

Production de quarkonia lourds aux grands collisionneurs

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Outline

- → Naive pQCD approach: Colour Singlet Model (CSM) vs. CDF Data
- → Fragmentation in the CSM
- \rightleftharpoons List of problems for the CSM
- \Rightarrow Why does it fail ?
- \Rightarrow Review of some other models
- \Rightarrow QCD-corrections: α_s^4
- \Rightarrow QCD-corrections: α_s^5 ?
- \Rightarrow s-channel cut contributions
- → 4-point function
- Results
- Conclusions and outlooks

Naive pQCD approach: Colour Singlet Model (CSM)

\clubsuit Perturbative creation of two quarks Q and \bar{Q} BUT

- → on-shell (x)
- → in a colour singlet state (we want a physical state thereafter)
- → with a vanishing relative momentum
- \rightarrow in a ${}^{3}S_{1}$ state (for J/ψ , ψ' and Υ)



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- Non-perturbative binding of quarks



Schrödinger wave function

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- \rightarrow in a 3S_1 state (for J/ψ , ψ' and Υ)

$\begin{array}{c} & \mathcal{Q} \\ & & \mathbf{LO} \\ & & \alpha_s^3 \frac{(2m_Q)^4}{P_T^8} \\ & & \mathbf{Q} \end{array}$

Non-perturbative binding of quarks





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Fragmentation in the CSM

✓ Introduction of quark and gluon fragmentation processes:

→ Effectively NLO (α_s^4 instead of α_s^3):



Cacciari, Greco, Phys.Rev.Lett.73:1586,1994

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- → Different p_T behaviour: P_T^{-4} vs. P_T^{-8} .
- \rightarrow Illustration for the ψ'

- \times Off by factor 30-100 for J/ψ and ψ'
- \times Off by factor 10 for Υ 's



List of problems for the CSM

- $\Rightarrow J/\psi$ and ψ' hadroproduction at the Tevatron : factor 30 100
- $\Rightarrow \Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ hadroproduction at the Tevatron : \pm factor 10
- $\Rightarrow J/\psi$ Inelastic electro-production at HERA but

the NLO CSM agrees with photo-production measurements

- $\Rightarrow J/\psi$ production in $\gamma\gamma$ collisions at LEP
- \Rightarrow Double charm production $(J/\psi + c\overline{c})$ at BELLE

I shall concentrate here on hadroproduction at the Tevatron

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→ Should the pair be produced in a colour singlet ? Can't it evolve ?

Colour Octet Mechanism

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Colour Octet Mechanism

→ Can't the quarks be produced off-shell ? with relative momentum \neq 0? s-channel cut contribution

for a recent review, see *e.g* JPL IJMPA **21** 3857-3915 (2006)

- \rightarrow Numerous soft-gluon emissions from the $Q\bar{Q}$ pair change its quantum state
- \rightarrow The quantum state is randomised; no more correlation with the hard part
- → The cross-section to produce a Q is obtained from σ_{onium} after distributing it between the other Q of the family:

$$\sigma_{onium} = \frac{1}{9} \int_{2m_Q}^{2m_{\bar{q}Q}} dm \frac{d\sigma_{Q\bar{Q}}}{dm}$$

✓ Solve the problem for cross-section data (implicit COM fragmentation channel: see later)

- **X** Nearly no predictivity: parameters to be fit and vary from one process to another
- **X** No possible systematic improvement of the model
- ***** Polarisation ?

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Soft Colour Interaction (SCI): Ingelman et al.

- $\rightarrow \sigma_{onium}$ is the colour singlet part of $\sigma_{Q\bar{Q}}$ (factor $\frac{1}{9}$ in the CEM)
- → Soft colour interactions are responsible for the colour bleaching
- \rightarrow Their number depends on the final state multiplicity: different p_T slope than CEM
- \rightarrow In the SCI model, they are accounted for by Monte Carlo technique
- ✓ Slight improvement of the data fit
- ✓ Distribution parameters in better agreent with spin multiplicity
- Same drawbacks as for CEM

for a recent review, see *e.g* JPL IJMPA **21** 3857-3915 (2006)

- → Re-scattering with comovers: Hoyer-Peigné
 - \rightarrow The $p\bar{p}$ collision creates a gluon field co-mobile with the ${\cal Q}$



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 - ✓ Nice distinction between Hadro- and Photo- production
 - * Property of the gluon field not known; its polarisation is postulated
 - **X** Implicit violation of factorisation theorem
 - heavy-quark fragmentation not yet considered



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- → Re-analysis of QCD higher-order contributions: Stirling et al.
 - \rightarrow gluon pair in octet state exchanged
 - \rightarrow Here NNLO pQCD effectively corresponds to LO BFKL
 - ✓ "Natural" enhancement of the production
 - Only total cross-section prediction
 - **X** Correct p_T slope from an input

for a recent review, see *e.g* JPL IJMPA **21** 3857-3915 (2006)

 \Rightarrow k_T factorisation and BFKL vertex

L. Szymanowski, N. Zotov, Baranov,... J. Collins, K. Ellis

- \rightarrow The initial gluons (called reggeons) are off-shell and with an intrinsic k_T
- → One uses unintegrated pdf instead of the pdf: $xg(x,\mu^2) = \int_0^{\mu^2} \frac{dq_T^2}{q_T^2} \mathcal{F}(x,q_T)$
- → Effective vertices derived from NNLLA BFKL, ...

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- → Effective vertices derived from NNLLA BFKL, ...
- \rightarrow For instance, for $gg \rightarrow Q\bar{Q}$, one starts from:



- → The $Q\bar{Q}$ is projected on a colour singlet or octet configuration
- ✓ For COM, smaller LDME's: good for photo-production (see later)
- Large uncertainty due to the updf
- **X** Choice of scale for α_s

for a recent review, see *e.g* JPL IJMPA **21** 3857-3915 (2006)

 → NRQCD applied to Heavy quarkonium → Colour Octet Mechanism Bodwin, Braaten, Lepage, Cho, Leibovich,...

→ NRQCD takes into account effects of other Fock states than $Q\bar{Q}$

$$\begin{aligned} |\mathcal{Q}_Q\rangle = \mathcal{O}(1) |Q\bar{Q}[\ ^3S_1^{(1)}]\rangle + \mathcal{O}(v) |Q\bar{Q}[\ ^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2) |Q\bar{Q}[\ ^1S_0^{(8)}g]\rangle \\ + \mathcal{O}(v^2) |Q\bar{Q}[\ ^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2) |Q\bar{Q}[\ ^3D_J^{(1,8)}gg]\rangle + \dots \end{aligned}$$

→ First introduced to cure IR divergences of the CSM in ${}^{3}P_{1}$ and ${}^{1}P_{1}$ decays

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- \rightarrow First introduced to cure IR divergences of the CSM in ${}^{3}P_{1}$ and ${}^{1}P_{1}$ decays
- → Key argument: physical states can be produced by coloured objects !
- \rightarrow Gluon fragmentation appears now at LO
 - Most solid theoretical background
 - ✓ Successful description of many process cross-sections
 - ***** Non-perturbative parameters $\langle \mathcal{O}^{\mathcal{Q}}[^{2S+1}L_J^{(1,8)}] \rangle$ are introduced for each new transition
 - ***** They can only be fixed by fits; perhaps some are calculable on the lattice ?
 - ***** Scaling rules should constrain them; but these are under discussion
 - Cannot account for polarisation measurements

Fragmentation via Colour Octets

Color Octet Mechanism:

Physical states can be produced by coloured pairs

 $\Rightarrow J/\psi$, ψ' and Υ can be produced by a single –coloured– gluon

 \Rightarrow Gluon fragmentation appears at Leading Order in α_s



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- \Rightarrow When $P_{gluon} \gg$, the gluon is nearly on-shell and transversally polarised
- \Rightarrow NRQCD spin symmetry: Q has the same polarisation as the gluon
- \Rightarrow Experimentally, one can study α such that:

 $\alpha = +1 \Leftrightarrow \text{Transverse} \ \alpha = 0 \Leftrightarrow \text{Unpolarised} \ \alpha = -1 \Leftrightarrow \text{Longitudinal}$

A Comment

Color Octet Mechanism:

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Can we test the fragmentation approximation ?

 $Q + Q\bar{Q}$: testing the quark-fragmentation approximation

 $\begin{array}{l} \textbf{P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007} \\ \textbf{\rightarrow} \ A \ priori \ \sigma(\mathcal{Q} + Q\bar{Q}) \ could \ be \ approximated \ by \ the \ fragmentation \ approx \\ \hline \ leading \ P_T \ behaviour \end{array}$

→ We would *just* miss some (sub-dominant) topologies like:



 $Q + Q\bar{Q}$: testing the quark-fragmentation approximation

P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007 \rightarrow A priori $\sigma(Q + Q\overline{Q})$ could be approximated by the fragmentation approx leading P_T behaviour

→ We would *just* miss some (sub-dominant) topologies like:



 \rightarrow However, the comparison with the full LO CSM for $pp \rightarrow Q + Q\bar{Q}$ shows

no ambiguity: The fragmentation approximation does not work !





P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007



 \Rightarrow Larger than $pp \rightarrow Qg$ at large P_T :

points at large NLO (α_S^4) corrections



P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007



 \Rightarrow Larger than $pp \rightarrow Qg$ at large P_T :

points at large NLO (α_S^4) corrections \Rightarrow New observables: $J/\psi + D$ meson; $\Upsilon + b$ tagged jet

 $J/\psi + c\bar{c}$: P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007



Full computation of $J/\psi + c\bar{c}$:

 $3 \times larger$ than the fragmentation approximation

 $J/\psi + c\bar{c}$: P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007 NLO (e.g. $J/\psi + gg$): J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007



Signification improvement, but we need something more...

 $J/\psi + c\bar{c}$: P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007 NLO (e.g. $J/\psi + gg$): J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007



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What about for the Υ ?



 $\Upsilon + b\overline{b}$: P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007 NLO (e.g. $\Upsilon + gg$): J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007



Close to an agreement with data

Can we do better ?

MadOnia: P.Artoisenet, F. Maltoni, T. Stelzer, arXiv:0712.2770

- → MadOnia: Automatic generation of tree-level quarkonium amplitudes
- → New P_T^{-4} process at α_s^5 : $gg \to Qggg$
- → Normally accounted by gluon fragmentation Is it reliable ?
- \rightarrow Possible check by imposing cuts on $gg \rightarrow Qggg$ generated by MadOnia

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 $p\bar{p} \rightarrow \mathcal{Q}jjj \ (j=g,u,d,s,c)$ with cuts:

first estimate of the impact of NNLO corrections (α_s^5)

P. Artoisenet *et al.*, in progress



P. Artoisenet *et al.*, in progress



 \rightarrow Still preliminary, need more study on theoretical uncertainties

→ Much closer, but still not enough...

What about for the Υ ?



P. Artoisenet et al., in progress





P. Artoisenet et al., in progress



- \rightarrow Exactly what is needed in normalisation and shape !
- → Still preliminary, need more study on theoretical uncertainties



P. Artoisenet et al., in progress

- → Cross sections seem OK
- → Polarisation ?



- → Uncertainties under study
- → Comparison with prompt measurements ?
- → Work still in progress for "real" NNLO

What about the J/ψ puzzle ?

s-channel cut contribution

J.P.L., J.R. Cudell, Yu.L. Kalinovsky, PLB 633, 301,2006

So far, people considered only such configurations idem for NRQCD



s-channel cut contribution
 J.P.L., J.R. Cudell, Yu.L. Kalinovsky,PLB 633, 301,2006
 Q Q

 \Rightarrow What about those ? (*i.e.* the usual contributions to $Im(\mathcal{M})$)

s-channel CUT



 \rightarrow Quark relative momentum not fixed to zero; 2 more integrals

→ $Q - \bar{Q} - Q$ vertex has one leg off-shell

Introduction of a 4-point function to preserve gauge-invariance

4-point function

 \rightarrow Accounts for such contributions



4-point function

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 C_1

→ Cannot be uniquely derived from the $Q - \bar{Q} - Q$ vertex $\Gamma^{(3)}$

 \rightarrow Yet, constrained by gauge-invariance

$$(\Gamma^{(4)}(c_1, c_2, q))^{\mu\nu} = \left(\frac{(2c_2 + q)^{\nu}}{(c_2 + q)^2 - m_Q^2}(\Gamma_1^{(3)} - F) + \frac{(2c_1' - q)^{\nu}}{(c_1 + q)^2 - m_Q^2}(\Gamma_2^{(3)} - F)\right)\gamma^{\mu}$$

with $F(c_1, c_2) = \Gamma_0 - h(c_1, c_2)\frac{(\Gamma_0 - \Gamma_1(c_1, c_2))(\Gamma_0 - \Gamma_2(c_1, c_2))}{\Gamma_0}$

h being an arbitrary crossing symmetric function H. Haberzettl, PRC56:2041,1997 H. Haberzettl et al. ,PRC58:40,1998



→ Limiting behaviour:

× low momentum: minimal substitution: $F = \Gamma_0$

S.D. Drell, T.D. Lee, PRD5:1738,1972

K. Ohta, PRC40:1335,1989

 \times large momentum: scaling: h = 1

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 \rightarrow Let's interpolate:

$$h(c_1.c_2) = 1 - a \frac{\kappa^2}{\kappa^2 - (c_1.c_2 + m_Q^2)}$$

H. Haberzettl, J.P.L, Phys. Rev. Lett.: 100,032006,2008

a and κ will be fixed by the data.



H. Haberzettl, J.P.L, Phys. Rev. Lett.: 100,032006,2008

With $\kappa = 4.5$ GeV and a = 4, we get for the Tevatron and RHIC:





H. Haberzettl, J.P.L, Phys. Rev. Lett.: 100,032006,2008

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- \Rightarrow Higher-order QCD corrections modify significantly the P_T scaling:
 - → Not a surprise: cf. fragmentation channels $(P_T^{-4} \text{ vs. } P_T^{-8})$
 - \rightarrow The surprise concerns the fragmentation approximations
 - → For the Υ , $\mathcal{O}(\alpha_S^5)$ bring an agreement with experiments (at last !)
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 - \rightarrow For the J/ψ and ψ' , we still miss something . . .
- So far,s-channel cuts (as well as real contributions) were overlooked
 - \rightarrow Not easy to deal with systematically
 - → Yet, they are likely to be significant.

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- \rightarrow s-channel cuts: application to photo-production (check), AA collisions

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- → Then the LHC...
 - → Needs of Monte Carlo
- \rightarrow For now, only the LO CSM and LO COM are implemented in PYTHIA



COM: S.Wolf, M. Bargiotti

A. Kraan, talk @ QWG07

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→ Future:

- → QCD-corrections: check uncertainties, polarisation at "NNLO"
- \rightarrow s-channel cuts: application to photo-production (check), AA collisions
- → Then the LHC...
 - → Needs of Monte Carlo
 - → For now, only the LO CSM and LO COM are implemented in PYTHIA COM: S.Wolf, M. Bargiotti
 - \rightarrow At least for Υ ,

MadOnia and NNLO matrix elements should be interfaced with PYTHIA

? A. Kraan, P. Artoisenet, F. Maltoni, ... ?

 \rightarrow Guide experimentalists to new channels: $Q + Q\bar{Q}$, ...