Heavy-quarkonium theory in the LHC era

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In collaboration with Mathias Butenschön and Zhiguo He
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Outline

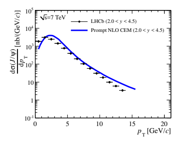
1. **Introduction:** CEM, CSM, NRQCD factorization
2. **NLO NRQCD:** General concept, singularities
3. **Global fit:** Unpolarized J/ψ yield
4. **Further tests:** ATLAS, FTPS, ZEUS
5. **Polarization:** HERA, Tevatron, LHC
6. η_c **yield:** LHC
7. **Summary:** NRQCD at the crossroads

Introduction: CEM, CSM, NRQCD factorization

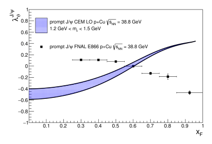
Color evaporation model [Fritzsch 77; Halzen 77; Glück Owens Reya 78]

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

- 1/9: statistical probability that $3 \times \bar{3}$ $c\bar{c}$ 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]



$\rightsquigarrow$ Talk by Vincent Cheung.

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 $\leadsto$ 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.
- Proof of factorization [Nayak Qiu Sterman 05; Nayak 15].
- Can explain unpolarized yield at Tevatron and elsewhere.

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 ($v^2 \approx 0.2$).

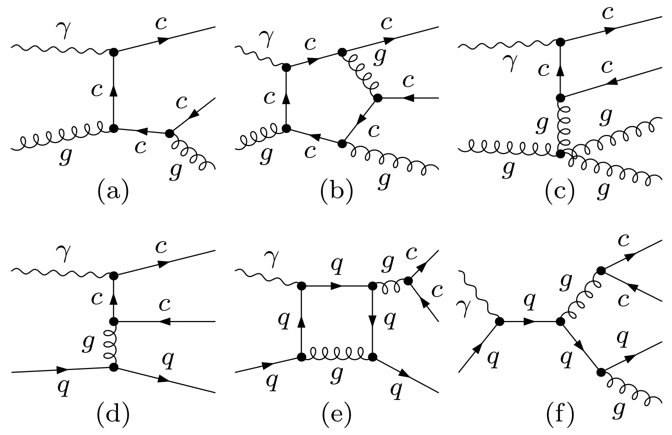
scaling	v^3 (CS state)	v^7 (CO states)	v^{11}
n	${}^3S_1^{[1]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{0/1/2}^{[8]}$	$\dots$

- 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 → 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 $c\overline{c}[n]$ production by projector application:

$$A_{c\overline{c}[^1S_0^{[8]}]} = \mathrm{Tr}\,[C_8\,\Pi_0\,A_{c\overline{c}}]\,|_{q=0}$$

$$A_{c\overline{c}[^3S_1^{[1/8]}]} = \epsilon_\alpha\,\mathrm{Tr}\left[C_{1/8}\,\Pi^\alpha\,A_{c\overline{c}}\right]|_{q=0}$$

$$A_{c\overline{c}[^3P_J^{[8]}]} = \epsilon_{\alpha\beta}\,\frac{d}{dq_\beta}\,\mathrm{Tr}\,[C_8\,\Pi^\alpha\,A_{c\overline{c}}]\,|_{q=0}$$

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

Main Difference to Previous Calculations

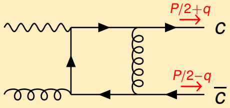
Virtual corrections: Two different approaches:

- 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.:

$I(q) \equiv$



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

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

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

Cancellation of divergences

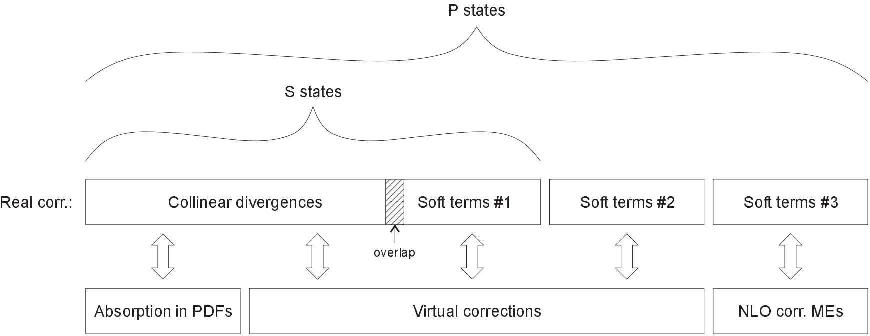
UV divergences: Cancellation within virtual corrections:

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

IR divergences: Cancellation between:

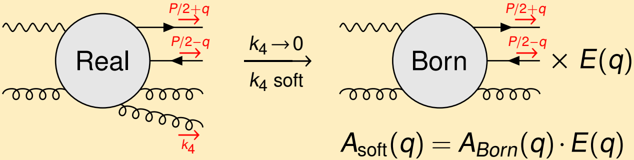
- Virtual corrections (loop integrals + wave function renormal.)
- Soft and collinear parts of real corrections
- Universal part absorbed into proton and photon PDFs
- Radiative corrections to long distance matrix elements

Overview of IR singularity structure



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:

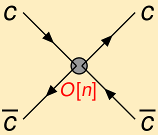
$$A_{\text{soft,s}} = A_{\text{soft}}(0) = A_{\text{Born,s}} \cdot E(0)$$
$$A_{\text{soft,p}} = A'_{\text{soft}}(0) = A_{\text{Born,p}} \cdot E(0) + A_{\text{Born,s}} \cdot E'(0)$$

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

Radiative Corrections to Long Distance MEs

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

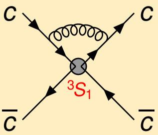
$$\langle O^{J/\psi}[n]\rangle =$$



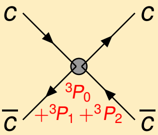
$O[n]$ = 4-fermion operators

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

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



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



- 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:

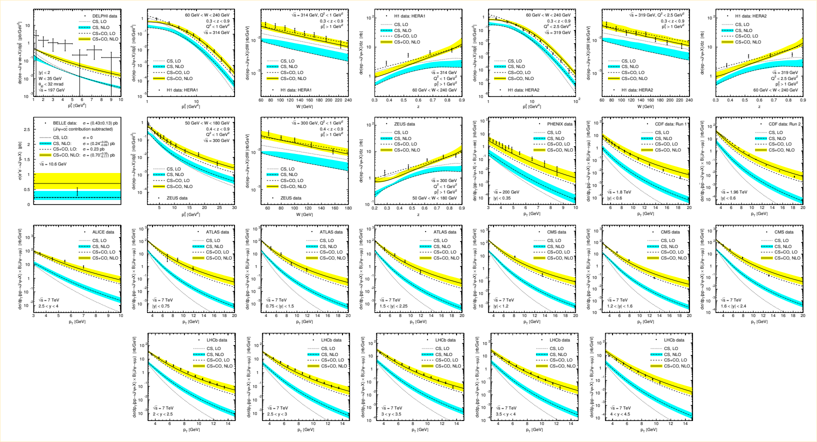
type	$\sqrt{s}$	collider	collaboration	reference
pp	200 GeV	RHIC	PHENIX	PRD82(2010)012001
$p\overline{p}$	1.8 TeV	Tevatron I	CDF	PRL97(1997)572; 578
$p\overline{p}$	1.96 TeV	Tevatron II	CDF	PRD71(2005)032001
pp	7 TeV	LHC	ALICE	NPB(PS)214(2011)56
			ATLAS	PoS(ICHEP 2010)013
			CMS	EPJC71(2011)1575
			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
χ^2/d.o.f.	$857/194 = 4.42$	$725/194 = 3.74$

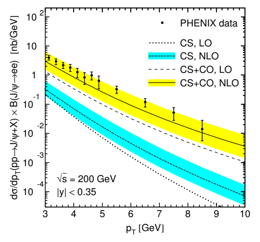
Note: CO LDMEs $\propto v^4 \times \langle\mathcal{O}[^3S_1^{[1]}]\rangle \rightsquigarrow$ NRQCD velocity scaling rules $\surd$

Comparison with world data

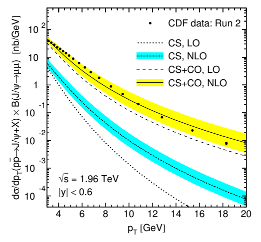


Comparison with RHIC and Tevatron

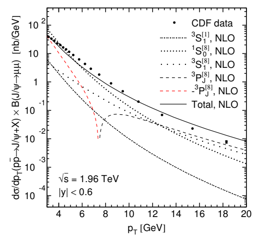
RHIC PHENIX



Tevatron II CDF

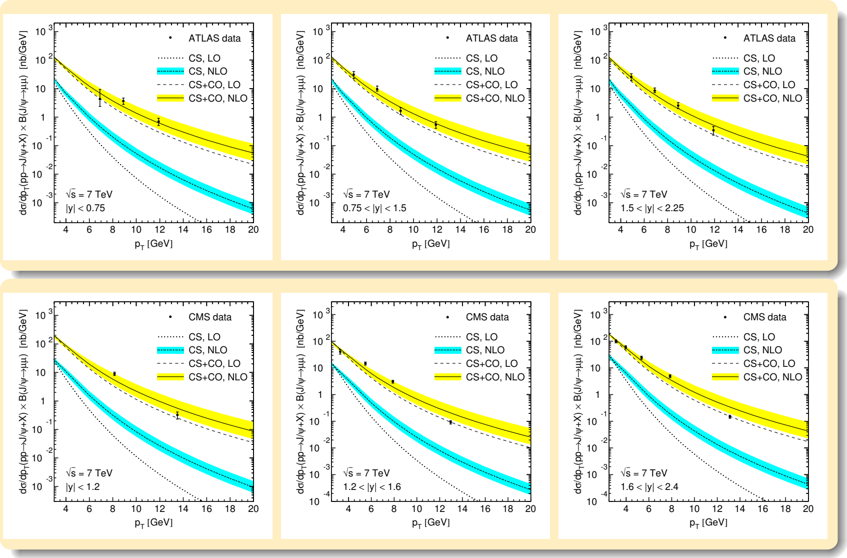


Decomposition of NLO NRQCD

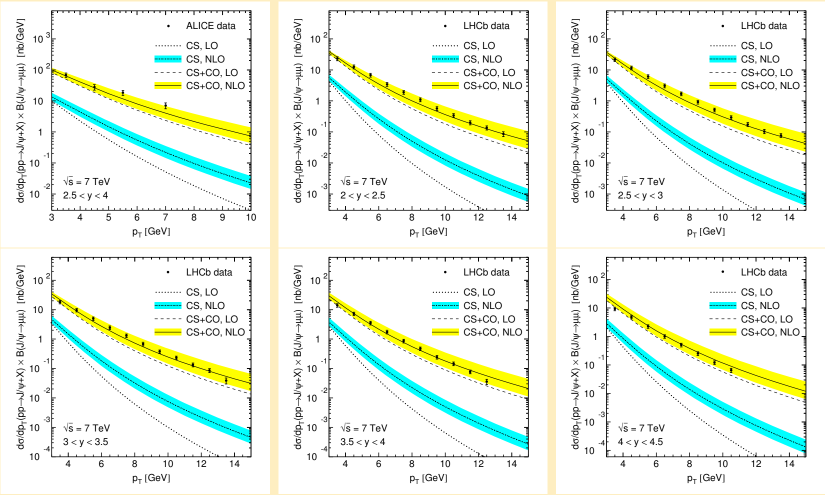


- Data well described by CS+CO at NLO.
- CS orders of magnitudes below data.
- Sizeable NLO corrections, especially in the $^3P_J^{[8]}$ channels.

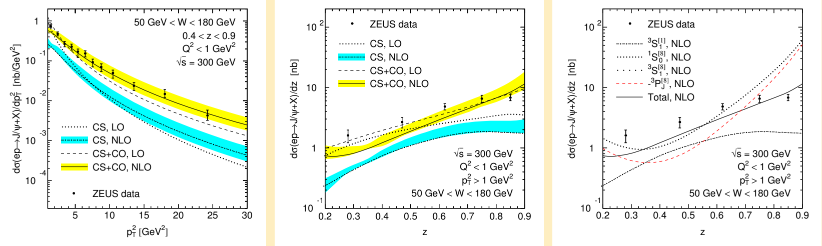
Comparison with ATLAS and CMS at LHC



Comparison with ALICE and LHBb at LHC

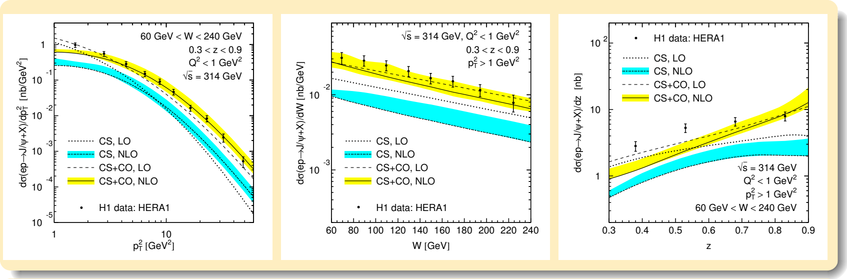


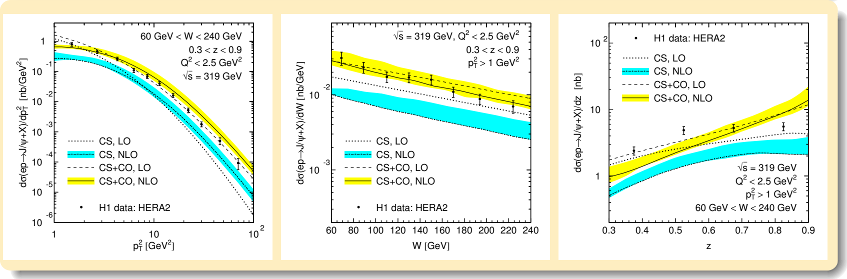
Comparison with ZEUS at HERA I



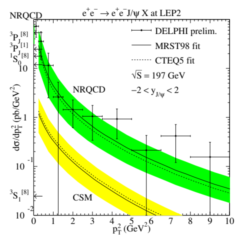
- $W =$ γp CM energy.
- $z =$ fraction of γ energy going to J/ψ in p rest frame.
- Compensation of ${}^1S_0^{[8]}$ vs. ${}^3P_J^{[8]}$ $\rightsquigarrow$ regular $z \to 1$ behavior.
- Data well described by CS+CO at NLO.
- CS factor of 3–5 below the data.

Comparison with H1 at HERA I and II

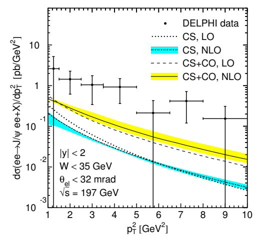




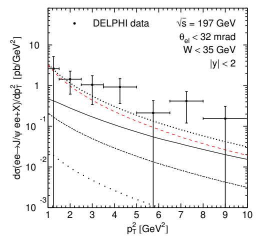
Comparison with DELPHI at LEP II



[Klasen BK Mihaila Steinhauser 02]



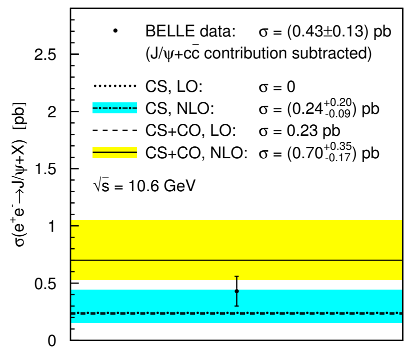
NLO NRQCD



Decomposition of NLO NRQCD

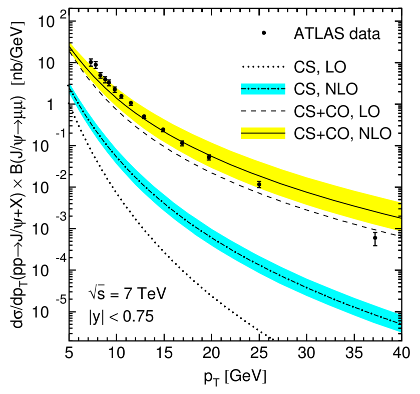
- Agreement with NRQCD at NLO worse than in 2002 at LO.
- Just 16 DELPHI events with $p_T > 1$ GeV.
- No results from ALEPH, L3, OPAL.
- Data exhausted by single-resolved contribution.

Comparison with Belle at KEKB



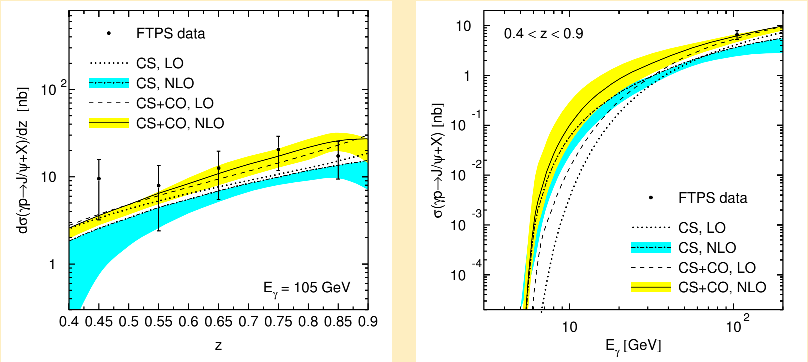
- At NLO, both CSM and NRQCD agree with data.
- # of charged tracks > 4, missing events not corrected for. $\rightsquigarrow$ Belle point likely higher.

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



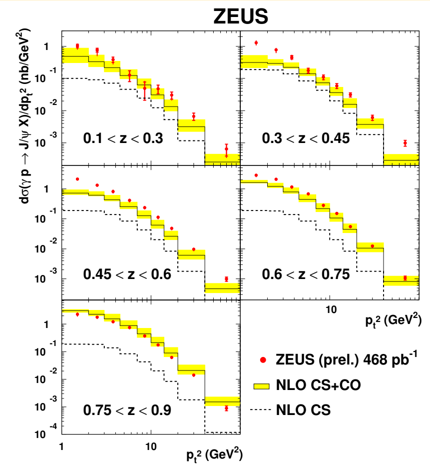
- Resummation of large logs $\ln(p_T^2/M^2)$ necessary at large p_T.
- New formalism to include non-leading powers in p_T^2/M^2 [Kang Qiu Sterman 2012].

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



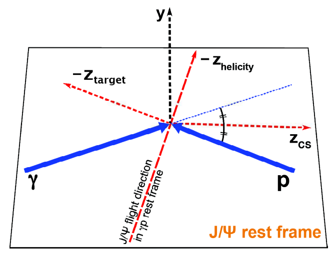
- Inelastic scattering of 105 GeV photons on hydrogen target.
- Data remarkably well described by CS+CO at NLO.

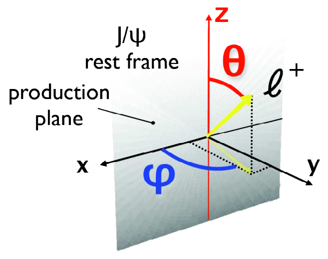
Comparison with ZEUS (after fit) [JHEP1302(2013)071]



- Notorious NRQCD overshoot at large z overcome.

Polarized J/ψ photo- and hadroproduction





Decay angular distribution:

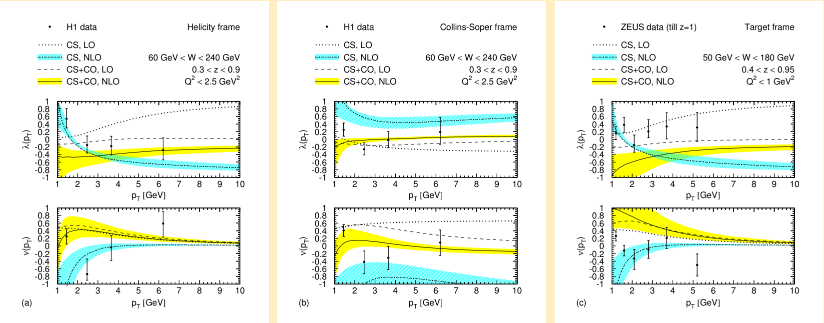
$$\frac{d\Gamma(J/\psi\to l^+l^-)}{d\cos\theta\, d\phi} \propto 1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos(2\phi)+\lambda_{\theta\phi}\sin(2\theta)\cos\phi$$

Polarization observables in spin density matrix formalism:

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

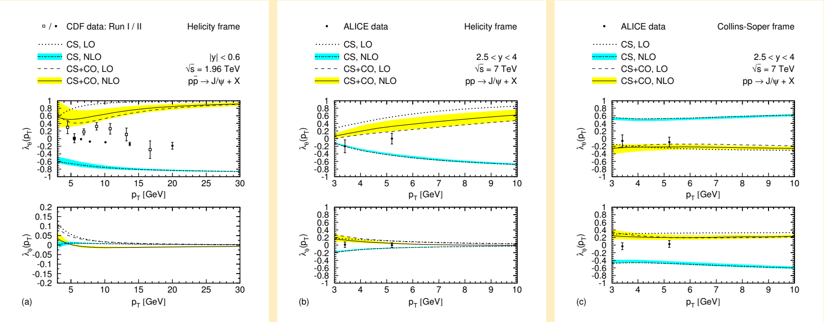
$\lambda=0,+1,-1$: unpolarized, transversely and longitudinally porarized.

Comparison with H1 and ZEUS



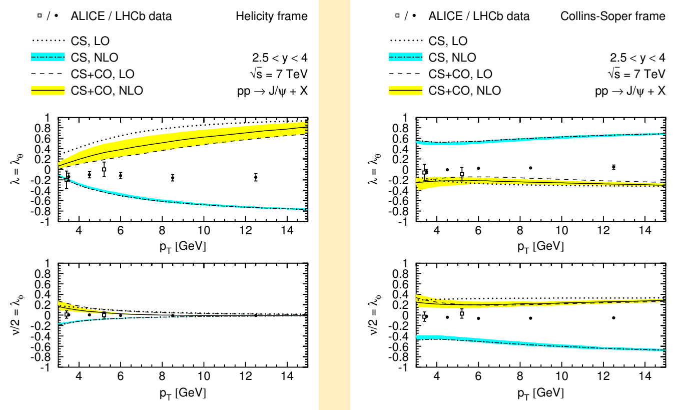
- No z cut on ZEUS data $\rightsquigarrow$ diffractive production included.
- Perturbative stability in NRQCD higher than in CSM.
- J/ψ preferrably unpolarized at large p_T.

Comparison with CDF and ALICE



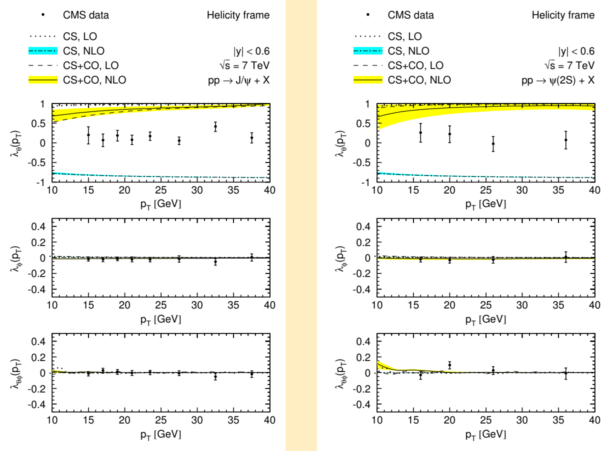
- CDF I [PRL85(2000)2886] and II [PRL99(2007)132001] data mutually inconsistent for $p_T < 12$ GeV.
- CDF J/ψ polarization anomaly persits at NLO.
- 4/8 ALICE [PRL108 (2012) 082001] points agree w/ NLO NRQCD within errors, others $< 2\sigma$ away.

Comparison with ALICE [PRL108 (2012) 082001] and LHCb [EPJC73(2013)2631] data on prompt J/ψ polarization



- ALICE and LHCb data mutually agree.
- NLO NRQCD predictions systematically disagree w/ data.

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



- NLO NRQCD predictions systematically disagree w/ data on λ_θ.

Comparison with Gong et al. and Chao et al.

e^+e^- yield | γp yield | $p\overline{p}/pp$ yield | CDF polariz.

BK, MB

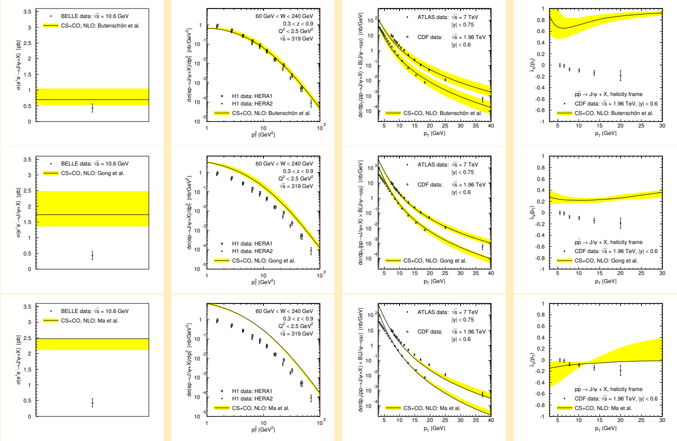
PRL108(2012)172002

Gong et al.

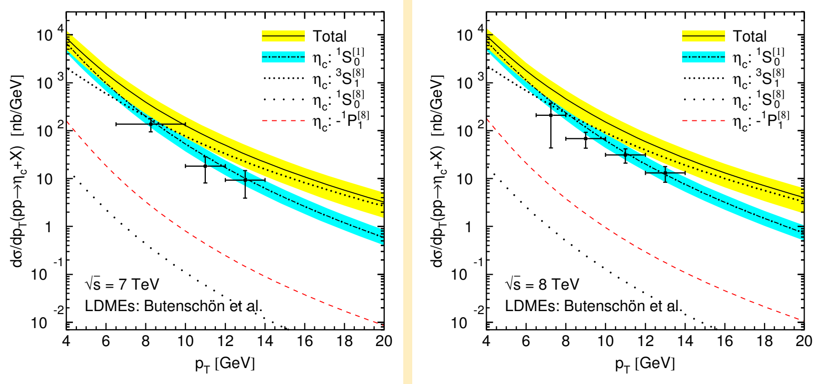
PRL110(2013)042002

Chao et al.

PRL108(2012)242004



LHCb data on η_c yield [EPJC75(2015)311]



7 TeV

8 TeV

M. Butenschoen, Z. He, BK, PRL114(2015)092004

Summary

- NRQCD factorization provides rigorous framework for production and decay of heavy quarkonia; predicts:
  - existence of CO states;
  - universality of LDMEs.
- NLO NRQCD nicely describes world data on unpolarized J/ψ yield.
- NLO CSM greatly undershoots data, except for e^+e^- annihilation.
- $\gamma\gamma$ scattering not conclusive yet.
- Hadroproduction data alone cannot reliably fix all 3 CO LDMEs.
- NLO NRQCD predictions for polarized J/ψ hadroproduction based on global analysis of J/ψ yield agrees with ALICE (low p_T), but strongly disagrees with CDF, CMS, and LHCb.
- NLO NRQCD predictions for η_c yield based on heavy-quark spin symmetry greatly overshoot LHCb data.
- NRQCD factorization remains among the hottest topics of QCD @ LHC.