J/Ψ Production: Challenges and Opportunities in pp, pA, ep, eA

- ✧ Notable puzzles?
- ✧ Production mechanism?
- ✧ The role of "A" – the medium?
- ✧ New observables?

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EXPLORING THE NATURE OF MATTER

J/ψ - production

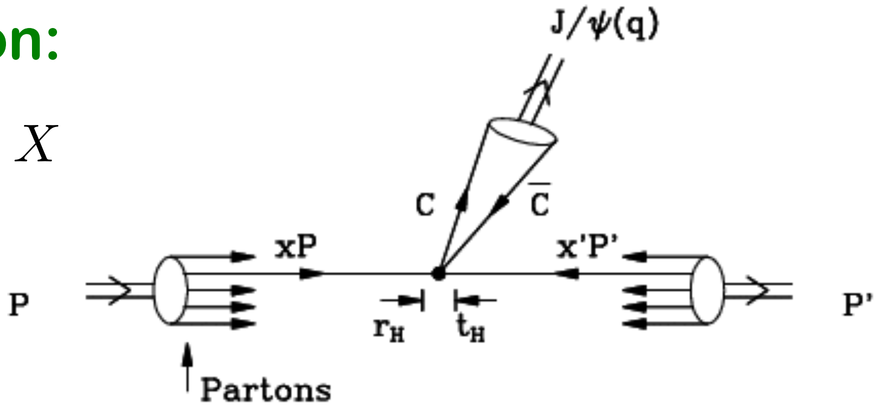
"J/ψ - production is still one of the most fascinating subjects in QCD, even after more than 40 years since its discovery in November, 1974"

- **It might be one of the simplest QCD bound states:**

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

- **Picture of high energy production:**

$$A(P_1) + B(P_2) \to H(P)[J/\psi, \psi', ...] + X$$



- **J/ψ is unlikely to be formed at:**

$$r_H \leq \frac{1}{2m_c} \sim \frac{1}{15} \text{ fm}$$

  Necessary to produce a charm quark pair!

  Momentum transfer > $2m_c \gtrsim 3.0 \text{ GeV}$

Production of a heavy quark pair is likely to be perturbative!

- **Key challenge:**

  Emergence of J/ψ from a produced charm 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:

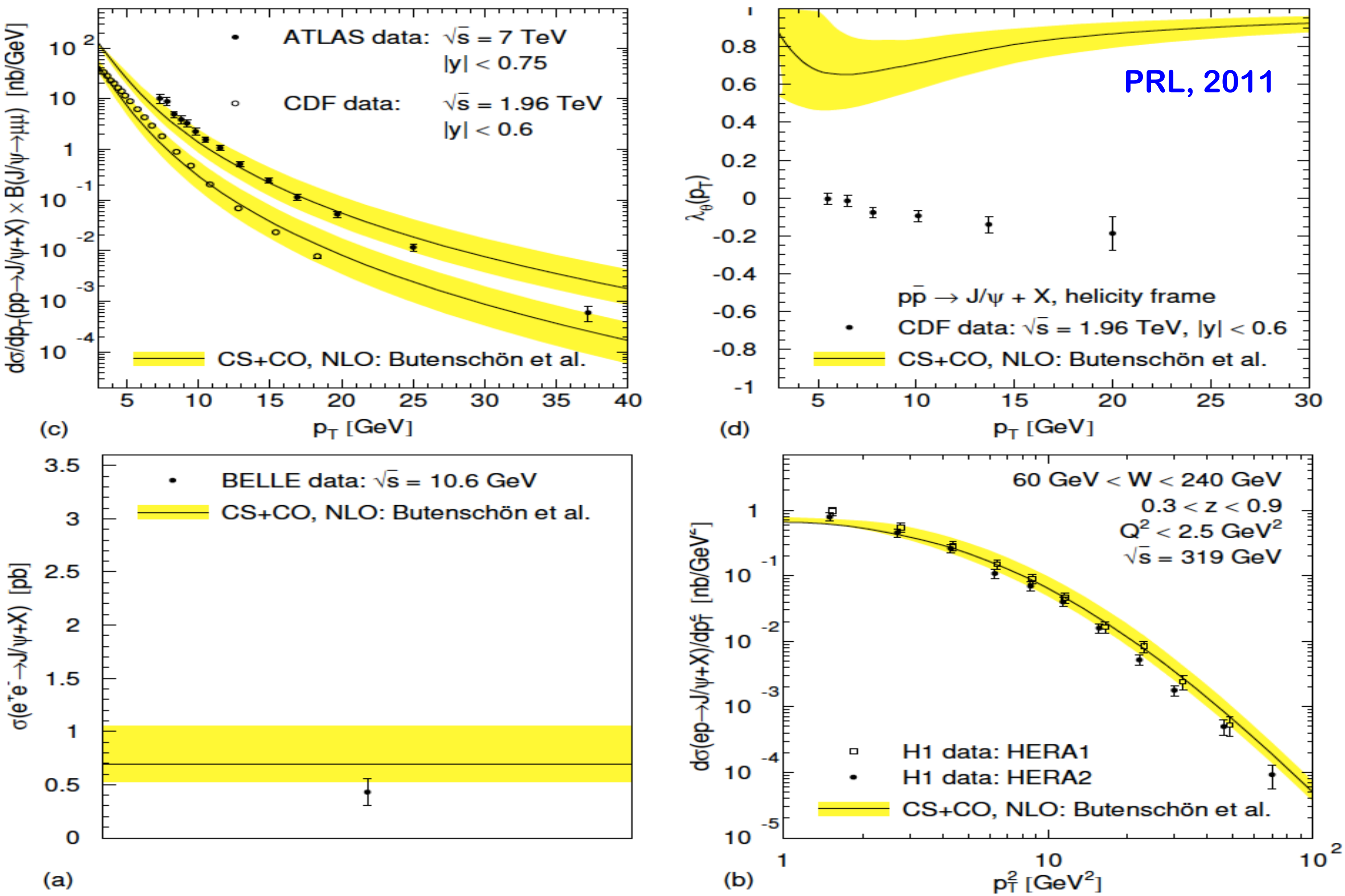
$$\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X)$$

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

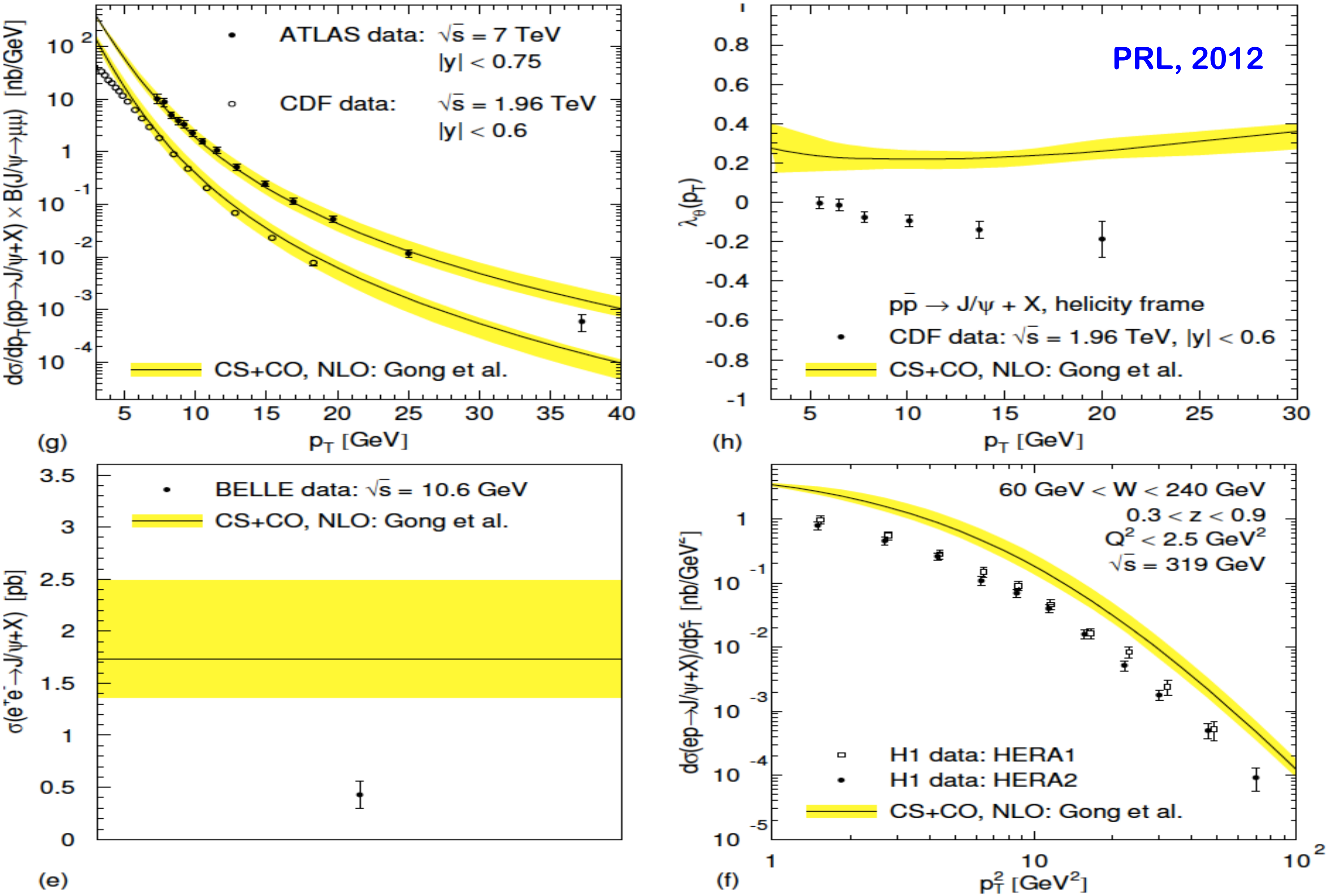
Message:

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

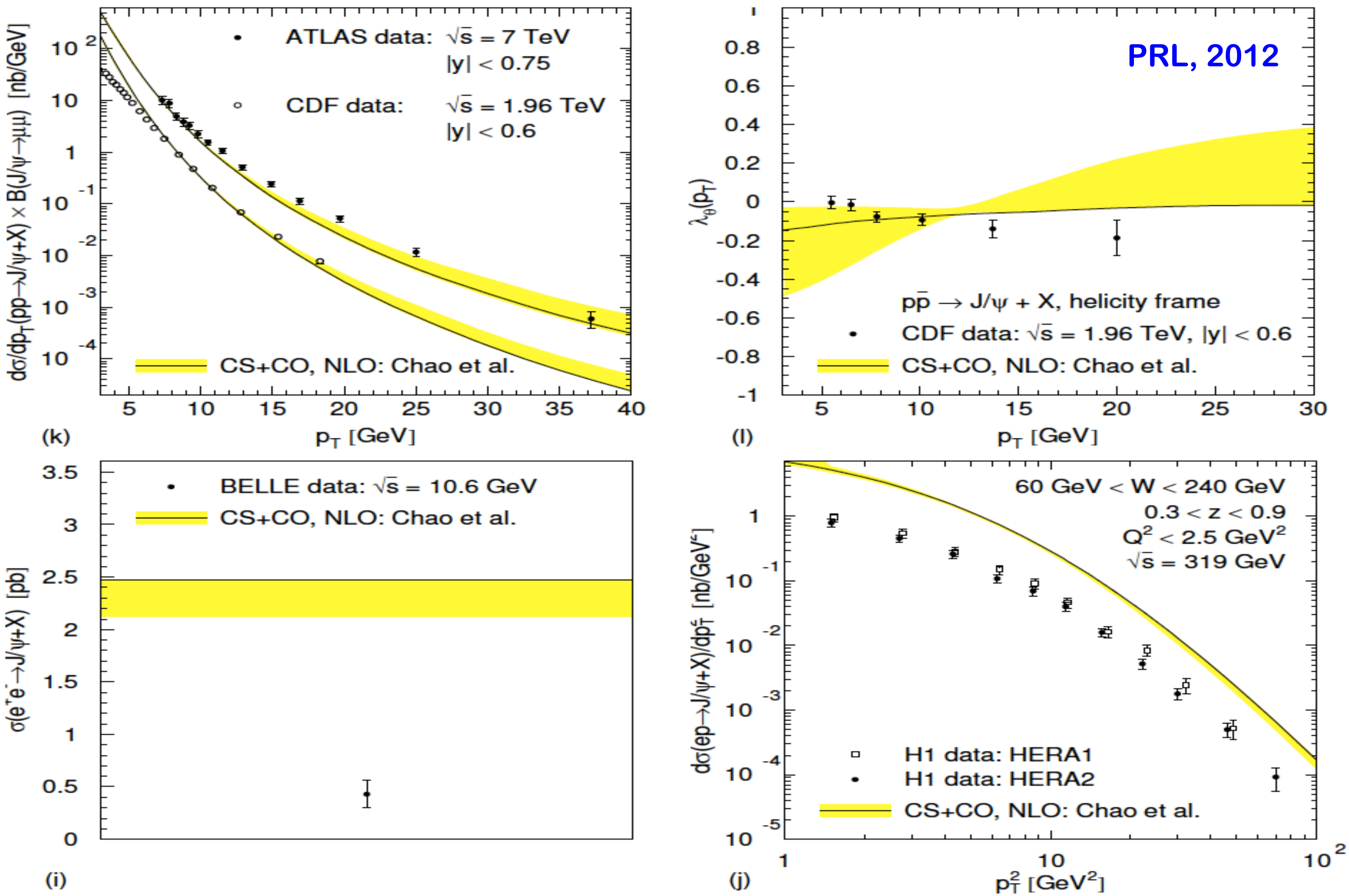
NLO theory fits – Butenschoen et al.



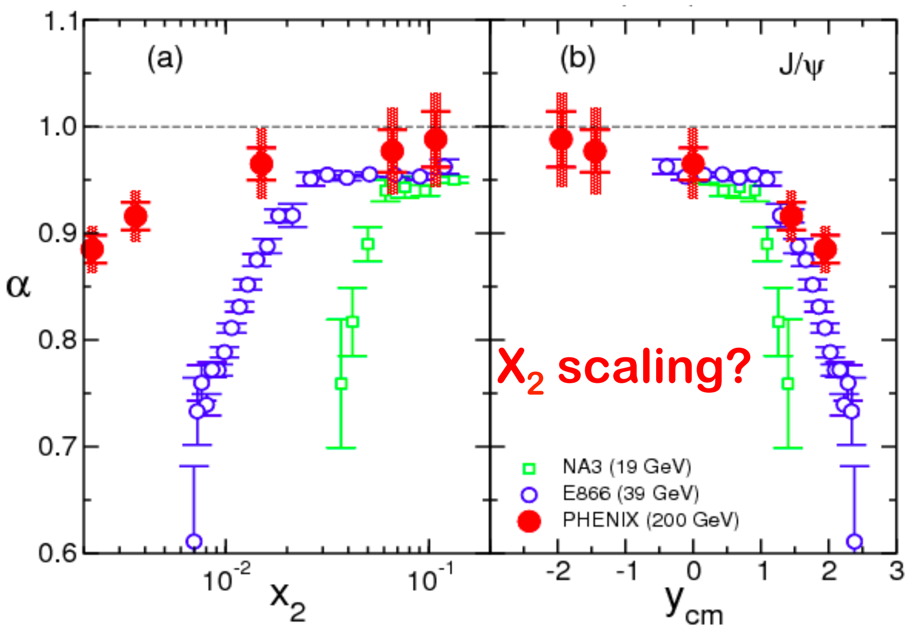
NLO theory fits – Gong et al.

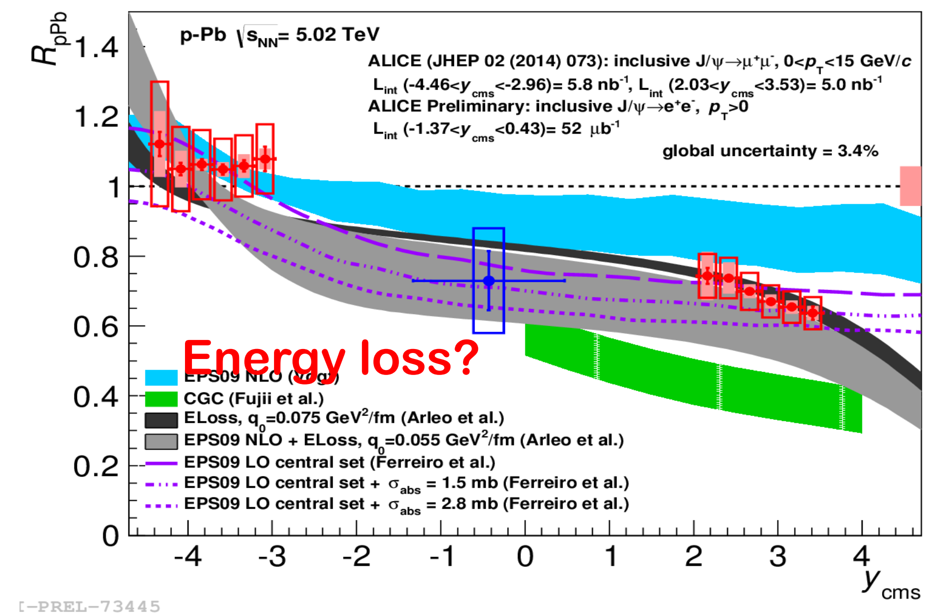


NLO theory fits – Chao et al.



Production in medium, cold or hot?





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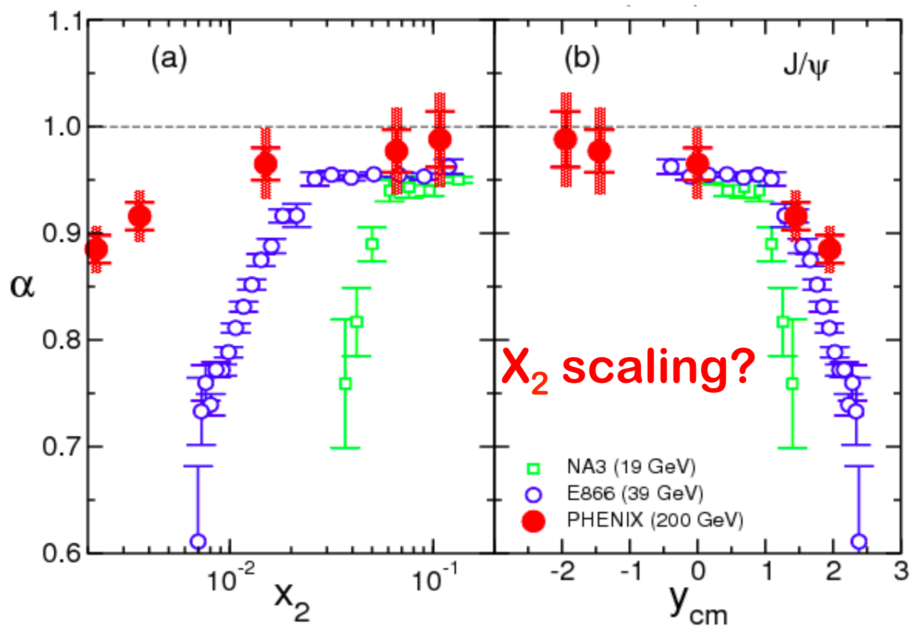
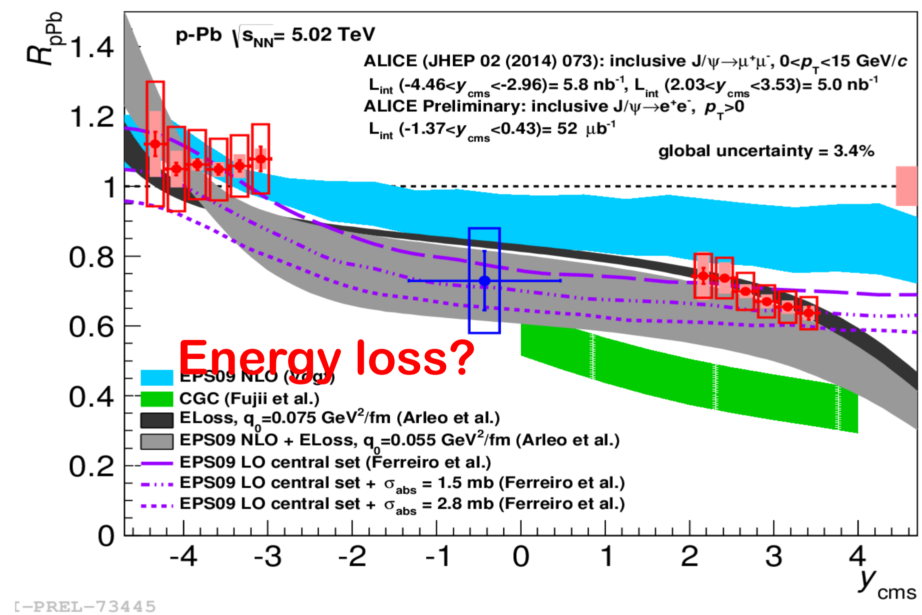
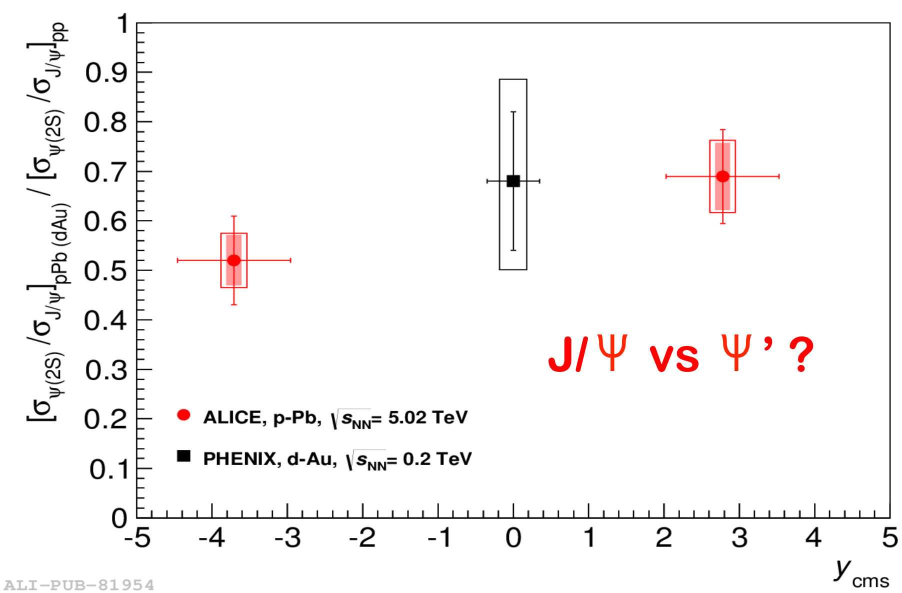
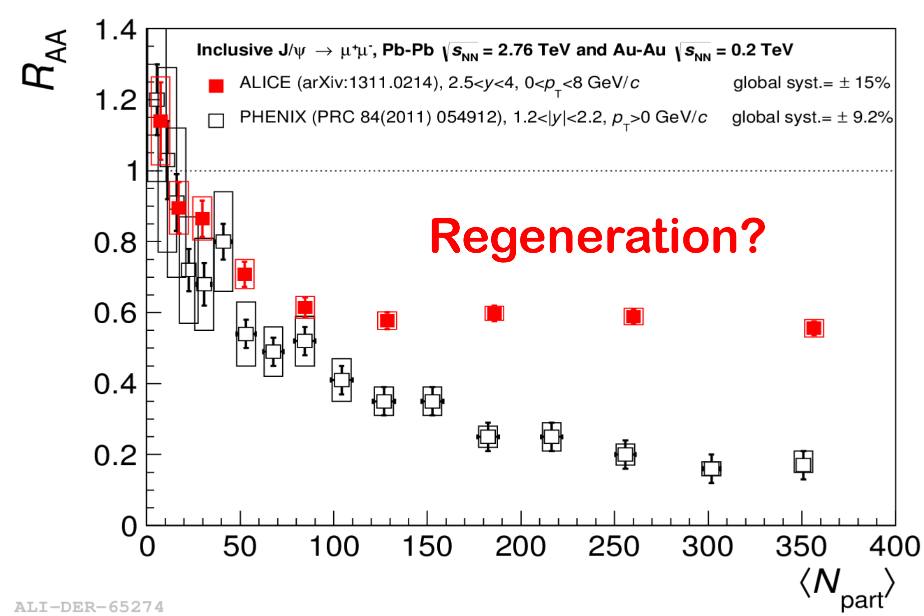




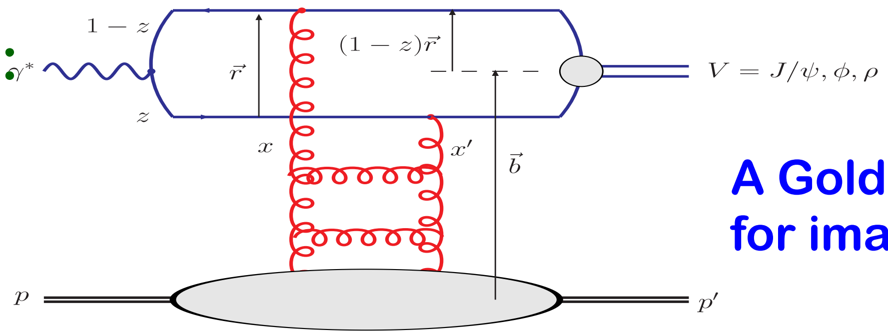




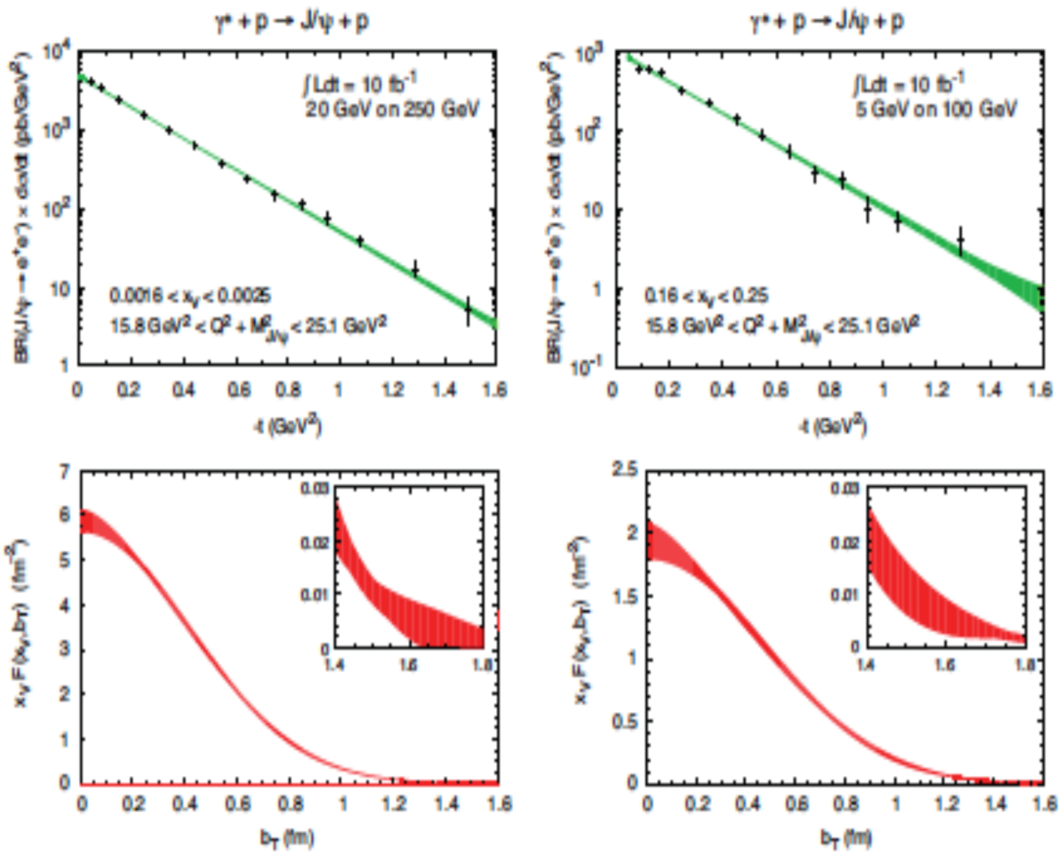
Critical role of J/ψ production at EIC

EIC WP, 1212.1701

- **Exclusive DIS:**



A Golden process for imagining gluon



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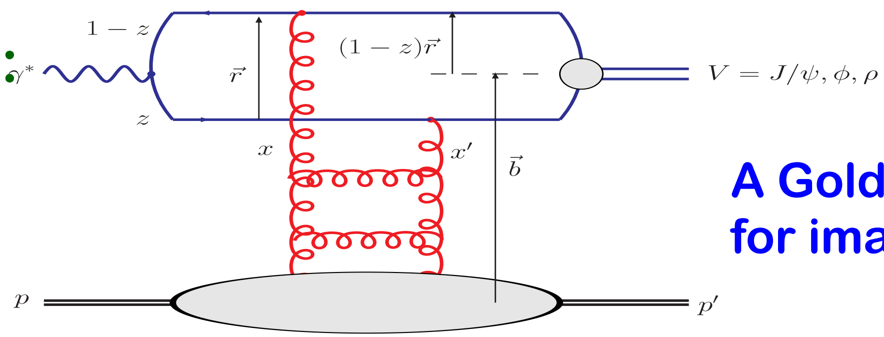
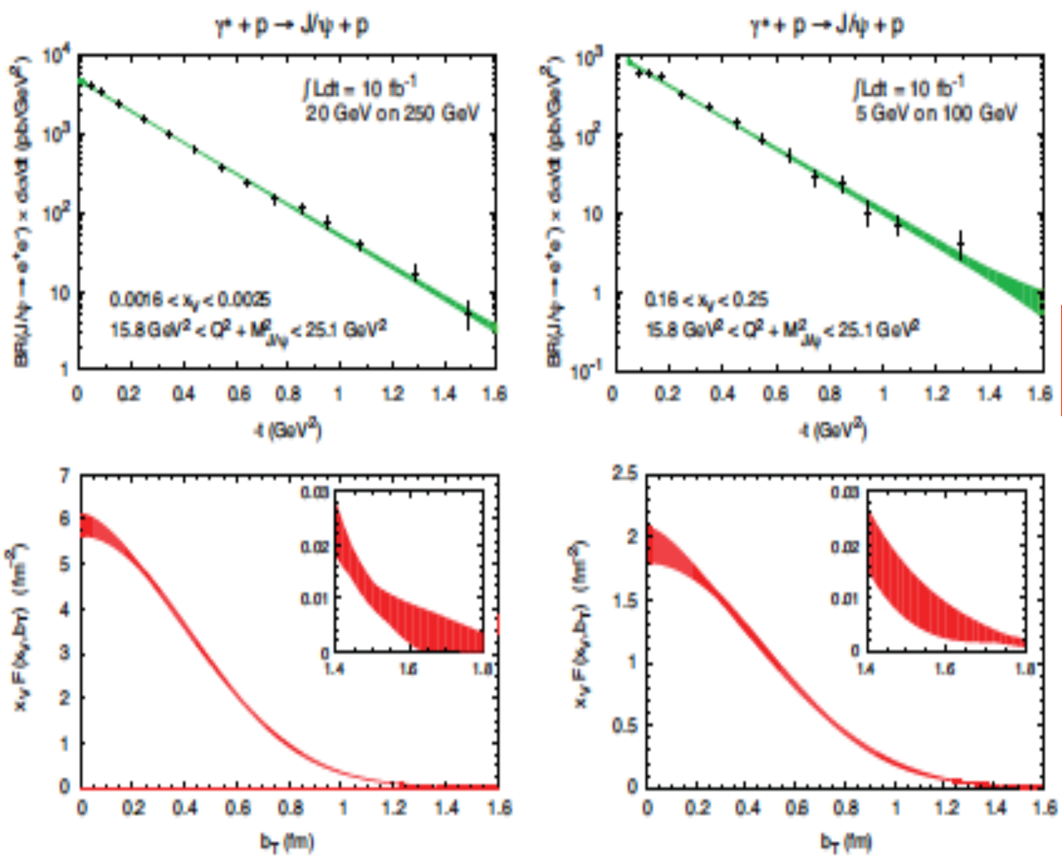


A Golden process
for imagining gluon

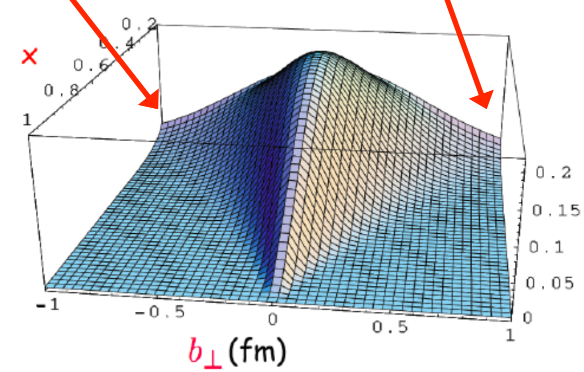


Allow us to ask "new"
fundamental questions:

Color confining radius?

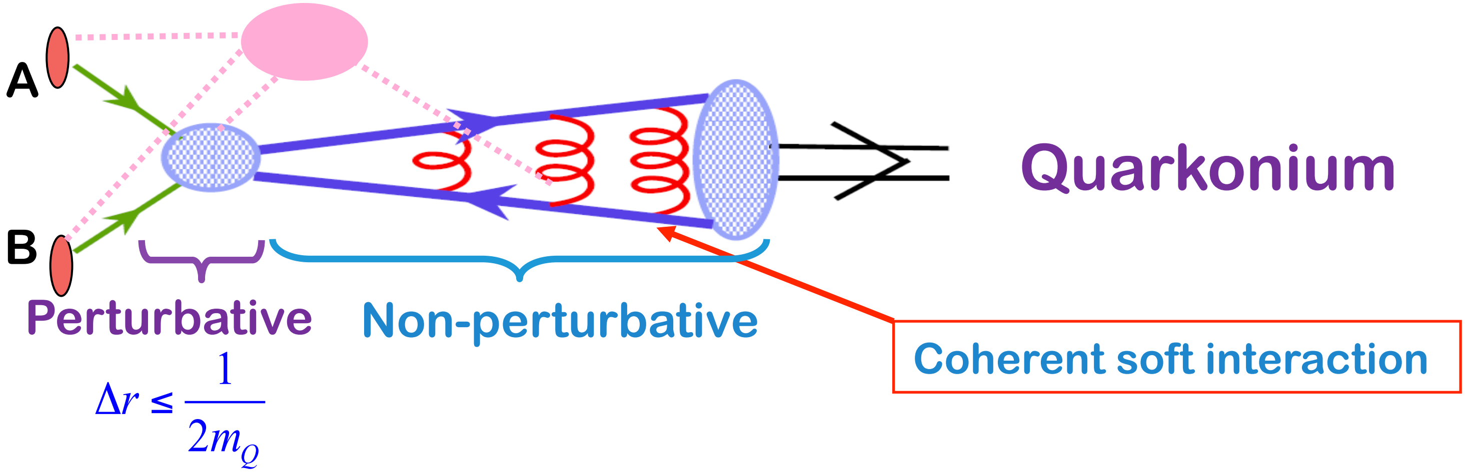
How far does glue density spread?

How fast does glue density fall?



Naive 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



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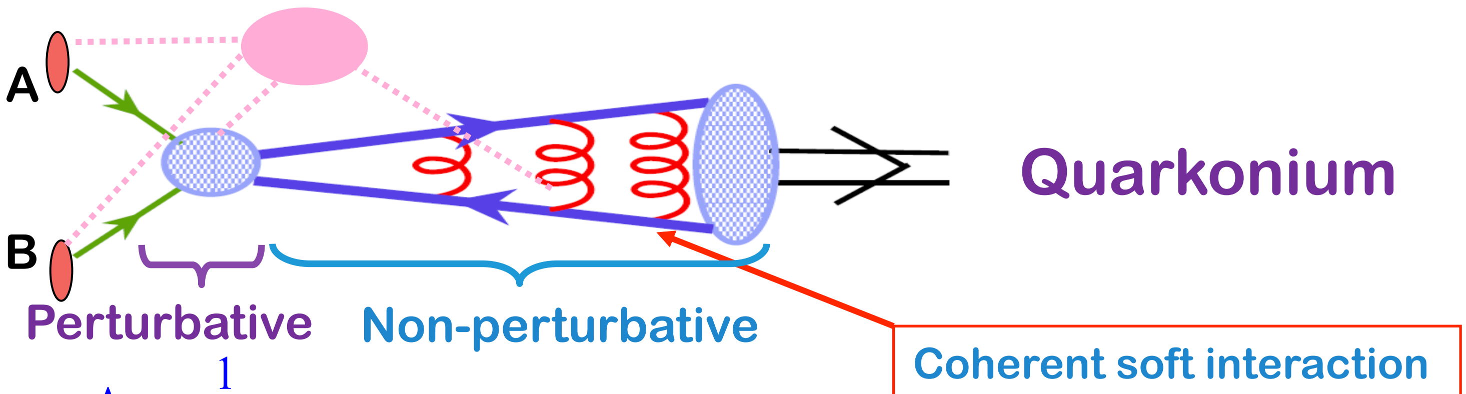
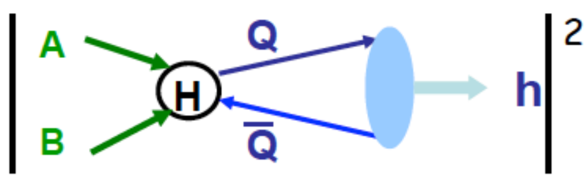


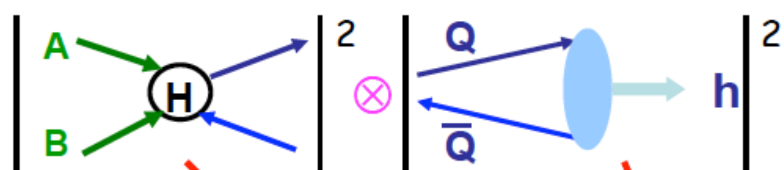
$$\Delta r \leq \frac{1}{2m_Q}$$

- Approximation:

$$\sigma_{AB\to h} \propto$$



$$\propto$$



$$+ \frac{\langle M_H^2 - 4m_Q^2 \rangle}{M_H^2}$$

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

Naive production mechanism

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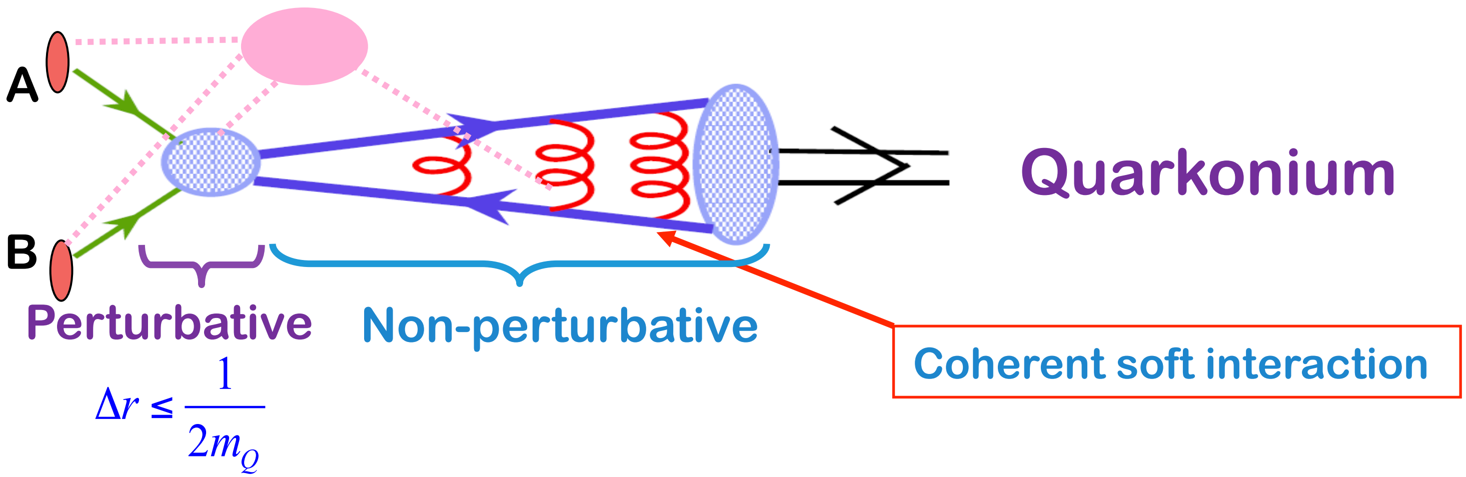


- Naïve factorization: on-shell pair production + hadronization

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

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

See Kniehl's talk

- **NRQCD factorization:**

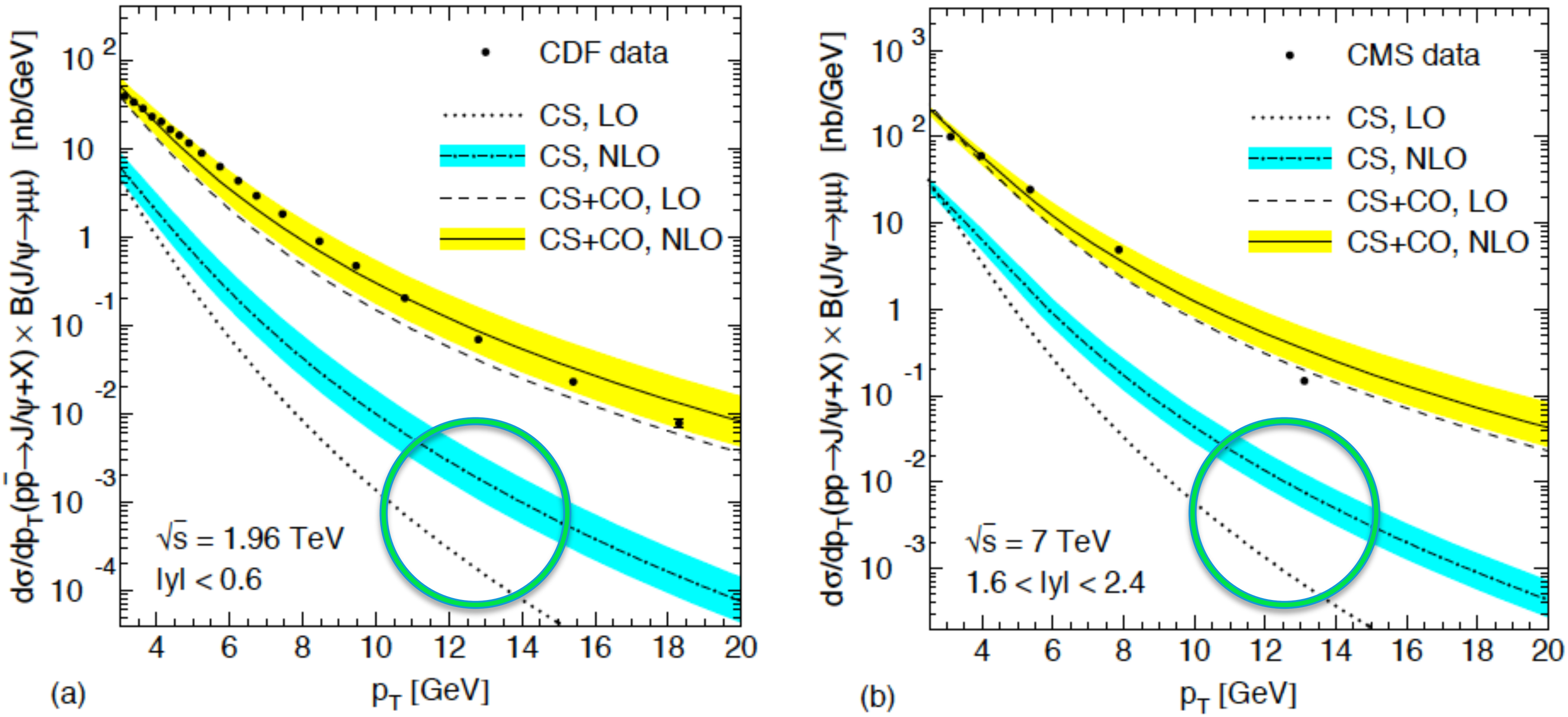
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \langle \mathcal{O}^H(n) \rangle$$

✧ **4 leading channels in v**

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

✧ **Full NLO in α_s**

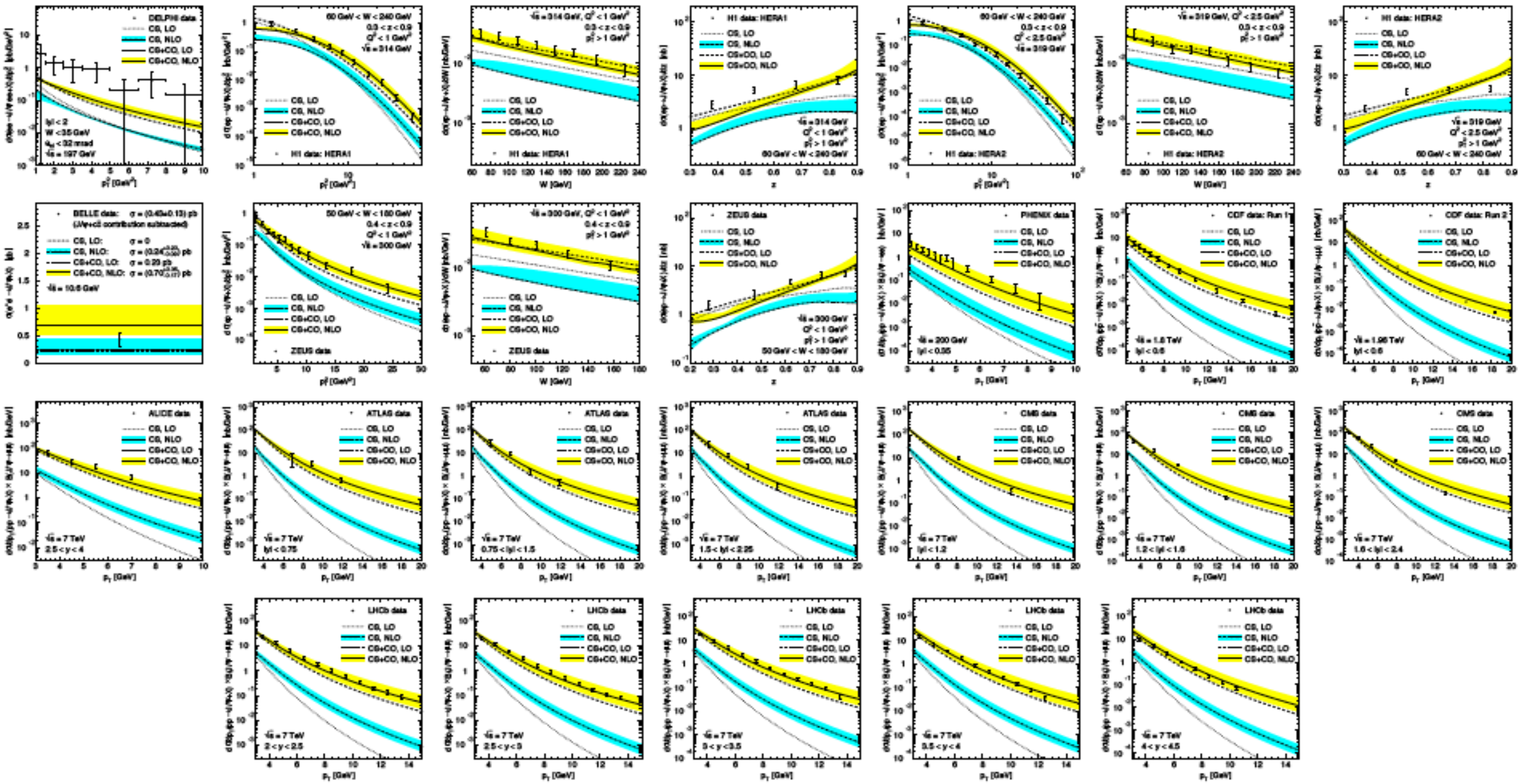
- **Phenomenology:**



- **Fine details – shape – high at large p_T?**

PRL 106, 022003 (2011)

NRQCD – global analysis



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

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

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

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

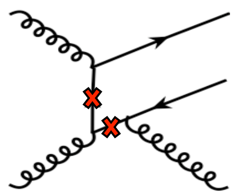
Butenschoen and Kniehl, arXiv: 1105.0820

Why high orders in CSM are so large?

Kang, Qiu and Sterman, 2011

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

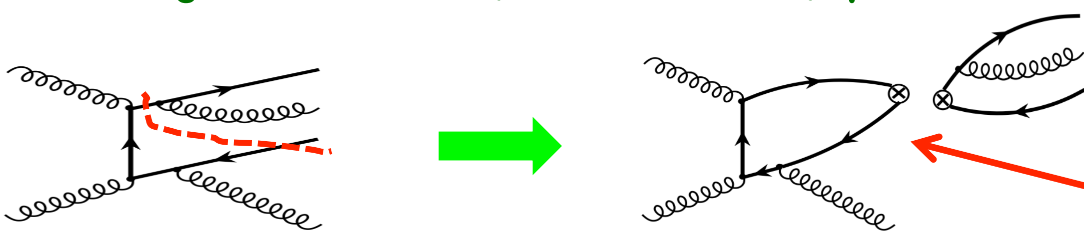
LO in α_s:



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

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

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

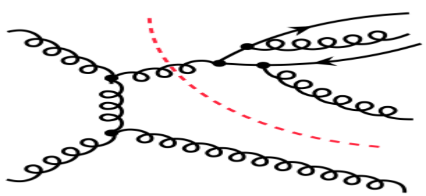


Relativistic projection to all "spin states"

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

$$\mu_0 \gtrsim 2m_Q$$

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



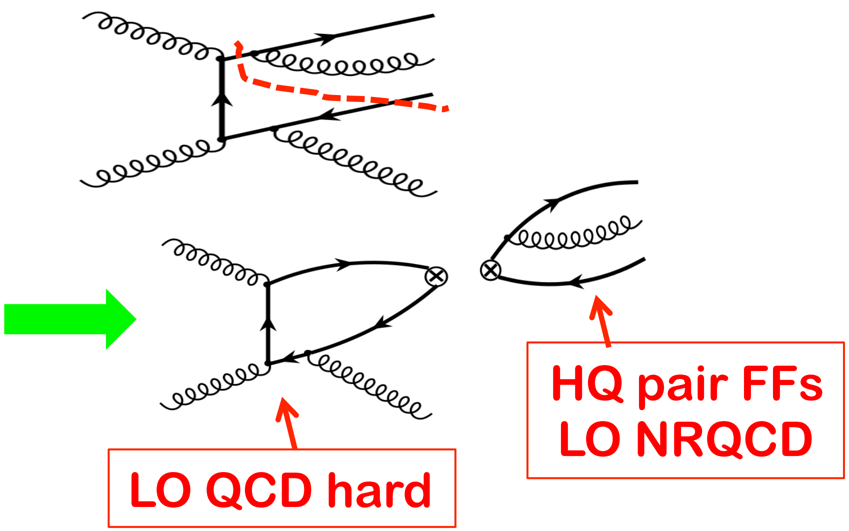
$$\hat{\sigma}^{\rm NNLP} \to \frac{\alpha_s^2(p_T)}{p_T^4} \otimes \alpha_s^3(\mu)\log^m(\mu^2/\mu_0^2)$$

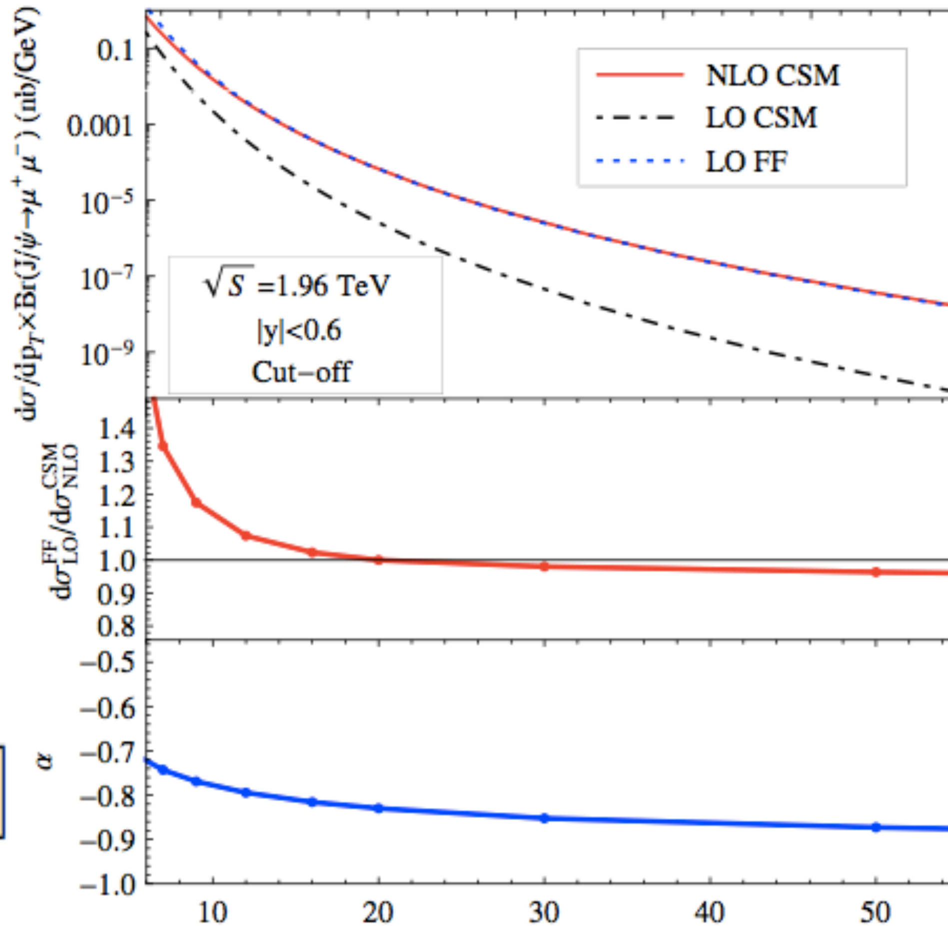
Leading order in α_s-expansion =\= leading power in $1/p_T$-expansion!

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!

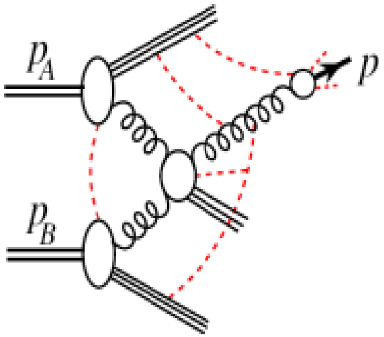
Cross section + polarization

QCD Factorization = better controlled HO corrections!

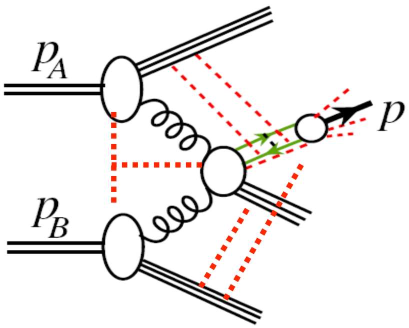
Factorization for heavy quarkonium production

Kang, Qiu and Sterman, 2009

- Factorized cross section ($P_T \gg M_c$):



$$E\frac{d\sigma_{AB\to J/\psi}}{d^3P} = \sum_{a,b,c}\phi_{a/A}\otimes\phi_{b/B}\otimes H^{(2)}_{ab\to c}\otimes D_{c\to J/\psi}$$
$$+\sum_{a,b}\phi_{a/A}\otimes\phi_{b/B}\otimes H^{(4)}_{ab\to Q\bar{Q}}\otimes \mathcal{D}^{(4)}_{Q\bar{Q}\to J/\psi}$$
$$+\sum_{a,b,c}\phi^{(4)}_{a/A}\otimes\phi_{b/B}\otimes H^{(4a)}_{ab\to c}\otimes D_{c\to J/\psi}$$
$$+\sum_{a,b,c}\phi_{a/A}\otimes\phi^{(4)}_{b/B}\otimes H^{(4b)}_{ab\to c}\otimes D_{c\to J/\psi}+\mathcal{O}\left(\frac{1}{P_T^4}\right)$$



- Expect the first two terms to dominate:
  - ✧ $H^{(4)}$ are IR safe and free of large logarithms
  - ✧ $D^{(4)}$ are fragmentation functions of 4-quark operators

Qiu, 1990

- New perturbative inputs:

  Calculation of $H^{(4)}$ and evolution of $D^{(4)}$

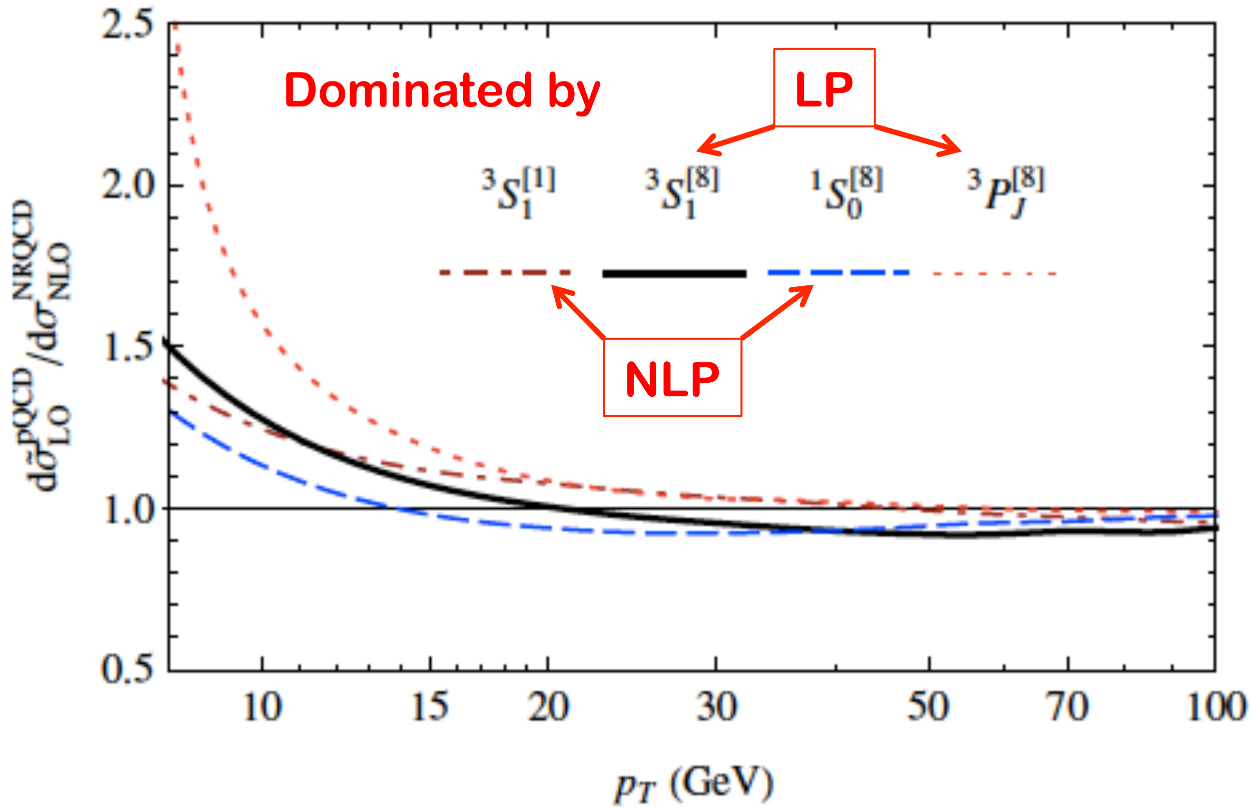
QCD factorization + NRQCD factorization

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

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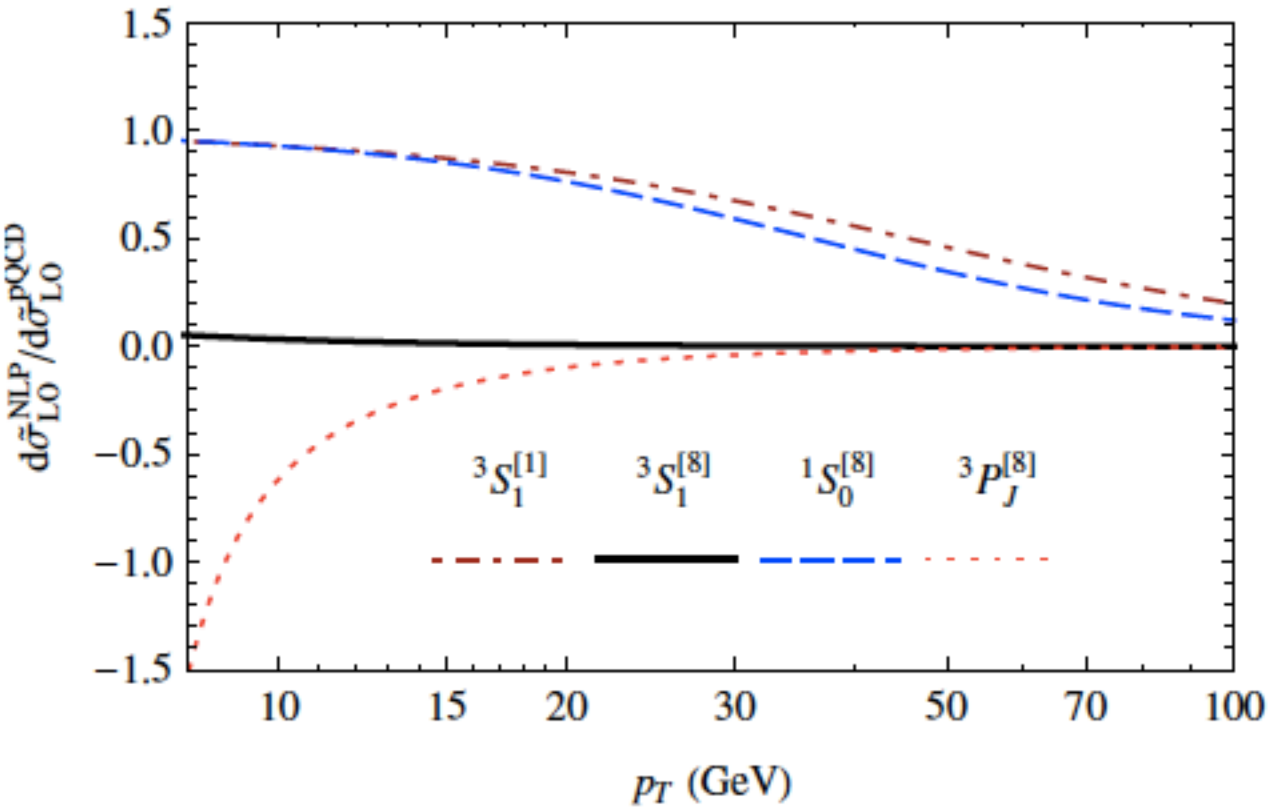
- LP vs. NLP (both LO):



NLP dominated

$^1S_0^{[8]}$

for wide pT

LP dominated

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

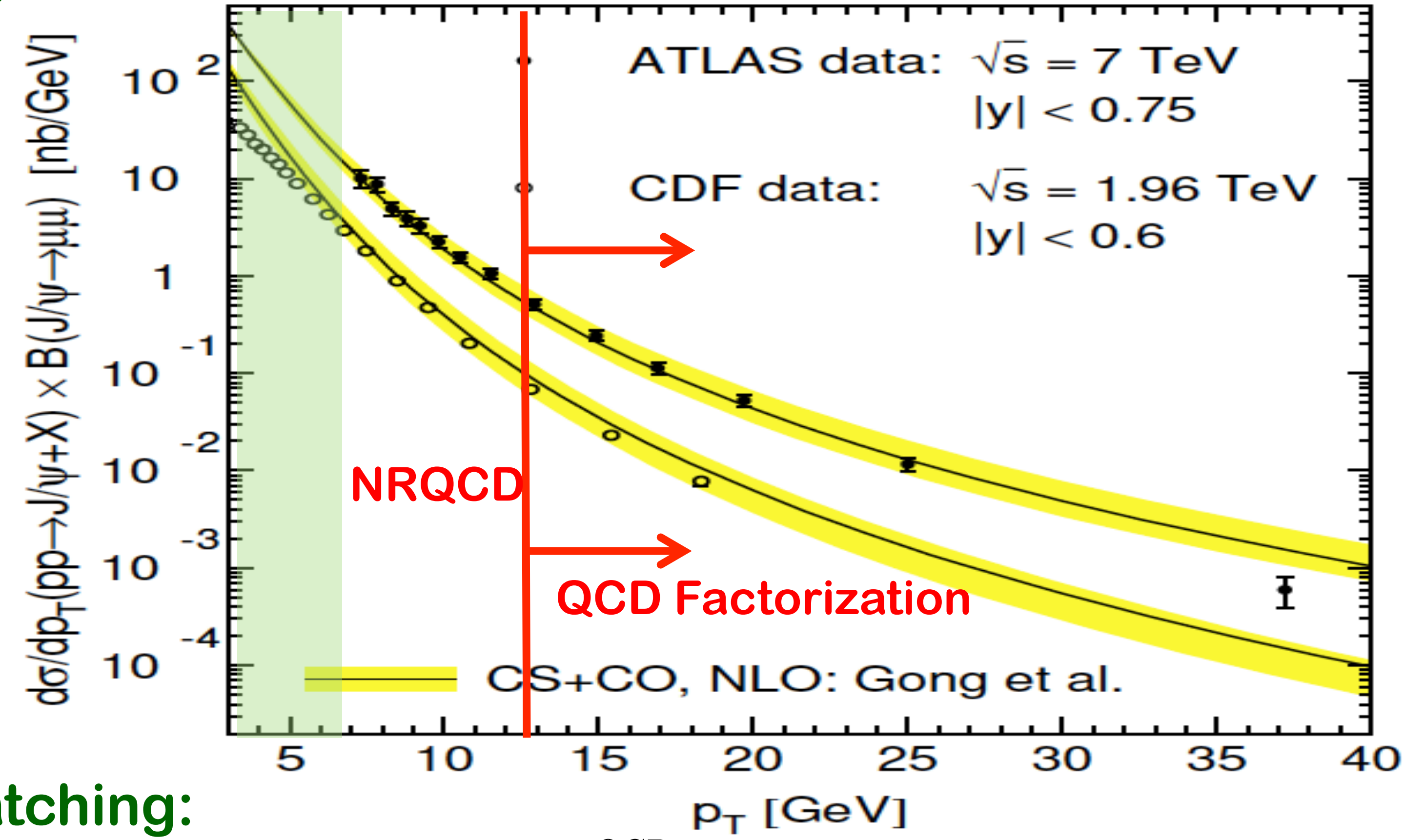
PT distribution is consistent with distribution of $^1S_0^{[8]}$

PRL, 2014

Matching between QCD and NRQCD

Kang, Ma, Qiu and Sterman, 2014

❑ Expectation:



❑ Matching:

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

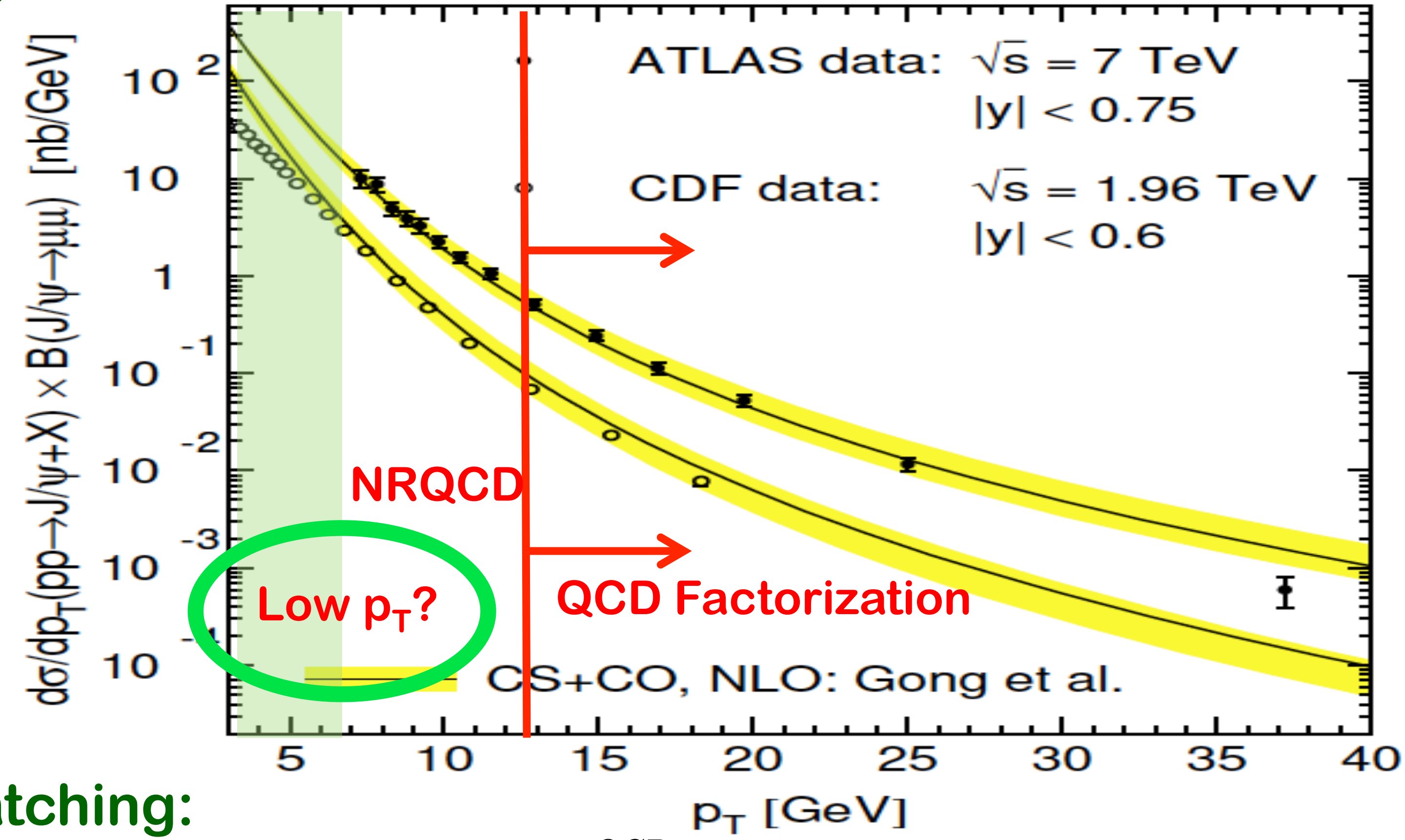
$$+ E_P \frac{d\sigma^{\text{NRQCD}}_{A+B\to H+X}}{d^3P}(P, m_Q \neq 0) - E_P \frac{d\sigma^{\text{QCD}-\text{Asym}}_{A+B\to H+X}}{d^3P}(P, m_Q = 0)$$

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

Matching between QCD and NRQCD

- **Expectation:**

Kang, Ma, Qiu and Sterman, 2014



- **Matching:**

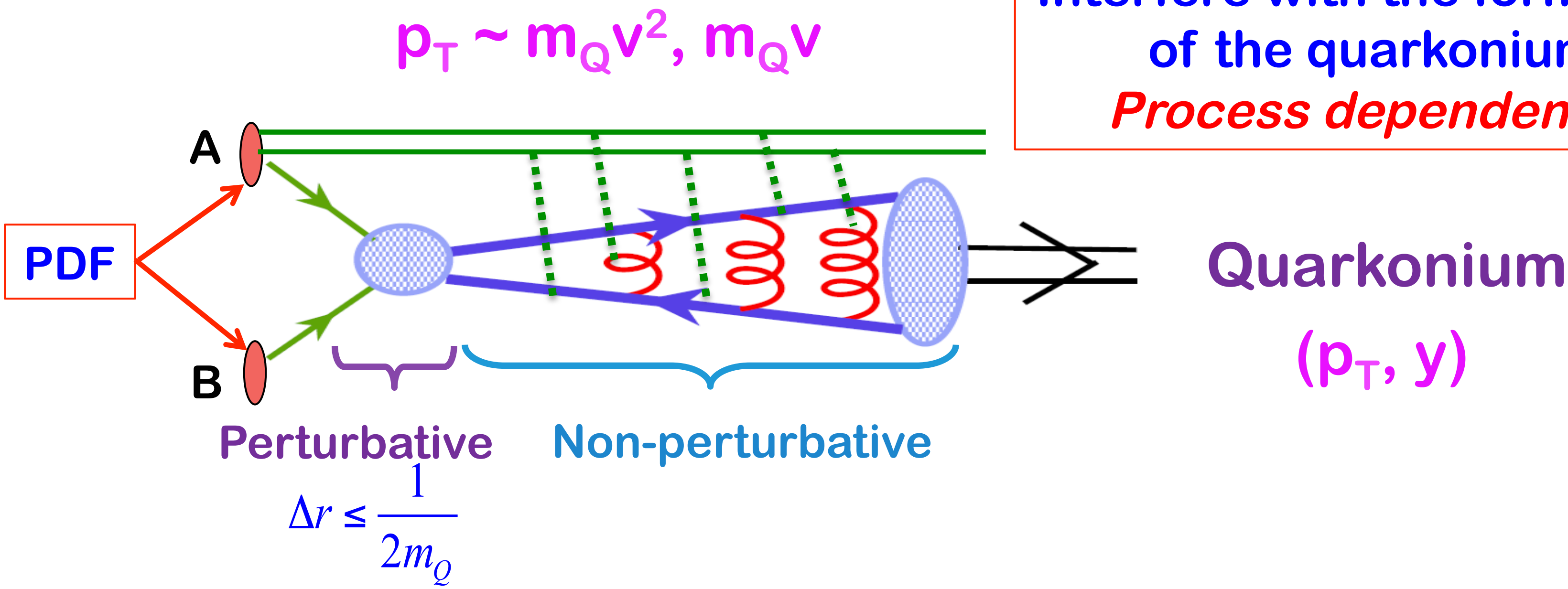
$$E_P \frac{d\sigma_{A+B\to H+X}}{d^3P}(P,m_Q) \equiv E_P \frac{d\sigma^{\rm QCD}_{A+B\to H+X}}{d^3P}(P,m_Q=0)$$

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

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:

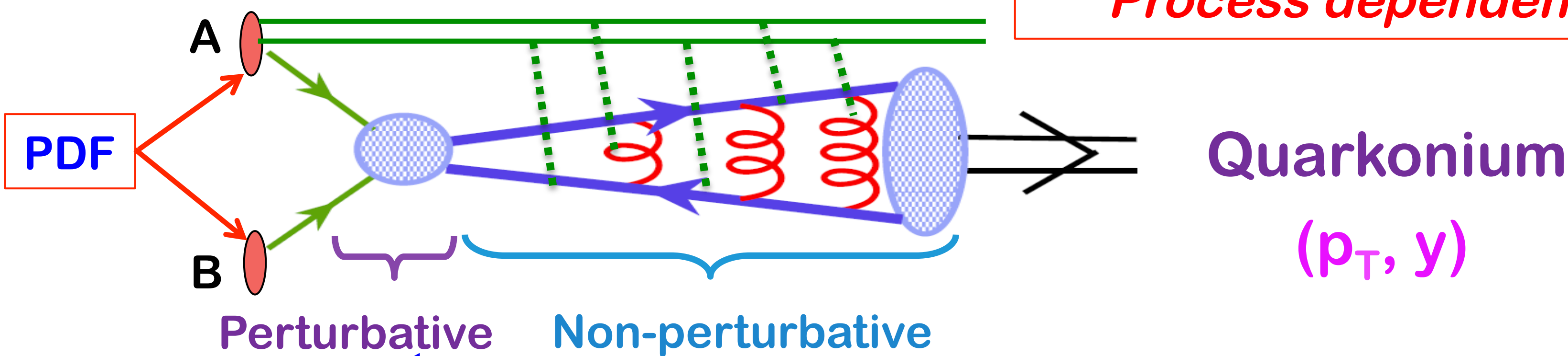
Break factorization – Process dependence – Alter p_T distribution, …

Production at low p_T (< M_Q)

- Spectator interaction – always there:

$p_T \sim m_Q v^2, m_Q v$

Interfere with the formation of the quarkonium
Process dependence



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

- The Challenge:

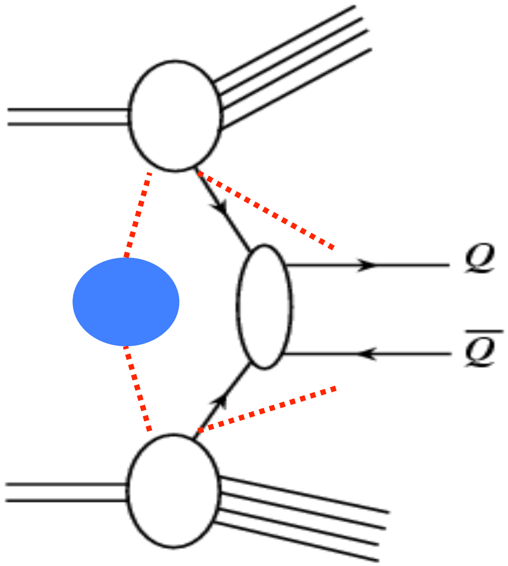
  Break factorization – Process dependence – Alter p_T distribution, …

- What if the gluon shower is so strong, playing the dominant role in determining the observed p_T spectrum when $p_T < m_Q$?

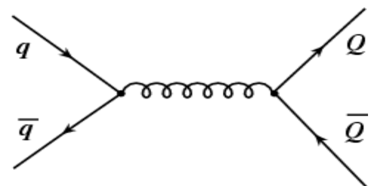
  Still have predictive power, if the breaking effect is not strong enough!

Production at low p_T (< M_Q)

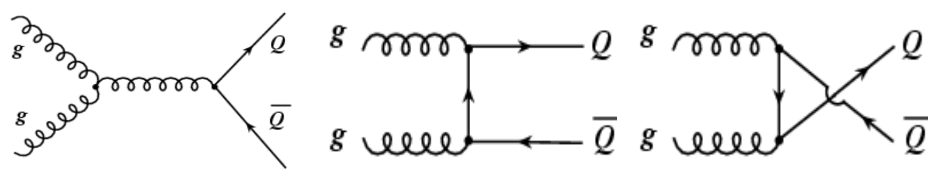
- Gluon shower – Sudakov resummation dominated?



✧ 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:

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

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

Upsilon production at hadron colliders

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

Use Drell-Yan as an example:

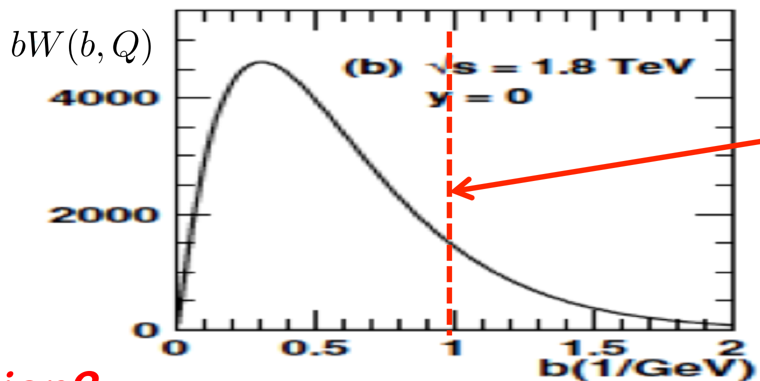
$$\frac{d\sigma^{DY}_{AB}}{dQ^2 dq_T^2}(Q,q_T,x_A,x_B) = \hat{H}_{f\bar{f}}(Q) \otimes \Phi_{f/A}(x_A,k_{a\perp}) \otimes \Phi_{\bar{f}/B}(x_B,k_{b\perp}) \otimes \mathcal{S}(k_{s\perp}) + Y(Q,q_T)$$

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

The b-space distribution:

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

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:

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

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

Upsilon production at hadron colliders

- **Expect good predictive power:**

  Peak of p_T-distribution is around 4 GeV
  >> intrinsic p_T
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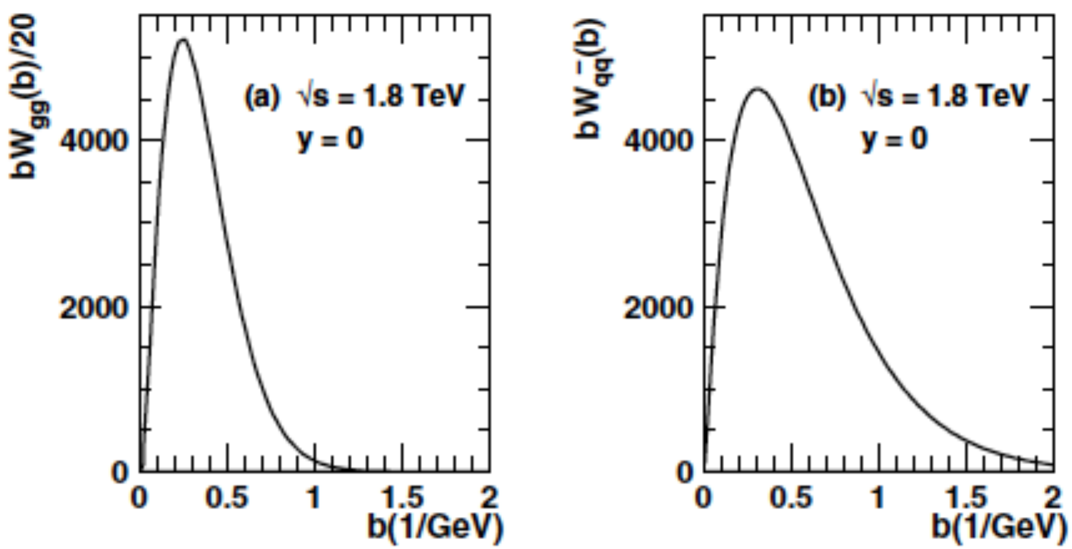
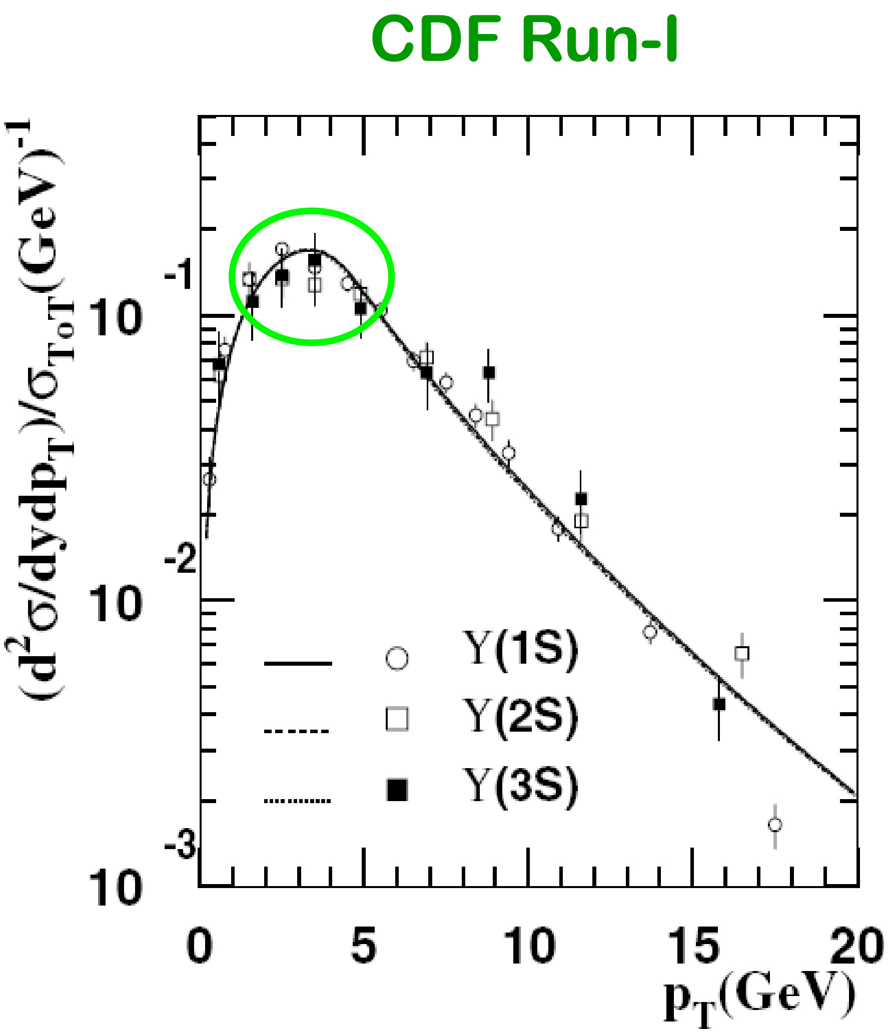
$$F_{ij}^{NP}=\exp\left\{-\ln\left(\frac{Q^2b_{max}^2}{c^2}\right)\{g_1[(b^2)^\alpha-(b_{max}^2)^\alpha]+g_2(b^2-b_{max}^2)\}-\bar{g}_2(b^2-b_{max}^2)\right\}$$

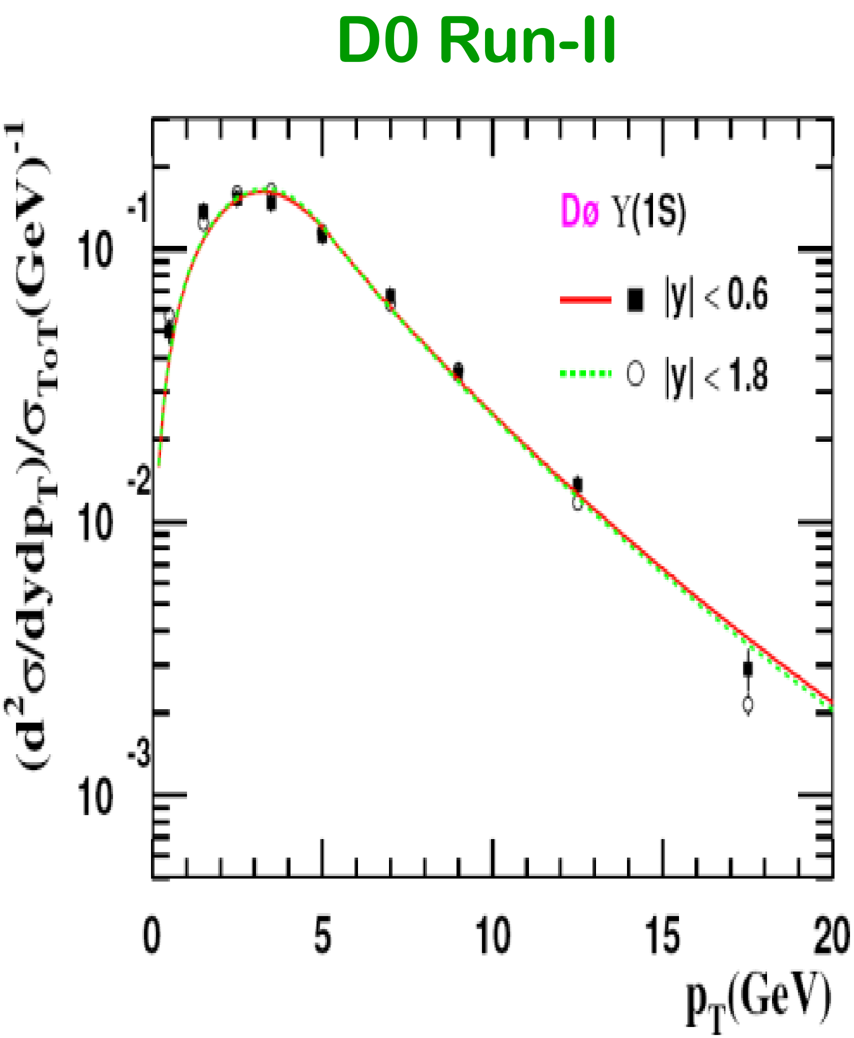
- **b-space distribution for Upsion production at Tevatron energy:**

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



Upsilon production at hadron colliders





- ❑ **Strong gluon shower:**

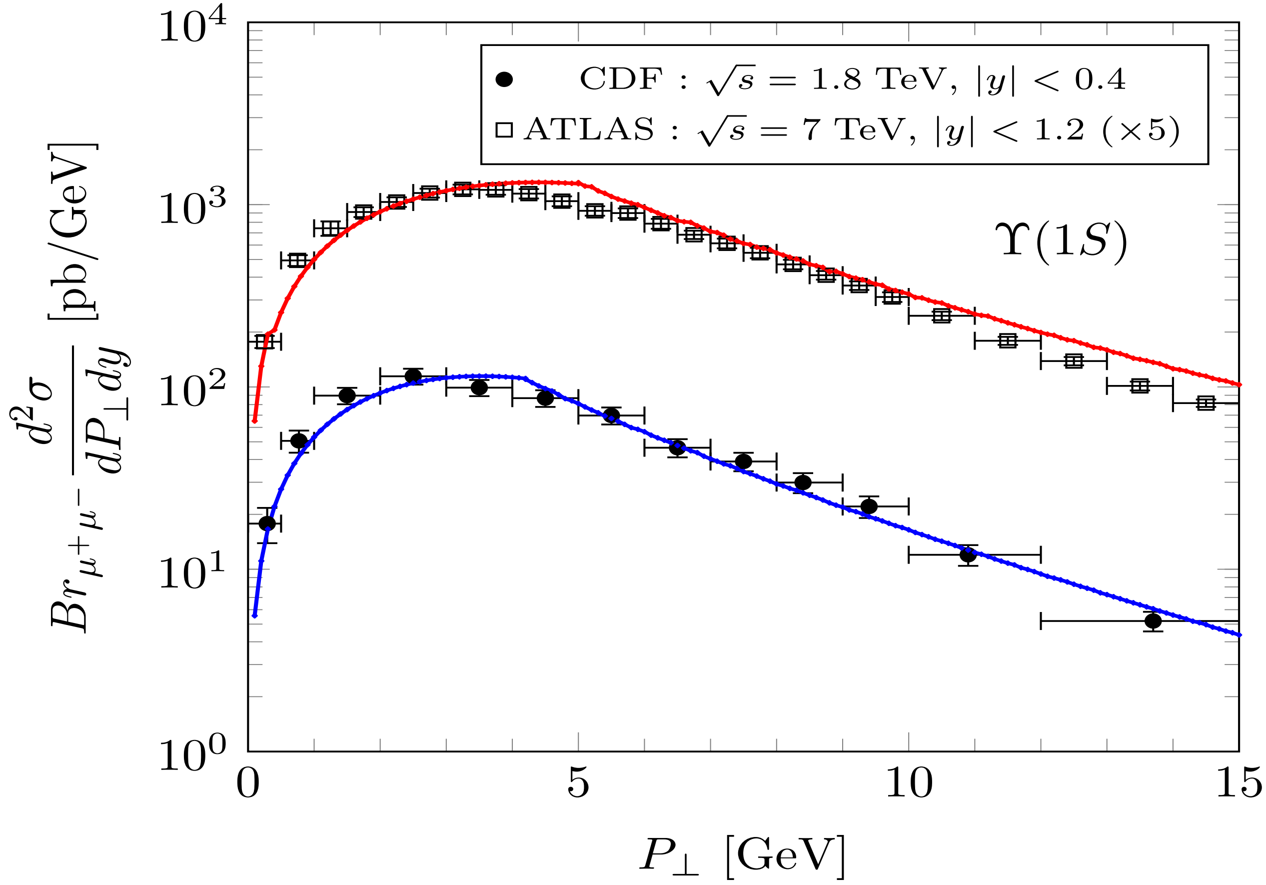
Berger, Qiu, Wang, 2005

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

Predictive power – Upsilon

Qiu, Watanabe, 2017

❑ Upsilon at the LHC:

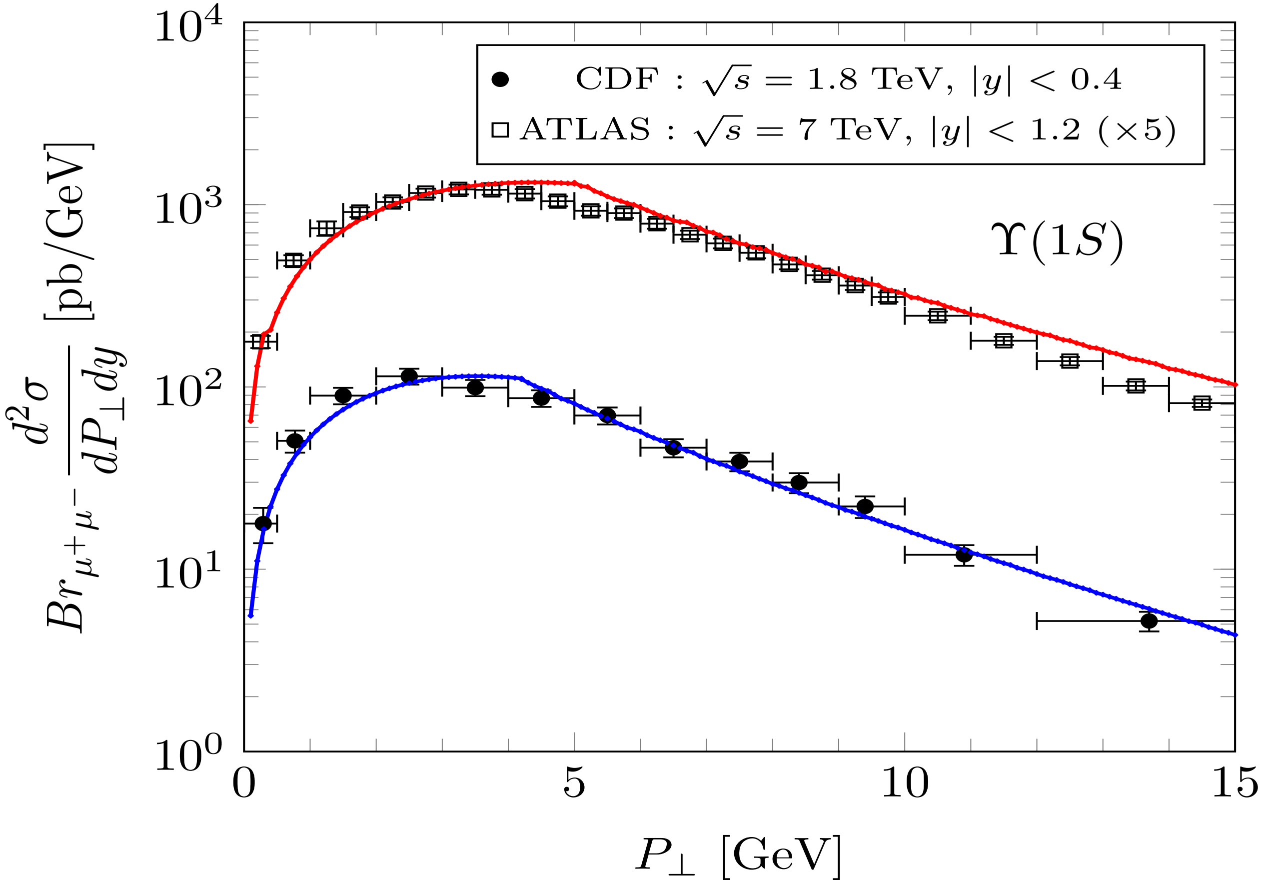


No adjustment on any parameter from Tevatron to the LHC!

Predictive power – Upsilon

Qiu, Watanabe, 2017

❑ **Upsilon at the LHC:**



No adjustment on any parameter from Tevatron to the LHC!

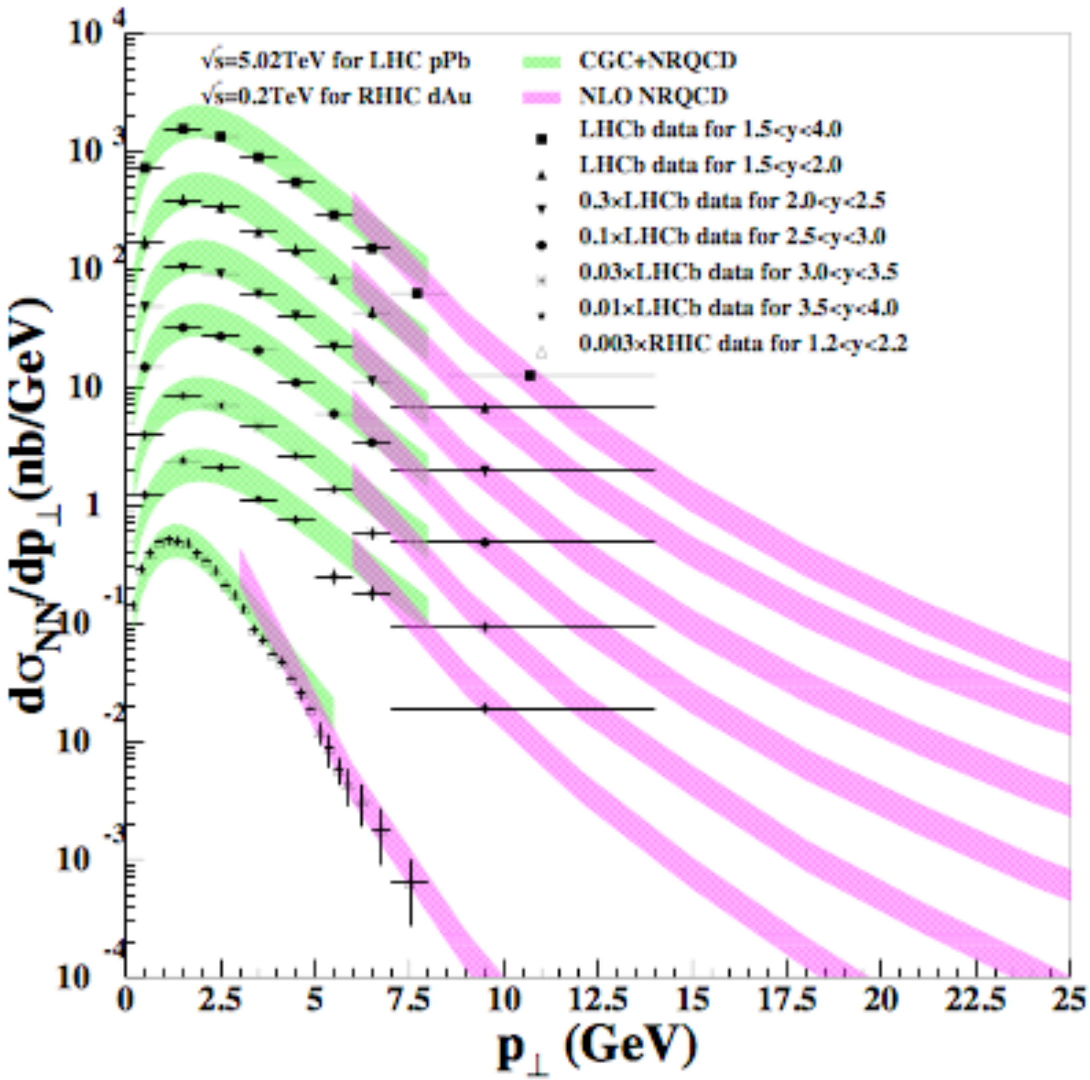
BUT: this does not apply for J/ψ at low PT,

logarithmic contribution from the shower is not strong enough!

Forward quarkonium production in p(d)+A

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

❑ CGC for low p_T region:



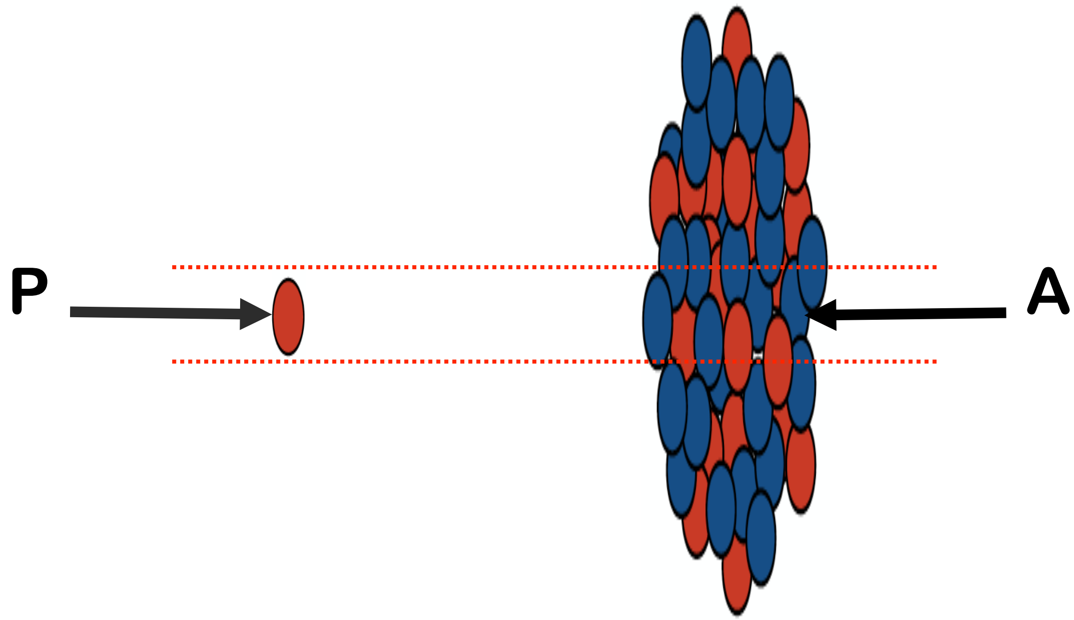
✧ Two free fitted parameters:
  transverse overlap area,
  saturation scale at initial rapidities
seem reasonable

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

✧ Better agreement with data than previous CGC calculations

Production in p(d)+A collisions

❑ Proton (deuteron) – Nucleus Collisions:



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

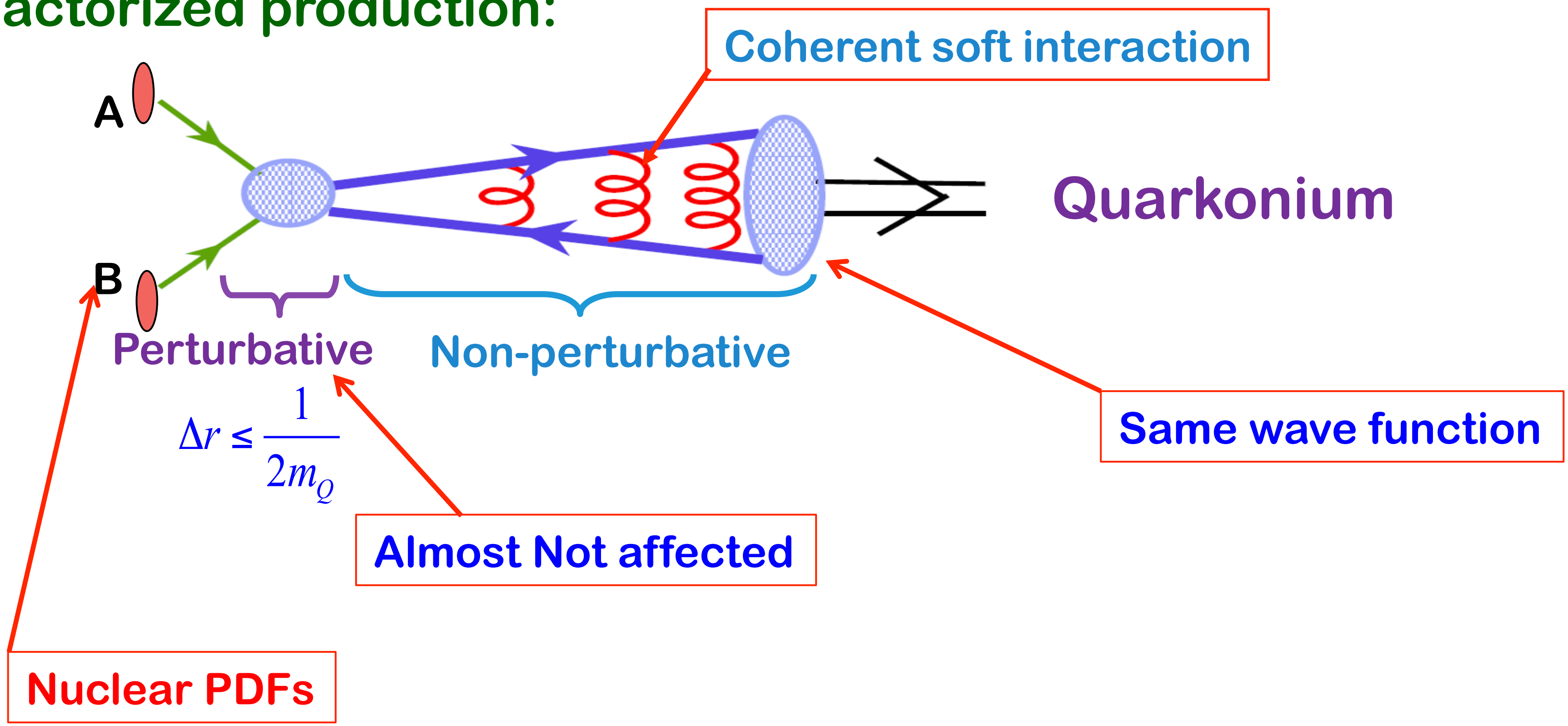
✧ Nuclei as potential filters of production mechanisms

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

Nucleus is not a simple superposition of nucleons!

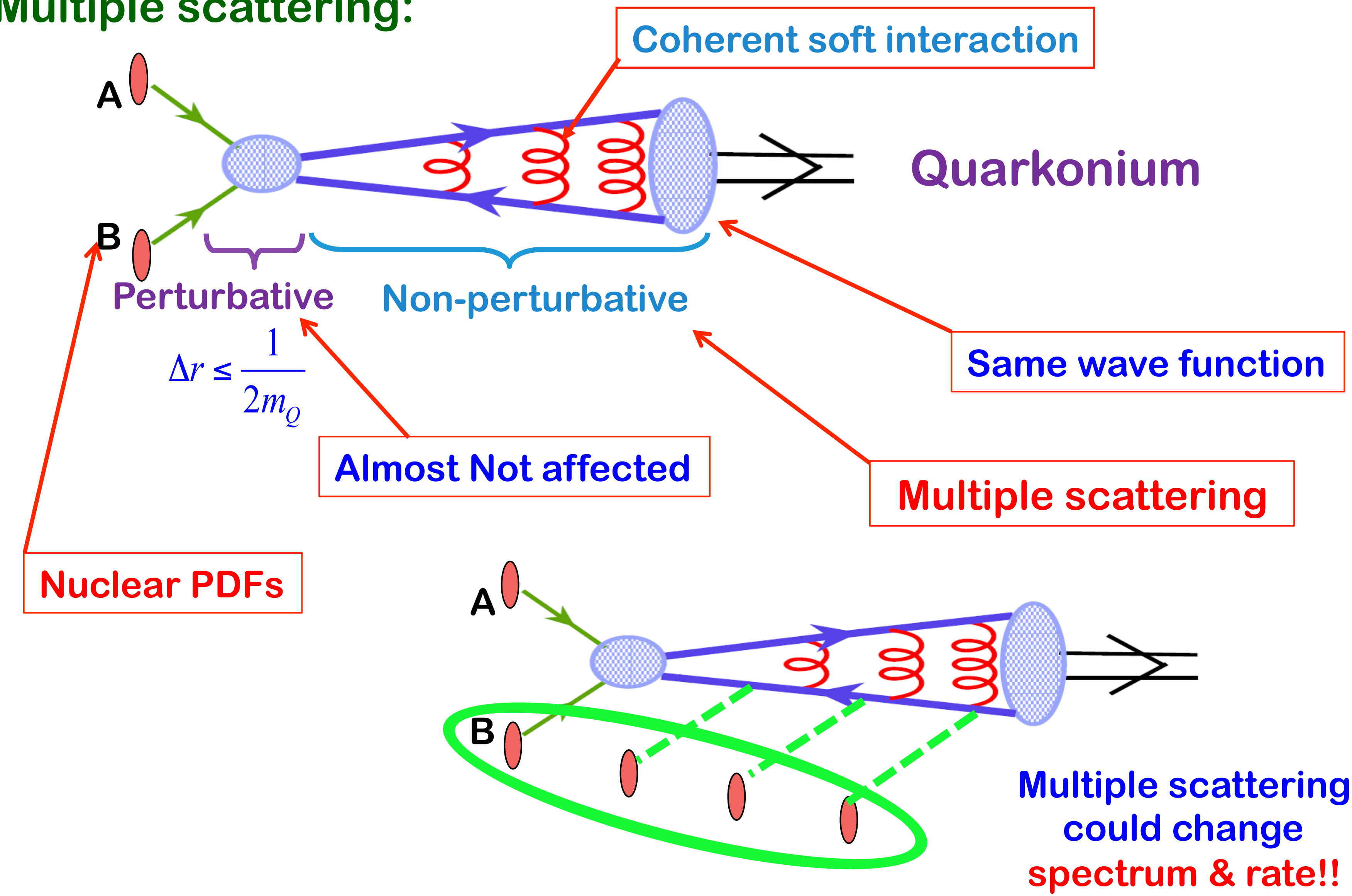
Production in p(d)+A collisions

- Factorized production:



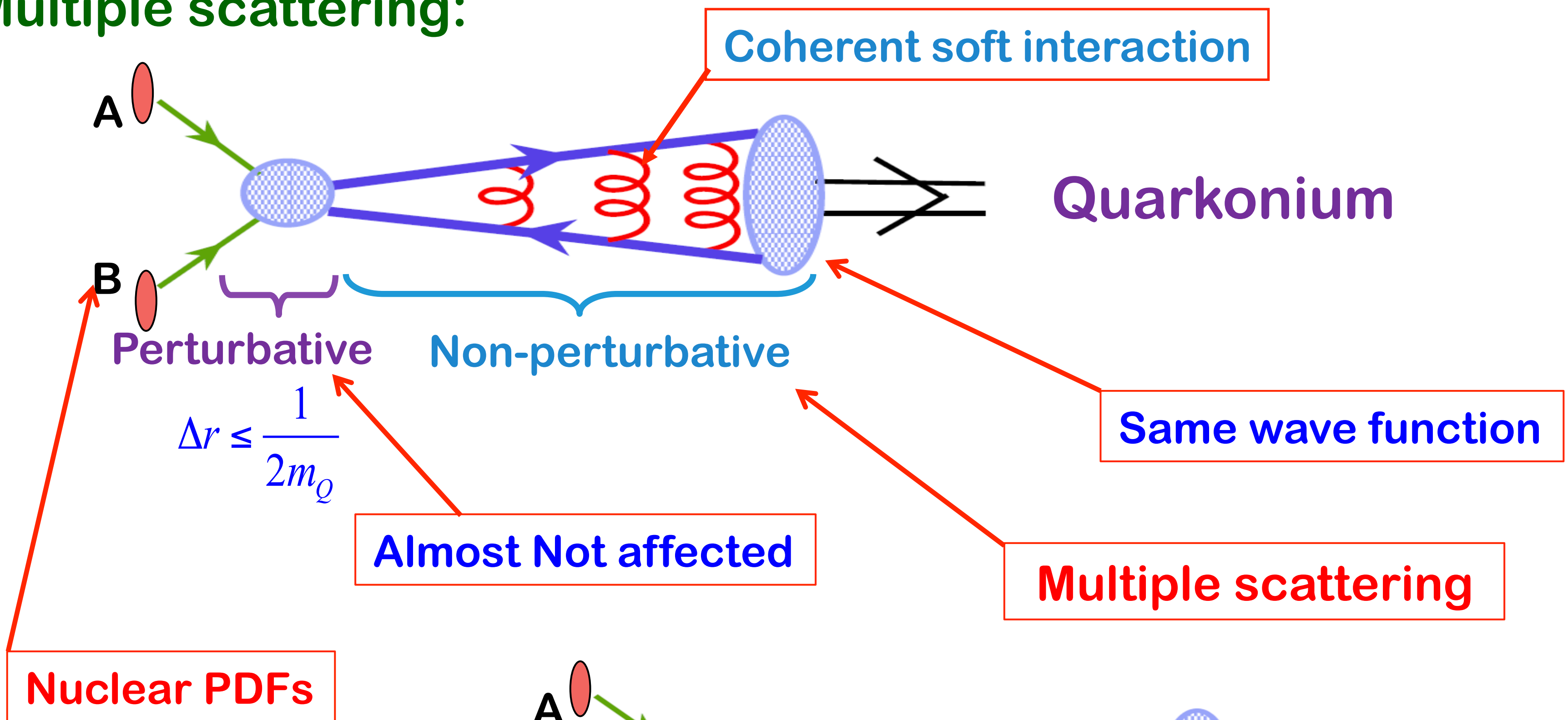
Production in p(d)+A collisions

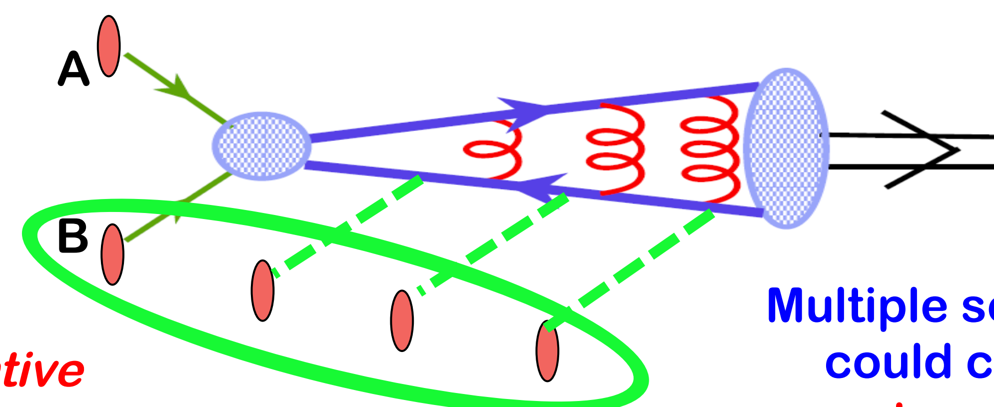
- Multiple scattering:



Production in p(d)+A collisions

- Multiple scattering:





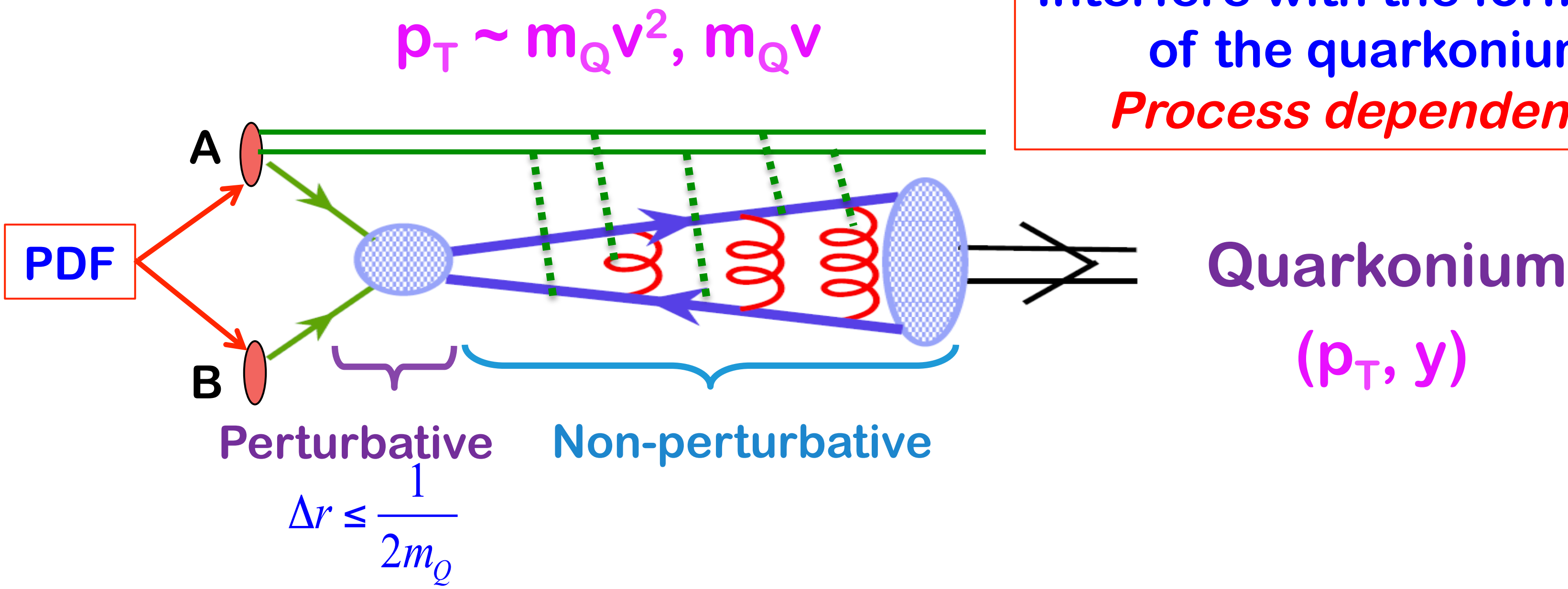
Can multiple scattering interfere with nonperturbative formation of quarkonia?

Multiple scattering could change spectrum & rate!!

Production at low p_T (< M_Q)

- Spectator interaction – always there:

Interfere with the formation of the quarkonium
Process dependence



- The Challenge:

Process dependence – Break of factorization – No predictive power

- The need:

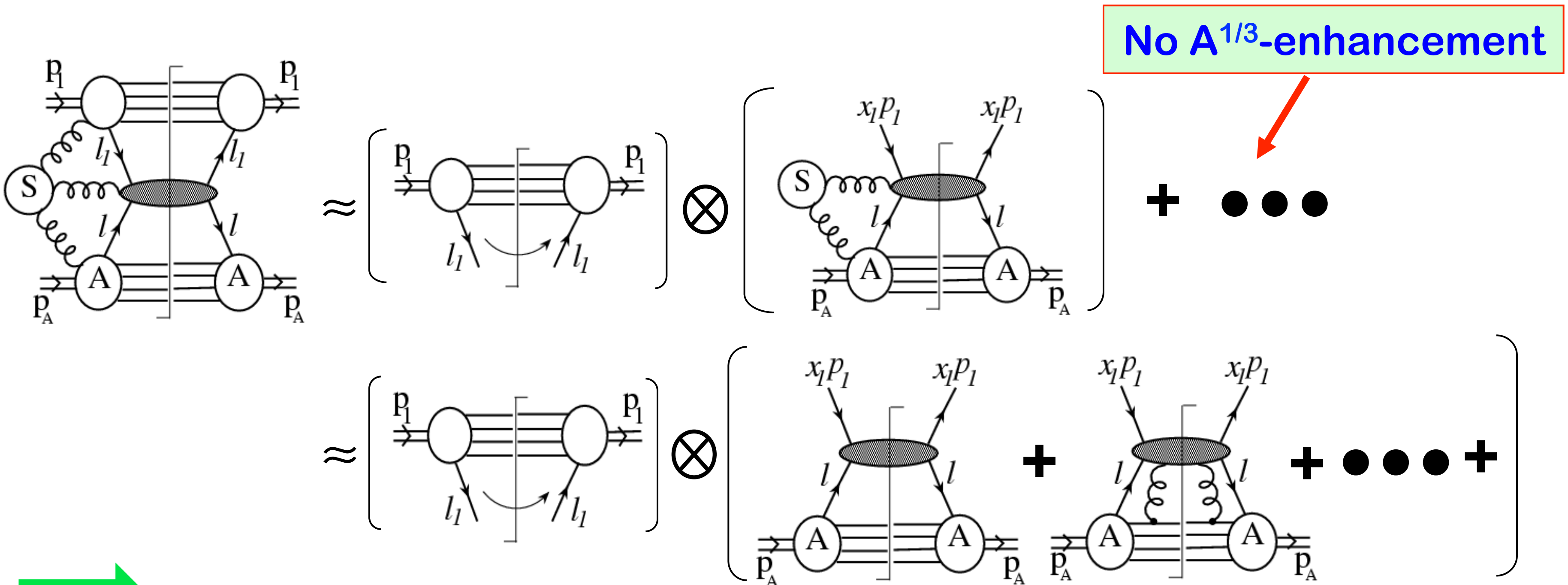
Controllable calculation of medium effect, extract medium properties, …

- The Opportunities:

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

Breaking of factorization in hadronic collisions

❑ A-enhanced power corrections, $A^{1/3}/Q^2$, may be factorizable:



✧ Total x-section: Factorization argument similar to DIS

Collinear power expansion – single scale

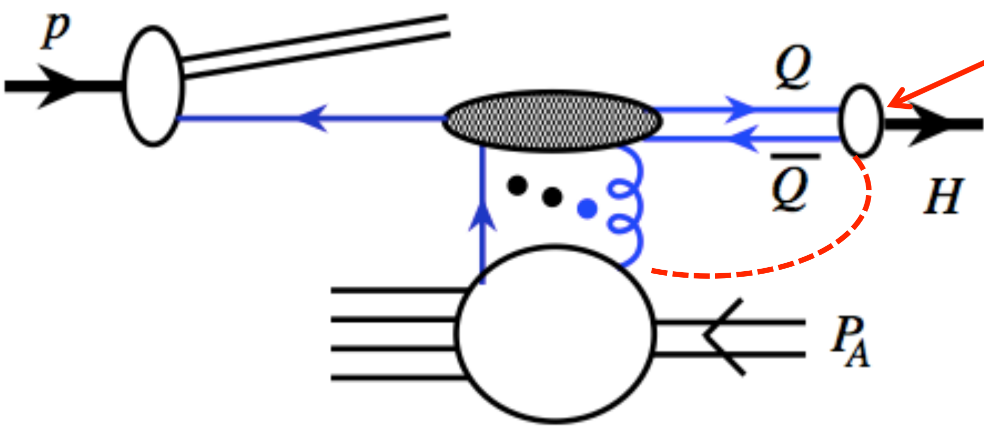
✧ P_T spectrum: Factorization argument similar to SIDIS

TMD or collinear – low P_T to high P_T

Production with multiple scattering

Brodsky and Mueller, PLB 1988

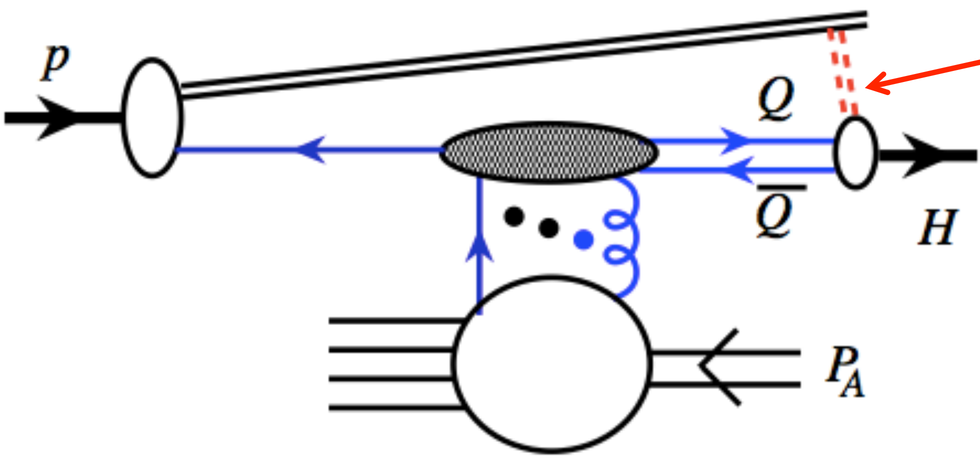
- ❑ *Backward* production in p(d)+A collisions:



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:



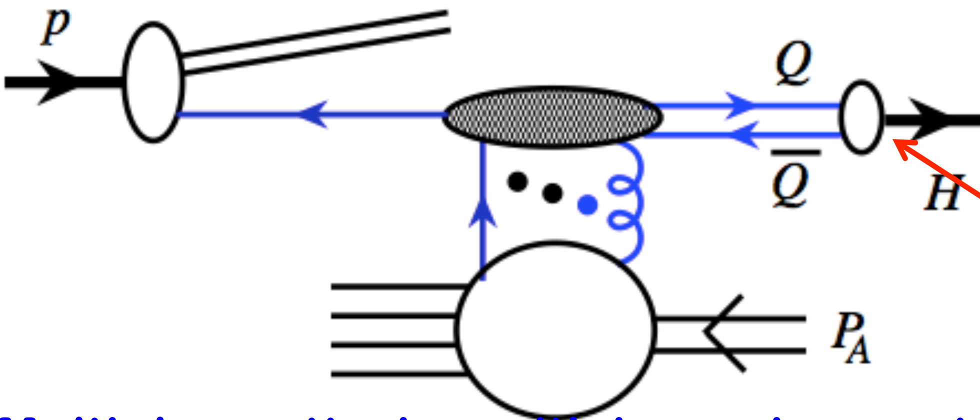
Co-mover interaction

to interfere with quarkonium formation - Break of factorization!!

Production with multiple scattering

Brodsky and Mueller, PLB 1988

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



✧ Time dilation

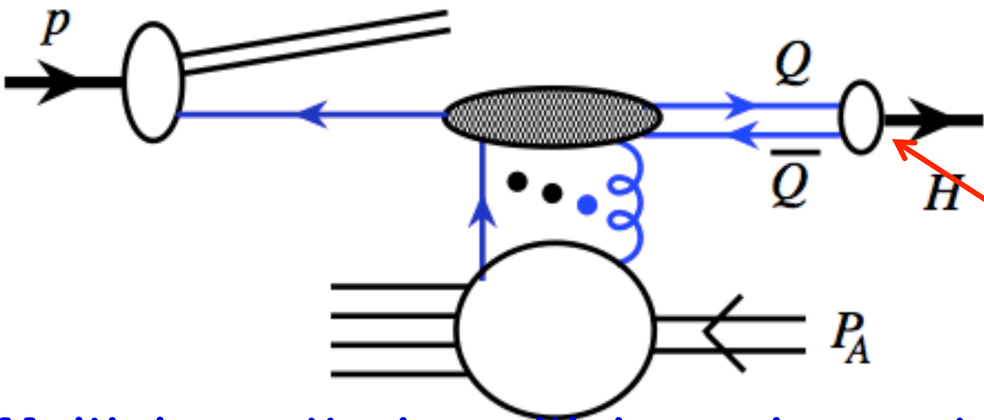
Non-perturbative formation of J/Ψ is far outside of nucleus

✧ Multiple scattering with incoming parton & heavy quarks, not J/Ψ

Production with multiple scattering

Brodsky and Mueller, PLB 1988

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

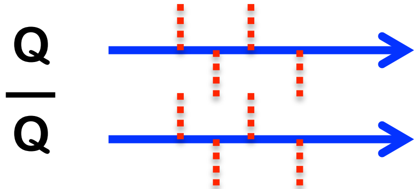


✧ Time dilation

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

✧ Multiple scattering with incoming parton & 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"

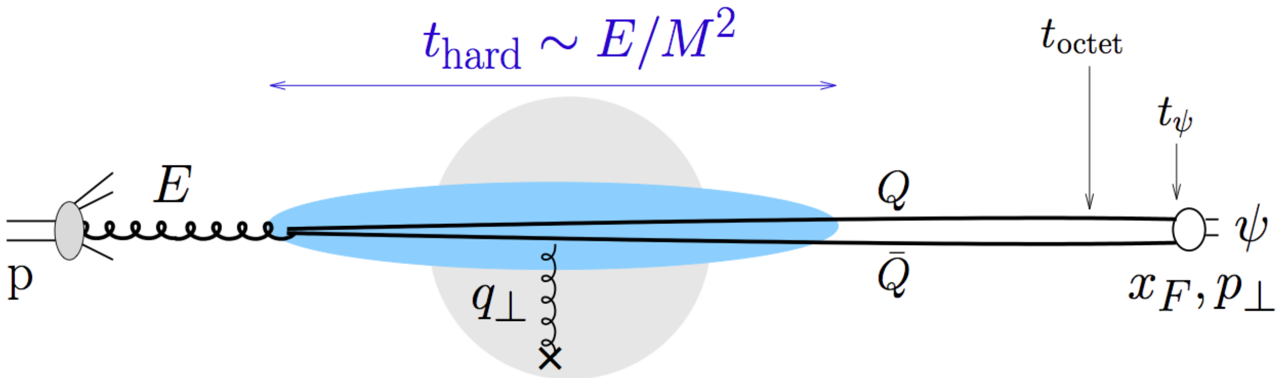
➡ Momentum imbalance – larger invariant mass

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

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

❑ Picture + assumptions:

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



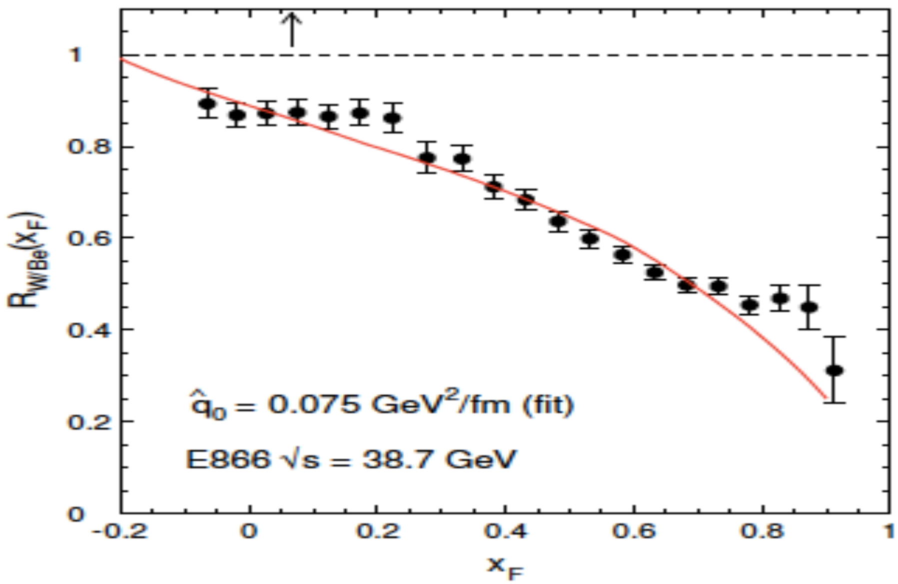
- Color neutralization happens on long time scales: $t_{\mathrm{octet}} \gg t_{\mathrm{hard}}$
- Medium rescatterings do not resolve the octet $c\bar{c}$ pair
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion

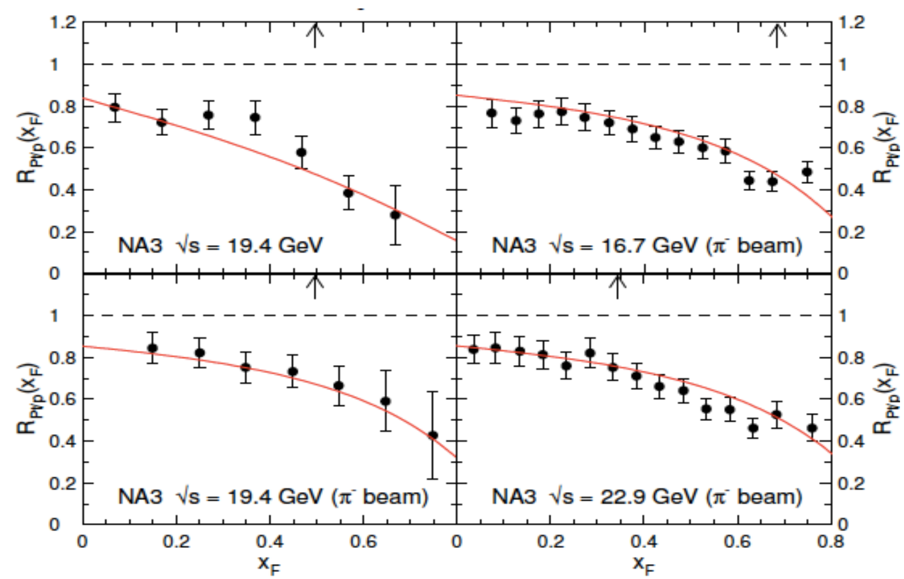
❑ Model energy loss:

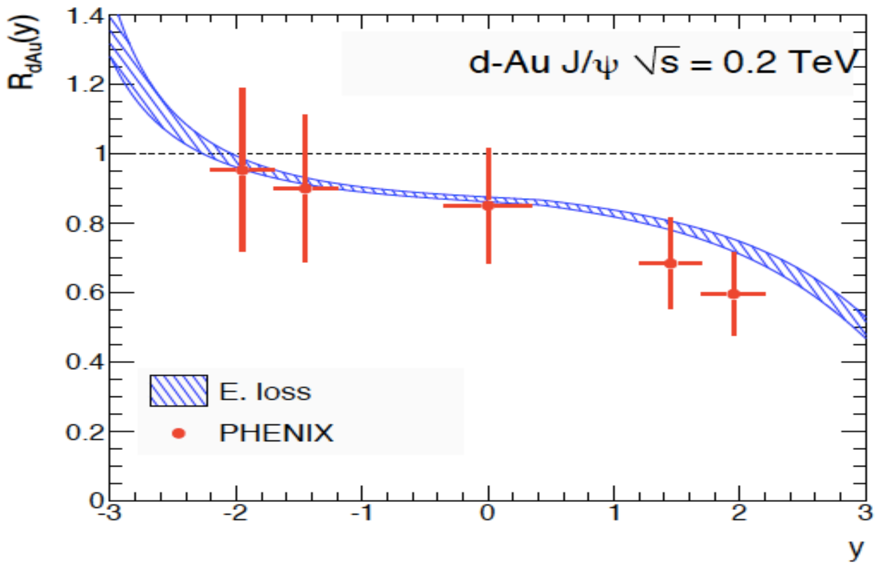
$$\frac{1}{A}\frac{d\sigma_{pA}}{dE}(E,\sqrt{s}) = \int_0^{\varepsilon_{\max}} d\varepsilon\, \mathcal{P}(\varepsilon, E)\, \frac{d\sigma_{pp}}{dE}(E+\varepsilon,\sqrt{s}) \qquad \hat{q}(x) \sim \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

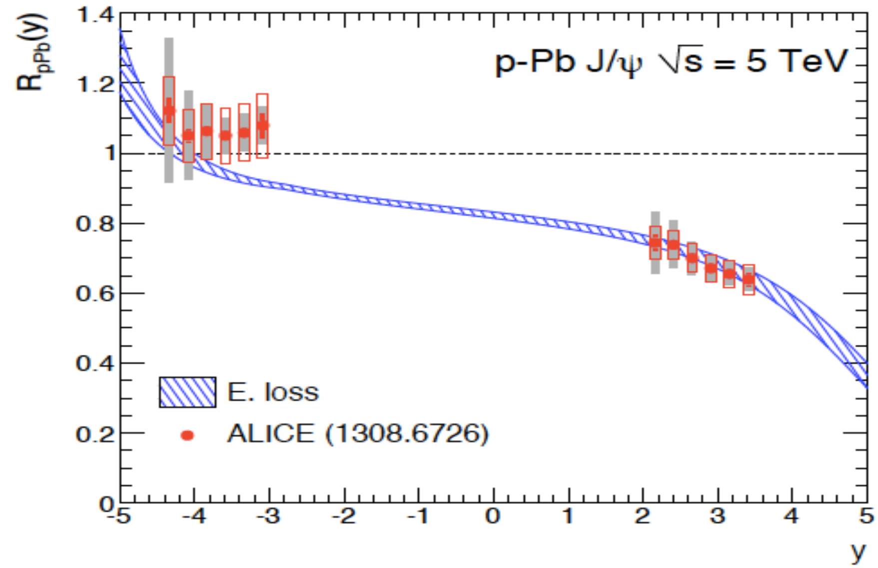
$\mathcal{P}(\varepsilon, E)$: **Quenching weight ~ scaling function of** $\sqrt{\hat{q}L}/M_\perp \times E$

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





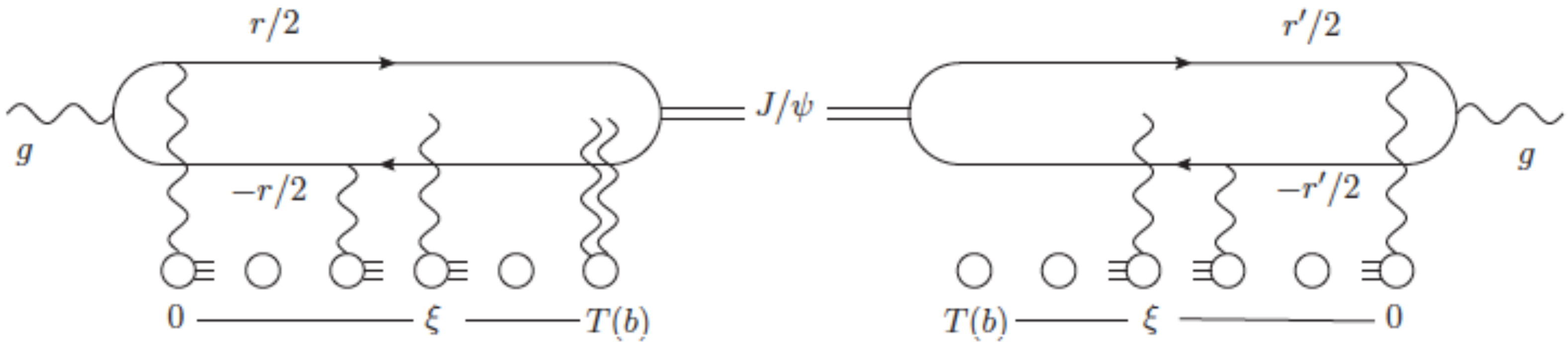


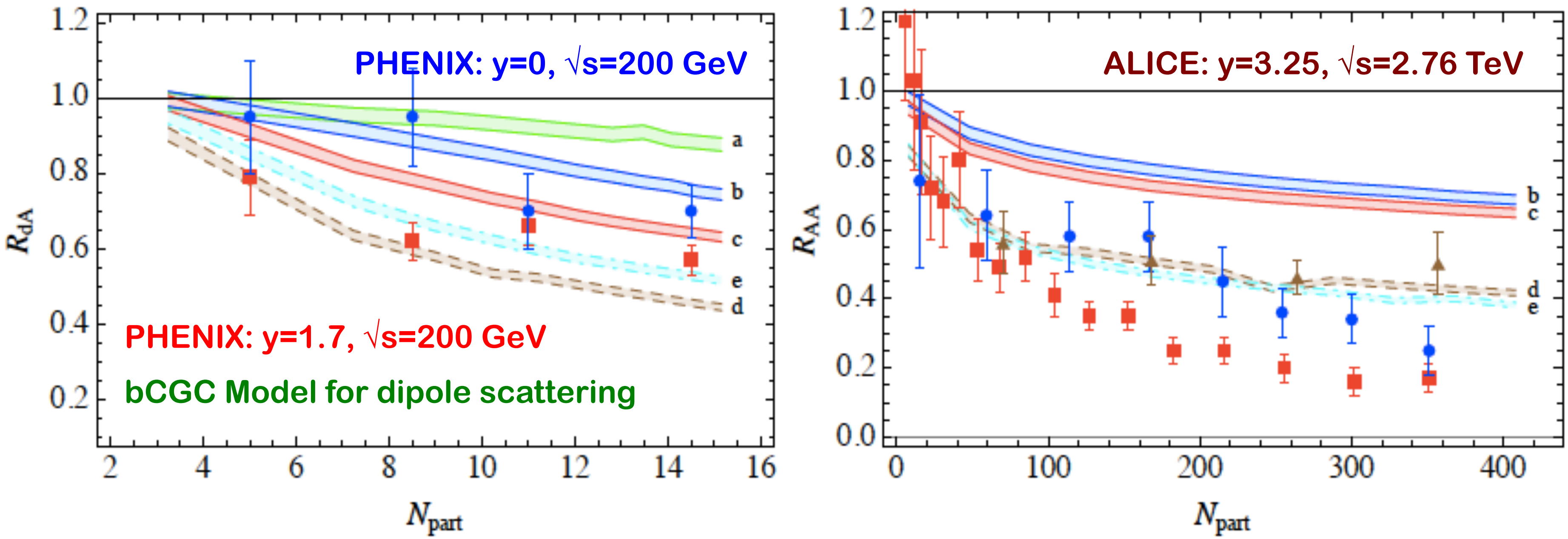


Multiple scattering in pA collisions

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

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



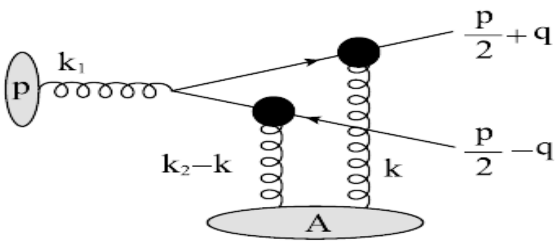


OK for pA, but, far off for AA – J/ψ melting in QGP (MS 1986)?

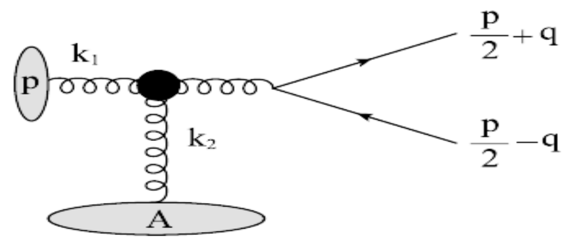
Forward quarkonium production in p(d)+A

- Calculation of multiple scattering:

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

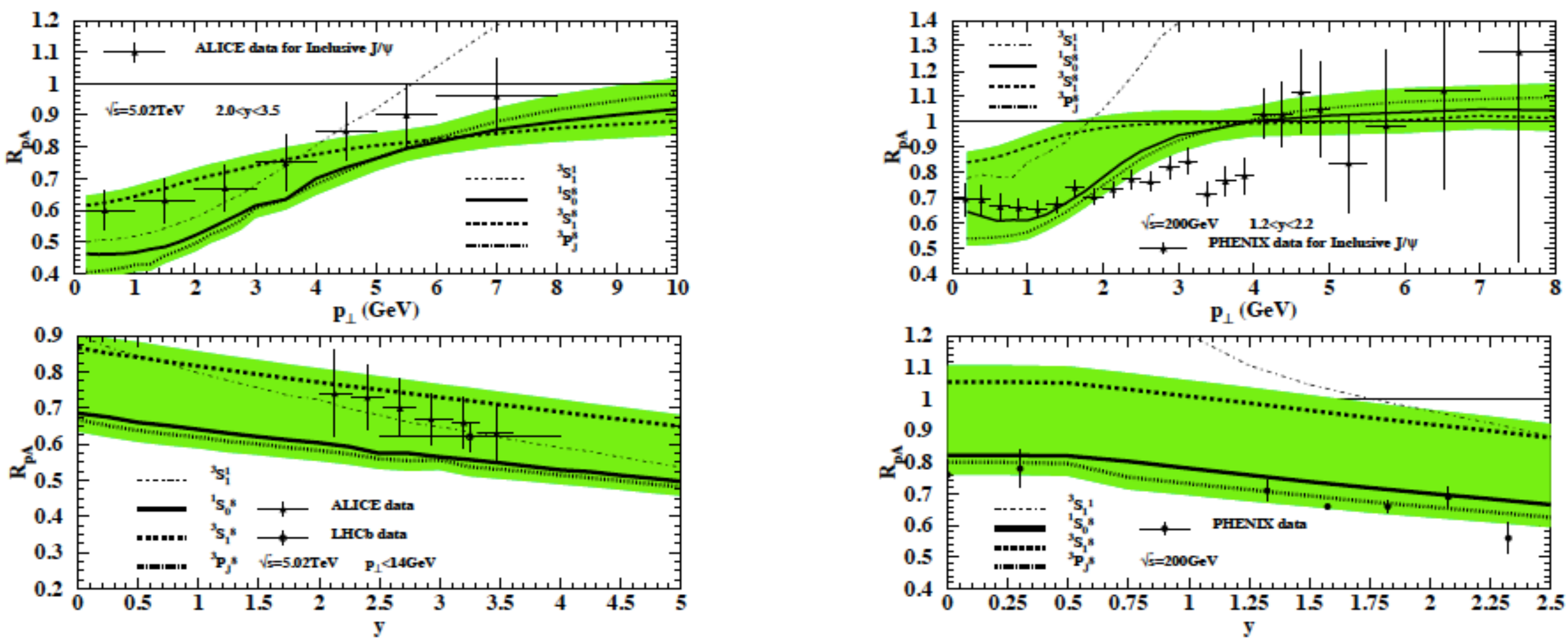


(a)



(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

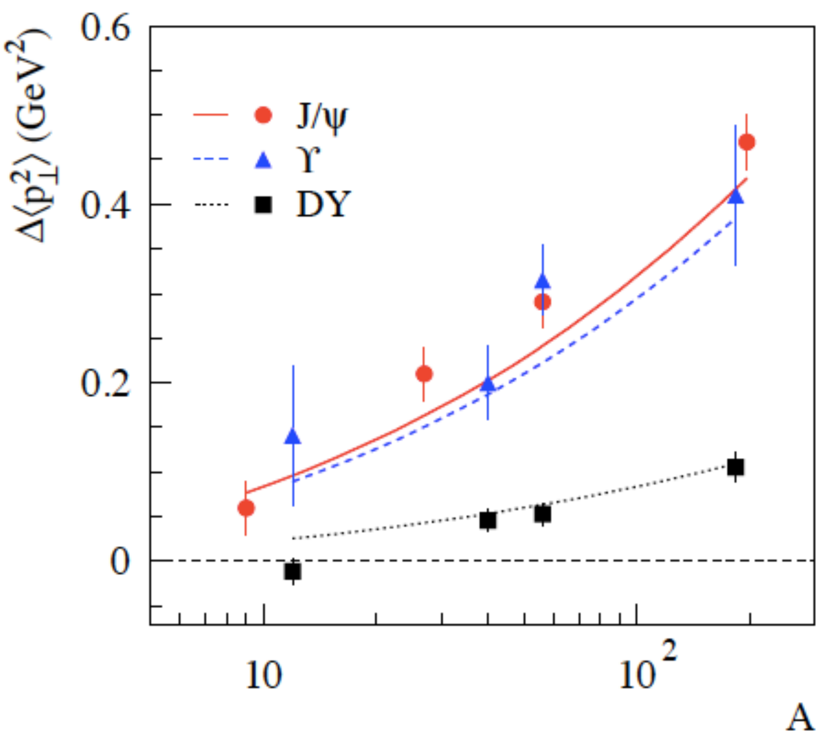
Kang, Qiu, PRD77(2008)

- **Broadening:**

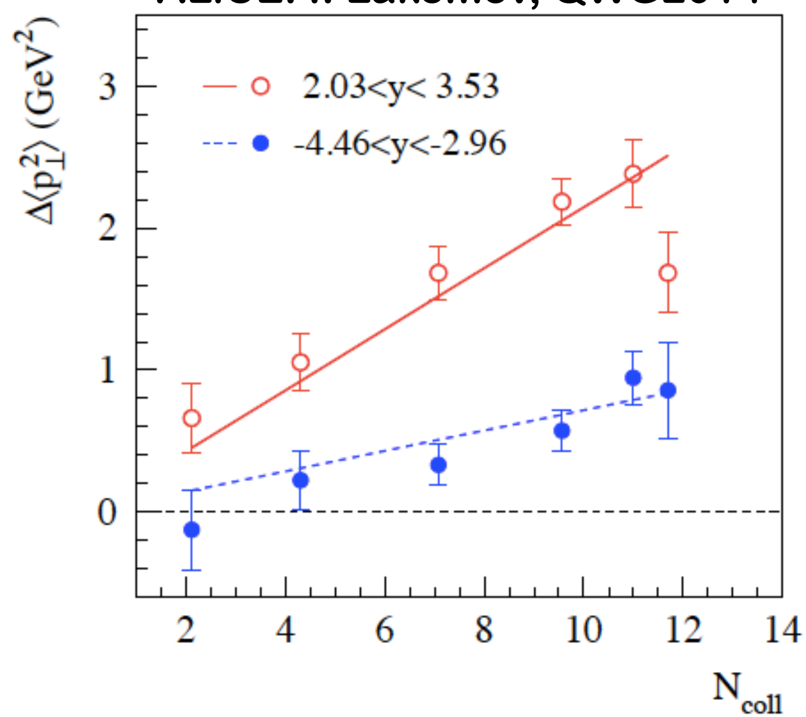
$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi} = C_A\left(\frac{8\pi^2\alpha_s}{N_c^2-1}(A^{1/3}-1)\lambda^2\right) \approx \Delta\langle q_T^2\rangle^{(F)}_{J/\psi}$$

Calculated in both NRQCD and CEM

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



ALiCE: I. Lakomov, QWG2014

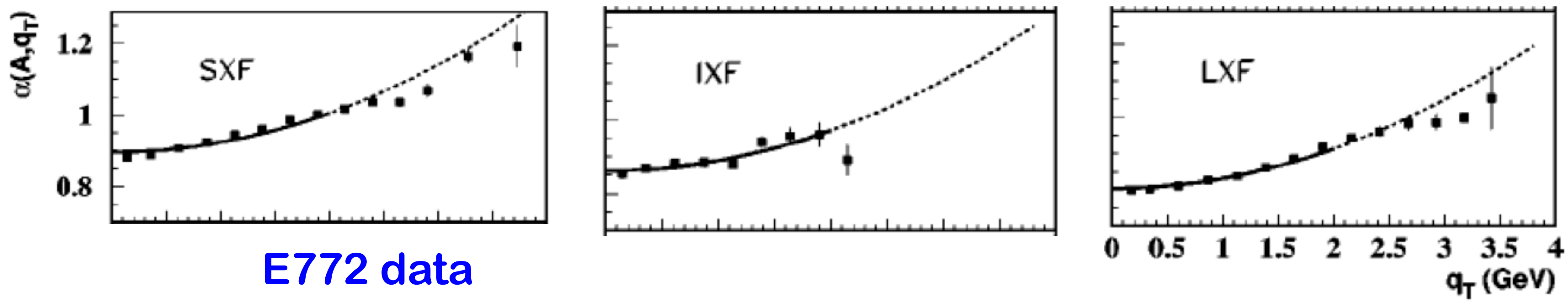


$$\left(A^{1/3}-1\right) \rightarrow \left(A^{1/3}-1\right) N_{\rm coll}/N_{\rm coll}^{\rm min.bias}.$$

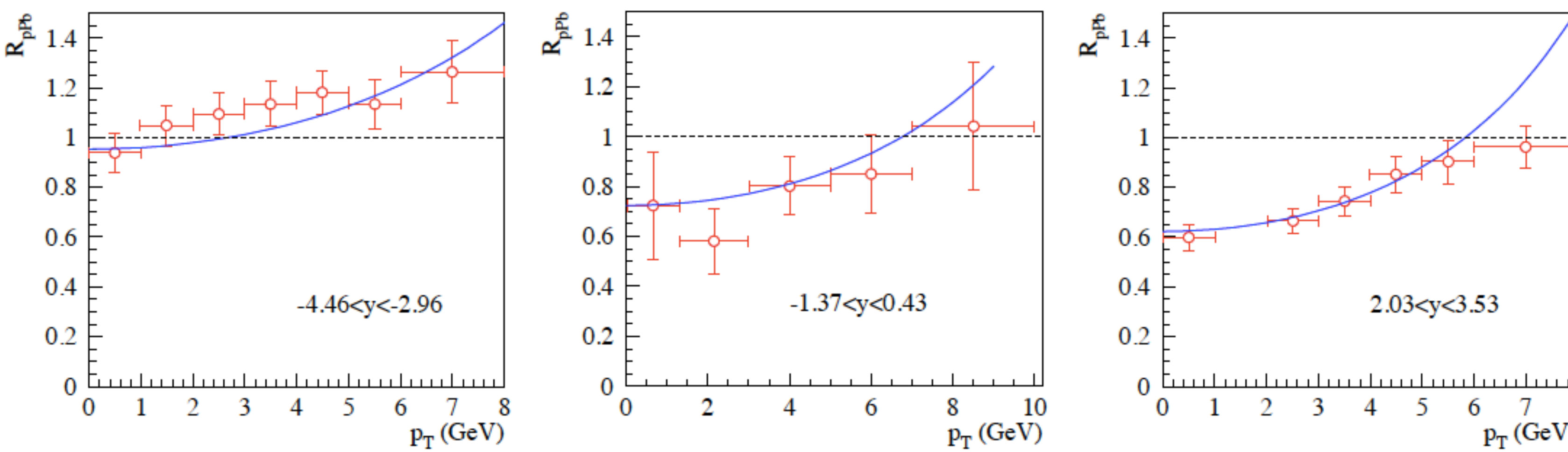
Quarkonium P_T-distribution in p(d)+A

❑ 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



ALICE data

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!

Backup slides

November revolution (1974)

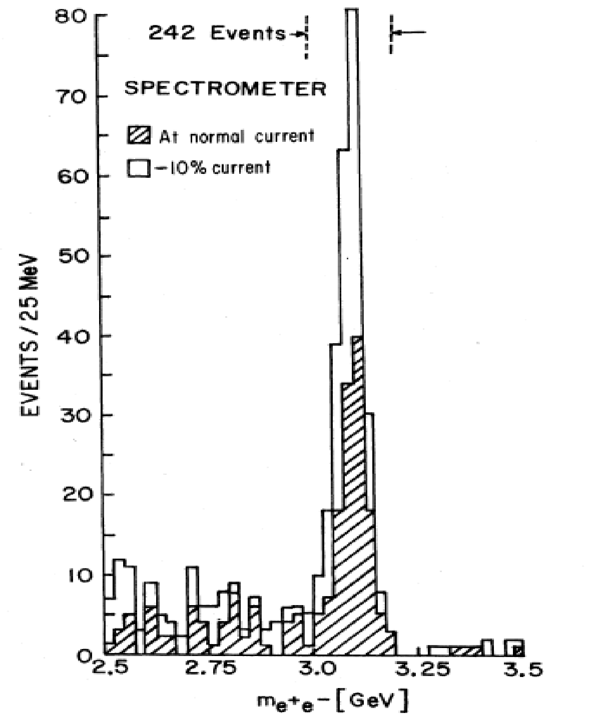
VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 19

Experimental Observation of a Heavy Particle J†

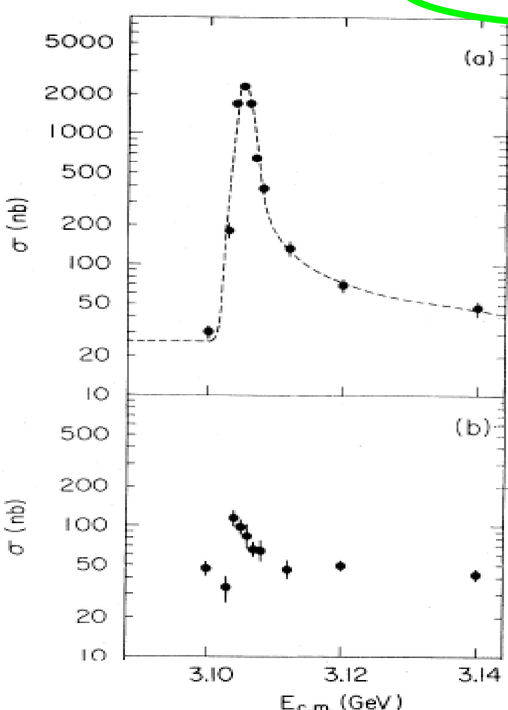
J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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*

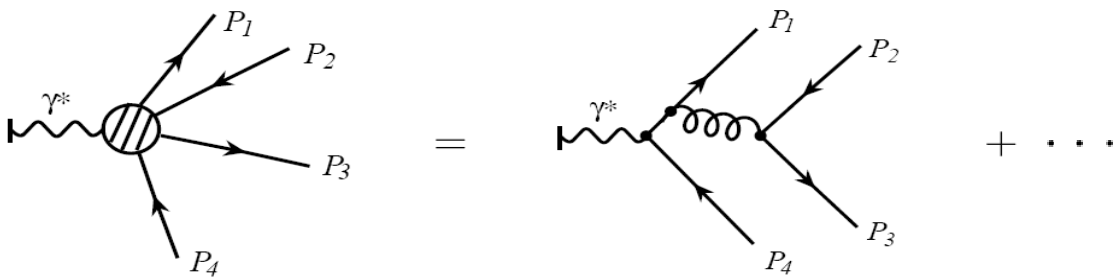
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡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

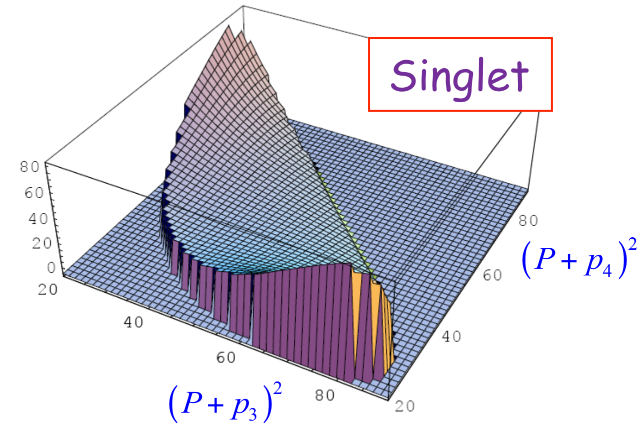
and

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)

Associated production at B-factory

- **Kinematically preferred configuration:**

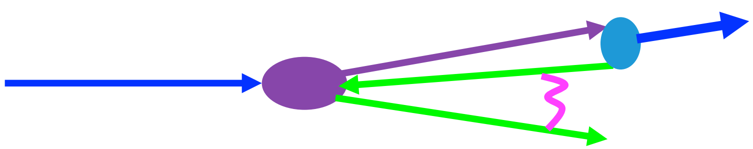




Production rate of a singlet charm quark pair is dominated by the phase space where $s_3=(P_1+P_2+P_3)^2$ or $s_4=(P_1+P_2+P_4)^2$ near its minimum

- **NRQCD formalism does not apply when there are more than one heavy quark velocity involved**

- **Color transfer enhances associated heavy quarkonium production**

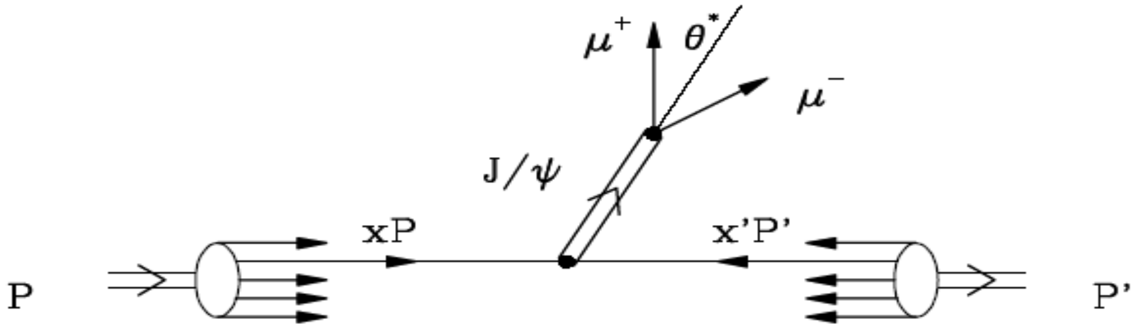


A heavy quark as a color source to enhance the transition rate for an octet pair to become a singlet pair

Nayak, Qiu, Sterman, PRL 2007

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

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

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

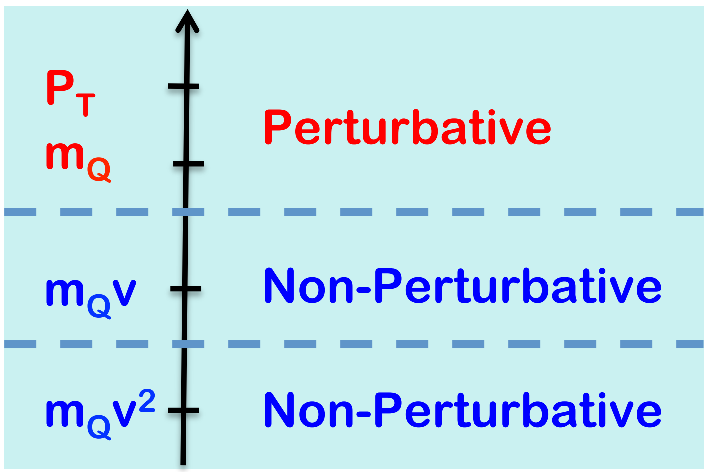
Heavy quarkonium

- 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?