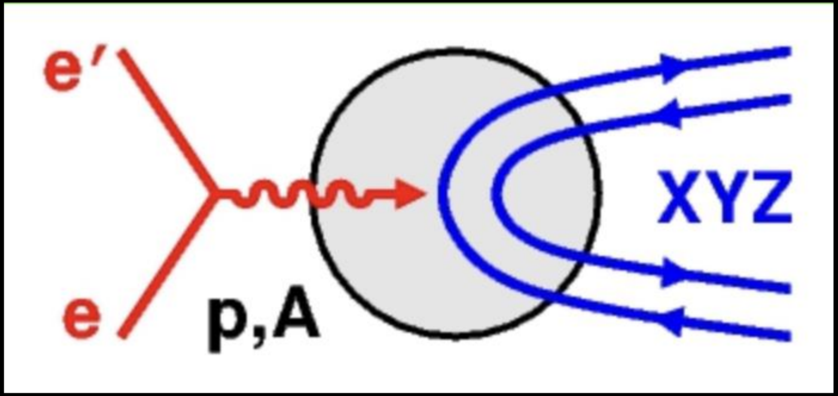
Ivan Vitev

Quarkonium structure and interactions with medium

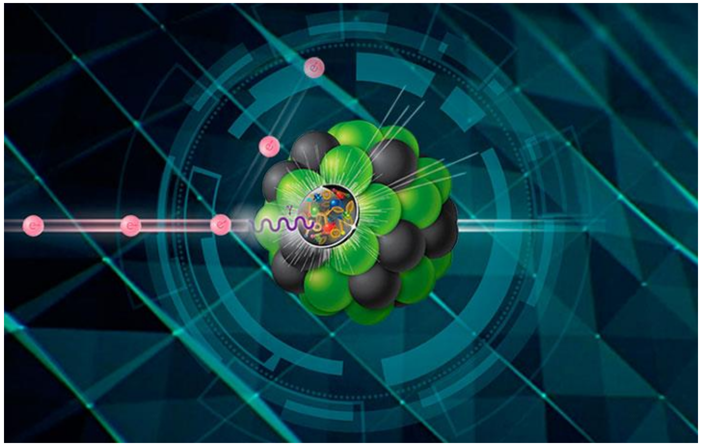


CFNS Workshop "Exotic Heavy Meson Spectroscopy with EIC: Detector/Physics Simulations and Feasibility"
CFNS, SUNY Stony Brook, NY
April 14-17, 2025

Los Alamos NATIONAL LABORATORY EST. 1943

Outline of the talk

- Quarkonium production in elementary collisions
- Open questions, new directions, and opportunities at the EIC
- Quarkonia in nuclei – Glauber gluons and NRQCD_G
- The physics of quarkonium dissociation
- Quarkonium observables at the EIC and connection to hadronization
- Conclusions and future directions



Bottom line up front: Quarkonia and exotics at the intersections of hadronic, heavy ion, and EIC science provides exciting theory advancement opportunities.

For complementary discussion for quarkonia in relation to TMDs, non-perturbative analysis, LDMEs, nuclear PDFs, exotics with nuclei, precision physics, small-x

D. Boer *et al. (2024)*

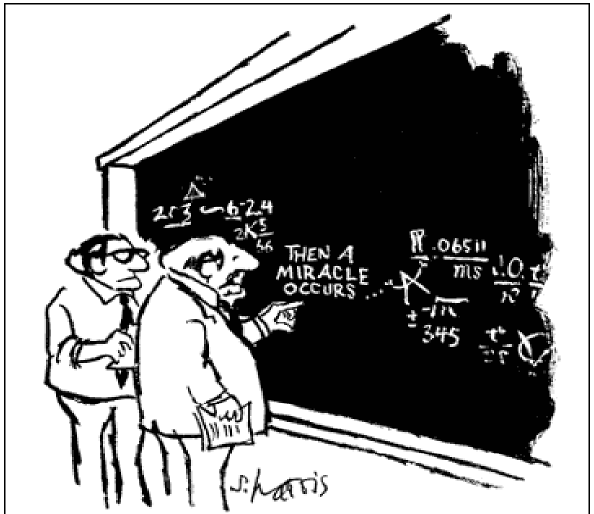
Ch. Naim *et al. in preparation (2025)*

Acknowledgment of support

U.S. DEPARTMENT OF ENERGY Office of Science

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Quarkonia in elementary collisions



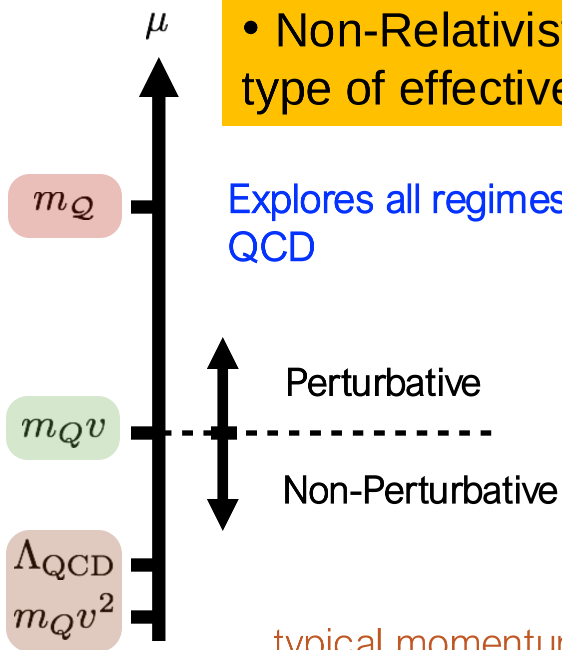
“I think you should be more explicit here in step two.”

Production of quarkonia

- Non-Relativistic QCD (NRQCD) - a particular type of effective theory (EFT)

Bodwin *et al.* (1995)

Cho *et al.* (1996)



Explores all regimes of QCD

$b\bar{b}: \quad v^2 \sim 0.1$

$c\bar{c}: \quad v^2 \sim 0.3$

Ultra-soft

$p_s^\mu \sim m_Q v(1,1,1,1)$

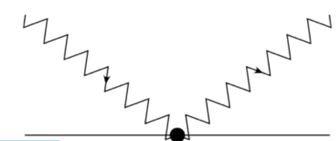
$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

$$\mathcal{L}_{\text{NRQCD}} = \mathcal{L}_{\text{light}} + \psi^\dagger\left(iD_0 + \frac{\mathbf{D}^2}{2M}\right)\psi + \chi^\dagger\left(iD_0 - \frac{\mathbf{D}^2}{2M}\right)\chi$$

QCD without the heavy flavor

ultra-soft

+ heavy - soft interactions at NLO



typical momentum if heavy quark: $|\mathbf{p}_Q| \sim m_Q v$

typical kinetic energy if heavy quark: $K_Q \sim m_Q v^2$

pNRQCD N. Brambilla *et al.* (2000)

vNRQCD M. Luke *et al.* (2000)

- NRQCD factorization formula. Short distance cross sections (perturbatively calculable) and long distance matrix elements (fit to data, scaling relations)

$$d\sigma(a+b \to \mathcal{Q} + X) = \sum_n d\sigma(a+b \to Q\overline{Q}(n) + X)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

Open questions - LDMEs

- Universality of LDMEs – Different data sets and ranges used, different reactions

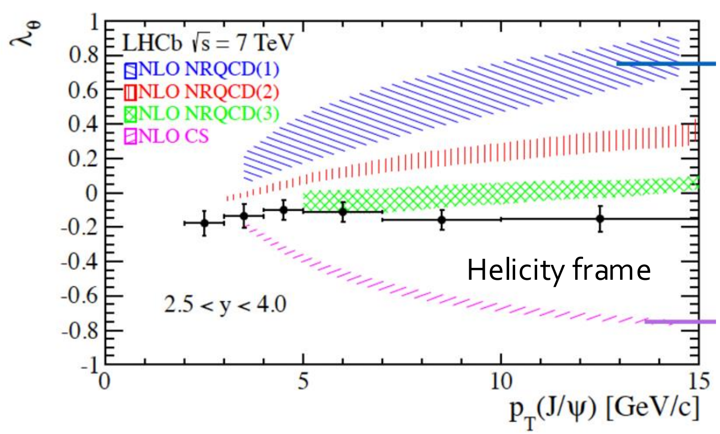
Boer et al. (2024)

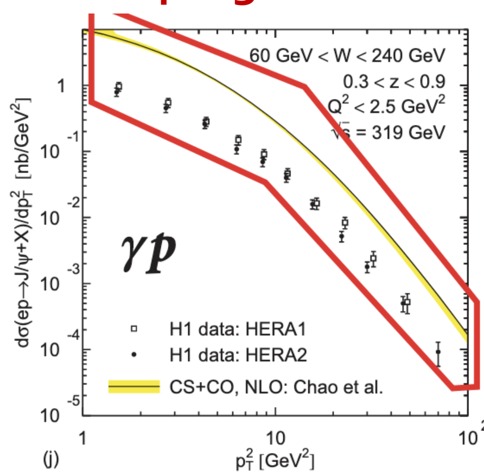
Acronym	Reference	J/ψ hadropr.	J/ψ photopr. and e^+e^-	J/ψ polar. in hadropr.	η_c hadropr. ($P_T > 6.5$ GeV)
BK11	Butenschön et al. [104, 105, 106, 107]	✓($P_T > 3$ GeV)	✓	✗	✗
H14	Chao et al. + η_c [114]	✓($P_T > 6.5$ GeV)	✗	✓	✓
Z14	Zhang et al. [115]	✓($P_T > 6.5$ GeV)	✗	✓	✓
G13	Gong et al. [109]	✓($P_T > 7$ GeV)	✗	✓	✗
C12	Chao et al. [108]	✓($P_T > 7$ GeV)	✗	✓	✗
B14	Bodwin et al. [80]	✓($P_T > 10$ GeV)	✗	✓	✗
pNRQCD	Brambilla et al. [110, 116]	✓($P_T > 15$ GeV)	✗	✓	✗✓

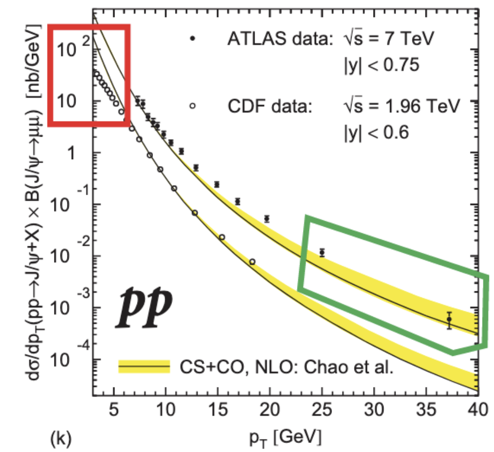
Values

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

Strong tensions still remain if one attempts global description





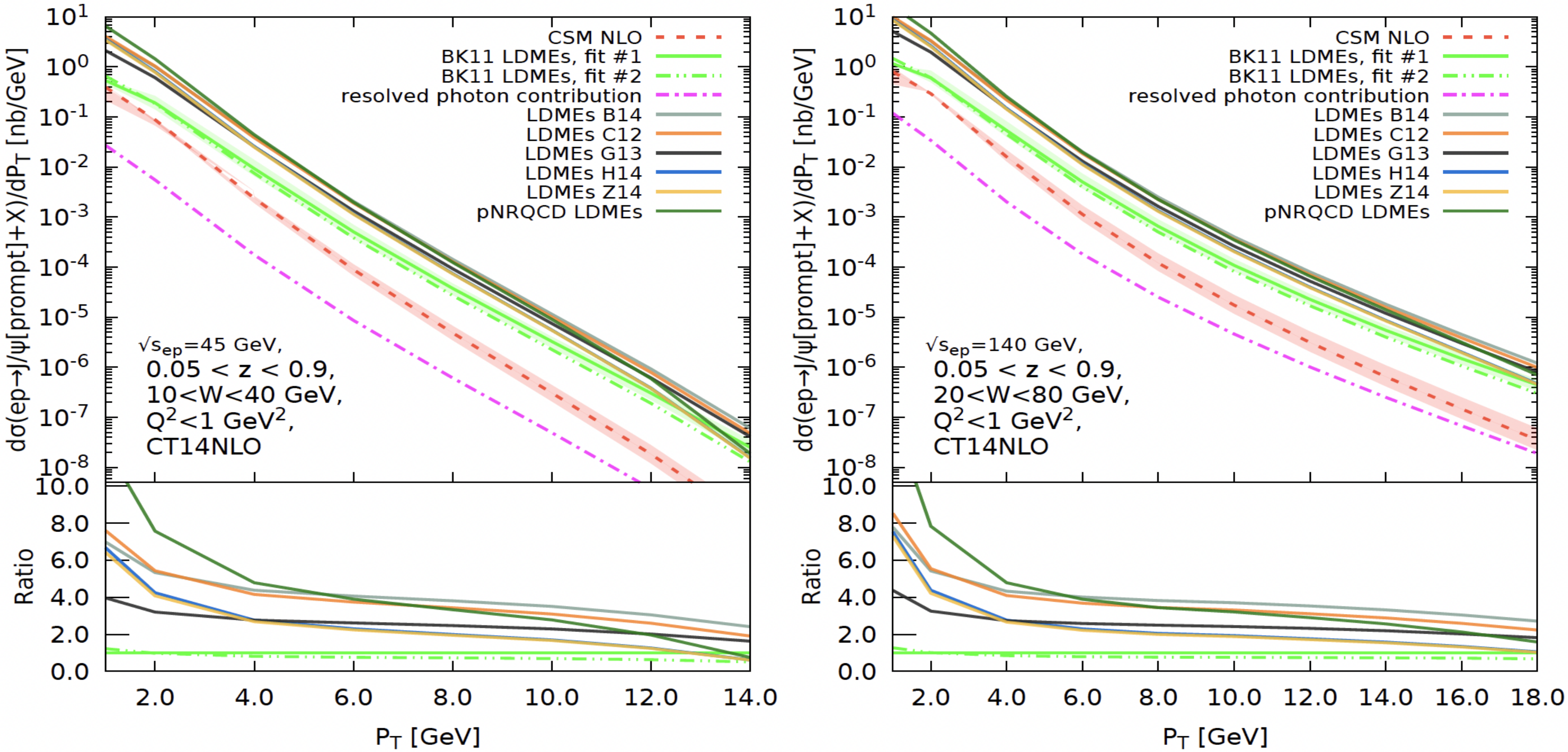


For polarization

And for cross sections

Projected EIC impact

- With the current LDMEs, predicted variation of the p_T differential cross section (e.g. J/ψ) can be a factor of 4 to 10. EIC can clearly help constrain the LDMEs much more accurately.



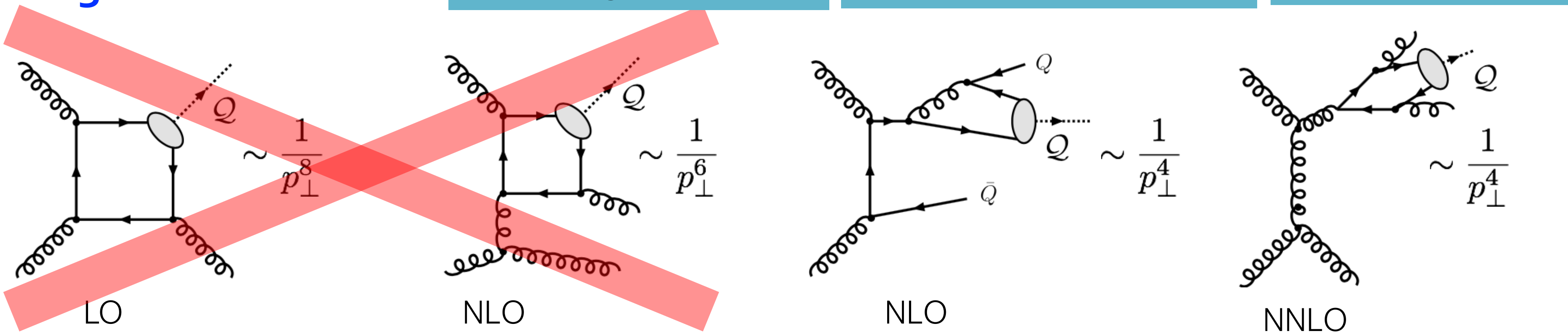
Two characteristic CM energies at the EIC

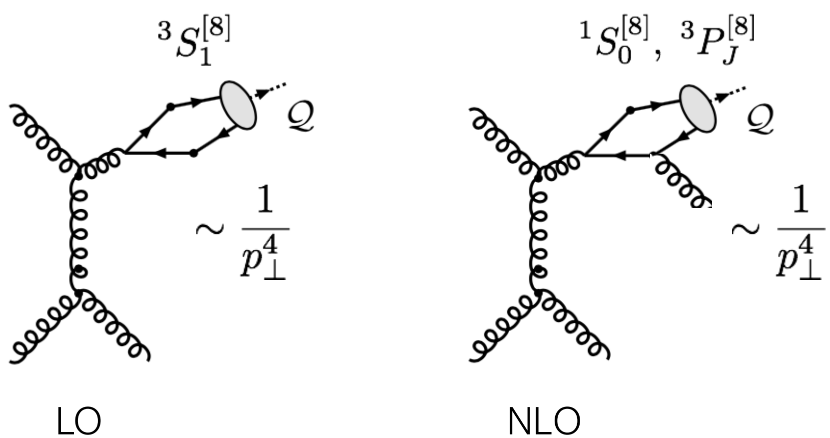
Boer et al. (2024)

Leading power factorization

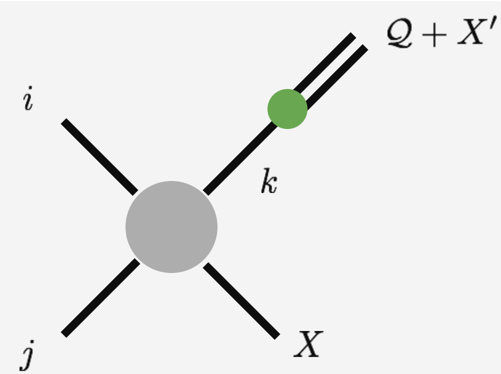
Singlet contribution

S. Fleming *et al.* (2012) | M. Baumgart *et al.* (2014) | Y. Ma *et al.* (2014)





(single) Parton fragmentation process



Octet contribution

Only a subset of contributions survive, now interpretable as parton fragmentation in quarkonia

LP example and applicability

$$\frac{d\sigma_h}{dp_\perp}(p_\perp) = \sum_i \int_z^1 \frac{dx}{x}\, \frac{d\sigma_i}{dp_\perp}\left(\frac{p_\perp}{x},\mu\right) D_{i/h}(x,\mu) + \mathcal{O}\left(\frac{m_h^2}{p_\perp^2}\right)$$

$p_T \gg m_Q$

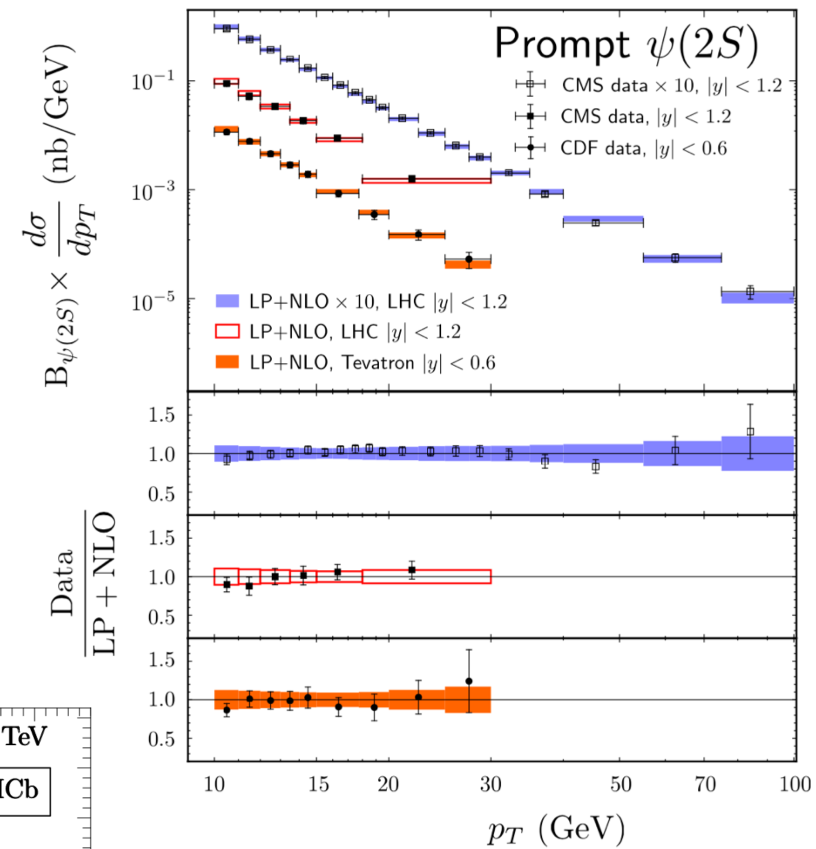
$$\ln\left(\frac{\mu}{p_T}\right) - \ln\left(\frac{\mu}{2m_Q}\right) \quad d_{i/n}(x,\mu)\langle\mathcal{O}_n^h\rangle$$

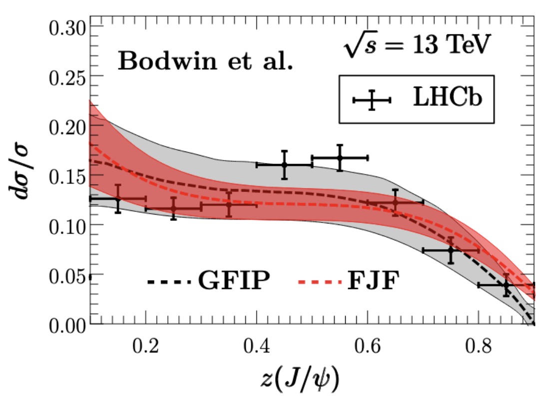
DGLAP Evolution

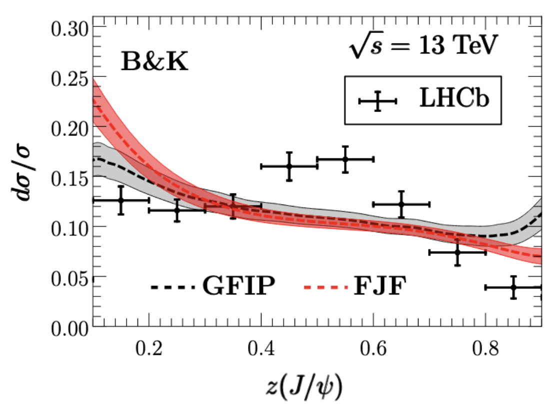
$$\mu\frac{d}{d\mu}D_{i/h}(z,\mu) = \sum_i \int_z^1 \frac{dx}{x}\, P_{ij}(x) D_{i/h}\left(\frac{z}{x},\mu\right)$$

Resummation of $\ln(p_T/m_h)$

New opportunities to constrain LDMEs







G. Bodwin *et al. (2016)*

R. Bain *et al. (2017)*

Opportunities in e+p at the EIC

TMD formalism and fragmentation at small and intermediate p_T

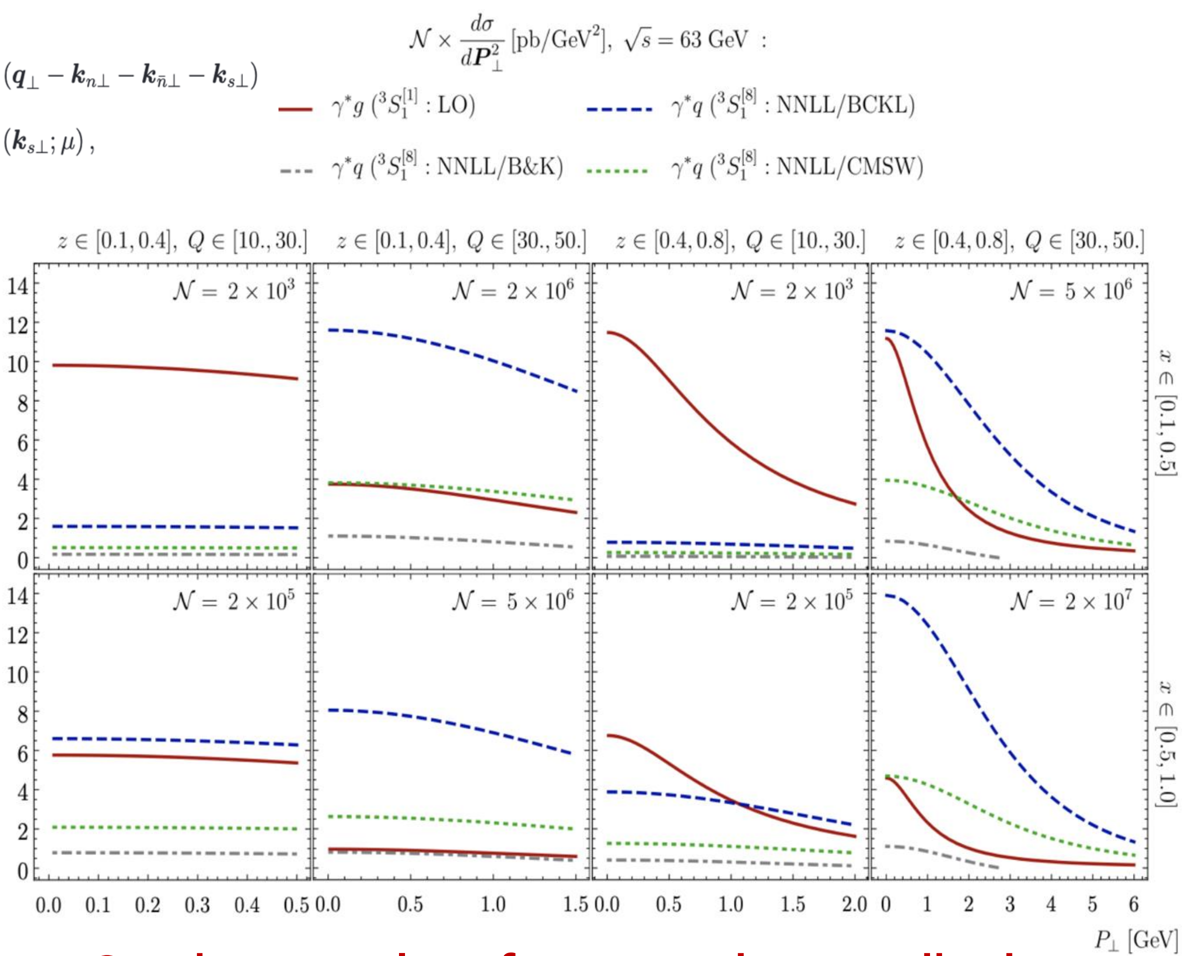
$$\frac{d\sigma}{dy\, d^2q_\perp} = \frac{4M^4\, H(M^2,\mu^2)}{2sM^2(N_c^2-1)}\, \Gamma^*_{\rho\sigma}\Gamma_{\mu\nu}(2\pi) \int d^2\boldsymbol{k}_{n\perp} d^2\boldsymbol{k}_{\bar{n}\perp} d^2\boldsymbol{k}_{s\perp}\, \delta^{(2)}\left(\boldsymbol{q}_\perp - \boldsymbol{k}_{n\perp} - \boldsymbol{k}_{\bar{n}\perp} - \boldsymbol{k}_{s\perp}\right)$$
$$\times\, G^{\sigma\nu}_{g/A}(x_A, \boldsymbol{k}_{n\perp}, S_A; \zeta_A, \mu)\, G^{\rho\mu}_{g/B}(x_B, \boldsymbol{k}_{\bar{n}\perp}, S_B; \zeta_B, \mu)\, S_{\eta_Q}\left[{}^1S_0^{[1]}\right](\boldsymbol{k}_{s\perp}; \mu)\,,$$

$$\tilde{S}_{\eta_Q}\left[{}^1S_0^{[1]}\right](\xi_T; \mu) = \frac{\tilde{S}^{(0)}_{\eta_Q}\left[{}^1S_0^{[1]}\right](\xi_T; \mu)}{\tilde{S}(\xi_T; \mu)}$$

Non-perturbative physics captured in shape functions

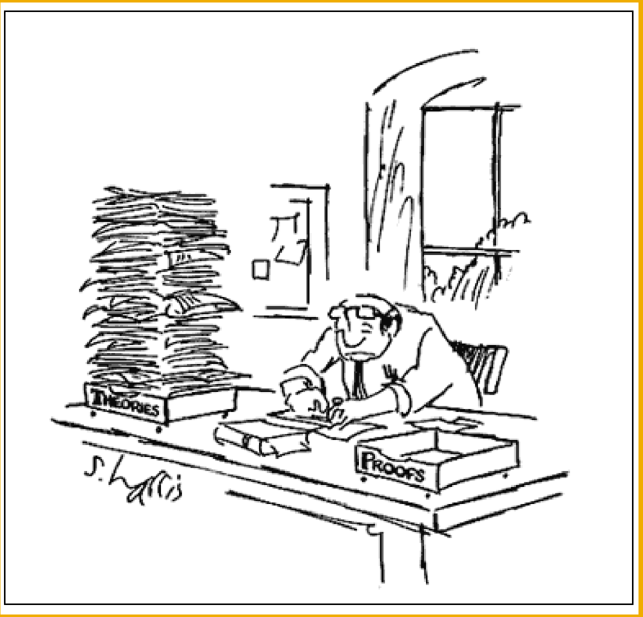
M. Echevarria (2019)

S. Fleming *et al.* (2019)

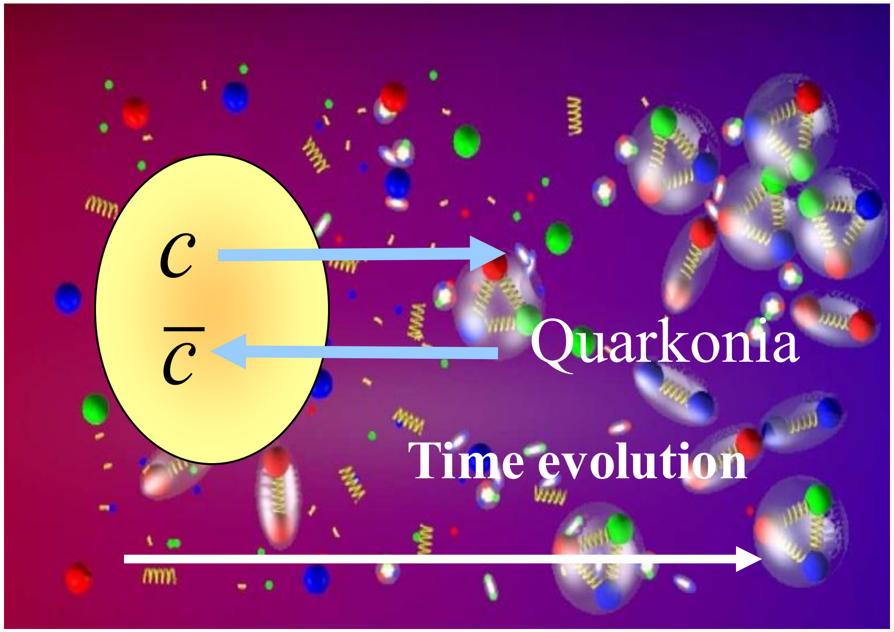


Quark versus gluon fragmentation contribution

Quarkonia in reactions with nuclei



NRQCD in a background medium



- Take a closer look at the NRQCD Lagrangian below

Scales in the problem

$p_s^\mu \sim m_Q v(1,1,1,1)$ soft ~ λ

$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$ ultrasoft ~ λ²

- Ultrasoft gluons included in covariant derivatives

- Soft gluons are included explicitly

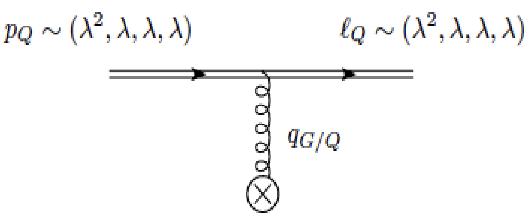
  - Double soft gluon emission
  - Heavy quark-antiquark potential
  - (can also be interaction with soft particles)

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_p \left|p^\mu A_p^\nu - p^\nu A_p^\mu\right|^2 + \sum_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \left\{ iD^0 - \frac{(\mathbf{p}-i\mathbf{D})^2}{2m} \right\} \psi_{\mathbf{p}} \\
&-4\pi\alpha_s \sum_{q,q',\mathbf{p},\mathbf{p}'} \left\{ \frac{1}{q^0}\psi^\dagger_{\mathbf{p}'}\left[A^0_{q'}, A^0_q\right]\psi_{\mathbf{p}} \right. \\
&\left. + \frac{g^{\nu 0}(q'-p+p')^\mu - g^{\mu 0}(q-p+p')^\nu + g^{\mu\nu}(q-q')^0}{(\mathbf{p}'-\mathbf{p})^2}\psi^\dagger_{\mathbf{p}'}\left[A^\nu_{q'}, A^\mu_q\right]\psi_{\mathbf{p}} \right\} \\
&\qquad + \psi \leftrightarrow \chi,\ T \leftrightarrow \bar{T} \\
&+ \sum_{\mathbf{p},\mathbf{q}} \frac{4\pi\alpha_s}{(\mathbf{p}-\mathbf{q})^2}\psi^\dagger_{\mathbf{q}} T^A \psi_{\mathbf{p}} \chi^\dagger_{-\mathbf{q}} \bar{T}^A \chi_{-\mathbf{p}} + \dots
\end{aligned}
$$

Allowed interactions in the medium

- At the level of the Lagrangian

$$\mathcal{L}_{\mathrm{NRQCD}_G} = \mathcal{L}_{\mathrm{NRQCD}} + \mathcal{L}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) + \mathcal{L}_{g-G/C}(A^{\mu,b}_{s}, A^{\mu,a}_{G/C}) + \psi \longleftrightarrow \chi$$



Possible scaling for the virtual gluons interacting with the heavy quarks

		0 1 2 3	+ − ⊥
(1)	$q_G \sim$	$(\lambda^2, \lambda^1, \lambda^1, \lambda^2)$	$\sim (\lambda^2, \lambda^2, \boldsymbol{\lambda}_\perp)_n$
(2)	$q_C \sim$	$(\lambda^2, \lambda^1, \lambda^1, \lambda^1)$	$\sim (\lambda^1, \lambda^1, \boldsymbol{\lambda}_\perp)_n$

- Energy component must always be suppressed
- Glauber gluons - transverse to the direction of propagation contribution
- Coulomb gluons - isotropic momentum distribution

- Calculated the leading power and next to leading power contributions 3 different ways

Background field method	**Perform a shift in the gluon field in the NRQCD Lagrangian then perform the power-counting**
Hybrid method	**From the full QCD diagrams for single effective Glauber/Coulomb gluon perform the corresponding power-counting, read the Feynman rules**
Matching method	**Full QCD diagrams describing the forward scattering of incoming heavy quark and a light quark or a gluon. We also derive the tree level expressions of the effective fields in terms of the QCD ingredients**

Example of the background field method

- Perform the label momentum representation and field substitution (u.s. -> u.s. + Glauber)

$$\psi(x) \to \sum_{\mathbf{p}} \psi_{\mathbf{p}}(x) ,$$

$$iD_\mu \to \mathcal{P}_\mu + i\partial_\mu - g(A_U^\mu + A_{G/C}^\mu)$$

$$iD_t = \underbrace{i\partial_t - gA_U^0 - gA_G^0}_{\sim \lambda^2} ,$$

$$i\mathbf{D} = \underbrace{\mathcal{P}}_{\sim\lambda} - (\underbrace{i\boldsymbol{\partial} + g\mathbf{A}_U + g\mathbf{n}A_G^{\mathbf{n}}}_{\sim\lambda^2}) + \mathcal{O}(\lambda^3) ,$$

$$\begin{aligned}\mathbf{E} &= \partial_t(\mathbf{A}_U + \mathbf{A}_G) + (\boldsymbol{\partial} + i\mathcal{P})(A_U^0 + A_G^0) + gT^c f^{cba}(A_U^0 + A_G^0)^b(\mathbf{A}_U + \mathbf{A}_G)^a \\ &= \underbrace{i\mathcal{P}_\perp A_G^0}_{\sim\lambda^3} + \mathcal{O}(\lambda^4) ,\end{aligned}$$

$$\begin{aligned}\mathbf{B} &= -(\boldsymbol{\partial} + i\mathcal{P}) \times (\mathbf{A}_U + \mathbf{A}_G) + \frac{g}{2}T^c f^{cba}(\mathbf{A}_U + \mathbf{A}_G)^b(\mathbf{A}_U + \mathbf{A}_G)^a \\ &= -\underbrace{(i\mathcal{P}_\perp \times \mathbf{n})\, A_G^{\mathbf{n}}}_{\sim\lambda^3} + \mathcal{O}(\lambda^4) .\end{aligned}$$

Example for a collinear source (note results depend on the type of source)

Substitute, expand and collect terms up to order λ3

- Results: depend on the type of the source of scattering in the medium

Leading medium corrections

$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(-gA^0_{G/C}\Big)\psi_{\mathbf{p}} \;\; (collinear/static/soft).$$

Sub-leading medium corrections

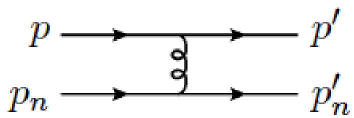
$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_G) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A_G^{\mathbf{n}}(\mathbf{n}\cdot\mathcal{P}) - i\big[(\mathcal{P}_\perp \times \mathbf{n})A_G^{\mathbf{n}}\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \;\; (collinear)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_C) = 0 \;\; (static)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_C) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2\mathbf{A}_C\cdot\mathcal{P} + [\mathcal{P}\cdot\mathbf{A}_C] - i\big[\mathcal{P}\times\mathbf{A}_C\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \;\; (soft)$$

The QCD forward scattering diagram expansion

- Looking at t-channel scattering we can also extract the form of the Glauber/Coulomb fields in terms of QCD ingredients (and recover Lagrangian)

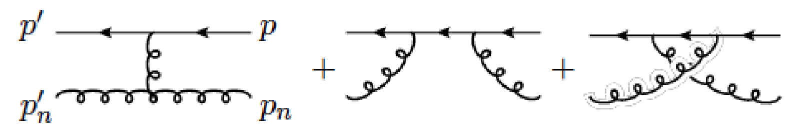
$t_{coll.} =$ 

Glauber field for collinear source

$$A_G^{\mu,a} = \frac{n^\mu}{\mathbf{q}_T^2} \sum_\ell \bar{\xi}_{n,\ell-\mathbf{q}_T} \frac{\bar{n}\!\!\!/}{2} (gT^a) \xi_{n,\ell}$$

Coulomb field for soft source

$$A_C^{\mu,a} \equiv \frac{1}{\mathbf{q}^2} \sum_\ell \bar{\phi}_{\ell-\mathbf{q}} \gamma^\mu (gT^A) \phi_\ell$$

$t_{g-coll.} =$ 

$$= t^{(0)}_{g-coll.} + t^{(1)}_{g-coll.} + \mathcal{O}(\lambda^2)\ .$$

Glauber field for collinear source

$$A_G^{\mu,a} = \frac{i}{2} g f^{abc} \frac{n^\mu}{\mathbf{q}_T^2} \sum_\ell \left[\bar{n} \cdot \mathcal{P}\ (\mathbf{B}^{b(0)}_{n\perp,\ell-\mathbf{q}_T} \cdot \mathbf{B}^{c(0)}_{n\perp,\ell}) \right]$$

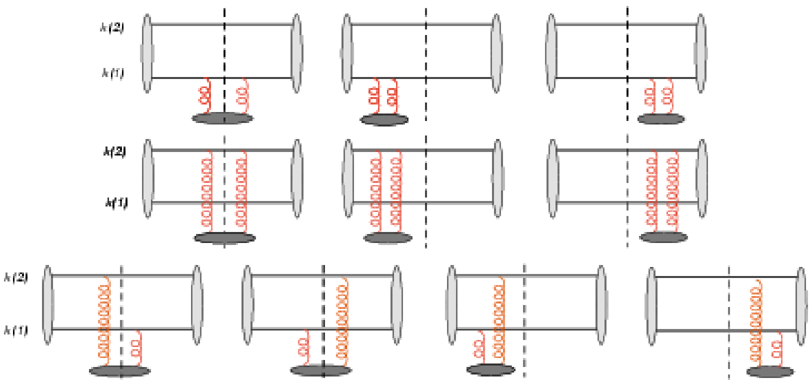
Coulomb field for soft source

Y. Makris et al. (2019)

$$A_C^{\mu,a} = f^{abc} \frac{ig}{2\,\mathbf{q}^2} \sum_\ell \left\{ \left[\mathcal{P}^\mu\ (\mathbf{B}^{b(0)}_{s,\ell-\mathbf{q}} \cdot \mathbf{B}^{c(0)}_{s,\ell}) \right] - 2(\mathbf{B}^{c(0)}_{s,\ell} \cdot \left[\boldsymbol{\mathcal{P}}) B^{\mu,b(0)}_{s,\ell-\mathbf{q}} \right] - 2(\mathbf{B}^{b(0)}_{s,\ell-\mathbf{q}} \cdot \left[\boldsymbol{\mathcal{P}}) B^{\mu,c(0)}_{s,\ell} \right] \right\}$$

- Note that for the gluon the last 2 diagrams are necessary for gauge invariance but the first diagram the leading forward scattering contribution
- In the medium the momentum exchange can get dressed ~ Debye screening

Collisional interactions of quarkonia in matter



Adil *et al.* (2006) | Sharma *et al.* (2012)

- Resum in impact parameter space, make Gaussian approximation

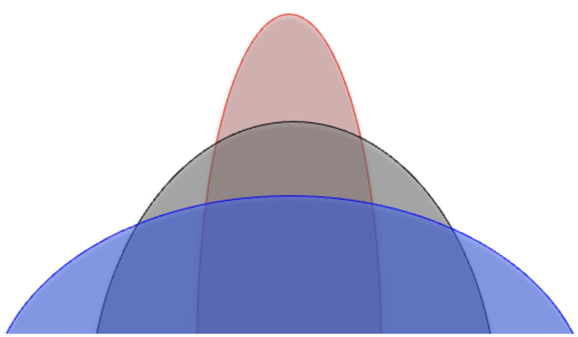
TMD physics with nuclei | W. Ke *et al.* (2022)

$$P_{f\leftarrow i}(\chi\mu_D^2\xi,T) = \left|\frac{1}{2(2\pi)^3}\int d^2\mathbf{k}dx\,\psi_f^*(\Delta\mathbf{k},x)\psi_i(\Delta\mathbf{k},x)\right|^2$$
$$= \left|\frac{1}{2(2\pi)^3}\int dx\ \mathrm{Norm}_f\mathrm{Norm}_i\,\pi\, e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}}e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}}\right.$$
$$\left.\times\frac{2[x(1-x)\Lambda(T)^2][\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}{[x(1-x)\Lambda(T)^2]+[\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}\right|^2.$$

Quarkonium structure

Heavy meson acoplanarity & distortion of the light cone wave function (meson decay)

Momentum space picture – may be counter intuitive (note that broadening in configuration space is narrowing in momentum space)



S. Aronson *et al.* (2017)

- **Initial wavefunction ~ vacuum**
- **Collisional broadening**
- **Thermal narrowing**

Time evolution of quarkonium states

Schrodinger eq. with input from LQCD

$$\psi(\mathbf{r}) = Y_l^m(\hat{r})R_{nl}(r)$$

$$\left[-\frac{1}{2\mu_{\rm red}}\frac{\partial^2}{\partial r^2}+\frac{l(l+1)}{2\mu_{\rm red}r^2}+V(r)\right]rR_{nl}(r)=(E_{nl}-2m_Q)rR_{nl}(r)$$

Quarkonium structure plays an essential role in evaluating the dissociation rate

l	n	E_{nl} (GeV)	$\sqrt{\langle r^2\rangle}$ (GeV^{-1})	k^2 (GeV^2)	Meson
0	1	0.700	2.24	0.30	J/ψ
0	2	0.086	5.39	0.05	$\psi(2S)$
1	1	0.268	3.50	0.20	χ_c
0	1	1.122	1.23	0.99	$\Upsilon(1S)$
0	2	0.578	2.60	0.22	$\Upsilon(2S)$
0	3	0.214	3.89	0.10	$\Upsilon(3S)$
1	1	0.710	2.07	0.58	$\chi_b(1P)$
1	2	0.325	3.31	0.23	$\chi_b(2P)$
1	3	0.051	5.57	0.08	$\chi_b(3P)$

Feed down taken into account

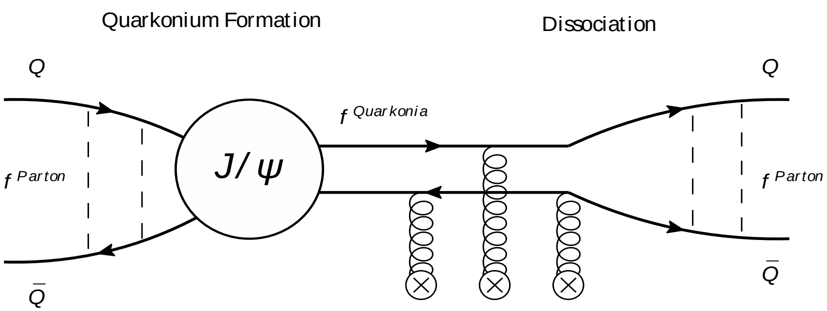
$$\psi(2S):\quad \mathrm{Br}\left[\psi(2S)\to J/\psi+X\right]=61.4\pm0.6\%$$

$$\chi_{c1}:\quad \mathrm{Br}\left[\chi_{c1}\to J/\psi+\gamma\right]=34.3\pm1.0\%$$

$$\chi_{c2}:\quad \mathrm{Br}\left[\chi_{c2}\to J/\psi+\gamma\right]=19.0\pm0.5\%$$

S. Aronson *et al.* (2017)

- Competition between formation of the proto-quarkonium state that interacts (O ~ 1fm interaction onset) and dissociation



- Dynamics reduces to a kinetic approximation

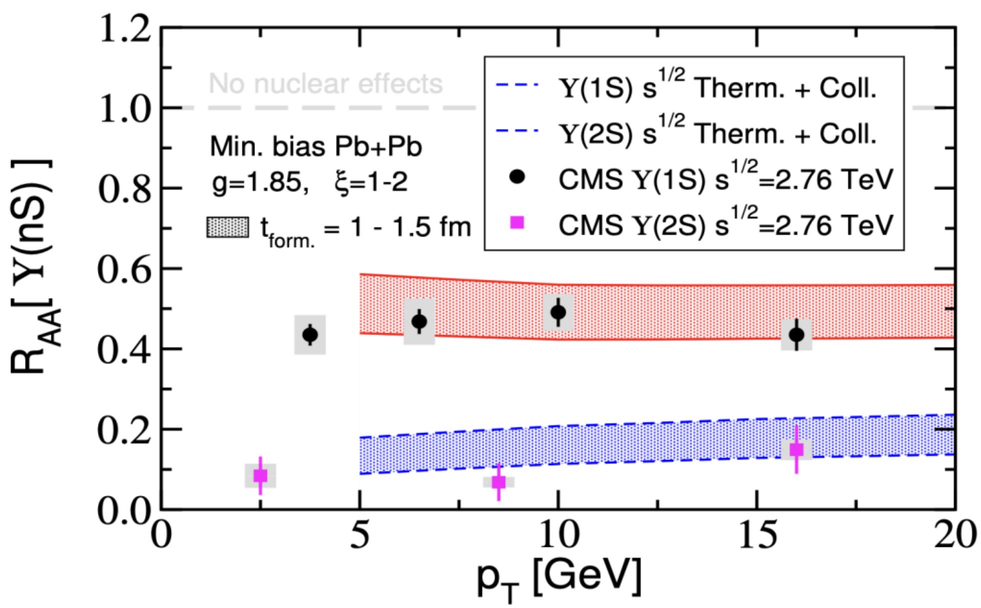
$$\partial_t f^{Parton}(E,t) = -\frac{1}{\langle\tau_{\rm form}(E,t)\rangle}f^{Parton}(E,t) + \frac{1}{\langle\tau_{\rm diss}(E,t)\rangle}f^{Quarkonia}(E,t)$$

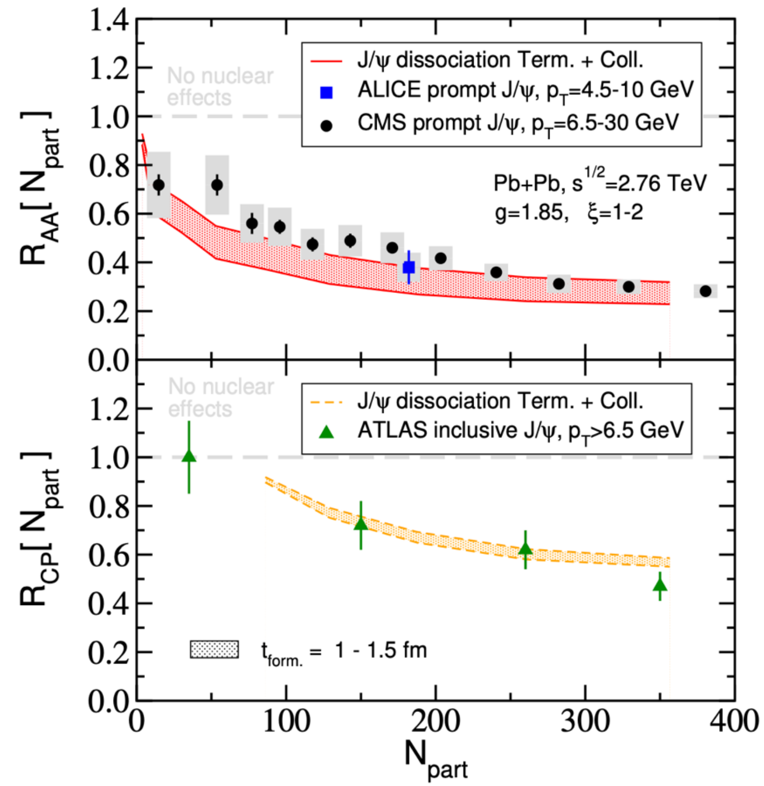
$$\partial_t f^{Quarkonia}(E,t) = +\frac{1}{\langle\tau_{\rm form}(E,t)\rangle}f^{Parton}(E,t) - \frac{1}{\langle\tau_{\rm diss}(E,t)\rangle}f^{Quarkonia}(E,t)$$

Centrality and p_T dependence

- In calculating the min bias results we found that the result is dominated by the first few centrality bins. Feed down taken into account

$$R_{AA}^{\text{min. bias}}(p_T) = \frac{\sum_i R_{AA}(\langle b_i \rangle) W_i}{\sum_i W_i} \qquad W_i = \int_{b_i\ \text{min}}^{b_i\ \text{max}} N_{\text{coll.}}(b)\, \pi\, b\, db$$





S. Aronson *et al.* (2017)

Uncertainties are related to the onset of the interactions

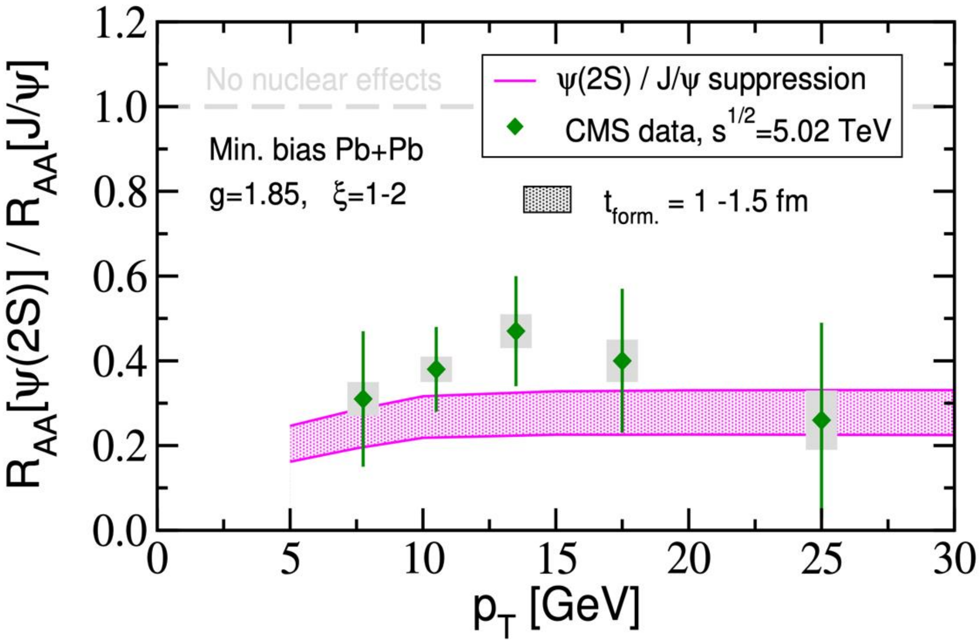
The possibility to determine centrality in DIS was proposed.
Hadron production is sensitive to geometry, can be done for quarkonia

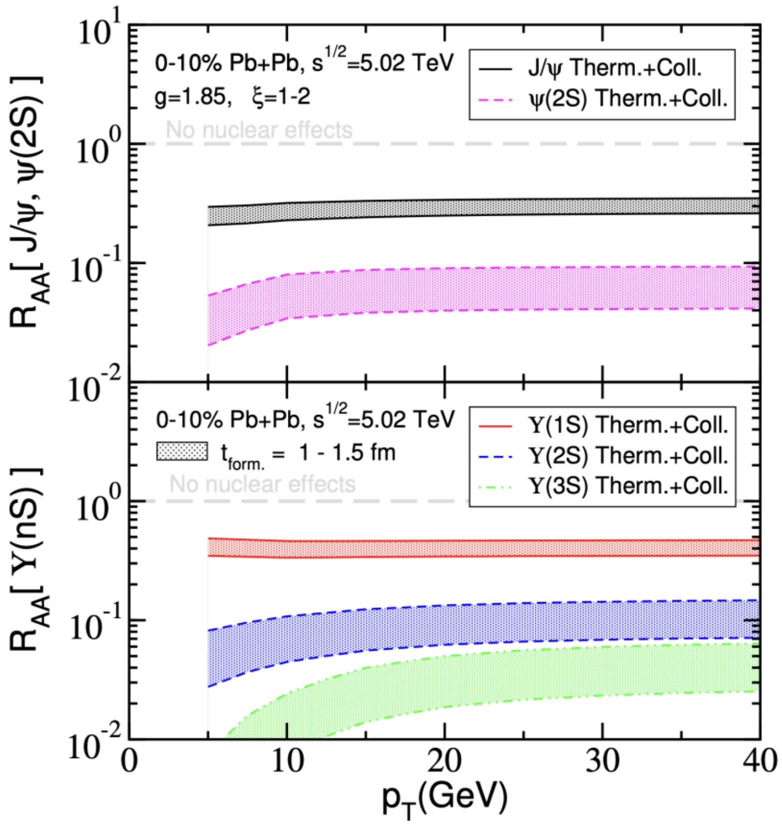
W. Chang *et al.* (2022)

Z. Liu *et al.* (2023)

Min bias and excited to ground state ratios

- Good description of the relative suppression of excited to ground states





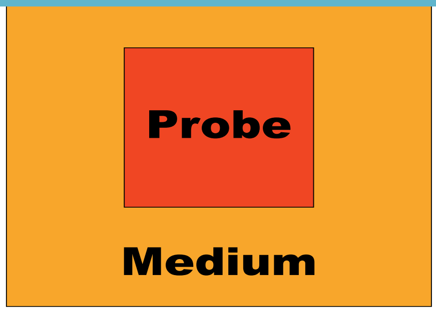
S. Aronson *et al.* (2017)

We see differences in suppression of Upsilon(2S) and Upsilon(3S). Latest measurements don't seem to see that clearly (I find it puzzling)

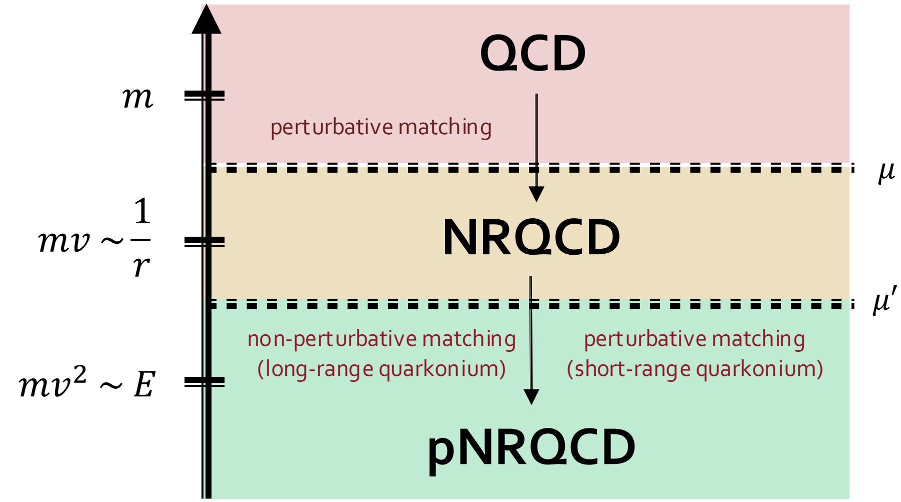
- Good separation the suppression of the ground and excited

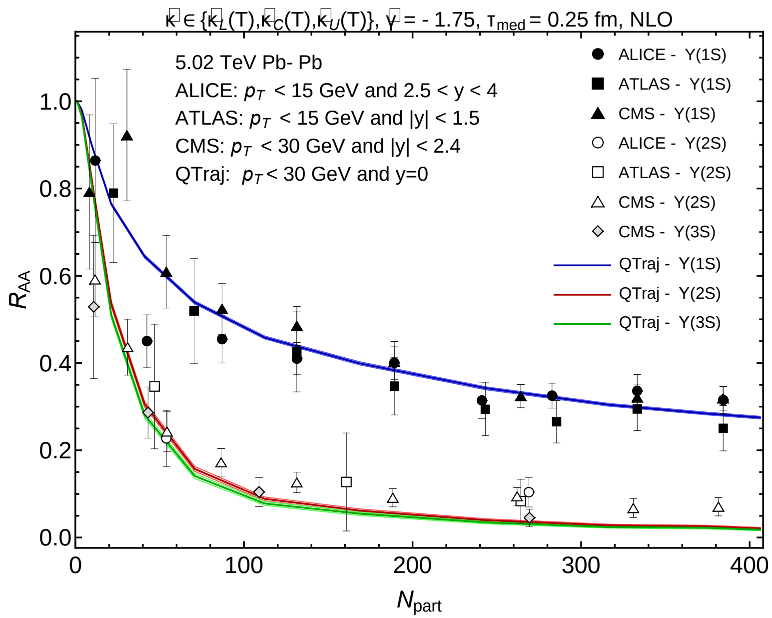
In-medium heavy quarkonium propagation – open quantum systems

Y. Akamatsu et al. (2015)



Probe = heavy-quarkonium state
Medium = light quarks and gluons that comprise the medium



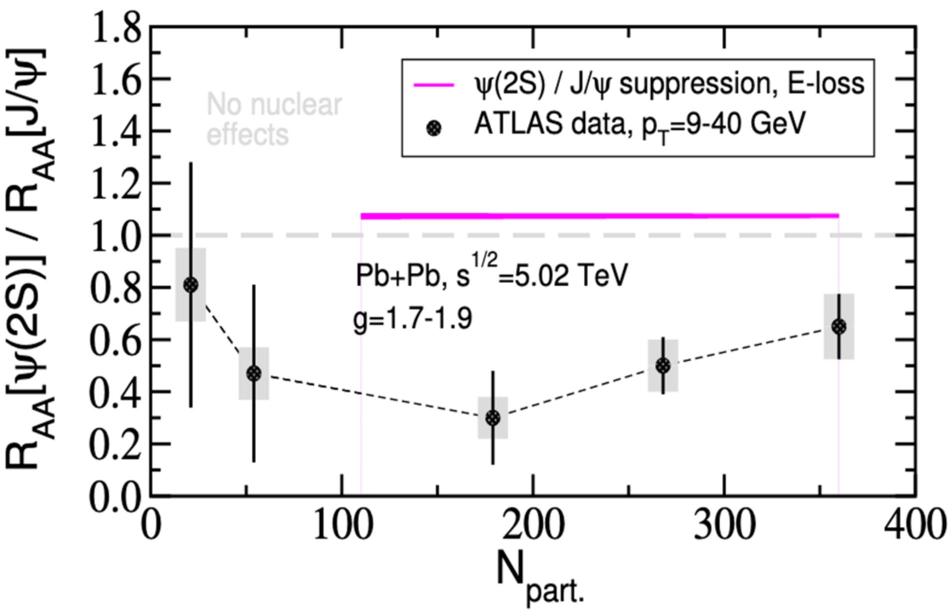


N. Brambilla et al. (2022)

- Can use **open quantum systems methods** and **effective field theory** methods to obtain ***quantum master equations*** for the evolution heavy quarkonium reduced density matrix.

- Current applications target **bottomonium propagation in the QGP,** however, similar methods **can be applied to non-thermal media** such as the matter through which heavy quarkonium states propagate at the EIC.

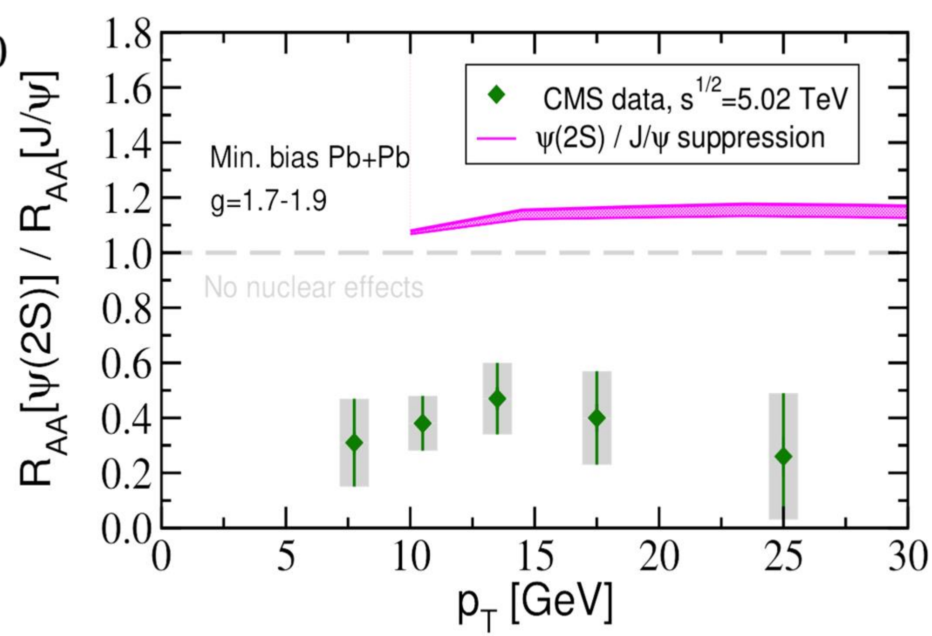
Energy loss and quarkonium suppression



Y. Makris et al. (2019)

The energy loss picture of quarkonium suppression in the p_T range measured by ATLAS and CMS (up to 40 GeV) is strongly disfavored (IMHO)

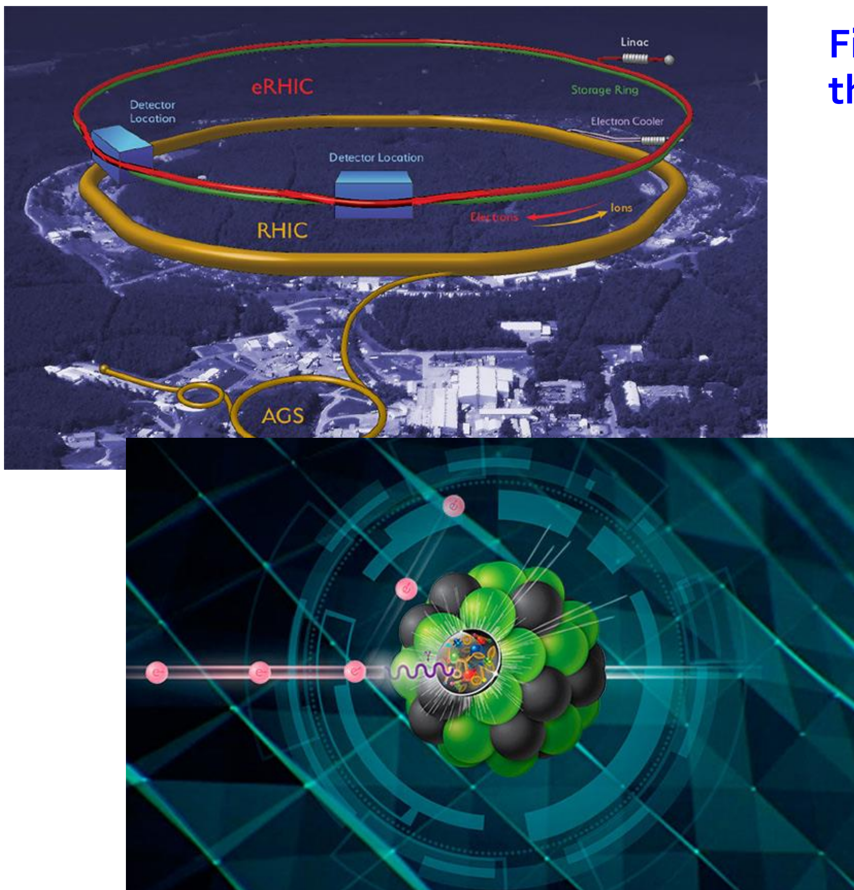
- In the double suppression ratio $R_{AA}(\psi(2S))/R_{AA}(J/\psi)$ the discrepancy is not simply in magnitude. There is a discrepancy in the sign of prediction



Comparison results for charmonia – QGP vs CNM

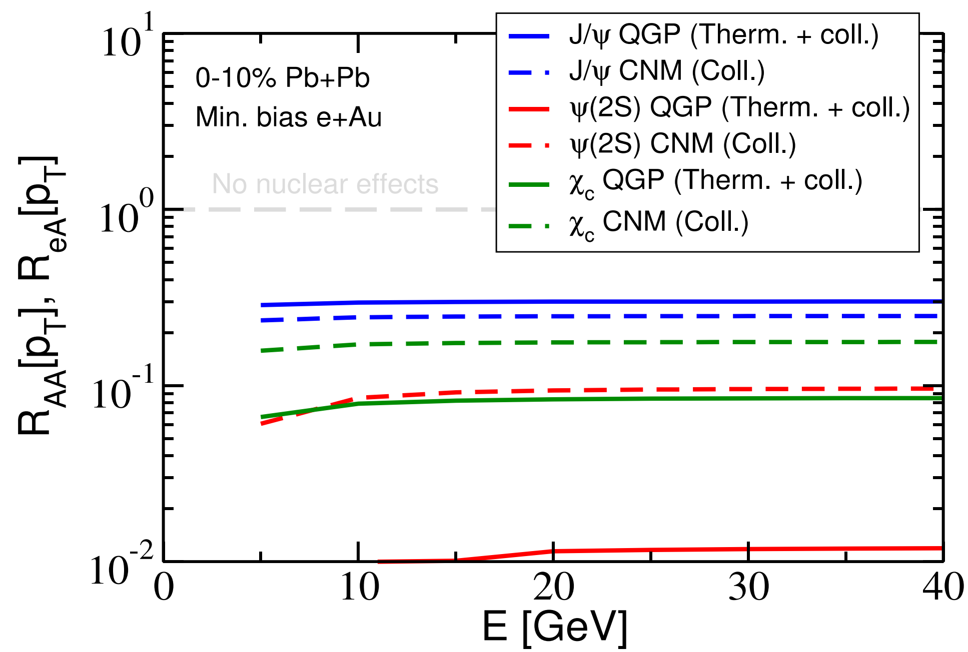
- Eliminate thermal wavefunction effects. Implement the new transport parameters for cold nuclear matter

I. Olivant et al. (2021)



First established that thermal screening effects in this model are small.

D. Boer et al. (2022)

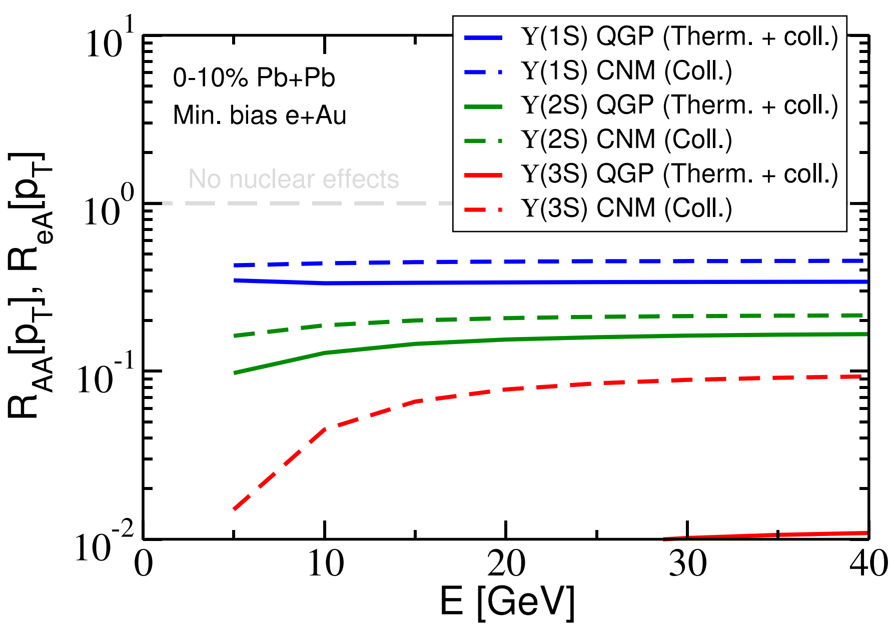


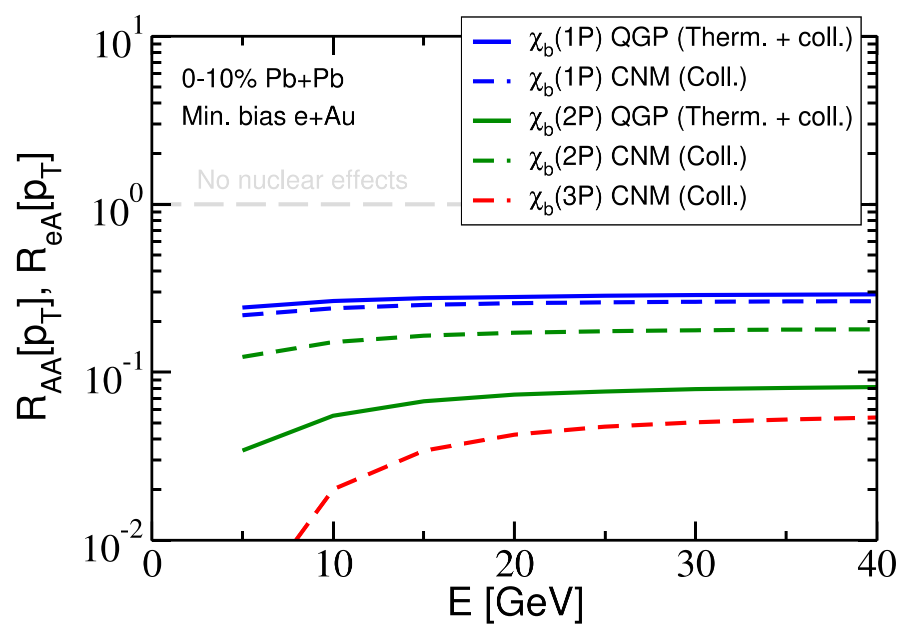
Note this is energy, not transverse momentum

Comparison results for bottomonia

- Dissociation from collisional interactions in cold nuclear matter is very large. For the very weakly bound states the QGP suppression is larger but the CNM one is still a factor of 5 -10. For the tightly bound states suppression is comparable – sometimes slightly smaller, sometimes slightly larger.

D. Boer et al. (2021)





For full EIC predictions we need to explore feed down corrections. Include kinematics.

Conclusions

- NRQCD (and extensions) is by now a mature theory. Still, we don’t have an adequate global description of quarkonia (not only polarization but also cross sections, different systems, etc)
- New theory developments include leading power factorization, TMD factorization, production of quarkonia inside jets. A quarkonium program at the EIC can shed light on many of those open questions
- To address reactions with nuclei, an effective theory of quarkonia in matter - NRQCD_G – was constructed. Derived the Feynman rules (3 different ways) to leading and subleading power for different sources of interactions in the medium
- We showed the connection to existing quarkonium dissociation phenomenology and demonstrated description of ground and excited charmonium and bottomonium states suppression in HIC
- Other approaches have been developed – transport models, open quantum systems, absorption models, energy loss models (few have connections to structure)
- The NRQCD_G framework is general and applicable to both hot (QGP) and cold (large nucleus) nuclear matter. Some interesting and encouraging results on dissociation in cold nuclear matter available. Large suppression in CNM.
- Additional discussion on quarkonia in ep, eA in recent Prog. Part. Nucl. Phys.

D. Boer *et al. (2024)*

NRQCD examples

• One has to be careful, the simple power counting approximately manifest in the LDMEs can be affected by the partonic cross section – a large number of singlet and octet; S wave and P wave terms enter

$$
\begin{aligned}
d\sigma(J/\psi) = {} & d\sigma(Q\bar{Q}([^3S_1]_1))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_1) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^1S_0]_8))\langle\mathcal{O}(Q\bar{Q}([^1S_0]_8) \to J/\psi)\rangle \\
& + d\sigma(Q\bar{Q}([^3S_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_0]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_0]_8) \to J/\psi)\rangle \\
& + d\sigma(Q\bar{Q}([^3P_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_2]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_2]_8) \to J/\psi)\rangle + \cdots
\end{aligned}
$$

• The situation is similar for bottomonia
• Excited states have their own expansion

The question is – is there a simplification at high p_T where the p_T dependence of the short distance cross section dominates