HEAVY FLAVOR AND QUARKONIUM PRODUCTION AT THE LHC

HEE SOK CHUNG

TECHNICAL UNIVERSITY OF MUNICH

XXVII INTERNATIONAL WORKSHOP ON DEEP INELASTIC SCATTERING AND RELATED SUBJECTS
8-12 APRIL 2019, TURIN

HEAVY FLAVOR PRODUCTION

- In QCD, inclusive B or D production cross sections are good tests of perturbative QCD and QCD factorization.
- Heavy flavored meson production in lepton and hadron colliders provided fragmentation functions, its universality, and tests of perturbative QCD through perturbative parton cross sections and DGLAP evolution.
- Production mechanism is in good theoretical control, although LHC data calls theory for more precision.
- Heavy flavor production can be a useful tool to probe QCD with TMD factorization and cold-nuclear-matter effects.

HEAVY QUARKONIUM PRODUCTION

- Experimentally, heavy quarkonia are well measured over wide kinematical ranges through clean decay channels like J/ψ or $\Upsilon(nS)$ into $\mu^+\mu^-$.
- Heavy quarkonium production in heavy ion collisions is considered to be good probes of hot and dense QCD, as the bound state is affected by medium effects.
- Nonperturbative matrix elements involving heavy quarkonia can be treated using effective field theory methods.
- Understanding the mechanism of heavy quarkonium production remains a challenge for theory.

HEAVY FLAVOR PRODUCTION

HEAVY FLAVOR PRODUCTION MECHANISM

- B and D meson inclusive cross sections are well described in the heavy quark fragmentation model, which finds justification in collinear factorization theorems.

$$\sigma(e^+e^- \to B + X) = \sigma_{e^+e^- \to b+X} \otimes D_{b\to B}$$

$$\sigma(pp \to B + X) = f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{ij\to b+X} \otimes D_{b\to B}$$

fragmentation function

parton distribution functions

- Nonperturbative heavy quark fragmentation functions extracted from measurements at lepton colliders (LEP, CESR, KEKB), combined with b quark production cross section computed in perturbative QCD, provide good description of data.

HEAVY FLAVOR PRODUCTION MECHANISM

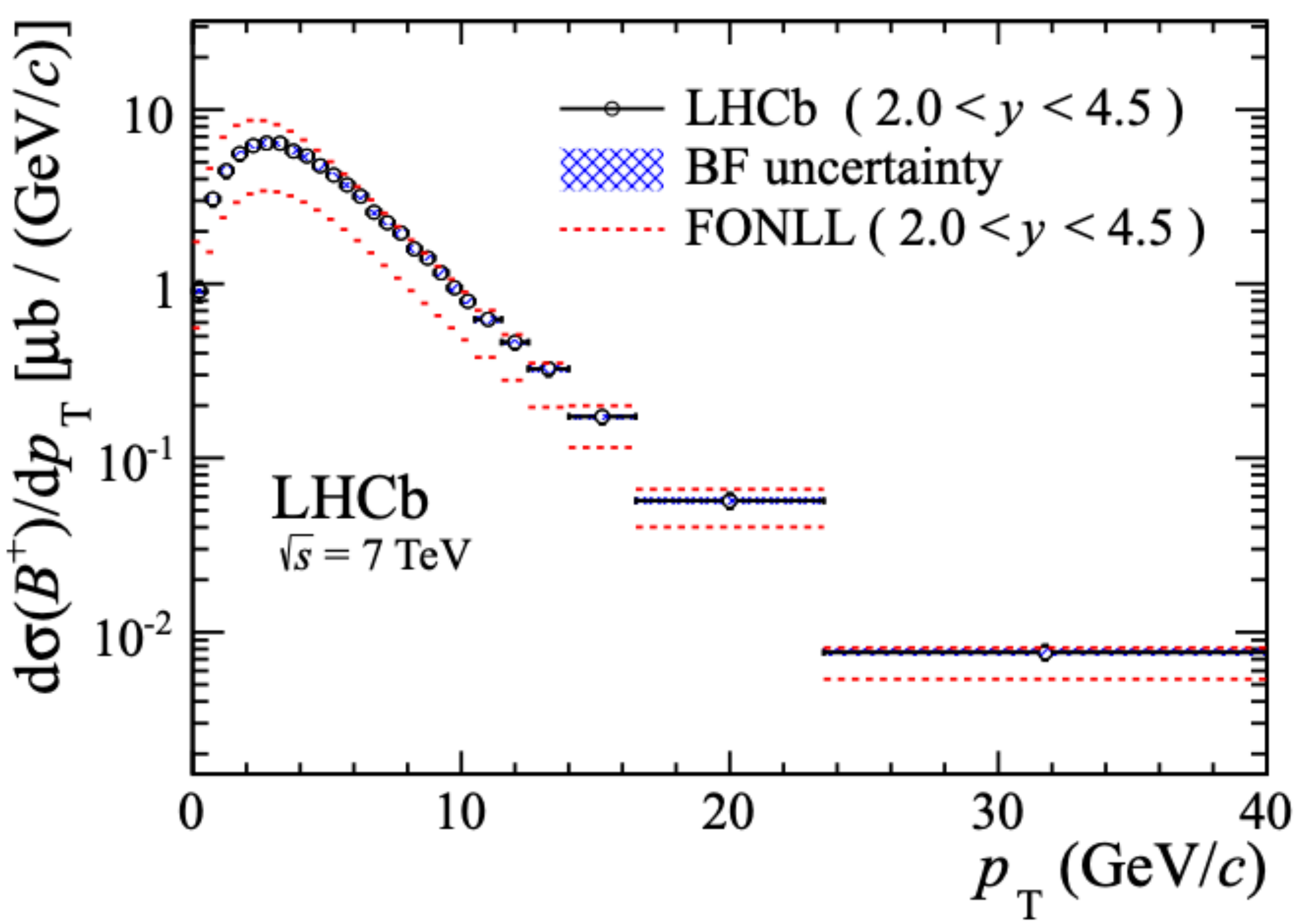
- Existing calculations use massless heavy quark for $p_T \gg m_Q$ and massive heavy quark for $p_T \approx m_Q$, and smoothly interpolate between the two.
- Hard parts are calculated up to NLO in α_s, and logarithms in p_T are resummed at large p_T.
- FONLL (Fixed Order + Next-to-Leading Logs) and General-mass variable-flavor-number (GM-VFN) scheme calculations are available in literature.

FONLL : Cacciari, Greco, Nason, JHEP 9805 (1998) 007,
Cacciari, Frixione, Nason, JHEP 0103 (2001) 006
GM-VFN : Aivazis, Collins, Olness, Tung, PRD50, 3102 (1994),
Kniehl, Kramer, Schienbein, Spiesberger, PRD71, 014018 (2005)

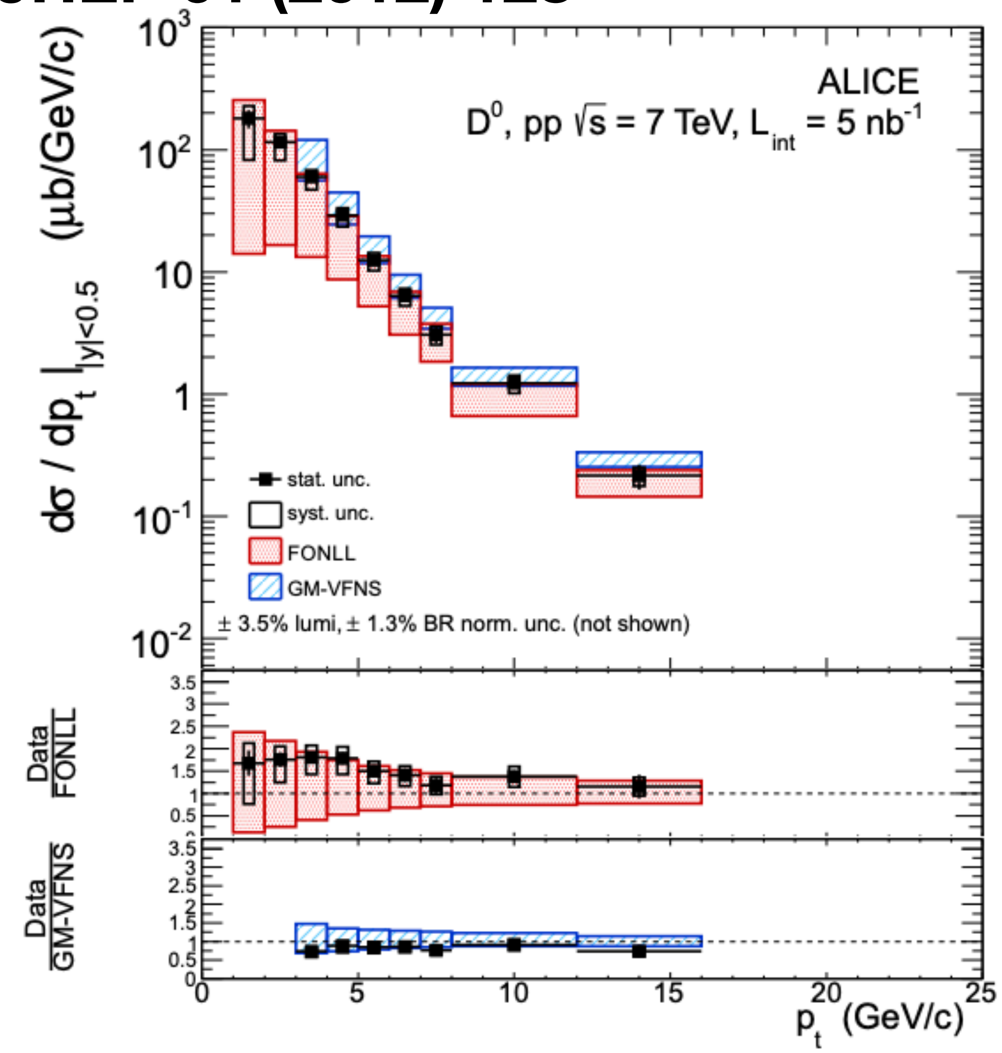
HEAVY FLAVOR PRODUCTION MECHANISM

- B and D meson production at the LHC

LHCb, JHEP08(2013)117



ALICE, JHEP 01 (2012) 128

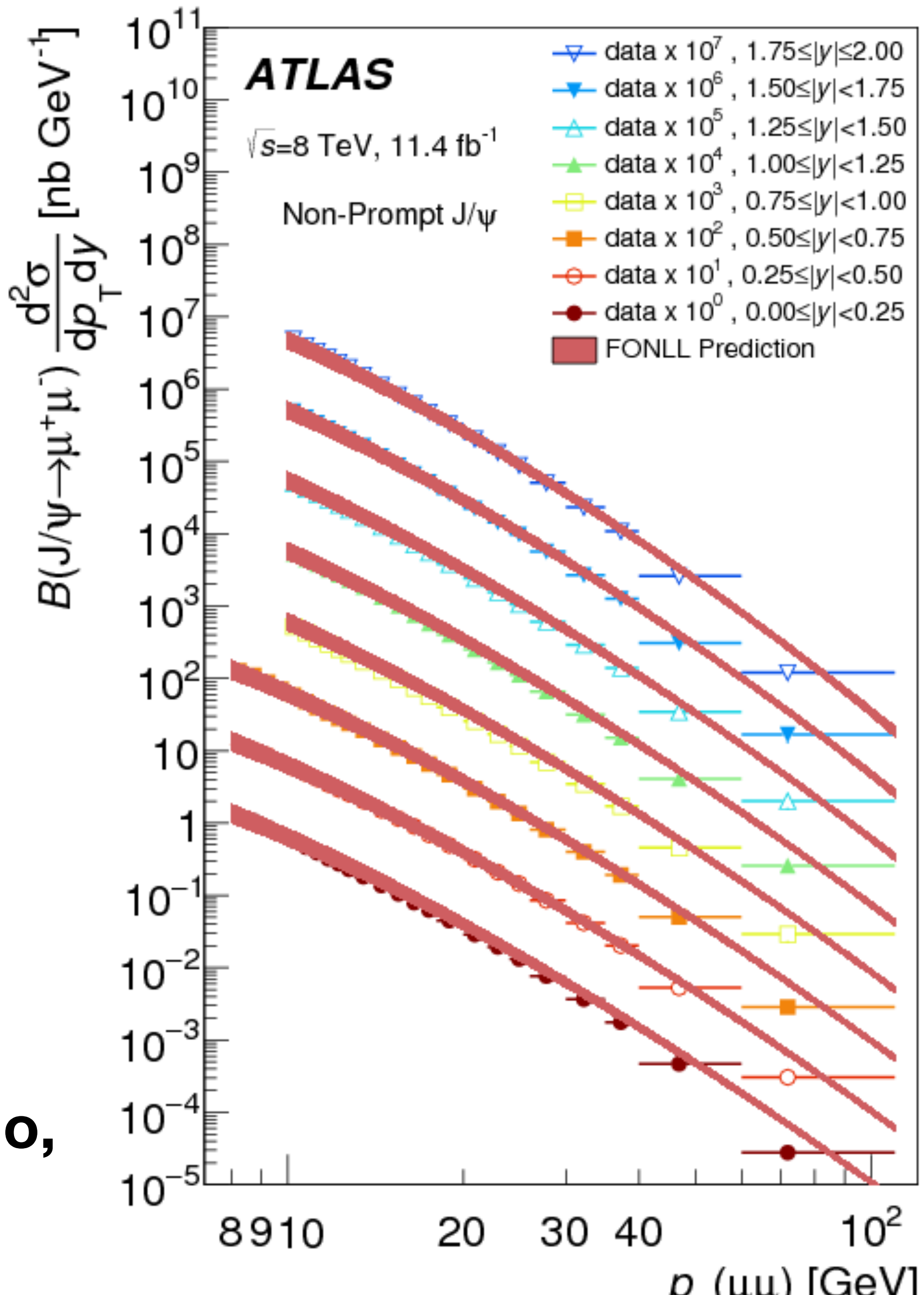


FONLL : Cacciari, Frixione, Houdeau, Mangano, Nason, Ridolfi, JHEP 1210 (2012) 137

GM-VFNS : Kniehl, Kramer, Schienbein, Spiesberger, EPJC72 (2012) 2082

HEAVY FLAVOR PRODUCTION MECHANISM

- B meson cross sections at large p_T from $B \rightarrow J/\psi + X$ (non-prompt J/ψ)
- Shows that perturbative QCD works well for single-hadron inclusive cross sections over a wide range of p_T



ATLAS, EPJC76, 283 (2016)
M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, G. Ridolfi, JHEP 1210 (2012) 137

HEAVY FLAVOR PRODUCTION MECHANISM

- At small p_T, the hadroproduction process can develop sensitivity to the intrinsic transverse momentum of initial-state partons. Data from the LHC at small p_T will be helpful to quantify the effect.

See Tuesday's talk by Rafał Maciuła

- Heavy flavor production also serves as good probes of cold-nuclear-matter (CNM) effects from pA collisions. Understanding cold-nuclear-matter effects is important in disentangling CNM effects from hot and dense medium effects from QGP.

Experimental results will be presented in other talks in this session.

HEAVY QUARKONIUM PRODUCTION

QUARKONIUM PRODUCTION

- Inclusive quarkonium production is measured over a wide kinematical range, and can be used to probe many areas of QCD.
- At very large p_T, collinear factorization formalism is valid.
- 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 processes in heavy ion collisions are sensitive to both cold-nuclear-matter effects and hot and dense medium effects.

QUARKONIUM PRODUCTION AND TMD

- Quarkonium cross sections at $p_T \approx m_Q$ or smaller can become sensitive to the intrinsic transverse momentum of initial-state partons. In such case, TMD factorization (k_T-factorization) is the appropriate formalism.
- In order to make predictions based on TMD PDFs, it is important to be able to calculate quarkonium production cross sections from parton collisions ***reliably***.

QUARKONIUM PRODUCTION AND QGP

- Quark-gluon plasma is expected to suppress $Q\bar{Q}$ bound states due to color screening in deconfined QCD medium.

  Matsui and Satz, PLB 178 (1986) 416

  Quantitative information come from measurements of R_{AA} in heavy-ion collisions, where anomalous suppression apart from cold-nuclear-matter (CNM) effects are expected.
- While CNM effects can be probed from R_{pA} from pA collisions, theoretical calculation of R_{AA} including hot medium effects is difficult, and most existing calculations are model dependent.
- In order to study how quarkonium in QGP affects R_{AA} quantitatively, ***good knowledge in quarkonium production mechanism*** is necessary.

QUARKONIUM PRODUCTION

- In order to make a QCD-based prediction we need a good understanding of quarkonium production mechanisms based on QCD.
- Large separation of scales naturally gives rise to effective field theory methods :
  quarkonium mass ~ heavy-quark mass ≫ binding energy leads to nonrelativistic effective field theories.
- Most studies on production mechanism focus on inclusive production at large p_T where theoretical predictions are expected to be more reliable.

QUARKONIUM PRODUCTION

- We introduce three popular approaches to inclusive quarkonium production.
  - Nonrelativistic effective field theory method (Nonrelativistic QCD)
  - Color singlet model
  - Color evaporation model

NONRELATIVISTIC EFFECTIVE THEORY

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

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

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

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

- 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.
- NRQCD have been successfully applied to spectroscopy and decay processes.

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.

- Nonperturbative matrix elements have known scalings in v.
- Sum over n is organized in powers of v; when the sum is truncated, cross section is given in terms of a finite number of nonperturbative matrix elements.

PRODUCTION IN NRQCD

- Unlike PDFs of fragmentation functions, which are functions of momentum fractions, NRQCD matrix elements are numbers.
- Nonperturbative matrix elements can be computed ***if*** they correspond to the color-singlet (CS) $Q\bar{Q}$ 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 (CO) $Q\bar{Q}$ Fock state.
- Hence, CO matrix elements are usually extracted from data.

HADROPRODUCTION IN NRQCD

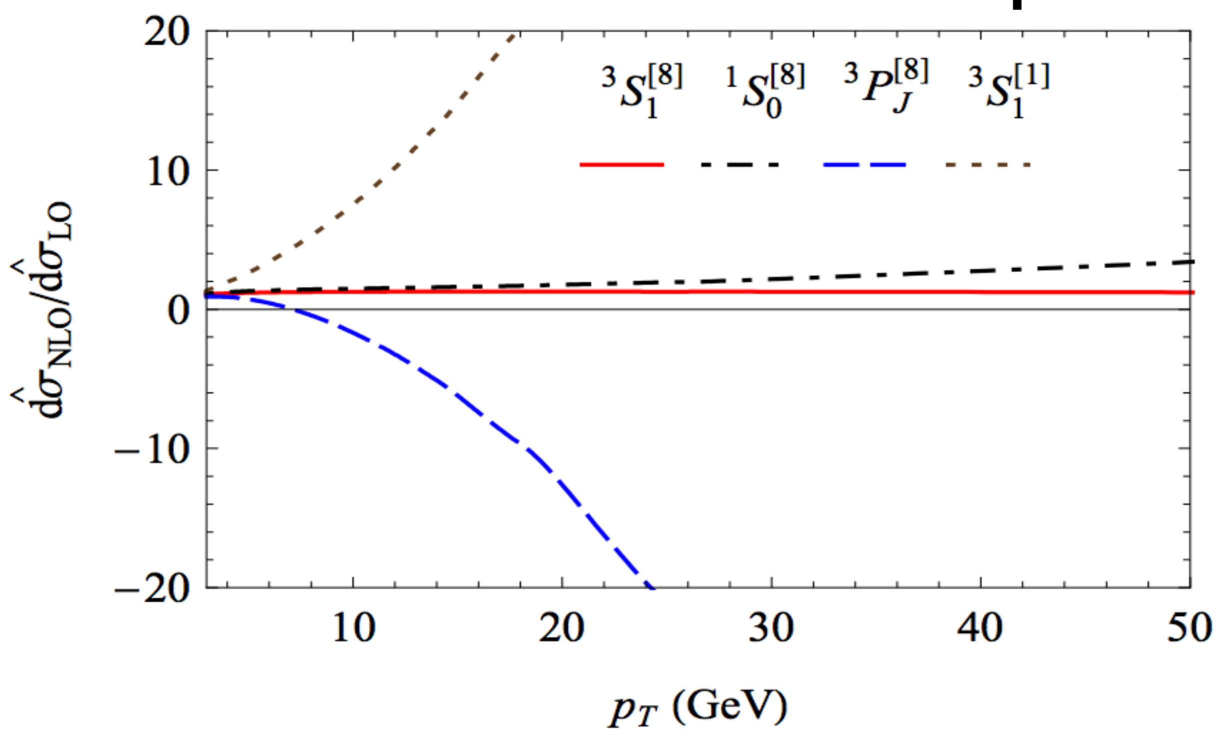
- In J/ψ or $\Upsilon(nS)$ hadroproduction at large p_T, CO $Q\bar{Q}$ cross sections are enhanced compared to the CS $Q\bar{Q}$ cross section. Hence, even though the CO matrix elements are suppressed compared to CS matrix elements, the CO contribution can dominate the cross section.

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

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

Leading-power (LP) fragmentation

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

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 NRQCD

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

- Leading order in v : ${}^3S_1^{[1]}$ **(color singlet)**

  Relative order v^3 : ${}^1S_0^{[8]}$ **(color octet, spin flip)**

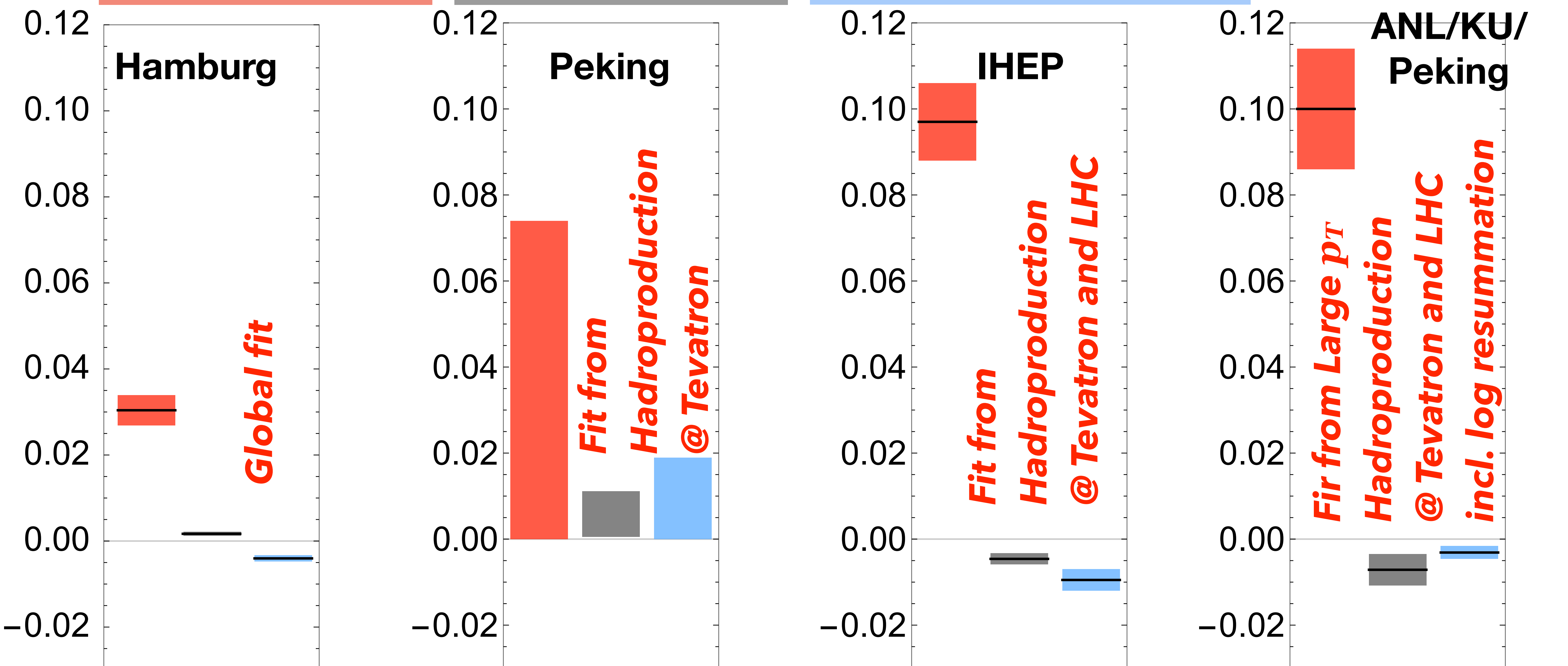
  Relative order v^4 : ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$ **(*J*=0,1,2) (color octet, non spin flip)**

- The approximate heavy-quark spin symmetry implies relation between $\langle \mathcal{O}^{J/\psi}({}^3P_J^{[8]}) \rangle$ for J=0,1,2.

- Determination of three unknown nonperturbative matrix elements lead to description of J/ψ production in NRQCD to relative order v^4

DETERMINATIONS OF J/ψ MATRIX ELEMENTS

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



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 general, determinations based on hadroproduction data tend to overestimate HERA ($ep \to J/\psi + X$) and Belle ($e^+e^- \to J/\psi + X$) measurements.

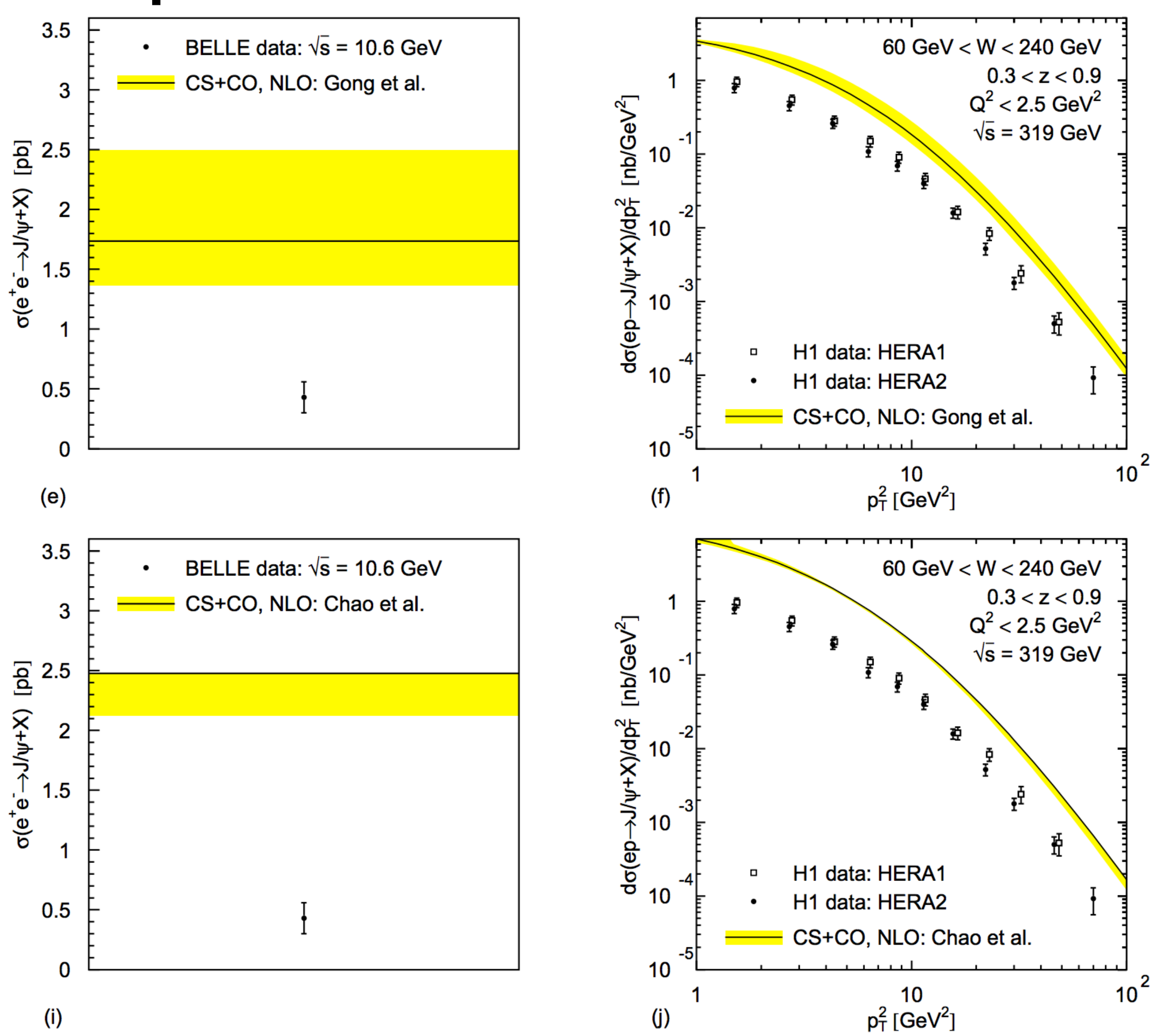
Butenschoen and Kniehl, MPLA28, 1350027 (2013)

- 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)

J/ψ PRODUCTION IN OTHER COLLIDERS

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



Butenschoen and Kniehl, MPLA28, 1350027 (2013)

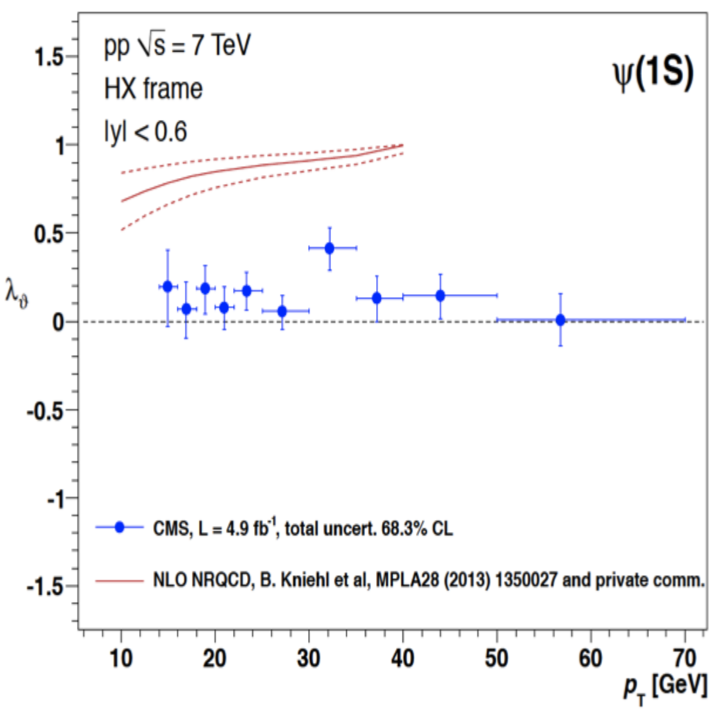
Matrix elements from Gong, Wan, Wang, Zhang, PRL110, 042002 (2013) (IHEP)

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

J/ψ POLARIZATION IN HADROPRODUCTION

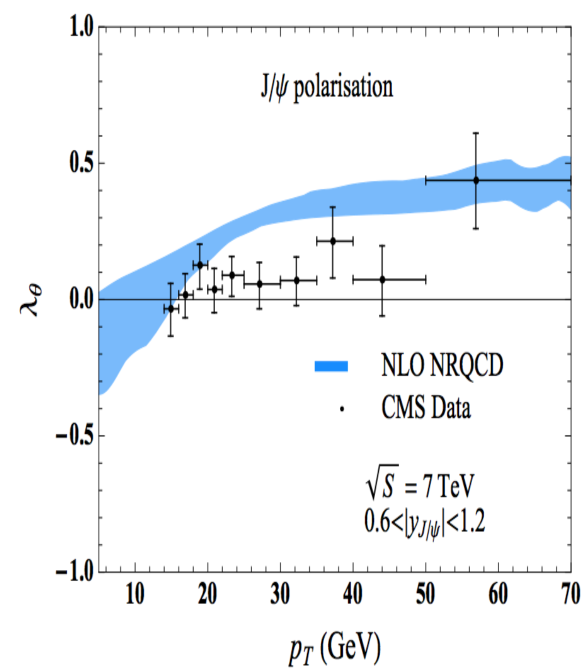
- Global fit leads to J/ψ polarization predictions that are incompatible with LHC measurements.

Hamburg



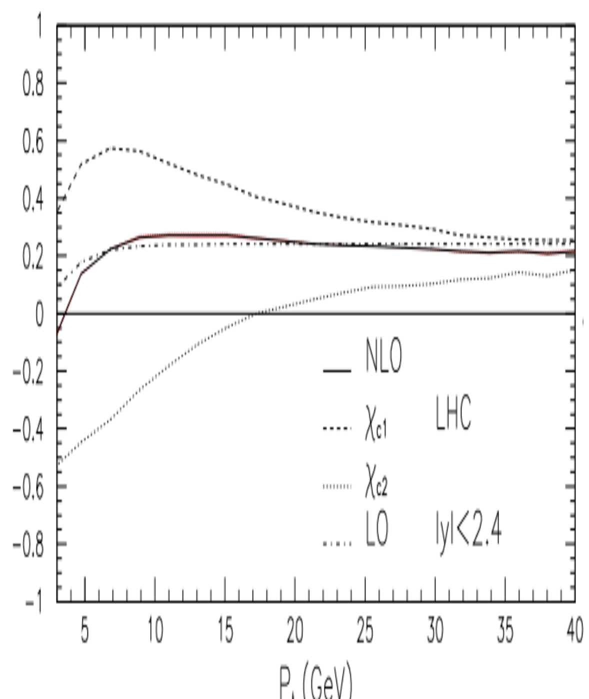
CMS, PLB727, 381 (2013)
Butenschoen and Kniehl, PRL108, 172002 (2012)

Peking



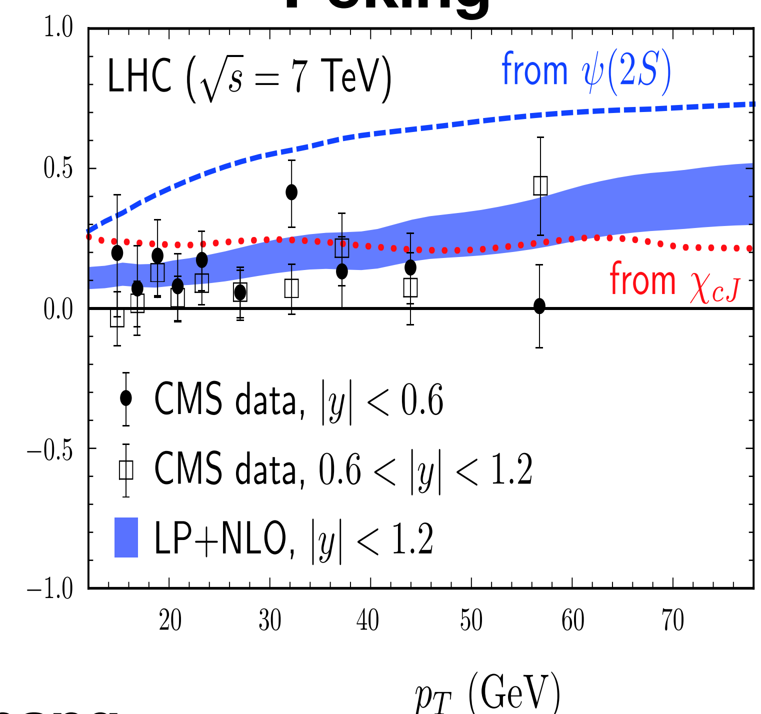
Shao, Han, Ma, Meng, Zhang, Chao, JHEP 1505 (2015) 103

IHEP



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

ANL/KU/ Peking

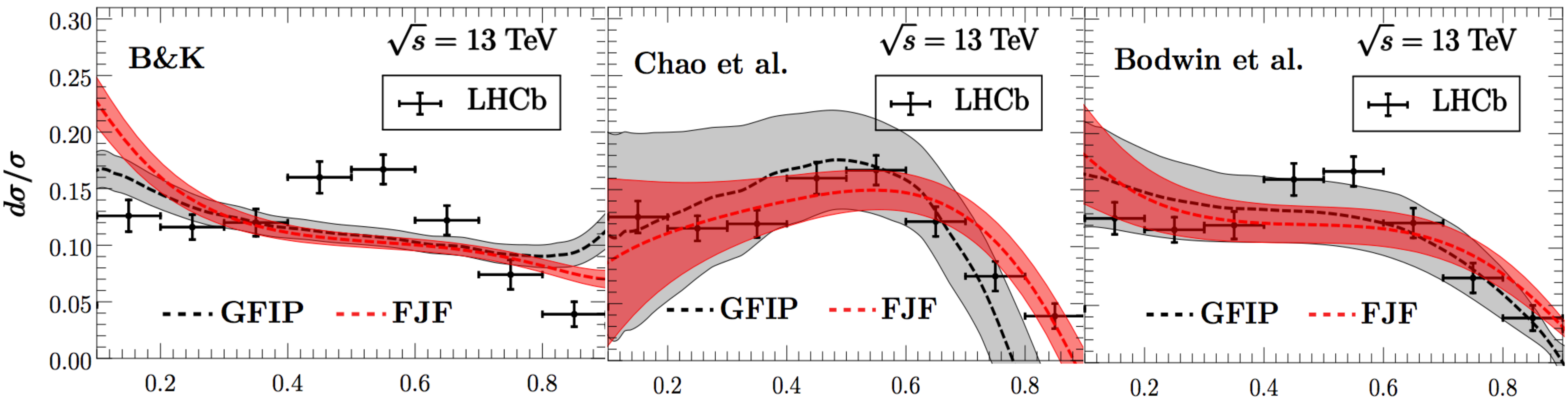


Bodwin, Chao, Chung, Kim, Lee, Ma, PRD93, 034041 (2016)

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)

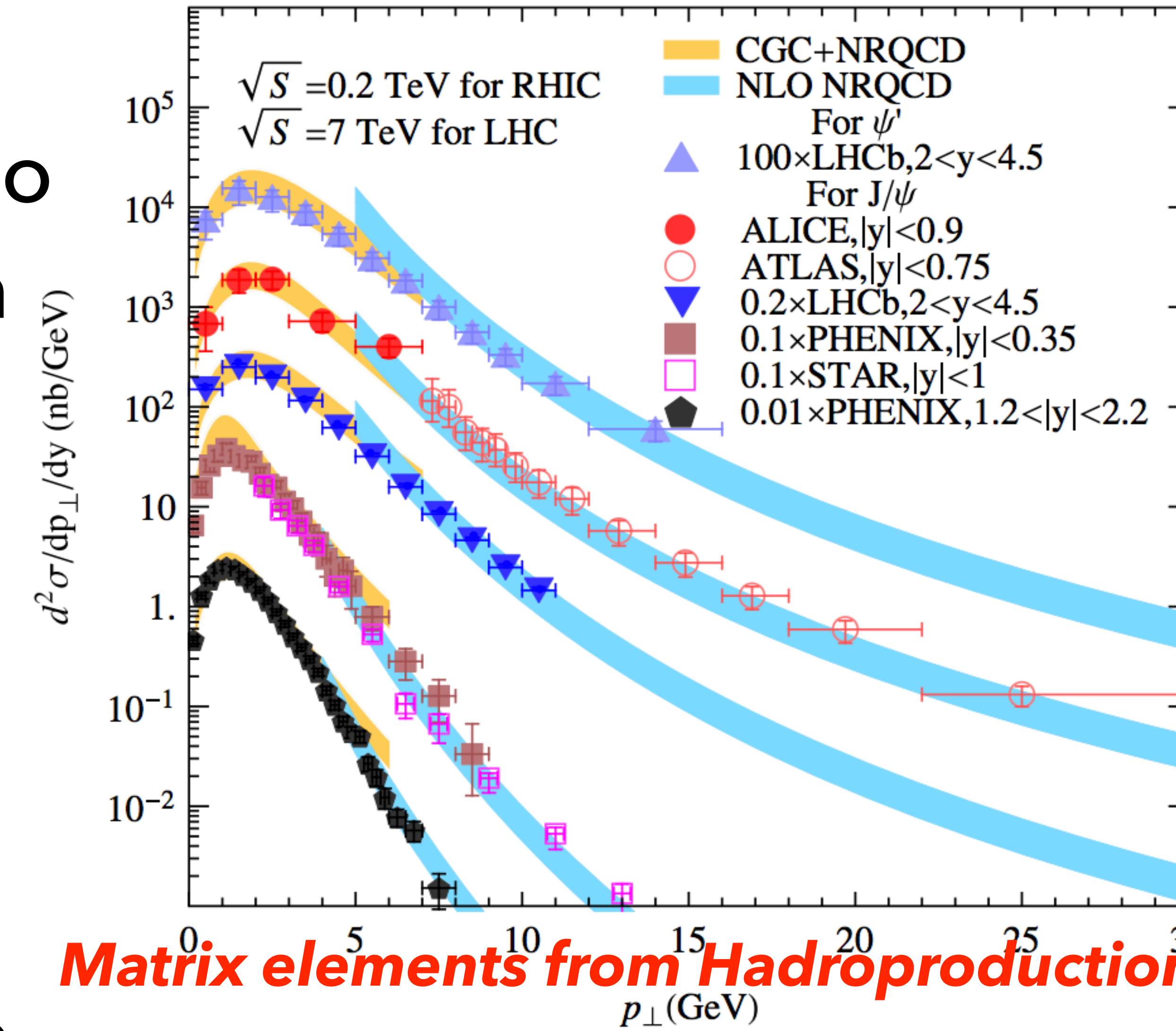


Matrix elements from Global fit

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)

Other approaches to quarkonium production with TMDs will be presented in this conference

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)

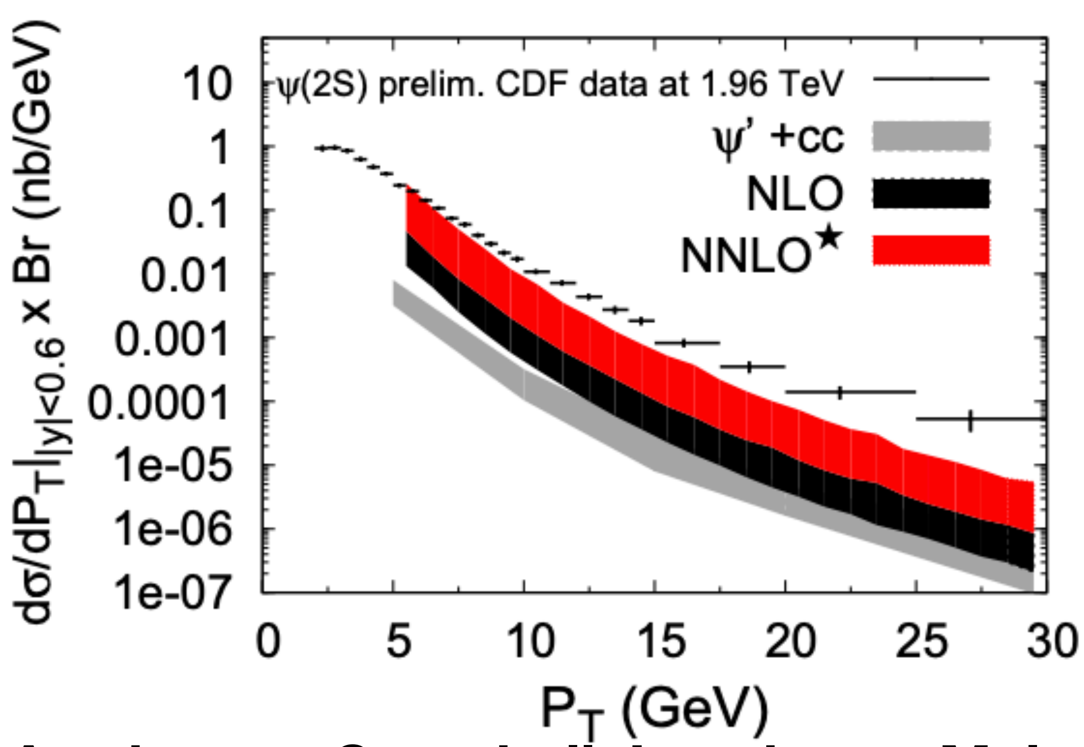
$\sigma_{Q\bar{Q}_{\rm CS}}$: perturbative cross section of color-singlet $Q\bar{Q}$

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

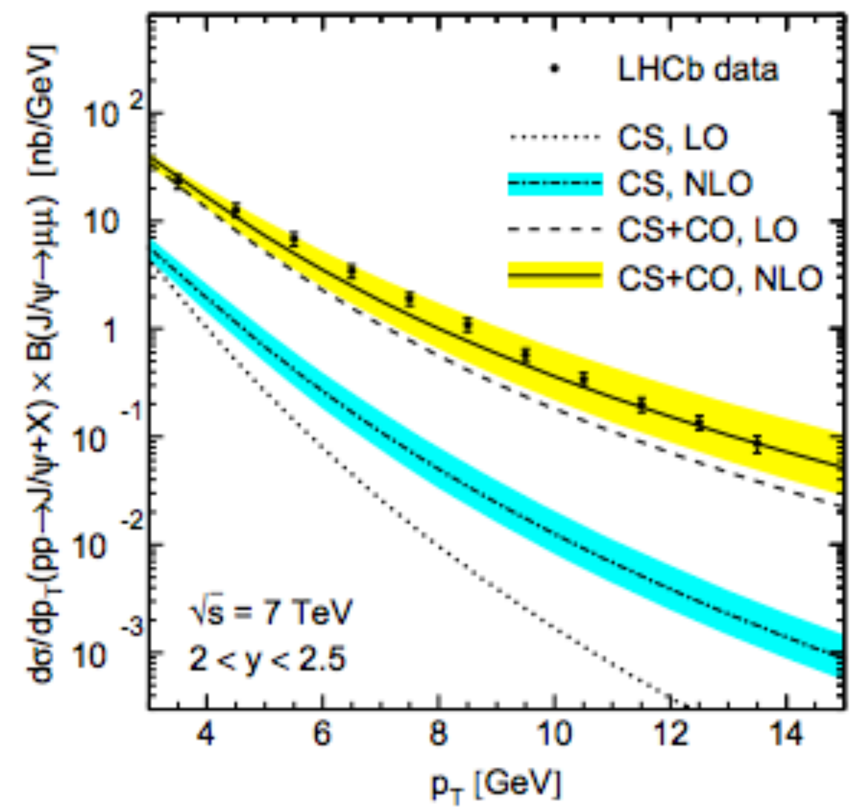
- For S-wave quarkonia, production cross section in CSM is equal to the cross section in NRQCD at leading order in v.
- CSM suffers from infrared divergence when applied to P-wave quarkonia; in NRQCD, this problem is resolved through operator renormalization that requires mixing with color-octet matrix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

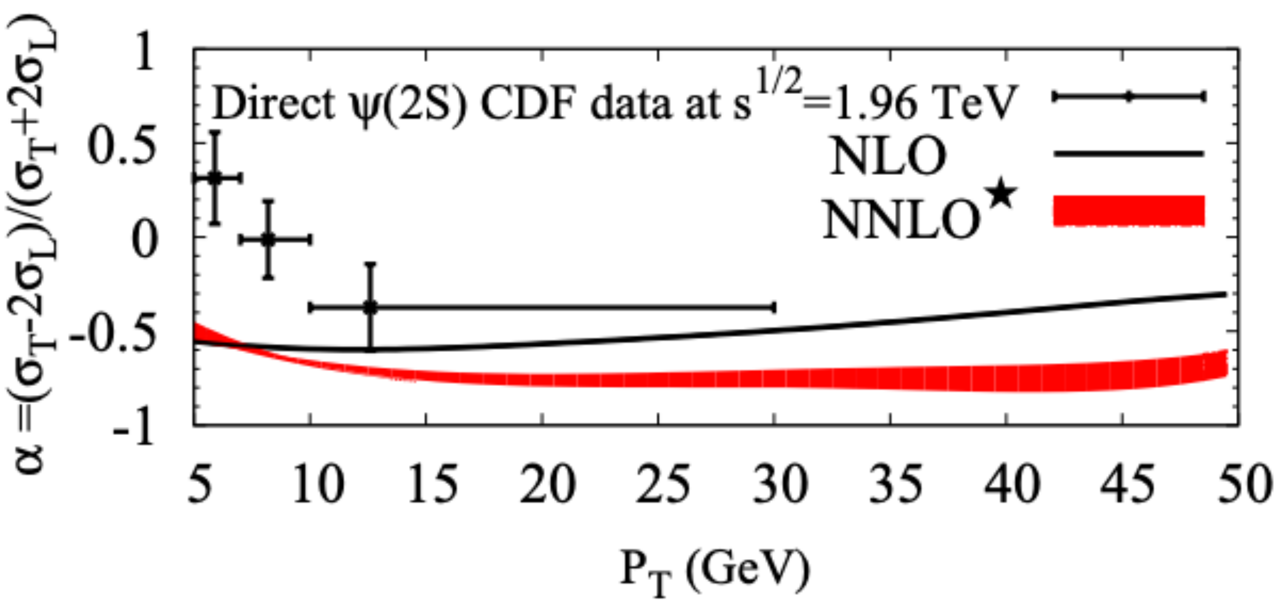


Butenschoen and Kniehl, MPLA28, 1350027 (2013)

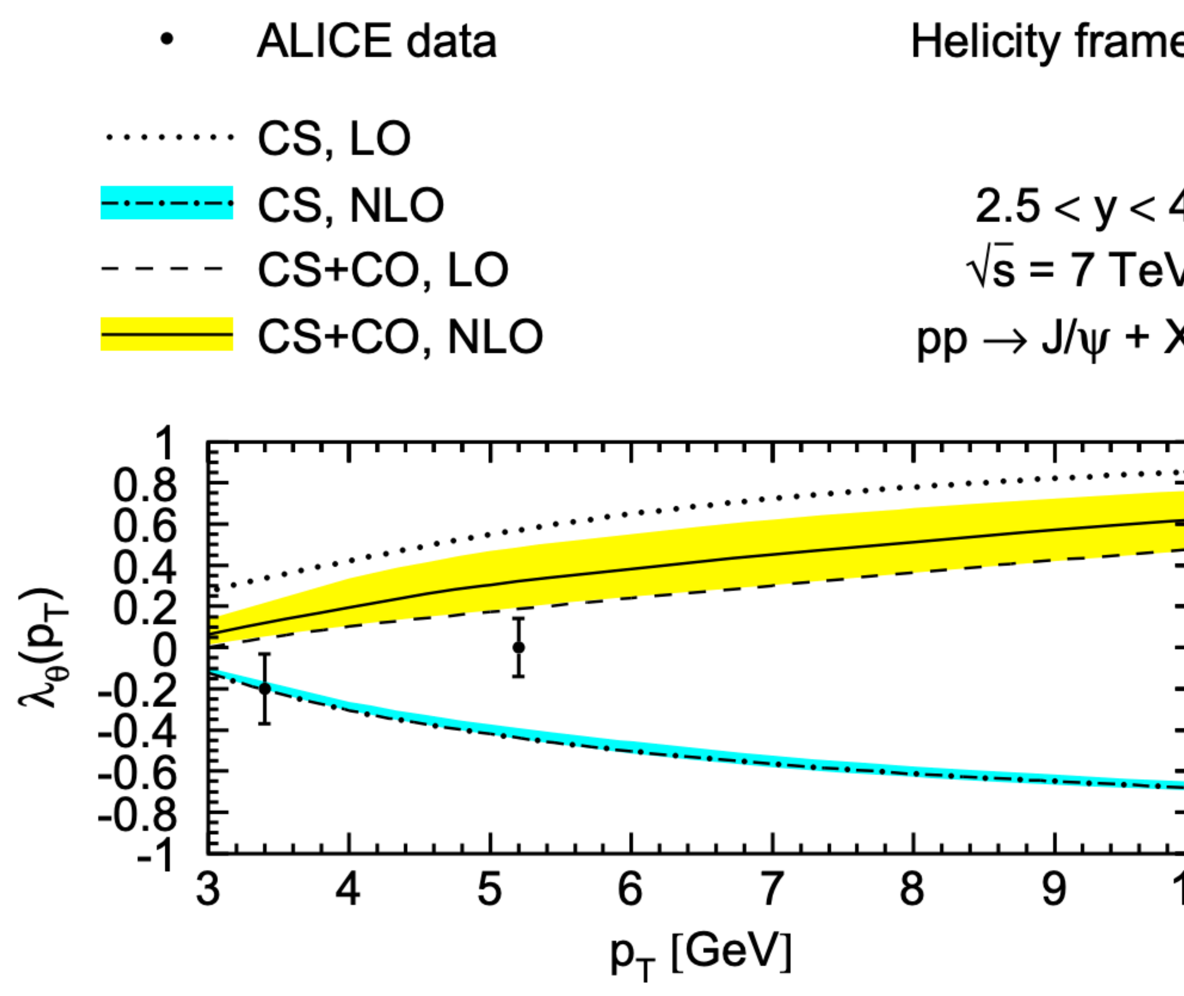
- CSM also suffers from large K factors that depend strongly on p_T. This also can be understood from expansion in $1/p_T$.

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)

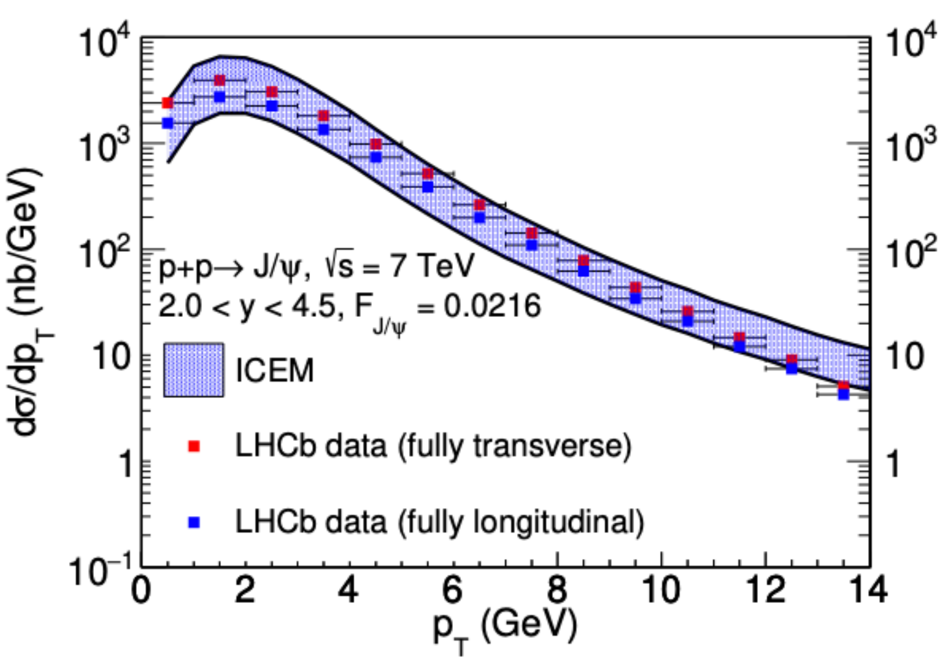
- The formalism is based on quark-hadron duality, but it is difficult to relate the phenomenological factor F_H with QCD.
- CEM predicts same shape in p_T for all charmonium/bottomonium states, which is in slight tension with measurements.

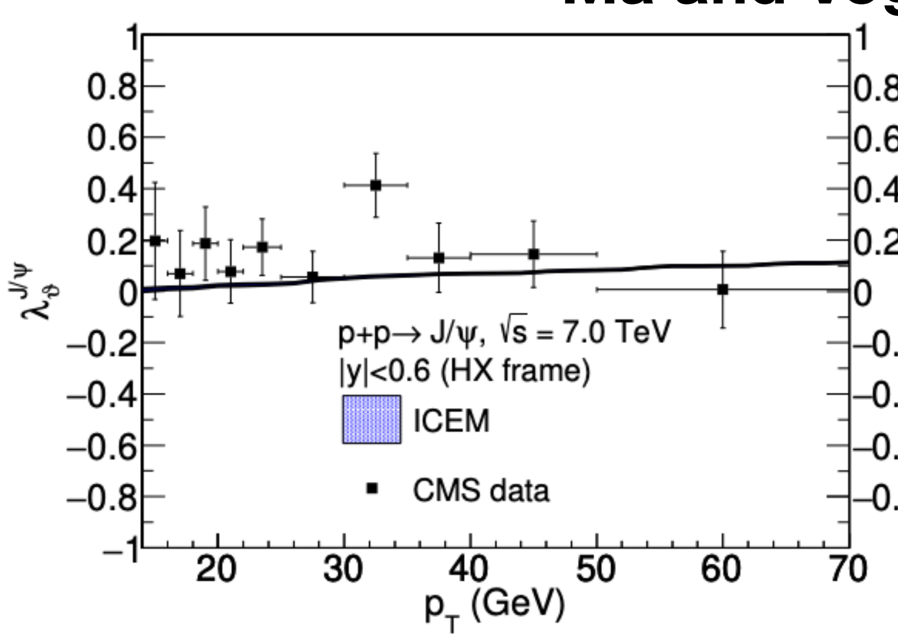
COLOR EVAPORATION MODEL (CEM)

- 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

SUMMARY

- Heavy flavored meson production mechanism is already in good theoretical control. With precision measurements at the LHC and more theoretical effort, Heavy flavored mesons will be useful tools to probe QCD in many areas.
- Heavy quarkonium production can be more sensitive to TMD PDFs, DPS and QGP effects, but production mechanism of heavy quarkonia is still a challenge for theory.

SOME TALKS AT DIS 2019 RELATED TO HEAVY FLAVOR / QUARKONIUM PRODUCTION

TMDs

- TUE, 11:30 : Francesco Murgia, Quarkonium production and TMDs at LHC (WG7)
- TUE, 11:50 : Pieter Taels, Gluon TMDs in quarkonium production at an EIC (WG7)
- TUE, 17:35 : Rafal Maciula, Production of J/ψ quarkonia in color evaporation model based on k_T-factorization (WG2)
- WED, 14:34 : Florent Scarpa, Studying gluon TMDs with J/ψ pair production at the LHC (WG6)
- THU, 9:45 : Melih Arslan Ozcelik, Constraining gluon PDFs and TMDs with quarkonium production (WG5)

Heavy ion collisions

- WED, 9:05 : Hans Dembinski, Heavy-flavour hadron production at LHCb (WG5)
- WED, 11:20 : Petr Chaloupka, Heavy-flavor hadron production in heavy-ion collisions (WG5)
- WED, 11:55 : Roberta Arnaldi, Quarkonium results in heavy-ion collisions (WG5)

Other

- WED, 9:40 : Paolo Iengo, Production of quarkonia and heavy flavour states in ATLAS (WG5)
- WED, 14:51 : Sookhyun Lee, J/psi polarization in p+p collisions at PHENIX (WG6)
- THU, 9:22 : Jean-Philippe Lansberg, Accessing double parton scatterings with associated-quarkonium production (WG2+WG4)
- THU, 10:45 : Hannu Paukkunen, Hadroproduction of open heavy flavour for PDF analyses (WG5)

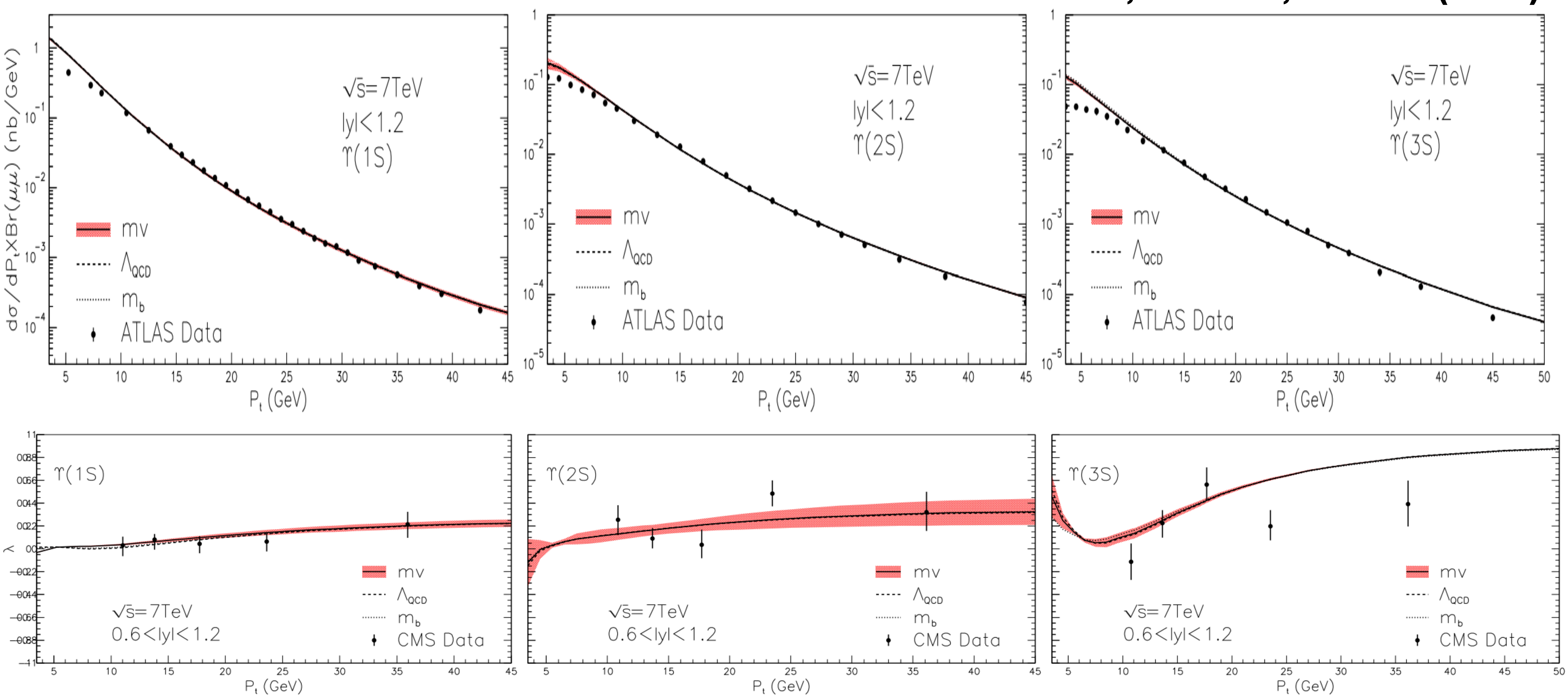
BACKUP

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

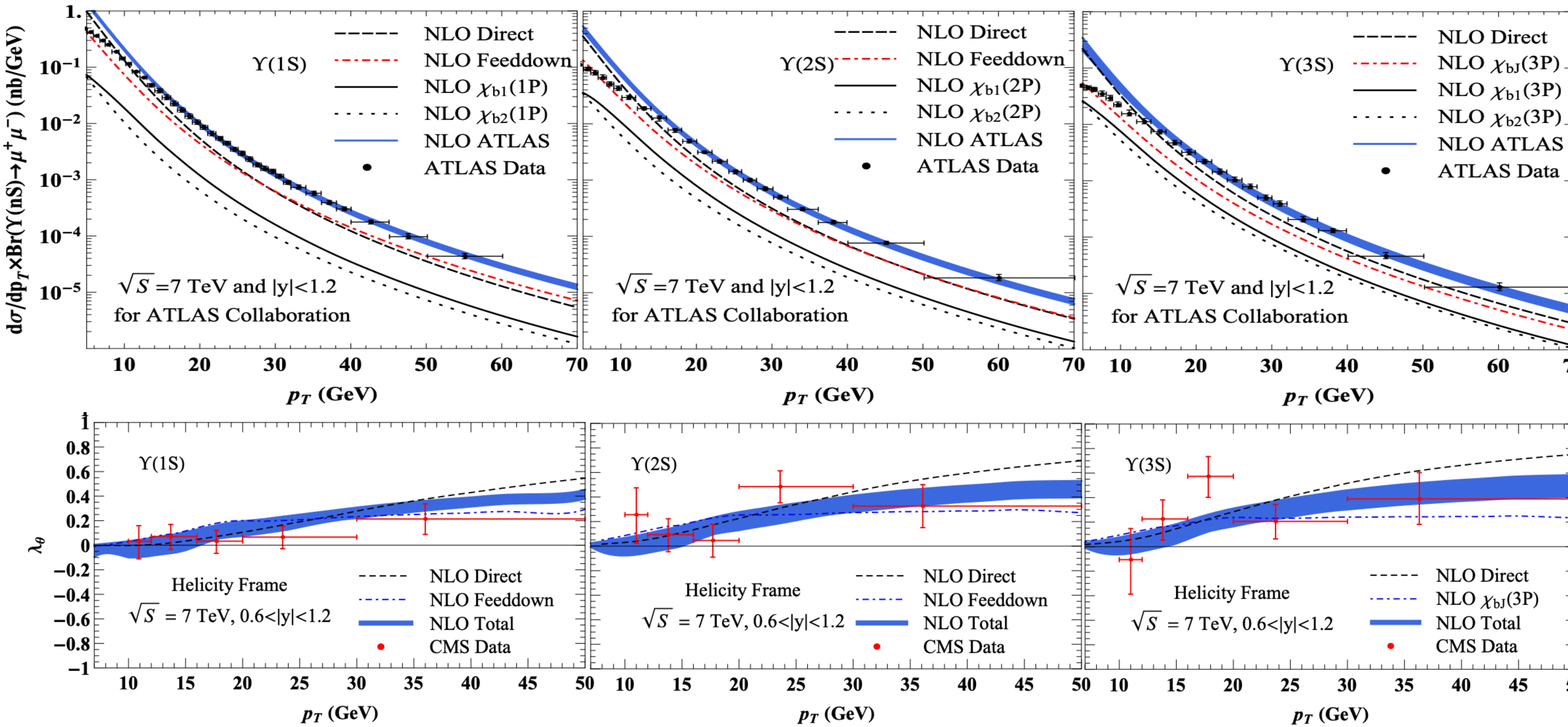
ATLAS, PRD87, 052004 (2013)
CMS, PRL110, 081802 (2013)



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

$\Upsilon(nS)$ HADROPRODUCTION IN NRQCD

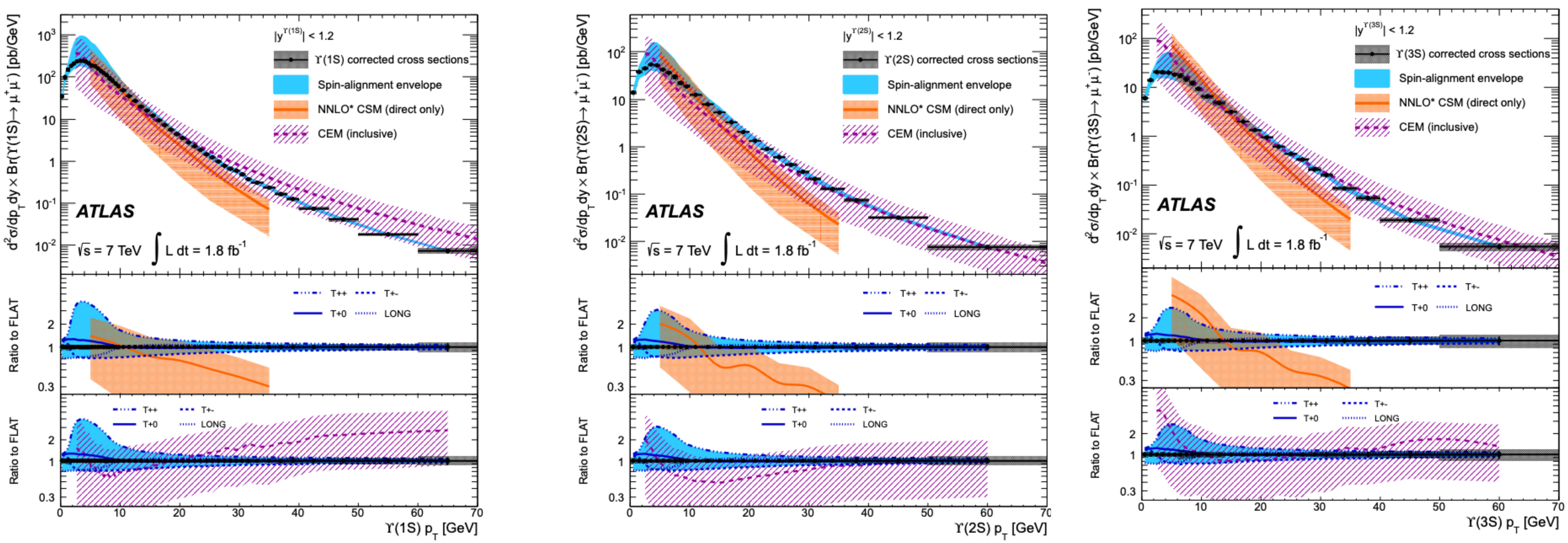
ATLAS, PRD87, 052004 (2013)
CMS, PRL110, 081802 (2013)



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

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

ATLAS, PRD87, 052004 (2013)



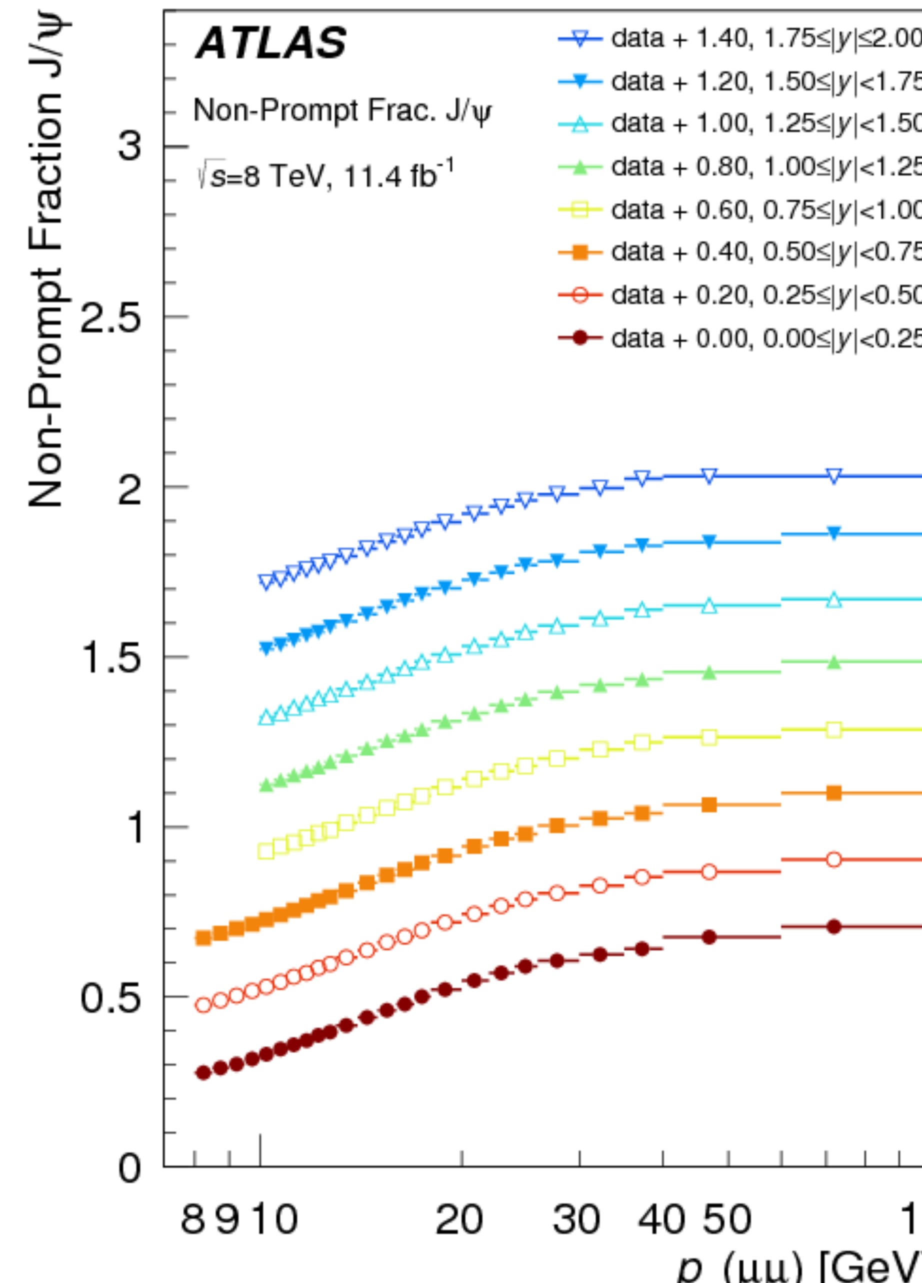
CSM : Artoisenet, Campbell, Lansberg, Maltoni, Tramontano, PRL101 (2008) 152001
Lansberg, EPJC61 (2009) 693

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.

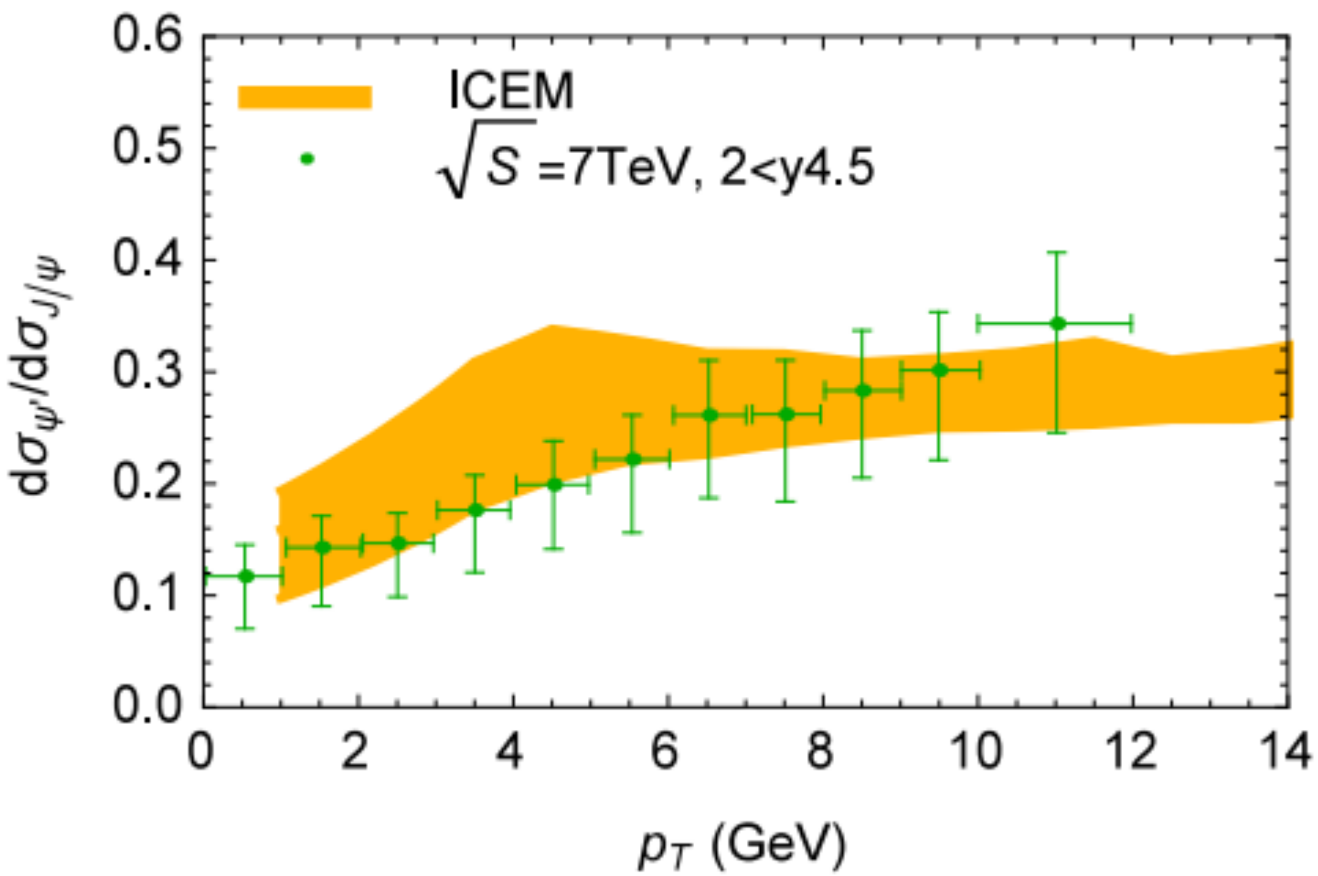
$$\frac{\text{Non-prompt}}{\text{Prompt} + \text{Non-prompt}}$$



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