Ivan Vitev

Toward and effective theory of quarkonium production in nuclear matter

Past, Present, and Future of Relativistic Heavy Ion Collisions
Miklos Gyulassy Symposium
Knoxville, TN, March 18, 2019

In collaboration with Y. Makris

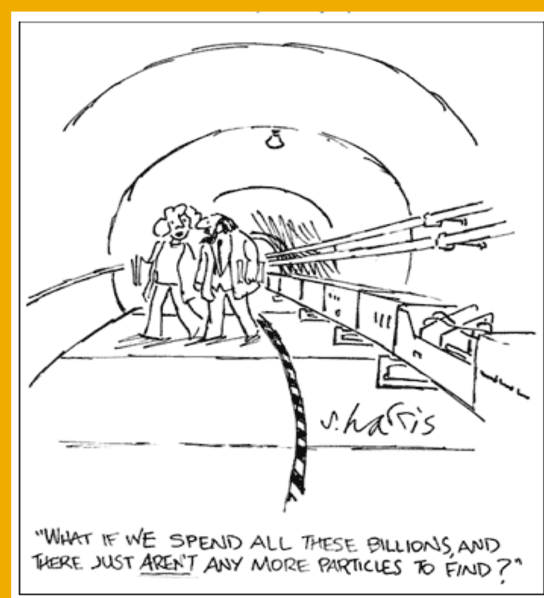
Outline of the talk

- Heavy ion collisions and motivation for quarkonium studies
- Quarkonium production in p+p collisions, NRQCD and LP factorization
- Energy loss calculations of charmonia excluded by data
- An effective theory of quarkonium production in matter
- Conclusions

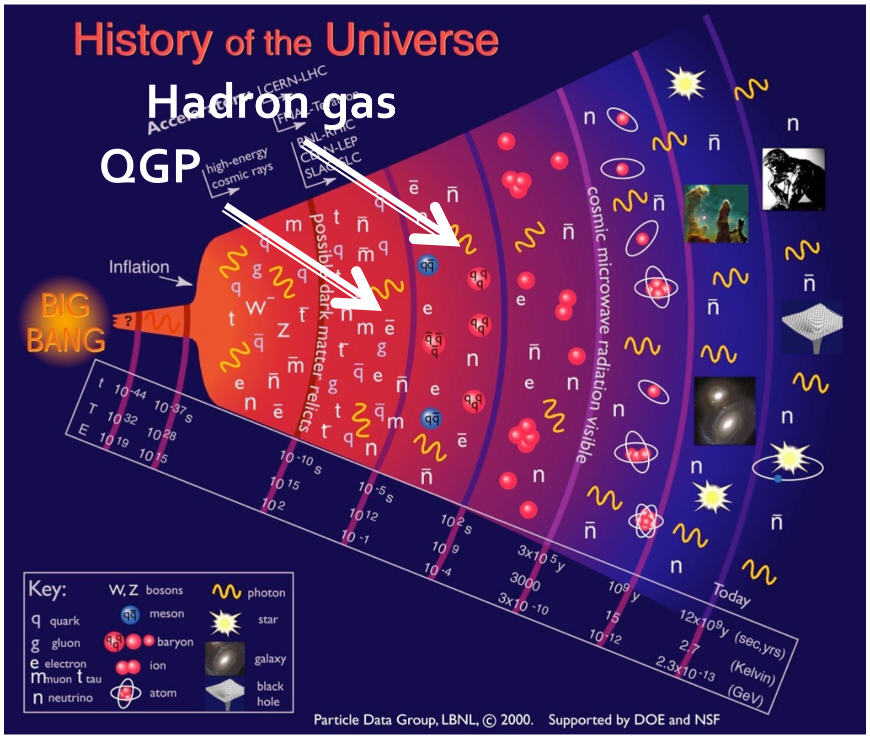
Thanks to the organizers for the invitation

Work in progress with Yiannis Makris

Introduction & Motivation

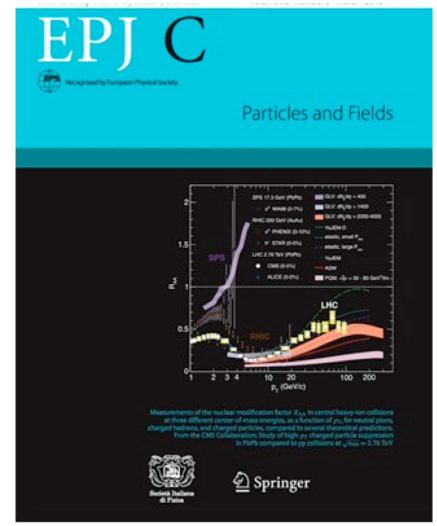


Background: QGP and the early universe



nature International weekly journal of science

The New York Times



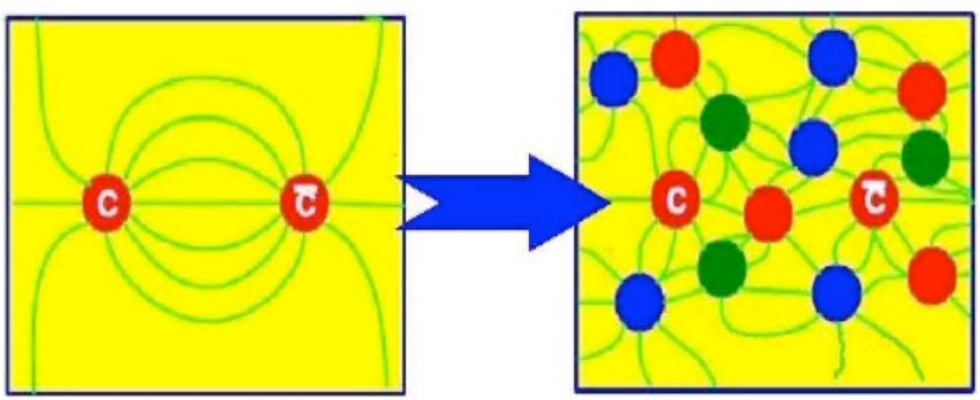
QGP: key discovery

- QGP is the earliest stage in the evolution of the universe that can be directly studied in the laboratory
- Discovered in 2000 - 2004, novel emergent properties that need to be studied → the big science question for the field
- The dense hadron gas phase is not well studied at all

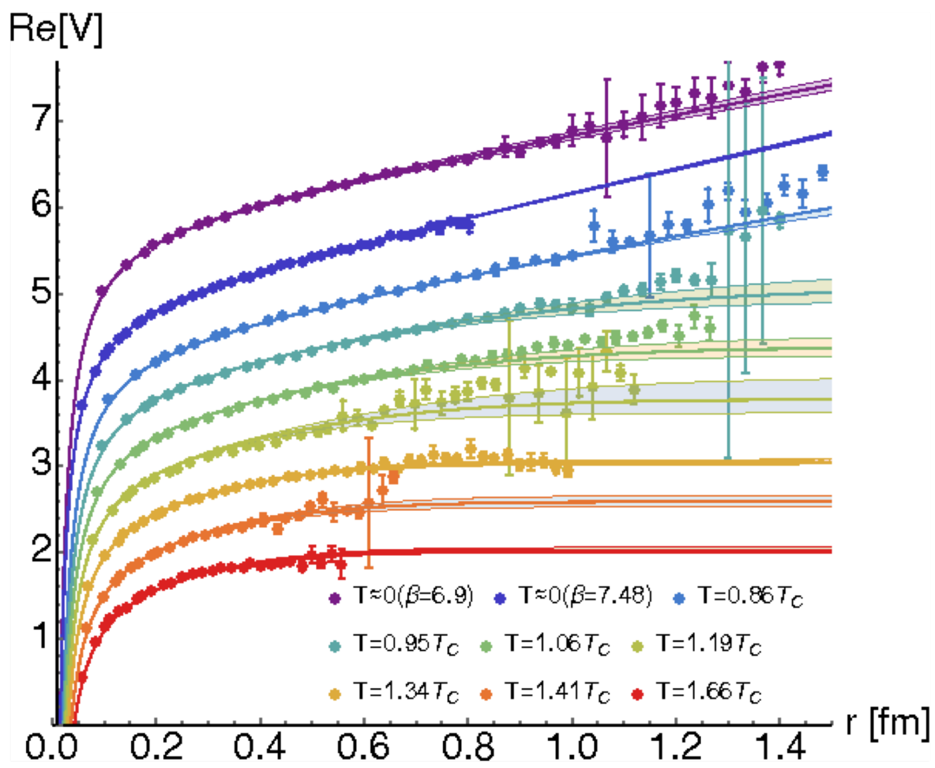
Quarkonia in the QGP

- 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)

- Can be encoded in an analytic parameter m_D

Thermometer for the QGP

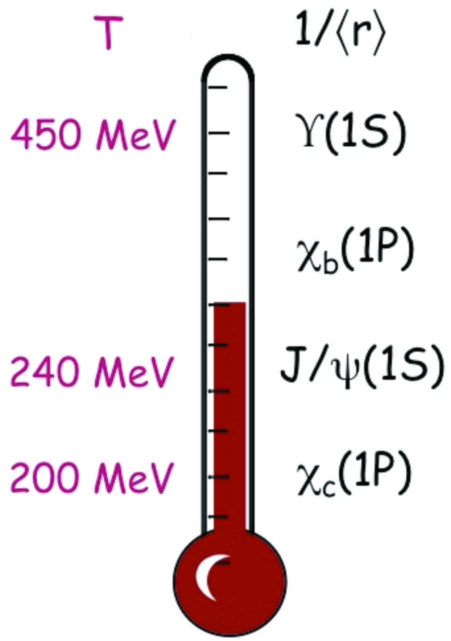
- It has been argued that the different "melting" temperatures for the various quarkonium states can provide a "thermometer", excited weekly-bound states disappear first, ground states disappear last

Mocsy *et al.* (2007)

Bazavov *et al.* (2013)

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

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



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	$\chi_b(3P)$

It is understood now that the situation is much more complicated

A historical note

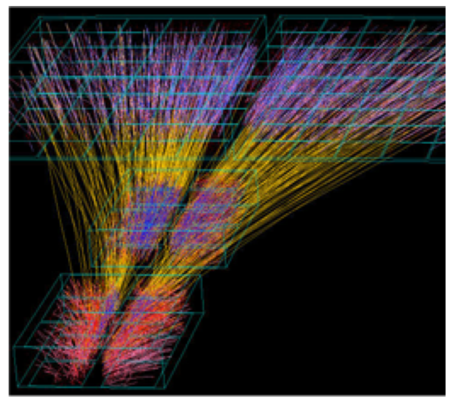
"It has been expected that in high energy collisions between heavy nuclei sufficiently high energy densities could be reached such that this new state of matter would be formed. Quarks and gluons would then freely roam within the volume of the fireball created by the collision."

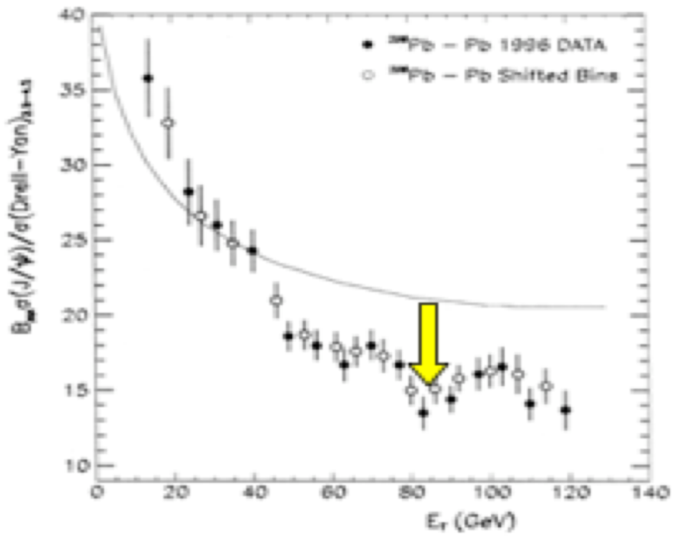
"A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma."

Heinz and Jacob. *(2000)*

Pundits happy, competition unhappy

- Non-monotonic J/ψ / DY as a function of the transverse energy





BROOKHAVEN BULLETIN

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BROOKHAVEN NATIONAL LABORATORY

Has CERN scooped RHIC? The answer is no. CERN stated that their evidence is indirect and "circumstantial." But their results do generate great confidence that the quark-gluon plasma may be directly observed for the first time when RHIC achieves full operational status.

Another historical observation

- Miklos Gyulassy's first (and only?) quarkonium paper

TRANSVERSE-MOMENTUM DEPENDENCE OF J/ψ PRODUCTION IN NUCLEAR COLLISIONS ☆

S. GAVIN and M. GYULASSY
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Mailstop 70A-3307, Berkeley, CA 94720, USA

Received 23 August 1988

The suppression of J/ψ production at transverse momenta $p_\perp < 2$ GeV/c in central $^{16}O + ^{238}U \to \psi + X$ at 200 A GeV has been interpreted as a possible signature of quark–gluon plasma formation. We show, however, that the observed $p_\perp$ dependence is consistent with extrapolations from $p + A \to \psi + X$ data, and that quasielastic initial-state parton scattering together with final-state inelastic hadronic reactions may explain the preliminary data.

Gavin and Gyulassy (1988)

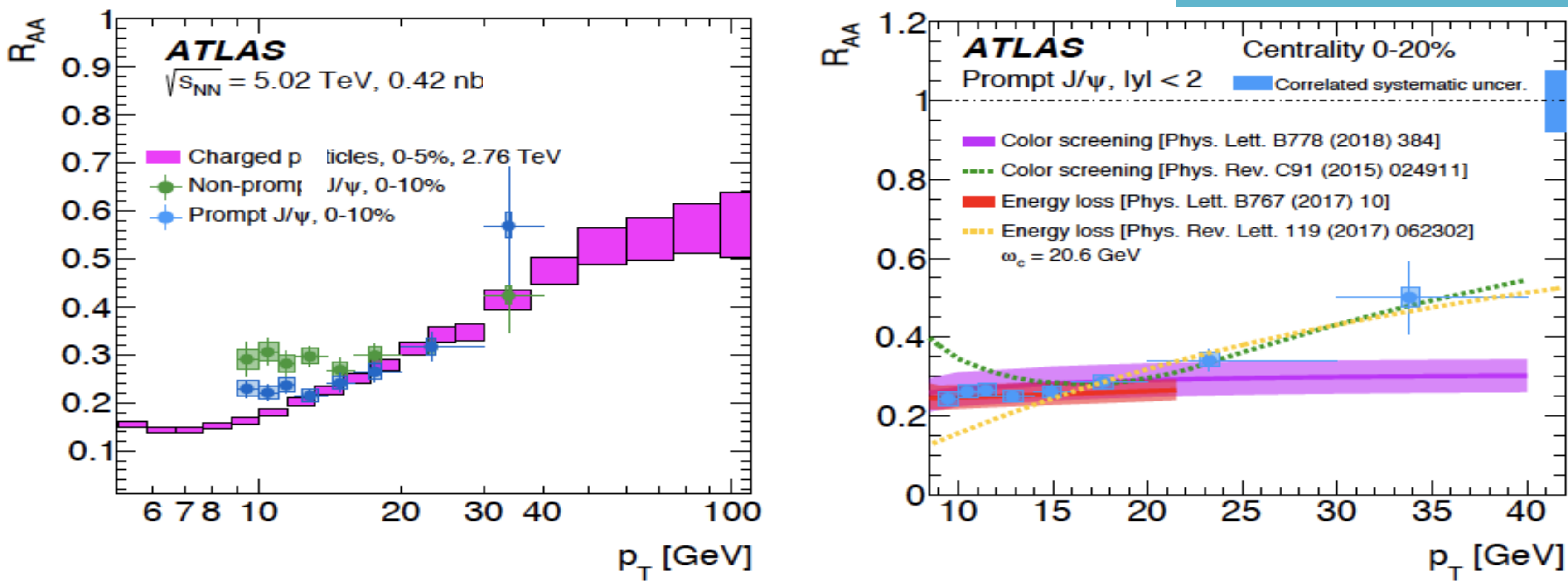
The talk is thus dedicated to the long lost art of showing that not every model explains every measurement*

***Excludes the CGC, LBT and AdS/CFT models**

Hypothesis about prompt quarkonia and energy loss

Data should be interpreted with care

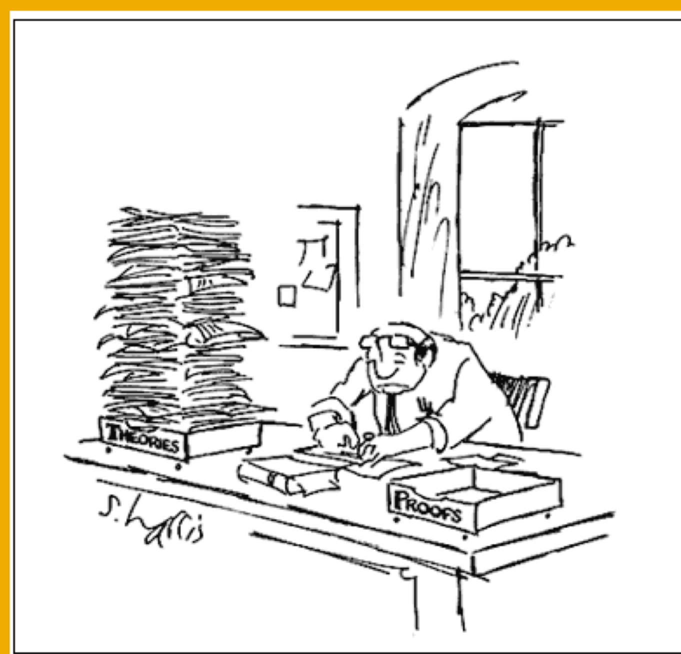
Aabud et al. (2018)



- Difference between models that incorporate similar physics. Incorporated at the level of quarkonium spectra (but if a quarkonium state radiates it will be destroyed)
- Models do not appear to be constrained by other data, such as light hadrons. No other quarkonium states considered.

An exciting possibility but needs to be revisited

NQCD, Leading power factorization & E-loss

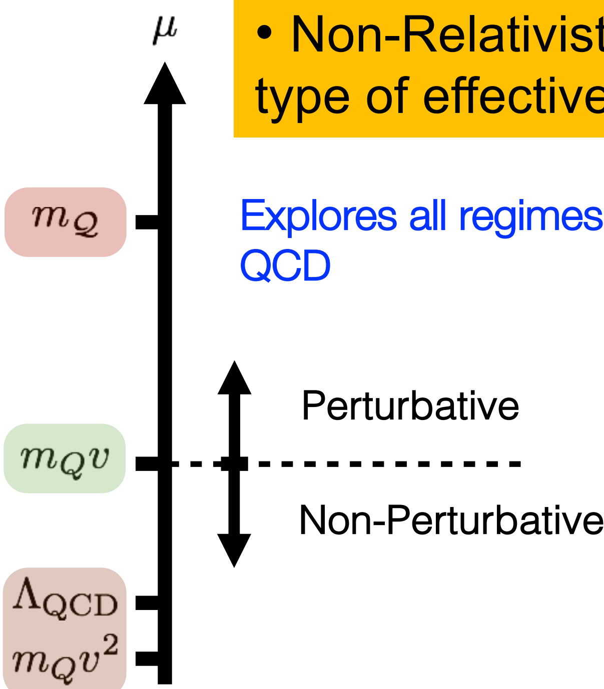


Production of quarkonia at intermediate and high p_T

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

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

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

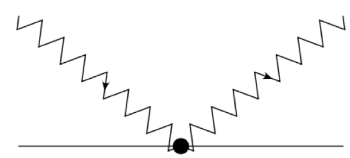
$p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

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

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 examples

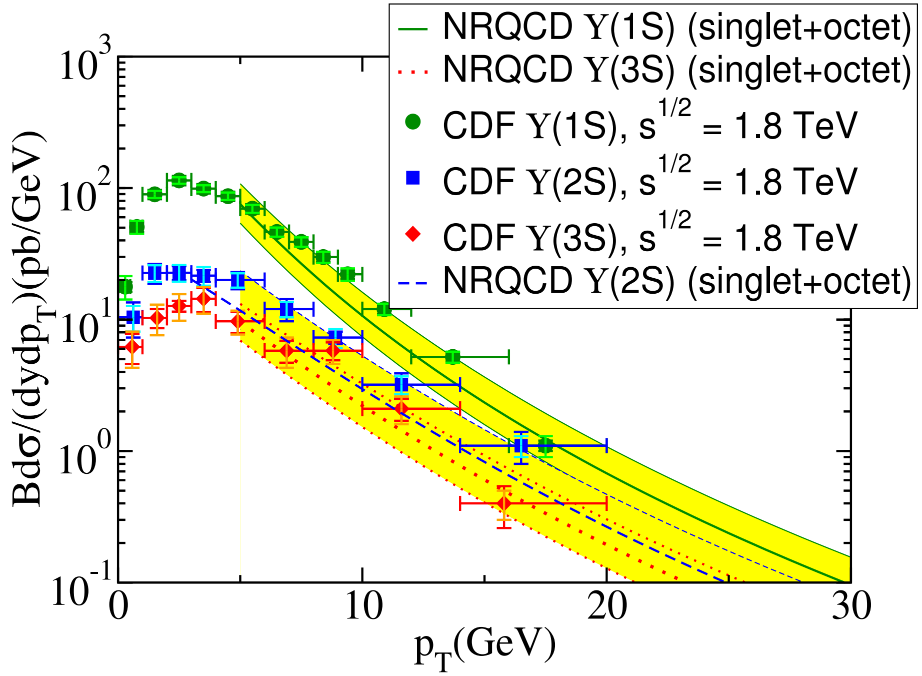
• One has to be careful, the simple power counting approximately manifest in the LDMEs can be affected by the partonic cross section – a large number of singlet and octet; S wave and P wave terms enter

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

• 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

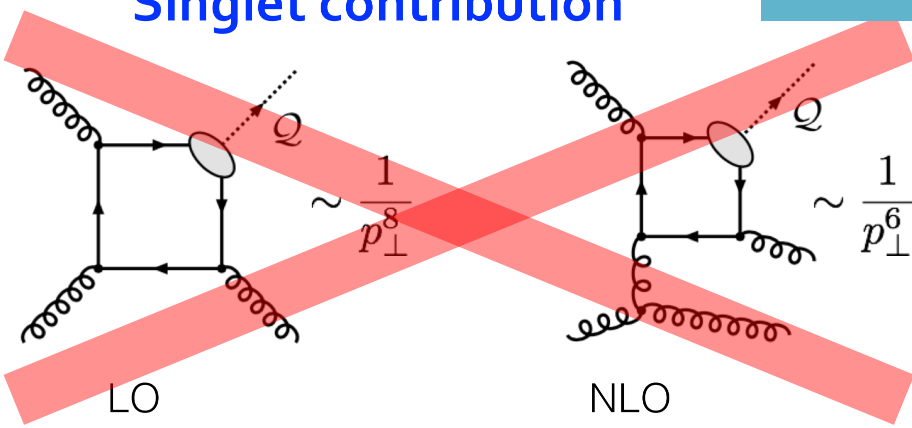


Leading power factorization

Singlet contribution

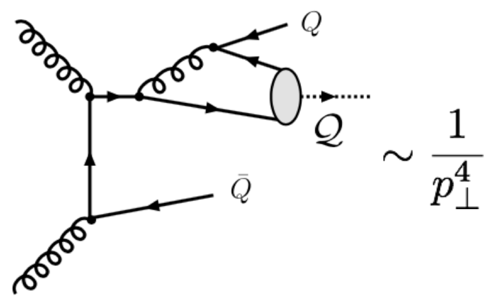
S. Fleming *et al.* (2012)

M. Baumgart *et al.* (2014)

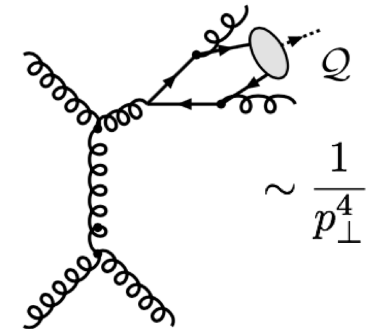


LO

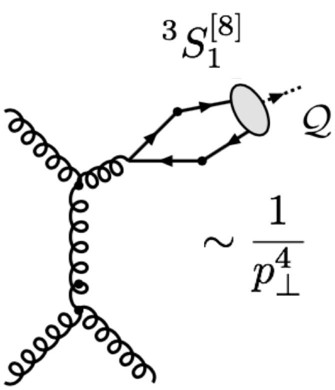
NLO



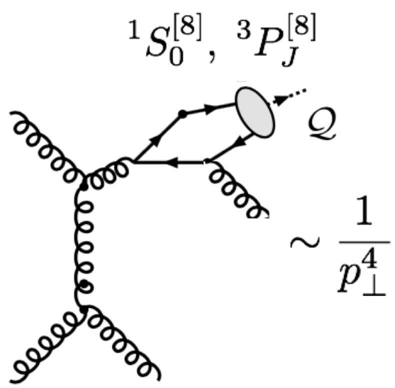
NLO



NNLO

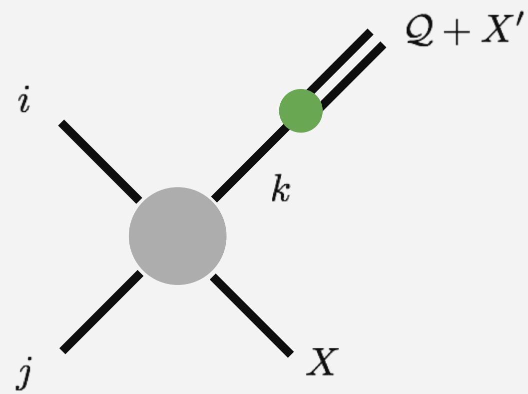


LO



NLO

(single) Parton fragmentation process



Octet contribution

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

LP example and applicability

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

$p_T \gg m_Q$

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

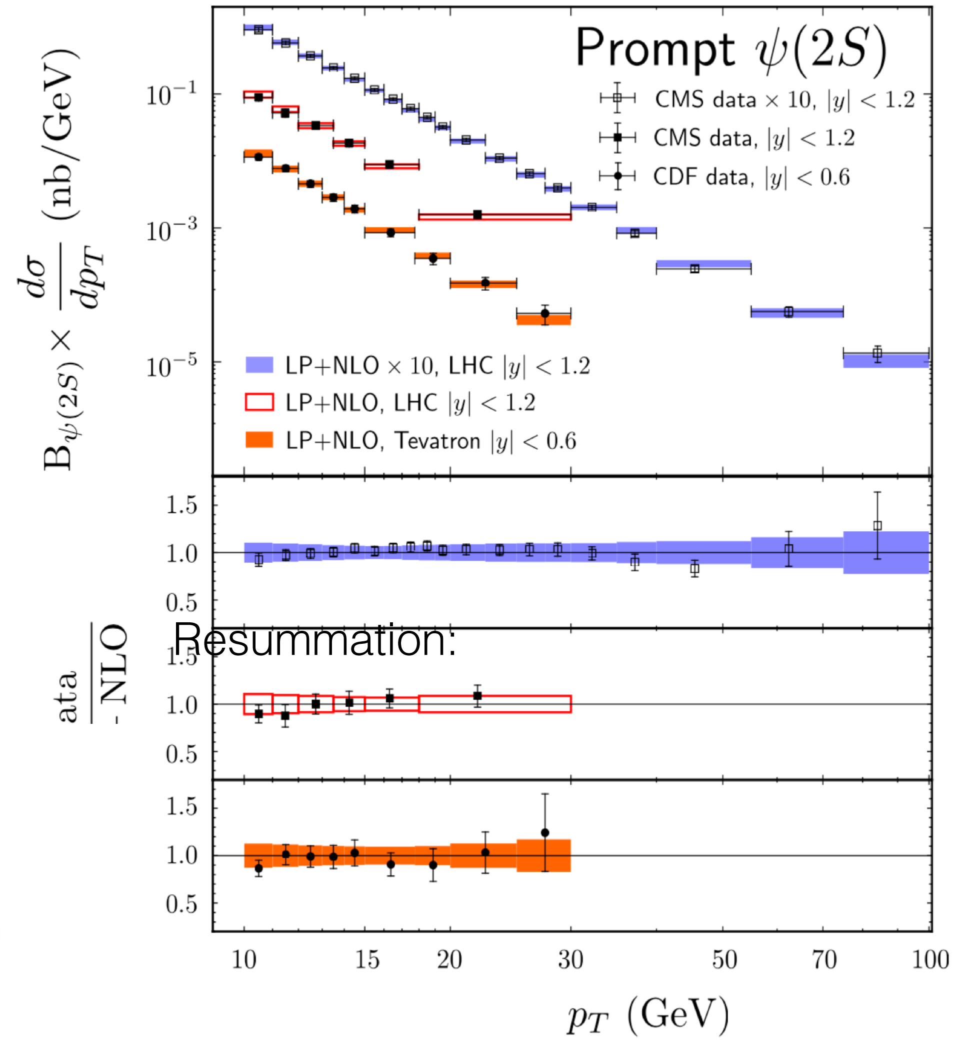
DGLAP Evolution

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

Resummation of $\ln(p_T/m_h)$

Contributios we take

Mechanism	Initiating parton	χ_{cJ}: ${}^3P_J^{[1]}$	χ_{cJ}, $J/\psi(1S)/\psi(2S)$: ${}^3S_1^{[8]}$	$J/\psi(1S)/\psi(2S)$: ${}^3P_J^{[8]}/{}^1S_0^{[8]}$	$J/\psi(1S)/\psi(2S)$: ${}^3S_1^{[1]}$
	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

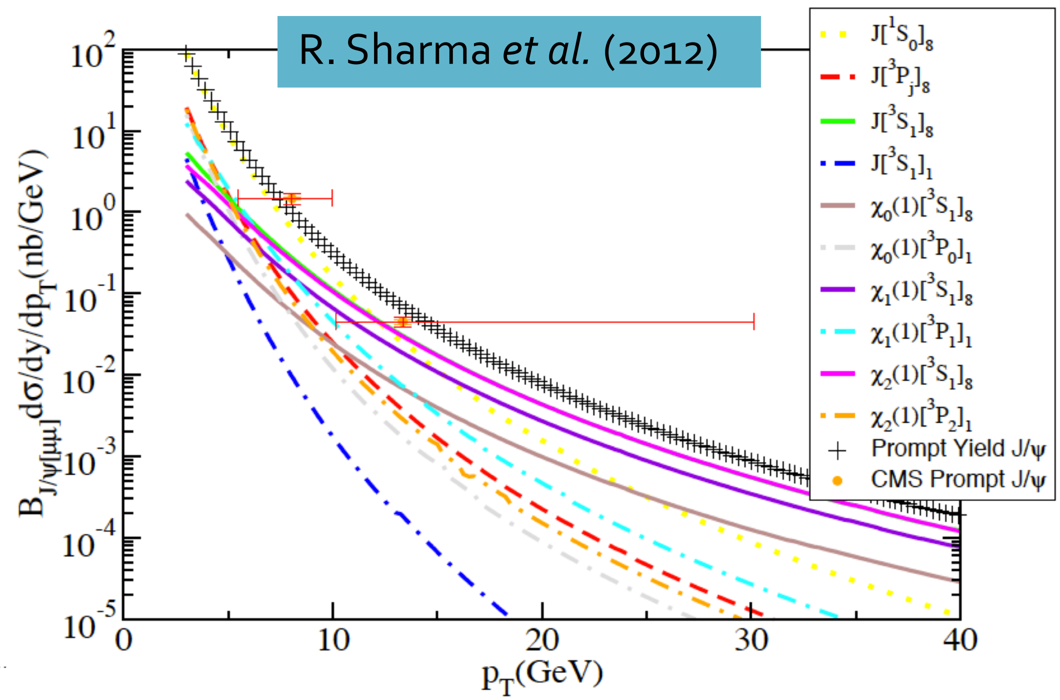


G. Bodwin *et al. (2016)*

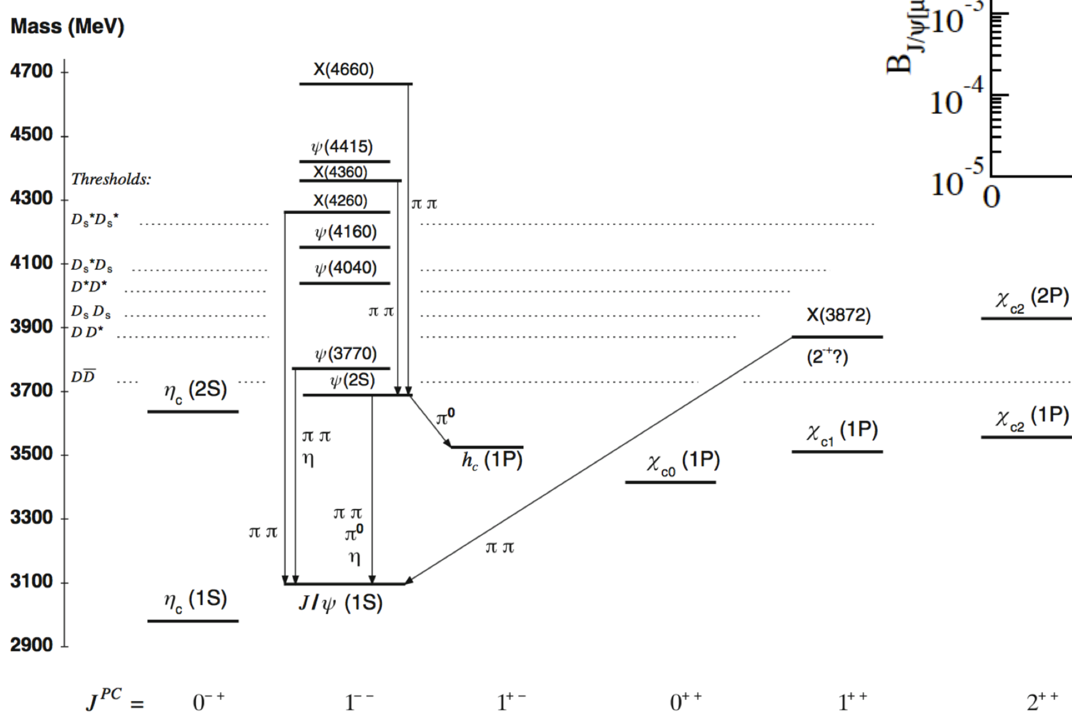
Feeddown is important

- Example of NRQCD calculation. You see both different high p_T behavior and feeddown

R. Sharma *et al.* (2012)



Charmonium states



Following feeddown contributions taken, others small

$$\psi(2S): \quad \mathrm{Br}\left[\psi(2S) \to J/\psi + X\right] = 61.4 \pm 0.6\%$$

$$\chi_{c1}: \quad \mathrm{Br}\left[\chi_{c1} \to J/\psi + \gamma\right] = 34.3 \pm 1.0\%$$

$$\chi_{c2}: \quad \mathrm{Br}\left[\chi_{c2} \to J/\psi + \gamma\right] = 19.0 \pm 0.5\%$$

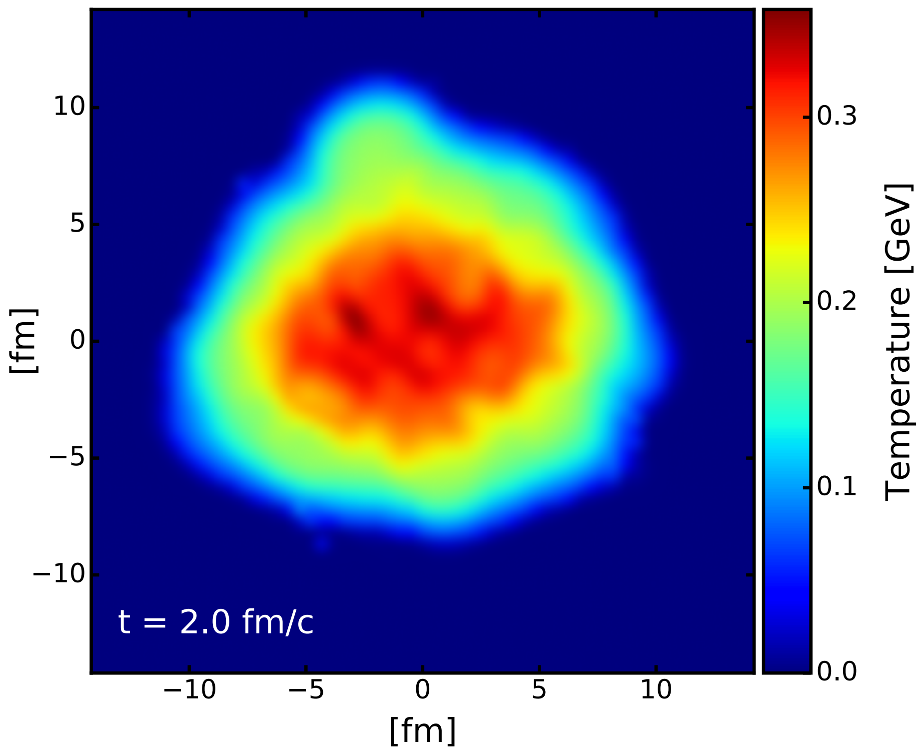
Energy loss results for quarkonia, constraints

Energy loss evaluation in hydrodynamic medium

- Evaluate the splitting functions in the small x limit – corresponds to traditional energy loss phenomenology

Z. Kang *et al.* (2016)

- Can make contact with other claims in the literature



Evaluate the medium-induced emission spectrum. Construct the probability of energy loss due to multiple gluon emission

$$\int_0^1 d\epsilon P(\epsilon) = 1, \qquad \int_0^1 d\epsilon \epsilon P(\epsilon) = \left\langle \frac{\Delta E}{E} \right\rangle$$

M. Gyulassy *et al.* (2003)

C. Shen *et al.* (2014)

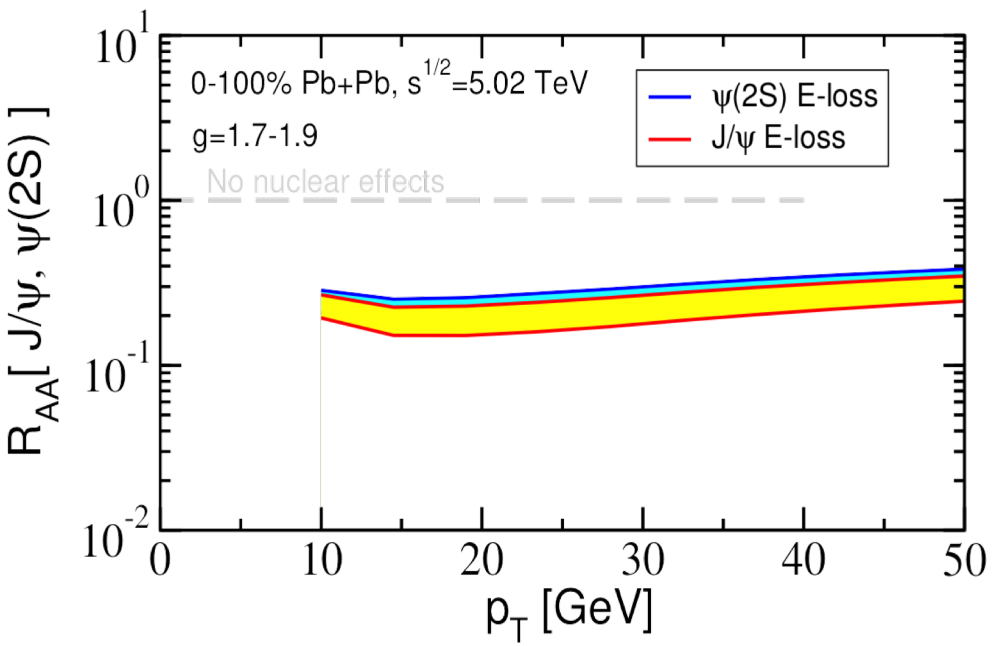
Obtain quenched partonic spectra with effective mass m_c and $2m_c$ where necessary

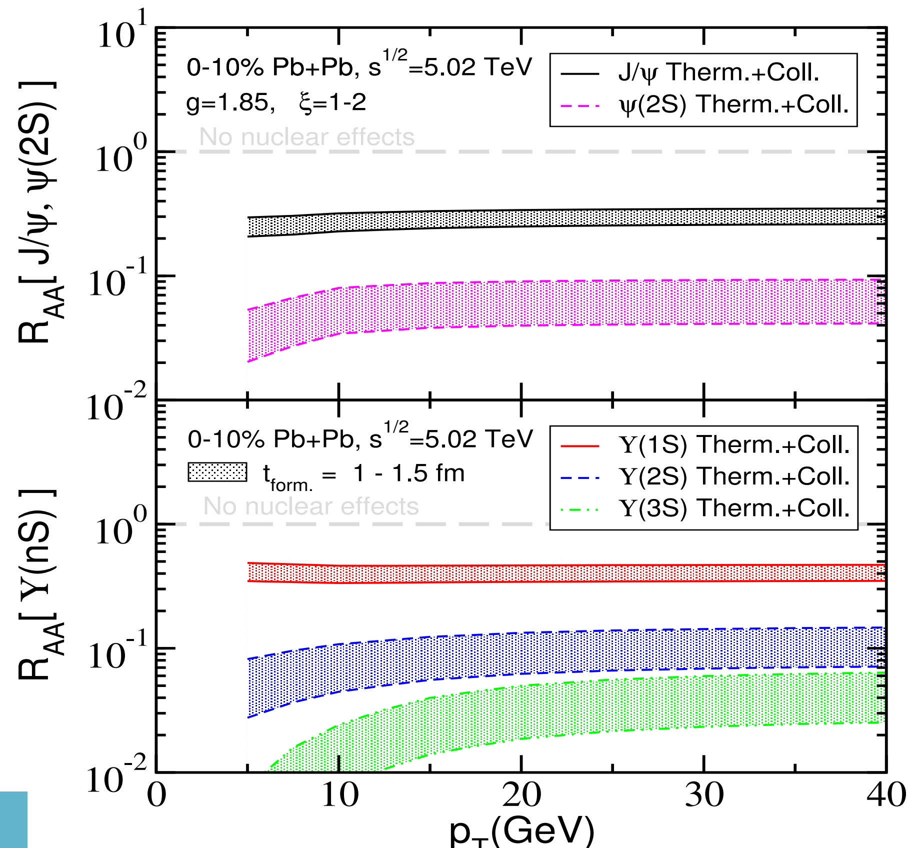
$$\frac{d\sigma_{AB}^{q,g\ Quench}(\mathbf{p})}{dyd^2\mathbf{p}} = \int_0^1 d\epsilon\ P(\epsilon) \frac{1}{(1-\epsilon)} \frac{d\sigma_{AB}^{q,g}\left(\frac{\mathbf{p}}{1-\epsilon}\right)}{dyd^2\mathbf{p}}$$

- Viscous second order Israel-Stewart event-by-event hydrodynamics

Comparison of energy loss vs dissociation models

- Completely different predictions for ground and excited states' suppression. Dissociation models depend on bunding, energy loss models depend on the flavor of partonic cross sections as steepness of spectra





Makris and Vitev (2019)

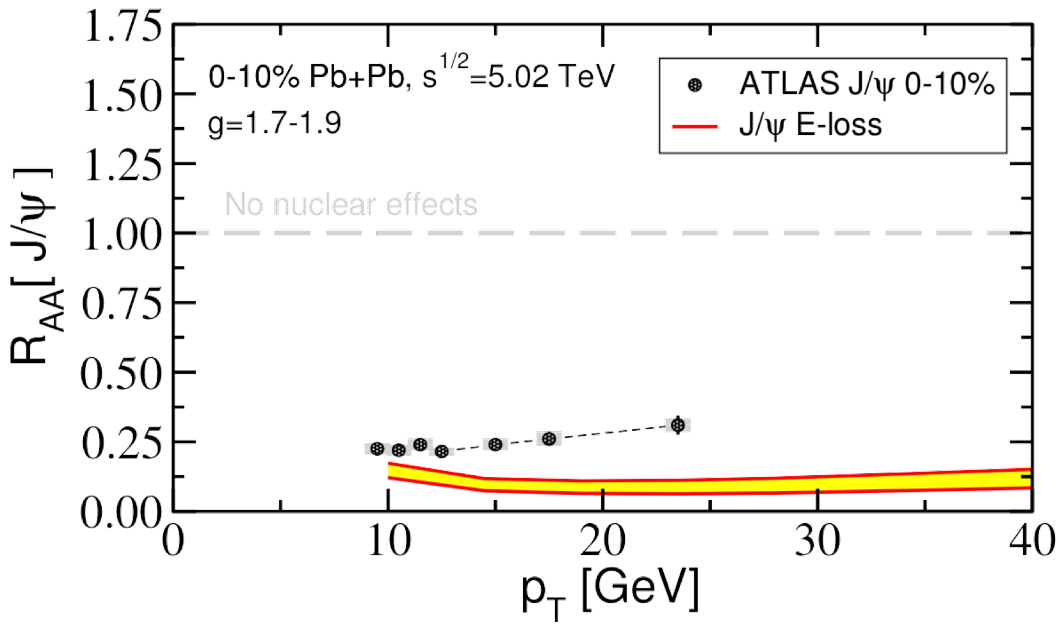
S. Aranson et al. (2017)

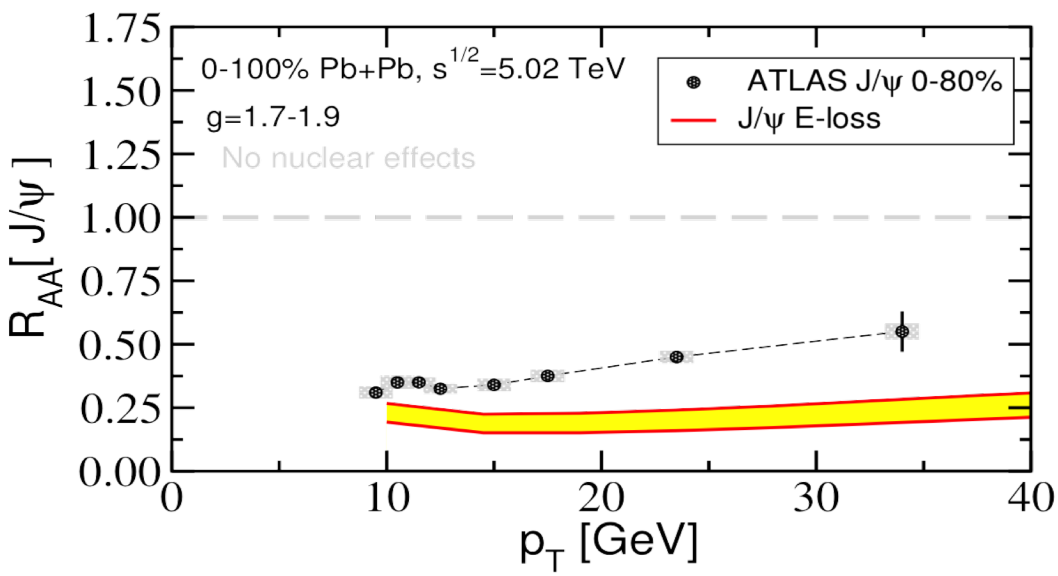
Comparison of J/ψ to data

- Suppression of J/ψ overestimated by factor of 2 to 3. Included χ_c and ψ(2S) feeddown.
- Persists over centralities. Somewhat different p_T dependence
- Differences are significan

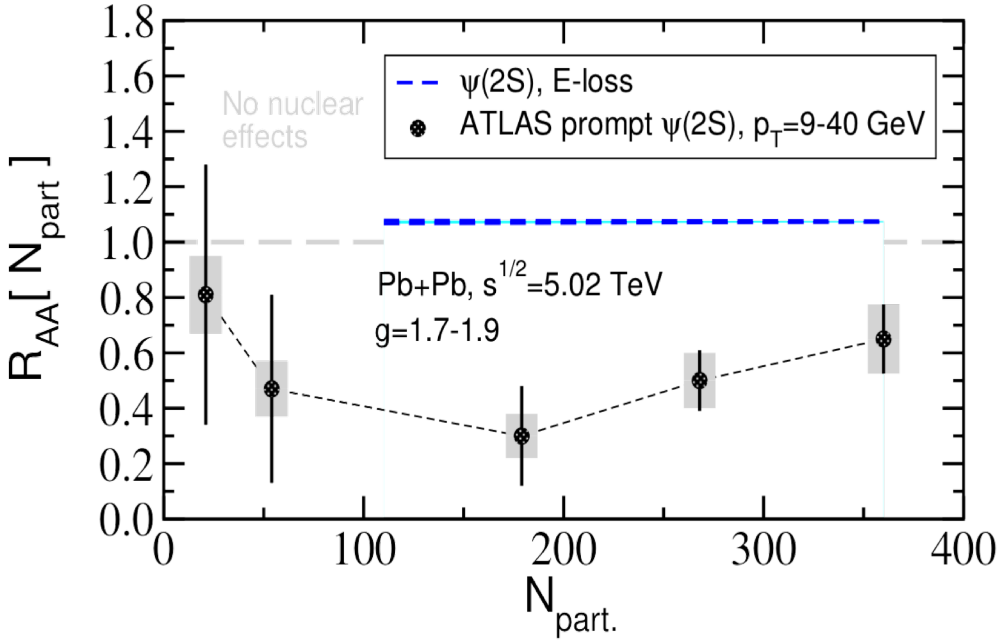
$$R_{AA}^{\text{min. bias}}(p_T) = \frac{\sum_i R_{AA}(\langle b_i \rangle) W_i}{\sum_i W_i}$$

$$W_i = \int_{b_i \text{ min}}^{b_i \text{ max}} N_{\text{coll.}}(b)\, \pi\, b\, db$$





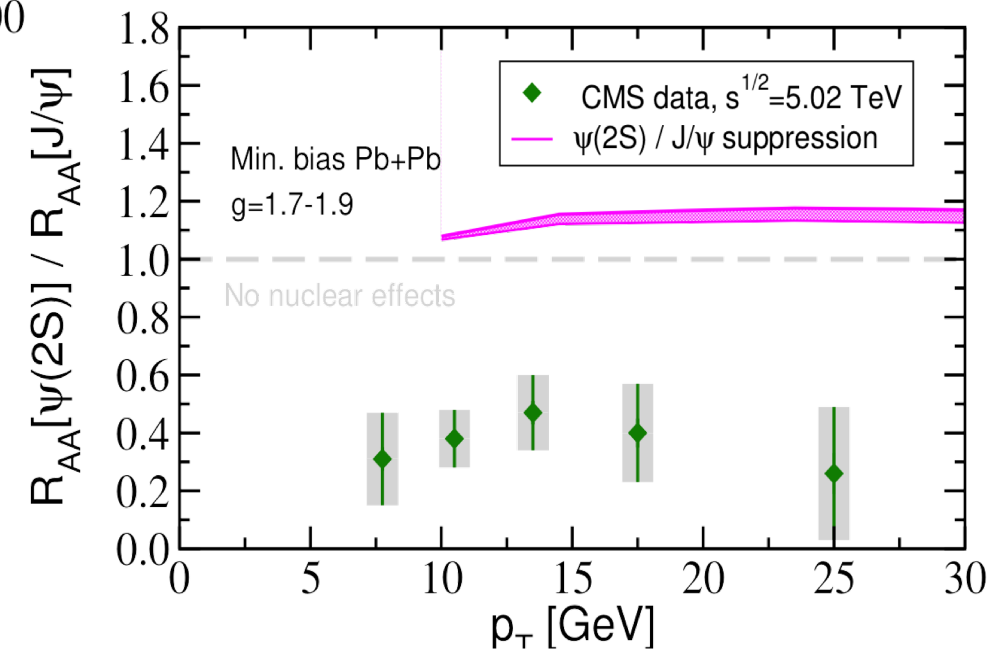
Double suppression ratio ψ(2S) / J/ψ



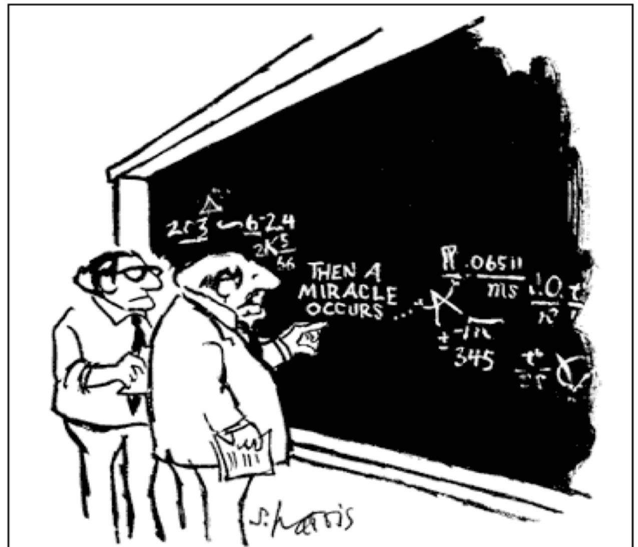
Makris and Vitev (2019)

- 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

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



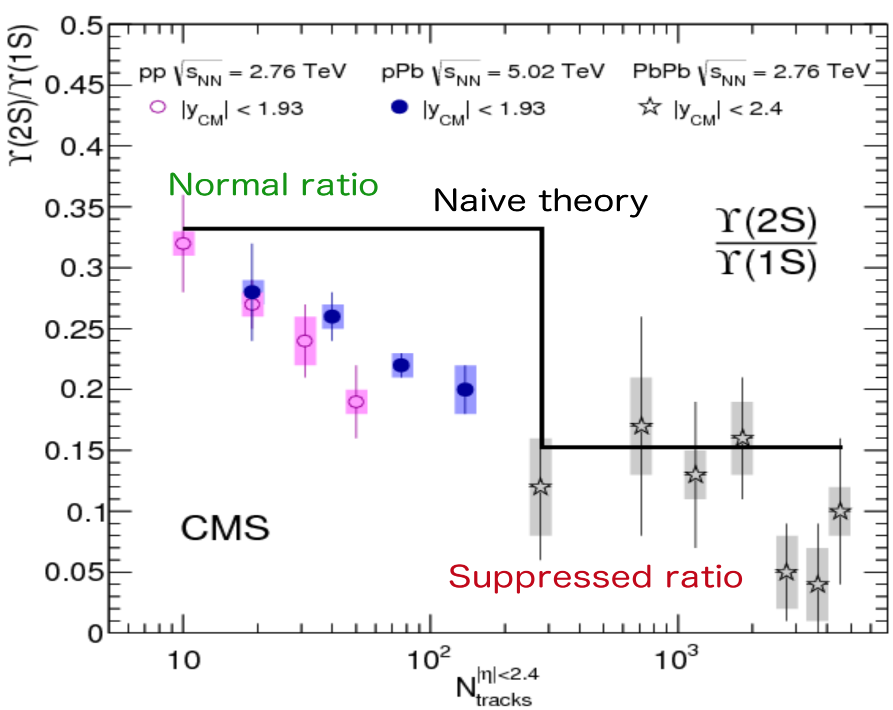
Effective theory of quarkonia in matter



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

Quarkonia as probes of different systems

- Suppression puzzle - similar dissociation behavior observed in small system, p+A and even in p+p (where QGP is not expected)
- Co-mover dissociation model– phenomenological cross section to break up quarkonia in a co-moving hadron gas.



Chatrachyan *et al.* (2014)

E. Ferreiro (2014)

- Suggests that an effective field theory framework may be the way to go. Capture the interactions without explicitly specifying their nature

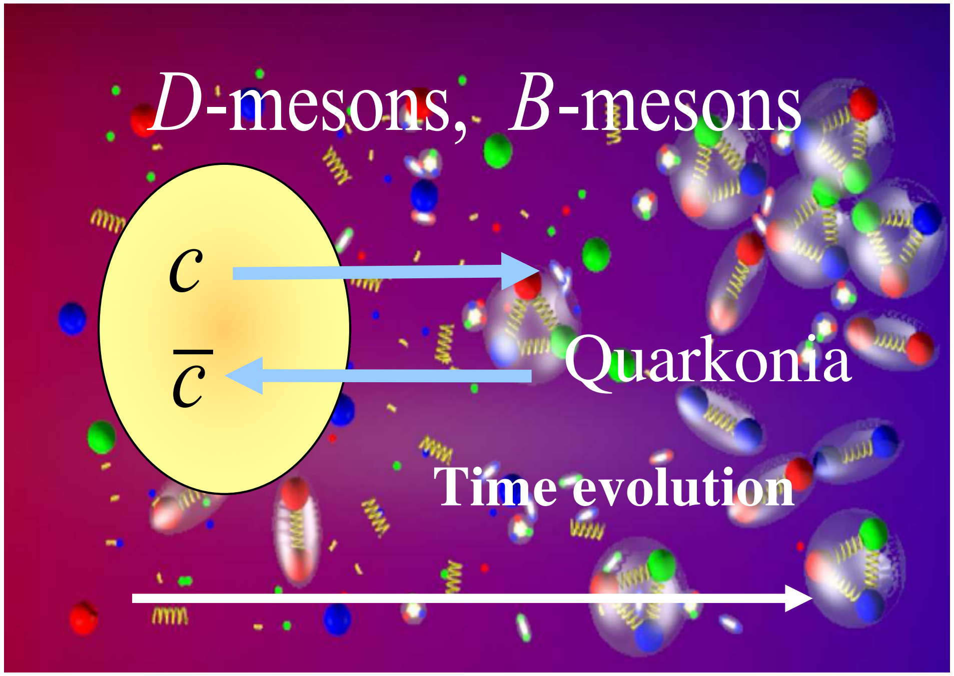
Lowest order

$$\mathcal{L}_0 = \mathcal{L}_{\text{light}} + \psi^\dagger \left(i\partial_0 - gA_0 + \frac{\boldsymbol{\nabla}^2}{2M} \right) \psi$$

First correction

$$\mathcal{L}_1 = -\frac{1}{M}\psi^\dagger (ig\mathbf{A}\cdot\boldsymbol{\nabla})\psi + \frac{c_4}{2M}\psi^\dagger (\boldsymbol{\nabla}\times g\mathbf{A})\cdot\boldsymbol{\sigma}\psi$$

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

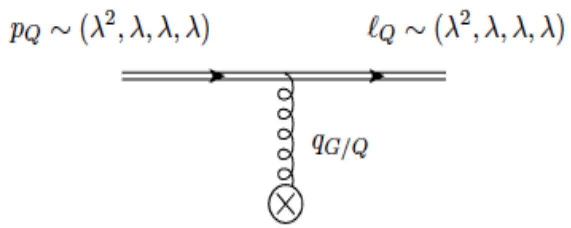
- Double soft gluon emission
- Heavy quark-antiquark potential
- (can also be interaction with soft particles)

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

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

- Depends on the type of the source of scattering in the medium

Leading medium corrections

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

Sub-leading medium corrections

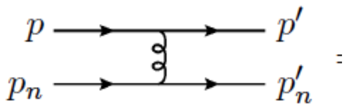
$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_{G}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\Big[(\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})A^{\mathbf{n}}_G\Big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}}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

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

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

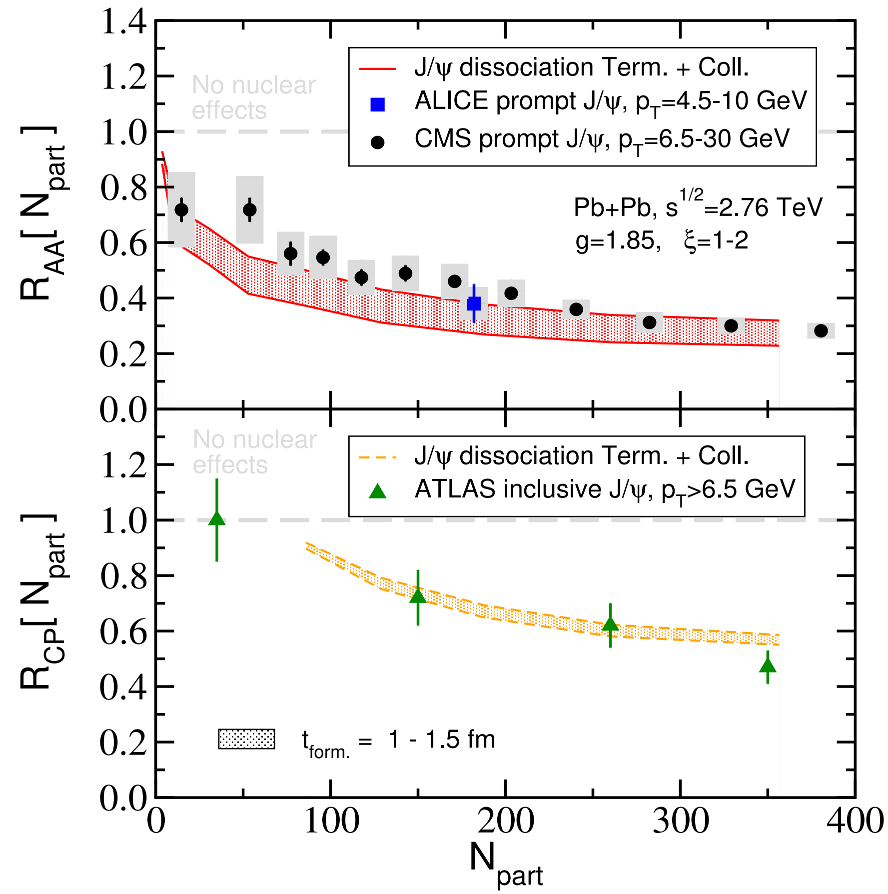
Possible phenomenology applications

- Looking at t-channel scattering we can also extract the form of the Glauber/Coulomb fields.

$t_{coll.} =$ 

R. Sharma et al. (2012)

S. Aronson et al. (2017)



Glauber field for collinear source

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

Coulomb field for soft source

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

- Phenomenology built so far is on the leading term – collisional dissociation, thermal effects put in quarkonium wavefunctions
- Will be very interesting to study medium-induced transitioins between states

Conclusions

- Quarkonium suppression still presents interesting and unresolved problems. Recently energy loss has also been proposed as mechanism for prompt quarkonium suppression
- The leading power factorization (high p_T) limit of NRQCD can be recast as parton fragmentation in quarkonia. This is the only limit where we can apply energy loss phenomenology
- We performed a detailed and self consistent calculation of J/ψ and ψ(2S) suppression from E-loss and showed that it severely overpredicts the J/ψ modification and gives the wrong hierarchy of ground/excited supp.
- Motivated by this we constructed an effective theory of quarkonia in matter - $NRQCD_{G.}$ Derived the Feynman rules to leading and subleading power for different sources of int. in the medium
- We expect rich phenomenology - the future it will be important to extend the leading modification to other nuclear media. Look at medium-induced transition between different states

NRQCD @ large pT (3S1)

For charmonium states: $\alpha_S(2m_c) \sim v^2 \sim 0.25$

Leading contributions from charm fragmentation

1 $\langle \mathcal{O}(^3S_1^{(1)}) \rangle \sim v^3$, $d(^3S_1^{(1)}) \sim \alpha_s^2$, $\longrightarrow$ $^3S_1^{(1)} :\sim \alpha_s^2 v^3$

Leading contributions from gluon fragmentation

2	$\langle \mathcal{O}(^3S_1^{(1)}) \rangle \sim v^3$,	$d(^3S_1^{(1)}) \sim \alpha_s^3$,	$\longrightarrow$	$^3S_1^{(1)} :\sim \alpha_s^3 v^3$
3	$\langle \mathcal{O}(^3S_1^{(8)}) \rangle \sim v^7$,	$d(^3S_1^{(8)}) \sim \alpha_s$,	$\longrightarrow$	$^3S_1^{(8)} :\sim \alpha_s v^7$
4	$\langle \mathcal{O}(^1S_0^{(8)}) \rangle \sim v^7$,	$d(^1S_0^{(8)}) \sim \alpha_s^2$,	$\longrightarrow$	$^1S_0^{(8)} :\sim \alpha_s^2 v^7$
4	$\langle \mathcal{O}(^3P_J^{(8)}) \rangle \sim v^7$,	$d(^3P_J^{(8)}) \sim \alpha_s^2$,	$\longrightarrow$	$^3P_J^{(8)} :\sim \alpha_s^2 v^7$

Introduction & Motivation

"THESE DAYS EVERYTHING IS HIGHER."

[redacted]

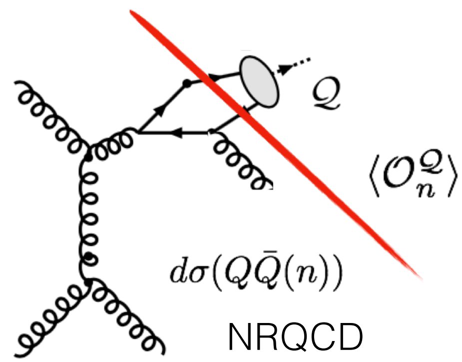
Fixed order NRQCD

Preferred at

$p_T \sim m_{\mathcal{Q}}$

includes corrections of

$p_T/m_{\mathcal{Q}}$



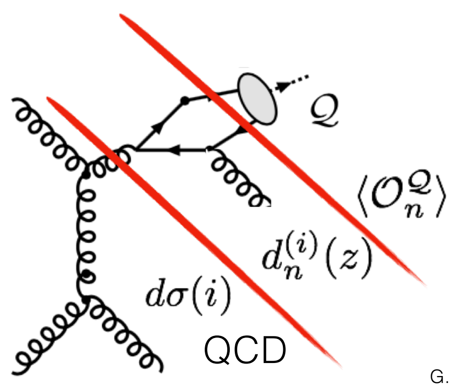
Leading Power NRQCD

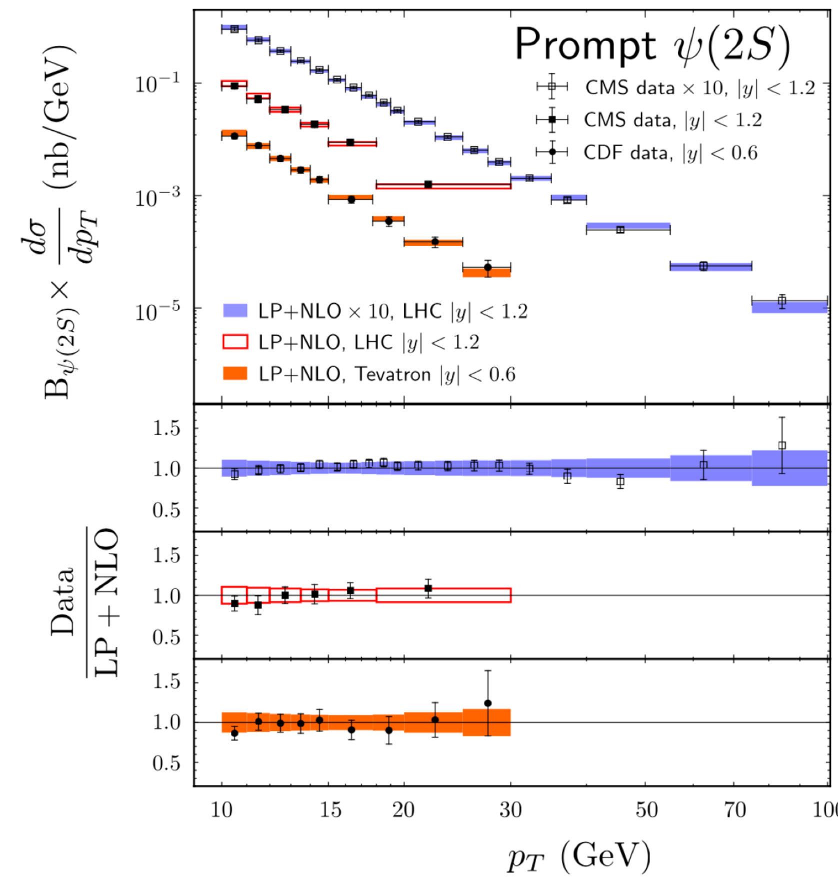
Preferred at

$p_T \gg m_{\mathcal{Q}}$

Resummation of

$\ln(p_T/m_{\mathcal{Q}})$





G. T. Bodwin, K-T. Chao, H. S. Chung, U-R. Kim,J. Lee, and Y-Q. Ma (PRD) 2016

A not so historical reality

- Enormous amount of data in heavy heavy ion collisions, ground and excited states, mid rapidity and forward rapidity, charmonia and bottomonia, RHIC and LHC energies

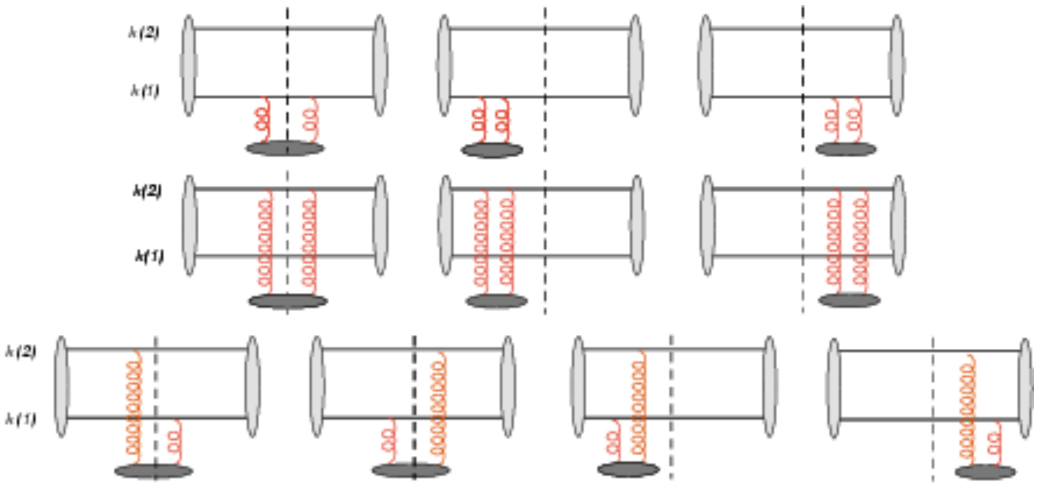
A. Andronic *et al.* (2015)

Probe	Colliding system	$\sqrt{s_{NN}}$ (GeV)	y	p_T (GeV/c)	Observables	Ref.
			PHENIX			
J/ψ	Au–Au	200	$1.2 < \lvert y\rvert < 2.2$	$p_T > 0$	yield and R_{AA}(cent., p_T, y)	[666–668]
			$\lvert y\rvert < 0.35$			
				$0 < p_T < 5$	$v_2(p_T, y)$	[669]
			$1.2 < \lvert y\rvert < 2.2$			[670]
	Cu–Cu		$1.2 < \lvert y\rvert < 2.2$	$p_T > 0$	yield and R_{AA}(cent., p_T, y)	[671]
			$\lvert y\rvert < 0.35$			
	Cu–Au		$1.2 < \lvert y\rvert < 2.2$		yield and R_{AA}(cent., y)	[672]
	U–U	193	$1.2 < \lvert y\rvert < 2.2$	$p_T > 0$	R_{AA}(cent.)	[673]
	Au–Au	62.4			yield(cent., p_T), R_{AA}(cent.)	[674]
		39				
Υ(1S+2S+3S)		200	$\lvert y\rvert < 0.35$		yield, R_{AA}(cent.)	[675]
			STAR			
J/ψ	Au–Au	200	$\lvert y\rvert < 1$	$p_T > 0$	yield and R_{AA}(cent., p_T)	[239, 676]
					v_2(cent., p_T)	[677]
	Cu–Cu				yield and R_{AA}(cent., p_T)	[277, 676]
	U–U	193			$R_{AA}(p_T)$	[678]
	Au–Au	62.4			yield, R_{AA}(cent., p_T)	
		39				
Υ(1S)		200			σ and R_{AA}(cent.)	[323]
Υ(1S+2S+3S)					R_{AA}(cent.)	
	U–U	193				[678]

Probe	Colliding system	$\sqrt{s_{NN}}$ (TeV)	y	p_T (GeV/c)	Observables	Ref.
			ALICE			
J/ψ	Pb–Pb	2.76	$\lvert y\rvert < 0.9$	$p_T > 0$	R_{AA}(cent., p_T)	[480, 679]
			$2.5 < y < 4$	$p_T > 0$	R_{AA}(cent., p_T, y)	[679, 680]
				$0 < p_T < 10$	v_2(cent., p_T)	[681]
ψ(2S)				$p_T < 3$	$\frac{(N_{\psi(2S)}/N_{J/\psi})_{Pb\text{–}Pb}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}}$(cent.)	[682]
				$3 < p_T < 8$		
Υ(1S)				$p_T > 0$	R_{AA}(cent., y)	[683]
			ATLAS			
J/ψ	Pb–Pb	2.76	$\lvert\eta\rvert < 2.5$	$p_T \gtrsim 6.5$	R_{CP}(cent.)	[684]
			CMS			
J/ψ (prompt)	Pb–Pb	2.76	$\lvert y\rvert < 2.4$	$6.5 < p_T < 30$	yield and R_{AA}(cent., p_T, y)	[482]
					v_2(cent., p_T, y)	[685]
			$1.6 < \lvert y\rvert < 2.4$	$3 < p_T < 30$		
			$\lvert y\rvert < 1.2$	$6.5 < p_T < 30$	yield and R_{AA}	[482]
			$1.2 < \lvert y\rvert < 1.6$	$5.5 < p_T < 30$		
			$1.6 < \lvert y\rvert < 2.4$	$3 < p_T < 30$		
ψ(2S) (prompt)			$1.6 < \lvert y\rvert < 2.4$	$3 < p_T < 30$	R_{AA}, $\frac{(N_{\psi(2S)}/N_{J/\psi})_{Pb\text{–}Pb}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}}$(cent.)	[686]
			$\lvert y\rvert < 1.6$	$6.5 < p_T < 30$		
Υ(1S)			$\lvert y\rvert < 2.4$	$p_T > 0$	yield and R_{AA}(cent., p_T, y)	[482]
Υ(nS)			$\lvert y\rvert < 2.4$	$p_T > 0$	R_{AA}(cent.)	[687, 688]
					$\frac{(N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{Pb\text{–}Pb}}{(N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{pp}}$(cent.)	[268]

- Also data in p+A collisions not shown
- In the last 2 years the number of quarkonium results in A+A has also doubled. Go toward higher precision, extended reach in p_T. Much better handle on the excited states

Collisional interactions of heavy meson states in matter



Adil *et al.* (2006)

- Momentum transfers q follow Glauber gluons scaling

$$|\psi_f(\mathbf{K},\Delta\mathbf{k})|^2 = \sum_{n=0}^{\infty}\frac{2^n\chi^n}{n!}\int\prod_{i=1}^{n} d^2\mathbf{q}_i \frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2\mathbf{q}_i} \times\left[\left(e^{-\mathbf{q}_n\cdot\vec{\nabla}_{\mathbf{K}}}-\hat{1}\right)\cosh\left(-\mathbf{q}_n\cdot\vec{\nabla}_{\Delta\mathbf{k}}\right) + \left(e^{-\mathbf{q}_n\cdot\vec{\nabla}_{\Delta\mathbf{k}}}-\hat{1}\right)\right]|\psi_0(\mathbf{K},\Delta\mathbf{k})|^2 .$$

- Resum in impact parameter space, make Gaussian approximation

$$|\psi_f(\mathbf{K},\Delta\mathbf{k})|^2 = \left[\frac{e^{-\frac{\mathbf{K}^2}{4\chi\mu^2\xi}}}{4\pi\chi\mu^2\xi}\right]\left[\mathrm{Norm}^2\,\frac{x(1-x)\Lambda^2}{\chi\mu^2\xi+x(1-x)\Lambda^2} \times e^{-\frac{\Delta\mathbf{k}^2}{4(\chi\mu^2\xi+x(1-x)\Lambda^2)}}\, e^{-\frac{m_1^2(1-x)+m_2^2x}{x(1-x)\Lambda^2}}\right] .$$

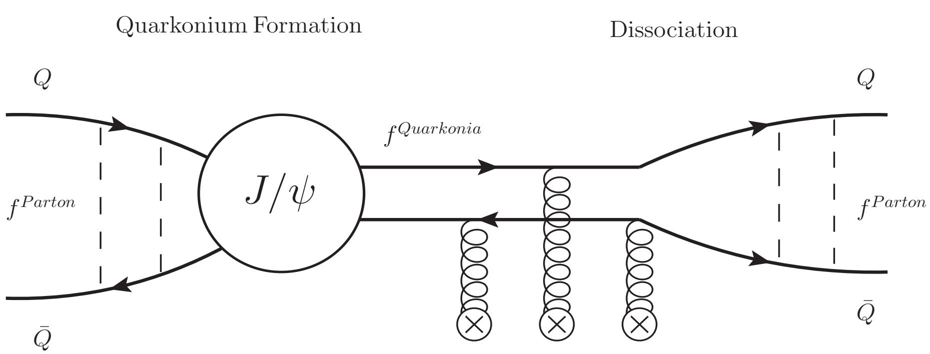
- Heavy meson acoplanarity
- Distortion of the light cone wave function (meson decay)

- Reduced transition probability

$$P_{\mathrm{surv.}}\left(\frac{\mu^2}{\lambda}L\xi\right) = \left|\int dx\,d^2\Delta k_\perp\, \psi^*_f(x,\Delta k_\perp)\psi_i(x,\Delta k_\perp)\right|^2$$

Time evolution of quarkonium states

- Competition between the energetic, heavy quark pairs ("partons") binding into quarkonia vs. dissociating into free quarks



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

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

This is the effect of the medium. Well-understood asymptotic limits

$$P_{f\leftarrow i}(\chi\mu_D^2\xi, T) = \left|\frac{1}{2(2\pi)^3}\int d^2\mathbf{k}dx\,\psi_f^*(\Delta\mathbf{k},x)\psi_i(\Delta\mathbf{k},x)\right|^2$$

$$= \left|\frac{1}{2(2\pi)^3}\int dx\,\mathrm{Norm}_f\mathrm{Norm}_i\,\pi\, e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}}\, e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}} \times \frac{2[x(1-x)\Lambda(T)^2][\chi\mu_D^2\xi + x(1-x)\Lambda_0^2]}{[x(1-x)\Lambda(T)^2]+[\chi\mu_D^2\xi + x(1-x)\Lambda_0^2]}\right|^2 .$$

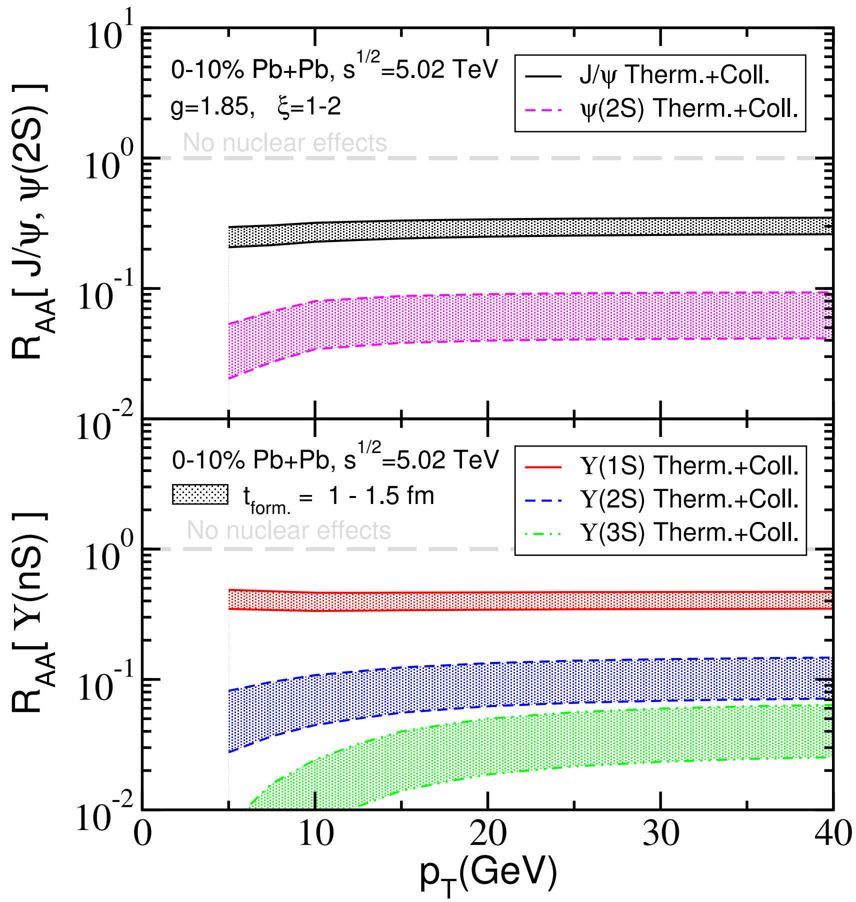
Formation time / interaction time
- take O(1 fm)

Dissociation time

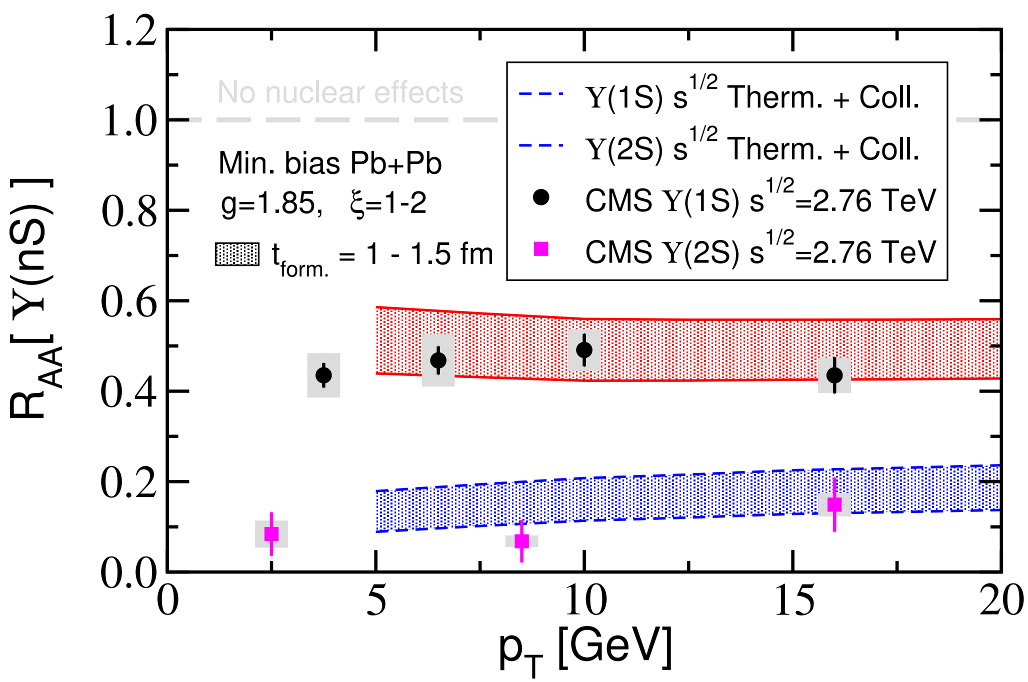
$$\frac{1}{t_{\text{diss.}}} = -\frac{1}{P_{f\leftarrow i}(\chi\mu_D^2\xi,T)}\frac{dP_{f\leftarrow i}(\chi\mu_D^2\xi,T)}{dt}$$

Phenomenological results

- We have centrality and p_T dependence at 2.76 TeV and 5.02 TeV around midrapidity
- Both ground and excited quarkonium states with consistent feed down



Approximately flat p_T dependence

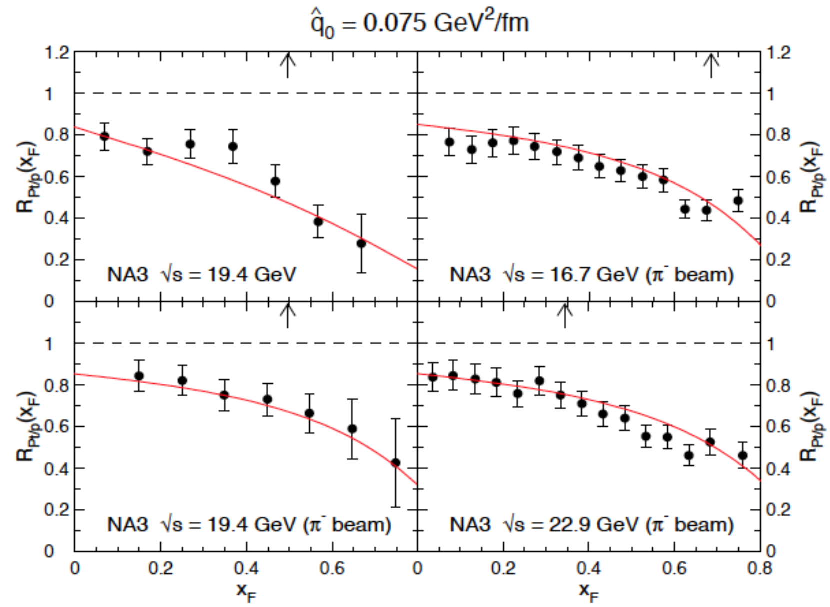


- Good separation the suppression of the ground and excited

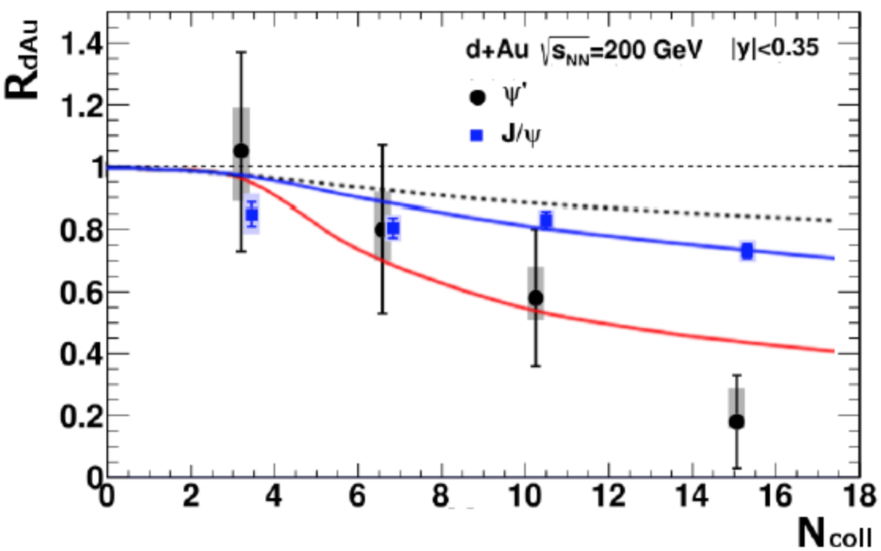
Energy loss for quarkonia in nuclei and co-mover dissociation

- Another radiative energy loss approach – Radiation off of a heavy quark. The Bertsch-Gunion spectrum is integrated from M to the cumulative broadening scale. It is suppressed by M_T at high p_T.

F. Arleo *et al.* (2012)



$$\Delta E \equiv \int_0^E \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \underset{M \gg \ell_\perp}{\simeq} N_c\, \alpha_s \frac{\ell_\perp - \Lambda}{M} E$$



- Co-mover dissociation model– phenomenological cross section to break up quarkonia in a co-moving hadron gas.

E. Ferreiro (2014)

$$\tau \frac{\mathrm{d}\rho^\psi}{\mathrm{d}\tau}(b,s,y) = -\sigma^{co-\psi}\rho^{co}(b,s,y)\,\rho^\psi(b,s,y)$$

$$S_\psi^{co}(b,s,y) = \exp\left\{-\sigma^{co-\psi}\rho^{co}(b,s,y)\ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

Determination of the LDMEs

- Perform LO NRQCD fit. Color singlet matrix elements can the related to the square of the wavefunction at the origin and its derivatives

$$\langle \mathcal{O}(c\bar{c}([^3S_1]_1) \to J/\psi)\rangle = 3\langle \mathcal{O}(c\bar{c}([^1S_0]_1) \to J/\psi)\rangle = 3N_c \frac{|R_{n=1}(0)|^2}{2\pi} = 1.2\ \mathrm{GeV}^3\ ,$$
$$\langle \mathcal{O}(c\bar{c}([^3S_1]_1) \to \psi(2S))\rangle = 3\langle \mathcal{O}(c\bar{c}([^1S_0]_1) \to \psi(2S))\rangle = 3N_c \frac{|R_{n=2}(0)|^2}{2\pi} = 0.76\ \mathrm{GeV}^3\ ,$$
$$\frac{1}{5}\langle \mathcal{O}(c\bar{c}([^3P_2]_1) \to \chi_{c2}(1P))\rangle = \frac{1}{3}\langle \mathcal{O}(c\bar{c}([^3P_1]_1) \to \chi_{c1}(1P))\rangle = \langle \mathcal{O}(c\bar{c}([^3P_0]_1) \to \chi_{c0}(1P))\rangle = 3N_c \frac{|R'_{n=1}(0)|^2}{2\pi} = 0.054 m^2_{\mathrm{charm}}\ \mathrm{GeV}^3\ ,$$

- Octet elements determined by fit to data

$$\langle \mathcal{O}(c\bar{c}([^3S_1]_8) \to J/\psi)\rangle = (0.0013 \pm 0.0013)\ \mathrm{GeV}^3\ ,$$
$$\langle \mathcal{O}(c\bar{c}([^1S_0]_8) \to J/\psi)\rangle = (0.018 \pm 0.0087)\ \mathrm{GeV}^3\ ,$$
$$= \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle/(m^2_{\mathrm{charm}})\ ,$$
$$\langle \mathcal{O}(c\bar{c}([^3S_1]_8) \to \psi(2S))\rangle = (0.0033 \pm 0.00021)\ \mathrm{GeV}^3\ ,$$
$$\langle \mathcal{O}(c\bar{c}([^1S_0]_8) \to \psi(2S))\rangle = (0.0080 \pm 0.00067)\ \mathrm{GeV}^3\ ,$$
$$= \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle/(m^2_{\mathrm{charm}})\ ,$$
$$\langle \mathcal{O}(c\bar{c}([^3P_1]_8) \to J/\psi)\rangle = 3 \times \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle\ ,$$
$$\langle \mathcal{O}(c\bar{c}([^3P_2]_8) \to J/\psi)\rangle = 5 \times \langle \mathcal{O}(c\bar{c}([^3P_0]_8) \to J/\psi)\rangle\ ,$$
$$\langle \mathcal{O}(c\bar{c}([^3S_1]_8) \to \chi_{c0}(1P))\rangle = (0.00187 \pm 0.00025)\ \mathrm{GeV}^3\ ,$$

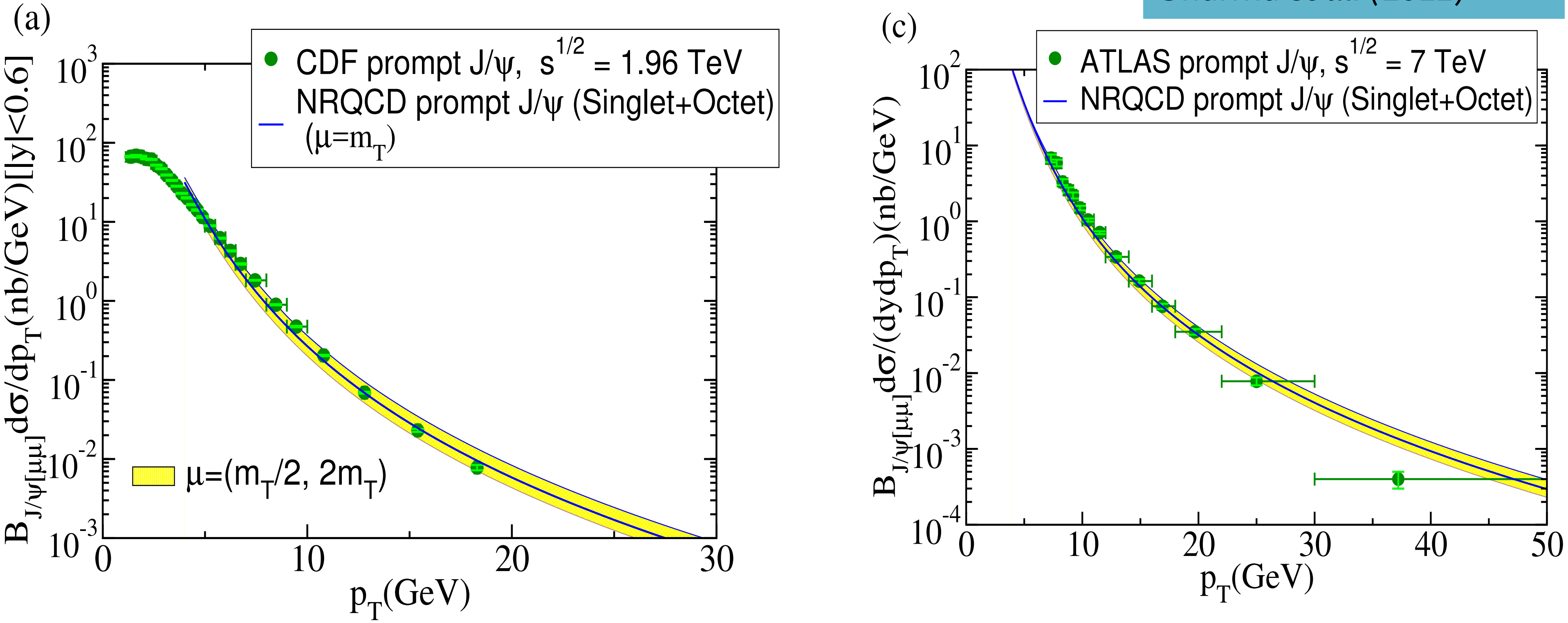
- Approximate scaling with velocity and mass
- Note that excited states such as χ have different expansion and different LDMEs

Sharma *et al.* (2012)

Example of charmonium production

• Limit of applicability p_T > 3-5 GeV. Same is true for other fixed order calculations, e.g. NLO

Sharma *et al.* (2012)



• Note, NLO fits exist mostly quarkonia by several groups, also include photoproduction. Tensions still remain with quarkonium polarization

Butenchoen *et al.* (2012)