INT Program INT–17–3

Spatial and Momentum Tomography of Hadrons and Nuclei

August 28 – September 29, 2017

Heavy Quarkonium Production at EIC Energies

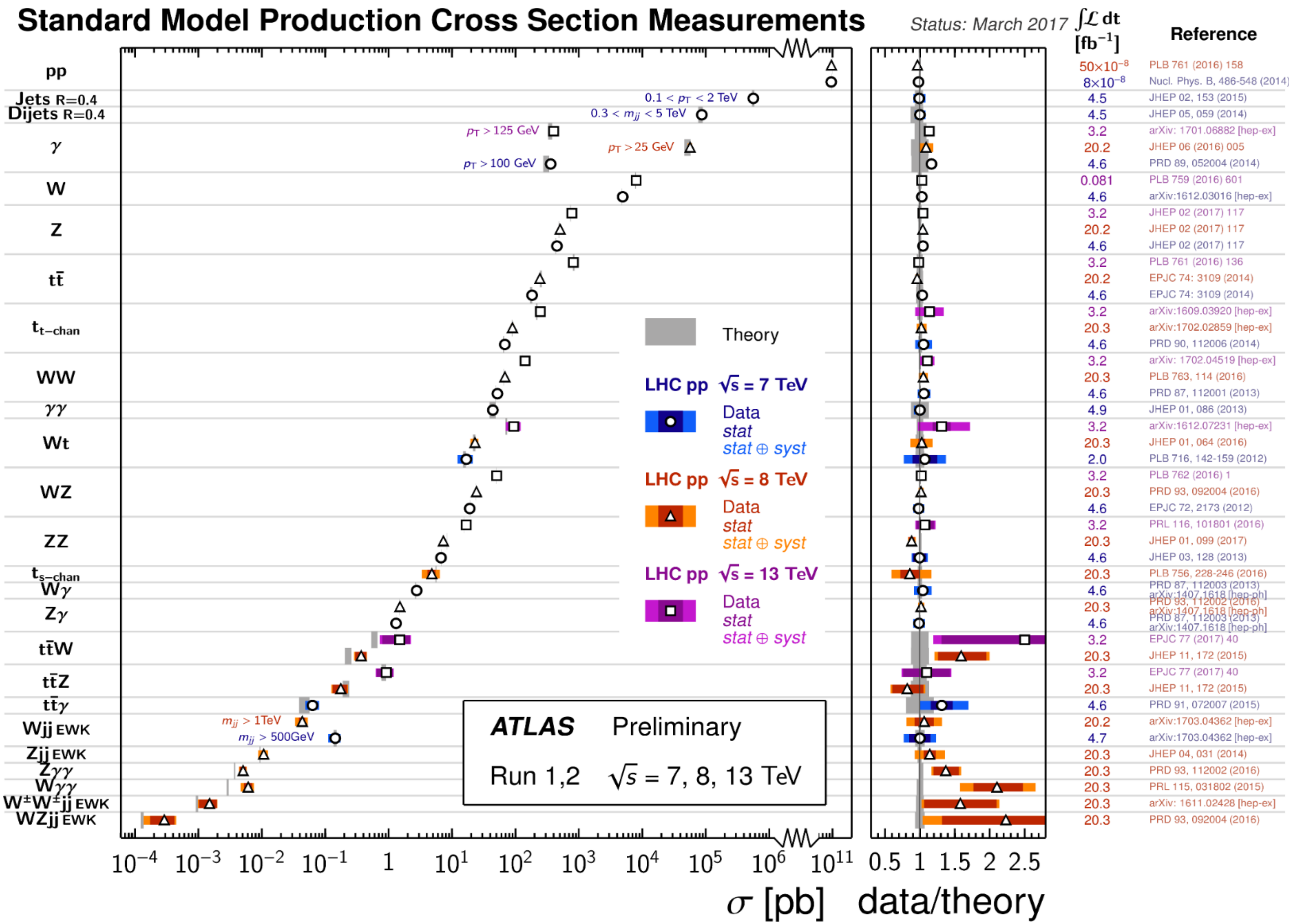
- ✧ Why heavy quarkonium?
- ✧ Production mechanism?
- ✧ EIC: Inclusive DIS, SIDIS, Exclusive, …
- ✧ Gluon distribution, imaging, threshold, …
- ✧ Summary and outlook

Theory Center

Jianwei Qiu

Jefferson Lab
EXPLORING THE NATURE OF MATTER

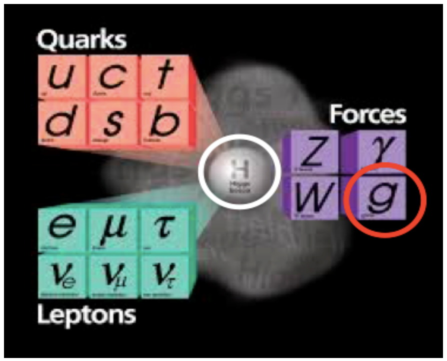
The great success of SM physics

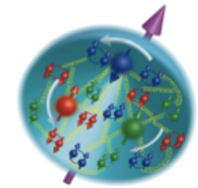


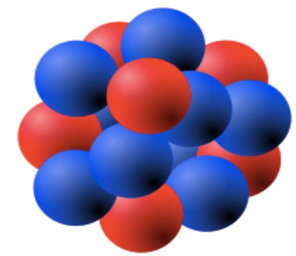
SM: Electroweak processes + QCD perturbation theory works!

QCD – Final frontier of the SM physics

- How QCD works to get all of us? – the next QCD frontier!



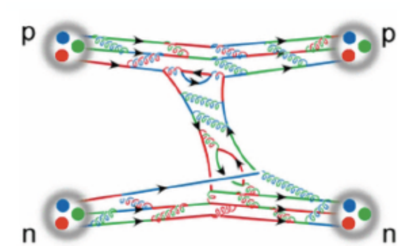




- How hadrons are emerged from quarks and gluons?
- What is the quark/gluon structure of nucleon and nuclei?
- How does QCD make up the properties of hadrons?

  Their mass, spin, magnetic moment, …

- How does the nuclear force arise from QCD?



- …

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?

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

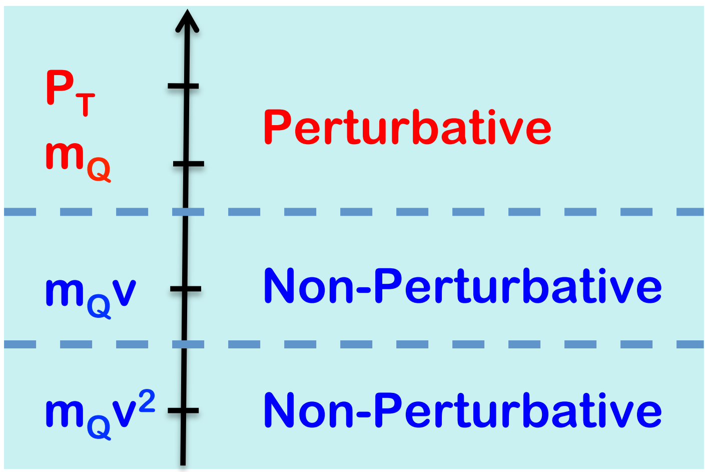
Heavy quarkonium

- **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]

- **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: $\sim$ 0.07 pb

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

❑ Ratio to light flavors:

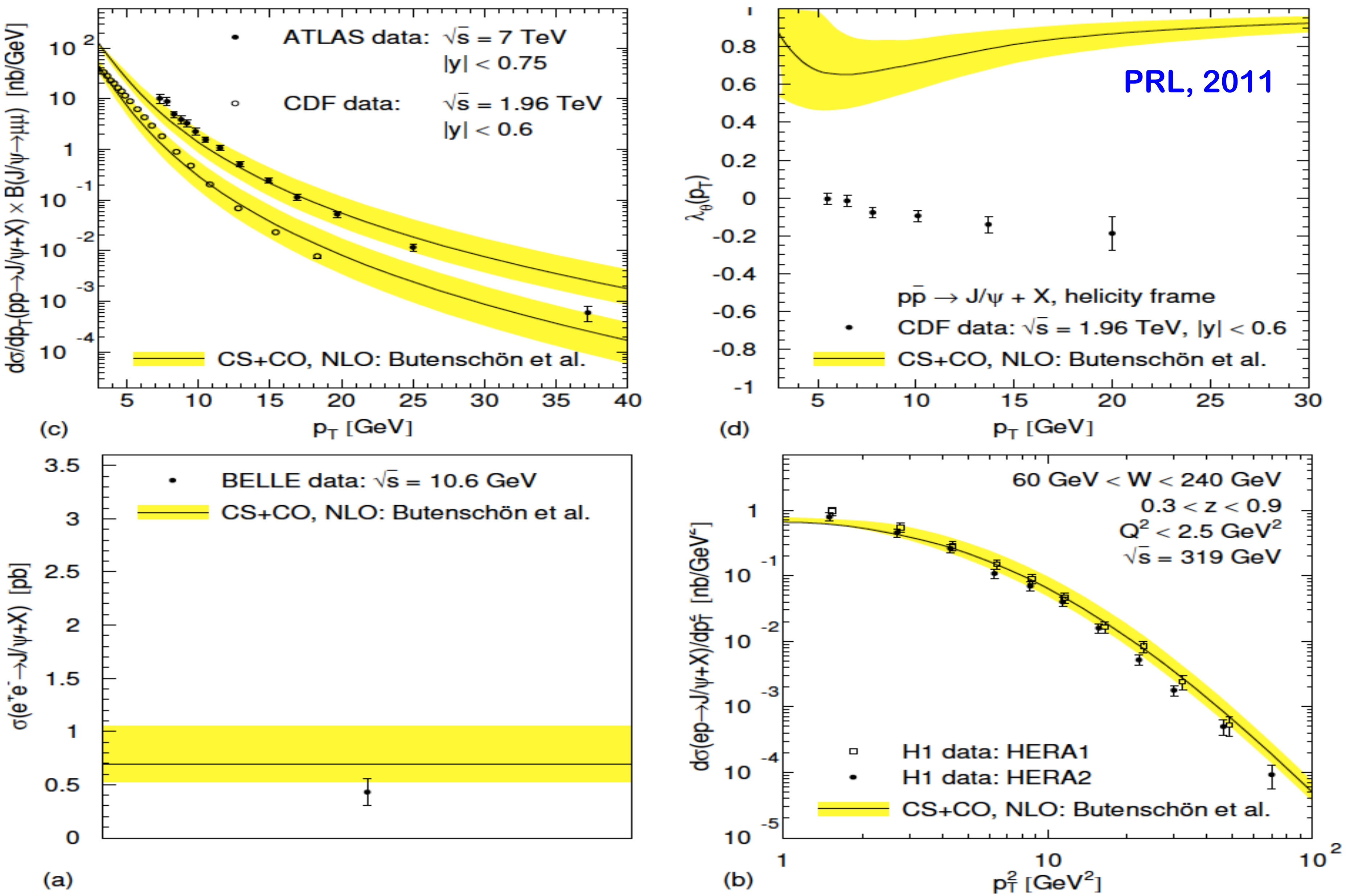
$$\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X)$$

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

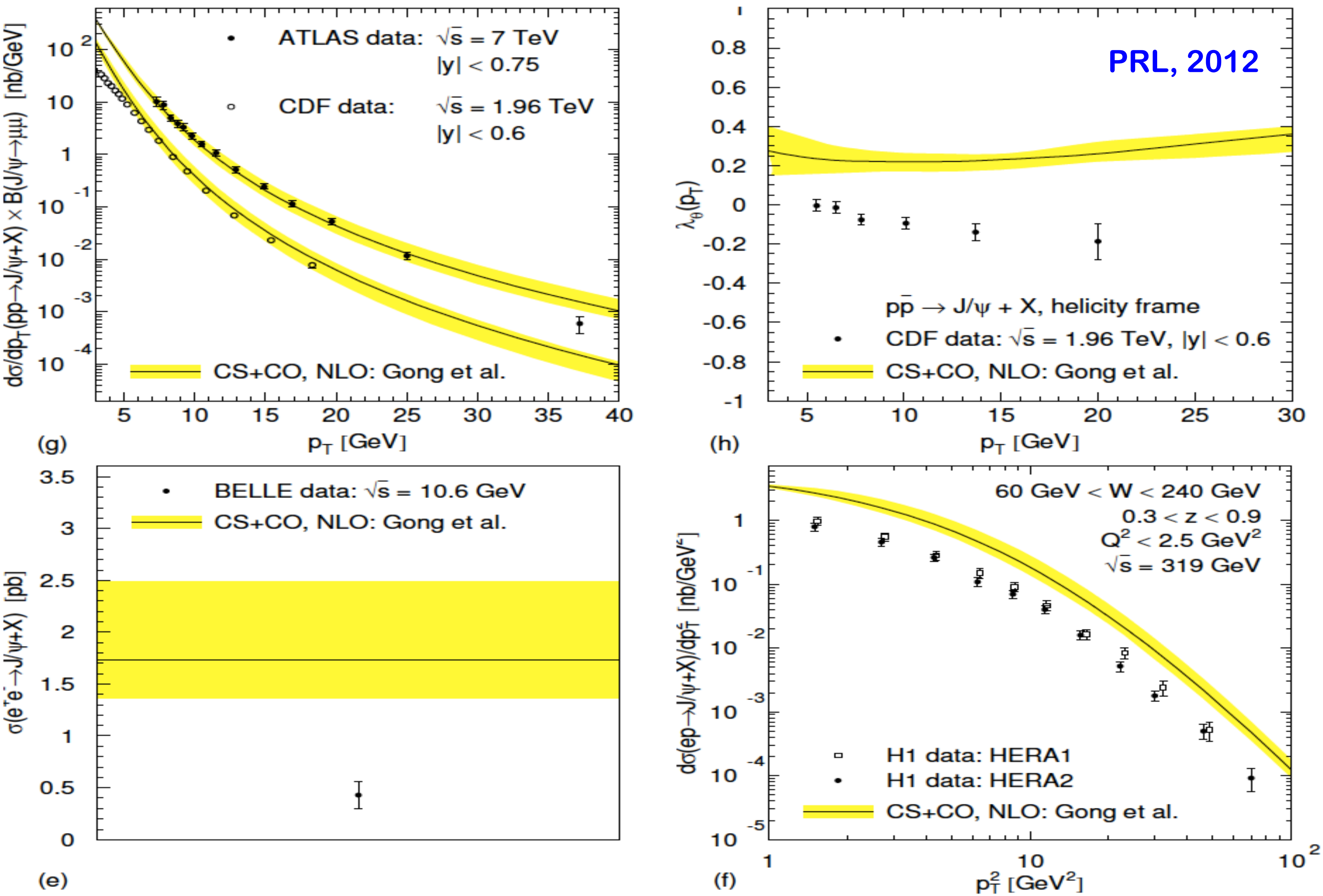
Message:

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

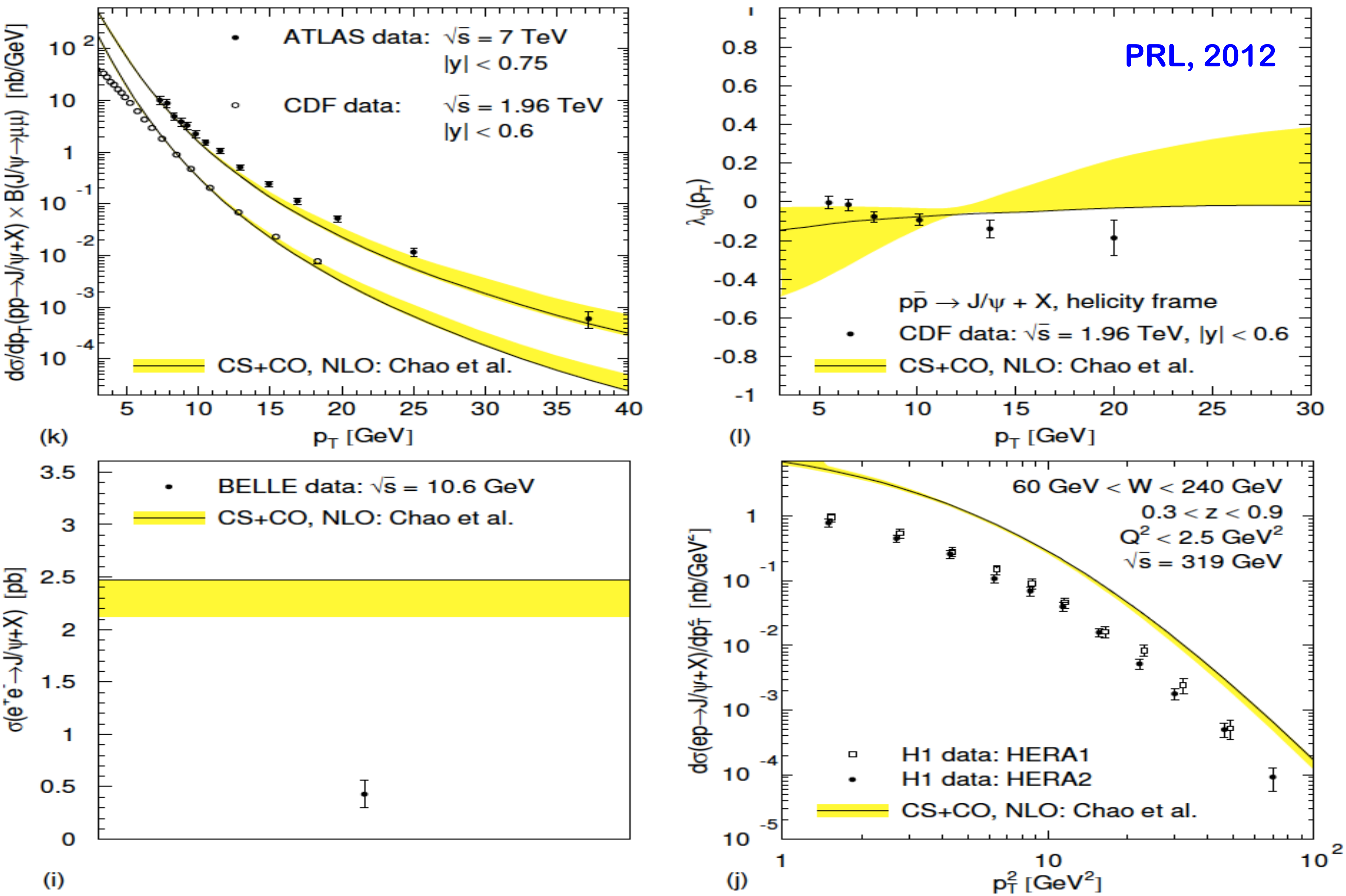
NLO theory fits – Butenschoen et al.



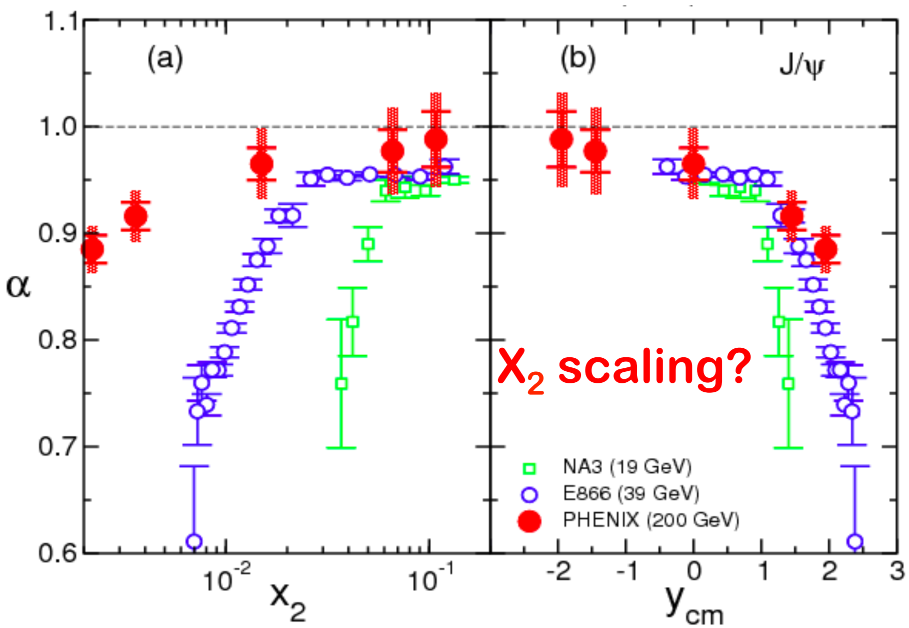
NLO theory fits – Gong et al.

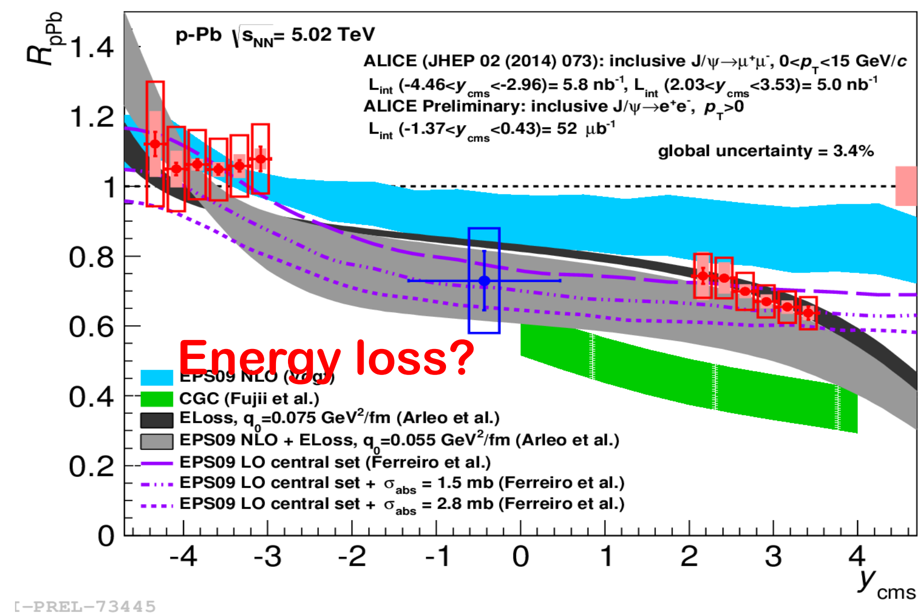


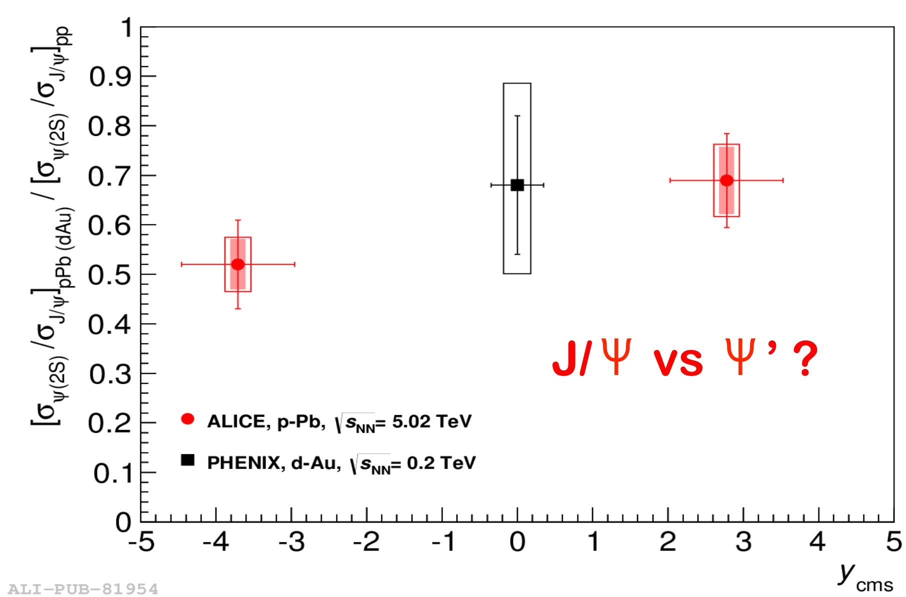
NLO theory fits – Chao et al.

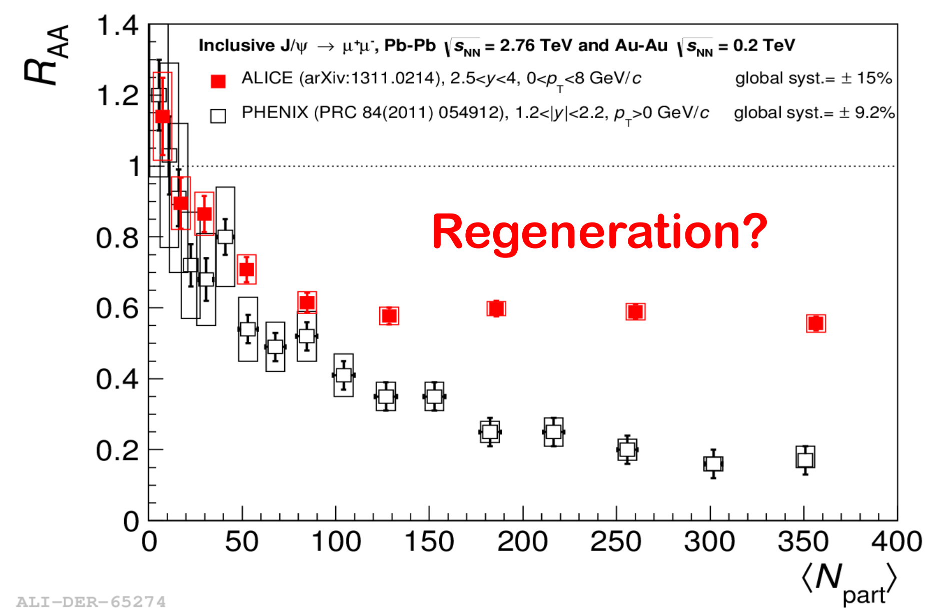


Production in medium, cold or hot?







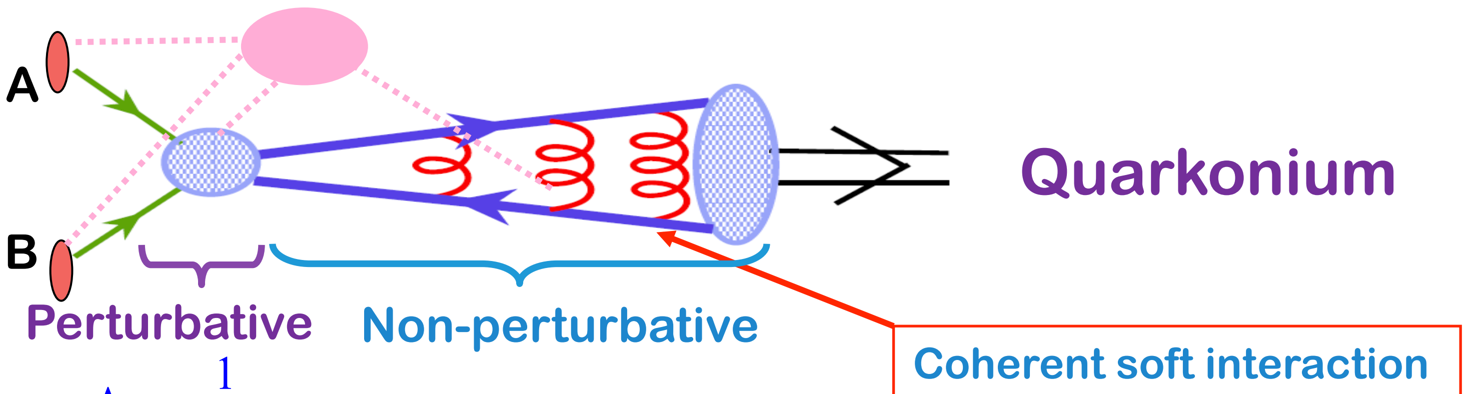


http://itp.phy.pku.edu.cn/conference/qwg2017/



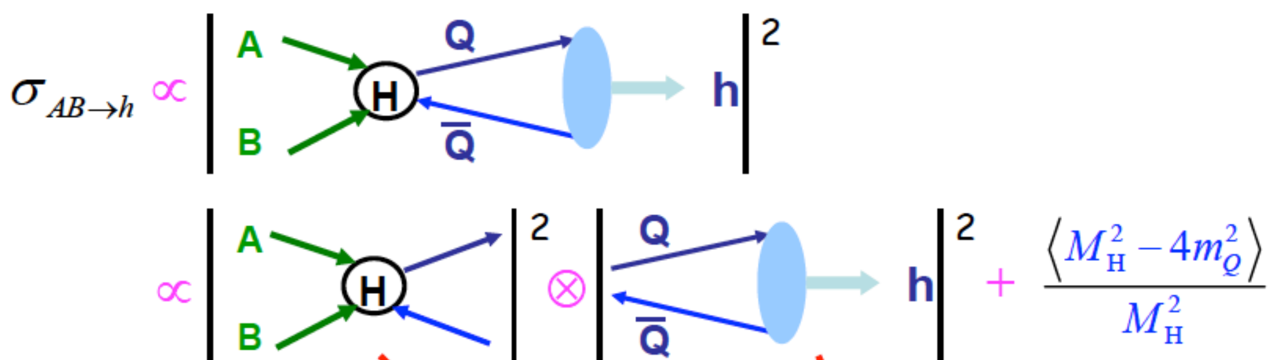

Basic production mechanism

- ❑ **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**



$$\Delta r \le \frac{1}{2m_Q}$$

- ❑ **Approximation:**



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

Basic production mechanism

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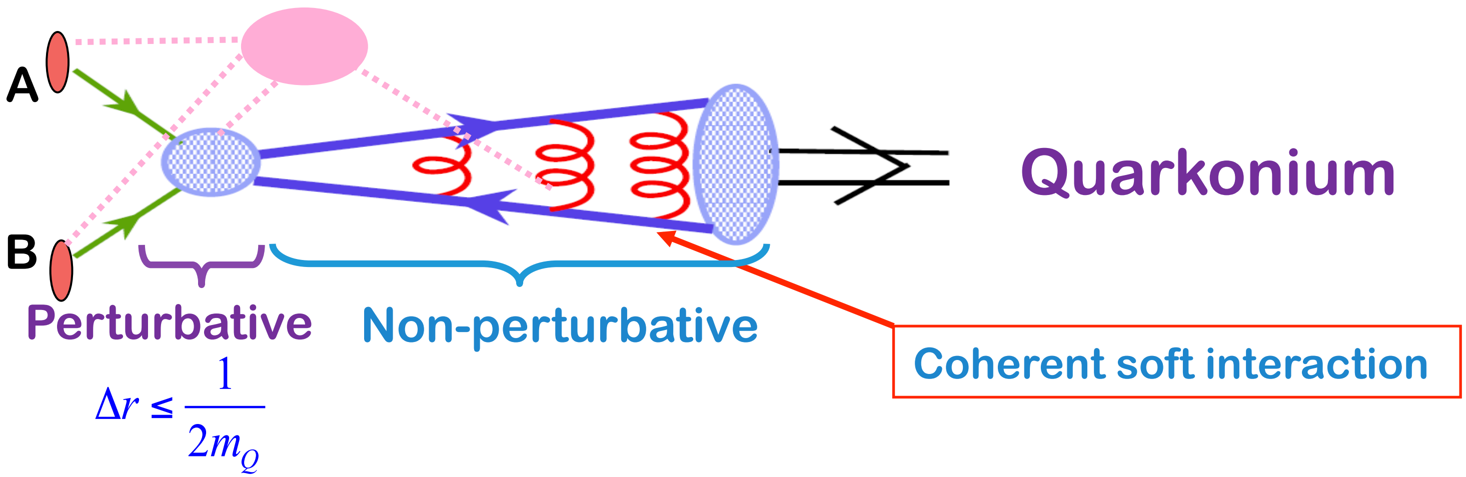


❑ **Naïve factorization: on-shell pair + hadronization**

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

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), …

  $P_T \gg M_H$: 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:**

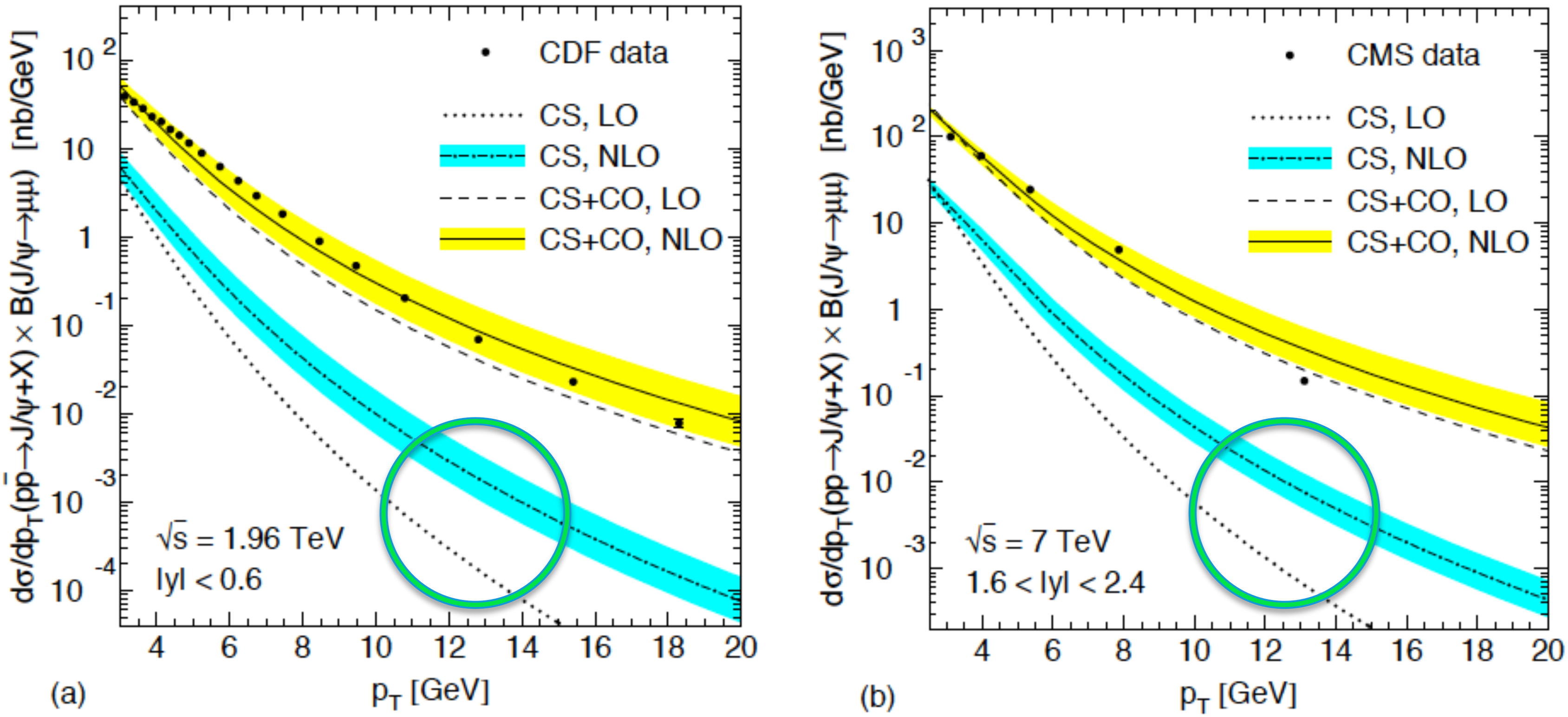
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X}\langle\mathcal{O}^H(n)\rangle$$

✧ **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)

NRQCD model

- **NRQCD Lagrangian:** $\mathcal{L}_{\rm NRQCD} = \mathcal{L}_{\rm light} + \mathcal{L}_{\rm heavy} + \delta\mathcal{L}$

Caswell, Lepage, Phys. Lett. B, 1986
Bodwin, Braaten, Lepage, PRD, 1995

$$\mathcal{L}_{\rm light} = -\frac{1}{2}{\rm tr}\, G_{\mu\nu}G^{\mu\nu} + \sum_{n_F=1}^{3\text{ or }4} \bar{q}\, i\not{D} q$$

$$\mathcal{L}_{\rm heavy} = \psi^\dagger \left(iD_t + \frac{\mathbf{D}^2}{2M}\right)\psi + \chi^\dagger\left(iD_t - \frac{\mathbf{D}^2}{2M}\right)\chi$$

Pauli spinor for antiquark (χ)

Pauli spinor for heavy quark (ψ)

$$\begin{aligned}\delta\mathcal{L}_{\rm bilinear} &= \frac{c_1}{8M^3}\left(\psi^\dagger(\mathbf{D}^2)^2\psi - \chi^\dagger(\mathbf{D}^2)^2\chi\right)\\ &+ \frac{c_2}{8M^2}\left(\psi^\dagger(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\psi + \chi^\dagger(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\chi\right)\\ &+ \frac{c_3}{8M^2}\left(\psi^\dagger(i\mathbf{D}\times g\mathbf{E} - g\mathbf{E}\times i\mathbf{D})\cdot\boldsymbol{\sigma}\psi + \chi^\dagger(i\mathbf{D}\times g\mathbf{E} - g\mathbf{E}\times i\mathbf{D})\cdot\boldsymbol{\sigma}\chi\right)\\ &+ \frac{c_4}{2M}\left(\psi^\dagger(g\mathbf{B}\cdot\boldsymbol{\sigma})\psi - \chi^\dagger(g\mathbf{B}\cdot\boldsymbol{\sigma})\chi\right),\end{aligned}$$

- **Limitation:**

Powerful for a process with available kinetic energy: $Mv^2 << Mc^2$

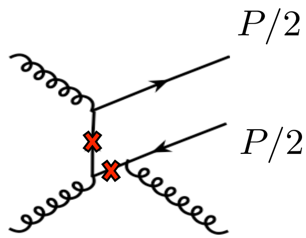
- ✧ Formalism is ideal for heavy quarkonium decay
- ✧ Additional complications for production with $s >> (2M)^2$

Why high orders in CSM are so large?

Kang, Qiu and Sterman, 2011

- **LO in α_s but higher power in $1/p_T$:**

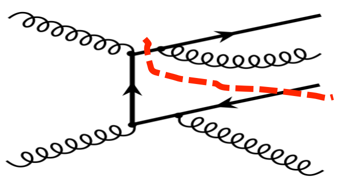
LO in α_s:

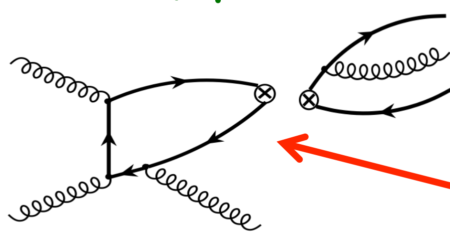


$$\hat{\sigma}^{\rm LO} \propto \frac{\alpha_s^3(p_T)}{p_T^8}$$

CSM and NRQCD
spin-1 projection
NNLP in $1/p_T$!

- **NLO in α_s but lower power in $1/p_T$:**



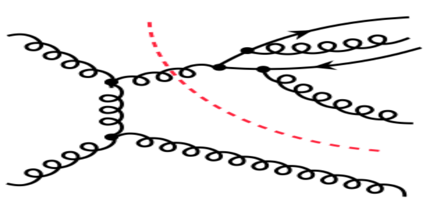


Relativistic projection to all "spin states"

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

$$\mu_0 \gtrsim 2m_Q$$

- **NNLO in α_s but leading power in $1/p_T$:**



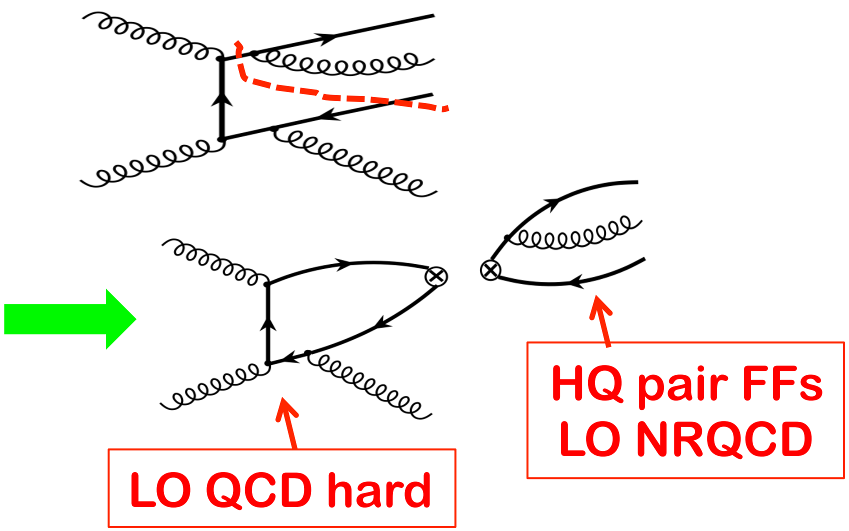
$$\hat{\sigma}^{\rm NNLP} \to \frac{\alpha_s^2(p_T)}{p_T^4} \otimes \alpha_s^3(\mu) \log^m(\mu^2/\mu_0^2)$$

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

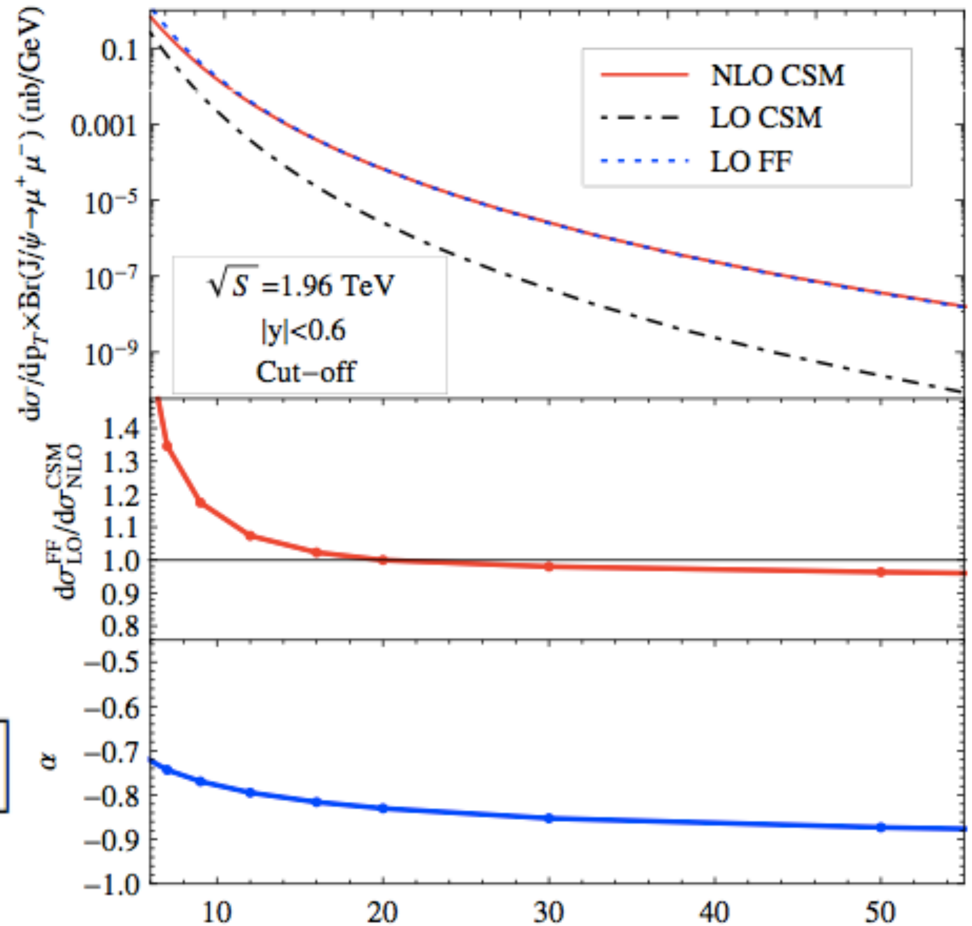
QCD factorization + NRQCD factorization

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!

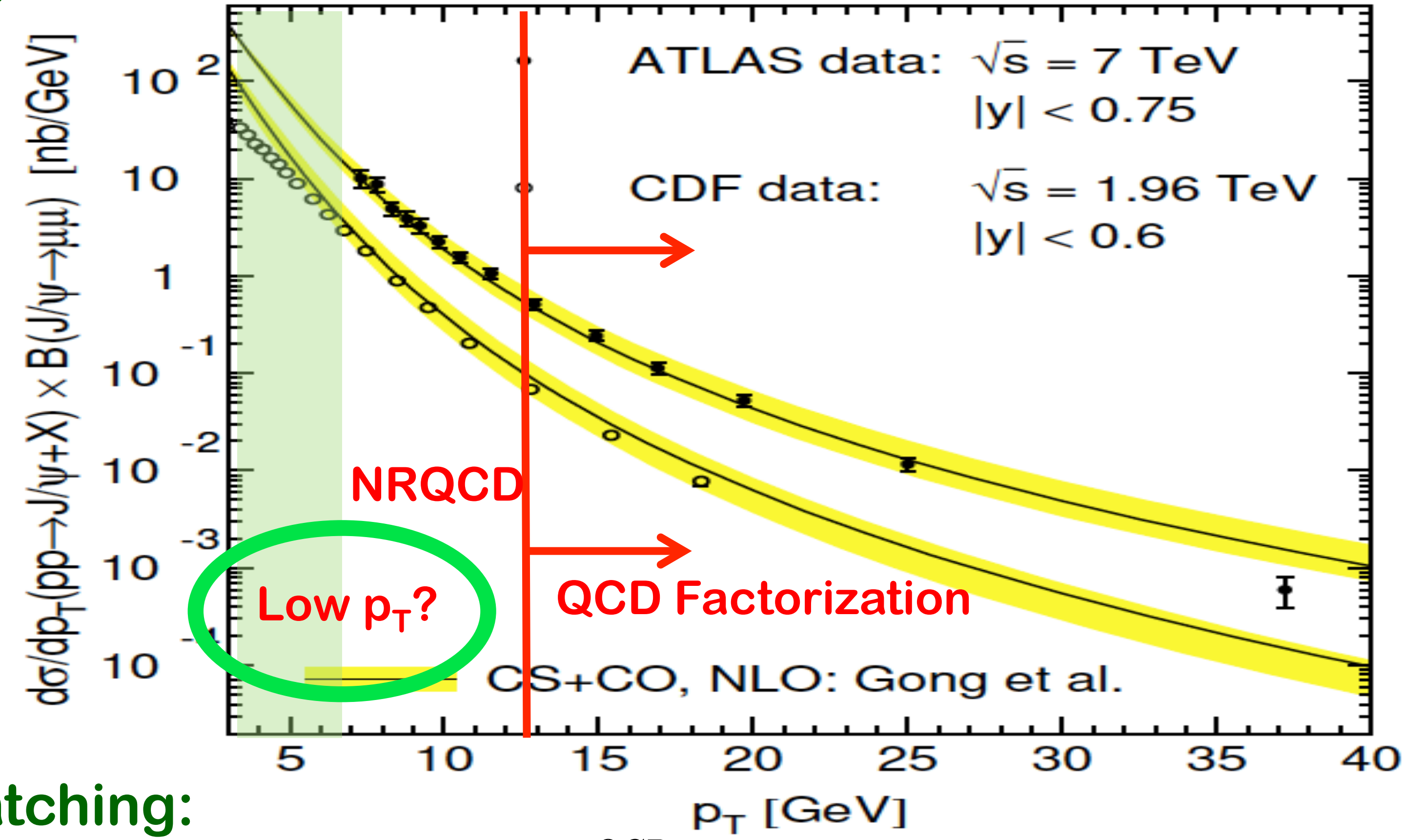
Cross section + polarization

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

Matching between different approaches

Kang, Ma, Qiu and Sterman, 2014

- Expectation:



- Matching:

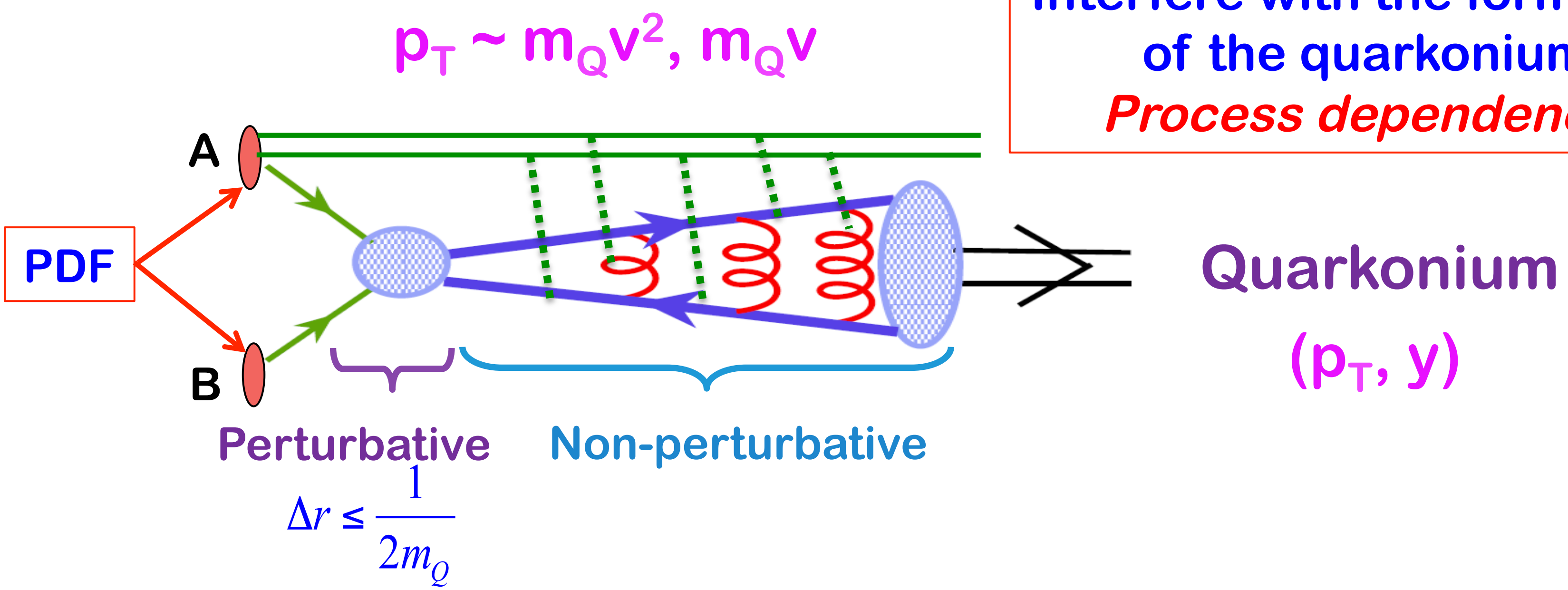
$$E_P \frac{d\sigma_{A+B\to H+X}}{d^3P}(P, m_Q) \equiv E_P \frac{d\sigma^{\rm QCD}_{A+B\to H+X}}{d^3P}(P, m_Q = 0)$$

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

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, …

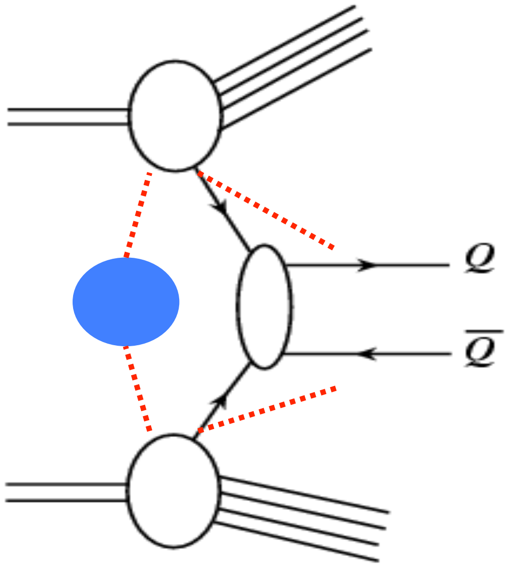
- Understand the factorization breaking:

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

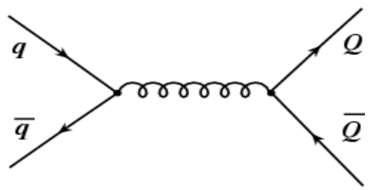
Even the Drell-Yan process is NOT fully factorizable!

Production at low p_T (< M_Q)

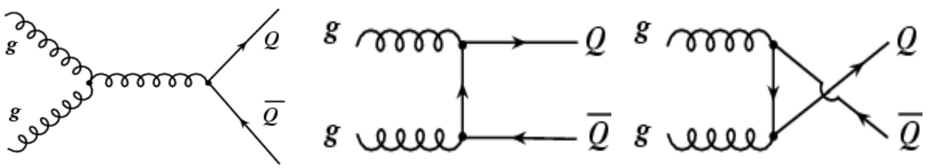
- Gluon shower – Sudakov resummation dominated?



✧ Quark-antiquark channel:



✧ Gluon-gluon channel:



- Assumption:

Leading double logarithms from the gluon shower are from initial-state active partons

⟹ Mimic the Drell-Yan type radiation pattern,
Resum the leading soft radiation into Sudakov form factor

Upsilon production at hadron colliders

❑ CSS formalism (the b-space approach to low P_T region):

Use Drell-Yan as an example:

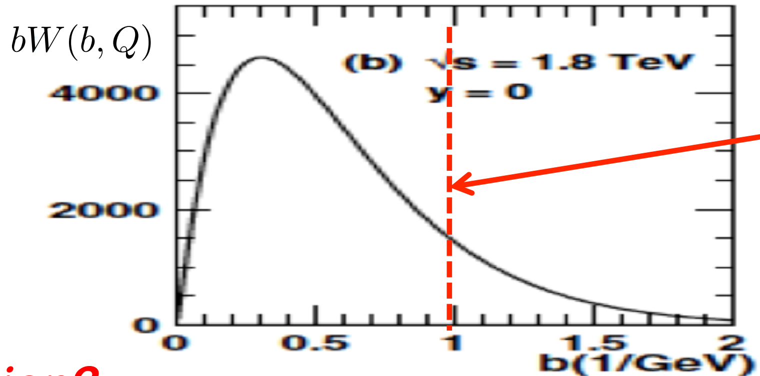
$$\frac{d\sigma^{DY}_{AB}}{dQ^2 dq_T^2}(Q,q_T,x_A,x_B) = \hat{H}_{f\bar{f}}(Q)\otimes\Phi_{f/A}(x_A,k_{a\perp})\otimes\Phi_{\bar{f}/B}(x_B,k_{b\perp})\otimes\mathcal{S}(k_{s\perp})+Y(Q,q_T)$$

$$= \frac{1}{2\pi}\int_0^\infty db\, J_0(bq_T)\, b\widetilde{W}_{AB}(b,Q;x_A,x_B) + \left[\frac{d\sigma^{(\rm Pert)}_{AB}}{dQ^2 dq_T^2} - \frac{d\sigma^{(\rm Asym)}_{AB}}{dQ^2 dq_T^2}\right]$$

The b-space distribution:

$$\widetilde{W}^{\rm Pert}_{AB}(b,Q;x_A,x_B) = \hat{H}_{f\bar{f}}(Q)\left[\mathcal{C}_{f/a}\otimes\Phi_{a/A}(x_A,1/b)\right]\otimes\left[\mathcal{C}_{\bar{f}/b}\otimes\Phi_{b/B}(x_B,1/b)\right]e^{-\mathcal{S}(b,Q)}$$

Predictive power: very sensitive to the role of non-perturbative contribution!



Ratio of areas large b vs. small b
Nonperturbative Vs. perturbative

The role of large-b region?

Good predictive power (not sensitive to the large-b region):

if the area under the b-space distribution is dominated by small-b region!

Upsilon production at hadron colliders

- Expect good predictive power:

  Peak of p_T-distribution is around 4 GeV
  >> intrinsic p_T
  >> the Q_s at this energies

  } Shower is the dominant source to the observed large p_T

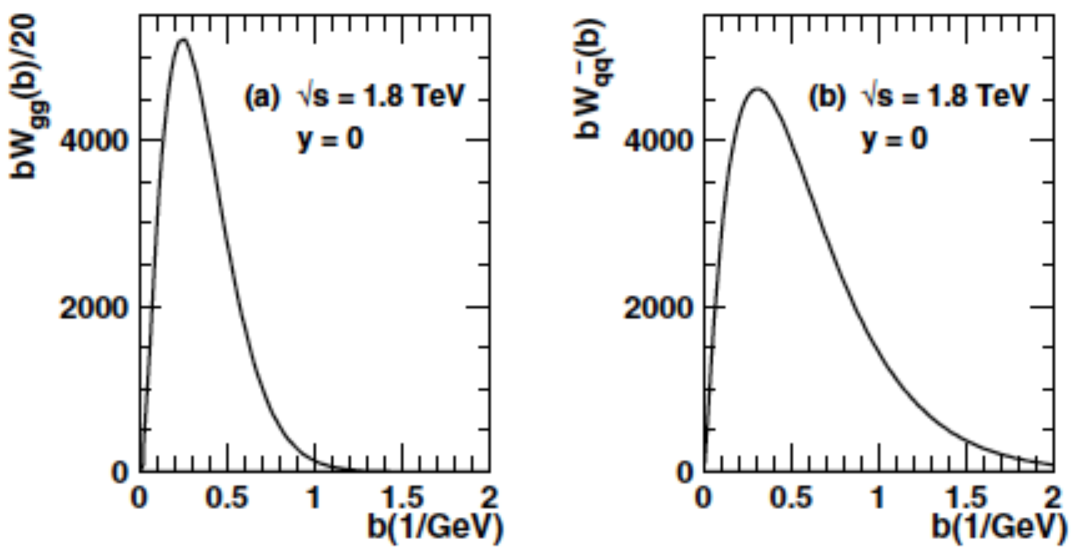
- Matching procedure to large-b region:

$$W_{ij}(b,Q,x_A,x_B)=\begin{cases} W_{ij}^{\text{pert}}(b,Q,x_A,x_B) & b\le b_{\max} \\ W_{ij}^{\text{pert}}(b_{\max},Q,x_A,x_B)F_{ij}^{NP}(b,Q;b_{\max}) & b>b_{\max} \end{cases}$$

$$F_{ij}^{NP}=\exp\left\{-\ln\left(\frac{Q^2b_{\max}^2}{c^2}\right)\{g_1[(b^2)^\alpha-(b_{\max}^2)^\alpha]+g_2(b^2-b_{\max}^2)\}-\bar{g}_2(b^2-b_{\max}^2)\right\}$$

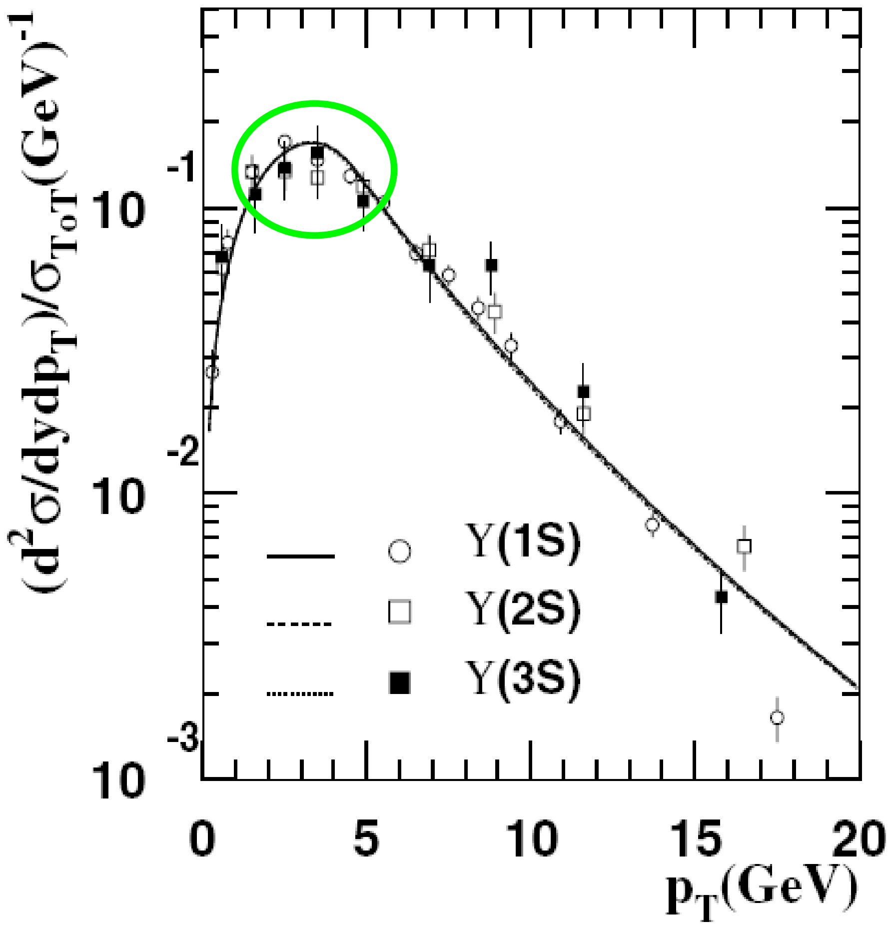
- b-space distribution for Upsion production at Tevatron energy:

  All parameters fixed by the derivatives to be continuous at $b = b_{max}$.

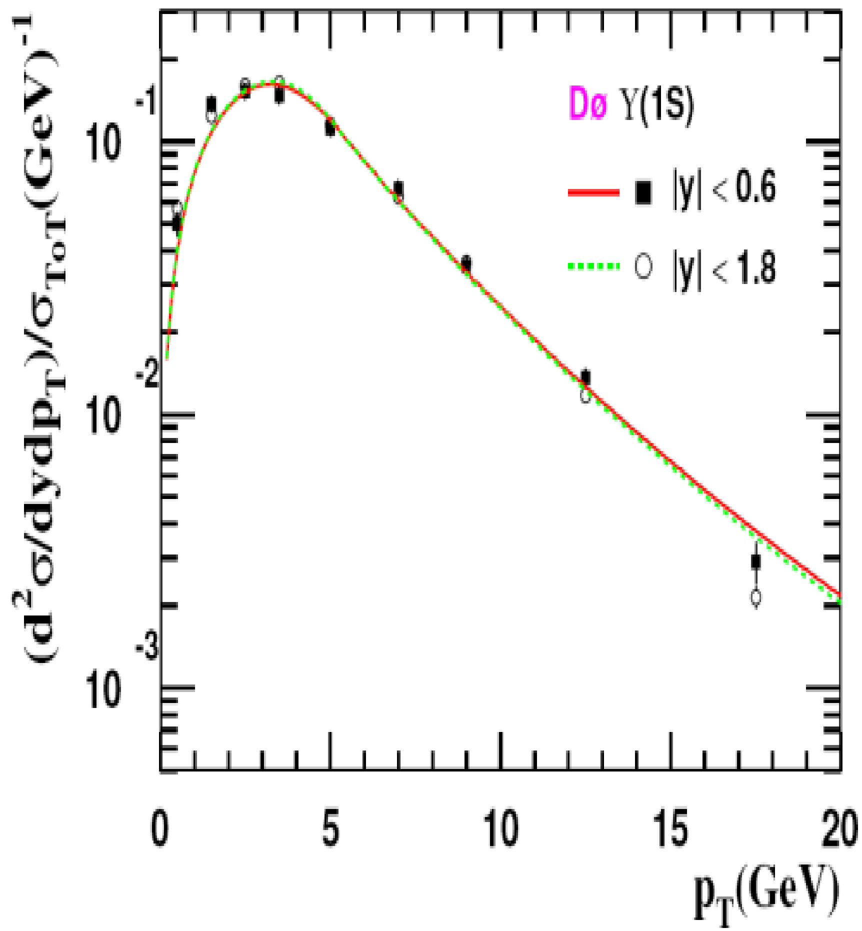


Upsilon production at hadron colliders

CDF Run-I



D0 Run-II



- ❑ **Strong gluon shower:**

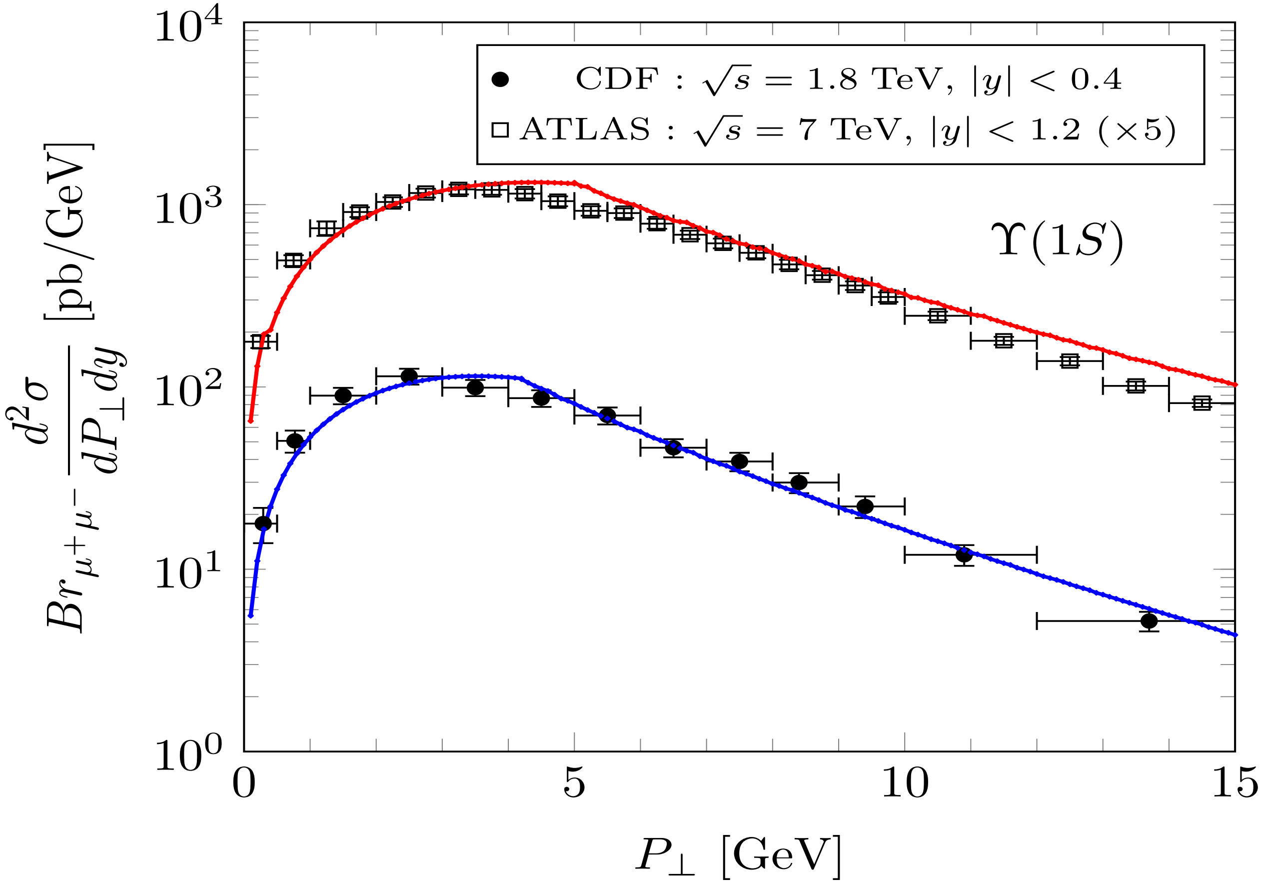
Berger, Qiu, Wang, 2005

Sufficiently large Q (Upsilon mass) + large shower phase space!

Predictive power – Upsilon

Qiu, Watanabe, 2017

❑ Upsilon at the LHC:



No adjustment on any parameter from Tevatron to the LHC!

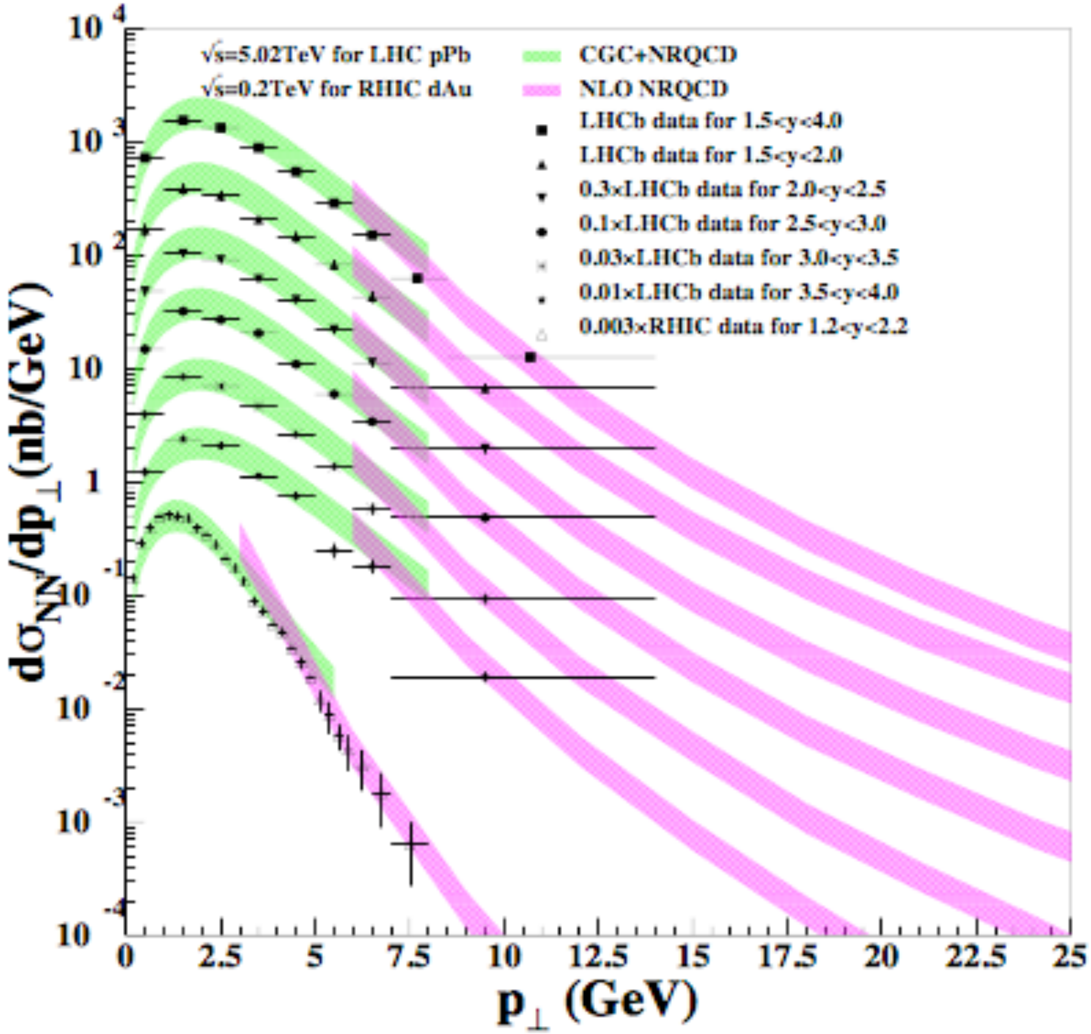
BUT: this does not apply for J/ψ at low PT,

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,

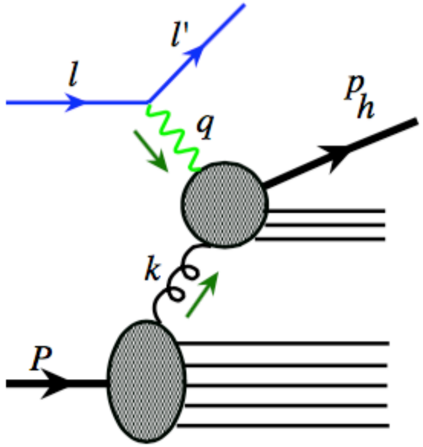
  seem to be smooth

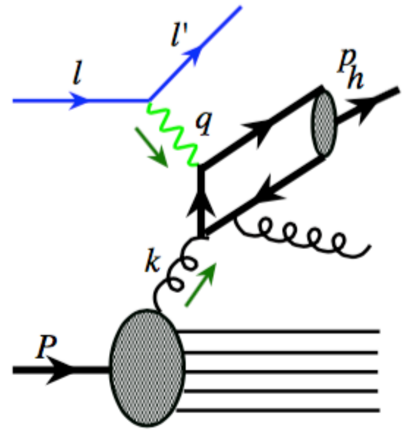
✧ Better agreement with data than previous CGC calculations

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

Heavy quarkonium production at EIC

❑ Semi-inclusive DIS:





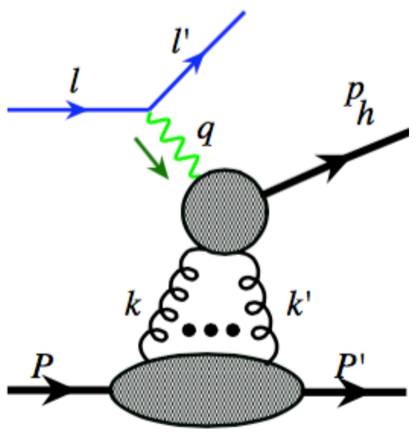
Low P_T: **Glue TMD ?**
CGC ?

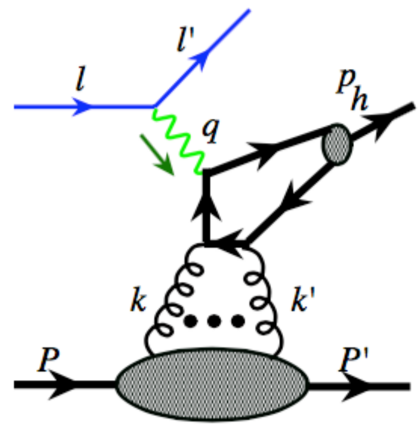
Shower vs.
multiple scattering

$P_T \sim Q$: **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?

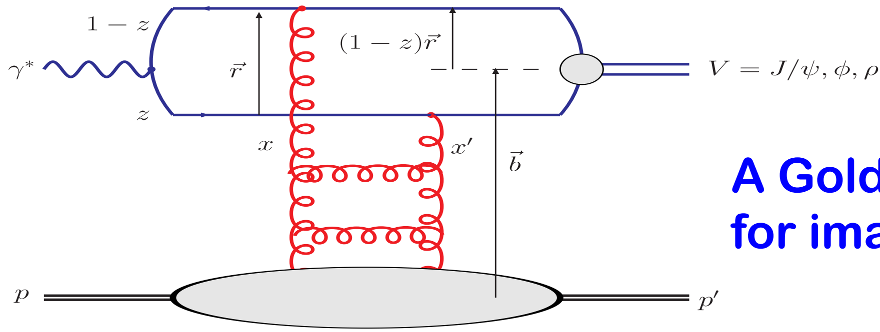
On-going effort, …

One facility covers all issues of quarkonium production!

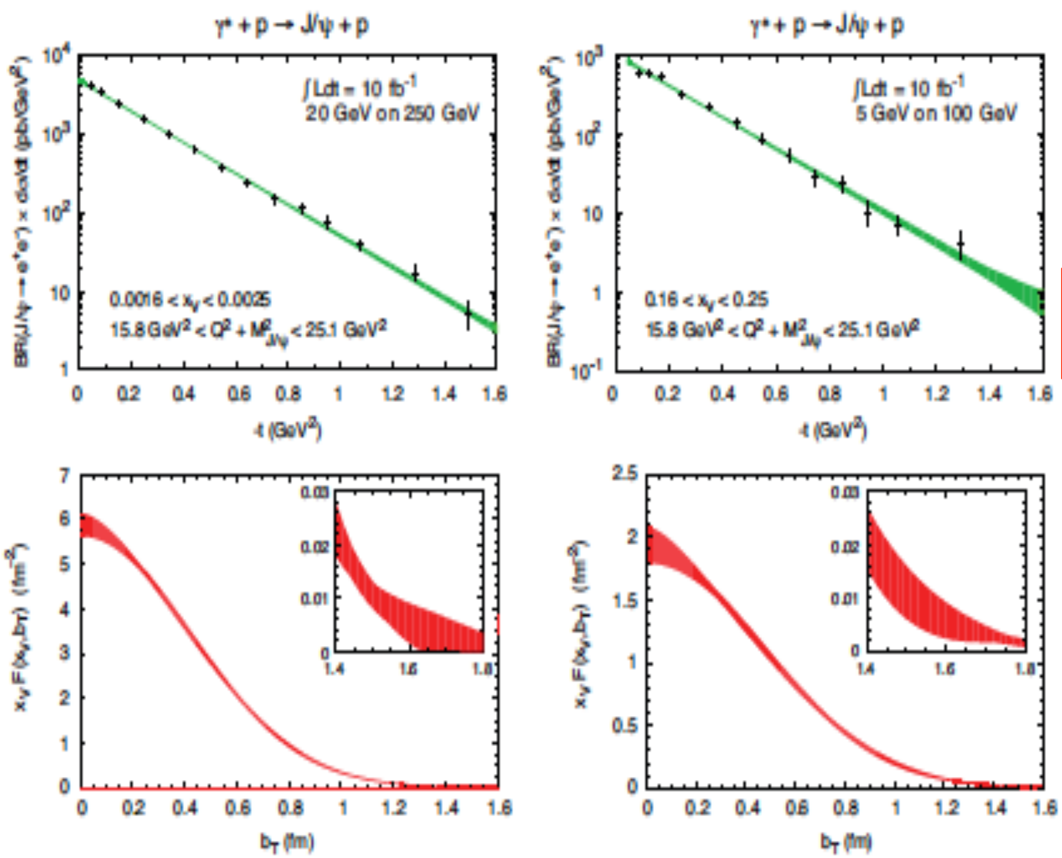
Critical role of J/ψ production at EIC

EIC WP, 1212.1701

- **Exclusive:**



A Golden process
for imagining gluon

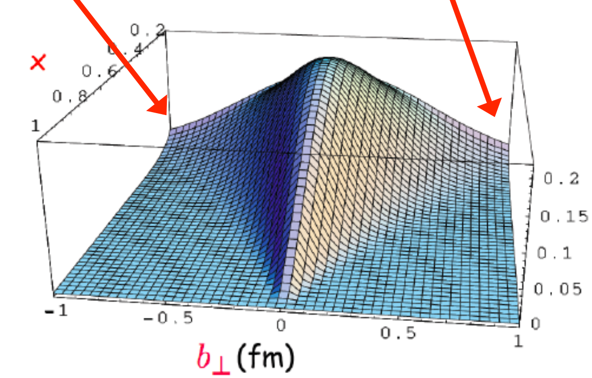


Allow us to ask "new"
fundamental questions:

Color confining radius?

How far does glue density spread?

How fast does glue density fall?

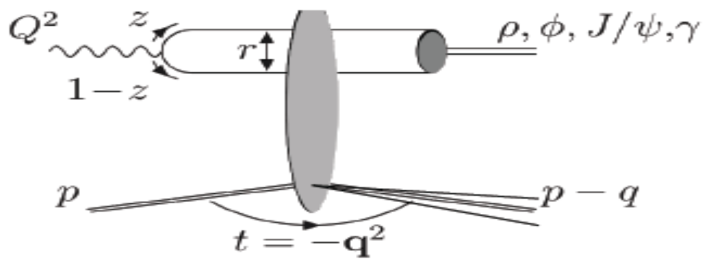


Can A be a bigger P at small-x?

Diffractive production in e+A at EIC

EIC WP, 1212.1701

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

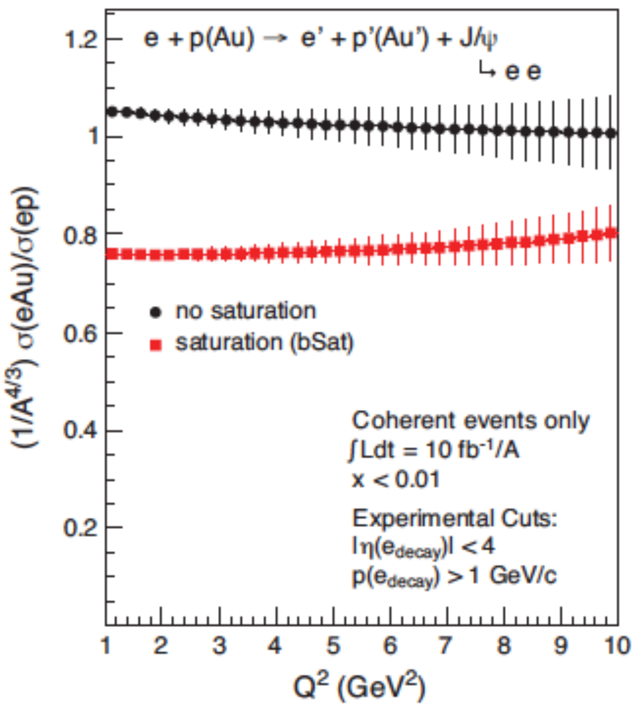


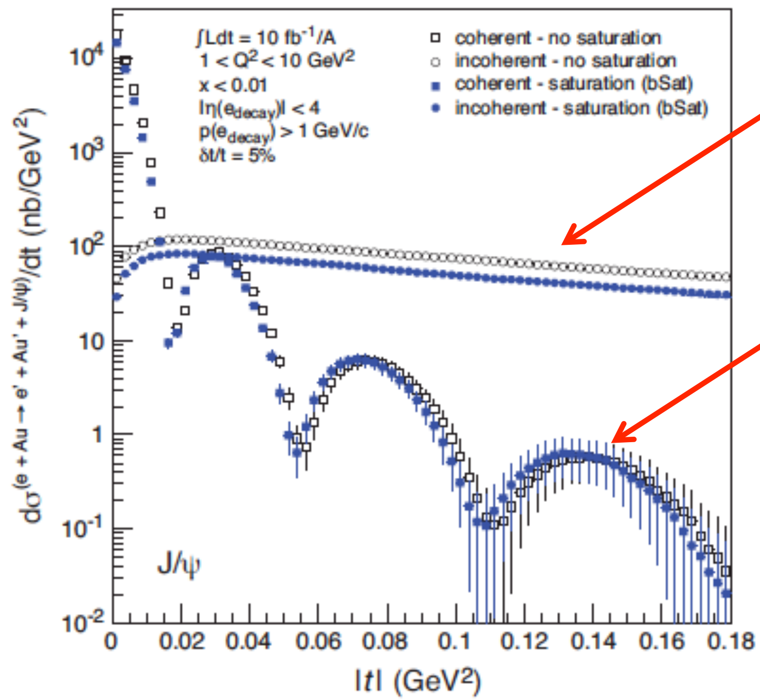
$$\frac{d\sigma}{dx_B dQ^2 dt}$$

- as a function of t

Fourier transform of the t-dependence

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





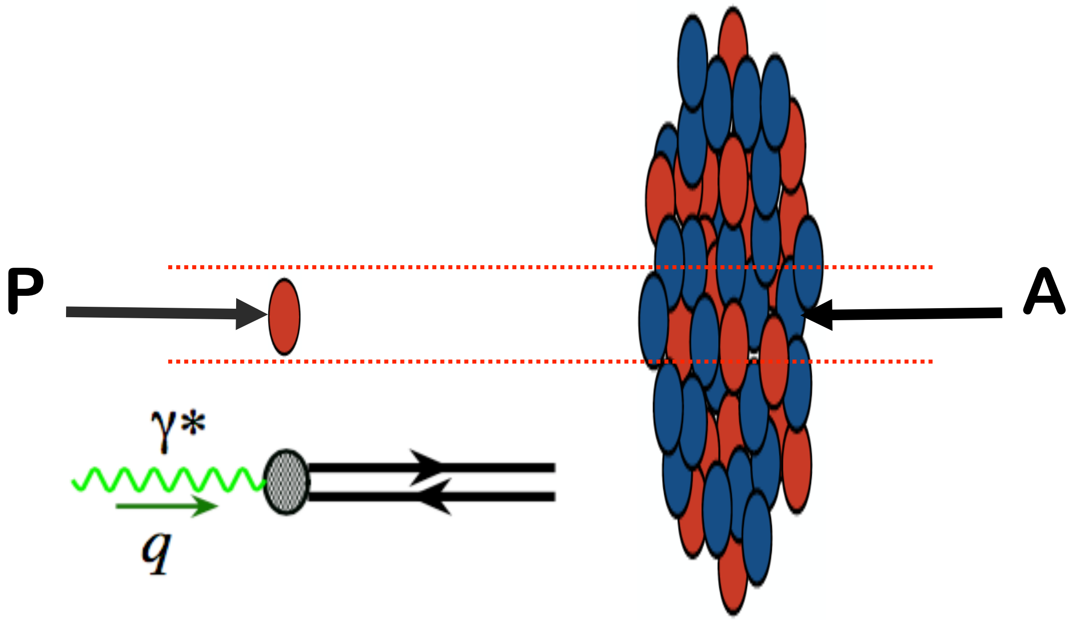
✧ **Incoherent:** Nucleus breaks up

✧ **Coherent:** Nucleus stays intact

Need EIC's Energy & Luminosity to do this!

What have we learned from p+A collisions?

- **Proton (deuteron) – Nucleus Collisions:**



✧ NO QGP (m_Q >> T)! ➡ Cold nuclear effect for the "production"

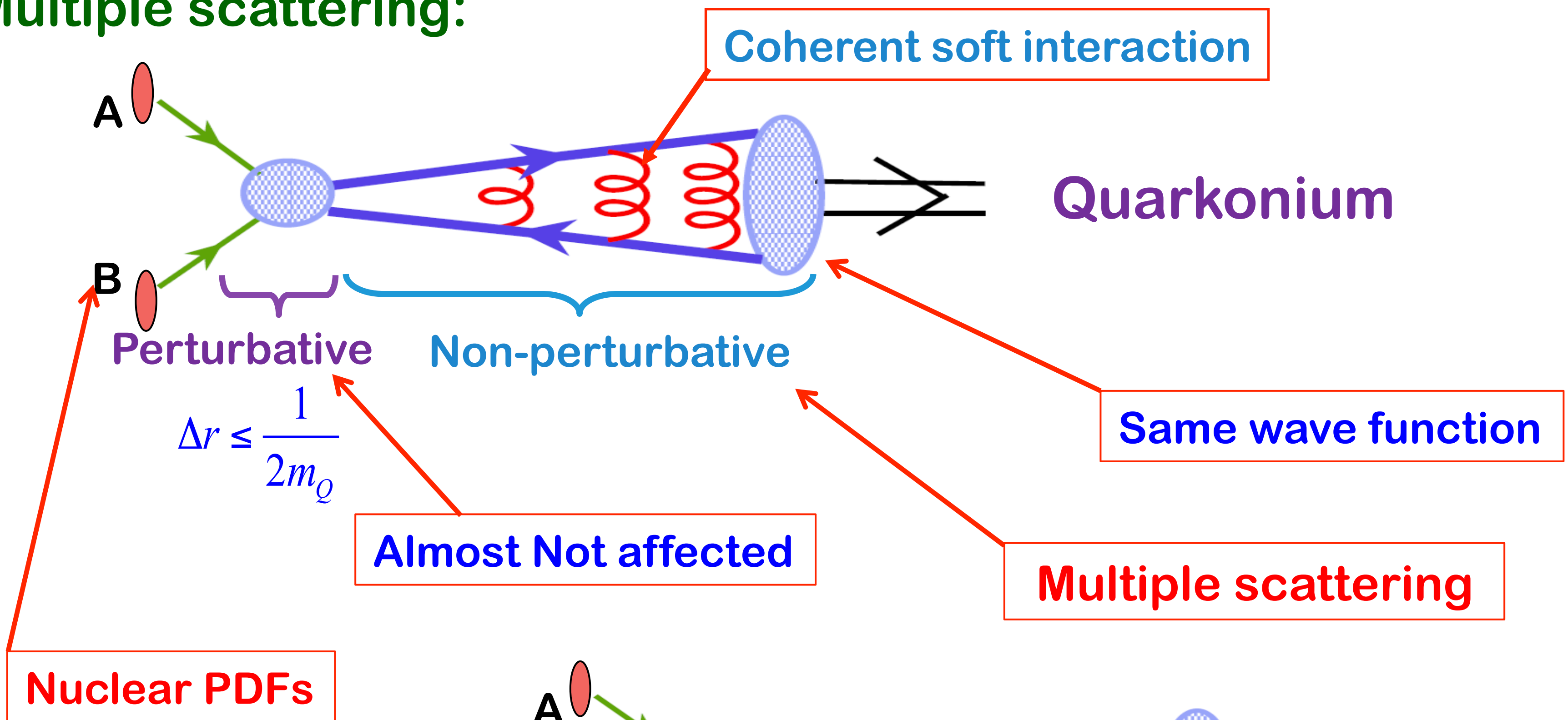
✧ Nuclei as potential filters of production mechanisms

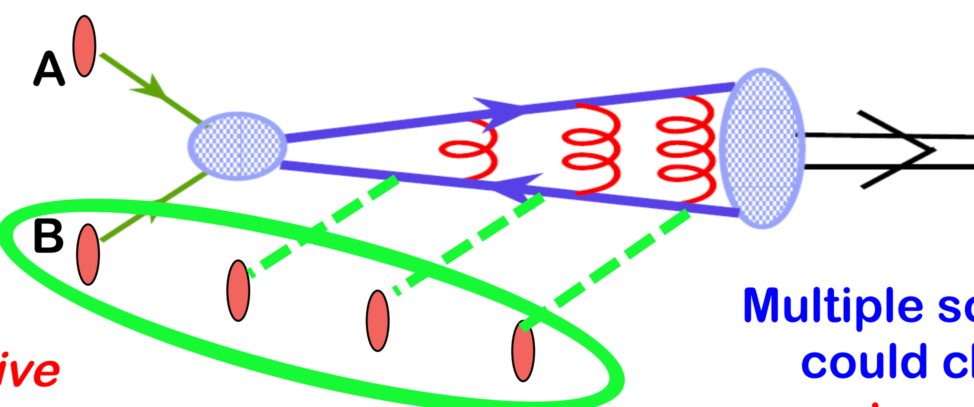
✧ Hard probe (m_Q >> 1/fm) ➡ quark-gluon structure of nucleus!

Nucleus is not a simple superposition of nucleons!

Production in p(d)+A collisions

- **Multiple scattering:**



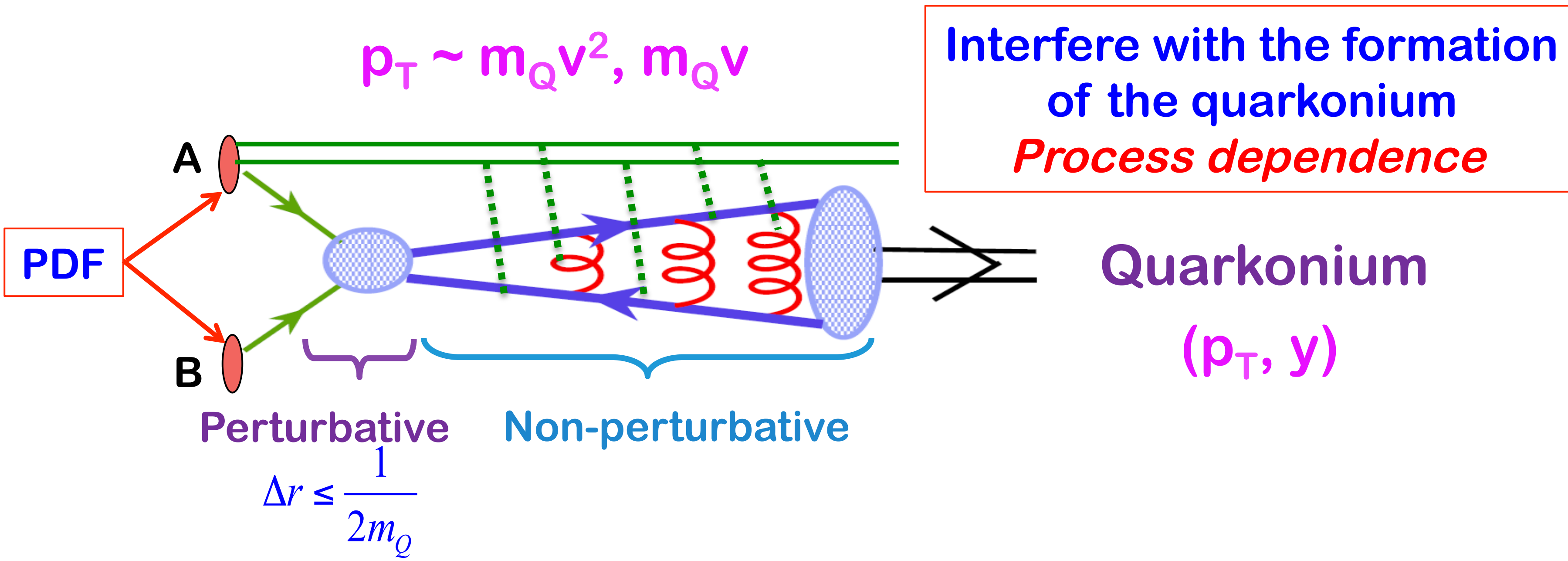


Can multiple scattering interfere with nonperturbative formation of quarkonia?

Multiple scattering could change spectrum & rate!!

Production at low p_T (< M_Q)

- ❑ Spectator interaction – always there for p+A, but, not for e+A!



- ❑ The Challenge:

  Process dependence – Break of factorization – No predictive power

- ❑ The need:

  Controllable calculation of medium effect, extract medium properties, …

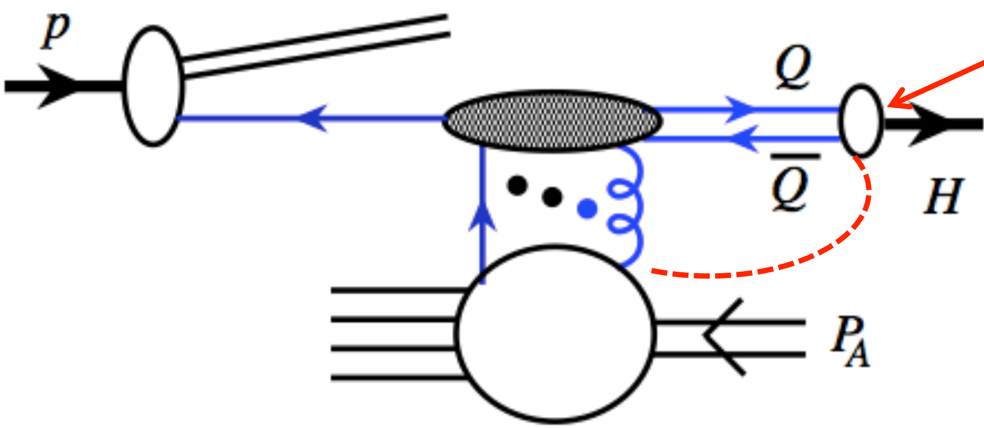
- ❑ The Opportunities:

  Medium as a "detector" or "filter" to probe "color neutralization", …

Production with multiple scattering

Brodsky and Mueller, PLB 1988

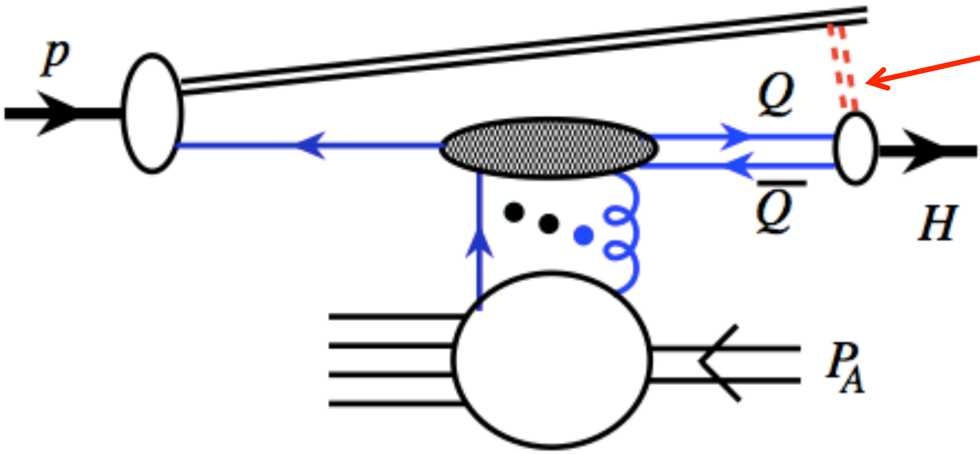
- ❑ *Backward* production in p(d)+A collisions:



J/Ψ could be formed Inside nucleus

Multiple scattering interfere with the non-perturbative hadronization – no factorization!!

- ❑ Production at low P_T (→0) in p(d)+A collisions:



Co-mover interaction

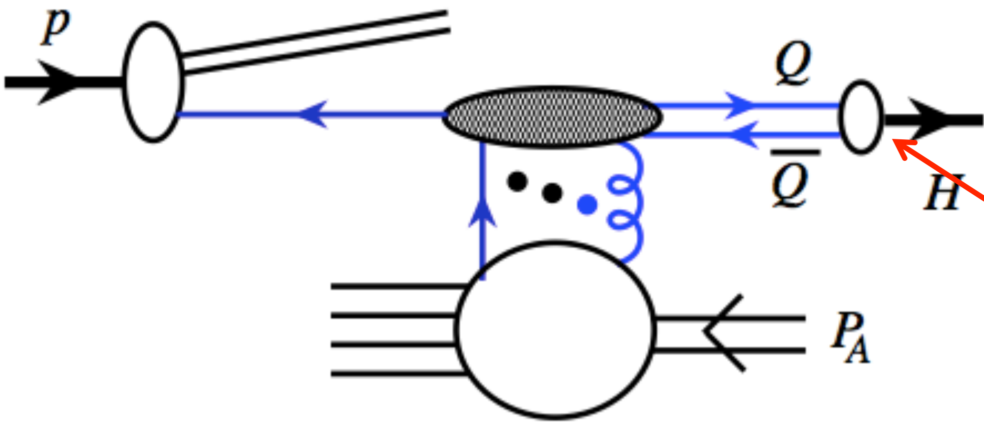
to interfere with quarkonium formation - Break of factorization!!

NOT a problem for e+A!

Production with multiple scattering

Brodsky and Mueller, PLB 1988

- ***Forward*** **production in p(d)+A collisions:**



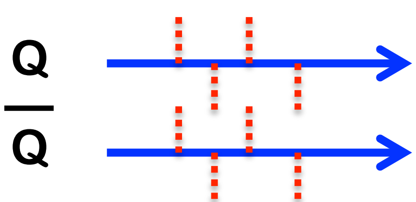
✧ Time dilation

Non-perturbative formation of J/Ψ is far outside of nucleus

✧ SAME for e+A!

✧ Multiple scattering between partons & heavy quarks, not J/Ψ

- Induced gluon radiation – energy loss – suppression at large y
- Modified P_T spectrum – transverse momentum broadening
- De-coherence of the pair – different $Q\bar{Q}$ state to hadronize – lower rate



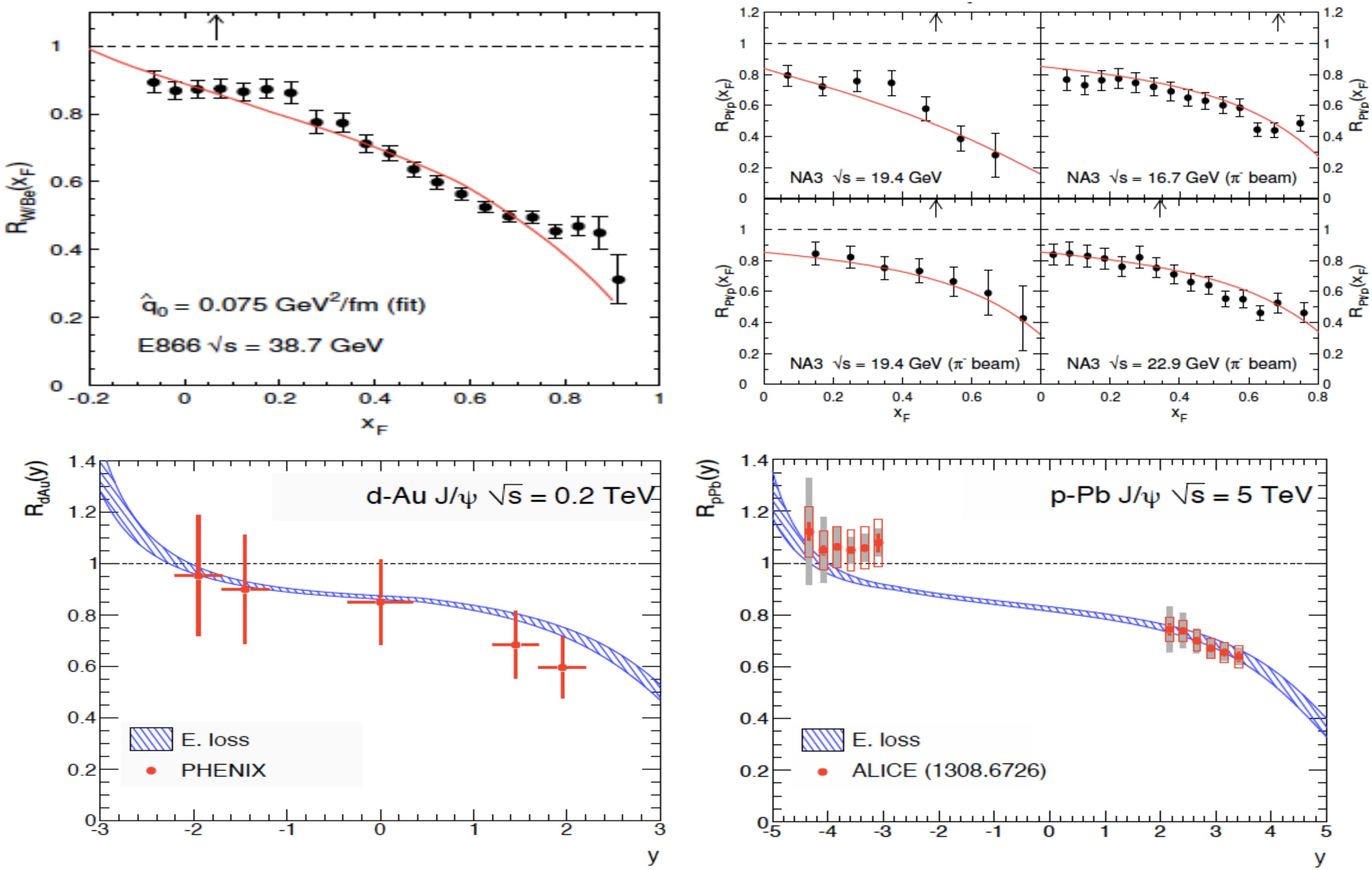
Soft multiple scattering – "random walk"

➡ Momentum imbalance – larger invariant mass

➡ Match to the tail of wave function - ``suppression"

A-dependence in rapidity y (x_F) in p+A

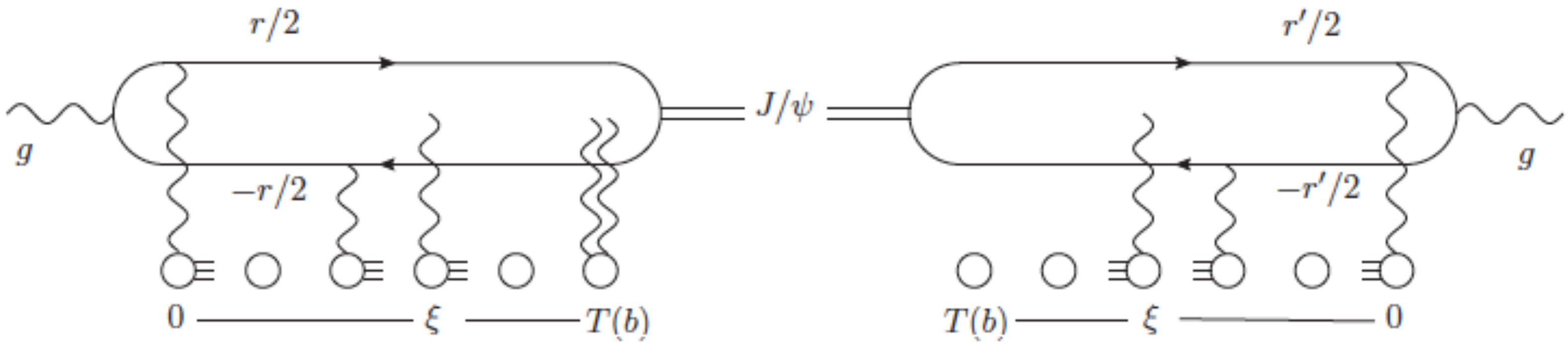
Arleo, Peigne, 2012, Arleo, Kolevatov, Peigne, 2014

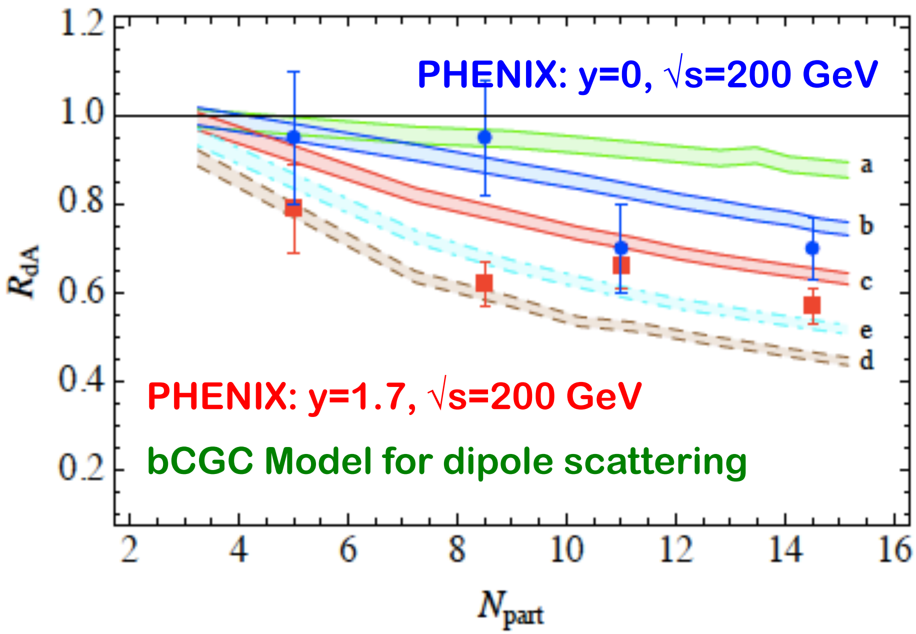


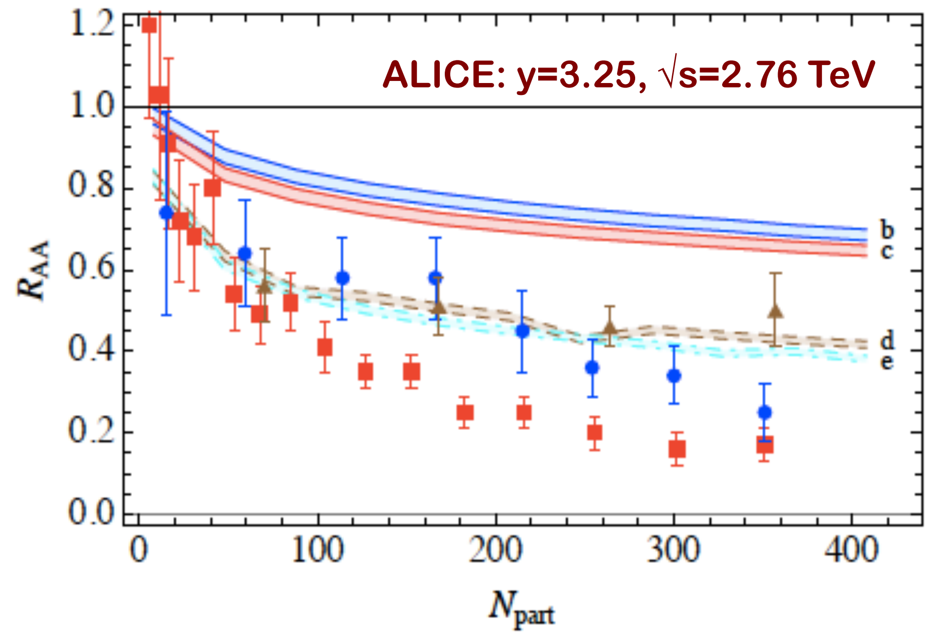
Multiple scattering in pA collisions

Dominguez, Kharzeev, Levin, Mueller, and Tuchin, 2011

$$\frac{d\sigma_{pA\to J/\psi X}}{d^2b\,dy} = x_1 G(x_1, m_c^2)\frac{d\sigma_{gA\to J/\psi X}}{d^2b}$$





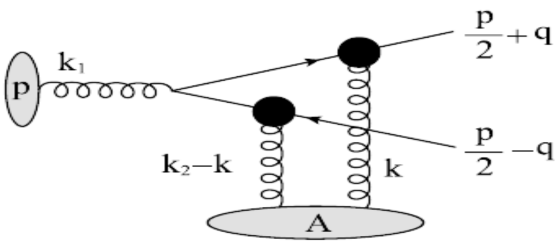


OK for pA, but, far off for AA – J/ψ melting in QGP (MS 1986)?

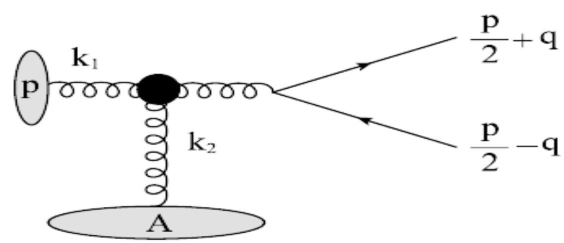
Forward quarkonium production in p(d)+A

- **Calculation of multiple scattering:**

Kang, Ma, Venugopalan, JHEP (2014)
Qiu, Sun, Xiao, Yuan PRD89 (2014)

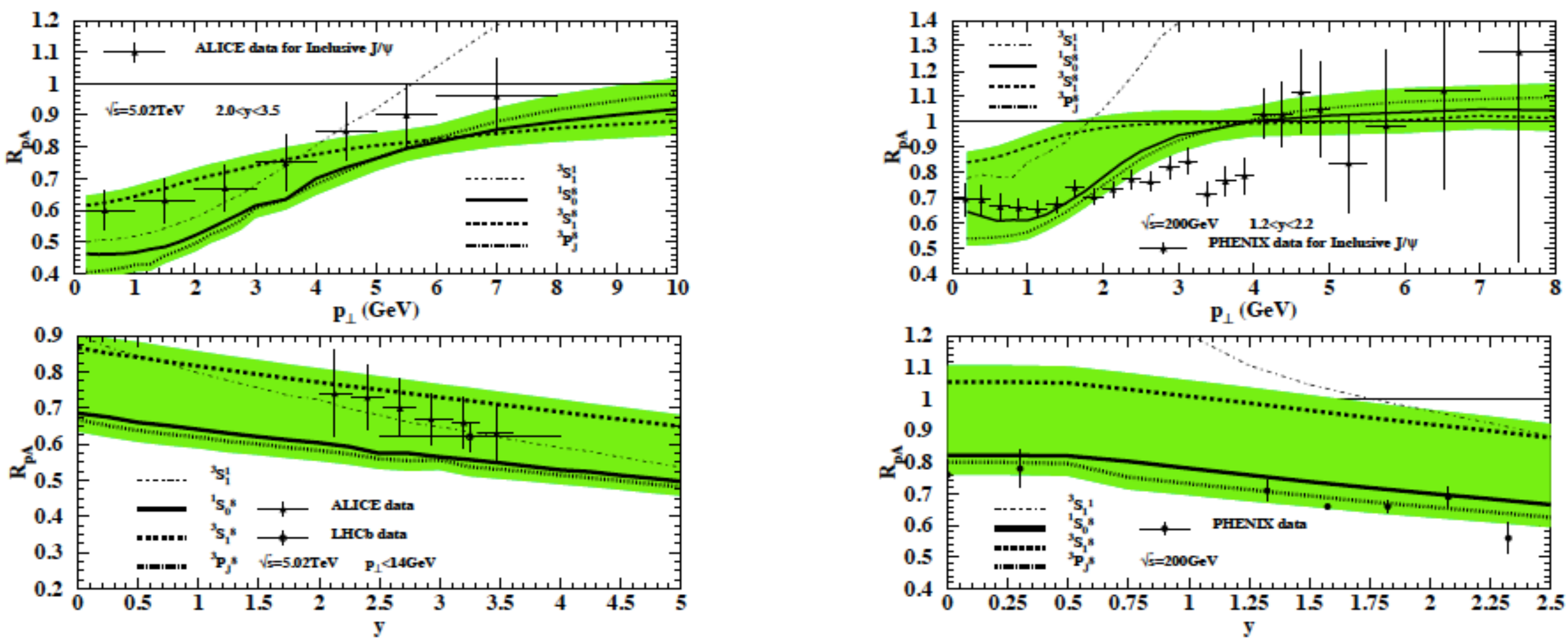


(a)



(b)

Coherent multiple scattering ⟹ suppression at large y



Ma, Venugopalan, Zhang, PRD92, 071901 (2015)

Quarkonium pT distribution

- Quarkonium production is dominated by low p_T region
- Low p_T distribution at collider energies:

  determined mainly by gluon shower of incoming partons

  – initial-state effect

  Qiu, Zhang, PRL, 2001
- Final-state interactions suppress the formation of J/ψ:

  Also modify the p_T spectrum – move low pT to high pT – broadening

  – Final-state effect
- Broadening:
  - Sensitive to the medium properties
  - Perturbatively calculable

$$\langle (q_T^2)^n \rangle = \frac{\int dq_T^2 (q_T^2)^n \, d\sigma / dq_T^2}{\int dq_T^2 \, d\sigma / dq_T^2}$$

$$\Delta \langle q_T^2 \rangle = \langle q_T^2 \rangle_{AB} - \langle q_T^2 \rangle_{NN}$$

- R_{pA} at low q_T:

Guo, Qiu, Zhang, PRL, PRD 2002

$$R(A,q_T) \equiv \frac{1}{A} \frac{d\sigma^{hA}}{dQ^2\, dq_T^2} \Big/ \frac{d\sigma^{hN}}{dQ^2\, dq_T^2} \equiv A^{\alpha(A,q_T)-1} \approx 1 + \frac{\Delta \langle q_T^2 \rangle}{A^{1/3} \langle q_T^2 \rangle_{hN}} \left[-1 + \frac{q_T^2}{\langle q_T^2 \rangle_{hN}} \right]$$

Quarkonium P_T-broadening in p(d)+A

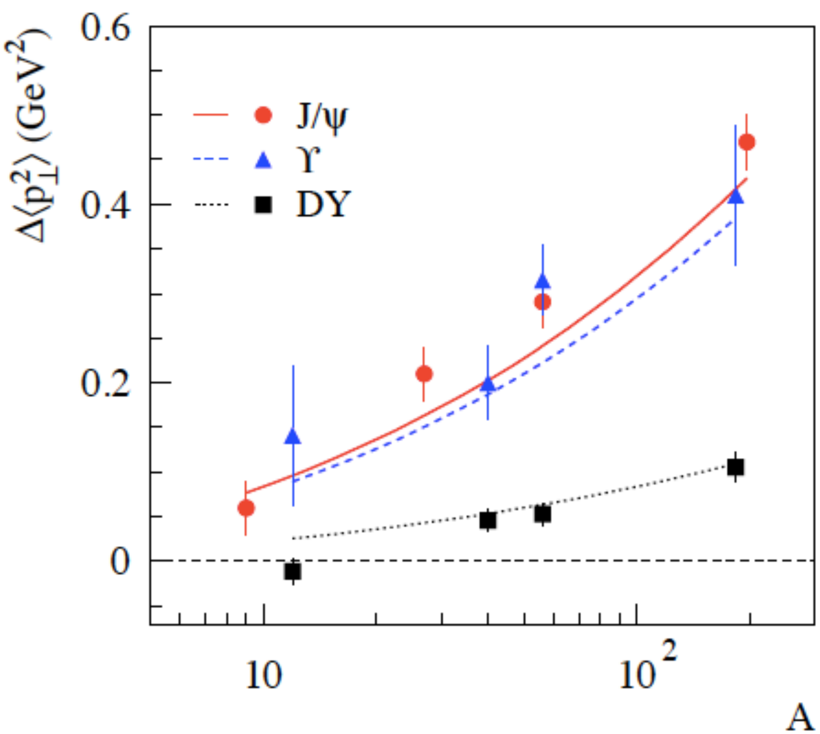
Kang, Qiu, PRD77(2008)

- **Broadening:**

$$\Delta\langle q_T^2\rangle_{J/\psi}^{(I)} = C_A\left(\frac{8\pi^2\alpha_s}{N_c^2-1}(A^{1/3}-1)\lambda^2\right) \approx \Delta\langle q_T^2\rangle_{J/\psi}^{(F)}$$

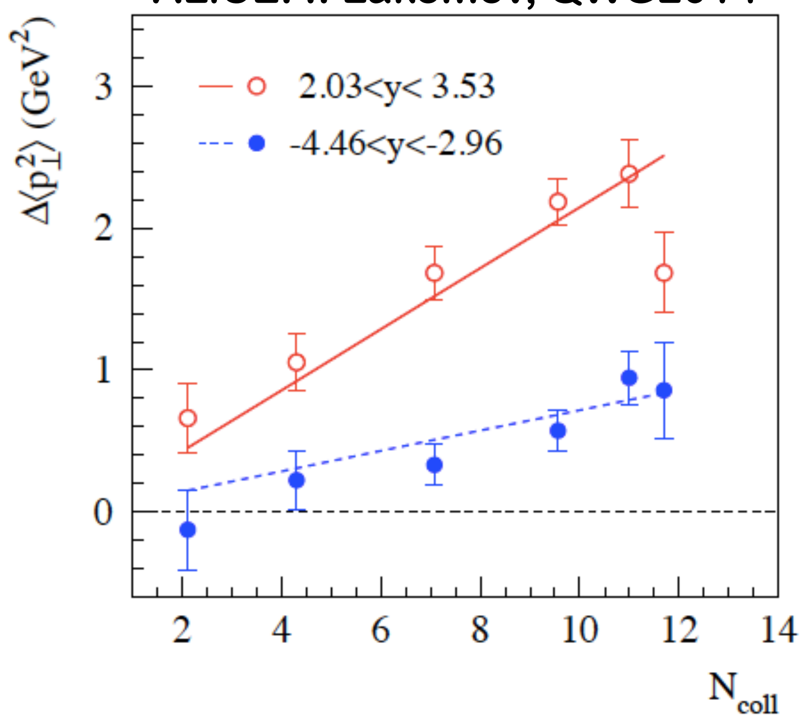
Calculated in both NRQCD and CEM

$$\lambda^2 = \kappa\,\ln(Q)\,x^{-\delta} \propto \hat{q}, \quad \kappa = 3.51\times10^{-3}\ 1/\mathrm{GeV}^2, \quad \delta = 1.71\times10^{-1}$$



$$\left(A^{1/3}-1\right) \to \left(A^{1/3}-1\right) N_{\rm coll}/N_{\rm coll}^{\rm min.bias}$$

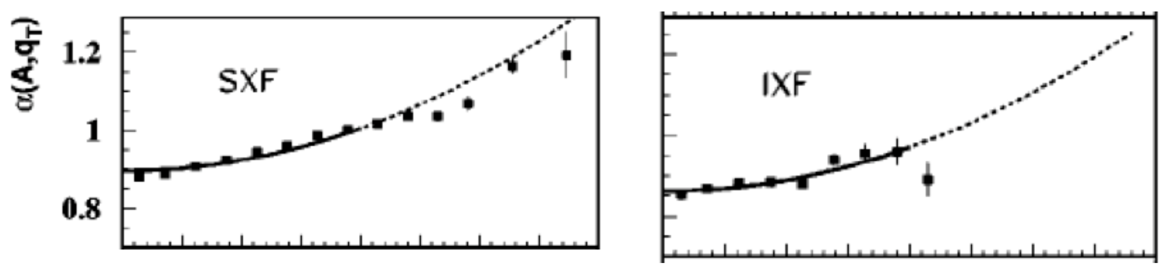
ALiCE: I. Lakomov, QWG2014

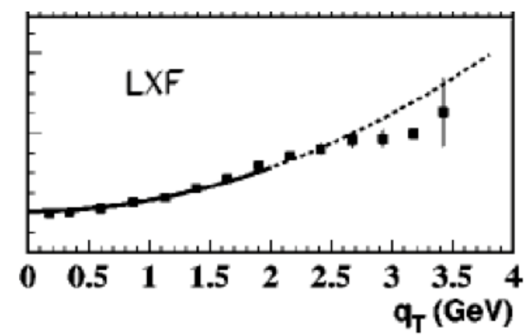


Quarkonium P_T-distribution in p(d)+A

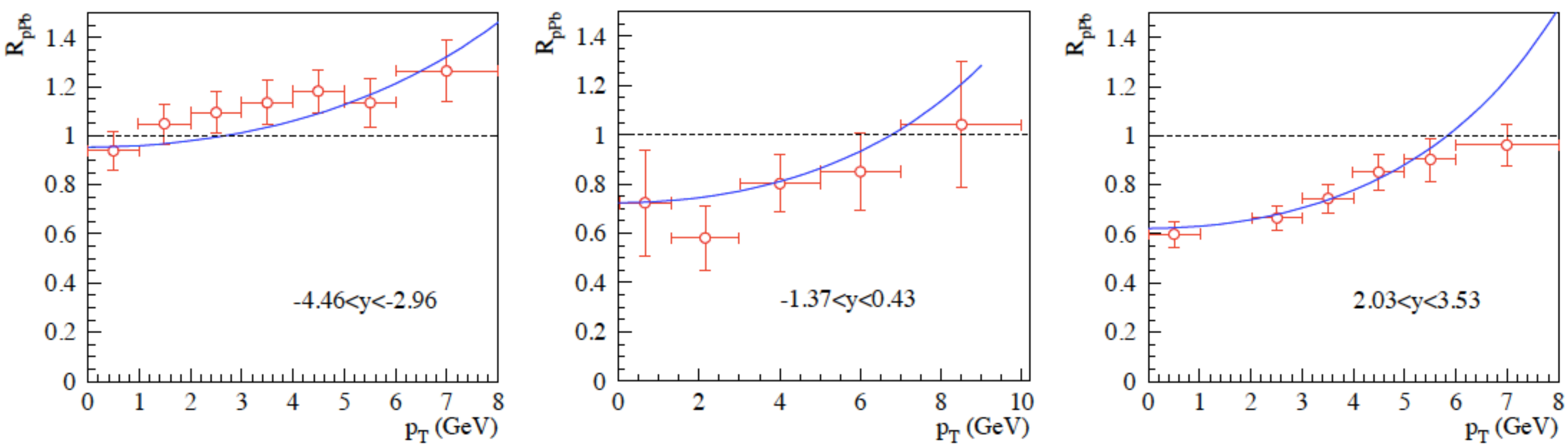
❑ Nuclear modification – low pT region:

$$\frac{d\sigma_{AB}}{dy d^2 p_T} \approx \frac{d\sigma_{AB}}{dy} \left[\frac{1}{\pi(\langle p_T^2 \rangle_{NN} + \Delta \langle p_T^2 \rangle_{AB})} e^{-p_T^2/(\langle p_T^2 \rangle_{NN} + \Delta \langle p_T^2 \rangle_{AB})} \right]$$





E772 data – consistent with theory



ALICE data – Theory prediction

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

- Exclusive production could be a golden process for imagining glue

- 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 – special role of different rapidity regions

Thank you!