QCD corrections to Heavy Quarkonium Production

HLPW 2008

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CP3

Plan

- Inclusive quarkonium production at the Tevatron
- Associated production at the Tevatron
- Conclusion

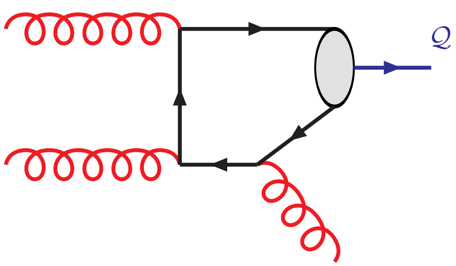
Naïve non-relativistic approach : the CS

- non-perturbative effects are factorized in the wave function

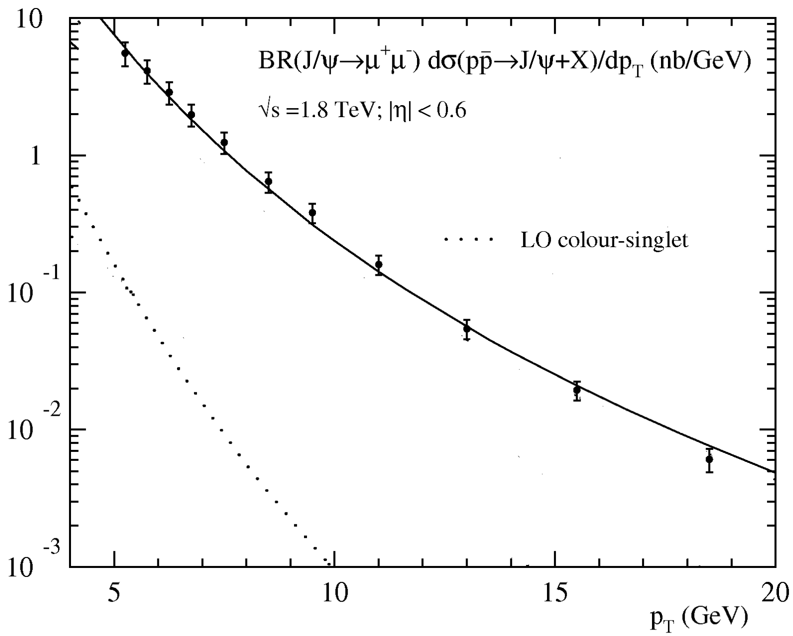
$$\sigma(ij \to \mathcal{Q}X) \approx \hat{\sigma}\left((ij \to Q\bar{Q} + X)\right)|\psi(0)|^2$$

  - $\hat{\sigma}(ij \to Q\bar{Q} + X)$: creation of an on-shell $Q\bar{Q}$ pair (perturbative expansion)
  - $\psi(0)$: Schrödinger wave function at the origin (non-perturbative parameter)
  - the $Q\bar{Q}$ pair is created with the same quantum numbers as the physical bound state
  - this model is very predictive

At LO in α_s and v



$$\frac{d}{dP_T^2}\hat{\sigma}(gg \to Q\bar{Q}({}^3S_1^{[1]})g)|\psi(0)|^2$$
$$\sim \alpha_s^3 \frac{1}{P_T^8}$$

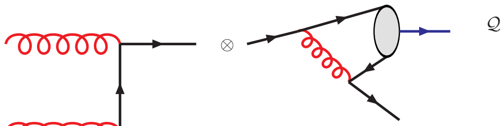


wrong P_T spectrum

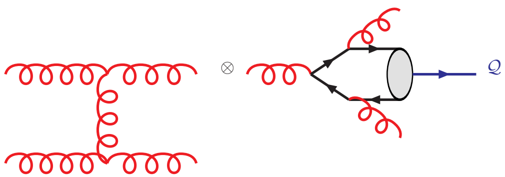
wrong normalization

[from M. Kramer, Prog. Part. Nucl. Phys. 47 : 141-201,2001.
experimental data : F. Abe et al (CDF collaboration), Phys. Rev. Lett. 79 (1997)]

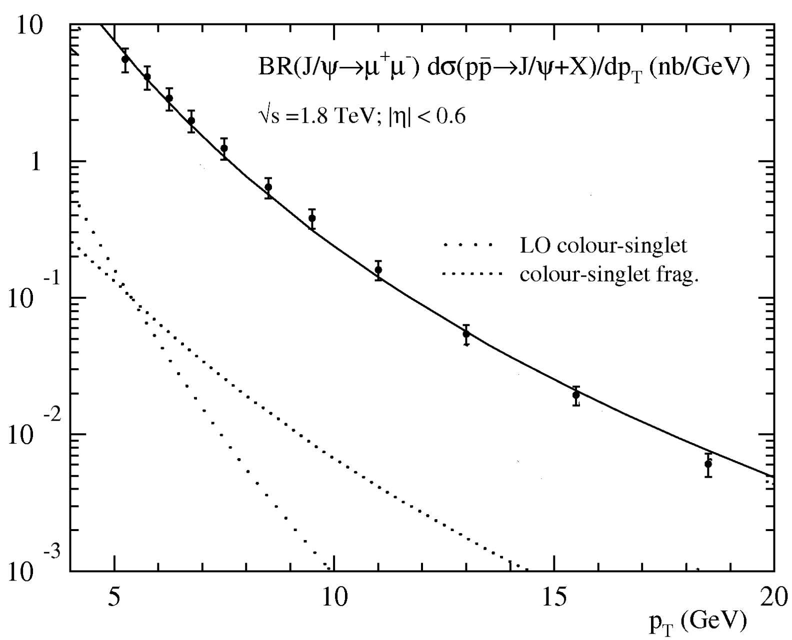
Frag. contribution (higher order in α_s)



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



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



P_T shape is right

wrong normalization

NRQCD expansion

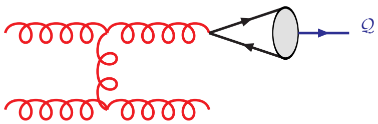
- non-pertubative effects are factorized into long distance matrix elements (LDME)

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

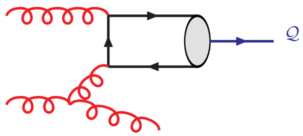
  - $\hat{\sigma}(i + j \to Q\bar{Q}(n) + X)$ is the short distance cross section
  - $\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle$ is the long distance matrix element

    their importance can be assessed using power counting rules
  - sum over all possible quantum states n of intermediate $Q\bar{Q}$ pair
  - the LDME are a priori unknown

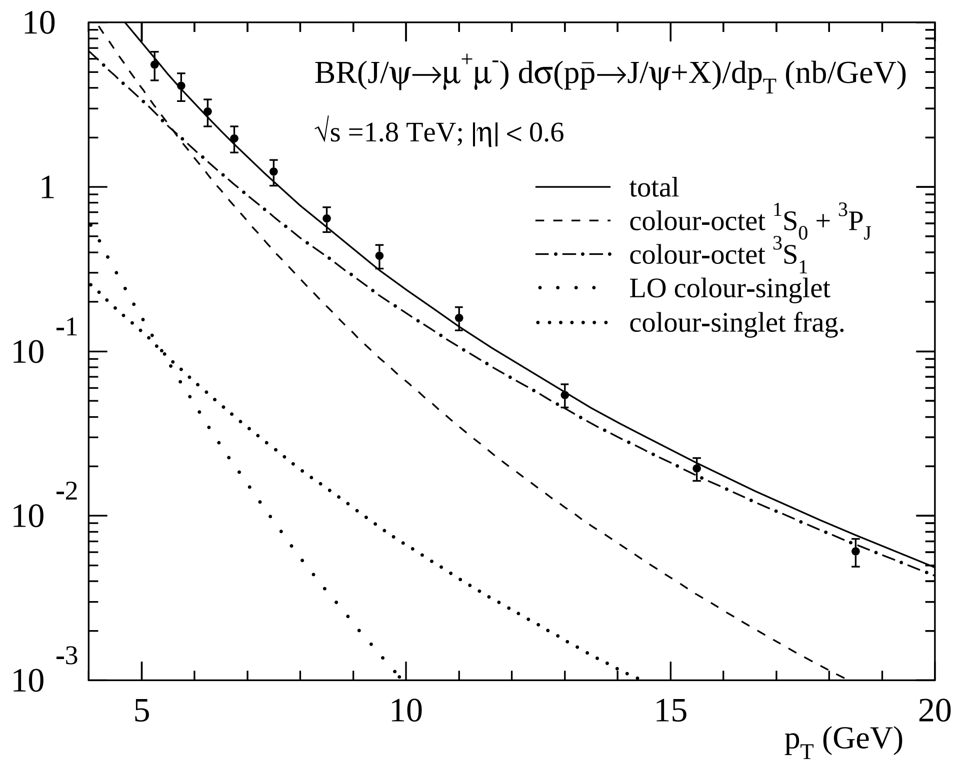
Consequence : color-octet transition



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



$$\frac{d}{dP_T^2}\hat{\sigma}(gg \to Q\bar{Q}({}^1S_0^{[8]}) + g)\langle\mathcal{O}^{\mathcal{Q}}({}^1S_0^{[8]})\rangle \quad \sim \alpha_s^3 \frac{(2m_c)^2}{P_T^6} v^4$$



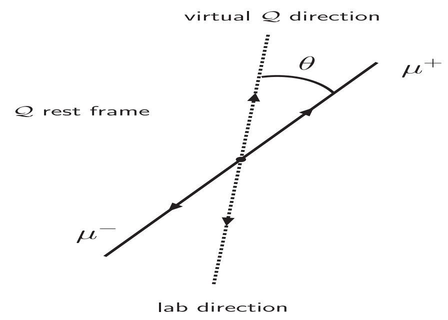
Fit of the color-octet LDME to reproduce the data

J/ψ production at the Tevatron

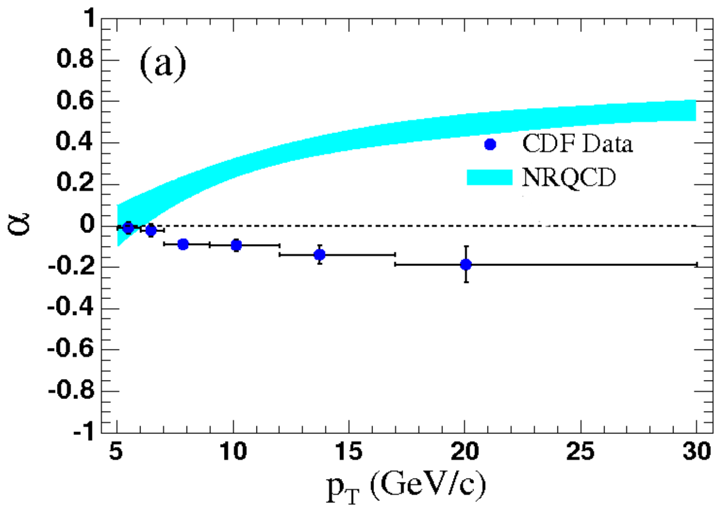
- extracted from the angular distribution of the produced leptons

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

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



- CDF data and NRQCD prediction for the prompt polarization



NRQCD prediction : transverse polarization at large P_T

data : unpolarized J/ψ

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

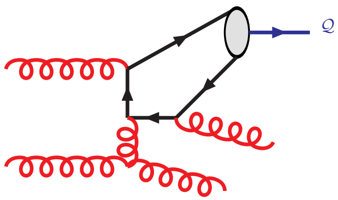
Appraisal

- Open questions :
  - role of the color-octet mechanism is not clear up to now (polarization problem)
  - Universality of the long distance matrix elements is not well established
- further possible studies :
  - higher order corrections in α_s to the inclusive production
  - more exclusive signatures to disentangle the various transitions

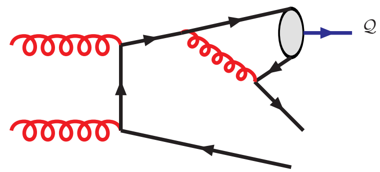
NLO correction to CS J/ψ production

[F. Maltoni, J. Campbell, F. Tramontano 2007]

- new channels :

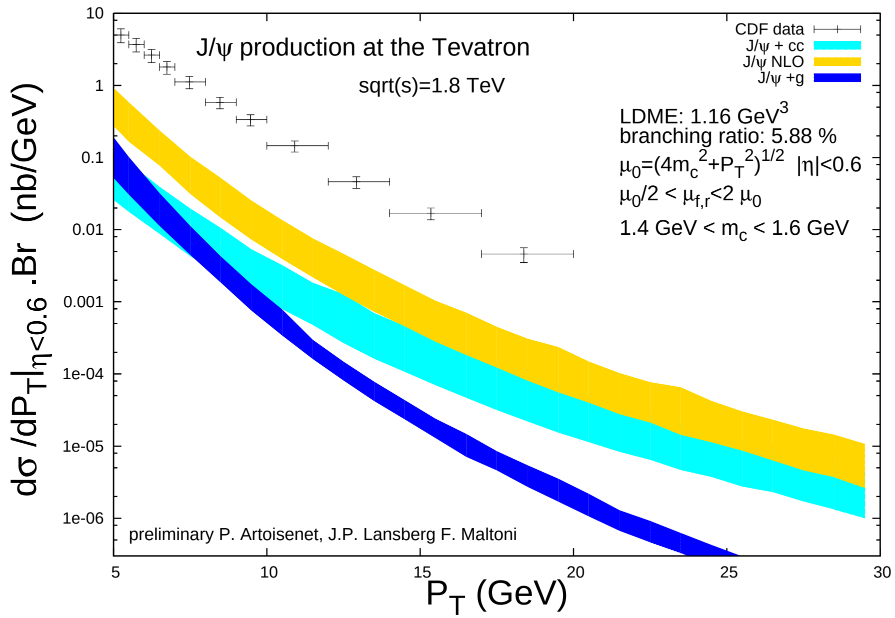


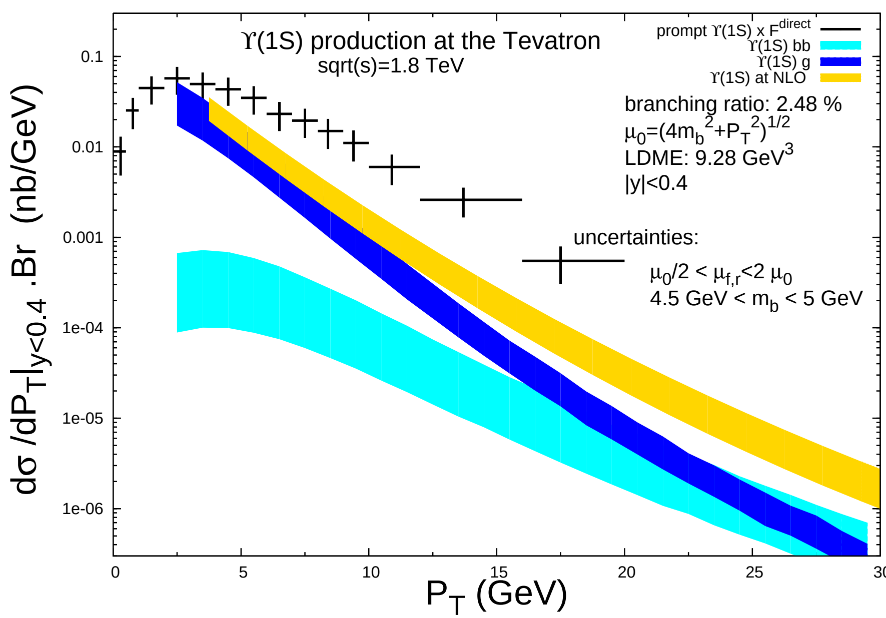
$\sim \alpha_s^4 \frac{1}{P_T^6}$



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

- comparison with the data



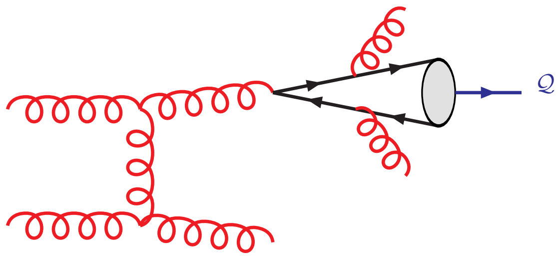


What is missing ?

We need new contributions with a more gentle P_T spectrum ($\frac{1}{P_T^4}$)

At α_s^5, we have both

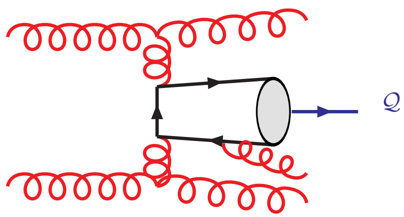
1. fragmentation channel



estimated in the

fragmentation approximation

2. high-energy enhanced channel



estimated in the

k_t factorization

These channels should dominate at large P_T

Real contribution from $\mathcal{Q} + 3$ jets

- technical difficulties : $p\bar{p} \to \mathcal{Q} + 3$ jets is challenging

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	

Real contribution from $\mathcal{Q} + 3$ jets

- technical difficulties : $p\bar{p} \to \mathcal{Q} + 3$ jets is challenging

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	

$\approx$ 2000 Feynman diagrams (reduced by a factor $\frac{1}{4}$ after the colour and spin projections are applied)

Real contribution from $\mathcal{Q} + 3$ jets

- technical difficulties : $p\bar{p} \longrightarrow \mathcal{Q} + 3$ jets is challenging

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	

≈ 2000 Feynman diagrams (reduced by a factor $\frac{1}{4}$ after the colour and spin projections are applied)

How can we deal with it ?

Real contribution from $\mathcal{Q}+3$ jets

- technical difficulties : $p\bar{p} \to \mathcal{Q}+3$ jets is challenging

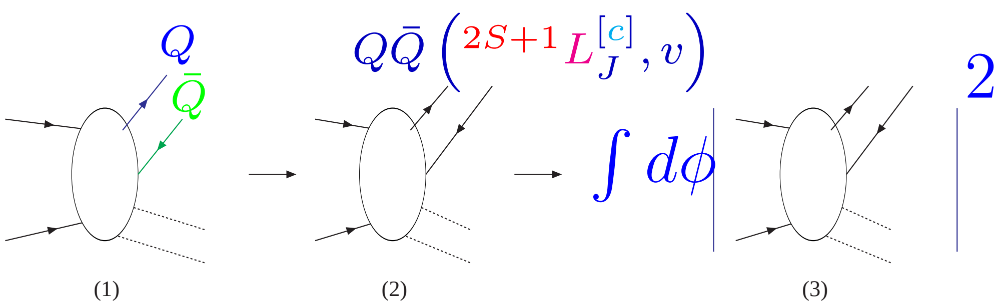
subprocesses :

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	

$\approx$ 2000 Feynman diagrams (reduced by a factor $\frac{1}{4}$ after the colour and spin projections are applied)

How can we deal with it ?

Solution : MadOnia (automatic tree-level computation of quarkonium amplitude) [P. A., F. Maltoni, T. Stelzer 2008]



(1) open quark amplitude (MadGraph)

(2) projected amplitude (MadOnia)

(3) phase-space integration

Real contribution from $Q + 3$ jets

- Physical difficulties : IR divergences in $p\bar{p} \to \Upsilon + 3jets$

  To cut the IR divergences, we impose

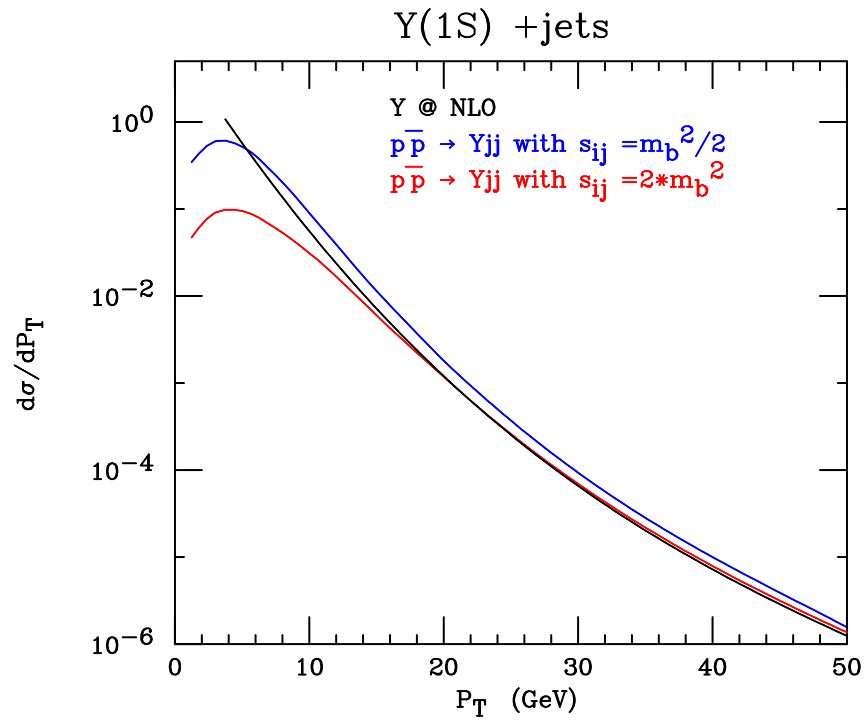
$$s_{i,j} > x \; m_b^2$$

At large P_T, the dependence in this cut is expected to be small, as

$$\frac{d\sigma}{dP_T} = \frac{c_1}{P_T^8} \log \frac{P_T^2}{x m_b^2} + \frac{c_2}{P_T^6} \log \frac{P_T^2}{x m_b^2} + \frac{c_3}{P_T^4}$$

Check of this approach with the NLO

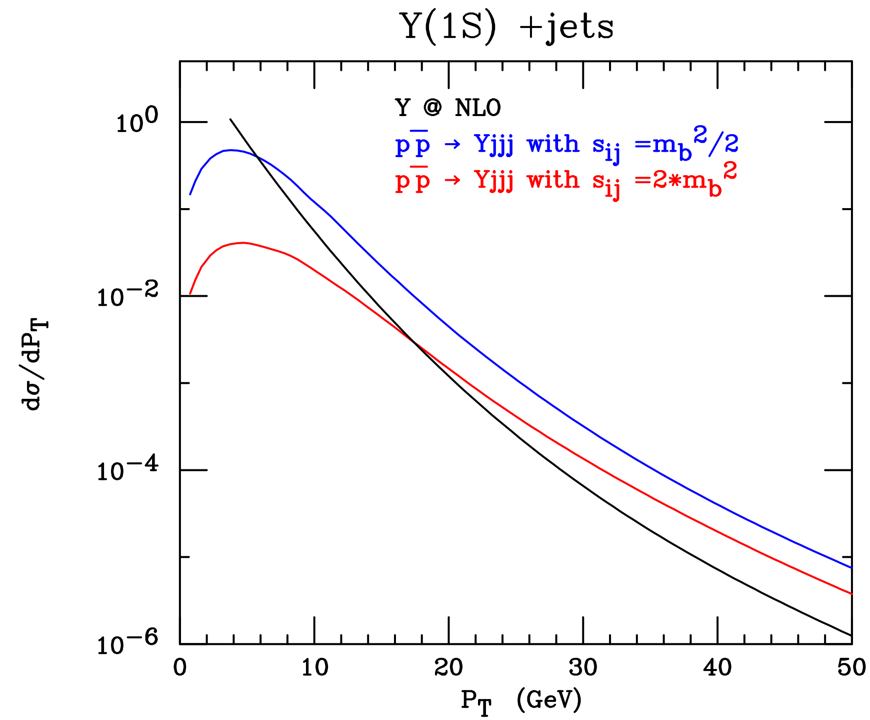
- $p\bar{p} \longrightarrow \Upsilon$ +2 jets versus full NLO



  - very small band at large P_T
  - good agreement with the full NLO at large P_T

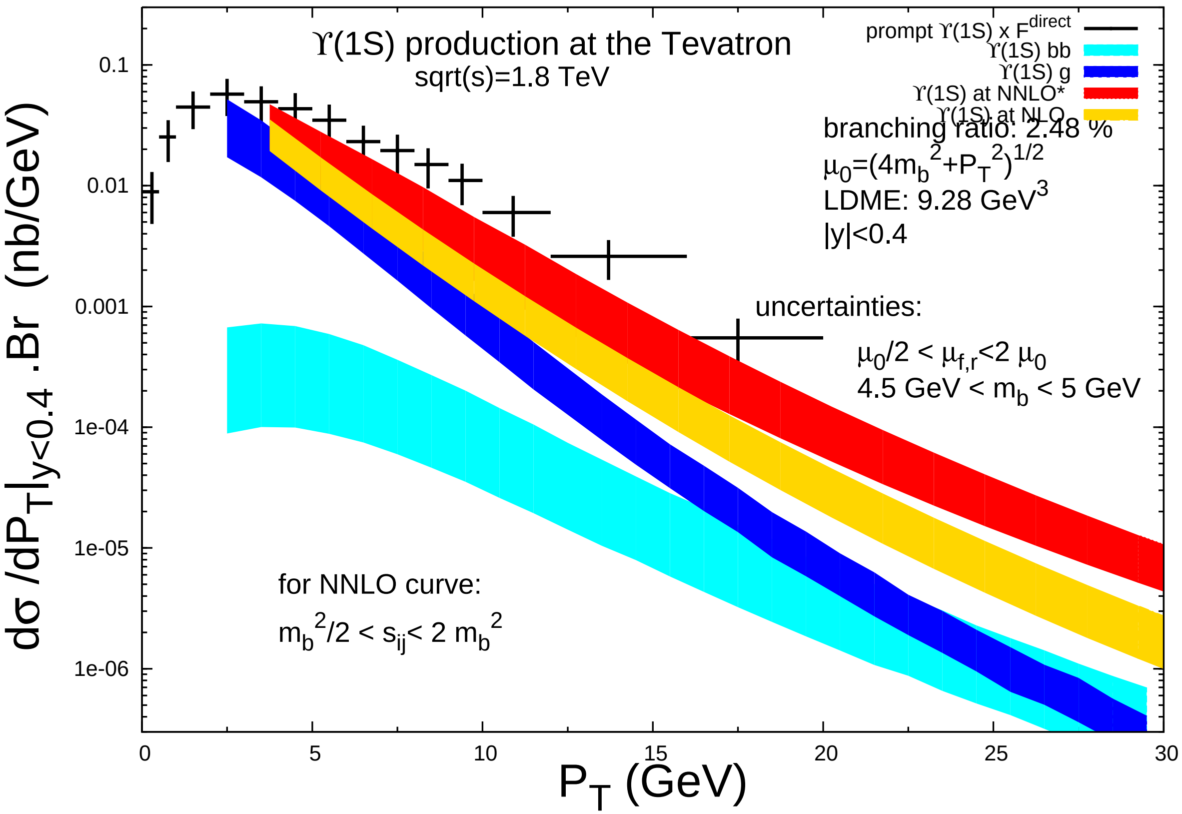
Check of this approach with the NLO

- $p\bar{p} \to \Upsilon$ +3 jets



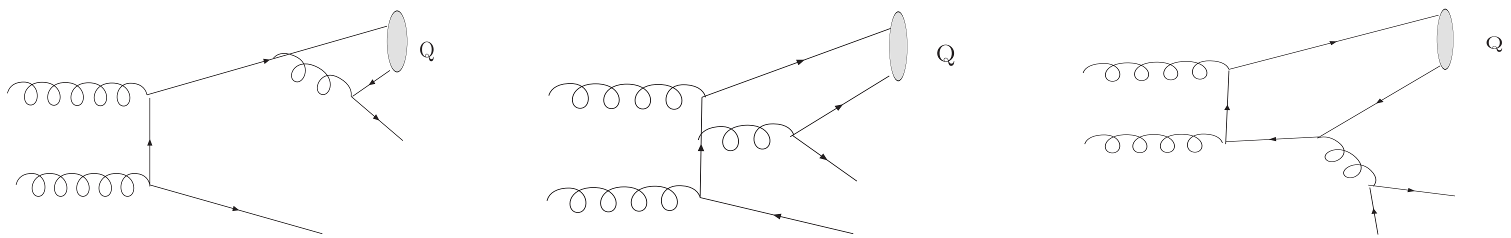
  - the width of the band (slowly) decreases with P_T
  - the contribution $\Upsilon + 3$ jets dominates over the NLO yield at large P_T

α_s^5 contributions to $\Upsilon(1S)$ production



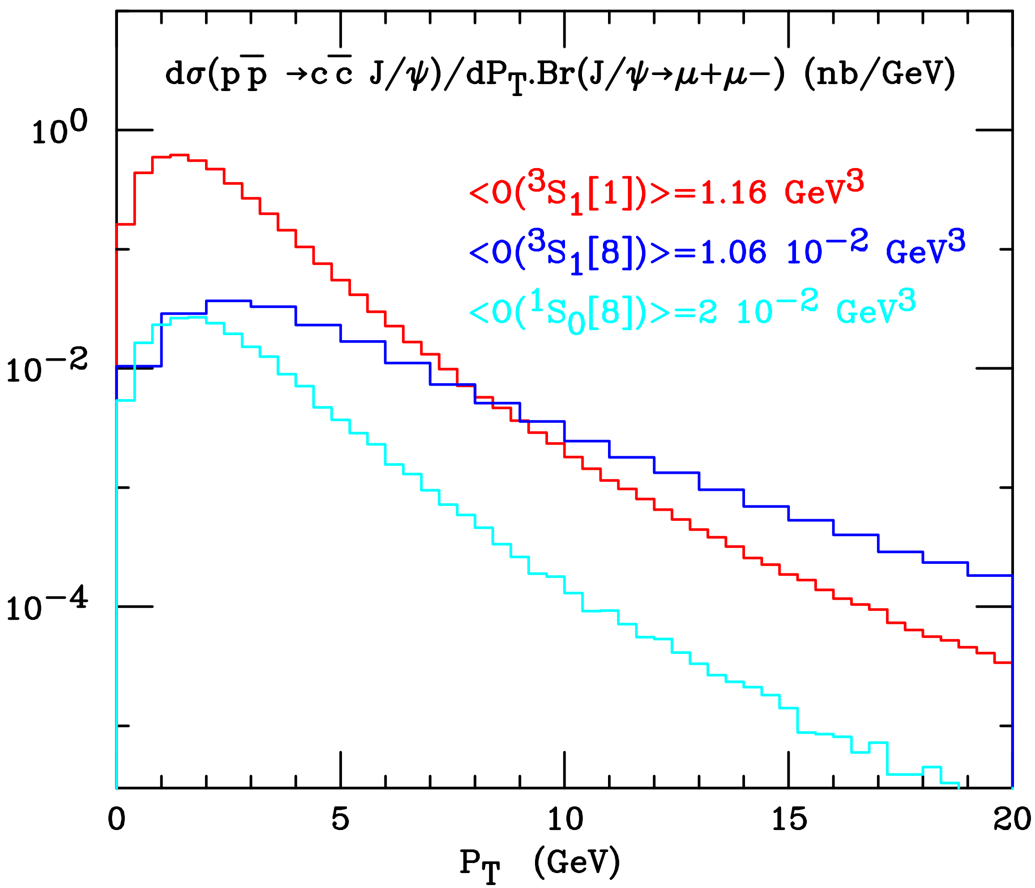
Associated production

- Analysis of the J/ψ production in association with a charm quark pair
  [P. A., J.P. Lansberg, F. Maltoni 2007]

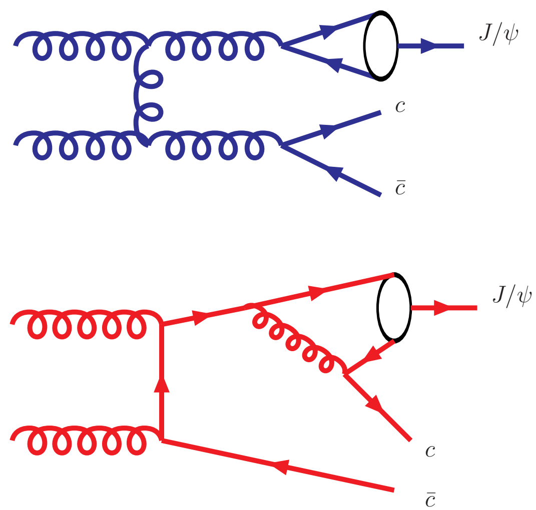


  - full calculation includes topologies that are not taken into account in the fragmentation approximation
  - theoretical prediction for this channel can be tested experimentally
  - new signature to study the various transitions and assess the universality of LDME

P_T spectrum

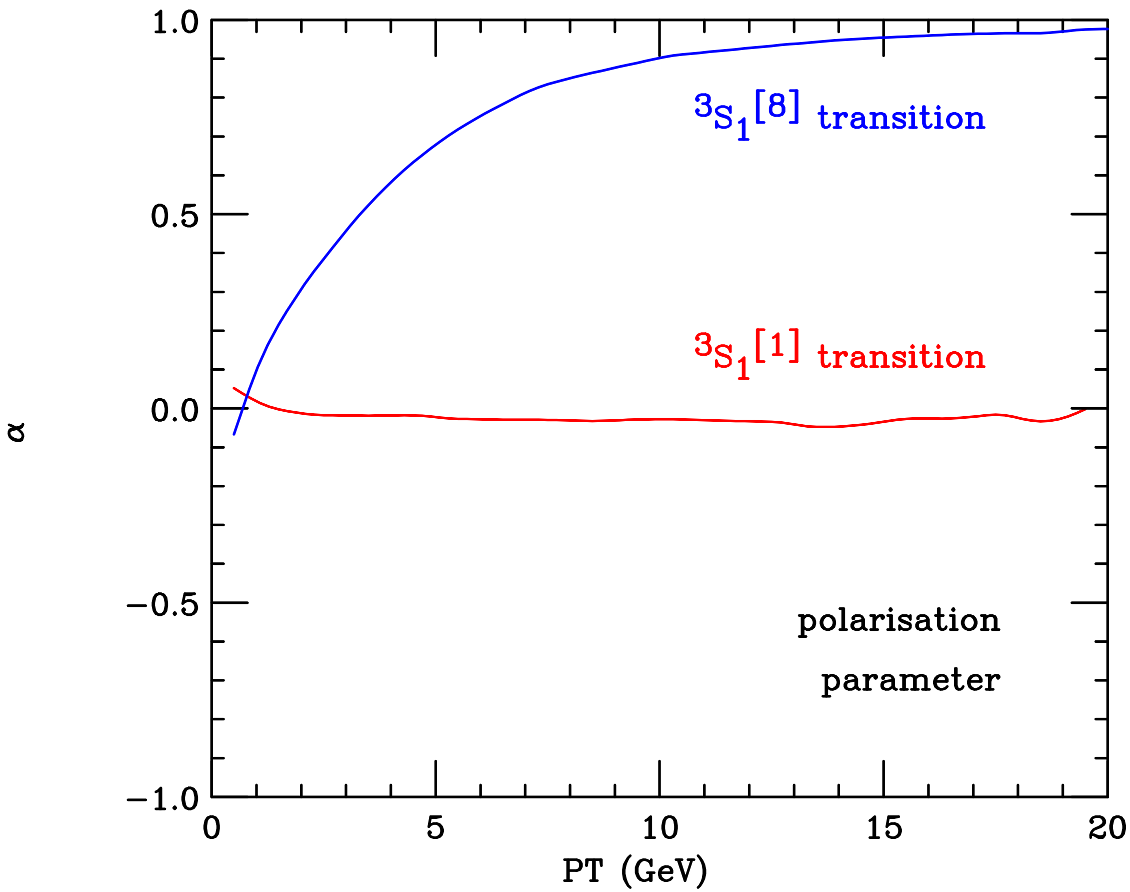


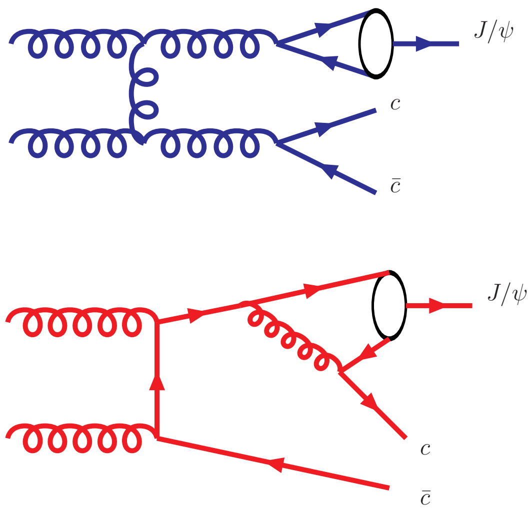
dσ(p p̄ →c c̄ J/ψ)/dP_T.Br(J/ψ→μ+μ−) (nb/GeV)
$<O(^3S_1[1])>=1.16$ GeV^3
$<O(^3S_1[8])>=1.06\ 10^{-2}$ GeV^3
$<O(^1S_0[8])>=2\ 10^{-2}$ GeV^3
10^0
10^{-2}
10^{-4}
0
5
10
15
20
P_T (GeV)



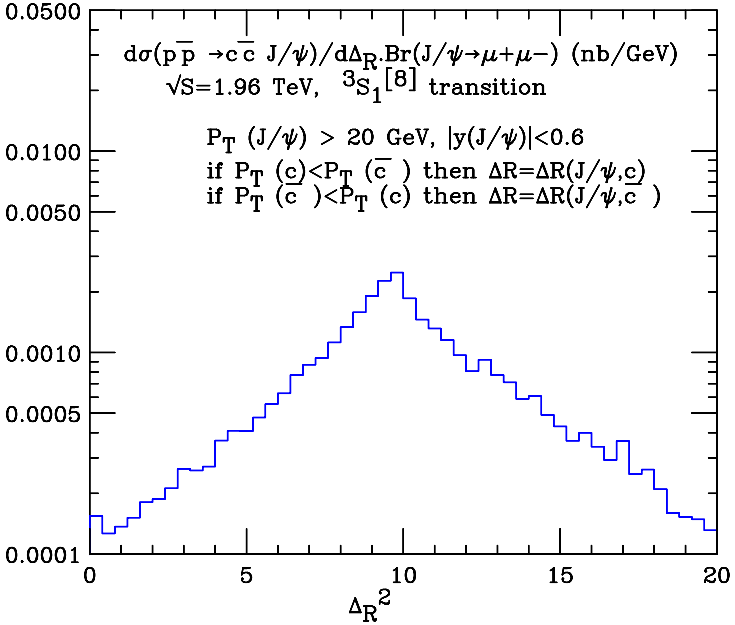
J/ψ
c
$\bar{c}$
J/ψ
c
$\bar{c}$

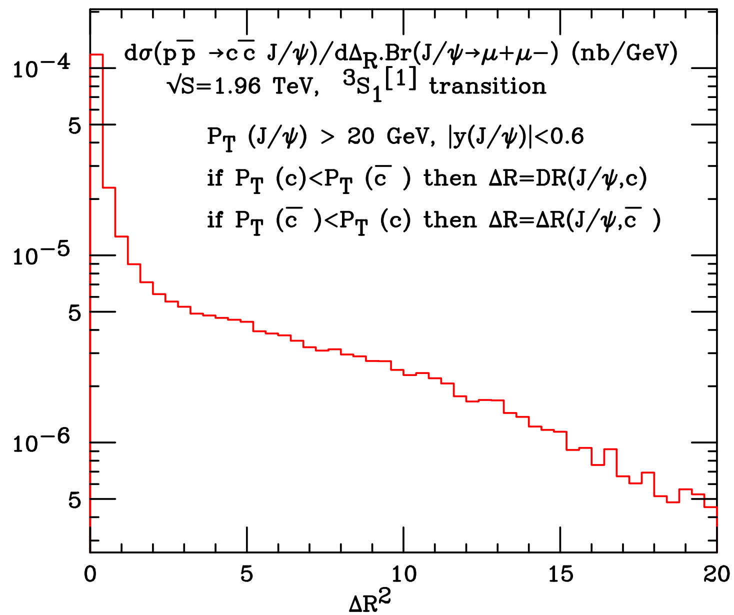
Polarization

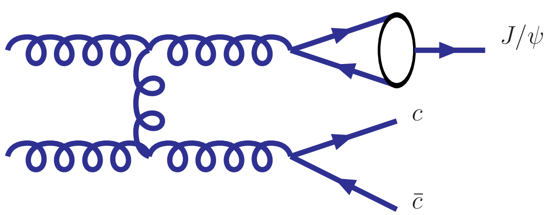


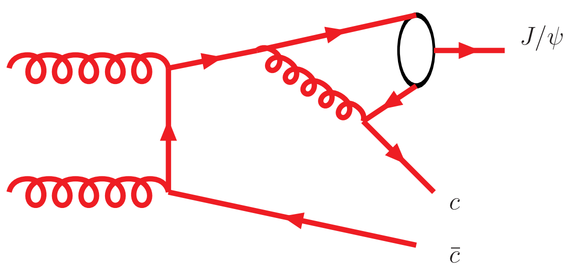


Charmed meson distribution





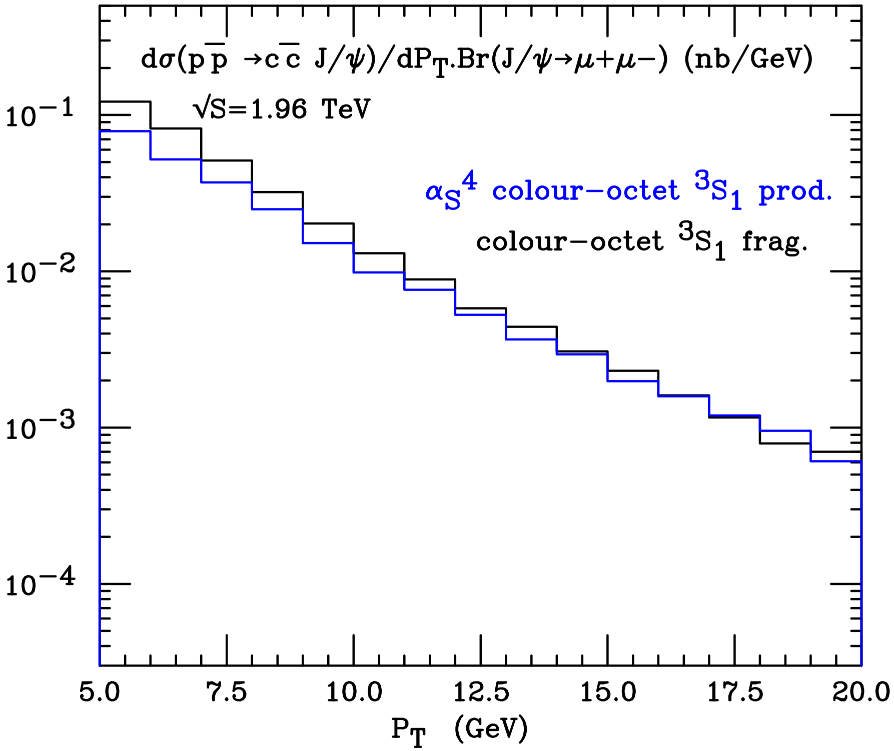


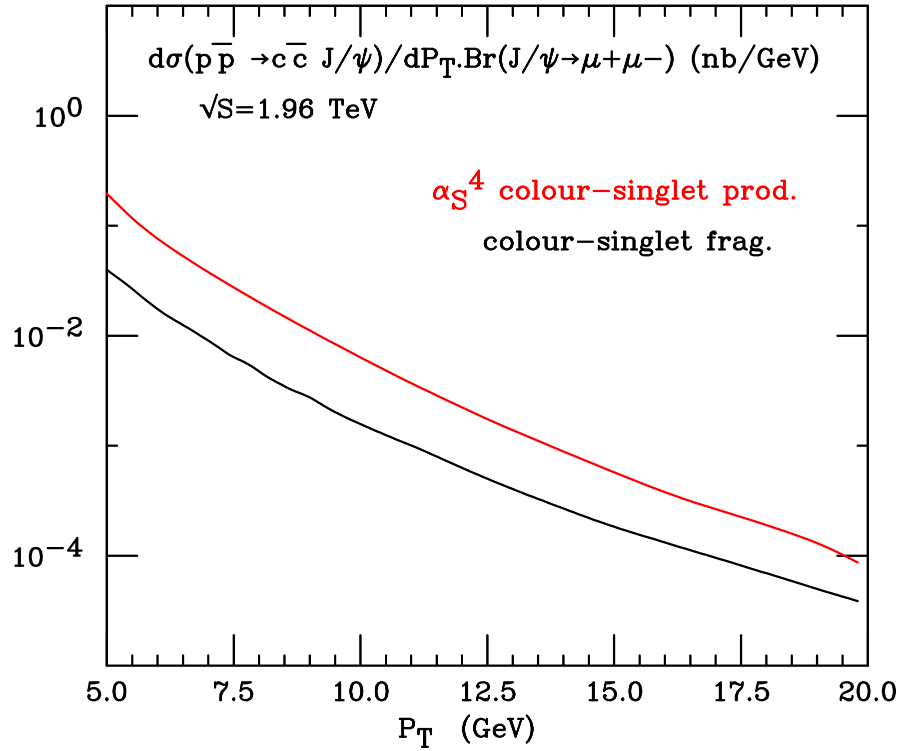


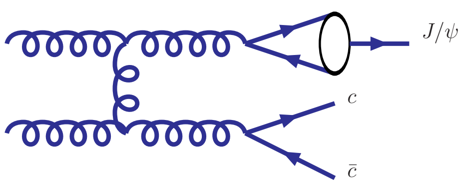
the softest charmed meson recoils against the J/ψ

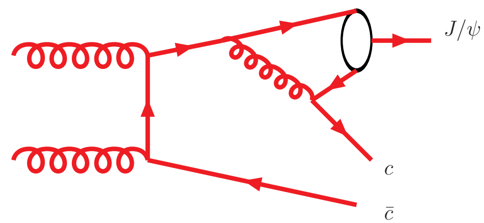
the softest charmed meson moves along with the J/ψ

Fragmentation approximation









invariant mass of the products of fragmentation is $2m_c$

invariant mass of the products of fragmentation is larger then $3m_c$

Conclusion

- J/ψ production at the Tevatron
  - inclusion of higher order correction in α_s reduces the discrepancy between the color-singlet yield and the data, but there is still a gap
  - the associated production $p\bar{p} \to J/\psi c\bar{c}$ is an interesting signature to study the production mechanisms
- $\Upsilon(1S)$ production at the Tevatron
  - with the inclusion of higher order correction in α_s, the color-singlet mechanism reproduces the data (with a large uncertainty)
  - the color-singlet yield has a longitudinal polarization