ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY

Institutional Member of the European Expert Committee NUPECC

Understanding the theory of quarkonium production in QCD: where do we stand ?

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Brookhaven National Laboratory

Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

New observables in quarkonium production

Trento, 29 Feb 2016 to 04 Mar 2016

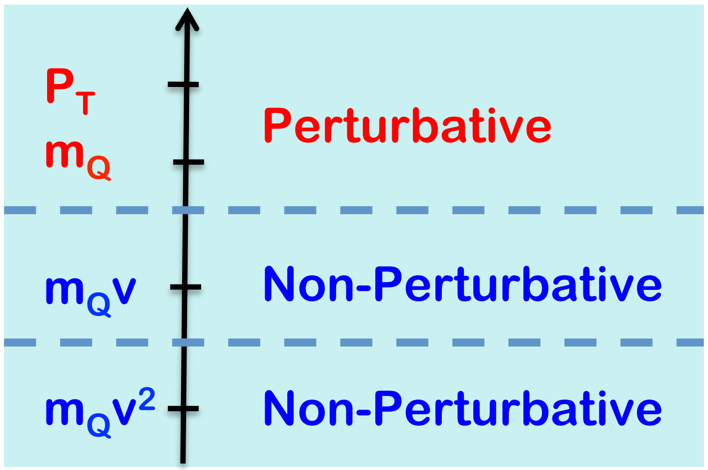
Heavy quarkonium

- **One of the simplest QCD bound states:**

  Localized color charges (heavy mass), non-relativistic relative motion

  Charmonium: $v^2 \approx 0.3$ **Bottomonium:** $v^2 \approx 0.1$

- **Well-separated momentum scales – effective theory:**



Hard — Production of $Q\bar{Q}$ **[pQCD]**

Soft — Relative Momentum **[NRQCD]**

Λ_{QCD}

Ultrasoft — Binding Energy **[pNRQCD]**

- **Cross sections and observed mass scales:**

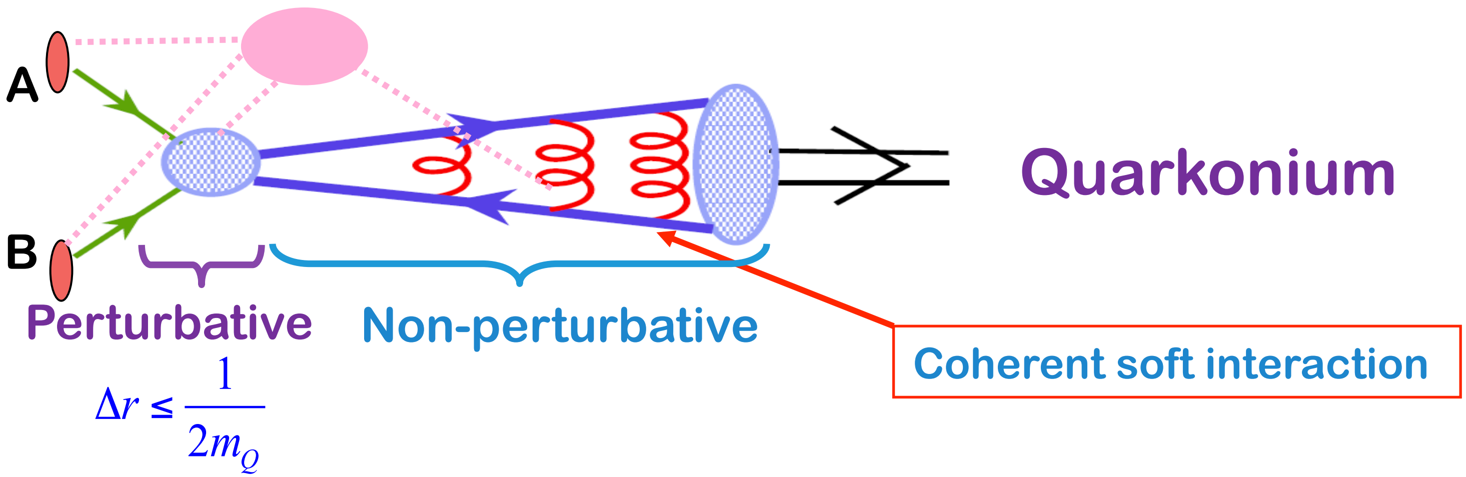
$$\frac{d\sigma_{AB\to H(P)X}}{dy\,dP_T^2} \qquad \sqrt{S}, \qquad P_T, \qquad M_H,$$

PQCD is "expected" to work for the production of heavy quarks

Difficulty: Emergence of a quarkonium from a heavy quark pair?

Basic production mechanism

- QCD factorization is likely to be valid for producing the pairs:
  - ✧ Momentum exchange is much larger than 1/fm
  - ✧ Spectators from colliding beams are "frozen" during the hard collision



- Approximation: on-shell pair + hadronization

$$\sigma_{AB\to J/\psi}(P_{J/\psi}) \approx \sum_n \int dq^2 \left[\sigma_{AB\to[Q\bar{Q}](n)}(q^2)\right] F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$$

Models & Debates

⇔ Different assumptions/treatments on $F_{[Q\bar{Q}(n)]\to J/\psi}(P_{J/\psi}, q^2)$
how the heavy quark pair becomes a quarkonium?

A long history for the production

- Color singlet model: 1975 –

  Einhorn, Ellis (1975),
  Chang (1980),
  Berger and Jone (1981), …

  Only the pair with right quantum numbers

  Effectively No free parameter!

- Color evaporation model: 1977 –

  Fritsch (1977), Halzen (1977), …

  All pairs with mass less than open flavor heavy meson threshold

  One parameter per quarkonium state

- NRQCD model: 1986 –

  Caswell, Lapage (1986)
  Bodwin, Braaten, Lepage (1995)
  QWG review: 2004, 2010

  All pairs with various probabilities – NRQCD matrix elements

  Infinite parameters – organized in powers of v and α_s

- QCD factorization approach: 2005 –

  Nayak, Qiu, Sterman (2005), …
  Kang, Qiu, Sterman (2010), …

  $P_T >> M_H$: M_H/P_T power expansion + α_s – expansion

  Unknown, but universal, fragmentation functions – evolution

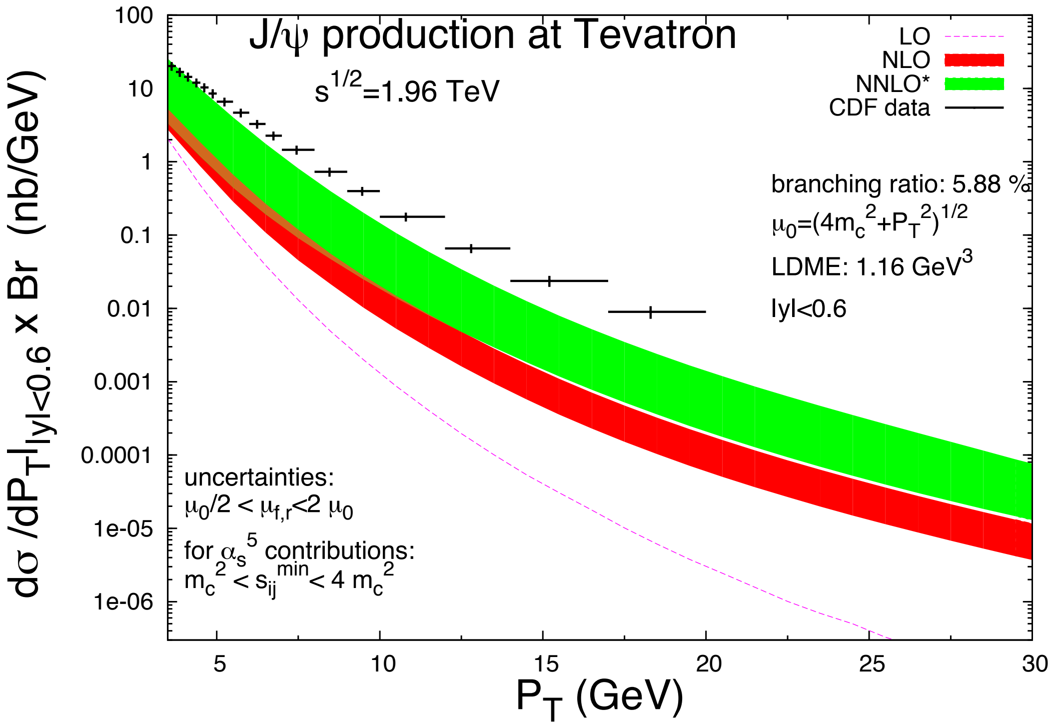
- Soft-Collinear Effective Theory + NRQCD: 2012 –

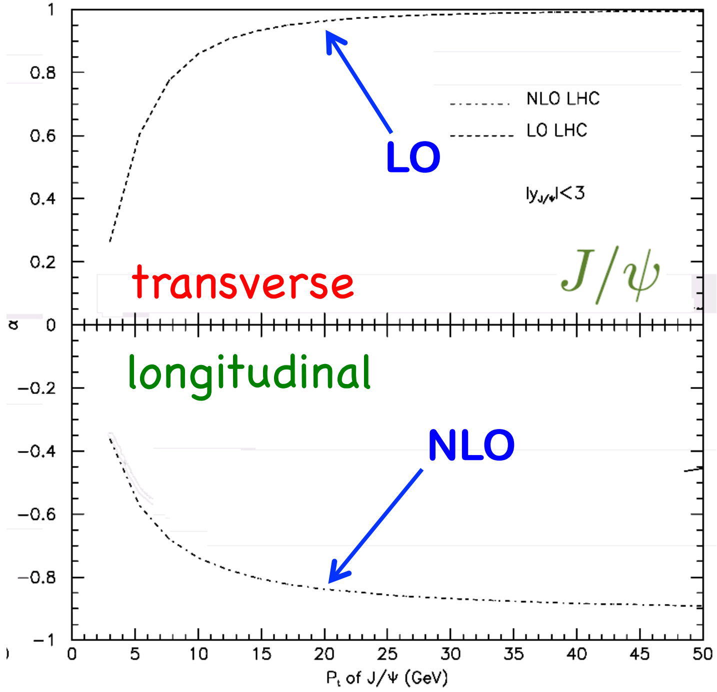
  Fleming, Leibovich, Mehen, …

Color singlet model (CSM)

❑ **Effectively No parameter:**

Campbell, Maltoni, Tramontano (2007),
Artoisenet, Lansburg, Maltoni (2007),
Artoisenet, et al. (2008)





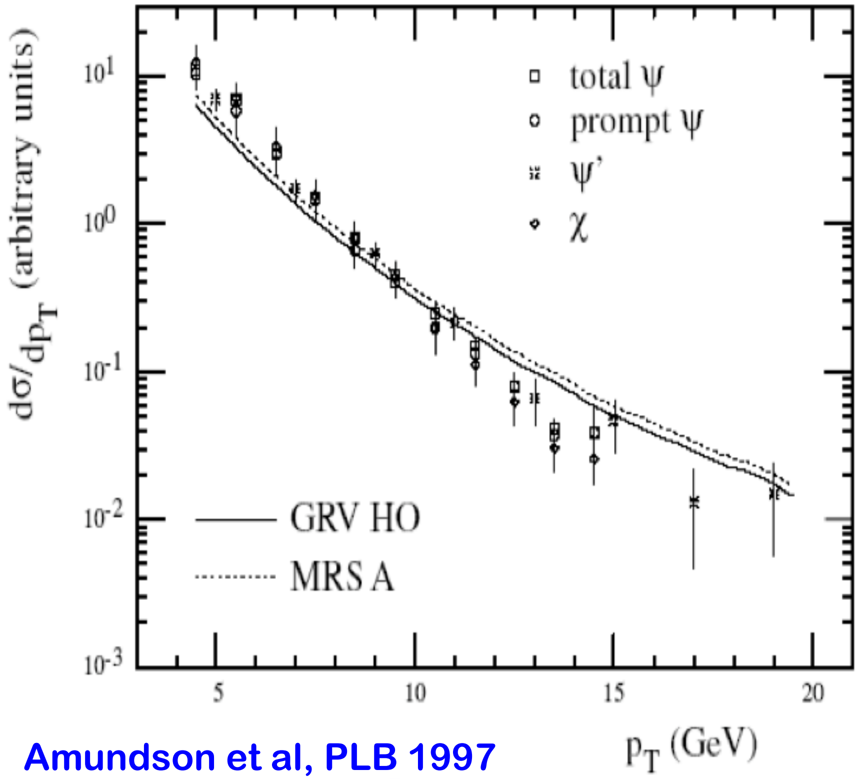
B. Gong et, al. PRL (2008)

❑ **Issues:**

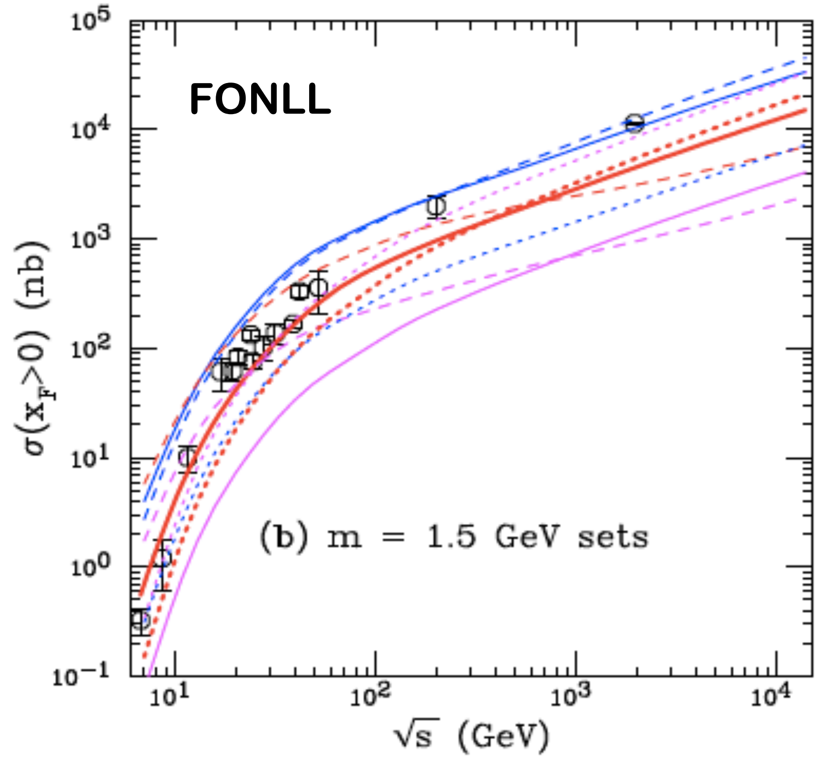
- ✧ **How reliable is the perturbative expansion?**
- ✧ **S-wave: large corrections from high orders**
- ✧ **P-wave: Infrared divergent – CSM is not complete**

Color evaporation model (CEM)

- One parameter per quarkonium:



Amundson et al, PLB 1997



Nelson, Vogt, Frawley, PRC 2013

- Question:
  - Better p_T distribution – the shape?
  - Need intrinsic k_T – its distribution?

NRQCD – most successful so far

See Kniehl's talk

- NRQCD factorization:

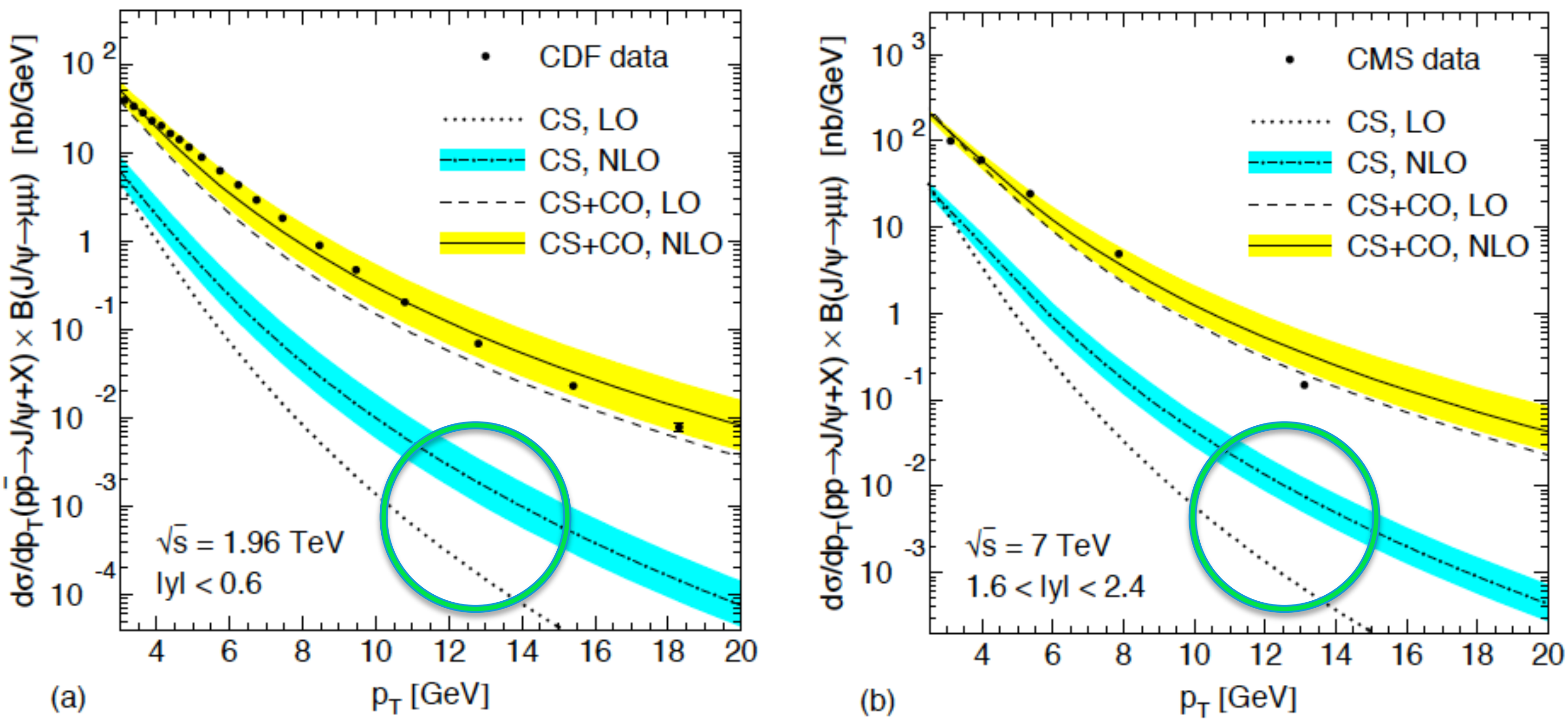
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \langle \mathcal{O}^H(n) \rangle$$

✧ **4 leading channels in v**

$${}^3S_1^{[1]},\ {}^1S_0^{[8]},\ {}^3S_1^{[8]},\ {}^3P_J^{[8]}$$

✧ **Full NLO in α_s**

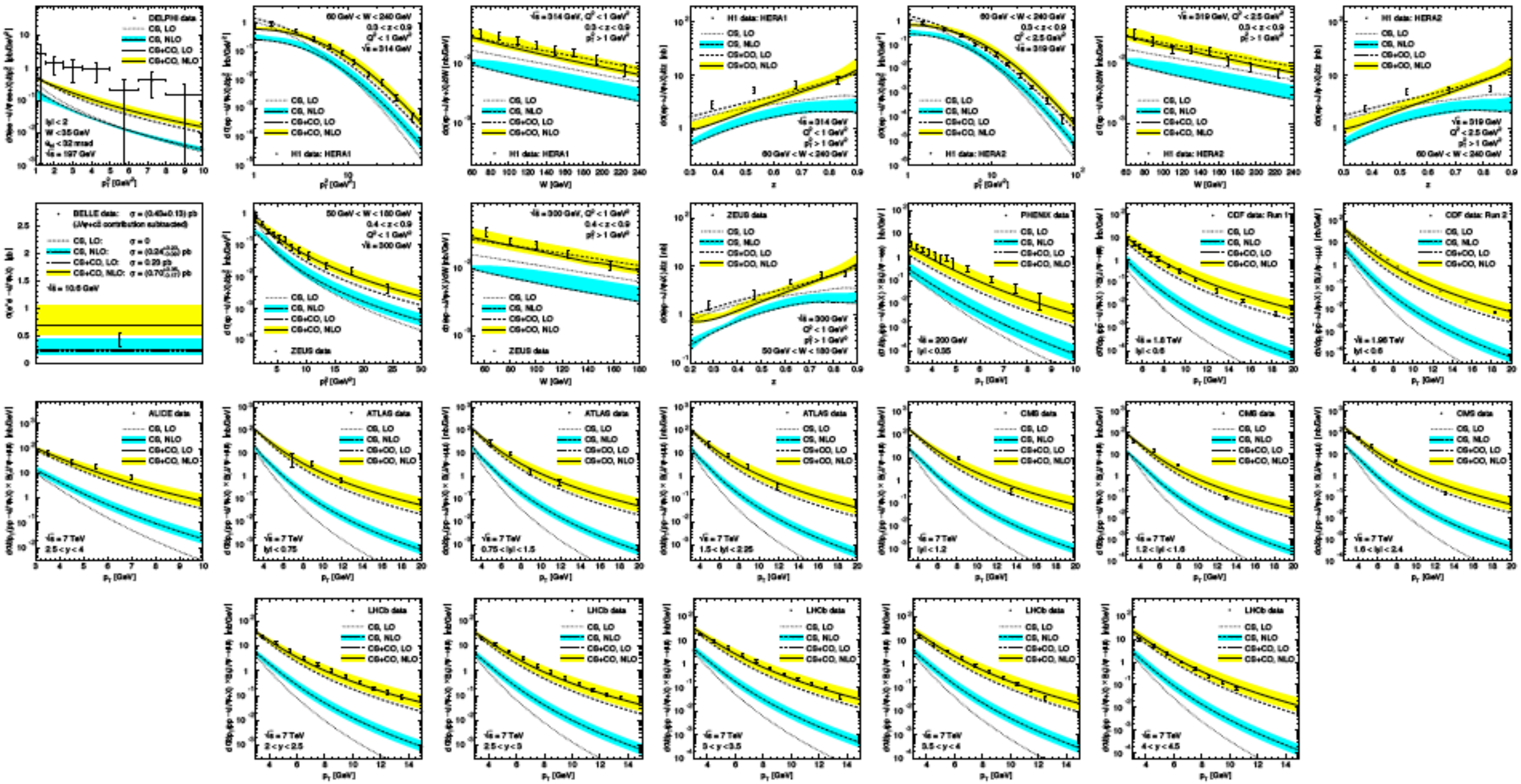
- Phenomenology:



- Fine details – shape – high at large p_T?

PRL 106, 022003 (2011)

NRQCD – global analysis



194 data points from 10 experiments, fix singlet $\langle O[^3S_1^{[1]}]\rangle = 1.32\ \text{GeV}^3$

→ $\langle O[^1S_0^{[8]}]\rangle = (4.97 \pm 0.44)\cdot 10^{-2}\ \text{GeV}^3$ $\langle O[^3S_1^{[8]}]\rangle = (2.24 \pm 0.59)\cdot 10^{-3}\ \text{GeV}^3$

$\langle O[^3P_0^{[8]}]\rangle = (-1.61 \pm 0.20)\cdot 10^{-2}\ \text{GeV}^5$

$\chi^2/d.o.f. = 857/194 = 4.42$

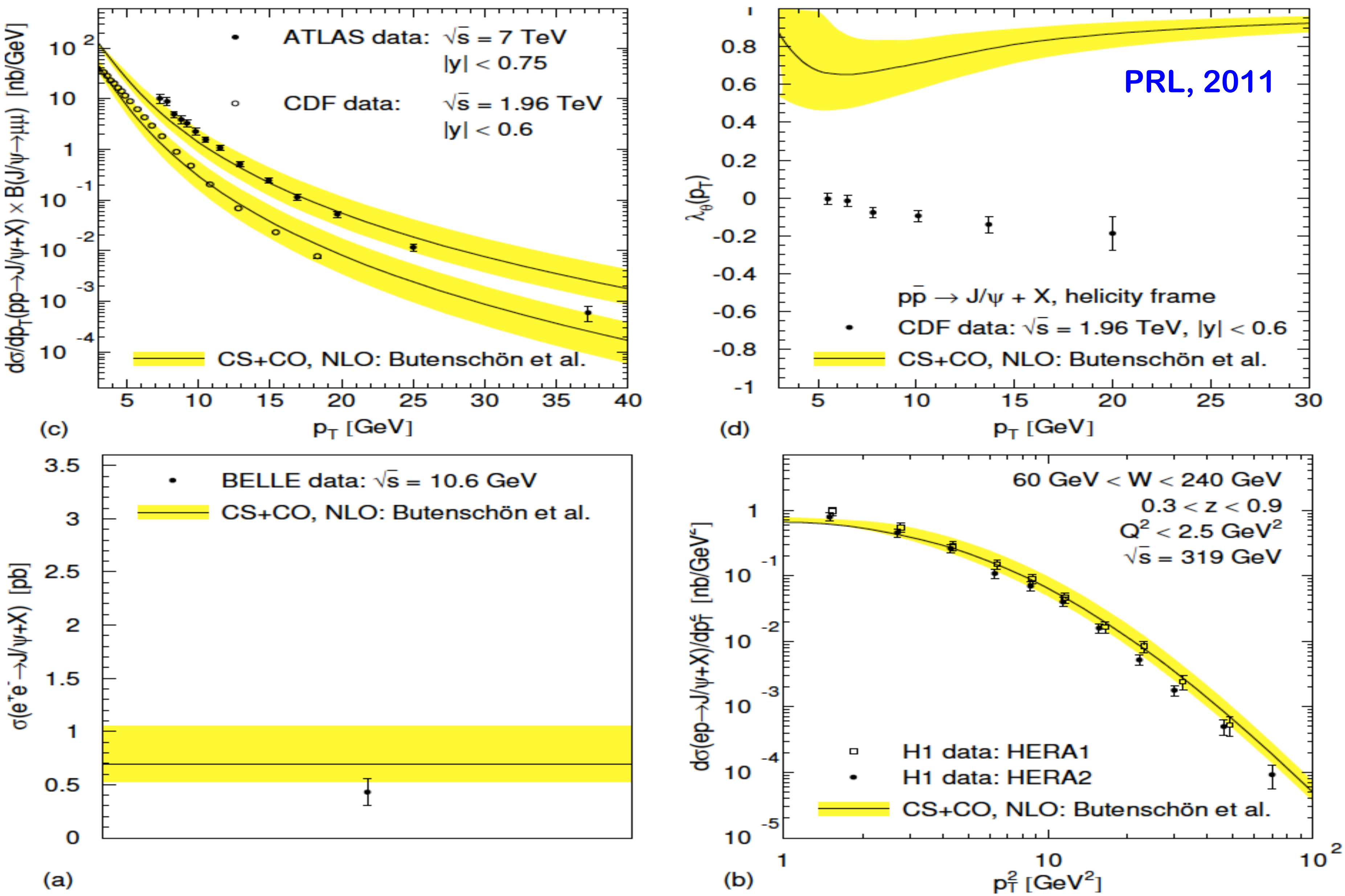
Butenschoen and Kniehl, arXiv: 1105.0820

Anomalies and surprises

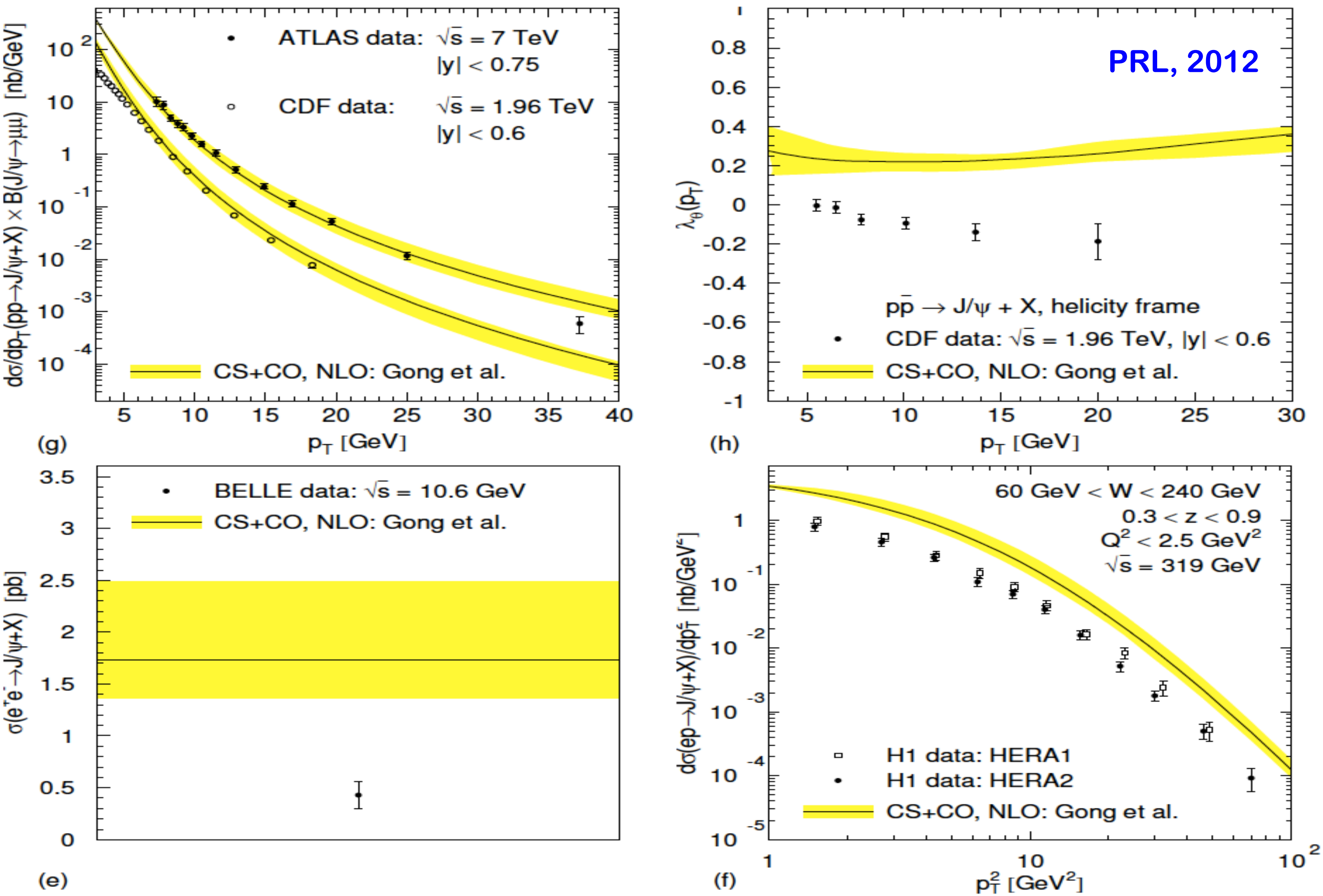
Also see Shao's talk

- Theory – the state of arts – NLO:
  - ✧ Very difficult to calculate, no analytical expression
    - ⟹ hard to obtain a clear physical picture on how various states of heavy quark pair are actually produced?
  - ✧ For some channels, NLO corrections are orders larger than LO
    - ⟹ questions whether higher order contributions are negligible, while it is extremely difficult, if not impossible, to go beyond the NLO
- Comparison with data:
  - ✧ Quarkonium polarization – "ultimate" test of NRQCD!
    - ⟹ Clear mismatch between theory predictions and data
  - ✧ Universality of NRQCD matrix elements – predictive power!
    - ⟹ Clear tension between different data sets, e^+e^-, ep, pp, …

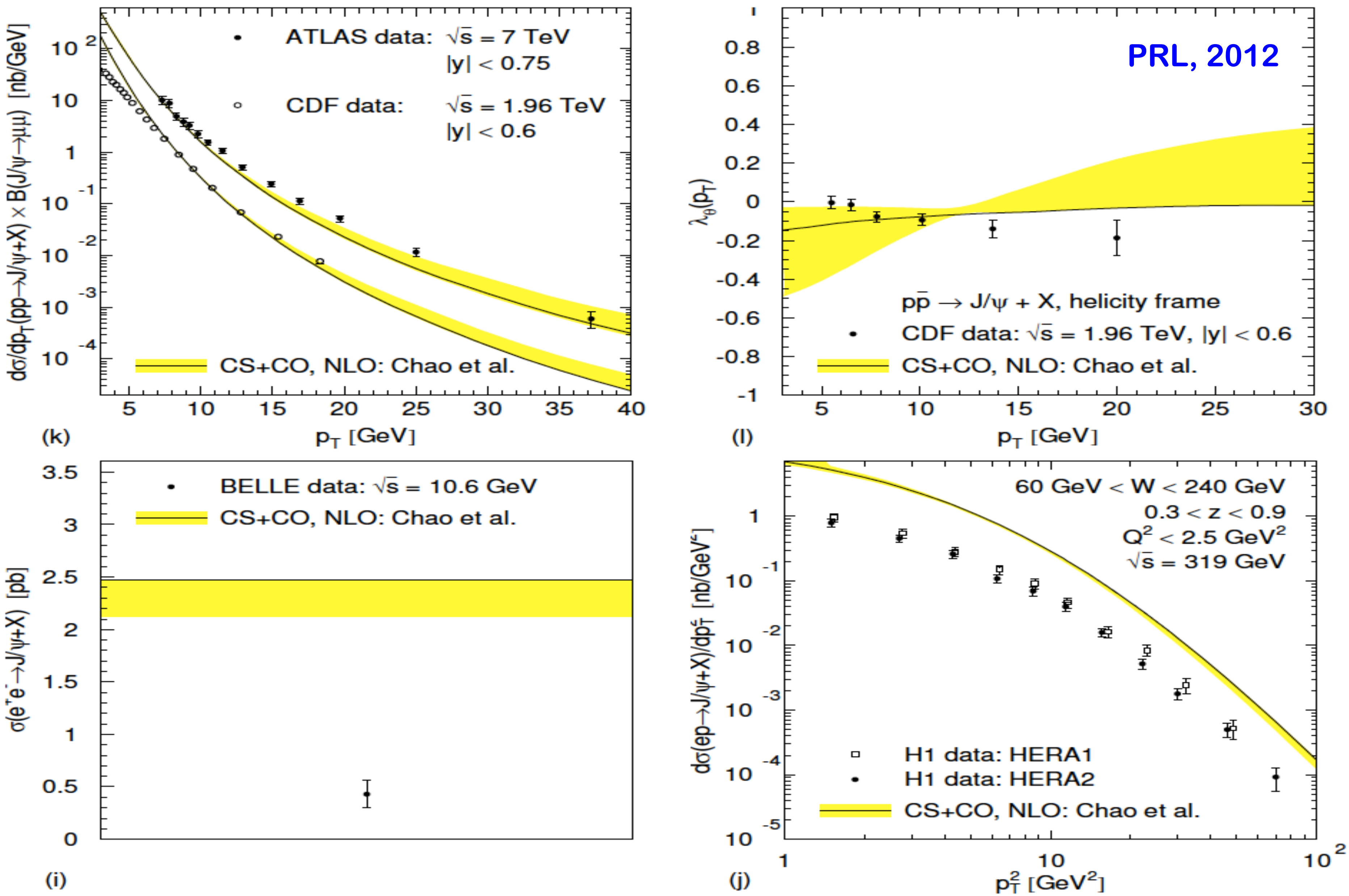
NLO theory fits – Butenschoen et al.



NLO theory fits – Gong et al.



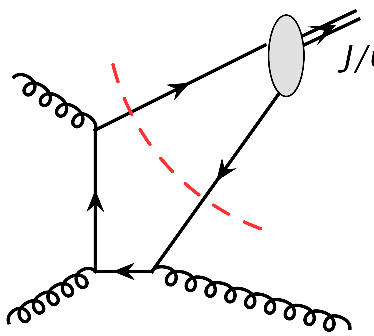
NLO theory fits – Chao et al.



Why high orders in NRQCD are so large?

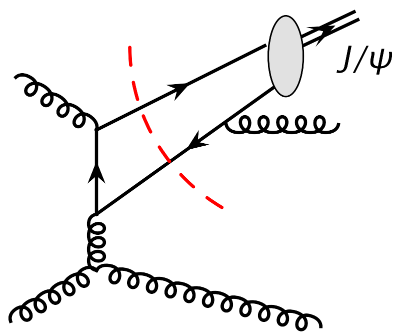
Kang, Qiu and Sterman, 2011

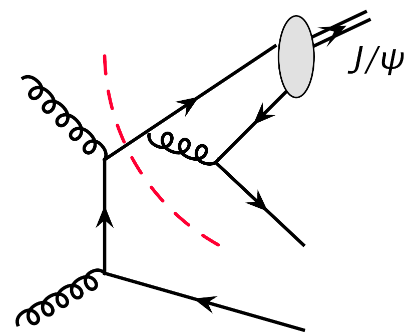
- Consider J/ψ production in CSM:



LO in α_s

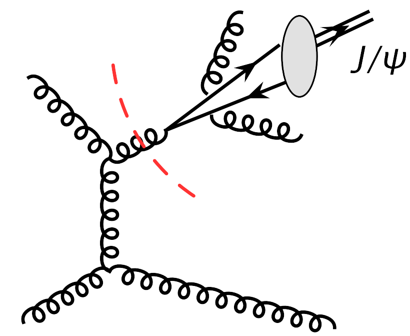
NNLP $\propto \alpha_s^3 \frac{m_Q^4}{p_T^8}$





NLO in α_s

NLP in $1/P_T$ $\propto \alpha_s^4 \frac{m_Q^2}{p_T^6}$



NNLO in α_s

LP: $\propto \alpha_s^5 \frac{1}{p_T^4}$

- ✧ High-order correction receive power enhancement
- ✧ Expect no further power enhancement beyond NNLO
- ✧ $[\alpha_s \ln(p_T^2/m_Q^2)]^n$ ruins the perturbation series at sufficiently large p_T

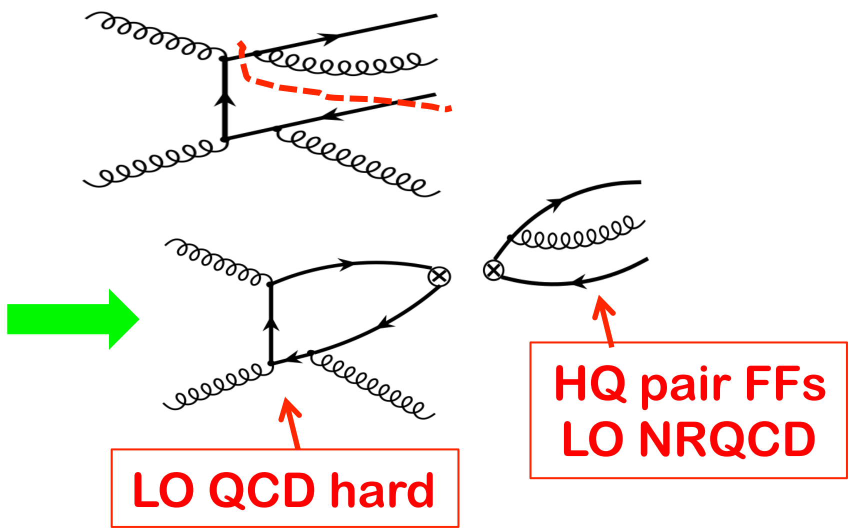
Leading order in α_s-expansion =\= leading power in $1/p_T$-expansion!

At high p_T, fragmentation contribution dominant

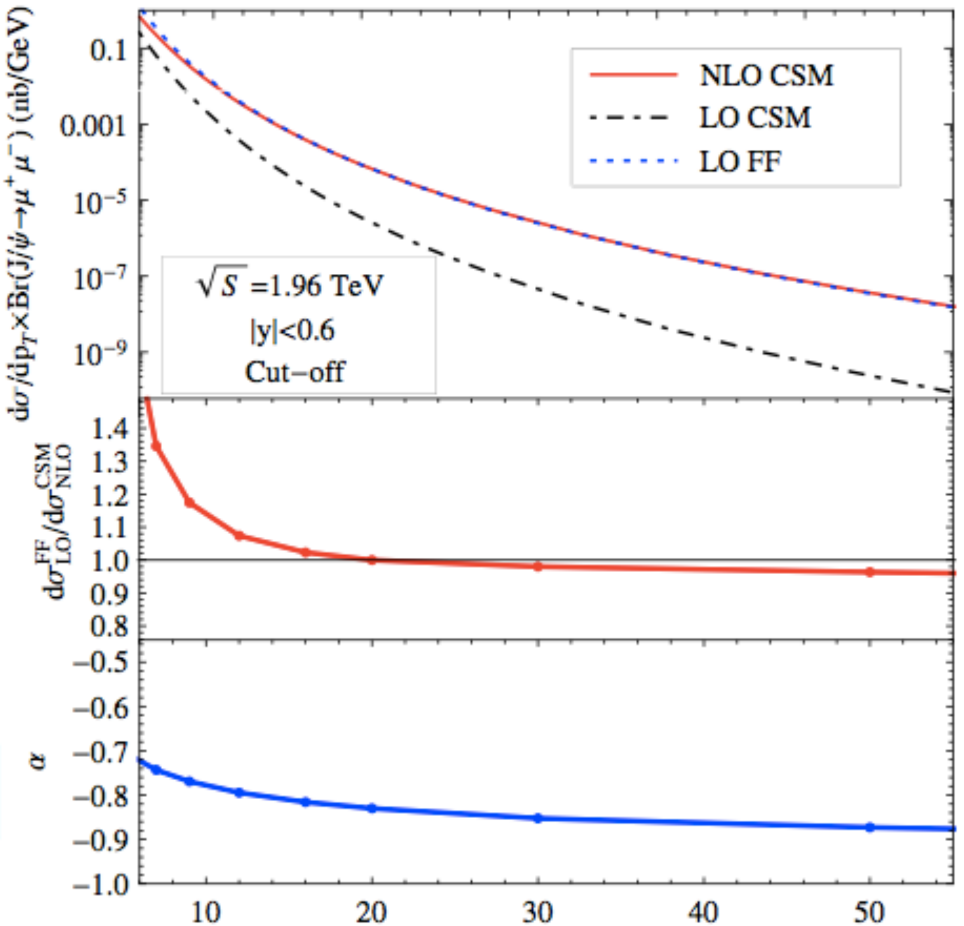
QCD factorization + NRQCD factorization

Kang, Qiu and Sterman, 2011

❑ Color singlet as an example:



$$\sigma_{\rm NRQCD}^{\rm (NLO)} \propto \Big[d\hat{\sigma}^{A({\rm LO})}_{ab\to[Q\bar{Q}(v8)]} \otimes \mathcal{D}^{({\rm LO})}_{[Q\bar{Q}(v8)]\to J/\psi} + d\hat{\sigma}^{S({\rm LO})}_{ab\to[Q\bar{Q}(a8)]} \otimes \mathcal{D}^{({\rm LO})}_{[Q\bar{Q}(a8)]\to J/\psi} \Big]$$



Reproduce NLO CSM for p_T > 10 GeV!

Cross section + polarization

QCD Factorization = better controlled HO corrections!

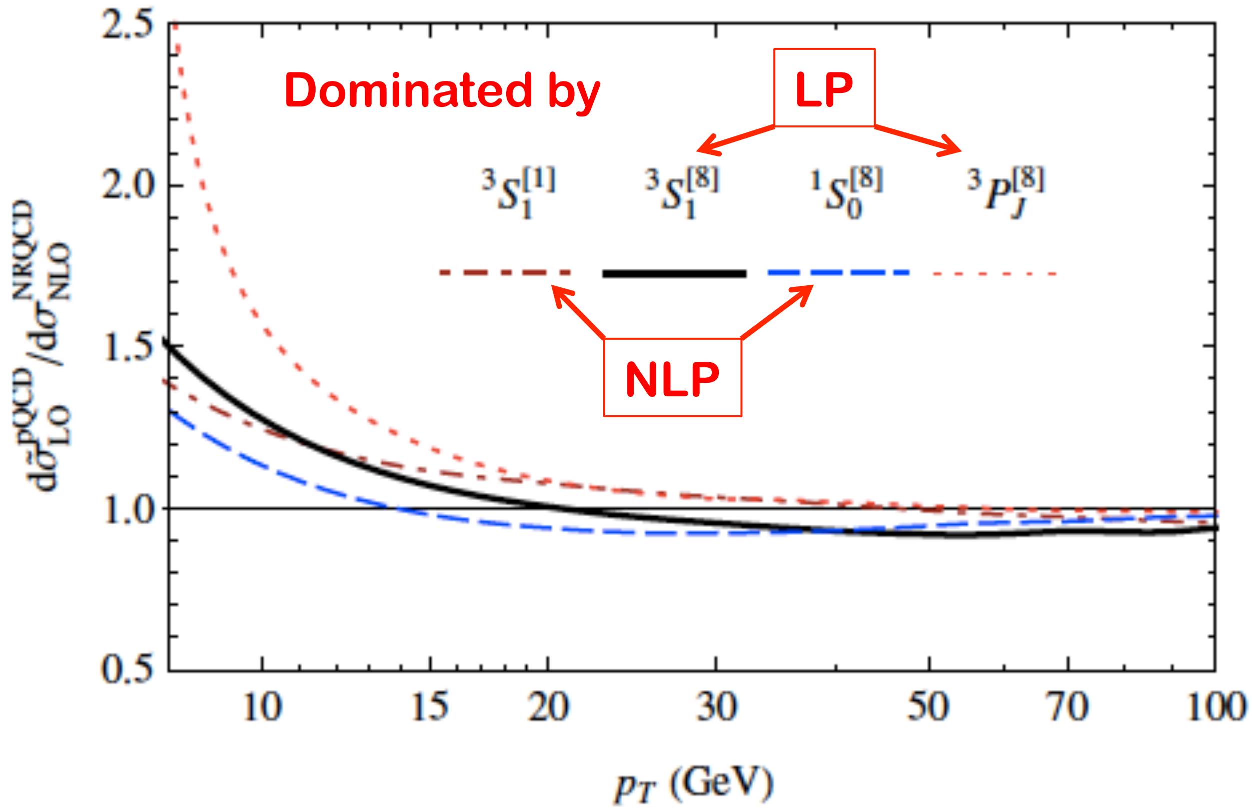
QCD factorization + NRQCD factorization

Kang, Ma, Qiu and Sterman, 2014

$$d\sigma_{A+B\to H+X}(p_T) = \sum_f d\hat{\sigma}_{A+B\to f+X}(p_f = p/z) \otimes D_{H/f}(z, m_Q)$$

$$+ \sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z, p(1\pm\zeta')/2z) \otimes \mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q)$$

- ❑ **Channel-by-channel comparison with NLO NRQCD:**



independent of NRQCD matrix elements

LO QCD analytical results reproduce NLO NRQCD calculations (numerical)

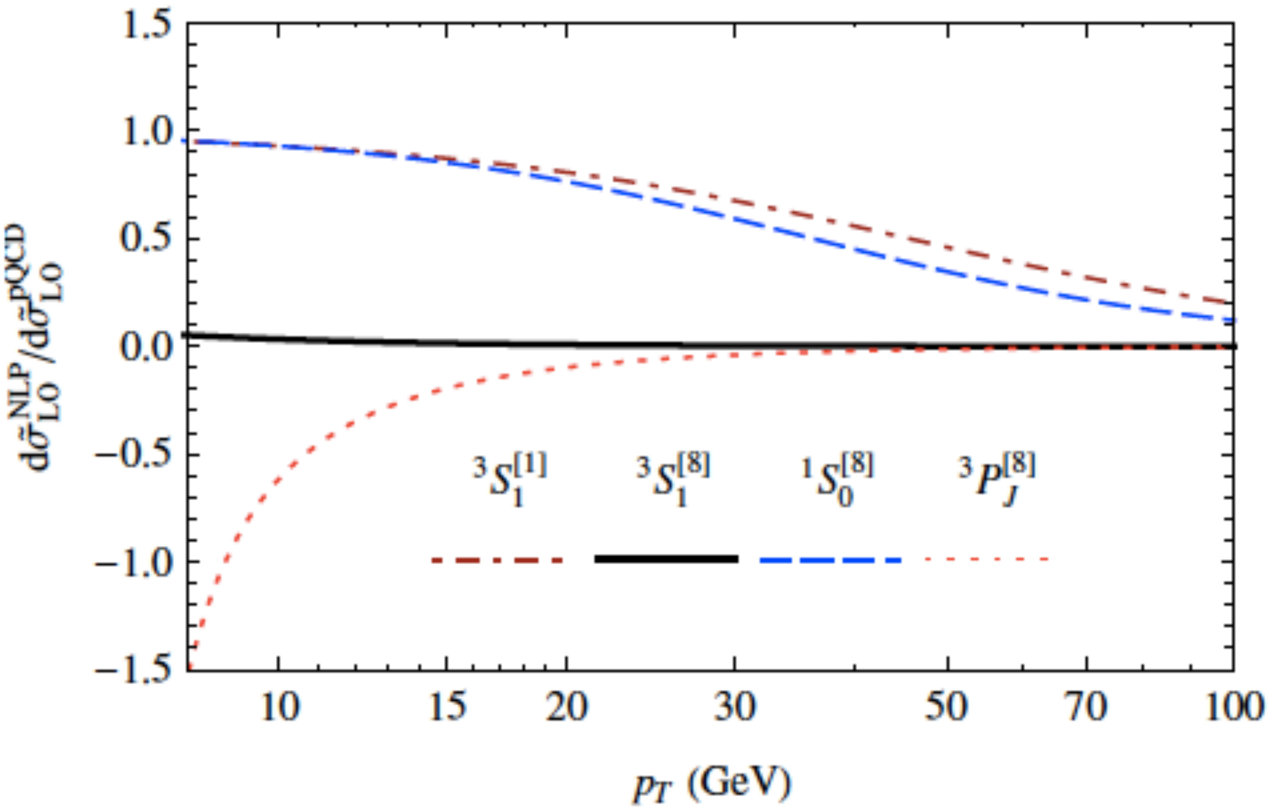
PRL, 2014

QCD factorization + NRQCD factorization

Kang, Ma, Qiu and Sterman, 2014

$$d\sigma_{A+B\to H+X}(p_T) = \sum_f d\hat{\sigma}_{A+B\to f+X}(p_f = p/z) \otimes D_{H/f}(z, m_Q)$$
$$+ \sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z, p(1\pm\zeta')/2z) \otimes \mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q)$$

- LP vs. NLP (both LO):



NLP dominated $^1S_0^{[8]}$ **for wide pT**

LP dominated $^3S_1^{[8]}$ and $^3P_J^{[8]}$

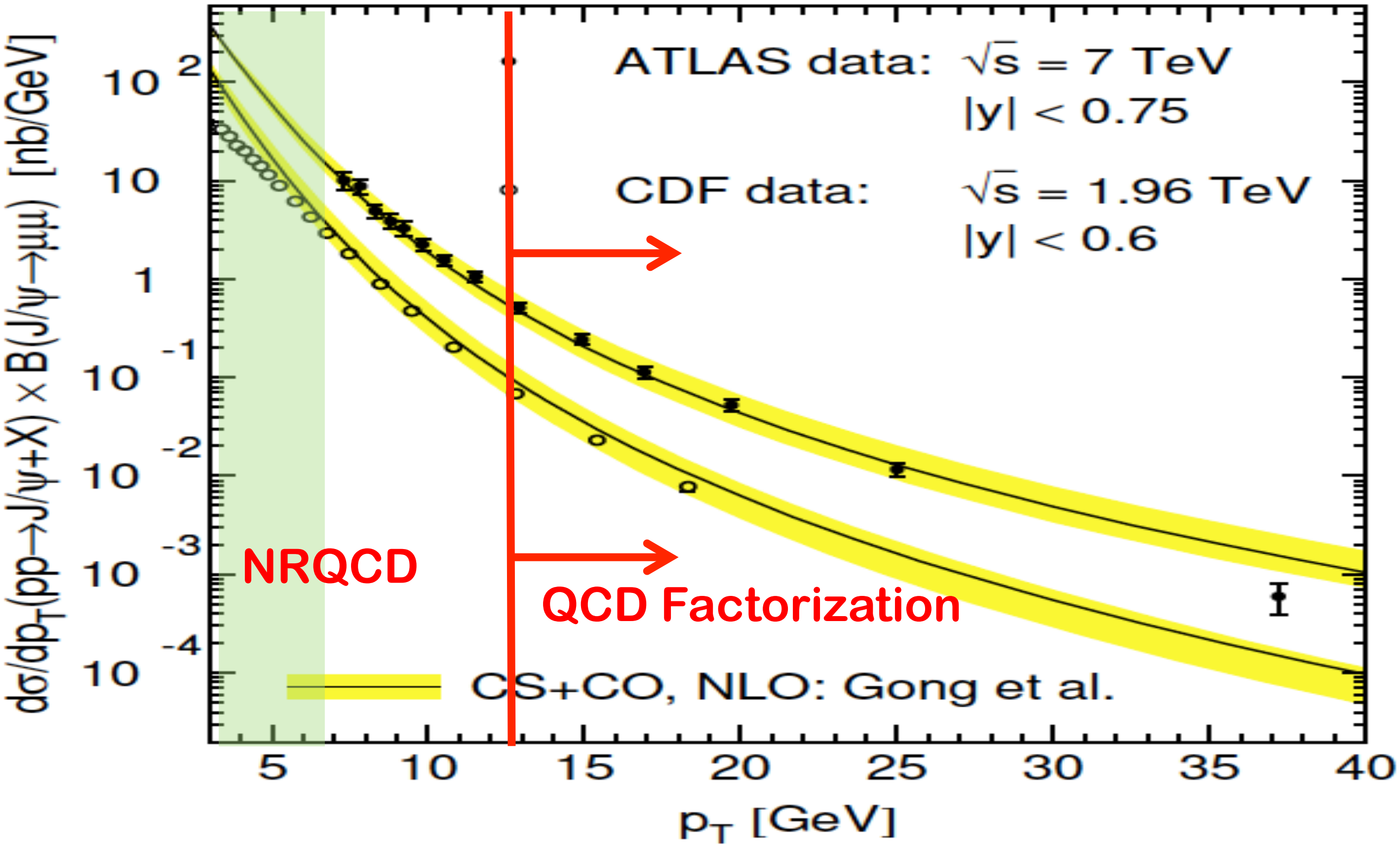
PT distribution is consistent with distribution of $^1S_0^{[8]}$

PRL, 2014

Matching between QCD and NRQCD

- Expectation:

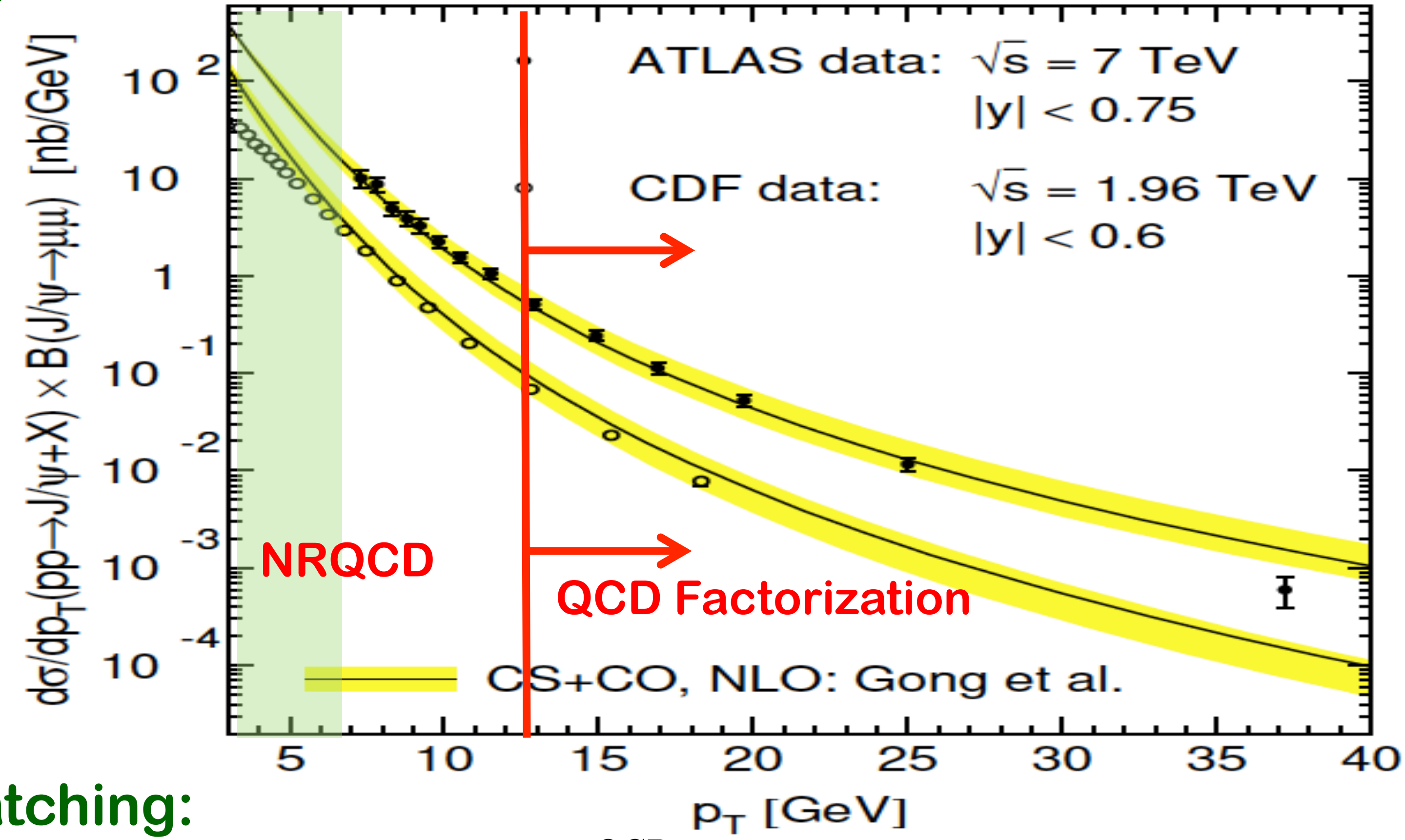
Kang, Ma, Qiu and Sterman, 2014



Matching between QCD and NRQCD

Kang, Ma, Qiu and Sterman, 2014

❑ Expectation:



❑ Matching:

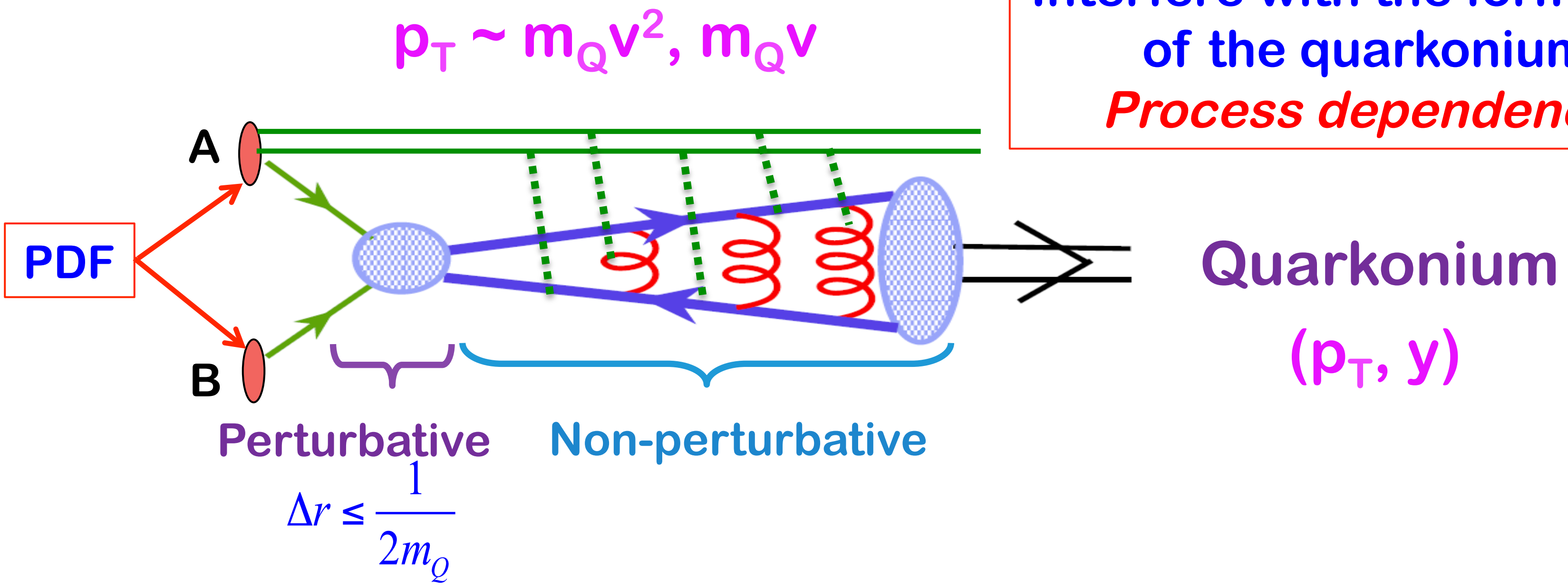
$$E_P \frac{d\sigma_{A+B\to H+X}}{d^3P}(P,m_Q) \equiv E_P \frac{d\sigma^{\rm QCD}_{A+B\to H+X}}{d^3P}(P,m_Q=0)$$

$$+E_P \frac{d\sigma^{\rm NRQCD}_{A+B\to H+X}}{d^3P}(P,m_Q\neq 0) - E_P \frac{d\sigma^{\rm QCD-Asym}_{A+B\to H+X}}{d^3P}(P,m_Q=0)$$

Mass effect + expanded P_T region ($P_T \gtrsim m_Q$)

Production at low p_T (< M_Q)

- Spectator interaction – always there:



Interfere with the formation of the quarkonium
Process dependence

- The bad:

Process dependence – Break of factorization – No predictive power

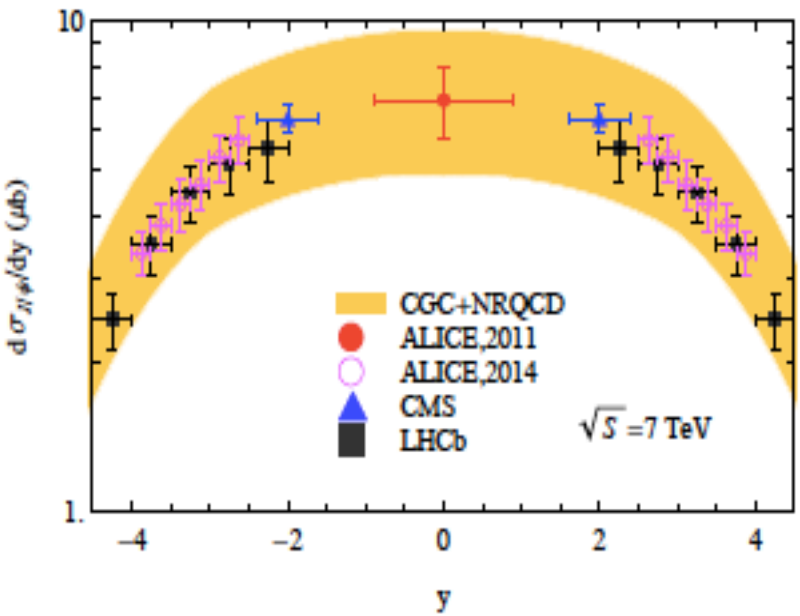
- The need:

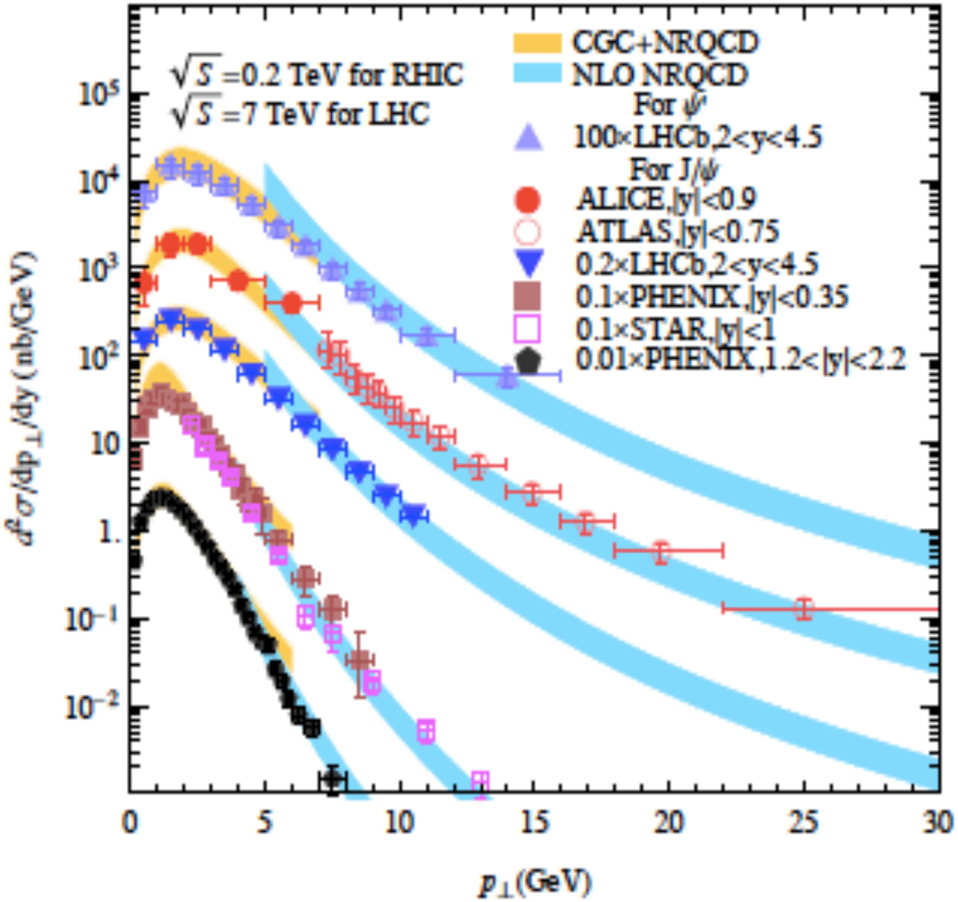
Controllable calculation of the medium effect?

Production at low p_T (< M_Q)

- Small-x "TMD" approach:
  – assuming factorization

Ma and Venugopalan
Phys. Rev. Lett. 113 (2014)



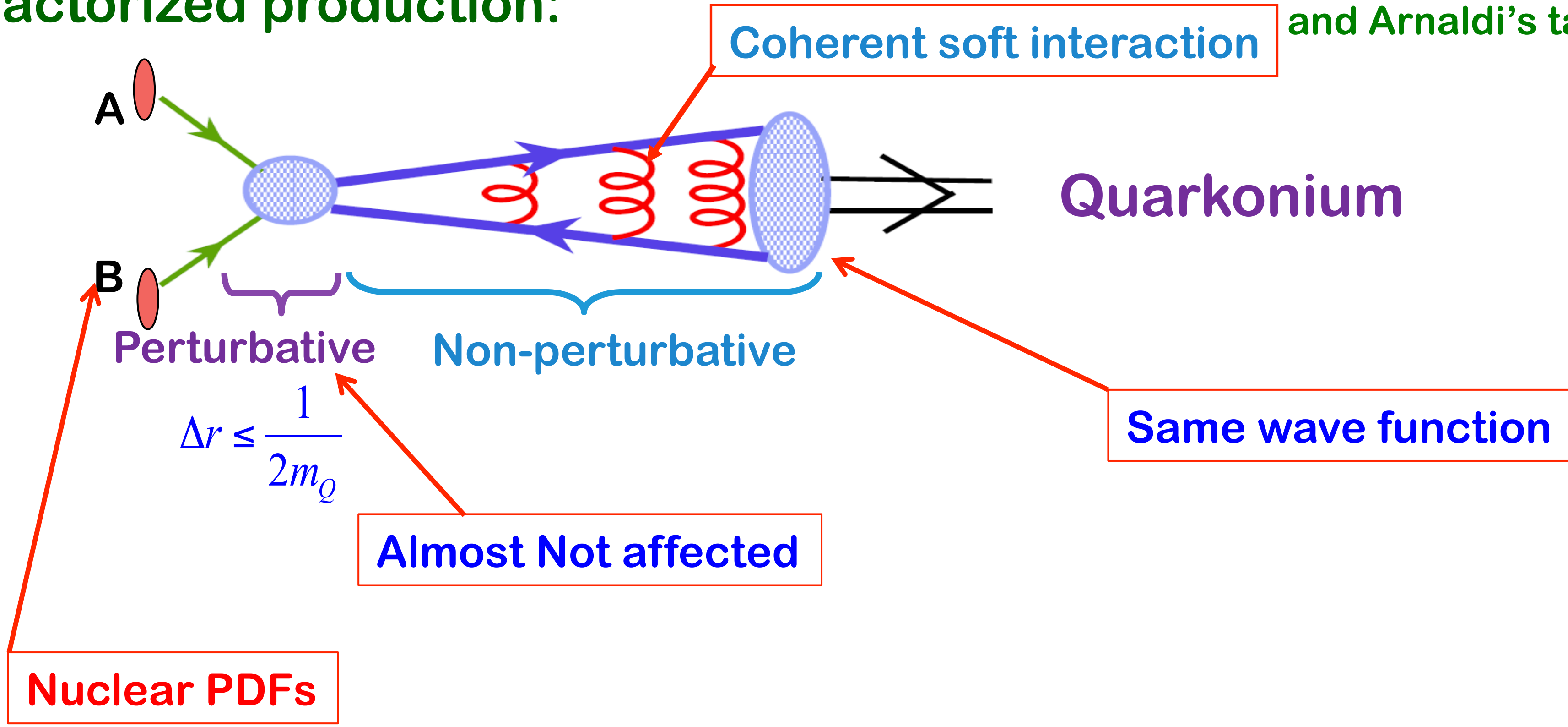


Also see talks by D. Boer and K. Watanabe

Production in p(d)+A collisions

- Factorized production:

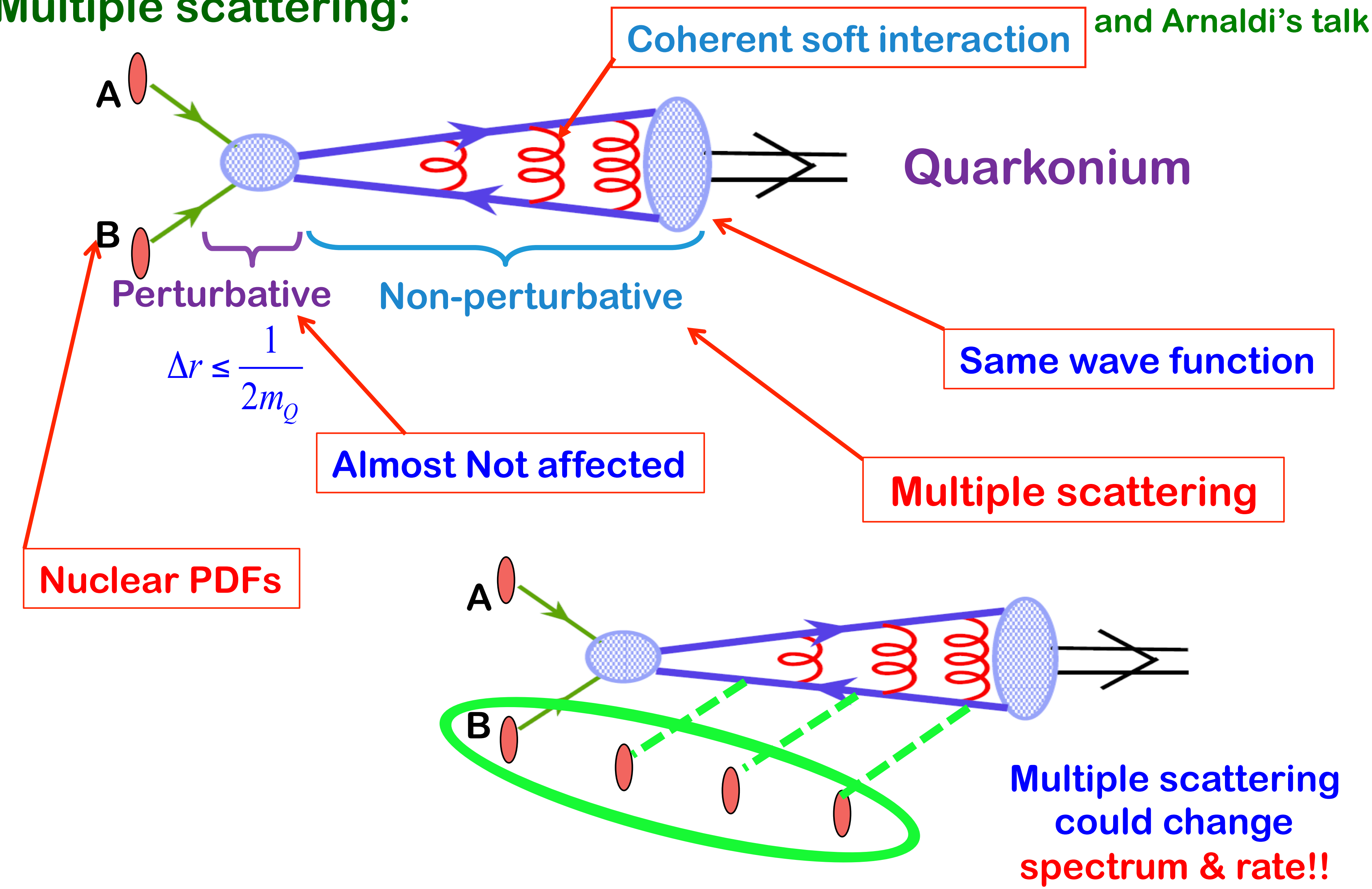
Also see Boer's talk and Arnaldi's talk



Production in p(d)+A collisions

- **Multiple scattering:**

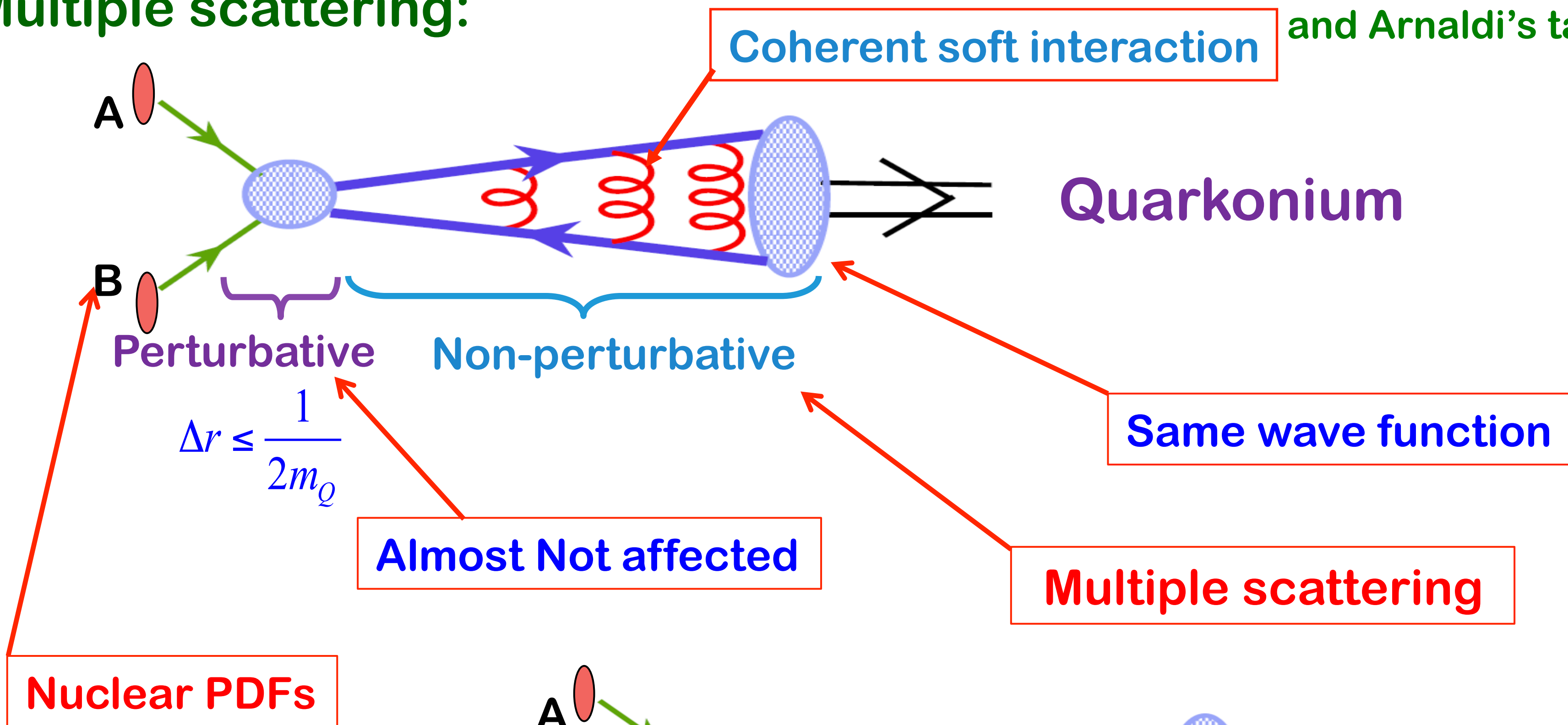
Also see Boer's talk and Arnaldi's talk

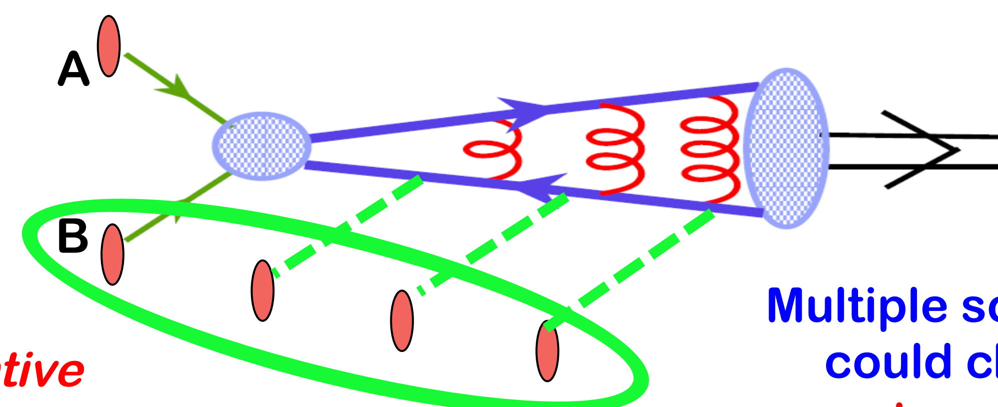


Production in p(d)+A collisions

- ❑ **Multiple scattering:**

Also see Boer's talk and Arnaldi's talk





Can multiple scattering interfere with nonperturbative formation of quarkonia?

Multiple scattering could change spectrum & rate!!

Summary

- It has been over 40 years since the discovery of J/Ψ
- When $p_T \gg m_Q$ at collider energies, earlier models calculations for the production of heavy quarkonia are not perturbatively stable

  LO in α_s-expansion may not be the LP term in $1/p_T$-expansion

- QCD factorization works for both LP and NLP (α_s for each power)
  - ✧ LP dominates: ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ channels
  - ✧ NLP dominates: ${}^1S_0^{[8]}$ and ${}^3S_1^{[1]}$ channels
  - ✧ From current data: ${}^3P_J^{[8]}$ likely to cancel ${}^3S_1^{[8]}$
    the production dominated by ${}^1S_0^{[8]}$
- Nuclear medium could be a good "filter" or a fermi-scale detector for studying how a heavy quarkonium is emerged from a pair of heavy quarks

Thank you!

Also see Zein-Eddine's talk

Backup slides

November revolution (1974)

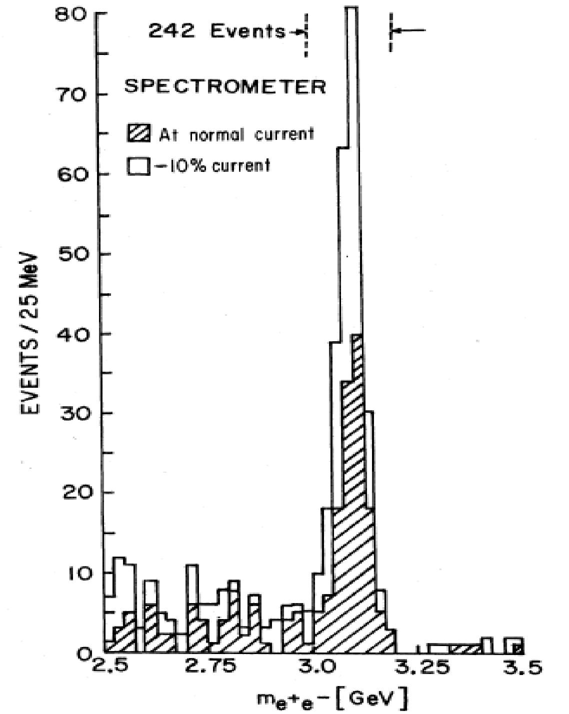
VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 19

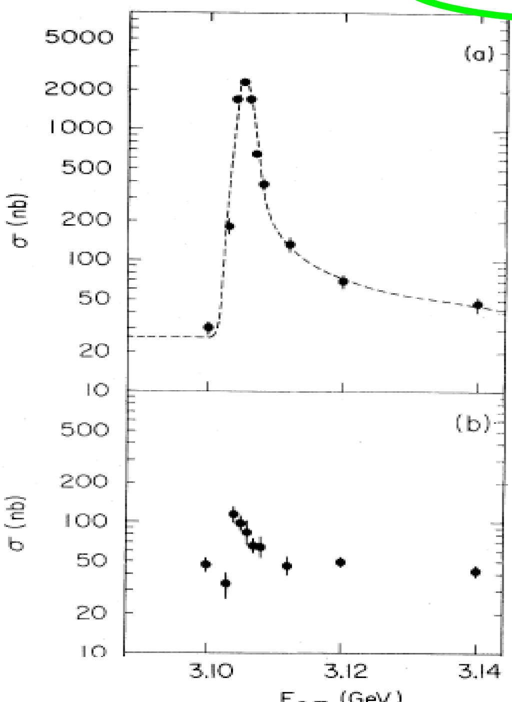
Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)





November, 1974

Discovery of a Narrow Resonance in e^+e^- Annihilation*

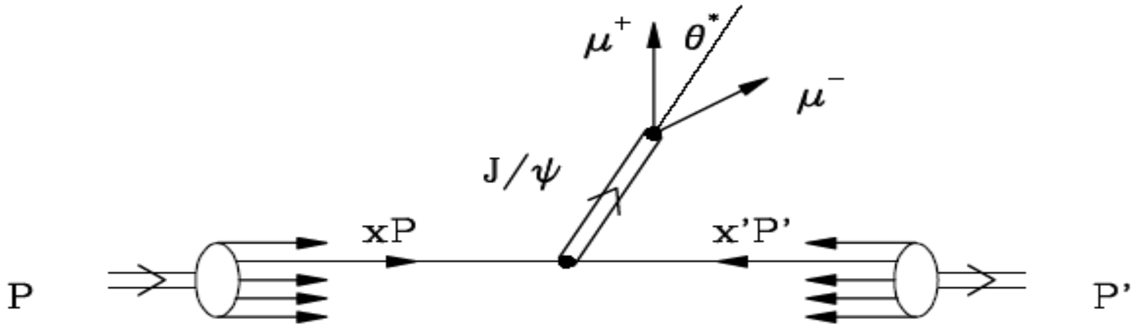
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

Heavy quarkonium polarization

- Measure angular distribution of $\mu^+\mu^-$ in J/ψ decay



- Normalized distribution – integrate over φ:

$$I(\cos\theta^*) = \frac{3}{2(\alpha+3)}\left(1+\alpha\cos^2\theta^*\right)$$

$$\alpha = \begin{cases} +1 & \text{fully transverse} \\ 0 & \text{unpolarized} \\ -1 & \text{fully longitudinal} \end{cases}$$

Also referred as λ_θ by LHC experiments

Heavy quarkonium polarization

Ma et al. 2014

- **Polarization = input fragmentation functions:**
  - ✧ Partonic hard parts and evolution kernels are perturbative
  - ✧ Insensitive to the properties of produced heavy quarkonia
- **Projection operators – polarization tensors:**

$$\mathcal{P}^{\mu\nu}(p) \equiv \sum_{\lambda=0,\pm1} \epsilon_\lambda^{*\mu}(p)\epsilon_\lambda^{\nu}(p) = -g^{\mu\nu} + \frac{p^\mu p^\nu}{p^2}$$

Unpolarized quarkonium

$$\mathcal{P}_T^{\mu\nu}(p) \equiv \frac{1}{2}\sum_{\lambda=\pm1} \epsilon_\lambda^{*\mu}(p)\epsilon_\lambda^{\nu}(p) = \frac{1}{2}\left[-g^{\mu\nu} + \frac{p^\mu n^\nu + p^\nu n^\mu}{p\cdot n}\right]$$

Transversely polarized quarkonium

$$\mathcal{P}_L^{\mu\nu}(p) \equiv \mathcal{P}^{\mu\nu}(p) - 2\mathcal{P}_T^{\mu\nu}(p) = \frac{1}{p^2}\left[p^\mu - \frac{p^2}{2p\cdot n}n^\mu\right]\left[p^\nu - \frac{p^2}{2p\cdot n}n^\nu\right]$$

Longitudinally polarized quarkonium

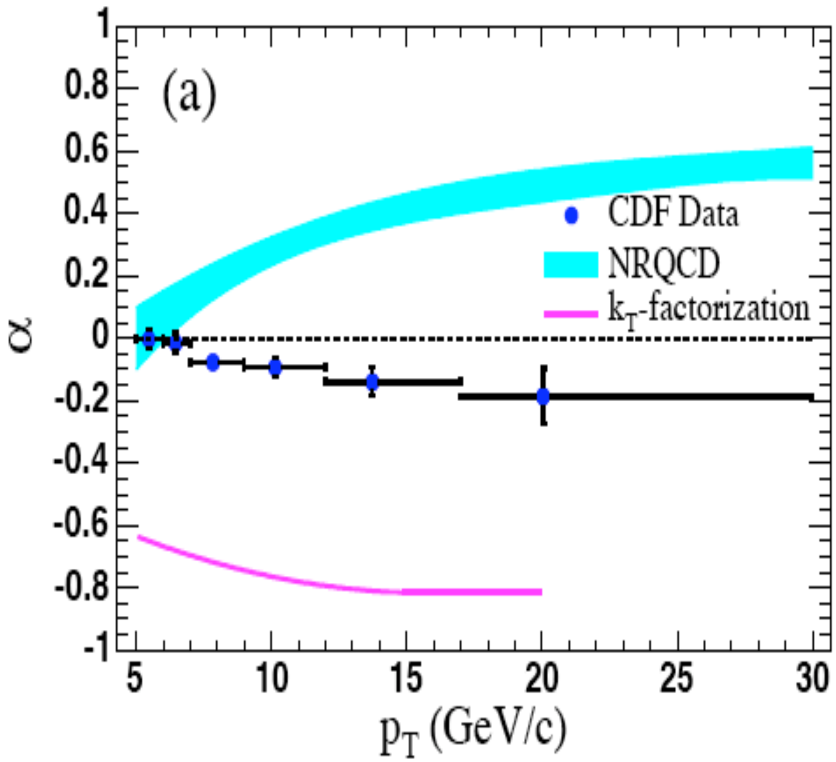
for produced the quarknium moving in +z direction with

$$p^\mu = (p^+, p^-, p_\perp) = p^+(1, 0, \mathbf{0}_\perp) \qquad p^2 = n^2 = 0$$

$$n^\mu = (n^+, n^-, n_\perp) = (0, 1, \mathbf{0}_\perp) \qquad p\cdot n = p^+$$

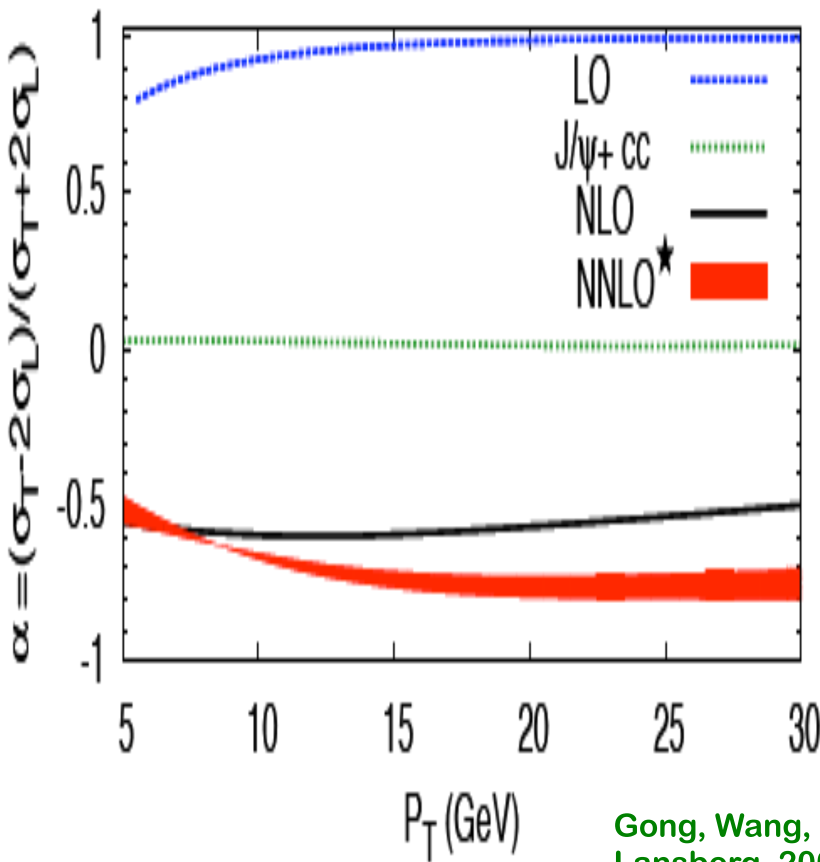
Theory predictions on J/ψ polarization

NRQCD



Cho & Wise, Beneke & Rothstein, 1995, …

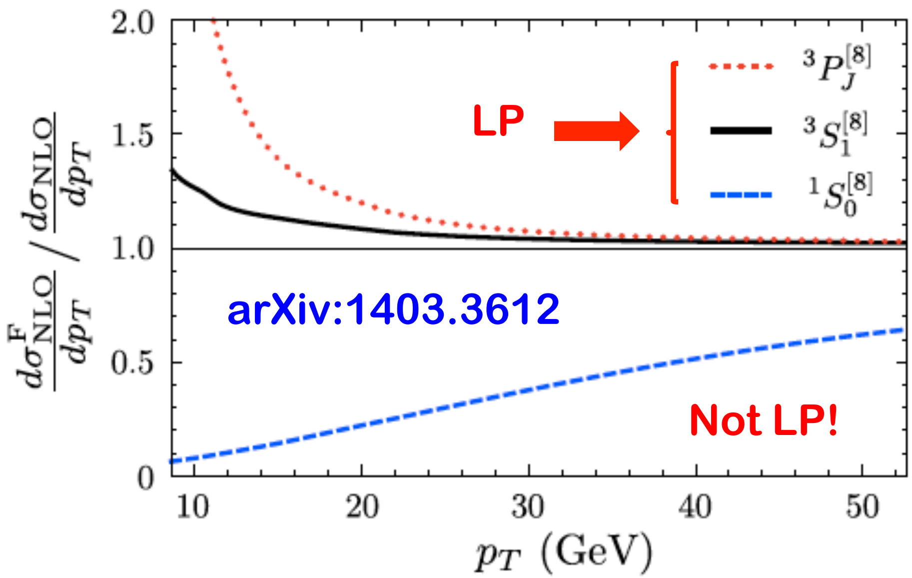
CSM

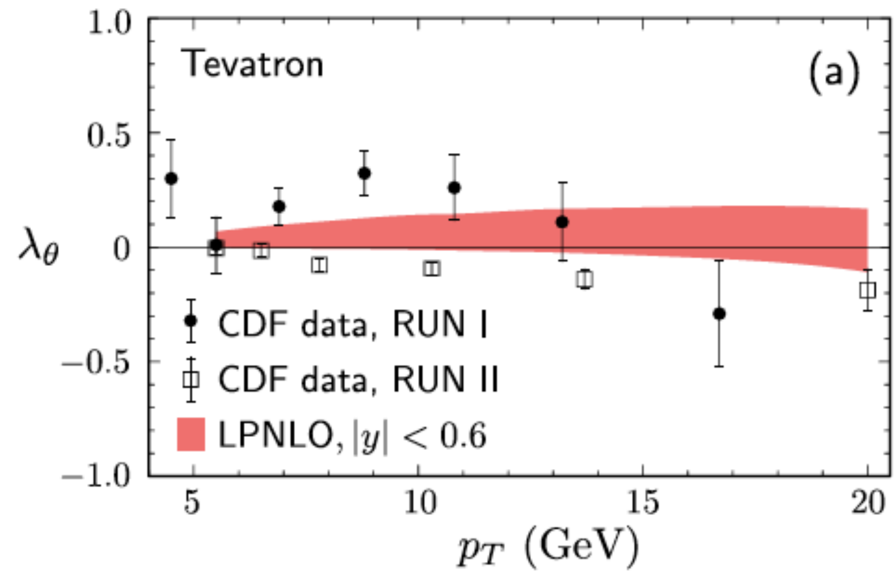


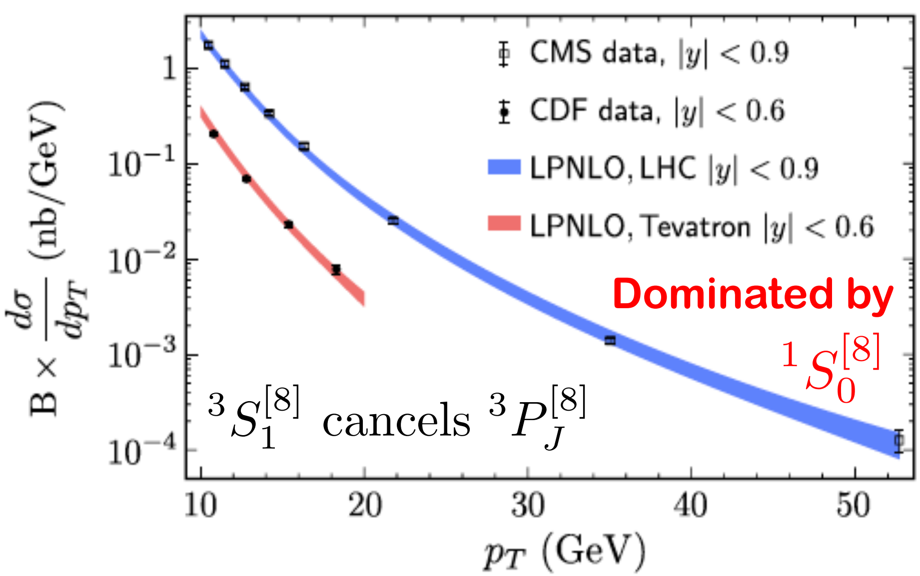
Gong, Wang, 2008
Lansberg, 2009

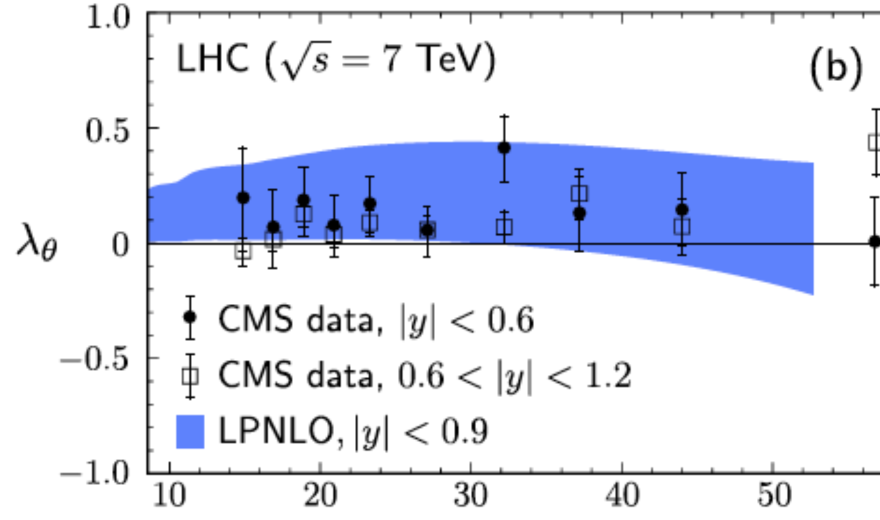
- ✧ **NRQCD:** Dominated by color octet – NLO is not a huge effect
- ✧ **CSM:** Huge NLO – change of polarization?

Leading power fragmentation – Bodwin et al.









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