Theoretical aspects of quarkonia production and suppression in cold and hot nuclear matter

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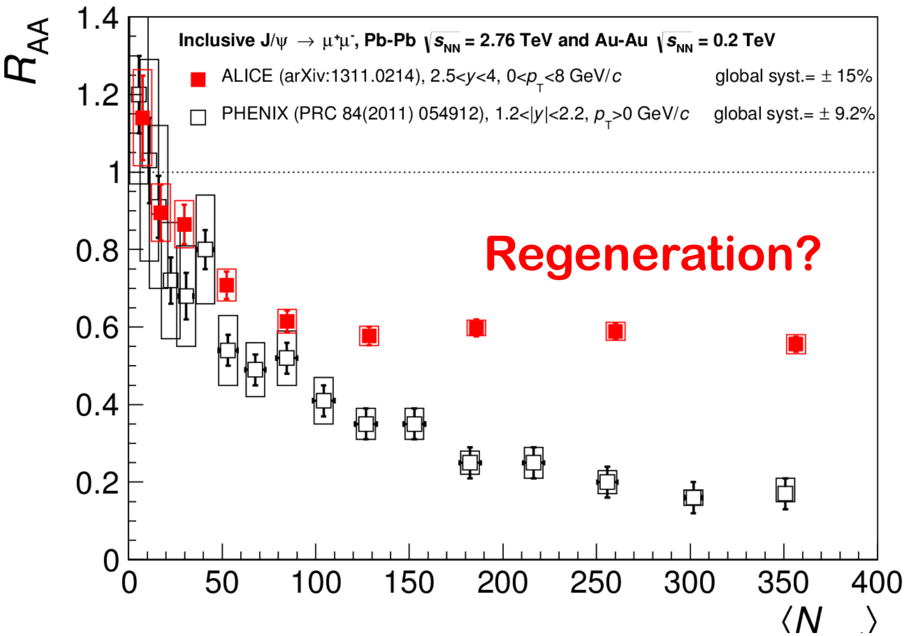
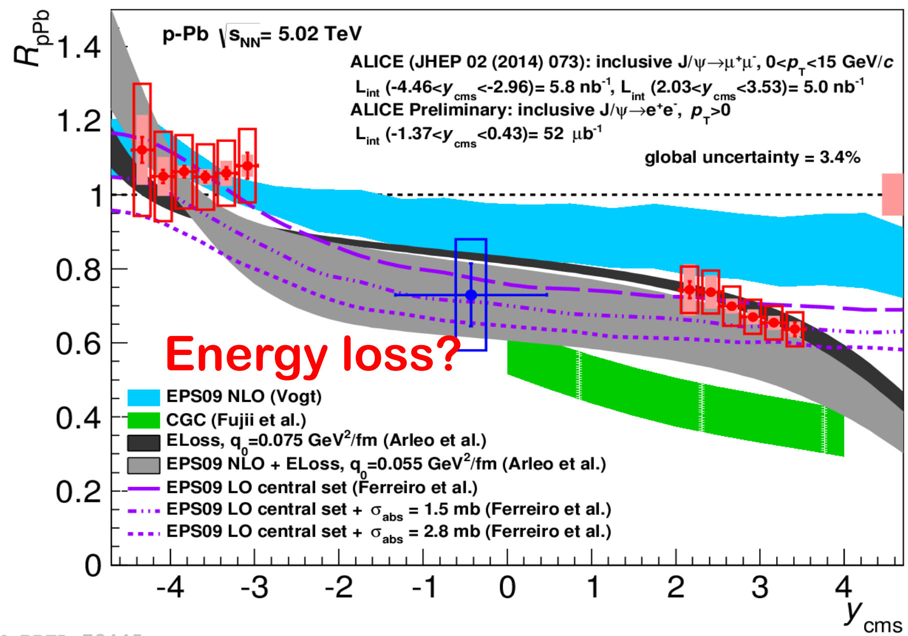
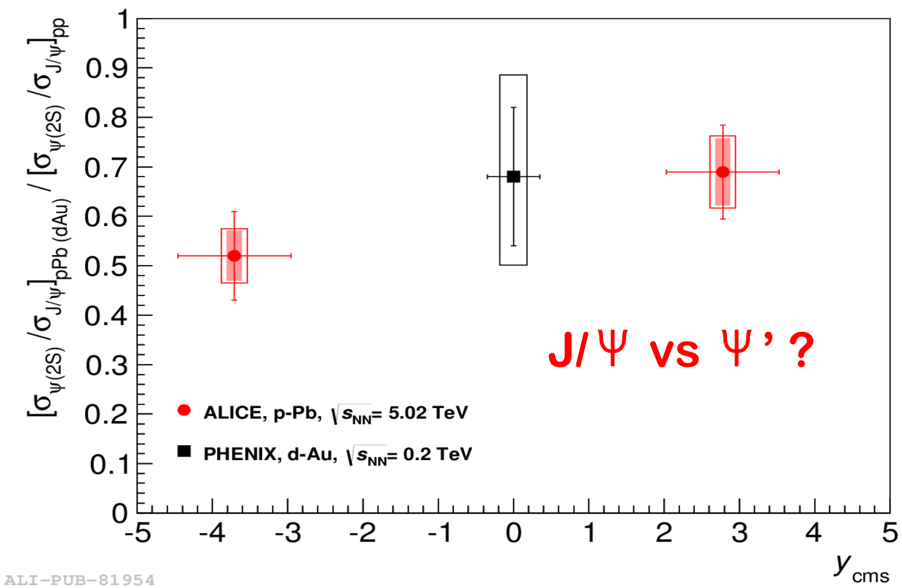
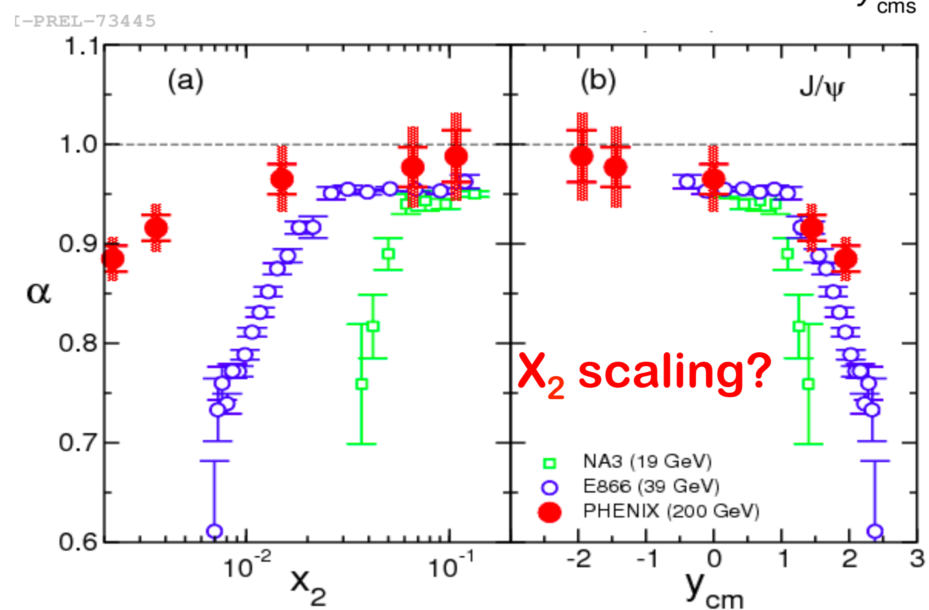
Apology for not being able to cover the tremendous amount of theoretical work done on this topic, …

Heavy quarkonium – puzzles









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

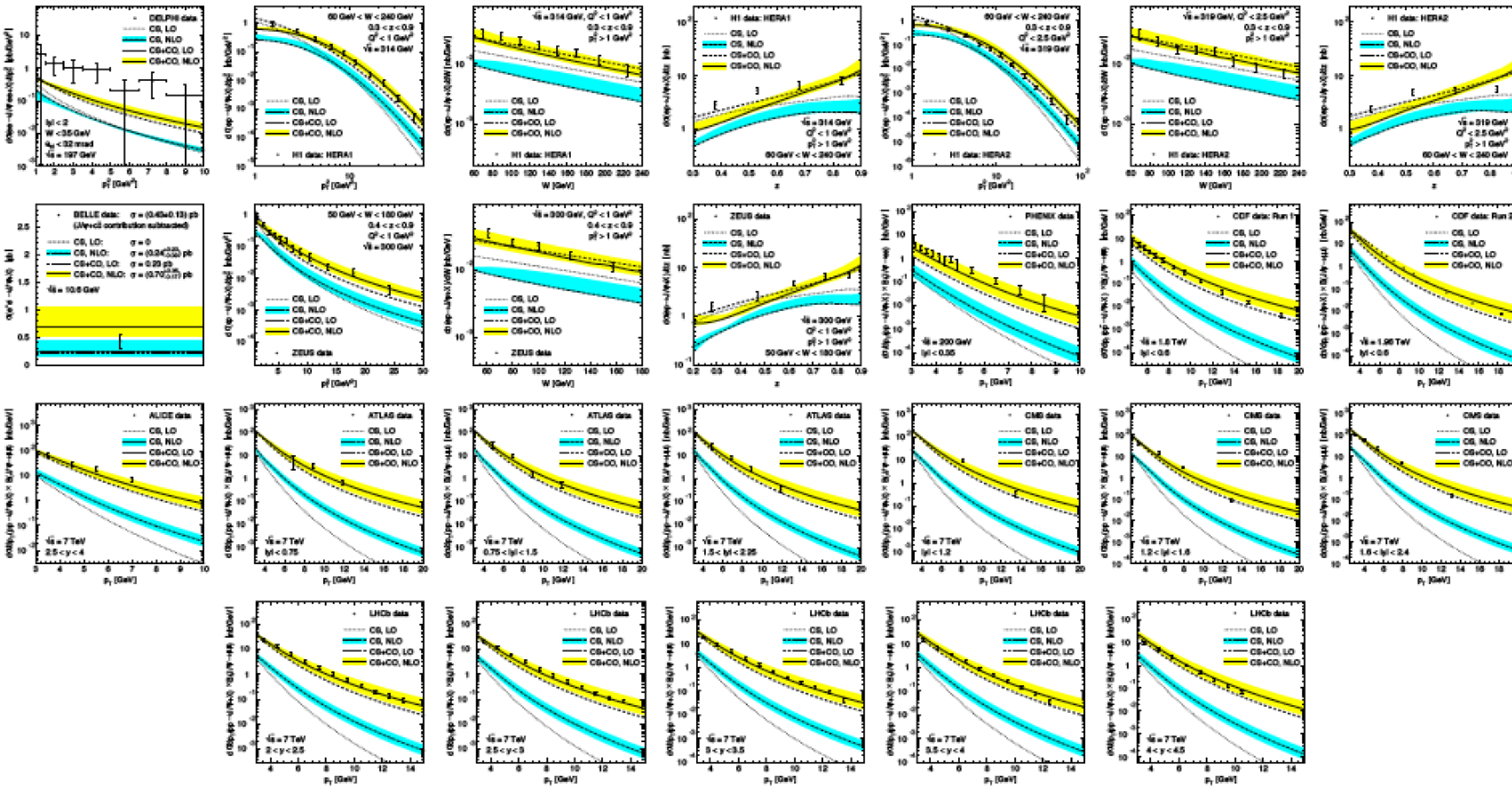
  Unknown, but universal, fragmentation functions – evolution

- Soft-Collinear Effective Theory + NRQCD: 2012 –

  See Bodwin's talk

  Fleming, Leibovich, Mehen, …

NRQCD – global analysis



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

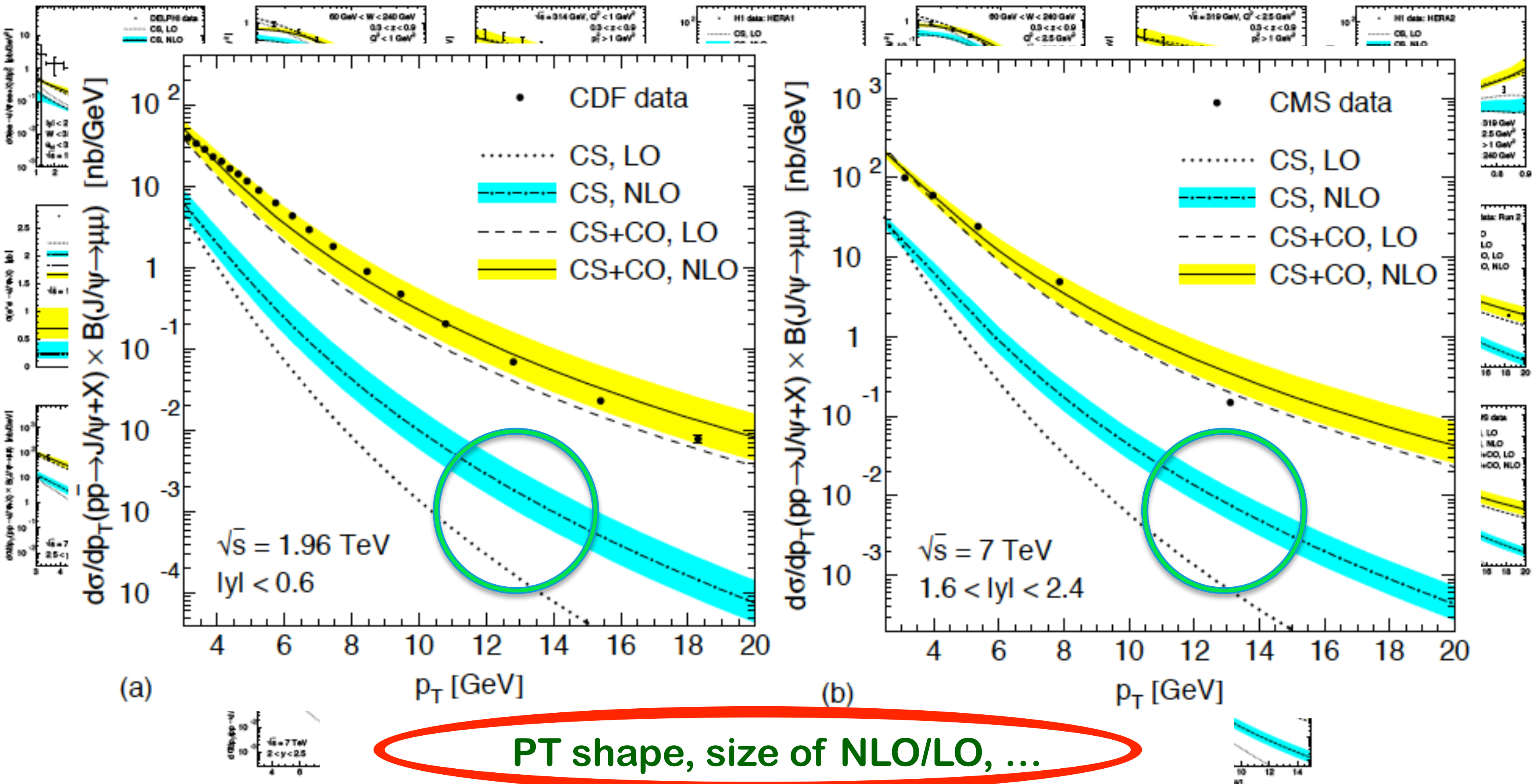
$\langle O[^1S_0^{[8]}]\rangle = (4.97 \pm 0.44)\cdot 10^{-2}\ \mathrm{GeV}^3$ $\langle O[^3S_1^{[8]}]\rangle = (2.24 \pm 0.59)\cdot 10^{-3}\ \mathrm{GeV}^3$

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

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

Butenschoen and Kniehl, arXiv: 1105.0820

NRQCD – global analysis



PT shape, size of NLO/LO, ...

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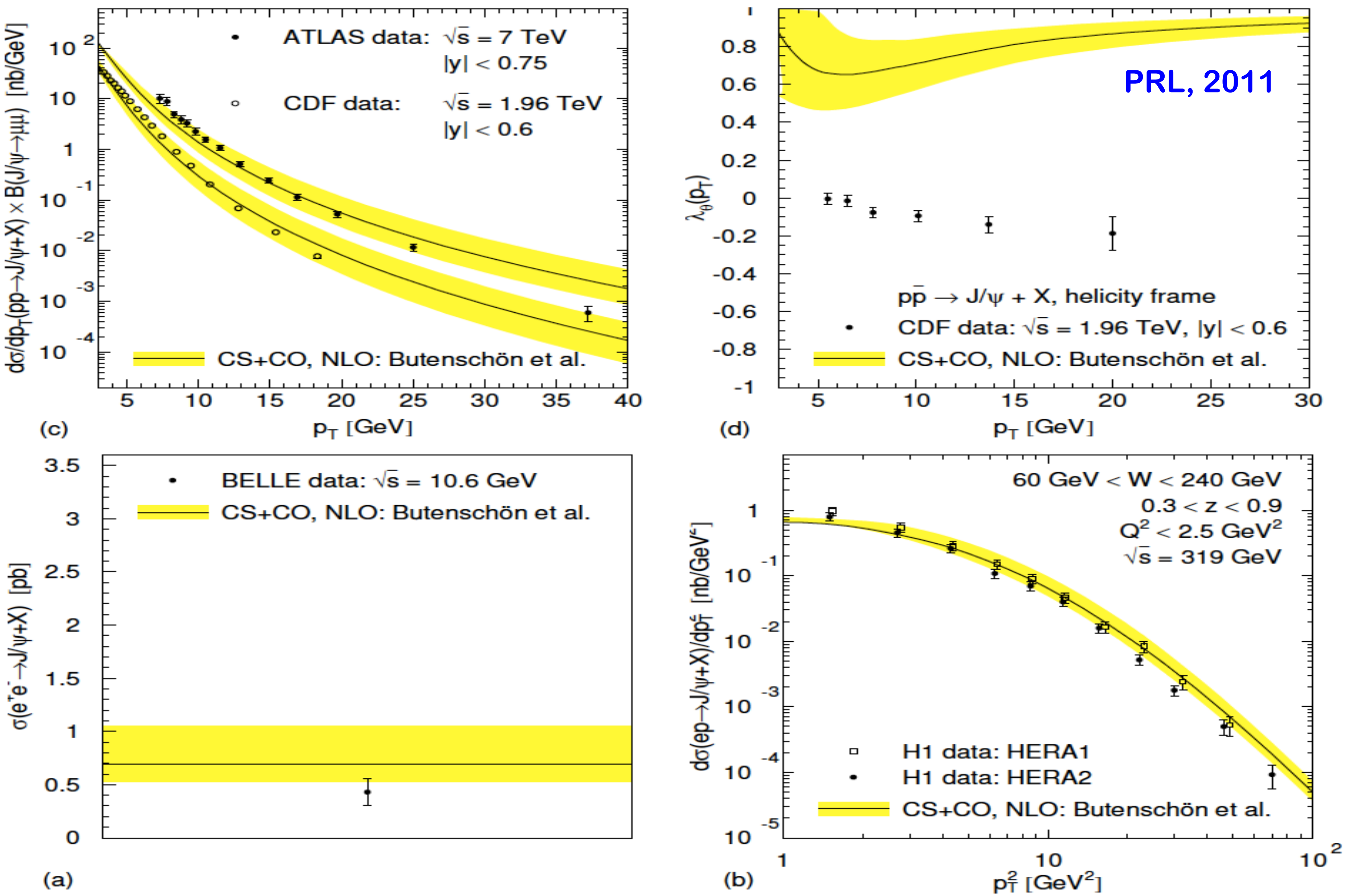
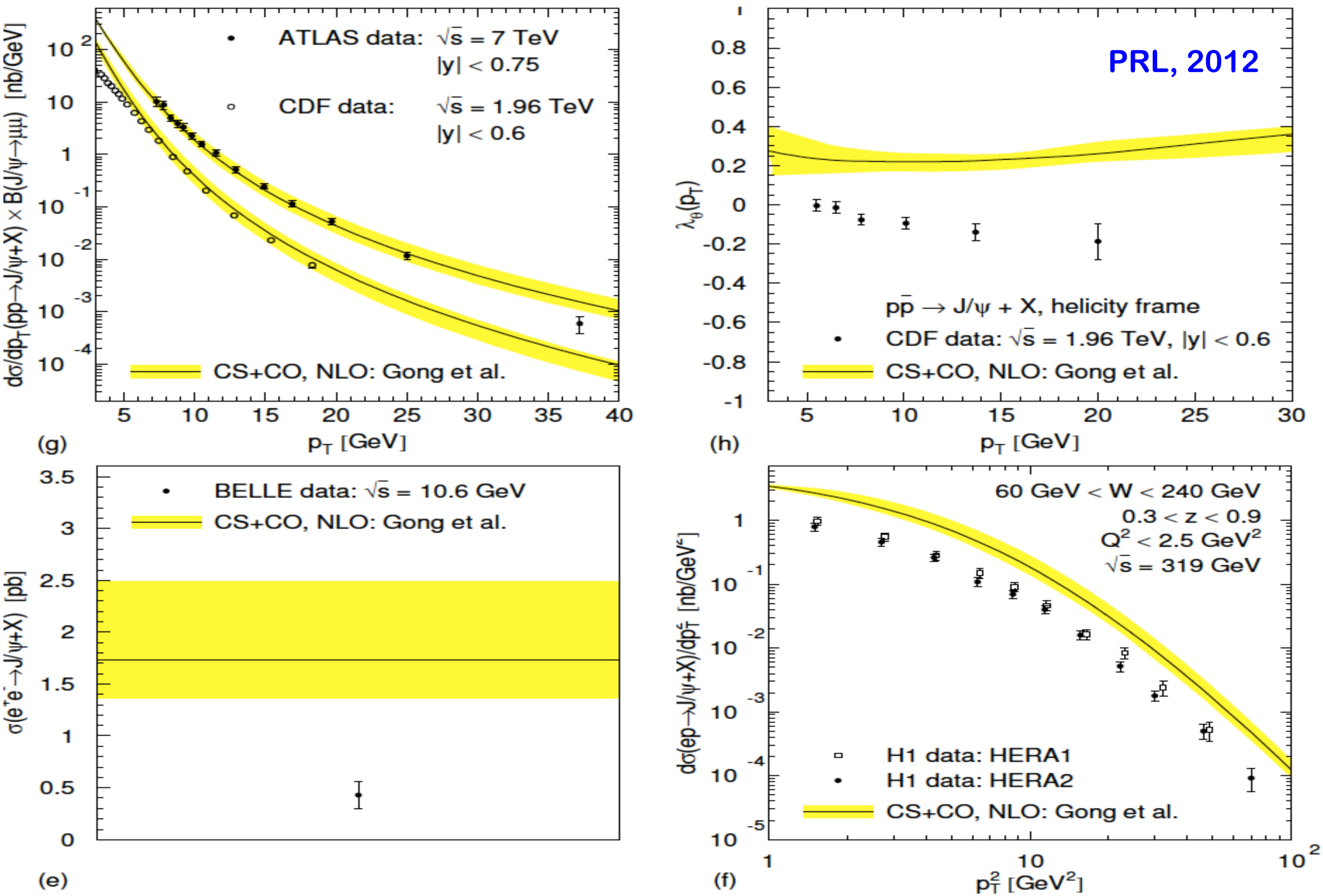
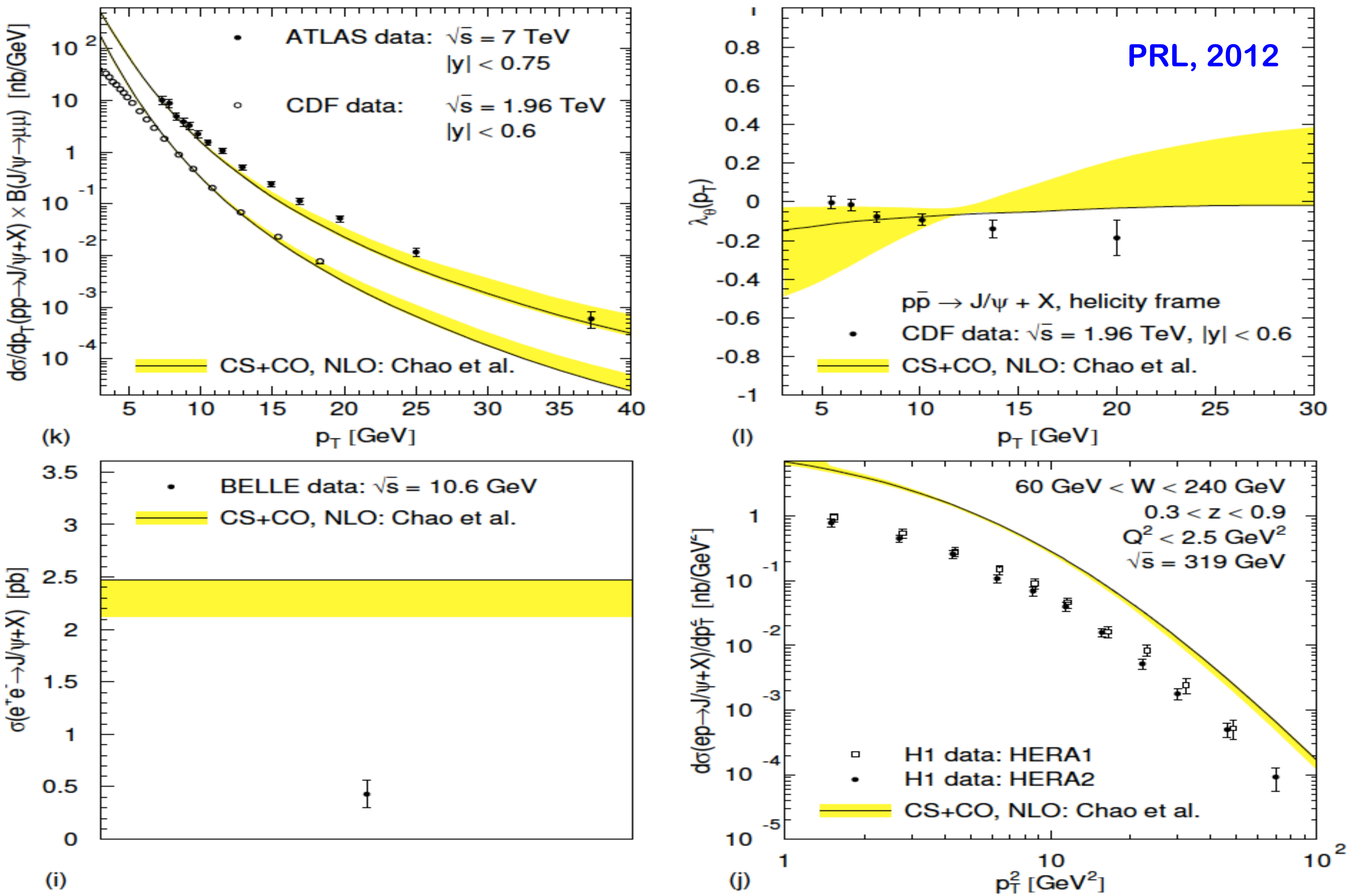
NLO NRQCD vs data – Butenschoen et al.



NLO NRQCD vs data – Gong et al.



NLO NRQCD vs data – Chao et al.

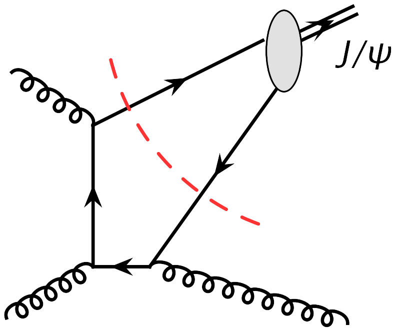


Why high orders in NRQCD are so large?

- Consider J/ψ production in CSM:

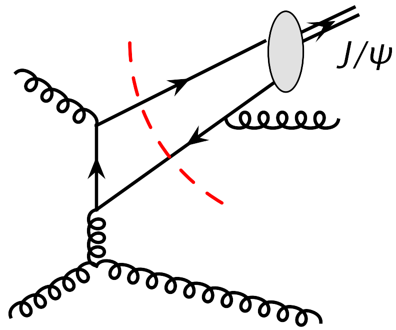
Kang, Qiu and Sterman, 2011

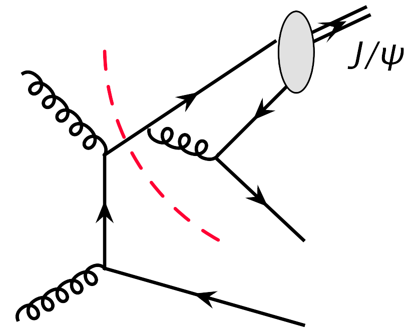
See also talk by H. Zhang



LO in α_s

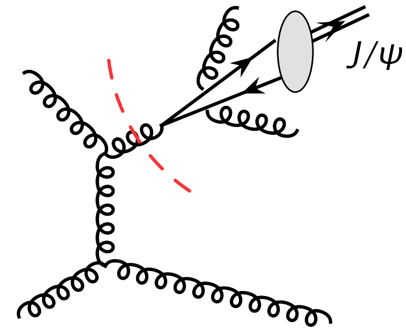
NNLP $\propto \alpha_s^3 \frac{m_Q^4}{p_T^8}$





NLO in α_s

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



NNLO in α_s

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

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

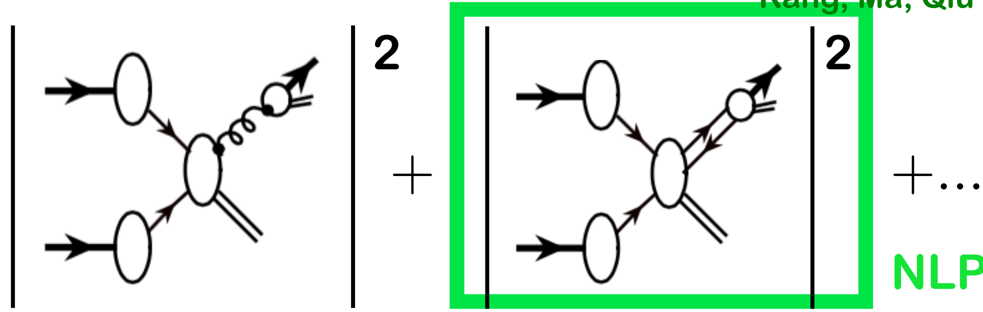
Leading order in α_s-expansion =\= leading power in 1/p_T-expansion!

At high p_T, fragmentation contribution dominant

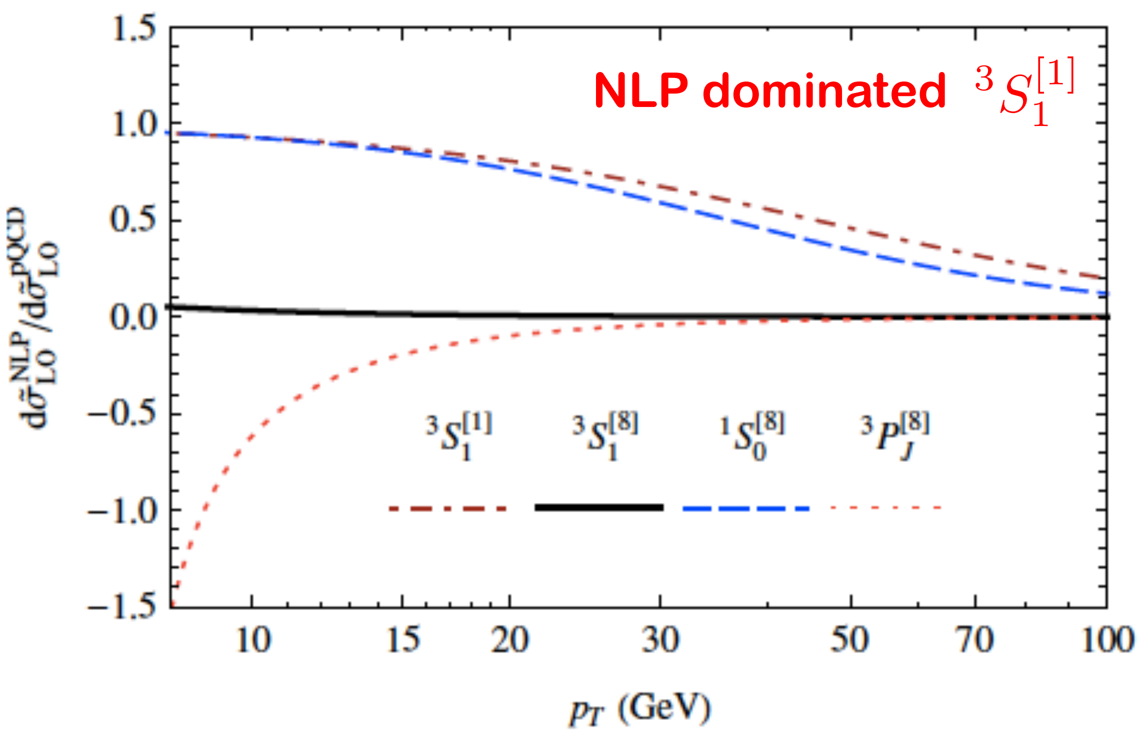
QCD factorization – Kang et al.

Kang, Ma, Qiu and Sterman, 2014

$$\frac{d\sigma_{AB\to H+X}}{dy\,dp_T^2} = $$



❑ Channel-by-channel, LP vs. NLP (both LO):



independent of NRQCD LDMEs

LP dominated

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

NLP dominated

$^1S_0^{[8]}$

for wide pT

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

QCD Factorization = better controlled HO corrections!

PRL, 2014

QCD factorization vs NRQCD factorization

See Bodwin's talk

- **Matching if both factorizable:**

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

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

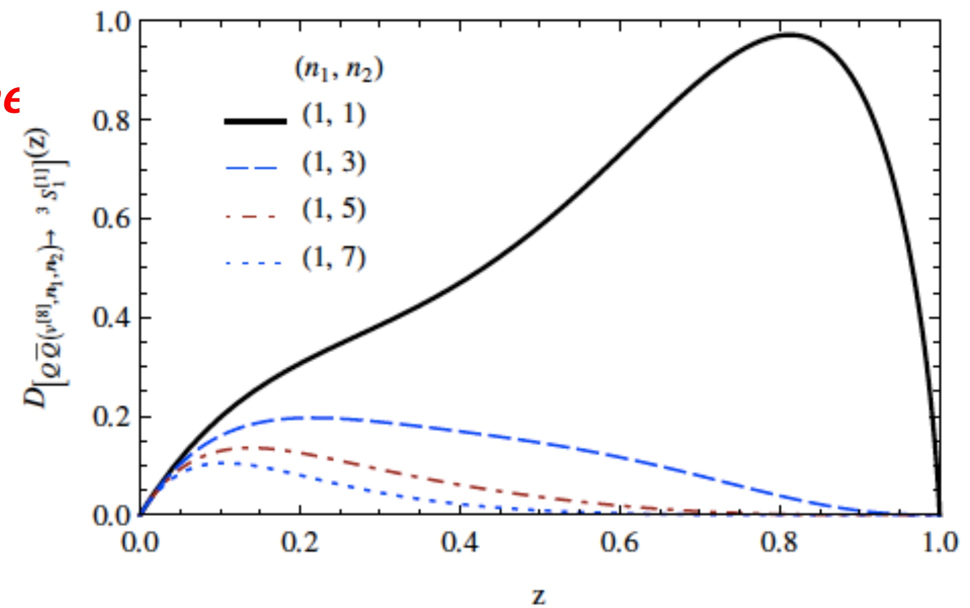
Mass effect + P_T region ($P_T \gtrsim m_Q$)

- **Fragmentation functions – nonperturbative!**

Responsible for "polarization",
relative size of production channe

- **Model of FFs:**
  - ✧ NRQCD factorization of FFs
  - ✧ Express all FFs in terms of *a few* NRQCD LDMEs

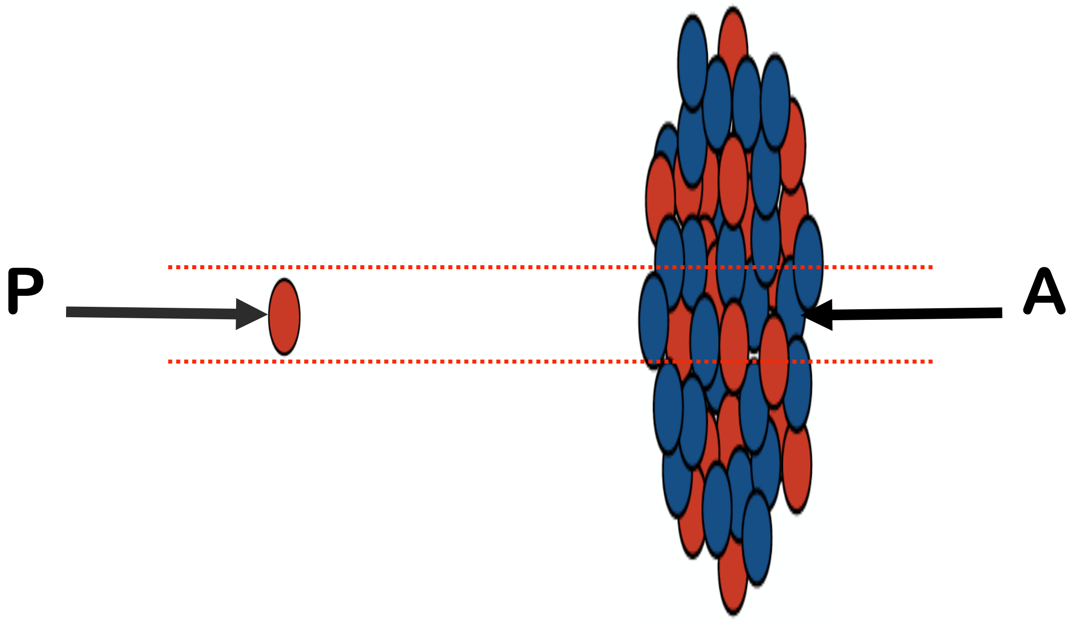
$$\mathcal{D}^{[n_1,n_2]}(z) \equiv \int_{-1}^{1} \frac{d\zeta_1\, d\zeta_2}{4} \zeta_1^{n_1} \zeta_2^{n_2} \mathcal{D}(z, \zeta_1, \zeta_2)$$



QCD factorization approach is ready to compare with Data

Production in p(d)+A collisions

❑ Proton (deuteron) – Nucleus Collisions:



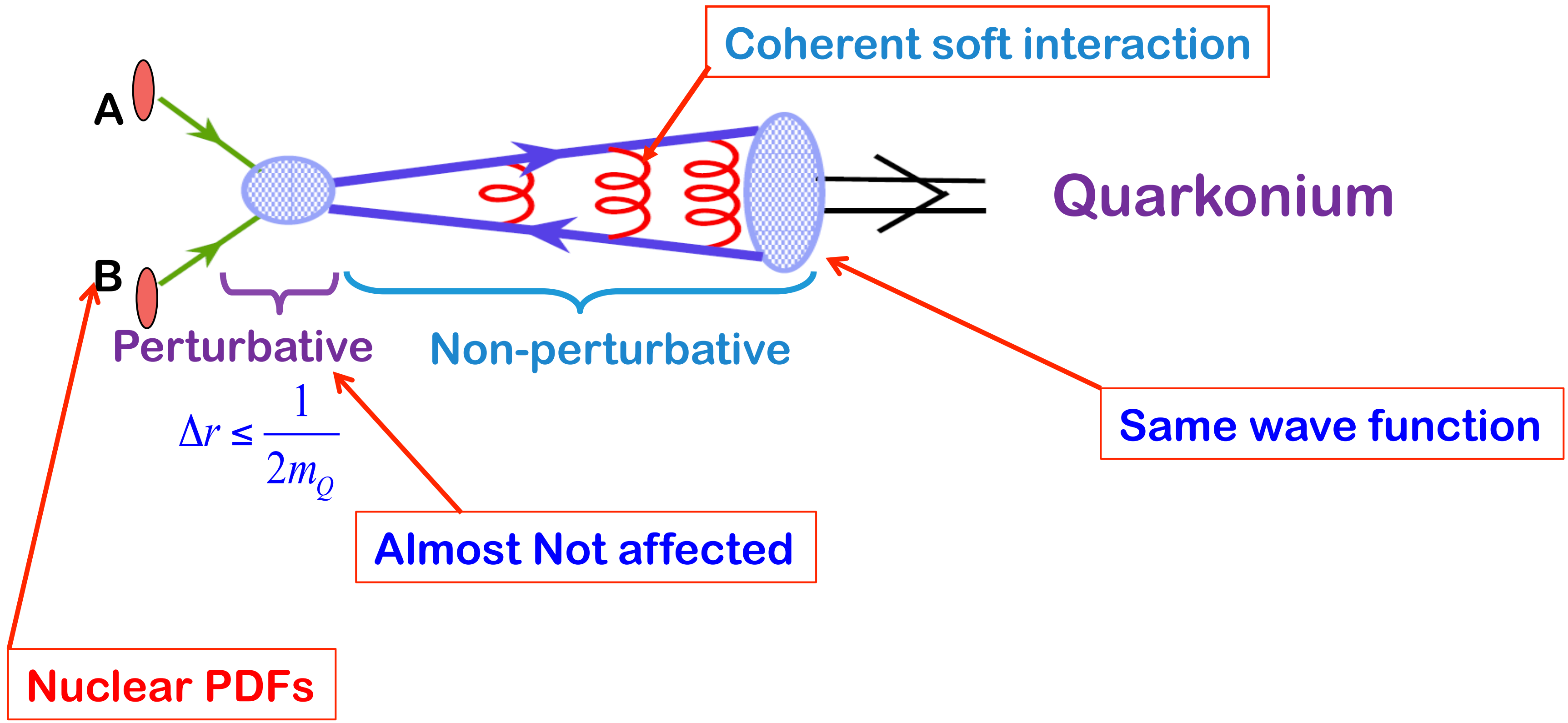
✧ NO QGP ($m_Q >> T$)! ➡ Cold nuclear effect for the "production"

✧ Necessary calibration for AA collisions

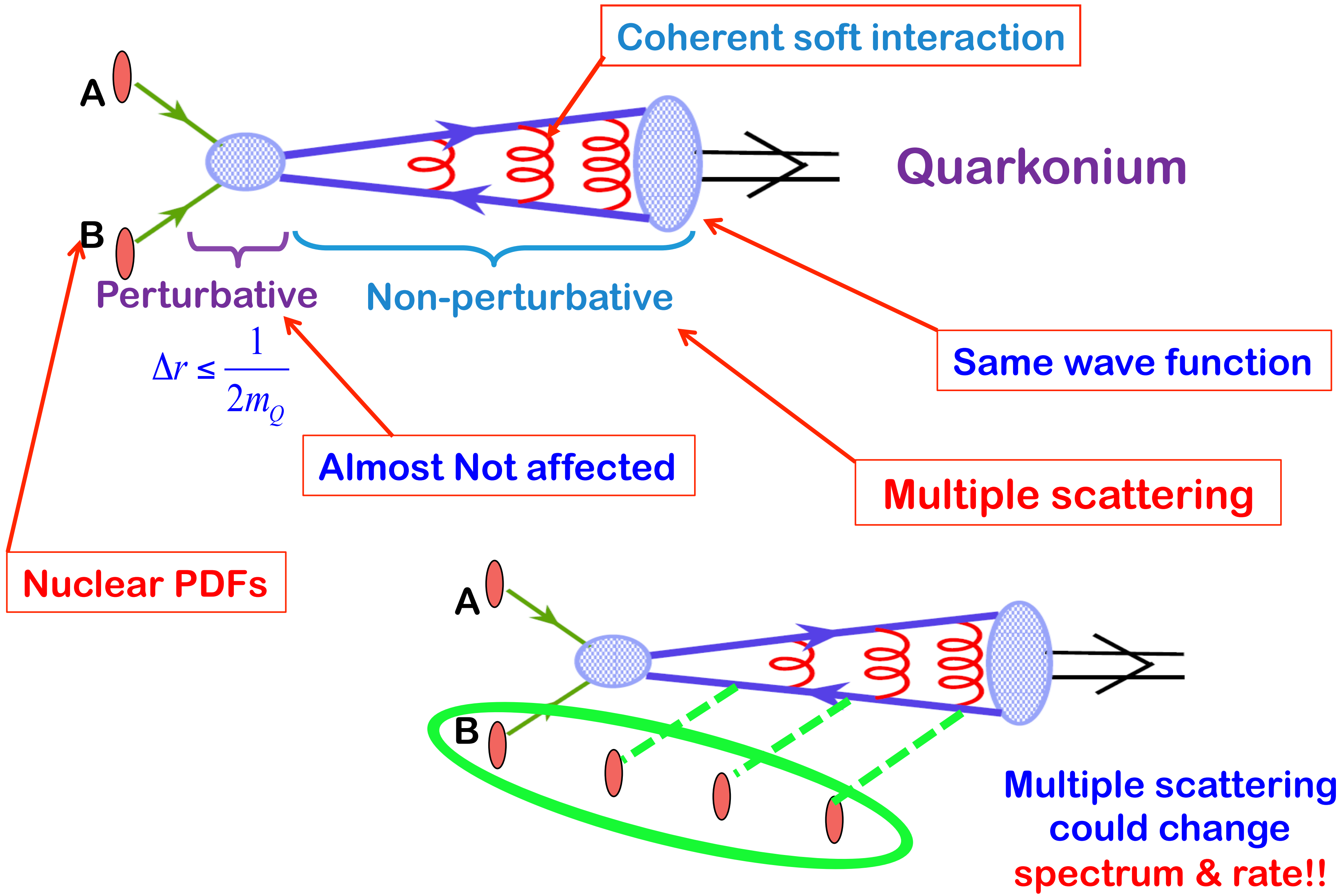
✧ Hard probe ($m_Q >> 1/fm$) ➡ quark-gluon structure of nucleus!

Nucleus is not a simple superposition of nucleons!

Production in p(d)+A collisions



Production in p(d)+A collisions



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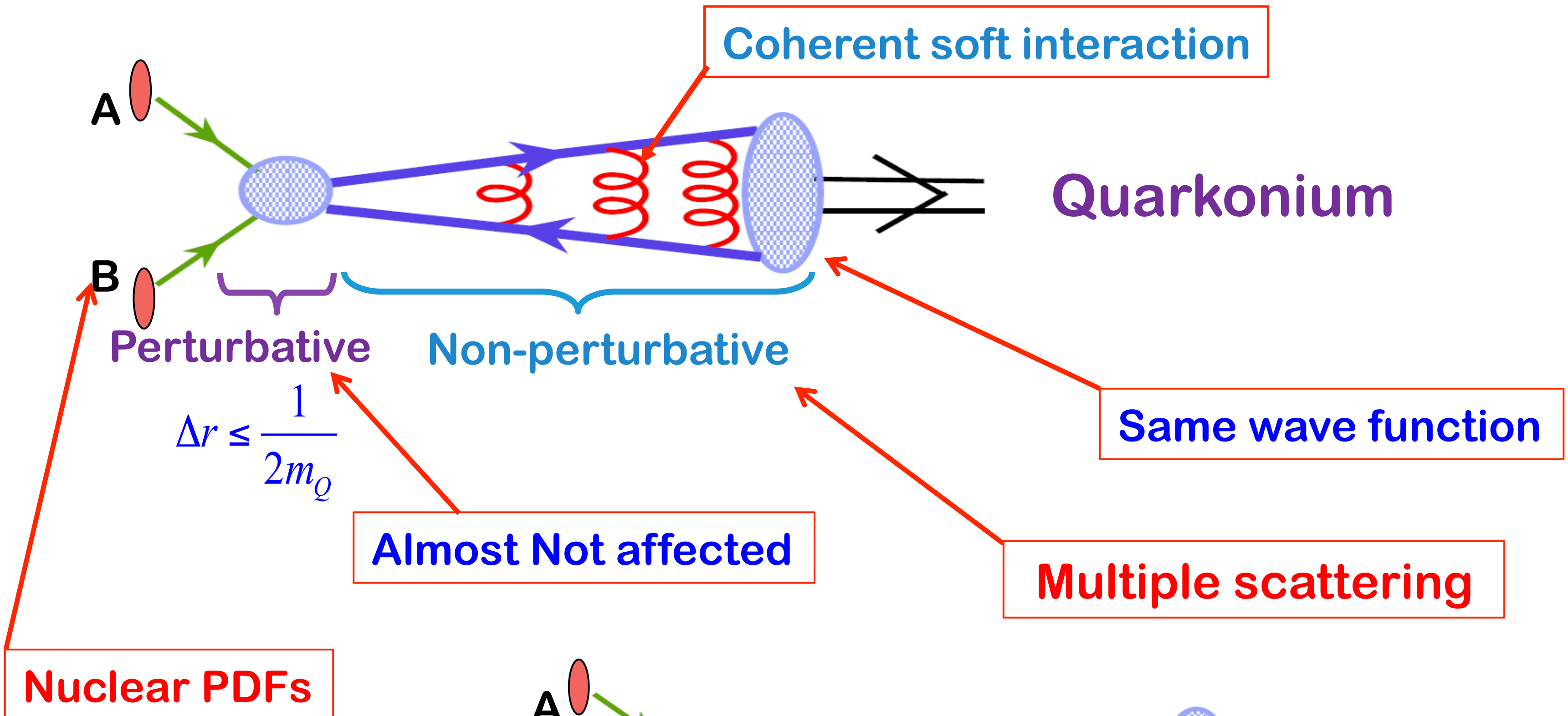
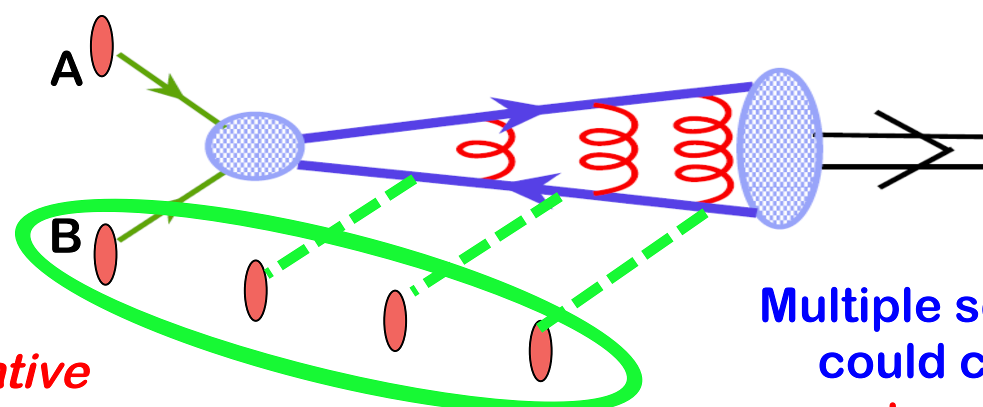




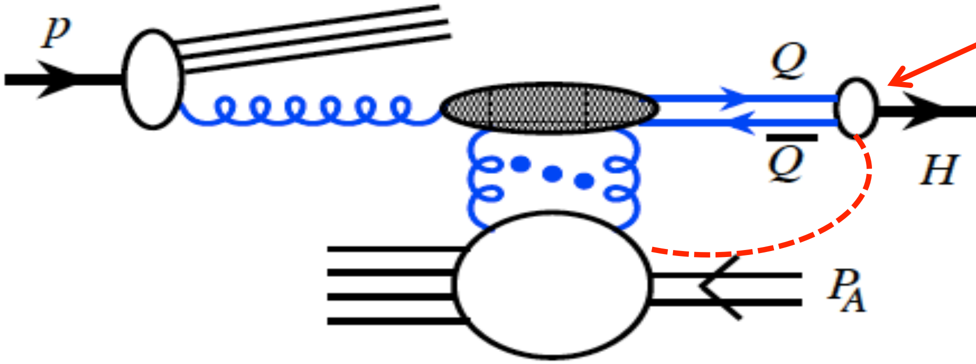
Can multiple scattering interfere with nonperturbative formation of quarkonia?

Multiple scattering could change spectrum & rate!!

Production with multiple scattering

Brodsky and Mueller, PLB 1988

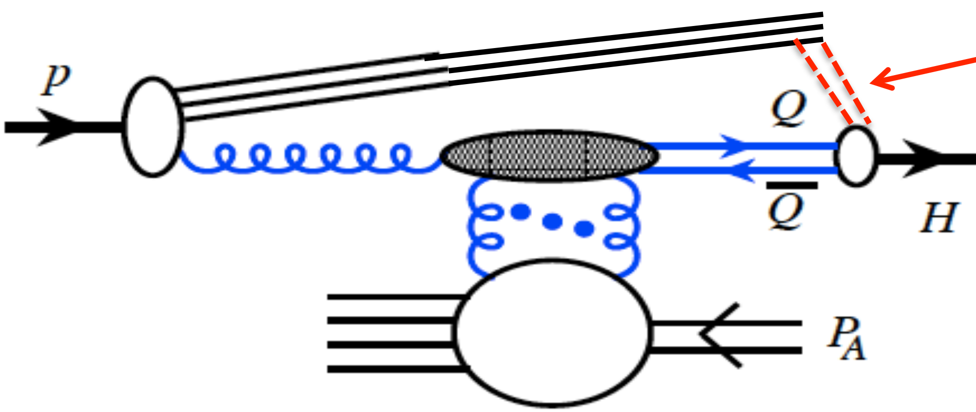
- ❑ *Backward* production in p(d)+A collisions:



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:



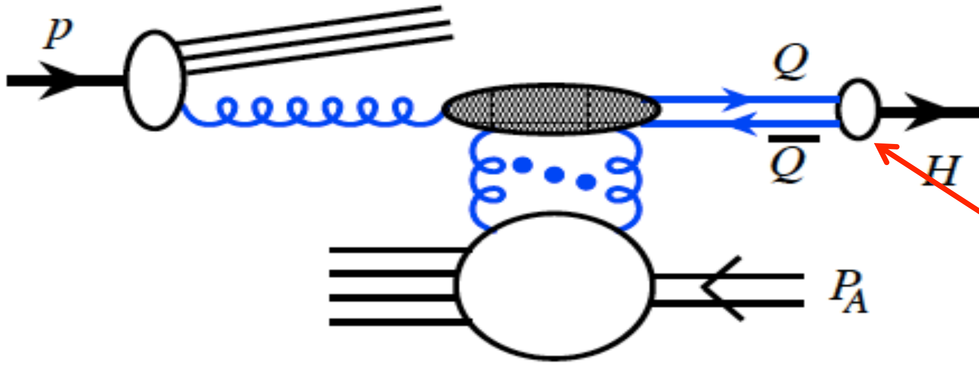
Co-mover interaction

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

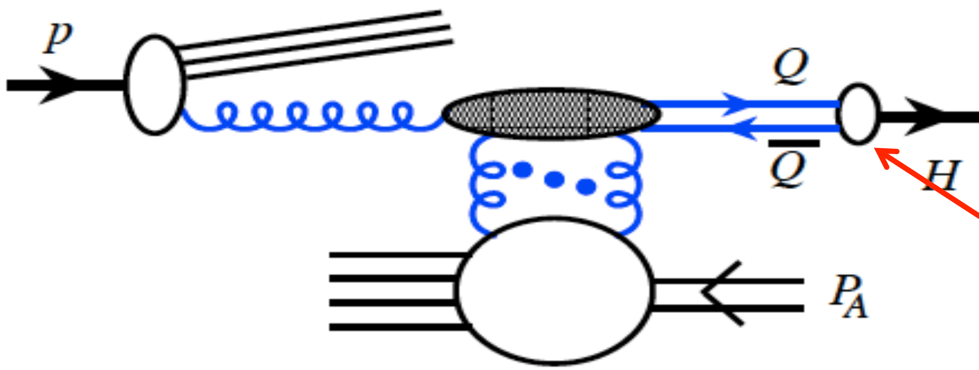
Non-perturbative formation of J/Ψ is far outside of nucleus

✧ 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

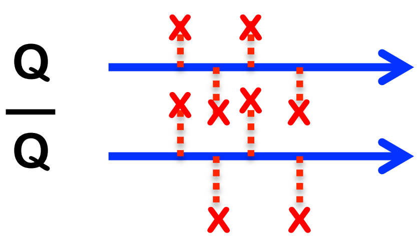
Non-perturbative formation of J/Ψ is far outside of nucleus

✧ 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 $Q\overline{Q}$ state to hadronize – lower rate



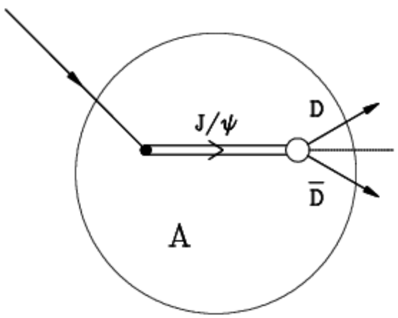
Soft multiple scattering – "random walk"

⇒ Momentum imbalance – larger invariant mass

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

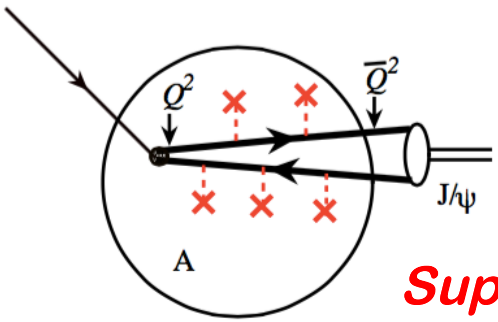
Suppression in total production rate

Glauber model



$$\frac{1}{AB}\,\frac{\sigma_{AB}}{\sigma_{NN}} \approx e^{-\rho_0\,\sigma_{\rm abs}\,L_{AB}}$$

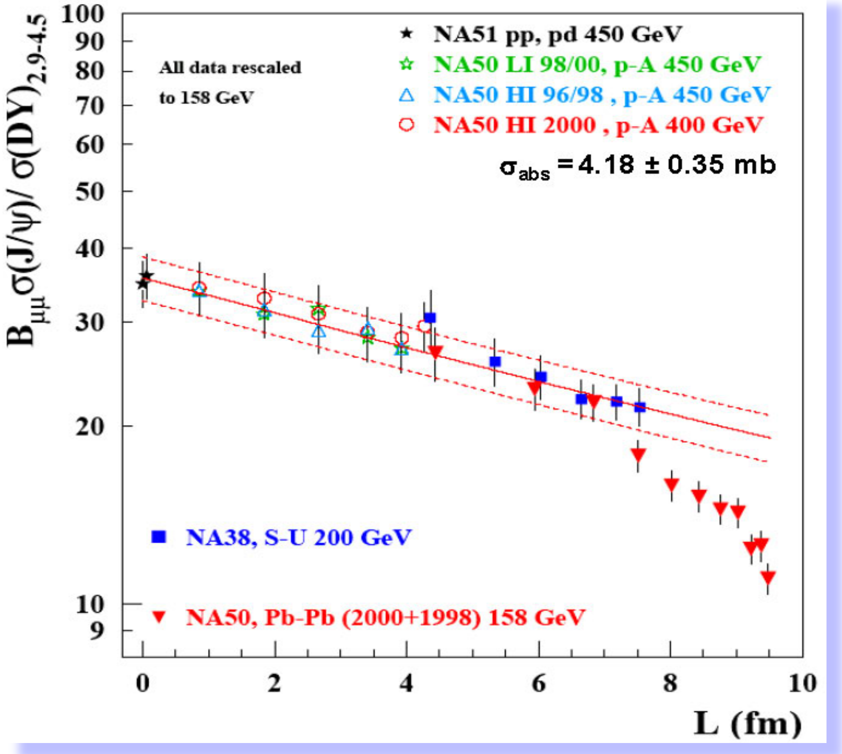
Multiple scattering of the pair

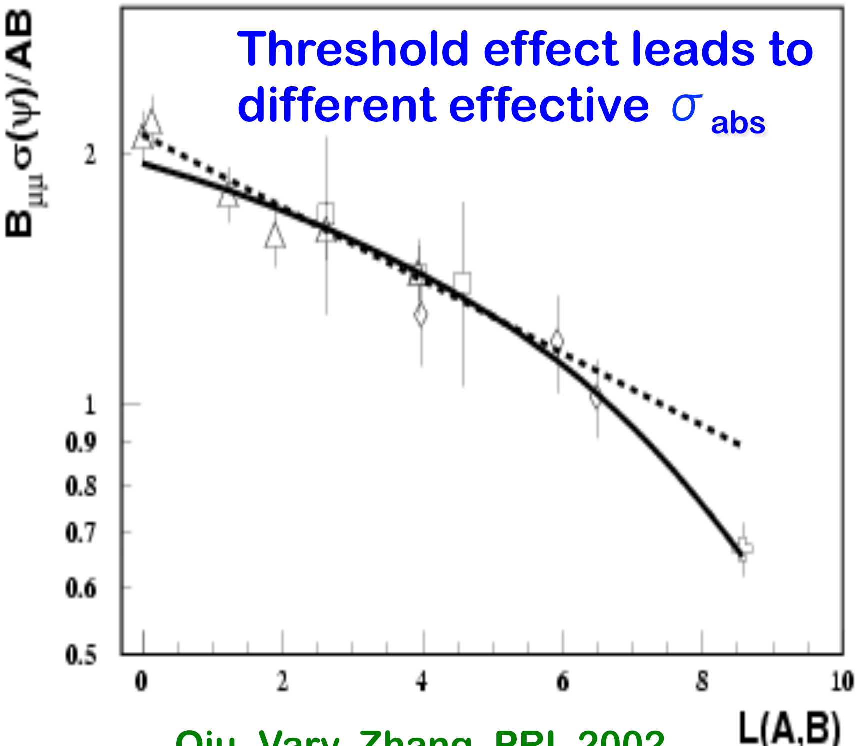


$$\overline{Q}^2 = Q^2 + \varepsilon\, L_{AB}$$

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

Suppression of J/ψ



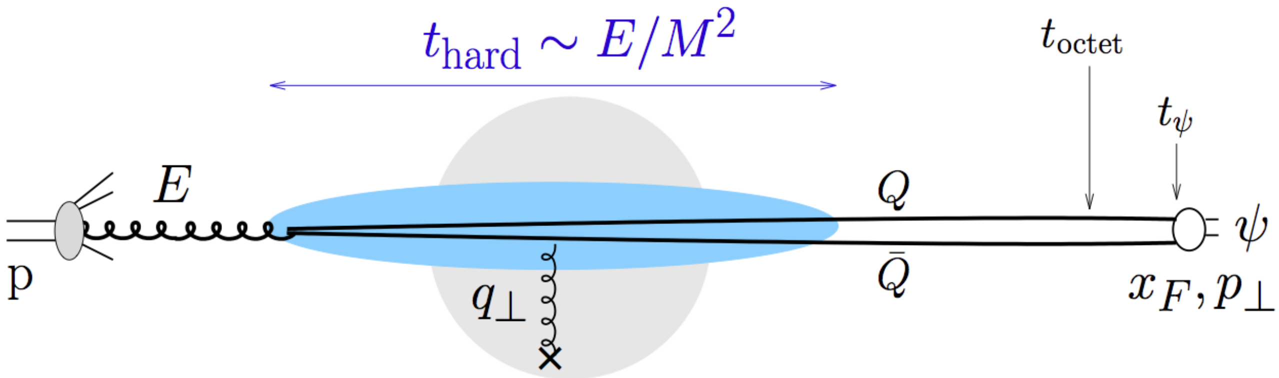


Qiu, Vary, Zhang, PRL 2002

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

❑ Picture + assumptions:

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



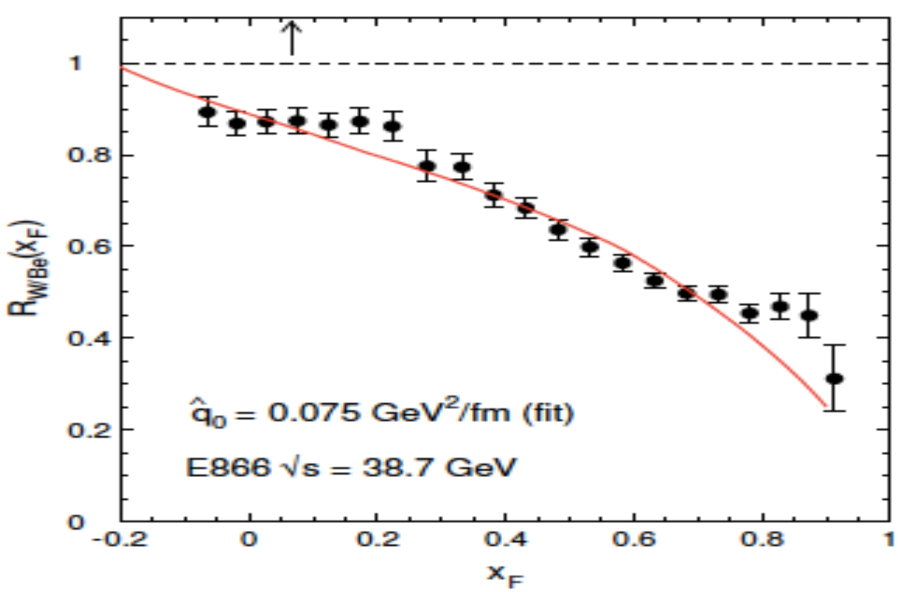
- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- Medium rescatterings do not resolve the octet $c\bar{c}$ pair
- Hadronization happens outside of the nucleus: $t_\psi \gtrsim L$
- $c\bar{c}$ pair produced by gluon fusion

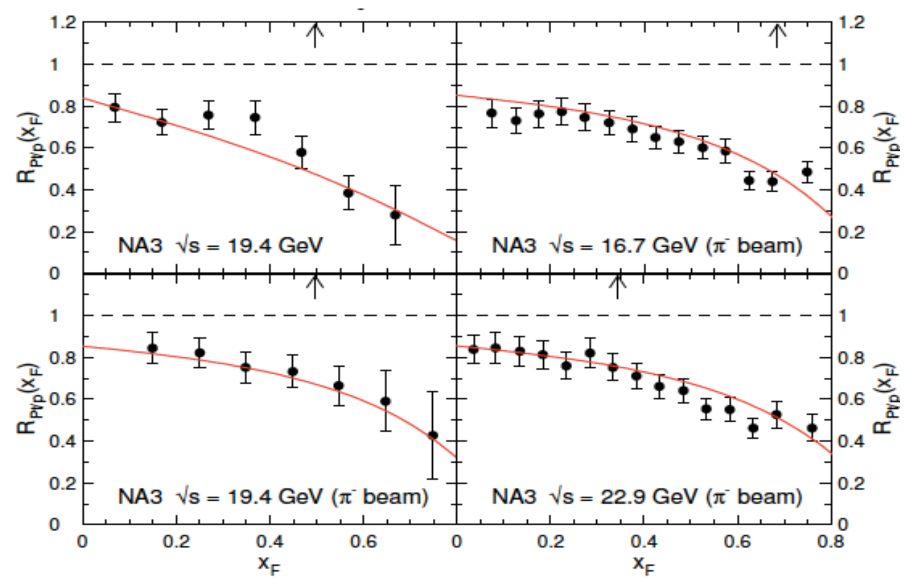
❑ Model energy loss:

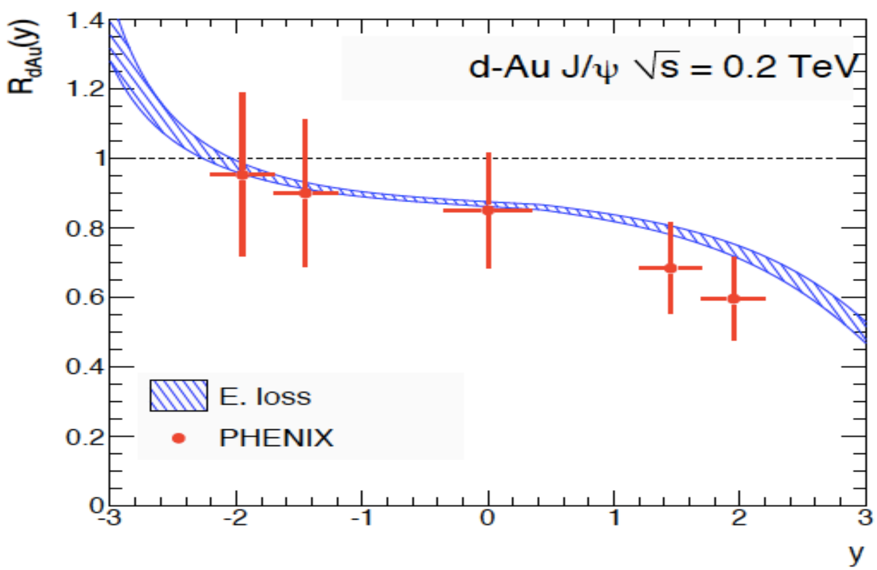
$$\frac{1}{A}\frac{d\sigma_{pA}}{dE}(E,\sqrt{s}) = \int_0^{\varepsilon_{\rm max}} d\varepsilon\, \mathcal{P}(\varepsilon, E)\, \frac{d\sigma_{pp}}{dE}(E+\varepsilon,\sqrt{s}) \qquad \hat{q}(x) \sim \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

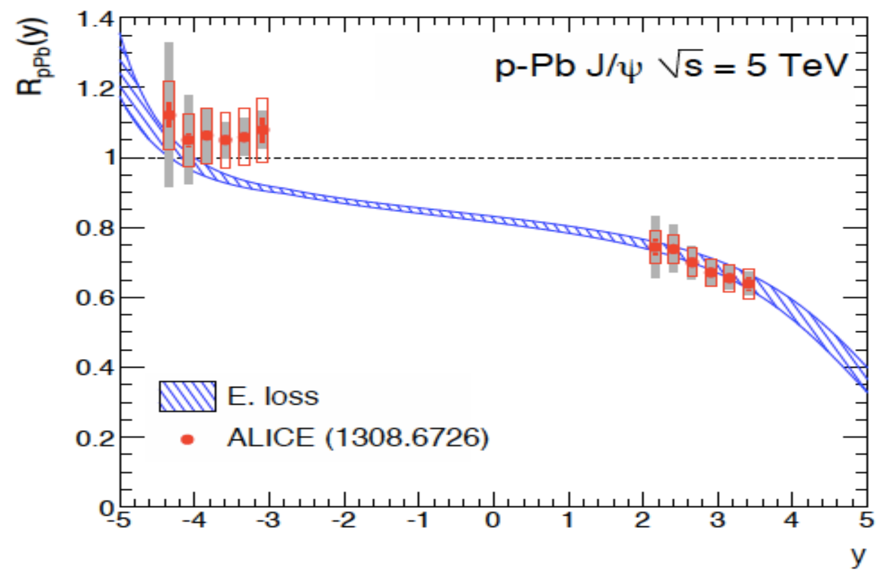
$\mathcal{P}(\varepsilon, E)$: **Quenching weight ~ scaling function of** $\sqrt{\hat{q}L}/M_\perp \times E$

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









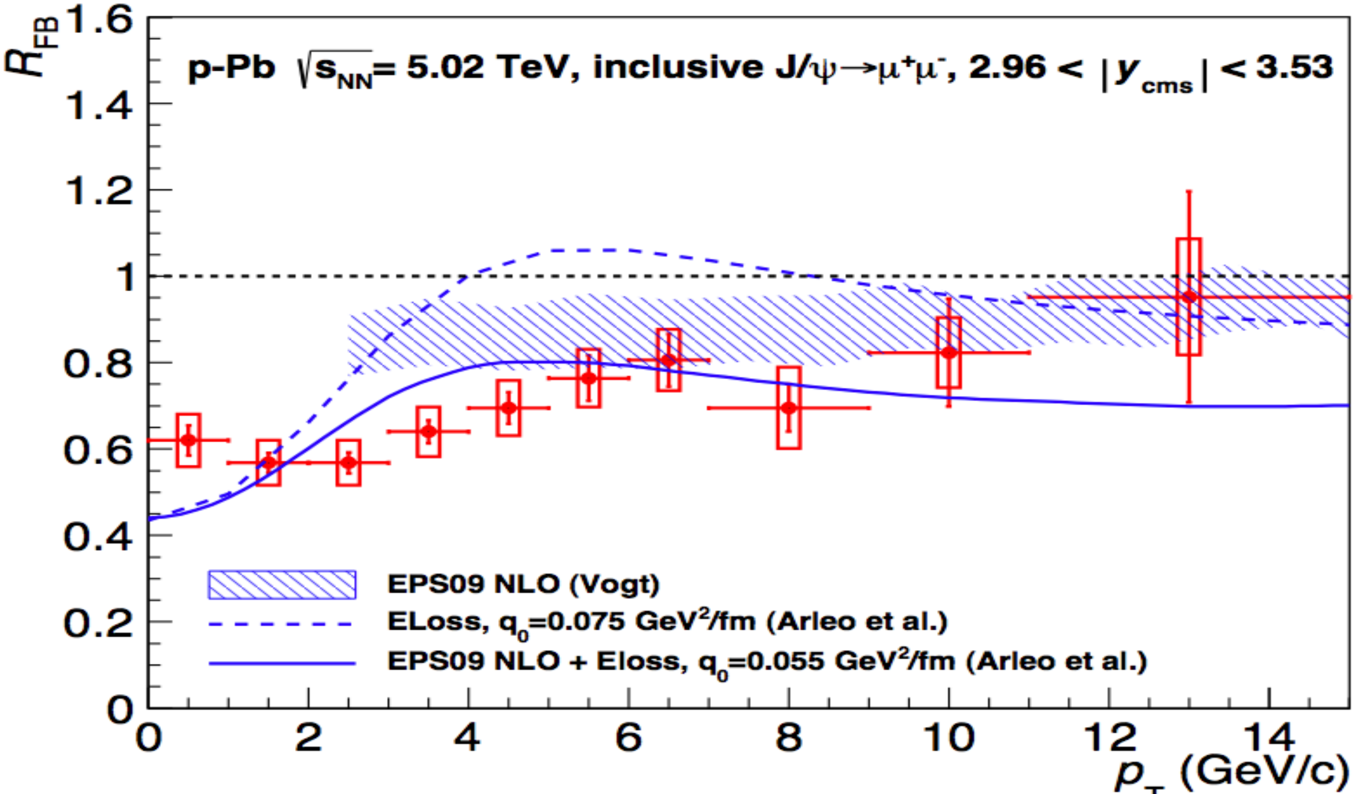
A-dependence in P_T in p(d)+A

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

- **Model:**

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

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



Not good Enough?

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

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

Quarkonium P_T-broadening in p(d)+A

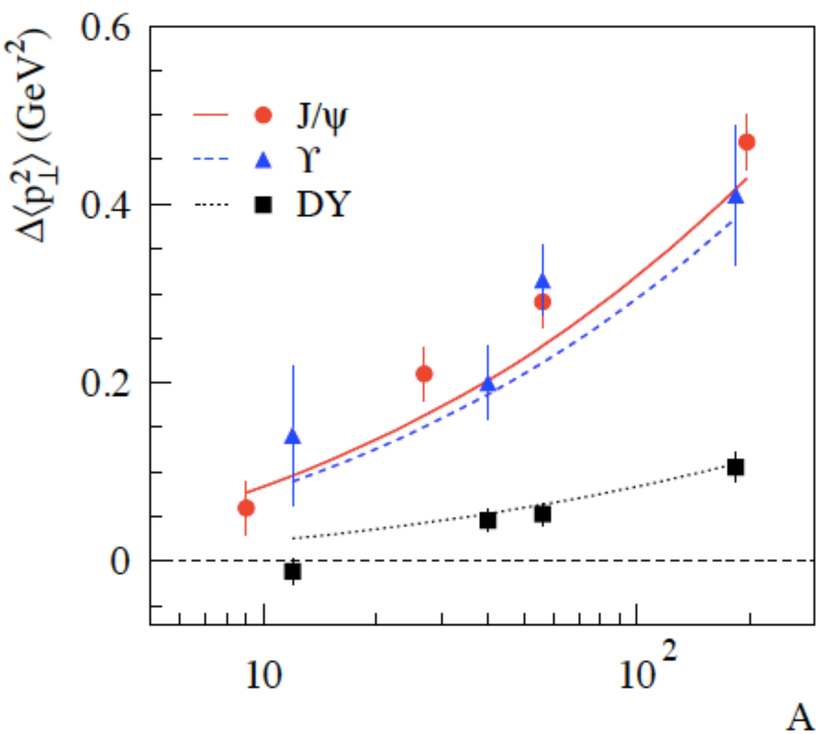
Kang, Qiu, PRD77(2008)

❑ Broadening:

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

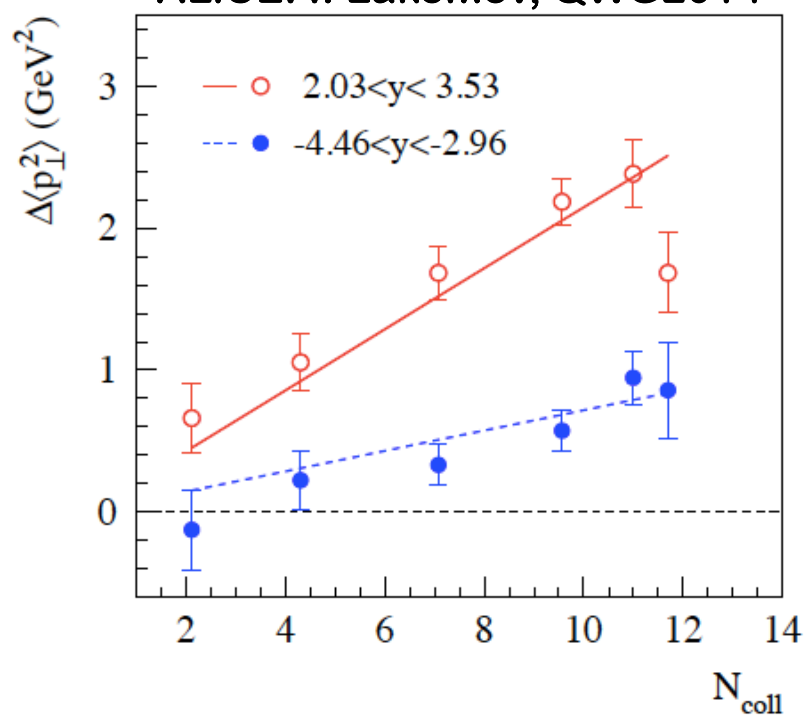
Calculated in both NRQCD and CEM

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



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

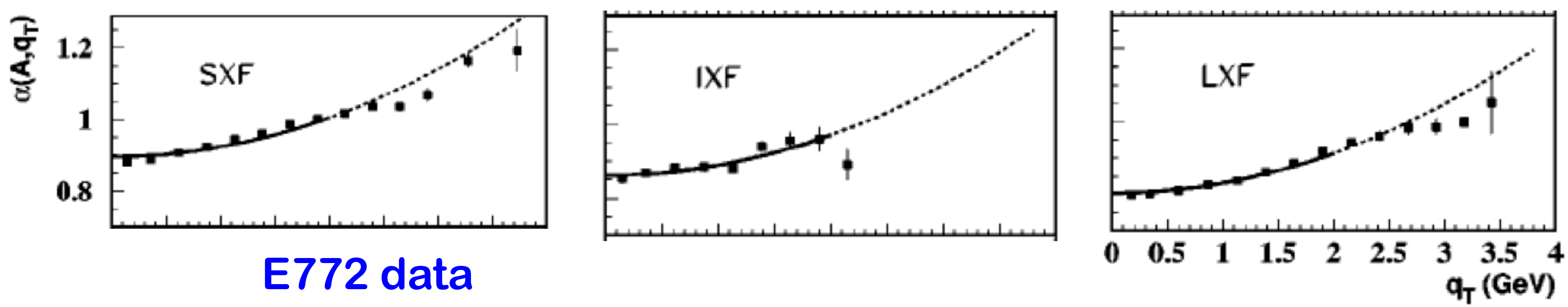
ALiCE: I. Lakomov, QWG2014



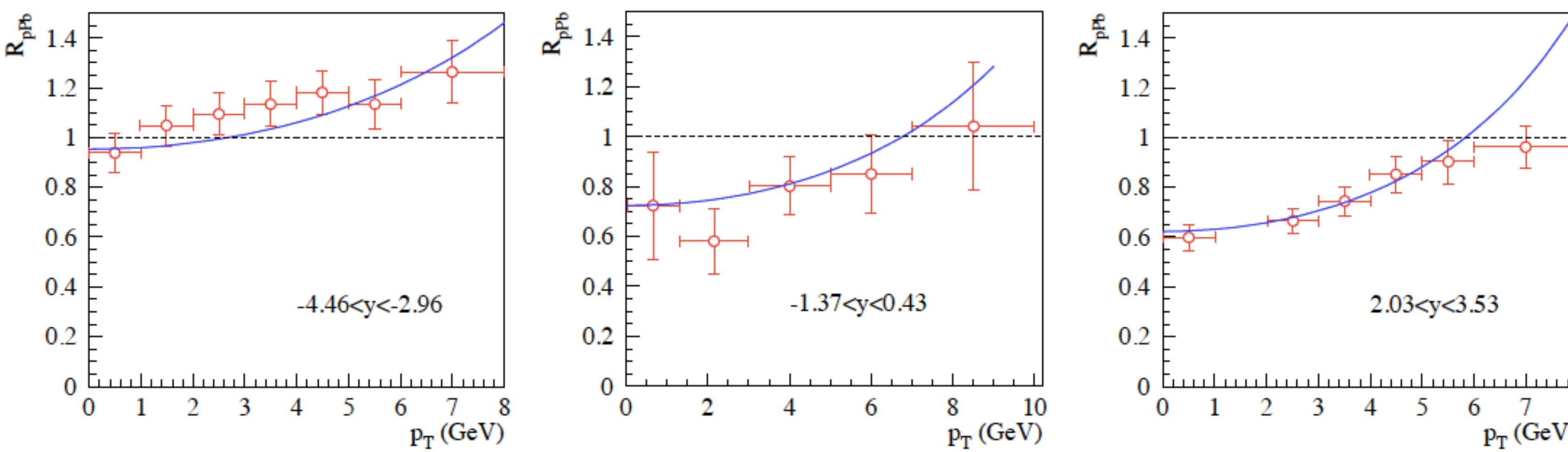
Quarkonium P_T-distribution in p(d)+A

❑ **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

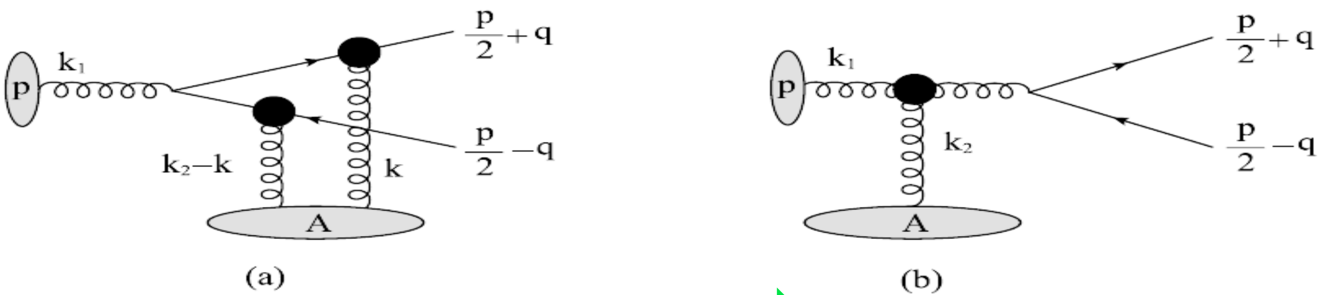


ALICE data

Forward quarkonium production in p(d)+A

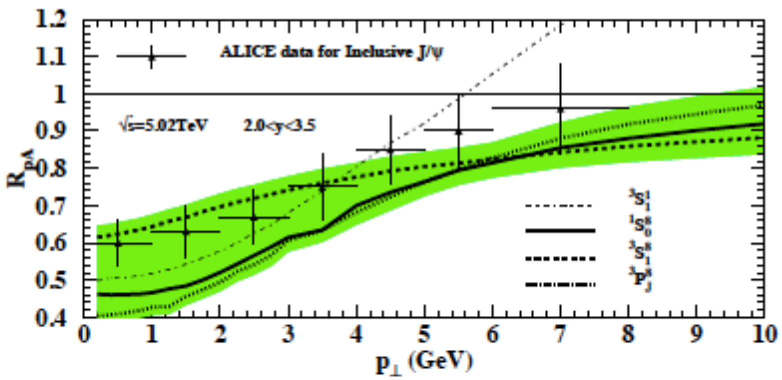
Kang, Ma, Venugopalan, JHEP (2014)
Qiu, Sun, Xiao, Yuan PRD89 (2014)

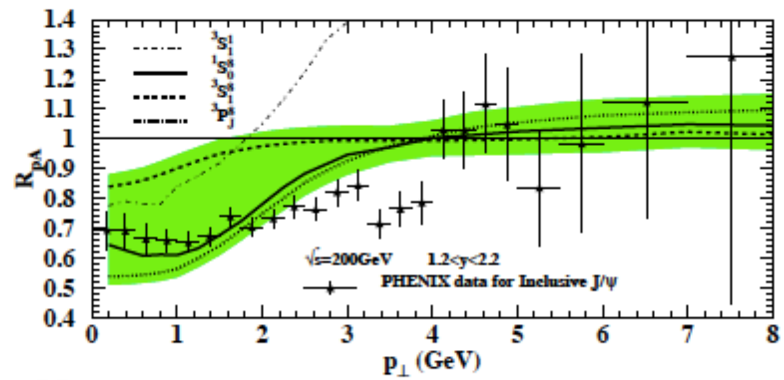
❑ Calculation of multiple scattering:

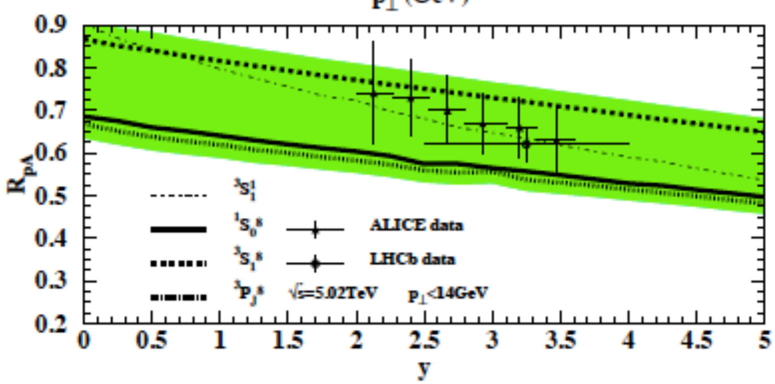


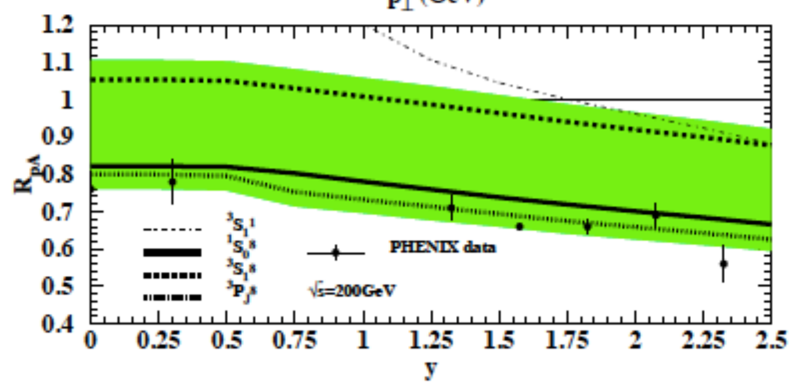
Coherent multiple scattering → **suppression at large y**

Ma et al 1503.07772

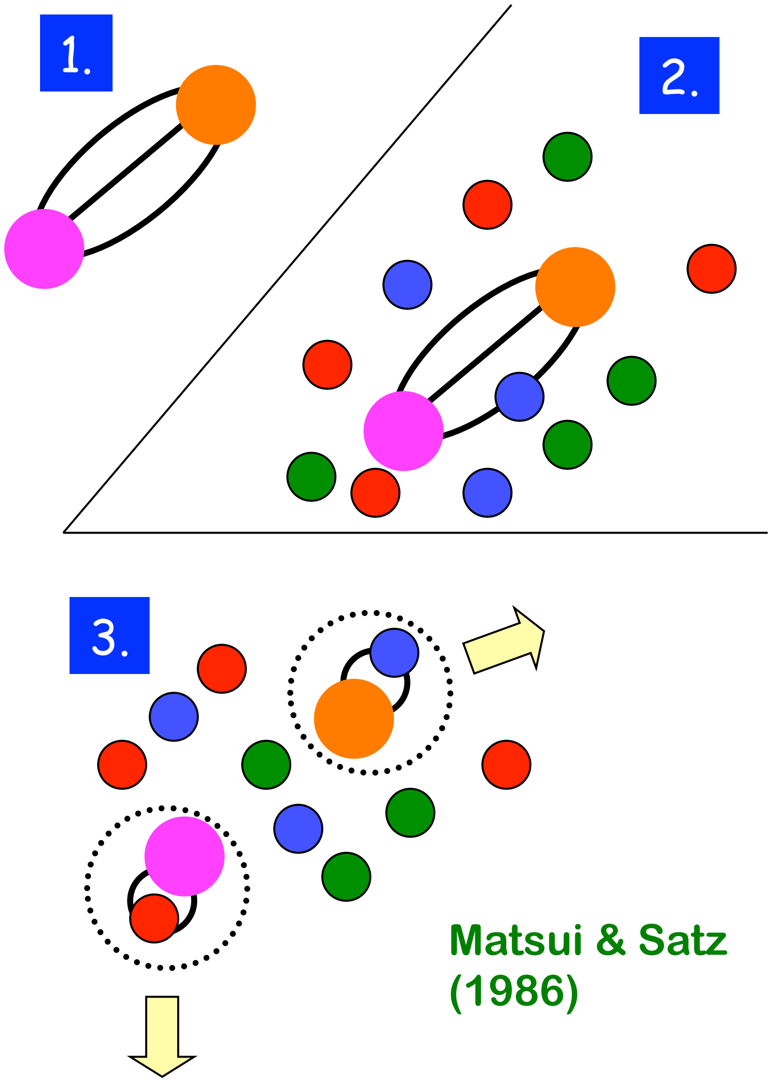






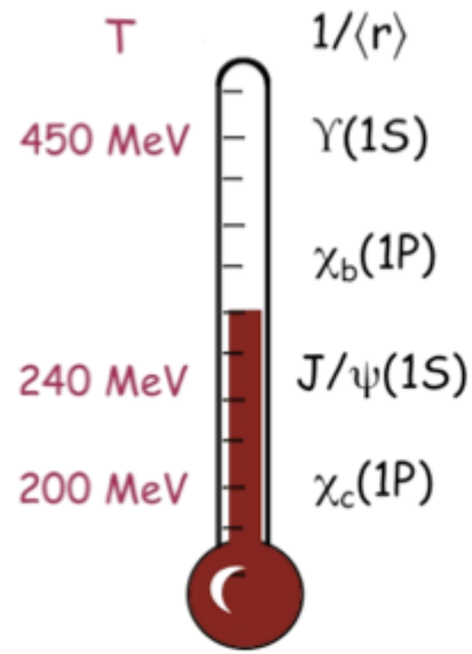


Melting a quarkonium in QGP – deconfinement



Matsui & Satz (1986)

QGP Thermometer



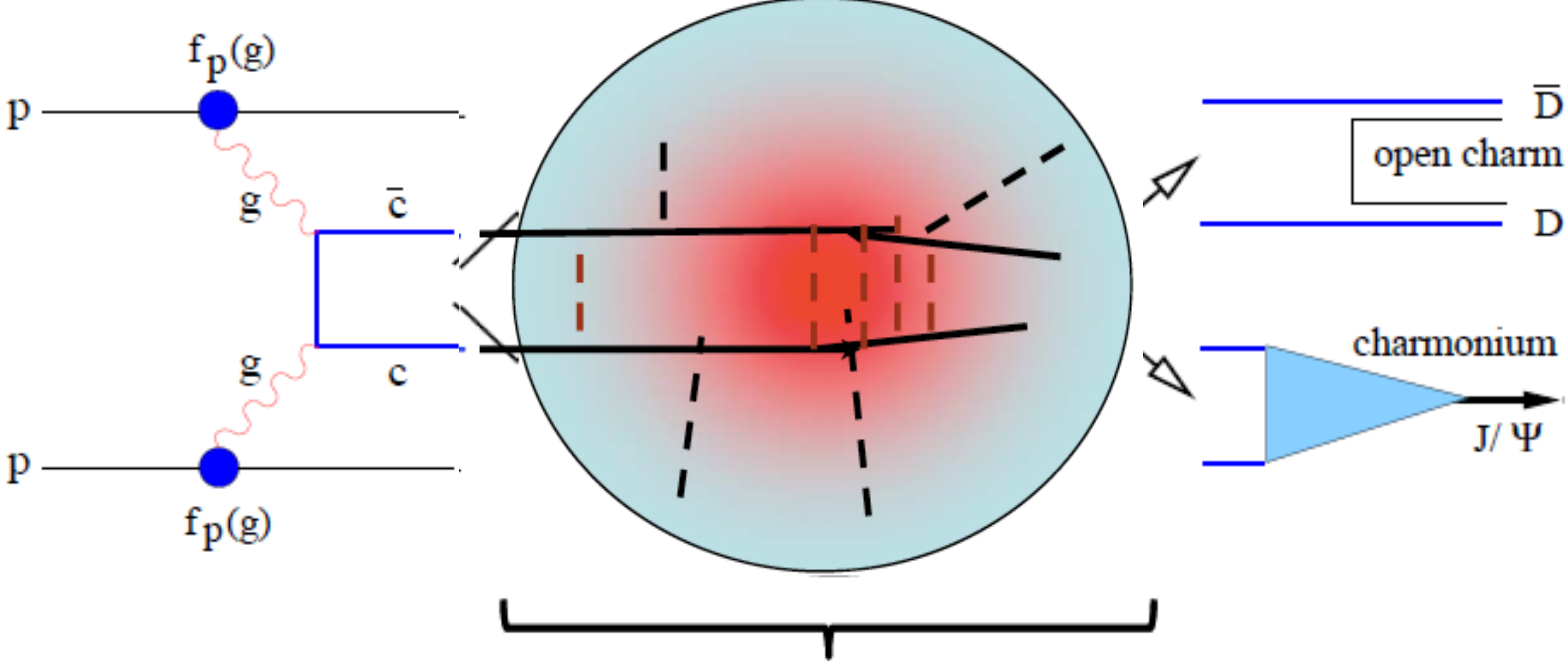
A. Mocsy, P. Petreczky, and MS, 1302.2180

See suppression at SPS, RHIC, and the LHC

But, Time dependent quarkonia formation!

Production in A+A collisions

Gossiaux and Katz



Very complicate QFT at finite T!

Need a full time-dependent, dynamical model of QGP with heavy quarks!

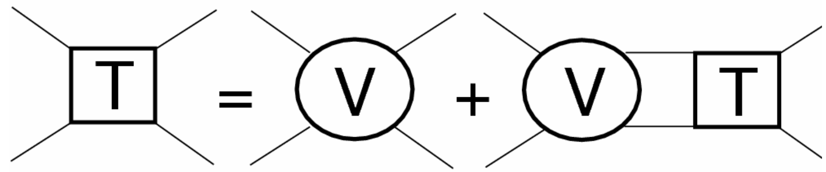
Many model approaches are available, ...

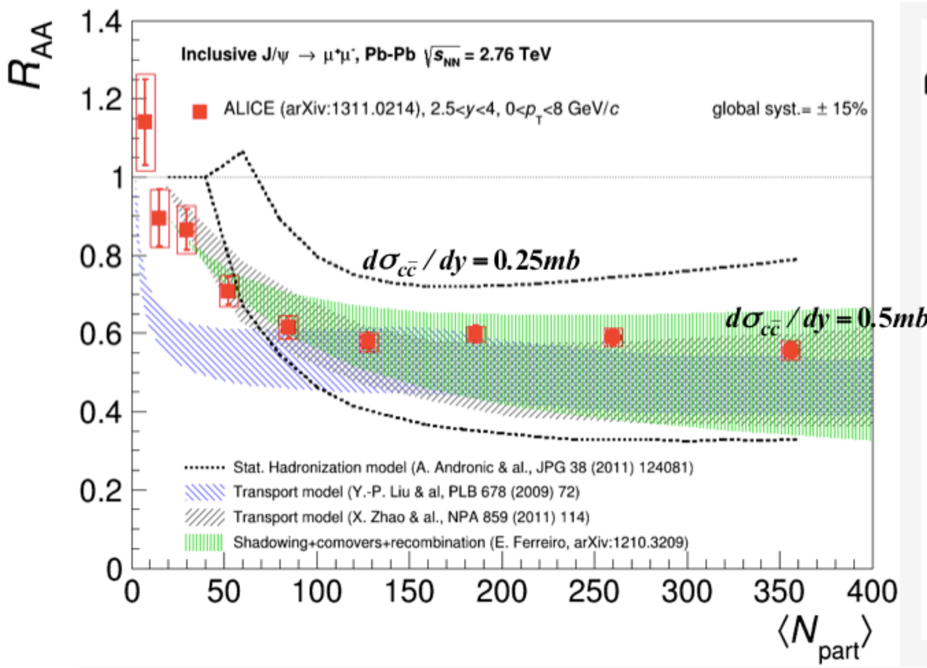
Thermodynamic Heavy-Quark T-Matrix in QGP

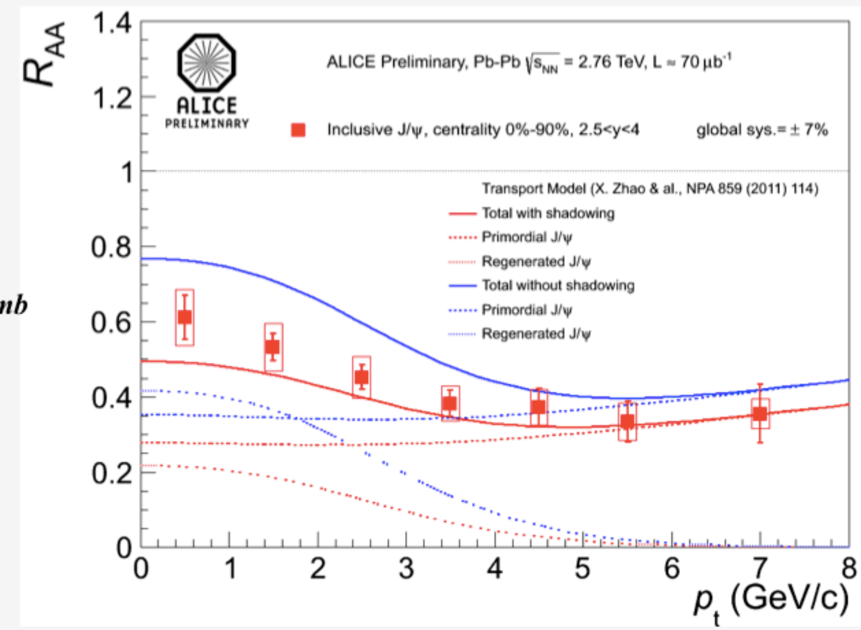
Rapp and Zhao, 2011

❑ Lippmann-Schwinger equation:

In-medium
QQbar T-matix:





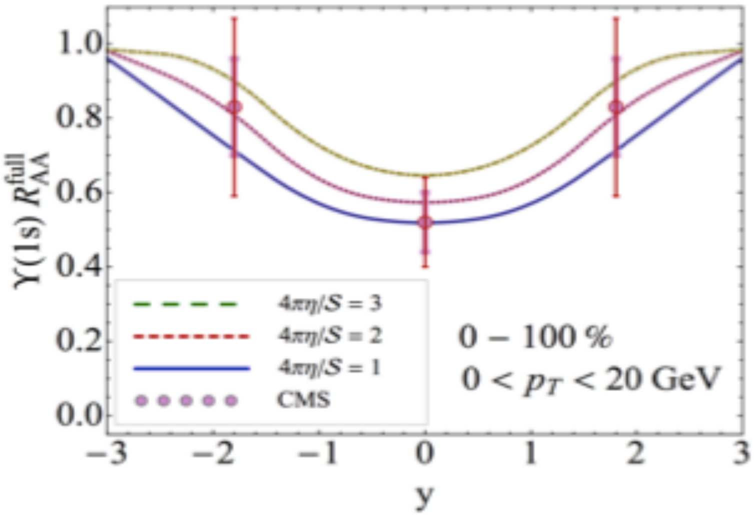


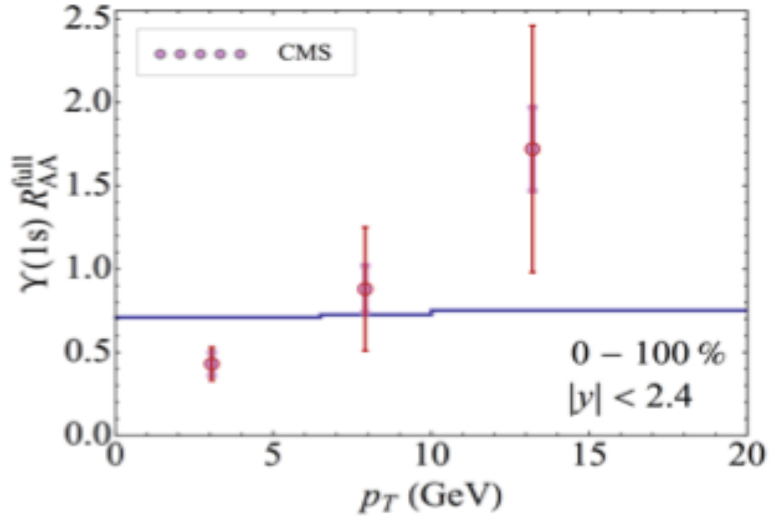
- regeneration becomes dominant
- uncertainties in σ_{cc}+shadowing

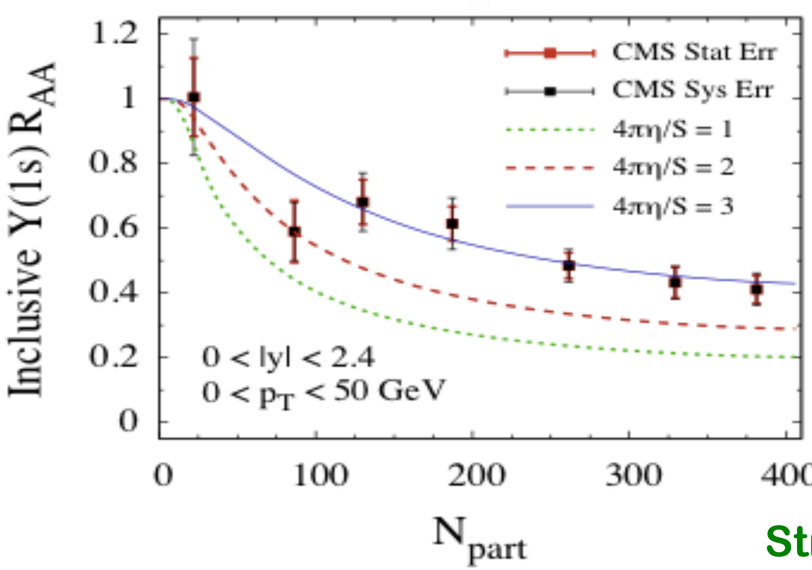
- low p_T maximum confirms regeneration
- too much high-p_T suppression?

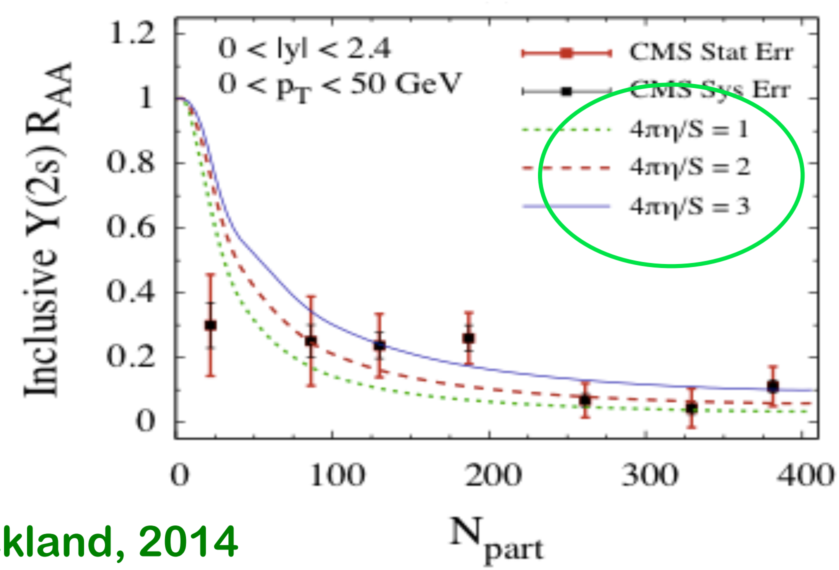
Inclusive bottomonium suppression

- Solve 3d Schrödinger EQ with complex-valued potential









Strickland, 2014

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

- Final-state multiple scattering could be an effective source of J/ψ suppression because of the sharp threshold behavior

- Heavy quarkonium production in hot medium is still an open problem/challenge – a lot of effort are underway

See also talks by Vogt, Yu, Zhao in parallel one

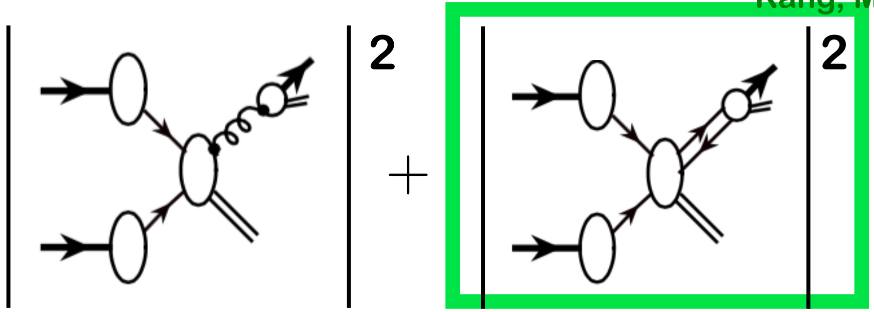
Thank you!

Backup slides

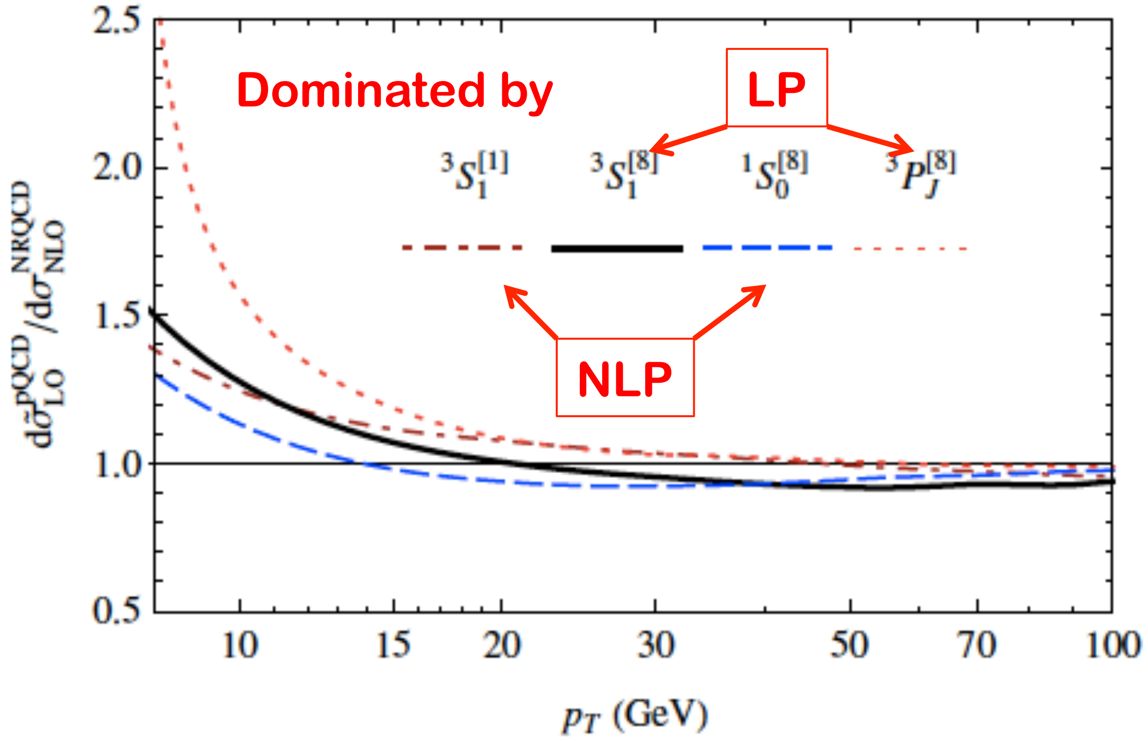
QCD factorization – Kang et al.

Kang, Ma, Qiu and Sterman, 2014

$$\frac{d\sigma_{AB\to H+X}}{dy\,dp_T^2} = \left| \cdots \right|^2 + \left| \cdots \right|^2 + \ldots$$



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



independent of NRQCD matrix elements

LO QCD analytical results reproduce NLO NRQCD calculations (numerical)

QCD Factorization = better controlled HO corrections!

PRL, 2014

Final-state multiple scattering - CEM

Kang, Qiu, PRD77(2008)

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

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

- 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

❑ Cross section:

Kang, Qiu, PRD77(2008)

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

❑ Broadening:

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

Hard parts:

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

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

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

Only color octet channel contributes

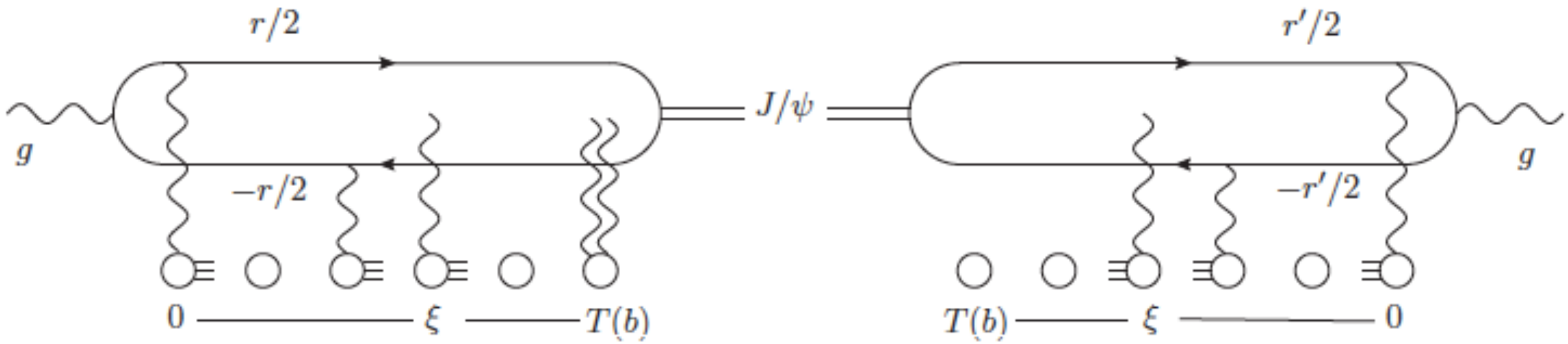
❑ Leading features:

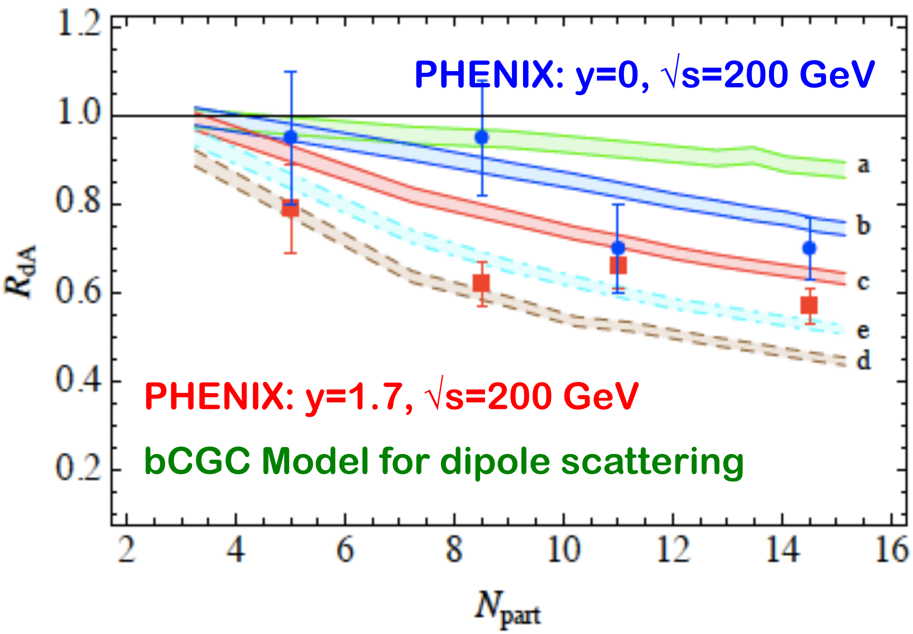
$$\Delta\langle q_T^2\rangle^{\rm NRQCD}_{\rm HQ} \approx \Delta\langle q_T^2\rangle^{\rm CEM}_{\rm HQ} \approx (2C_A/C_F)\Delta\langle q_T^2\rangle_{\rm DY}$$

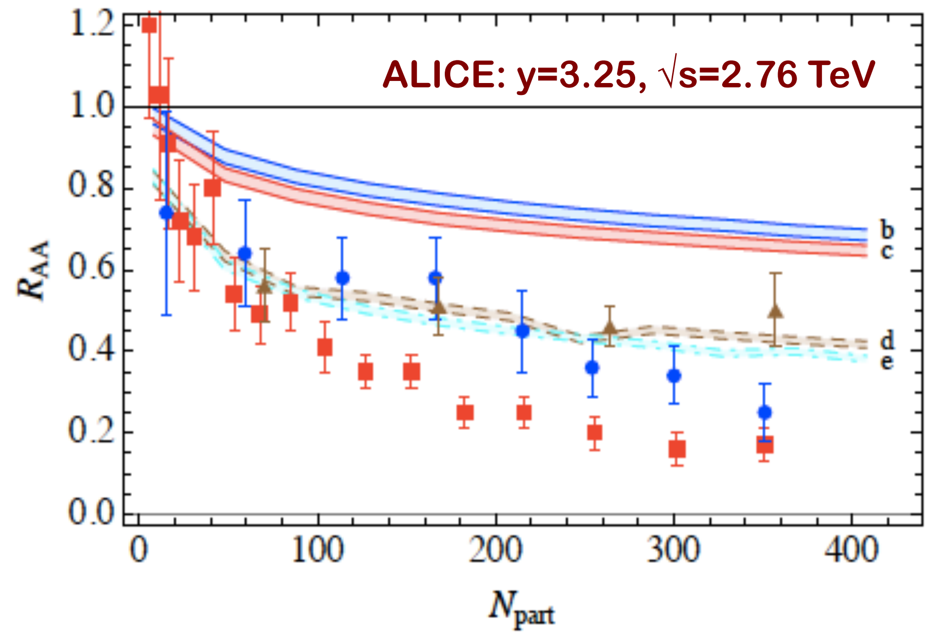
Multiple scattering in cold nuclear matter

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)?