INT Program INT–18–3

Probing Nucleons and Nuclei in High Energy Collisions

October 1 – November 16, 2018

Heavy Quarkonium Production in Quantum Chromodynamics

Jianwei Qiu

Theory Center, Jefferson Lab

November revolution (1974)

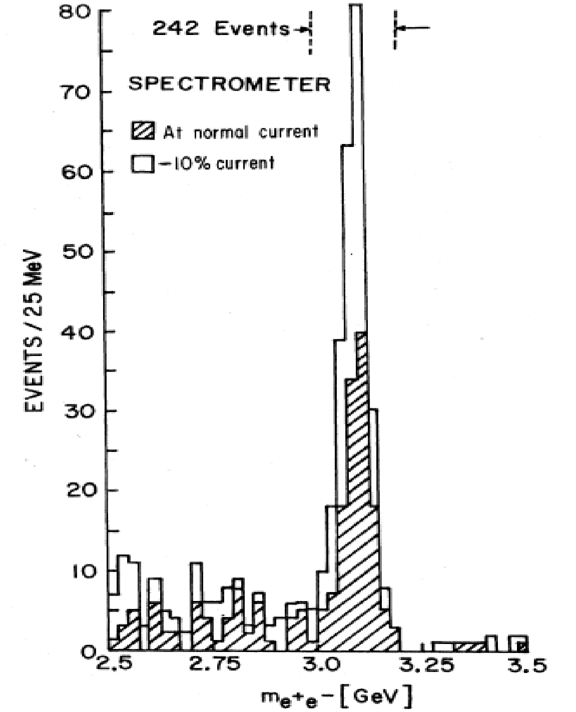
VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 19

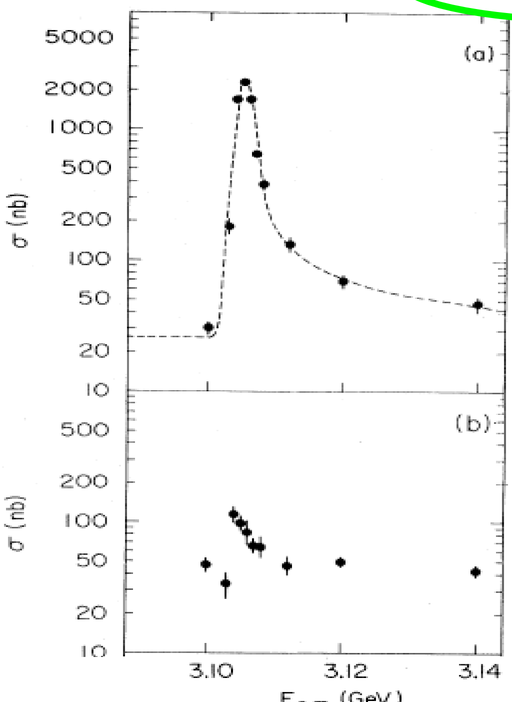
Experimental Observation of a Heavy Particle J†

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)

Standard Model since Nov 1974

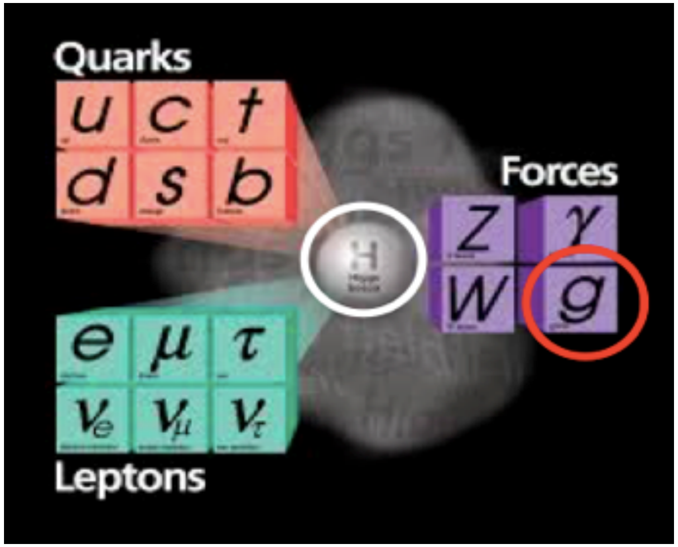
❑ Elementary particles – new periodic table:

Flavor	Mass
u	$1.5 - 4.5$ MeV
d	$5.0 - 8.5$ MeV
s	$80 - 155$ MeV
c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV
t	174.3 ± 5.1 GeV

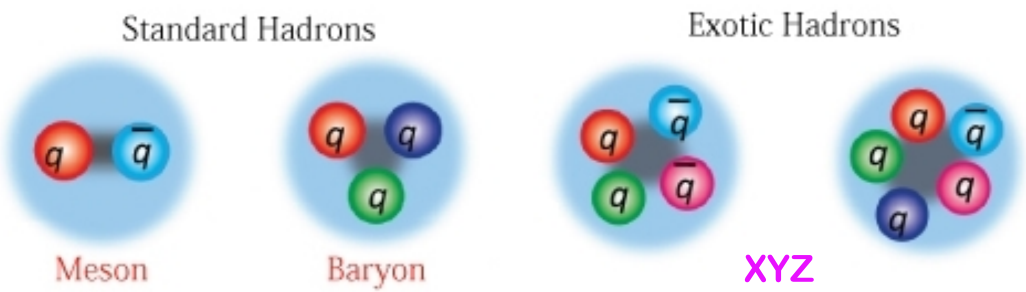
Light quarks (u, d, s)

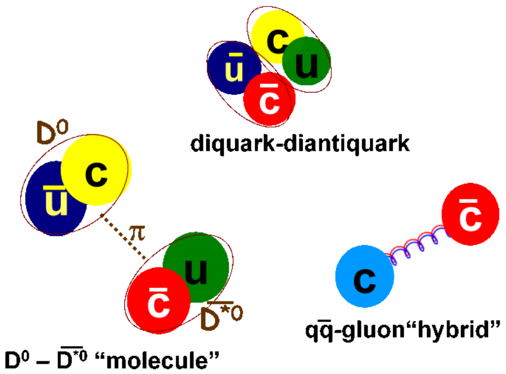
Λ_{QCD}

heavy quarks (c, b, t)



❑ Hadrons – bound states of quarks and gluons:





Outline of the rest of my talk

- ❑ **Dual roles of heavy quarkonium physics**

  QCD bound states vs. "localized" probes

- ❑ **Production mechanism?**

  Successes and failures of NRQCD factorization

- ❑ **EIC: Inclusive, Semi-inclusive, Exclusive, …**

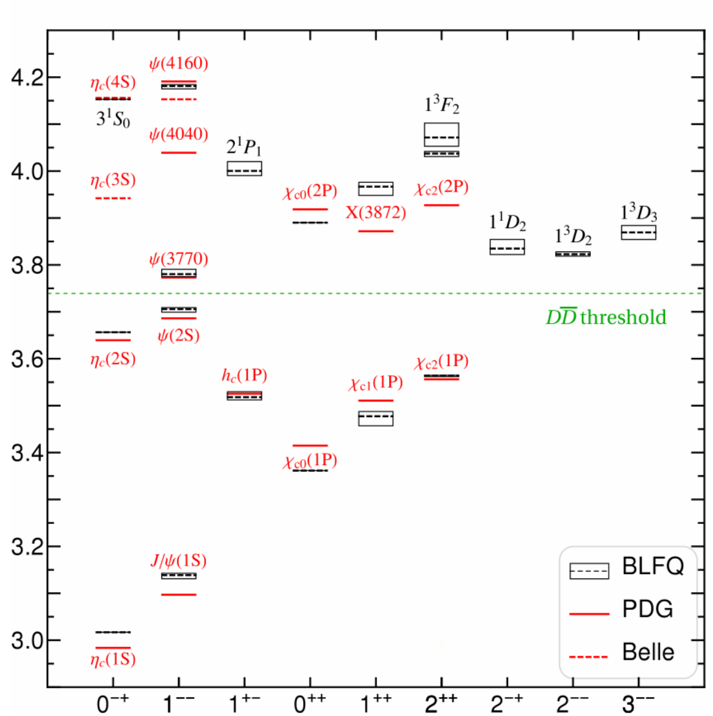
- ❑ **Gluon distribution, imaging, near threshold, …**

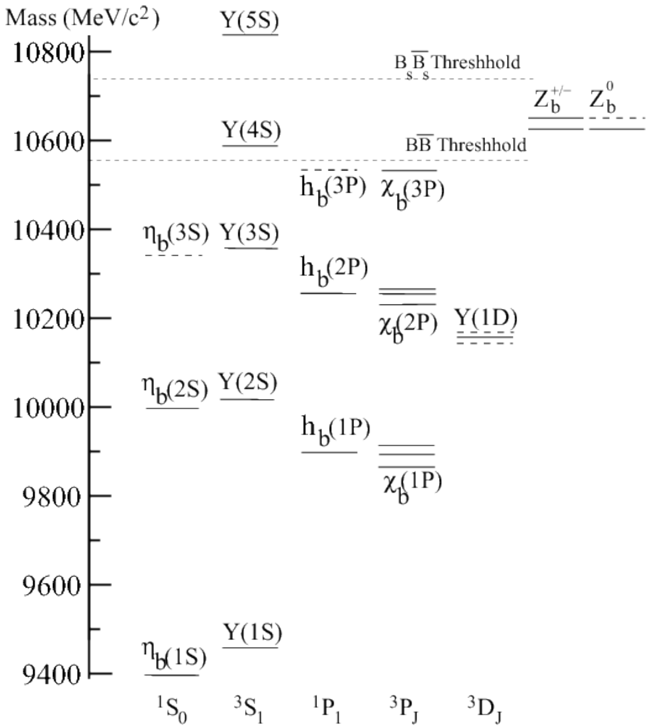
- ❑ **Summary and outlook**

If we do not understand heavy quarkonia, we do not know QCD!

Dual roles of heavy quarkonium physics

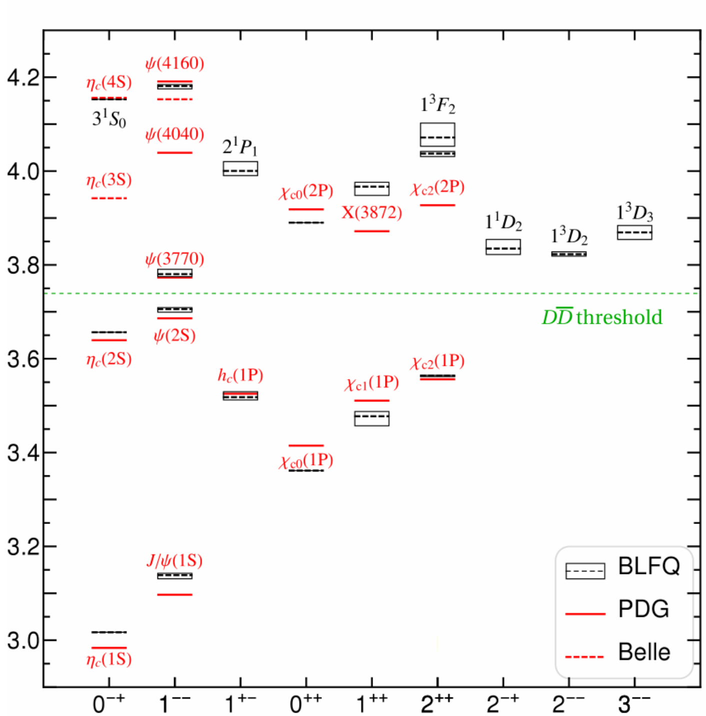
❑ **QCD bound states – spectroscopy, decay, production, …**

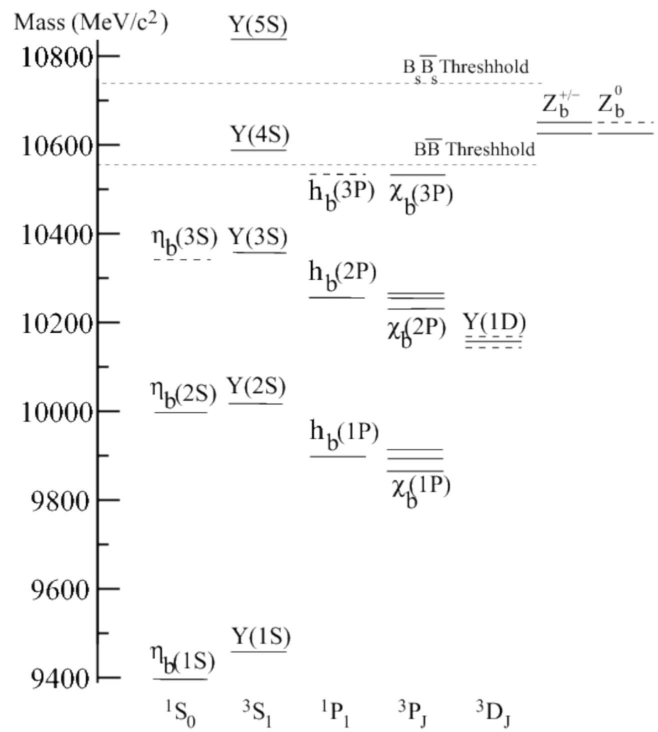




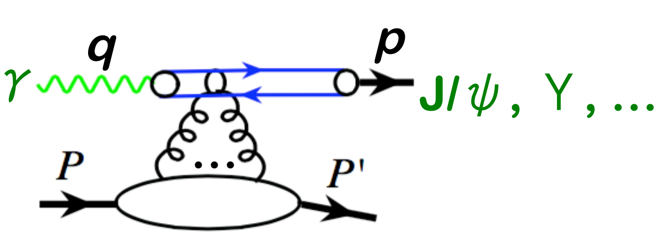
Dual roles of heavy quarkonium physics

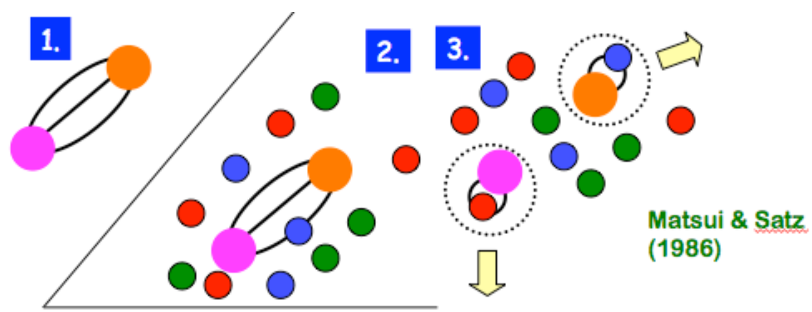
- ❑ QCD bound states – spectroscopy, decay, production, …

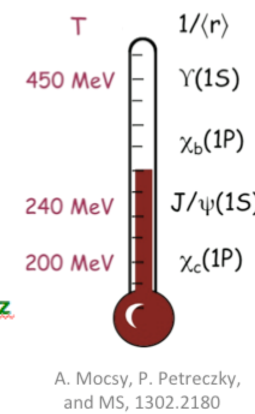




- ❑ "Localized" probes – structure, medium properties, …







Why QCD is so hard to deal with?

- It is strongly coupled – nonlinear + nonperturbative!
- It is relativistic – nontrivial QCD vacuum!
- No localized heavy mass/charge center – nucleus in an atom!
- Gluons are "dark" and carry "color" – intellectual challenge!

How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?

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Heavy quarkonium:

- ✧ **Heavy quark as relatively localized heavy mass/charge center**
- ✧ **Heavy quark in the pair's rest frame is almost non-relativistic**
- ✧ **Production of heavy quark pair could be perturbative**
- ✧ **Top decays too quickly, strange is too light, …**

➡ **Charmonium ($c\bar{c}$) + Bottomonium ($b\bar{b}$)**

c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV

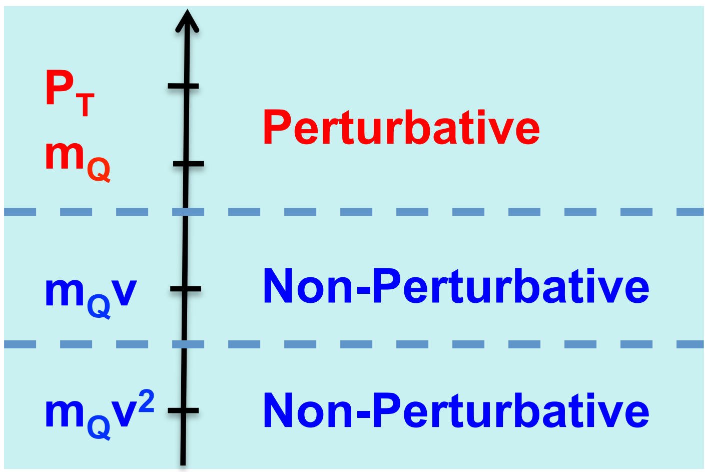
Heavy quarkonium

- 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]

⇐ $\Lambda_{\rm QCD}$

Ultrasoft — Binding Energy [pNRQCD]

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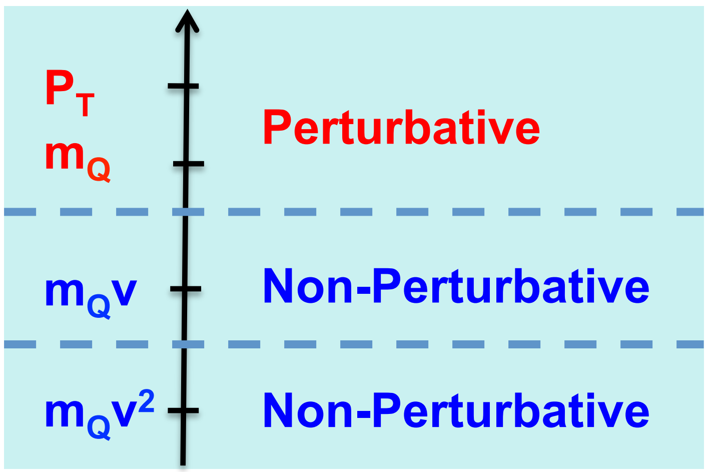

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Soft — Relative Momentum [NRQCD]

← $\Lambda_{\rm QCD}$

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?

Double $c\bar{c}$ production in e+e- collisions

Inclusive production:

$$\sigma(e^+e^- \to J/\psi c\bar{c})$$

Belle: $(0.87^{+0.21}_{-0.19} \pm 0.17)$ pb

NRQCD: $: \; 0.07$ pb

Kiselev, et al 1994,
Cho, Leibovich, 1996
Yuan, Qiao, Chao, 1997

Ratio to light flavors:

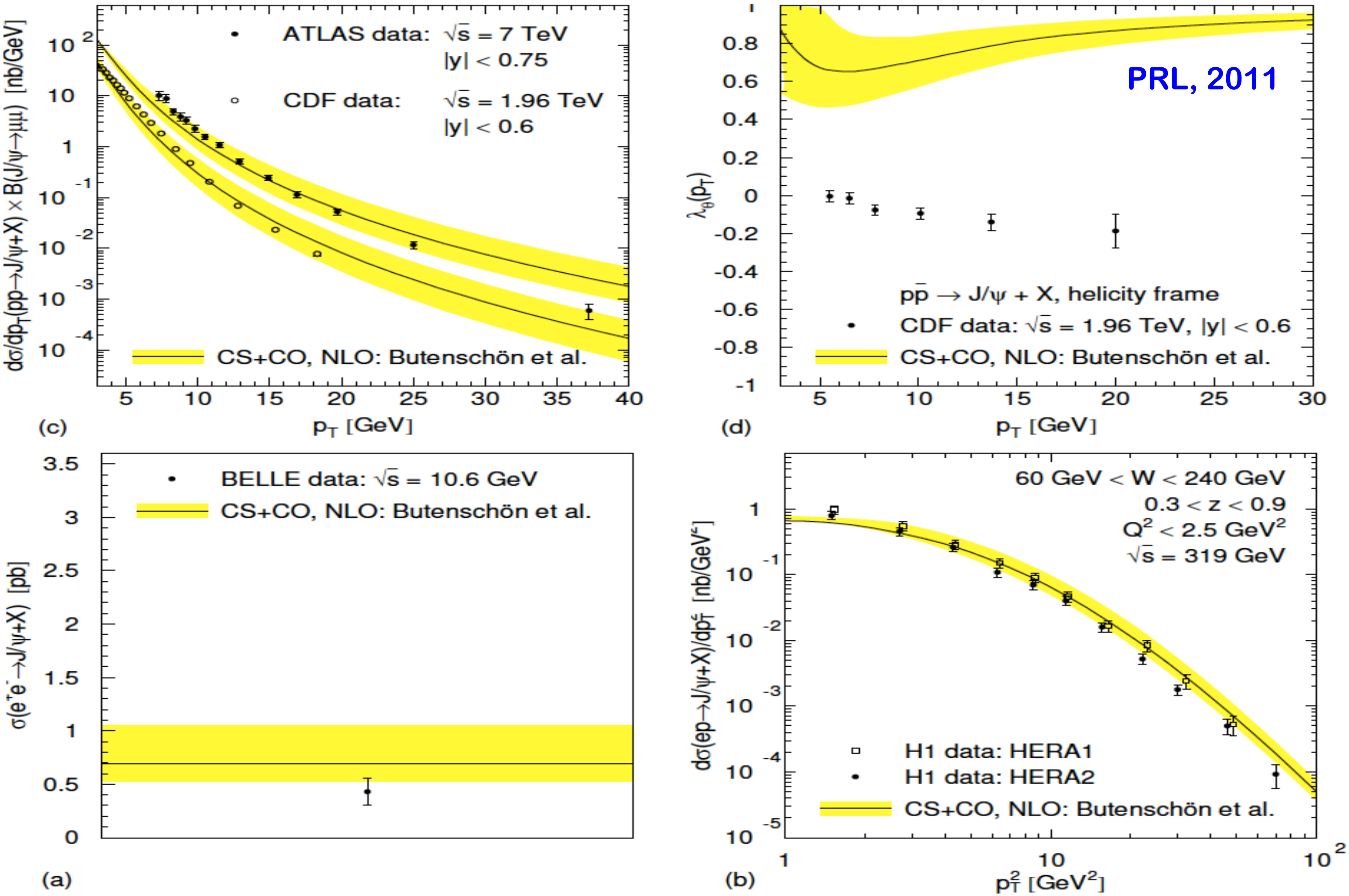
$$\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X)$$

Belle: $0.59^{+0.15}_{-0.13} \pm 0.12$

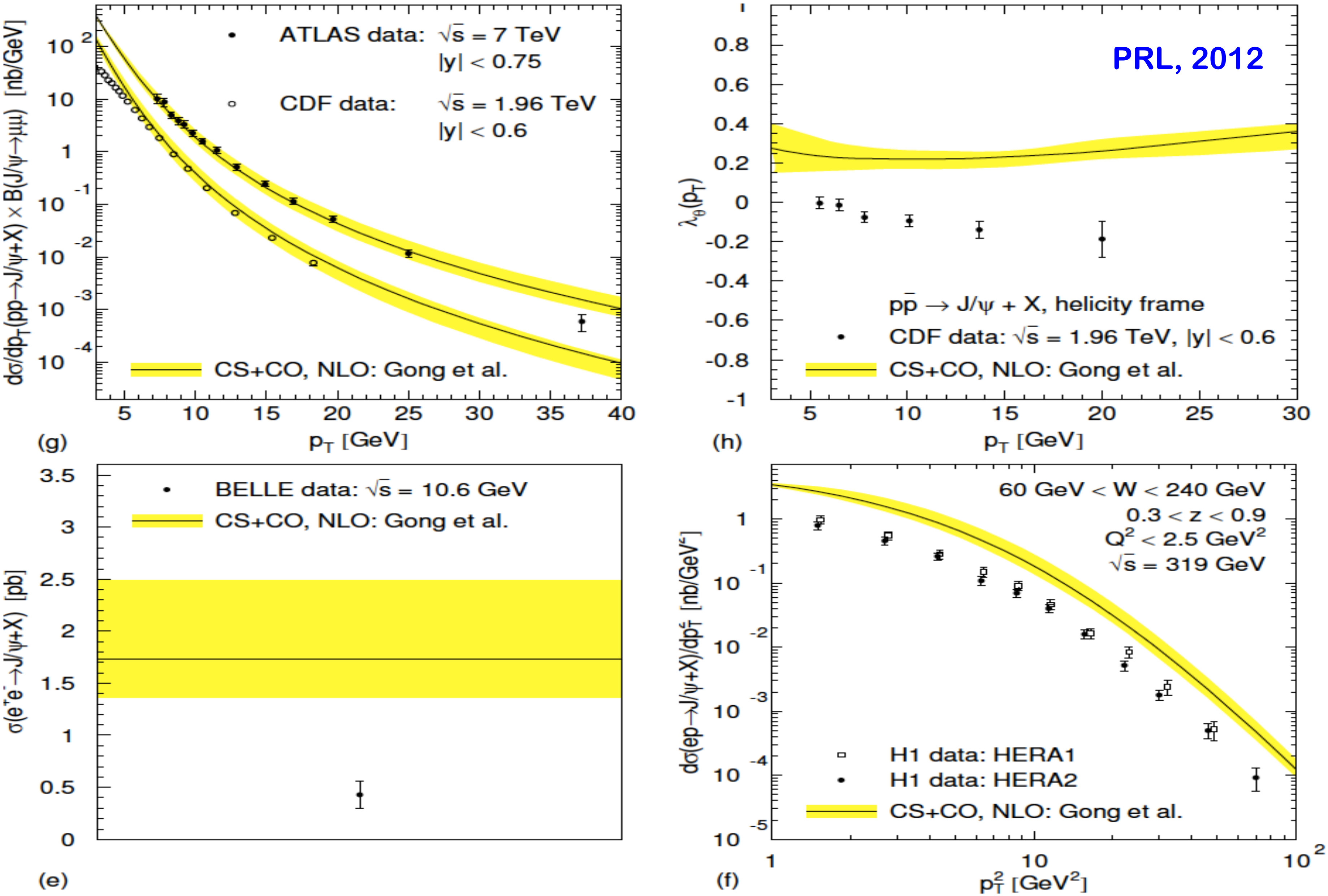
Message:

Production rate of $e^+e^- \to J/\psi c\bar{c}$ **is larger than all these channels:** $e^+e^- \to J/\psi gg \, , e^+e^- \to J/\psi q\bar{q} \, , \; \ldots$ **combined ?**

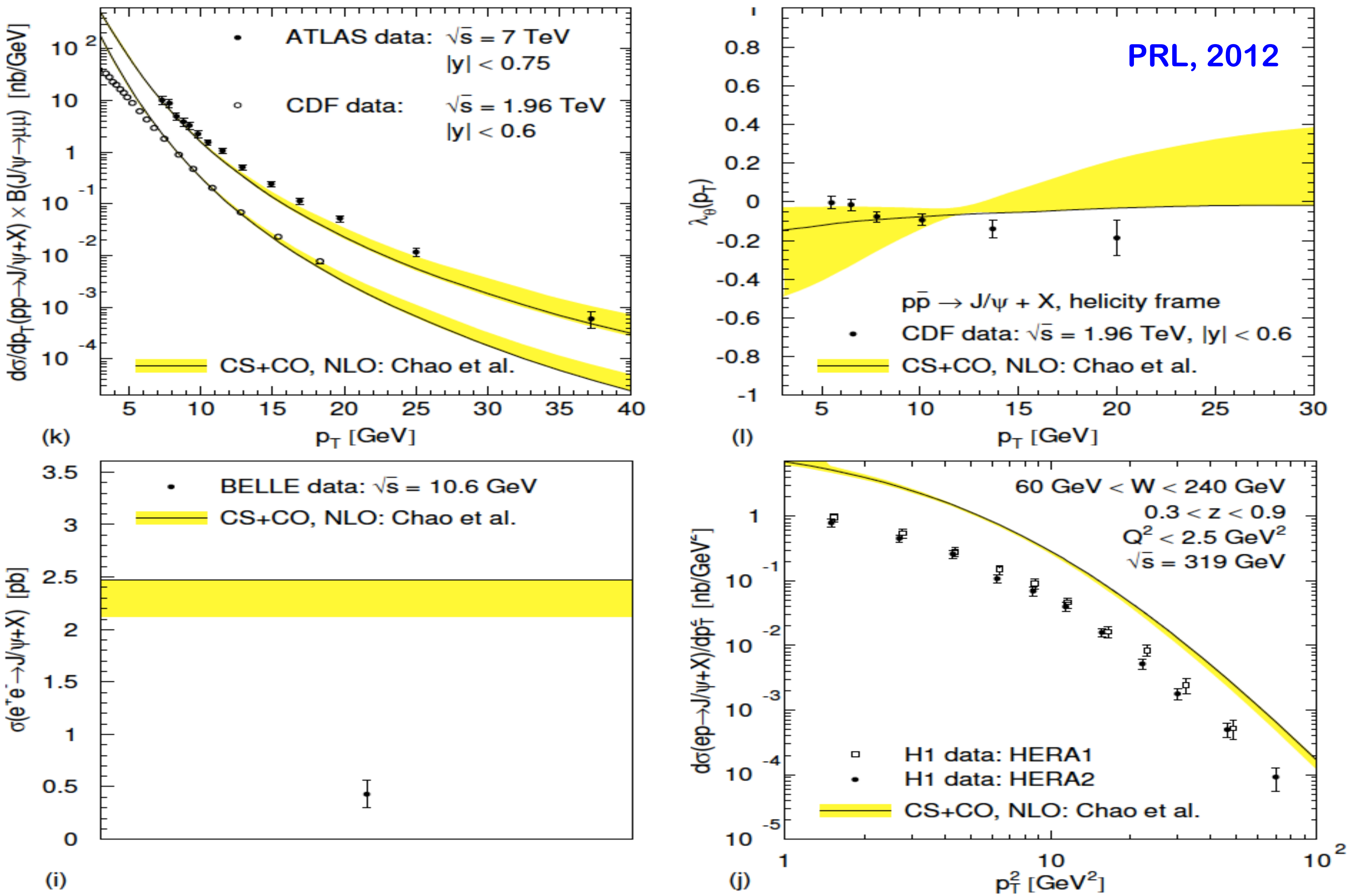
NLO theory fits – Butenschoen et al.



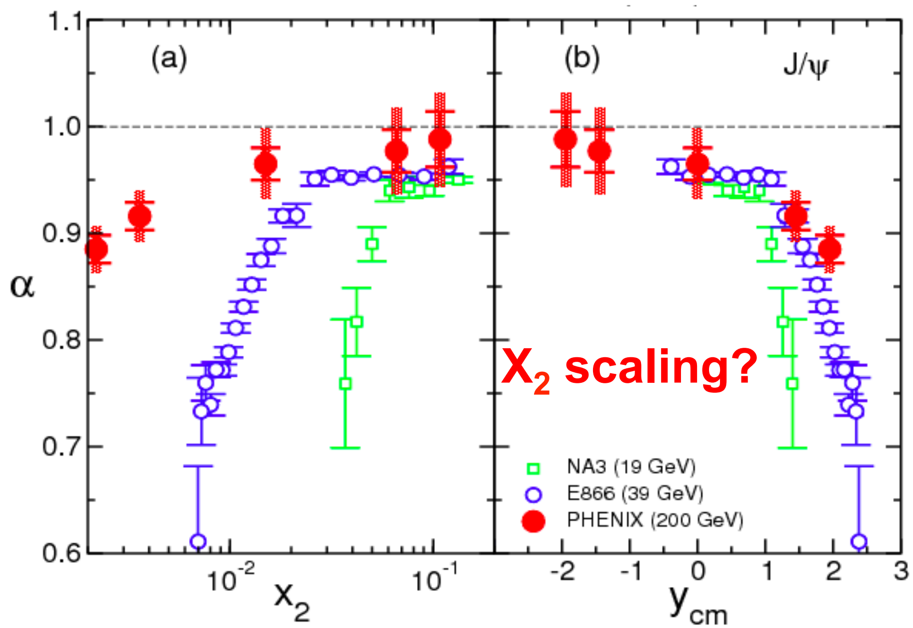
NLO theory fits – Gong et al.

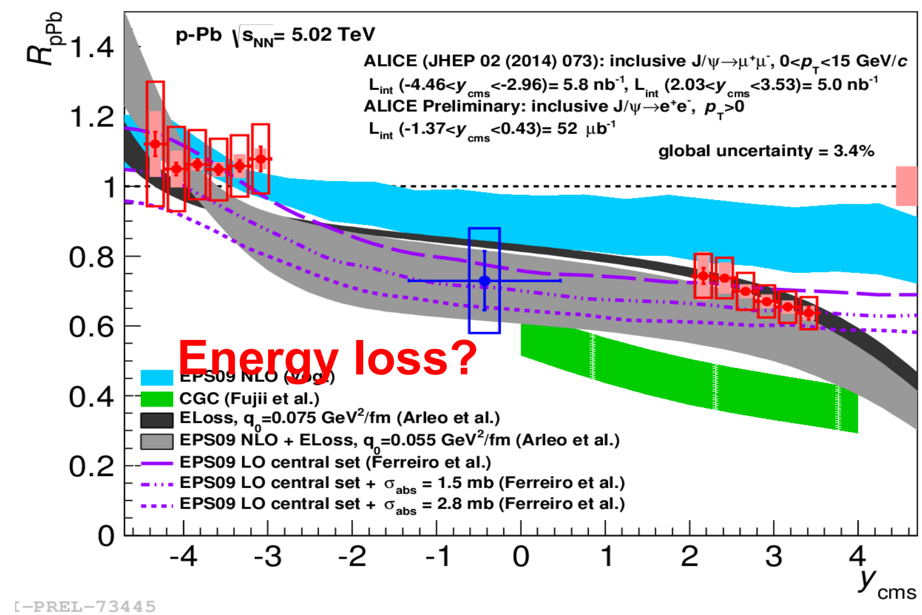


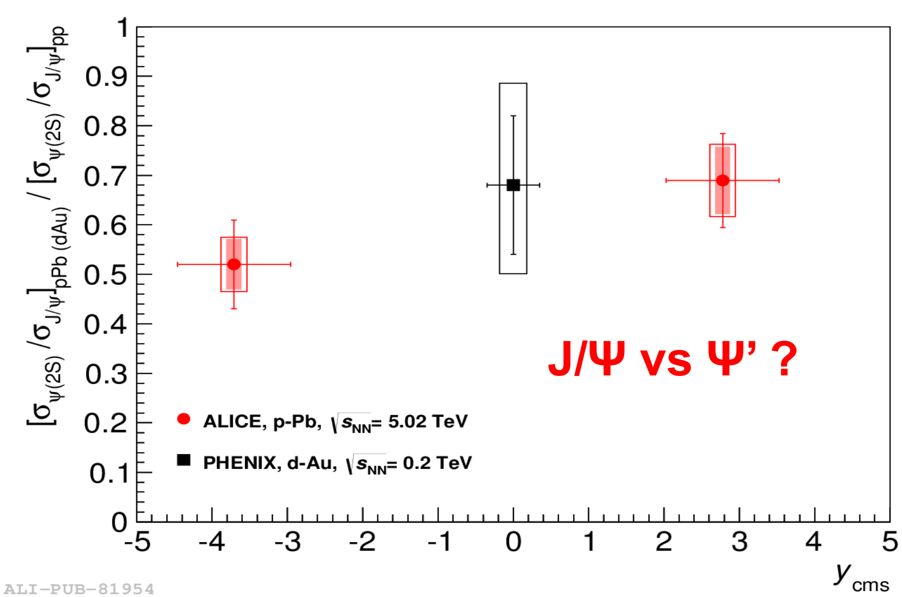
NLO theory fits – Chao et al.

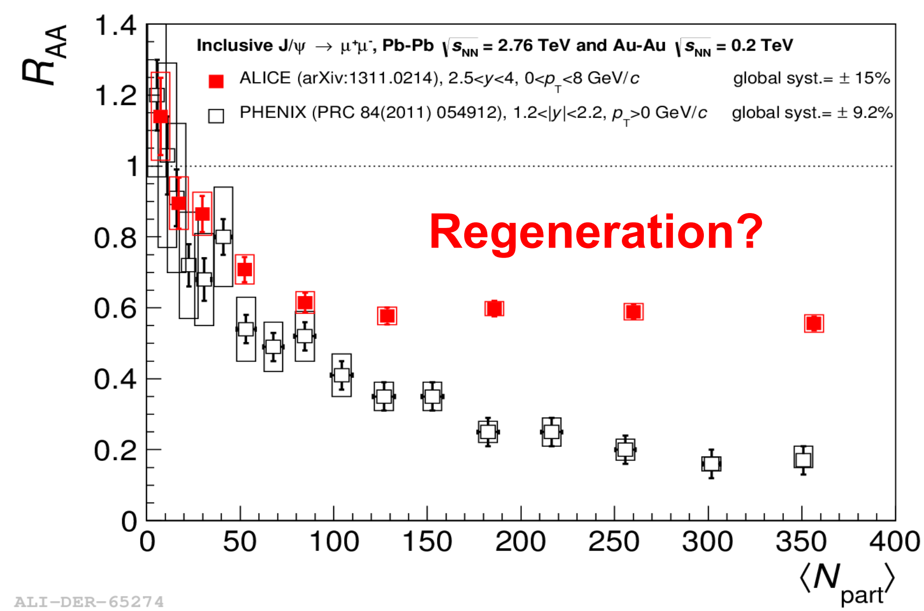


Production in medium, cold or hot?



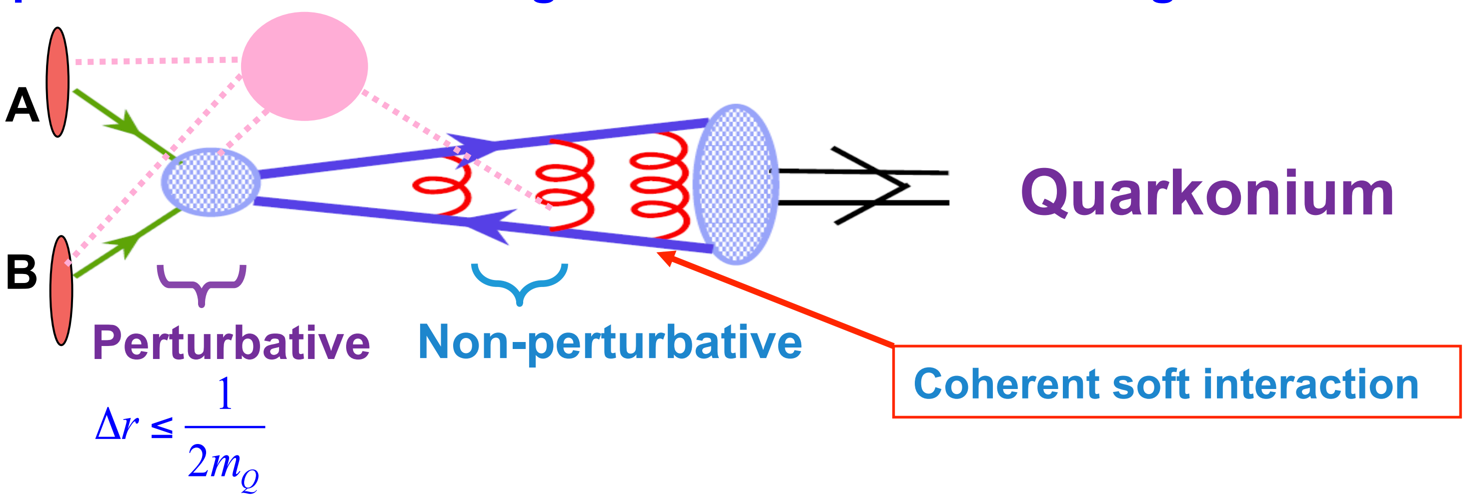




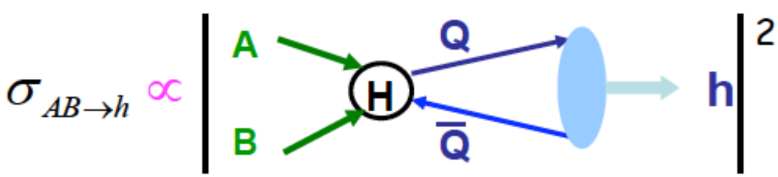


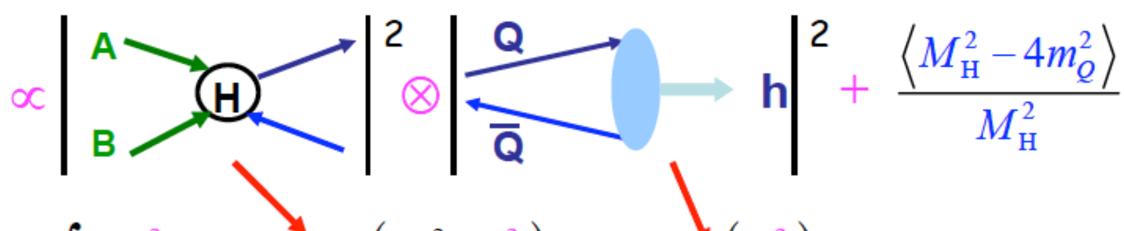
Basic production mechanism

- **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:**





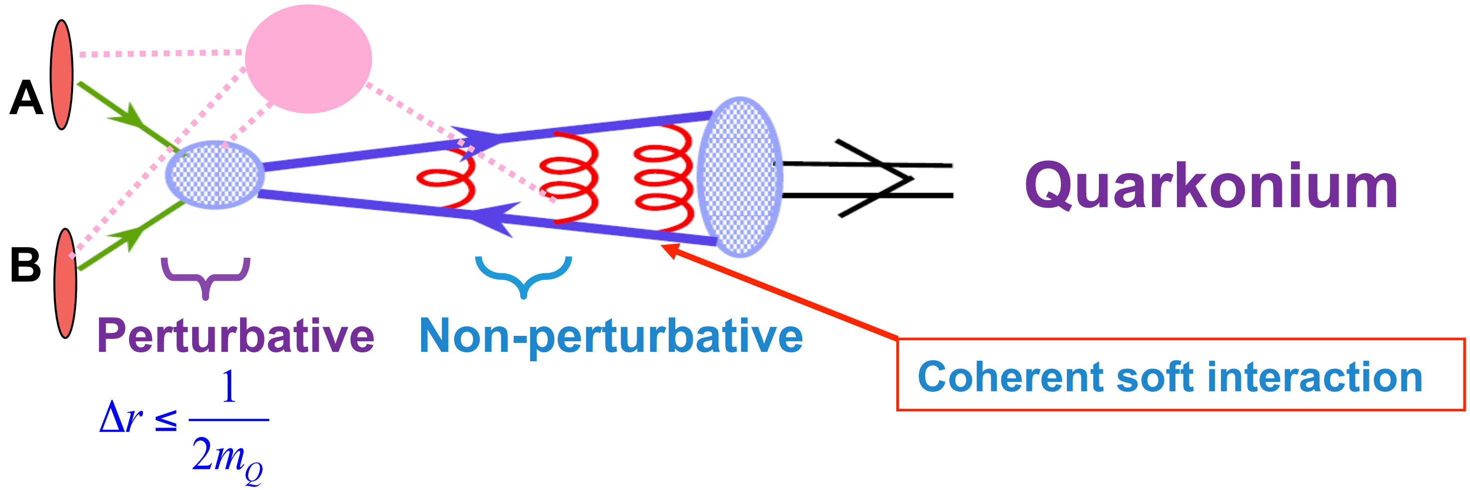
$$\Rightarrow \sigma_{AB\to h} = \int dq^2 \; \hat{\sigma}_{AB\to[Q\bar{Q}]}\left(m_Q^2, q^2\right) F_{[Q\bar{Q}]\to h}\left(q^2\right) + \ldots$$

Basic production mechanism

❑ **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**



❑ **Naïve factorization: on-shell pair + hadronization**

$$\sigma_{AB\to J/\psi} = \sum_{[Q\bar{Q}(n)]} \int d\Gamma_{[Q\bar{Q}]}\, \hat{\sigma}_{AB\to[Q\bar{Q}(n)]}(p_Q, p_{\bar{Q}}) F_{[Q\bar{Q}(n)]\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

Models & Debates

⬄ **Different assumptions/treatments on** $F_{[Q\bar{Q}(n)]\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$

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, …

NRQCD – most successful so far

Bodwin, Braaten, Lepage, PRD, 1995

- NRQCD factorization:

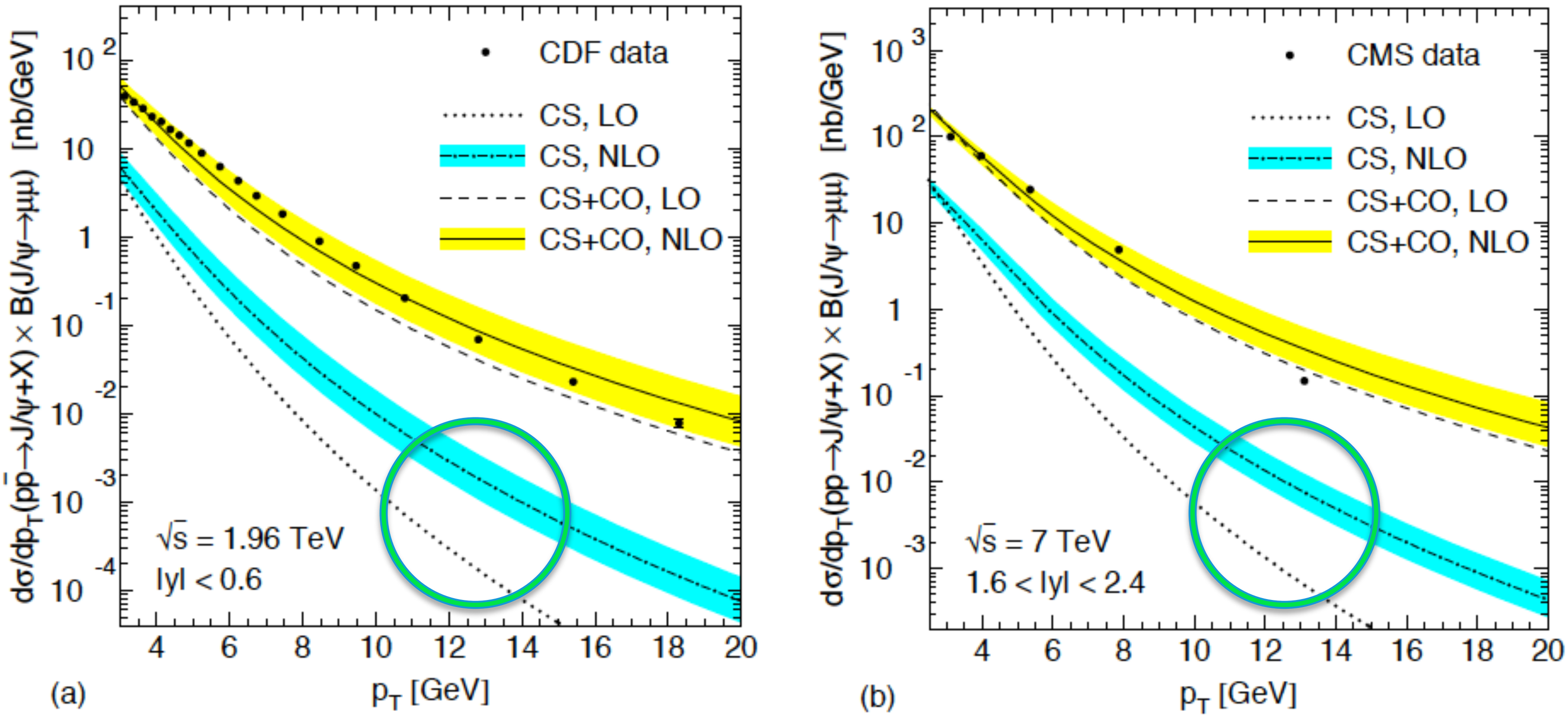
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \langle \mathcal{O}^H(n) \rangle$$

✧ **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)

Production at collider energies

G.T. Bodwin, et al., PRD 1995

- **NRQCD factorization:**

Expansion in powers of both α_s and *v* !

$$d\sigma_{A+B\to H+X}(p_T) = \sum_n d\hat{\sigma}_{A+B\to[Q\bar{Q}(n)]+X}(p_T)\,\langle\mathcal{O}_n^H\rangle$$

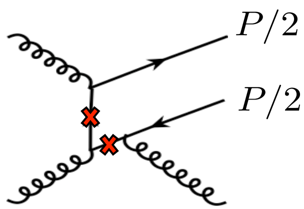
Hadronization

- **Re-organization is needed when $p_T \gg m_Q$:**

Z.B. Kang, et al., PRL 2011

CS channel as a case study

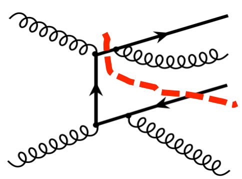
LO in α_s:

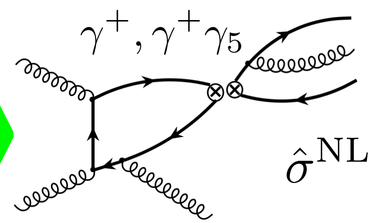


$$\hat{\sigma}^{\rm LO} \propto \frac{\alpha_s^3(p_T)}{p_T^8}$$

P_T Power!

NLO in α_s:

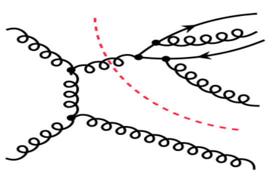




$$\hat{\sigma}^{\rm NLO} \to \frac{\alpha_s^3(p_T)}{p_T^6} \otimes \alpha_s(\mu)\log(\mu^2/\mu_0^2)$$

$$\mu_0 \gtrsim 2m_Q$$

NNLO in α_s:



$$\hat{\sigma}^{\rm NNLP} \to \frac{\alpha_s^2(p_T)}{p_T^4} \otimes \alpha_s^3(\mu)\log^m(\mu^2/\mu_0^2)$$

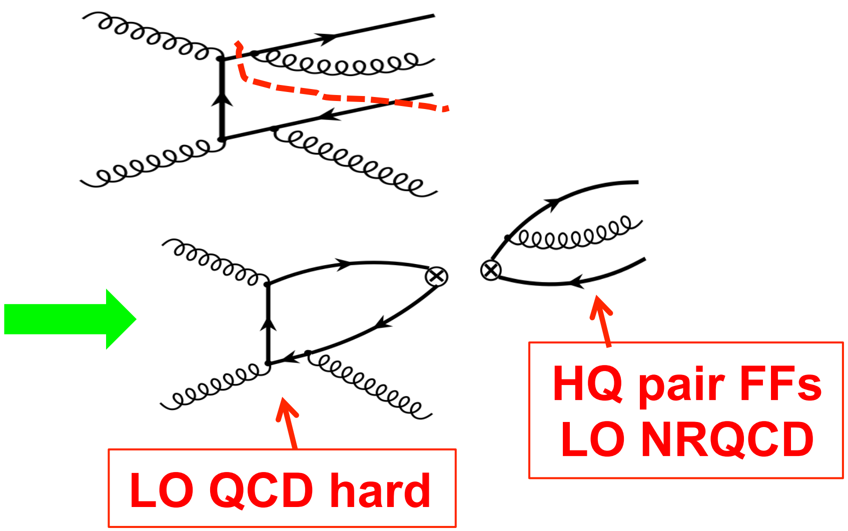
✧ **When $p_T \gg m_Q$, the expansion in powers of α_s is not reliable!**

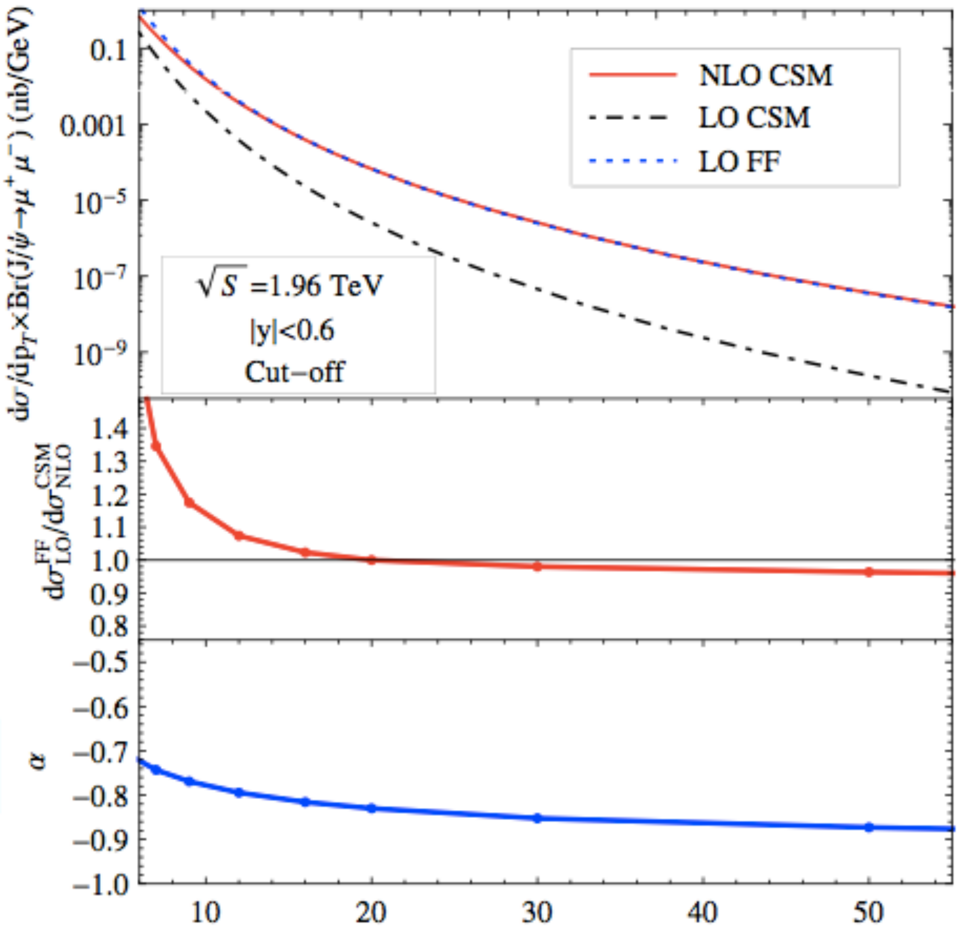
✧ **Leading order inα_s-expansion =\= leading power in $1/p_T$-expansion!**

QCD factorization + NRQCD factorization

Kang, Qiu and Sterman, 2011

❑ Color singlet as an example:





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

Reproduce NLO CSM for p_T > 10 GeV!

Cross section + polarization

Different kinematics, different approximation,
Dominance of different production channels!

Production at collider energies

G.T. Bodwin, et al., PRD 1995

❑ NRQCD factorization:

Expansion in powers of both α_s and v !

$$d\sigma_{A+B\to H+X}(p_T) = \sum_n d\hat{\sigma}_{A+B\to[Q\bar{Q}(n)]+X}(p_T)\,\langle\mathcal{O}_n^H\rangle$$

❑ PQCD factorization:

G.T. Nayak, et al., PRD2005
Z.B. Kang, et al., PRD2014

$$d\sigma_{A+B\to H+X}(p_T) = \sum_i d\tilde{\sigma}_{A+B\to i+X}(p_T/z,\mu)\otimes D_{H/i}(z,\mu)$$

LP

NLP

$$+\sum_n d\tilde{\sigma}_{A+B\to[Q\bar{Q}(n)]+X}(p_T/z,\zeta_1,\zeta_2,\mu)\otimes\mathcal{D}_{H/[Q\bar{Q}(n)]}(z,\zeta_1,\zeta_2,\mu)$$

Model: Using NRQCD factorization for the INPUT fragmentation functions

Y.Q. Ma, et al., PRD2014

$$D_{H/i}(z,\mu_0) = \sum_n d_{i\to[Q\bar{Q}(n)]}(z,\mu_0)\,\langle\mathcal{O}_n^H\rangle$$

$$\mathcal{D}_{H/[Q\bar{Q}(m)]}(z,\zeta_1,\zeta_2,\mu_0) = \sum_n d_{[Q\bar{Q}(m)]\to[Q\bar{Q}(n)]}(z,\zeta_1,\zeta_2,\mu_0)\,\langle\mathcal{O}_n^H\rangle$$

❑ PQCD improved NRQCD factorization:

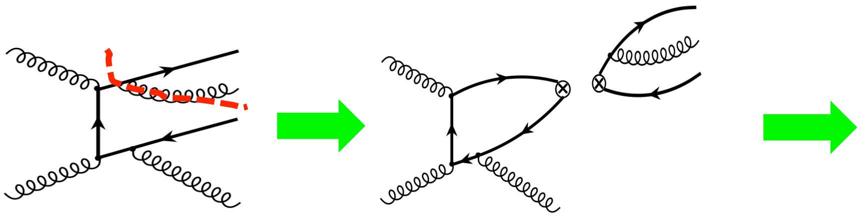
Evolution
= resummation

$$d\hat{\sigma}_{A+B\to[Q\bar{Q}(n)]+X}(p_T) = \sum_i d\tilde{\sigma}_{A+B\to i+X}(p_T/z)\otimes d_{i\to[Q\bar{Q}(n)]}(z)$$

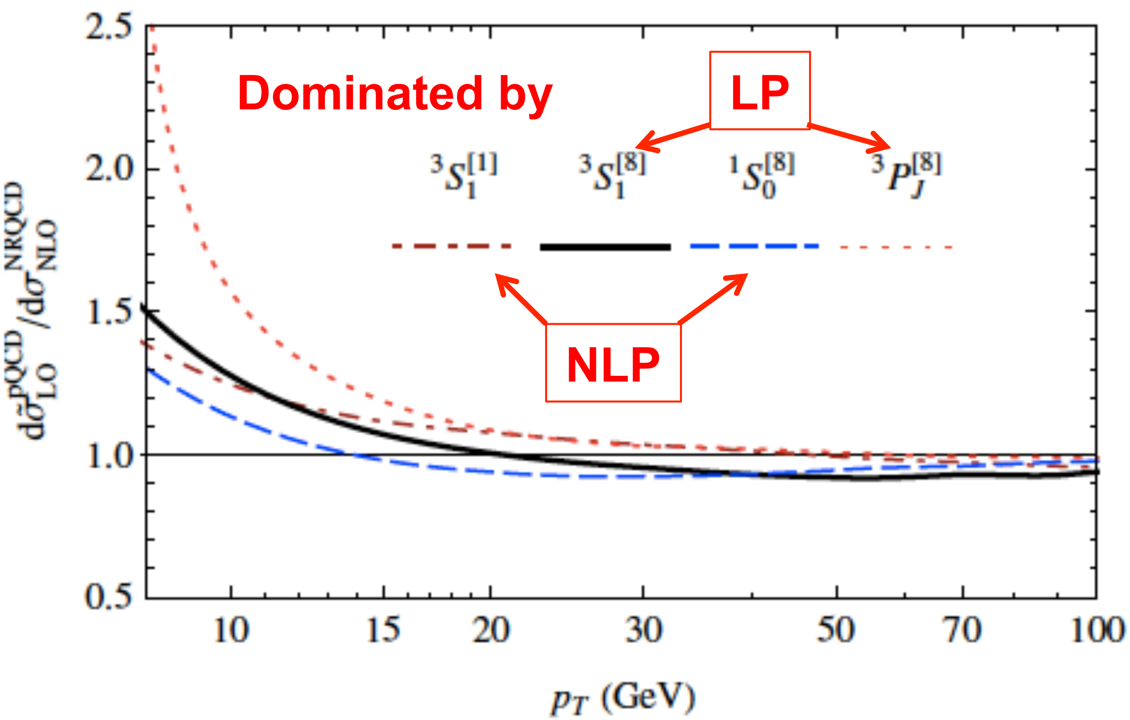
$$+\sum_m d\tilde{\sigma}_{A+B\to[Q\bar{Q}(m)]+X}(p_T/z,\zeta_1,\zeta_2)\otimes d_{[Q\bar{Q}(m)]\to[Q\bar{Q}(n)]}(z,\zeta_1,\zeta_2)$$

Channel-by-channel comparison

❑ NRQCD vs. PQCD improved NRQCD:



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



LO analytical results reproduce NLO NRQCD calculations (numerical)

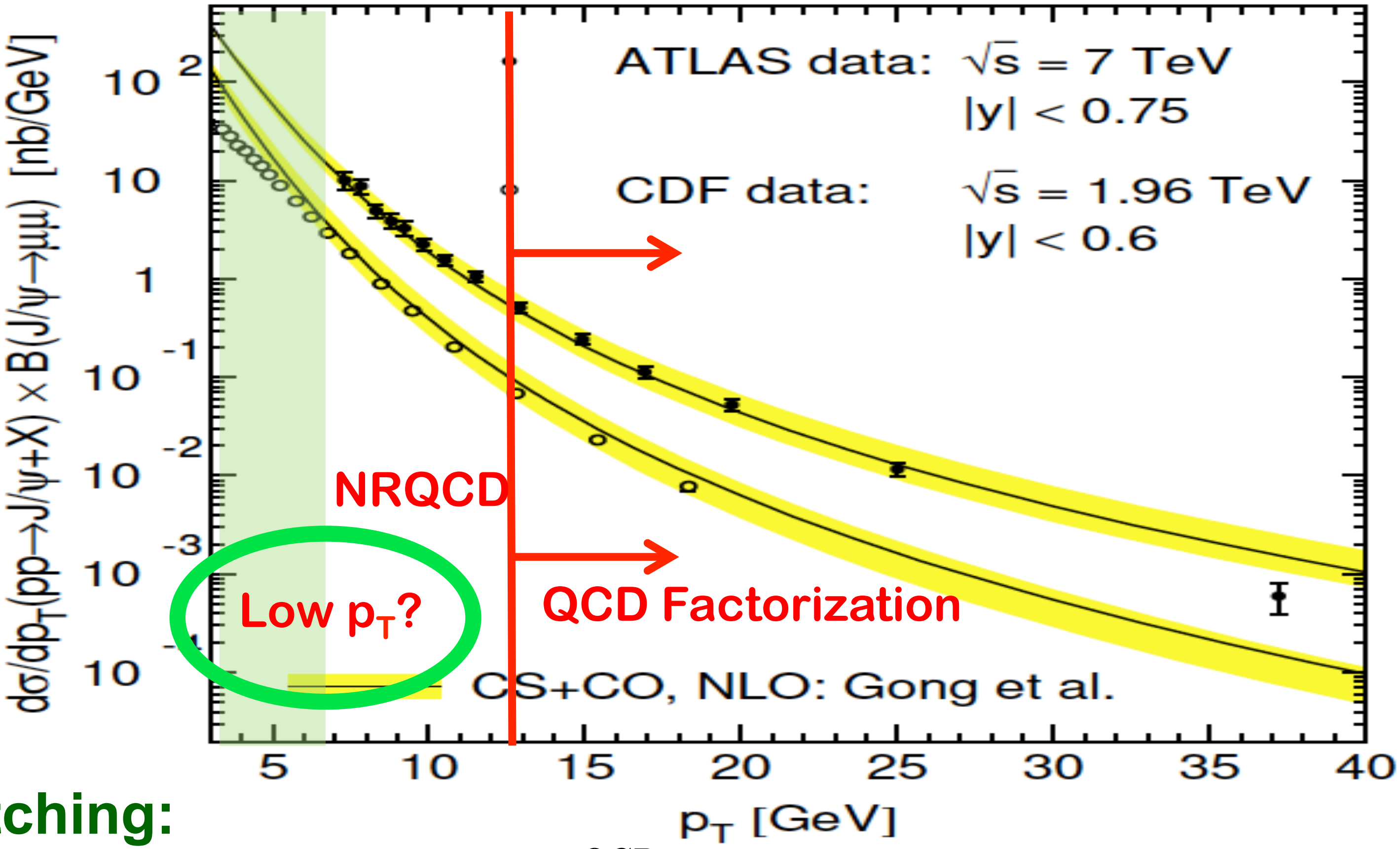
P_T – distribution is not sufficient for fixing all NRQCD matrix elements

Need more physical observables!

Matching between different approaches

Kang, Ma, Qiu and Sterman, 2014

- **Expectation:**



- **Matching:**

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

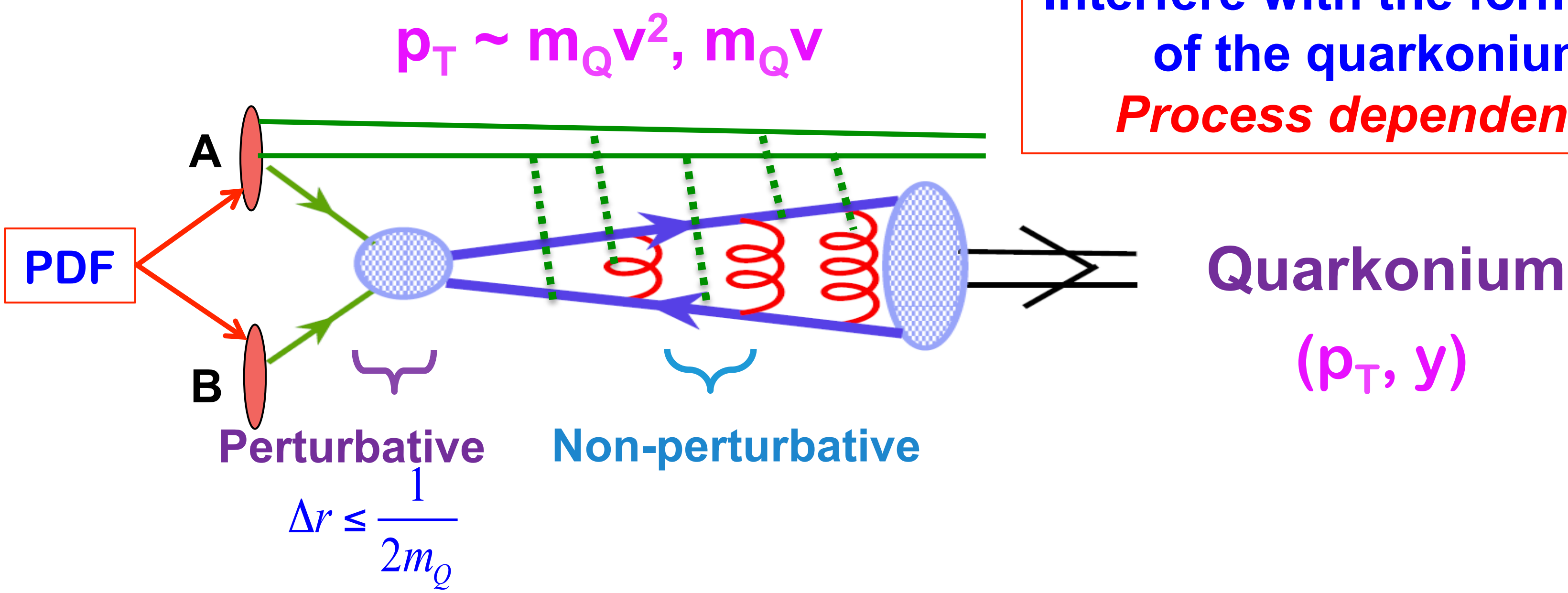
$$+E_P \frac{d\sigma^{\rm NRQCD}_{A+B\to H+X}}{d^3P}(P, m_Q\neq 0) - E_P \frac{d\sigma^{\rm QCD-Asym}_{A+B\to H+X}}{d^3P}(P, m_Q=0)$$

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 Challenge:

Break factorization – Process dependence – Alter p_T distribution, …

- Understand the factorization breaking:

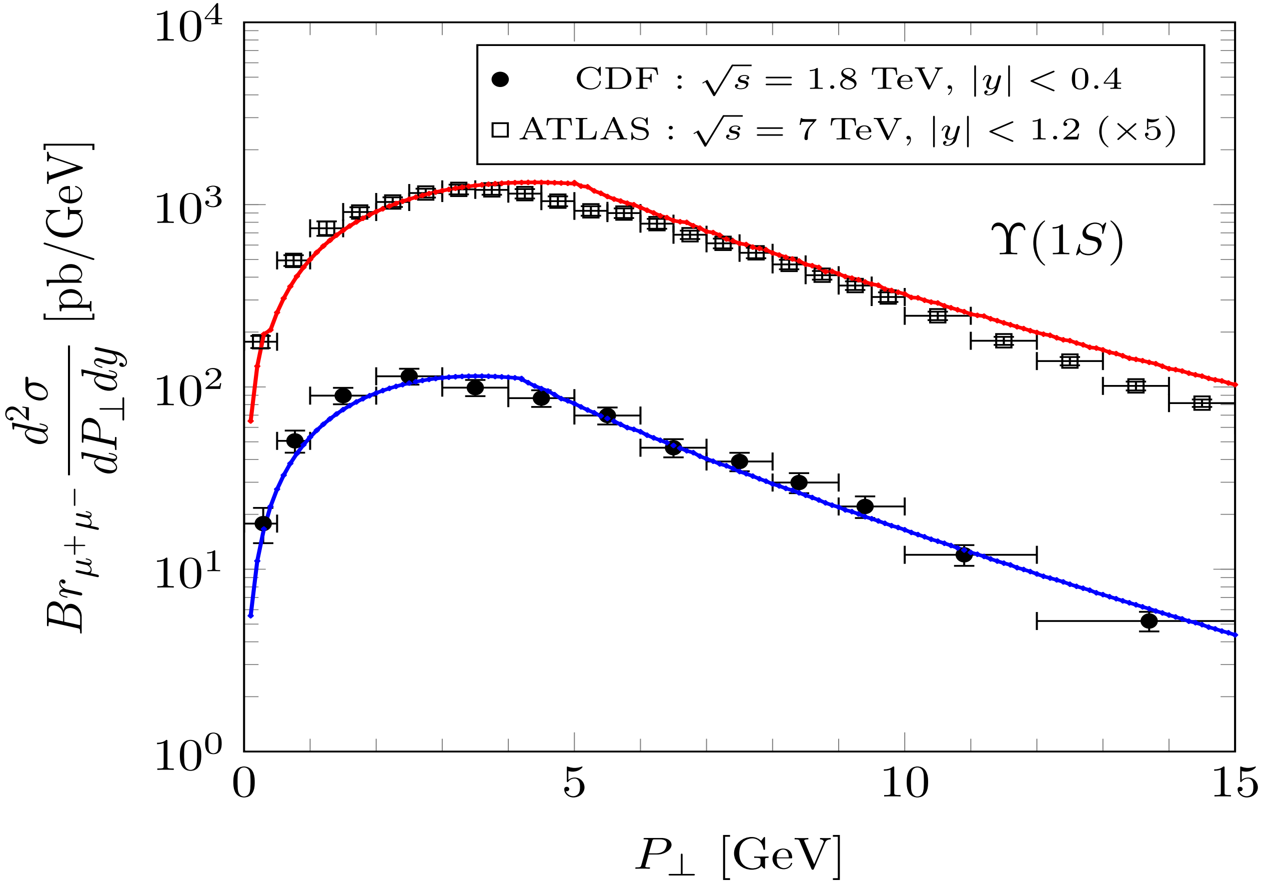
If the breaking effect is controllable, we still have predictive power!

Even the Drell-Yan process is NOT fully factorizable!

Predictive power – Upsilon

Qiu, Watanabe, 2017

❑ Upsilon at the LHC:



No adjustment on any parameter from Tevatron to the LHC!

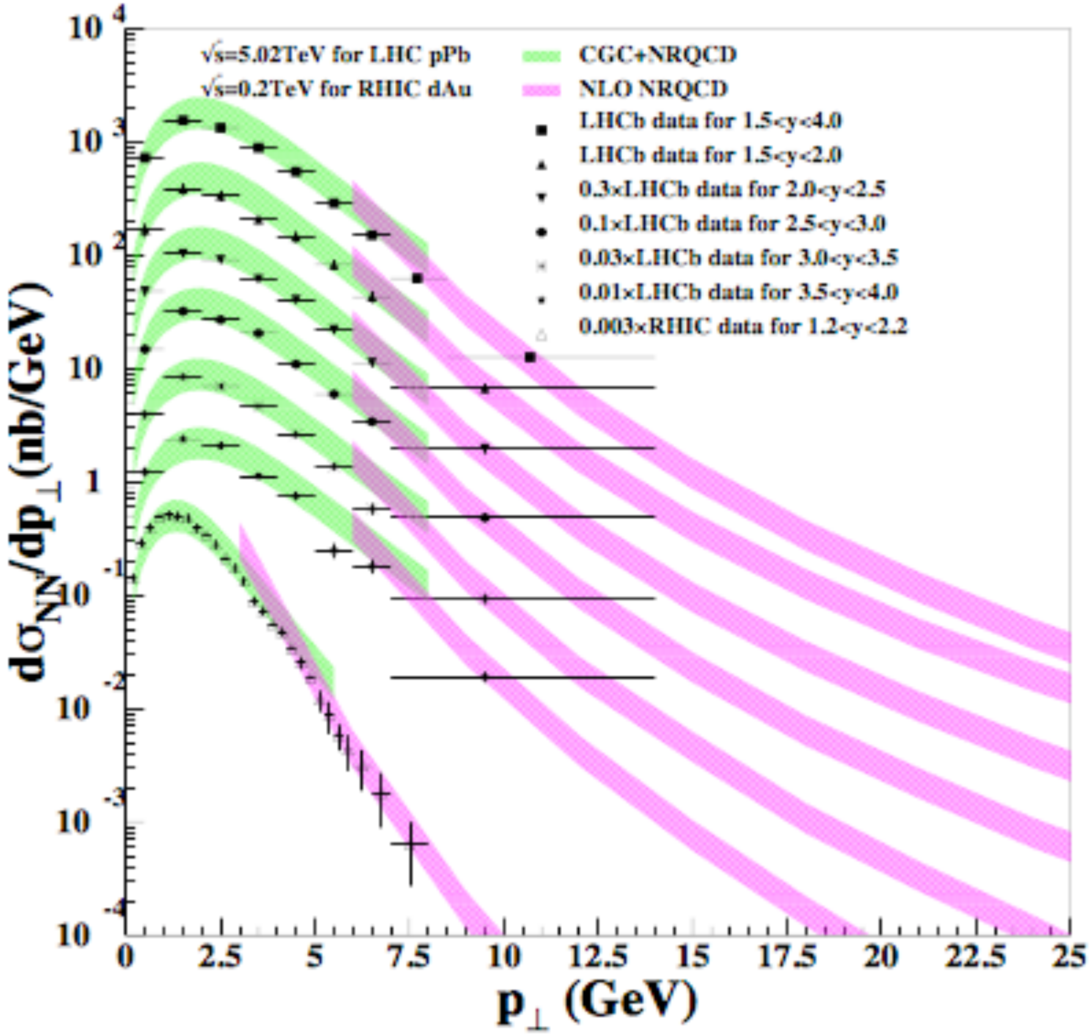
BUT: this does not apply for J/ψ at low PT,

logarithmic contribution from the shower is not strong enough!

Forward quarkonium production in p(d)+A

❑ CGC for low p_T region:

Ma et al. Phys.Rev. D92 (2015) 071901



✧ Two free fitted parameters:
 transverse overlap area,
 saturation scale at initial rapidities
 seem reasonable

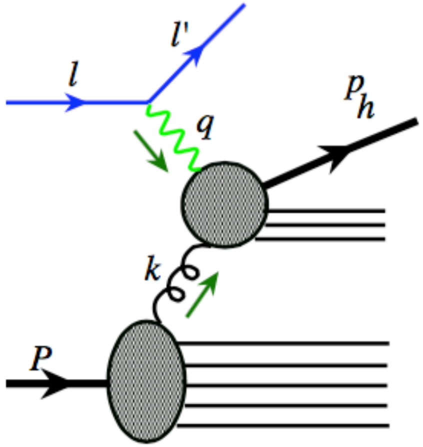
✧ Matching to NLO NRQCD calculation,
 modulo small shadowing effect,
 seem to be smooth

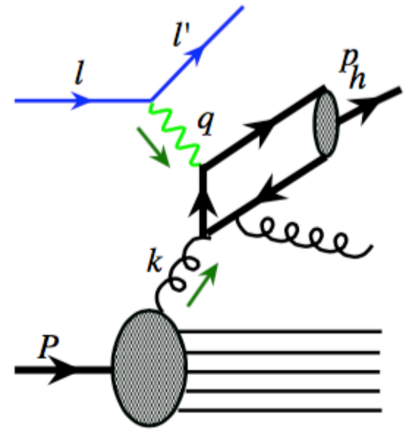
✧ Better agreement with data than previous CGC calculations

To understand what we could calculate, test, and learn at EIC energies!

Heavy quarkonium production at EIC

❑ Semi-inclusive DIS:





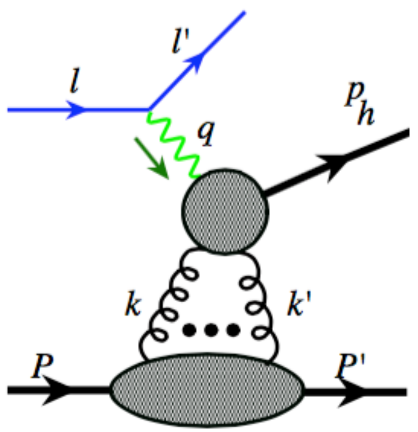
Low P_T: **Glue TMD ?**
CGC ?

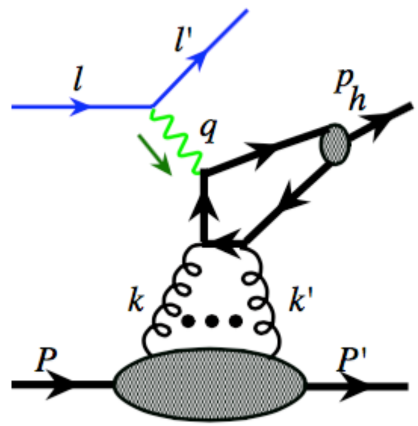
Shower vs. multiple scattering

$P_T \sim Q$: **Gluon PDF**

High P_T: LP +NLP FFs

❑ Exclusive / Gap:





$$\frac{d\sigma}{dt}(x_B, Q^2) \propto \text{GPDs}$$

Imaging gluon density distribution

$$\frac{d\sigma}{dt}(x_B, Q^2)$$

Near threshold

$\propto$ Trace Anomaly?

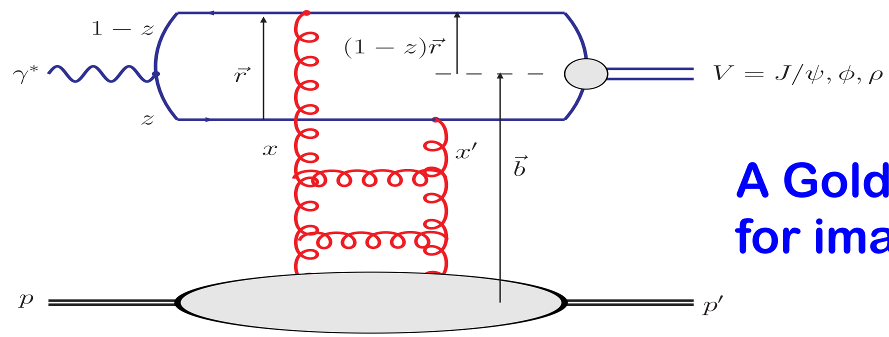
On-going effort, …

One facility covers all issues of quarkonium production!

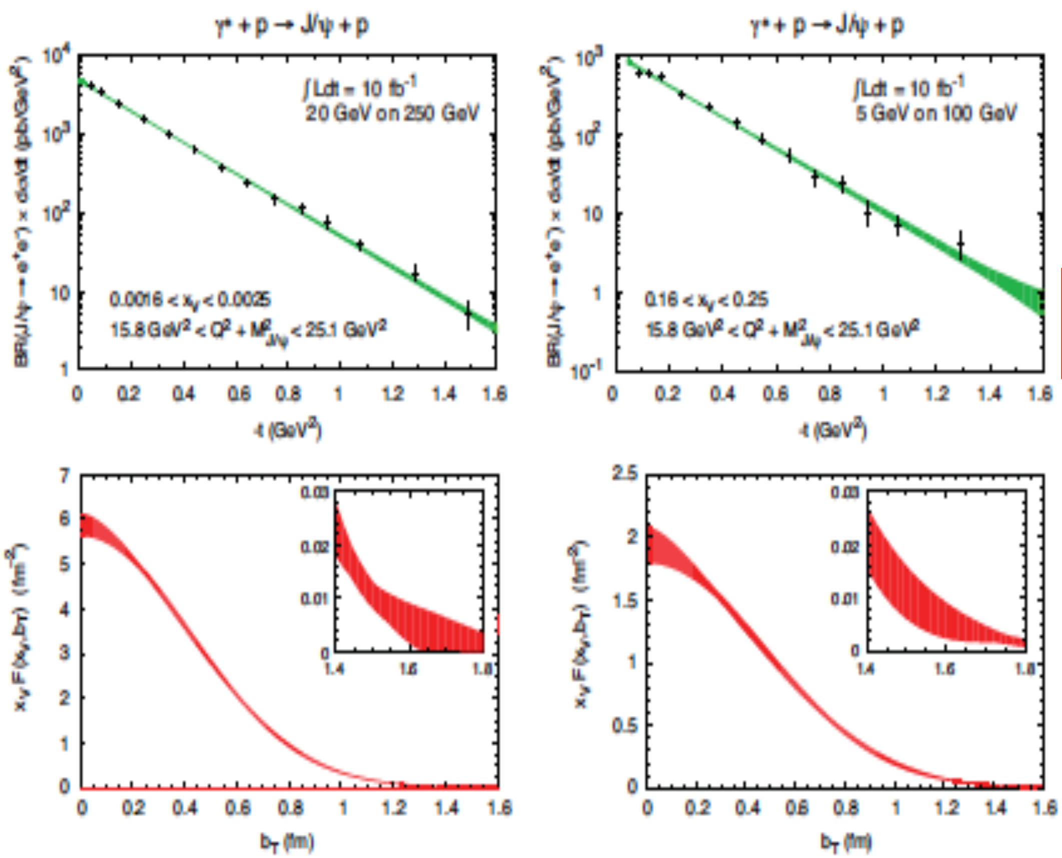
Critical role of J/ψ production at EIC

EIC WP, 1212.1701

- **Exclusive:**



A Golden process
for imagining gluon

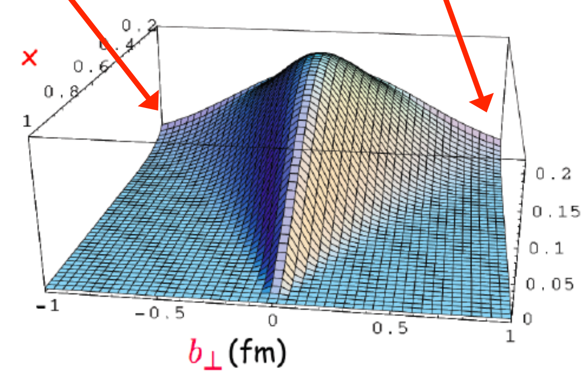


Allow us to ask "new"
fundamental questions:

Color confining radius?

How far does glue density spread?

How fast does glue density fall?

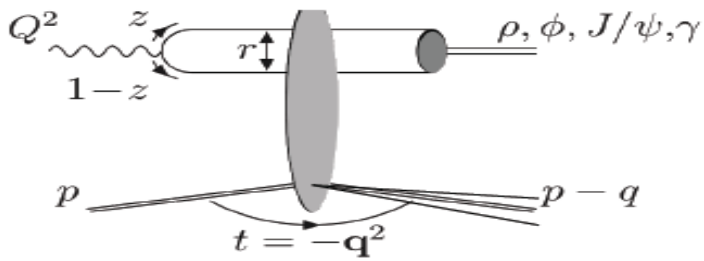


Can A be a bigger P at small-x?

Diffractive production in e+A at EIC

EIC WP, 1212.1701

- Diffractive vector meson (Φ, J/ψ, ..) production:

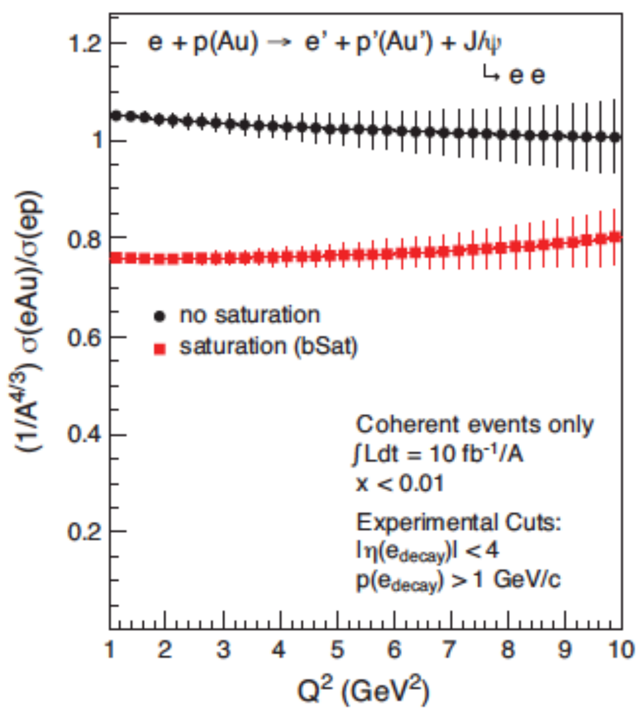


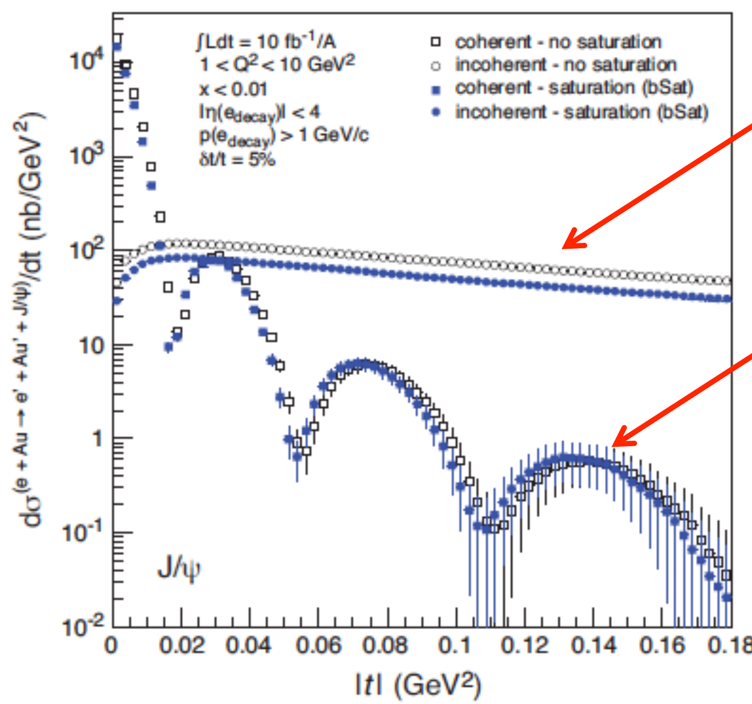
$$\frac{d\sigma}{dx_B dQ^2 dt}$$

• as a function of t

Fourier transform of the t-dependence

- J/ψ-production – probe for saturation and nuclear imaging:





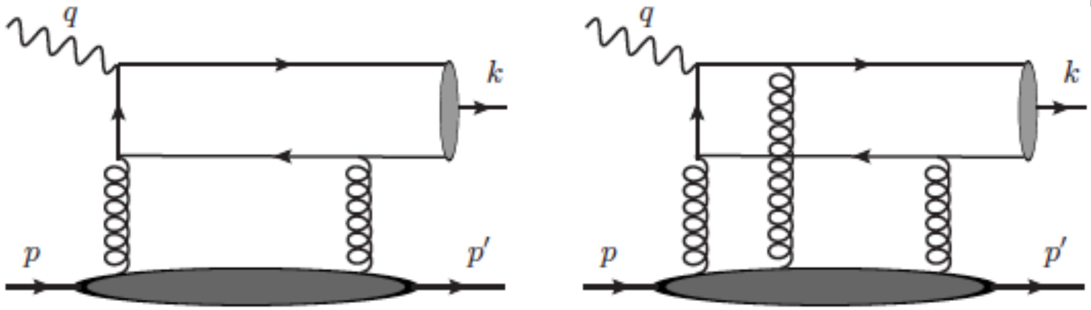
✧ **Incoherent:** Nucleus breaks up

✧ **Coherent:** Nucleus stays intact

Need EIC's Energy & Luminosity to do this!

Heavy quarkonium photoproduction

❑ Exclusive processes:



(a) (b)

Heavy quarkonium:

$^3S_1$ (J/ψ, Υ, …)

$^1P_1$ (h_c, h_b, …)

…

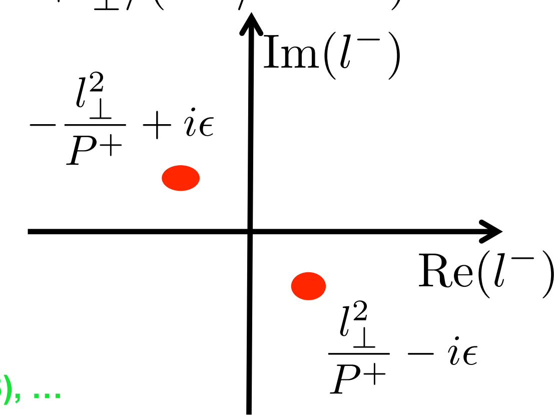
❑ Necessary condition for collinear factorization:

$$P = p - p'$$

$$\vec{P}/2 + \vec{l} \Rightarrow (P/2+l)^2 + i\epsilon \Rightarrow l^- = -l_\perp^2/(P^+/2 - l^+) + i\epsilon$$

$$\vec{P}/2 - \vec{l} \Rightarrow (P/2-l)^2 + i\epsilon \Rightarrow l^- = +l_\perp^2/(P^+/2 - l^+) - i\epsilon$$

Heavy quark to ensure: $P^+ \gg \langle l_\perp^2 \rangle$

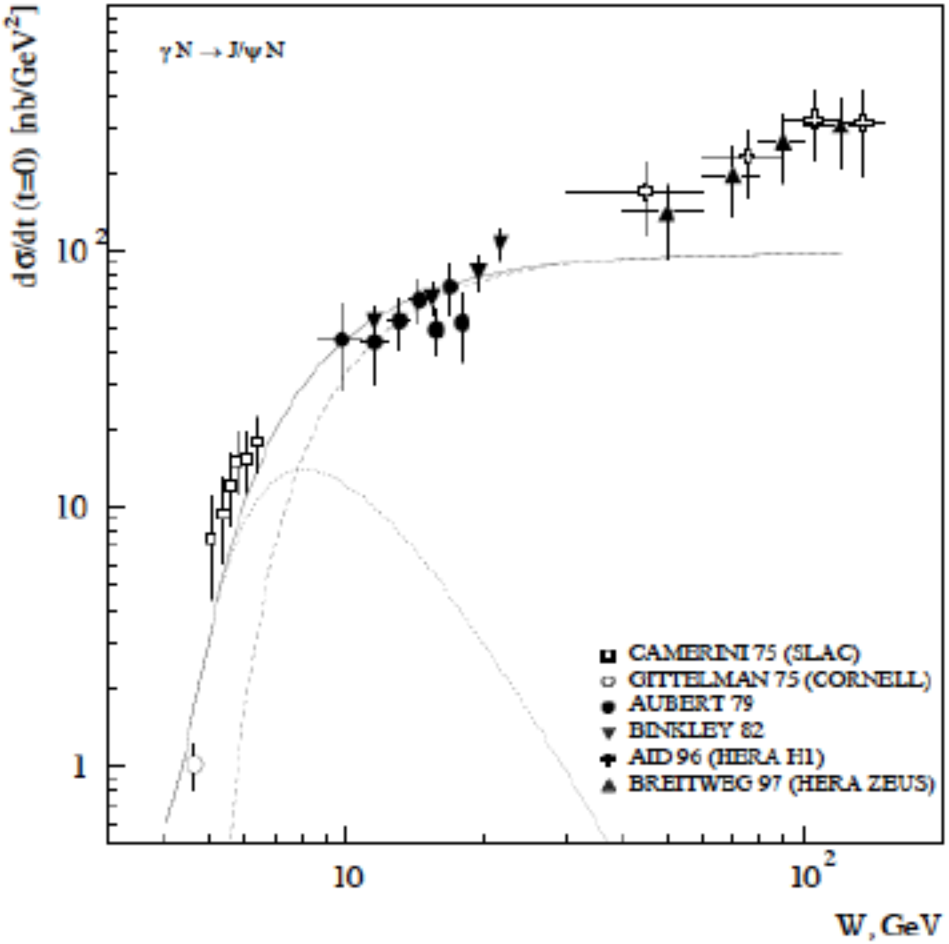


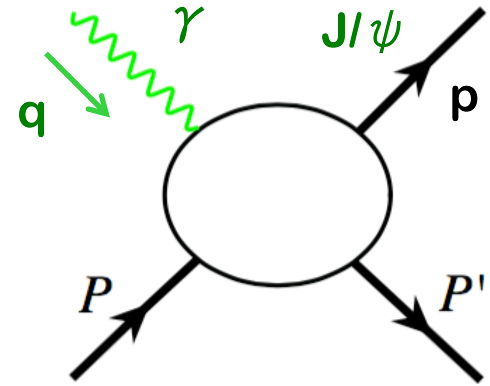
❑ Polarization states of the quarkonium:

Help select various twist-2 and twist-3 GPDs

Brodsky et al (2001), Ivanov et al. (2017), Aslan et al (2018), Cui et al (2018), …

Heavy quarkonium photoproduction

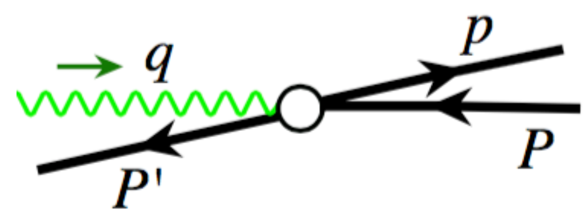




$$W^2 = (P+q)^2$$

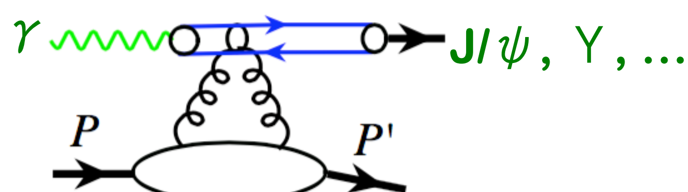
$$t = (P' - P)^2$$

✧ **Large W region:** $W^2 \gg |t|$



Collinear factorization works
Good for gluon GPDs

Two gluon exchange:

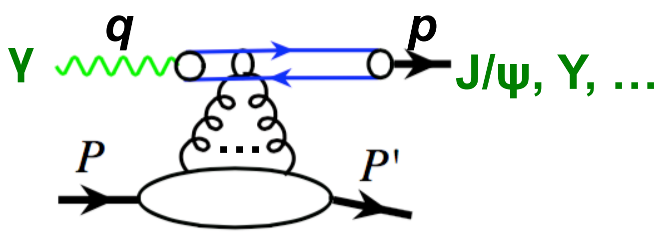


Gluon GPDs at twist-2

Operator for Trace Anomaly is twist-4

Heavy quarkonium photoproduction

- **Threshold region:** $W^2 \geq |t|$



What dominates the exchange?

Y. Hatta, D.L. Yang, 1808.02163
Also see Sterman's talk

- **Holographic J/ψ production:**

$$\frac{d\sigma}{dt} = \frac{\alpha_{em}}{4(W^2 - M_p^2)^2} \overline{\Sigma}_{pol} \overline{\Sigma}_{spin} \left| \langle P | \vec{\epsilon} \cdot \vec{J}(0) | P' p \rangle \right|^2 \qquad \sigma_{tot} = \int_{t_{min}}^{t_{max}} \frac{d\sigma}{dt}\, dt$$

✧ How to calculate the scattering amplitude?

$$\langle P | \vec{\epsilon} \cdot \vec{J}(q) | P' p \rangle = (2\pi)^4 \delta^4(P + q - P' - p) \langle P | \vec{\epsilon} \cdot \vec{J}(0) | P' p \rangle$$

✧ Y. Hatta, D.L. Yang (1801.02163) – gauge/string duality:

$$\langle P | \epsilon \cdot J(0) | P' k \rangle = -\frac{2\kappa^2}{f_\psi R^3} \int_0^{z_m} dz \frac{\delta S_{D7}(q,k,z)}{\delta g_{\mu\nu}} \frac{z^2 R^2}{4} \langle P | T^{gTT}_{\mu\nu} | P' \rangle + \frac{2\kappa^2}{f_\psi R^3} \frac{3}{8} \int_0^{z_m} dz \frac{\delta S_{D7}(q,k,z)}{\delta \phi} \frac{z^4}{4} \langle P | \frac{1}{4} F^{\mu\nu}_a F^a_{\mu\nu} | P' \rangle$$

Gluon from Traceless $T^{\mu\nu}$

Trace Anomaly

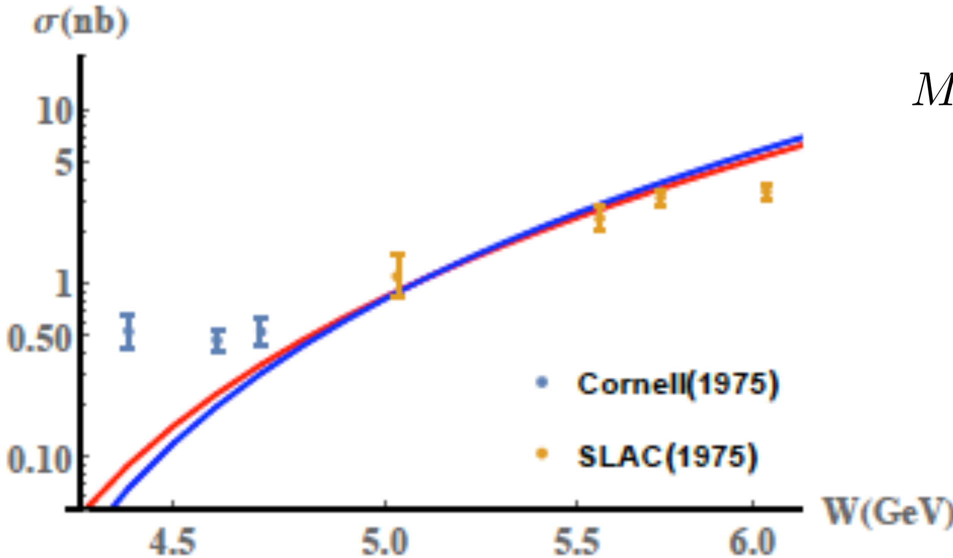
Dilaton field

$2\kappa^2 = \frac{8\pi^2}{N_c^2} R^3$ – 5D gravitational constant

The Role of Trace Anomaly

❑ Numerical estimate:

Y. Hatta, D.L. Yang, 1808.02163



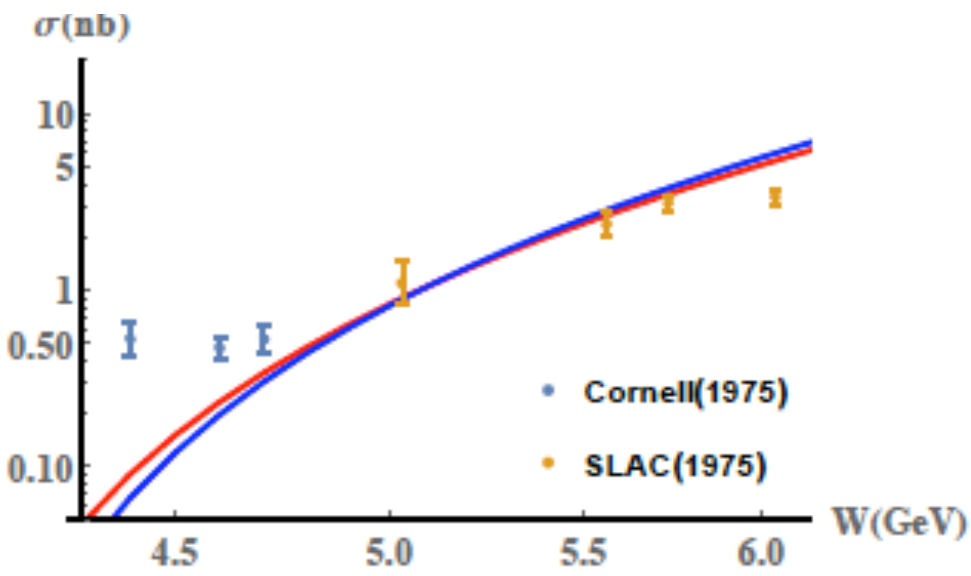
$$M_a = \frac{\langle P|H_a|P\rangle}{\langle P|P\rangle}\bigg|_{\text{at rest}} = (1-b)\,\frac{1}{4}\,M_p$$

Max. contribution from Tracd Anomaly

$b = 0$

Min. contribution from Tracd Anomaly

$b = 1$



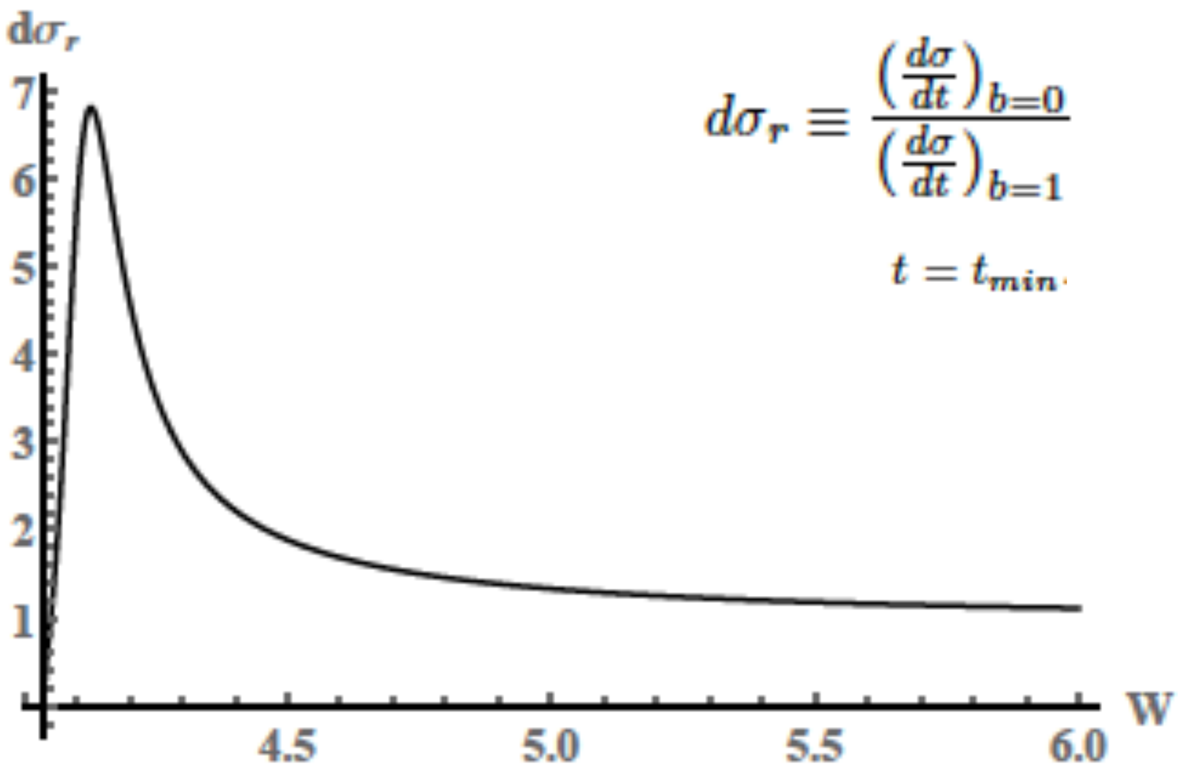
✧ Normalization is fitted

✧ Not expected to work for large W^2

The Role of Trace Anomaly

- **Numerical estimate:**

Y. Hatta, D.L. Yang, 1808.02163



$$d\sigma_r \equiv \frac{\left(\frac{d\sigma}{dt}\right)_{b=0}}{\left(\frac{d\sigma}{dt}\right)_{b=1}}$$

$$t = t_{min}.$$

$$M_a = \left.\frac{\langle P|H_a|P\rangle}{\langle P|P\rangle}\right|_{\text{at rest}}$$

$$= (1-b)\,\frac{1}{4}\,M_p$$

Max. contribution from Tracd Anomaly

$$b = 0$$

Min. contribution from Tracd Anomaly

$$b = 1$$

As expected, the Trace Anomaly contribution is the most relevant near threshold regime!

Summary

- It has been over 40 years since the discovery of J/Ψ, but, still not completely sure about its production mechanism
- EIC kinematics covers all potential issues/physics of heavy quarkonium production + opportunity for the threshold production

  Connection to the trace anomaly (proton mass), XYZ states, …

- NRQCD factorization is expected to work for $P_T \sim Q$, and QCD factorization works for both LP and NLP at high P_T

  Challenge for low P_T region or near the threshold

- Exclusive production could be a golden process for GPDs
- Nuclear medium could be a good "filter" or a fermi-scale "detector" for studying the emergence of a quarkonium from a havey quark pair

  Special role of the rapidity!

Thank you!