Quarkonium production in the LHC era:
QCD corrections and new observables

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Part I

QCD corrections in the CSM and the $P_T$ spectrum
Reminder: QCD corrections for \( \Upsilon \) at the Tevatron
Reminder: QCD corrections for $\Upsilon$ at the Tevatron


$QCD$ corrections and new observables
July 7, 2012 3 / 15
Reminder: QCD corrections for $\Upsilon$ at the Tevatron

Reminder: QCD corrections for $\Upsilon$ at the Tevatron


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

LO
NLO
NNLO
NNLO$^\star$

$\alpha_3^3P_T^{--8}$

$\alpha_4^4P_T^{--6}$

$\alpha_5^5P_T^{--4}$

+ double $t$-channel gluon exchange at $\alpha_5^5$

Attention: the NNLO$^\star$ is not a complete NNLO

$\psi$ or $\Upsilon$

$\alpha_3^3$
$P_T^{--8}$

$\alpha_4^4$
$P_T^{--6}$

$\alpha_5^5$
$P_T^{--4}$
QCD corrections for $\Upsilon$ at the Tevatron & the LHC


$\Upsilon(3S)$ (GeV/c) $\Upsilon$ of $T_p$

$[\text{nb/(GeV/c)}]$ $T_p/\sigma_3 S \times B_3 S$

$10^3$ $10^4$ $10^5$ $10^6$

$LHCb$ $\sqrt{s} = 7 \text{ TeV}$

$p_T$ of $\Upsilon(3S)$ (GeV/c)

$10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$

LHCb data $(2.0 < y < 4.5)$
Direct NNLO* CSM $(2.0 < y < 4.5)$
Direct NLO CSM $(2.0 < y < 4.5)$

$\Upsilon(3S)$: 100 % direct; $\Upsilon(2S)$: 60-70 % direct; $\Upsilon(1S)$: 50 % direct
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CMS, Talk by K. Yi/K. Ulmer on Thursday, CMS-BPH11001

$\psi$ or $\Upsilon$

$\alpha_3^3 S P^{-8}$

$\Upsilon(1S)$

$|y| < 2$

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L = 36$ pb$^{-1}$

$\frac{d^2 \sigma}{dp_T^2} \times B(\mu)$

CSM theory curve extrapolated to prompt: $\times 2$
Part II

$P_T$ integrated yields
CSM predictions account for the $P_T$-integrated yield

→ The yield vs. $\sqrt{s}$, $y$

\footnote{NLO not stable at large $\sqrt{s}$ (small $x$) and small $P_T$}

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010; JPL, PoS(ICHEP 2010), 206 (2010)

(Here only LO curves$^1$)
CSM predictions account for the $P_T$-integrated yield

The yield vs. $\sqrt{s}$, $y$

- Unfortunately, very large th. uncertainties: masses, scales ($\mu_R$, $\mu_F$), gluon PDFs at low $x$ and $Q^2$, ...
- Good agreement with RHIC, Tevatron and LHC data (multiplied by a constant $F_{\text{direct}}$)

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1NLO not stable at large $\sqrt{s}$ (small $x$) and small $P_T$

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$F_{J/\psi}^{direct} = 59 \pm 10\%$

LO gg CSM

PHENIX / CDF /Prelim. ALICE data

$\sqrt{s}$ (TeV)

$1$ NLO not stable at large $\sqrt{s}$ (small $x$) and small $P_T$
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\[ F^{direct}_{\Upsilon(1S)} = 51\pm12\% \]

LO gg CSM

STAR/CDF/CMS data

\[ \frac{d\sigma^{\Upsilon(1S)}_{direct}}{dy} \times Br \] (pb)

\[ \frac{d\sigma^{\Upsilon(1S)}_{direct}}{dy} \times Br \] (nb)

NLO not stable at large $\sqrt{s}$ (small $x$) and small $P_T$
Cross section ratio at LO

- Despite the uncertainties, CSM predictions are parameter free!
Cross section ratio at LO

- Despite theoretical uncertainties, CSM predictions are parameter free!
- At LO in $v^2$, one *de facto* predicts direct cross-section ratios

\[ \frac{\sigma(\text{direct } \Upsilon(3S))}{\sigma(\text{direct } \Upsilon(1S))} = \frac{|\psi_{3S}(0)|^2}{|\psi_{1S}(0)|^2} \sim 0.34 \]

\[ \frac{\sigma(\text{direct } \Upsilon(2S))}{\sigma(\text{direct } \Upsilon(1S))} = \frac{|\psi_{2S}(0)|^2}{|\psi_{1S}(0)|^2} \sim 0.45 \]

\[ \text{Br}_{\ell\ell} \simeq 7.4 \text{ nb} \]

\[ \text{Br}_{\ell\ell} \simeq 1.0 \text{ nb} \]

Extrapolated $3S$ direct yield: $0.34 \times 150 \text{ nb} \sim 50 \text{ nb}$

$\Upsilon(3S)$ yield likely not 100% direct

JT Lansberg (IPNO)
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$$\sigma(\Upsilon(1S)(|y| < 2)) Br_{\ell\ell} \sim 7.4 \text{ nb} \xrightarrow{50\% \text{ direct}} \sigma(\text{direct } \Upsilon(1S)) \sim 150 \text{ nb}$$

CMS, PRD 83, 112004 (2011)
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CMS, PRD 83, 112004 (2011)

- **NEW**: the 3S yield likely not 100% direct
  - cf. $\chi_b(3P)$ observation by ATLAS

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- $P_T$ dependence of cross section ratios:
Cross section ratio at LO

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- $P_T$ dependence of cross section ratios:
- Mass effects at low $P_T$: not incoded in the $v^2$ results: $M_{\Upsilon(nS)}^{\text{NRQCD}} = 2m_b$
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\frac{\sigma(\text{direct } \Upsilon(3S))}{\sigma(\text{direct } \Upsilon(1S))} = \frac{|\psi^{3S}(0)|^2}{|\psi^{1S}(0)|^2} \approx 0.34 \quad \frac{\sigma(\text{direct } \Upsilon(2S))}{\sigma(\text{direct } \Upsilon(1S))} = \frac{|\psi^{2S}(0)|^2}{|\psi^{1S}(0)|^2} \approx 0.45
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\[
\sigma(\Upsilon(1S)(|y| < 2)) Br_{\ell\ell} \approx 7.4 \text{ nb} \quad \overset{50\% \text{direct}}{\longrightarrow} \quad \sigma(\text{direct } \Upsilon(1S)) \approx 150 \text{ nb}
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\sigma(\Upsilon(3S)(|y| < 2)) Br_{\ell\ell} \approx 1.0 \text{ nb} \quad \overset{100\% \text{direct}}{\longrightarrow} \quad \sigma(\text{direct } \Upsilon(3S)) \approx 45 \text{ nb}
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\[ CMS, PRD 83, 112004 (2011) \]

\( P_T \) dependence of cross section ratios:
- Mass effects at low \( P_T \): not incoded in the \( v^2 \) results: \( M^{\Upsilon(nS)}_{\text{NRQCD}} = 2m_b \)
- Feed-down: simple kinematical effect: \( P_T^{\text{daughter}} \sim \frac{M^{\text{daughter}}_{\text{NRQCD}}}{P_T^{\text{mother}}} \cdot P_T^{\text{mother}} \)
Cross section ratio at LO

- Despite the uncertainties, CSM predictions are parameter free!
- At LO in $v^2$, one *de facto* predicts direct cross-section ratios
- Simple ratios of Schrödinger wave function at the origin:

$$\frac{\sigma(\text{direct } Y(3S))}{\sigma(\text{direct } Y(1S))} = \frac{|\psi^{3S}(0)|^2}{|\psi^{1S}(0)|^2} \sim 0.34$$

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- \(P_T\) dependence of cross section ratios:
  - Mass effects at low \(P_T\): not encoded in the \(v^2\) results: \(M_{NRQCD}^{Y(nS)} = 2m_b\)
  - Feed-down: simple kinematical effect: \(P_T^{\text{daughter}} \sim \frac{M_{daughter}}{M_{mother}} P_T^{\text{mother}}\)
  - Harmless if \(\frac{d\sigma}{dP_T} \propto P_T^{-n}\) with \(n\) fixed, not if \(n\) changes, esp. true at low \(P_T\)
Colour Octet Dominance is challenged for low/mid $P_T J/\psi$ in $pp$.

- No need of CO contributions at low $P_T$: see slides on yields.

No evidence of CO contributions at low $P_T$. See slides on yields.
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  - Recent Belle update of $e^+e^- \rightarrow J/\psi + X_{\text{non } cc} > 2\text{ch.tr.} = 0.43 \pm 0.09 \pm 0.09 \text{ pb}$
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  - $e^+ e^- \rightarrow J/\psi gg$ CS at NLO + rel. corr.: 0.4-0.7 pb

  no space for CO ($^1S_0$ or $^3P_J$) in $B$-factory data

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  - $e^+e^- \rightarrow J/\psi gg$ CS at NLO + rel. corr. : 0.4-0.7 pb
    - no space for CO ($^1S_0$ or $^3P_J$) in B-factory data
  - $e^+e^- \rightarrow J/\psi gg$ CO at NLO: 0.9-1.0 pb using universality with Tevatron
    - IF one ignores the CSM: upper bound on CO
      $$\langle 0|\mathcal{O}^{J/\psi}[^1S_0^8]|0\rangle + 4.0 \langle 0|\mathcal{O}^{J/\psi}[^3P_0^8]|0\rangle / m_c^2 \leq (2.0 \pm 0.6) \times 10^{-2} \text{ GeV}^3$$


Impact of $\chi_c$'s and $\chi_b$'s


The most important and overlooked theory paper on quarkonium physics in 2010!

LHCb, arXiv:1204.1462
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LHCb: first indication that the $\chi_c$ fraction increases
Note: NLO NRQCD does not necessarily mean “Colour Octet dominance”
At NLO, the Colour-Singlet and Colour-Octet transition yields depend –for the $P$ waves– on the unphysical scale $\Lambda_{NRQCD}$ and the NRQCD subtraction scheme
Impact of $\chi_c$’s and $\chi_b$’s

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- About 40 % of $\Upsilon(1S)$ are from $\chi_b$

- No information about the $P_T$ dependence of the $\chi_b$ fraction

Part III

QCD corrections and polarisation
QCD corrections, feed-down and polarisation


\[
\alpha = \frac{\sigma_T - 2 \sigma_L}{\sigma_T + 2 \sigma_L}
\]

P_T (GeV)

LO \quad \Upsilon + bb \quad NLO \quad NNLO

©

Polarisation from \chi^Q

Feed-down unknown at NLO:

If \chi^Q \rightarrow 3S_1 \gamma is E1:

\(\alpha_{\max}\) from \chi^Q = +1.

\(\alpha_{\min}\) from \chi^Q = -0.45 for all P_T, any n.

F_{\Upsilon(1S)} = 0.1 for all P_T.

F_{\Upsilon(1S)}_{\text{direct}} = 0.5, F_{\Upsilon(2S)}_{\text{direct}} = 0.7 for all P_T.

old CDF data

NNLO # prompt
NLO prompt

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QCD corrections, feed-down and polarisation


→ Complete modification of the CSM polarisation at NLO (also at NNLO*)

\[ \alpha = \frac{\sigma_T - 2 \sigma_L}{\sigma_T + 2 \sigma_L} \]

\( P_T \) (GeV)

For the \( \Upsilon \):

- \( \Upsilon(1S) \):
  - \( F_{\Upsilon (1S)} \) direct = 0.5
  - \( F_{\Upsilon (2S)} \) direct = 0.7

For the \( \Upsilon(2S) \):

- \( F_{\Upsilon (2S)} \) prompt = 0.1 for all \( P_T \)

- \( \alpha_{\max} \) from \( \chi\) (nP) = +1 for all \( P_T \), any n

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old CDF data

NNLO # prompt

NLO prompt

LO

NLO

NNLO*

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

Prompt \( J/\psi \) CDF data at \( s^{1/2} = 1.96 \) TeV

NLO direct

NNLO # direct

NLO prompt

NNLO # direct

J.P. Lansberg (IPNO)
QCD corrections, feed-down and polarisation


→ **Complete modification of the CSM polarisation at NLO (also at NNLO*)**

→ **Polarisation from \( \chi_Q \)** Feed-down **unknown at NLO:**
QCD corrections, feed-down and polarisation


→ Complete modification of the CSM polarisation at NLO (also at NNLO*)

→ Polarisation from $\chi_Q$ Feed-down unknown at NLO:
- If $\chi_Q \rightarrow ^3 S_1 \gamma$ is E1: $\alpha_{from\chi_Q}^{max} = +1.00$ and $\alpha_{from\chi_Q}^{min} = -0.45$
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J.P. Lansberg (IPNO)
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J.P. Lansberg (IPNO)

J.P. Lansberg, Preliminary

© Prompt $J/\psi$ CDF data at $s^{1/2} = 1.96$ TeV
NLO direct
NNLO* direct

© Prompt $J/\psi$ CDF data at $s^{1/2} = 1.96$ TeV
LO
NLO
NNLO


© For the $\Upsilon$($1S$):

$F_{\Upsilon}(1S)$ direct = 0.5, $F_{\Upsilon}(2S)$ direct = 0.7 for all $P_T$.
QCD corrections, feed-down and polarisation

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For the $\Upsilon(1S)$:

J.P. Lansberg, Preliminary

Prompt $J/\psi$ CDF data at $s^{1/2} = 1.96$ TeV

NLO prompt

NNLO* prompt


→ QCD corrections and new observables

July 7, 2012 10 / 15
Is the CO yield transverse or unpolarised at large $P_T$?

- M. Buttenschön & B. Kniehl

PRL 108:172002, 2012
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  - Global fit: $pp$, $ep$, $\gamma\gamma$, $e^+e^-$ (w/o rel. corr.)
  - Keep the transverse polarisation for the CO yield
  - OK with ALICE, KO with CDF

PRL 108:172002, 2012
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PRL 108:172002, 2012

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Keep the transverse polarisation for the CO yield

OK with ALICE, KO with CDF

These studies do not include $\chi_c$ feed-down...
Is the CO yield transverse or unpolarised at large $P_T$?

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  - Less global fit with focus on high $P_T$ pp data

Figure 4: Predictions for the ATLAS measurement [29]. Note that these data are not part of our global fit, since they became public after our global fit was finished. The bands are again constructed by variation of the renormalization, factorization and NRQCD scales. At very high $p_T$, it will be necessary to resum large logarithms $\log(p_T^2/M_{J/\Psi}^2)$. For instance, at $p_T = 40$ GeV, $\alpha_s \log(p_T^2/M_{J/\Psi}^2) \approx 0.7$. 

$\sqrt{s} = 7$ TeV
$|y_{J/\Psi}| < 0.75$
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J.P. Lansberg (IPNO) QCD corrections and new observables

July 7, 2012 11 / 15
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Part IV

New observables
Double charm: $J/\psi + D$

$\rightarrow J/\psi + D$ or $J/\psi + \text{lepton}$ in the yield integrated over $P_T$

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010
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plot for RHIC kinematics
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First measurement by LHCb (pDT ≥ 3 GeV ⇒ p charm quark T not small)

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$\rightarrow$ First measurement by LHCb ($p_T^D \geq 3$ GeV $\Rightarrow p_T^{charm\ quark}$ not small)

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plot for RHIC kinematics

LHCb arXiv:1205.0975
\( J/\psi + \text{prompt} \gamma \)

- At high energy, 2 gluons in the initial states: no quark
$J/\psi$ + prompt $\gamma$

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- CS rate at NLO $\simeq$ conservative (high) expectation from CO

R. Li and J. X. Wang, PLB 672, 51, 2009

CS rate at NNLO $\star$, CS rate clearly above (high) expectation from CO


Clearly, new info on CS vs CO w.r.t inclusive case!

Possible: see $(c, b) - \text{jet} + \gamma$ studies by D0 up to $P_{\gamma T} \simeq 150$ GeV!

D0, PRL 102 (2009) 192002.
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- CO rates may be clearly lower if \( ^1S_0^8 \) and \( ^3P_J^8 \) are indeed suppressed (at NLO)
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J.P. Lansberg (IPNO)
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\[
\begin{align*}
\frac{d\sigma}{dP_T}\left|_{y<3.0} \right. & \times Br(\gamma) \quad \text{at } P_T \simeq 150 \text{ GeV} \\
\end{align*}
\]

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Conclusions and Outlooks

- LO pQCD (CSM) reproduces the yield:
  relevant for heavy-ion studies: LO CSM is $gg \rightarrow Qg$

- LO CSM fails as far as $d\sigma/dP_T$ is concerned
- QCD corrections open leading $P_T$ channel: they are needed!

- $2 \rightarrow 3, 2 \rightarrow 4$ channels
- Drawback: large theoretical uncertainties...
- Dominant contributions are known only at Born order ($gg \rightarrow J/\psi gg$)
- (N)NLO corrections alter the polarization: transverse $\rightarrow$ longitudinal (in HX)
- CO fits of xsection disagree in their prediction of polarisation
- Need for new observables, need for NLO evaluations at the LHC or elsewhere!

- Given the precision of the data at low $P_T$, one should re-think the opportunity of extracting $g(x)$ with quarkonium

A Fixed Target ExpeRiment at the LHC (AFTER) can also provide much information on quarkonia

see http://after.in2p3.fr and my talk earlier today

J.P. Lansberg (IPNO)

QCD corrections and new observables

July 7, 2012
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*J.P. Lansberg (IPNO)*

QCD corrections and new observables

July 7, 2012 15 / 15
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Part V

Backup
Many hopes were put in quarkonium studies to extract gluon PDF.
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- in photo/lepto production (DIS)
- but also in $g - g$-fusion process
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- mainly because of the presence of a natural “hard” scale: $m_Q$
- and the good detectability of a dimuon pair
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**J/ψ Production at large transverse momentum at hadron colliders**

E.W.N. Glover\(^1\)*, A.D. Martin\(^2\), W.J. Stirling\(^2\)

1 Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, England
2 Physics Department, University of Durham, Durham, DH1 3LE, England

Received 7 October 1987

**Abstract.** We calculate $J/ψ$ hadroproduction and emphasize the importance of the $J/ψ$ signal as a measure of $b\overline{b}$ production via the decay $B\rightarrow ψX$ and of the gluon structure function at low $x$ via $χ$ hadroproduction followed by $χ\rightarrow ψγ$ decay. We compare with UA1 data and data at ISR energies and make predictions for $ψ$ production at TEVATRON energies.
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- but also in $g - g$-fusion process
- mainly because of the presence of a natural "hard" scale: $m_Q$
- and the good detectability of a dimuon pair
Impact of QCD corrections to CSM at mid and high $P_T$

![Graph showing $d\sigma/dP_T$ for $|y|<0.4$ and $|y|<0.6$ with CDF data and different LO, NLO, NNLO curves.]

- LO
- NLO
- NNLO

For NNLO* curves:
- $m_c^2 < s_{ij}$
- $m_c^2 < 4m_c^2$

LO ≈ NLO
NLO ≈ NNLO*

The NNLO* is not a complete NNLO → possibility of uncanceled logs!

Two possibilities:
- ↓ NNLO
- ↓ CO contributions likely significant
- CS alone is enough

Issues with polarization unless $S$[8]1


↔ NNLO Collinear fact.

J.P. Lansberg (IPNO)
Impact of QCD corrections to CSM at mid and high $P_T$

For $\Upsilon(1S)$ prompt data and LO, NLO, NNLO:

- $\Upsilon(1S)$ production
  - at $\sqrt{s}=1.96$ TeV
  - scale and mass uncertainties combined in quadrature

For NNLO* curves:

- $m_{c^2} < s_{ij}^{\text{min}} < 4 m_{c^2}$

CO contributions likely significant
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Issues with polarisation unless

$S[8]_3$ and $S[8]_0$ & $S[8]_3$ facts.

$\psi(2S)$ production

- at $\sqrt{s}=1.96$ TeV

- CDF data

- for NNLO curves:
  - $m_{c^2} < s_{ij}^{\text{min}} < 4 m_{c^2}$

J.P. Lansberg (IPNO)
QCD corrections and new observables
July 7, 2012 18 / 15
The NNLO$^*$ is not a complete NNLO $\rightarrow$ possibility of uncanceled logs!
Impact of QCD corrections to CSM at mid and high $P_T$

The NNLO* is not a complete NNLO $\rightarrow$ possibility of uncanceled logs!

Two possibilities?

- $\text{NNLO} \approx \text{NLO}$
- $\text{NNLO} \approx \text{NNLO}^*$
Impact of QCD corrections to CSM at mid and high $P_T$

The NNLO* is not a complete NNLO $\rightarrow$ possibility of uncanceled logs!

Two possibilities?

NNLO $\simeq$ NLO

↓

CO contributions likely significant

NNLO $\simeq$ NNLO*

↓

CS alone is enough
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Two possibilities?

- **NNLO $\simeq$ NLO**
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  - Issues with polarisation unless $^{3}S_{1}^{[8]}$ small

- **NNLO $\simeq$ NNLO***
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Impact of QCD corrections to CSM at mid and high $P_T$

The NNLO* is not a complete NNLO → possibility of uncanceled logs!

**Two possibilities?**

- **NNLO $\simeq$ NLO**
  - CO contributions likely significant
  - Issues with polarization unless $^3S_1^{[8]}$ small
  - $e^+ e^-$ constraints on $^1S_0^{[8]}$ & $^3P_J^{[8]}$

- **NNLO $\simeq$ NNLO***
  - CS alone is enough
  - Ok with polarization
  - $k_T$ fact. $\leftrightarrow$ NNLO Collinear fact.?
Analogy with the $P_T$ spectrum for the $Z^0$ boson

![Graph showing the $\gamma(1S)$ prompt data $\times F_{\text{direct}}$ compared to LO, NLO, and NNLO predictions.](image)
QCD corrections for $\psi(2S)$ at the Tevatron


ψ(2S) production at sqrt(s)=1.96 TeV
LO  NLO  NNLO*
CDF data
scale and mass uncertainties combined in quadrature

for NNLO* curves:
$m_c^2 < s_{ij}^{\min} < 4 m_c^2$

Disclaimer: comparison to be done with the CMS data:
published in JHEP 1202 (2012) 011
QCD corrections for $\psi(2S)$ at the Tevatron & the LHC

LHCb, arxiv:1204.1258

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