Heavy Quarkonium Production

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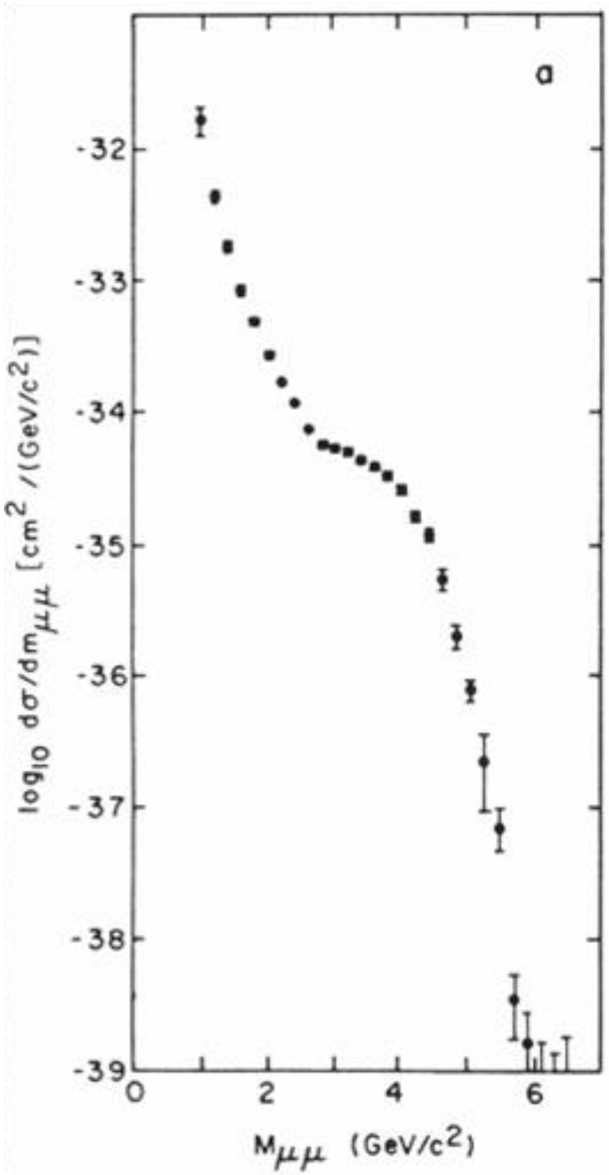
Based on works done with Z.-B. Kang, Y.-Q. Ma, G. Nayak,
G. Sterman, H. Zhang, …

KEK Theory Center Workshop on
Hadron physics with high-momentum hadron beams at J-PARC in 2015
KEK, Tsukuba, Japan, March 13-16, 2015

The Lederman's Shoulder



Phys. Rev. Lett. 25, 1523 (1970)

Production of muon pairs at AGS, BNL

$$p(29\,\mathrm{GeV}) + U \Longrightarrow \mu^+\mu^-(M_{\mu\mu}) + X$$

"…, the cross section varies smoothly as

$$\frac{d\sigma}{dM_{\mu\mu}} \approx \frac{10^{-32}}{M_{\mu\mu}^5}\ \mathrm{cm}^2 \left(\frac{\mathrm{GeV}}{c}\right)^{-2}$$

and exhibits no resonant structure. …"

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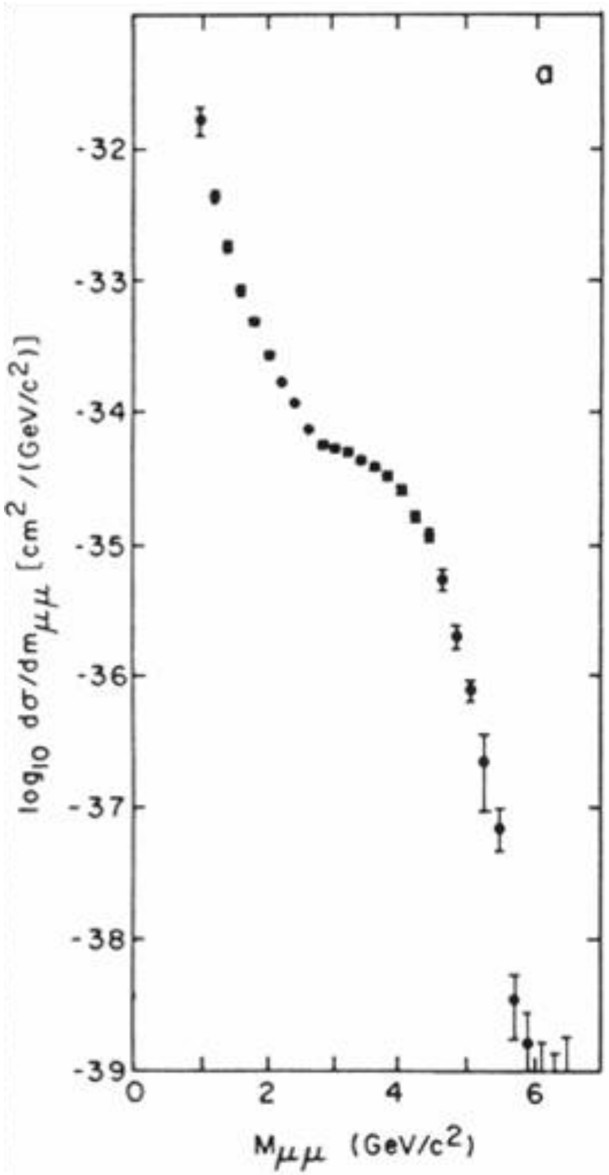

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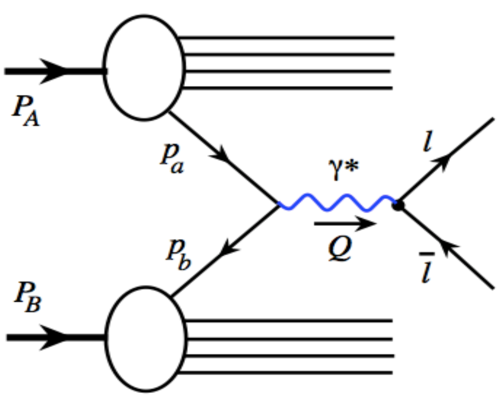
Discovery of the Drell-Yan mechanism:



Phys. Rev. Lett. 25, 316 (1970), Erratum-ibid. 25 (1970) 902

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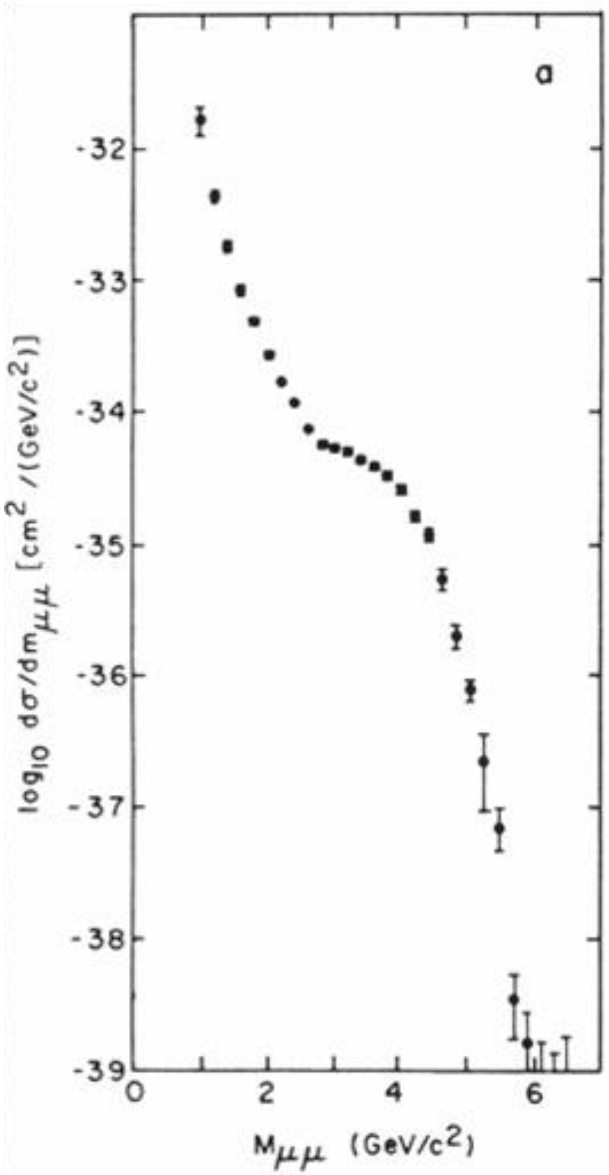

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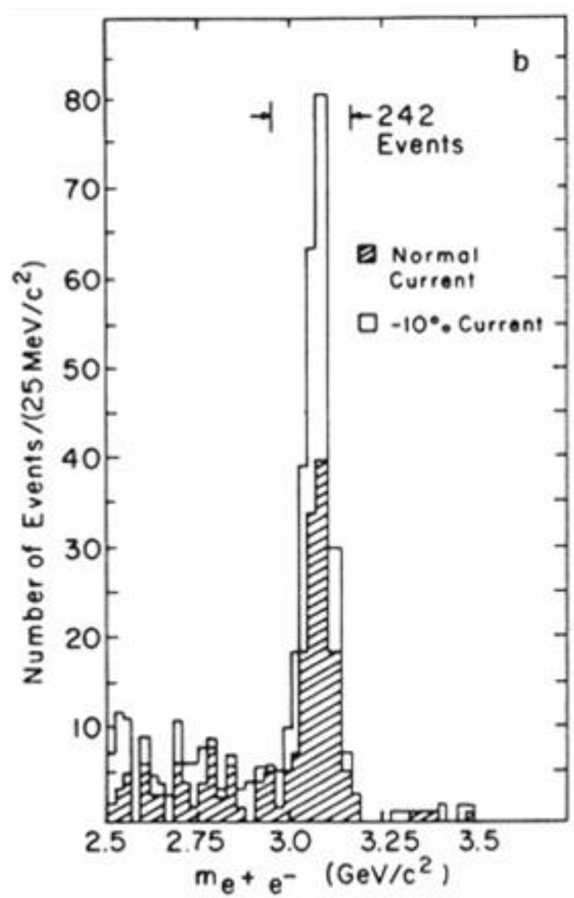
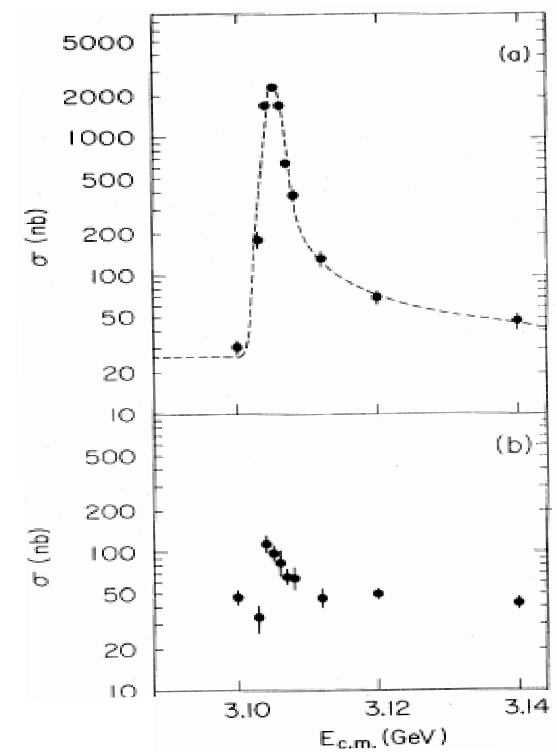
Discovery of the J/ψ - November, 1974



(SLAC)



Outline

Exclusive J/ψ production in π^- p collisions

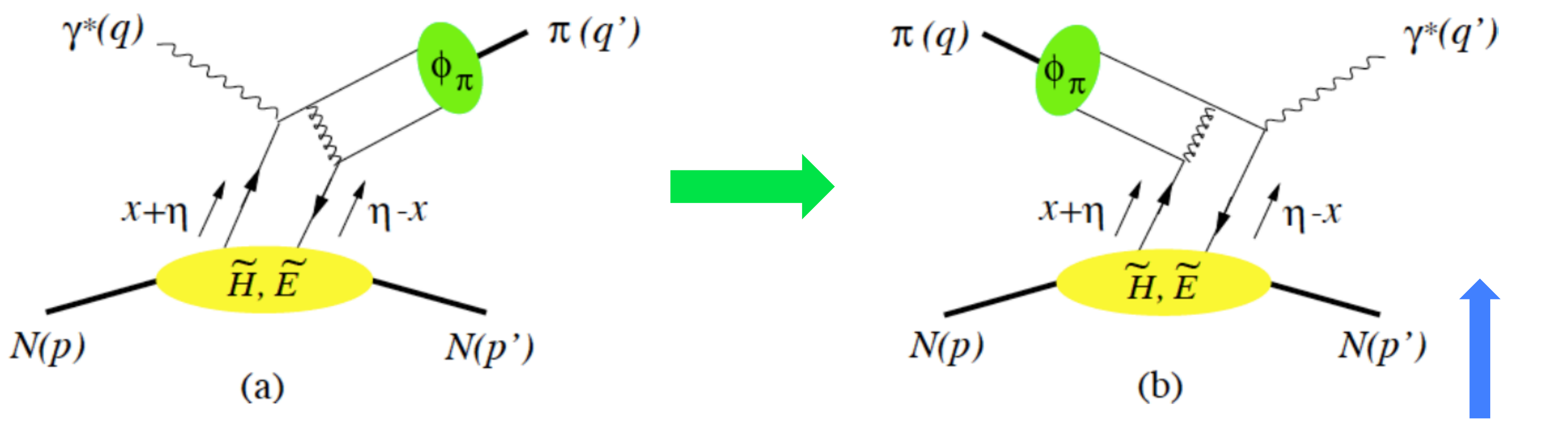
Heavy quarkonium production in pp, pA, π^-p, … collisions

Summary and outlook

Exclusive J/ψ production in $\pi^- p$ collisions

- **Proposal:**

Phys. Lett. B523, 265 (2001) 265



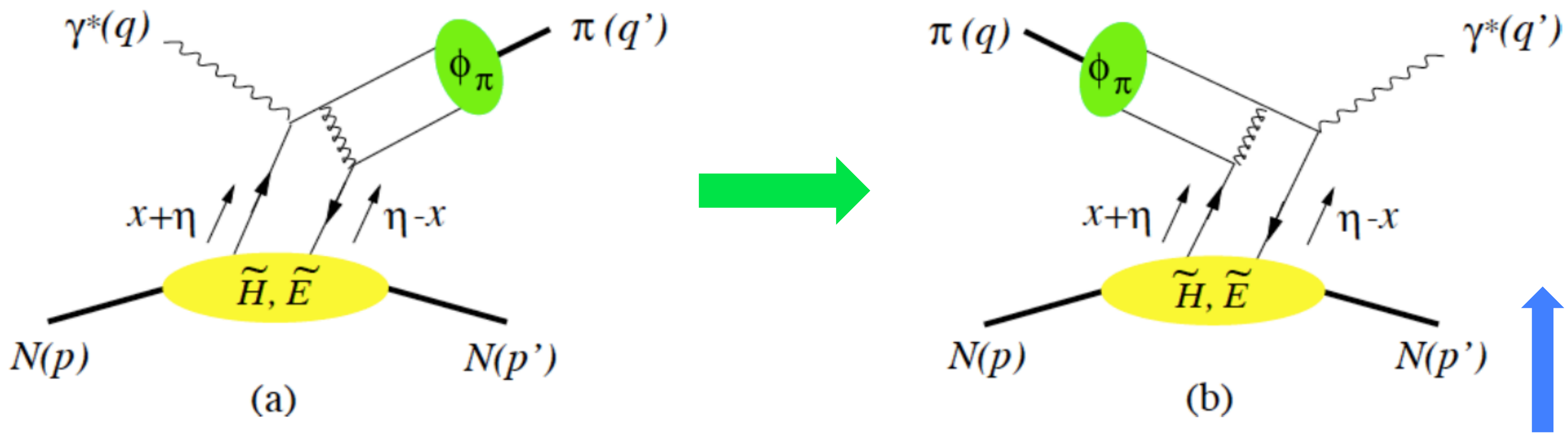
$|t| << Q$

- **Factorization:**
  - ✧ **Necessary conditions:**
    - Active partons are perturbatively pinched to be on-shell
    - Separation of physics at different scales
    - …

Exclusive J/ψ production in $\pi^- p$ collisions

- **Proposal:**

Phys. Lett. B523, 265 (2001) 265



$|t| << Q$

- **Factorization:**
  - Necessary conditions:
    - Active partons are perturbatively pinched to be on-shell
    - Separation of physics at different scales
    - …
  - Concerns:
    - Separation of DA? – the gluon is Not necessary far off-shell
    - Nonperturbative resonances – if the time-like exchange is far off-shell
    - …

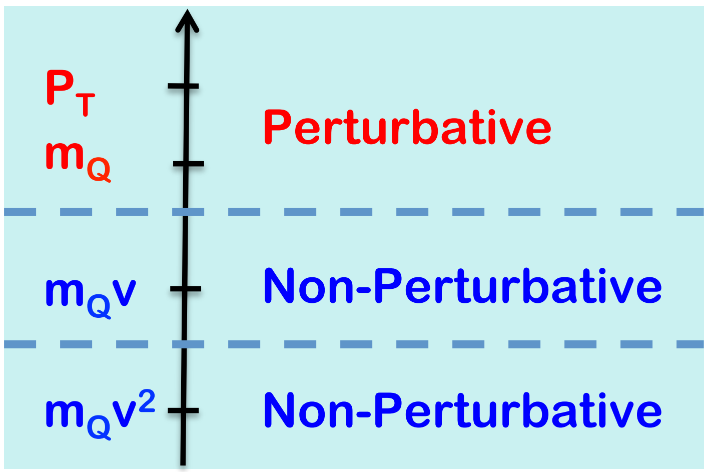
Heavy quarkonium production

- **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:**

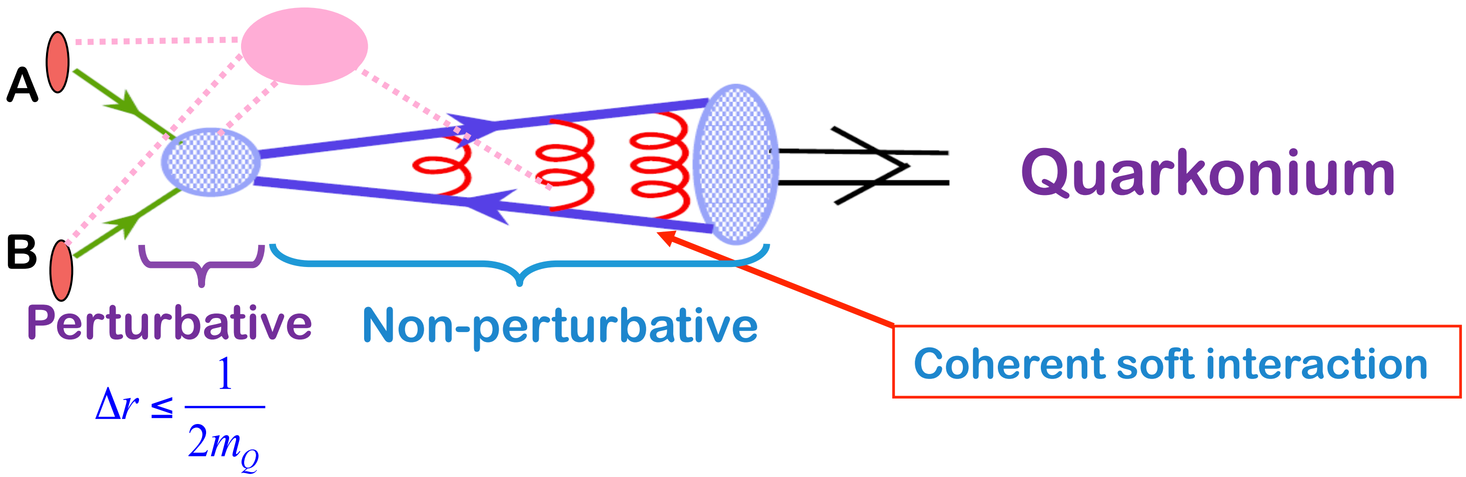
$$\frac{d\sigma_{AB\to H(P)X}}{dy\,dP_T^2} \qquad \sqrt{S}, \qquad P_T, \qquad M_H,$$

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

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

Basic production mechanism

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



- Approximation: on-shell pair + hadronization

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

Models & Debates

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

A long history for the production

- Color singlet model: 1975 –

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

  Only the pair with right quantum numbers

  Effectively No free parameter!

- Color evaporation model: 1977 –

  Fritsch (1977), Halzen (1977), …

  All pairs with mass less than open flavor heavy meson threshold

  One parameter per quarkonium state

- NRQCD model: 1986 –

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

  All pairs with various probabilities – NRQCD matrix elements

  Infinite parameters – organized in powers of v and α_s

- QCD factorization approach: 2005 –

  Nayak, Qiu, Sterman (2005), …
  Kang, Qiu, Sterman (2010), …
  Kang, Ma, Qiu, Sterman (2014)

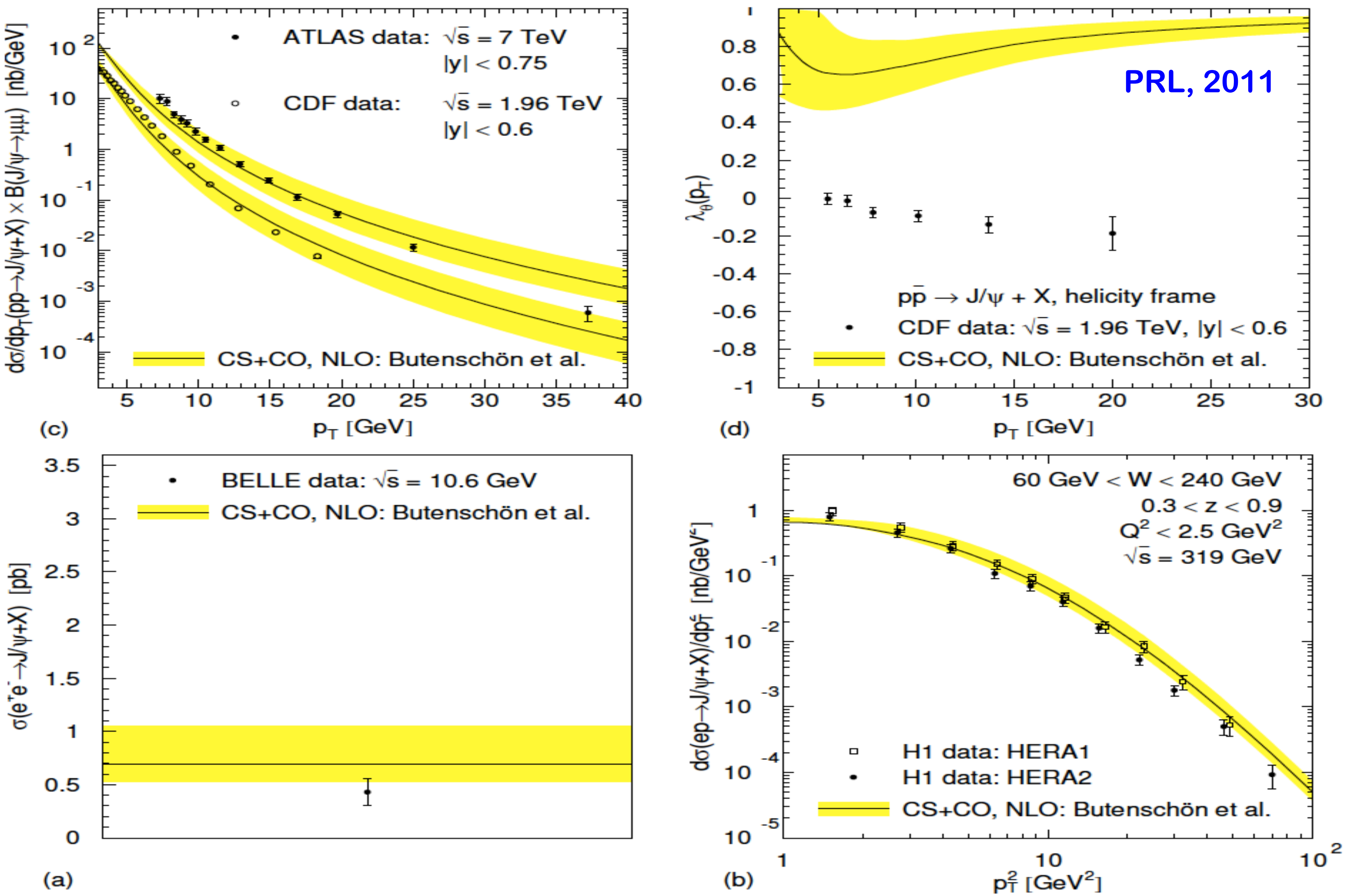
  $P_T >> M_H$: M_H/P_T power expansion + α_s – expansion

  Unknown, but universal, fragmentation functions – evolution

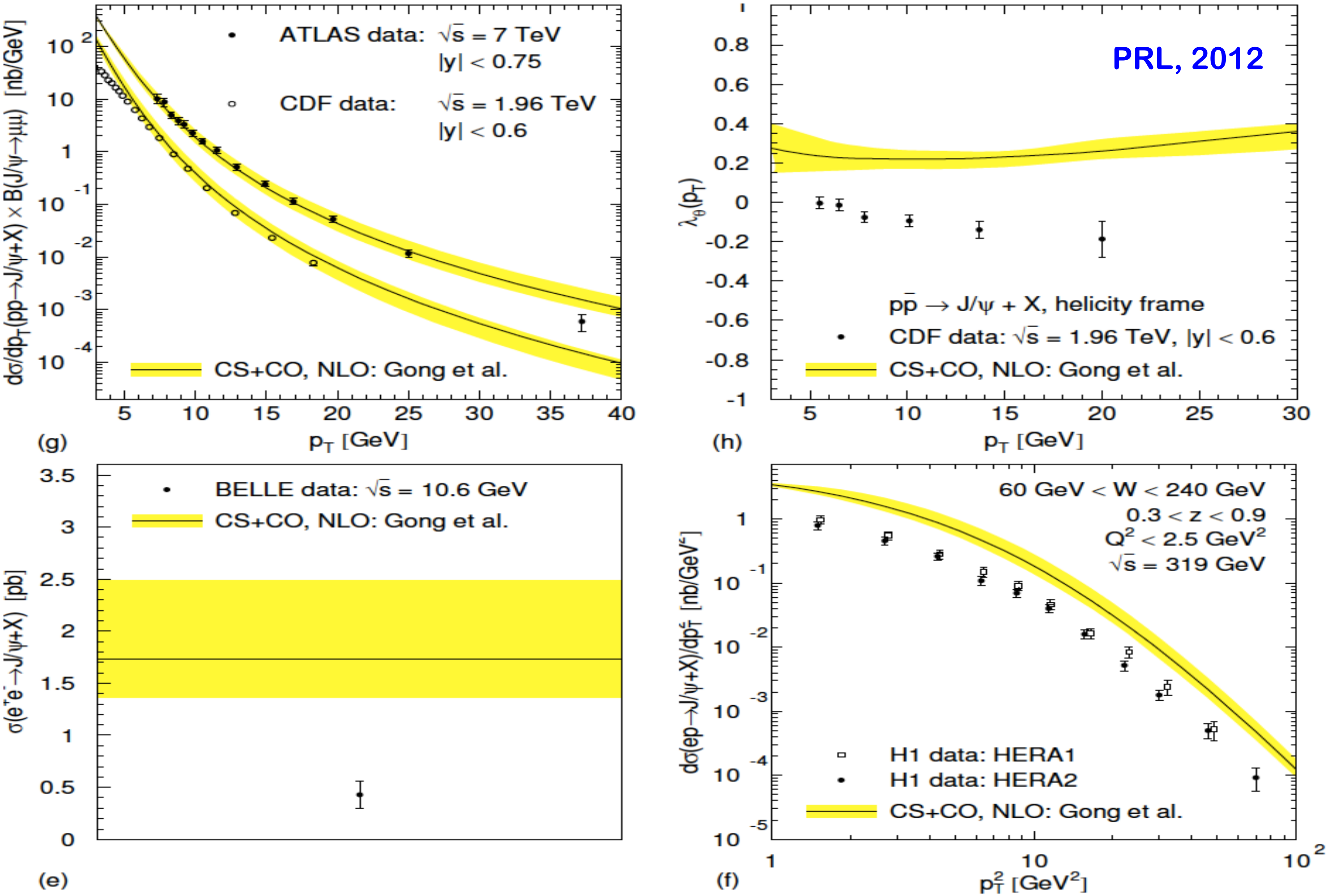
- Soft-Collinear Effective Theory + NRQCD: 2012 –

  Fleming, Leibovich, Mehen, …

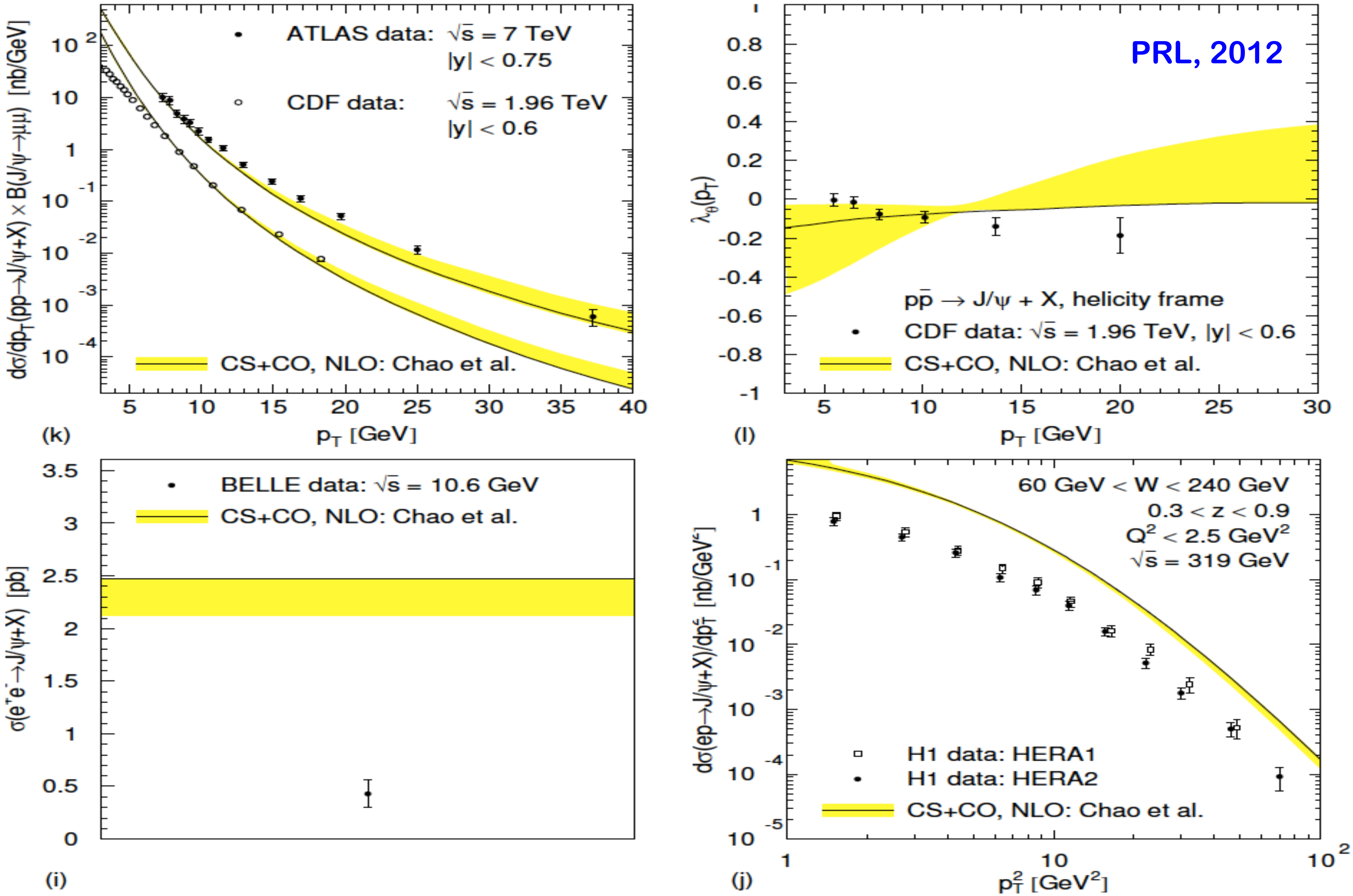
NLO NRQCD vs data – Butenschoen et al.



NLO NRQCD vs data – Gong et al.



NLO NRQCD vs data – Chao et al.



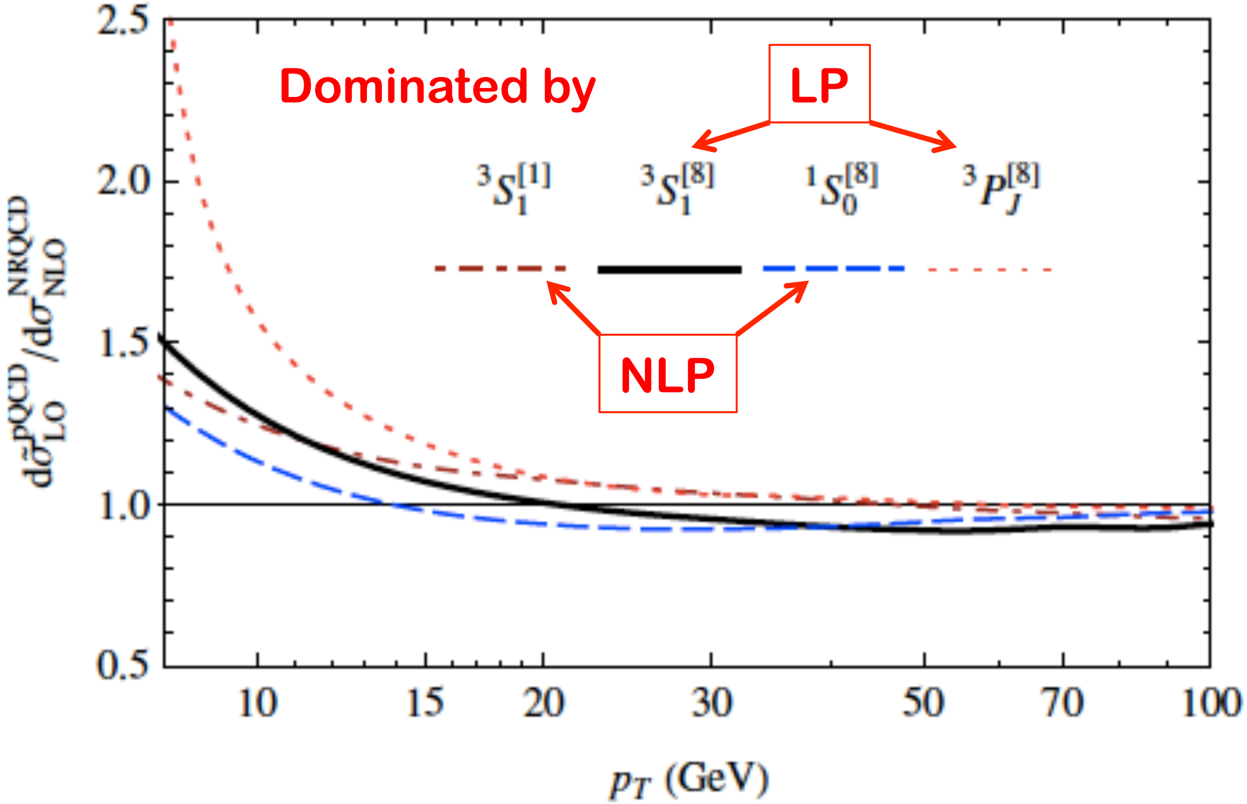
QCD factorization – Kang et al.

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

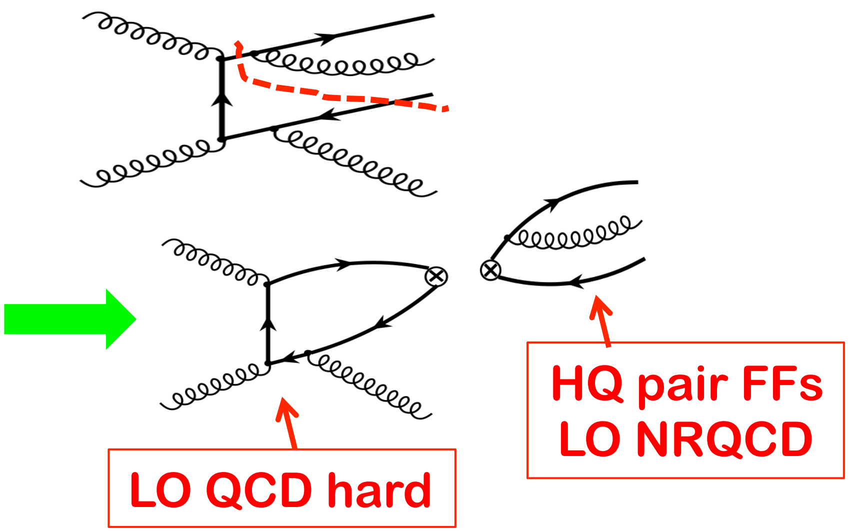
LO QCD analytical results reproduce NLO NRQCD calculations (numerical)

PRL, 2014

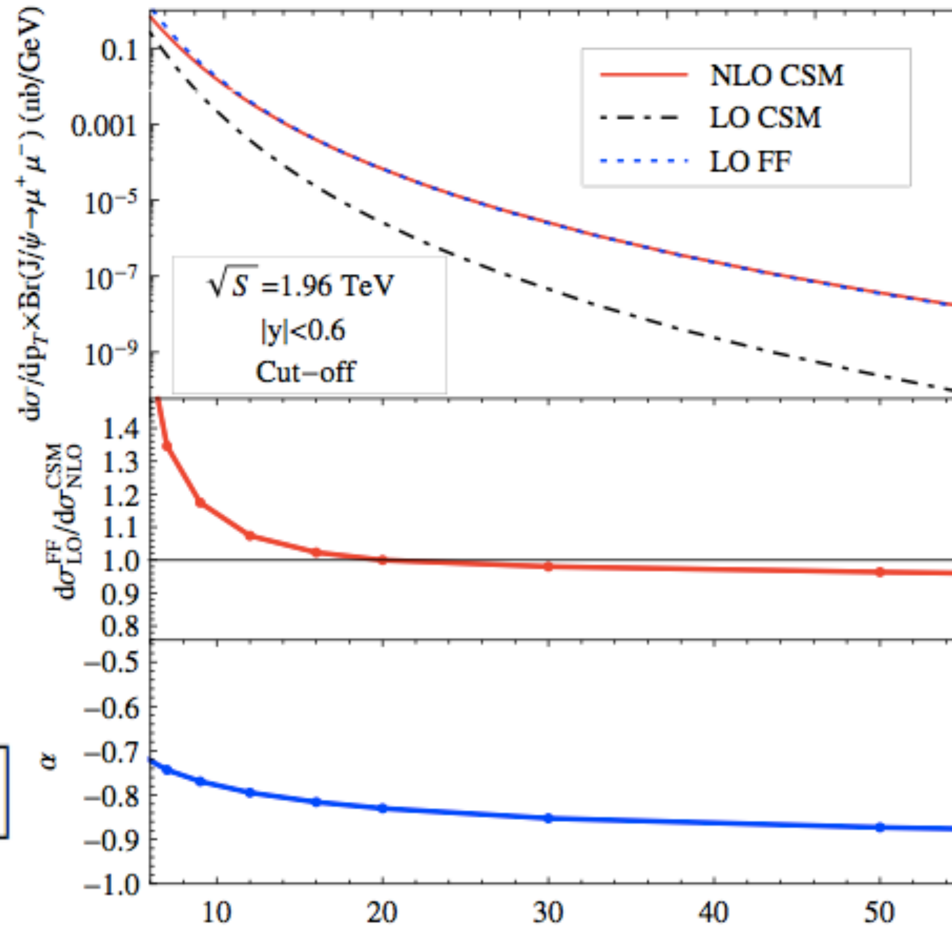
LO QCD + LO NRQCD factorization

Kang, Ma, Qiu and Sterman, 2014

❑ Color singlet as an example:



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



Reproduce NLO CSM for p_T > 10 GeV!

Cross section + polarization

QCD Factorization = better controlled HO corrections!

QCD factorization vs NRQCD factorization

- **QCD factorization – valid to the 1st two powers in $1/P_T$:**
  - ✧ Expand physical cross section in powers of $1/P_T$ (LP + NLP + …)
  - ✧ Factorization at each power in $1/p_T$: perturbative coef. $\otimes$ fragmentation
  - ✧ Factorization of LP and NLP is "proved" to be valid for all powers of α_s

- **NRQCD factorization – conjectured:**
  - ✧ Expand physical cross section in powers of relative velocity of HQ
  - ✧ Expand the coefficient of each term in powers of α_s
  - ✧ Verified to NNLO in α_s for the leading power term in the *v*-expansion

- **Connection or matching:**

  If NRQCD factorization for fragmentation functions is valid,

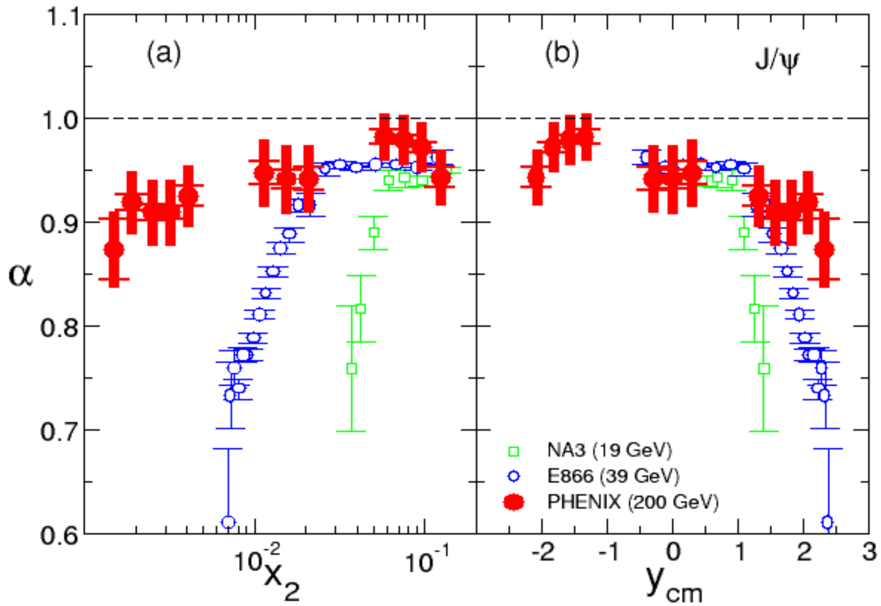
$$E_P \frac{d\sigma_{A+B\to H+X}}{d^3P}(P, m_Q) \equiv E_P \frac{d\sigma^{\rm QCD}_{A+B\to H+X}}{d^3P}(P, m_Q = 0)$$

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

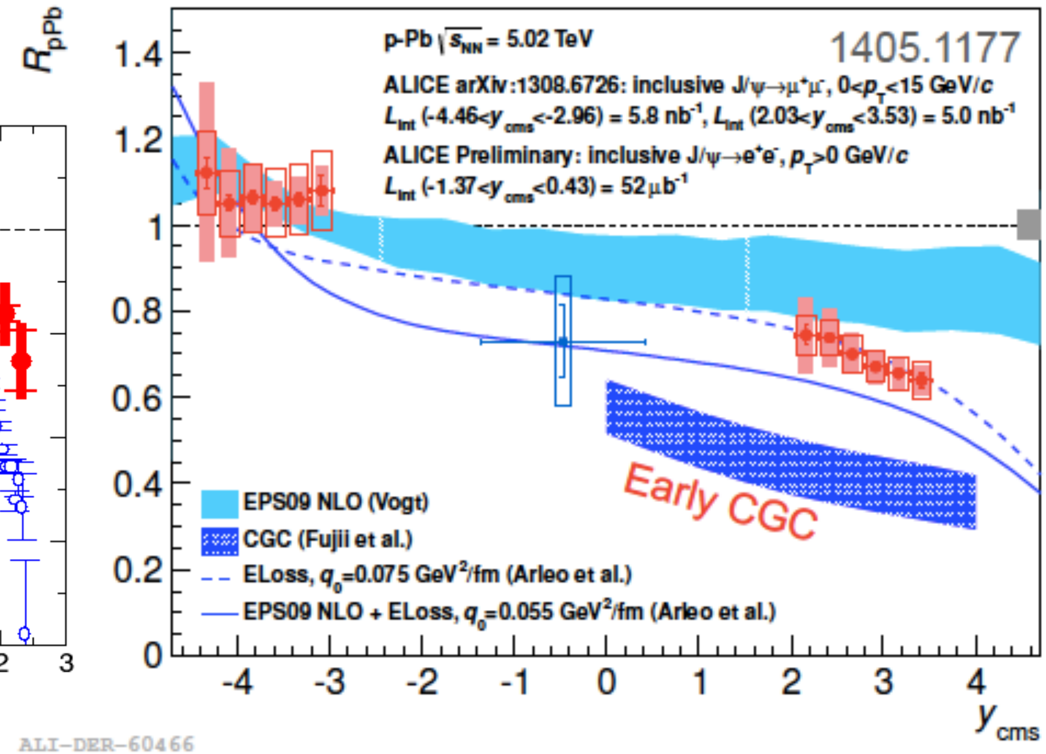
  Mass effect + P_T region ($P_T \gtrsim m_Q$)

Production in p+A collisions

❑ Puzzling rapidity dependence:



Fixed target + RHIC exp'ts



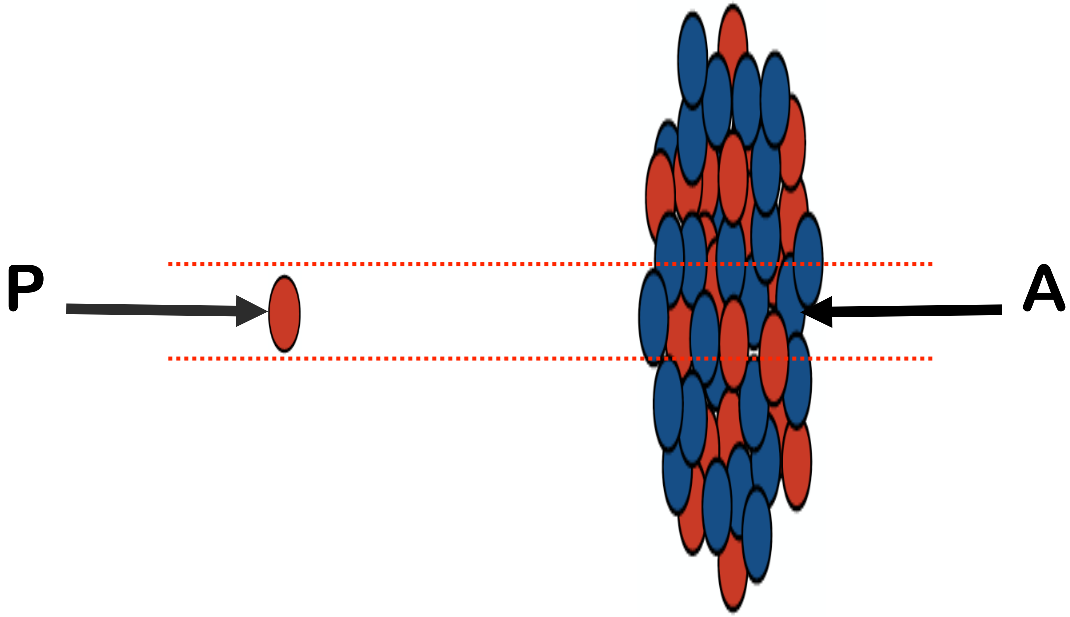
LHCb has similar forward rapidity result

✧ x_F – scaling (not x_2-scaling) in low energy data

✧ Less suppression from LHC data
(early CGC calculation does not work)

Production in p(d)+A collisions

❑ Proton (deuteron) – Nucleus Collisions:



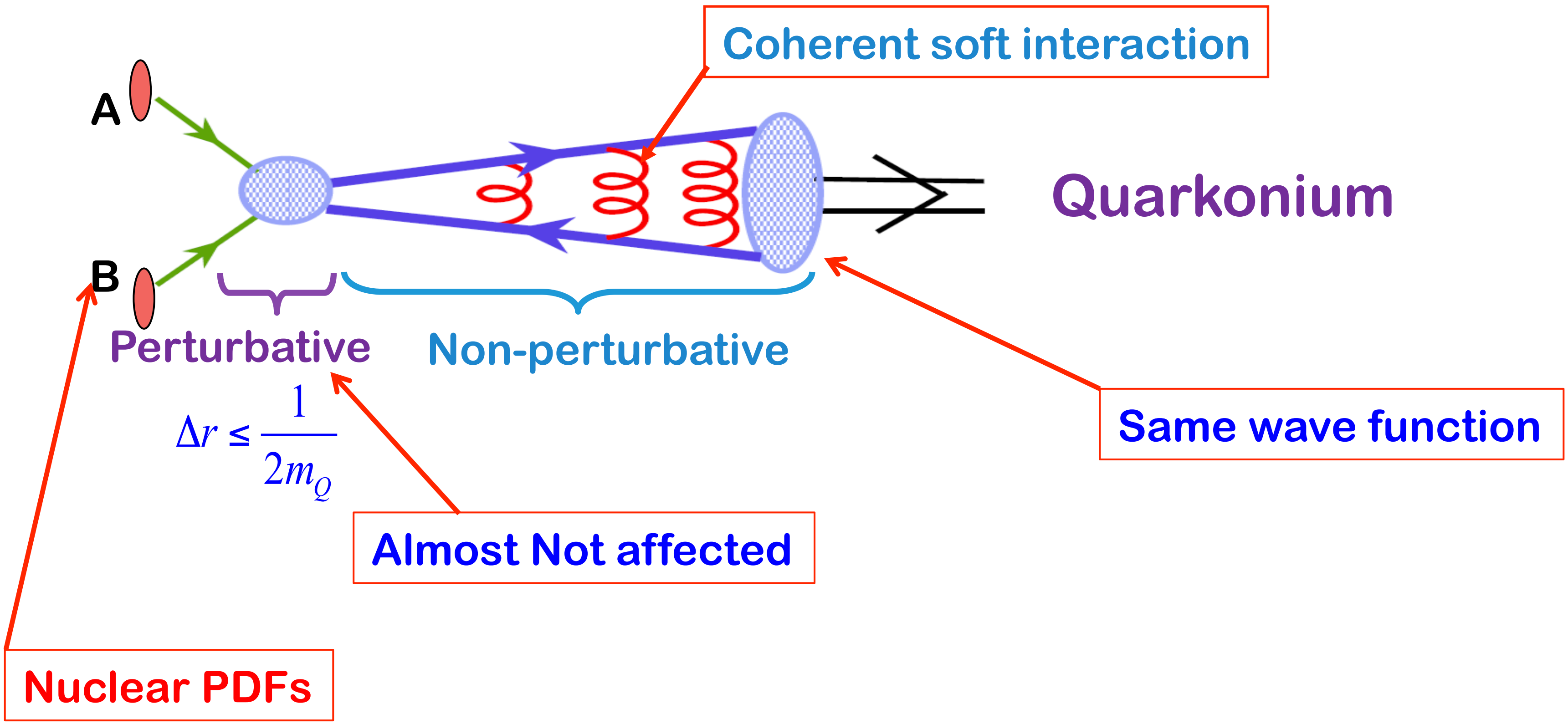
✧ NO QGP ($m_Q >> T$)! ➡ Cold nuclear effect for the "production"

✧ Nuclei as potential filters of production mechanisms

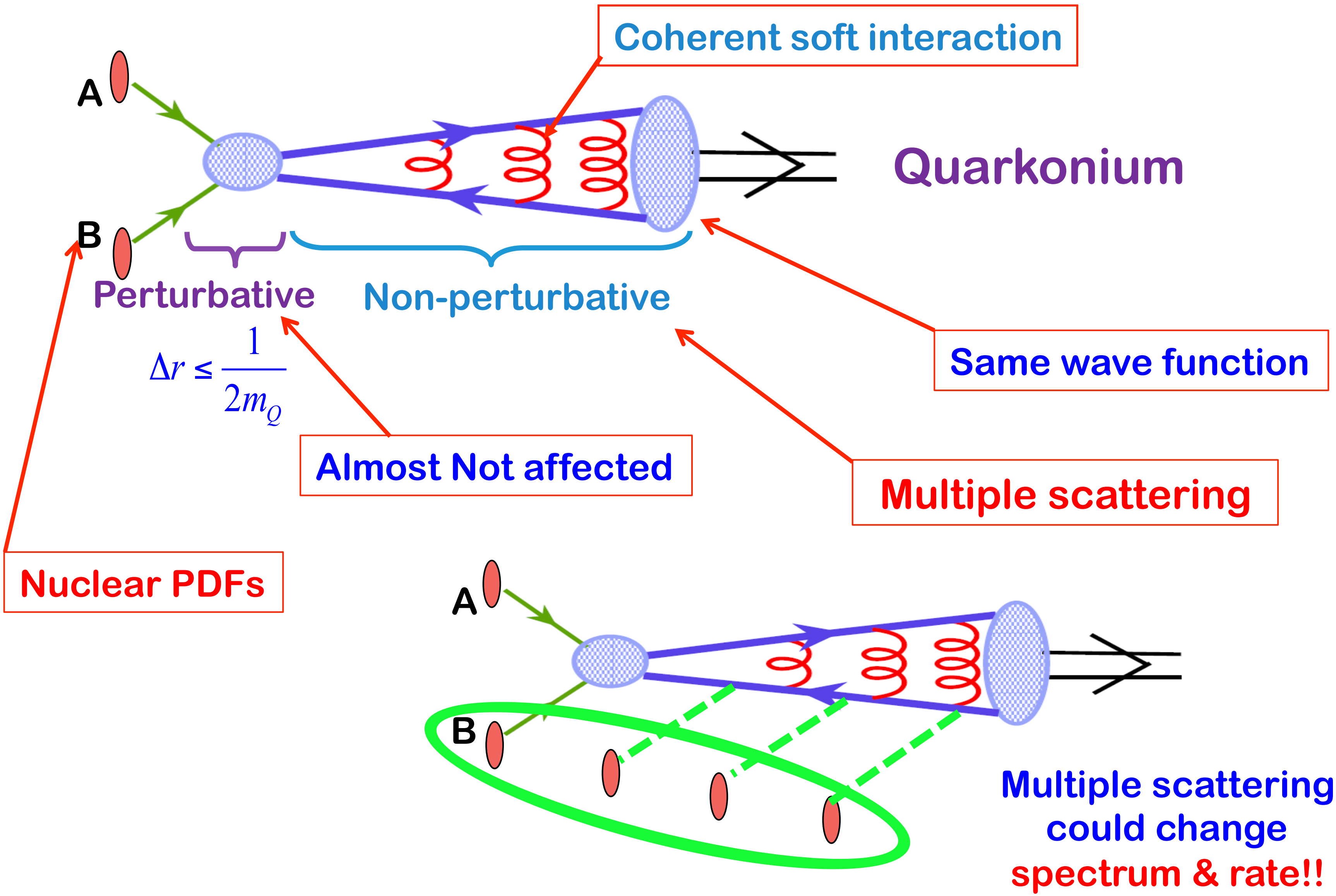
✧ Hard probe ($m_Q >> 1/fm$) ➡ quark-gluon structure of nucleus!

Nucleus is not a simple superposition of nucleons!

Production in p(d)+A collisions



Production in p(d)+A collisions



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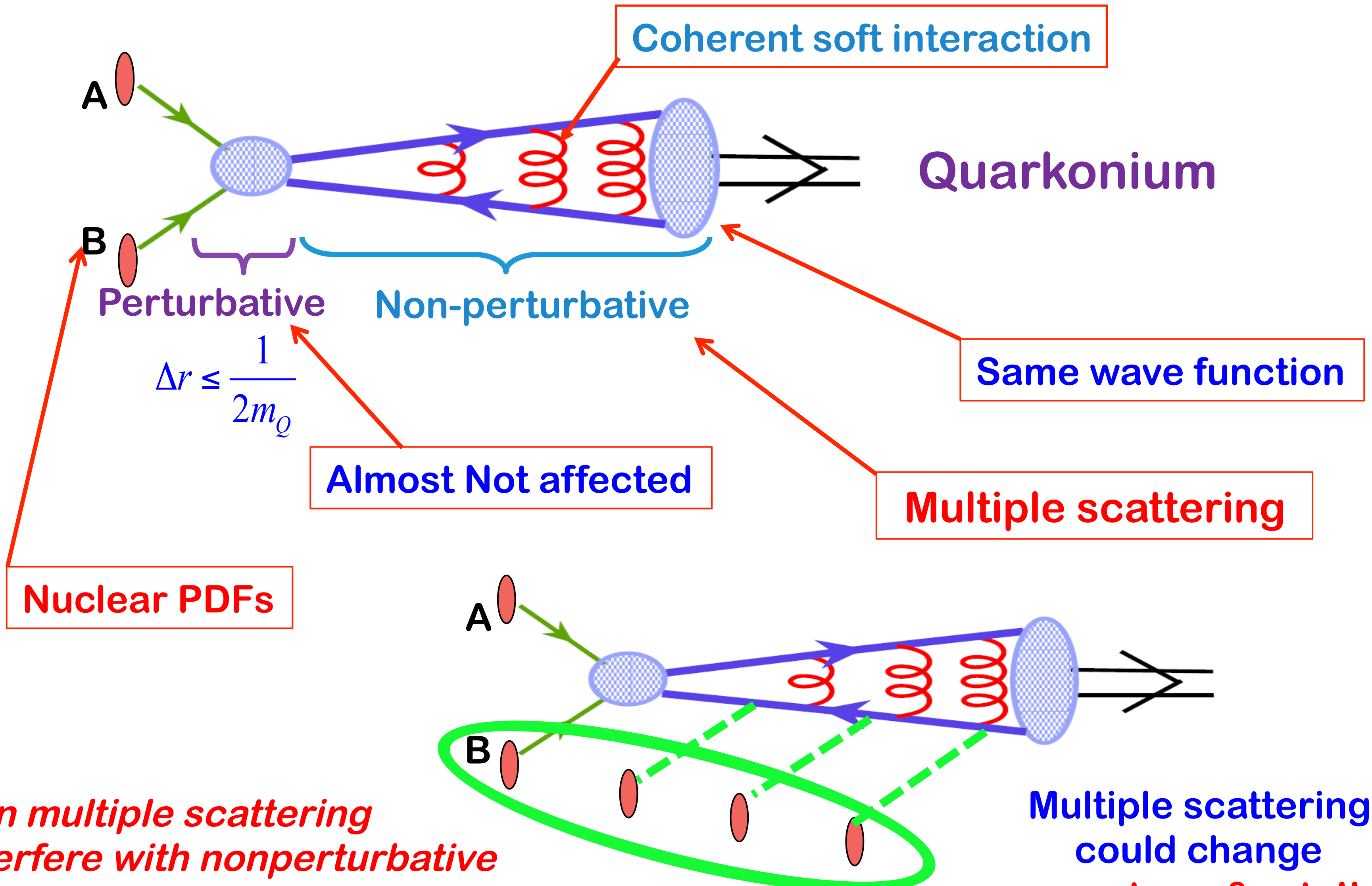
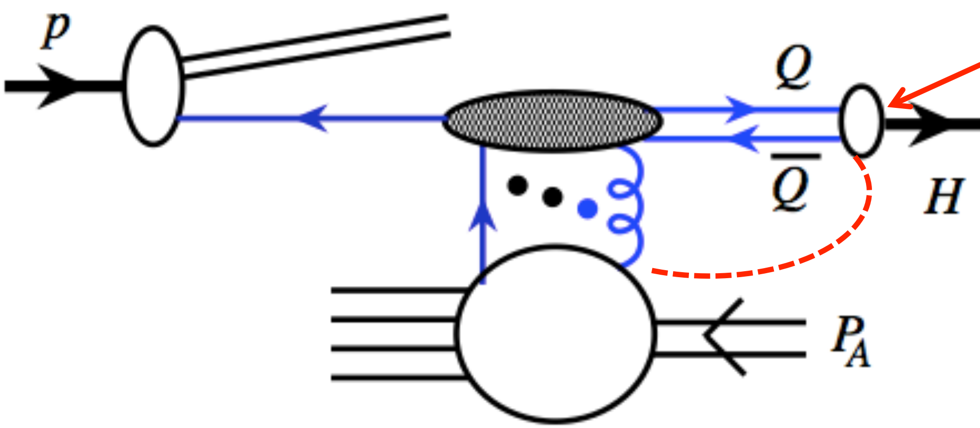


Can multiple scattering interfere with nonperturbative formation of quarkonia?

Production with multiple scattering

Brodsky and Mueller, PLB 1988

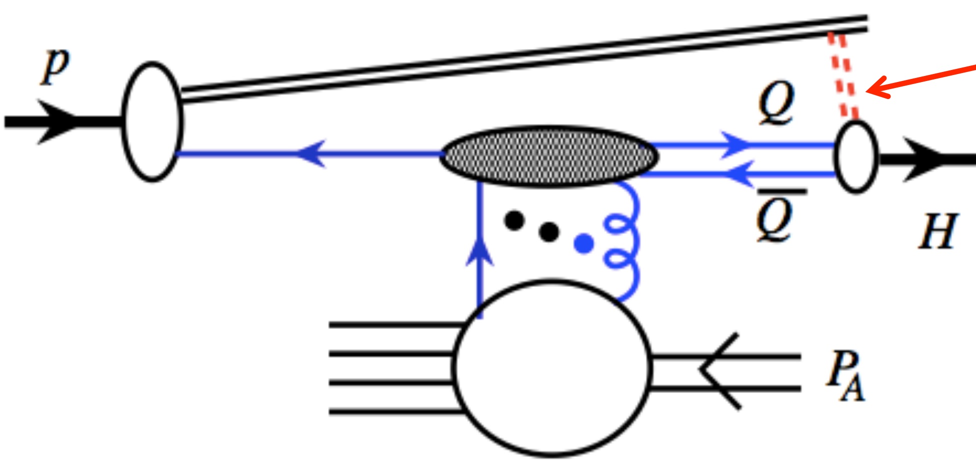
- ❑ *Backward* production in p(d)+A collisions:



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:



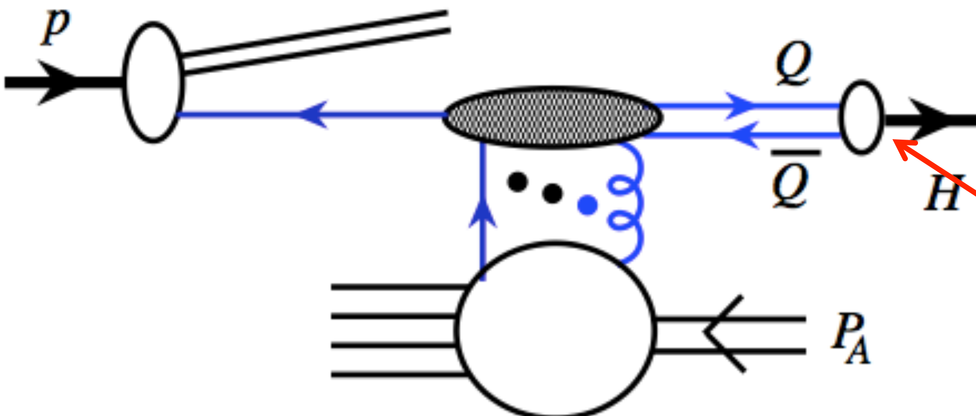
Co-mover interaction

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

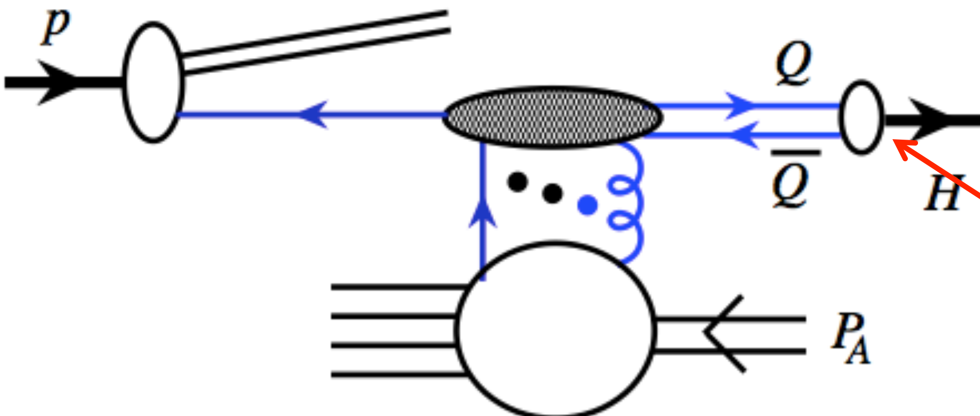
Non-perturbative formation of J/Ψ is far outside of nucleus

✧ 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:

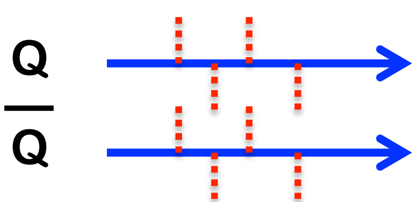


✧ Time dilation

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



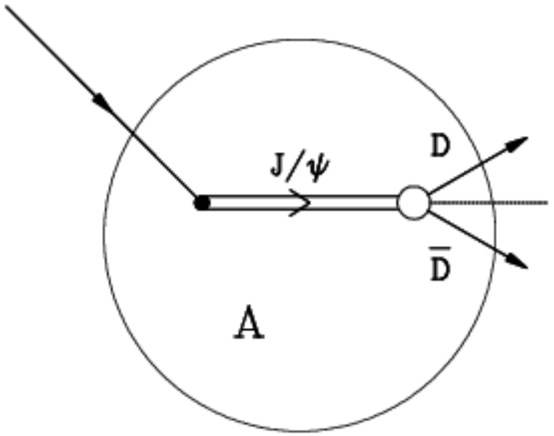
Soft multiple scattering – "random walk"

⇒ Momentum imbalance – larger invariant mass

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

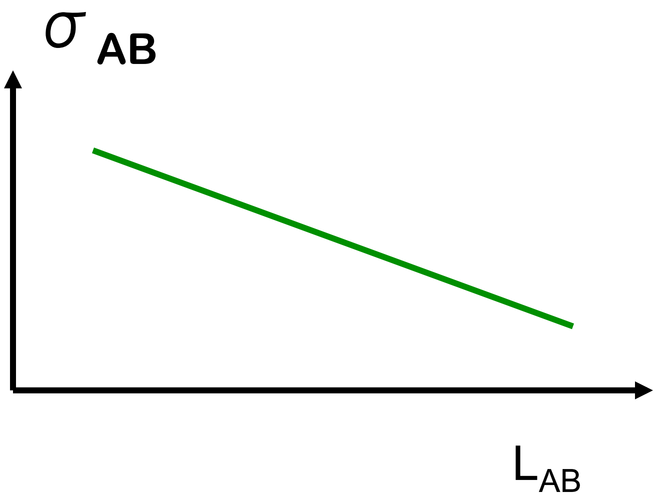
Suppression in total production rate

- If J/ψ were produced at the collision point:
  - ✧ Nuclear effect in PDFs
  - ✧ Medium dependence from J/ψ-nucleon absorption



- Glauber model:

$$\sigma_{AB} \approx AB\sigma_{NN} e^{-\rho_0 \sigma_{\text{abs}}^{J/\psi} L_{AB}}$$



- Expect a straight line on a semi-log plot
- Need a much too larger σ_{abs}

Suppression in total production rate

Qiu, Vary, Zhang, PRL 2002

- ❑ **J/ψ is NOT produced at hard collision!**
- ❑ **Final-state:**

  Increases the invariant mass

  of the pair – hit open threshold

  $\overline{Q}^2 > Q^2$

  $$q^2 \Rightarrow q^2 + \varepsilon L_{AB}$$

  Suppression of J/ψ

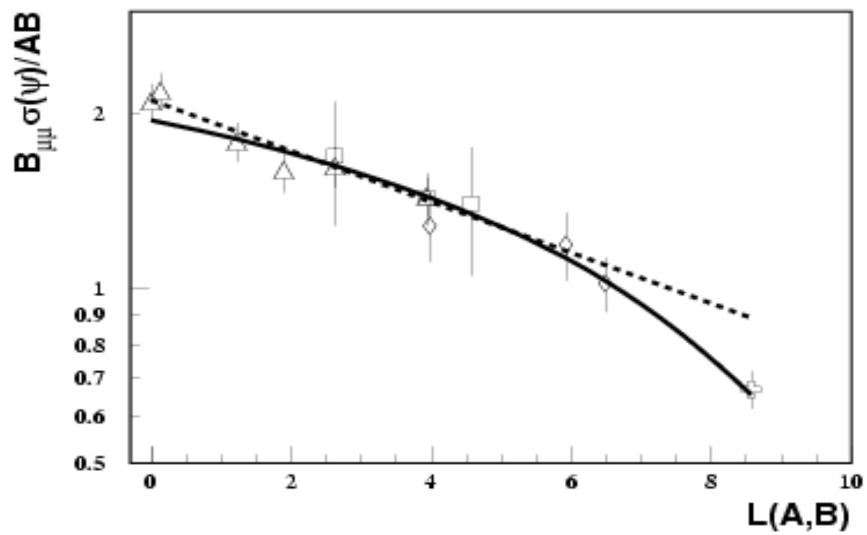
  $$\varepsilon \sim \hat{q} \sim \langle \Delta q_T^2 \rangle$$

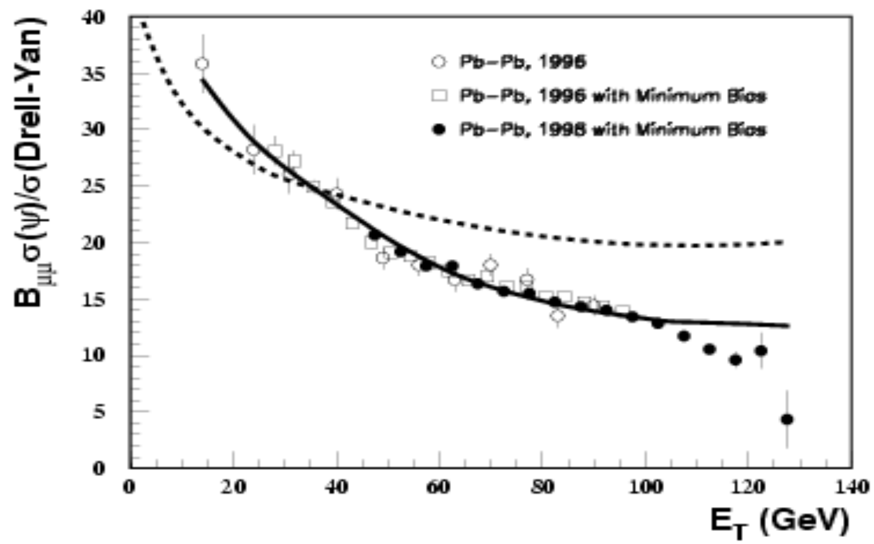
- ❑ **Threshold effect leads to different effective σ_{abs}**

  Curved line for R_{pA}

- ❑ **Different suppression for ψ'**

  Difference in threshold behavi

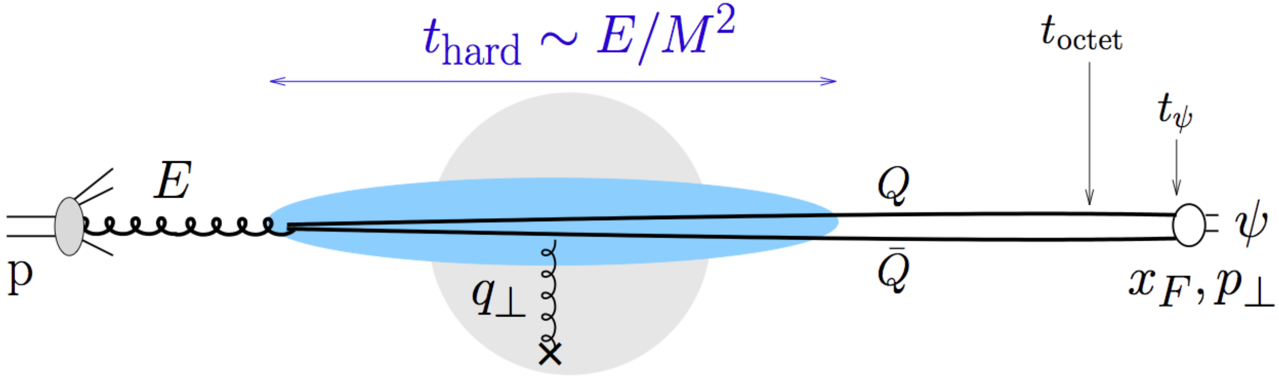




A-dependence in rapidity y (x_F) in p+A

❑ Picture + assumptions:

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



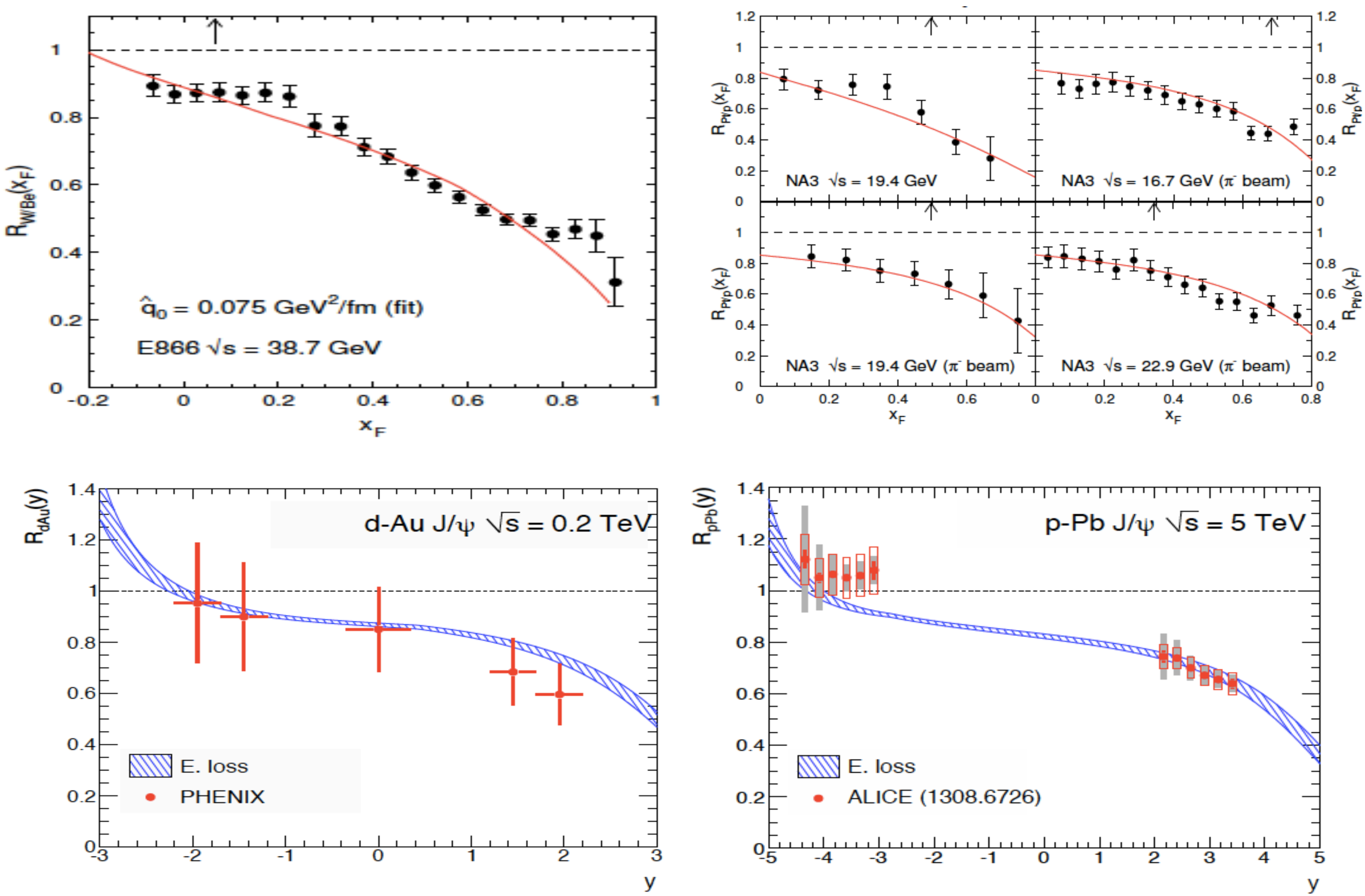
- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- Medium rescatterings do not resolve the octet $c\bar{c}$ pair
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion

❑ Model energy loss:

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

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

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



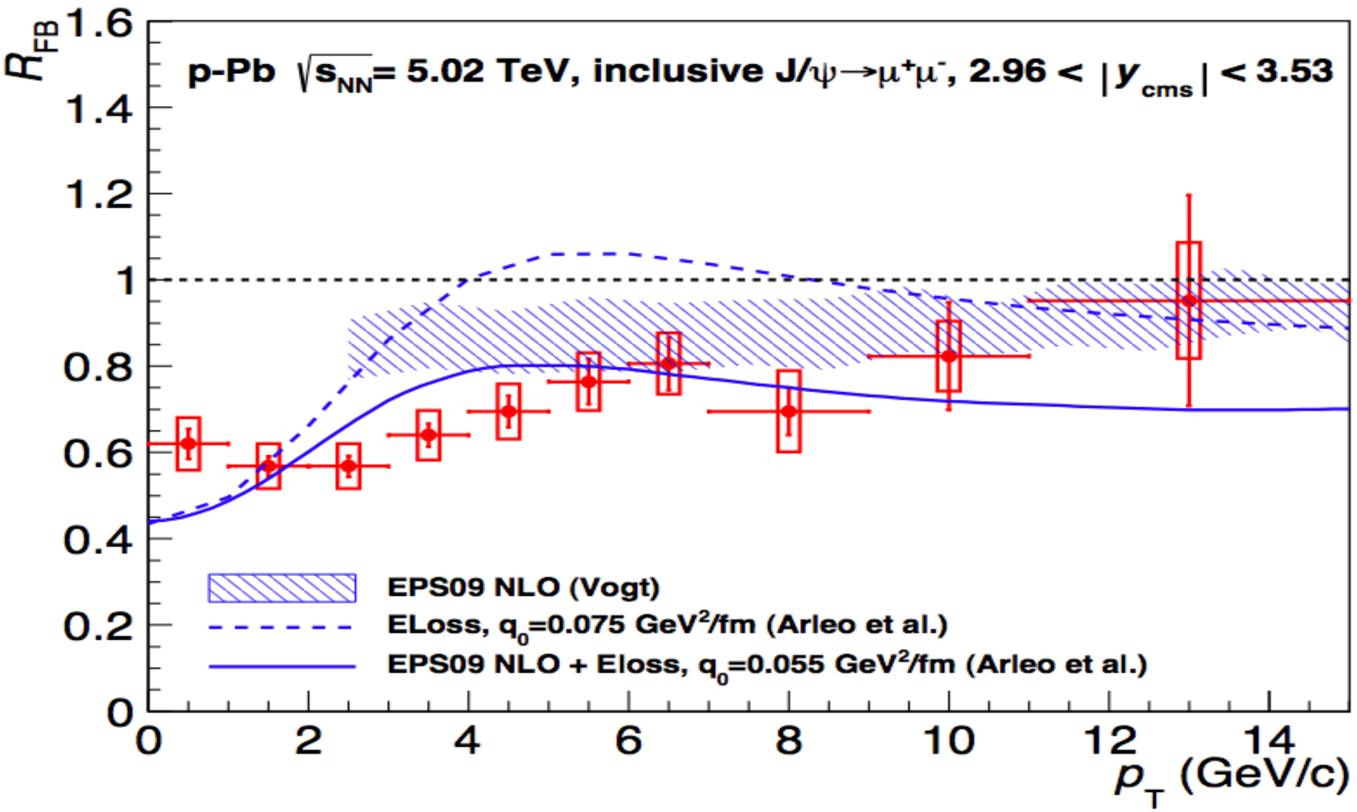
A-dependence in P_T in p+A

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

- **Model:**

$$\frac{1}{A}\frac{d\sigma_{\rm pA}^{\psi}}{dE\ d^2\vec{p}_\perp} = \int_\varepsilon \int_\varphi \mathcal{P}(\varepsilon, E)\,\frac{d\sigma_{\rm pp}^{\psi}}{dE\ d^2\vec{p}_\perp}\left(E+\varepsilon, \vec{p}_\perp - \Delta\vec{p}_\perp\right)$$

- **Nuclear A-dependence:** $R_{\rm pA}^{\psi}(y, p_\perp) \simeq R_{\rm pA}^{\rm loss}(y, p_\perp) \cdot R_{\rm pA}^{\rm broad}(p_\perp)$

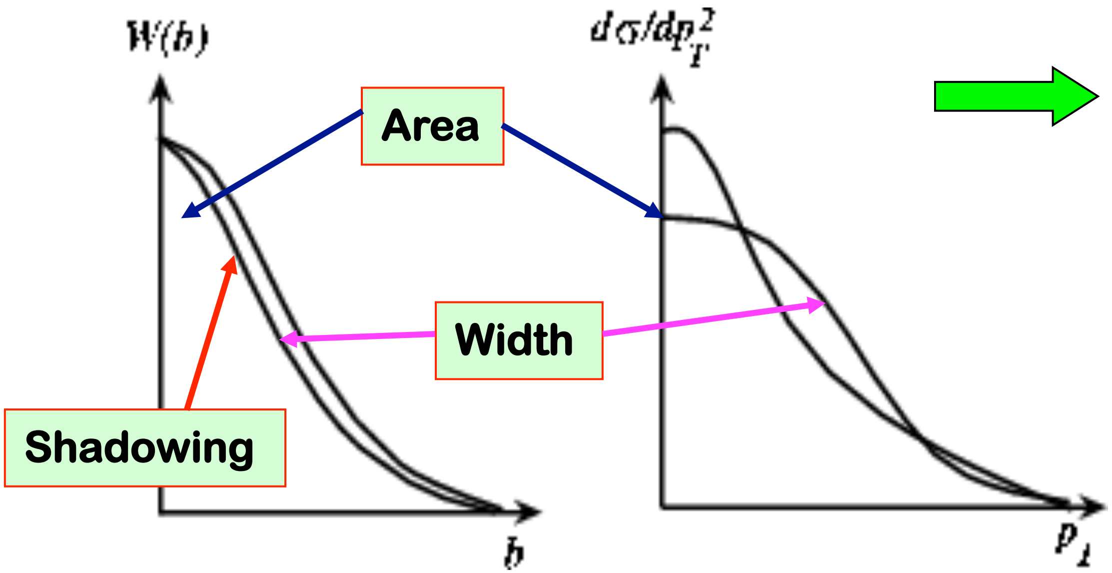


Quarkonium P_T distribution

- Quarkonium production is dominated in low p_T region
- Both quarkonium and Drell-Yan low p_T distributions at collider energies are determined by the gluon shower of incoming partons (initial-state effect)

Qiu, Zhang, PRL, 2001

- Because of heavy quark mass, final-state interactions suppress the formation of J/ψ, but should not be an important factor for low p_T spectrum



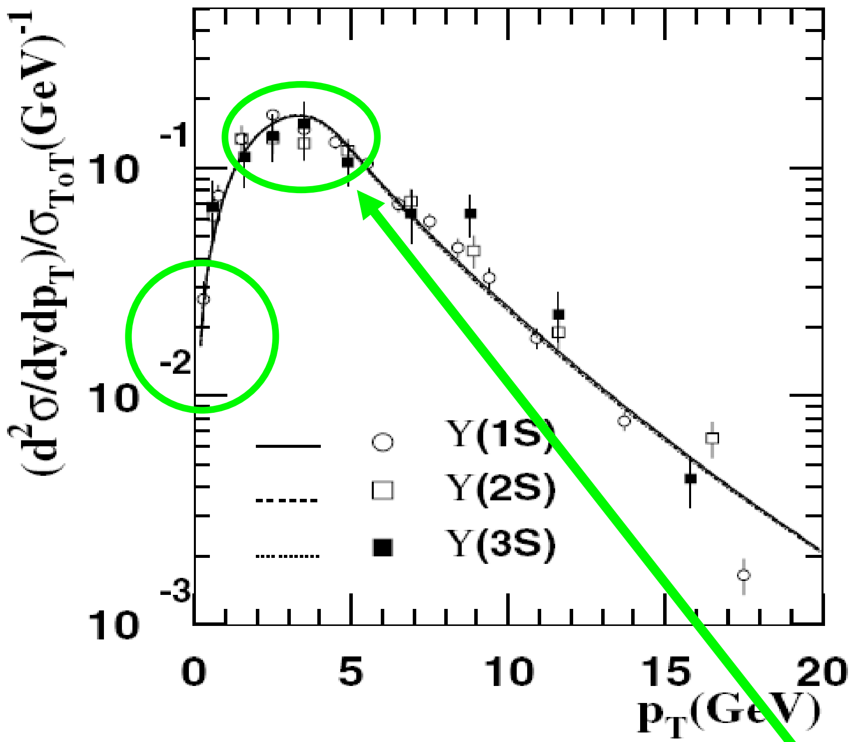
- ✧ Similar p_T broadening, but, different magnitude
- ✧ Extra overall suppression for J/ψ

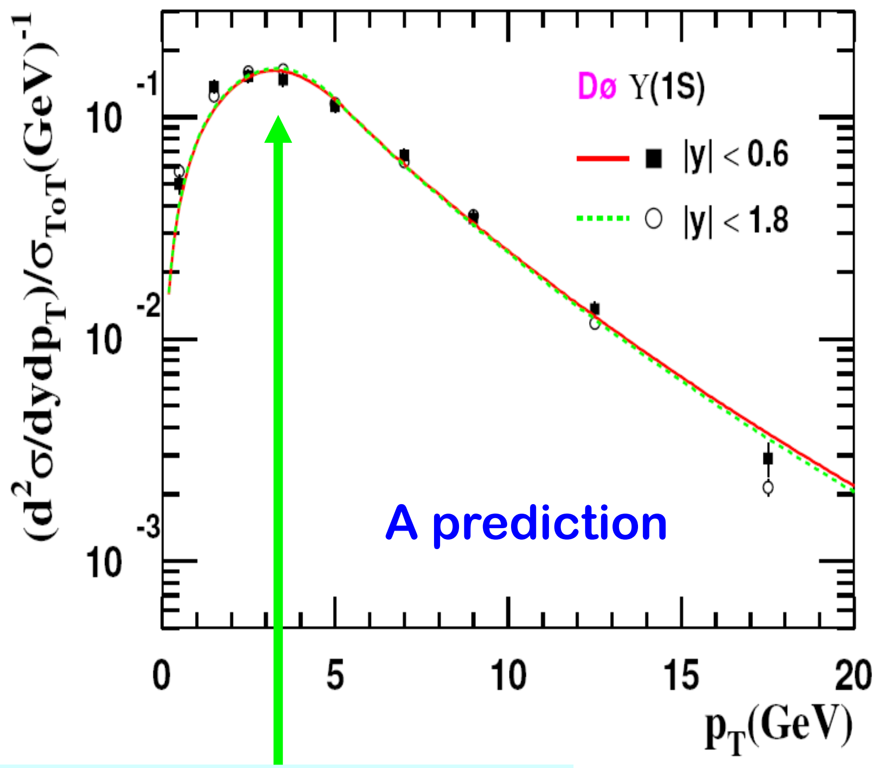
Guo, Qiu, Zhang, PRL, PRD, 2000

Quarkonium P_T distribution

- Y-spectrum is almost perturbative:

Berger, Qiu, Wang, PRD 2005





Dominated by perturbative small-b contribution in its Fourier conjugate space

I) Intrinsic

II) Shower – Sudakov

III) Perturbative tail

all order resummation of soft gluon shower

A-dependence in P_T in p+A

Guo, Qiu, Zhang, PRL, PRD 2002

- Ratio of x-sections:

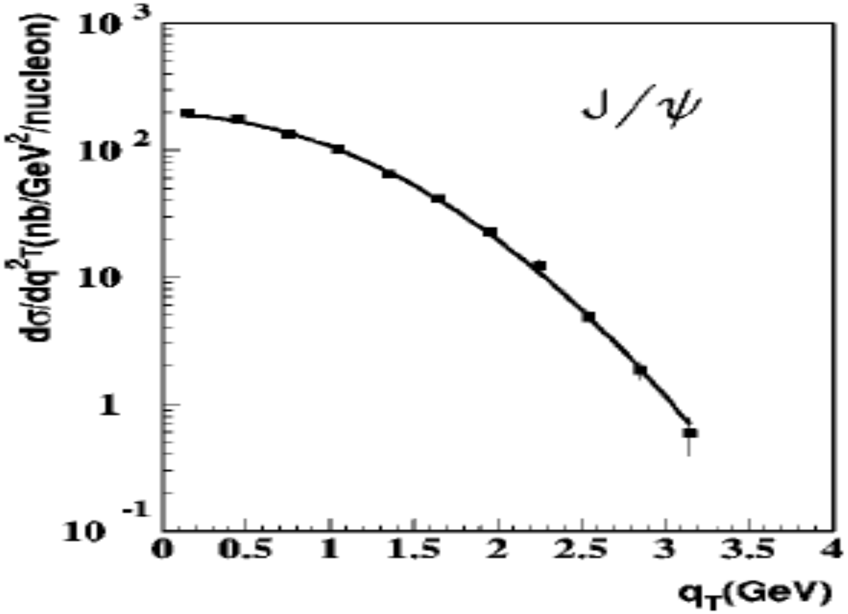
$$R(A,q_T) \equiv \frac{1}{A}\,\frac{d\sigma^{hA}}{dQ^2\,dq_T^2} \Big/ \frac{d\sigma^{hN}}{dQ^2\,dq_T^2} \equiv A^{\alpha(A,q_T)-1}$$

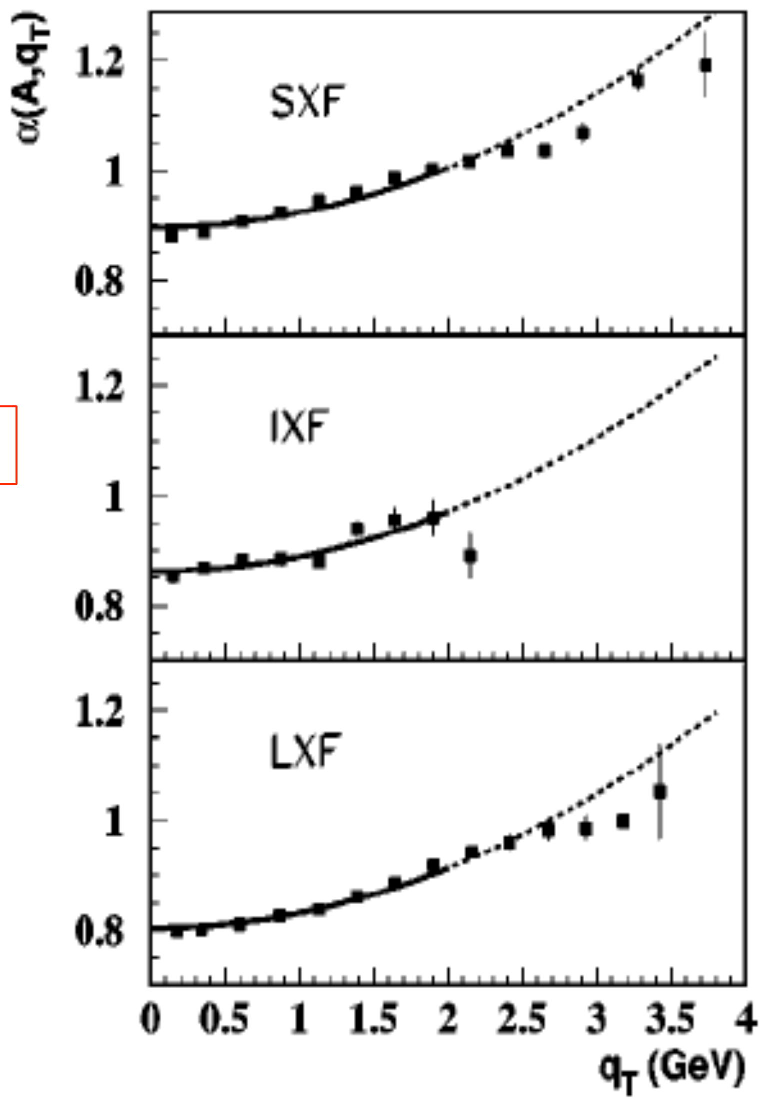
$$\approx 1 + \frac{\Delta\langle q_T^2\rangle}{A^{1/3}\langle q_T^2\rangle_{\rm DY}^{hN}}\left[-1 + \frac{q_T^2}{\langle q_T^2\rangle_{\rm DY}^{hN}}\right]$$

Similar formula for J/ψ

- Spectrum and ratio:

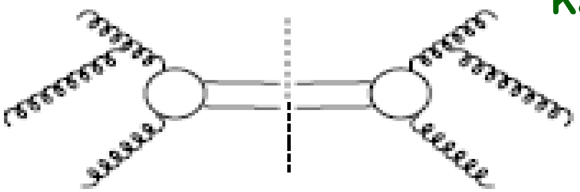
E772 data





Quarkonium P_T-broadening in p+A

Kang, Qiu, PRD77(2008)



- **Initial-state only:**

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

$$\Delta\langle q_T^2\rangle_{DY} \approx C_F\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\lambda^2 A^{1/3}\right)$$

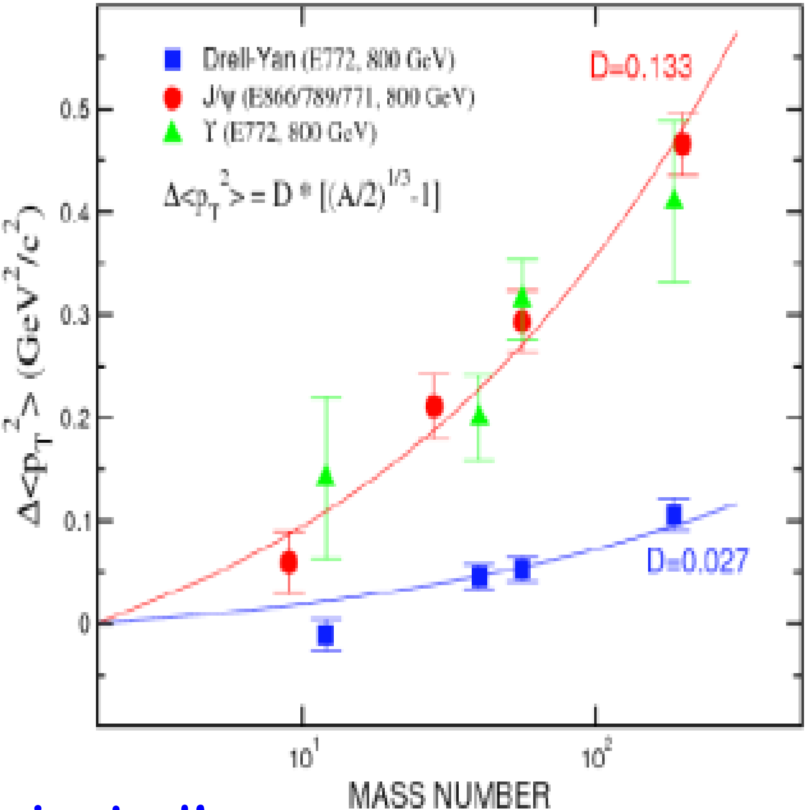
- **Experimental data from d+A:**

Clear $A^{1/3}$ dependence

But, wrong normalization!

$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi} \Big/ \Delta\langle q_T^2\rangle_{DY}\Big|_{thy} = C_A/C_F = 2.25$$

$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi} \Big/ \Delta\langle q_T^2\rangle_{DY}\Big|_{exp} = 0.133/0.027 \approx 4.9$$



Final-state effect – octet channel dominated!

Only depend on observed quarkonia

J.C.Peng, hep-ph/9912371

Johnson,et al, 2007

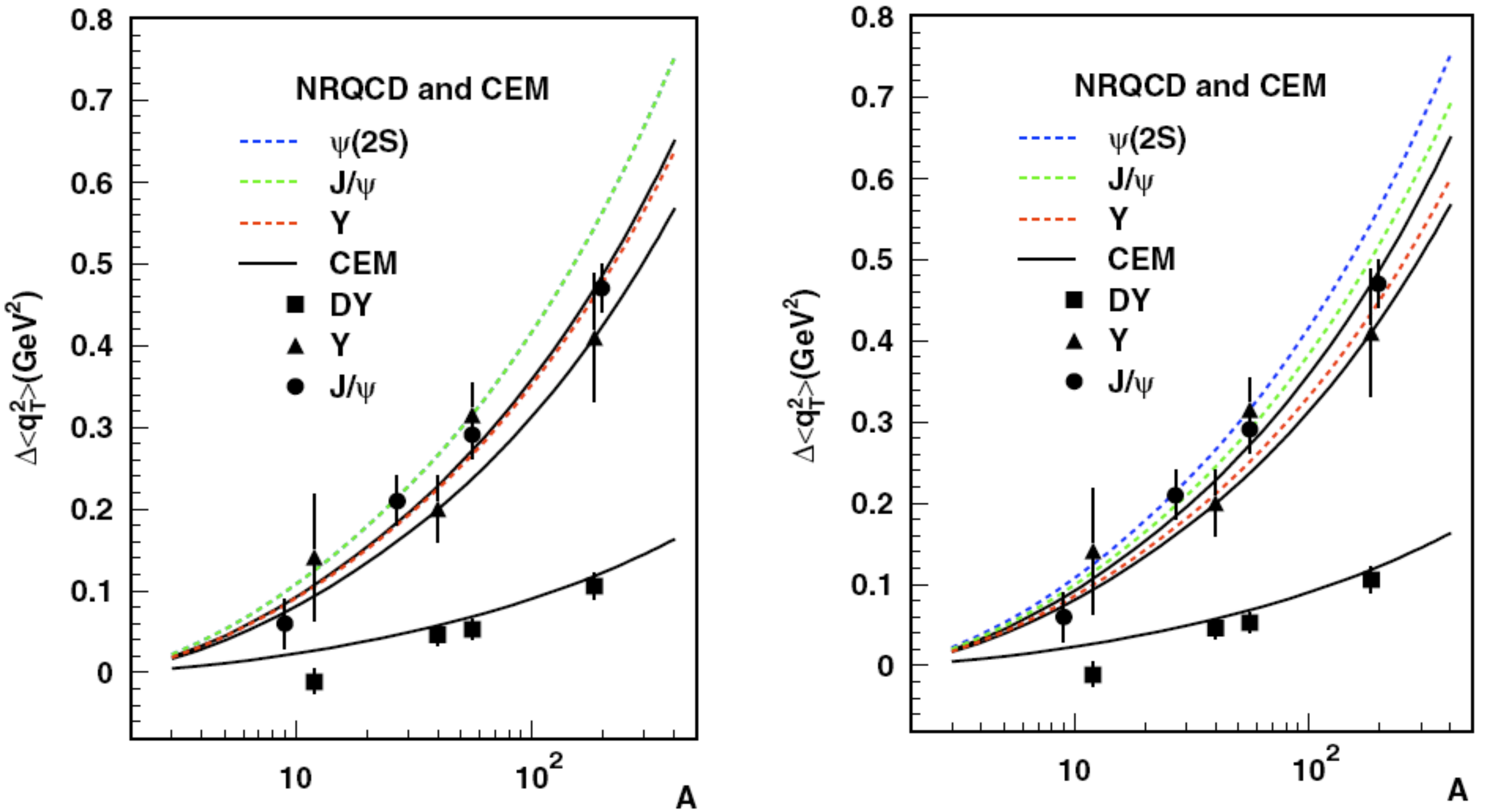
Broadening of heavy quarkonia in p(d)+A

Kang, Qiu, PRD77(2008)

- ❑ Final-state effect is important:

$$\Delta\langle q_T^2\rangle_{J/\psi}^{(I+F)} \Big/ \Delta\langle q_T^2\rangle_{\rm DY}\Big|_{\rm thy} \approx 2C_A/C_F = 4.5$$

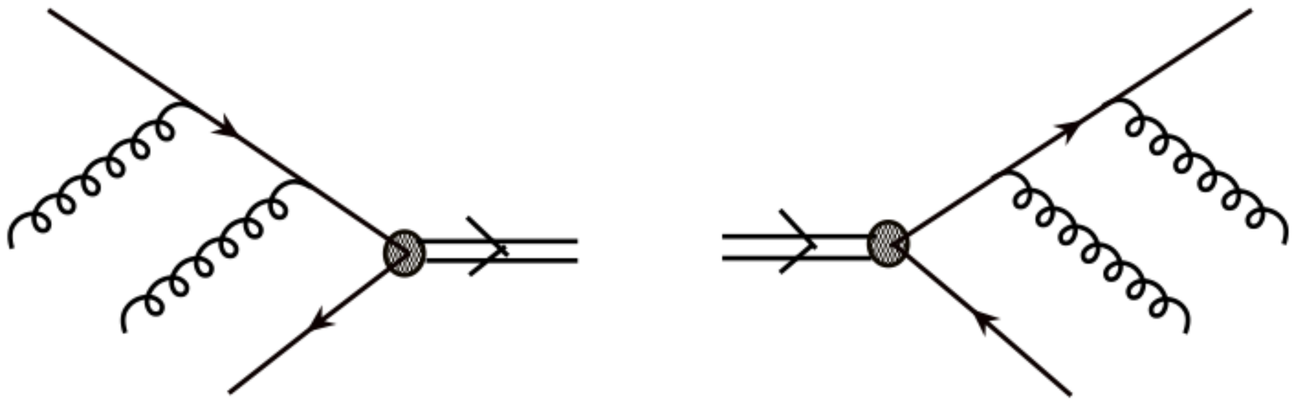
in both CEM and NRQCD



- ❑ Mass – independence, not very sensitive to the feeddown

Rapidity dependence in p+A

❑ **Resummed multiple scattering:**



$$\sigma_{PA}(p_T, x_F) \propto \sum_{a,b} \xi_g^2 \, x \frac{d}{dx} \left[f_{a/p}(x_F + x) f_{b/A}(x) \right]_{x = x_2(x_F, Q)}$$

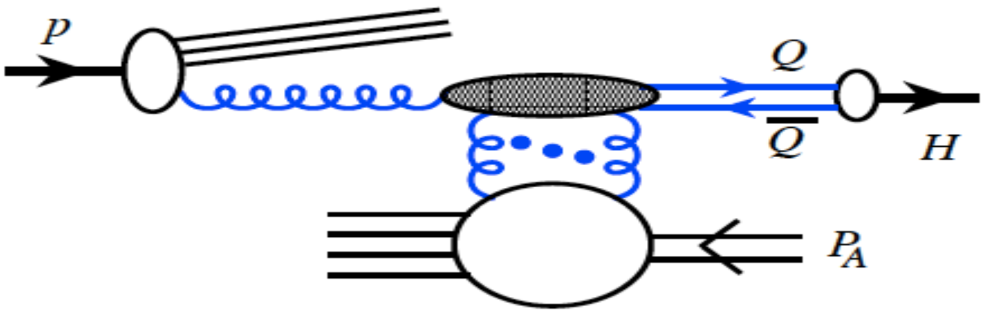
In the forward region,

$$\frac{d}{dx} \left[f_{a/p}(x_F + x) \right]_{x = x_2(x_F, Q)} \gg \frac{d}{dx} \left[f_{b/A}(x) \right]_{x = x_2(x_F, Q)}$$

$$x_1 = x_F + x_2 \qquad\qquad x_2 = \frac{1}{2} \left[\sqrt{x_F^2 + 4Q^2/s} - x_F \right]$$

Quarkonium p_T distribution in high energy pA

❑ QCD factorization for $A^{1/3}$ enhanced contribution:



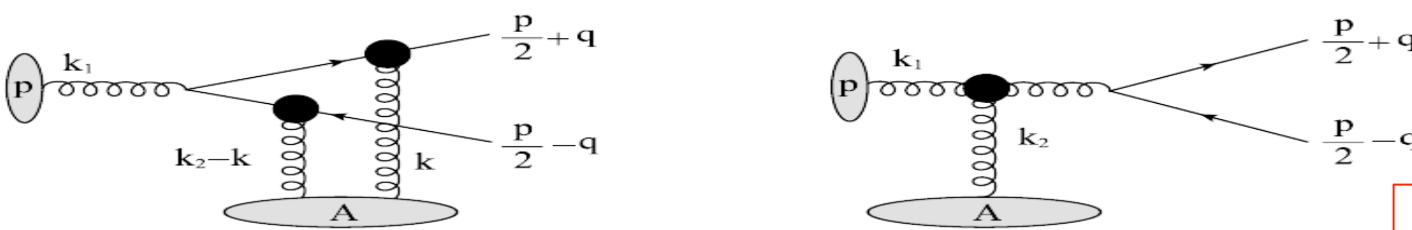
Time dilation factor:

$$\frac{1}{mv}\left(\frac{P_{\|}}{M}\right) \gg \frac{1}{P_{\perp}} \sim \frac{1}{Q_s(A)}$$

$$\Leftrightarrow\ y \gg \ln\left(\frac{2mv}{P_T}\right) \sim \ln\left(\frac{Mv}{Q_s(A)}\right)$$

Condition for multiple scattering not to interfere with hadronization

❑ Heavy quarkonium production in pA collisions:



(a) (b)

No numerical prediction yet

✧ **Kang et al.:** 1309.7337 — NRQCD, CEM, $P_T \sim Q_s >> M$, …
– small-x evolution + CGC multiple scattering

✧ **Qiu et al.:** 1310.2230 — NRQCD, CEM, $P_T \sim Q_s << M$
– Coherent multiple scatteing + Sudakov resummation

Summary

- Heavy quarkonium production has been a powerful tool to test and challenge our understanding of strong interaction and QCD

- Both initial-state and final-state multiple scattering are relevant for nuclear dependence of quarkonium production – could redistribute both the p_T and y dependence

- Nuclei could be excellent filters to help identify the production and suppression mechanism via the multiple scattering

- J-PARC program on heavy quarkonium production could provide very important contributions to the search of the true production mechanism of heavy quarkonia

Thank you!

Backup slides

Final-state multiple scattering - CEM

- Double scattering – $A^{1/3}$ dependence:

Kang, Qiu, PRD77(2008)

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm CEM} \approx \int dq_T^2 q_T^2 \int_{4m_Q^2}^{4M_Q^2} dQ^2 \frac{d\sigma^D_{hA\to Q\bar{Q}}}{dQ^2 dq_T^2} \Big/ \int_{4m_Q^2}^{4M_Q^2} dQ^2 \frac{d\sigma_{hA\to Q\bar{Q}}}{dQ^2}$$

- Multiparton correlation:

$$T_{g/A}^{(F)}(x) = T_{g/A}^{(I)}(x) = \int \frac{dy^-}{2\pi} e^{ixp^+y^-} \int \frac{dy_1^- dy_2^-}{2\pi} \theta(y^- - y_1^-)\theta(-y_2^-) \times \frac{1}{xp^+} \langle p_A | F_\alpha{}^+(y_2^-) F^{\sigma +}(0) F^+{}_\sigma(y^-) F^{+\alpha}(y_1^-) | p_A \rangle$$

$$= \lambda^2 A^{4/3} \phi_{g/A}(x)$$

- Broadening – twice of initial-state effect:

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm CEM} = \left(\frac{8\pi^2\alpha_s}{N_c^2-1}\lambda^2 A^{1/3}\right) \frac{(C_F + C_A)\sigma_{q\bar{q}} + 2C_A\sigma_{gg}}{\sigma_{q\bar{q}} + \sigma_{gg}}$$

$$\approx 2C_A\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\lambda^2 A^{1/3}\right)$$

if gluon-gluon dominates,
and if $r_F > R_A$

Final-state multiple scattering - NRQCD

Kang, Qiu, PRD77(2008)

- Cross section:

$$\sigma_{hA\to H}^{\rm NRQCD} = A\sum_{a,b}\int dx'\phi_{a/h}(x')\int dx\phi_{b/A}(x)\left[\sum_n H_{ab\to Q\bar{Q}[n]}\langle \mathcal{O}^H(n)\rangle\right]$$

- Broadening:

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm NRQCD} = \left(\frac{8\pi^2\alpha_s}{N_c^2-1}\lambda^2 A^{1/3}\right)\frac{(C_F+C_A)\sigma_{q\bar{q}}^{(0)} + 2C_A\sigma_{gg}^{(0)} + \sigma_{q\bar{q}}^{(1)}}{\sigma_{q\bar{q}}^{(0)} + \sigma_{gg}^{(0)}}$$

Hard parts:

$$\hat{\sigma}_{q\bar{q}}^{(0)} = \frac{\pi^3\alpha_s^2}{M^3}\frac{16}{27}\delta(\hat{s}-M^2)\langle\mathcal{O}^H({}^3S_1^{(8)})\rangle$$

$$\hat{\sigma}_{q\bar{q}}^{(1)} = \frac{\pi^3\alpha_s^2}{M^3}\frac{80}{27}\delta(\hat{s}-M^2)\langle\mathcal{O}^H({}^3P_0^{(8)})\rangle$$

$$\hat{\sigma}_{gg}^{(0)} \equiv \frac{\pi^3\alpha_s^2}{M^3}\frac{5}{12}\delta(\hat{s}-M^2)\left[\langle\mathcal{O}^H({}^1S_0^{(8)})\rangle + \frac{7}{m_Q^2}\langle\mathcal{O}^H({}^3P_0^{(8)})\rangle\right]$$

Only color octet channel contributes

- Leading features:

$$\Delta\langle q_T^2\rangle_{\rm HQ}^{\rm NRQCD} \approx \Delta\langle q_T^2\rangle_{\rm HQ}^{\rm CEM} \approx (2C_A/C_F)\Delta\langle q_T^2\rangle_{\rm DY}$$