J/ψ plus W or Z Production: Consequences for NLO LDME Fits [arXiv: 2207.09366]

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1. New Results for pp $\longrightarrow J/\psi$ + W or Z
2. NLO Fits of NRQCD: State After new Results

1.1 Quarkonium Production within NRQCD

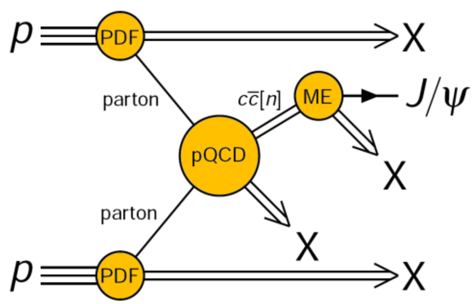
- Quarkonium production candidate theory: **Nonrelativistic QCD (NRQCD)**
  - Effective field theory based on **scale hierarchy** $Mv^2 \ll Mv \approx \Lambda_{QCD} \ll M$
- **Factorization theorem:** $$\sigma_H = \sum_n \sigma_{Q\bar{Q}[n]} \cdot \langle O^H[n] \rangle$$
  - $\boldsymbol{n}$: Every possible Fock state, including color-octet (CO) states
  - $\boldsymbol{\sigma_{Q\bar{Q}[n]}}$: Production rate of $Q\bar{Q}[n]$, calculated in perturbative QCD
  - $\boldsymbol{\langle O^H[n] \rangle}$: Nonperturbative long distance matrix elements (**LDMEs**): Describe $Q\bar{Q}[n] \to H$, supposedly universal, taken from fits to data
- **Scaling rules** (here $H = J/\psi$):

Scaling	v^3	v^7 ("CO states")	v^{11}
n	${}^3S_1^{[1]}$	${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$	$\ldots$

  - Double expansion in α_s und v
  - Leading term in v expansion (${}^3S_1^{[1]}$) equals Color-Singlet Model
- Key test for NRQCD factorization: **Are the LDMEs universal?**

1.2 The NRQCD Calculations

- **Factorization formulas** (here J/ψ hadroproduction):



- **Convolute partonic cross section with PDFs:**

$$\sigma_{\text{hadr}} = \sum_{i,j} \int dx\, dy\, f_{i/p}(x)\, f_{j/p}(y) \cdot \sigma_{\text{part,i,j}}$$

- **NRQCD factorization:**

$$\sigma_{\text{part,i,j}} = \sum_{n} \sigma(ij \to c\bar{c}[n] + X) \cdot \langle O^{J/\psi}[n] \rangle$$

- Amplitudes for $Q\bar{Q}[n]$ production by **projector** application, e.g.

$$A_{Q\bar{Q}[^3S_1^{[1/8]}]} = \varepsilon_\alpha \mathrm{Tr}\left[C\,\Pi^\alpha A_{Q\bar{Q}}\right]\big|_{q=0}$$

$$A_{Q\bar{Q}[^3P_J^{[1/8]}]} = \varepsilon_{\alpha\beta}\, \frac{d}{dq_\beta} \mathrm{Tr}\left[C\,\Pi^\alpha A_{Q\bar{Q}}\right]\big|_{q=0}$$

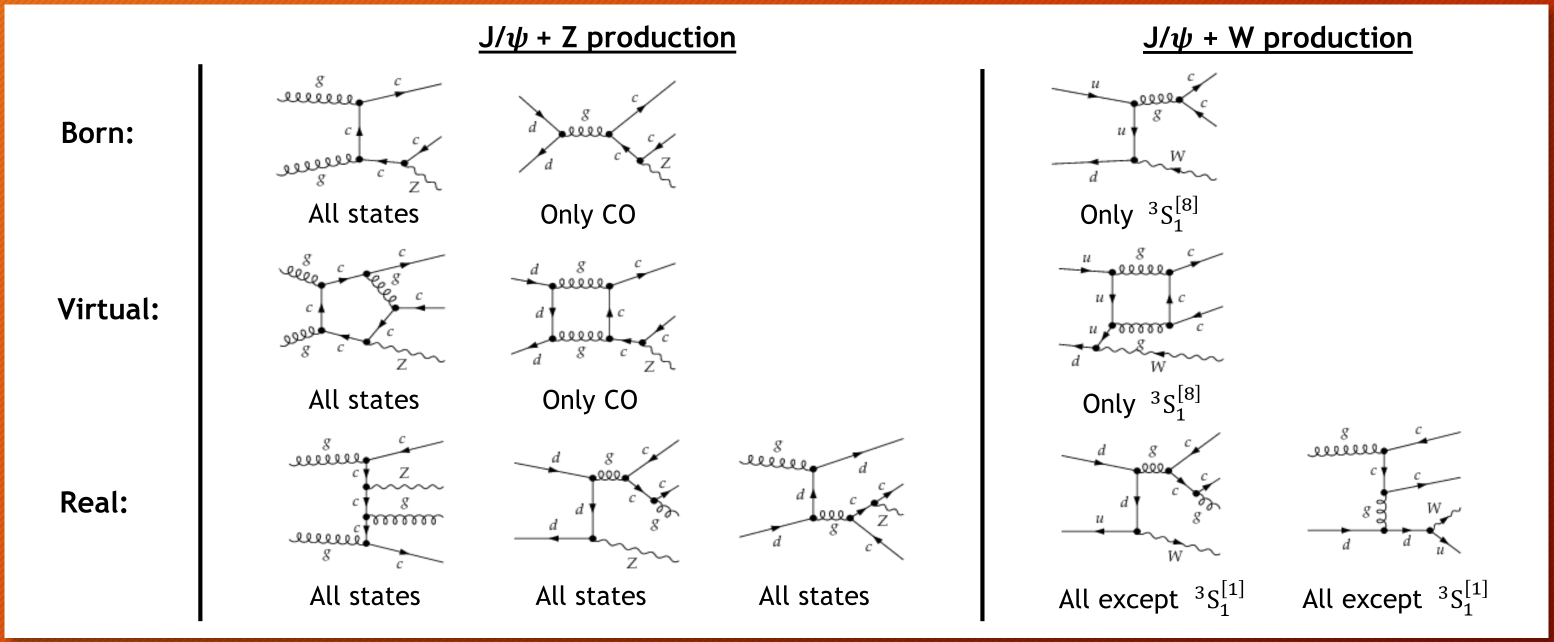
Derivatives $\Longrightarrow$ Larger expressions,
higher propagator powers,
non-standard IR singularity structure.

  - $A_{Q\bar{Q}}$: Amputated pQCD amplitude for open $Q\bar{Q}$ production
  - q: Relative momentum between Q and $\bar{Q}$
  - ϵ: Quarkonium polarization vectors

1.3 pp $\longrightarrow$ J/ψ + W or Z

- **Experimental data:**
  - $pp \longrightarrow J/\psi + W^{\pm} + X$ [ATLAS (2014); ATLAS (2020)]
  - $pp \longrightarrow J/\psi + Z + X$ [ATLAS (2015)]
- **Born** calculations: [Kniehl, Palisoc, Zwirner (2002)]
  - Additional contrib. in $c\bar{c}[\,^3S_1^{[1]}] + W^{\pm}$ [Lansberg, Lorcé (2013)]
- Previous **NLO** calculations:
  - $pp \longrightarrow c\bar{c}[\,^1S_0^{[8]}, \,^3S_1^{[8]}, \,^3P_J^{[8]}] + W^{\pm} + X$ [Li, Song, Zhang, Ma (2011)]
  - $pp \longrightarrow c\bar{c}[\,^3S_1^{[1]}, \,^3S_1^{[8]}] + Z + X$ [Song, Ma, Li, Zhang, Guo (2011)]
  - $pp \longrightarrow c\bar{c}[\,^3S_1^{[1]}] + Z + X$ (+polarization) [Gong, Lansberg, Lorcé, Wang (2013)]
- **This Work:** Analysis with missing channels (also ψ(2S) and χ_{cJ} feeddown)
  - $pp \longrightarrow c\bar{c}[\,^1S_0^{[8]}, \,^3P_J^{[8]}, \,^3P_J^{[1]}] + Z + X$ at NLO
  - $pp \longrightarrow c\bar{c}[\,^3P_J^{[1]}] + W^{\pm} + X$ at NLO
- **Most complex** NLO NRQCD calculation so far, because ***P* state virtual corrections** and **additional *W*/*Z* mass scale.**

1.4 Contributions and Example Diagrams



- $\mathrm{J}/\psi + W^{\pm}$: At LO only $^3S_1^{[8]}$, and $^3S_1^{[1]}$ not even at NLO:
  - **Much simpler** to calculate than $\mathrm{J}/\psi + \mathrm{Z}$ (No *P* state virtual corrections)
  - Caution: Formally NLO, but actually LO?
    For $^3S_1^{[1]}$ not even leading contributions considered.

1.5 Organization of the NLO Calculation

Diagram generation with FeynArts

FORM and Mathematica: Treat squared amplitudes

Two Methods for Virtual Corrections:

FORM: Our generalization of Passarino-Veltman reduction ⟶ Scalar integrals

FORM/AIR: IBP ⟶ Master integrals

FORM/AIR: Cancel scalar products by denominators and directly apply IBP

Mathematica script: Simplification (few GB ⟶ few MB)

Two Methods for Cross Section Evaluation:

Phase space slicing implementation

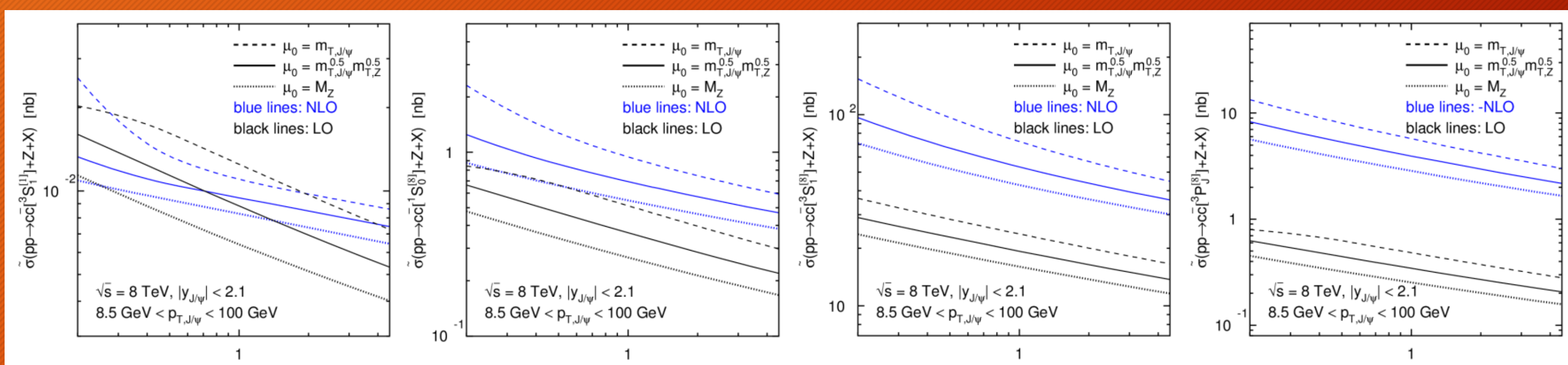
Dipole subtraction building on Catani/Seymour and Phaf/Weinzierl

- *New*: Structure of singularities for bound states
- *New*: Additional dipoles for P states

[MB, Kniehl: NPB 905 (2020) 114843, NPB 957 (2020) 115056]

1.6 Scale Choices

- **Renormalization** and **factorization** scale μ_r and μ_f choices:
  1. $\mu_r = \mu_f = m_{T,J/\psi}$ [Song, Ma, Li, Zhang, Guo (2011)]
  2. $\mu_r = \mu_f = \sqrt{m_{T,J/\psi} m_{T,W/Z}}$ [Kniehl, Palisoc, Zwirner (2002)]
  3. $\mu_r = \mu_f = M_{W/Z}$ [Gong, Lansberg, Lorcé, Wang (2013)]



- $M_{W/Z}$ and $\sqrt{m_{T,J/\psi} m_{T,W/Z}}$: Smaller NLO scale dependence compared to $m_{T,J/\psi}$.
- $m_{T,J/\psi}$ and $\sqrt{m_{T,J/\psi} m_{T,W/Z}}$: Particularly small K factor in $c\bar{c}[\,^3S_1^{[1]}] + Z$.

⇨ Use $\mu_r = \mu_f = \sqrt{m_{T,J/\psi} m_{T,W/Z}}$, but **vary scales by factor 4** up and down.

1.7 Double Parton Scattering

- We calculate single parton scattering (SPS).
  But J/ψ and W/Z may originate from **different partonic interactions**
  $\Longrightarrow$ **Double parton scattering** (DPS)
- Usual DPS model: The two partonic interactions are independent, double parton PDFs factorize into single parton PDFs.

$\Longrightarrow$ **Pocket formula:** $\sigma_{DPS} = \frac{\sigma_{J/\psi}\sigma_{W/Z}}{\sigma_{\text{eff}}}$ with σ_{eff} universal „effective scattering area“

- In ATLAS J/ψ + W or Z papers: DPS contributions estimated using $\sigma_{\text{eff}} = 15^{+5,8}_{-4,2}$ mb from ATLAS W + 2 jet measurement:

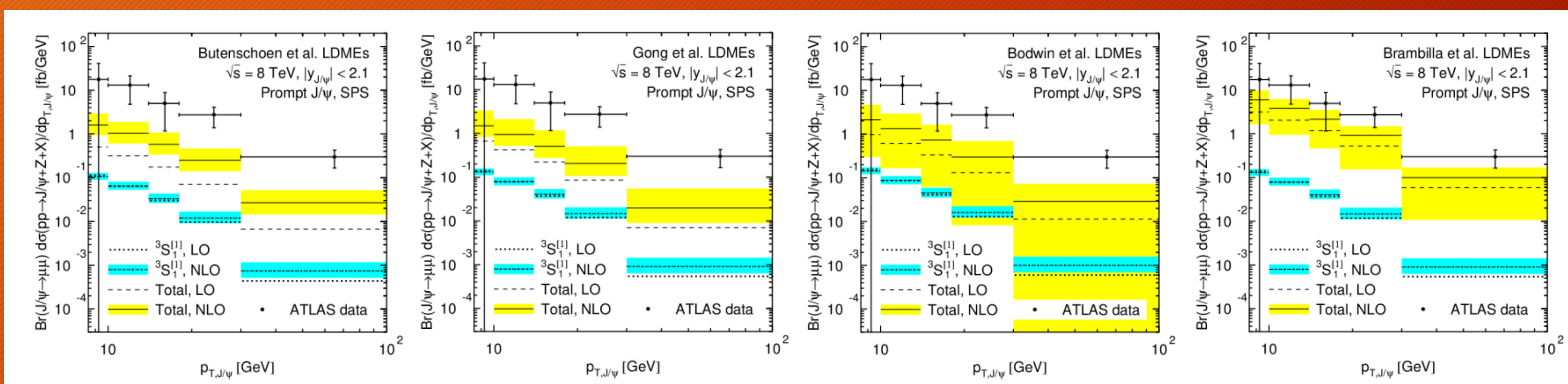
Table 5 The inclusive (SPS + DPS) cross-section ratio $\mathrm{d}R^{\text{incl}}_{Z+J/\psi}/\mathrm{d}p_{\mathrm{T}}$ for prompt and non-prompt J/ψ. Estimated DPS contributions for each bin, based on the assumptions made in this study, are presented

$p_{\mathrm{T}}^{J/\psi}$ (GeV)	Inclusive prompt ratio ($\times 10^{-7}$/ GeV) value $\pm$ (stat) $\pm$ (syst) $\pm$ (spin)			Estimated DPS ($\times 10^{-7}$/ GeV) assuming $\sigma_{\text{eff}} = 15$ mb
(8.5, 10)	10.8 ± 5.6	± 1.9	± 3.1	5.5 ± 2.1
(10, 14)	5.6 ± 1.9	± 0.8	± 1.2	1.7 ± 0.6
(14, 18)	1.9 ± 1.1	± 0.1	± 0.3	0.4 ± 0.1
(18, 30)	0.87 ± 0.37	± 0.12	± 0.09	0.05 ± 0.02
(30, 100)	0.090 ± 0.037	± 0.012	± 0.006	0.0004 ± 0.0002

- We compare to **DPS subtracted data.**
- **Minor role of DPS** supported by measurement of **angular distribution $\Delta\phi$**
  (SPS: Peak at back-to-back,
  DPS: Random distribution)

1.8 Results for J/ψ + Z

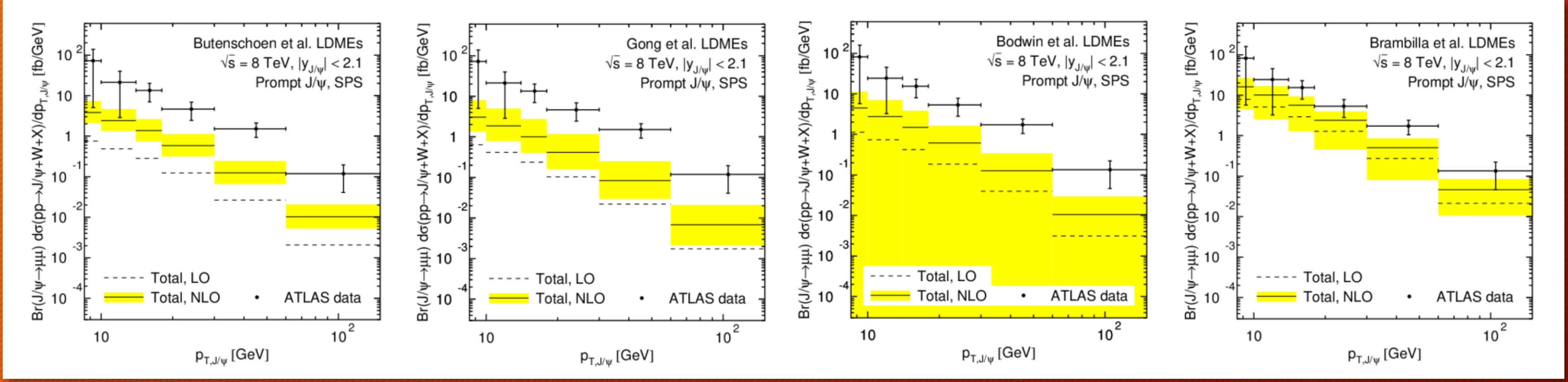
- Predictions using different LDME sets. **Uncertainty bands** due to
  1. Renormalization and factorization scale variation: $\frac{1}{4} < \mu_r = \mu_f < 4$
  2. NRQCD scale variation: $\frac{1}{2} < \mu_\Lambda < 2$
  3. LDME fit errors (assuming no correlations)



- ${}^3S_1^{[1]}$: LO ⟶ NLO stable. Including CO: **Reasonable *K* factors** (<6). CO important.
- **Only one** LDME set (Brambilla et al.) **reasonably compatible** with data.
- Other sets: **Factors 10 below data.** If difference due to DPS, DPS would need to be 10 times larger than SPS, contradicting physics picture and $\Delta\phi$ measurement.

1.9 Results for J/ψ + $W^{\pm}$

- **Similar picture** for J/ψ + W: (Reminder: No ${}^3S_1^{[1]}$ contributions here)

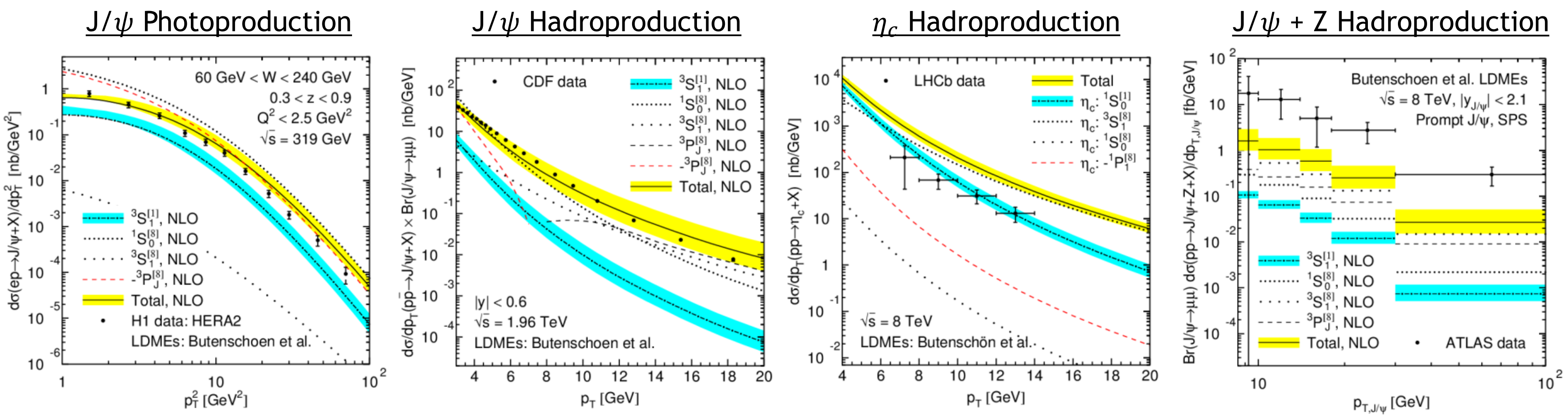


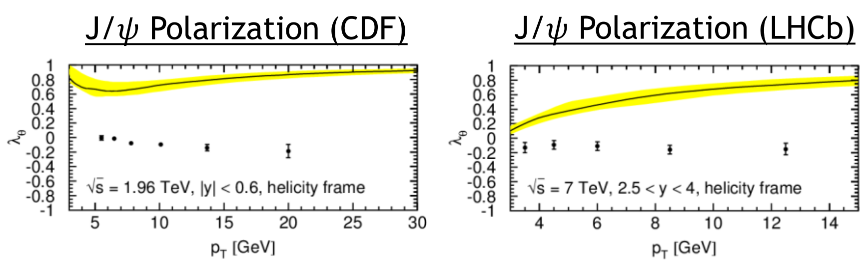
- Reasonable agreement for **Brambilla et al.** LDME set, predictions using **other** LDME sets **fall short of data** by factor 10.
- Caution: For all states except ${}^3S_1^{[8]}$, NLO is actually leading order.
  ⇨ **Large NNLO** corrections can be expected.

2.1 NLO LDME Fits

- **CS LDME $\langle O^{J/\psi}({}^3S_1^{[1]})\rangle$:** Usually not fitted, but from $\Gamma(J/\psi \longrightarrow e^+e^-)$ or potential model
- **Fitted CO LDMEs:** $\langle O^{J/\psi}({}^1S_0^{[8]})\rangle$, $\langle O^{J/\psi}({}^3S_1^{[8]})\rangle$, $\langle O^{J/\psi}({}^3P_0^{[8]})\rangle$
- Some fits consider **$\psi(2S)$, χ_{cJ} feeddown:**
  - Corresponding CS LDMEs again usually from decay rates/potential models.
  - Fit CO LDMEs $\langle O^{J/\psi}({}^1S_0^{[8]})\rangle$, $\langle O^{J/\psi}({}^3S_1^{[8]})\rangle$, $\langle O^{J/\psi}({}^3P_0^{[8]})\rangle$; $\langle O^{\chi_{c0}}({}^3S_1^{[8]})\rangle$.
- **Data fitted to:**
  - J/ψ hadroproduction with high transverse momentum p_T included in all fits.
  - Different fits include different further observables.
- In the following:
  - Take LDME sets **from 6 fits** and give predictions for: J/ψ photoproduction, hadroproduction of J/ψ (+polarization), η_c and $J/\psi + Z$. (Selection criteria: Full NLO calculations and sufficiently precise data available)
  - **η_c (h_c) LDMEs** are related to J/ψ (χ_{c0}) LDMEs via **heavy quark spin symmetry.**
  - Uncertainty bands: Only **scale variations** everywhere

2.2 Butenschön et al. LDMEs



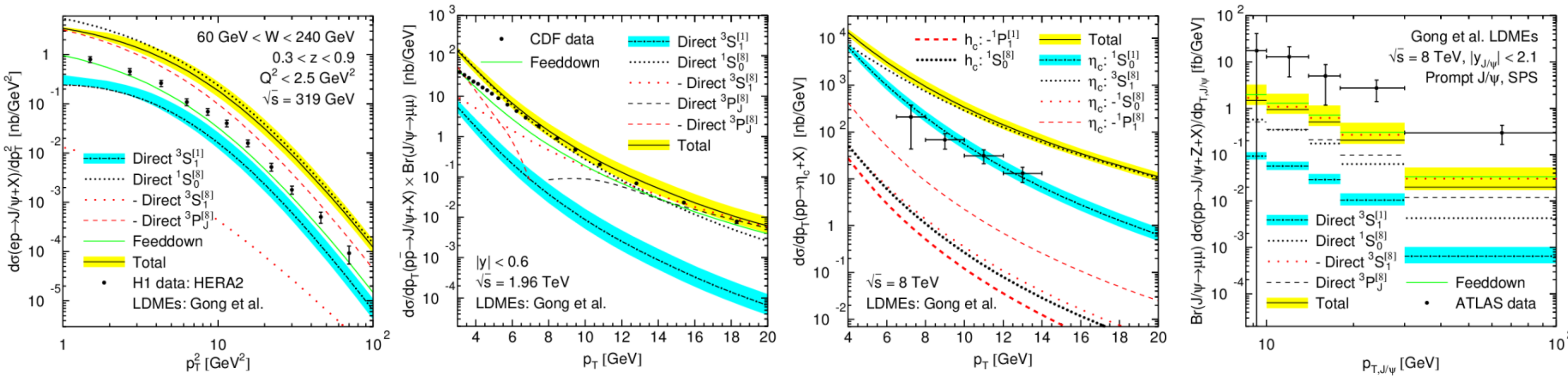


- Fit to 194 data points of J/ψ photo- and hadro-production, $\gamma\gamma$- and e^+e^- scattering
- $<O^{J/\psi}$(1S08)>=4.97$\pm$0.44, $<O^{J/\psi}$(3S18)>=0.22$\pm$0.06, $<O^{J/\psi}$(3P08)>=-1.61$\pm$0.20 [in 10^{-2} GeV^3 or 10^{-2} GeV^5]
- Ref.: [MB, Kniehl, PRD 84, 051501 (2011)]

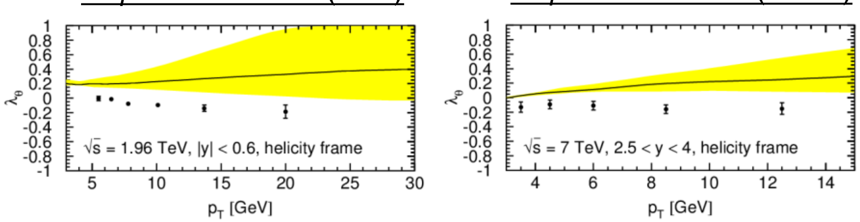
- Data fitted to is described within scale uncertainties, other observables not.

2.3 Gong et al. LDMEs

J/ψ Photoproduction · J/ψ Hadroproduction · η_c Hadroproduction · J/ψ + Z Hadroproduction



J/ψ Polarization (CDF) · J/ψ Polarization (LHCb)

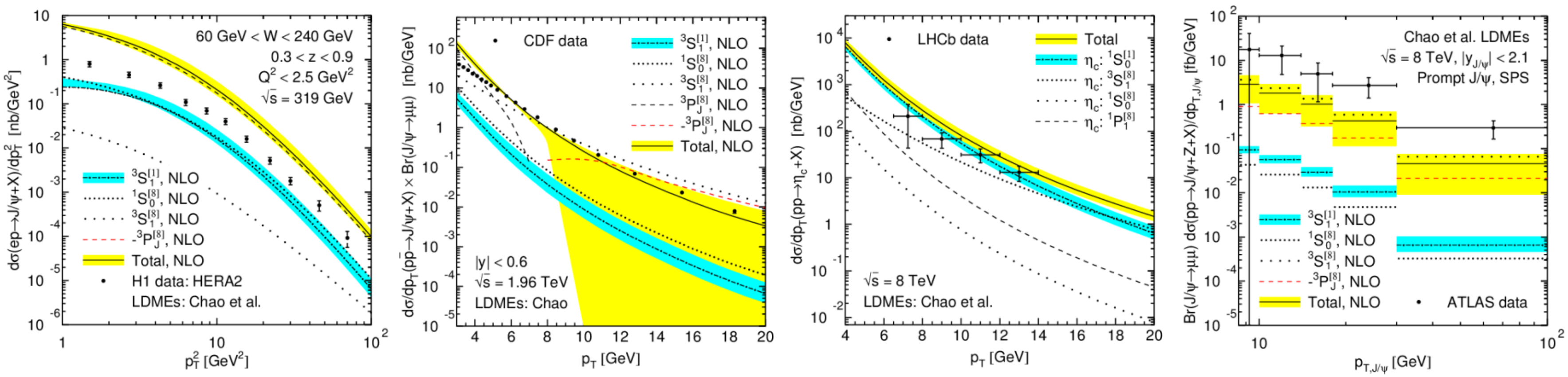


- Fit to J/ψ, ψ(2S), χ_{cJ} hadroprod. yield with $p_T > 7$ GeV.
- $<O^{J/\psi}$(1S08)>=0.97 $\pm$0.09, $<O^{J/\psi}$(3S18)>=-0.46 $\pm$0.13, $<O^{J/\psi}$(3P08)>=-2.14 $\pm$0.56, $<O^{\psi(2S)}$(1S08)>=-0.01 $\pm$0.87, $<O^{\psi(2S)}$(3S18)>=0.34 $\pm$0.12, $<O^{\psi(2S)}$(3P08)>=0.95 $\pm$0.54, $<O^{\chi_{c0}}$(3S18)>=0.22 $\pm$0.01 [in 10^{-2} GeV^3 or 10^{-2} GeV^5]
- Ref.: [Gong, Wan, Wang, Zhang, PRL 110, 042002 (2013)]

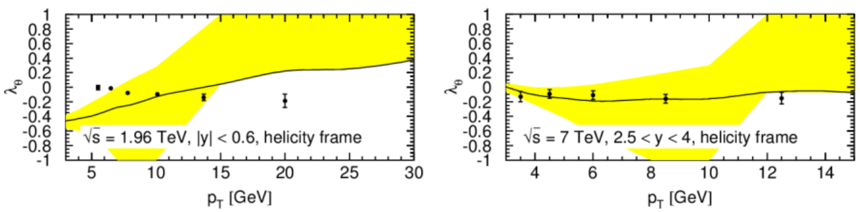
- Data fitted to is described, other observables not.
  Also: Direct $J/\psi + Z$ production unphysically negative.

2.5 Chao et al. LDMEs: With η_c

J/ψ Photoproduction | J/ψ Hadroproduction | η_c Hadroproduction | J/ψ + Z Hadroproduction



J/ψ Polarization (CDF) | J/ψ Polarization (LHCb)

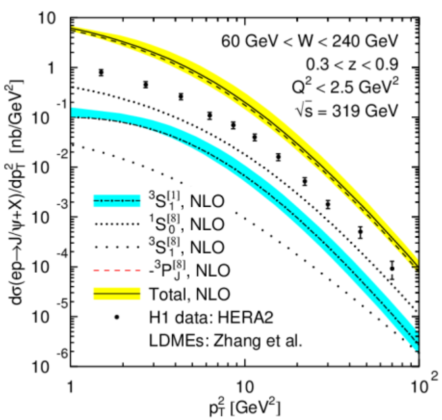


- Fit to CDF J/ψ yield $p_T > 7$ GeV (contraining two linear combinations M_0 and M_1) plus the LHCb η_c production data (constraining $\langle O^{J/\psi}(1S08)\rangle$)
- $\langle O^{J/\psi}(1S08)\rangle = 0.73 \pm 0.73$, $\langle O^{J/\psi}(3S18)\rangle = 1.0 \pm 0.3$, $\langle O^{J/\psi}(3P08)\rangle = 3.8 \pm 1.1$ [in 10^{-2} GeV^3 or 10^{-2} GeV^5]
- Ref.: [Han, Ma, Meng, Shao, Chao, PRL 114 (2015) 092005]

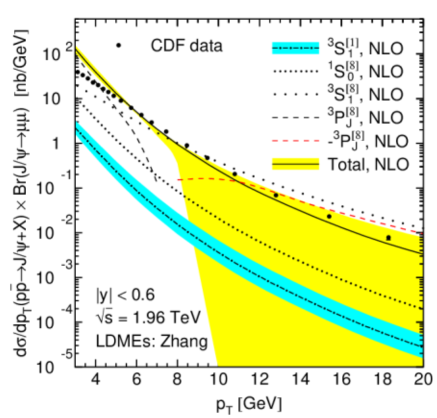
- Nontrivial: Largely unpolarized J/ψ compatible with data (although tensions to CDF data). But: J/ψ hadroproduction $p_T < 7$ GeV, J/ψ photo- and $J/\psi + Z$ production not described.

2.6 Zhang et al. LDMEs

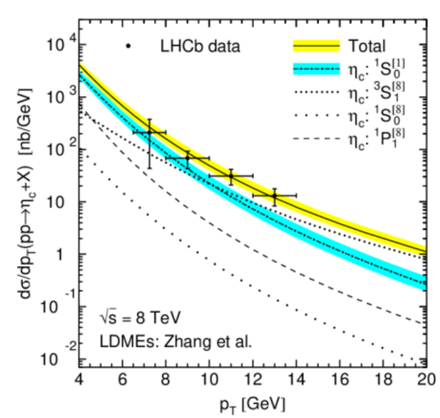
J/ψ Photoproduction



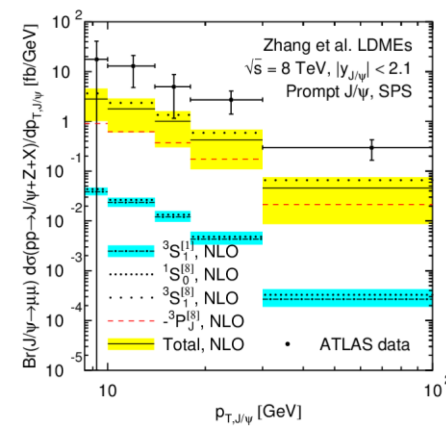
J/ψ Hadroproduction



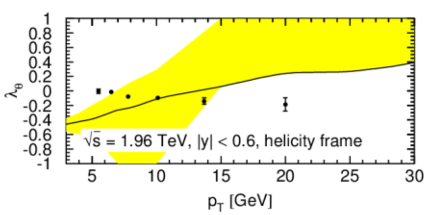
η_c Hadroproduction



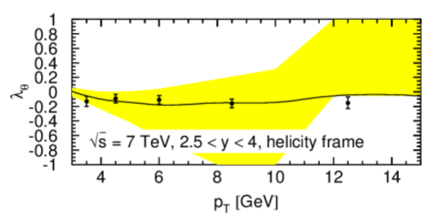
J/ψ + Z Hadroproduction



J/ψ Polarization (CDF)



J/ψ Polarization (LHCb)

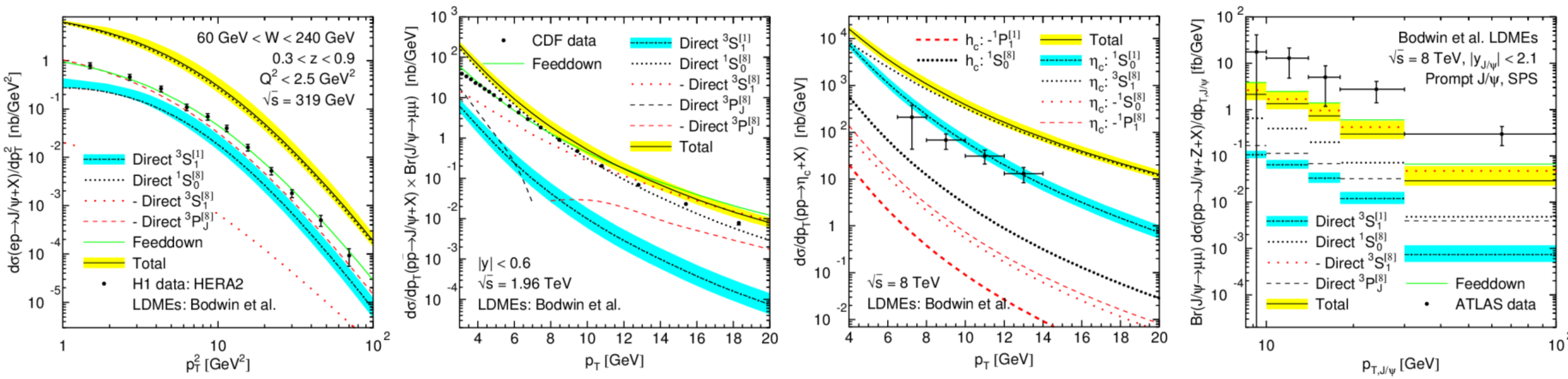


- Fit very similar to Chao et al. fit from previous slide.
- Difference: Also fitted: $<O^{J/\psi}$(3S11)>=(0.48$\pm$0.24) GeV^3
- $<O^{J/\psi}$(1S08)>=0.74 $\pm$0.30, $<O^{J/\psi}$(3S18)>=1.0 $\pm$0.3, $<O^{J/\psi}$(3P08)>=3.8 $\pm$0.5 [in 10^{-2} GeV^3 or 10^{-2} GeV^5]
- Ref.: [Zhang, Sun, Sang, Li, PRL 114, (2015) 092006]

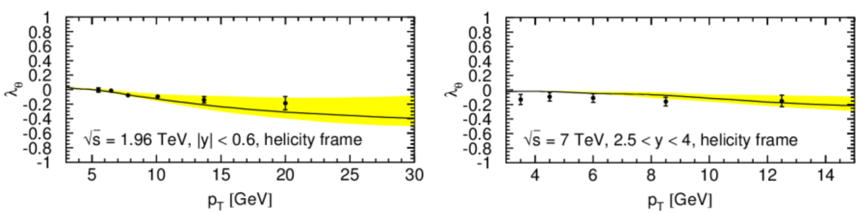
- Compared to Chao et al. fit on previous slide: Even better description of η_c production, at the expense of introducing also tensions with other determinations of $<O^{J/\psi}({}^3S_1^{[1]})>$.

2.7 Bodwin et al. LDMEs

J/ψ Photoproduction | J/ψ Hadroproduction | η_c Hadroproduction | J/ψ + Z Hadroproduction



J/ψ Polarization (CDF) | J/ψ Polarization (LHCb)

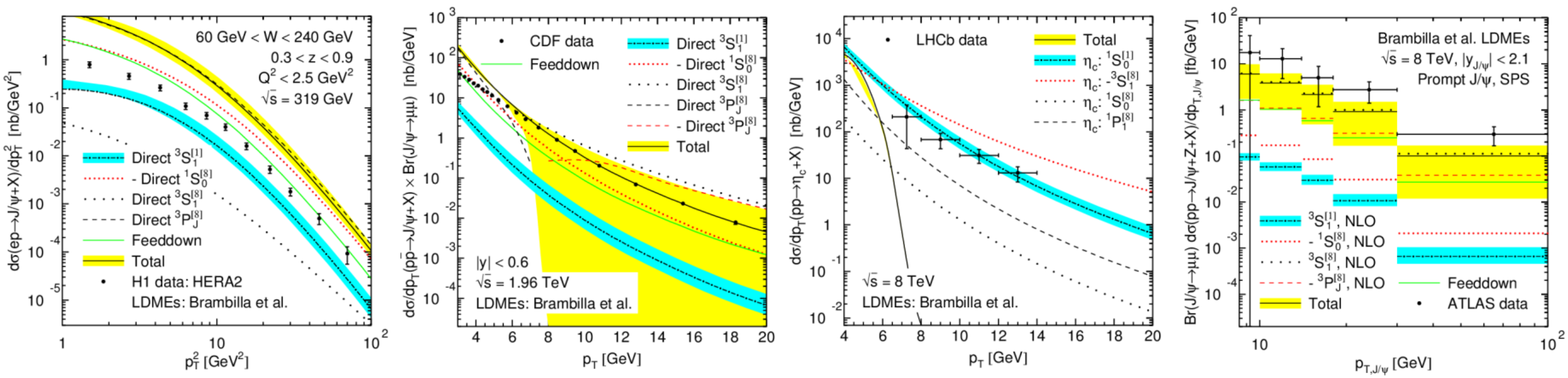


- Fit to J/ψ,ψ(2S), χ_{cJ} hadroproduction yield with $p_T > 3m_H$.
- Includes resummed FFs (we don't here → 2nd plot: small deviations)
- $<O^{J/\psi}$(1S08)>=11±1.4, $<O^{J/\psi}$(3S18)>=-0.71±0.36, $<O^{J/\psi}$(3P08)>=-0.70±0.34, $<O^{\psi(2S)}$(1S08)>=3.14±0.79, $<O^{\psi(2S)}$(3S18)>=-0.16 ±0.28, $<O^{\psi(2S)}$(3P08)>=-0.26±0.27, $<O^{\chi_{c0}}$(3P01)>=7.94 ±2.43, $<O^{\chi_{c0}}$(3S18)>=0.57±0.13 [10^{-2} GeV$^{3\text{ or }5}$]
- Ref.: [Bodwin, Chao, Chung, Kim, Lee, Ma, PRD 93, 034041 (2016)]

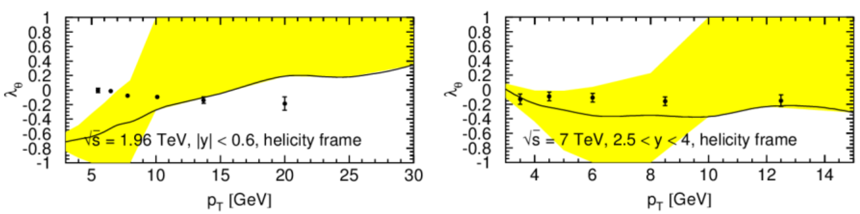
- Nontrivial outcome: Unpolarized J/ψ compatible with data.
  But: Small- and mid-p_T J/ψ hadro-; J/ψ photo-, η_c and J/$\psi + Z$ production not described.
  Also: **Direct J/$\psi + Z$** production unphysically **negative.**

2.8 Brambilla et al. LDMEs

J/ψ Photoproduction | J/ψ Hadroproduction | η_c Hadroproduction | J/ψ + Z Hadroproduction



J/ψ Polarization (CDF) | J/ψ Polarization (LHCb)



- Fit to $J/\psi, \psi(2S)$ hadroproduction yield with $p_T > 3m_H$ imposing a constraint derived using pNRQCD
- <$O^{J/\psi}$(1S08)>=-4.76±1.50, <$O^{J/\psi}$(3S18)>=1.71±0.19, <$O^{J/\psi}$(3P08)>=6.75 ±0.77, <$O^{\psi(2S)}$(1S08)>=-2.84 ±0.89, <$O^{\psi(2S)}$(3S18)>=1.02 ±0.11, <$O^{\psi(2S)}$(3P08)>=4.02 ±0.46, <$O^{\chi_{c0}}$(3P01)>=0, <$O^{\chi_{c0}}$(3S18)>=0 [in 10^{-2} GeV^3 or 10^{-2} GeV^5]
- Ref.: [Brambilla, Chung, Vairo, Wang, PRD 105, L111503 (2022)]

- Fit similar to previous Chao et al. and Zhang et al. fits. Differences: **Better description** of $J/\psi + Z$ production at the expense of a **negative** η_c cross section

Summary

- NRQCD factorization is **candidate theory** for Quarkonium production. Prediction: Universality of LDMEs.
- Ongoing work: Test LDME universality phenomenologically. Most data from J/ψ production and related observables.
- **New results** presented here: Complete NLO NRQCD calculation for **J/ψ + W or Z** production:
  - Only Brambilla et al. LDME set **roughly compatible** with data.
  - Other LDME sets **undershoot ATLAS data** by one order of magnitude. Difference not explicable via double parton scattering.
- **Overall picture** however: There is **no consistent NLO description** of all data with same set of LDMEs, even if restricted to high p_T.
- Some ways forward:
  - Maybe more terms in **v or α_s expansion**
  - Further resummation of **large logarithms** in various kinematic regions
  - Changes in the formalism (Definition LDMEs in polarized production? Heavy Quark Spin Symmetry?)