STATUS OF QUARKONIUM PRODUCTION

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XVIII INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE
16-21 AUGUST 2019, GUILIN, CHINA

OUTLINE

- Nonrelativistic effective field theory approach to heavy quarkonium
- Exclusive electromagnetic heavy quarkonium production
- Inclusive production of heavy quarkonium

NONRELATIVISTIC QCD

- NRQCD provides a description of a heavy quarkonium state as nonrelativistic Fock state expansion

$$|H\rangle = O(1)|Q\bar{Q}\rangle + O(v)|Q\bar{Q}g\rangle + O(v^2)|Q\bar{Q}gg\rangle + \cdots$$

Caswell, Lepage, PLB167, 437 (1986)
Bodwin, Braaten, Lepage, PRD51, 1125 (1995), PRD55, 5853 (1997)

$v^2 \approx 0.3$ for charmonia,
$v^2 \approx 0.1$ for bottomonia.

- At leading order in v, the leading Fock state is given by $Q\bar{Q}$ in a color-singlet state.
- At higher orders in v, the Fock states can involve $Q\bar{Q}$ in color-octet states. These originate from interactions of the form $-\frac{1}{2m}\int d^3x\, \psi^\dagger(\boldsymbol{D}^2 + g_s\, c_F \boldsymbol{\sigma}\cdot \boldsymbol{B})\psi$ in NRQCD.

EXCLUSIVE QUARKONIUM PRODUCTION

- Exclusive production amplitudes can be factorized into nonperturbative NRQCD matrix elements and perturbative short-distance coefficients.

$$\mathcal{A}_H = \sum_n c_n \langle H | \mathcal{O}_n | 0 \rangle$$

- The matrix elements $\langle H | \mathcal{O}_n | 0 \rangle$ have known scalings in v, which are determined from the dimension of the operators and from the probability of the $Q\bar{Q}$ Fock state they create.
- The sum is organized in powers of v and truncated to desired accuracy.
- Same matrix elements appear in electromagnetic decays.

PRODUCTION OF P-WAVE QUARKONIA

- At leading order in v, one NRQCD matrix element appears, which is sensitive to the color-singlet P-wave $Q\bar{Q}$ Fock state. This matrix element can be related to the first derivative of the quarkonium wavefunction at the origin.
- The $Q\bar{Q}g$ Fock state contribution can appear from the $\boldsymbol{p}\cdot\boldsymbol{A}$ interaction, which changes one unit of orbital angular momentum ($\Delta L=\pm 1$). At relative order v^2, a color-octet NRQCD matrix element appears, which is sensitive to the color-octet S-wave Fock state. To relative order v^2,

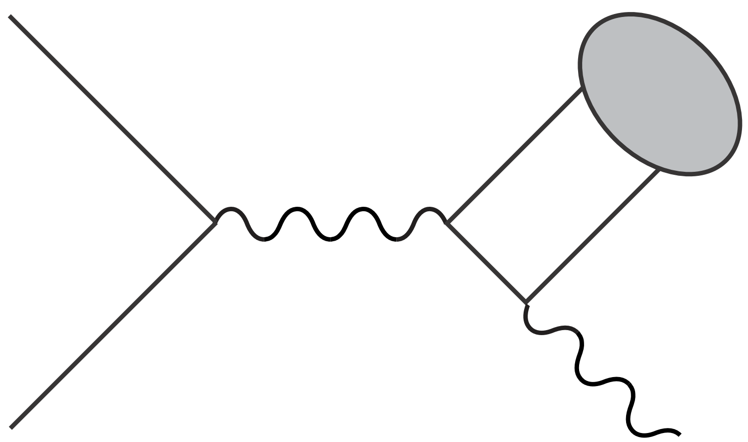
$$\mathcal{A} = c_0\langle\chi_{c0}|\chi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\boldsymbol{D}}\cdot\boldsymbol{\sigma})\psi|0\rangle + c_2\langle\chi_{c0}|\chi^\dagger(-\tfrac{i}{2}\overleftrightarrow{\boldsymbol{D}}\cdot\boldsymbol{\sigma})(-\tfrac{i}{2}\overleftrightarrow{\boldsymbol{D}})^2\psi|0\rangle + c_E\langle\chi_{c0}|\chi^\dagger(ig\boldsymbol{E}\cdot\boldsymbol{\sigma})\psi|0\rangle$$

$e^+e^- \to \chi_{cJ} + \gamma$

- First proposed as a way to probe C=+1 heavy quarkonia in e^+e^- colliders, calculated in 2008 at LO in α_s and v

HSC, Yu, Lee, D78, 074022 (2008)

- Order-$\alpha_s v^0$ and v^2 corrections have been computed.



Sang and Chen, PRD81 (2010) 034028
Li, He, Chao, PRD80 (2009) 114014
Li, Xu, Liu, Zhang, JHEP01 (2014) 022
Chao, He, Li, Meng, arXiv:1310.8597
Xu, Li, Liu, Zhang, JHEP10 (2014) 71
Brambilla, Chen, Jia, Shtabovenko, Vairo, PRD97 (2018) 096001

- For J=1, theoretical prediction at $\sqrt{s} = 10.6\ \mathrm{GeV}$ is in agreement with Belle measurement

Brambilla, Chen, Jia, Shtabovenko, Vairo, PRD97 (2018) 096001

Theory $\sigma(e^+e^- \to \chi_{c1} + \gamma) = (15.4 \pm 6.7)\ \mathrm{fb}$

Experiment $\sigma(e^+e^- \to \chi_{c1} + \gamma) = 17.3^{+4.2}_{-3.9} \pm 1.7\ \mathrm{fb}$

Belle, PRD98 (2018) 092015

$e^+e^- \to \chi_{cJ} + \gamma$

- Evidence for J=1 and 2 has been reported by BESIII. The reported Born cross sections are in fair agreement with theoretical predictions.

BESIII, Chin.Phys. C39 (2015) 041001

- One obstacle for reducing theoretical uncertainties is our poor knowledge of the NRQCD matrix elements, especially for the color octet matrix element.

- Matrix elements are usually constrained from potential models and/or from electromagnetic decay rates ($\chi_{cJ} \to \gamma\,\gamma$). Calculation of the matrix elements based on the potential NRQCD effective field theory is in preparation.

Brambilla, HSC, Müller, Vairo, in preparation

PRODUCTION OF S-WAVE QUARKONIA

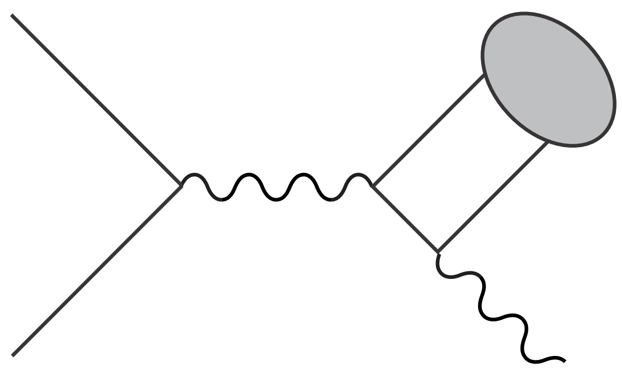
- At leading order in v, one NRQCD matrix element appears, which is sensitive to the color-singlet S-wave $Q\bar{Q}$ Fock state. This matrix element can be related to the quarkonium wavefunction at the origin.
- The $Q\bar{Q}g$ Fock state can appear from $\boldsymbol{p}\cdot\boldsymbol{A}$ and $\boldsymbol{\sigma}\cdot\boldsymbol{B}$ interactions, which come with $\Delta L=\pm 1$ and a spin flip ($\Delta S=\pm 1$), respectively. The $Q\bar{Q}gg$ Fock state can appear from $\boldsymbol{A}^2$ ($\Delta L=0$, $\Delta S=0$).
- For a spin-triplet S-wave (${}^3S_1$) quarkonium, color-octet matrix elements that are sensitive to the P-wave spin-triplet (${}^3P_J$), S-wave spin triplet (${}^3S_1$), and S-wave spin singlet (${}^1S_0$) color-octet Fock states appear to relative order v^3 accuracy.

$e^+e^- \to \eta_c + \gamma$

- First proposed as a way to probe $C=+1$ heavy quarkonia in e^+e^- colliders, calculated in 2008 at LO in α_s and v

HSC, Yu, Lee, D78, 074022 (2008)

- Order-$\alpha_s v^0$, $\alpha_s^2 v^2$, $\alpha_s^0 v^2$ and $\alpha_s v^2$ corrections have been computed.



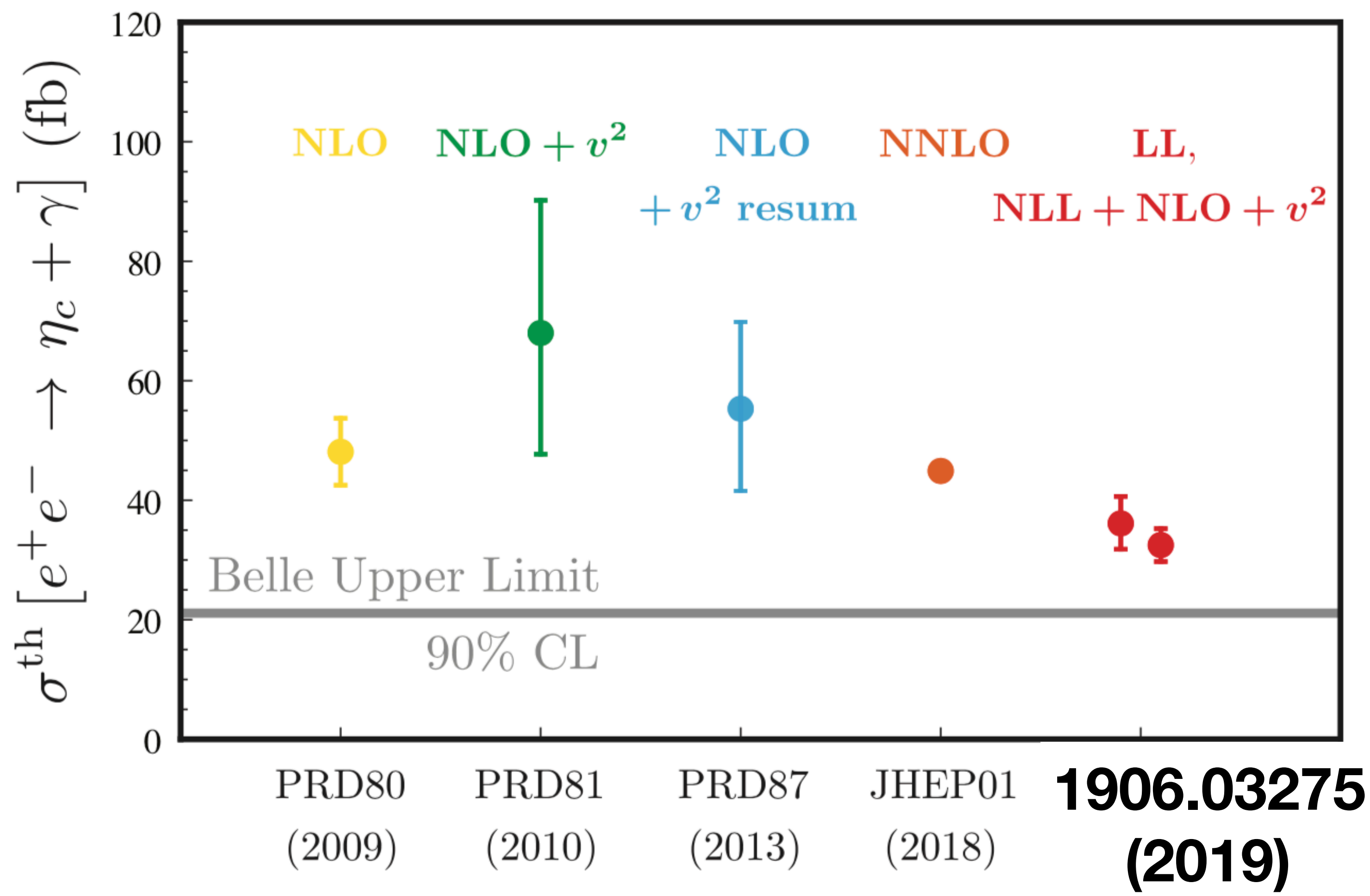
Sang and Chen, PRD81 (2010) 034028
Braguta, PRD82 (2010) 074009
Li, He, Chao, PRD80 (2009) 114014
Feng, Jia, Sang, PRL115 (2015) 222001
Chen, Liang, Qiao, JHEP01 (2018) 091
Fan, Lee, Yu, PRD87 (2013) 094032
Xu, Li, Liu, Zhang, JHEP10 (2014) 71

- Recently, logarithms of m^2/s have been resummed to next-to-leading-logarithmic (NLL) accuracy, based on pioneering work by Y. Jia and D. Yang.

Jia and Yang, NPB814 (2009) 217
HSC, Ee, Kang, Kim, Lee, Wang, 1906.03275 (2019)

$e^+e^- \to \eta_c + \gamma$

- Belle reported an upper limit, which seems to be in tension with theoretical predictions.



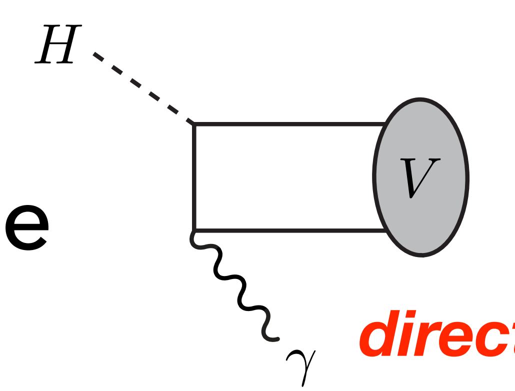
Belle, PRD98 (2018) 092015

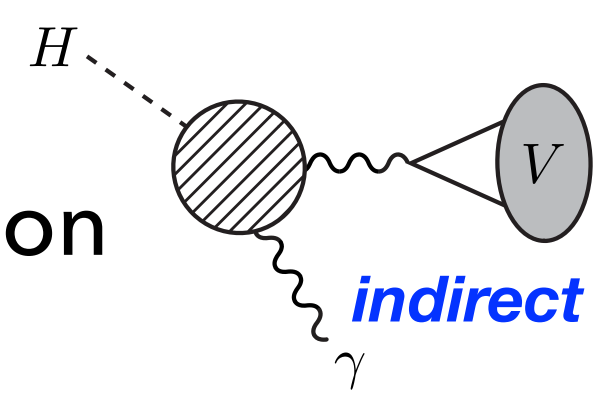
- BESIII also reported evidence of this process.

BESIII, PRD96 (2017) 051101

Higgs → $J/\psi + \gamma$

- First proposed as a way to measure the Higgs-charm coupling.
  Bodwin, Petriello, Stoynev, Velasco, PRD88 (2013) 053003
- Rate is sensitive to both size and sign of the coupling, due to the interference of ***direct*** and ***indirect*** processes.
- SM Branching ratio is about $3{\times}10^{-6}$.
- Order-v^2 corrections and LL resummation reduce uncertainties to about 5%.
  Bodwin, HSC, Ee, Lee, Petriello, PRD90 (2014) 113010
- Order-v^3 and v^4 corrections and NLL resummation reduce uncertainties to about 3%.





Bodwin, HSC, Ee, Lee, PRD95 (2017) 054018, PRD96 (2017) 116014
Brambilla, HSC, Lai, Shtabovenko, Vairo, 1907.06473

$e^+e^- \to J/\psi + \eta_c$

- This particular process gained a lot of attention because the measured cross section is much larger than the LO theoretical prediction.

Experiment

$$\sigma \times B_{>2} = 25.6 \pm 2.8 \pm 3.4 \text{ fb}$$ **Belle, PRD70 (2004) 071102**

$$\sigma \times B_{>2} = 17.6 \pm 2.8 \pm 2.1 \text{ fb}$$ **BABAR, PRD72 (2005) 031101**

Theory (LO)

$$\sigma = 3.78 \pm 1.26 \text{ fb}$$ **Braaten and Lee, PRD67 (2003) 054007**

$$\sigma = 5.5 \text{ fb}$$ **Liu, He, Chao, PLB557 (2003) 45**

$B_{>2}$: η_c branching fraction to more than 2 charged tracks

- Large and positive order-v^2 and order-α_s corrections seem to resolve the discrepancy.

However…

Braaten and Lee, PRD67 (2003) 054007
Zhang, Gao, Chao, PRL96 (2006) 092001
He, Fan, Chao, PRD75 (2007) 074001
Bodwin, Lee, Yu, PRD77 (2008) 094018

$e^+e^- \to J/\psi + \eta_c$

- The large order-α_s correction comes from double logarithms $\log^2(m^2/s)$, which can spoil the convergence of perturbation theory.
  Jia, Wang, Yang, JHEP1110 (2011) 105
- These are ***NOT*** the usual logarithms in the light-cone formalism.
- The origin of the logarithms were identified as endpoint logarithms, but an all-orders treatment is still out of reach.
  Bodwin, HSC, Lee, PRD90 (2014) 074028
- Brodsky and Lepage expected that such endpoint logarithms would be Sudakov suppressed. ***If this is true***, radiative corrections could reduce the theoretical prediction below measurement.
  Brodsky and Lepage, Adv. Ser. Direct. High Energy Phys. 5 (1989) 93
- Updated measurement is highly anticipated.

INCLUSIVE QUARKONIUM PRODUCTION

- Inclusive quarkonium production can be used to probe many areas of QCD.
- At small p_T, production process can be sensitive to TMD PDFs and low-x physics.
- Double quarkonium / associated production is sensitive to double parton scattering.
- Quarkonium production in heavy ion collisions can be used to probe QGP.
- In order to extract information about QCD from these processes, we need knowledge of the quarkonium production mechanism based on QCD.

INCLUSIVE PRODUCTION IN NRQCD

- Production cross section is given by a factorization formula

$$\sigma_H = \sum_n \sigma_{Q\bar{Q}(n)} \langle \mathcal{O}(n) \rangle_H$$

Bodwin, Braaten, Lepage, PRD51, 1125 (1995), PRD55, 5853 (1997)

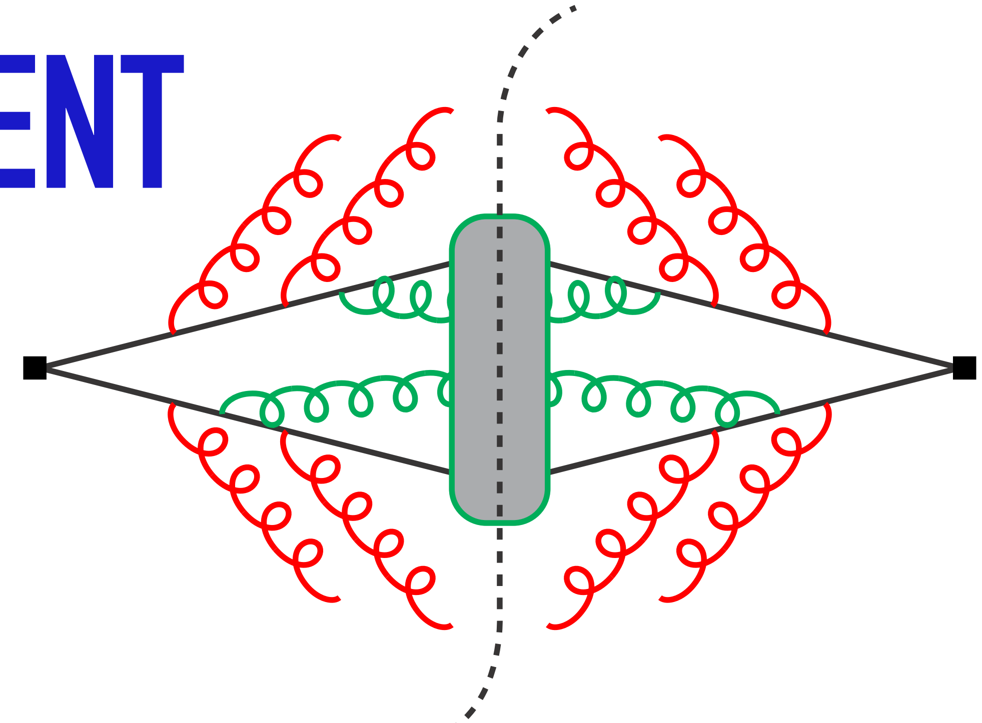
n : spin and color state of $Q\bar{Q}$

$\sigma_{Q\bar{Q}(n)}$: perturbative cross section of $Q\bar{Q}$

$\langle \mathcal{O}(n) \rangle_H$: Nonperturbative matrix element, probability for $Q\bar{Q}$ in state n to evolve into quarkonium $H + anything$.

- This formalism is expected to be valid at large p_T.
- At $p_T \approx m_H$, unless the soft-gluon interactions between the $Q\bar{Q}$ and initial- and final-state particles cancel (or factorize), the validity of the formalism can be spoiled.

PRODUCTION MATRIX ELEMENT



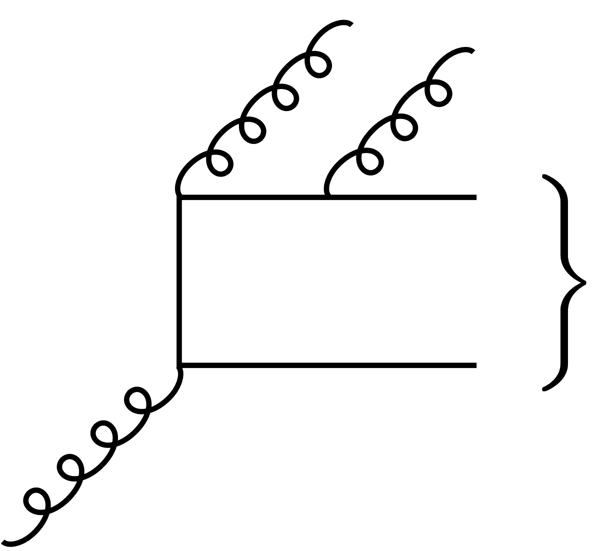
- A schematic form of the production matrix element :

$$\langle 0|\psi^\dagger \mathcal{K}_n \chi a_H^\dagger a_H \chi^\dagger \mathcal{K}'_n \psi|0\rangle$$

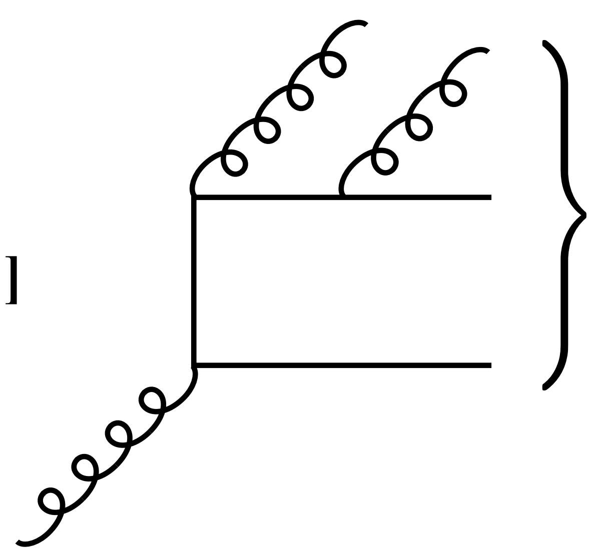
- Production matrix elements can be computed ***if*** they correspond to the color-singlet $Q\bar{Q}$ Fock state at leading order in v. The CS matrix element at leading order in v is given by the quarkonium wavefunction at the origin.
- It is not known how to compute nonperturbative matrix elements corresponding to the color-octet $Q\bar{Q}$ Fock state.
- Hence, CO matrix elements are usually extracted from data.

PRODUCTION MATRIX ELEMENT

- In an inclusive production, the produced quarkonium can be accompanied by arbitrarily soft gluons. A $Q\bar{Q}$ produced in a color-octet state can combine with gluons to form a heavy quarkonium state. If the gluon is soft (hard), the effect is nonperturbative (perturbative).
- For example, one diagram can contribute to different Fock states depending on the scale of the gluons.



${}^3S_1{}^{[1]}$



${}^3P_J{}^{[8]}$ or ${}^1S_0{}^{[8]}$

- In many processes, CO Fock states can be produced with less powers of α_s.

PRODUCTION MATRIX ELEMENT

- The NRQCD factorization scale separates perturbative and nonperturbative scales.
- Gluons with energies above the factorization scale are perturbative and belong to the perturbative cross section, and gluons with energies below the factorization scale belong to the nonperturbative NRQCD matrix elements.
- Cross section should not depend on an artificial factorization scale; the scale dependence cancels between perturbative cross sections and nonperturbative NRQCD matrix elements, and can induce mixing between channels.

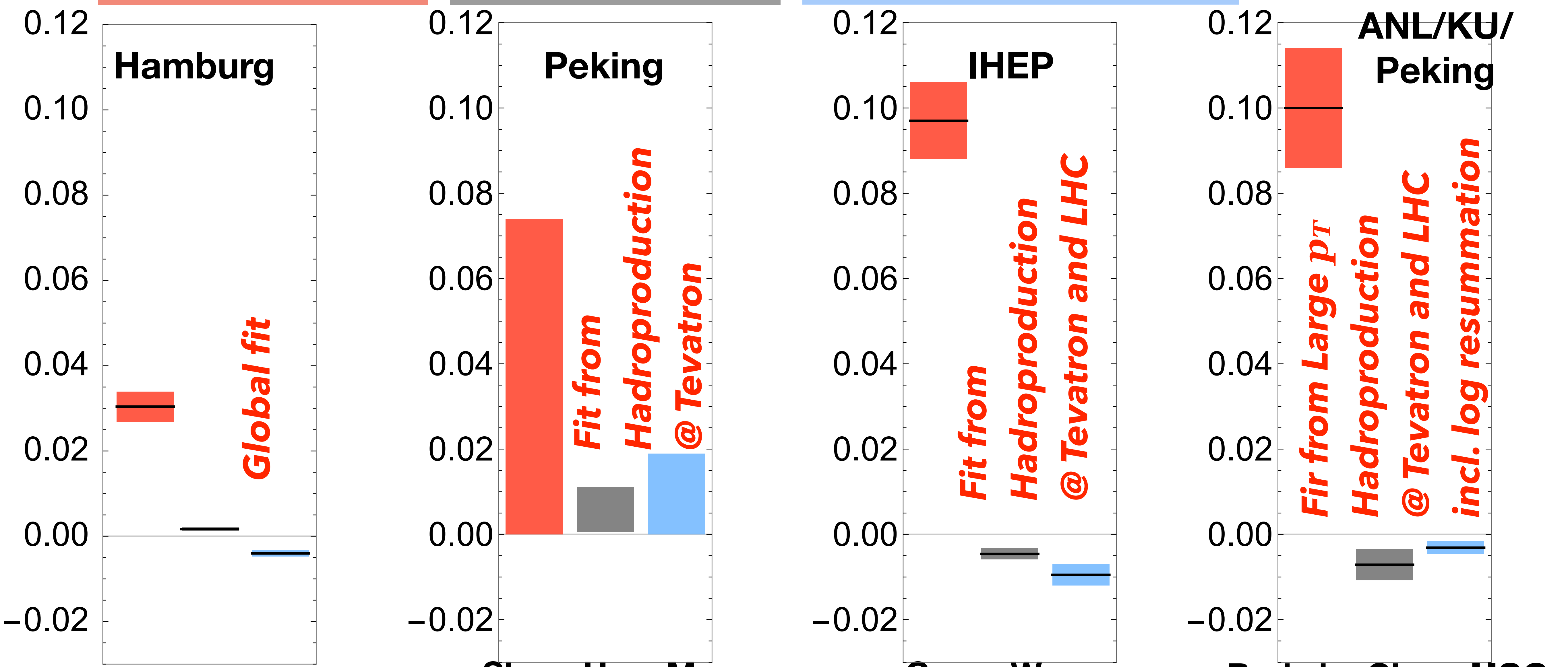
INCLUSIVE PRODUCTION OF J/ψ

$$d\sigma_{J/\psi+X} = \sum_n d\sigma_{Q\bar{Q}(n)+X} \langle \mathcal{O}^{J/\psi}(n) \rangle$$

- Leading order in v : ${}^3S_1{}^{[1]}$ **(color singlet)**
  Relative order v^3 : ${}^1S_0{}^{[8]}$ **(color octet, spin flip)**
  Relative order v^4 : ${}^3S_1{}^{[8]}$, ${}^3P_J{}^{[8]}$ **(*J*=0,1,2)** **(color octet, non spin flip)**
- Determination of three unknown matrix elements lead to description of J/ψ cross section to relative order v^4.
- In many processes, cross section is sensitive to CO channels due to enhancement of perturbative cross sections for CO Fock states.
- The ${}^3S_1{}^{[8]}$ and ${}^3P_J{}^{[8]}$ channels mix under change of NRQCD factorization scale at NLO in α_s.

DETERMINATIONS OF J/ψ MATRIX ELEMENTS

$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$, $\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$, $\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/m_c^2$ (GeV^3)



Butenschoen and Kniehl, PRD84, R051501 (2011)

Shao, Han, Ma, Meng, Zhang, Chao, JHEP 1505 (2015) 103

Gong, Wan, Wang, Zhang, PRL110, 042002 (2013)

Bodwin, Chao, HSC, Kim, Lee, Ma, PRD93, 034041 (2016)

DETERMINATIONS OF J/ψ MATRIX ELEMENTS

- Phenomenological determinations of J/ψ matrix elements depend strongly on choice of data.
  In particular, they lead to different combinations of ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ matrix elements.
- In general, determinations based on hadroproduction data tend to overestimate HERA ($ep \to J/\psi+X$) and Belle ($e^+e^- \to J/\psi+X$) measurements.

  Butenschoen and Kniehl, MPLA28, 1350027 (2013)
- On the other hand, global fits are in tension with LHC measurements of J/ψ polarization and J/ψ momentum distribution in jet.

  Butenschoen and Kniehl, MPLA28, 1350027 (2013)
  CMS, PLB727, 381 (2013)
  Bain, Dai, Leibovich, Makris, Mehen, PRL119, 032002 (2017)

SUMMARY

- Exclusive production of heavy quarkonium provide good tests of the nonrelativistic EFT formalism, as well as resummation and evolution in perturbative QCD.
- In order to obtain precise theoretical predictions, nonperturbative matrix elements, including ones sensitive to color octet Fock states, need to be determined accurately.
- Measurements of exclusive production and decay processes are invaluable in constraining such nonperturbative quantities.

SUMMARY

- A satisfactory theoretical description of inclusive production mechanism of heavy quarkonium is still missing.
- Predictions depend strongly on nonperturbative quantities that are determined phenomenologically. Different determinations lead to contradicting predictions.
- First-principles calculation of color octet matrix elements from knowledge of color octet Fock states is still out of reach.
- Ongoing experiments call for theoretical effort towards understanding of inclusive production mechanism based on QCD.

BACKUP

INCLUSIVE PRODUCTION OF χ_{QJ}

$$d\sigma_{\chi_{QJ}+X} = \sum_n d\sigma_{Q\bar{Q}(n)+X} \langle \mathcal{O}^{\chi_{QJ}}(n) \rangle$$

- Leading order in v : ${}^3P_J{}^{[1]}$ and ${}^3S_1{}^{[8]}$
  (color singlet) **(color octet, spin non flip)**
- The color singlet matrix element is given by the derivative of the quarkonium wavefunction at the origin.
- Description of χ_{QJ} cross section at leading order in v requires determination of one unknown color octet nonperturbative matrix element.
- The ${}^3S_1{}^{[8]}$ and ${}^3P_J{}^{[1]}$ channels mix under change of NRQCD factorization scale at NLO in α_s.

HADROPRODUCTION IN NRQCD

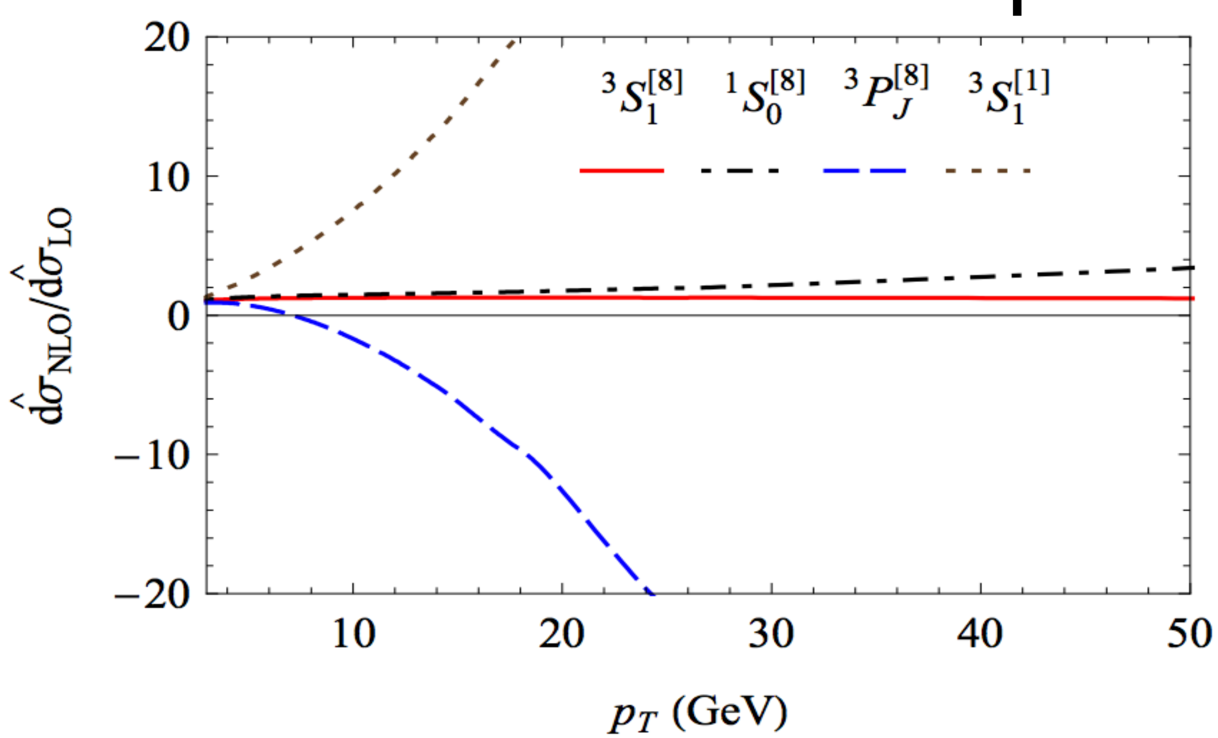
- In J/ψ or $\Upsilon(nS)$ hadroproduction at large p_T, CO $Q\bar{Q}$ cross sections are enhanced compared to the CS $Q\bar{Q}$ cross section. Hence, even though the CO matrix elements are suppressed compared to CS matrix elements, the CO contribution can dominate the cross section.

Cho and Leibovich, PRD53, 150 (1996)
PRD53, 6203 (1996)

- In many quarkonium production processes, the CS cross section tends to underestimate the measured cross section at large p_T. In such case, the CO contributions can fill in the gap between measured cross section and the CS contribution.

HADROPRODUCTION IN NRQCD

- Perturbative $Q\bar{Q}$ cross sections are generally available up to NLO accuracy in α_s. NLO cross sections can have shapes that are very different from LO, because new fragmentating contributions become available at NLO accuracy and give rise to K factors that depend strongly on p_T.



Ma, Wang, Chao, PRL106, 042002 (2011)

- We can understand this from QCD factorization theorems that apply to the leading and next-to-leading power contributions in the expansion in powers of $1/p_T$

HADROPRODUCTION IN NRQCD

$$\frac{d\sigma_H}{dp_T^2} = \sum_{i=g,q,\bar{q}} \frac{d\sigma_i}{dp_T^2} \otimes D_{i\to H}(z,\mu) \quad (\sim 1/p_T^4)$$

Leading-power (LP) fragmentation

$$+\sum_n \frac{d\sigma_{Q\bar{Q}(n)}}{dp_T^2} \otimes D_{Q\bar{Q}(n)\to H}(z,\zeta_1,\zeta_2,\mu) \quad (\sim 1/p_T^6)$$

Next-to-leading-power (NLP) fragmentation

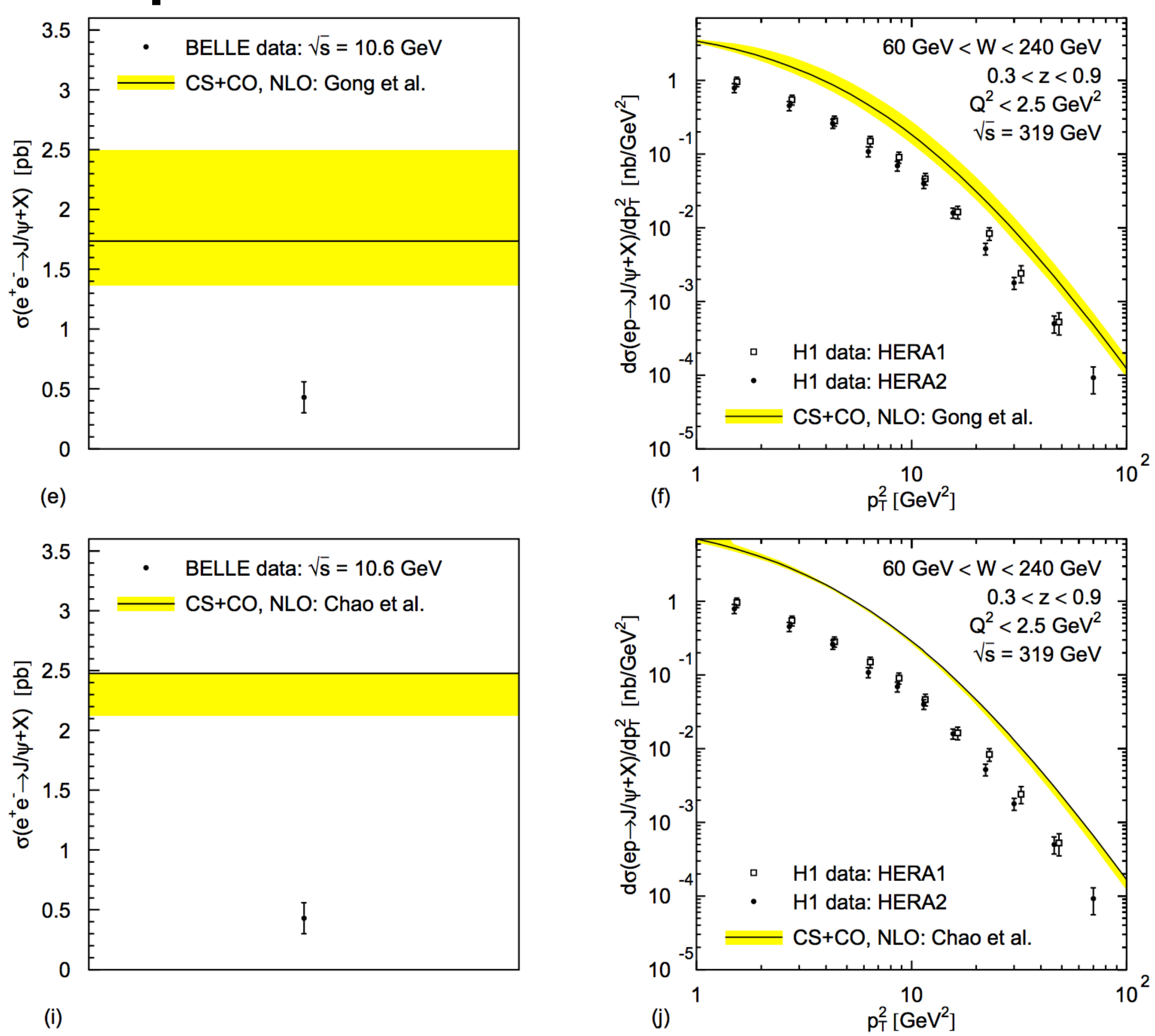
$$+O(1/p_T^8)$$

- When $p_T \gg m_c$, shape of the cross section at large p_T can be well understood from expansion in $1/p_T$.
- It is difficult to extend to $p_T \approx m_Q$.

J.C.Collins and D.E.Soper, NPB194, 445 (1982)
Z.-B. Kang, J.-W. Qiu, G. Sterman, PRL108, 102002 (2012)
S. Fleming, A. K. Leibovich, T. Mehen, I. Z. Rothstein, PRD86, 094012 (2012)
Y.-Q. Ma, J.-W. Qiu, G. Sterman, H. Zhang, PRL113, 142002 (2014)

J/ψ PRODUCTION IN OTHER COLLIDERS

- Matrix elements extracted from hadroproduction lead to predictions incompatible with leptoproduction / photoproduction



Butenschoen and Kniehl, MPLA28, 1350027 (2013)

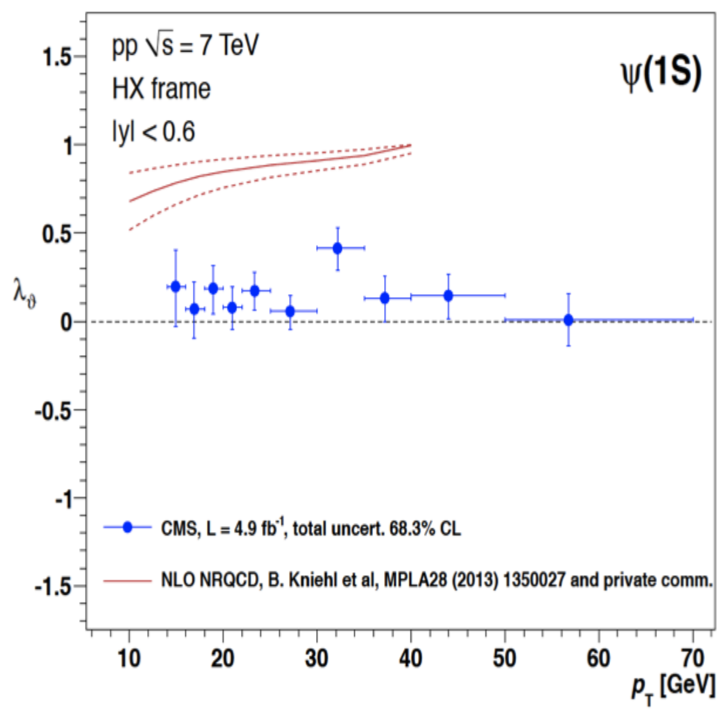
Matrix elements from Gong, Wan, Wang, Zhang, PRL110, 042002 (2013) (IHEP)

Matrix elements from Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012) (Peking)

J/ψ POLARIZATION IN HADROPRODUCTION

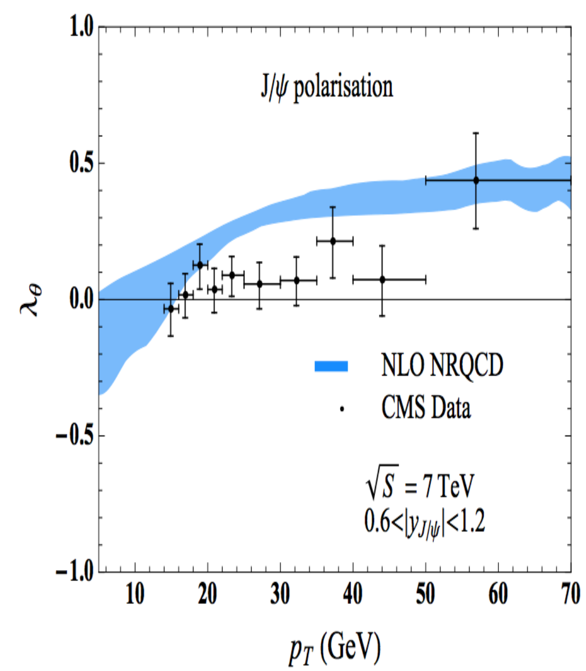
- Global fit leads to J/ψ polarization predictions that are incompatible with LHC measurements.

Hamburg



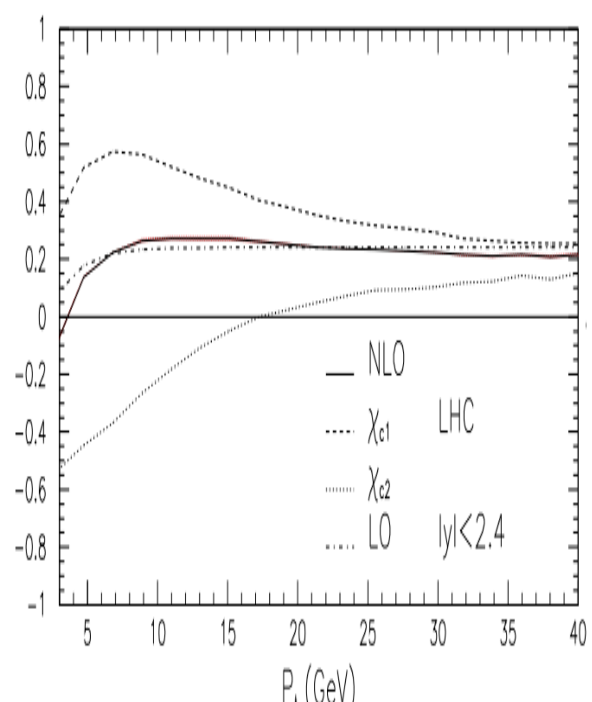
CMS, PLB727, 381 (2013)
Butenschoen and Kniehl, PRL108, 172002 (2012)

Peking



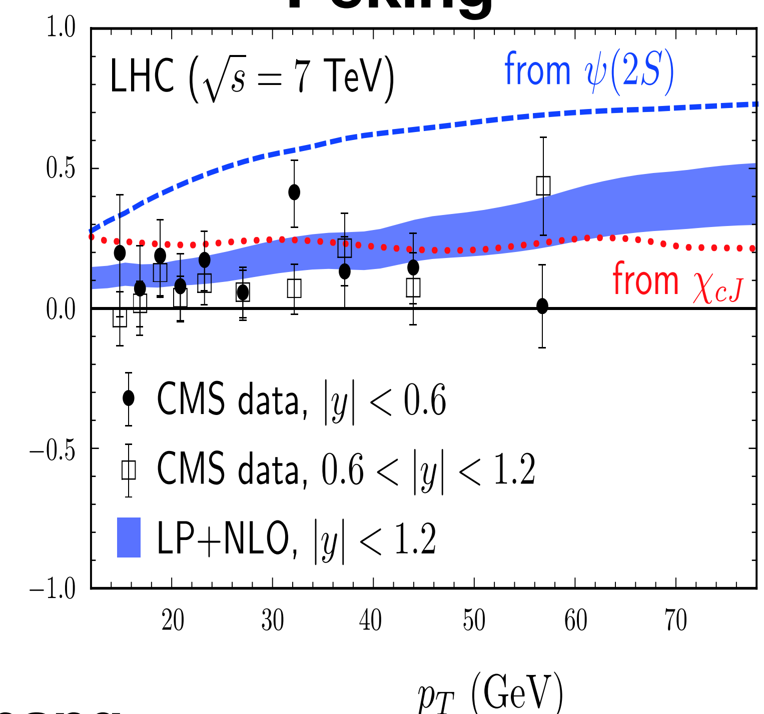
Shao, Han, Ma, Meng, Zhang, Chao, JHEP 1505 (2015) 103

IHEP



Gong, Wan, Wang, Zhang, PRL110, 042002 (2013)

ANL/KU/ Peking

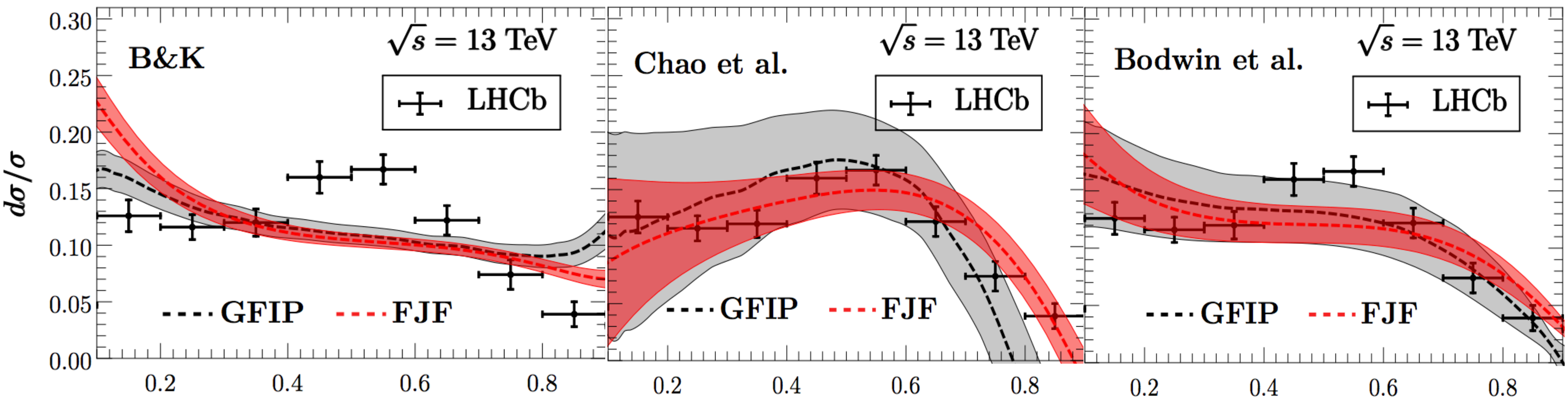


Bodwin, Chao, Chung, Kim, Lee, Ma, PRD93, 034041 (2016)

J/ψ MOMENTUM DISTRIBUTION IN JET

- Global fit also in tension with to J/ψ momentum distribution in jet with LHC measurements

Bain, Dai, Leibovich, Makris, Mehen, PRL119, 032002 (2017)



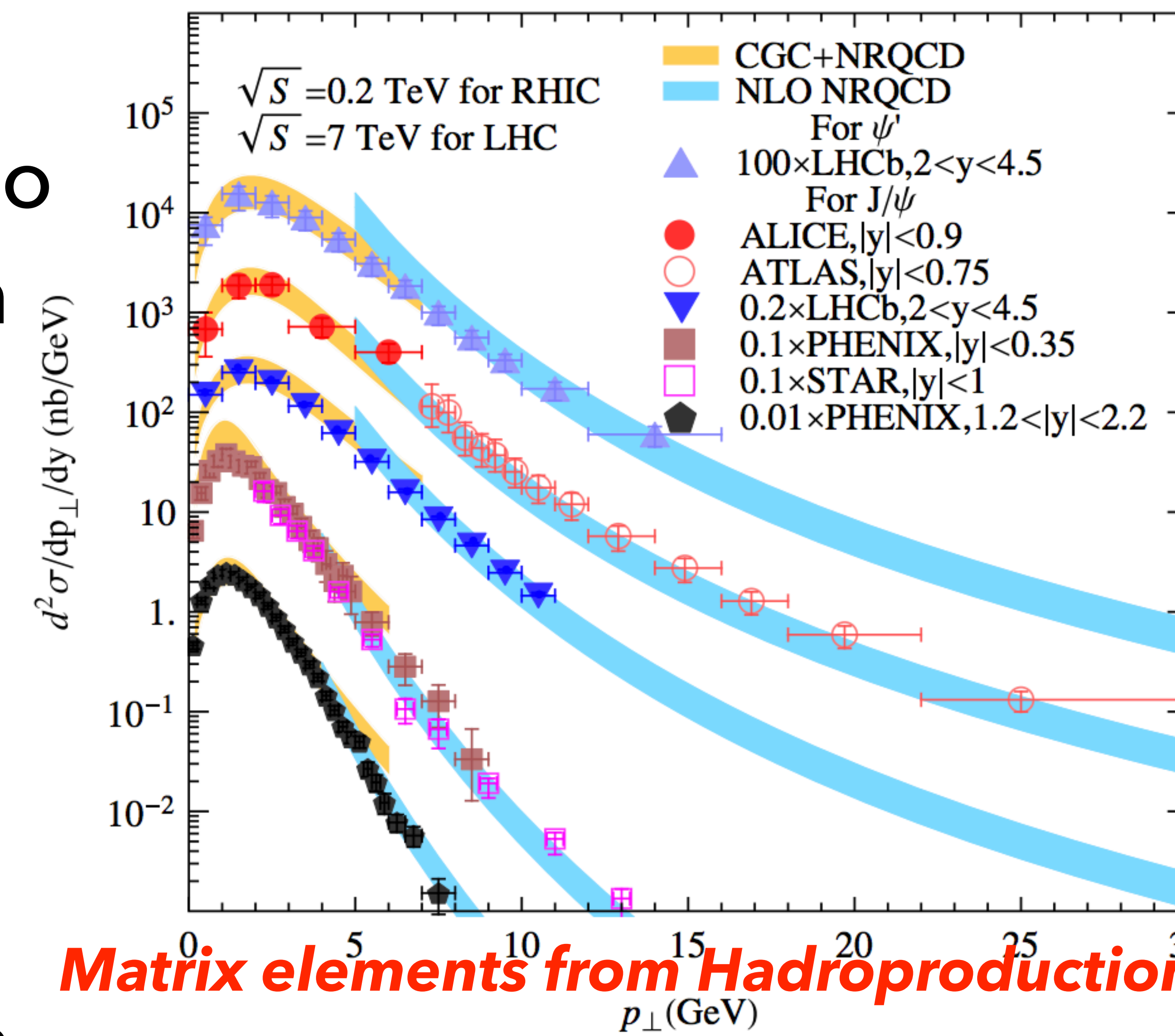
Matrix elements from Global fit

Matrix elements from Hadroproduction

J/ψ PRODUCTION IN NRQCD WITH TMD

- At small p_T, Hadroproduction cross section can be sensitive to intrinsic transverse momentum of initial-state partons.

- By combining CGC and collinear factorization approaches, it is possible to obtain good agreement with hadroproduction data over the whole p_T region.



Matrix elements from Hadroproduction

Yan-Qing Ma and Raju Venugopalan, PRL113, 192301 (2014)

COLOR SINGLET MODEL (CSM)

- One of the oldest model of heavy quarkonium production is CSM.

$$\sigma_H = \sigma_{Q\bar{Q}_{\rm CS}} \langle \mathcal{O}_{\rm CS} \rangle_H$$

Ellis, Einhorn, Quigg, PRL36, 1263 (1976)
Carlson, Suaya, PRD14, 3115 (1976)
Chang, NPB172, 425 (1980)

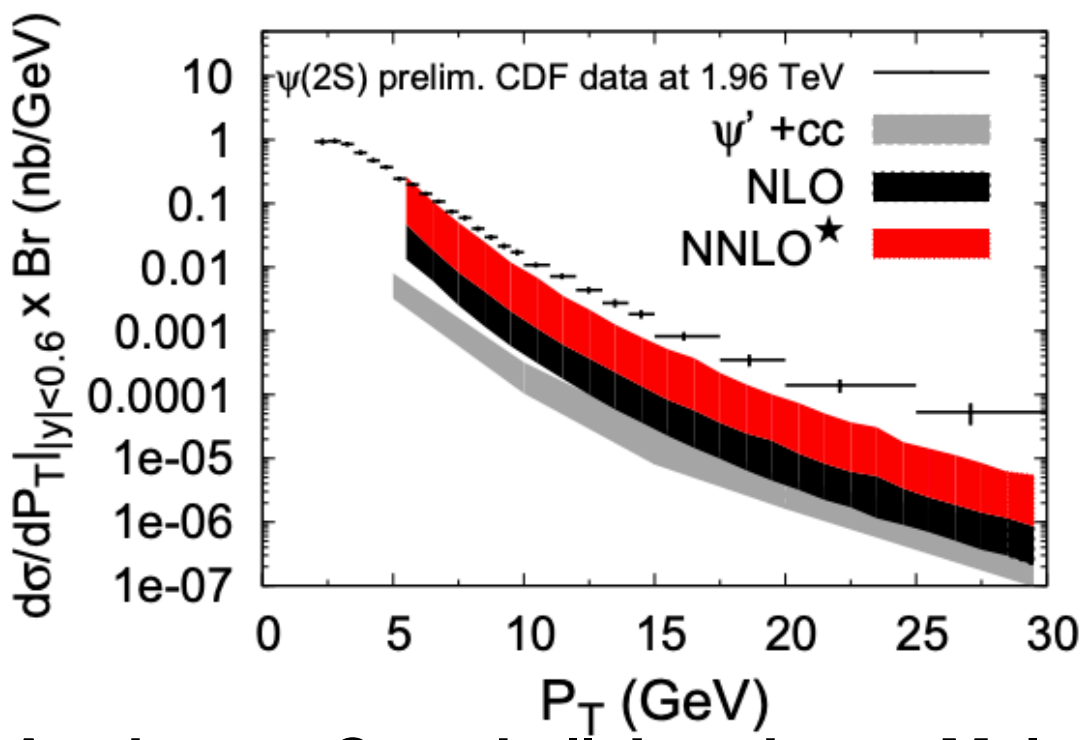
$\sigma_{Q\bar{Q}_{\rm CS}}$: perturbative cross section of color-singlet $Q\bar{Q}$

$\langle \mathcal{O}_{\rm CS} \rangle_H$: color-singlet matrix element, given by the quarkonium wavefunction at the origin

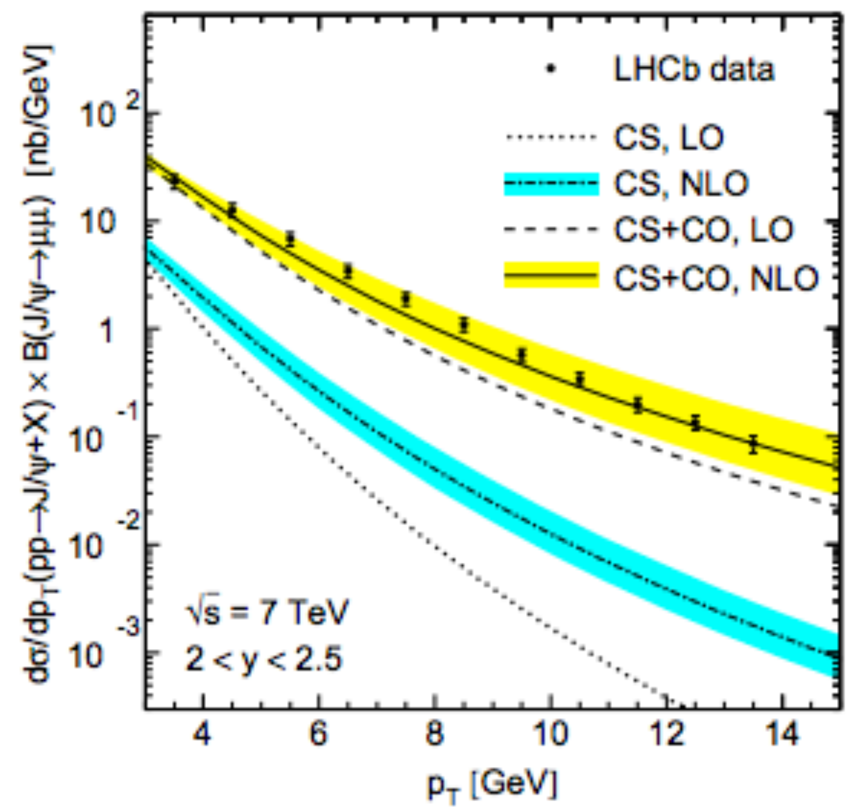
- For S-wave quarkonia, production cross section in CSM is equal to the cross section in NRQCD at leading order in v.
- CSM suffers from infrared divergence when applied to P-wave quarkonia; in NRQCD, this problem is resolved through operator renormalization that requires mixing with color-octet matrix elements.

COLOR SINGLET MODEL (CSM)

- CSM predictions underestimate hadroproduction cross sections at large p_T.



Artoisenet, Campbell, Lansberg, Maltoni, Tramontano, PRL101 (2008) 152001
Lansberg, EPJC61 (2009) 693

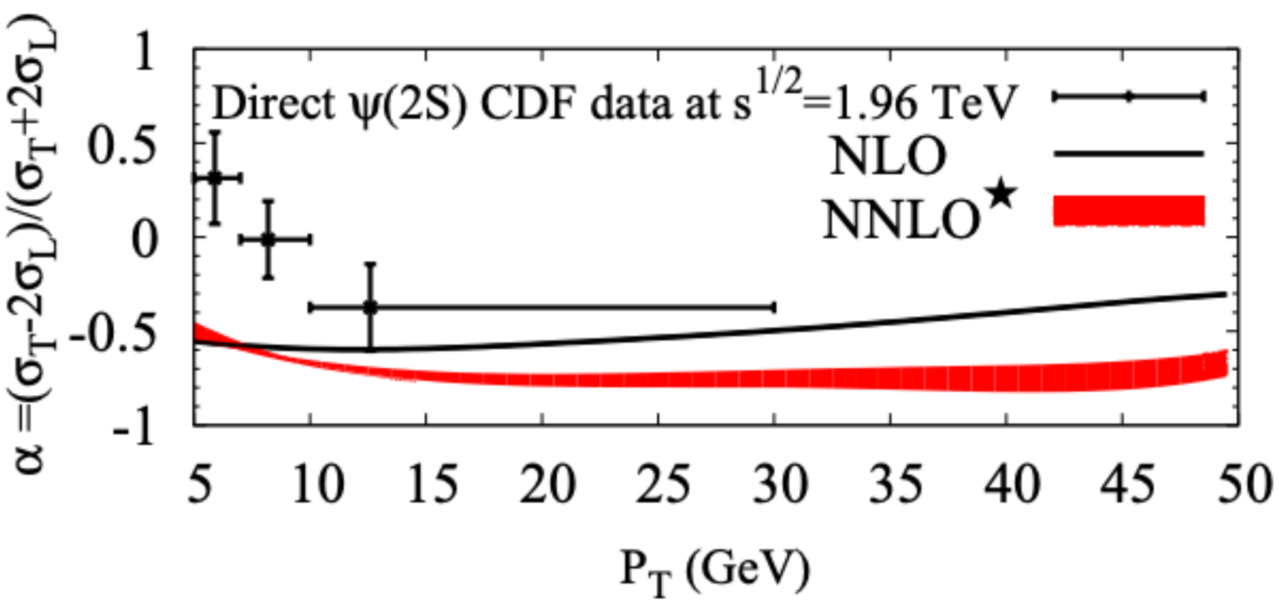


Butenschoen and Kniehl, MPLA28, 1350027 (2013)

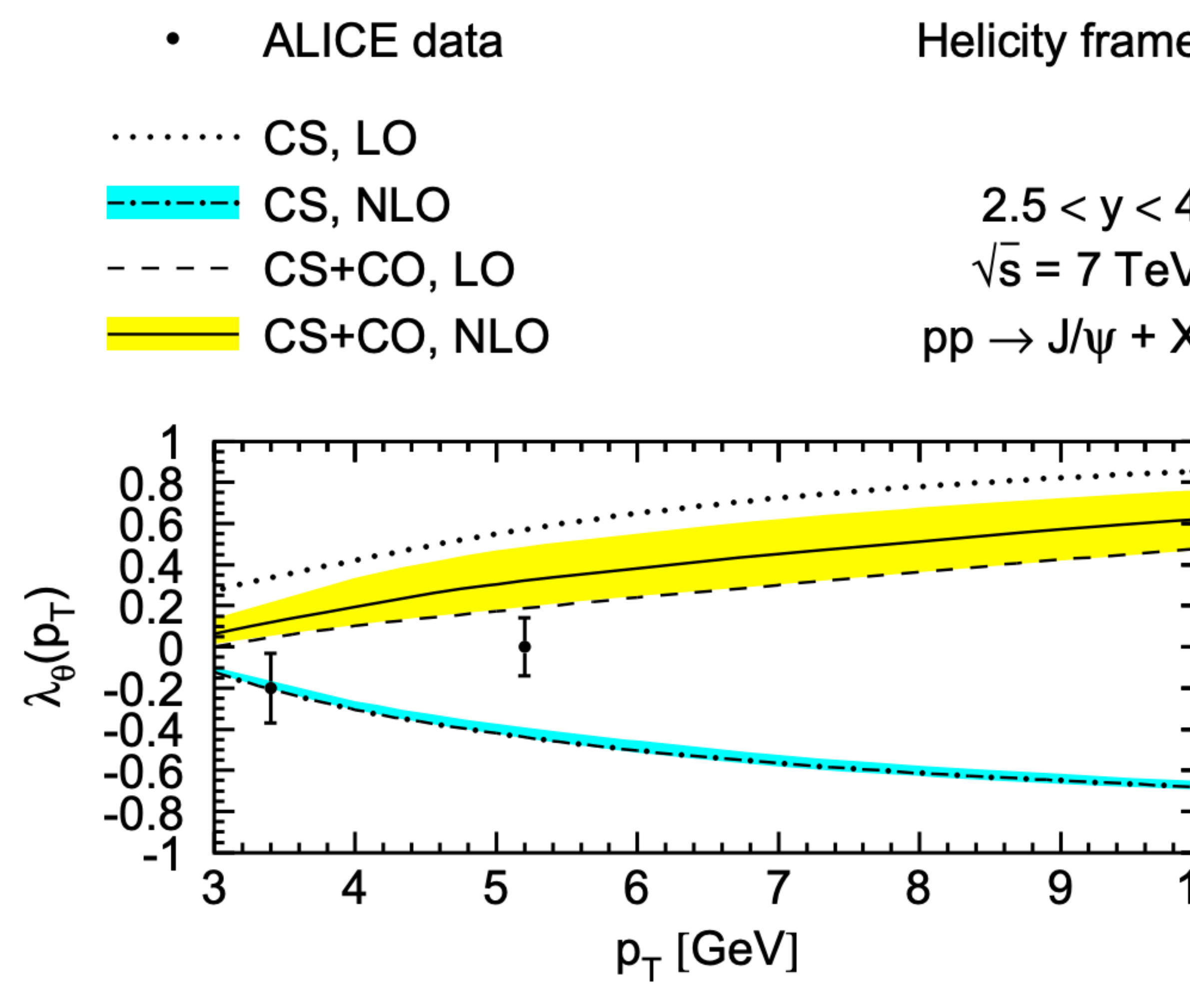
- CSM also suffers from large K factors that depend strongly on p_T. This also can be understood from expansion in $1/p_T$.

COLOR SINGLET MODEL (CSM)

- CSM predicts longitudinal polarization at large p_T, which disagrees with measurement.



Lansberg, EPJC61 (2009) 693



Butenschoen and Kniehl, MPLA28, 1350027 (2013)

COLOR EVAPORATION MODEL (CEM)

- In CEM, the quarkonium cross section is given by perturbative cross section of $Q\bar{Q}$ integrated over the $Q\bar{Q}$ invariant mass up to the $D\bar{D}$ threshold, multiplied by a phenomenological factor F_H specific to quarkonium H.

$$\frac{d\sigma_H}{d^3P} = F_H \int_{2m_Q}^{2m_D} dm_{Q\bar{Q}} \frac{d\sigma_{Q\bar{Q}}}{dm_{Q\bar{Q}} d^3P}$$

Fritzsch, PLB67, 217 (1977)
Halzen, PLB69, 105 (1977)

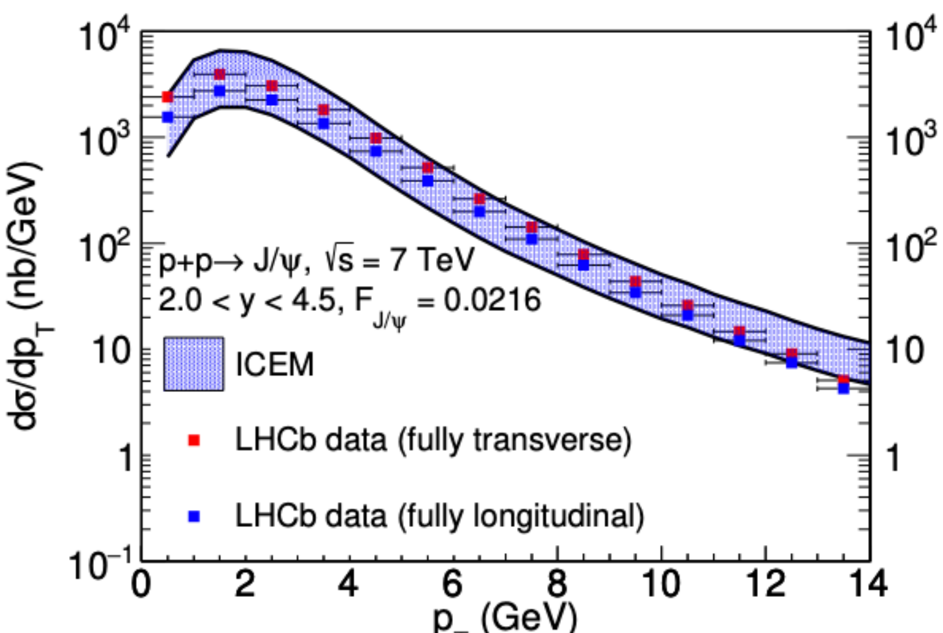
- The formalism is based on quark-hadron duality, but it is difficult to relate the phenomenological factor F_H with QCD.
- CEM predicts same shape in p_T for all charmonium/bottomonium states, which is in slight tension with measurements.

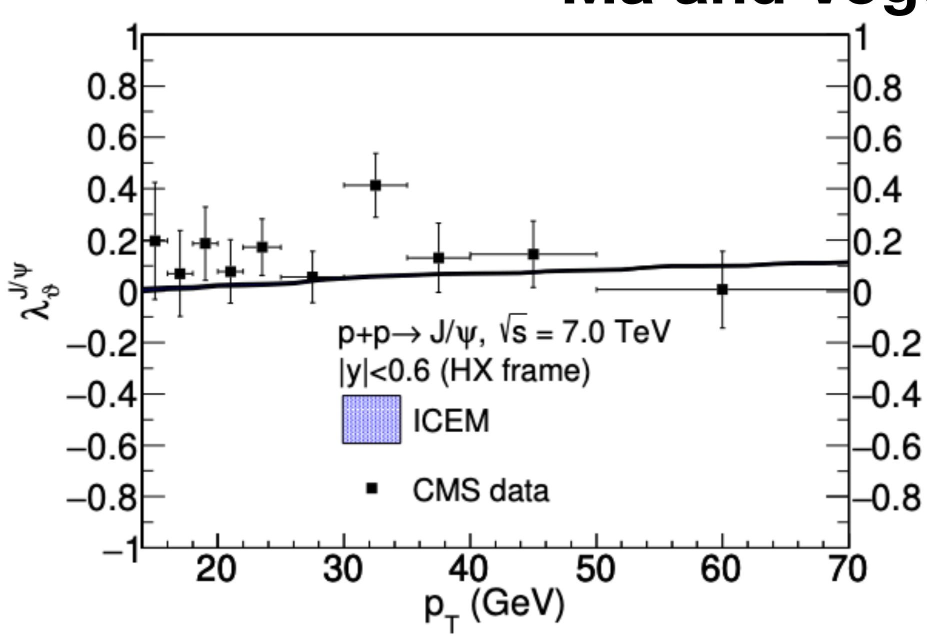
COLOR EVAPORATION MODEL (CEM)

- Recently, “Improved CEM” was proposed, where difference between $Q\bar{Q}$ mass and quarkonium mass is taken into account. ICEM is in good agreement with hadroproduction cross section and polarization.

$$\frac{d\sigma_H}{d^3P} = F_H \int_{m_H}^{2m_D} dm_{Q\bar{Q}} \frac{d\sigma_{Q\bar{Q}}}{dm_{Q\bar{Q}} d^3P}\Bigg|_{P_{Q\bar{Q}}=(m_{Q\bar{Q}}/m_H)P}$$

Ma and Vogt, PRD94 (2016), 114029





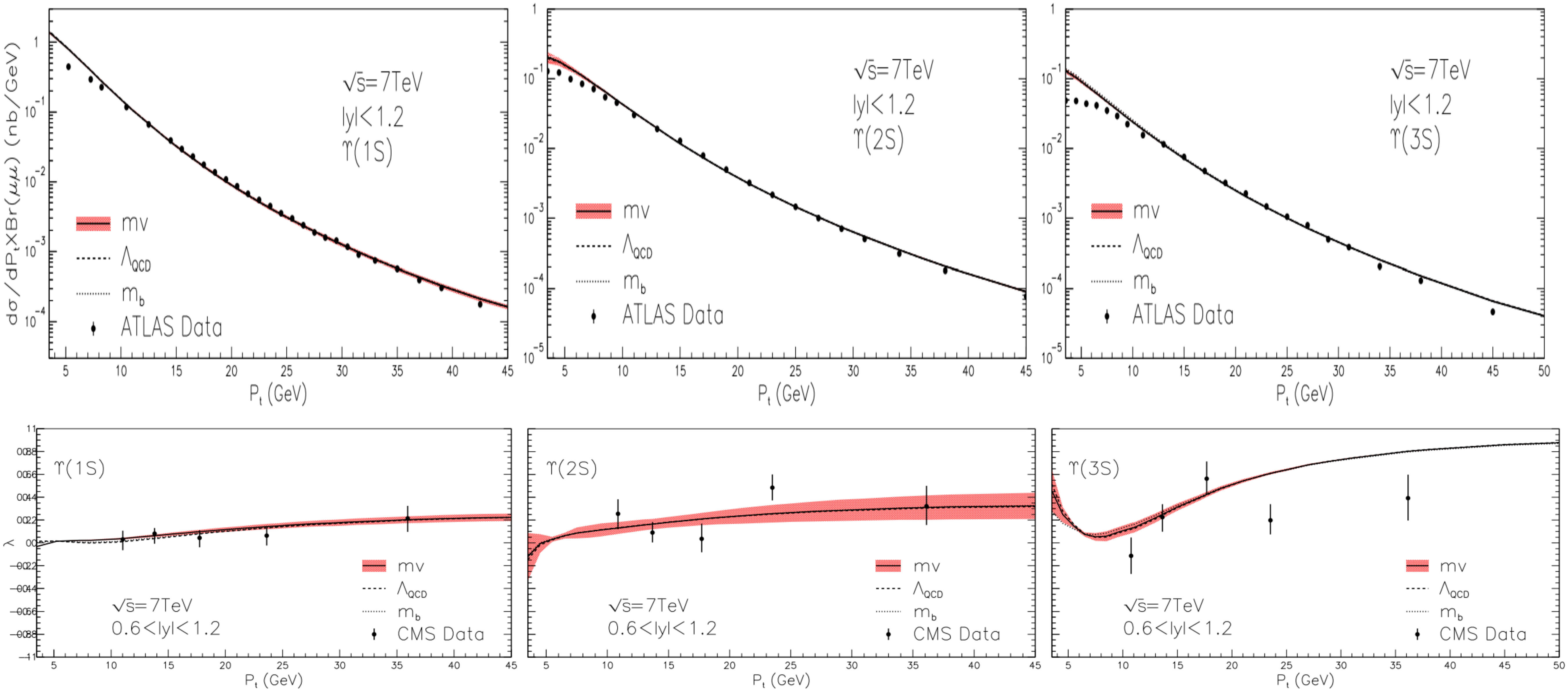
Cheung and Vogt, PRD99 (2019), 034007

FEEDDOWNS TO QUARKONIUM PRODUCTION

- Heavy quarkonia can be produced in hadron colliders from
  - Direct production : quarkonium is directly produced in a hard process.
  - Feeddown : quarkonium is produced in decays of heavier, directly produced quarkonia ($\chi_{cJ} \to J/\psi+\gamma$, $\psi(2S) \to J/\psi+X$, $\chi_{bJ}(nP) \to \Upsilon(mS)+\gamma$, $\Upsilon(nS) \to \Upsilon(mS)$).
  - Nonprompt : charmonium is produced in decays of B mesons.
- Non-prompt production can be measured separately from prompt production, and can also be computed reliably.

$\Upsilon(nS)$ HADROPRODUCTION IN NRQCD

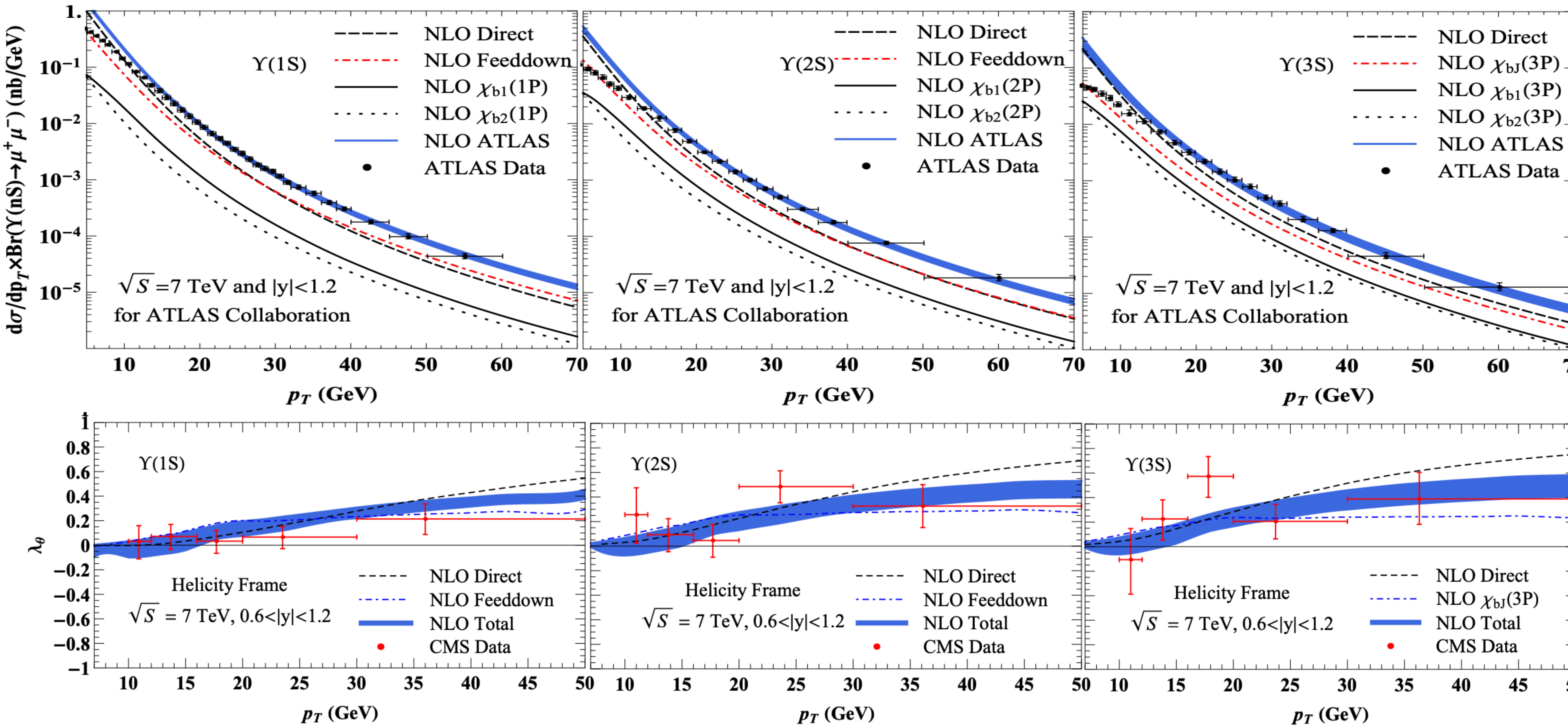
ATLAS, PRD87, 052004 (2013)
CMS, PRL110, 081802 (2013)



Gong, Wan, Wang, Zhang, PRL 112, 032001 (2014)

$\Upsilon(nS)$ HADROPRODUCTION IN NRQCD

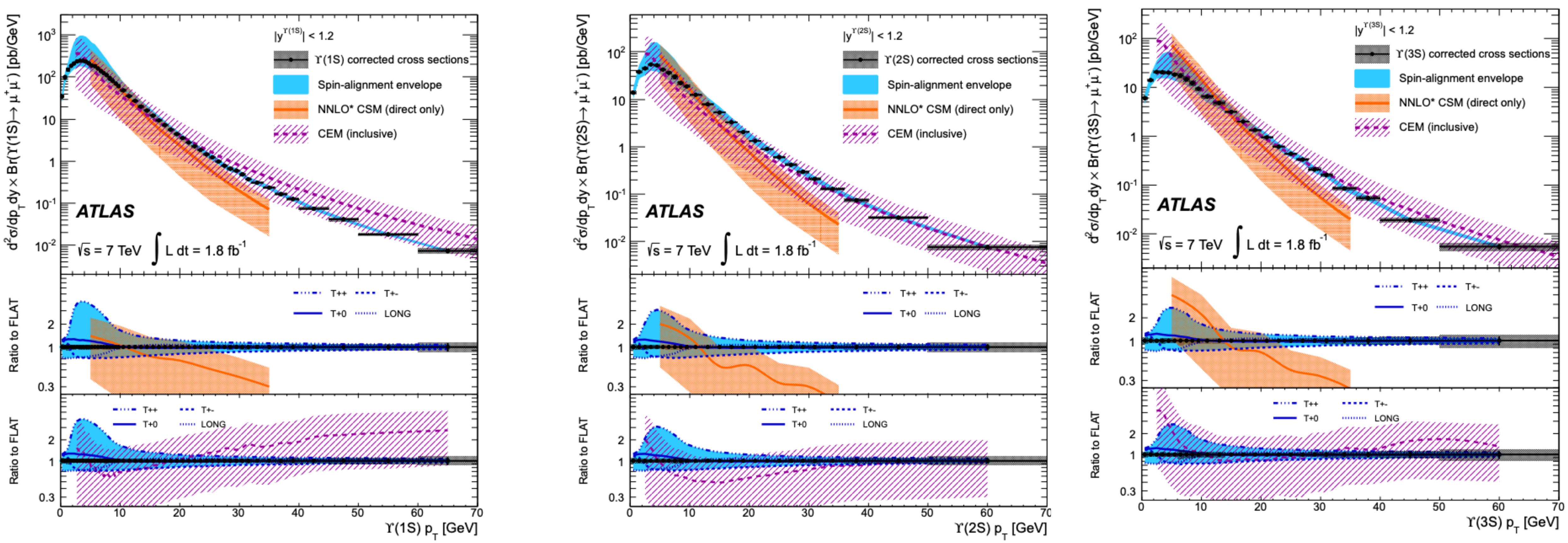
ATLAS, PRD87, 052004 (2013)
CMS, PRL110, 081802 (2013)



Han, Ma, Meng, Shao, Zhang, Chao, PRD 94, 014028 (2016)

$\Upsilon(nS)$ HADROPRODUCTION IN CSM AND CEM

ATLAS, PRD87, 052004 (2013)



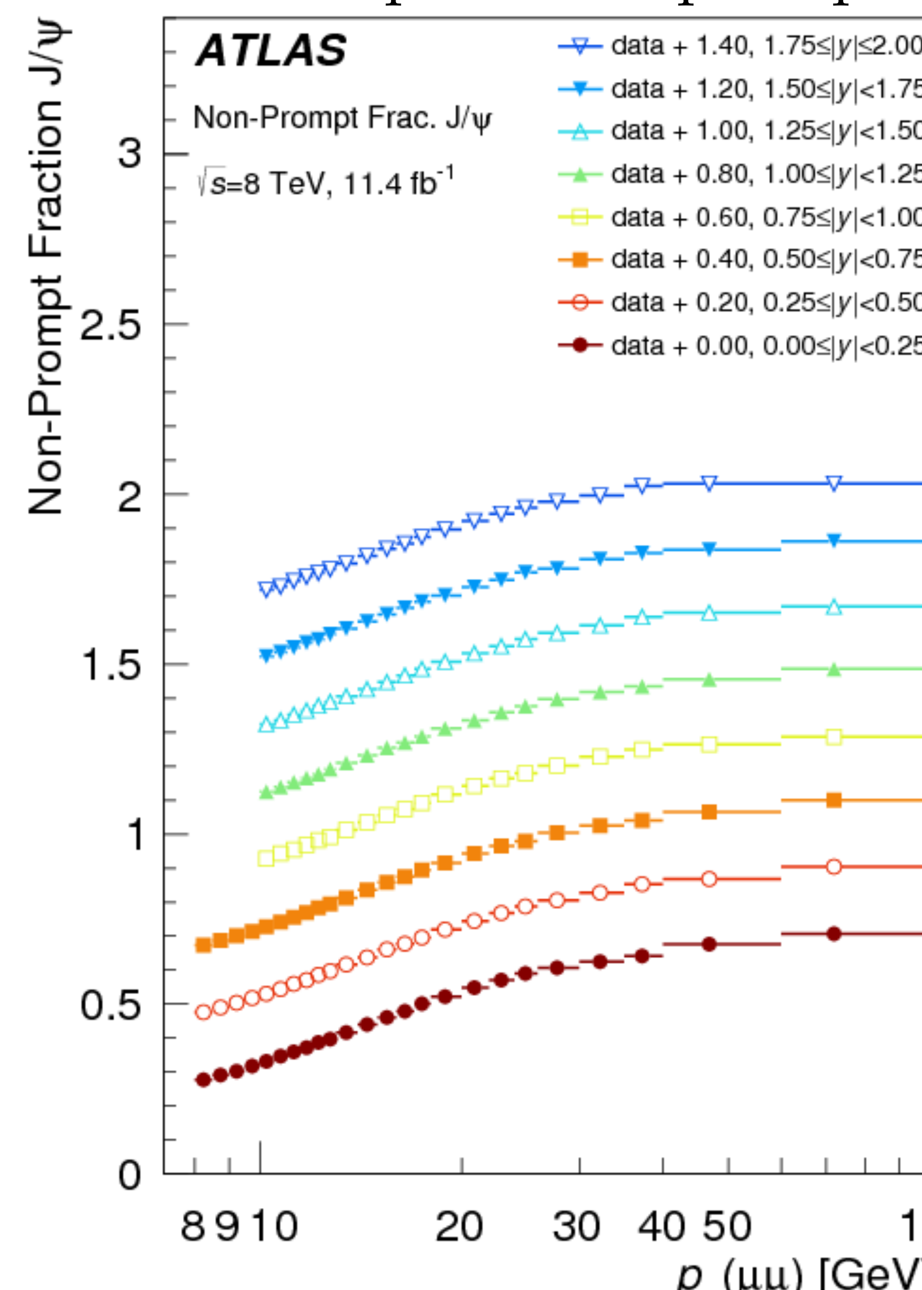
CSM : Artoisenet, Campbell, Lansberg, Maltoni, Tramontano, PRL101 (2008) 152001
Lansberg, EPJC61 (2009) 693

CEM : Frawley, Ullrich, Vogt, Phys. Rept. 462 (2008) 125

QUARKONIUM PRODUCTION

- Fragmentation does not provide a good description of prompt quarkonium production unless p_T is extremely large.
- Comparison of p_T distributions of prompt and non-prompt J/ψ cross sections show that the fragmentation mechanism would only dominate the charmonium cross section when $p_T \gtrsim 100$ GeV.

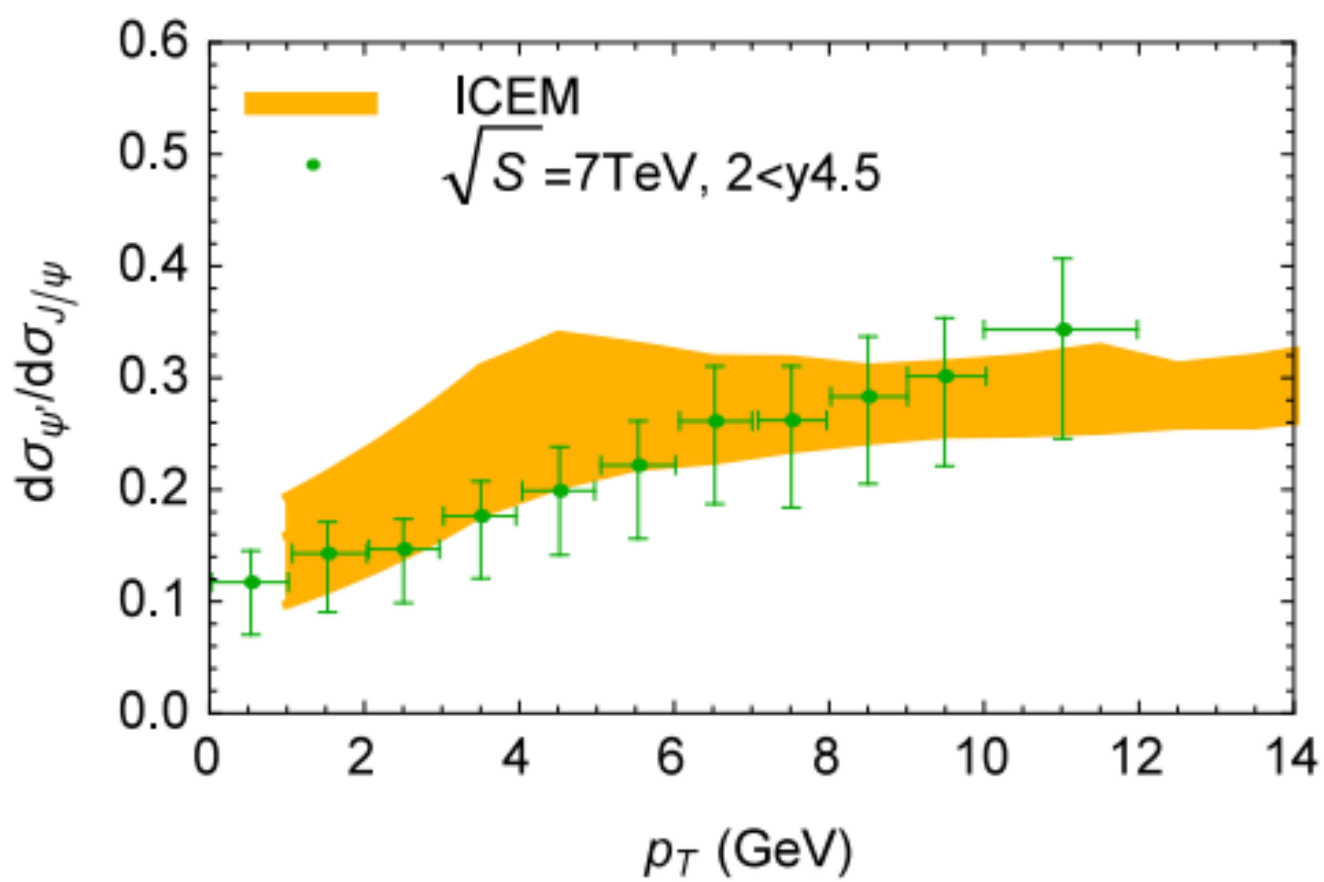
$$\frac{\text{Non-prompt}}{\text{Prompt} + \text{Non-prompt}}$$



Atlas, EPJC 76(5), 1-47, (2016)

CEM AND ICEM

- Ratio of $\psi(2S)$ to J/ψ cross section versus p_T. While CEM predicts constant ratio over p_T, ICEM is in better agreement with data.



Ma and Vogt, PRD94 (2016), 114029
LHCb, EPJC 72 (2012) 2100