Unraveling Gluon Jet Quenching through J/ψ Production in Heavy-Ion Collisions

Shan-Liang Zhang

Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter,
South China Normal University

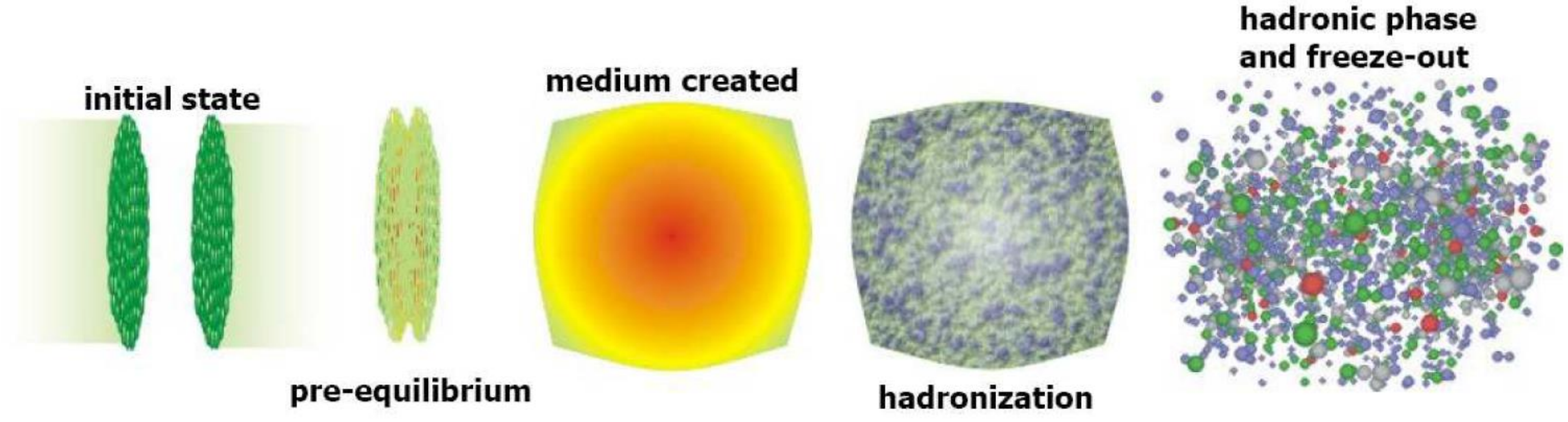
In collaboration with Jinfeng Liao, Guang-You Qin,Enke Wang, and Hongxi Xing

09 July. 2022

Outline

- Introduction
- Framework
- Numerical results
- Summary

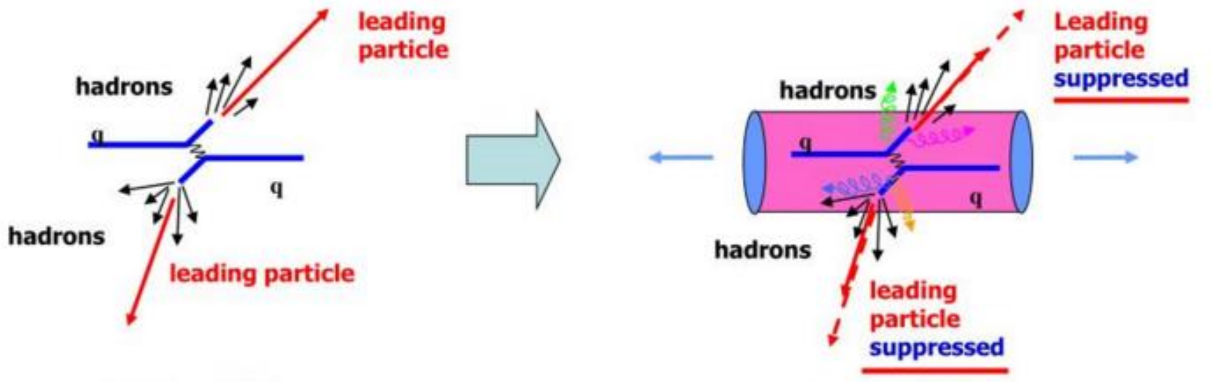
Introduction



1-10fm/c

The Signatures of QGP:

- Global observables
- Strange enhancements
- Photon and dilepton measurements
- Early thermalization and flow
- Fluctuations and correlations
- The J/ψ-meson
- Jet quenching



Jet quenching

X. N.Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).

- Nuclear modification factor

$$R_{AA} = \frac{\sigma_{NN}}{\langle N_{bin} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

  -hadron: fundamental transport properties of QGP $\hat{q}$

  -jet: jet energy lose distributions.

  K. M. Burke et al. (JET), Phys. Rev. C 90, 014909(2014)

  D. Everett et al. (JETSCAPE), Phys. Rev. Lett. 126,242301 (2021)

  Y. He, L.G. Pang, and X.N. Wang, Phys. Rev. Lett. 122, 252302 (2019),

- Jet substructures

  -Put insight into jet-medium interactions and properties of QGP;

  ATLAS,Phys. Rev. Lett. 123, 042001(2019)

  CMS, Phys.Lett.B 825 (2022) 136842

- Separate identification of quark and gluon jet quenching(color-charge)

  -multivariate analysis of jet substructure observables

  -averaged jet charge

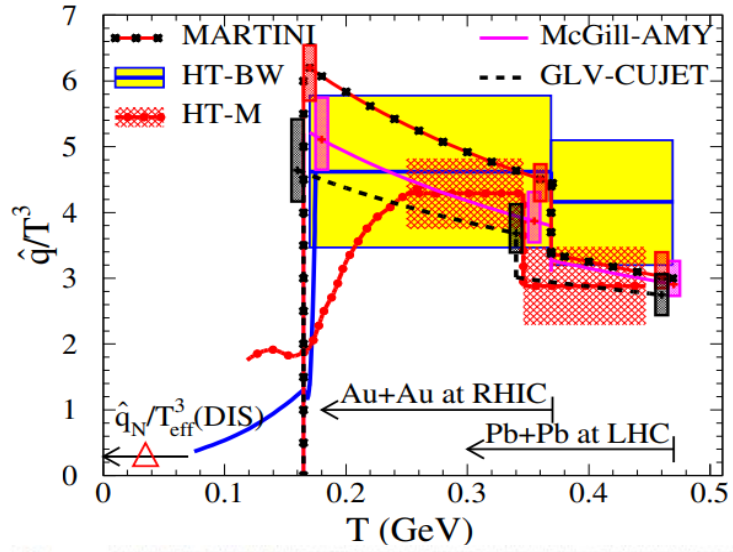
  -Z/γ-tagged jet/hadron….

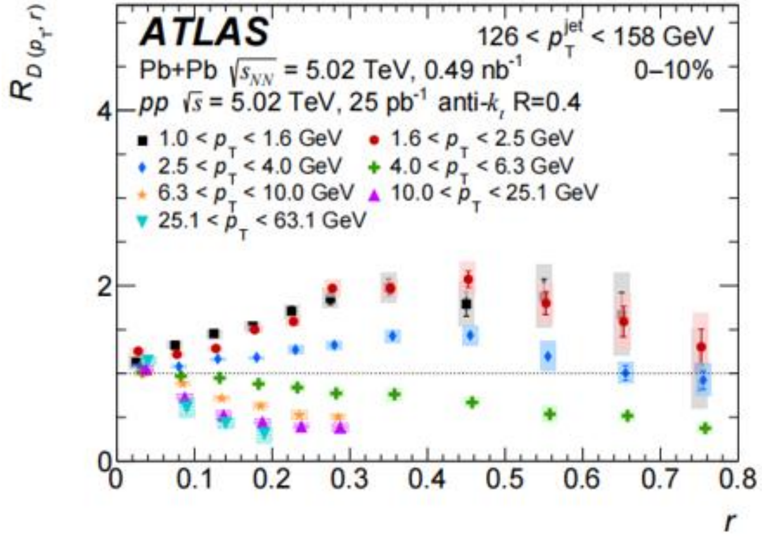
  Y.T. Chien and R. Kunnawalkam Elayavalli, arXiv:1803.03589;

  S.Y. Chen, B.W. Zhang, and E.K. Wang, Chin. Phys.C 44,024103 (2020),

  S.L. Zhang, T. Luo, X.N. Wang, and B.W. Zhang, Phys. Rev. C 98, 021901 (2018),

Phys. Rev. C 90, 014909

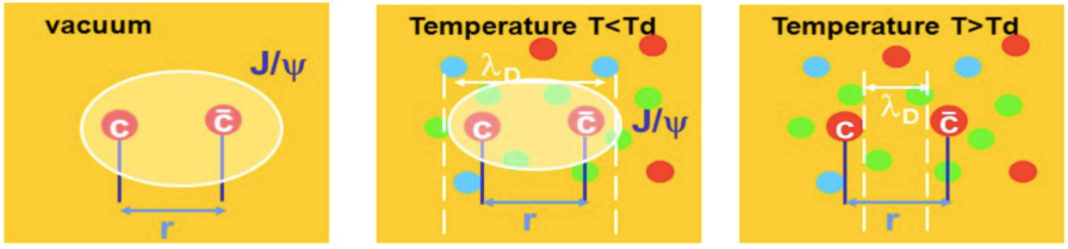




What and why Quarkonium?

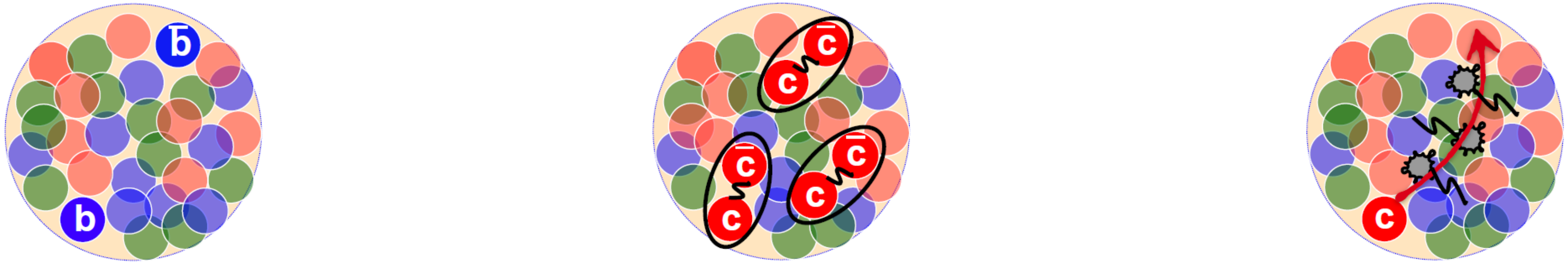
- **Early creation:** experience entire evolution of quark-gluon plasma
- **Proposed signature of deconfinement**: quark-antiquark potential color-screened by surrounding partons → *dissociation*
  - **J/ψ suppression was proposed as a direct proof of QGP formation**

T. Matsui and H. Satz
PLB 178 (1986) 416



$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

QGP | QGP @ high energy density | QGP



Suppression
Medium-induced dissociation

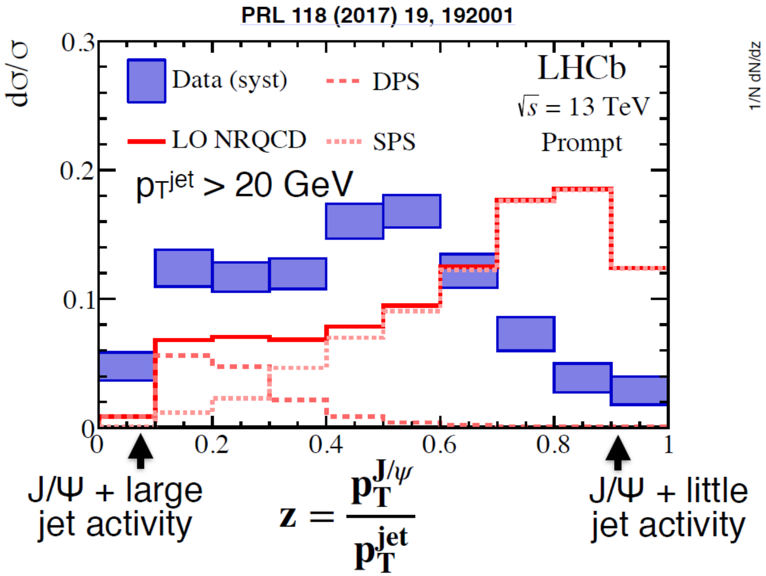
+Enhancement
Regeneration

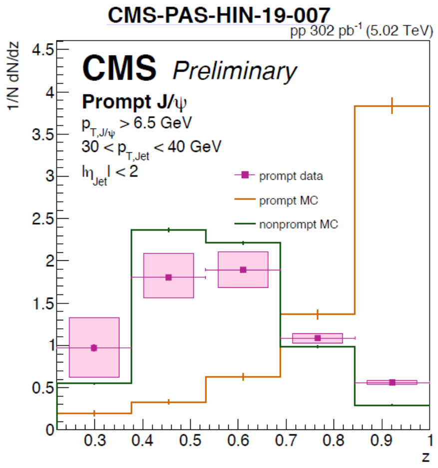
+Parton energy loss
at high p_T

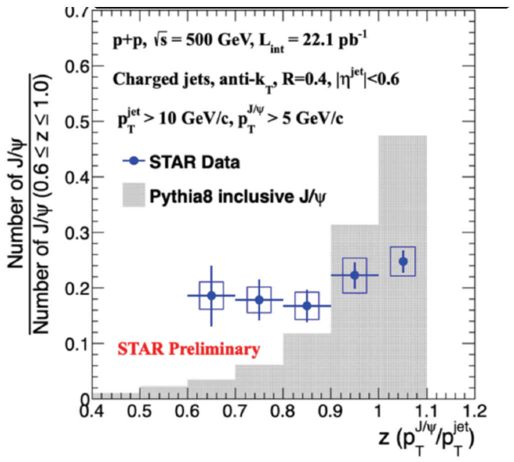
Quarkonia are good probes of the medium evolution

J/ψ in jets in pp

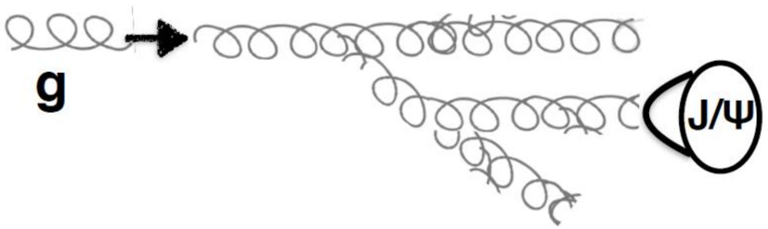
- Parton-parton scattering not enough to describe J/ψ production.

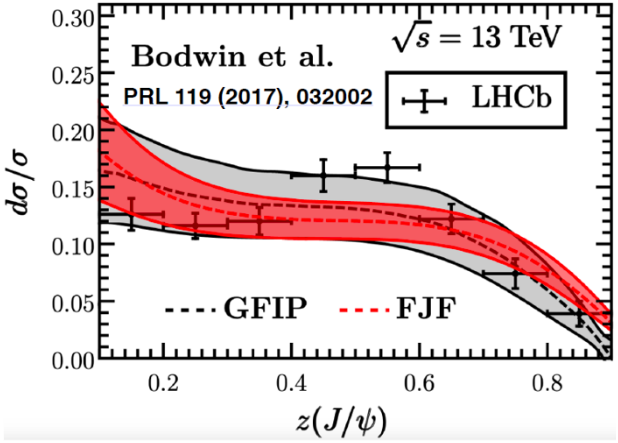


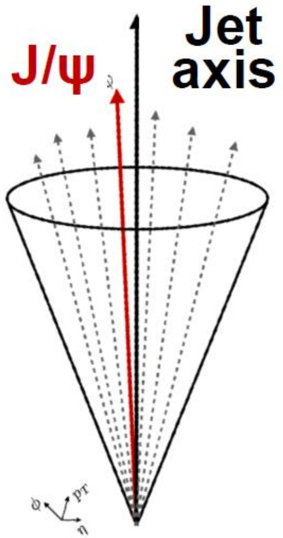




- Model including J/ψ produced in parton showers well successfully describe LHCb data. **PRL 119, 032002 (2017)**







How do we study quarkonia?

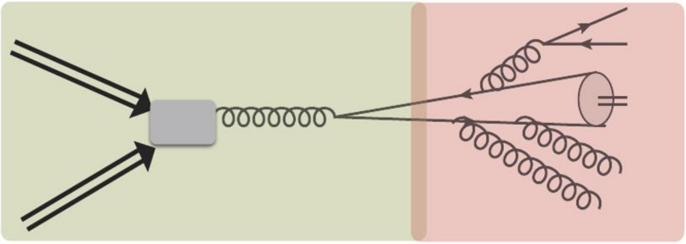
Leading Power factorization – fragmentation dominates ~ $1/p_T^4$

NRQCD Factorization + **Leading Power Factorization**

$$d\sigma^{J/\psi} = \sum_i d\sigma^i \otimes D_{i\to J/\psi}(z)$$

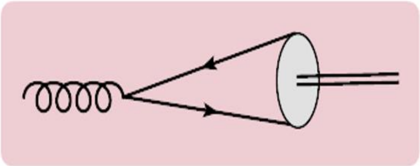
$$D_{i\to J/\psi}(z) = \sum_n \langle \mathcal{O}^{J/\psi}(n)\rangle d_{i\to c\bar{c}(n)}$$

Perturbative regime (SDCs) x Non-perturbative effects (LDMEs)

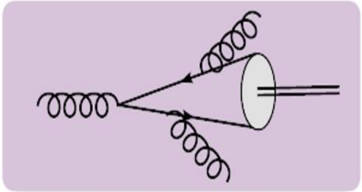


Fragmentation Mechanisms Dominate at high p_T

$^3S_1^{(8)}(g) \sim \alpha_s v^7$

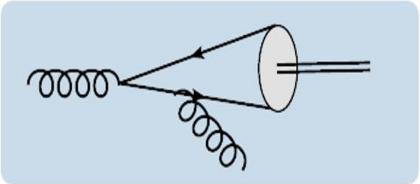


$^3S_1^{(1)}(g) \sim \alpha_s^3 v^3$

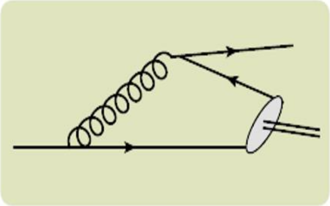


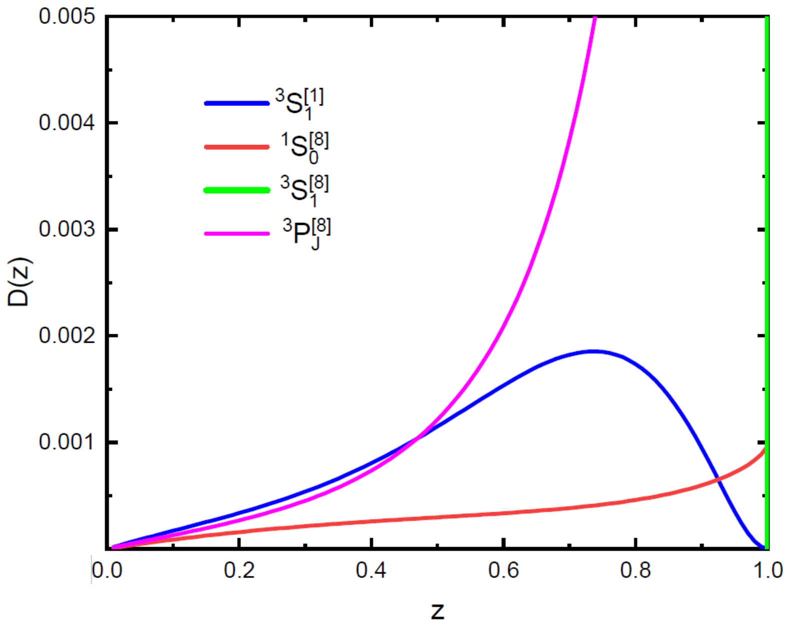
$^3P_J^{(8)}(g) \sim \alpha_s^2 v^7$

$^1S_0^{(8)}(g) \sim \alpha_s^2 v^7$



$^3S_1^{(1)}(c) \sim \alpha_s^2 v^3$

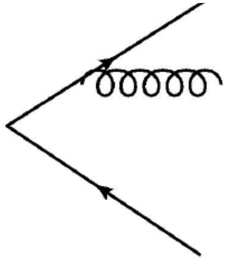




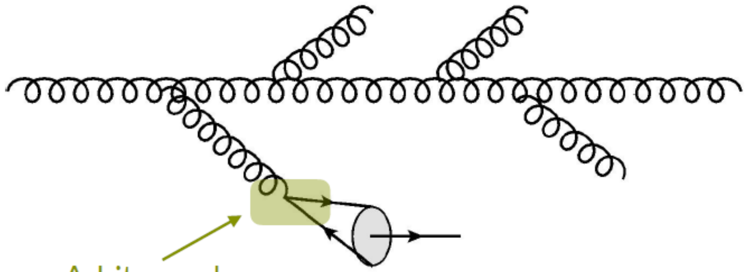
How do we study Quarkonium?

Gluon Fragmentation Improved PYTHIA (GFIP)

pp→ $g/c + X$



PYTHIA + Convolution



2. PYTHIA ⟶ No hadronization, adjust shower pT cutoff

3. Convolve NRQCD FFs w/ random final state gluon

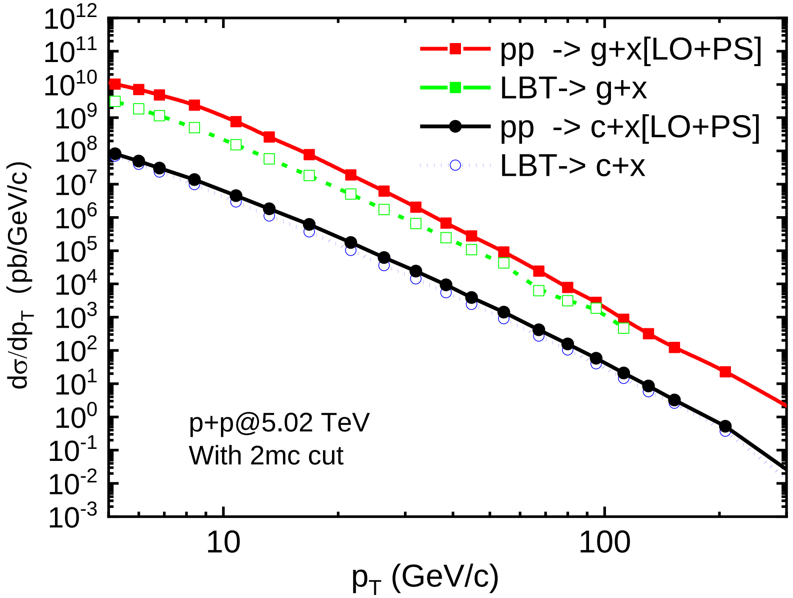
Bain et. al., arXiv:1603.06981

PRL 119, 032002 (2017)

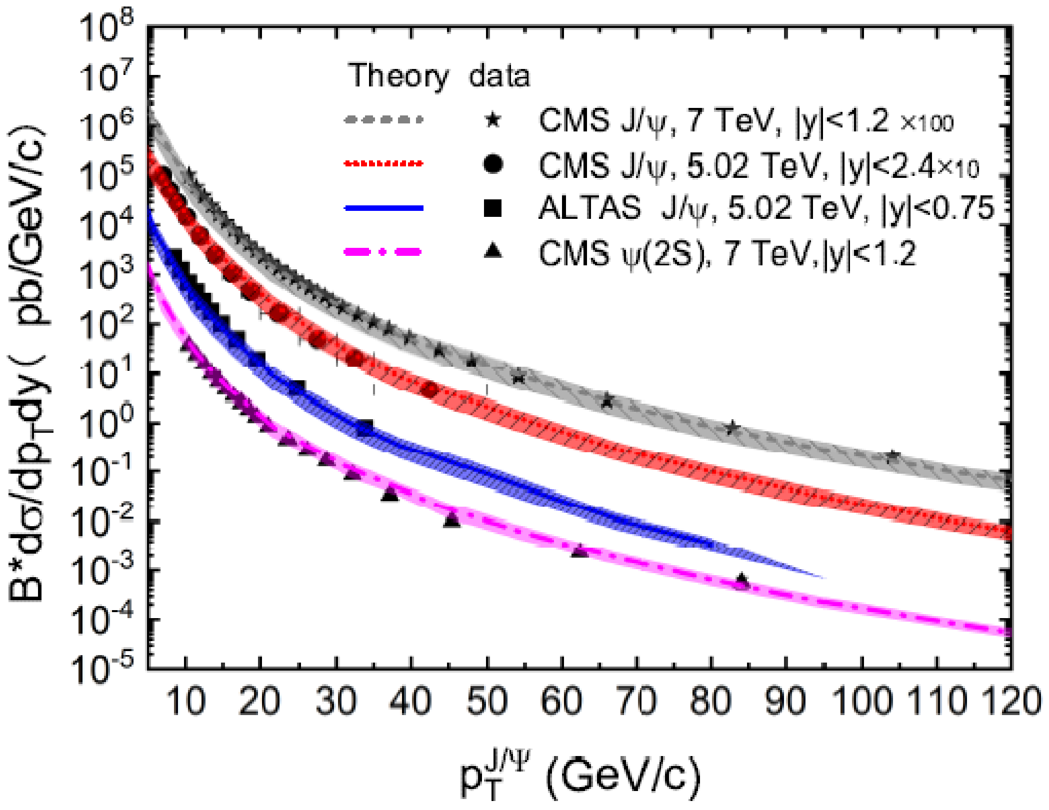
Bodwin PhysRevLett.113.022001; PhysRevD.93.034041

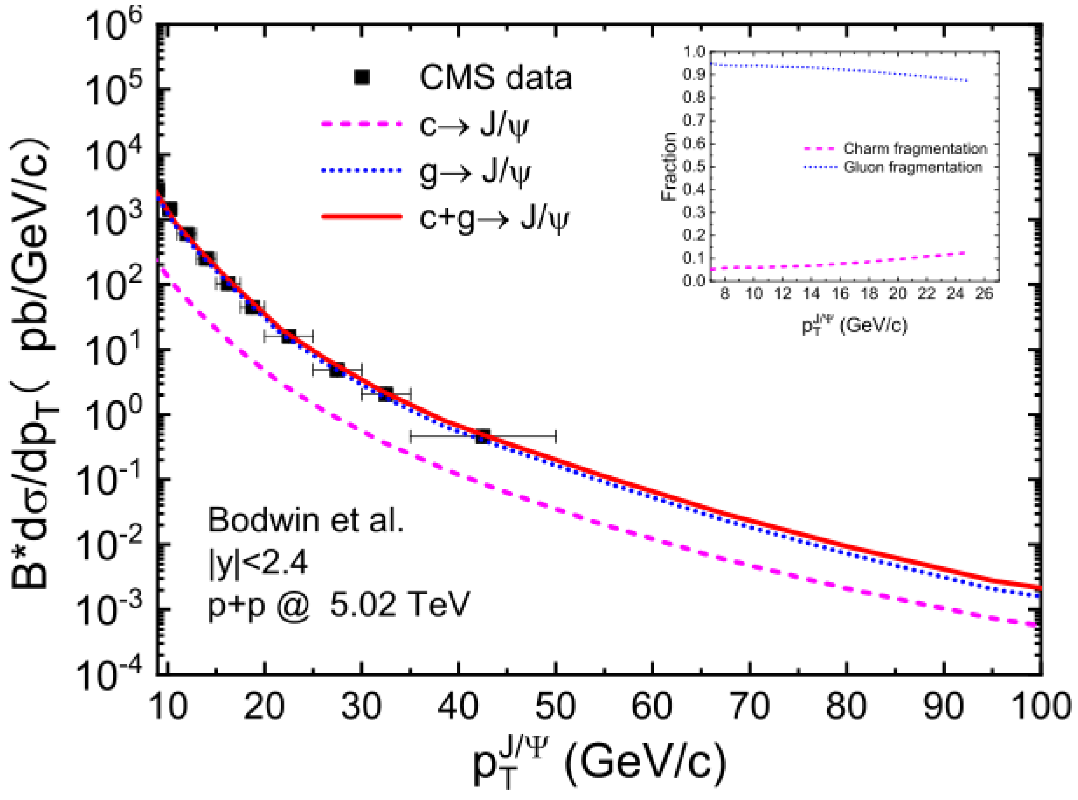
	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_J^{[8]})\rangle$ 10^{-2} GeV^5
J/ψ	1.32± 0.2	9.9±2.2	1.1±1.0	1.1±1.0
$\psi(2S)$	0.76± 0.2	3.14± 0.79	-0.157± 0.28	-0.2565±0.27225

$$\frac{d\sigma^{J/\Psi}}{dp_T^{J/\Psi}} = \sum_i \int \frac{d\sigma^i}{dp_T^i}\left(\frac{p_T^{J/\Psi}}{z}\right) \times D_{i\to c\bar{c}(n)}(z)\frac{dz}{z} * \langle O(n)\rangle$$



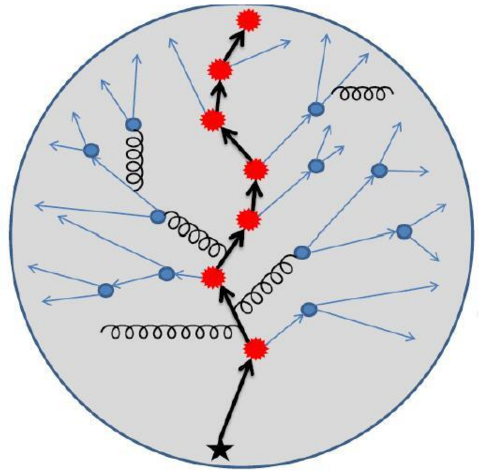
J/ψ p_T distributions in pp:





- Gluon fragmentation dominates (> 70%) the high-p_T J/ψ production.

Linear Boltzmann Transport (LBT) model


Medium Excitation

Linear Boltzmann jet Transport

- Elastic collision + Induced gluon radiation.
- Follow the propagation of recoiled parton.
- Back reaction of the Boltzmann transport.

H. Li, F. L, G. l. Ma, X. N. W and Y. Z, PhysRevLett.106.012301; X. N. Wang and Y. Zhu, PhysRevLett.111.062301; Y. He, T. Luo, X. N. Wang and Y. Zhu, PhysRevC.91.054908.

$$p_1 \cdot \partial f_a(p_1) = -\int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times \frac{1}{2} \sum_{b(c,d)} [f_a(p_1) f_b(p_2) - f_c(p_3) f_d(p_4)] |M_{ab\to cd}|^2 \times S_2(s,t,u)(2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4)$$

Elastic Scattering--Complete set of 2-2 scattering processes.

Radiation--Higher Twist: Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004).

$$\frac{dN_g}{dx dk_\perp^2\, dt} = \frac{2\alpha_s C_A P(x) k_\perp^4}{\pi (k_\perp^2 + x^2 M^2)^4} \hat{q} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

LBT: light/heavy flavor hadron, single inclusive jets, γ-hadron/jet.

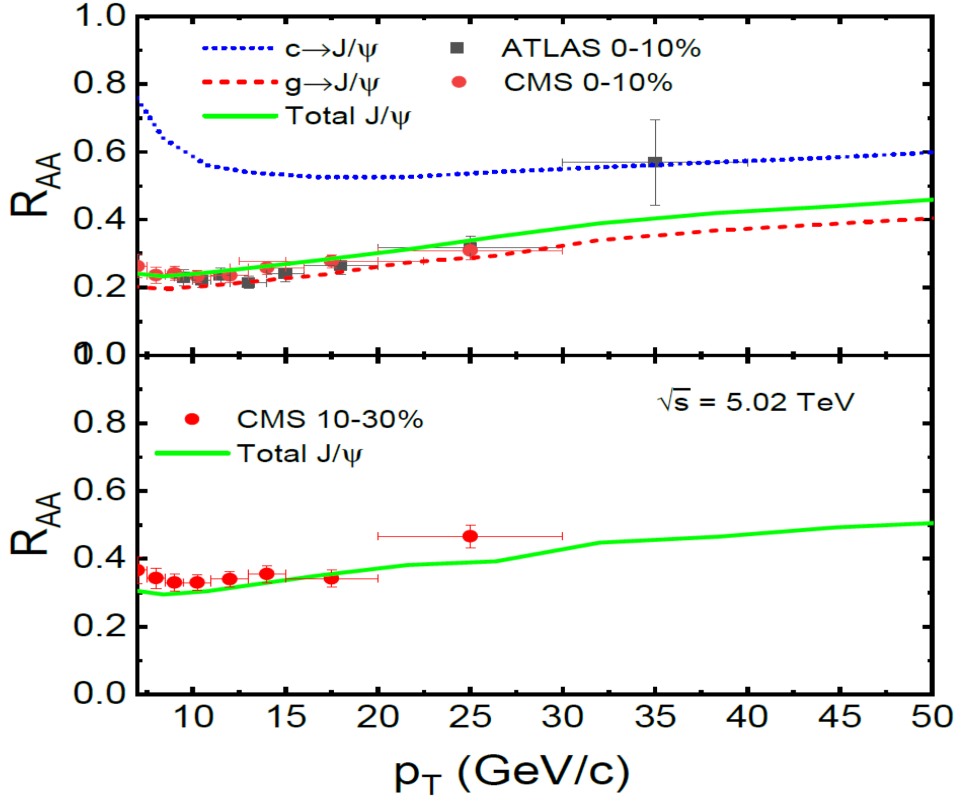
T. Luo, S. Cao, Y. He and X. N. Wang, arXiv:1803.06785;
W. Chen, S. Cao, T. Luo, L. G. Pang and X. N. Wang, Phys. Lett. B 777, 86 (2018);
S. Cao, T. Luo, G. Y. Qin and X. N. Wang, Phys. Rev. C 94, no. 1, 014909 (2016).

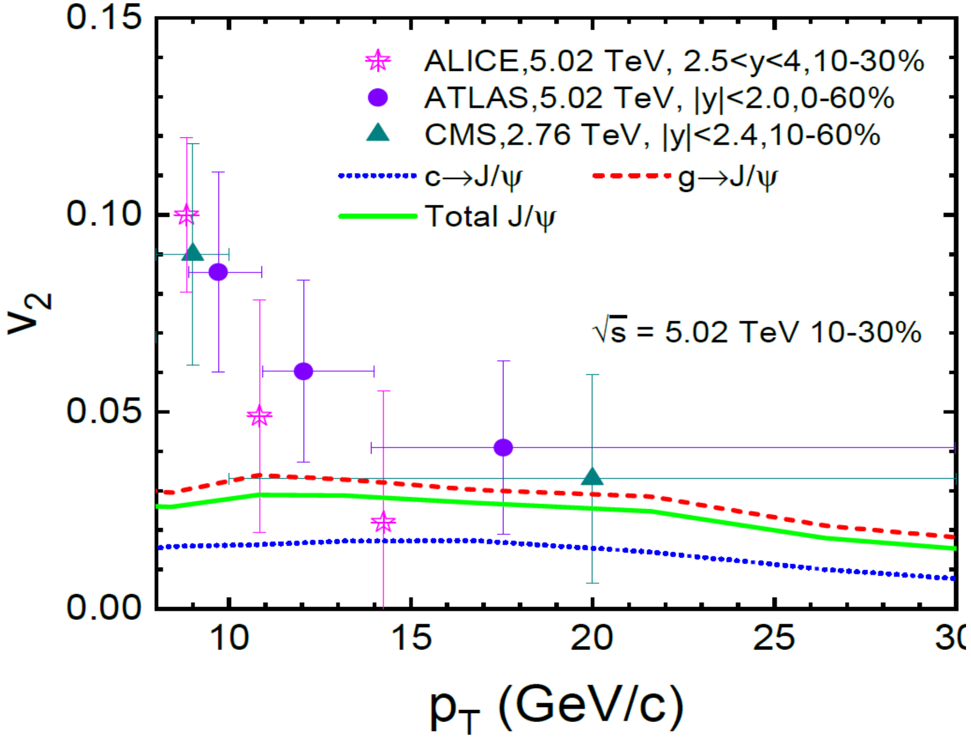
Large p_T J/ψ suppression in Pb+Pb:

$$v_2(p_T) \equiv \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

$$\frac{d\sigma^{AA}}{dp_T} = \sum_i \int \frac{d\Delta p_T^i}{\langle \Delta p_T^i \rangle} \frac{d\sigma^{pp}(p_T + \Delta p_T^i)}{dp_T} W^i(x) \otimes D_{i\to J/\psi}$$

$$v_2(p_T^{J/\psi}) = \sum_i \frac{1}{\sigma_i^{J/\psi}(p_T^{J/\psi})} \int \frac{d\sigma^i}{dp_T^i}\left(\frac{p_T^{J/\psi}}{z}\right) v_2^i\left(\frac{p_T^{J/\psi}}{z}\right) \times D_{i\to c\bar{c}(n)}(z) \frac{dz}{z} * \langle O(n) \rangle \quad (8)$$





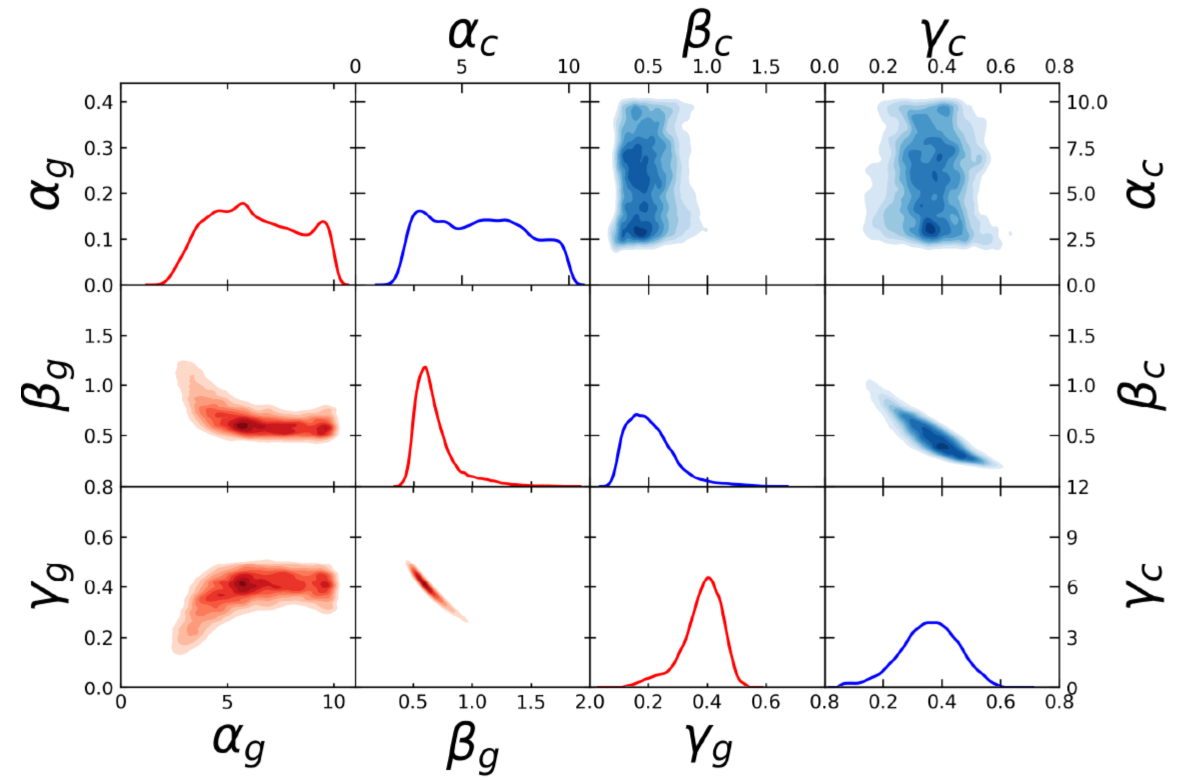
- Gluon energy loss dominate suppression of large p_T J/ψ suppression and elliptic flow v_2.

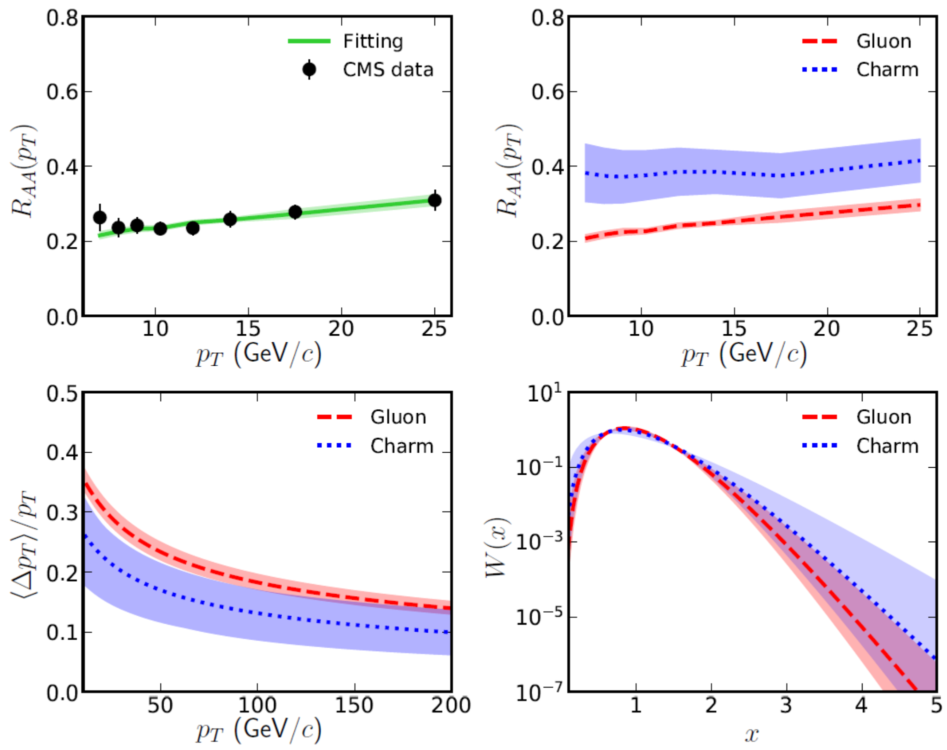
Gluon and Charm quark energy loss in Pb+Pb:

$$\frac{d\sigma^{AA}}{dp_T} = \sum_i \int \frac{d\Delta p_T^i}{\langle \Delta p_T^i \rangle} \frac{d\sigma^{pp}(p_T + \Delta p_T^i)}{dp_T} W^i(x) \otimes D_{i\to J/\psi}$$

$$W^i(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)} \quad \begin{cases} x = \Delta p_T^i / \langle \Delta p_T^i \rangle \\ \langle \Delta p_T^i \rangle = \beta_i p_T^{\gamma_i} \log(p_T) \end{cases}$$

(0 – 10%)5.02 TeV			
	α	β	γ
Gluon	6.46±1.51	0.62±0.06	0.40±0.03
Charm	5.77±2.24	0.47±0.16	0.38±0.08





Summary

- Based on the leading power NRQCD and the LBT model, we find that high p_T J/ψ production in AA collisions can be served as a robust probe to the gluon jet quenching.
  -The gluon fragmentation dominates (> 70%) the high-pT J/ψ production.
  -high-p_T J/ψ R_{AA} and v_2 are mainly driven by the gluon energy loss effect.

- We have quantitatively extracted the fraction of average energy loss $\langle \Delta p_T \rangle / p_T$ and the energy loss distributions W(x) for the gluons in QGP.

J/ψ in jets in PbPb