Review of heavy quarkonium production mechanism in pp collisions from low to high p_t

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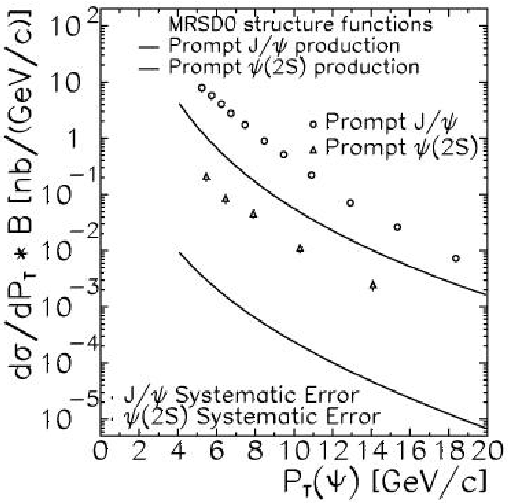
A good laboratory

- J/ψ discovery (1974), Υ discovery (1977).
- good features
  - Heavy enough for perturbative calculations
  - Clear signal
  - Simple structure
- J/ψ suppression as a signature of quark-gluon plasma (QGP)[1]
  - Hot-nuclear-matter (HNM) effects: pA (dA) collisions
  - Cold-nuclear-matter (CNM) effects: AA collisions

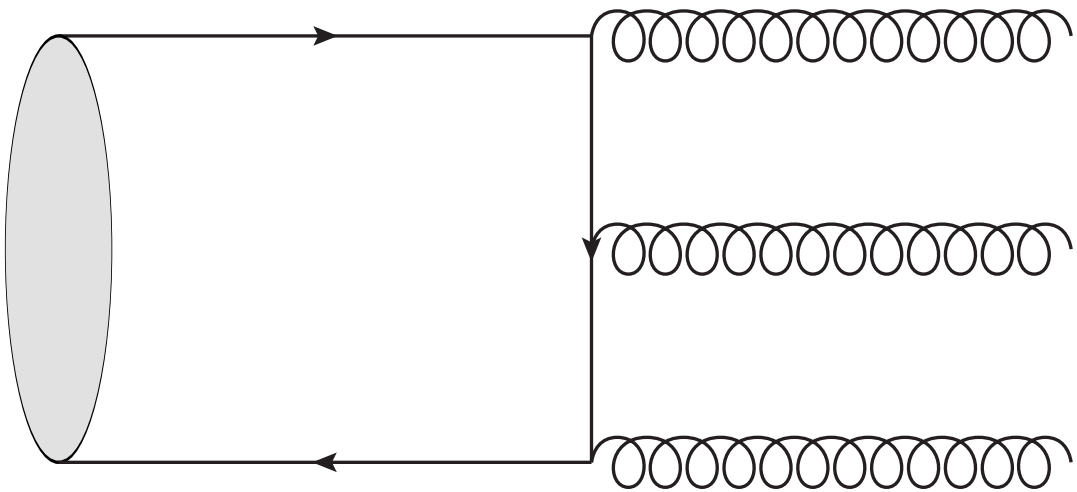
[1] Matsui, Satz, PLB 178, 416 (1986)

Colour-singlet Model (CSM)

- ψ' (J/ψ) surplus[2]
- IR divergence at LO: e.g. h_c radiative decay



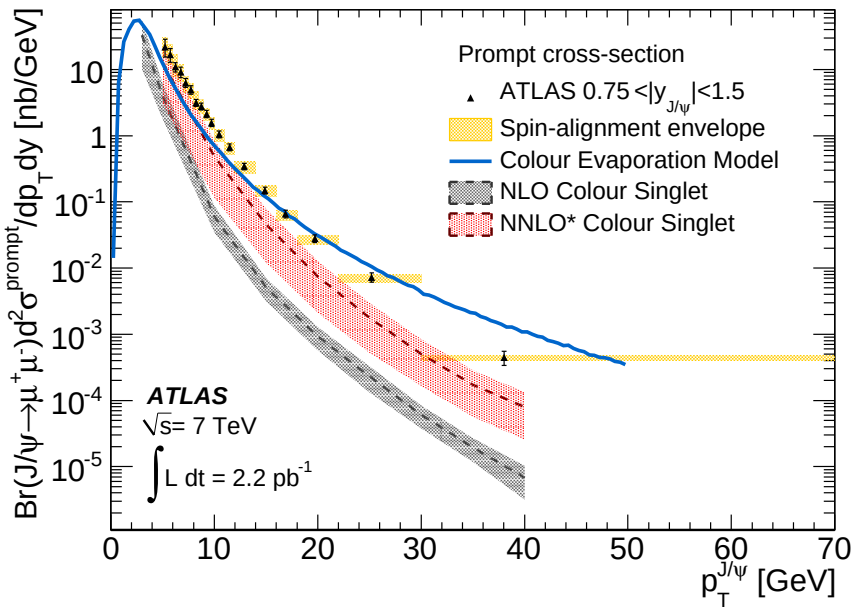
h_c

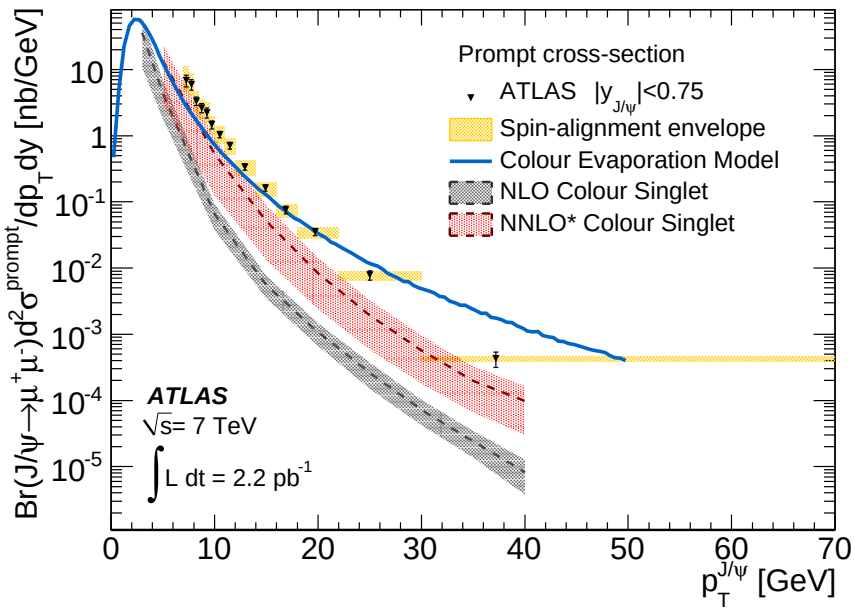


[2]CDF Collaboration, PRL 69, 3704 (1992)

Colour-evaporation Model (CEM)

- poor agreement with p_t spectrum of ψ hadroproduction[3]
- wrong for ratio: e.g. $\sigma(\chi_{c1}) : \sigma(\chi_{c2})$, $\sigma(\chi_c) : \sigma(J/\psi)$
- do not apply to polarization





[3] Schuler and Vogt, PLB 387, 181 (1996); ATLAS, NPB 850, 387 (2011)

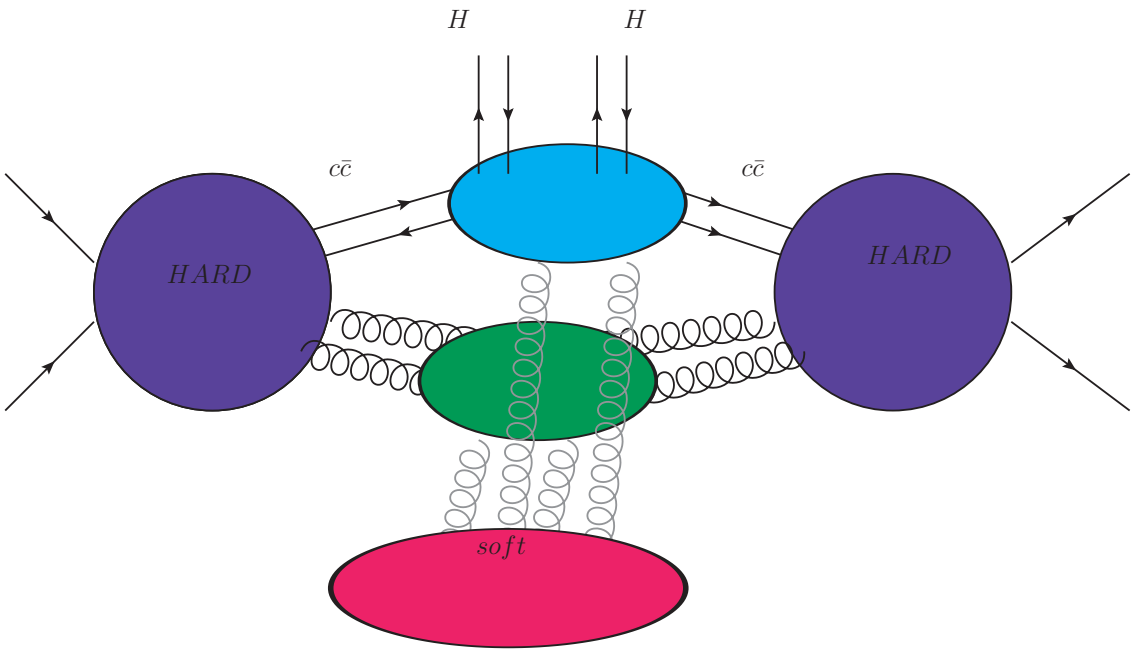
Nonrelativistic QCD (NRQCD)[5]

- Seperated scales m_Q, $m_Q v^2$
- $v^2 = 0.3$ for charmonium, $v^2 = 0.1$ for bottomonium
- Time scales: heavy quark pair fluctuation $\sim 1/m_Q$; hadronization $\sim 1/(m_Q v^2)$
- NRQCD Factorization (proof up to NNLO[4])

$$d\sigma(H) = \sum_n df_n \langle \mathcal{O}^H(n) \rangle$$

- f_n: Short-distance coefficient (SDC): production of a heavy quark pair, to be calculated perturbatively
- $\langle \mathcal{O}^H(n) \rangle$: Long-distance matrix element (LDME): hadronization, to be extracted from experiment

[4] Nayak, Qiu and Sterman, PRD 72, 114012 (2005)
[5] Bodwin, Braaten and Lepage, PRD 51, 1125 (1995)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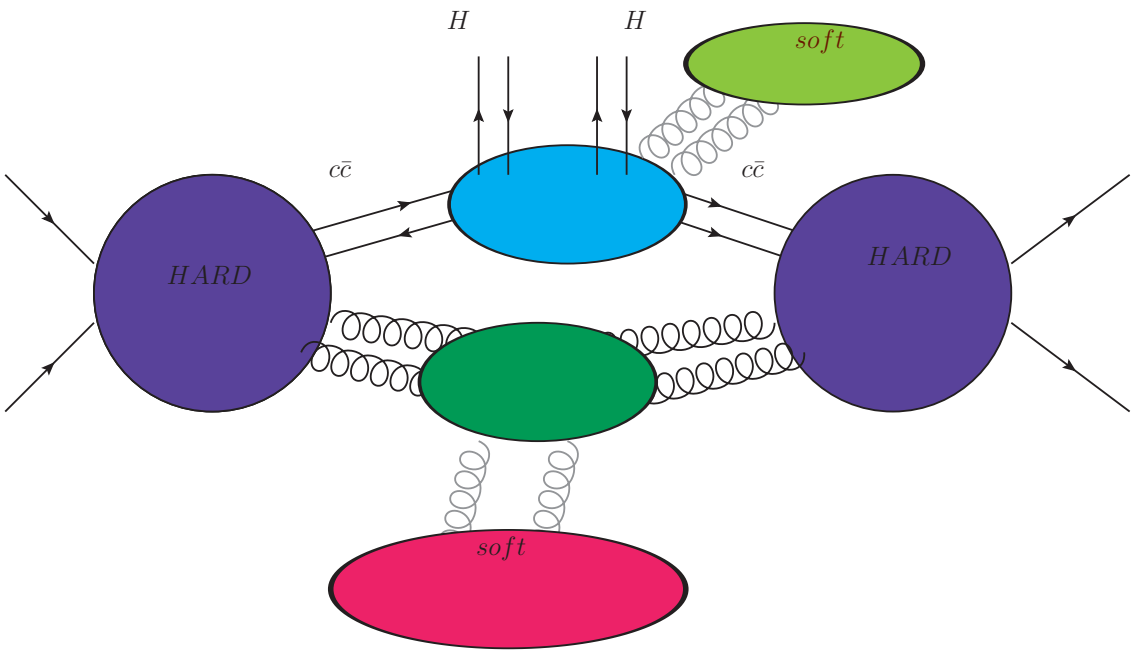
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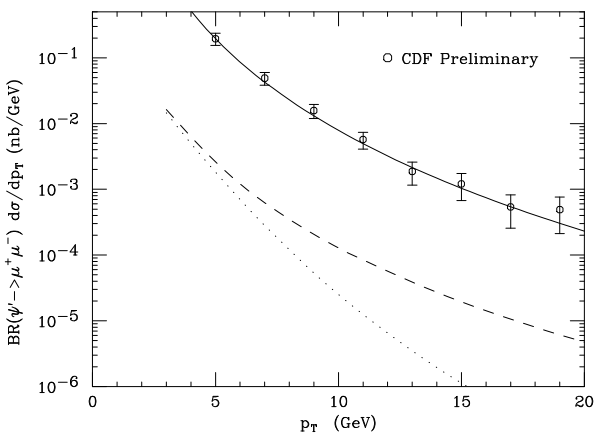
NRQCD

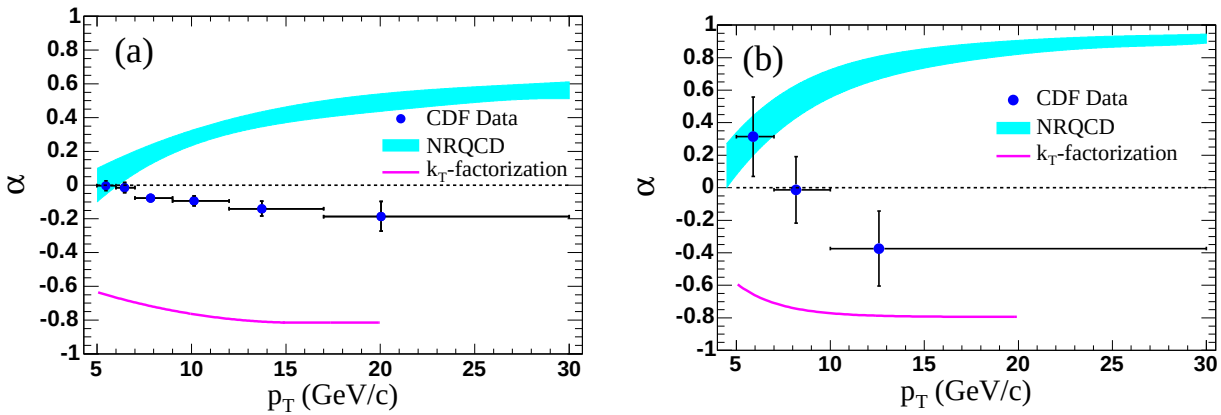
- Expansion in v
- ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ involved in ψ (Υ) production up to $O(v^4)$
- CSM and CEM are special cases
  - CSM: Colour-octet (CO) channels omitted
  - CEM: higher order in v involved[6]
- NRQCD tackled the weakness of CSM
  - IR divergences cancelled
  - NRQCD prediction for ψ' hadroproduction



[6] Bodwin, Braaten and Lee, PRD 72, 014004 (2005)

J/ψ polarization puzzle

- LO NRQCD failed in the description of ψ polarization[7]
- $\alpha = \frac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L}$



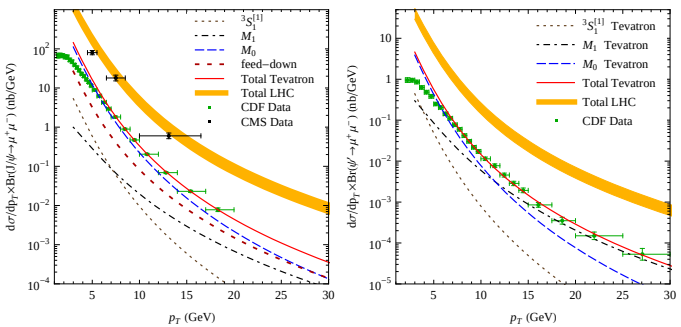
- high p_t limit
  - dominant channel: ${}^3S_1^{[8]}$
  - dominant mechanism: gluon fragmentation $\rightarrow$ transversely polarized

[7] Braaten, Kniehl and Lee, PRD 62, 094005 (2000); CDF Collaboration, PRL 99, 132001 (2007)

NLO era

NLO for CS[8] and CO[9]

- CS: enhanced by one order, still far below the data
- ${}^1S_0^{[8]}$: p_t^{-6} →another small p_t^{-4} part introduced
- ${}^3S_1^{[8]}$: almost unchanged
- ${}^3P_J^{[8]}$: positive→minus, $p_t^{-6} \to p_t^{-4}$
- $df({}^3P_J^{[8]}) = r_0 df({}^1S_0^{[8]}) + r_1 df({}^3S_1^{[8]})$ (medium and high p_t, roughly)

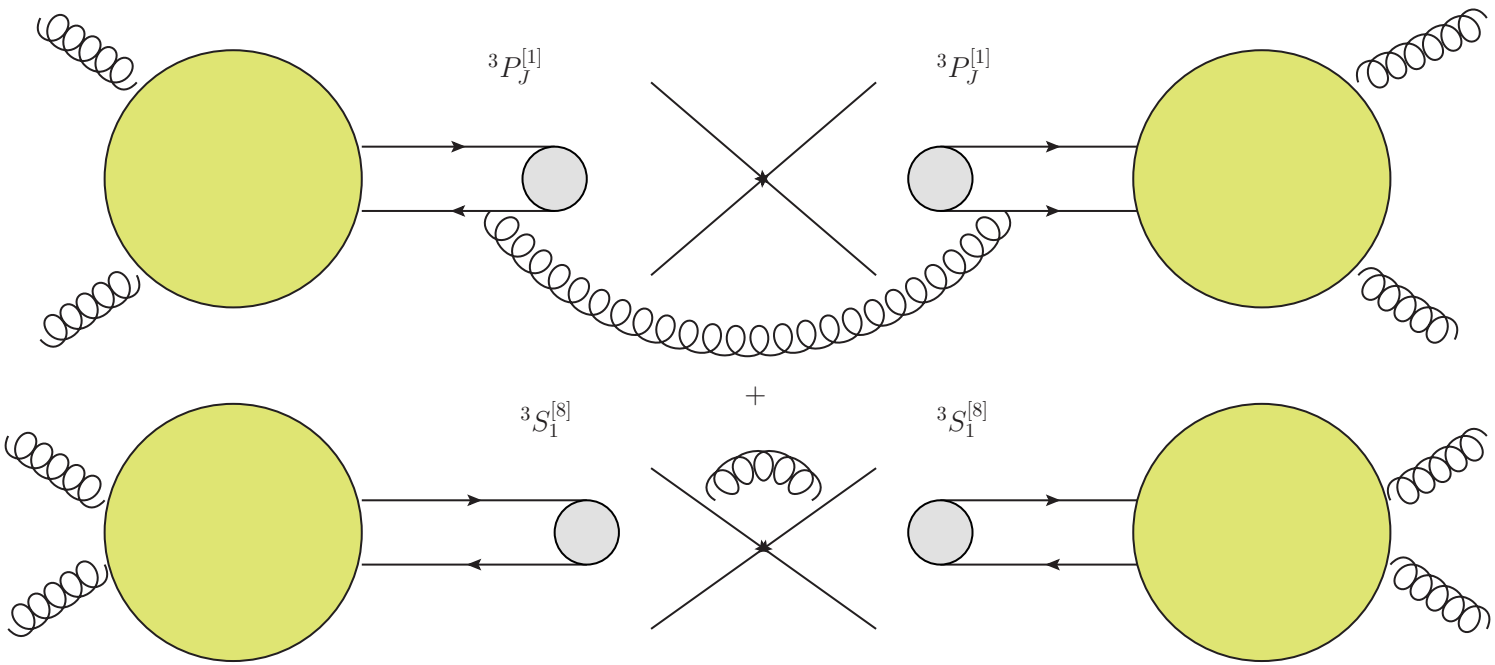


[8] Campbell, Maltoni and Tranmontano, PRL 98, 252002 (2007)

[9] Ma, Wang and Chao, PRL 106, 042002 (2011); Butenschon and Kniehl, PRL 106, 022003 (2011)

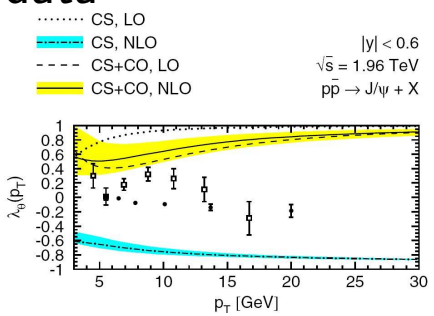
P-wave states at NLO

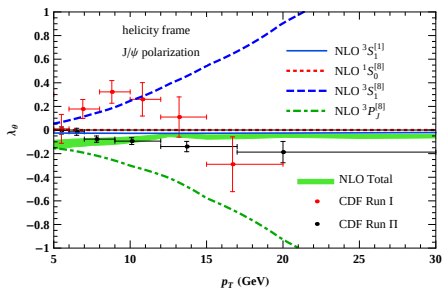
- QCD corrections to s-wave LDMEs cancel the sigularities in the SDCs
- χ_c production: ${}^3P_J^{[1]}$ and ${}^3S_1^{[8]}$ associated
- J/ψ production: ${}^3P_J^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3S_1^{[1]}$ associated
- Only the combination of the associated channels is divergence free and NRQCD scale (μ_Λ) independent

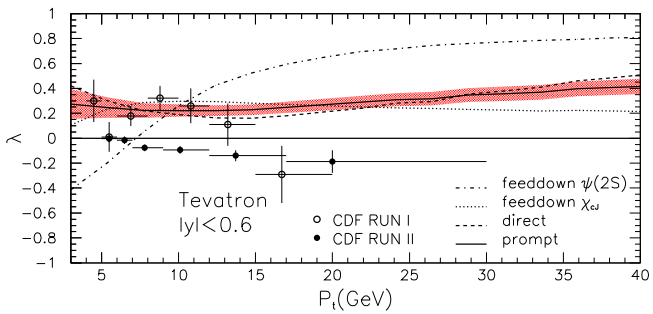


Polarization at NLO

- Left[10](missing feeddown): Global fit, transversely polarized, bad agreement
- Middle[11](missing feeddown): ${}^1S_0^{[8]}$ dominance, agree with CDF Run II data
- Right[12](complete): agree with CDF Run I data, contradict CDF Run II data





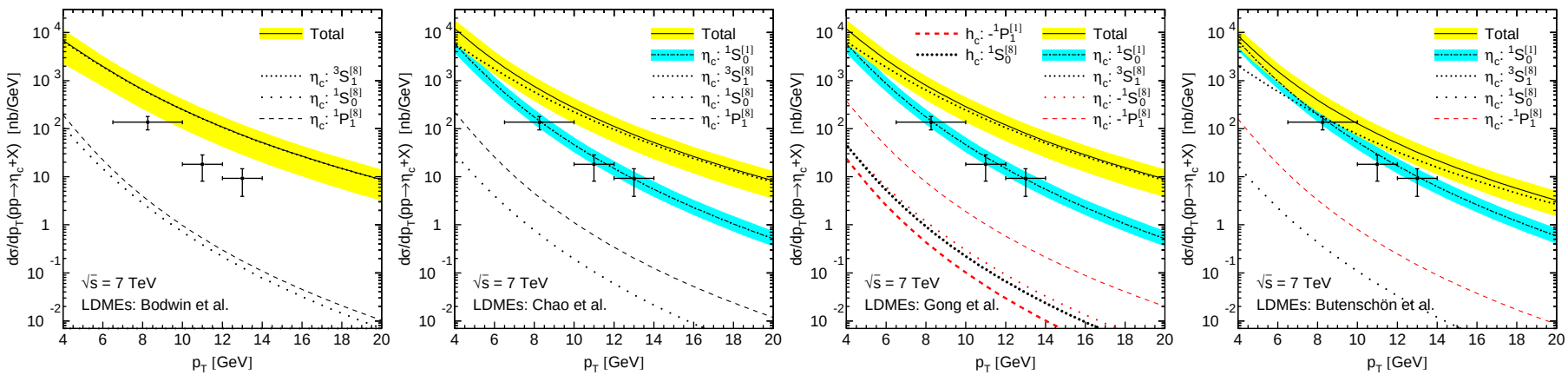


- Different fitting strategy→different LDMEs→different phenomenology
- Three LDMEs to be determined, too many!

[10] Butenschoen and Kniehl, PRL 108, 172002 (2012)
[11] Chao, Ma, Shao, Wang and Zhang, PRL 108, 242004 (2012)
[12] Gong, Wan, Wang and HFZ, PRL 110, 042002 (2013)

${}^1S_0^{[8]}$ dominance picture faces challenge

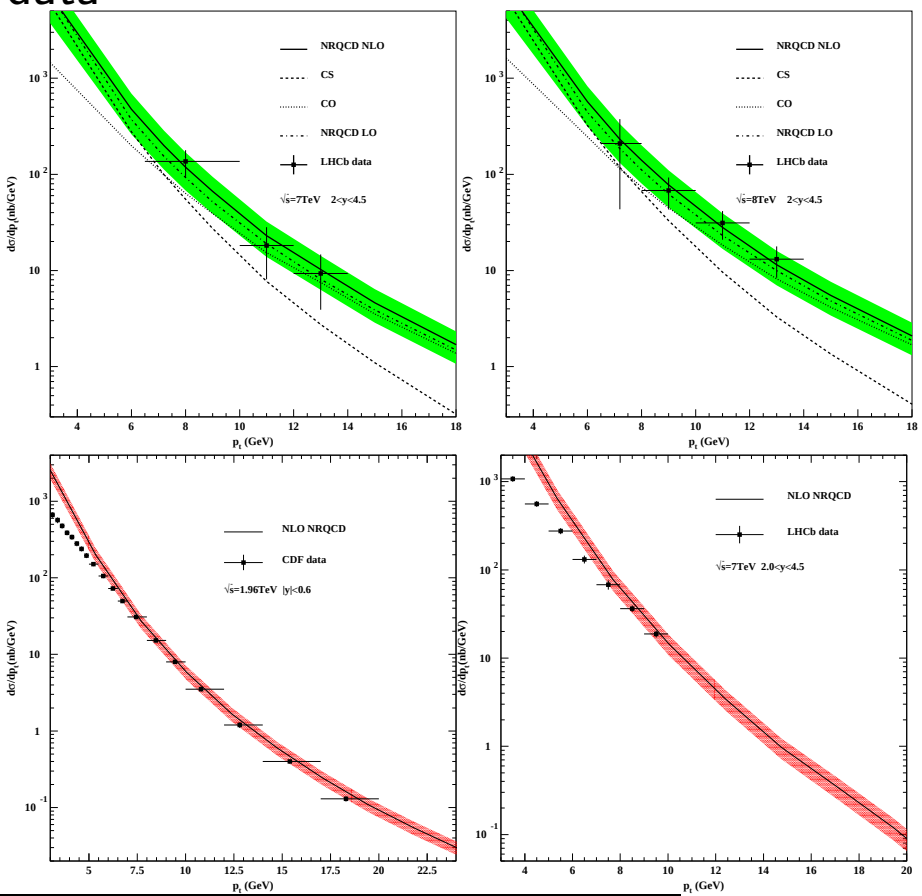
- Why ${}^1S_0^{[8]}$ dominance?
  - p_t spectrum: NLO ${}^1S_0^{[8]}$ similar to direct J/ψ
  - Polarization: ${}^1S_0^{[8]}$ unpolarized
- Challenges
  - Violate velocity scaling rule
  - Violate η_c hadroproduction data[13]



[13] Butenschoen, He and Kniehl, PRL 114, 092004 (2015); LHCb, EPJC 75, 311 (2015)

η_c and J/ψ hadroproduction data reconciled

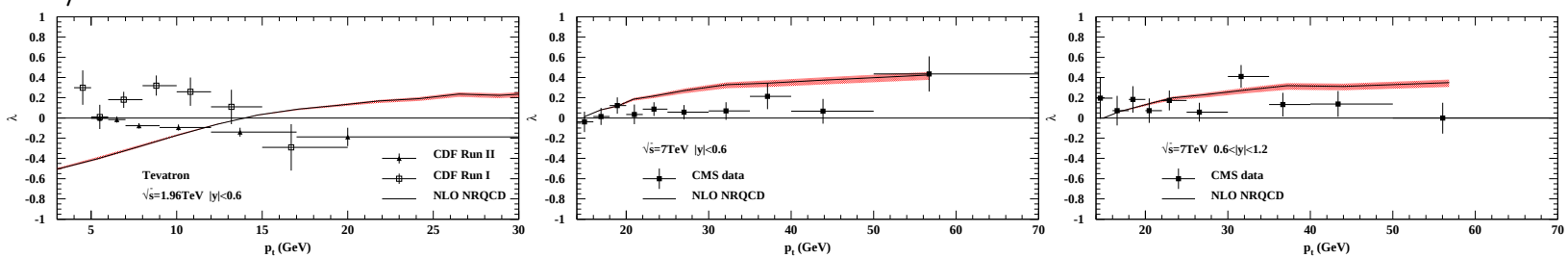
- η_c data help to determine LDMEs, consistent with J/ψ hadroproduction data[14]



[14] Han, Ma, Meng, Shao and Chao, PRL 114, 092005 (2015); HFZ, Sun, Sang and Li, PRL 114, 092006 (2015)

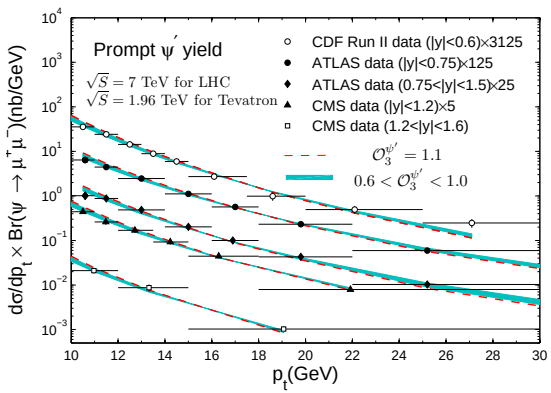
J/ψ polarization puzzle remains

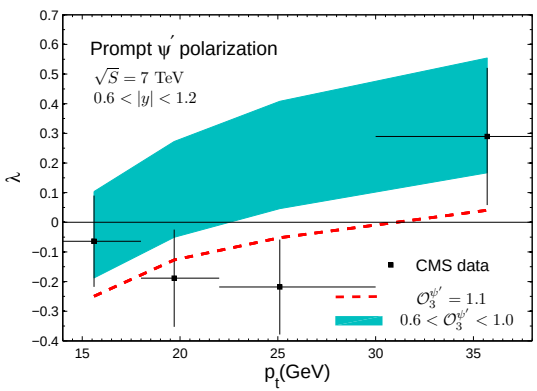
- Bad agreement with J/ψ polarization in midrapidity region
- σ_T/σ_L: 2.3 vs. 1.2



Charmonia hadroproduction and polarization data reconciled[15]

- New discovery in phenomenology 1)
  - The unique key parameter to govern the polarization: $R_{J/\psi} \equiv \langle O^{J/\psi}(^3S_1^{[8]}\rangle / \langle O^{J/\psi}(^3P_0^{[8]}\rangle$
  - Equation to govern the yield: $\langle \mathcal{O}^{\psi}(^3S_1^{[8]})\rangle = k_\psi \langle \mathcal{O}^{\psi}(^3P_0^{[8]})\rangle + b_\psi$
  - $k_{J/\psi} = 0.367$, $b_{J/\psi} = 0.00348 \pm 0.00011\text{GeV}^3$, $R_{J/\psi} = 0.546 \pm 0.006$
  - The polarization is extremely sensitive to $R_{J/\psi}$
  - narrow yield band→huge polarization band



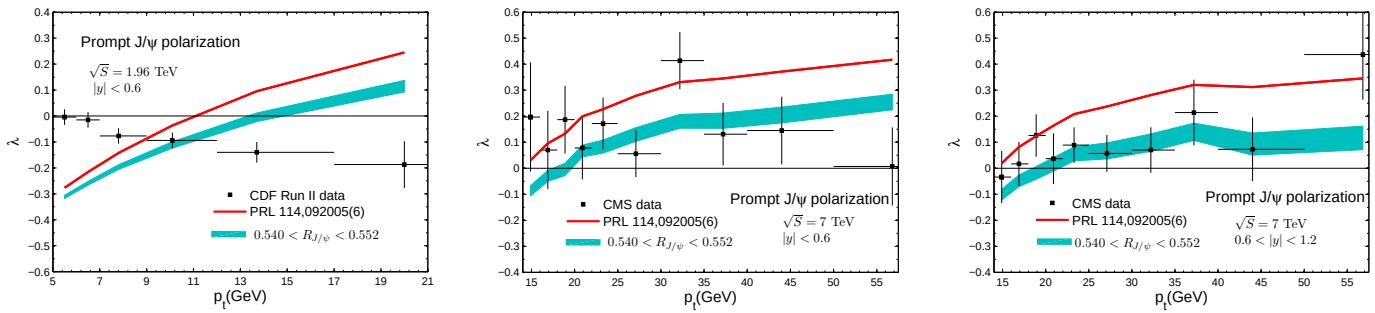


- Conclusion
  - Minimizing χ^2 in the fit to yield data is not reasonable!
  - Yield data does not provide information for polarization!

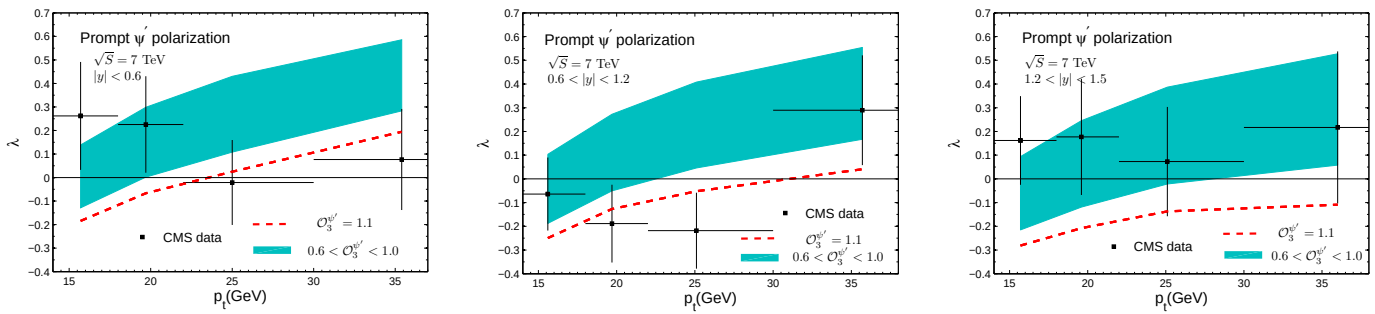
[15] Sun and HFZ, 1505.02675

Charmonia hadroproduction and polarization data reconciled

- New discovery in phenomenology 2)
  - J/ψ polarization understood

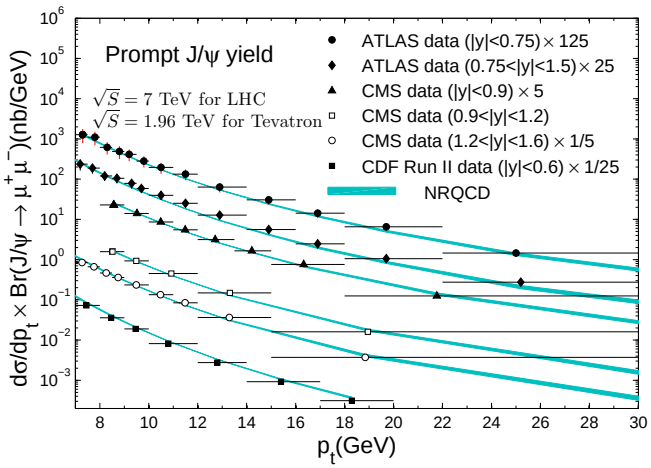


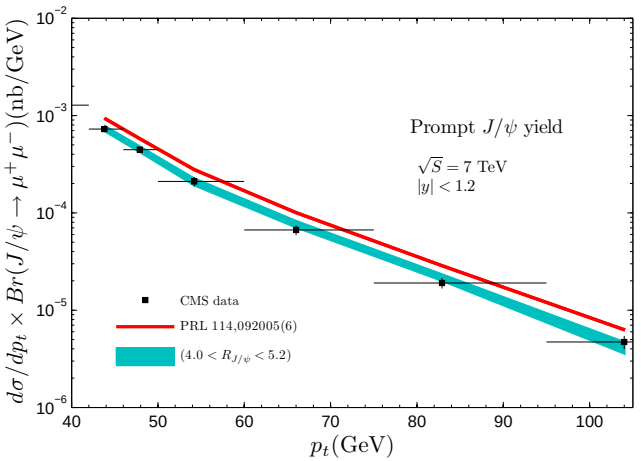
  - Relativistic corrections will improve CDF predictions
  - $\psi(2s)$ polarization can also be understood



Charmonia hadroproduction and polarization data reconciled

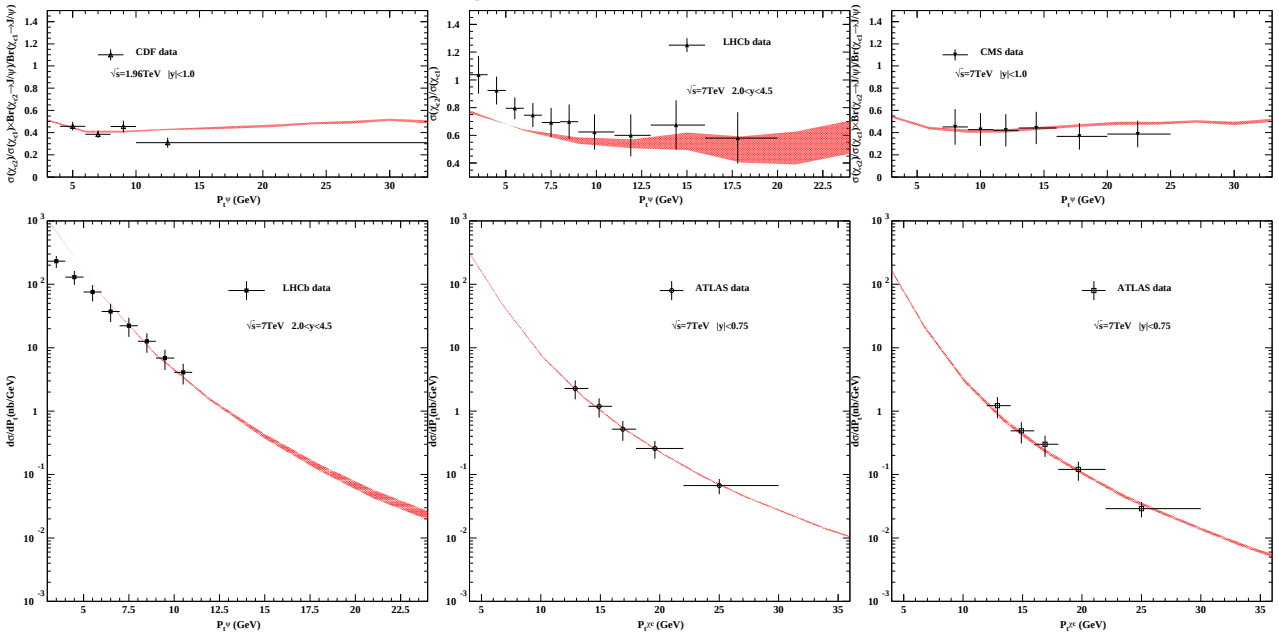
- J/ψ yield data can also be described





χ_c, the best laboratory to test NRQCD

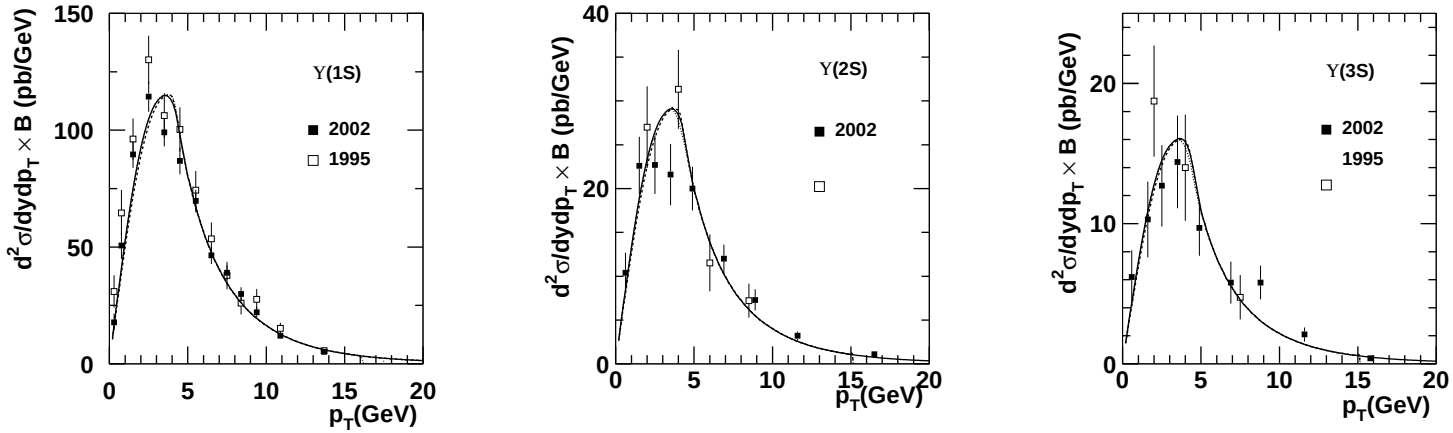
- Only one free parameter
- Good agreement with all the existing data[16]



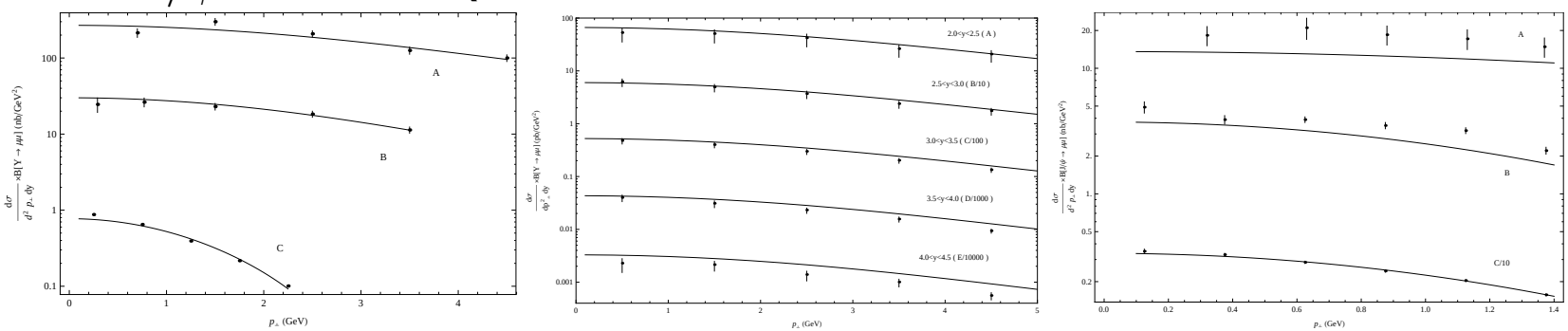
[16] Ma, Wang and Chao, PRD 83, 111503(R) (2011); Shao, Ma, Wang and Chao, PRL 112, 182003 (2014); HFZ, Yu, Zhang and Jia, 1410.4032 (2014)

Collins-Soper-Sterman (CSS) resummation

- Υ: CSS+CEM[17]



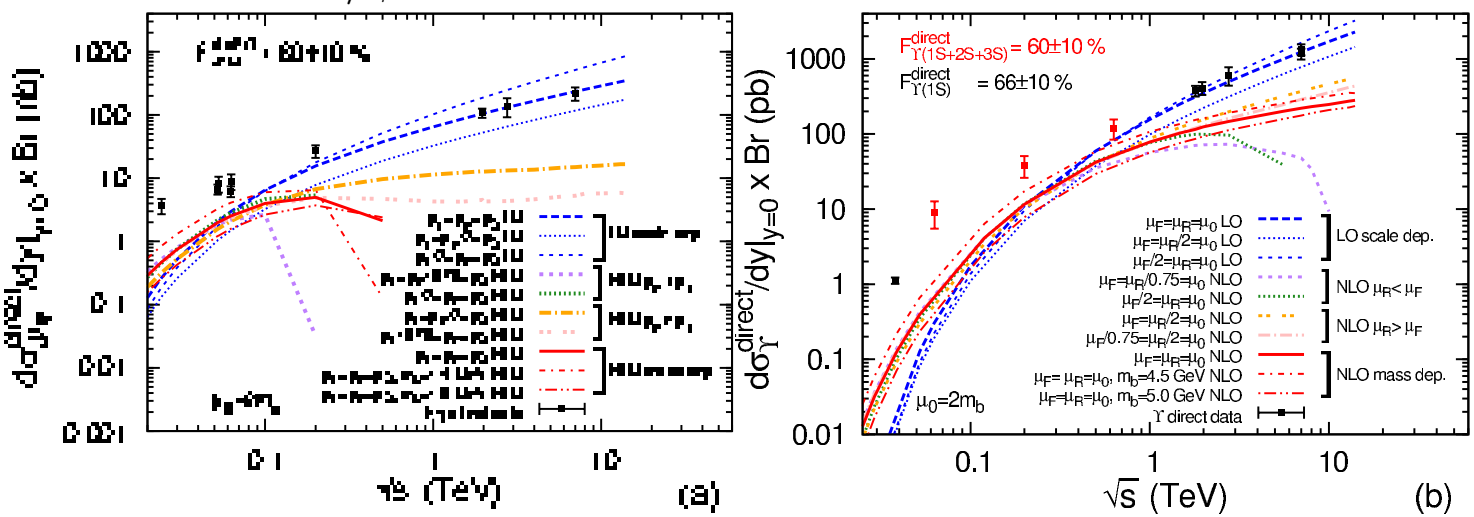
- Υ and J/ψ: CSS+NRQCD[18]



[17] Berger, Qiu and Wang, PRD 71, 034007 (2005)
[18] Sun, Yuan and Yuan, PRD 88, 054008 (2013)

$log(x)$ resummation is important for J/ψ

- Colour-singlet cross sections as a function of c.m. energy[19]
- $d\sigma/dy$ is free of $log^2(p_t/m_c)$, still negative cross sections
- The only large log: $log(x)$
- Υ better than J/ψ



[19] Feng, Lansberg and Wang, EPJC 75, 313 (2015)

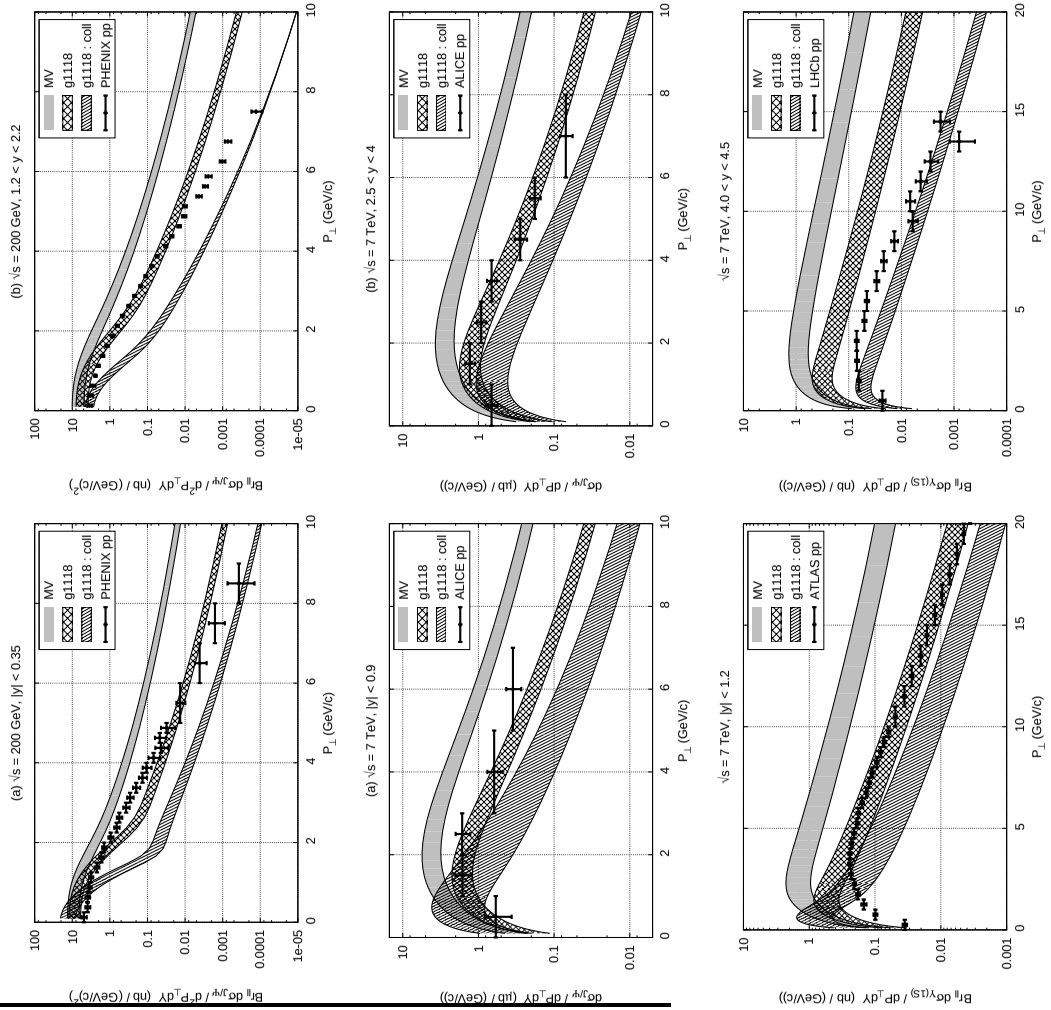
Colour Glass Condensate (CGC)[20]

- Dilute-dense approximation
- $x > x_0$: dilute; $x < x_0$: dense
- Resum $log(x)$
- JIMWLK evolution

[20] Mclerran and Venugopalan, PRD 49, 2233; 49, 3352; 50, 2225 (1994)

CGC+CEM[21]

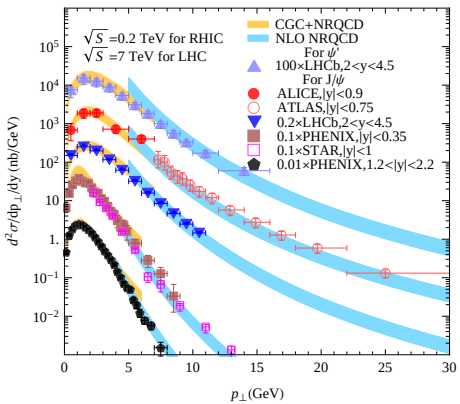
- Bad agreement

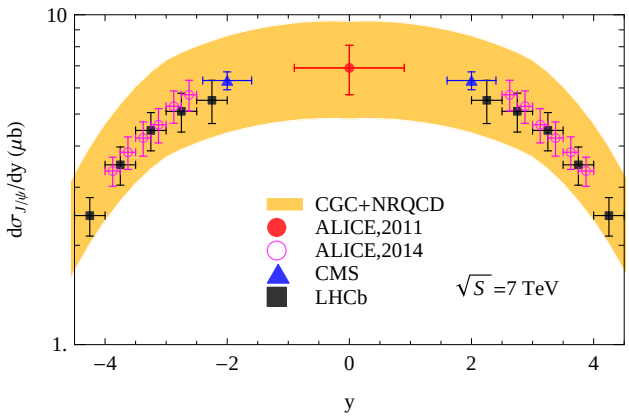


[21] Fujii and Watanabe, NPA 915, 1 (2013)

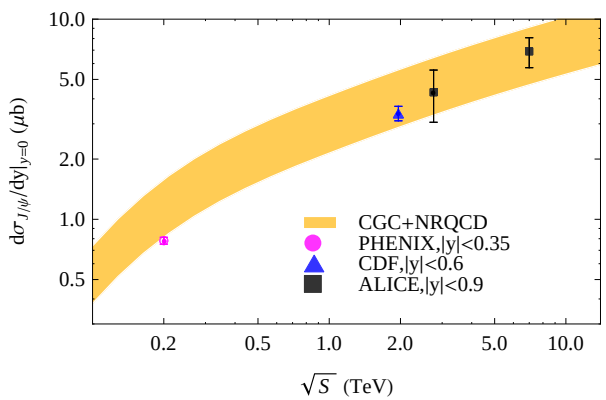
CGC+NRQCD[22]

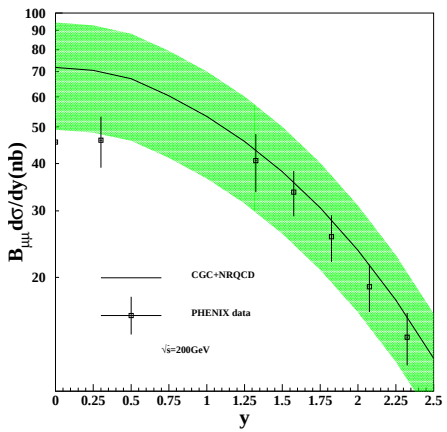
- Good agreement





- Not good in midrapidity region at low energy where dilute-dense approximation is ruined (HFZ)

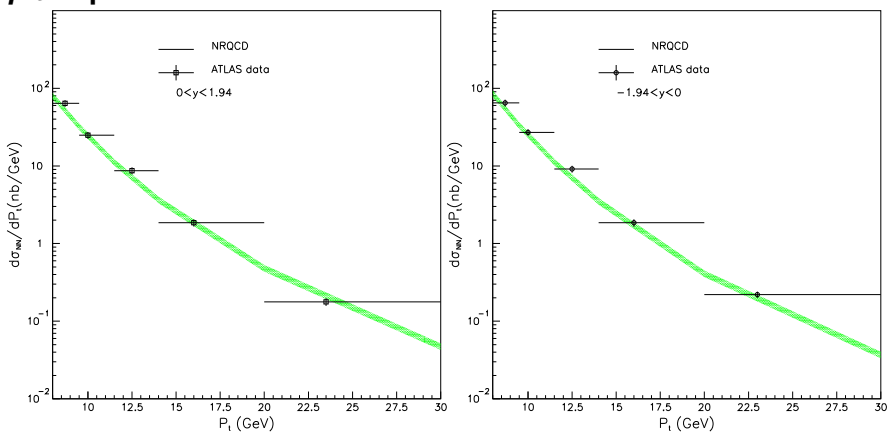




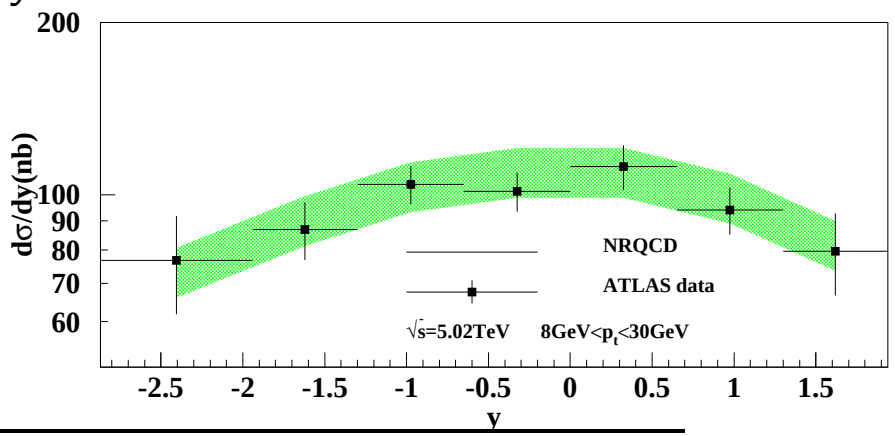
[22] Kang, Ma and Venugopalan, JHEP 1401, 056 (2013); Ma and Venugopalan, PRL 113, 192301 (2014)

J/ψ production in pA collisions at high p_t[24]

- EPS09 employed[23]
- p_t spectrum



- y distribution



[23] Eskola, Paukkunen and Salgado, JHEP 0904, 065 (2009)
[24] HFZ and etc., in preparation

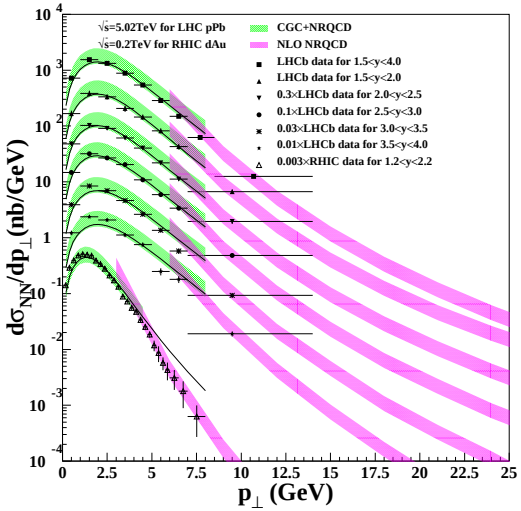
J/ψ production in pA collisions[25]

- Two free parameters: $Q_{s0,A}$ and R_A
- $Q^2_{s0,A} = N \times Q^2_{s0,p}$
  - $N \approx 3$ for $\gamma = 1.113$; $N \approx 1.5$ for $\gamma = 1$
  - We set $\gamma = 1$, $N = 2$ as a tentative choice
- $R_{pA} \equiv \frac{d\sigma_{pA}}{A \times d\sigma_{pp}}$
  - $R_{pA} \to \frac{R_A^2}{AR_p^2} \frac{Q^2_{s0,A}}{Q^2_{s0,p}}$ (high p_t)
  - $R_{pA} \to 1$ at high p_t, a natural assumption to determine R_A

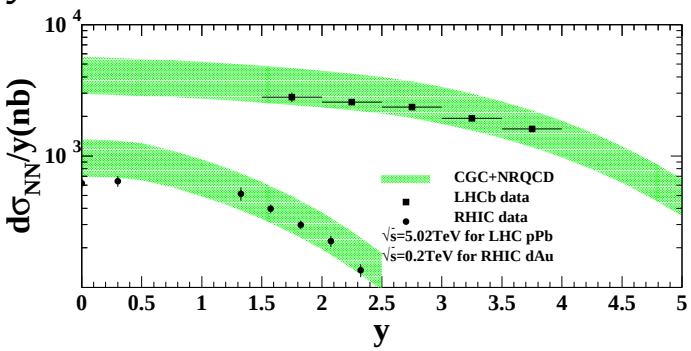
[25] Ma, Venugopalan and HFZ, 1503.07772 (2015)

J/ψ production in pA collisions

- p_t spectrum

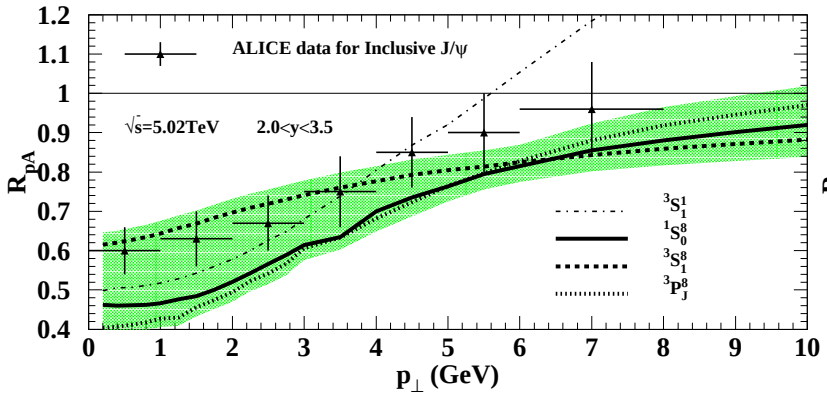


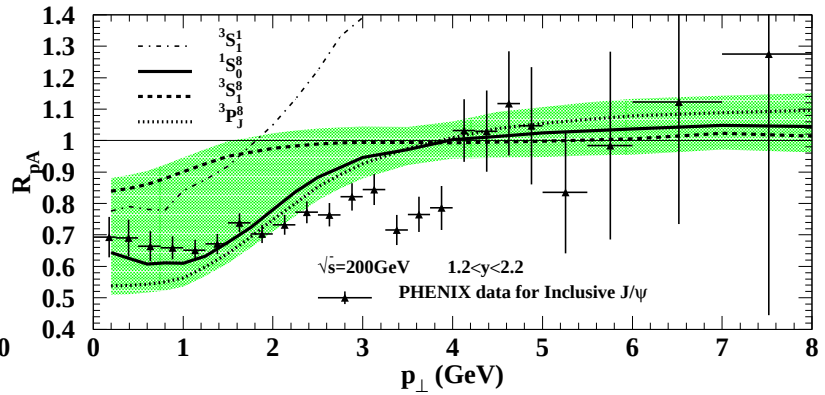
- y distribution



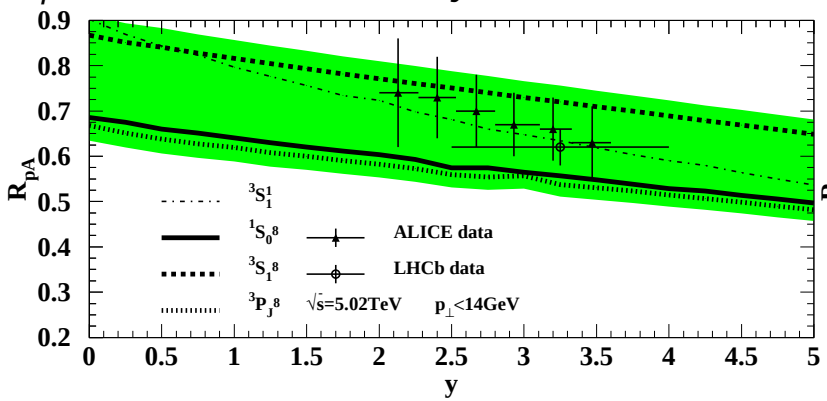
J/ψ suppression

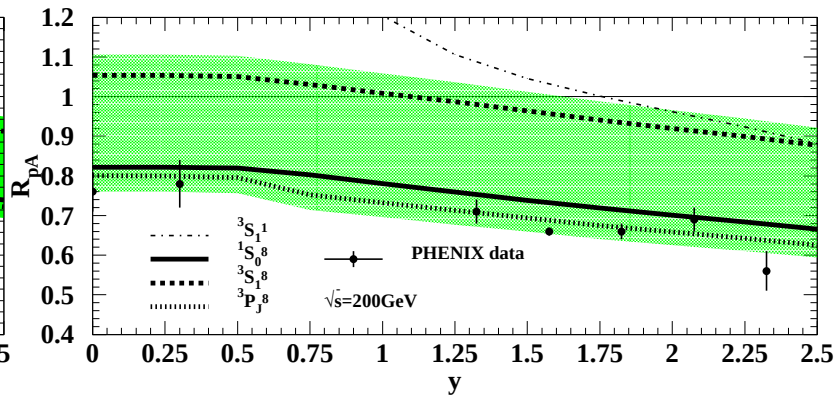
- R_{pA} as a function of p_t





- R_{pA} as a function of y





Summary

- NRQCD can describe both ψ production and polarization
- Minimizing χ^2 is not appropriate in the determination of the LDMEs
- Small-x resummation is required in small p_t region
- CGC+NRQCD provide good description of both pp and pA data
- pQCD+NRQCD can describe the high-p_t J/ψ production data in pA collision

Thanks!