New mechanisms and open problems in quarkonium production

J.P. Lansberg
SLAC – Stanford U.

International Workshop on Heavy Quarkonia 2008
Nara Women’s University, Japan
2-5 December 2008

Many thanks to my collaborators
Part I

Past (up to 2007)
Basic pQCD approach: the Colour Singlet Model (CSM)


- Perturbative creation of 2 quarks $Q$ and $\bar{Q}$ BUT
  - on-shell ($\times$)
  - in a colour singlet state
  - with a vanishing relative momentum
  - in a $^3S_1$ state (for $J/\psi$, $\psi'$ and $\Upsilon$)
- Non-perturbative binding of quarks

→ Schrödinger wave function
Basic pQCD approach: the Colour Singlet Model (CSM)

Perturbative creation of 2 quarks $Q$ and $\bar{Q}$ BUT

- on-shell ($\times$)
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Non-perturbative binding of quarks $\rightarrow$ Schrödinger wave function

\[ \alpha_s^3 \frac{(2m_Q)^4}{P_T^8} \]

CDF, PRL 79:572 & 578, 1997
CDF, PRL 88:161802, 2002

\[ \text{BR}(J/\psi \rightarrow \mu^+ \mu^-) \frac{d\sigma(pp \rightarrow J/\psi + X)}{dp_T} \text{ (mb/GeV)} \]
\[ \sqrt{s} = 1.8 \text{ TeV}; |\eta| < 0.6 \]

LO colour-singlet

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Basic pQCD approach: the Colour Singlet Model (CSM)


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$\sum \alpha_s \frac{(2m_Q)^4}{P_T^8}$

$\Rightarrow$ Schrödinger wave function

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- Non-perturbative binding of quarks $\rightarrow$ Schrödinger wave function
$J/\psi$ production in $\gamma\gamma$ collisions at LEP II

$e^+e^- \rightarrow e^+e^- J/\psi X$ at LEP2

- DELPHI prelim.
- MRST98 fit
- CTEQ5 fit
- $\sqrt{S} = 197$ GeV
- $-2 < y_{J/\psi} < 2$

CSM

DELPHI, PLB 565 76, 2003
$J/\psi$ photoproduction at HERA

LO CSM also fails in photoproduction at HERA...


E.g. H1, EPJC 25, 2, 2002; ZEUS, EPJC 27, 173, 2003
**$J/\psi$ photoproduction at HERA**

LO CSM also fails in photoproduction at HERA...

However NLO CSM is in agreement the data!

NLO revisited: see P. Artoisenet’s talk
Why does the CSM fail?

Why does the CSM (basic pQCD approach) fail?

Specifically large QCD-corrections? Why so?

hints: NLO contributions for $\gamma p$, $P_T$ scaling of fragmentation channels: $\frac{1}{P^4_T}$ vs. $\frac{1}{P^8_T}$
Why does the CSM fail?

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- Hypotheses/constraints of the model too strong?
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→ Should the pair be perturbatively produced in a color singlet? Can’t it evolve?
  e.g. Colour Octet Mechanism, Colour Evaporation Model
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Hypotheses/constraints of the model too strong?

Should the pair be perturbatively produced in a color singlet? Can't it evolve?

e.g. Colour Octet Mechanism, Colour Evaporation Model

Can't the quarks be produced off-shell? with relative momentum $\neq 0$?

s-channel cut contribution

For a recent review of various solutions proposed, see e.g. JPL IJMPA 21 3857-3915 (2006)
Why does the CSM fail?

One of the solutions proposed: the Color Octet Mechanism

**Color Octet Mechanism**: physical states can be produced by *coloured pairs*

Bodwin, Braaten, Lepage, Cho, Leibovich,...

---

**Experimentally, this is clearly contradicted!**

\[
\alpha = +1 \Leftrightarrow \text{Transverse}, \quad \alpha = 0 \Leftrightarrow \text{Unpolarised}, \quad \alpha = -1 \Leftrightarrow \text{Longitudinal}
\]

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<table>
<thead>
<tr>
<th>(GeV/c)</th>
<th>TP</th>
<th>CDF Data</th>
<th>NRQCD</th>
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\[
\alpha = -1 \]

---

J.P. Lansberg (SLAC – Stanford U.)
One of the solutions proposed: the Color Octet Mechanism

Color Octet Mechanism: physical states can be produced by coloured pairs

Bodwin, Braaten, Lepage, Cho, Leibovich, ...

→ $J/\psi, \psi'$ and $\Upsilon$ can be produced by a single gluon

 ✓ Gluon fragmentation then LO in $\alpha_s$: larger rates

$\langle \text{GeV/c} \rangle$

$T_P$

$\alpha$

-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

CDF Data
NRQCD

$J/\psi$

$\Upsilon$

$\langle \text{GeV/c} \rangle$

$T_P$

$\alpha$

-1
-0.8
-0.6
-0.4
-0.2
0
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CDF Data
NRQCD

$\Psi(2S)$

CDF, PRL 99: 132001, 2007
One of the solutions proposed: the Color Octet Mechanism

Color Octet Mechanism: physical states can be produced by coloured pairs

- $J/\psi$, $\psi'$ and $\Upsilon$ can be produced by a single gluon
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- NRQCD spin symmetry: $Q$ has the same polarisation as the gluon

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* Experimentally, *this is clearly contradicted*!

$$\alpha = +1 \iff \text{Transverse} \quad \alpha = 0 \iff \text{Unpolarised} \quad \alpha = -1 \iff \text{Longitudinal}$$
Part II

Present
Describing the low-$P_T$ region: the s-channel cut

So far, one considered only such configurations
idem for NRQCD

\[ Q \]

CSM CUT

\[ \text{JPL, J.R. Cudell, Yu.L. Kalinovsky, PLB633:301, 2006} \]

A bit challenging:
- Quark relative momentum not fixed to zero; 2 more integrals
- $c - \bar{c} - Q$ vertex has one leg off-shell

Introduction of a 4-point function – the $c - \bar{c} - Q - g$ coupling – to preserve gauge-invariance
Describing the low-$P_T$ region: the $s$-channel cut

📈 So far, one considered only such configurations idem for NRQCD

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

JPL, J.R. Cudell, Yu.L. Kalinovsky, PLB633:301,2006

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Introduction of a 4-point function – the \(c - \bar{c} - Q - g\) coupling – to preserve gauge-invariance
The s-channel cut contribution: first evaluation

If the $c - \bar{c} - Q - g$ coupling is constrained to satisfy:

→ gauge invariance,
→ low energy limit,
→ scaling limit,

it can be parametrised using two constants.
The s-channel cut contribution: first evaluation

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it can be parametrised using two constants.

If those are fixed to fit Tevatron data up to mid $P_T$:

\[
\frac{d\sigma}{dP_T} \cdot |\eta| < 0.6 \times \text{Br} \quad (\text{nb/GeV})
\]

\[
\begin{align*}
\text{CDF data} & \quad \sigma_{\text{tot}} \\
\text{LO CSM: } J/\psi + cc & \quad \sigma_{L} \\
\text{LO CSM: } J/\psi + g & \quad \sigma_{T}
\end{align*}
\]

PHENIX data are very well described!

This has to be tested: $ep, \gamma\gamma \rightarrow \text{Need for more observables!}$

What about the real part?
The s-channel cut contribution: first evaluation

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H. Haberzettl, J.P.L, PRL 100,032006,2008

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PHENIX data are very well described!

- s-channel cut contributions are large, specifically at small \(P_T\)
- This has to be tested: \(ep, \gamma\gamma\) → Need for more observables!
- What about the real part?
Describing the low-\(P_T\) region: the s-channel cut

The s-channel cut contribution: first prediction verified!

H. Haberzettl, J.P.L, PRL 100,032006,2008
M. Donadelli, for the PHENIX Collab, talk at PANIC 2008, Nov.2008

\[
\begin{array}{c|c}
|y| < 0.35 & |y| \in [1.2,2.2] \\
\hline
\text{s-channel cut} & \text{s-channel cut} \\
\end{array}
\]

Quarkonium production

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The s-channel cut contribution: first prediction verified!

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![Graph showing the s-channel cut contribution with data points and a fit curve.](image-url)
Describing the mid- and high-$P_T$ region: QCD corrections

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


Significant improvement, but we need something more. . .

Confirmed by B. Gong and J. X. Wang who computed the polarisation as well


What about for the $\Upsilon$?

J. P. Lansberg (SLAC – Stanford U.)
Describing the mid- and high-$P_T$ region: QCD corrections

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CDF data $J/\psi + g$

$J/\psi$ production at the Tevatron
sqrt(s) = 1.8 TeV

$\frac{d\sigma}{dP_T}|_{\eta < 0.6} \cdot Br$ (nb/GeV)

$P_T$ (GeV)

Br: 5.88%, $<0>: 1.16$ GeV

$\mu_0/(2 < \mu_f < 2 \mu_0)$

1.4 GeV $< m_c < 1.6$ GeV

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Describing the mid- and high-\( P_T \) region: QCD corrections

\( J/\psi + c\bar{c} \): 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

\[ \frac{d\sigma}{dP_T} |_{\eta < 0.6} \cdot \text{Br} \quad (\text{nb/GeV}) \]

\( P_T \) (GeV)

CDF data
\( J/\psi + g \)
\( J/\psi + cc \)

unc. band:
\( \mu_0/2 < \mu_{f,r} < 2 \mu_0 \)

1.4 GeV < \( m_c < 1.6 \) GeV

J/\psi production at the Tevatron
\( \sqrt{s} = 1.8 \) TeV

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\( \mu_0 = (4m_b^2 + P_T^2)^{1/2} \)

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Describing the mid- and high-\(P_T\) region: QCD corrections

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\[ \text{Phys. Rev. Lett. 100, 232001 (2008)} \]

What about for the \(\Upsilon\)?
Describing the mid- and high-$P_T$ region: QCD corrections

**QCD corrections:** $\alpha_s^4$ (NLO) for $\Upsilon$

$\Upsilon + c\bar{c}$: 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

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**Graph:**

- **Legend:**
  - LO
  - $\Upsilon + bb$
  - NLO
  - $\Upsilon (1S)$ prompt data $x F_{\text{direct}}$

**Axes:**
- $d\sigma/dP_T |_{|y|<0.4} \times Br$ (pb/GeV)
- $P_T$ (GeV)

---

Close to an agreement with data

Can we do better?
NLO QCD corrections to the Colour Octet Mechanism


- NLO corrections to COM channels have tiny effects on $d\sigma/dt$ and $\alpha$
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NLO QCD corrections to the Colour Octet Mechanism

- NLO corrections to COM channels have tiny effects on $d\sigma/dt$ and $\alpha$

- Confirmation that COM cannot describe the polarisation

- We definitely need something else!
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ contributions: NNLO*

MadOnia: Automatic generation of tree-level quarkonium amplitudes


Validation at $\alpha_s^4$: the full NLO is amazingly well reproduced by $jj \rightarrow Qjj$.

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

First estimate of the impact of NNLO contributions ($\alpha_s^5$).
Describing the mid- and high-$P_T$ region: QCD corrections

\[ \alpha_s^5 \text{ corrections contributions: NNLO}^* \]

- New $P_T^{-4}$ process at $\alpha_s^5$: $gg \rightarrow Qggg$
- Normally accounted by gluon fragmentation

Let us check!
Describing the mid- and high-$P_T$ region: QCD corrections

\( \alpha_s^5 \) contributions: \textbf{NNLO}\(^*\)

$\rightarrow$ New $P_T^{-4}$ process at $\alpha_s^5$: $gg \rightarrow Qggg$

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$\rightarrow$ We propose to evaluate the $\alpha_s^5$ contributions by computing $jj \rightarrow Qjjj$

generated by MadOnia and imposing cuts on the kinematics

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$\alpha_s^5$ corrections contributions: NNLO


$\frac{d\sigma}{dP_T}|_{|y|<0.4} \times Br (\text{pb}/\text{GeV})$

$P_T$ (GeV)

$\Upsilon (1S)$ prompt data $\times F^{\text{direct}}$

LO

$\Upsilon + \bar{b}b$

NLO

Exactly what is needed in normalisation and shape!

J.P. Lansberg (SLAC – Stanford U.)

Quarkonium production

QWG2008 – 5 Dec. 2008 16 / 27
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO*


Exactly what is needed in normalisation and shape!

J.P. Lansberg (SLAC – Stanford U.)
Describing the mid- and high-\(P_T\) region: QCD corrections

\[ \alpha_s^5 \]

Contributions: NNLO* 

\[ \frac{d\sigma}{dP_T} \big|_{|y|<0.6} \times Br \ (nb/GeV) \]

\(P_T\) (GeV)

\(\psi(2S)\) prelim. CDF data at 1.96 TeV

\(\psi' + cc\)

NLO

NNLO

See A. Annovi’s talk

J.P. Lansberg, 0811.4005 [hep-ph], to appear in EPJC (proceedings of HP 2008)
Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO

P. Artoisenet, AIP Proc. Conf 1038
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ψ(2S) prelim. CDF data at 1.96 TeV
ψ' +CC
NLO
NNLO

$\checkmark$ Nearly as good as for $\Upsilon$

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Describing the mid- and high-$P_T$ region: QCD corrections

$\alpha_s^5$ corrections contributions: NNLO*

\[ \frac{d\sigma}{dP_T|_{|y|<0.6}} \times \text{Br} \ (\text{nb/GeV}) \]

$\psi(2S)$ prelim. CDF data at 1.96 TeV

$\psi'$ +cc

NLO

NNLO

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✓ Nearly as good as for $\Upsilon$

✗ Still a small gap opening at large $P_T$: CO? Any Ideas?
Describing the mid- and high-\(P_T\) region: QCD corrections

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NLO

NNLO

\[ \text{See A. Annovi's talk} \]

✔ Nearly as good as for ψ

✗ Still a small gap opening at large \(P_T\): CO? Any Ideas?

✗ Large uncertainty attached to the choice of \(\mu_r\)
Describing the mid- and high-$P_T$ region: QCD corrections

$\Upsilon$ and $J/\psi$ polarisation in hadroproduction at $O(\alpha_S^5)$

J.P. Lansberg, 0811.4005 [hep-ph], to appear in EPJC (proceedings of HP 2008)

→ Cross sections seem OK (still not clear for $\psi$)
→ Polarisation ?
Describing the mid- and high-$P_T$ region: QCD corrections

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→ Cross sections seem OK (still not clear for $\psi$)

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![Graph showing $\alpha$ vs $P_T$ for different order calculations and for $\Upsilon + bb$, $\Upsilon$, and $J/\psi$](image)

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

![Graph showing $\alpha$ vs $P_T$ for $\psi(2S)$ CDF data at $s^{1/2} = 1.96$ TeV](image)

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

Comparison with prompt measurements from CDF and $D^0$?

Feed-down from $\chi_c$, $\chi_b$ not known at NLO

"Q polarization in HI collisions as a possible signature of the QGP"

"The QGP is expected to screen away the nonperturbative physics; therefore those quarkonia which escape from the plasma should possess polarization as predicted by perturbative QCD. We estimate the expected $J/\psi$ polarization at small $P_T$, and find that $\alpha \approx 0.35 - 0.4$.

A priori no longer valid in view of the (N)NLO results..."
Describing the mid- and high-$P_T$ region: QCD corrections

**ϒ and $J/\psi$ polarisation in hadroproduction at $O(\alpha_S^5)$**


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![Graph showing polarisation vs. $P_T$](image)

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$\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$

$P_T$ (GeV)

LO $\Upsilon + bb$
NLO
NNLO#

Direct $\psi(2S)$ CDF data at $s^{1/2} = 1.96$ TeV
NLO
NNLO#

→ Comparison with prompt measurements from CDF and $D\phi$?
→ Feed-down from $\chi_c$, $\chi_b$ not known at NLO
→ “$Q$ polarization in HI collisions as a possible signature of the QGP”


“The QGP is expected to screen away the nonperturbative physics; therefore those quarkonia which escape from the plasma should possess polarization as predicted by perturbative QCD. We estimate the expected $J/\psi$ polarization at small $P_T$, and find that $[\ldots] \alpha \simeq 0.35 - 0.4.$”
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$P_T$ (GeV)

-1  0  1

10  15  20  25  30  35  40  45  50

LO $\Upsilon + bb$
NLO
NNLO

Direct $\psi$(2S) CDF data at $s^{1/2}=1.96$ TeV

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NLO
NNLO

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A priori no longer valid in view of the (N)NLO results...
What about RHIC results?
Describing the mid- and high-$P_T$ region: QCD corrections

What about RHIC results?

NLO* curves calculated yesterday to compare with prelim. STAR data

* thanks to T. Ullrich

\[
\frac{1}{2\pi P_T} \frac{d\sigma}{dP_T dy} |_{|y|<1.0} \times Br
\]

Prelim. STAR (incl. B feed-down)
Prelim. CSM at NLO* (NO $\chi_c$ + B feed-down)

$\mu = 0.5 (m_c^2 + P_T^2)^{1/2}, 2m_c^2 < s_{ij}^{\min} < 4m_c^2$

We shall add NNLO* and $\chi_c$ + B feed-down

The discrepancies between CSM results and data are now everywhere below a factor of 3!
What about RHIC results?

NLO* curves calculated yesterday to compare with prelim. STAR data

\[ \frac{1}{2\pi} \frac{d\sigma}{dP_T dy} \mid_{|y|<1.0} \times Br \]

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Part III

Future
Need for more observables!

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- let us see how it can be a new valuable observable

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- On the pure theory side
  - → Part of the NLO QCD-corrections to **inclusive** production $(pp \to QX)$
    - which contains e.g. $\frac{1}{p_T^4}$ contributions
  - → **Test of the fragmentation approximation**
  - → NRQCD factorisation? **Colour transfer mechanism?**

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$Q + Q\bar{Q}$: CSM vs. COM

If we ignore changes in the fits of COM matrix elements due to QCD corrections:
- CSM contributions dominate at low $P_T$.
- COM contributions dominate from $P_T \geq 15$ GeV.

Integrated cross section largely dominated by CSM contributions.

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**Q + Q̅Q:** polarisation

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

![Graphs showing polarisation with COM ("old" matrix elements)](image-url)
Need for more observables!

$\mathcal{Q} + \mathcal{Q}\bar{Q}$: polarisation

$J/\psi + c\bar{c}$: polarisation with COM ("old" matrix elements)

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

P. Artoisenet, private communication
Need for more observables!

New observables: production via $\gamma\gamma$ in Ultra-Peripheral Collisions at the LHC


Graphs showing the production of $J/\psi + X$ via direct $\gamma\gamma$ fusion in pp collisions at 14 TeV and PbPb collisions at 5.5 TeV.

Quarkonium production

J.P. Lansberg (SLAC – Stanford U.)


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- we need to include resolved and double resolved contributions, before going further
Part IV

Conclusions and Outlooks
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- **Off-shell effects** via $s$-channel cut contributions are large at low $P_T$
  - Best description of low $P_T$ data: $d\sigma/dP_T$ and $\alpha$
Conclusions and Outlooks II

... but QCD-corrections bring agreements in

- $\gamma p$ for $J/\psi$
- $e^+e^-$ for $J/\psi + \eta_c$
- $pp$ for $\Upsilon (J/\psi)$


Time has come for another look ? new observables ? on the one hand, avoiding the presence of Colour Octets on the other hand, testing the presence ofColour Octets and for which QCD-corrections will not open new (dominant) channels (first) new observable:


Other proposals are welcome!

J.P. Lansberg (SLAC – Stanford U.)
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Q$^+Q^-\bar{Q}$, R. Li and J. X. Wang, arXiv:0811.0963 [hep-ph]


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What about $Q + \gamma$, R. Li and J. X. Wang, arXiv:0811.0963 [hep-ph]


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