Quarkonium and Exotic Hadron Production in Electron-ion and Heavy-ion Collisions

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Workshop on the Spectroscopy Program at EIC and Future Accelerators

Contents

- Exotic hadron physics opportunity with EIC
    1. Quarkonium production
    2. X(3872) production
    3. Doubly heavy baryon production
- Heavy quark bound state transport in nuclear matter
    1. Nuclear DIS: cold nuclear medium
    2. Use our knowledge of transport in quark-gluon plasma
    3. Doubly charmed baryon in heavy ion collisions

XYZ Exotics

- XYZ: contain $Q\overline{Q}$, not fit into quarkonium
- X(3872): $J^{PC} = 1^{++}$ near $D\overline{D}^*$ threshold
  - Decay into $\pi^+\pi^- J/\psi$
  - What is its structure? Is it a molecule of $D\overline{D}^*$ ($\overline{D}D^*$) ?
  - Study exotics at EIC, high luminosity, estimate production rate
  - Use quarkonium as benchmark

Quarkonium Production in DIS

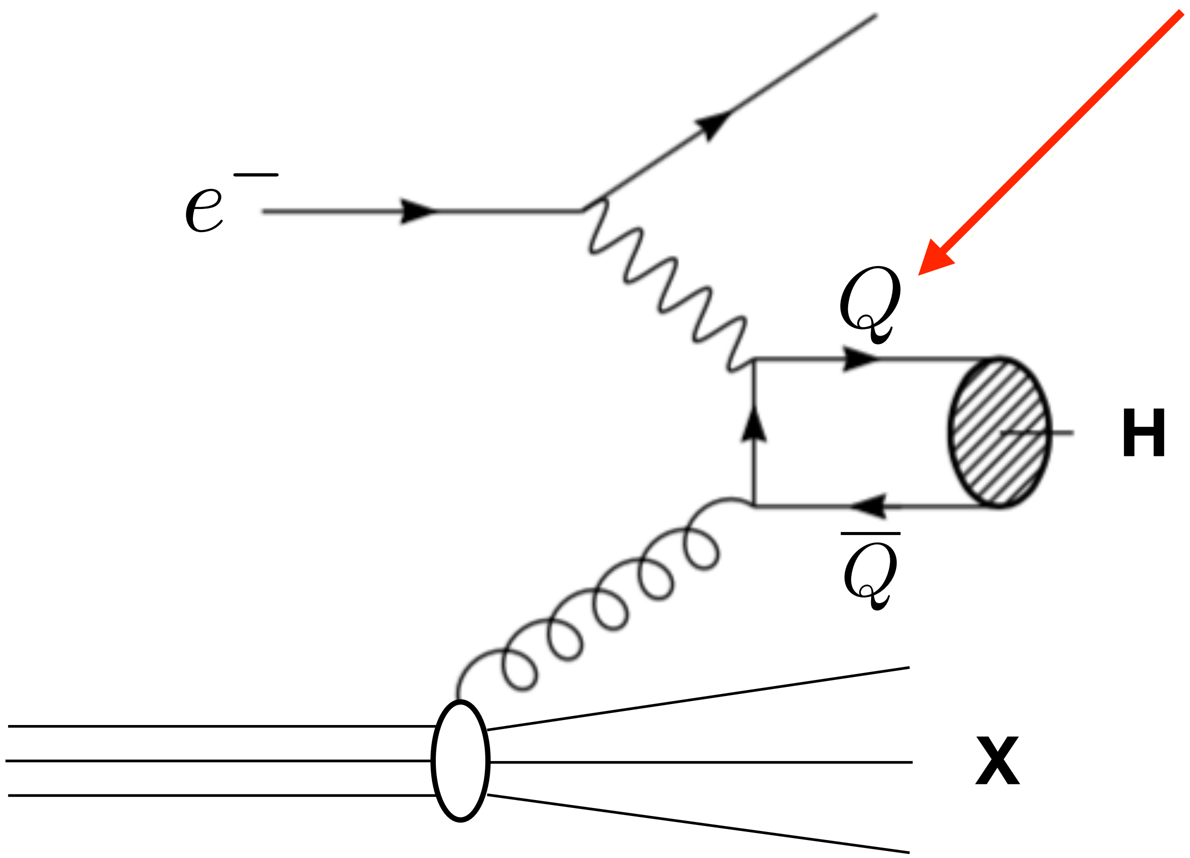
NRQCD factorization

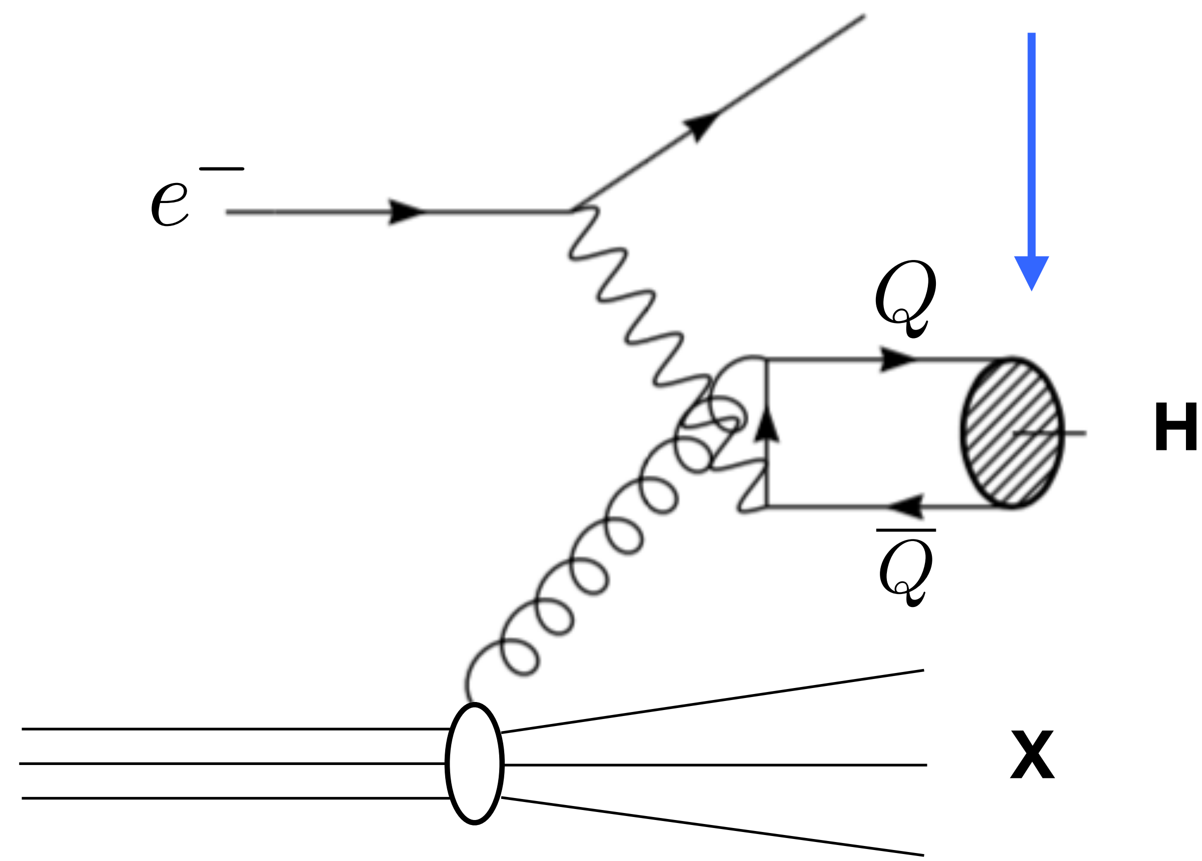
$$d\sigma(e^- + p \to H + X) = \sum_n d\sigma(e^- + p \to Q\overline{Q}(n) + X)\langle \mathcal{O}^H(n) \rangle$$

Short-distance production of heavy quark pair (calculable)

Long-distance matrix element: coalescence into quarkonium (fit)

LO octet production



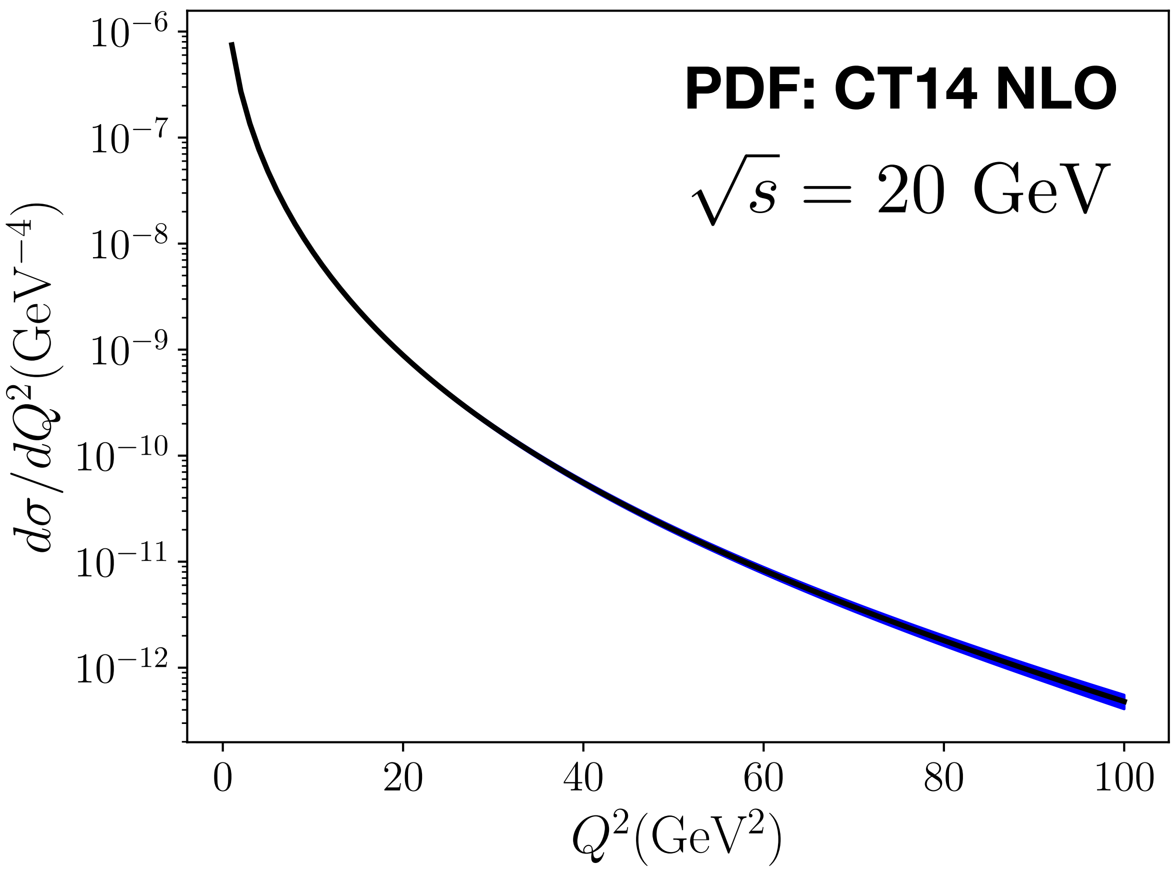


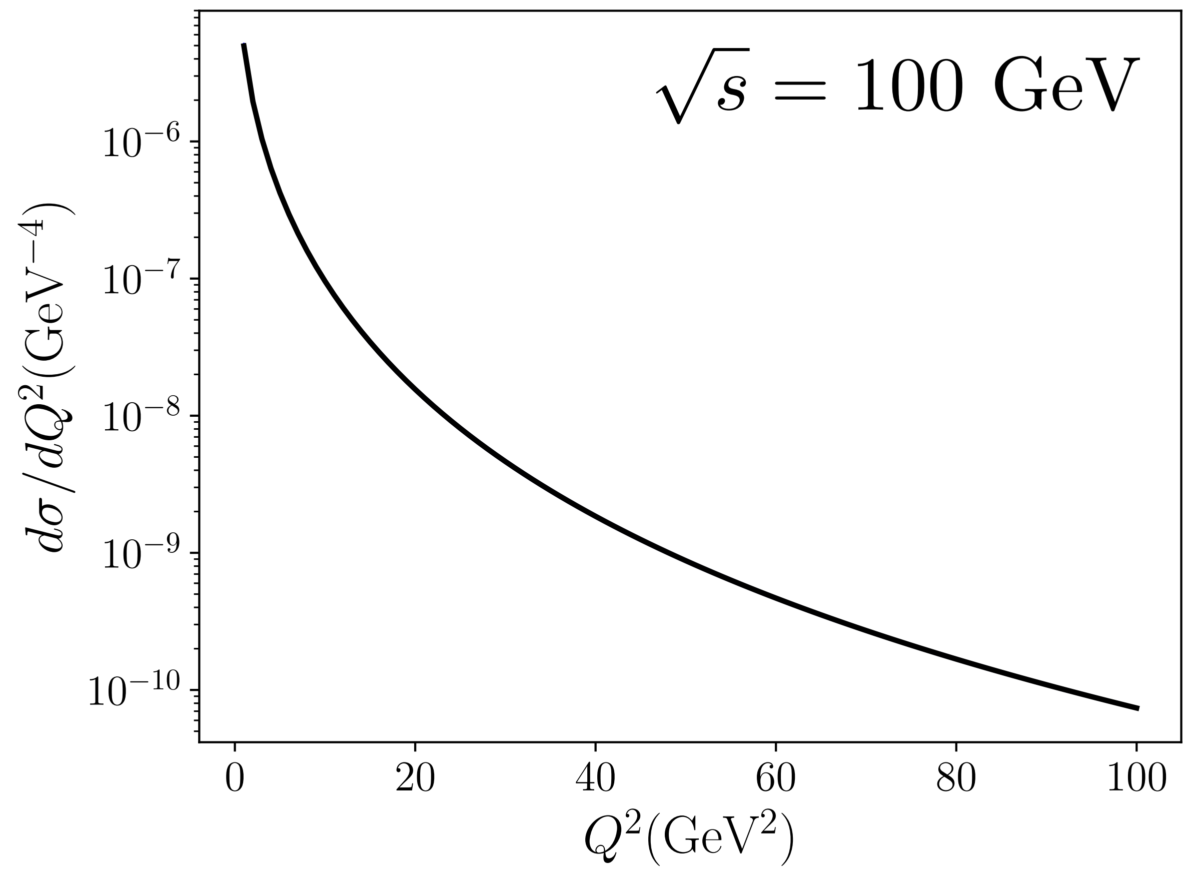
Quarkonium Cross Section

NRQCD factorization

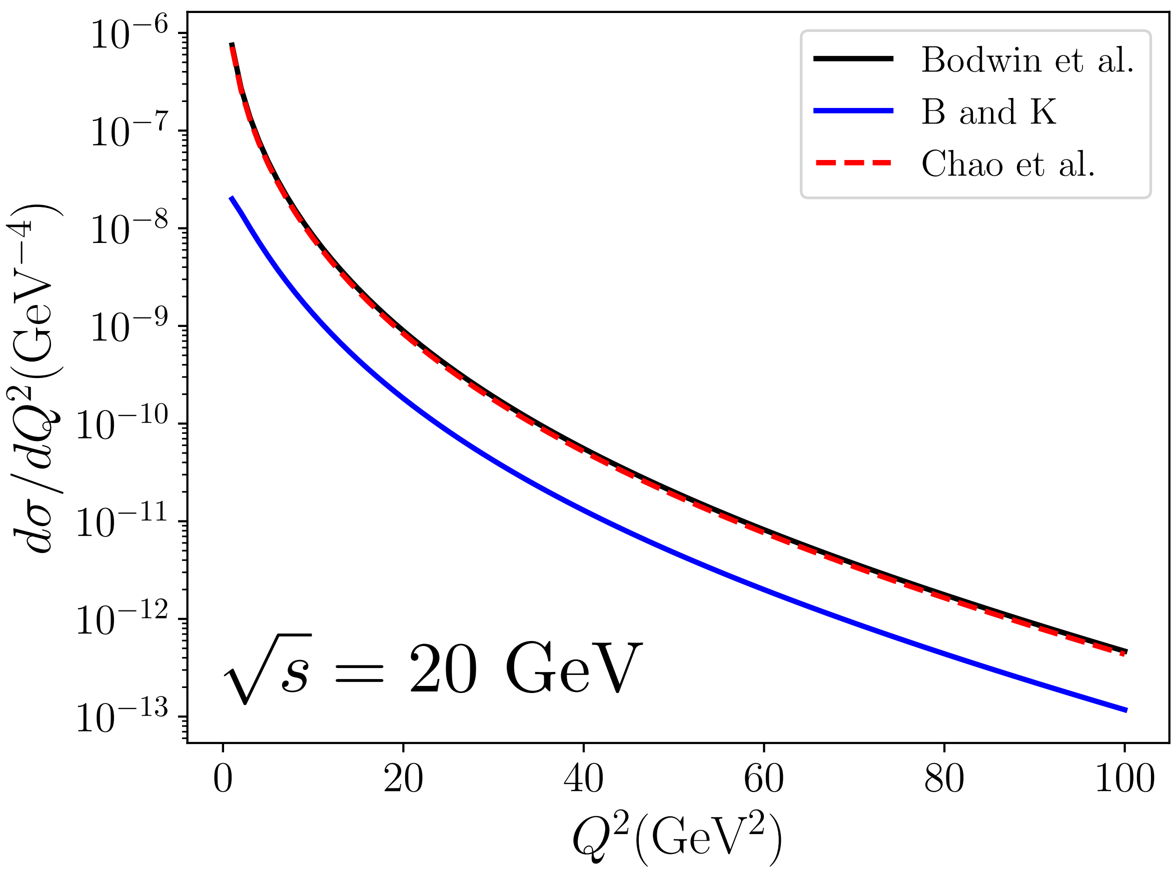
$$\sigma(e+p\to e+\psi+X)=\int\frac{dQ^2}{Q^2}\int dy\int dx\; f_{g/p}(x)\,\delta(xys-(2m_c)^2-Q^2)$$
$$\times\frac{2\alpha_s(\mu^2)\alpha^2e_c^2\pi^2}{m_c(Q^2+(2m_c)^2)}\left\{\frac{1+(1-y)^2}{y}\left[\langle\mathcal{O}_8^\psi({}^1S_0)\rangle+\frac{3Q^2+7(2m_c)^2}{Q^2+(2m_c)^2}\frac{\langle\mathcal{O}_8^\psi({}^3P_0)\rangle}{m_c^2}\right]\right.$$
$$\left.-y\frac{8(2m_c)^2Q^2}{(Q^2+(2m_c)^2)^2}\frac{\langle\mathcal{O}_8^\psi({}^3P_0)\rangle}{m_c^2}\right\},$$

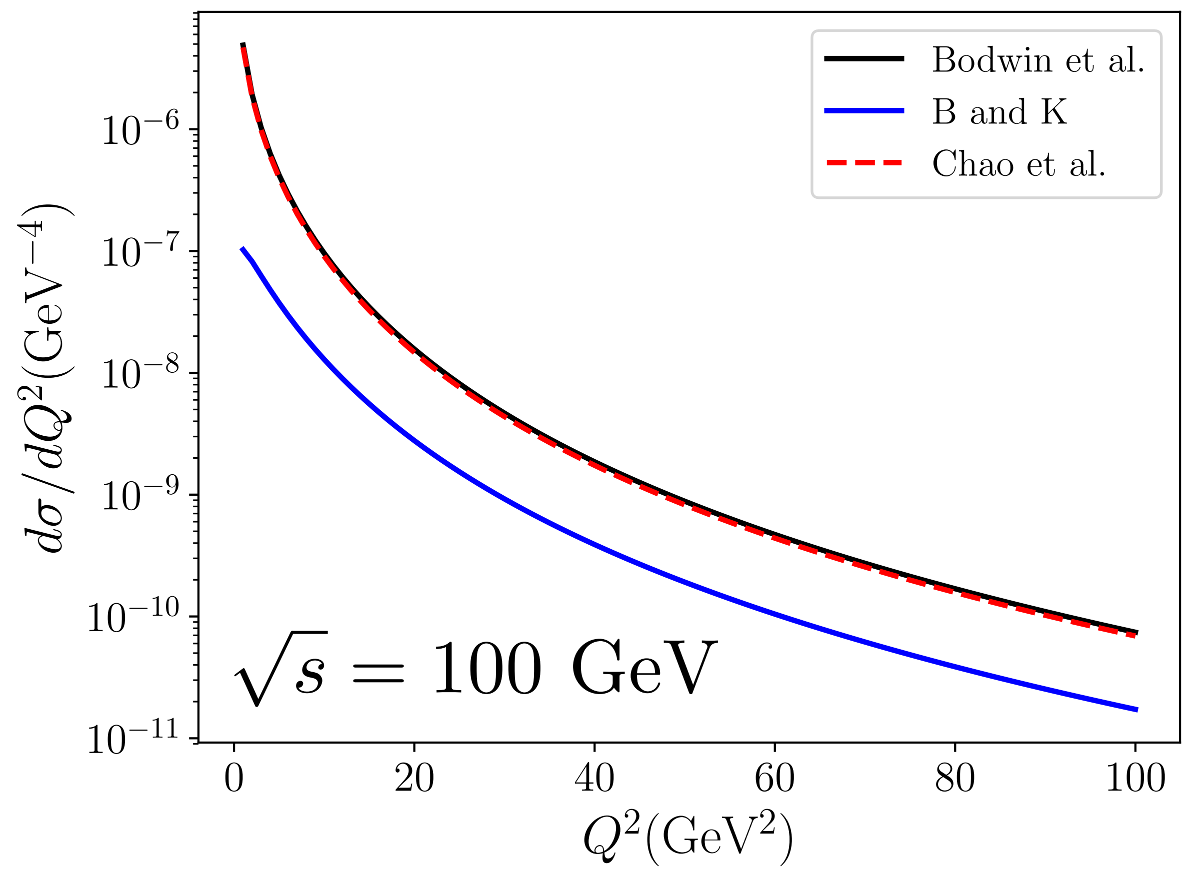
S.Fleming and T.Mehen PRD 57, 1846 (1998)





Long-distance Matrix Element Uncertainty





	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$ × GeV^3	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$ $\times 10^{-2}$ GeV^3	$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ $\times 10^{-2}\mathrm{GeV}^3$	$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/m_c^2$ $\times 10^{-2}\mathrm{GeV}^3$
B & K [5, 6]	1.32 ± 0.20	0.224 ± 0.59	4.97 ± 0.44	-0.72 ± 0.88
Chao, et al. [12]	1.16 ± 0.20	0.30 ± 0.12	8.9 ± 0.98	0.56 ± 0.21
Bodwin et al. [13]	1.32 ± 0.20	1.1 ± 1.0	9.9 ± 2.2	0.49 ± 0.44

Contribute at LO

Need to check results at NLO

X(3872) Production Cross Section

NRQCD factorization

$$\sigma[X(3872)] = \sum_n \hat{\sigma}[c\bar{c}_n] \, \langle \mathcal{O}_n^X \rangle$$

Fit from data
Independent of models of X structures

$$\mathrm{Br}[X \to J/\psi \pi^+\pi^-] \left(\langle \mathcal{O}_8^X(^3S_1) \rangle + 0.159 \, \langle \mathcal{O}_8^X(^1S_0) \rangle + 0.085 \, \langle \mathcal{O}_1^X(^1S_0) \rangle \right.$$
$$\left. + 0.00024 \, \langle \mathcal{O}_1^X(^3S_1) \rangle \right) = (2.7 \pm 0.6) \times 10^{-4} \ \mathrm{GeV}^3$$

P.Artoisenet, E.Braaten PRD 81 114018 (2010)

Assume equal contributes from different colors and spins, neglect P wave

$$\mathrm{Br}[X \to J/\psi \pi^+\pi^-] \langle \mathcal{O}_8^X(^1S_0) \rangle \approx 8.3 \times 10^{-5} \ \mathrm{GeV}^3$$

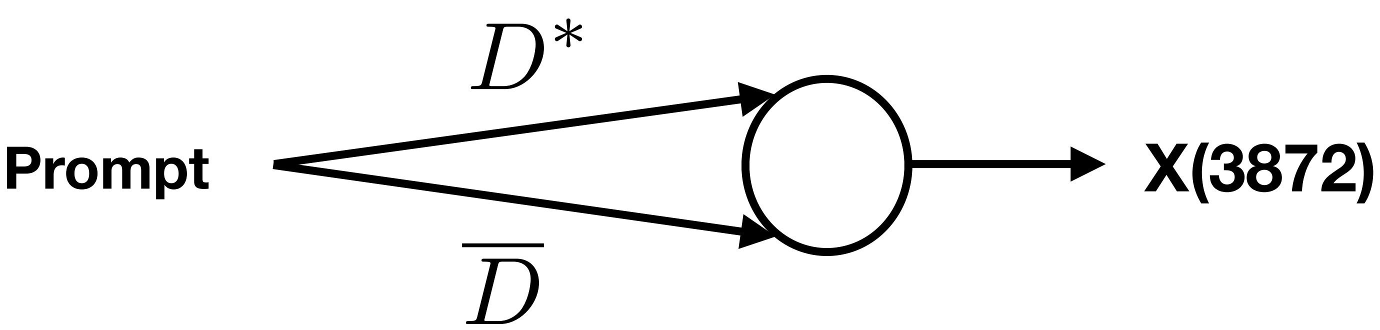
Inclusive prompt cross section

$$\mathrm{Br}[X \to J/\psi \pi^+\pi^-] \sigma(X(3872), Q^2 > 1 \ \mathrm{GeV}) \approx 2.6 \ \mathrm{pb} \qquad \sqrt{s} = 100 \ \mathrm{GeV}$$

Luminosity: $10^{34} \ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **0.026 Br*X(3872) per second**

Study Structure of X(3872) at EIC?

If molecule of $\overline{D}D^*$

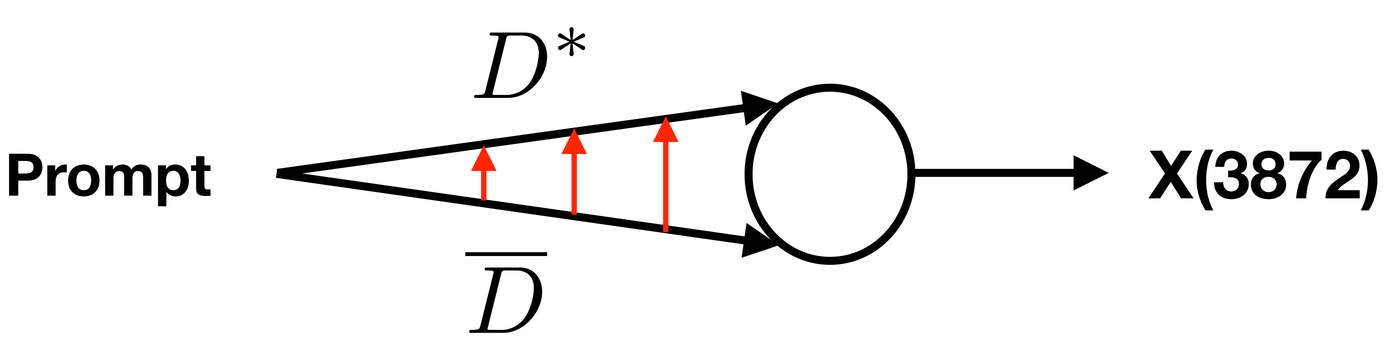


Produced with small
relative momentum

Give cross section too small
at Tevatron, cannot explain data

C. Bignamini, B. Grinstein, F. Piccinini, A.D. Polosa,
C. Sabelli, PRL 103, 162001 (2009)

Rescattering enhances production



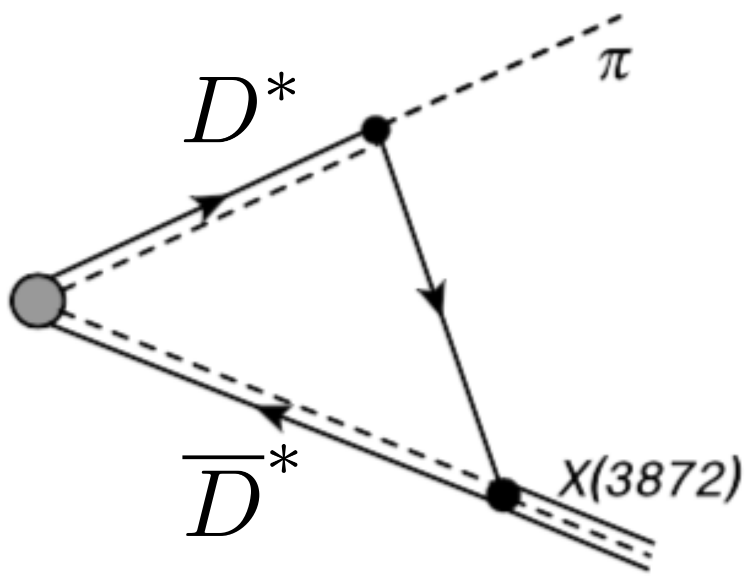
Near threshold, nonrelativistic scattering in c.o.m. frame

$$f(E) = \frac{1}{-1/a + \sqrt{-2\mu E - i\epsilon}}$$

P.Artoisenet, E.Braaten PRD 81 114018 (2010)

Study Structure of X(3872) at EIC?

If rescattering matters:



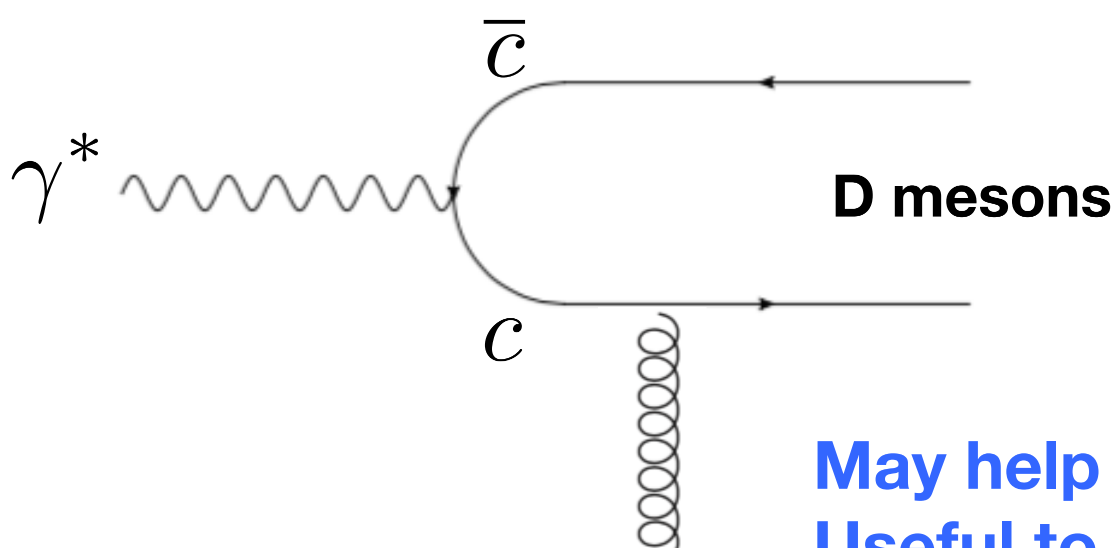
Rescattering of $D^*\overline{D}^*$ gives X(3872) and pion

$$\sigma(X(3872)\pi) \approx \sigma(X(3872))$$

For X-pion relative momentum < 190 MeV

E.Braaten, L.P.He, K.Ingles arXiv:1811.08876

Measure X and X+pion at EIC



Compare cross sections of X w/o soft pion v.s. X w/ soft pion

May help to understand the structure of X(3872)
Useful to measure line shape of decay channel

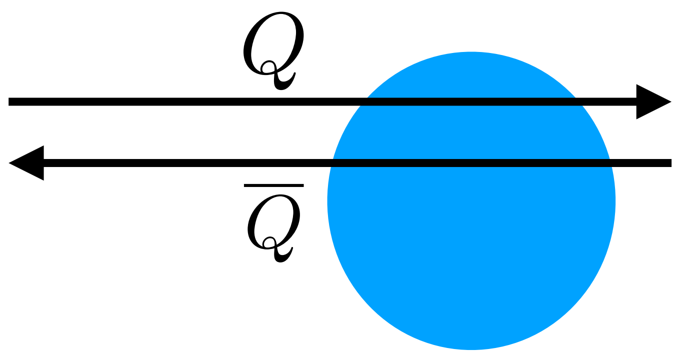
Doubly Heavy Baryon in Electron-ion Collisions

NRQCD factorization

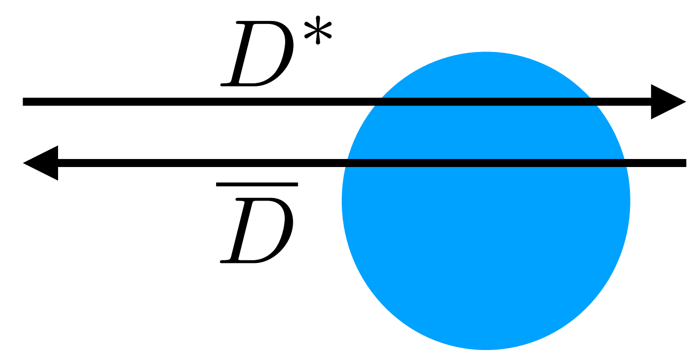
-	JLEIC	
$\sqrt{S_{\mathrm{NN}}}$ (GeV)	e-Au (40.1)	e-Pb (39.7)
events (Ξ_{cc}/year)	8.25×10^7	8.04×10^7
events (Ξ_{bc}/year)	5.37×10^5	5.04×10^5
events (Ξ_{bb}/year)	2.69×10^2	2.15×10^2
events ($\lvert c\bar{b}\rangle$/year)	2.88×10^5	2.80×10^5

Courtesy of Xing-Gang Wu

Nuclear Deep Inelastic Scattering

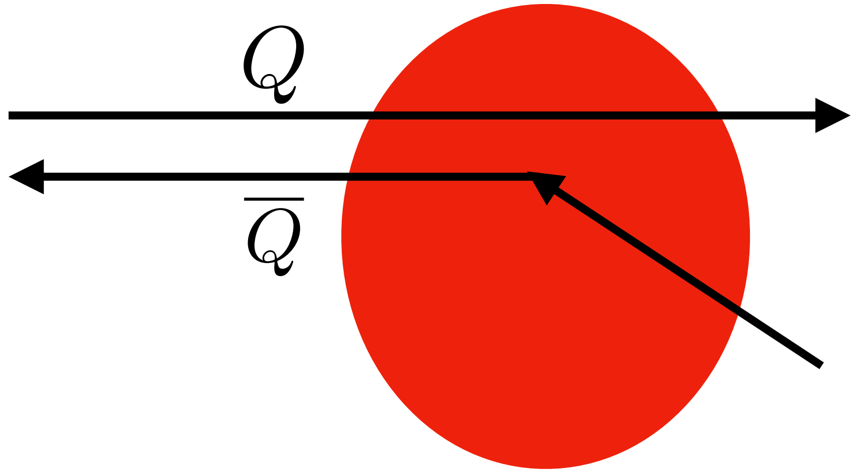


Cold nuclear matter



Cold nuclear matter

Transport in nuclear medium: heavy ion collisions



Quark-gluon plasma

Study nuclear modification factor R_{AA} & azimuthal angular anisotropy (gamma + p) using DIS on nucleon as reference?

Transport in Medium: Open Quantum System

$$\rho(t=0) = \rho_S \otimes \rho_E$$

System & environment

(Heavy quark pairs & QGP)

Unitary evolution

Time reversible

$$U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)$$

System & environment

Trace out (integrate out) environment

$$\rho_S(t=0)$$

System(heavy quark pairs)

Non-unitary

Time-irreversible

$$\mathrm{Tr}_E\left[U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)\right]$$

Evolution equation of system of heavy quark pairs (bound or unbound)

Lindblad equation

Open Quantum System & Transport Equation

Lindblad equation

$$\rho_S(t) = \rho_S(0) + \sum_{a,b,c,d} \gamma_{ab,cd}(t)\Big(L_{ab}\rho_S(0)L^{\dagger}_{cd} - \frac{1}{2}\{L^{\dagger}_{cd}L_{ab}, \rho_S(0)\}\Big)$$

$$-i\sum_{ab}\sigma_{ab}(t)[L_{ab}, \rho_S(0)] + \mathcal{O}(H_I^3)\,.$$

Potential NRQCD to describe system

N.Brambilla,M.A.Escobedo,J.Soto,A.Vairo PRD97 (7), 074009

Weakly Coupled QGP ⟶

$$D^{>\,ab}_{\mu\nu}(t,\boldsymbol{x}) = \langle A^a_\mu(t,\boldsymbol{x})A^b_\nu(0,0)\rangle_T$$

$$D^{>\,ab}_{\mu\nu}(q) = (1+n_B(q_0))\sum_\lambda \epsilon^{\lambda *}_\mu \epsilon^\lambda_\nu \delta^{ab}\rho_F(q)$$

Replace correlations for other nuclear medium

Markovian approximation

X.Yao, T.Mehen arXiv:1811.07027

Apply Wigner transform to system density matrix

Boltzmann equation

$$\frac{\partial}{\partial t}f_{nl}(\boldsymbol{x},\boldsymbol{k},t) + \boldsymbol{v}\cdot\nabla_{\boldsymbol{x}}f_{nl}(\boldsymbol{x},\boldsymbol{k},t) = \mathcal{C}^{(+)}_{nl}(\boldsymbol{x},\boldsymbol{k},t) - \mathcal{C}^{(-)}_{nl}(\boldsymbol{x},\boldsymbol{k},t)$$

Open Quantum System & Transport Equation

Lindblad equation

$$\rho_S(t) = \rho_S(0) + \sum_{a,b,c,d} \gamma_{ab,cd}(t)\left(L_{ab}\rho_S(0)L^\dagger_{cd} - \frac{1}{2}\{L^\dagger_{cd}L_{ab}, \rho_S(0)\}\right) - i\sum_{ab}\sigma_{ab}(t)[L_{ab}, \rho_S(0)] + \mathcal{O}(H_I^3)\,.$$

Thermal correction to Hamiltonian
Static screening of potential

Boltzmann equation

Recombination **Dissociation**

$$\frac{\partial}{\partial t} f_{nl}(\boldsymbol{x}, \boldsymbol{k}, t) + \boldsymbol{v}\cdot\nabla_{\boldsymbol{x}} f_{nl}(\boldsymbol{x}, \boldsymbol{k}, t) = \mathcal{C}^{(+)}_{nl}(\boldsymbol{x}, \boldsymbol{k}, t) - \mathcal{C}^{(-)}_{nl}(\boldsymbol{x}, \boldsymbol{k}, t)$$

Open Quantum System & Transport Equation

Lindblad equation

$$\rho_S(t) = \rho_S(0) + \sum_{a,b,c,d} \gamma_{ab,cd}(t)\Big(L_{ab}\rho_S(0)L^{\dagger}_{cd} - \frac{1}{2}\{L^{\dagger}_{cd}L_{ab}, \rho_S(0)\}\Big) - i\sum_{ab}\sigma_{ab}(t)[L_{ab}, \rho_S(0)] + \mathcal{O}(H_I^3)\,.$$

Thermal correction to Hamiltonian
Static screening of potential

Static screening, dissociation & recombination in same theoretical framework

Derive transport equation from QCD in theoretically controlled way

Recombination **Dissociation**

Boltzmann equation

$$\frac{\partial}{\partial t} f_{nl}(\boldsymbol{x}, \boldsymbol{k}, t) + \boldsymbol{v}\cdot\nabla_{\boldsymbol{x}} f_{nl}(\boldsymbol{x}, \boldsymbol{k}, t) = \mathcal{C}^{(+)}_{nl}(\boldsymbol{x}, \boldsymbol{k}, t) - \mathcal{C}^{(-)}_{nl}(\boldsymbol{x}, \boldsymbol{k}, t)$$

Approach Equilibrium: Coupled with Open Heavy Flavor Transport

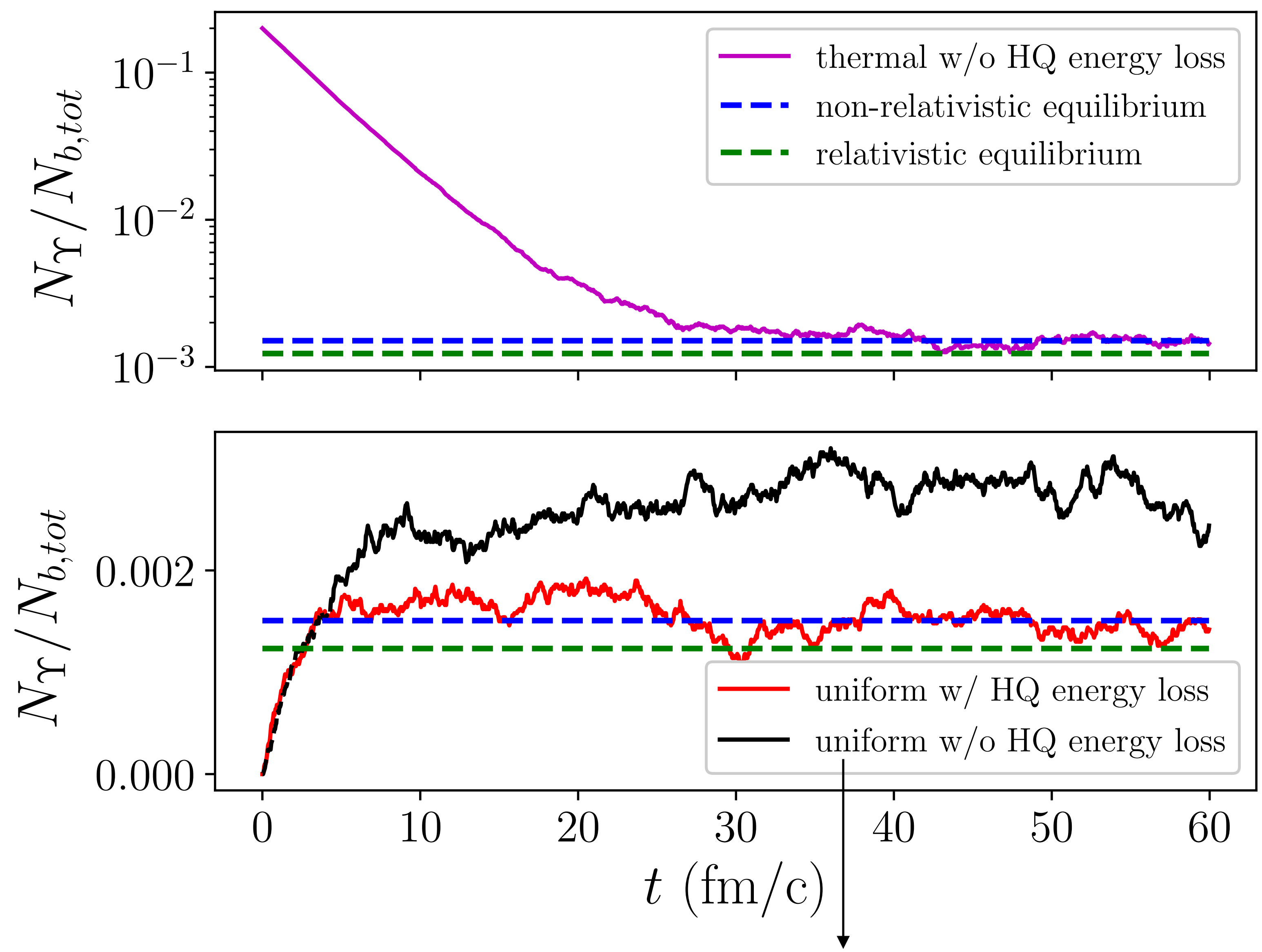
Setup:
QGP box w/ const T, 1S state and b quarks: total b flavor = 50 (fixed)
Initial momenta sampled from thermal or uniform distributions

XY, B.Mueller, Phys. Rev. C 97, no. 1, 014908 (2018)

Recombination from QCD effective field theory and real dynamics of HQ

Dissociation-recombination interplay drives to detailed balance

Heavy quark energy gain/loss necessary to drive kinetic equilibrium of quarkonium



sampled from uniform distribution between 0-1 GeV

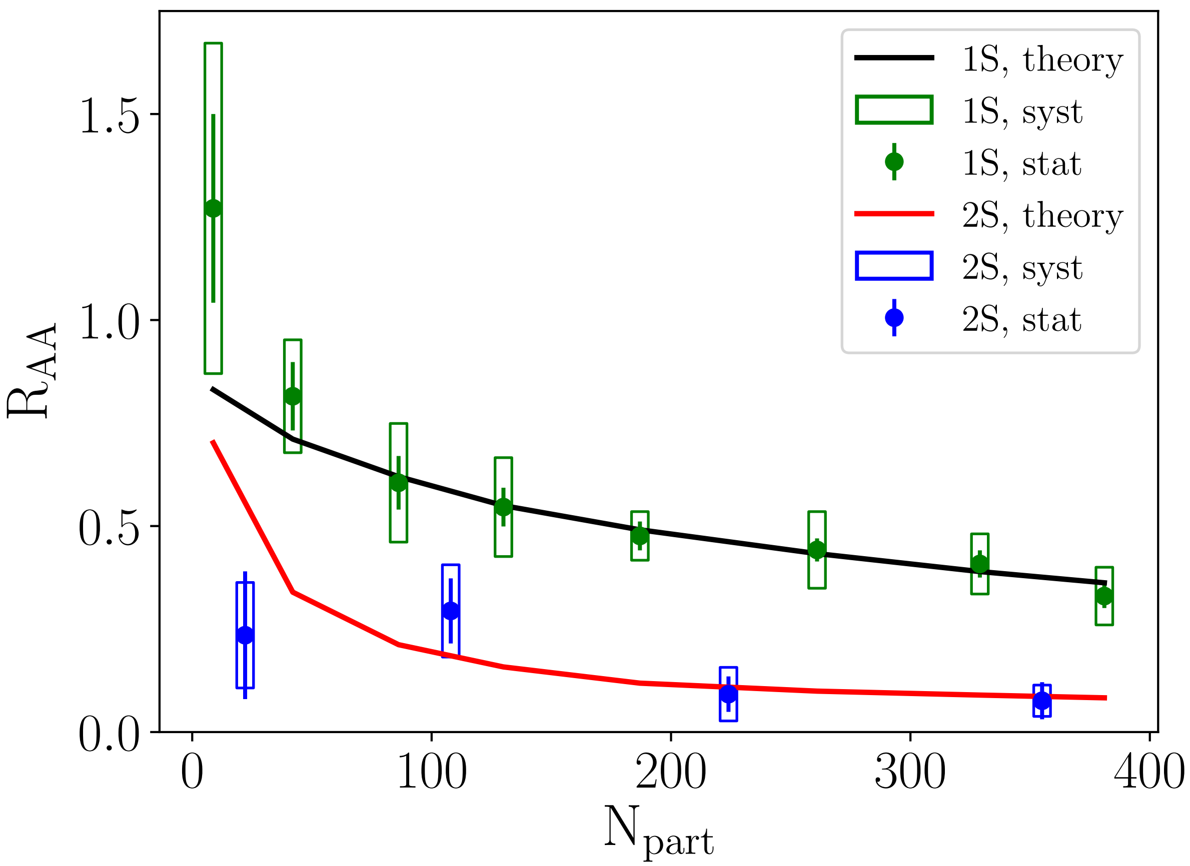
Upsilon in 2760 GeV PbPb Collision

Fix $\alpha_s = 0.3$

Tune $T_{\mathrm{melt}}(2S) = 210\ \mathrm{MeV}$

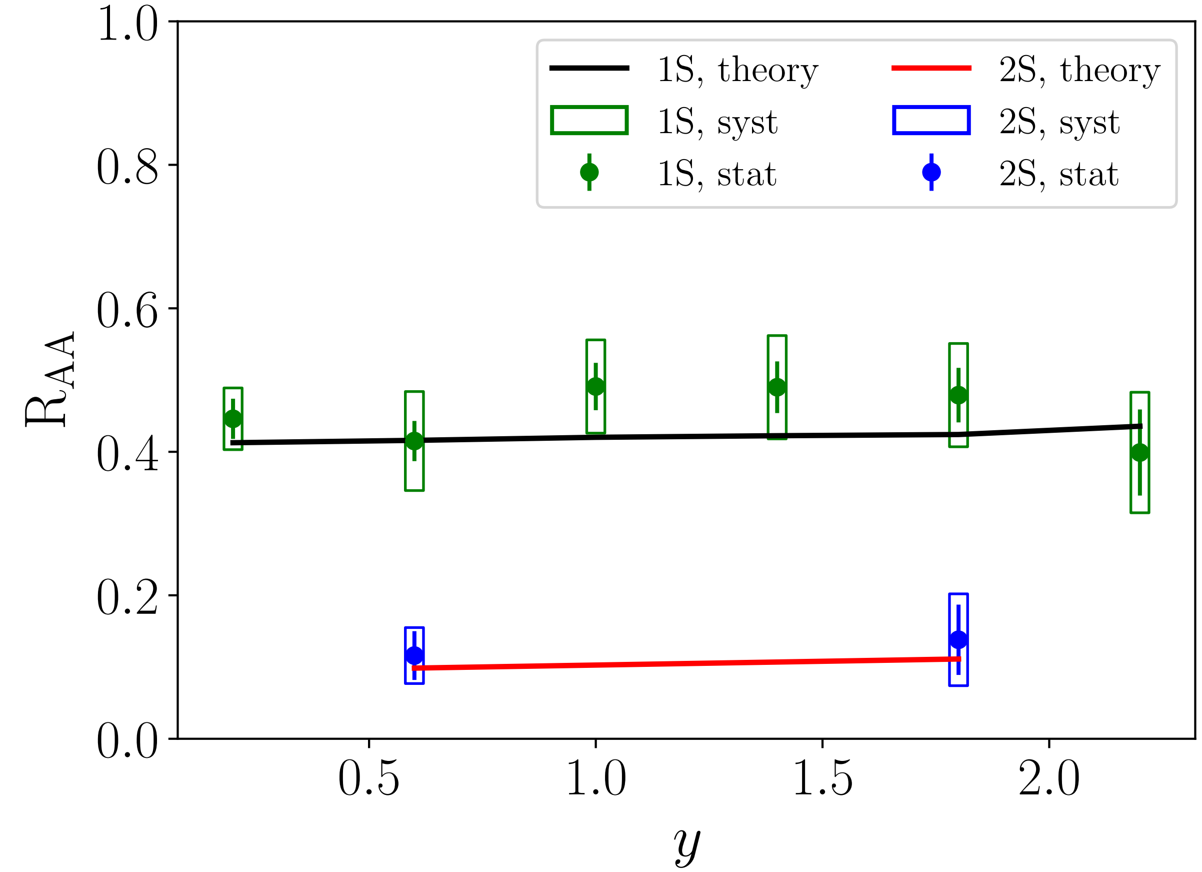
Tune $V_s = -C_F \frac{0.42}{r}$

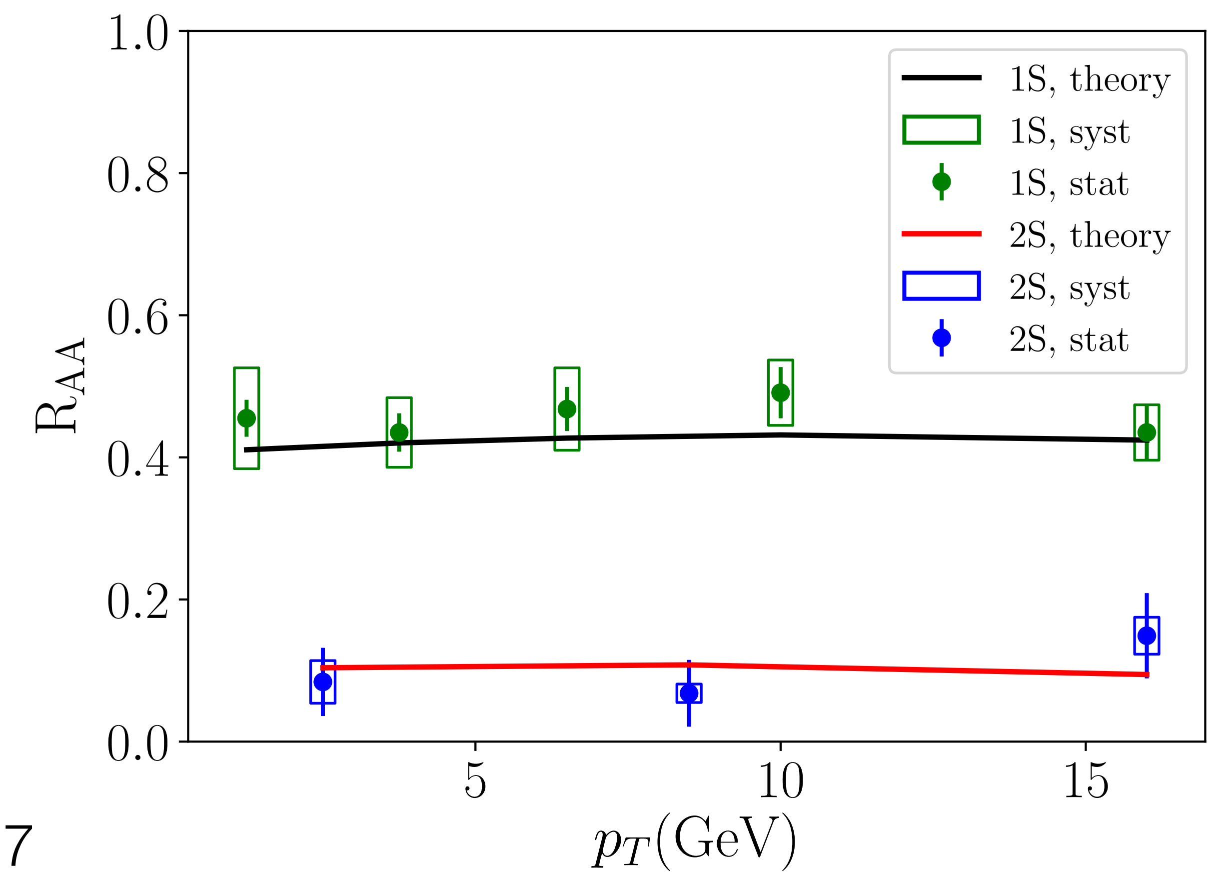
Cold nuclear matter effect ~ 0.87 (PYTHIA + nPDF)



CMS Phys.Lett. B
770 (2017) 357-379

X.Yao, W.Ke, Y.Xu, S.Bass
and B.Müller arXiv:1807.06199

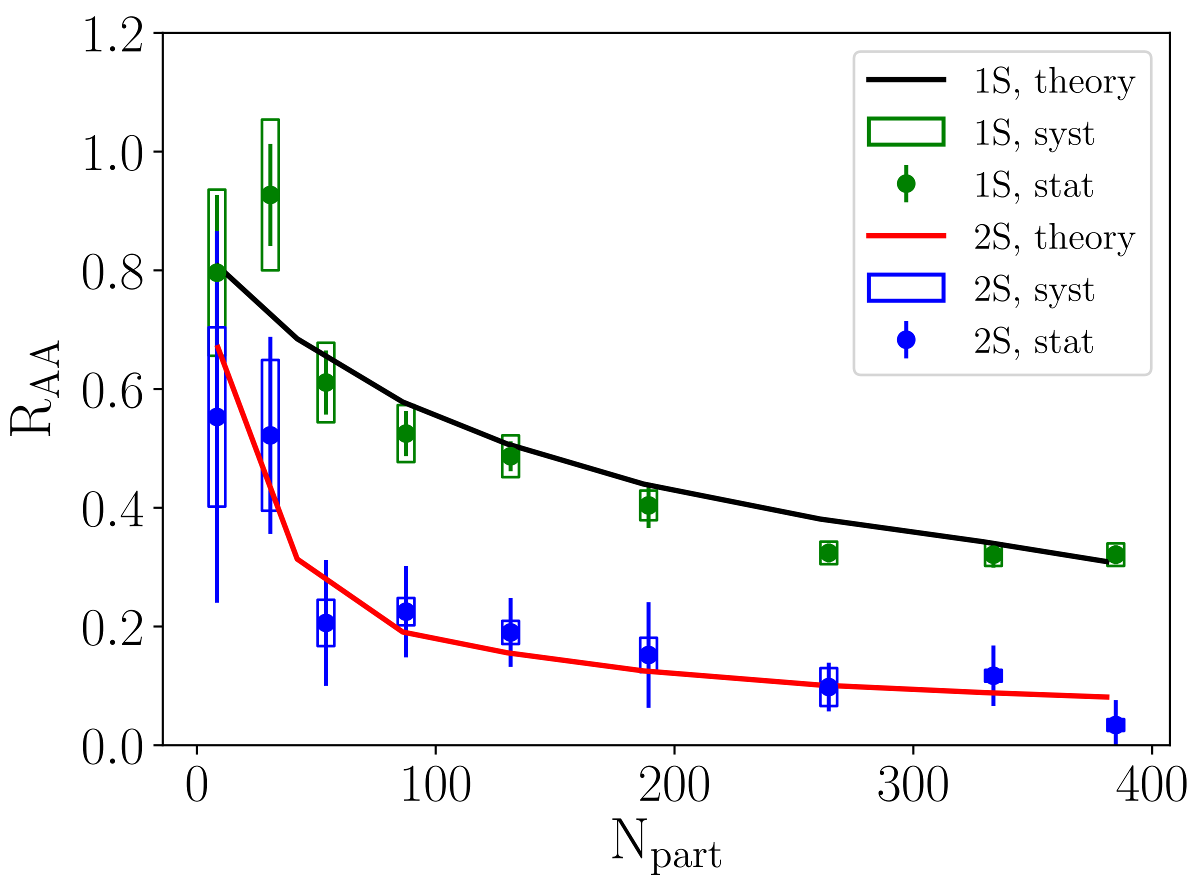


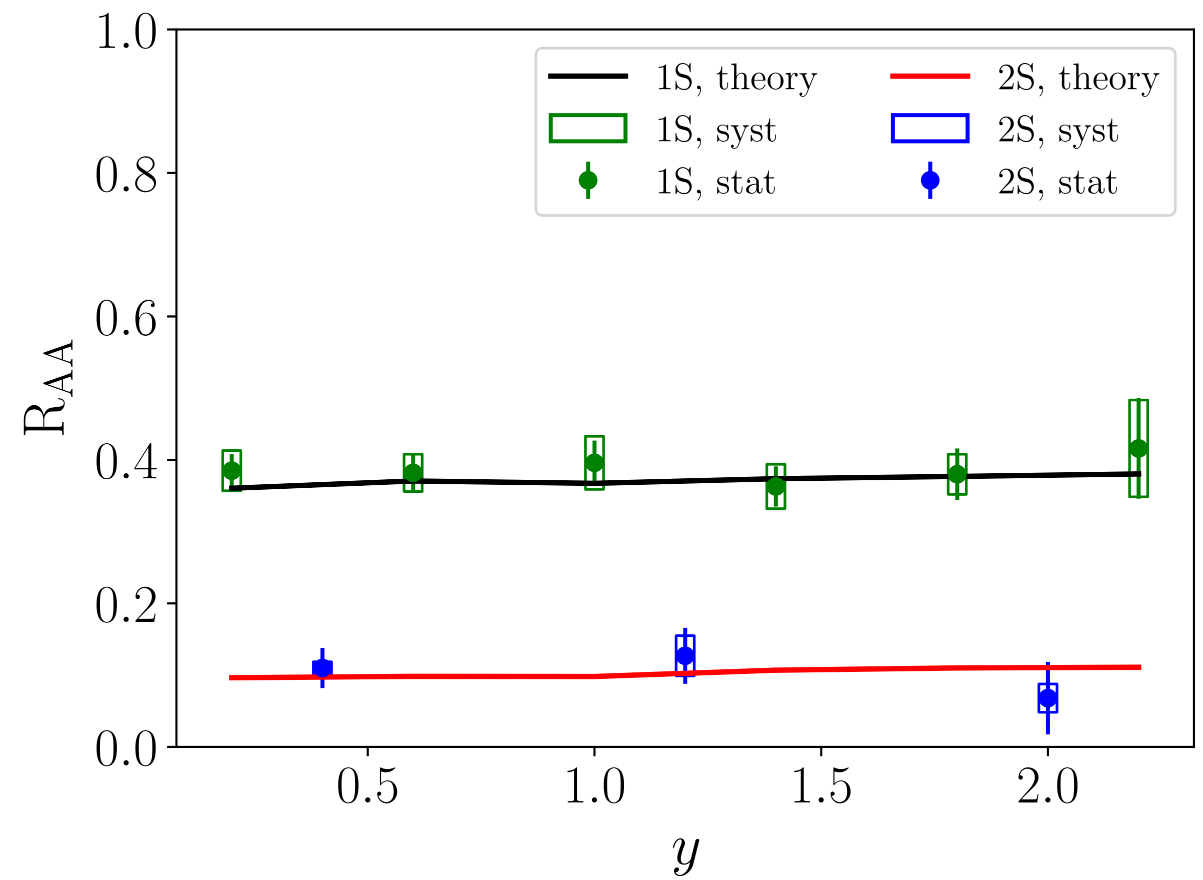


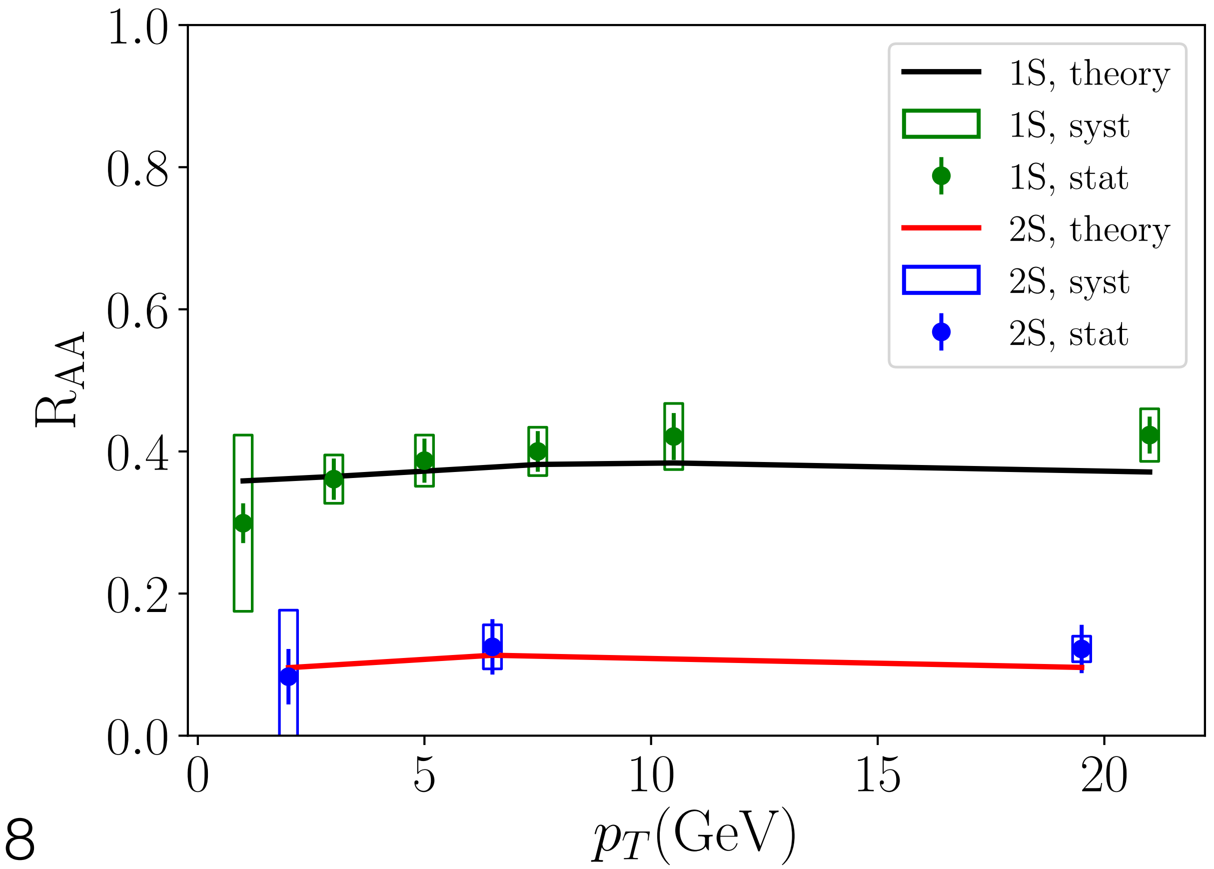
Upsilon in 5020 GeV PbPb Collision

Use same set of parameters

Cold nuclear matter effect ~ 0.85 (PYTHIA + nPDF)







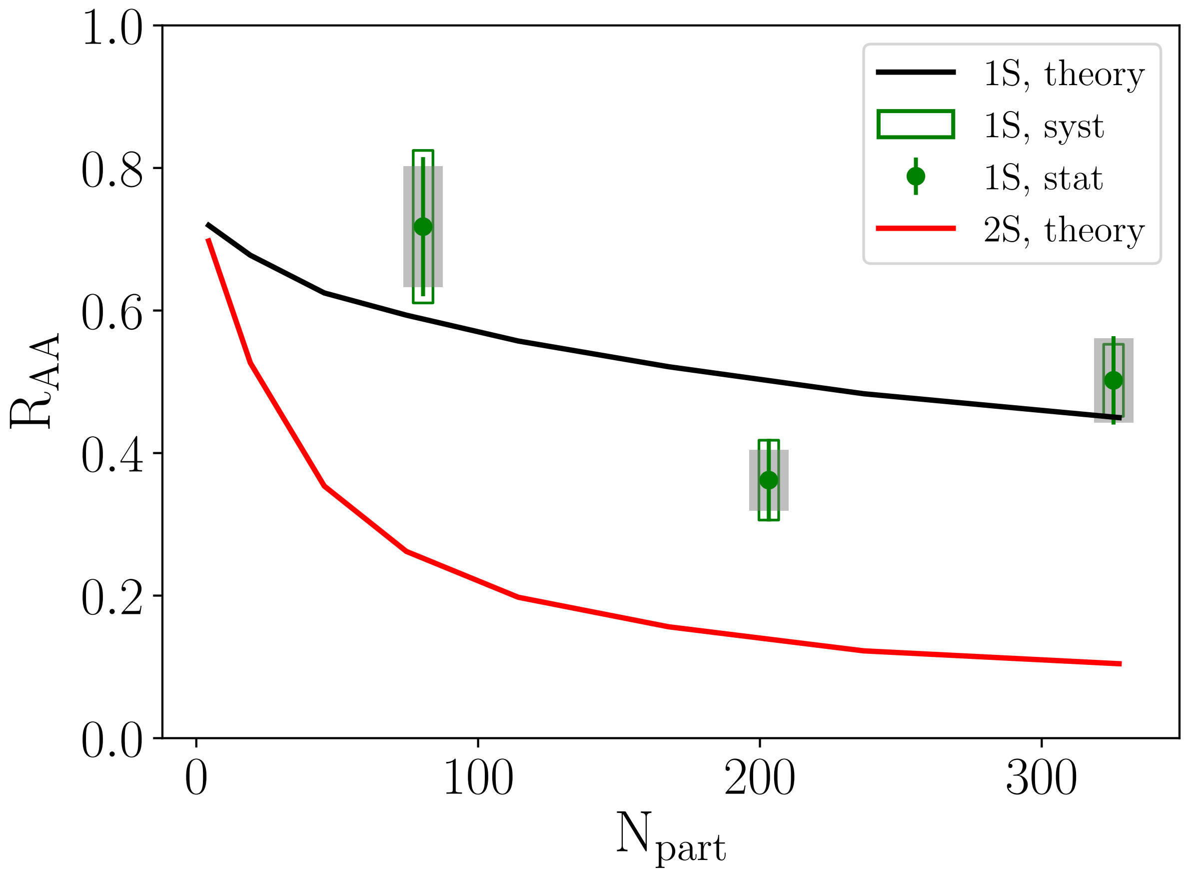
CMS arXiv:1805.09215

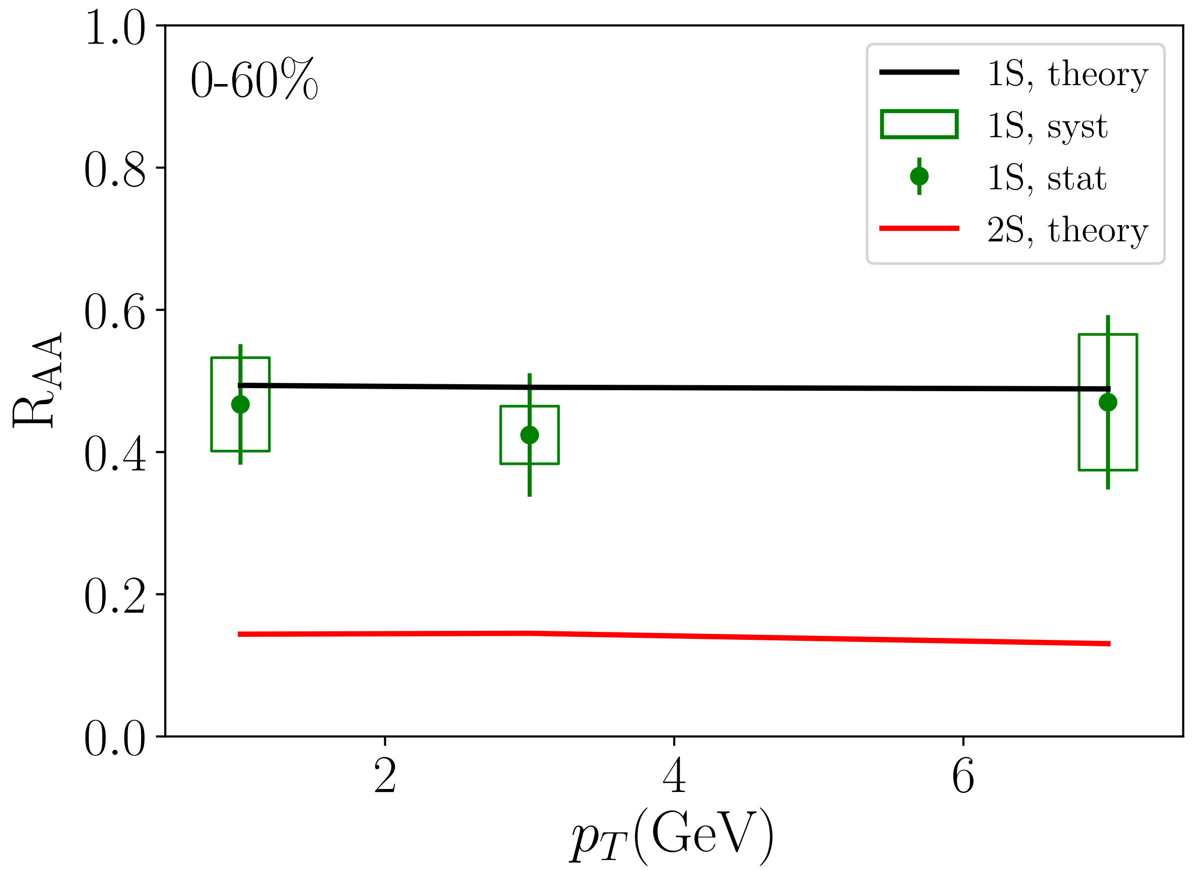
X.Yao, W.Ke, Y.Xu, S.Bass
and B.Müller arXiv:1812.02238

Upsilon in 200 GeV AuAu Collision

Use same set of parameters

Cold nuclear matter effect ~ 0.72

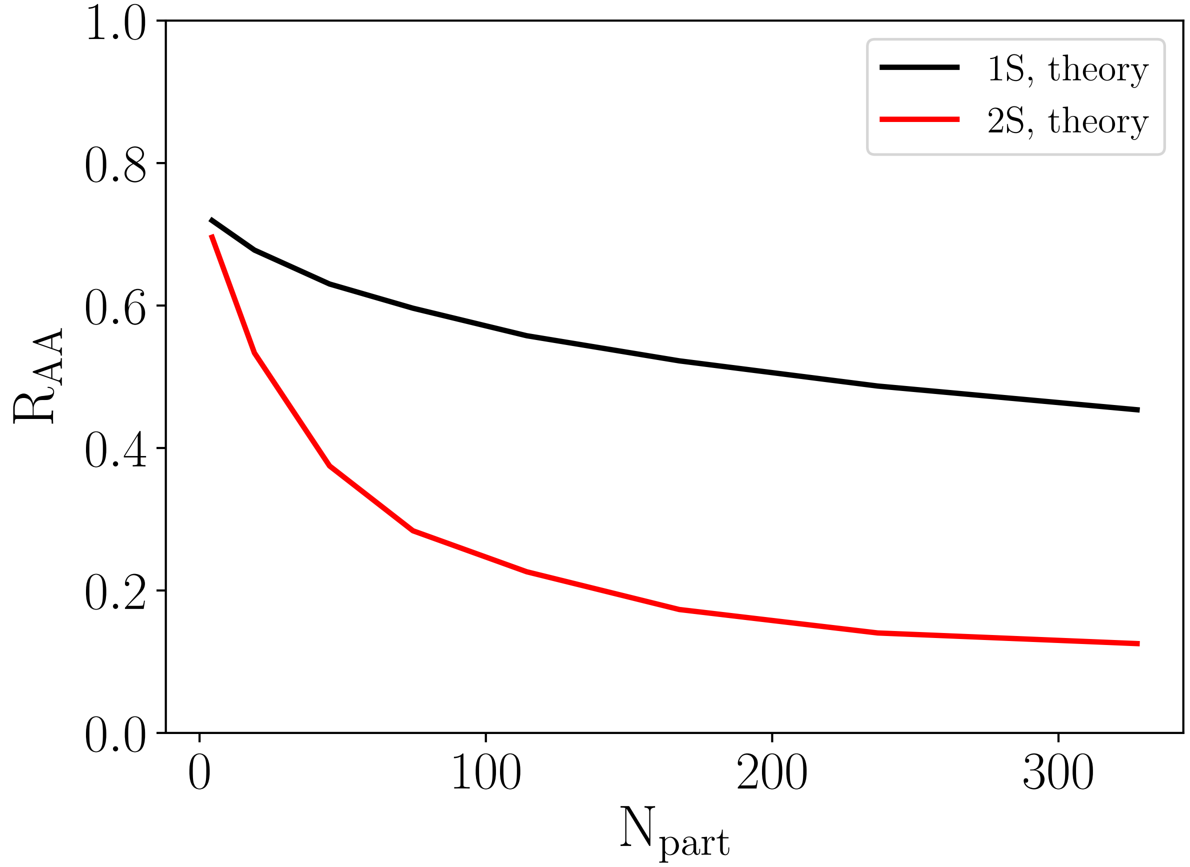


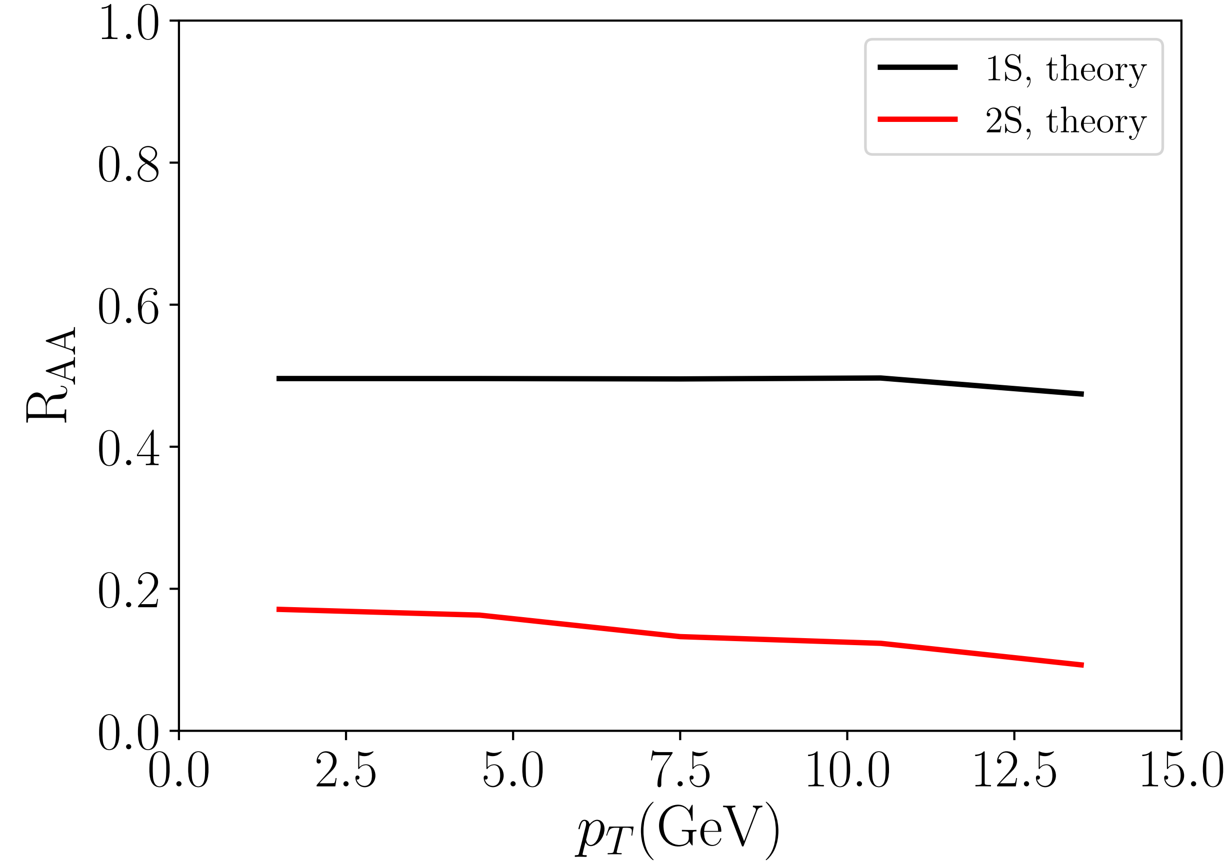


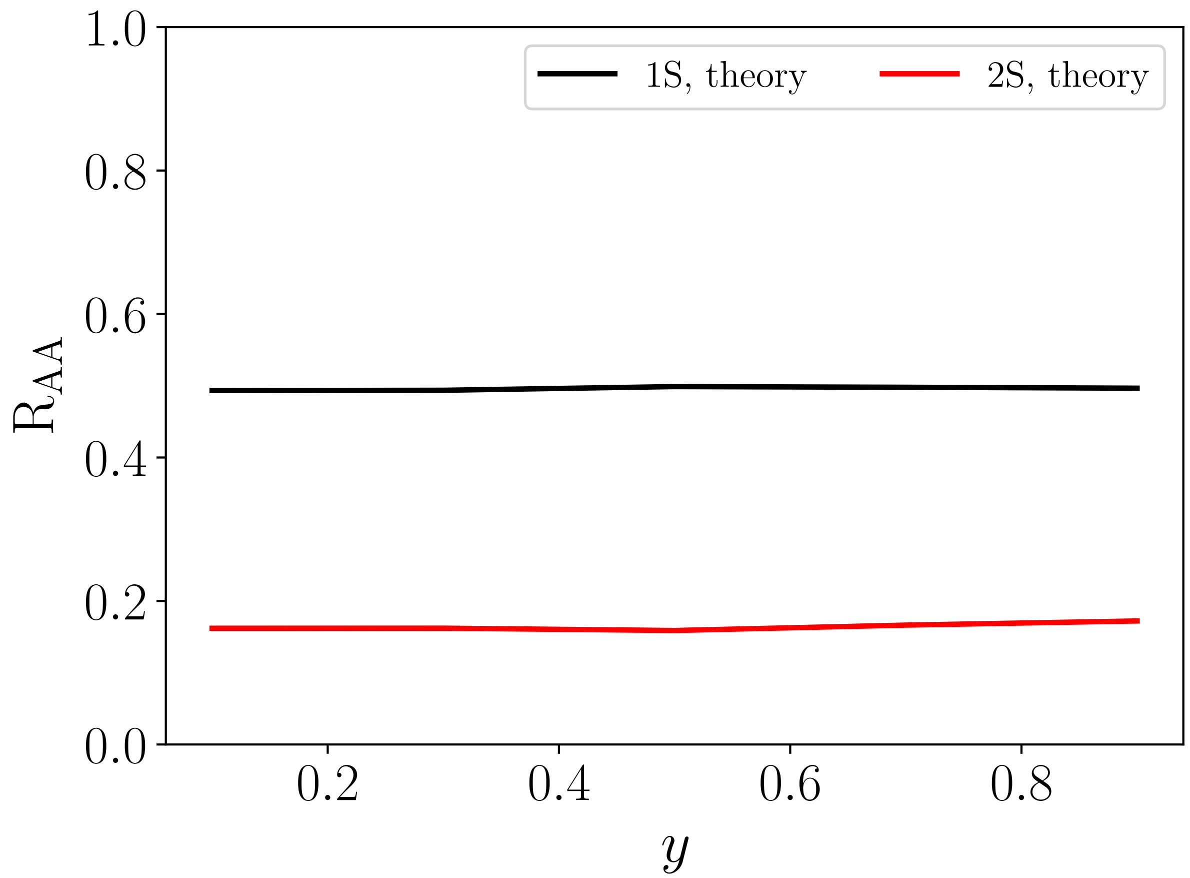
STAR measures 2S+3S

STAR Talks at QM 17&18

Upsilon in 200 GeV AuAu Collision







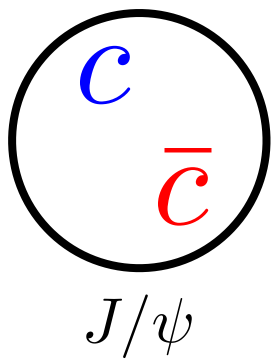
Predictions for kinematics in sPHENIX
|y| < 1

Doubly Charmed Baryon

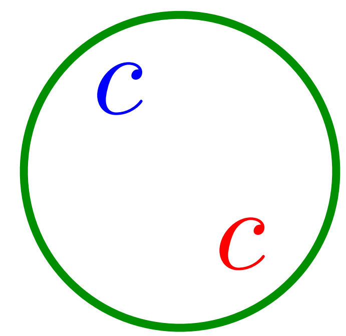
- LHCb observed a new baryon Ξ_{cc}^{++}(ccu): u bound around cc core

LHCb, Phys. Rev. Lett. 119, no.11,112001 (2017)

- Pair of heavy Q in anti-triplet forms bound state (diquark)



$Q\bar{Q}$ singlet
color neutral
exist in vacuum



cc diquark (1S)

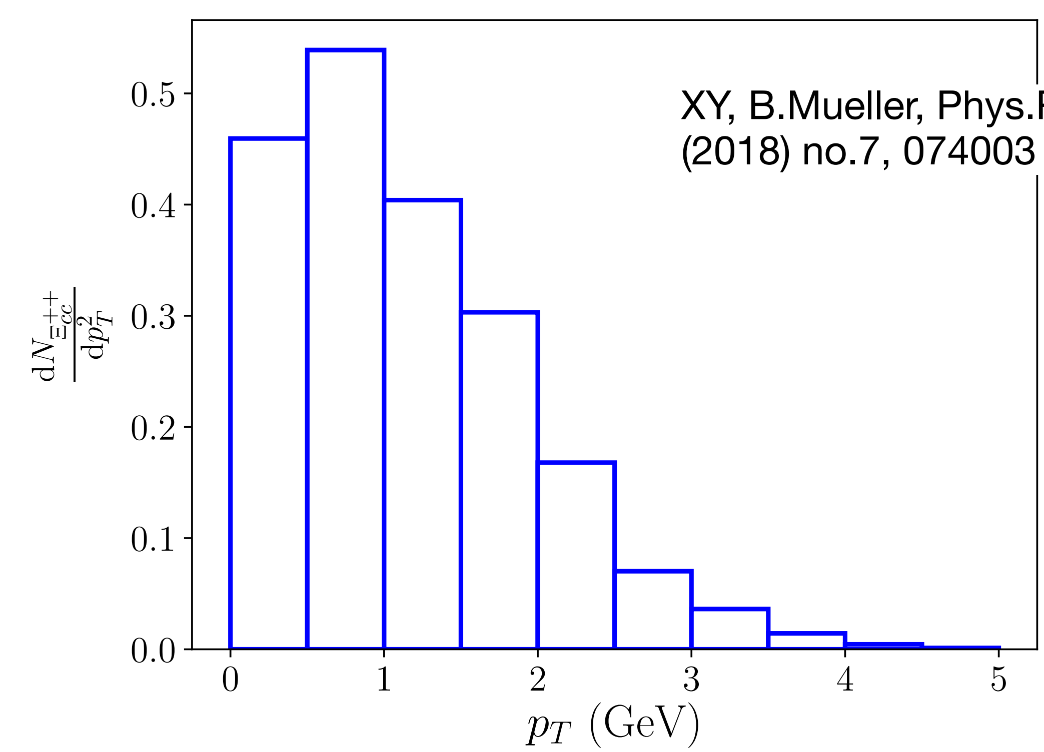
QQ anti-triplet
colored
not exist in vacuum
exist in QGP

- Heavy diquark in QGP: dissociation, recombination (similar to quarkonium), carry color, energy loss different from quarkonium, hadronize into doubly charmed baryon

Predicted production rate of Ξ_{cc}^{++} in 2760 GeV PbPb, -1<y<1, 0<pT<5 GeV,
0.02 per collision

With melting temperature = 250 MeV:
0.0125 per collision

Compare: c quark rate ~10 per collision



XY, B.Mueller, Phys.Rev.D97 (2018) no.7, 074003

Summary

- Quarkonium, X(3872) and doubly heavy baryon production at EIC: NRQCD factorization
- Measure cross sections of X+pion and X+no pion and line shape to test molecular structure
- Nuclear DIS: transport in cold nuclear medium, open quantum system, quarkonium production in heavy-ion collisions
- Doubly charmed baryon in electron-ion and heavy-ion collisions