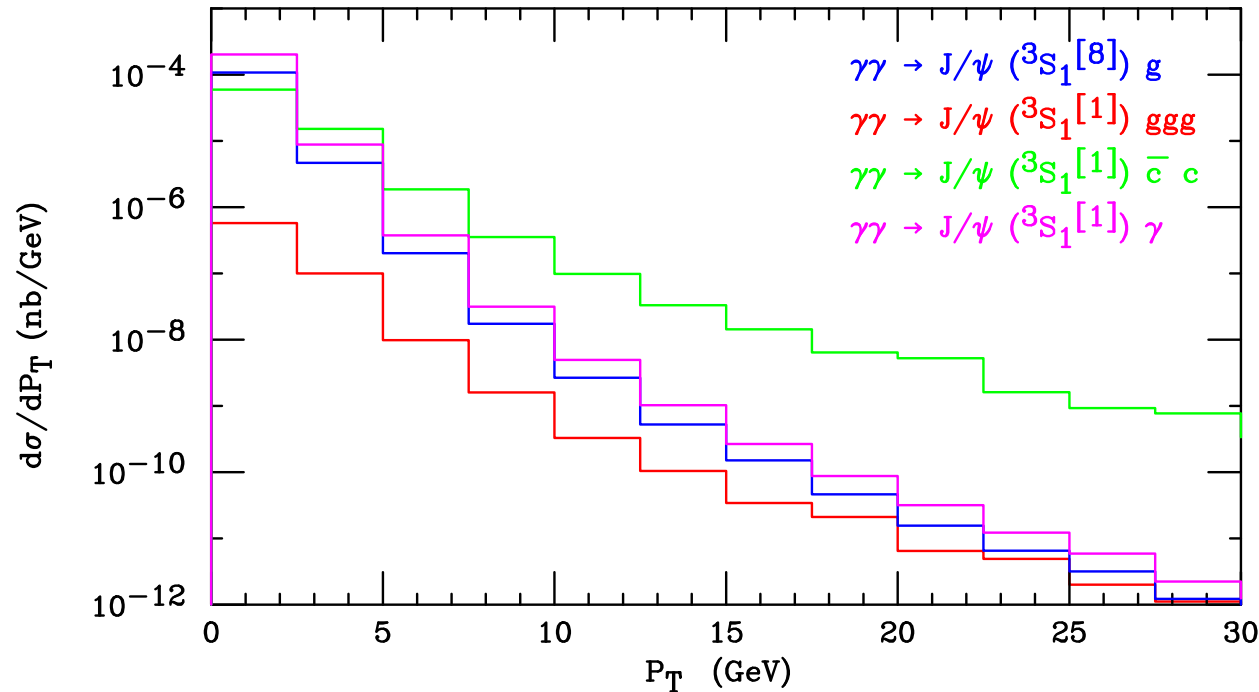
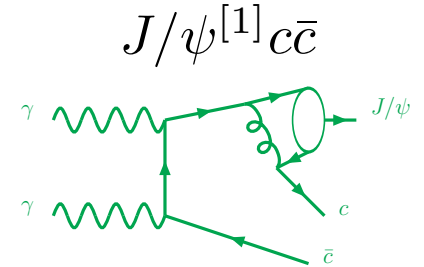
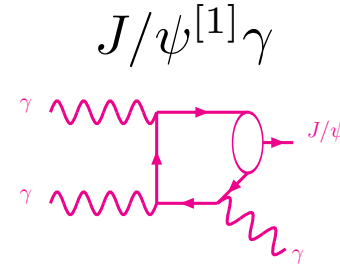
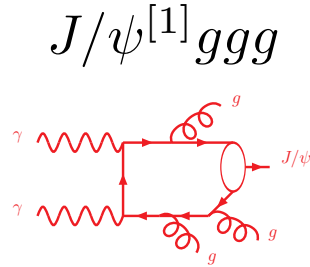
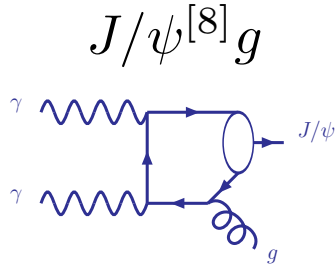
# Illustration

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



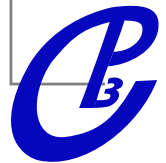
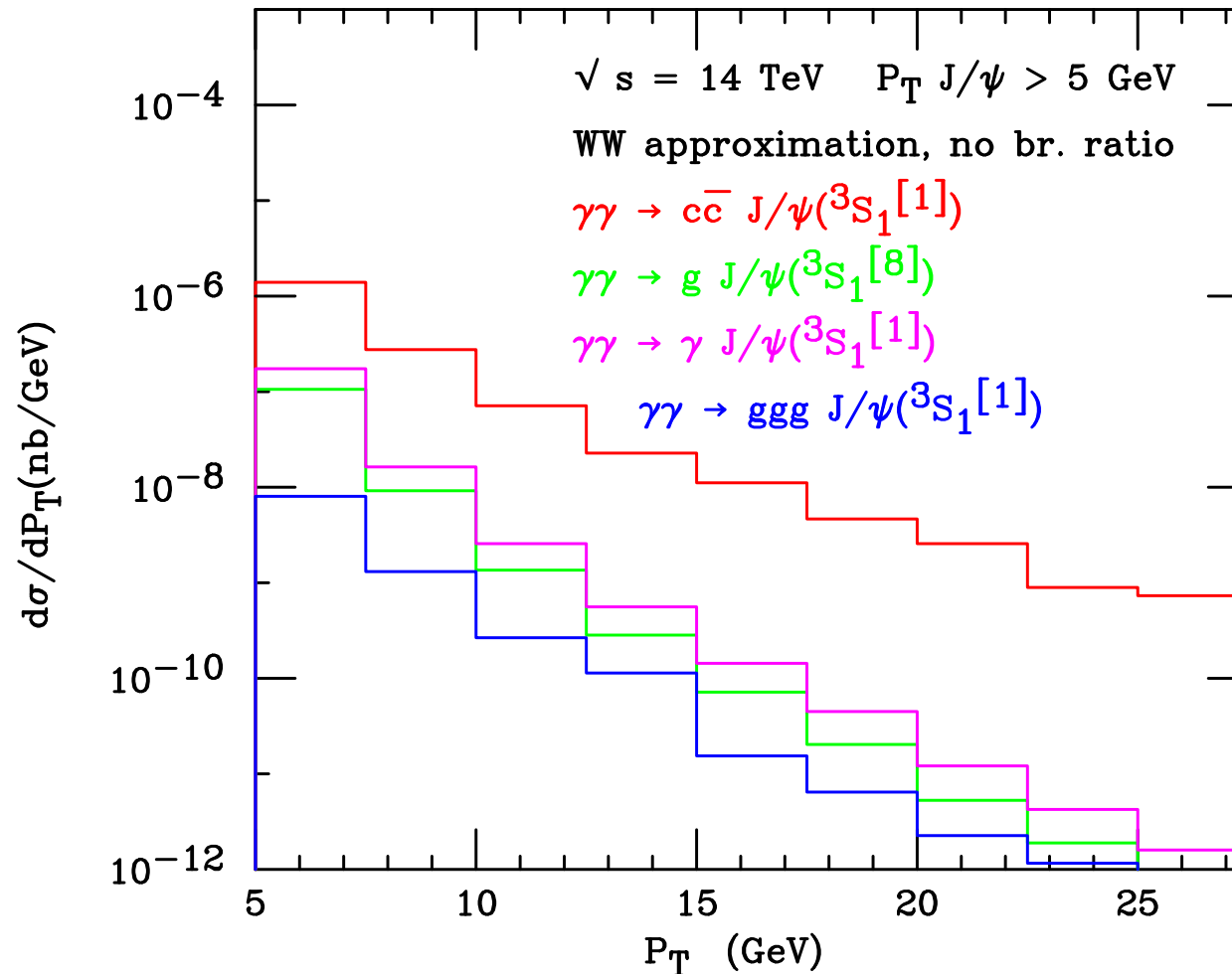
# Illustration

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



# Illustration

- $J/\psi$  production from  $\gamma\gamma$  collisions (LHC,  $\sqrt{s} = 14$  TeV)

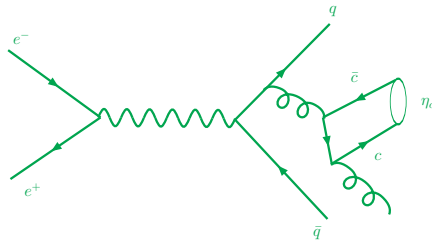


# Illustration

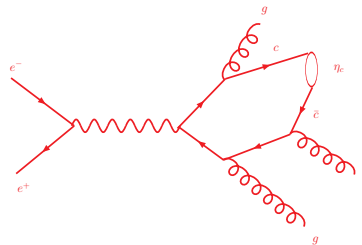
  $e^+e^- \rightarrow \eta_c + X @ 10.6 \text{ GeV}$

subprocesses:

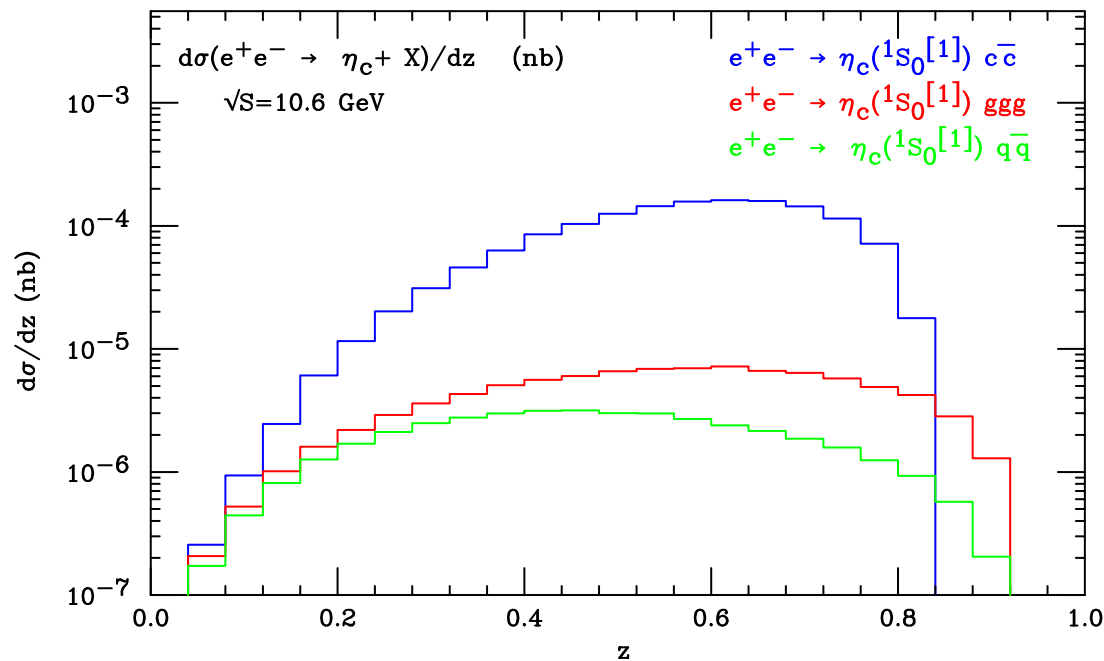
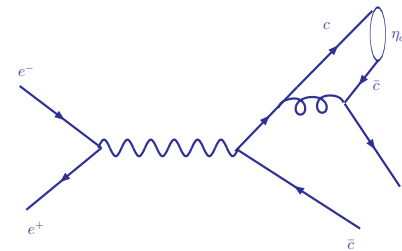
$$e^+e^- \rightarrow \eta_c q\bar{q}g$$



$$e^+e^- \rightarrow \eta_c ggg$$



$$e^+e^- \rightarrow \eta_c c\bar{c}$$



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

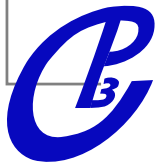
$$\sigma(\eta_c ggg) = 3.72 \text{ fb}$$

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

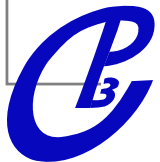
Remarks:

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

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



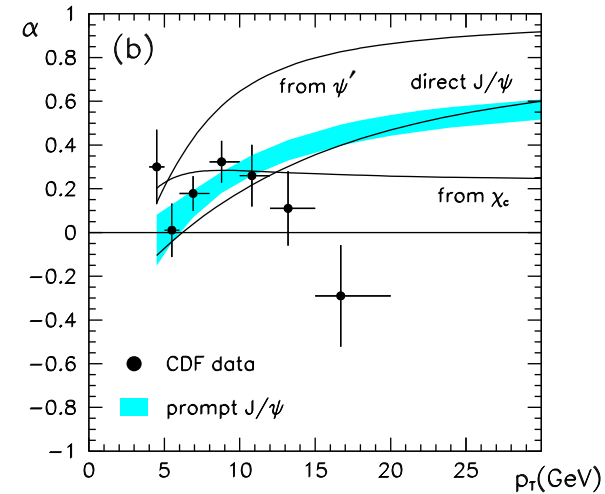
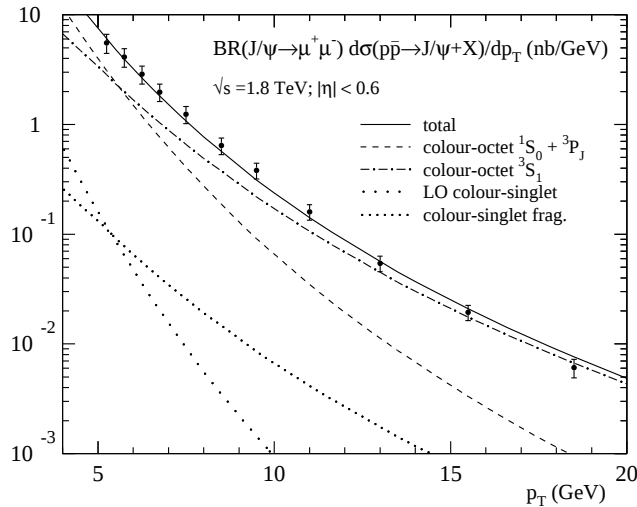
# Ongoing studies: $J/\psi$ and $\Upsilon$ hadroproduction



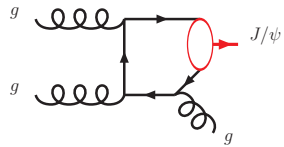
# $J/\psi$ production at the Tevatron

## inclusive production: current status

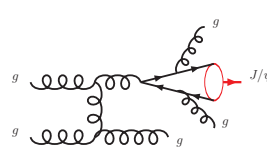
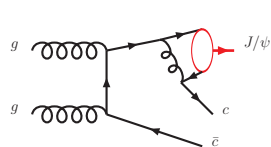
[from M. Kramer, Prog. Part. Nucl. Phys. 47: 141-201,2001.]



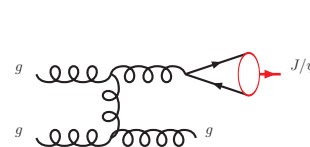
LO color-singlet



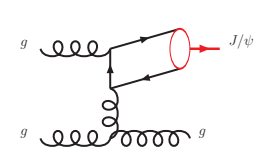
color-singlet frag.



color-octet  $^3S_1$



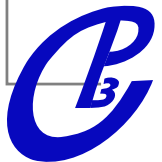
color-octet  $^1S_0$



cross section in the **fragmentation approximation**

$$d\sigma_{J/\psi}(P) \simeq \int_0^1 dz d\sigma_c\left(\frac{P}{z}, \mu_{frag}\right) D_{c \rightarrow J/\psi}(z, \mu_{frag})$$

and similarly for the fragmentation from a gluon.



# $J/\psi$ production at the Tevatron

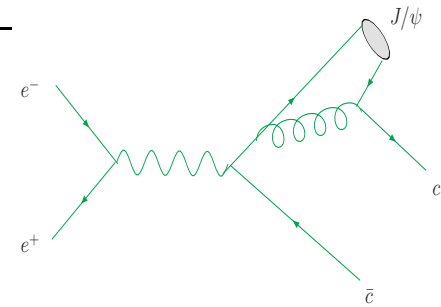
- associated  $J/\psi$  production

$$p\bar{p} \rightarrow J/\psi c\bar{c}$$

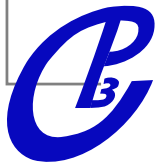
motivation:

- situation in  $e^+e^-$  annihilation

|                             | $\sigma(e^+e^- \rightarrow J/\psi + c\bar{c})$ |
|-----------------------------|------------------------------------------------|
| Belle                       | $0.87^{+0.21}_{-0.19} \pm 0.17 \text{ pb}$     |
| NRQCD prediction            | $0.0897 \text{ pb}$                            |
| (LO in $v$ and $\alpha_s$ ) |                                                |



Color transfer between the active charm-quark pair and one of the spectator charm quark might lead to an enhancement



# $J/\psi$ production at the Tevatron

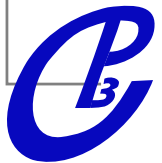
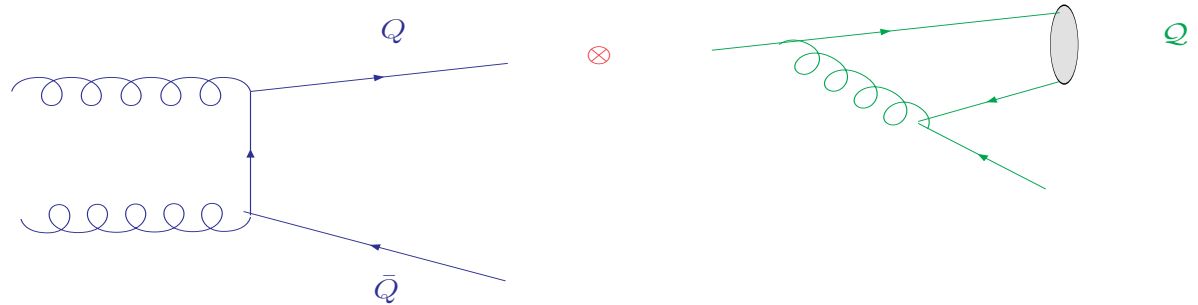
- associated  $J/\psi$  production

$$p\bar{p} \rightarrow J/\psi c\bar{c}$$

**motivation:**

- includes topologies that are not taken into account in the **fragmentation approximation**

$$d\sigma_{\mathcal{Q}}(P) \simeq \int_0^1 dz d\sigma_{Q_i}(\frac{P}{z}, \mu_{frag}) D_{Q_i \rightarrow \mathcal{Q}}(z, \mu_{frag})$$



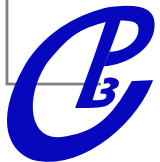
# $J/\psi$ production at the Tevatron

- associated  $J/\psi$  production

$$p\bar{p} \rightarrow J/\psi c\bar{c}$$

motivation:

- part of the  $\alpha_s^4$  color-singlet **inclusive**  $J/\psi$  production
- it could be **tested experimentally**
- this new channel offers the opportunity to check the **universality** of the Long Distance Matrix Elements



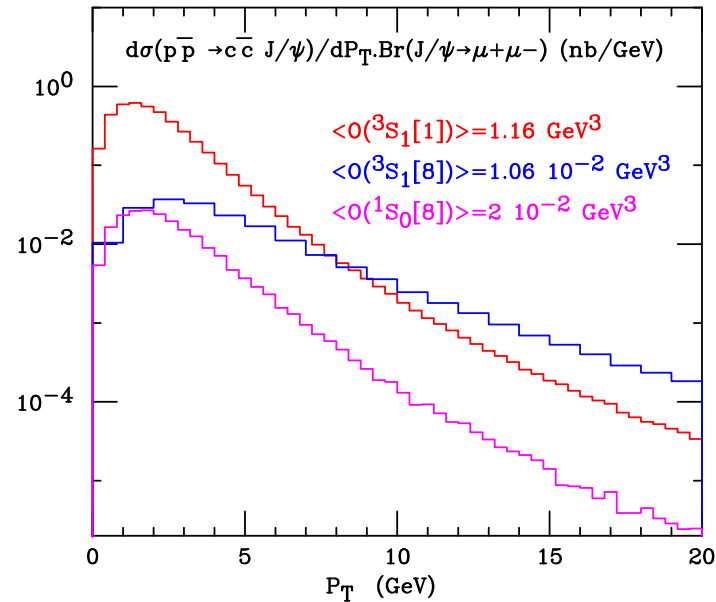
# $J/\psi$ production at the Tevatron



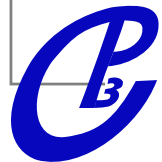
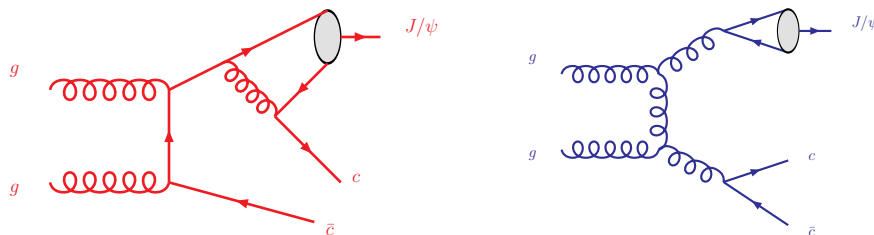
associated  $J/\psi$  production

$$p\bar{p} \rightarrow J/\psi c\bar{c}$$

$P_T$  distributions:



dominant topologies in the region  $P_T \gg m_c$ :



# $J/\psi$ production at the Tevatron

associated  $J/\psi$  production

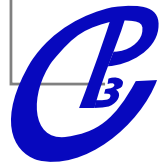
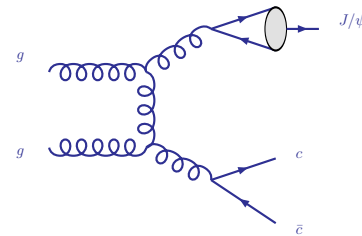
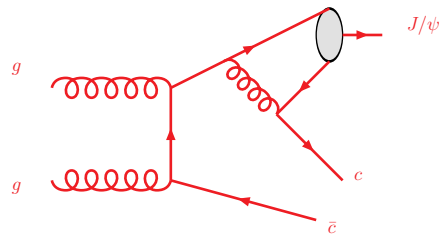
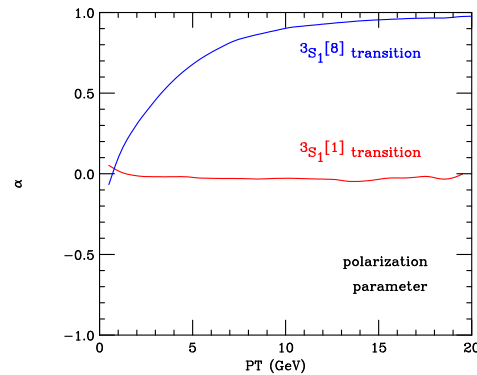
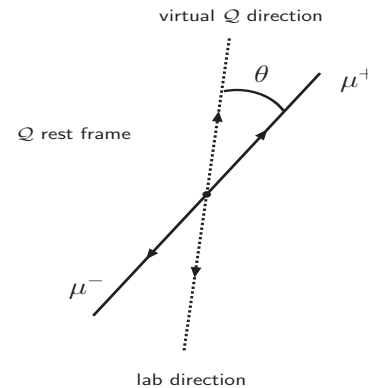
$$p\bar{p} \rightarrow J/\psi c\bar{c}$$

$J/\psi$  polarization:

extracted from the angular distribution of the produced leptons

$$I(\cos \theta) = \frac{3}{2(\alpha+3)} (1 + \alpha \cos^2 \theta)$$

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$



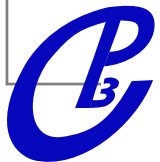
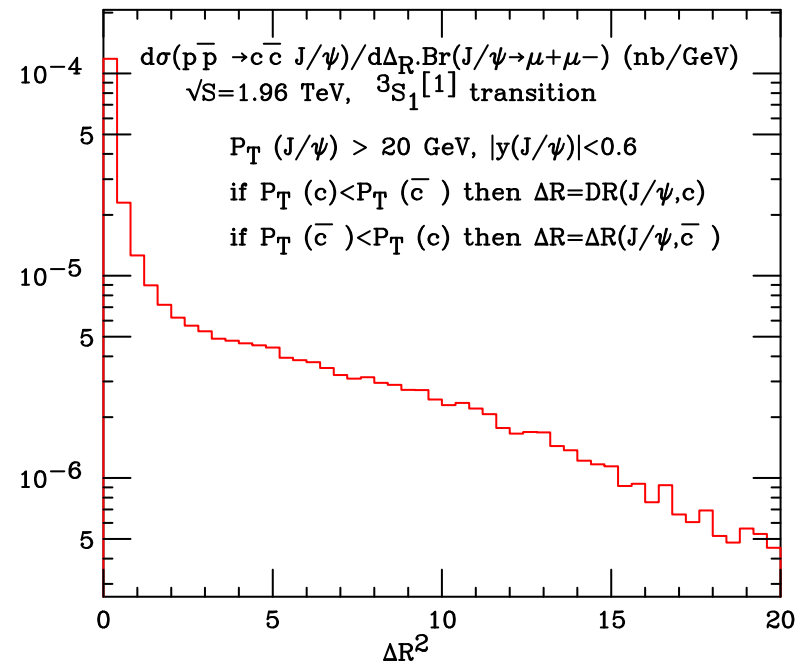
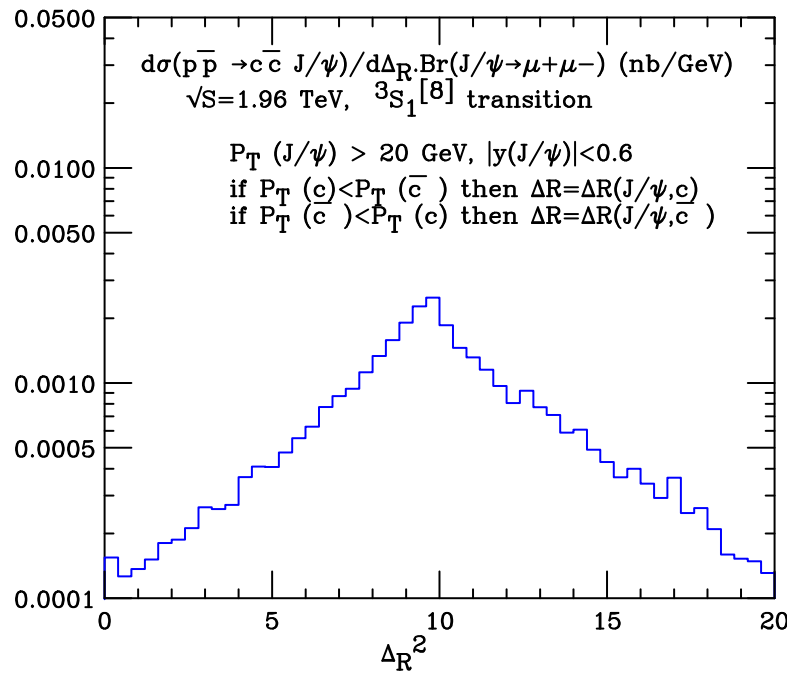
# $J/\psi$ production at the Tevatron



associated  $J/\psi$  production

$$p\bar{p} \rightarrow J/\psi c\bar{c}$$

angular separation  $\Delta R(J/\psi, c)$ :



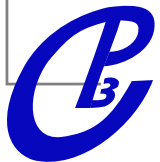
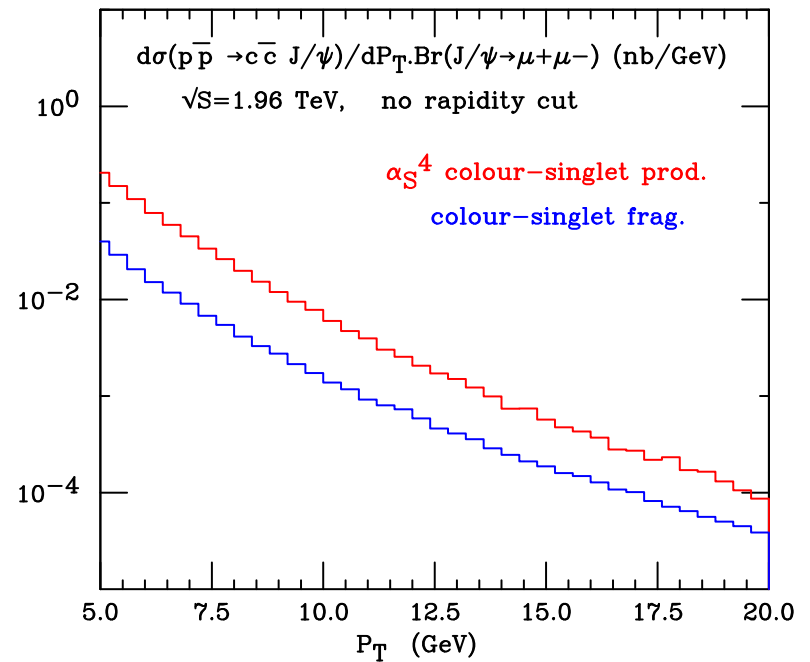
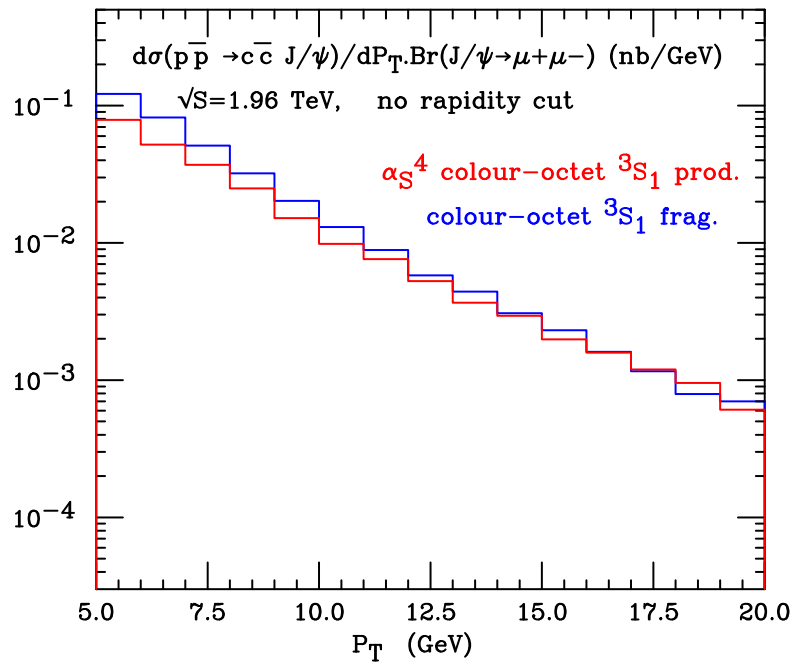
# $J/\psi$ production at the Tevatron



associated  $J/\psi$  production

$$p\bar{p} \rightarrow J/\psi c\bar{c}$$

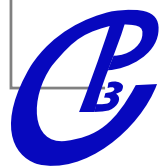
comparison with the fragmentation approximation:



# $\Upsilon + 3 \text{ jets at the Tevatron}$

 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_uxdgbbx3S11   |
| gu_uddxbbx3S11  | ud_udgbbx3S11     | uux_ddxgbbx3S11  | uxg_uxddxbbx3S11  | dxux_uxdxgbbx3S11 |
| gu_uggbbx3S11   | udx_uxdgbbx3S11   | uux_gggbbx3S11   | uxg_uxggbbx3S11   |                   |



# $\Upsilon + 3 \text{ jets at the Tevatron}$

 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  | <b>gg_gggbbx3S11</b> | gux_uxddxbbx3S11  |
| ug_uuuxbbx3S11  | uxdx_uxdxgbbx3S11 | uxu_uuxgbbx3S11  | dxg_uuxuxbbx3S11     | gg_uuxgbbx3S11    |
| gux_uxggbbx3S11 | uu_uugbbx3S11     | uxg_uuxuxbbx3S11 | uxux_uxuxgbbx3S11    | dxu_uxdgbbx3S11   |
| gu_uddxbbx3S11  | ud_udgbbx3S11     | uux_ddxgbbx3S11  | uxg_uxddxbbx3S11     | dxux_uxdxgbbx3S11 |
| gu_uggbbx3S11   | udx_uxdgbbx3S11   | uux_gggbbx3S11   | uxg_uxggbbx3S11      |                   |

$\approx 2000$  Feynman diagrams before projection

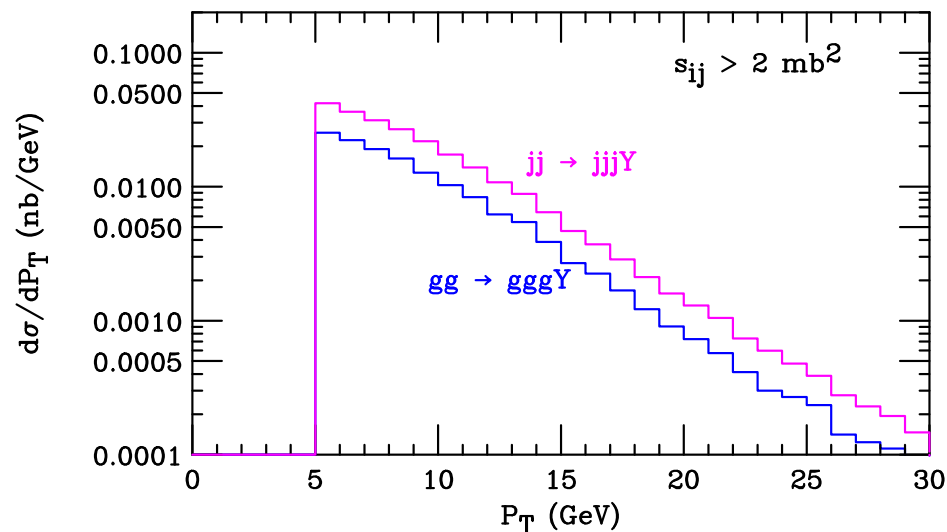


# $\Upsilon + 3 \text{ jets at the Tevatron}$

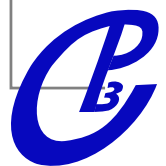
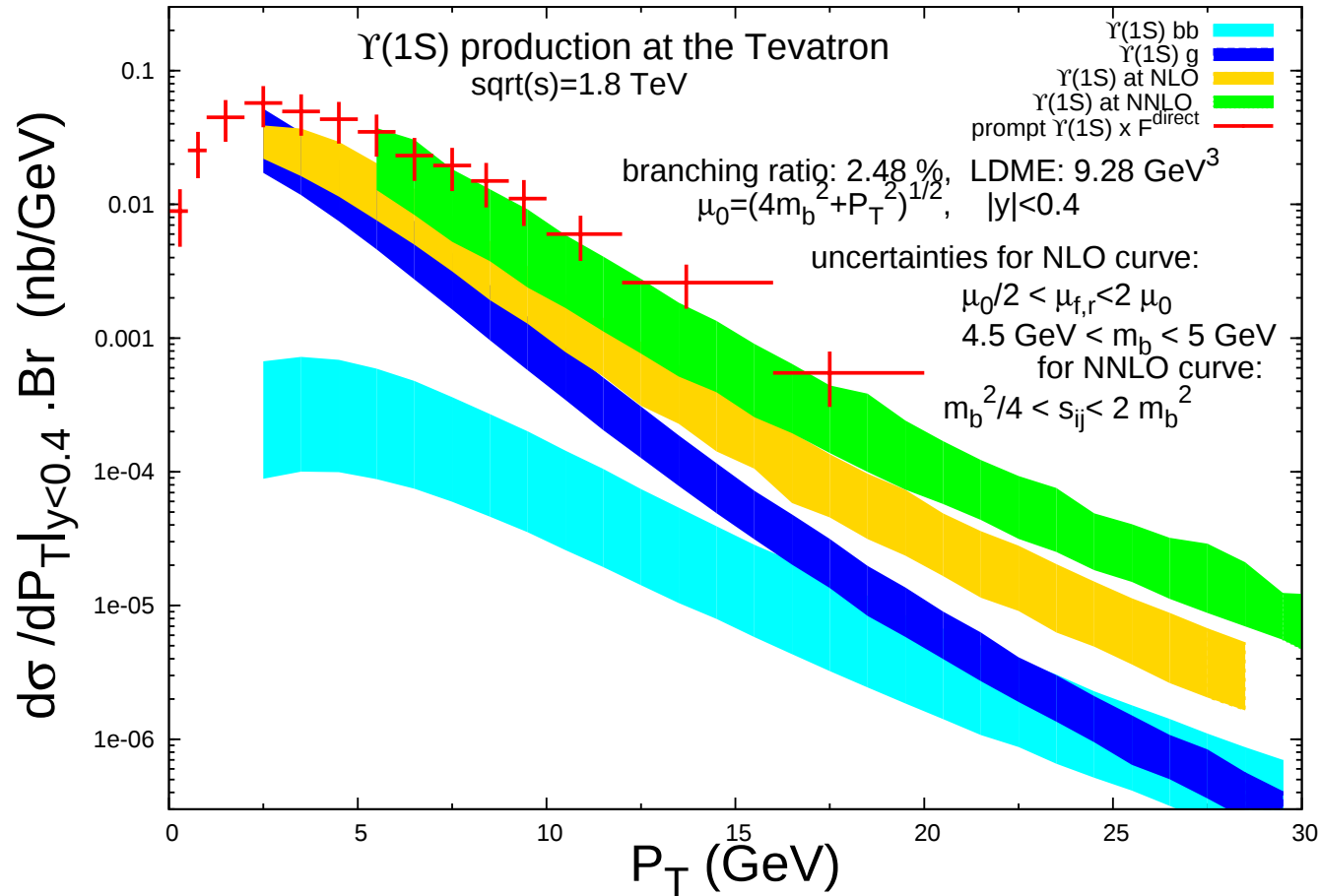
subprocesses:

|                 |                   |                  |                      |                   |
|-----------------|-------------------|------------------|----------------------|-------------------|
| 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  | <b>gg_gggbbx3S11</b> | 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_uxdxgbbx3S11  | uux_gggbbx3S11   | uxg_uxggbbx3S11      |                   |

$\approx 2000$  Feynman diagrams before projection



# $\Upsilon + 3 \text{ jets at the Tevatron}$



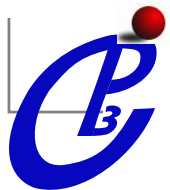
# Conclusion & Perspectives

● **MadOnia** is an amplitude generator for quarkonium production within NRQCD which is:

- universal (new models can be defined)
- user-friendly
- flexible

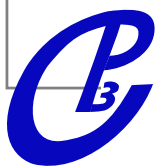
● Examples of application:

- $\gamma\gamma \rightarrow J/\psi + X$  at Lep II
- $e^+e^- \rightarrow \eta_c + X$  at B factories
- $p\bar{p} \rightarrow J/\psi + c\bar{c}$  at the Tevatron
- $p\bar{p} \rightarrow \Upsilon + 3 \text{ jets}$  at the Tevatron



work in progress: event generator with interfaces to Pythia and Herwig

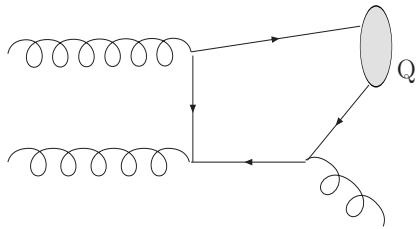
# Back-up Slides



# Quarkonium hadroproduction

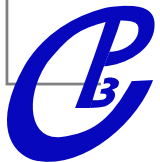
- color-singlet  $J/\psi$  hadroproduction

- leading-order color-singlet  $J/\psi$  production



$$\frac{d}{dP_T^2} \hat{\sigma}(gg \rightarrow Q\bar{Q}(^3S_1^{[1]})g) \langle \mathcal{O}^Q(^3S_1) \rangle$$
$$\sim \alpha_s^3 \frac{(2m_Q)^4}{P_T^8}$$

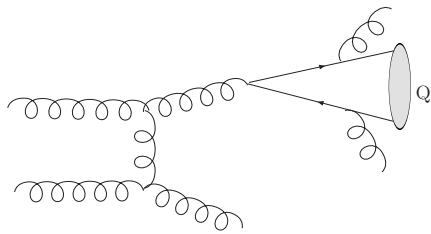
$\langle \mathcal{O}^Q(^3S_1) \rangle$  can be determined -from potential methods  
-from  $J/\psi$  leptonic decay width



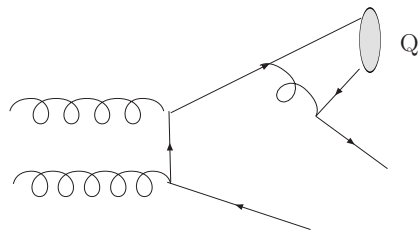
# Quarkonium hadroproduction

● color-singlet  $J/\psi$  hadroproduction

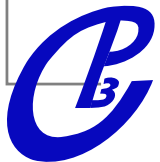
● color-singlet  $J/\psi$  production via fragmentation ( $P_T \gg m_Q$ )



$$\frac{d}{dP_T^2} \hat{\sigma}(gg \rightarrow gg) \otimes D(g \rightarrow Q(^3S_1^{[1]}) + gg) + \mathcal{O}\left(\frac{m_Q}{P_T}\right) \\ \sim \alpha_s^5 \frac{1}{P_T^4}$$



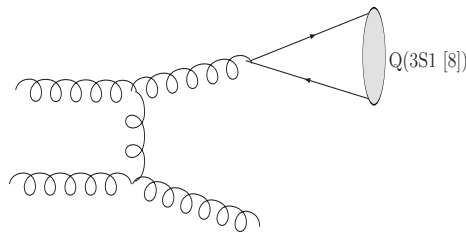
$$\frac{d}{dP_T^2} \hat{\sigma}(gg \rightarrow Q\bar{Q}) \otimes D(Q \rightarrow Q(^3S_1^{[1]}) + Q) + \mathcal{O}\left(\frac{m_Q}{P_T}\right) \\ \sim \alpha_s^4 \frac{1}{P_T^4}$$



# Quarkonium hadroproduction

- **color-octet**  $J/\psi$  hadroproduction

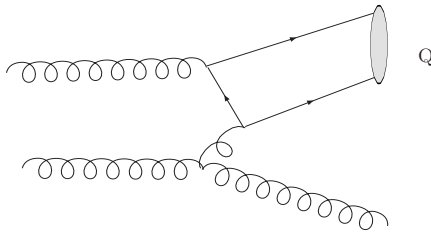
- $J/\psi$  production via a **color-octet**  $^3S_1^{[8]}$  state



$$\frac{d}{dP_T^2} \hat{\sigma}(gg \rightarrow gQ\bar{Q}(^3S_1^{[8]})) \langle \mathcal{O}^Q(^3S_1^{[8]}) \rangle$$

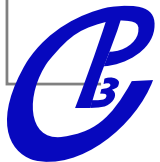
$$\sim \alpha_s^3 \frac{1}{P_T^4} v^4$$

- $J/\psi$  production via a **color-octet**  $^1S_0^{[8]}$  ( $^3P_J^{[8]}$ ) state

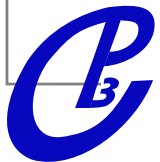


$$\frac{d}{dP_T^2} \hat{\sigma}(gg \rightarrow Q\bar{Q}(^1S_0^{[8]}) + g) \langle \mathcal{O}^Q(^1S_0^{[8]}) \rangle$$

$$\sim \alpha_s^3 \frac{(2m_c)^2}{P_T^6} v^4$$



# Successes and open questions at the Tevatron



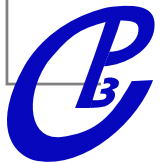
# $J/\psi$ production at the Tevatron

- data collected by the CDF collaboration  
identification of the leptonic decay products

|                                           | $J/\psi$            | $\psi(2S)$          |
|-------------------------------------------|---------------------|---------------------|
| $Br(\mathcal{Q} \rightarrow \mu^+ \mu^-)$ | $0.0588 \pm 0.0010$ | $0.0073 \pm 0.0008$ |

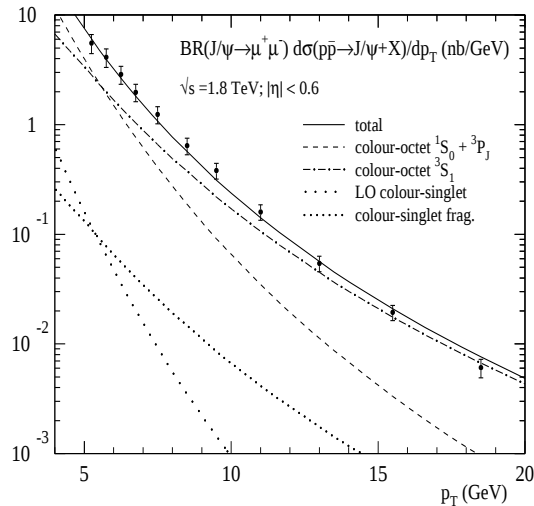
the  $J/\psi$  production is

- prompt if the produced  $J/\psi$  does not come from the decay of a  $B$  meson
- direct if the produced  $J/\psi$  is prompt and does not come from the decay of a charmonium state



# $J/\psi$ production at the Tevatron

## ● direct $J/\psi$ production (run I)



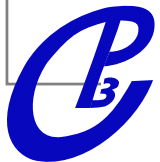
PDF: CTEQ5L

$$\mu = \sqrt{P_T^2 + 4m_c^2}$$

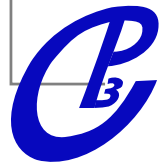
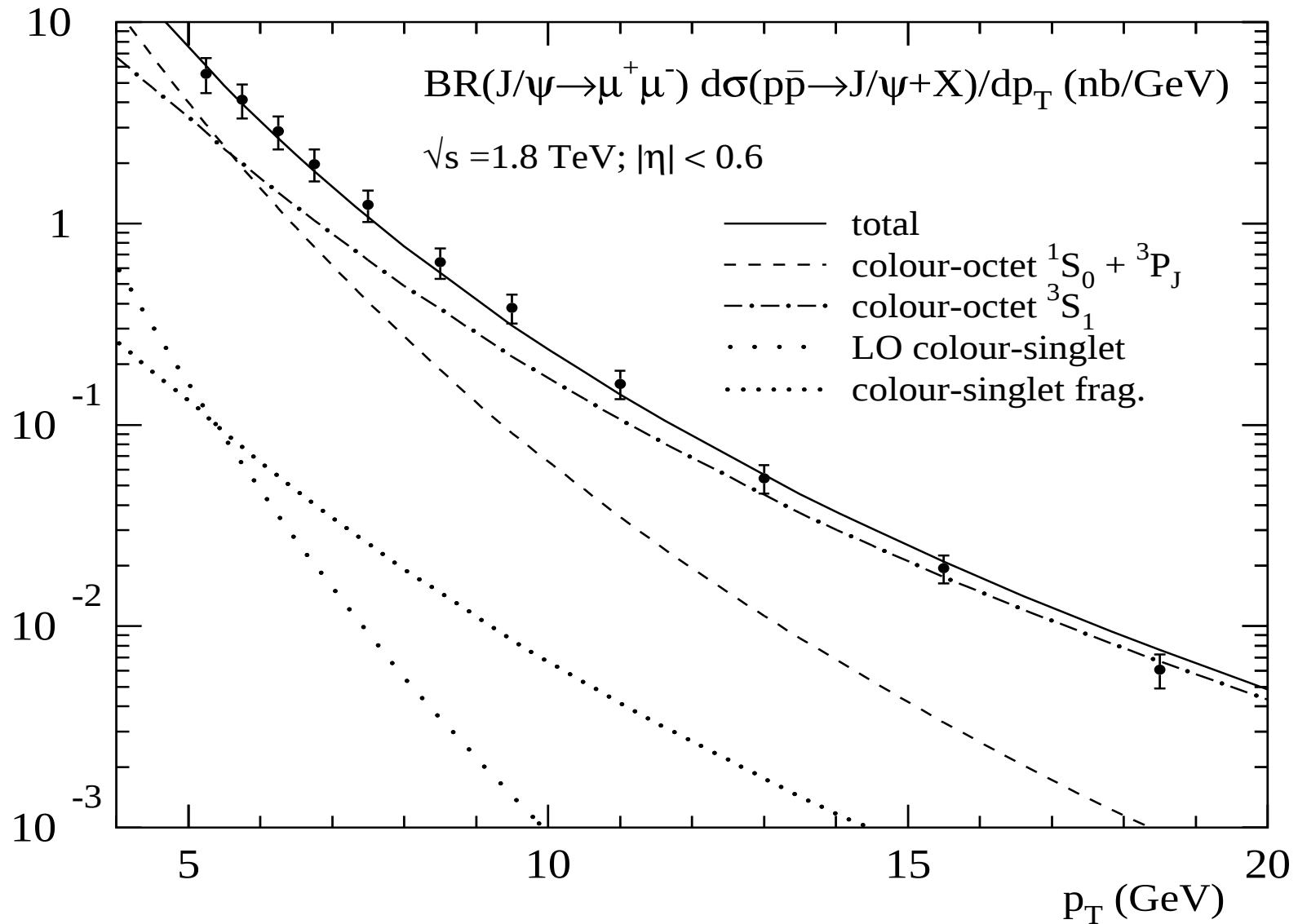
$$m_c = 1.5 \text{ GeV}$$

[from M. Kramer, Prog. Part. Nucl. Phys. 47: 141-201,2001.

experimental data: F. Abe et al (CDF collaboration), Phys. Rev. Lett. 79 (1997)]

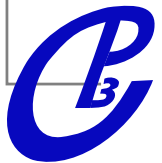


# $J/\psi$ production at the Tevatron



# $J/\psi$ production at the Tevatron

- success of the **color-octet** mechanism
- **color-singlet** predictions for  $J/\psi$  and  $\psi'$  productions are far **below the data**, if the long distance matrix elements are fixed by potential methods.
- **color-octet mechanism** can reproduce the experimental  $P_T$  shape
- two **color-octet long distance matrix elements** are **fitted** to the data. They roughly scale as  $v^4$  compared to the leading LDME, as predicted by NRQCD.



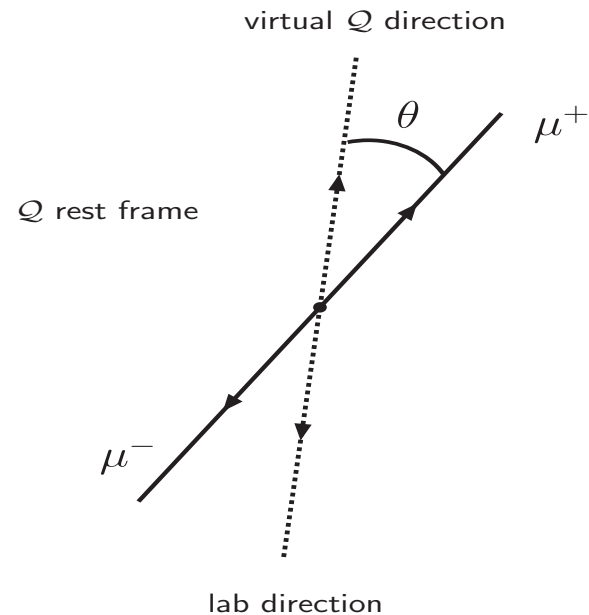
# $J/\psi$ production at the Tevatron

## ● $J/\psi$ polarization

extracted from the angular distribution of the produced leptons

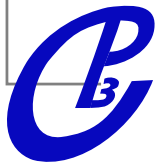
$$I(\cos \theta) = \frac{3}{2(\alpha+3)}(1 + \alpha \cos^2 \theta)$$

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$



# $J/\psi$ production at the Tevatron

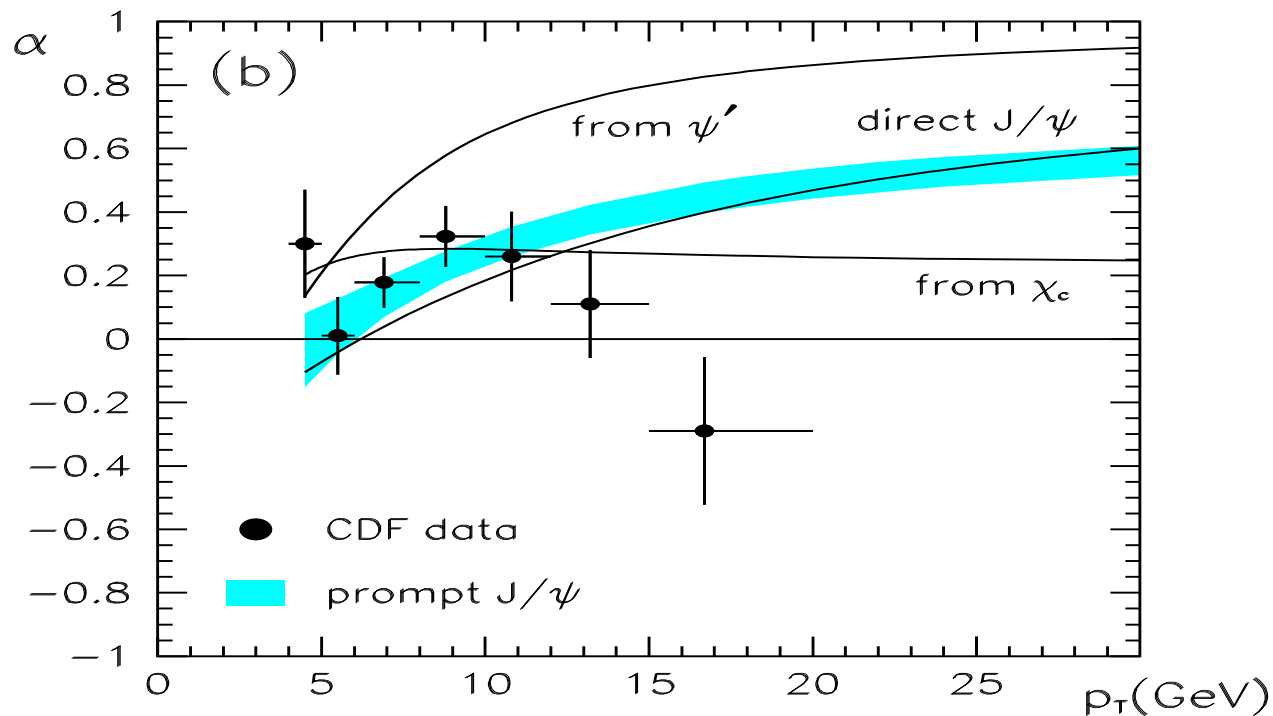
- **polarization**: NRQCD prediction vs data



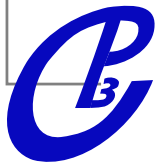
# $J/\psi$ production at the Tevatron

● polarization: NRQCD prediction vs data

● Prompt  $J/\psi$  polarization at the Tevatron, run I

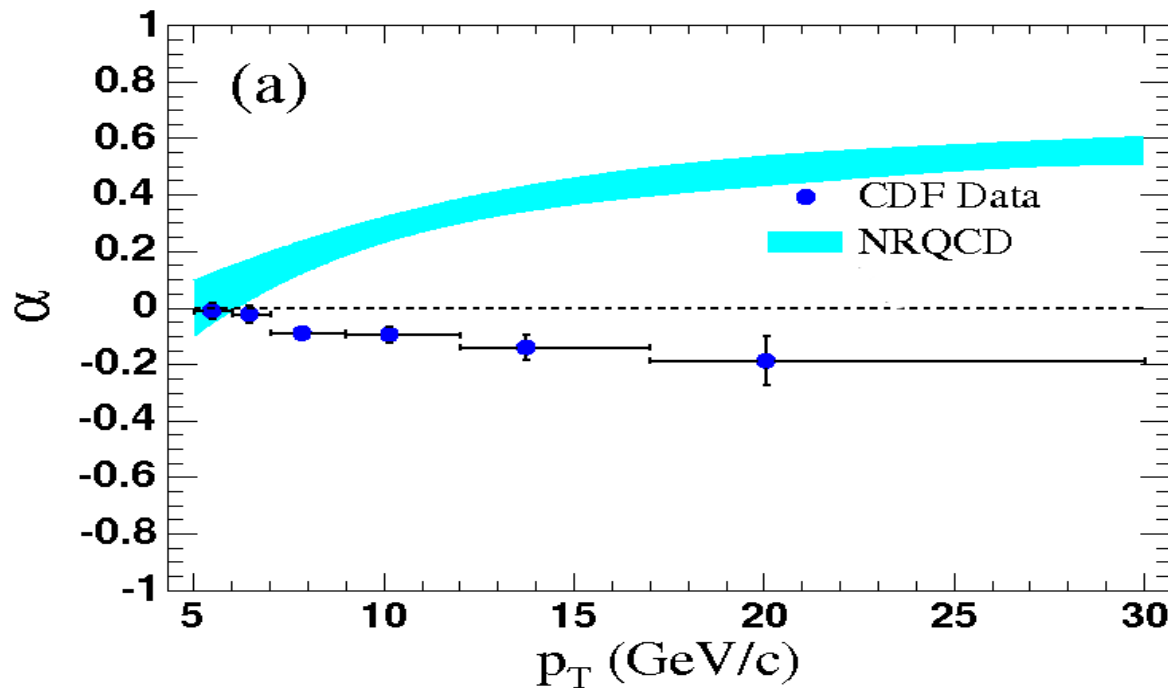


[from Braaten, Kniehl and Lee Phys. Rev. D 62 (2000) 094005. Exp. data: T. Affolder *et al* (CDF collaboration), Phys. Rev. Lett. 85 2886 (2000)]

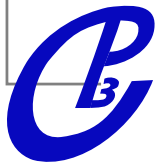


# $J/\psi$ production at the Tevatron

- polarization: NRQCD prediction vs data
- Prompt  $J/\psi$  polarization at the Tevatron, run II



[from A. Abulencia *et al* (CDF collaboration), hep-ex/07040638]



# $J/\psi$ production at the Tevatron

- polarization: NRQCD prediction vs data
- Prompt  $\psi'$  polarization at the Tevatron, run II

