Testing NRQCD factorization with J/ψ yield and polarization

Bernd Kniehl

II. Institut für Theoretische Physik, Universität Hamburg

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In collaboration with Mathias Butenschön
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Outline

1. **Introduction:** Heavy quarkonia, NRQCD, J/ψ production
2. **Technology**: Treatment of divergences, automation
3. **Global fit:** Unpolarized J/ψ production
4. **Polarized photoproduction:** HERA
5. **Polarized hadroproduction:** Tevatron vs. LHC
6. **Summary:** NRQCD at the crossroads

Heavy Quarkonia

Heavy quarkonia: Bound states of heavy quark and its antiquark.

- Charmonia ($c\overline{c}$) and Bottomonia ($b\overline{b}$)
- Top decays too fast for bound state.

Charmonium spectrum ($c\overline{c}$):

$n\,^{2S+1}L_J$	Name	Mass
$1\,^1S_0$	η_c	2980 MeV
$1\,^3S_1$	J/ψ	3097 MeV
$1\,^3P_0$	χ_{c0}	3415 MeV
$1\,^3P_1$	χ_{c1}	3511 MeV
$1\,^1P_1$	h_c	3526 MeV
$1\,^3P_2$	χ_{c2}	3556 MeV
$2\,^1S_0$	η_c'	3637 MeV
$2\,^3S_1$	ψ'	3686 MeV

- 1974: Discovery of J/ψ:
  First observation of heavy quarks
- Long lifetime of $c\overline{c}$: Spectrum and radiative transitions seen
  $\Longrightarrow$ Potential models
- Calculation of energy spectrum:
  Challenge for lattice QCD.
- Production and decay rates:
  One of first applications for perturbative QCD.

Color-singlet model vs. NRQCD factorization

Classic approach: Color-singlet model

- $c\overline{c}$ pair in physical color-singlet state, e.g. $c\overline{c}[{}^3S_1^{[1]}]$ for J/ψ.
- Nonperturbative information in J/ψ wave function at origin.
- Leftover IR divergences for P-wave quarkonia $\rightsquigarrow$ inconsistent!
- Predicted cross section factor 10^1–10^2 below Tevatron data.

NRQCD factorization:

- Rigorous effective field theory [Bodwin, Braaten, Lepage]
- Based on factorization of soft and hard scales
  (Scale hierarchy: $Mv^2, Mv \ll \Lambda_{\mathrm{QCD}} \ll M$)
- Theoretically consistent: no leftover singularities.
- NNLO proof of factorization in fragmentation [Nayak, Qiu, Sterman]
- Can explain hadroproduction at Tevatron.

NRQCD factorization in a nutshell

Factorization theorem: $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \cdot \langle O^{J/\psi}[n] \rangle$

- n: every possible Fock state, including color-octet states.
- $\sigma_{c\bar{c}[n]}$: production rate of $c\bar{c}[n]$, calculated in perturbative QCD.
- $\langle O^{J/\psi}[n] \rangle$: long-distance matrix elements (LDMEs), nonperturbative, extracted from experiment, universal?

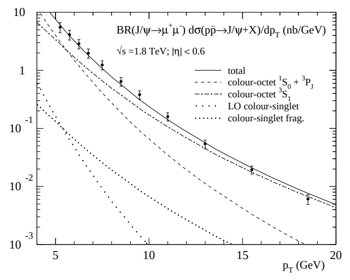
Scaling rules: LDMEs scale with relative velocity v ($v^2 \approx 0.2$).
For J/ψ:

scaling	v^3	v^7	v^{11}
n	${}^3S_1^{[1]}$	${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_{0/1/2}^{[8]}$	$\ldots$

- Double expansion in v and α_s.
- Leading term in v ($n = {}^3S_1^{[1]}$) corresponds to color-singlet model.

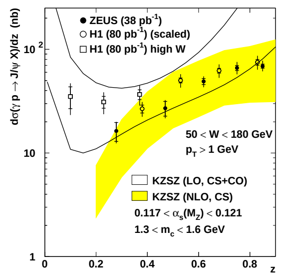
J/ψ Production: NRQCD vs. Experiment

Hadroproduction at Tevatron:



- Color octet states important
  $\Longrightarrow$ Great success for NRQCD

Photoproduction at HERA:



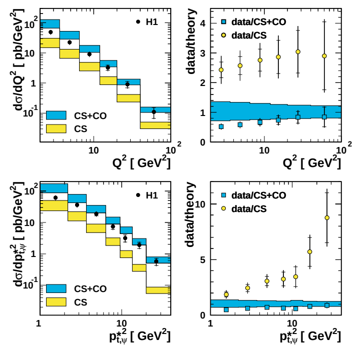
- MEs from fits to Tevatron data.
- Importance of color octet unclear

Our work: NRQCD calculation for photo- and hadroproduction and e^+e^- annihilation at NLO

$\Longrightarrow$ Establish universality of long distance matrix elements.

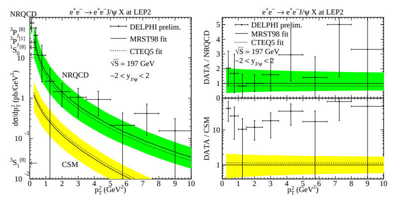
Production of J/ψ: NRQCD vs. Experiment (cont.)

Electroproduction at HERA:



BK, Zwirner, NPB(2002)

Two-Photon Collisions at LEP II:

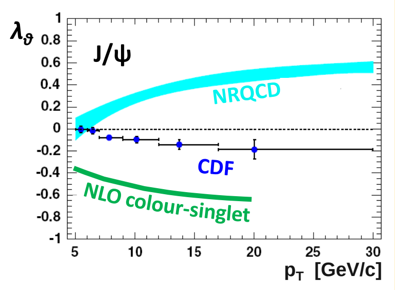


Klasen, BK, Mihaila, Steinhauser, PRL(2002)

Evidence of color-octet mechanism at LO

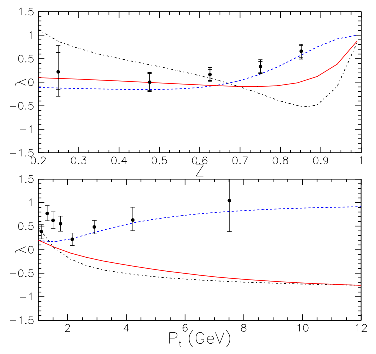
Production of J/ψ: NRQCD vs. Experiment (cont.)

Polarization at Tevatron:



Braaten, BK, Lee, PRD(2000);
Gong, Wang, PRL(2008)

Polarization at HERA:



Chang, Li, Wang, PRD(2009)

$$\frac{d\sigma}{d\cos\vartheta} \propto 1 + \lambda_\vartheta \cos^2\vartheta$$

Puzzling situation: LO NRQCD and NLO CSM fail

$\Longrightarrow$ How about NLO NRQCD?

Organisation of our Calculation

FeynArts: Generate Feynman diagrams

Mathematica script: Apply color projectors. Evaluate color factors with FeynCalc.

FORM: Apply spin projectors. Treat squared amplitudes.

Two methods for virtual corrections:

FORM: Perform our tensor reduction
$\Longrightarrow$ Scalar integrals

FORM: Use Integration by parts relations
$\Longrightarrow$ Master integrals (uses AIR)

FORM: Cancel scalar products by denominators. Neg. propagator powers. Directly apply IBP relations (uses AIR).
$\Longrightarrow$ Master integrals
(Not for ${}^1S_0$ spin singlet state)

Mathematica script: Simplify results due to kinematics (Size dramatically reduced)

Analytical check: Results of two methods equal. All divergences cancel.

Numerical evaluation:

FORTRAN: Phase space integrations with VEGAS. Phase space slicing method.

Global fit at NLO in NRQCD

Fit CO LDMEs to all available world data on J/ψ inclusive production:

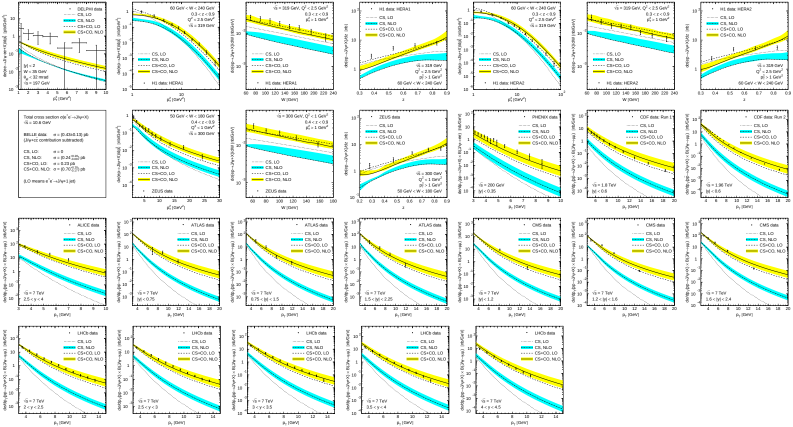
type	$\sqrt{s}$	collider	collaboration	reference
pp	200 GeV	RHIC	PHENIX	PRD82(2010)012001
$p\overline{p}$	1.8 TeV	Tevatron I	CDF	PRL97(1997)572; 578
$p\overline{p}$	1.96 TeV	Tevatron II	CDF	PRD71(2005)032001
pp	7 TeV	LHC	ALICE	NPB(PS)214(2011)56
			ATLAS	PoS(ICHEP 2010)013
			CMS	EPJC71(2011)1575
			LHCb	EPJC71(2011)1645
γp	300 GeV	HERA I	H1, ZEUS	EPJ25(2002)25; 27(2003)173
γp	319 GeV	HERA II	H1	EPJ68(2010)401
$\gamma\gamma$	197 GeV	LEP II	DELPHI	PLB565(2003)76
e^+e^-	10.6 GeV	KEKB	BELLE	PRD79(2009)071101

- Fit values:

10^{-2} GeV^{3+2L}	
$\langle\mathcal{O}(^1S_0^{[8]})\rangle$	4.97 ± 0.44
$\langle\mathcal{O}(^3S_1^{[8]})\rangle$	0.224 ± 0.059
$\langle\mathcal{O}(^3P_0^{[8]})\rangle$	-1.61 ± 0.20

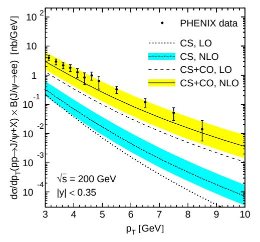
- $\chi^2/\text{d.o.f.} = 857/194 = 4.42$ for default prediction
- $\propto v^4\langle O_1(^3S_1)\rangle \rightsquigarrow$ NRQCD velocity scaling rules $\surd$

Comparison with world data

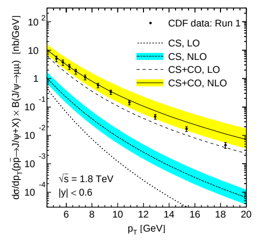


Comparison with RHIC and Tevatron

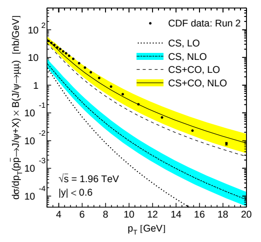
RHIC
PHENIX



Tevatron I
CDF



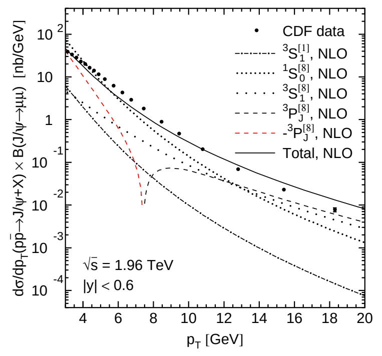
Tevatron II
CDF



- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

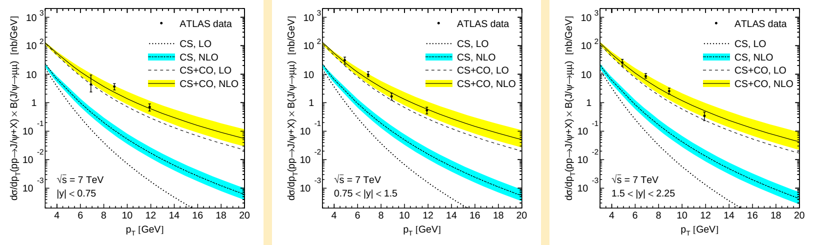
Comparison with Tevatron (cont.)

Relative importance of CO processes:



- Short-distance $\sigma(c\overline{c}[{}^3P_J^{[8]}]) < 0$ for $p_T \gtrsim 7$ GeV.
- But: Short-distance cross sections and LDMEs unphysical (NRQCD scale and scheme dependence) $\rightsquigarrow$ No problem!

Comparison with ATLAS at LHC



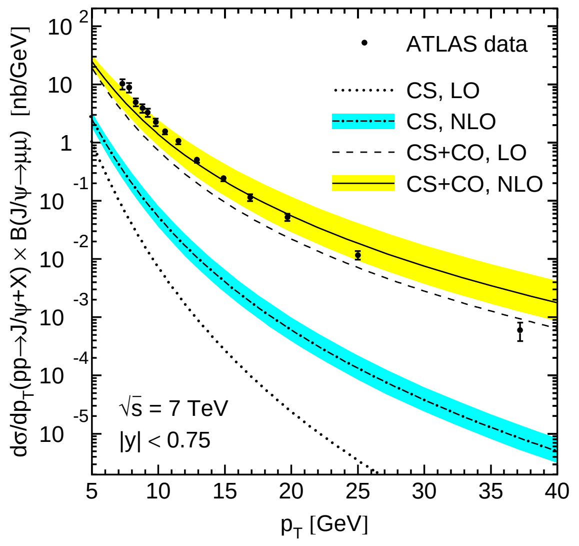
ATLAS $|y| < 0.75$

ATLAS $0.75 < |y| < 1.5$

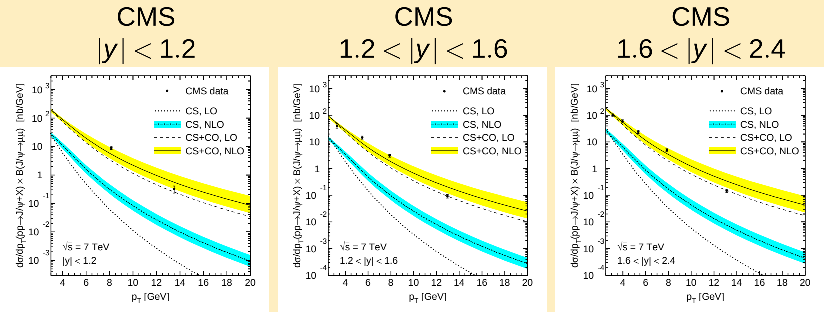
ATLAS $1.5 < |y| < 2.25$

- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with ATLAS (after fit) NPB850(2011)387



Comparison with CMS at LHC



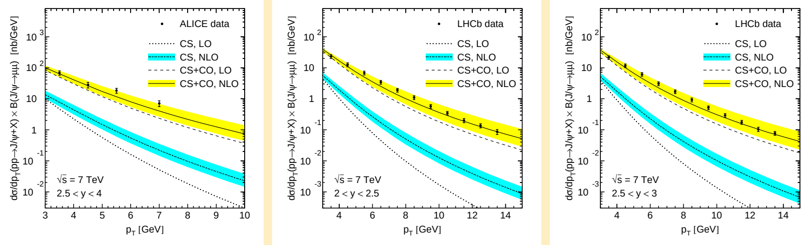
CMS $|y| < 1.2$

CMS $1.2 < |y| < 1.6$

CMS $1.6 < |y| < 2.4$

- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with ALICE and LHBb at LHC



ALICE $2.5 < y < 4.0$

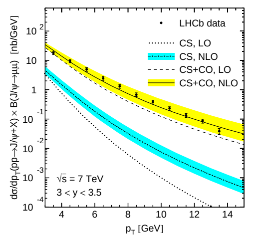
LHCb $2.0 < y < 2.5$

LHCb $2.5 < y < 3.0$

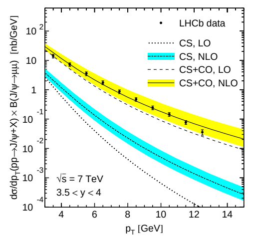
- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with LHBb at LHC (cont.)

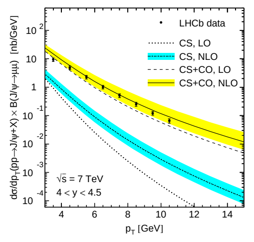
LHCb
$3.0 < y < 3.5$



LHCb
$3.5 < y < 4.0$

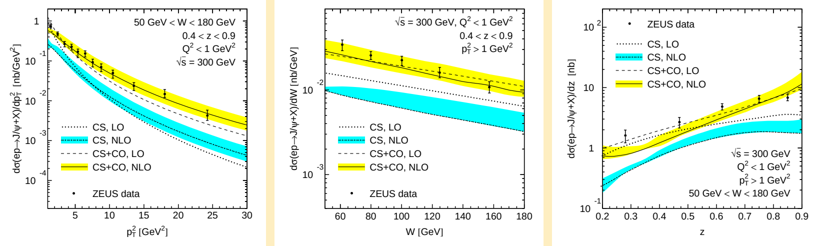


LHCb
$4.0 < y < 4.5$



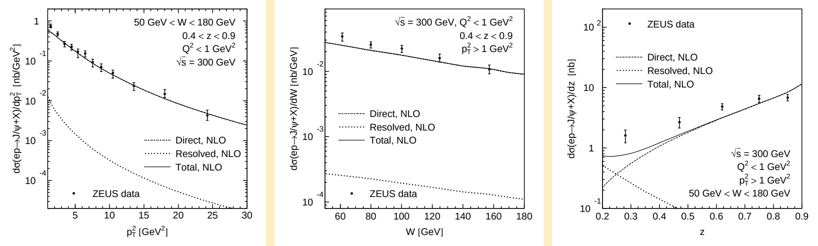
- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.

Comparison with ZEUS at HERA I (1)



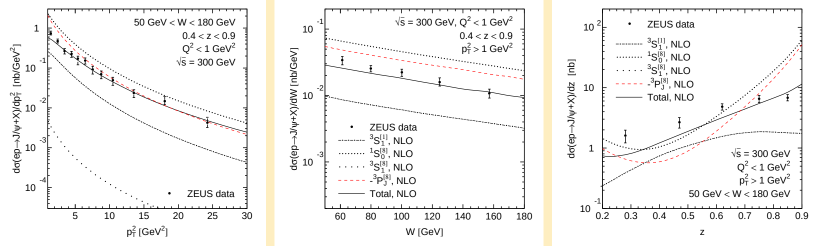
- $W =$ γp CM energy.
- $z =$ fraction of γ energy going to J/ψ in p rest frame.
- Singularity for $z \to 1$ eliminated by shape function in SCET.
- Data well described by CS+CO at NLO.
- CS factor of 3–5 below the data.

Comparison with ZEUS at HERA I (2)



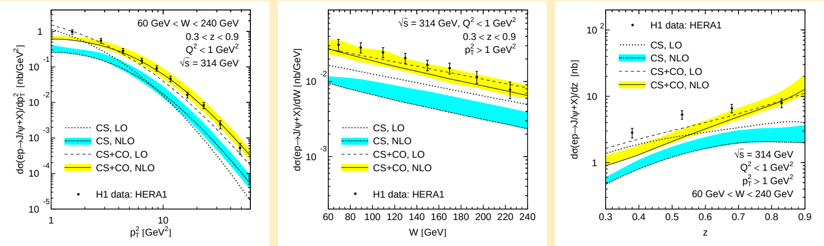
- Data for $0.4 < z < 0.9$ exhausted by direct photoproduction.
- Resolved photoproduction only relevant for $z \lesssim 0.4$.

Comparison with ZEUS at HERA I (3)



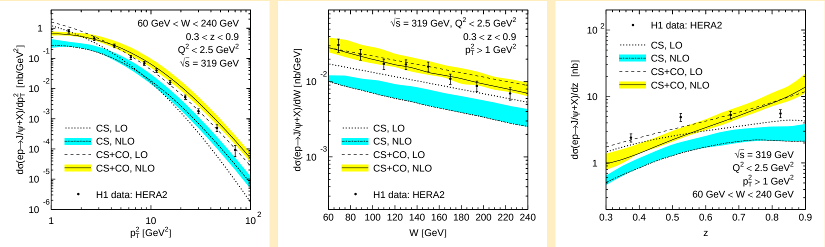
- $\langle \mathcal{O}({}^3P_0^{[8]})\rangle < 0 \rightsquigarrow {}^3P_0^{[8]}$ contribution negative.
- Negative interference with ${}^1S_0^{[8]}$ contribution beneficial.
- ${}^3S_1^{[8]}$ contribution negligible here.

Comparison with H1 at HERA I



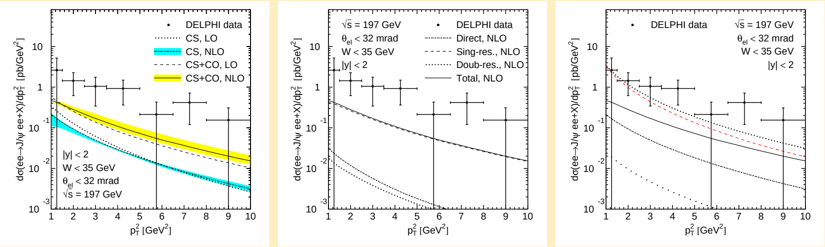
- Data well described by CS+CO at NLO.
- CS factor of 3–5 below data.

Comparison with H1 at HERA II



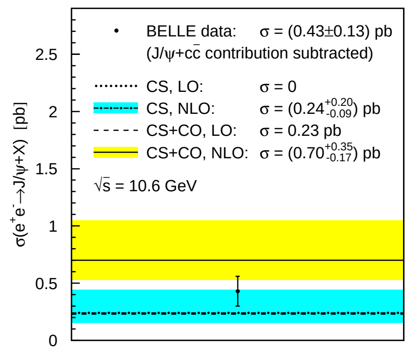
- Data well described by CS+CO at NLO.
- CS factor of 3–5 below the data.

Comparison with DELPHI at LEP II



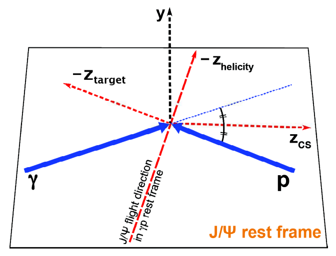
- Agreement with NRQCD at NLO worse than 2002 with LO.
- Just 16 DELPHI events with $p_T > 1$ GeV.
- No results from ALEPH, L3, OPAL.
- Data exhausted by single-resolved contribution.

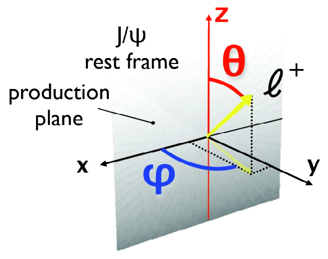
Comparison with BELLE at KEKB



- At NLO, both CSM and NRQCD agree with data.

Polarized J/ψ photoproduction





Decay angular distribution:

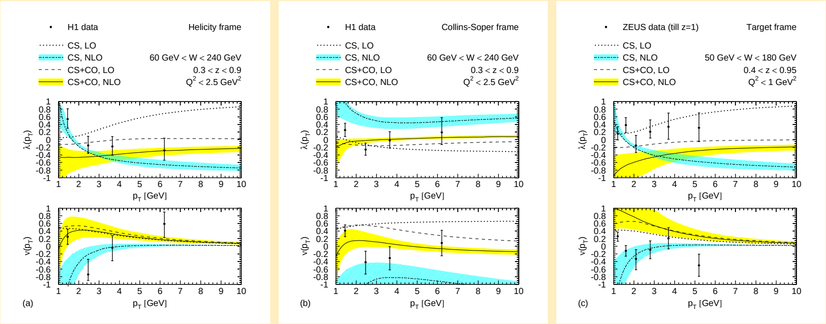
$$\frac{d\Gamma(J/\psi \to l^+l^-)}{d\cos\theta\, d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta)\cos\phi$$

Polarization observables in spin density matrix formalism:

$$\lambda_\theta = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_\phi = \frac{d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}}, \qquad \lambda_{\theta\phi} = \frac{\sqrt{2}\mathrm{Re}\, d\sigma_{10}}{d\sigma_{11} + d\sigma_{00}}$$

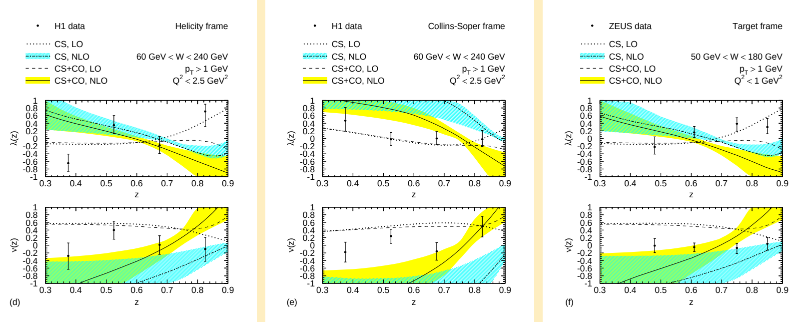
$\lambda = 0, +1, -1$: unpolarized, transversely and longitudinally porarized.

Comparison with H1 and ZEUS



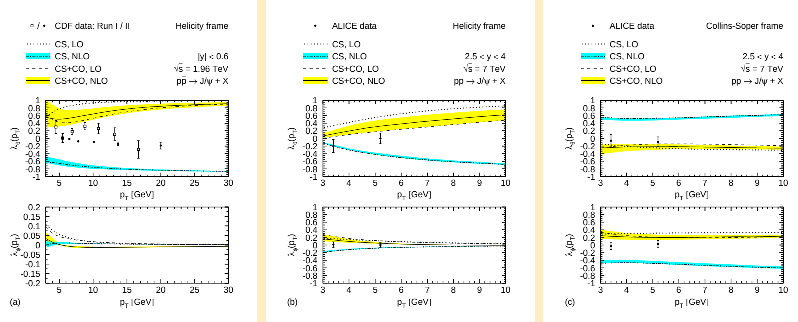
- No z cut on ZEUS data $\rightsquigarrow$ diffractive production included.
- Perturbative stability in NRQCD higher than in CSM.
- J/ψ preferrably unpolarized at large p_T.

Comparison with H1 and ZEUS (cont.)



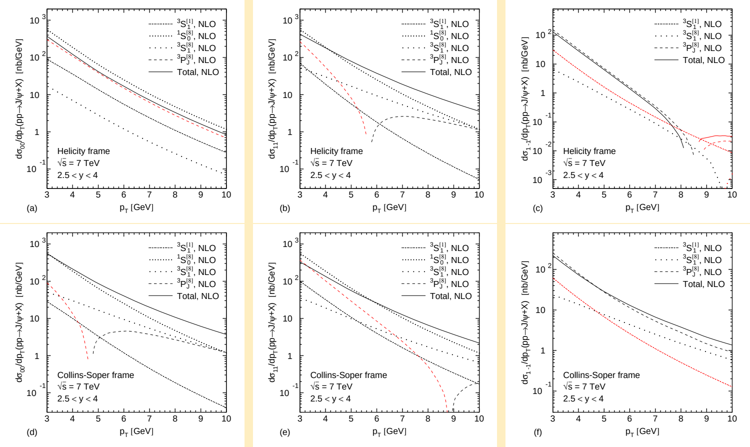
- Large scale uncertainties due to low cut $p_T > 1$.
- Overall χ^2 w.r.t. default prediction more than halved by going from CSM to NRQCD.

Comparison with CDF and ALICE



- CDF I and II data mutually inconsistent for $p_T < 12$ GeV.
- CDF J/ψ polarization anomaly persits at NLO (10–20σ).
- 4/8 ALICE points agree w/ NLO NRQCD within errors, others $< 2\sigma$ away.

Decomposition for ALICE



- $d\sigma_{\mathrm{unpol}} = d\sigma_{00} + 2d\sigma_{11}$; $d\sigma_{1,-1}$ auxiliary.
- Previously unknown $^3P_J^{[8]}$ NLO correction significant.

Summary

- NRQCD provides rigorous factorization theorem for production and decay of heavy quarkonia; predicts:
  - existence of CO states;
  - universality of LDMEs.
- Previous LO tests not conclusive.
- Here: first global analysis of unpolarized-J/ψ world data at NLO.
- Hadro- and photoproduction: striking evidence of NRQCD vs. CSM.
- $\gamma\gamma$ scattering, e^+e^- annihilation: not conclusive yet.
- Contributions from feed-down and B decays throughout small against theoretical uncertainties.
- Hadroproduction data alone cannot reliably fix all 3 CO LDMEs and give misleading results for their linear combinations; cf.
  Ma et al., PRL106(2011)042002; PRD84(2011)114001;
  MB & BK, AIPConfProc1343(2011)409.

Summary (cont.)

- Case for NRQCD less strong in polarized J/ψ photoproduction at HERA.
- Polarized J/ψ hadroproduction at Tevatron in severe conflict with NLO NRQCD, while first LHC data nicely agree.
- NRQCD factorization in jeopardy! $\rightsquigarrow$ Hot topic, especially in lack of BSM signals!

Backup Slides

Dependence on low-p_T cut: Global fit

Vary low-p_T cut on pp and $p\overline{p}$ data:

	$p_T > 1$ GeV	$p_T > 2$ GeV	$p_T > 3$ GeV	$p_T > 5$ GeV	$p_T > 7$ GeV
Data left	148 points	134 points	119 points	86 points	60 points
$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle$	5.68 ± 0.37	4.25 ± 0.43	4.97 ± 0.44	4.92 ± 0.49	3.91 ± 0.51
$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle$	0.90 ± 0.50	2.94 ± 0.58	2.24 ± 0.59	2.23 ± 0.62	2.96 ± 0.64
$\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$	-2.23 ± 0.17	-1.38 ± 0.20	-1.61 ± 0.20	-1.59 ± 0.22	-1.16 ± 0.23

$\rightsquigarrow$ Global fit insensitive to low-p_T cut on pp and $p\overline{p}$ data as long as γp, $\gamma\gamma$ (74 points with $p_T > 1$ GeV), and e^+e^- data (1 point) are retained.

Vary low-p_T cut on γp and $\gamma\gamma$ data:

	$p_T > 1$ GeV	$p_T > 2$ GeV	$p_T > 3$ GeV	$p_T > 5$ GeV	$p_T > 7$ GeV
Data left	74 points	30 points	15 points	5 points	1 points
$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle$	4.97 ± 0.44	5.10 ± 0.92	4.05 ± 1.17	5.44 ± 1.27	9.56 ± 1.59
$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle$	2.24 ± 0.59	2.11 ± 1.22	3.52 ± 1.56	1.73 ± 1.68	-3.66 ± 2.09
$\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$	-1.61 ± 0.20	-1.58 ± 0.48	-0.97 ± 0.63	-1.63 ± 0.68	-3.73 ± 0.83

$\rightsquigarrow$ Global fit insensitive to moderate low-p_T cut on γp and $\gamma\gamma$ data as long as pp and $p\overline{p}$ data (119 points with $p_T > 3$ GeV), and e^+e^- data (1 point) are retained.

Dependence on low-p_T cut: Fit to pp and $p\bar{p}$ data only

Vary low-p_T cut:

Data left	$p_T > 1$ GeV 148 points	$p_T > 2$ GeV 134 points	$p_T > 3$ GeV 119 points	$p_T > 5$ GeV 86 points	$p_T > 7$ GeV 60 points
$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	8.54 ± 0.52	16.85 ± 1.23	11.02 ± 1.67	1.68 ± 2.20	2.18 ± 2.56
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	-2.66 ± 0.69	-13.36 ± 1.60	-5.56 ± 2.19	8.75 ± 2.98	10.34 ± 3.55
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	-3.63 ± 0.23	-7.70 ± 0.61	-4.46 ± 0.87	2.20 ± 1.23	3.50 ± 1.50
M_0	2.25 ± 0.12	3.51 ± 0.19	3.29 ± 0.20	5.50 ± 0.29	8.24 ± 0.58
M_1	6.37 ± 0.19	5.80 ± 0.19	5.54 ± 0.20	3.27 ± 0.29	1.63 ± 0.43

$\rightsquigarrow$ Fit highly sensitive to low-p_T cut.

Comparison with fit to unpolarized, direct CDF II data with $p_T > 7$ GeV
Y.-Q. Ma, K. Wang, and K.-T. Chao, Phys. Rev. D **84**, 114001 (2011):

$M_0 = (8.54 \pm 1.02) \times 10^{-2}$ GeV^3

$M_1 = (1.67 \pm 1.05) \times 10^{-3}$ GeV^3