Heavy-quarkonium theory in the LHC era

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Outline

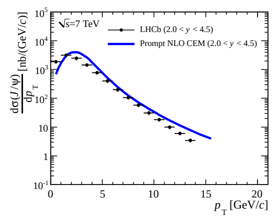
1. **Introduction:** CEM, CSM, NRQCD factorization
2. **NLO NRQCD:** General concept, singularities
3. **Global fit:** Unpolarized J/ψ yield
4. **Further tests:** ATLAS, FTPS, ZEUS
5. **Polarization:** HERA, Tevatron, LHC
6. **Summary:** NRQCD at the crossroads

Introduction: CEM, CSM, NRQCD factorization

Color evaporation model [Fritzsch 77; Halzen 77; Glück Owens Reya 78]

$$\sigma_{J/\psi} \approx \frac{1}{9}\rho_{J/\psi} \int_{2m_c}^{2m_D} ds_{c\bar{c}} \frac{d\sigma_{c\bar{c}}}{ds_{c\bar{c}}}$$

- $1/9$: statistical probability that $3 \times \overline{3}$ $c\overline{c}$ pair is asymtotically in color-single state
- $\rho_{J/\psi}$: fraction of charmonia that materialize as J/ψ
- Based local parton-hadron duality
- Assumes soft-gluon exchange with underlying event
- ${}^{2S+1}L_J^{[c]}$ quantum numbers do not enter
- Useful qualitative picture, rather than rigorous theory



[Schuler Vogt 96; Vogt 99; Frawley Ullrich Vogt 08]

Color-singlet model vs. NRQCD factorization

Color-singlet model [Berger Jones 81; Baier Rückl 81]

- $c\overline{c}$ 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 [Bodwin Braaten Lepage 95]

- Rigorous effective field theory
- Based on factorization of soft and hard scales
  (Scale hierarchy: $Mv^2 \lesssim \Lambda_{\mathrm{QCD}} \ll Mv \ll M$)
- Theoretically consistent: no leftover singularities.
- NNLO proof of factorization [Nayak Qiu Sterman 05]
- 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 [Lepage Magnea^2 Nakhleh Hornbostel 92]
LDMEs scale with relative velocity v ($v^2 \approx 0.2$).

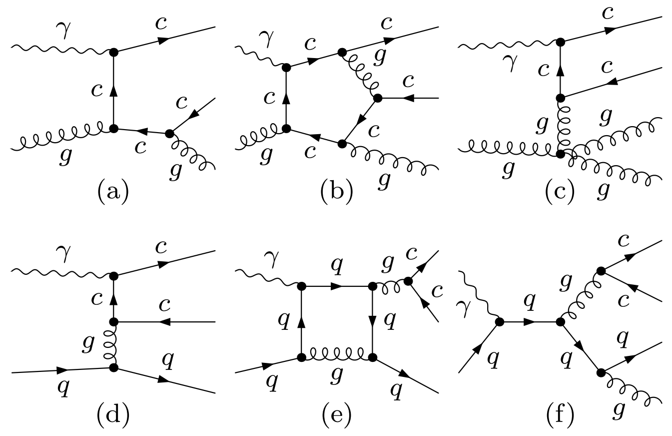
scaling	v^3 (CS state)	v^7 (CO states)	v^{11}
n	${}^3S_1^{[1]}$	${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_{0/1/2}^{[8]}$	$\dots$

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

NLO NRQCD calculations

- Petrelli Cacciari Greco Maltoni Mangano 98:
  Photo- and hadroproduction (only $2 \to 1$ processes)
- Klasen BK Mihaila Steinhauser 05:
  Two-photon scattering (w/o resolved photons)
- Butenschön BK 09:
  Photoproduction (w/o resolved photons)
- Zhang Ma Wang Chao 10:
  e^+e^- annihilation
- Ma Wang Chao 10, Butenschön BK 10:
  Hadroprduction
- Butenschön BK 11:
  γp and $\gamma\gamma$ (resolved photons) $\rightsquigarrow$ global fit of CO LDMEs
- Butenschön BK 11:
  Polarization in photoproduction
- Butenschön BK 12, Chao Ma K. Wang Y.-J. Zhang 12, Gong, Wan, J.-X. Wang, H.-F. Zhang 12, Shao, Ma, K. Wang, Chao 14:
  Polarization in hadroprduction

Sample diagrams for J/ψ photoproduction in NRQCD



Color and spin projection

Amplitudes for $c\bar{c}[n]$ production by projector application:

$$A_{c\bar{c}[^1S_0^{[8]}]} = \mathrm{Tr}\,[C_8\,\Pi_0\,A_{c\bar{c}}]\,|_{q=0}$$
$$A_{c\bar{c}[^3S_1^{[1/8]}]} = \varepsilon_\alpha\,\mathrm{Tr}\,\left[C_{1/8}\,\Pi^\alpha\,A_{c\bar{c}}\right]|_{q=0}$$
$$A_{c\bar{c}[^3P_J^{[8]}]} = \varepsilon_{\alpha\beta}\,\frac{d}{dq_\beta}\,\mathrm{Tr}\,[C_8\,\Pi^\alpha\,A_{c\bar{c}}]\,|_{q=0}$$

- $A_{c\bar{c}}$: amputated pQCD amplitude for open $c\bar{c}$ production.
- q: relative momentum between c and $\bar{c}$.
- $C_{1/8}$: color projectors
- $\Pi_{0/1}$: spin projectors
- ε: polarization vectors and tensors

Main Difference to Previous Calculations

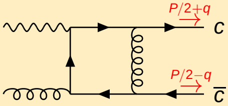
Virtual corrections: Two different approaches:

- First loop integration, then projectors: (Previous publications)
  - − Loop integrals Coulomb divergent.
- First projectors, then loop integration: (Our method)
  - \+ No Coulomb singularities.
  - \+ One scale less in loop integration.
  - − Loop integrals not standard form.

Where do Coulomb divergences come from?

- Projectors: Relative momentum $q \to 0$.
- Scalar diagrams with gluon between external c and $\overline{c}$, e.g.:

$I(q) \equiv$



$$\lim_{q\to 0} I(q) = \frac{A}{q^2} + \frac{B}{\varepsilon} + C$$

But: $I(0) = \frac{B}{\varepsilon} + C$

- $\Longrightarrow$ No Coulomb singularities in dimensional regularization!

Cancellation of divergences

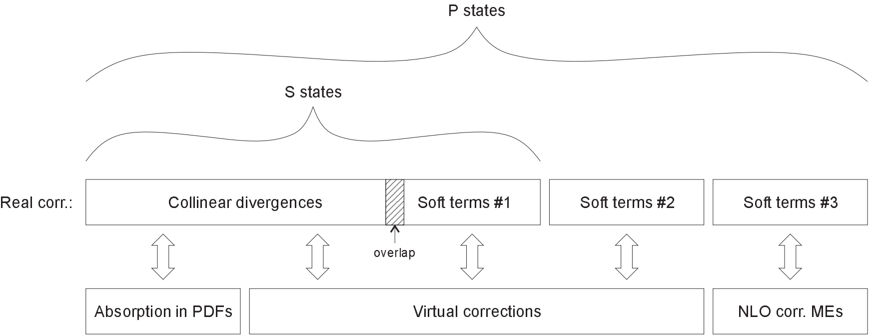
UV divergences: Cancellation within virtual corrections:

- Loop integrals
- Charm mass renormalization
- Strong coupling constant renormalization
- Wave function renormalization of external particles

IR divergences: Cancellation between:

- Virtual corrections (loop integrals + wave function renormal.)
- Soft and collinear parts of real corrections
- Universal part absorbed into proton and photon PDFs
- Radiative corrections to long distance matrix elements

Overview of IR singularity structure



P states

S states

Real corr.:

Collinear divergences

Soft terms #1

Soft terms #2

Soft terms #3

overlap

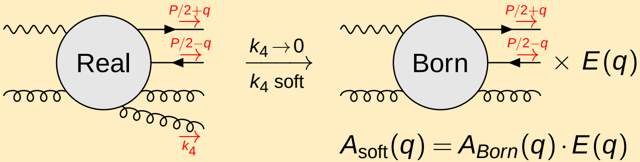
Absorption in PDFs

Virtual corrections

NLO corr. MEs

Structure of Soft Singularities

Soft limits of the real corrections:



$$A_{\text{soft}}(q) = A_{Born}(q) \cdot E(q)$$

S and P states: Soft #1 + Soft #2 + Soft #3 terms:

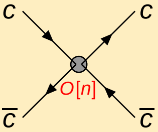
$$A_{\text{soft,s}} = A_{\text{soft}}(0) = A_{\text{Born,s}} \cdot E(0)$$
$$A_{\text{soft,p}} = A'_{\text{soft}}(0) = A_{\text{Born,p}} \cdot E(0) + A_{\text{Born,s}} \cdot E'(0)$$

$$|A_{\text{soft,s}}|^2 = |A_{\text{Born,s}}|^2 \cdot E(0)^2$$
$$|A_{\text{soft,p}}|^2 = |A_{\text{Born,p}}|^2 \cdot E(0)^2 + 2\,\text{Re}\,A^*_{\text{Born,s}} A_{\text{Born,p}} \cdot E(0) E'(0) + |A_{\text{Born,s}}|^2 \cdot E'(0)^2$$

Radiative Corrections to Long Distance MEs

In NRQCD: Long distance MEs = $c\bar{c}$ scattering amplitudes:

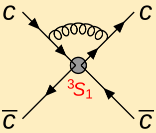
$\langle O^{J/\psi}[n]\rangle =$



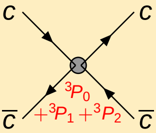
$O[n] =$ 4-fermion operators

$(n = {}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}, \ldots)$

Corrections to $\langle \mathbf{O}^{J/\psi}[{}^3\mathbf{S}_1^{[1/8]}]\rangle$ with NRQCD Feynman rules:



$+$ similar diagrams $\propto \dfrac{4\alpha_s}{3\pi m_c^2}\left(\dfrac{1}{\varepsilon_{\mathrm{UV}}} - \dfrac{1}{\varepsilon_{\mathrm{IR}}}\right)\cdot$



- UV singularity cancelled by renormalization of 4-fermion operat.
- IR singularity cancels soft #3 terms of p states!

Global fit at NLO in NRQCD

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

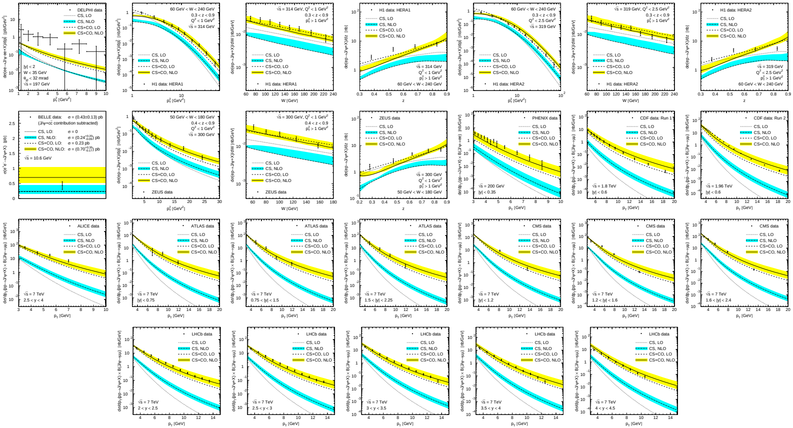
type	$\sqrt{s}$	collider	collaboration	reference
pp	200 GeV	RHIC	PHENIX	PRD82(2010)012001
$p\overline{p}$	1.8 TeV	Tevatron I	CDF	PRL97(1997)572; 578
$p\overline{p}$	1.96 TeV	Tevatron II	CDF	PRD71(2005)032001
pp	7 TeV	LHC	ALICE	NPB(PS)214(2011)56
			ATLAS	PoS(ICHEP 2010)013
			CMS	EPJC71(2011)1575
			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 for CO LDMEs:

10^{-2} GeV^{3+2L}	feed-down included	feed-down subtracted
$\langle\mathcal{O}[^1S_0^{[8]}]\rangle$	4.97 ± 0.44	3.04 ± 0.35
$\langle\mathcal{O}[^3S_1^{[8]}]\rangle$	0.224 ± 0.059	0.168 ± 0.046
$\langle\mathcal{O}[^3P_0^{[8]}]\rangle$	-1.61 ± 0.20	-0.908 ± 0.161
$\chi^2/\text{d.o.f.}$	$857/194=4.42$	$725/194=3.74$

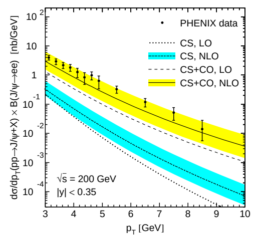
Note: CO LDMEs $\propto v^4\times\langle\mathcal{O}[^3S_1^{[1]}]\rangle \rightsquigarrow$ NRQCD velocity scaling rules $\surd$

Comparison with world data

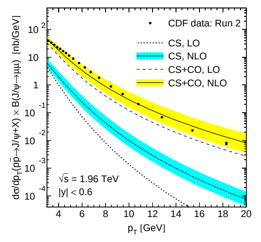


Comparison with RHIC and Tevatron

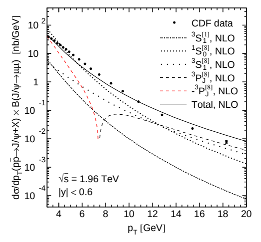
RHIC
PHENIX



Tevatron II
CDF

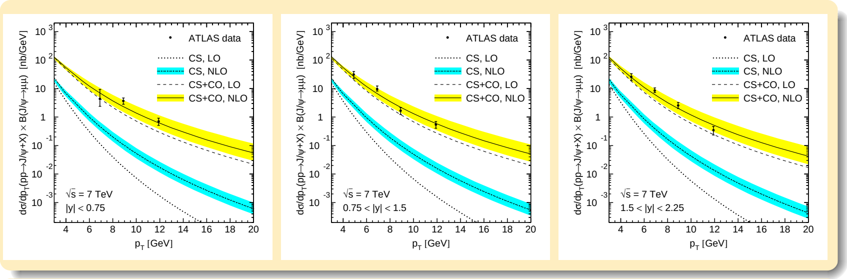


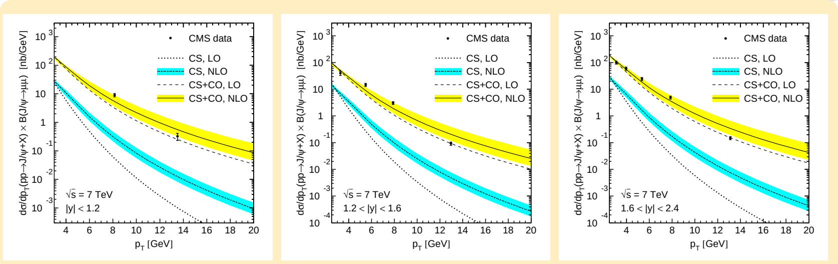
Decomposition of
NLO NRQCD



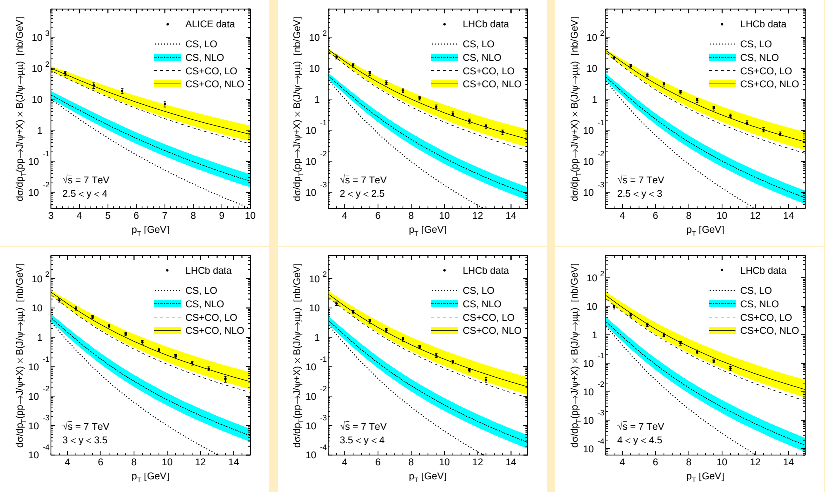
- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.
- Sizeable NLO corrections, especially in the ${}^3P_J^{[8]}$ channels.

Comparison with ATLAS and CMS at LHC

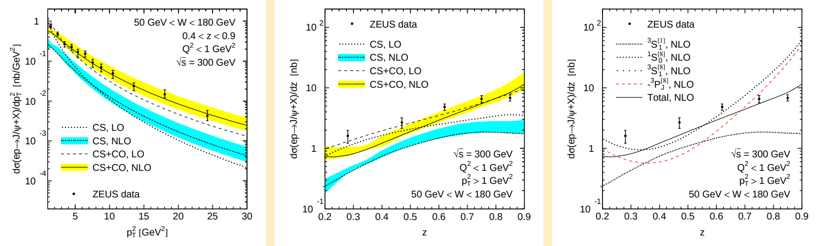




Comparison with ALICE and LHBb at LHC

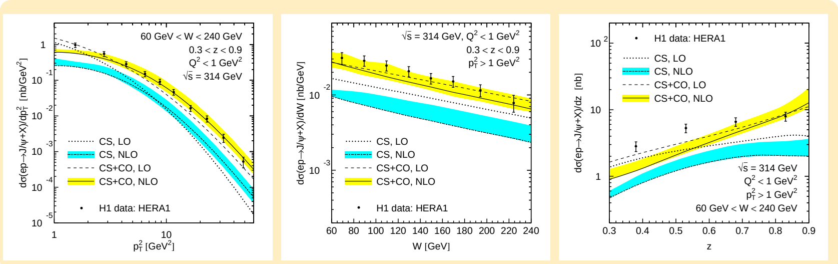


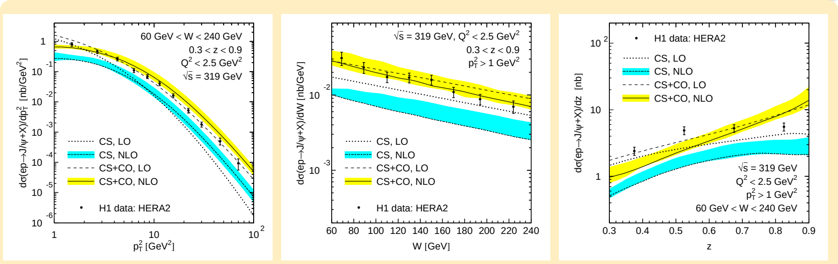
Comparison with ZEUS at HERA I



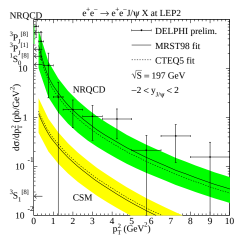
- $W = \gamma p$ CM energy.
- $z =$ fraction of γ energy going to J/ψ in p rest frame.
- Compensation of ${}^1S_0^{[8]}$ vs. ${}^3P_J^{[8]}$ $\rightsquigarrow$ regular $z \to 1$ behavior.
- Data well described by CS+CO at NLO.
- CS factor of 3–5 below the data.

Comparison with H1 at HERA I and II

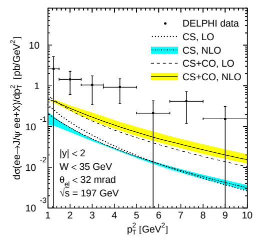




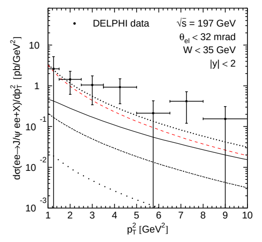
Comparison with DELPHI at LEP II



[Klasen BK Mihaila Steinhauser 02]



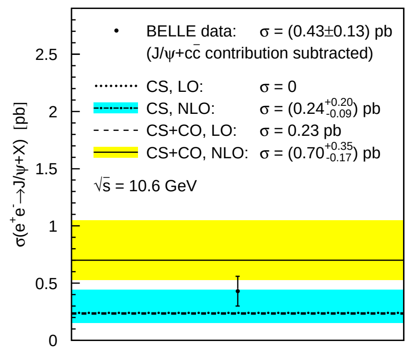
NLO NRQCD



Decomposition of NLO NRQCD

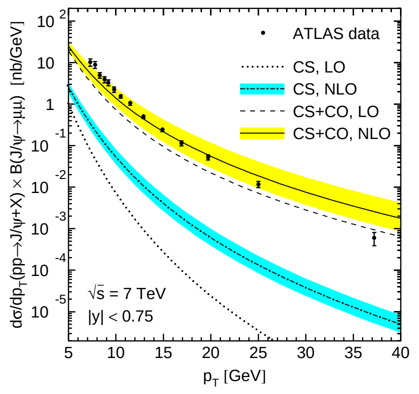
- Agreement with NRQCD at NLO worse than in 2002 at LO.
- Just 16 DELPHI events with $p_T > 1$ GeV.
- No results from ALEPH, L3, OPAL.
- Data exhausted by single-resolved contribution.

Comparison with Belle at KEKB



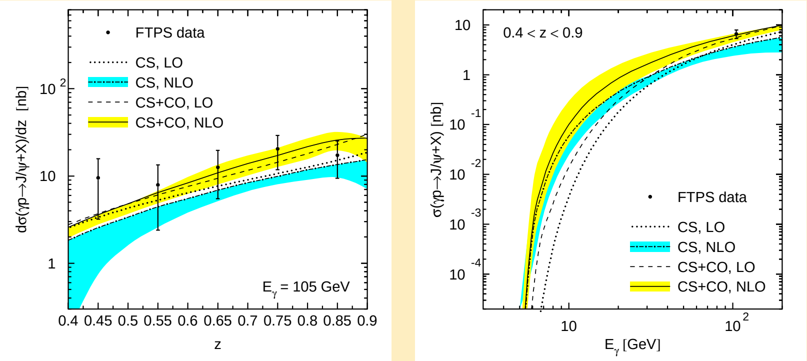
- At NLO, both CSM and NRQCD agree with data.
- # of charged tracks $>$ 4, missing events not corrected for.
  $\rightsquigarrow$ Belle point likely higher.

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



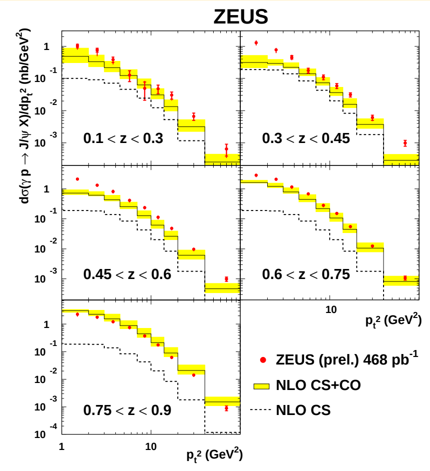
- Resummation of large logs $\ln(p_T^2/M^2)$ necessary at large p_T.
- New formalism to include non-leading powers in p_T^2/M^2 [Kang Qiu Sterman 2012].

Comparison with Fermilab Tagged-Photon Spectrometer data (excluded from fit) [PRL52(1984)795]



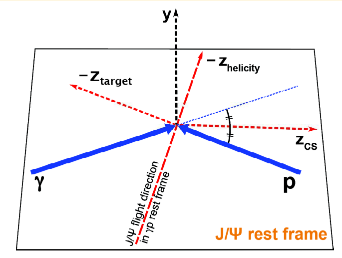
- Inelastic scattering of 105 GeV photons on hydrogen target.
- Data remarkably well described by CS+CO at NLO.

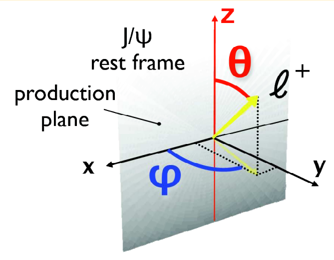
Comparison with ZEUS (after fit) [JHEP1302(2013)071]



- Notorious NRQCD overshoot at large z overcome.

Polarized J/ψ photo- and hadroproduction





Decay angular distribution:

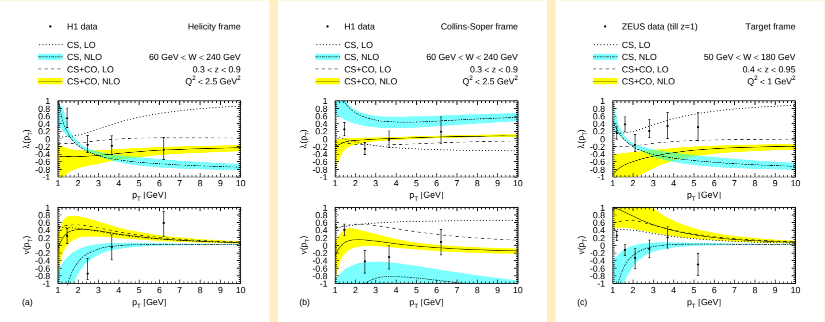
$$\frac{d\Gamma(J/\psi \to l^+l^-)}{d\cos\theta\, d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta)\cos\phi$$

Polarization observables in spin density matrix formalism:

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

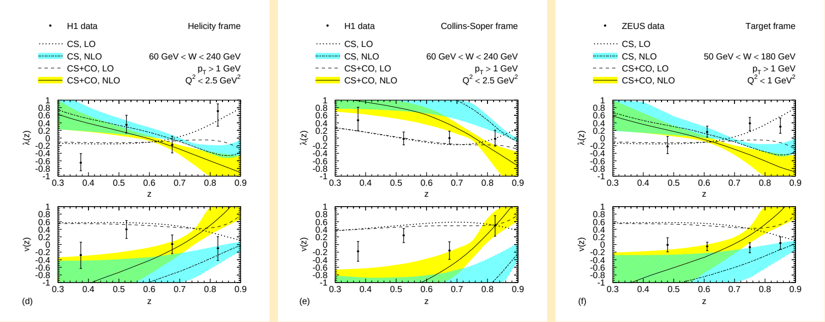
$\lambda = 0, +1, -1$: unpolarized, transversely and longitudinally porarized.

Comparison with H1 and ZEUS



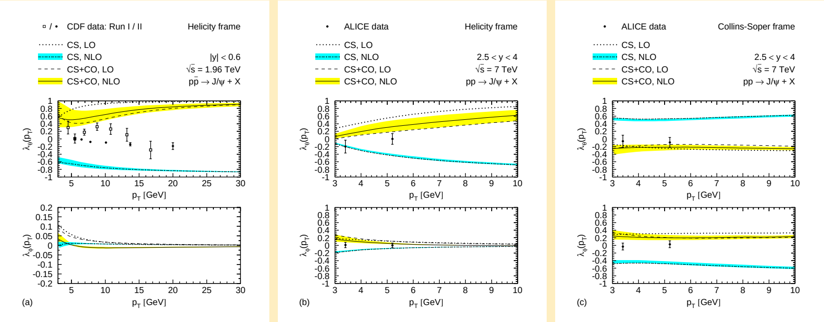
- No z cut on ZEUS data $\rightsquigarrow$ diffractive production included.
- Perturbative stability in NRQCD higher than in CSM.
- J/ψ preferrably unpolarized at large p_T.

Comparison with H1 and ZEUS (cont.)



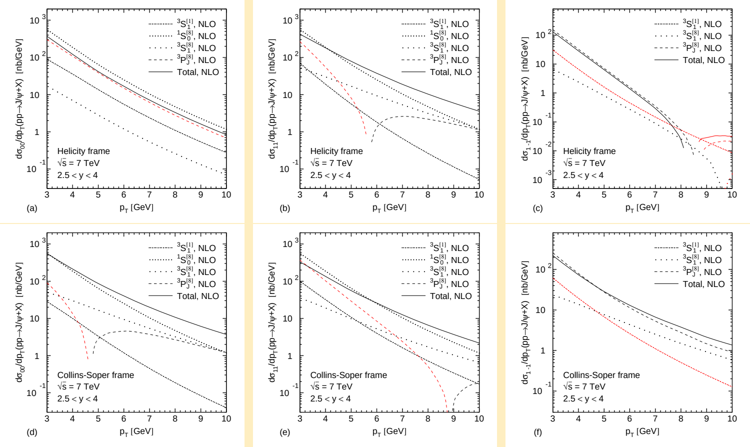
- Large scale uncertainties due to low cut $p_T > 1$.
- Overall χ^2 w.r.t. default prediction more than halved by going from CSM to NRQCD.

Comparison with CDF and ALICE



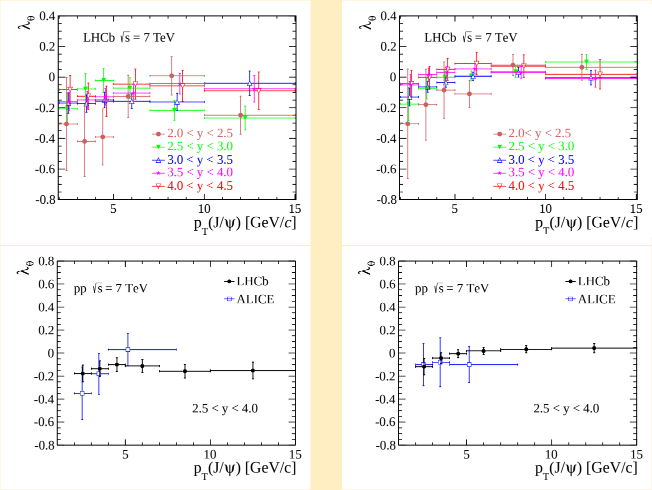
- CDF I and II data mutually inconsistent for $p_T < 12$ GeV.
- CDF J/ψ polarization anomaly persits at NLO.
- 4/8 ALICE points agree w/ NLO NRQCD within errors, others $< 2\sigma$ away.

Decomposition for ALICE



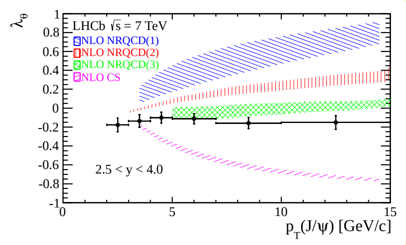
- $d\sigma_{\text{unpol}} = d\sigma_{00} + 2d\sigma_{11}$; $d\sigma_{1,-1}$ auxiliary.
- Previously unknown ${}^3P_J^{[8]}$ NLO correction significant.

LHCb data on prompt J/ψ polarization [EPJC73(2013)2631]



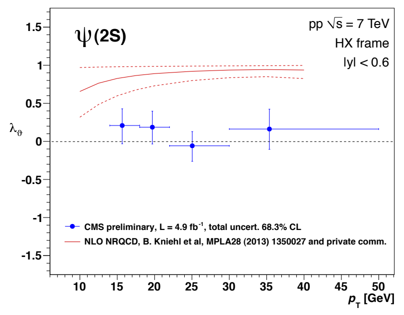
helicity frame Collins-Soper frame

Comparison with LHCb and CMS polarization data



prompt J/ψ polarization

LHCb, EPJC73(2013)2631

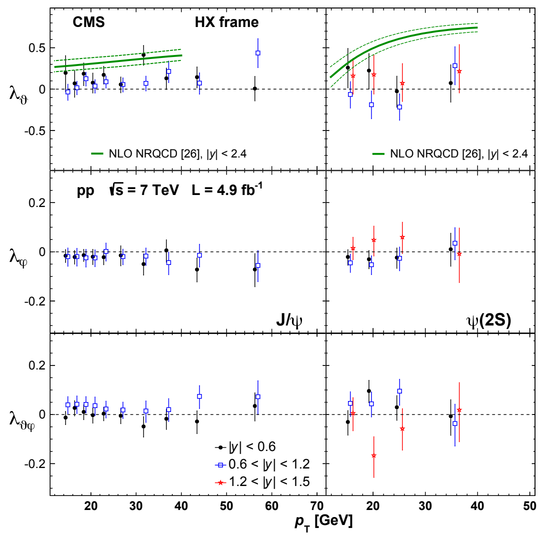


ψ' polarization

CMS, PLB727(2013)381

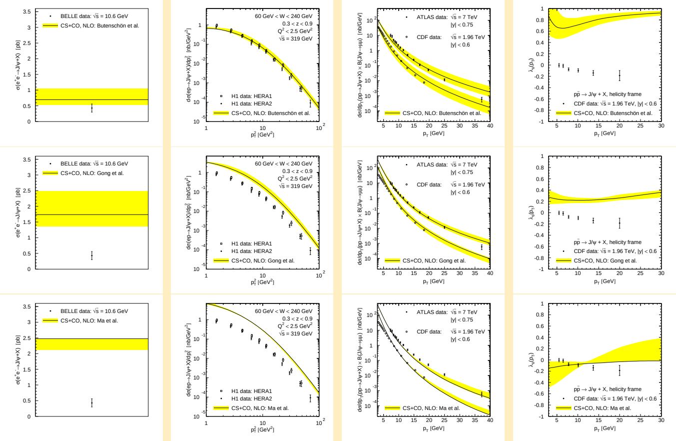
- (1): Global NLO NRQCD fit to J/ψ yield [PRD84(2011)051501(R)]
- New NLO NRQCD fit to ψ' yield from HERA, Tevatron, and LHC

CMS data on J/ψ and ψ' polarization [PLB727(2013)381]



Comparison with Gong et al. and Chao et al.

	e^+e^- yield	γp yield	$p\overline{p}/pp$ yield	CDF polariz.
BK, MB PRL108(2012)172002				
Gong et al. PRL110(2013)042002				
Chao et al. PRL108(2012)242004				



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 for NRQCD.
- CSM greatly undershoots data, except for e^+e^- annihilation.
- $\gamma\gamma$ scattering not conclusive yet.
- Contributions from feed-down and B decays throughout small against theoretical uncertainties $\rightsquigarrow$ subtracted in fit.
- Hadroproduction data alone cannot reliably fix all 3 CO LDMEs.

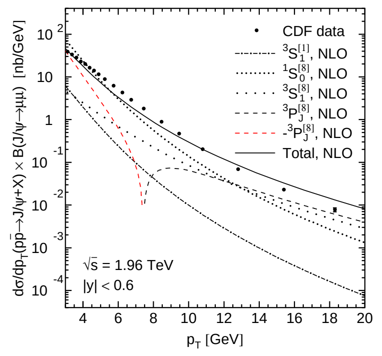
Summary (cont.)

- Case for NRQCD less strong in polarized J/ψ photoproduction at HERA.
- NLO NRQCD predictions for polarized J/ψ hadroproduction based on global analysis of J/ψ yield agrees with ALICE, but disagrees with CDF, CMS, and LHCb.
- NRQCD factorization remains among the hottest topics of QCD @ LHC.

Backup Slides

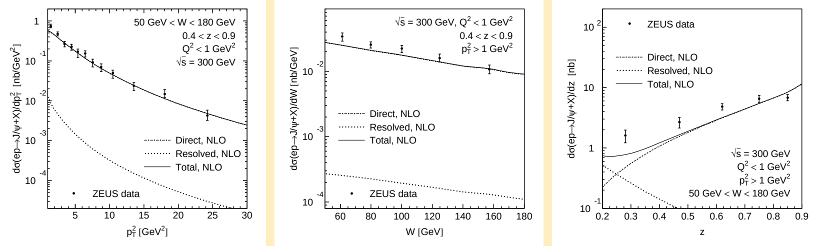
Comparison with Tevatron (cont.)

Relative importance of CO processes:



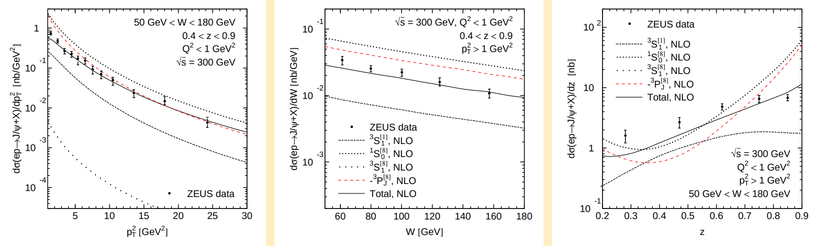
- Short-distance $\sigma(c\overline{c}[^3P_J^{[8]}]) < 0$ for $p_T \gtrapprox 7$ GeV.
- But: Short-distance cross sections and LDMEs unphysical (NRQCD scale and scheme dependence) $\rightsquigarrow$ No problem!

Comparison with ZEUS at HERA I (cont.)



- 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 (cont.)



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

Dependence on low-p_T cut: Global fit

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

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
$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle$	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

$\leadsto$ 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:

Data left	$p_T > 1$ GeV 74 points	$p_T > 2$ GeV 30 points	$p_T > 3$ GeV 15 points	$p_T > 5$ GeV 5 points	$p_T > 7$ GeV 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

$\leadsto$ 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):

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

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