Theoretical Aspects Quarkonium Production in Vacuum

Geoffrey Bodwin (ANL)

- Brief Review of NRQCD Factorization
- Status of a Proof of NRQCD Factorization
- Why is large p_T important?
- What are LP and NLP factorization (fragmentation)?
- What happens in Hadroproduction at LO in α_s?
- What happens in Hadroproduction at NLO in α_s?
- Why are there so many different NLO predictions?
- What happens to J/ψ polarization in NLO?
- What do we expect beyond NLO in α_s?
- How do we go beyond NLO in α_s?
- Outstanding Problems
- Conclusions and Outlook

Brief Review of NRQCD Factorization

- NRQCD Factorization Conjecture (Bodwin, Braaten, Lepage (1995)):
  The inclusive cross section for producing a quarkonium at large momentum transfer (p_T) can be written as

$$\sigma(H) = \sum_n F_n(\Lambda)\langle 0|\mathcal{O}_n^H(\Lambda)|0\rangle.$$

- The $F_n(\Lambda)$ are the "short-distance" coefficients (SDCs).
  - The SDCs are essentially the partonic cross sections to make a $Q\bar{Q}$ pair convolved with the parton distributions.
- The $\langle 0|\mathcal{O}_n^H(\Lambda)|0\rangle$ are the NRQCD long-distance matrix elements (LDMEs).
  - The LDMEs are the probability for a $Q\bar{Q}$ pair to evolve into a heavy quarkonium.

- The SDCs depend on the production process.
  They can be calculated in QCD perturbation theory.
- The LDMEs are nonperturbative, but they are conjectured to be universal (process independent).
- The LDMEs have a known scaling with the heavy-quark velocity v.
  - $v^2 \approx 0.23$ for the J/ψ. $v^2 \approx 0.1$ for the $\Upsilon(1S)$.
  - The sum in the factorization formula is a v expansion.
- In phenomenology, the v expansion in the factorization formula is truncated at a particular order in v.
- A key feature of NRQCD factorization: Quarkonium production can occur through color-octet, as well as color-singlet, $Q\bar{Q}$ states.
  - The color-singlet production LDMEs are simply related to color-singlet decay LDMEs.
  - The color-octet LDMEs must be determined from fits to measured production cross sections.
- If we drop all of the color-octet contributions and retain only the leading color-singlet contribution, then we have the color-singlet model (CSM).

- The current phenomenology of production of S-wave quarkonia (J/ψ, $\psi(2S)$, and $\Upsilon(nS)$) makes use of LDMEs through relative order v^4:

$$\begin{aligned}
&\langle \mathcal{O}^H({}^3S_1^{[1]})\rangle \quad (O(v^0)),\\
&\langle \mathcal{O}^H({}^1S_0^{[8]})\rangle \quad (O(v^3)),\\
&\langle \mathcal{O}^H({}^3S_1^{[8]})\rangle \quad (O(v^4)),\\
&\langle \mathcal{O}^H({}^3P_J^{[8]})\rangle \quad (O(v^4)).
\end{aligned}$$

  – Calculations show that the ${}^3S_1^{[1]}$ contributions are negligible for J/ψ hadroproduction.
  – The $\langle \mathcal{O}^H({}^3P_J^{[8]})\rangle$ ($J = 0, 1, 2$) are related by the heavy-quark spin symmetry.
  – Three color-octet LDMEs need to be determined phenomenologically for each state.

Status of a Proof of NRQCD Factorization

- Nayak, Qiu, Sterman (2005, 2006): Factorization holds through NNLO, up to corrections of relative order m_Q^2/p_T^2.
- It is not known if this result generalizes to higher orders in α_s.
- An all-orders proof is essential because soft gluons can violate factorization, and the α_s that is associated with soft gluons is not small.
- In the absence of further theoretical progress, we must rely on experiment to prove or to disprove NRQCD factorization.

Why is large p_T important?

- Existing proofs of factorization for light hadrons all require p_T significantly greater than the hadron masses.
  - Power corrections $\propto (m_H^2/p_T^2)^n$ get out of control when $p_T \sim m_H$.
  - There are known violations of factorization at order m_H^4/p_T^4.
- Phenomenologically, Drell-Yan factorization doesn't work until $p_T \geq 3m_H$.
- Suggests that we should require $p_T \geq 3m_{\rm quarkonium.}$

What are LP and NLP factorization (fragmentation)?

- Leading power (LP) fragmentation:
  (Collins, Soper (1982))
  - $d\sigma/dp_T^2 \sim 1/p_T^4$.

$$d\sigma[a+b \to \text{quarkonium}+X] \sim \underbrace{d\sigma[a+b \to c+X]}_{\text{hard scattering}} \otimes \underbrace{D[c \to \text{quarkonium}+X]}_{\text{fragmentation fn.}}.$$

- Next-to-leading power (NLP) fragmentation:
  (Kang, Qiu, and Sterman (2011); Fleming, Leibovich, Mehen, Rothstein (2012))
  - $d\sigma/dp_T^2 \sim m_Q^2/p_T^6$.

$$d\sigma[a+b \to \text{quarkonium}+X] \sim \underbrace{d\sigma[a+b \to Q\bar{Q}+X]}_{\text{hard scattering}} \otimes \underbrace{D[Q\bar{Q} \to \text{quarkonium}+X]}_{\text{fragmentation fn.}}.$$

- Believed to hold to all orders in perturbation theory up to corrections of order m_Q^4/p_T^8.

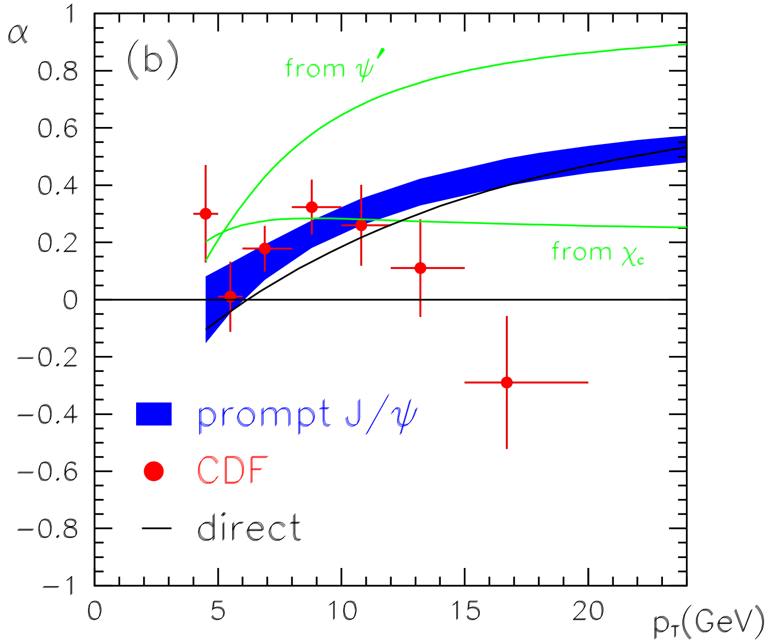
- Not very predictive by itself because the nonperturbative fragmentation functions are unknown.
- If NRQCD factorization holds, then the fragmentation functions can be written as a sum of NRQCD LDMEs times perturbatively calculable short-distance coefficients.
  - Then, the fragmentation approach provides powerful a way to identify and compute the contributions (LP and NLP) that are most important at high p_T.
  - Much simpler than a full perturbative calculation at any given order in α_s.
  - Also provides a framework in which to resum logs of p_T^2/m_Q^2.

What happens in Hadroproduction at LO in α_s?

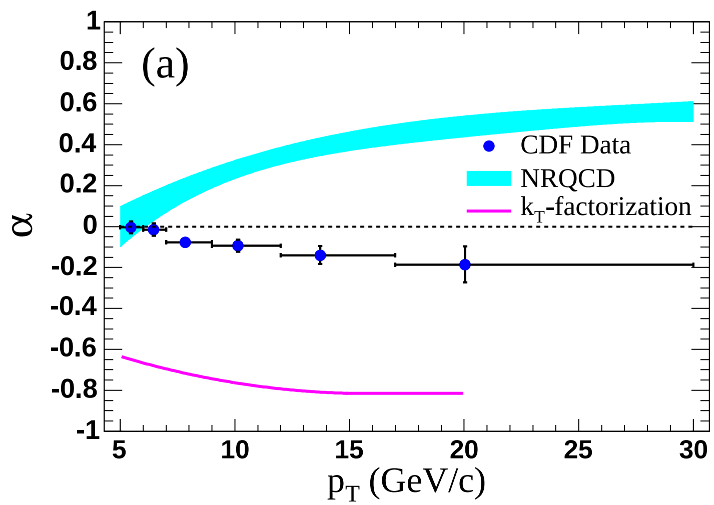
- Only the ${}^3S_1^{[8]}$ contribution has LP behavior in LO.
  - Dominates at large p_T.
- The ${}^3S_1^{[8]}$ contribution is transversely polarized.
- LO NRQCD factorization predicts large transverse polarization at large p_T.
- This prediction is not borne out by the data.

J/ψ Polarization in LO

CDF Run I:



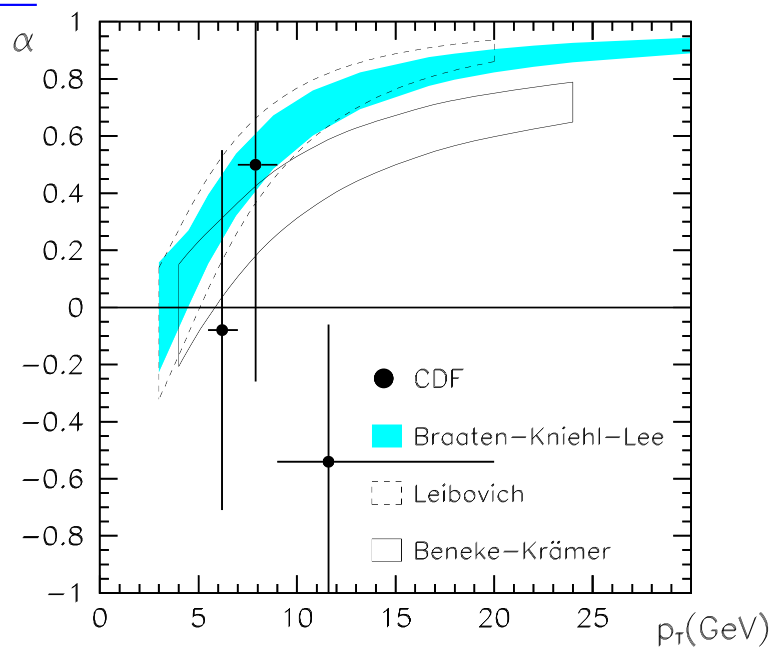
CDF Run II:



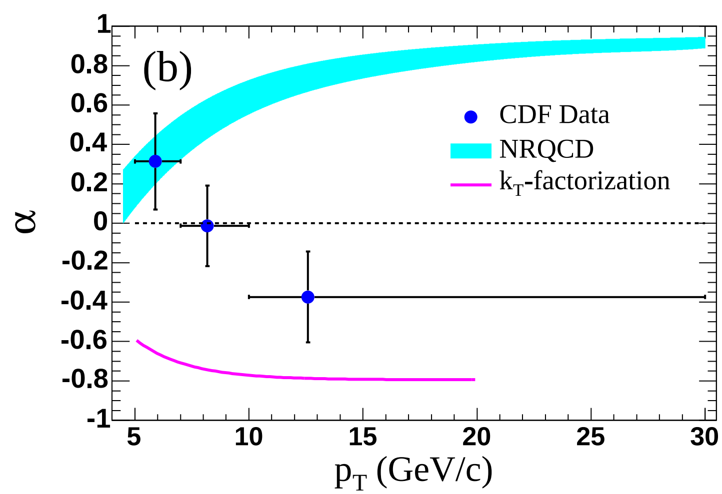
- $\alpha \equiv \lambda_\theta = \begin{cases} 1 & \text{transverse} \\ 0 & \text{unpolarized} \\ -1 & \text{longitudinal} \end{cases}$
- LO NRQCD prediction (Braaten, Kniehl, Lee (1999)).
- Run I results are marginally compatible with the LO NRQCD prediction.
- The Run II results are incompatible with the LO NRQCD prediction.
- The Run I and Run II results are inconsistent with each other.

$\psi(2S)$ Polarization in LO

Run: I



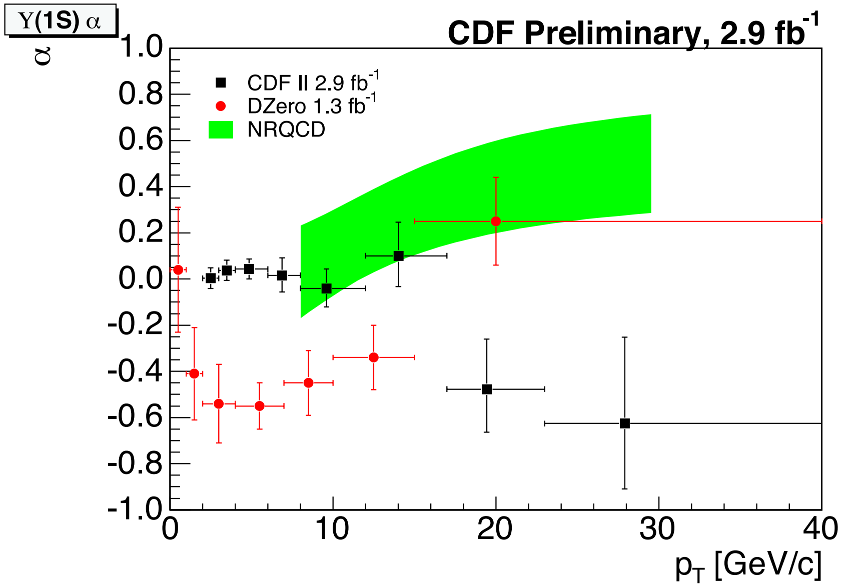
Run: II



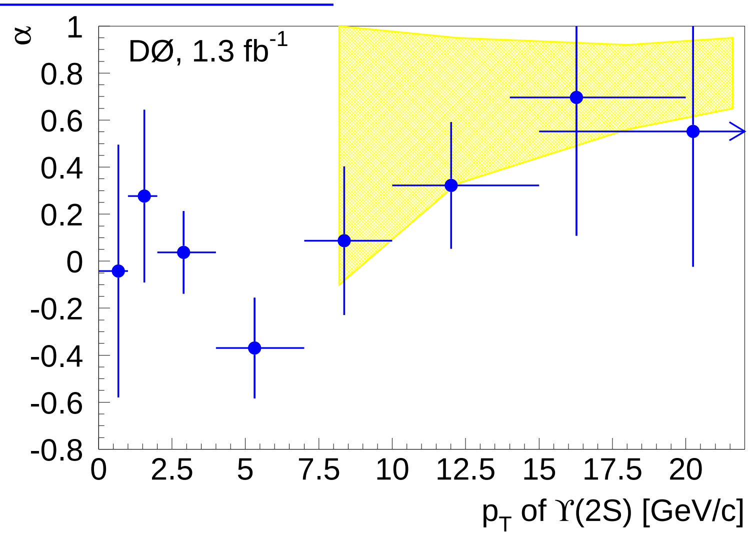
- The error bars on the Run I data are too large to make a stringent test.
- The Run II data are incompatible with the LO NRQCD prediction.

Υ Polarization in LO

$\Upsilon(1S)$ Polarization:

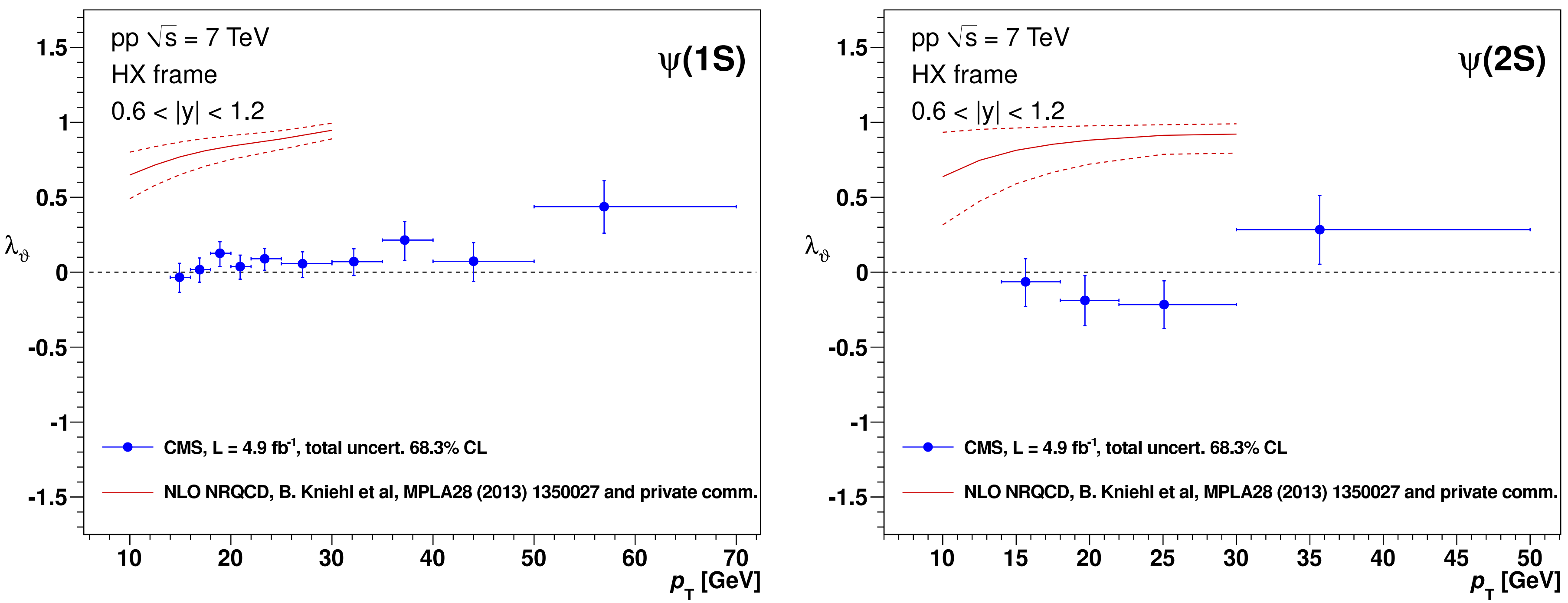


$\Upsilon(2S)$ Polarization:



- In the $\Upsilon(1S)$ case, the D0 results (red) are incompatible with the CDF results (black).
- Both the CDF and D0 results are incompatible with the LO NRQCD prediction (green) (Braaten and Lee (2000)), but in different regions of p_T.
- In the $\Upsilon(2S)$ case, the theoretical and experimental error bars are too large to make a stringent test.

- It was thought that these discrepancies between theory and experiment might not be definitive because
  - there are inconsistencies in the experimental data,
  - p_T might not be high enough for factorization to work.
- These ideas were laid to rest by the CMS (2013) polarization measurement.



What happens in Hadroproduction at NLO in α_s?

- There is a large k factor ~ -10 in the ${}^3P_J^{[8]}$ channel.
- On the other hand, NLO corrections to the ${}^3S_1^{[8]}$ and ${}^1S_0^{[8]}$ channels are small.

Explanation

- Enhancements at high p_T from LP behavior can overcome a power of α_s.
- The ${}^3P_J^{[8]}$ channel receives a large (negative) correction in NLO because it first shows LP behavior in NLO (gluon fragmentation).
- The ${}^3S_1^{[8]}$ channel receives a small correction in NLO because it already has LP behavior in LO (gluon fragmentation).
- The ${}^1S_0^{[8]}$ channel first shows LP behavior in NLO (gluon fragmentation). But the NLO correction happens to be small (no IR enhancement).

Why are there so many different NLO predictions?

- Three groups have carried out complete NLO calculations.
  - PKU group (Kuang-Ta Chao's group): Ma, Wang, Chao
  - Hamburg group (Bernd Kniehl's group): Butenschön, Kniehl
  - IHEP group (Jianxiong Wang's group): Gong, Wan, Wang, Zhang
- All three groups agree on the SDCs for hadroproduction.
- However, they extract very different NRQCD LDMEs and make different predictions because of different assumptions about the data used in the fits.
- The PKU group (2010) fits the CDF J/ψ data for $p_T > 7$ GeV.
  They were able to determine only 2 linear combinations of LDMEs unambiguously:

$$
\begin{aligned}
M_{0,r_0} &= \langle O^{J/\psi}(^1S_0^{[8]})\rangle + (r_0/m_c^2)\langle O^{J/\psi}(^3P_0^{[8]})\rangle = (7.4 \pm 1.9) \times 10^{-2}\ \text{GeV}^3, \\
M_{1,r_1} &= \langle O^{J/\psi}(^3S_1^{[8]})\rangle + (r_1/m_c^2)\langle O^{J/\psi}(^3P_0^{[8]})\rangle = (0.05 \pm 0.02) \times 10^{-2}\ \text{GeV}^3.
\end{aligned}
$$

$r_0 = 3.9$ and $r_1 = -0.56$.

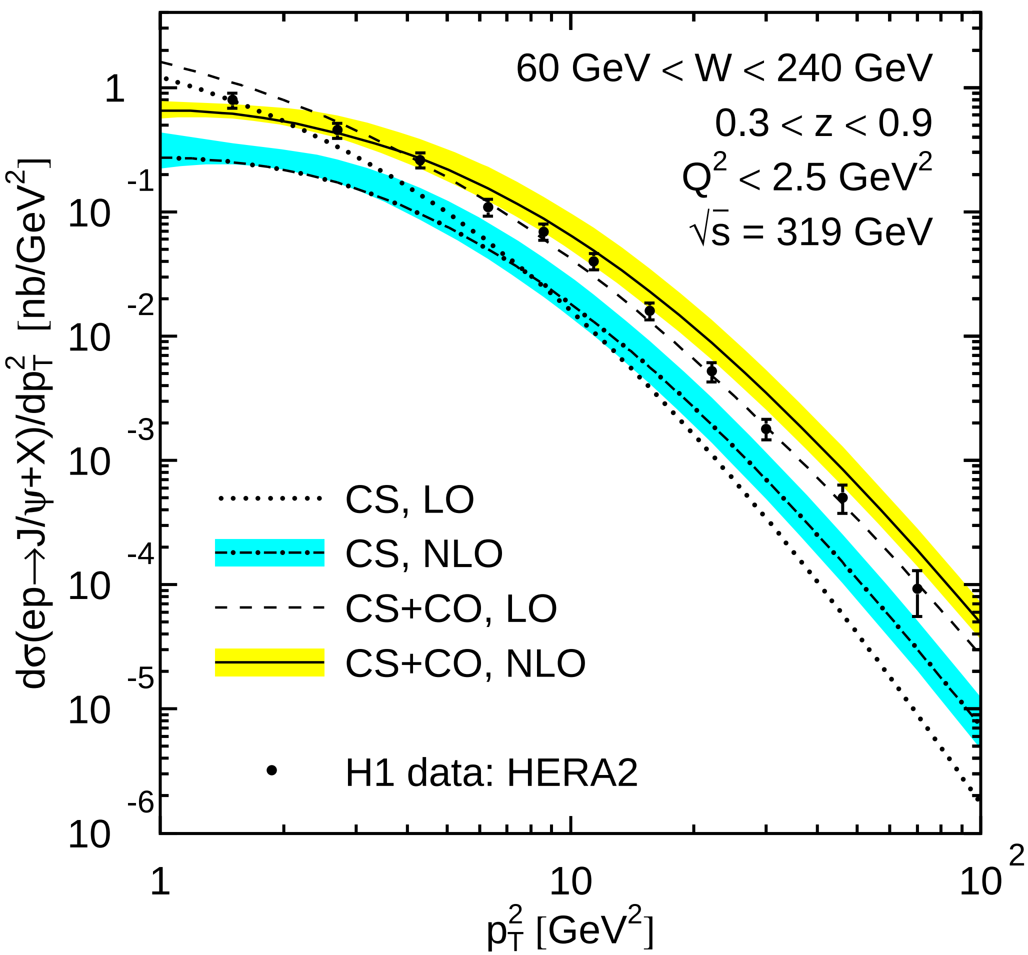
- The Hamburg group (2011) determined all 3 color-octet LDMEs by making a global fit to data with $p_T > 3$ GeV from the Tevatron, LHC, RHIC, HERA, LEP II, KEKB.
  - They made use of their computations of NLO corrections to $p\bar{p}$, pp, ep, $\gamma\gamma$, and e^+e^- production.
  - Their LDMEs are very different from those of the PKU group:

$$M_{0,r_0} = (2.17 \pm 0.56) \times 10^{-2} \text{ GeV}^3,$$
$$M_{1,r_1} = (0.62 \pm 0.08) \times 10^{-2} \text{ GeV}^3.$$

- The IHEP group (2012) fit the CDF J/ψ, $\psi(2S)$, and χ_{cJ} data for $p_T > 7$ GeV.
  - They included NLO feeddown contributions from $\psi(2S)$ and χ_{cJ} in their fit.
  - They were able to determine all 3 color-octet LDMEs.
  - They obtained a quality of fit and a result for the LDME linear combinations that is similar to that of the PKU group:

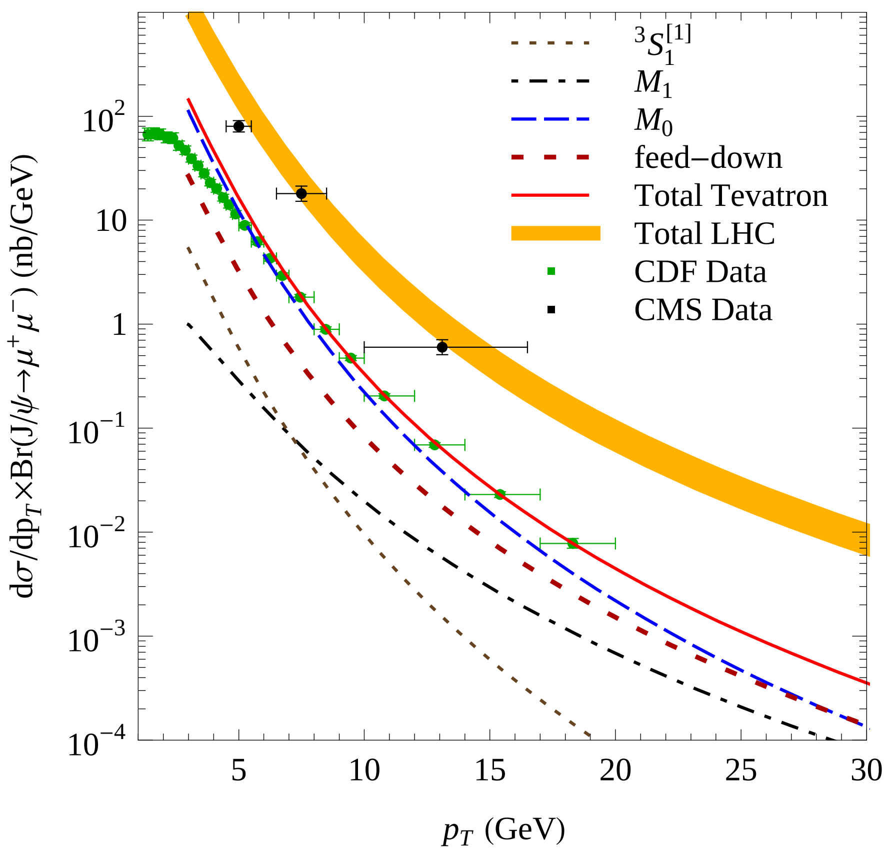
$$M_{0,r_0} = (6.00 \pm 0.98) \times 10^{-2} \text{ GeV}^3,$$
$$M_{1,r_1} = (0.07 \pm 0.02) \times 10^{-2} \text{ GeV}^3.$$

- Most of the difference between the Hamburg-group fit and the others comes from the use of HERA (H1 (2002, 2005)) data.

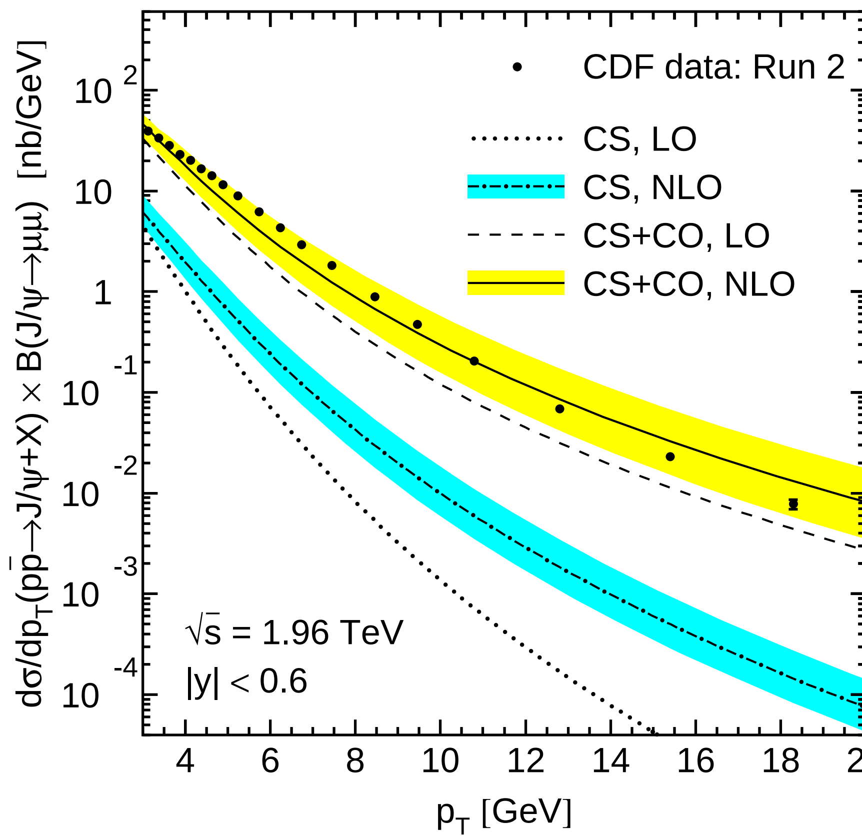


- The HERA data lie at $p_T \lesssim 8$ GeV.
- Does NRQCD factorization hold at such low values of p_T?

- Although the Hamburg-group fits agree with the data, within uncertainties, there are tensions in the shapes.
- The shape of the PKU-group fit agrees with the CDF data better than the shape of the Hamburg-group (2011) global fit.

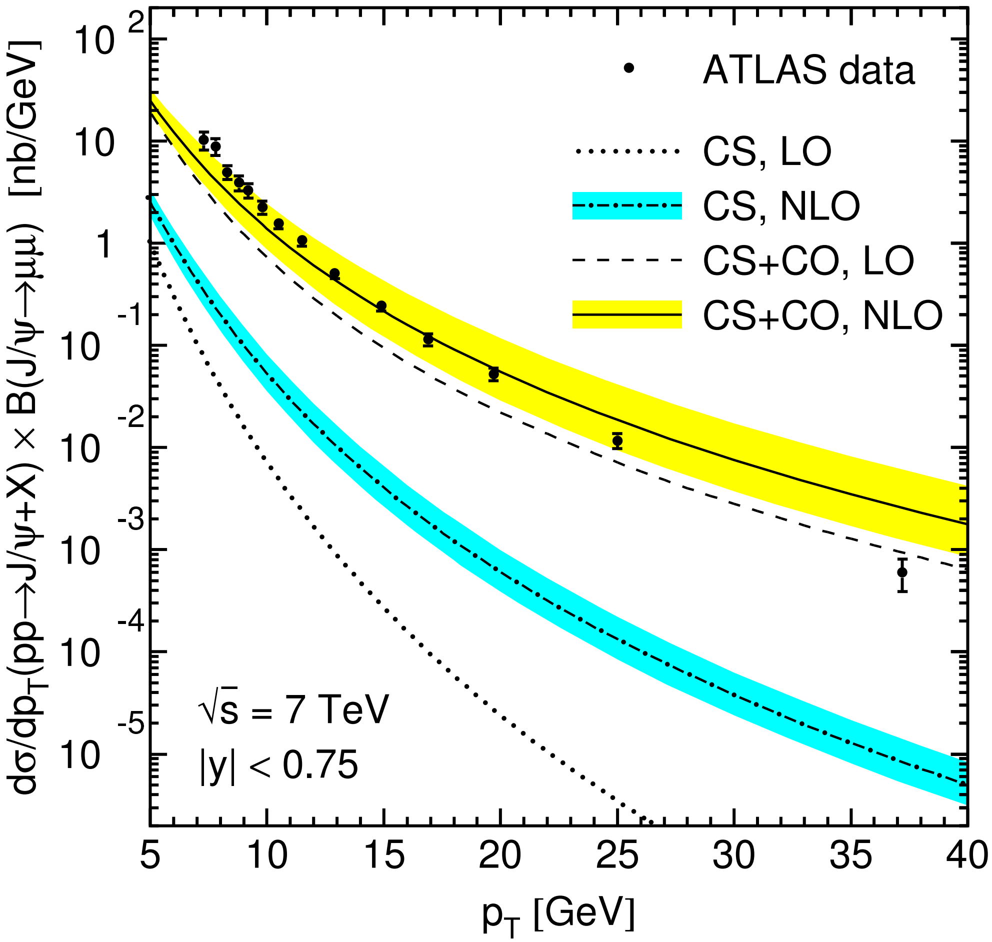


PKU group



Hamburg group

- The shape discrepancy between the Hamburg-group prediction and the data becomes more apparent at high p_T.



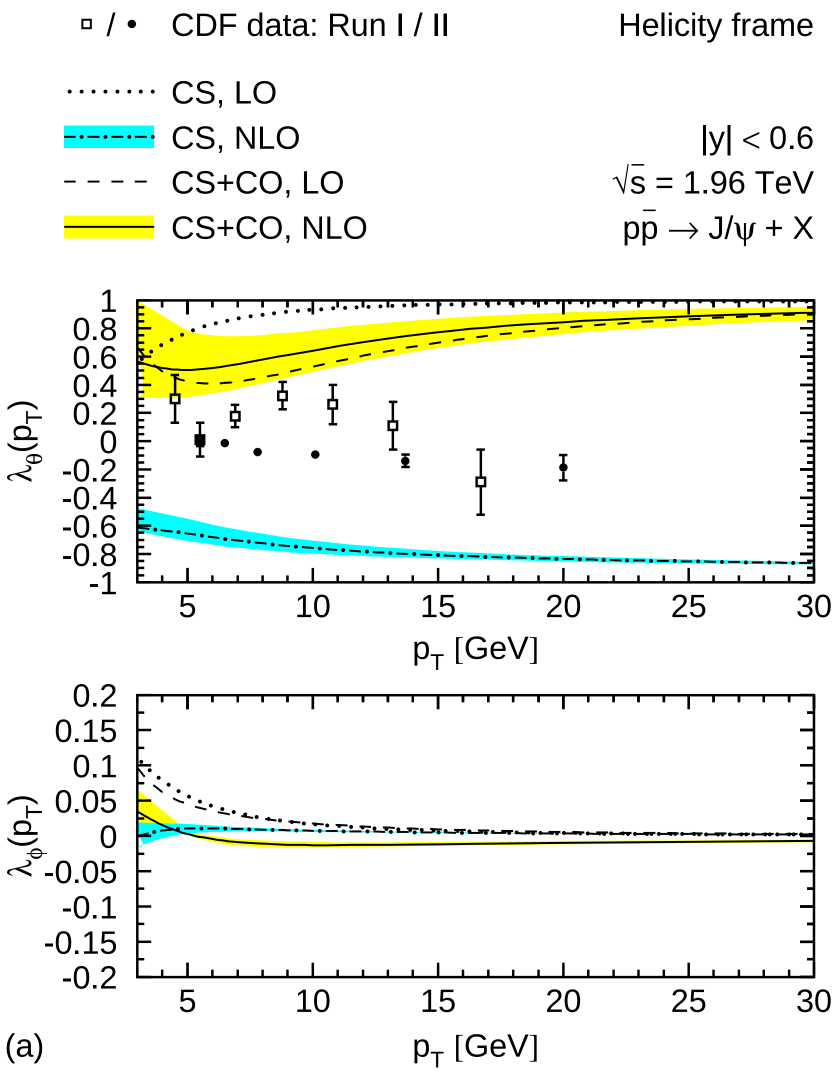
- ATLAS (2011) data.
- Not included in the Hamburg-group global fit.

- All of this suggests that NRQCD factorization may not work until p_T is much greater than the quarkonium mass.

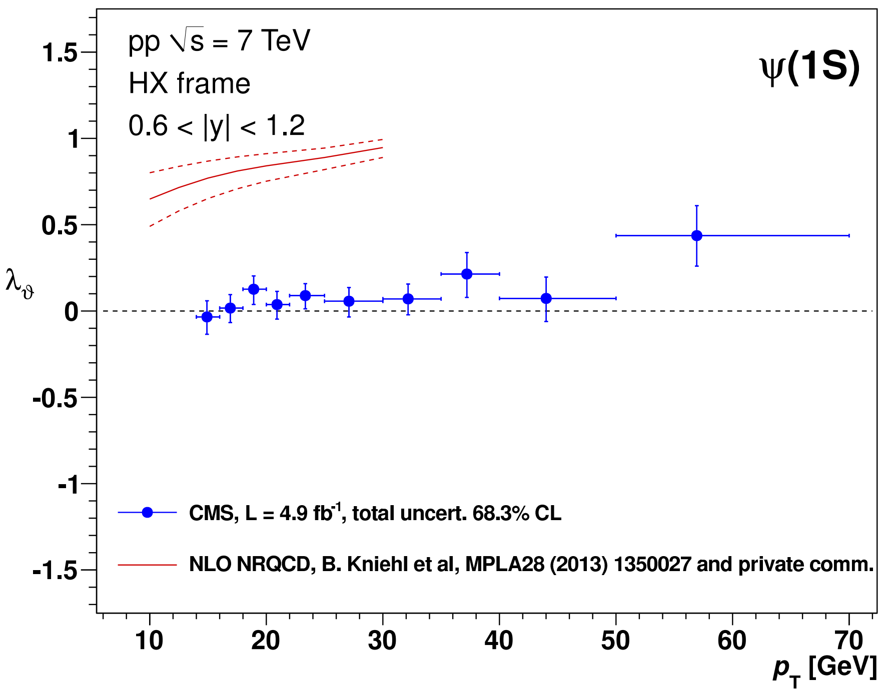
What happens to J/ψ polarization in NLO?

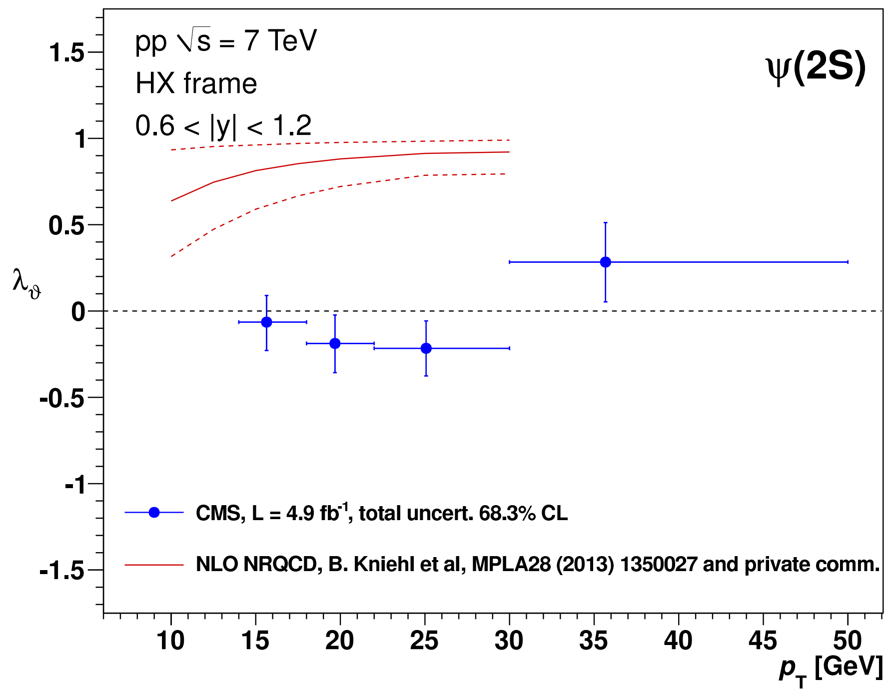
- At high p_T, the ${}^3P_J^{[8]}$ channel is mostly transversely polarized—just like the ${}^3S_1^{[8]}$ channel.
- Large NLO corrections to the ${}^3P_J^{[8]}$ channel give it the same shape as the ${}^3S_1^{[8]}$ channel at high p_T.
- The contribution from the ${}^3P_J^{[8]}$ channel could cancel the contribution from the ${}^3S_1^{[8]}$ channel.
- The resulting ${}^1S_0^{[8]}$ dominance would result in near-zero polarization.

Hamburg group (2011): NLO Prediction for J/ψ Polarization



- Uses the Hamburg-group (2011) global fit of the J/ψ production cross sections.
- The contributions of the ${}^3P_J^{[8]}$ and ${}^3S_1^{[8]}$ channels add to produce substantial polarization at high p_T.
- The prediction is in disagreement with the CDF data.

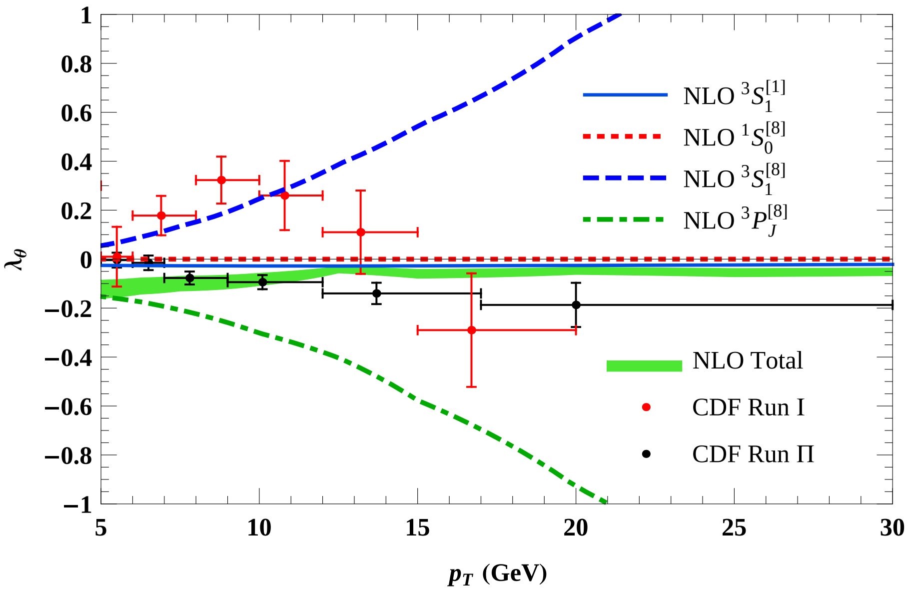




- The prediction based on the Hamburg-group (2011) global fit is also in disagreement with the CMS data.

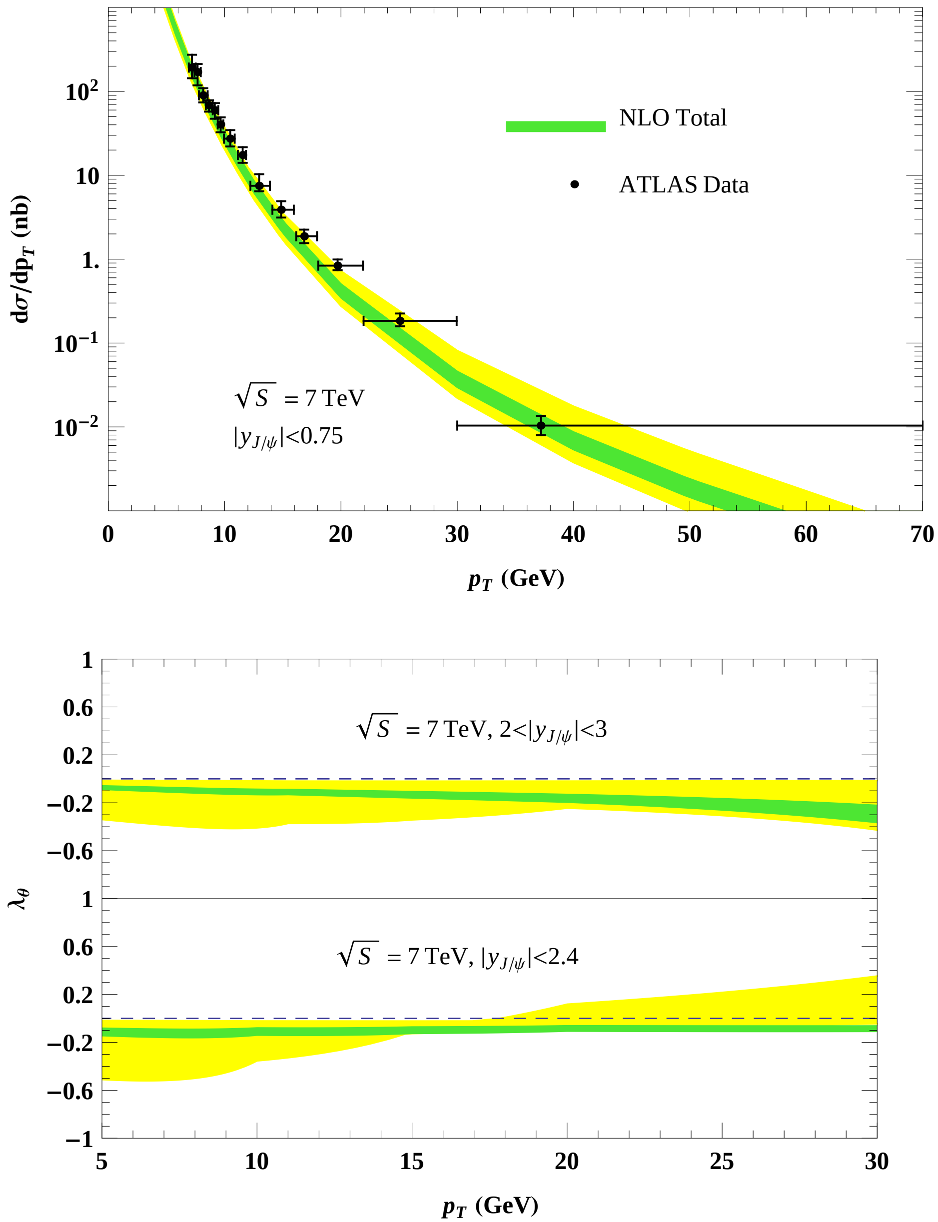
Chao, Ma, Shao, Wang, Zhang (PKU Group)(2012): Fit to J/ψ Polarization in NLO

- Two LDME combinations are insufficient to predict the polarization.
- Fix all three LDMEs by including the CDF Run II J/ψ polarization measurement in the fit, as well as the CDF Run II measurements of $d\sigma/dp_T$.



- The $^3S_1^{[8]}$ and $^3P_J^{[8]}$ contributions largely cancel.
- $^1S_0^{[8]}$ dominance $\Rightarrow$ near-zero polarization.

- The PKU-group (2012) LDMEs still give reasonable predictions for the LHC p_T spectra.



- The PKU-group (2012) LDMEs predict a slightly longitudinal polarization at the LHC.

- However, the PKU-group LDMEs seem to be incompatible with the HERA data, even at $p_T \approx 8$ GeV.

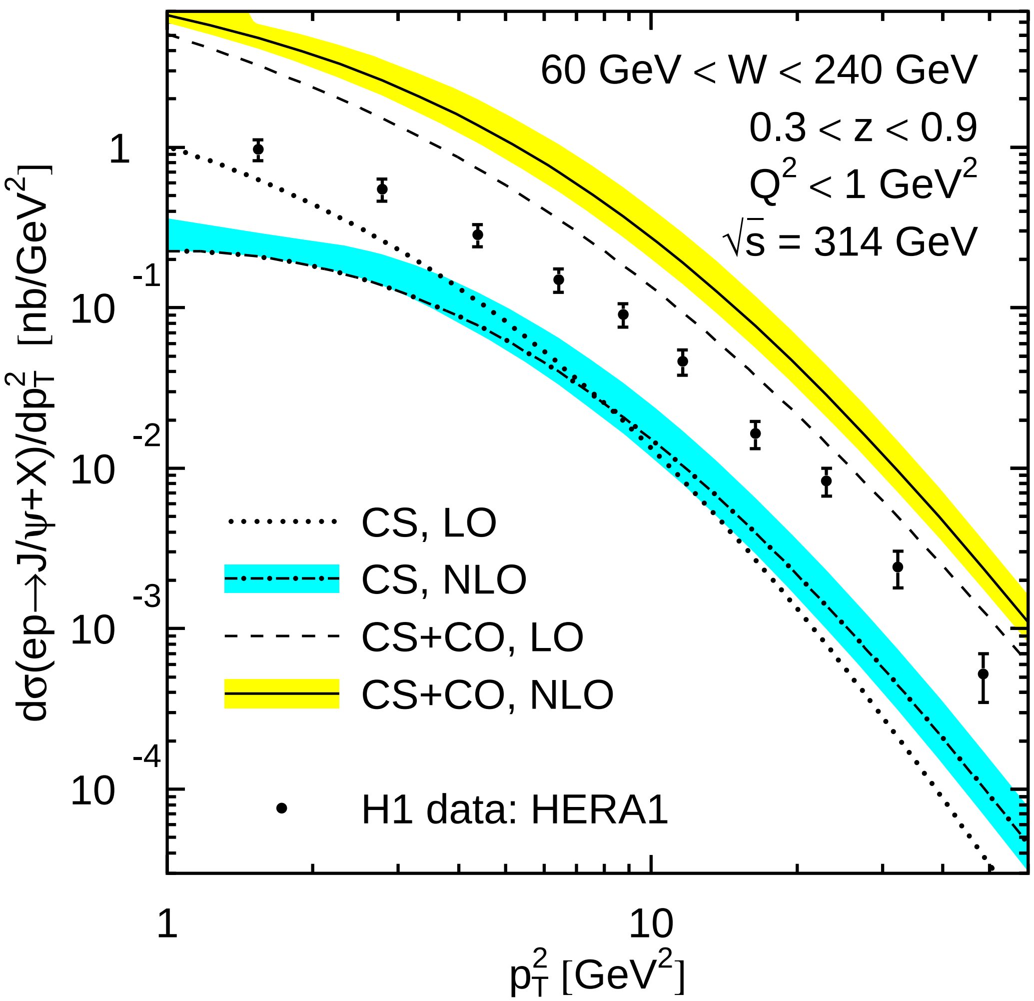


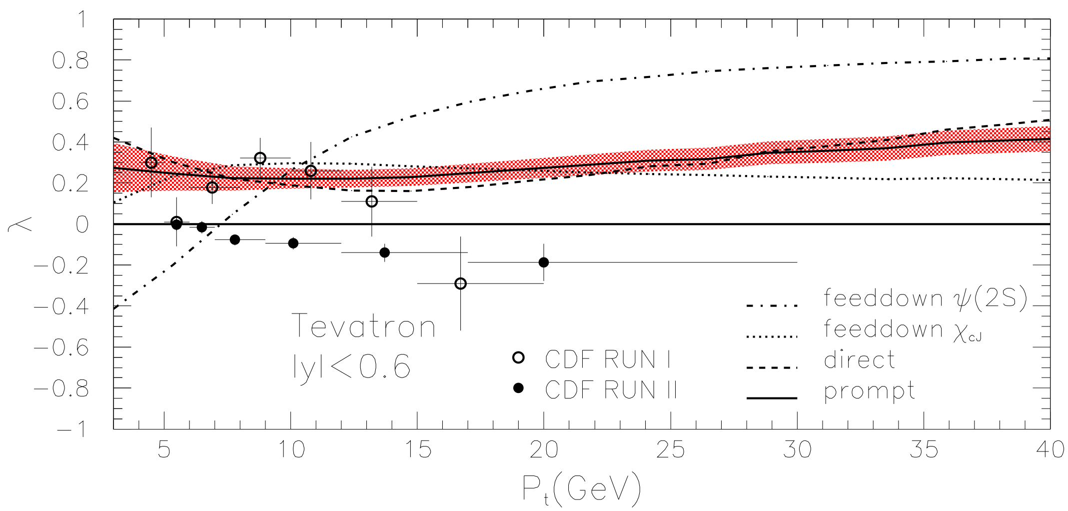
Figure courtesy of Mathias Butenschön.

- Is higher p_T needed in order suppress non-factorizing contributions?

IHEP group (2013): NLO Prediction for J/ψ polarization

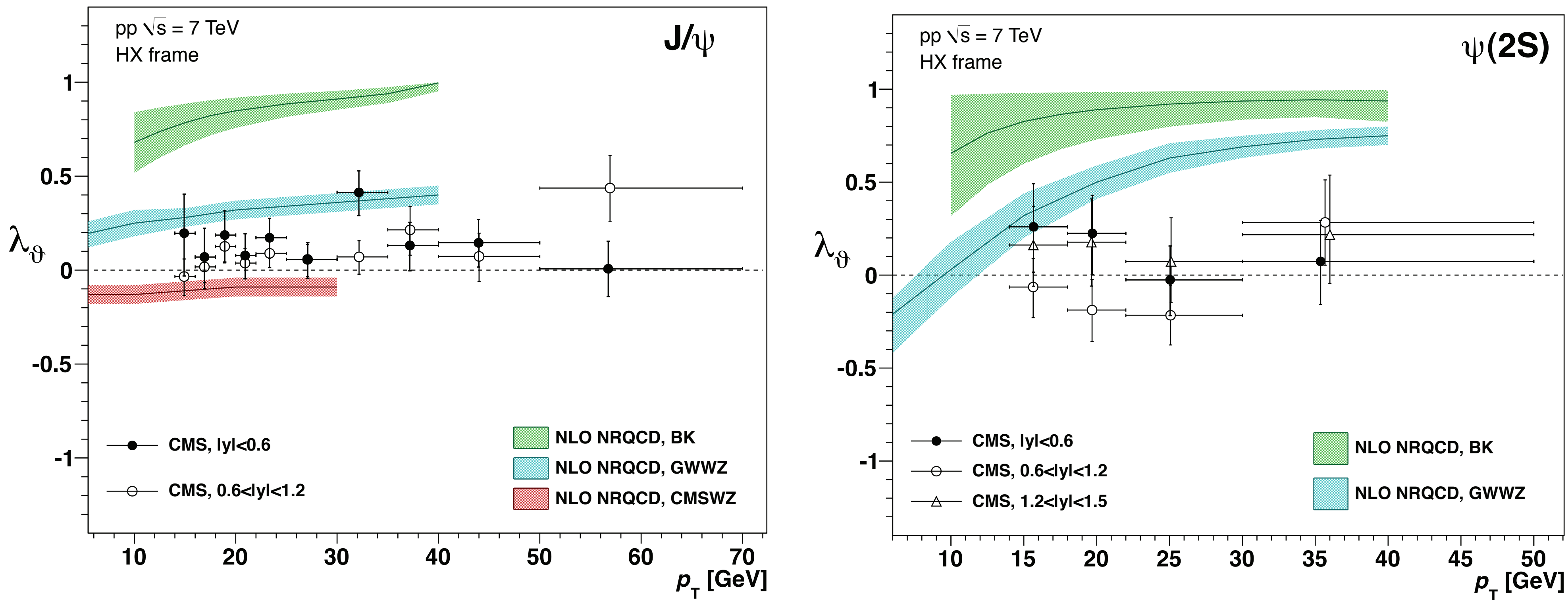
- Makes use of the LDMEs from a fit to the CDF (2005, 2009) and LHCb (2011, 2012) J/ψ, χ_{cJ}, and $\psi(2S)$ production cross sections.
- Effects of feeddown from χ_{cJ} and $\psi(2S)$ states calculated and included in fits and polarization predictions.

J/ψ Polarization at CDF:



- The prediction for CDF shows less transverse polarization than that of the Hamburg group.
- Agrees with the CDF Run I data, but not with the CDF Run II data.

J/ψ Polarization at CMS:



- The IHEP-group prediction (blue band) shows less transverse polarization than the Hamburg-group prediction (green band).
- Still in disagreement with the CMS data.

Conclusion about NLO Polarization

- NLO calculations either fail to make a polarization prediction (PKU) or make predictions that disagree with the data (Hamburg, IHEP).

What do we expect beyond NLO in α_s?

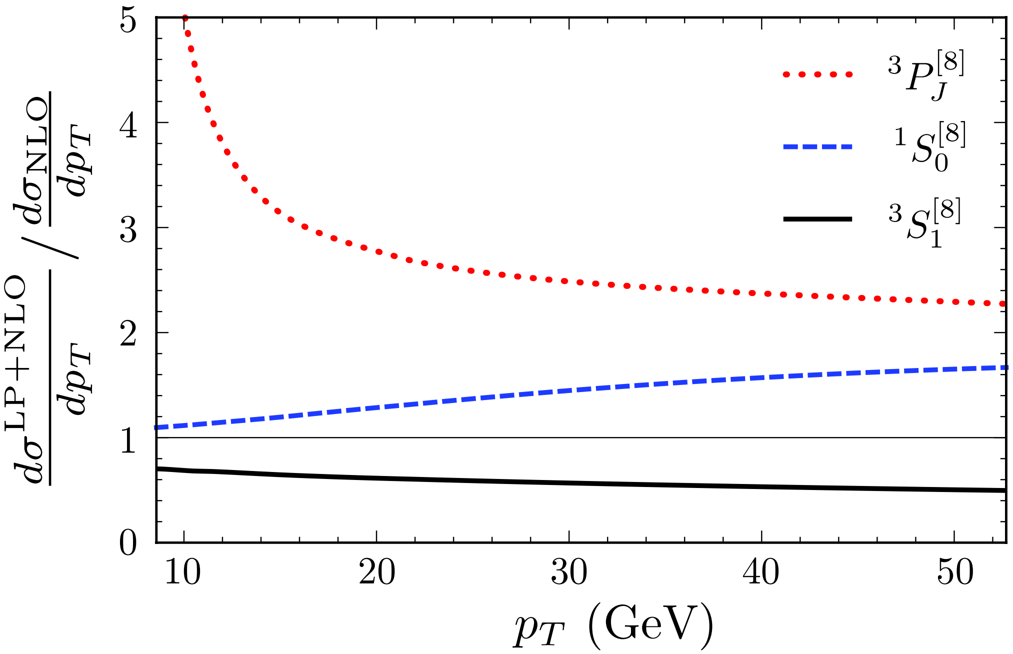
- Since all three color-octet channels have LP behavior at NLO, we expect further corrections to have "normal" k factors: factor of two or less.
- Exception: The LO and NLO corrections in the ${}^3P_J$ channel have opposite signs and cancel completely at $p_T \approx 7$ GeV.
  - NNLO corrections could be very important in this channel.

How do we go beyond NLO in α_s?

- Full NNLO calculations are probably not feasible at present.
- Use LP and NLP factorization to simplify the calculation.
- LP and NLP factorization are only valid for p_T significantly larger than the quarkonium mass.

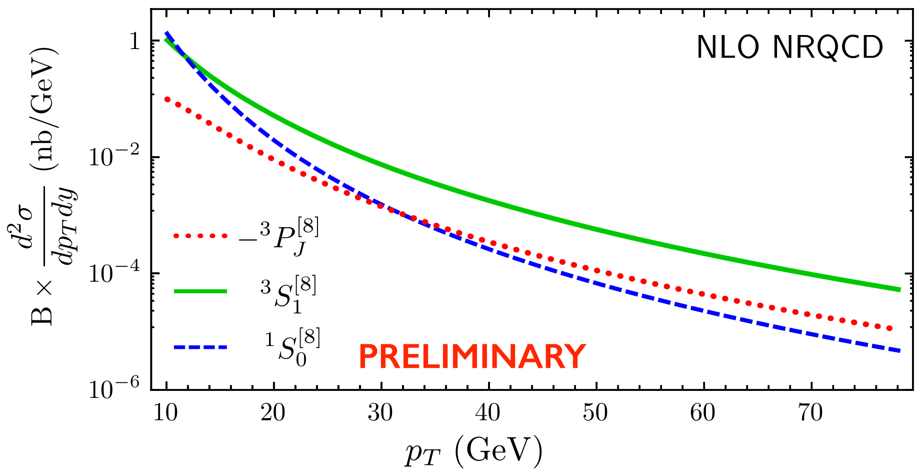
LP-Fragmentation Corrections to J/ψ Hadroproduction

- Bodwin, Chung, Kim, Lee (2014):
  - Fragmentation functions through α_s^2.
  - Parton-production cross sections through NLO (α_s^3).
  - Resummation of leading logs of p_T^2/m_c^2.

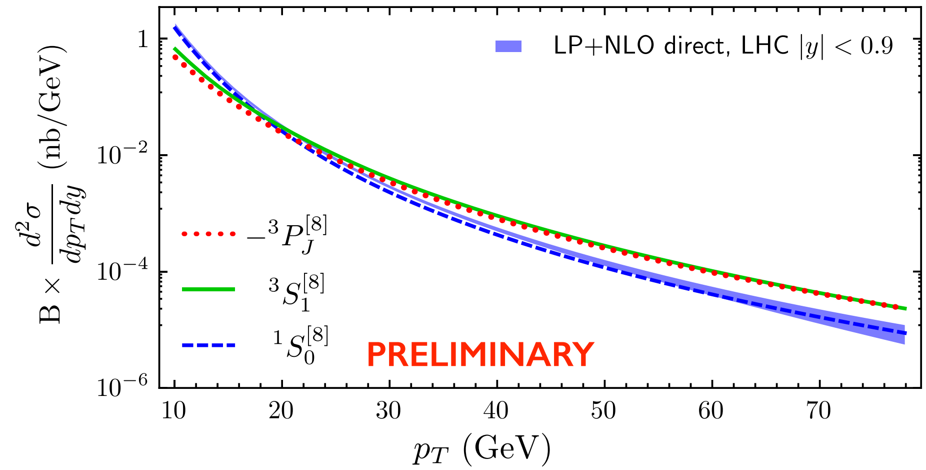


- As expected, the $^3P_J^{[8]}$ channel receives large corrections.

- The ${}^3P_J^{[8]}$ contribution now has almost the same shape as the ${}^3S_1^{[8]}$ contribution.

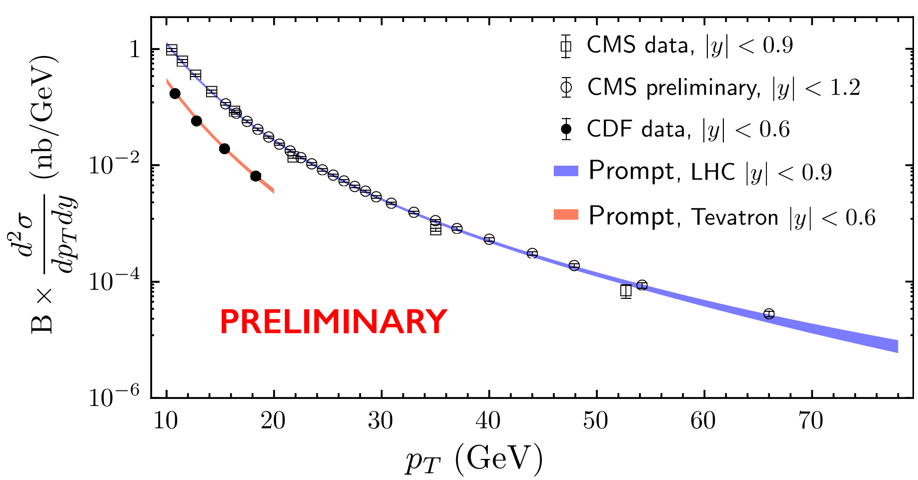


NLO

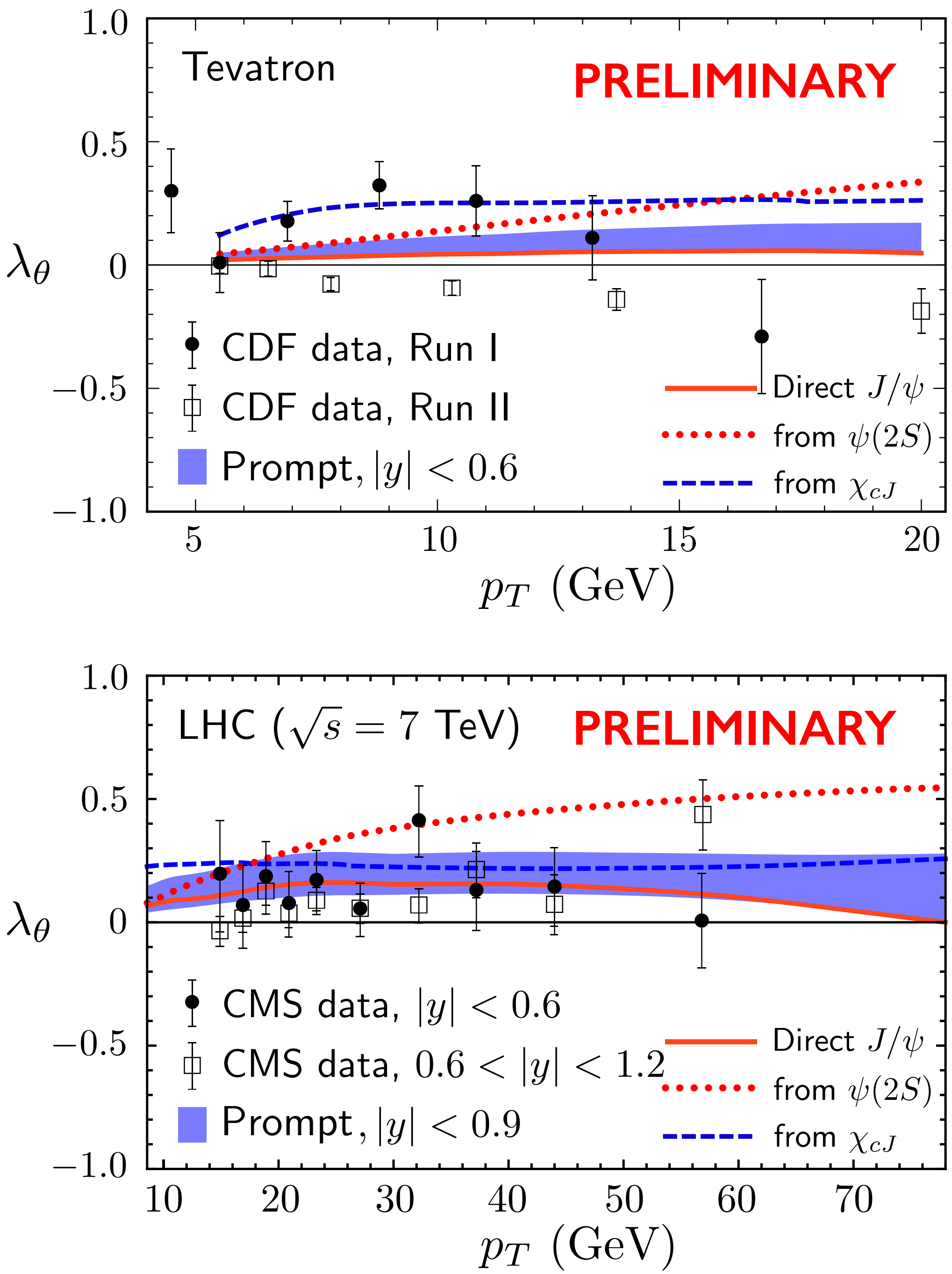


LP+NLO

- Bodwin, Chao, Chung, Kim, Lee, Ma (in progress): Include feeddown from χ_{cJ} and $\psi(2S)$ states.



- Fit to the CDF and CMS hadroproduction cross sections at $p_T > 10$ GeV $\approx 3m_{J/\psi}$ fixes the LDMEs.

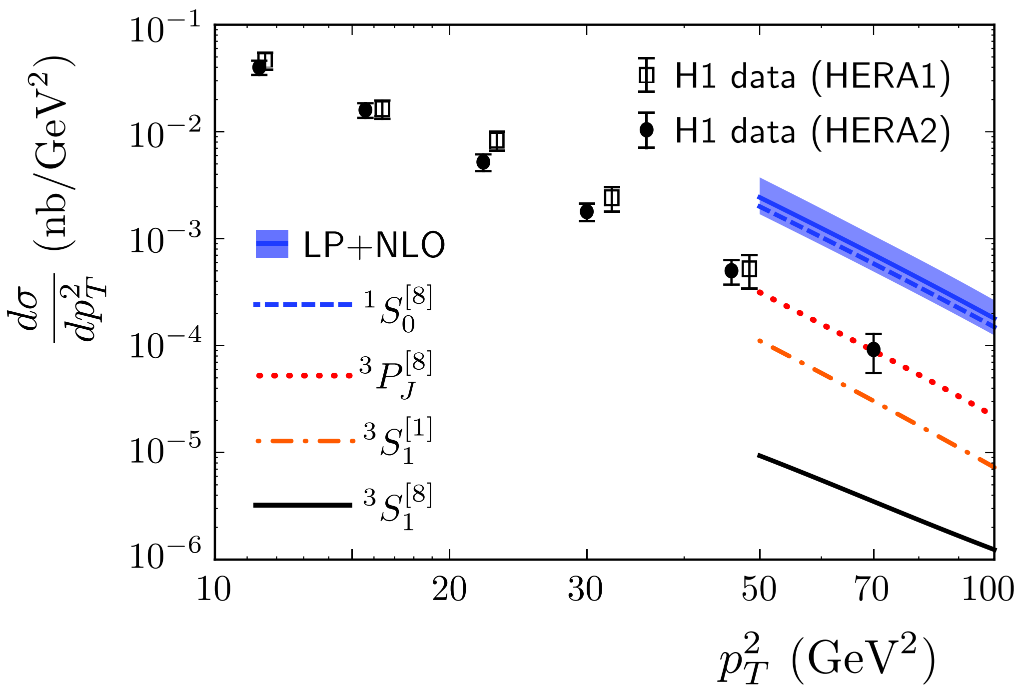


- The ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ contributions largely cancel: ${}^1S_0^{[8]}$ dominance.
- Prediction of near-zero polarization.

Outstanding Problems

J/ψ Photoproduction at HERA

- Bodwin, Chung, Kim, Lee (2015): LP-fragmentation corrections do not resolve the discrepancy between theory and experiment for photoproduction.

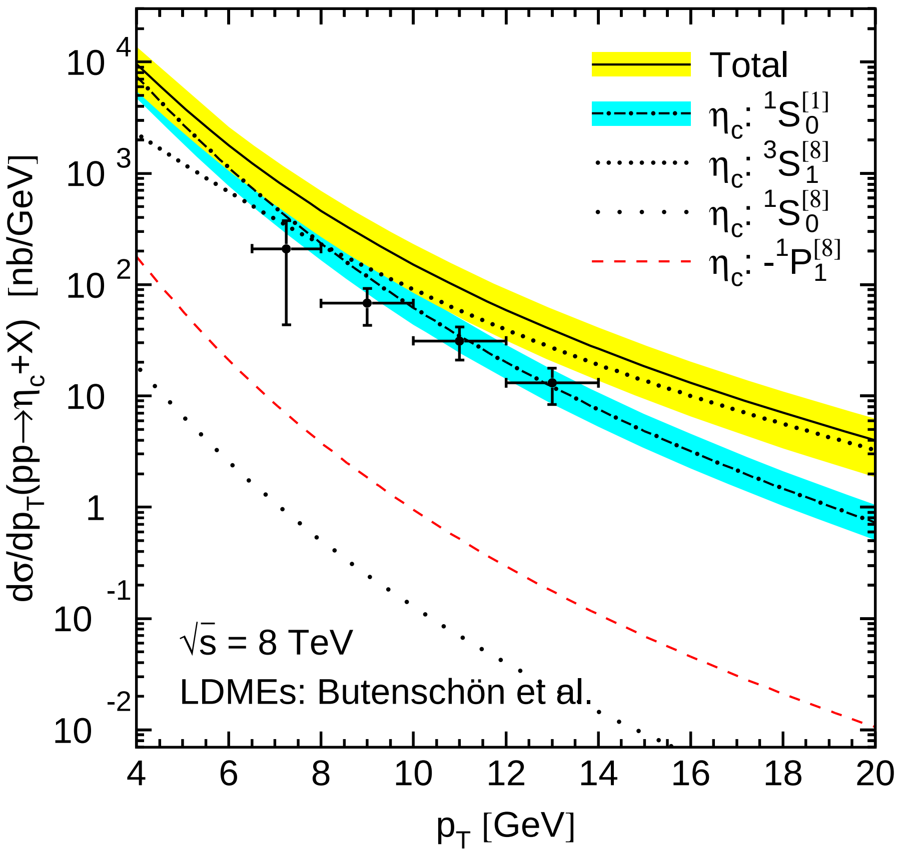


- Additional LP-fragmentation corrections beyond NLO are small.
- The p_T of the highest measured point is only about 8 GeV.
  Maybe too small for NRQCD factorization to hold.
- But theory and data are not trending toward each other as p_T increases.

η_c Production at LHCb

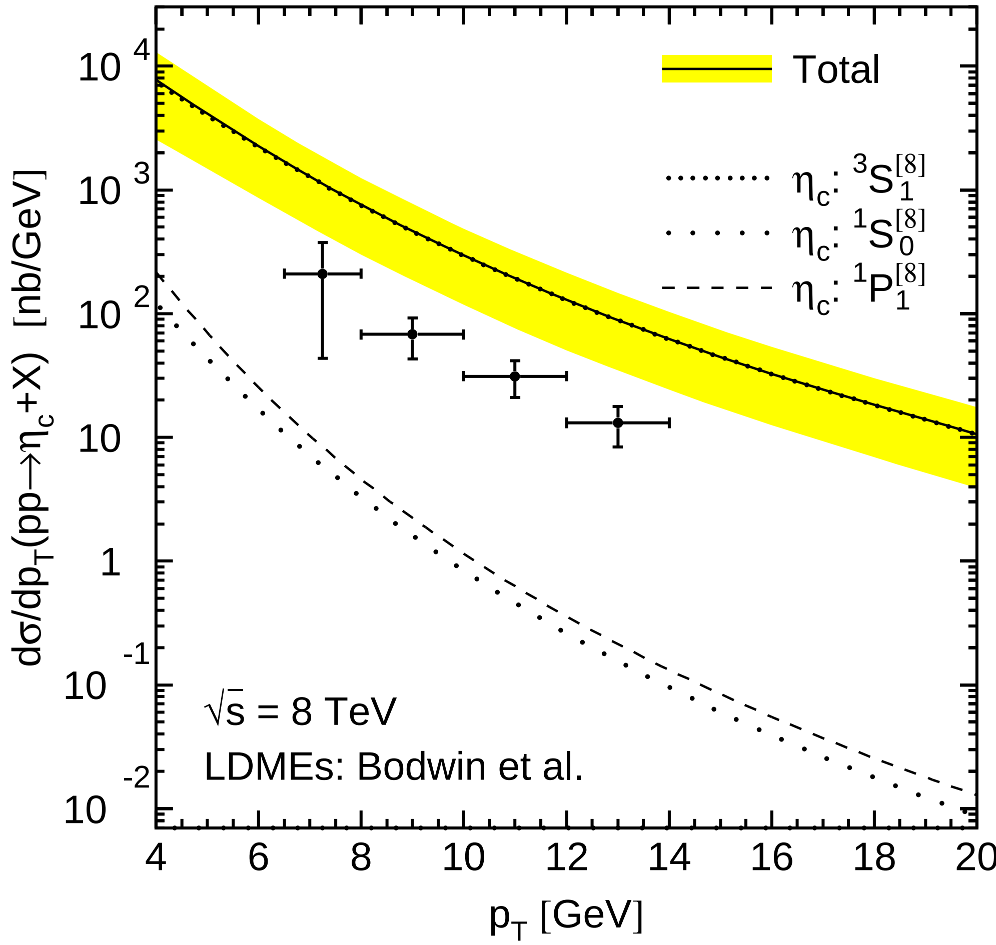
Butenschön and Kniehl (2014)

- The NLO prediction for the η_c cross section overshoots the LHCb (2014) measurement by a factor of about 6.



- The η_c LDMEs are fixed by using the heavy-quark spin symmetry of NRQCD to relate them to the J/ψ LDMEs.
  Good up to corrections of relative order v^2.
- The color-singlet contribution alone accounts for the measured cross section.

- Use of the Bodwin *et al.* LDMEs from LP+NLO fits to the J/ψ cross-section makes the situation worse.

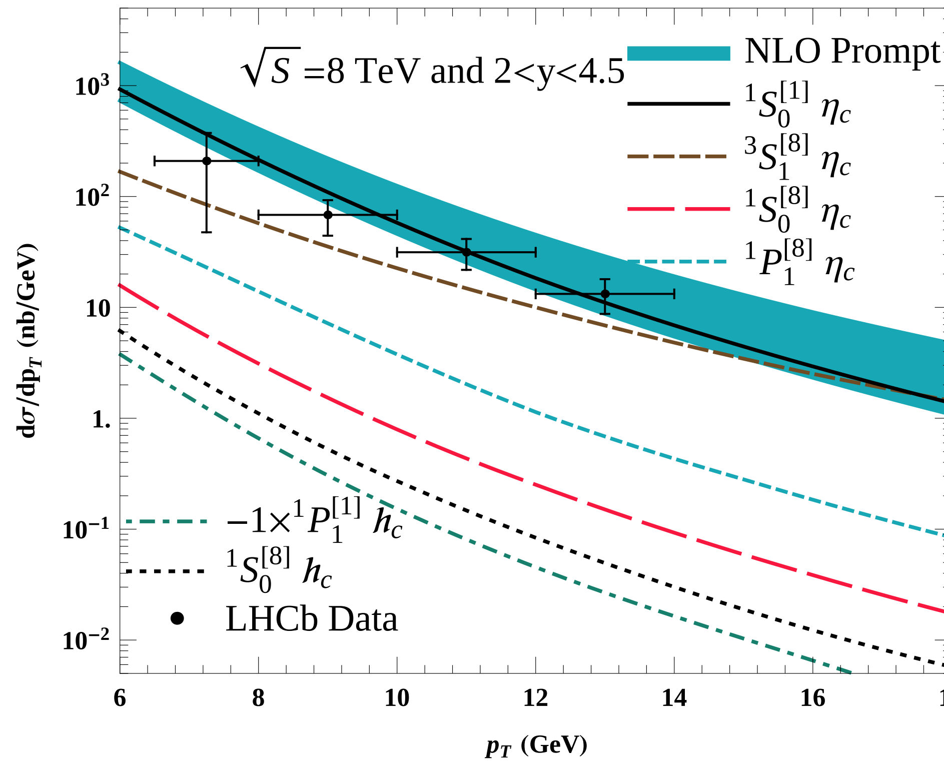


Han, Ma, Meng, Shao, Chao (PKU Group) (2014)

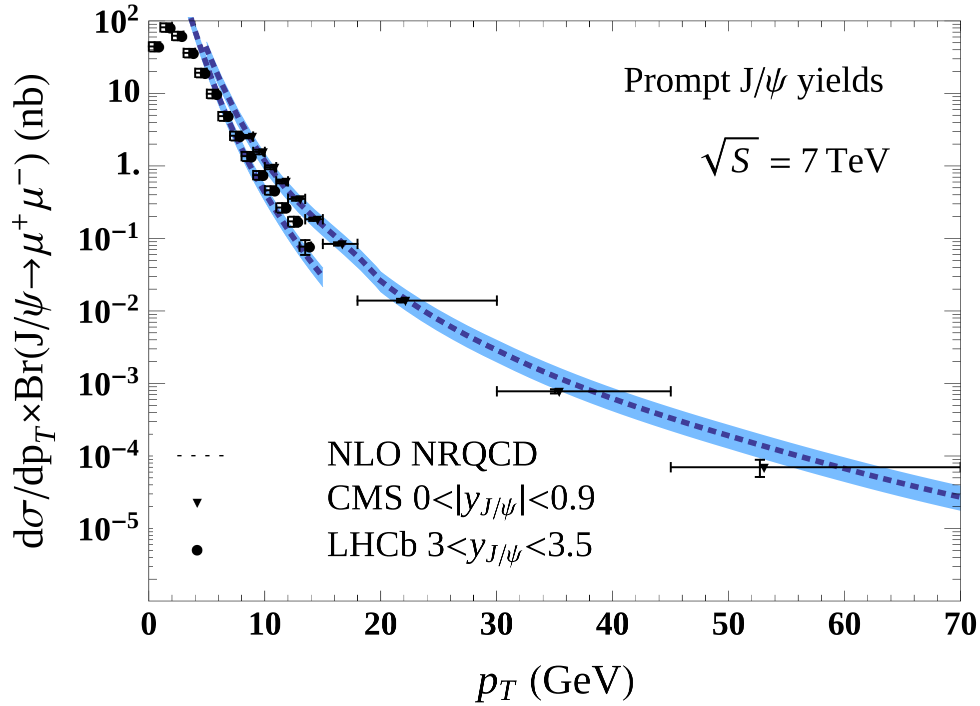
- Apply an additional constraint to the PKU 2010 LDME fit:

$$0 < \langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}\rangle < 0.0146 \text{ GeV}^3 \quad \Longrightarrow \quad 0 < \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}\rangle < 0.0146 \text{ GeV}^3$$

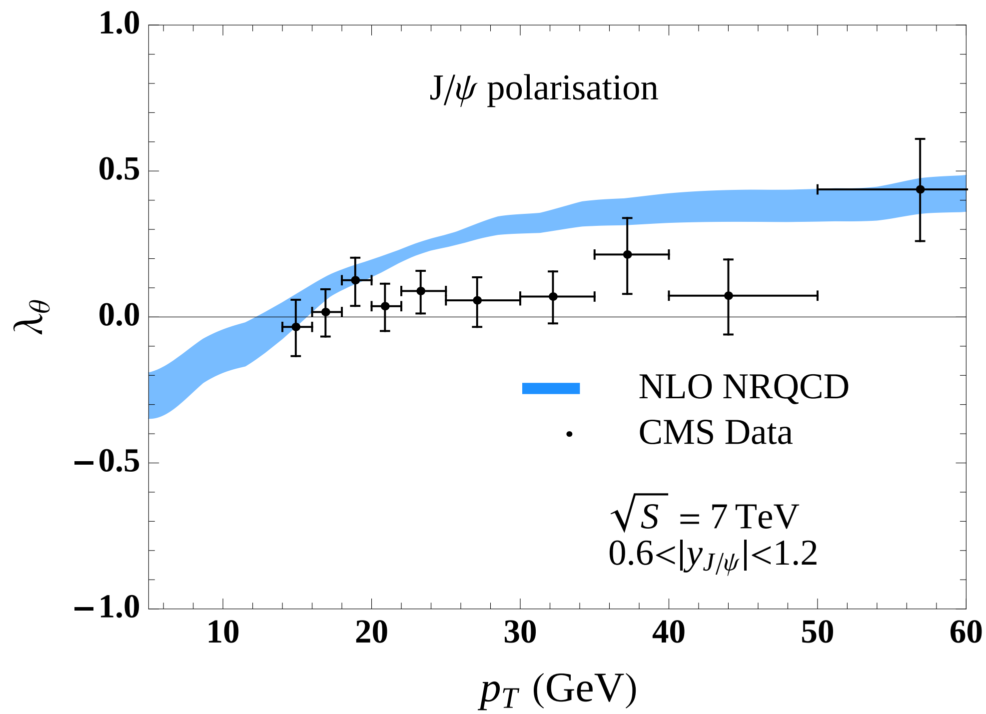
- They obtain reasonable agreement with the η_c cross-section data.



- The fit to the J/ψ cross-section data is still reasonable, as well.



- However, there is tension between the data and the prediction for the J/ψ polarization.



A Possible Weakness in the Measurement

- LHCb measures the relative rates of the η_c and J/ψ in the $p\bar{p}$ channel.
- $\mathrm{BF}(\eta_c \to p\bar{p})$ is determined from a global fit to BFs that has a very poor $\chi^2/\mathrm{d.o.f.}$
- Direct measurements of $\mathrm{BF}(\eta_c \to p\bar{p})$ have large uncertainties.
- A 2σ deviation to the low side would boost the cross section by a factor 3.

Conclusions and Outlook

- Theoretical predictions for quarkonium production have undergone a major transformation in recent years.
  LO $\Rightarrow$ NLO $\Rightarrow$ LP+NLO $\Rightarrow$ LP+NLP+NLO ??
- Much of this transformation has been driven by high-quality collider measurements.
- The J/ψ hadroproduction cross sections and polarization are now well described by theory.
- However, important discrepancies between theory and experiment remain.
  - J/ψ photoproduction
  - η_c hadroproduction

What do we need from theory?

- NLO calculations for more processes
  - double-charmonium production
  - $J/\psi + Z$, $J/\psi + W^{\pm}$
  - $J/\psi +$ jet
- LP and NLP calculations for more processes
- New ideas for additional experimental tests of theory
- A proof or disproof of NRQCD factorization

What do we need from experiment?

- Check of the η_c cross-section measurement
- Measurements at the highest accessible values of p_T in order to minimize effects of non-factorizing contributions
- Measurements of direct-production cross sections and polarizations in order avoid confusion from feeddown effects
- Measurements of χ_{cJ} cross sections and polarizations
  - Particularly interesting because only one LDME must be determined from phenomenology.
  - Initial cross-section measurements show good agreement between theory and experiment, but uncertainties are still large.
  - The color-singlet LDME from fits to experiment agrees well with potential-model values:
    Suggests that NRQCD factorization is working.

- Measurements of $\Upsilon(nS)$ and $\chi_b(nP)$ cross sections and polarizations at higher precision and higher p_T (some measurements already exist)
  Tests NRQCD in a new regime in which v^2 is much smaller than for charmonium systems.
  - The v expansion should work much better for $\Upsilon(nS)$ than for J/ψ.
  - Different v^2 may mean different relative sizes of LDMEs.

  Non-factorizing contributions may be suppressed only at $p_T \gg m_\Upsilon$.
- Measurements of additional production processes
  - double-charmonium production
  - $J/\psi + Z$, $J/\psi + W^\pm$
  - $J/\psi +$ jet

Outlook

- Thanks to the interplay between theory and experiment, we have come a long way in understanding quarkonium production.
- We are not yet at the end of the story.

Backup Slides

- The current phenomenology of production of P-wave quarkonia (χ_{cJ}) makes use of LDMEs through relative order v^4:

$$\langle \mathcal{O}^H({}^3P_J^{[1]}) \rangle \quad (O(v^4)),$$
$$\langle \mathcal{O}^H({}^3S_1^{[8]}) \rangle \quad (O(v^4)).$$

  – The $\langle \mathcal{O}^H({}^3P_J^{[1]}) \rangle$ ($J = 0, 1, 2$) are related by the heavy-quark spin symmetry. They can be determined from potential models.

  – Only one LDME ($\langle \mathcal{O}^H({}^3S_1^{[8]}) \rangle$) has to be determined from phenomenology.

Why isn't the CSM a viable description of production?

- The CSM is theoretically inconsistent.
  - Uncanceled infrared divergences at leading order in v for production of P-wave states and at higher orders in v for other states.
- The CSM predictions in NLO fall well below the observed cross sections.

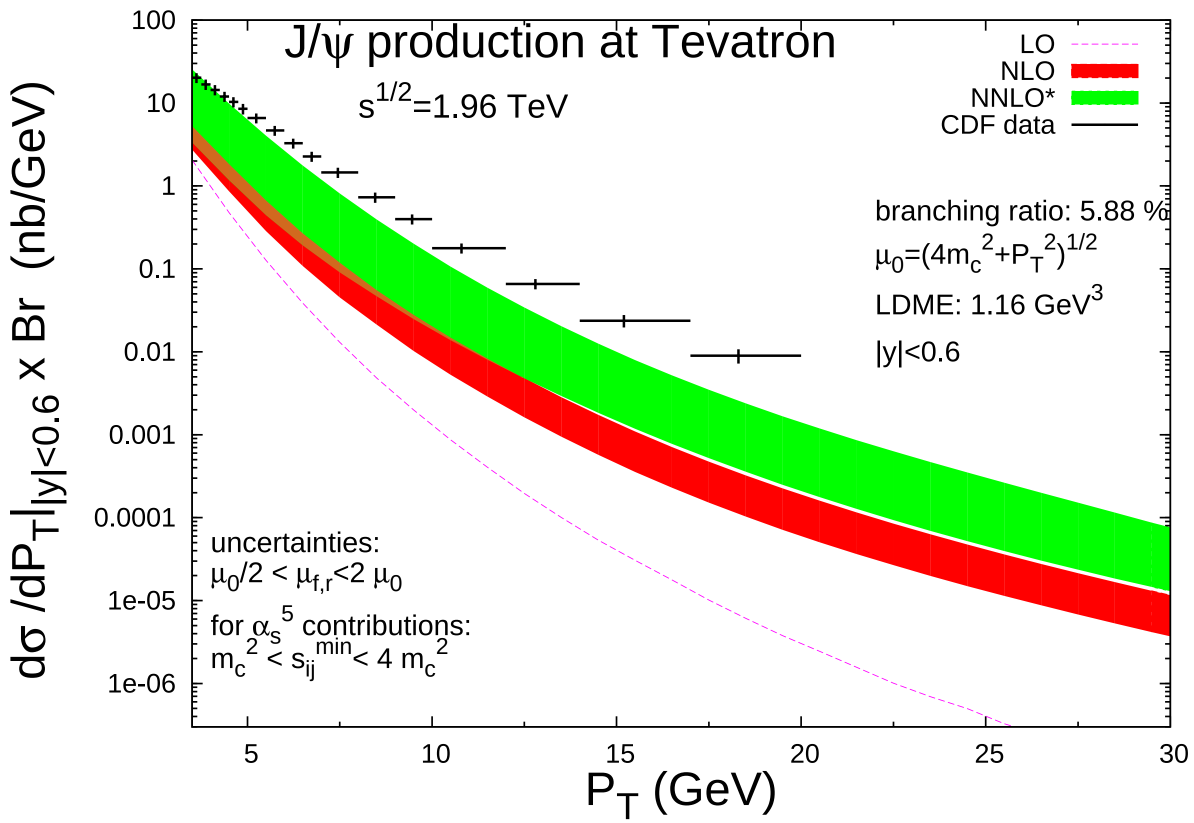
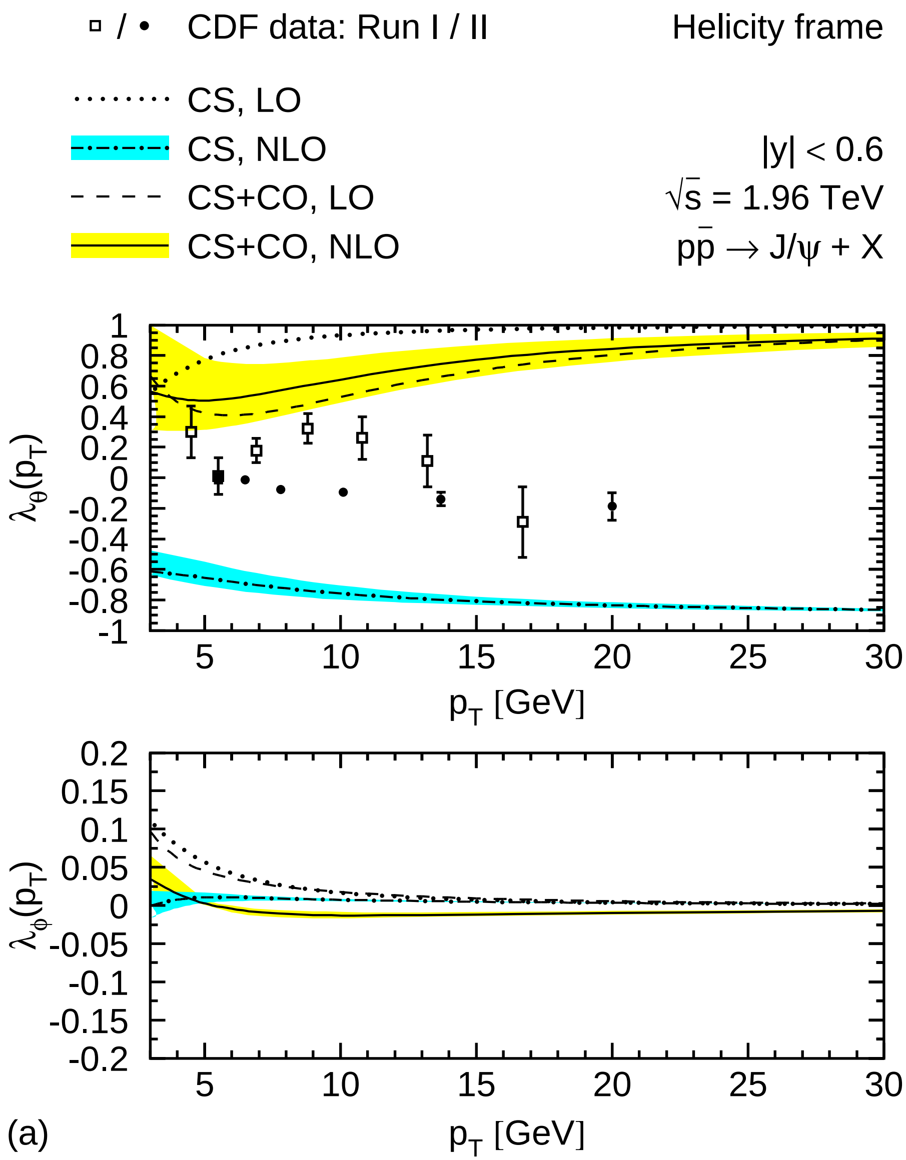


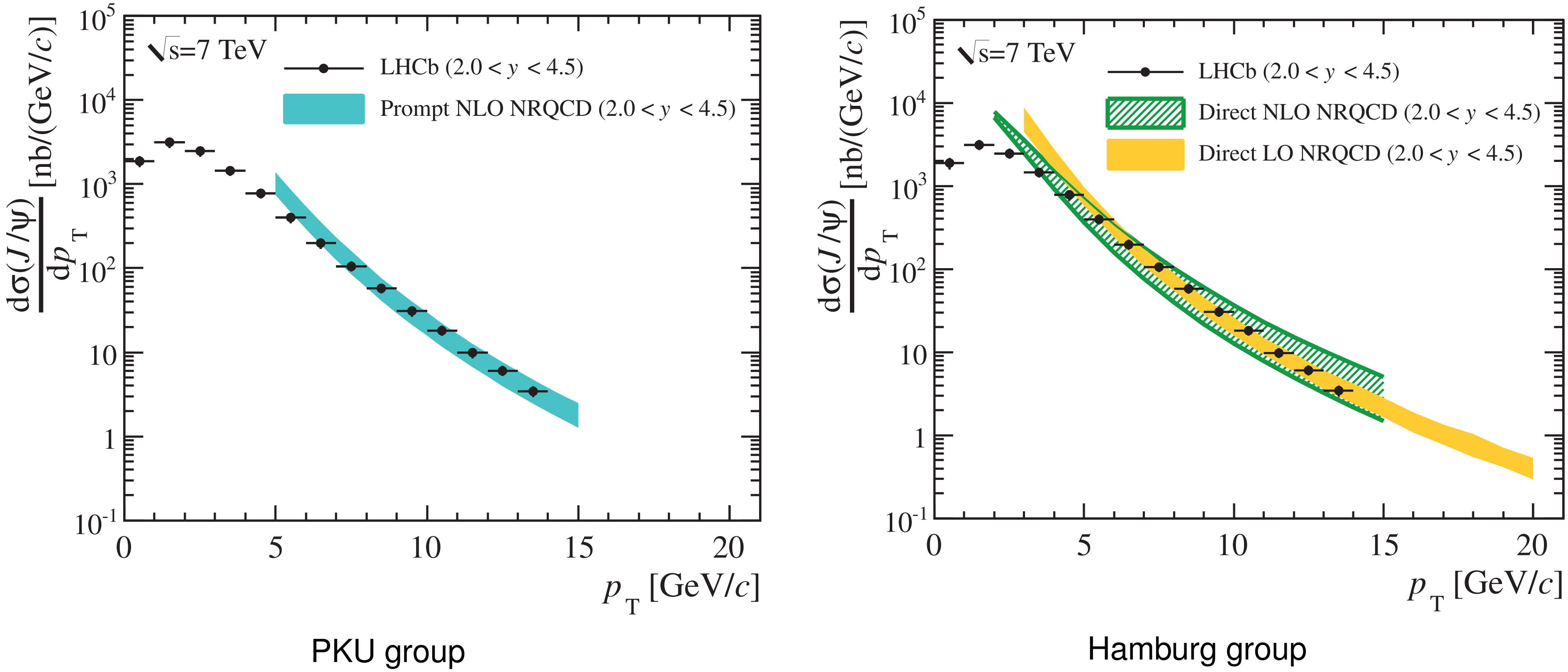
Figure courtesy of Pierre Artoisenet.

- The NNLO* calculation is an estimate based on real-emission contributions only.
- When the virtual contributions are added, the true NNLO contribution will likely be smaller.

- The CSM predictions in NLO do not describe the polarization data.



- There is also a slight discrepancy in shape between the LHCb data and the Hamburg-group (2010) NLO fit to the Tevatron and HERA data.



Why isn't the CEM viable as a description of production?

- The Color Evaporation Model (CEM) says that rate to produce a quarkonium is proportional to the rate to produce a $Q\bar{Q}$ pair, regardless of the quantum numbers of the $Q\bar{Q}$ pair or the quarkonium.
  - Not plausible in quantum field theory: Different $Q\bar{Q}$ states will have different overlaps with a given quarkonium state.
- The CEM requires an *ad hoc* modification, k_T smearing, in order to describe the data reasonably well.
- Nevertheless, because of its simplicity, the CEM is a useful way to describe production when a fundamental theory is not necessary, *e.g.* in studies of production in media.

Why isn't the k_T-Factorization Approach getting more attention?

- The k_T-Factorization Approach could, in principle, yield valid results. But...
- it relies on k_T-dependent parton distributions, which are poorly determined;
- calculations are usually carried out within the CSM;
- calculations are usually carried out only in LO.

$e^+e^- \to J/\psi + X(\text{non-}c\bar{c})$

- Belle (2009):

$$\sigma(e^+e^- \to J/\psi + X(\text{non-}c\bar{c})) = 0.43 \pm 0.09 \pm 0.09 \text{ pb}.$$

- NLO calculation (Zhang, Ma, Wang, Chao (2009), Butenschön and Kniehl (2011)):

$$\sigma(e^+e^- \to J/\psi + X(\text{non-}c\bar{c})) = 0.99^{+0.35}_{-0.17} \text{ pb} \qquad (\mu = \sqrt{s}/2).$$

  – NRQCD LDMEs from the Butenschön-Kniehl (2011) global fit.
  – Includes feeddown estimate of 0.29 pb from Zhang, Ma, Wang, Chao (2009).

- The comparison with the Belle data favors the Butenschön-Kniehl value of M_{0,r_0}.

Comments

- The most recent Belle (2009) measurements give

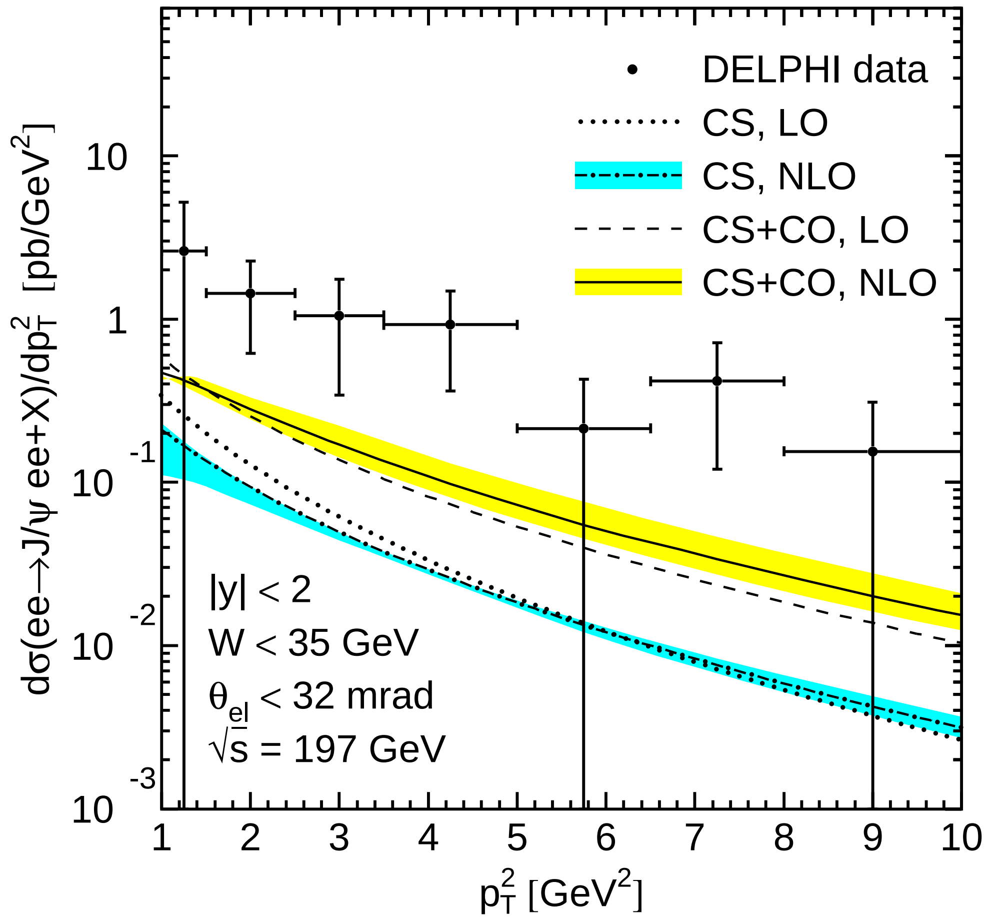
$$\begin{aligned}\sigma(e^+e^- \to J/\psi + X) &= \sigma(e^+e^- \to J/\psi + c\bar{c} + X) + \sigma(e^+e^- \to J/\psi + X(\text{non-}c\bar{c})) \\ &= 1.17 \pm 0.12^{+0.13}_{-0.12} \text{ pb}.\end{aligned}$$

- However, BaBar (2001) obtained

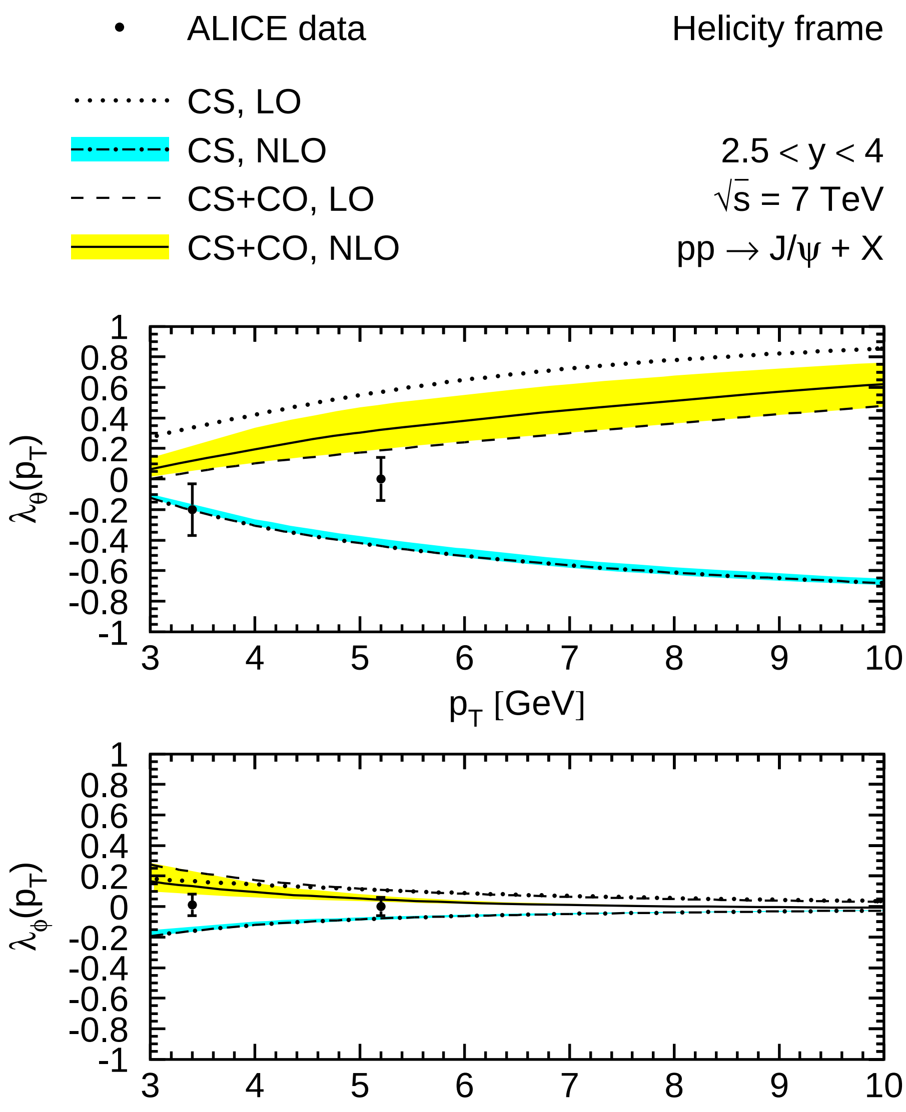
$$\sigma(e^+e^- \to J/\psi + X) = 2.52 \pm 0.21 \pm 0.21 \text{ pb.}$$

- Most of the data are at $p_T \lesssim 3$ GeV. Does factorization hold at such small values of p_T?

J/ψ Production in $\gamma\gamma$ Scattering at LEP II



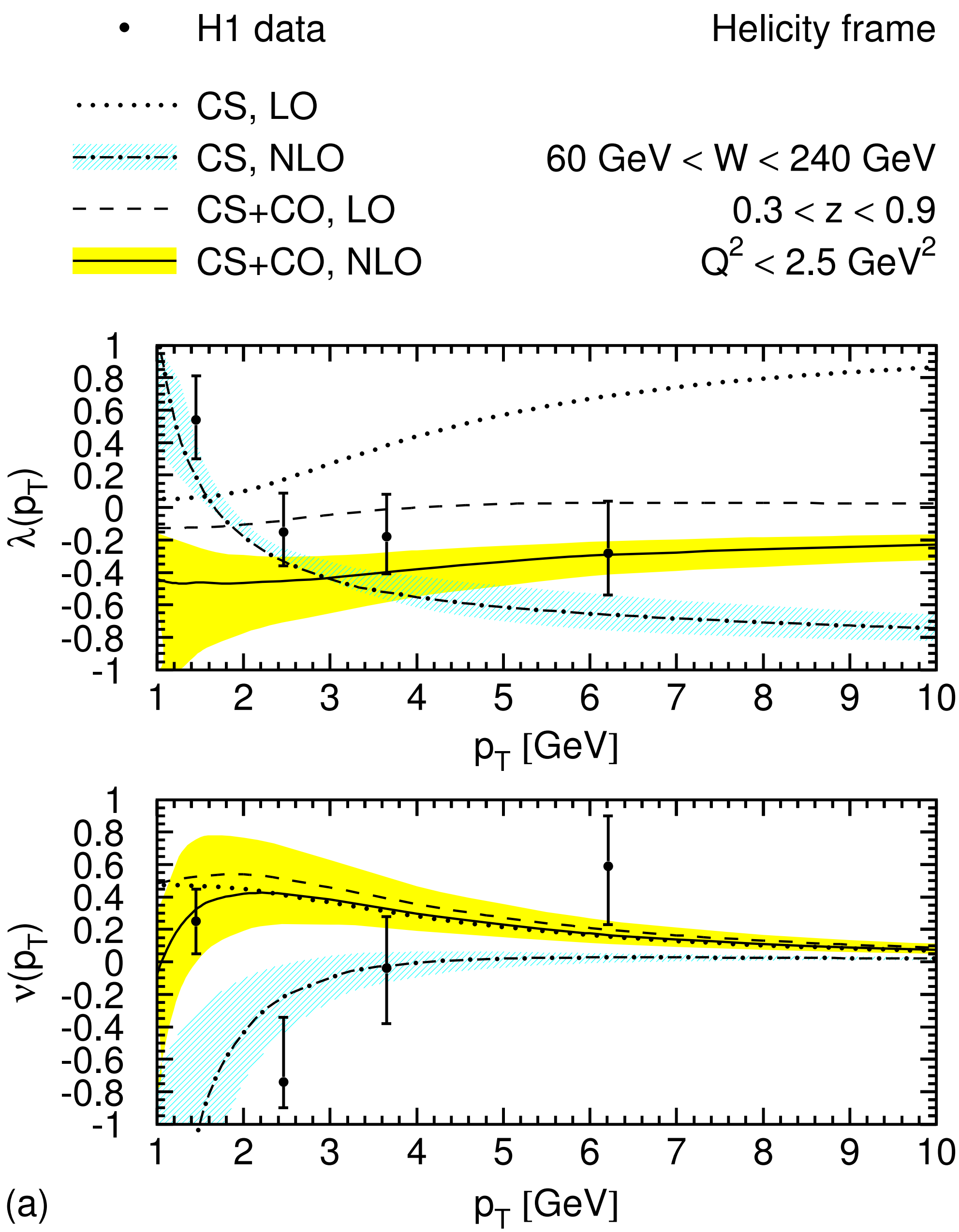
- The DELPHI (2003) data are slightly incompatible with the prediction of the Butenschön and Kniehl (2011) global fit.
- The error bars are large, especially at high p_T.
- Factorization may not hold at low values of p_T.



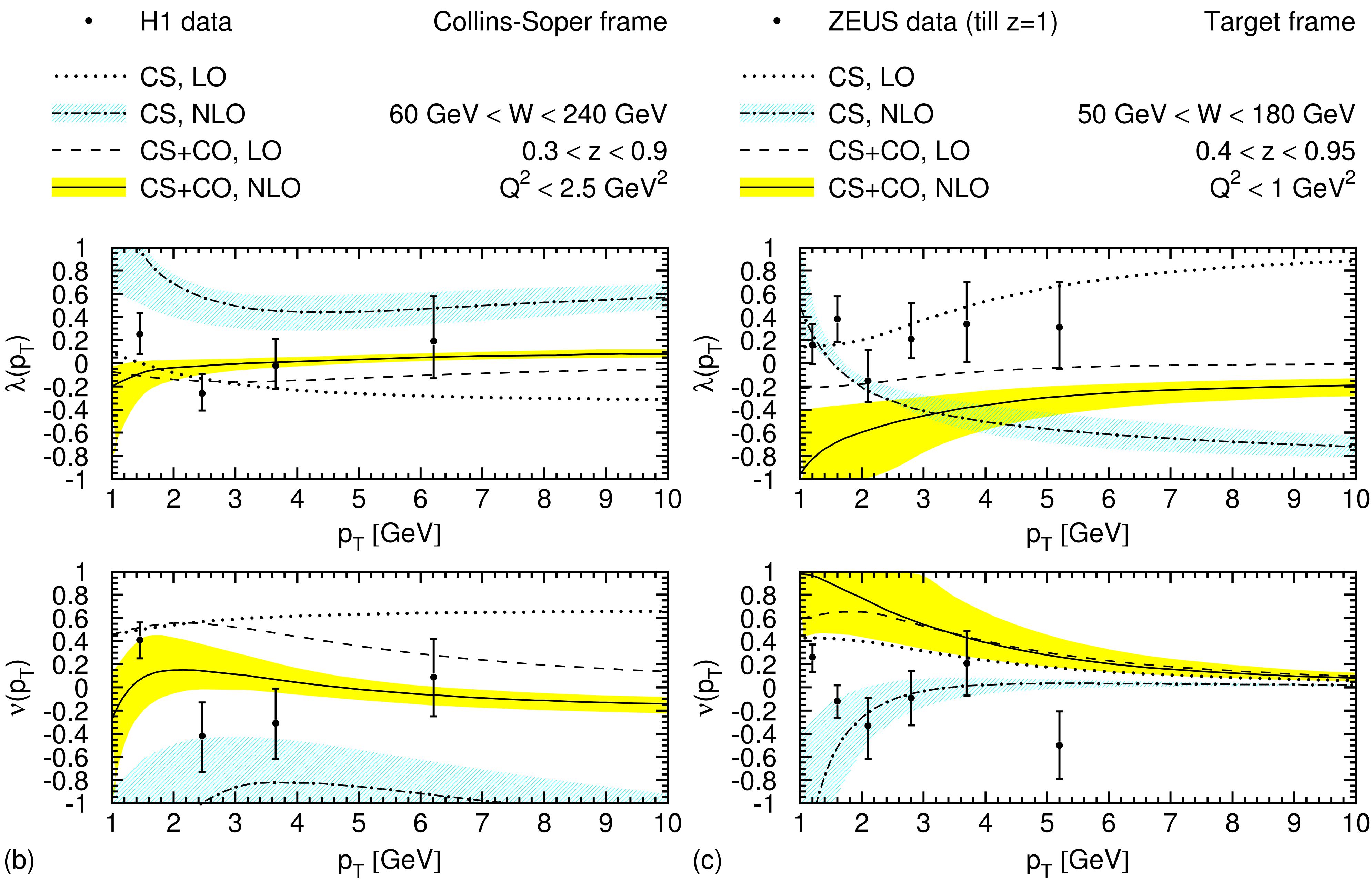
(b)

- The prediction from the Butenschön and Kniehl (2011) global fit is in agreement with the ALICE (2012) data.
- But the theory is for direct production, while the ALICE data includes production in B-meson decays and feed-down from χ_{cJ} states and the $\psi(2S)$.

- The Butenschön and Kniehl (2011) global fit can also be used to predict the polarization in inelastic J/ψ photoproduction at HERA.



- The data are roughly compatible with the theory at large p_T, but the error bars are large.



H1 data
Collins-Soper frame
CS, LO
CS, NLO
60 GeV < W < 240 GeV
CS+CO, LO
0.3 < z < 0.9
CS+CO, NLO
Q^2 < 2.5 GeV^2
ZEUS data (till z=1)
Target frame
CS, LO
CS, NLO
50 GeV < W < 180 GeV
CS+CO, LO
0.4 < z < 0.95
CS+CO, NLO
Q^2 < 1 GeV^2
λ(p_T)
ν(p_T)
p_T [GeV]
(b)
(c)