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An effective theory of quarkonia in QCD matter

In collaboration with Yiannis Makris, JHEP 1910 (2019) 111

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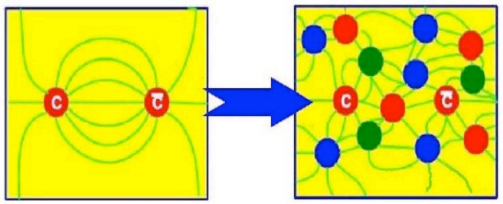
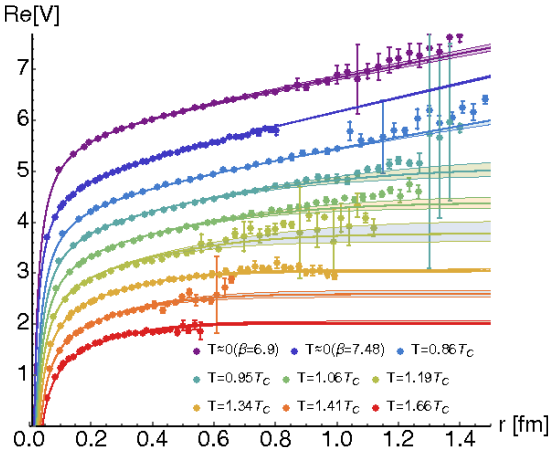
Quarkonia in the QGP

- Quarkonia (e.g. J/ψ,ϒ), bound states of the heaviest elementary particles, long considered standard candle to characterize QGP properties
- Most sensitive to the space-time temperature profile



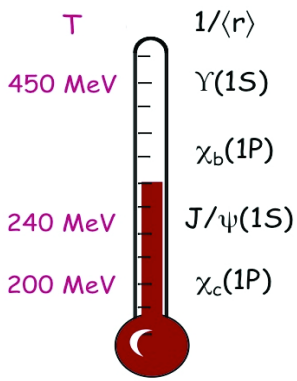
Matsui *et al.* (1986)



Rothkopf *et al.* (2016)

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

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



Mocsy *et al.* (2007)

Bazavov *et al.* (2013)

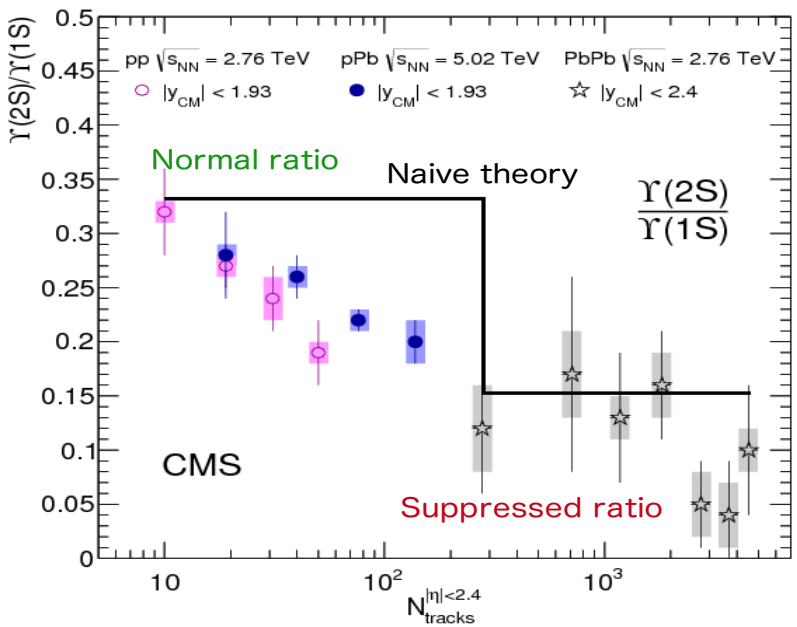
l	n	E_{nl} (GeV)	$\sqrt{\langle r^2\rangle}$ (GeV^{-1})	k^2 (GeV^2)	Meson
0	1	0.700	2.24	0.30	J/ψ
0	2	0.086	5.39	0.05	$\psi(2S)$
1	1	0.268	3.50	0.20	χ_c
0	1	1.122	1.23	0.99	$\Upsilon(1S)$
0	2	0.578	2.60	0.22	$\Upsilon(2S)$
0	3	0.214	3.89	0.10	$\Upsilon(3S)$
1	1	0.710	2.07	0.58	$\chi_b(1P)$
1	2	0.325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

Dynamics is more complicated – non-equilibrium transport, recombination …

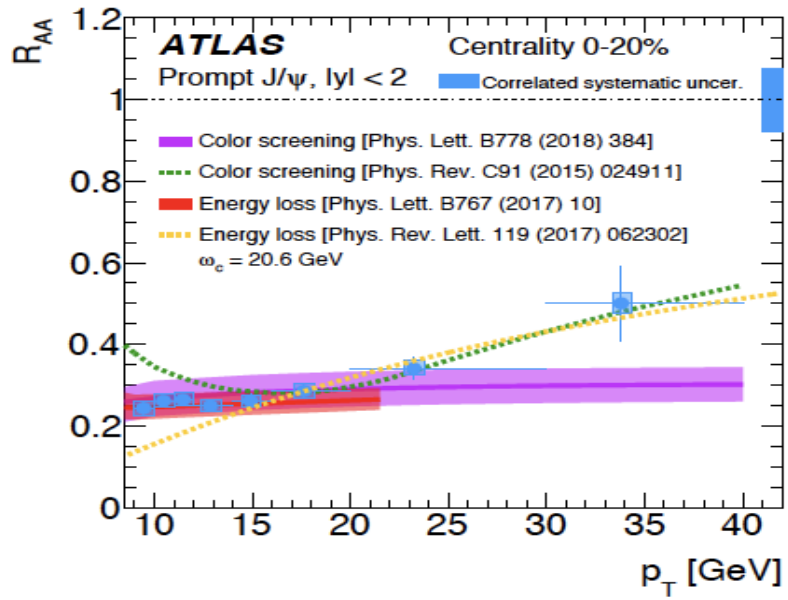
Challenges and hypothesae

- Suppression puzzle - similar dissociation behavior observed in small system, p+A and even in p+p (where QGP is not expected)
- Recently proposed co-mover dissociation model, energy loss model – need cross check and microscopic explanation (if applicable)

E. Ferreiro (2014)

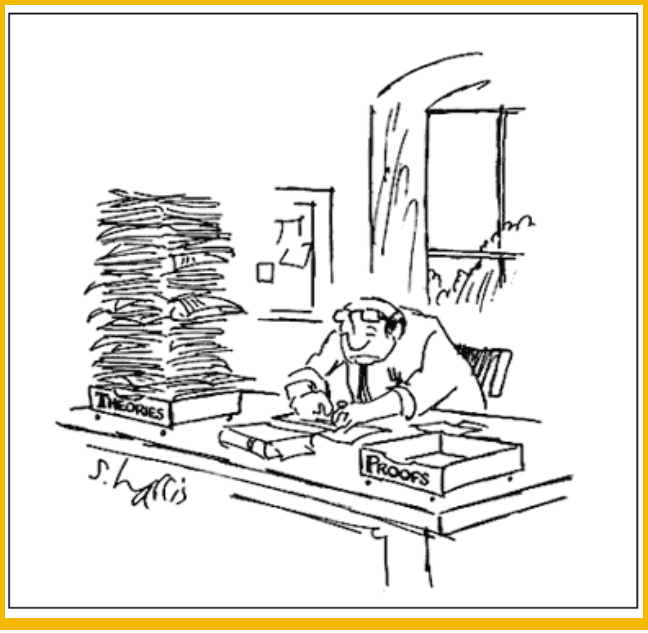


Chatrachyan *et al.* (2014)



- EFT - capture the interactions without explicitly specifying their nature

Zooming in on the correct theory – excluding energy loss

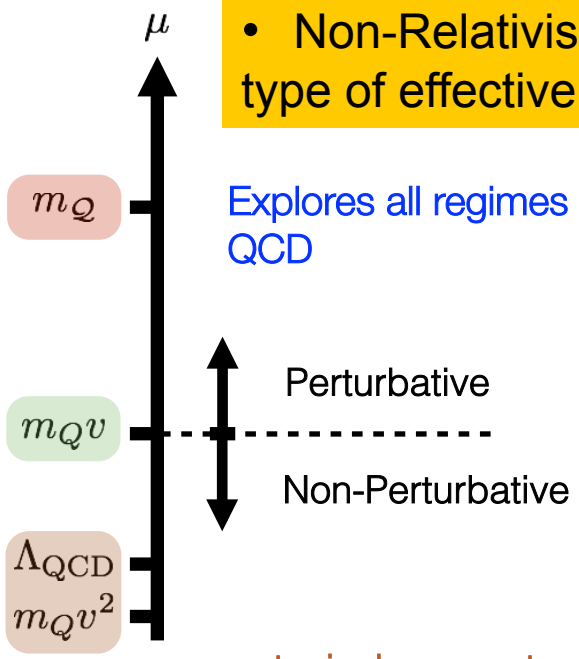


Production of quarkonia at intermediate and high p_T

- 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

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

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

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

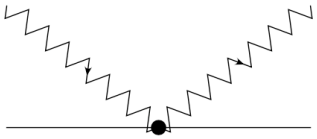
QCD without the heavy flavor

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: $K_Q \sim m_Q v^2$



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

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

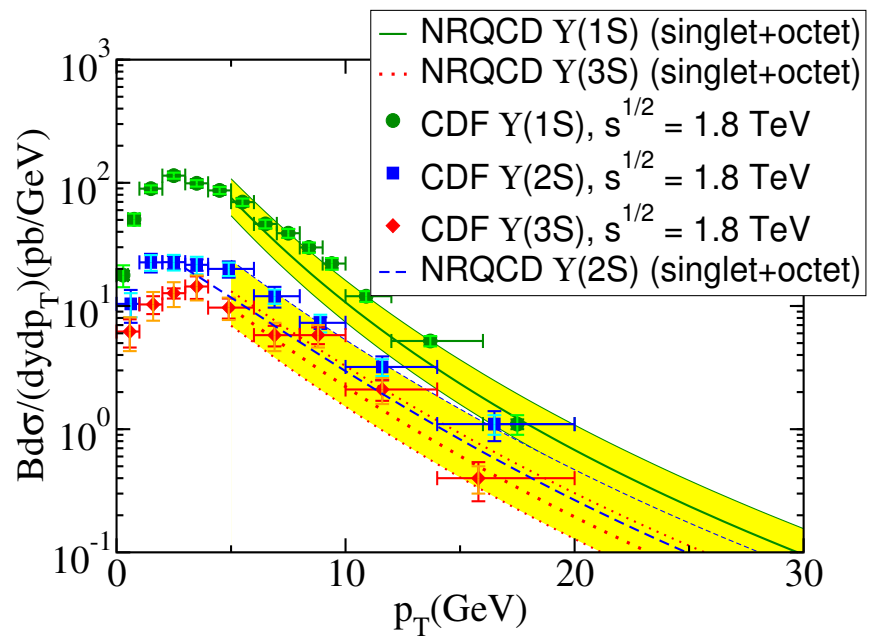
NRQCD practical examples

- 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

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

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

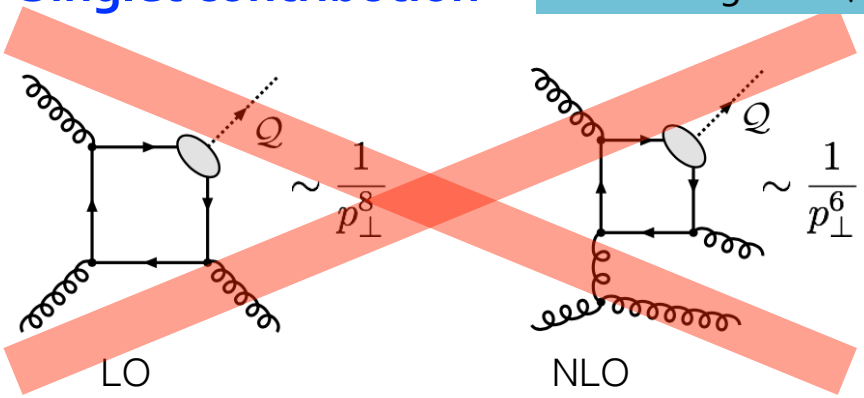
The question is – is there a simplification at high p_T where the p_T dependence of the short distance cross section dominates (and expressions simplify)



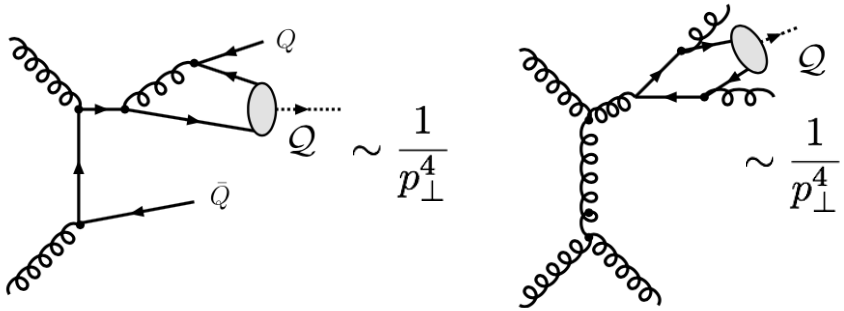
Leading power factorization

Singlet contribution

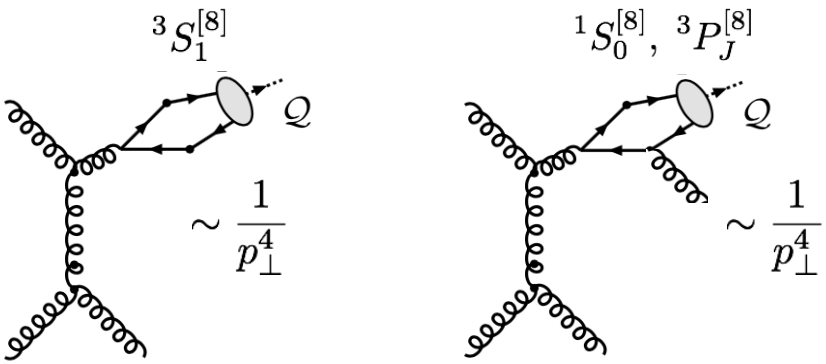
S. Fleming *et al.* (2012) | M. Baumgart *et al.* (2014) | Y. Ma *et al.* (2014)



LO NLO

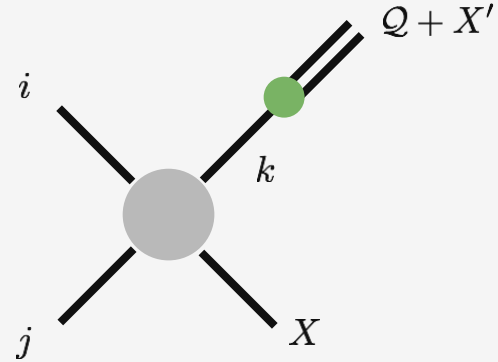


NLO NNLO



LO NLO

(single) Parton fragmentation process



Octet contribution

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

LP example and applicability

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

$p_T \gg m_Q$

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

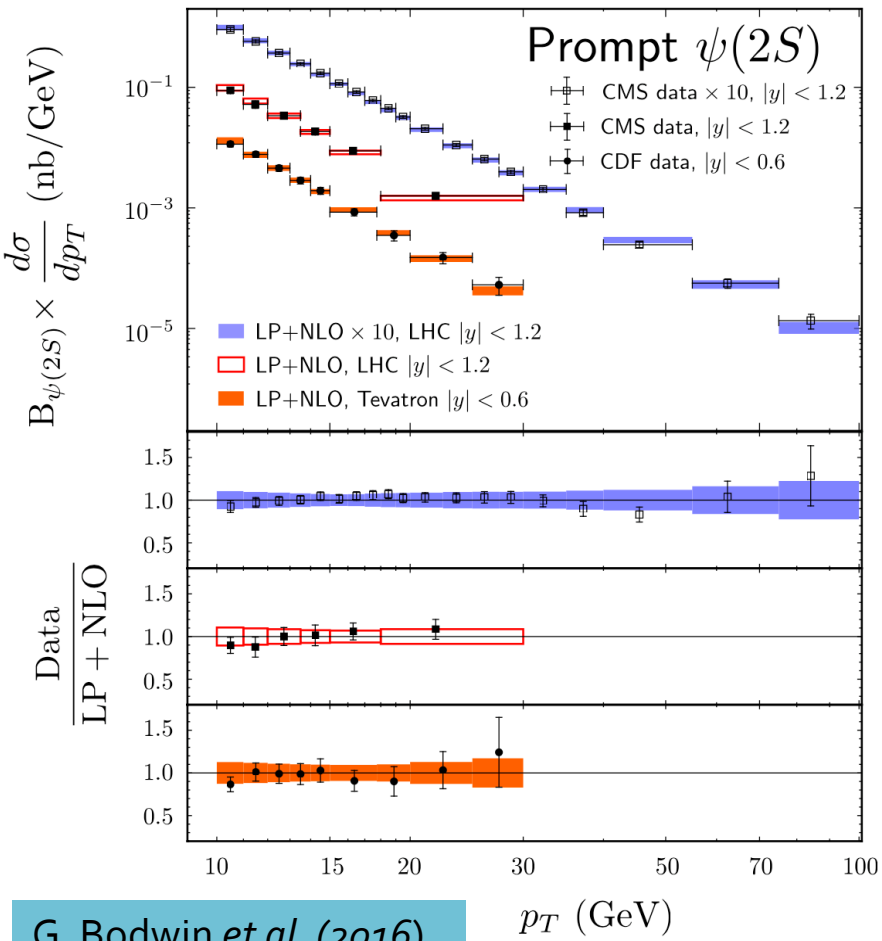
DGLAP Evolution

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

Resummation of $\ln(p_T/m_h)$

Contributions we take in our work

Mechanism	Initiating parton	χ_{cJ}		$J/\psi(1S)/\psi(2S)$	
		$^3P_J^{[1]}$	$^3S_1^{[8]}$	$^3P_J^{[8]}/^1S_0^{[8]}$	$^3S_1^{[1]}$
	g	α_s^2	α_s	α_s^2	α_s^3
	Q	α_s^2	α_s^2	α_s^3	α_s^2
	q	α_s^3	α_s^2	α_s^3	α_s^4



G. Bodwin *et al.* (2016)

Applicability must be determined phenomenologically

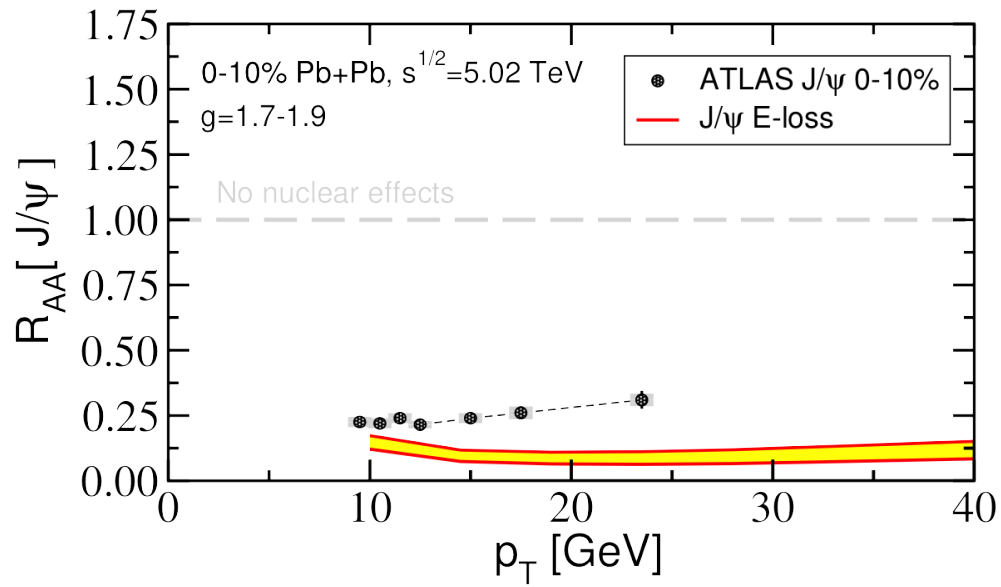
Comparison of energy loss phenomenology to data

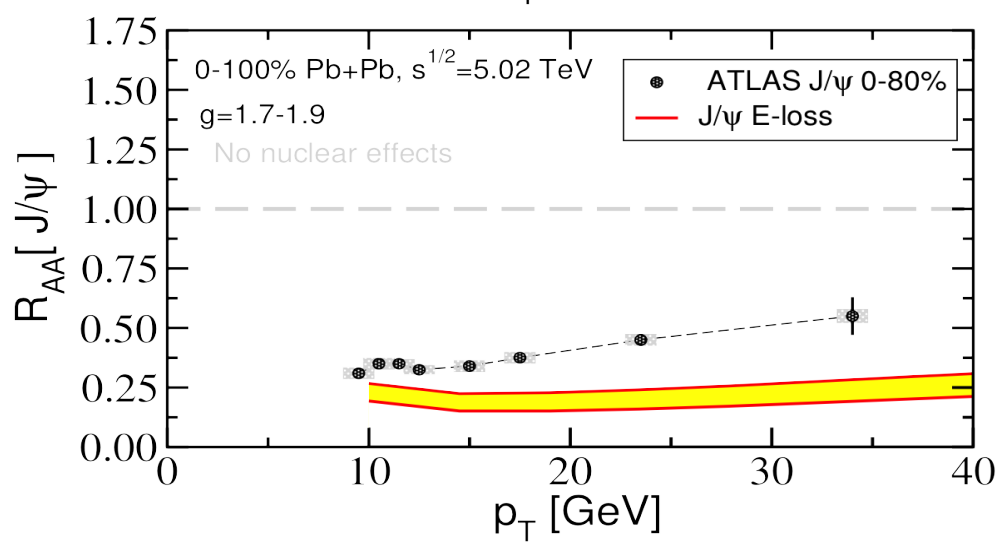
- Suppression of J/ψ overestimated by factor of 2 to 3. Constrained by light hadrons
- Included χ_c and ψ(2S) feeddown.

$$\psi(2S): \quad \mathrm{Br}\left[\psi(2S) \to J/\psi + X\right] = 61.4 \pm 0.6\% \,,$$
$$\chi_{c1}: \quad \mathrm{Br}\left[\chi_{c1} \to J/\psi + \gamma\right] = 34.3 \pm 1.0\% \,,$$
$$\chi_{c2}: \quad \mathrm{Br}\left[\chi_{c2} \to J/\psi + \gamma\right] = 19.0 \pm 0.5\% \,.$$

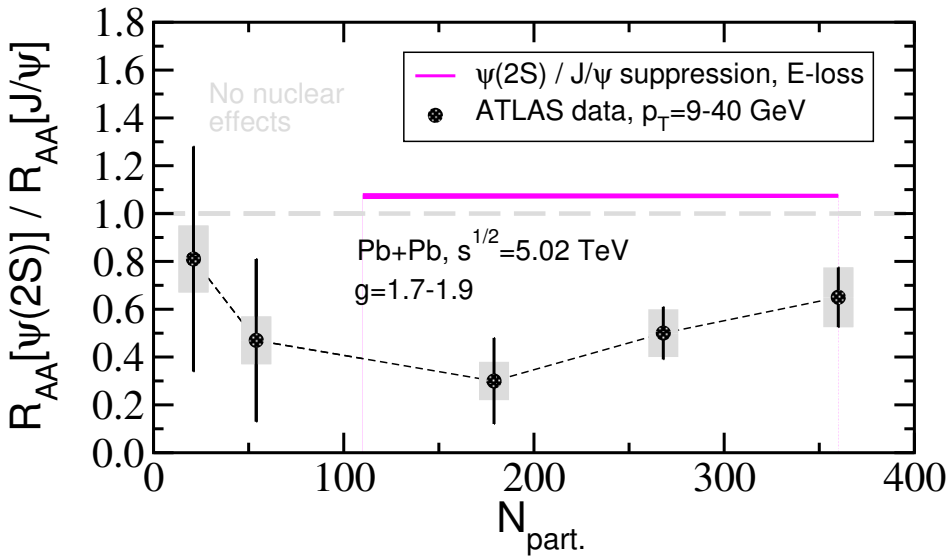
- Discrepancy persists over centralities. Somewhat different p_T dependence

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





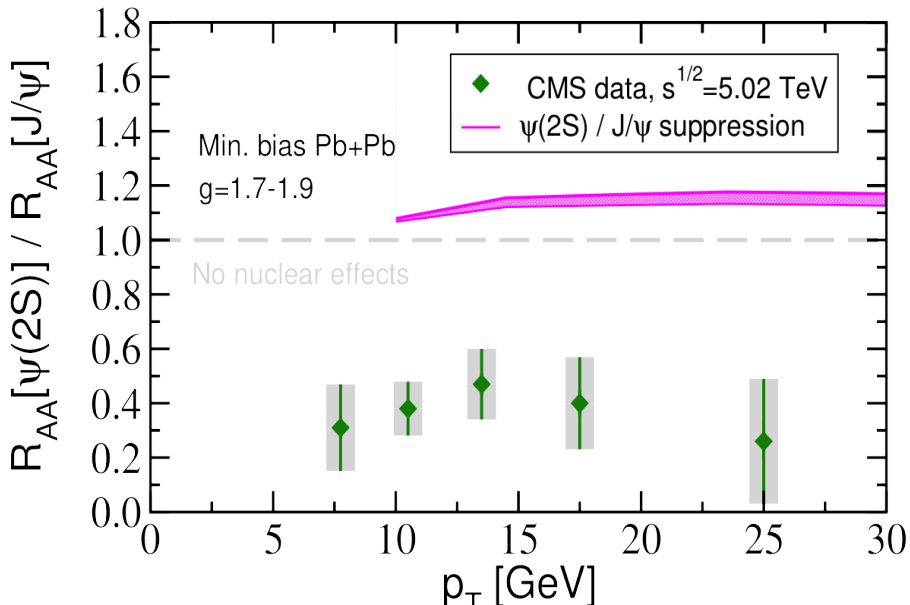
Double suppression ratio ψ(2S) / J/ψ



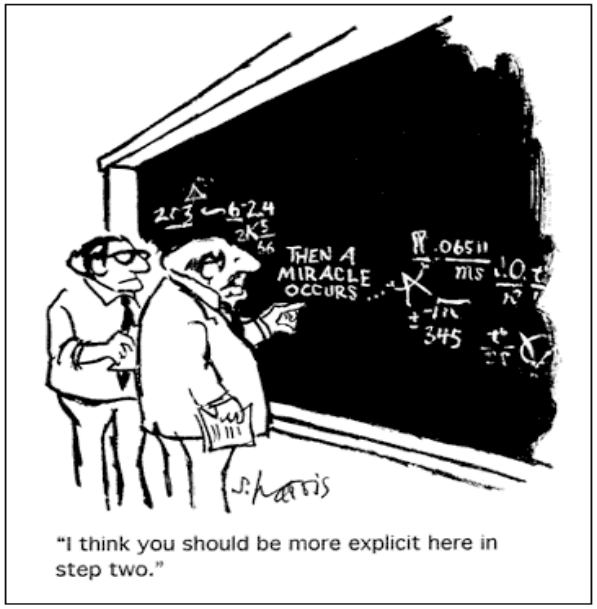
- In the double suppression ratio $R_{AA}(\psi(2S))/R_{AA}(J/\psi)$ the discrepancy is not simply in magnitude. There is a discrepancy in the sign of the theoretical prediction

Makris and Vitev (2019)

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

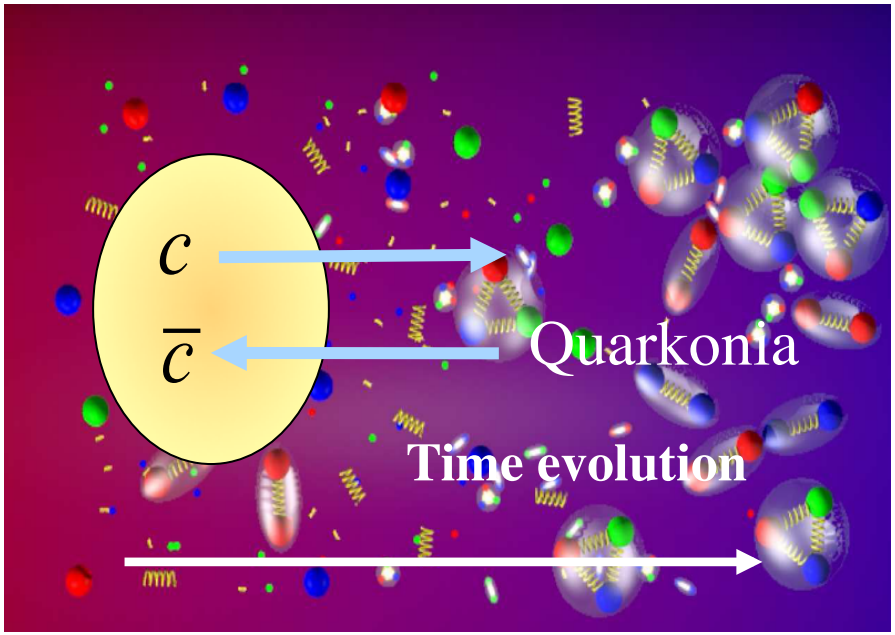


NRQCD with Glauber Gluons & phenomenology



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

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 ~ λ^2

- Ultrasoft gluons included in covariant derivatives

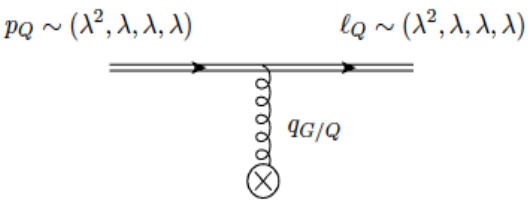
- Soft gluons are included explicitly
  - Double soft gluon emission
  - Heavy quark-antiquark potential
  - (can also be interaction with soft particles)

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

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

Source	Collinear	Static	Soft
$A^\mu_C \sim$	n.a.	$(\lambda^1, \lambda^2, \lambda^2, \lambda^2)$	$(\lambda^1, \lambda^1, \lambda^1, \lambda^1)$
$A^\mu_G \sim$	$(\lambda^2, \lambda^3, \lambda^3, \lambda^2)$	n.a.	n.a.

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 (collinear source)

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

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

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

$$iD_t = \underbrace{i\partial_t - gA^0_U - gA^0_G}_{\sim\lambda^2} \,,$$

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

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

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

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

Substitute, expand and collect terms up to order λ^3

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

Leading medium correction

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

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

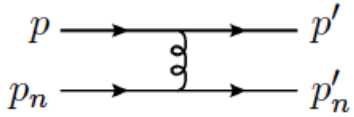
Sub-leading medium corrections

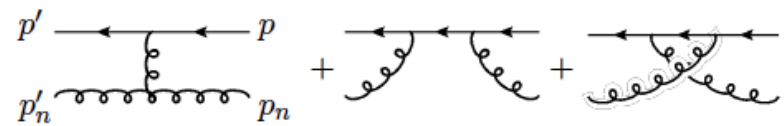
$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_C) = 0 \quad (static)$$

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

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)

$t_{coll.} =$ 

$t_{g-coll.} =$ 

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

Glauber field for collinear source

$$A^{\mu,a}_G = \frac{n^\mu}{\mathbf{q}_T^2} \sum_\ell \bar{\xi}_{n,\ell-\mathbf{q}_T} \frac{\bar{\not{n}}}{2} (gT^a) \xi_{n,\ell}$$

Coulomb field for soft source

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

Glauber field for collinear source

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

Coulomb field for soft source

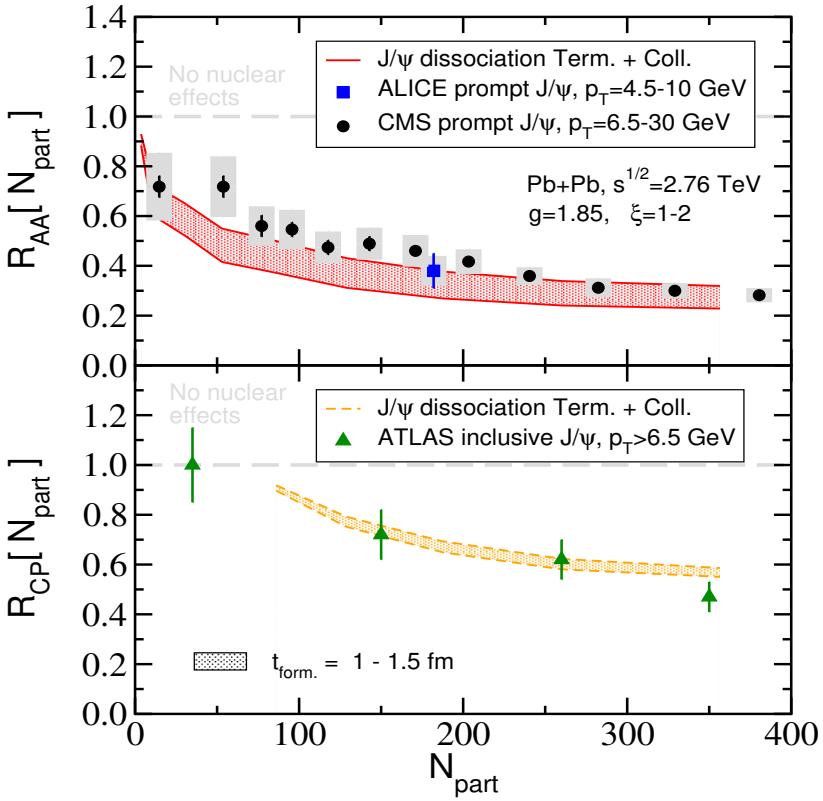
Y. Makris et al. (2019)

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

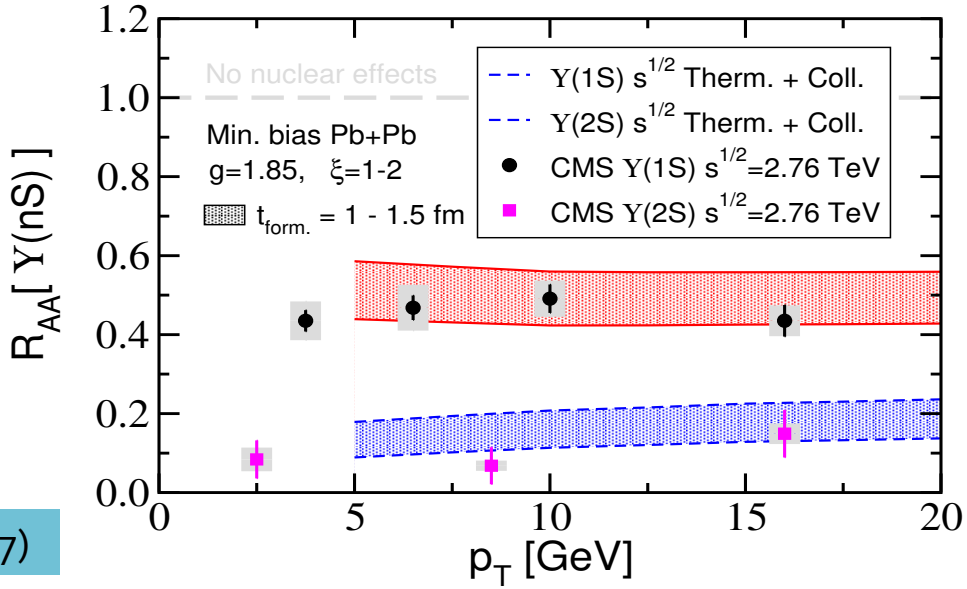
- Note that for the gluon the last 2 diagrams are necessary for gauge invariance but the first diagram the leading forward scattering contribution
- In the medium the momentum exchange can get dressed ~ Debye screening

Possible phenomenology applications

- Phenomenology built so far is connected to the leading term – collisional dissociation, thermal effects put in quarkonium wavefunctions. Also neglected possible transitions between different color states



- If one takes into account the modification of the heavy quark potential in the medium - distinct suppression of ground and excited states



R. Sharma et al. (2012)

S. Aronson et al. (2017)

Conclusions

- Effective theories of QCD have enabled important conceptual and technical breakthroughs in our understanding of strong interactions and very significant improvement in the accuracy of the theoretical predictions.
- In the the leading power factorization (high p_T) limit of NRQCD we investigated energy loss phenomenology and showed that it severely overpredicts the J/ψ modification and gives the wrong hierarchy of ground/excited suppression.
- Motivated by this we constructed an effective theory of quarkonia in matter - $NRQCD_G$. 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
- In the future it will be interesting to investigate off-diagonal transitions and have an evolution of a matrix of states