J/Psi at high pT in AA collisions

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

Based on arXiv:2208.08323
In collaboration with:
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Unraveling Gluon Jet Quenching through J/ψ Production in Heavy-Ion Collisions

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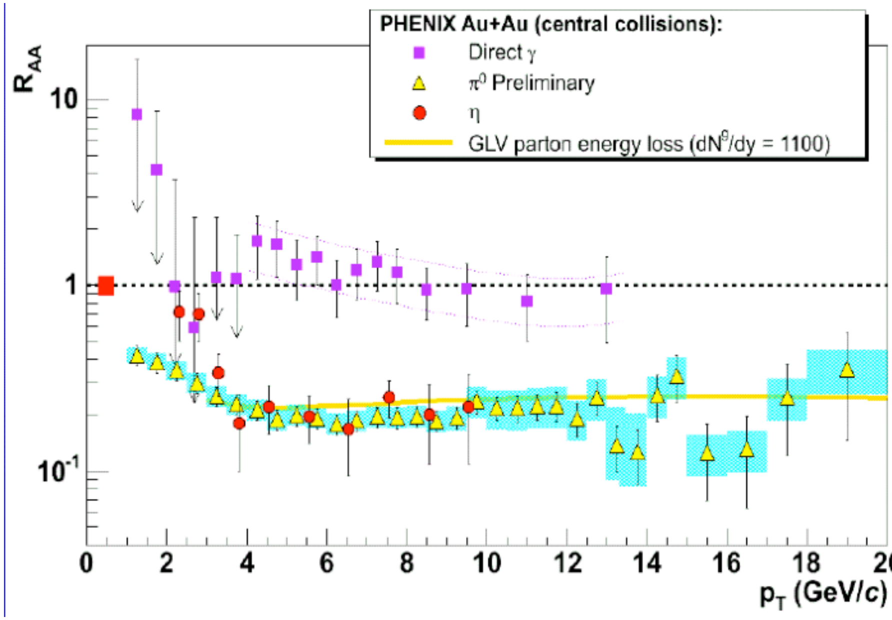
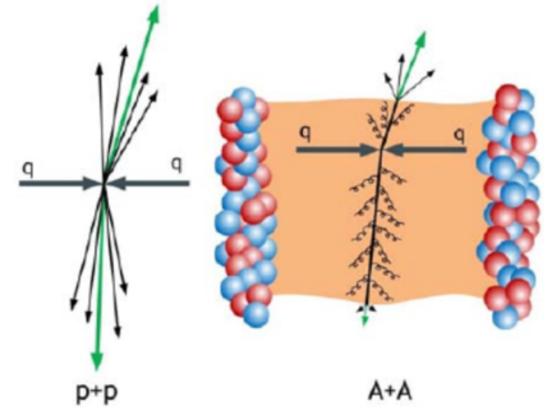
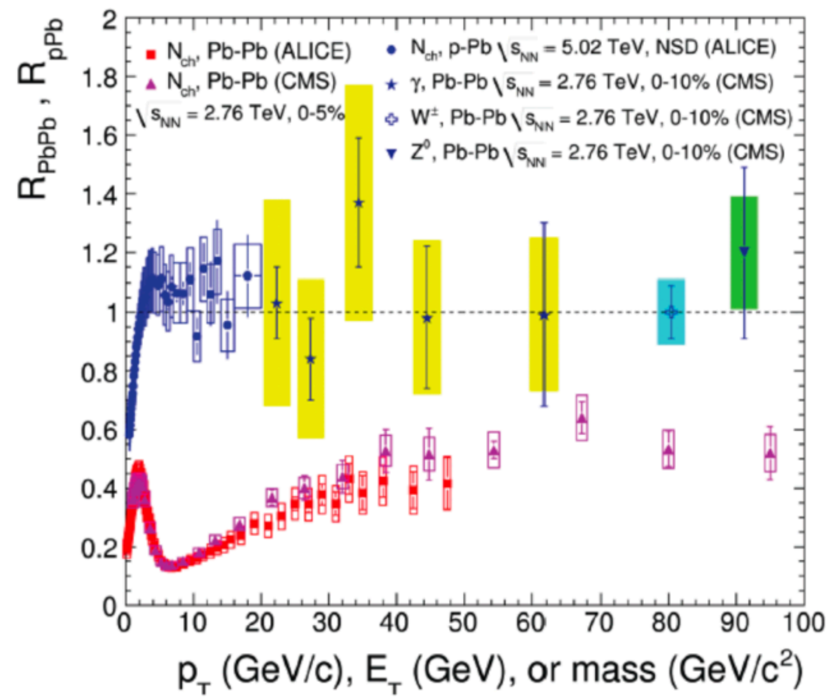
(Dated: August 18, 2022)

Jet quenching has long been regarded as one of the key signatures for the formation of quark-gluon plasma in heavy-ion collisions. Despite significant efforts, the separate identification of quark and gluon jet quenching has remained as a challenge. Here we show that J/ψ in high transverse momentum (p_T) region provides a uniquely sensitive probe of in-medium gluon energy loss since its production at high p_T is particularly dominated by gluon fragmentation. Such gluon-dominance is first demonstrated for the baseline of proton-proton collisions within the framework of leading power NRQCD factorization formalism. We then use the linear Boltzmann transport model combined with hydrodynamics for the simulation of jet-medium interaction in nucleus-nucleus collisions. The satisfactory description of experimental data on both nuclear modification factor R_{AA} and elliptic flow v_2 reveals, for the first time, that the gluon jet quenching is the driving force for high p_T J/ψ suppression. This novel finding is further confirmed, in a robust and model-independent way, by the data-driven Bayesian analyses of relevant experimental measurements, from which we also obtain the first quantitative extraction of the gluon energy loss distribution in the quark-gluon plasma.

A Colorful Plasma



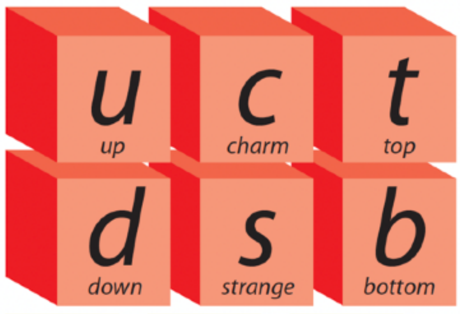


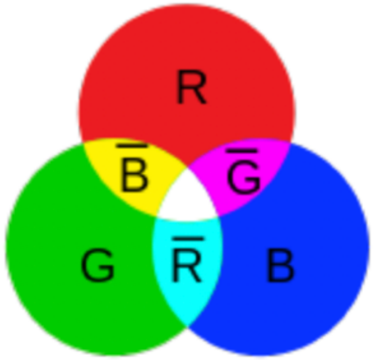


Formation of a colorful plasma that quenches only the hard probes with color charges

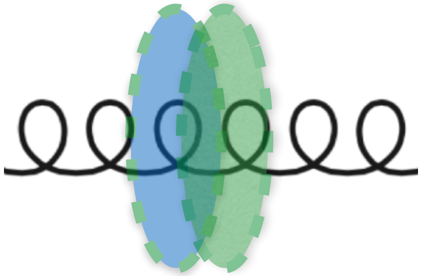
The Colorful Probes

Quarks





Gluons



SU(3) fundamental rep.

SU(3) adjoint rep.

Jet-medium interactions are controlled by color charges of the probe.

It would be a wonderful test of such basic QCD feature if one can cleanly separate in-medium energy loss of different parton types.

It is very difficult: most final high pT hadrons have mixed contributions.

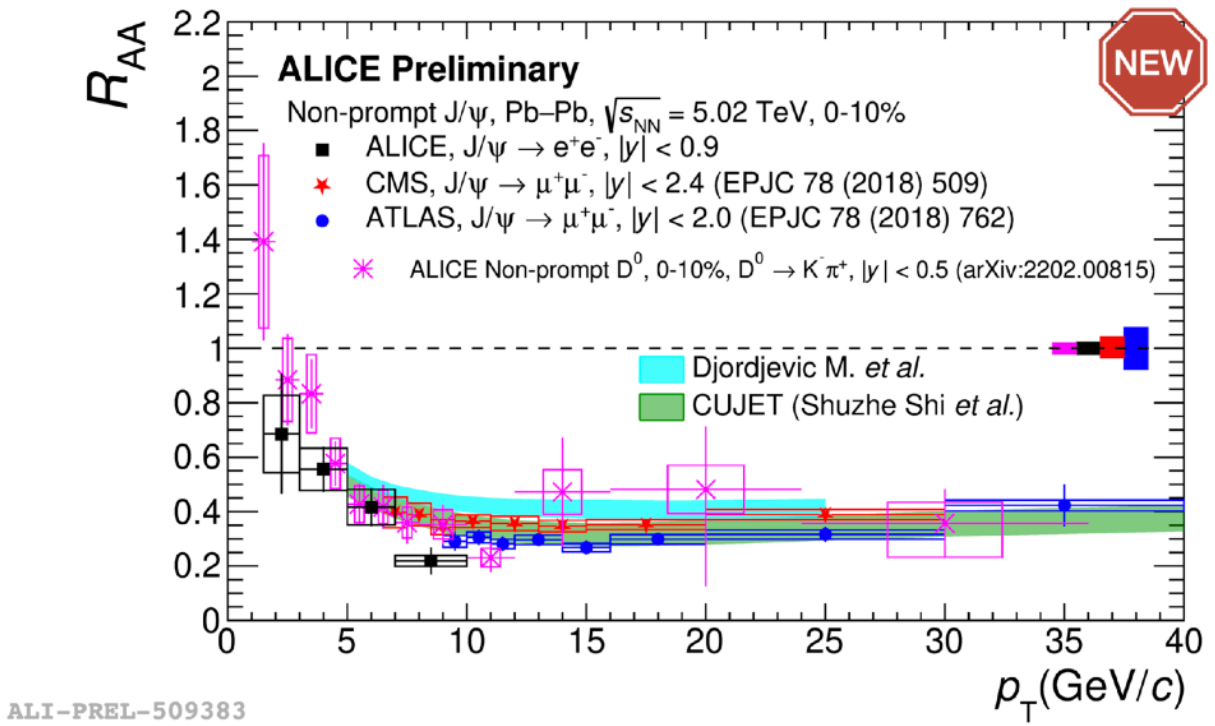
The high pT (prompt) J/Psi provides unique access to the gluon energy loss in the quark-gluon plasma.

Non-Prompt J/Psi

To be clear: there are non-prompt J/Psi at high pT which are of their own interests (e.g. access to B).

As an example:

From: ALICE@QM2022



CUJET3:
Shi, JL, Gyulassy, arXiv:1808.05461;1804.01915.
Xu, JL, Gyulassy, arXiv:1508.00552;1411.3673

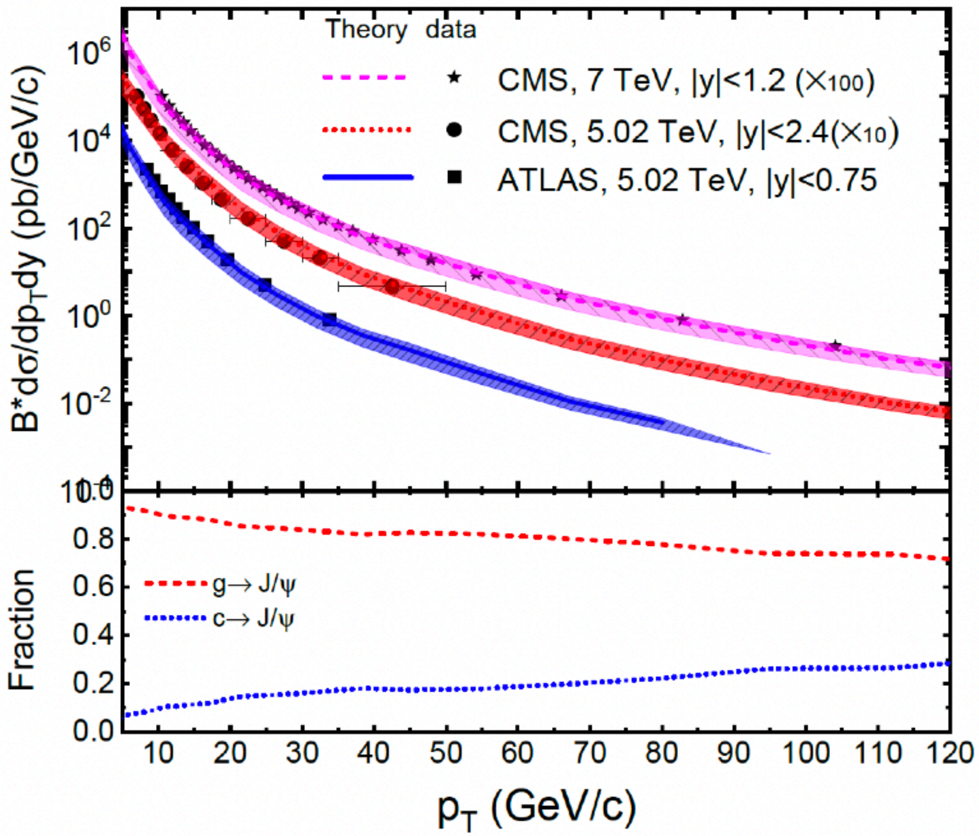
Baseline Production (pp Collisions)

$$d\sigma[AB \to J/\psi + X] = \sum d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi}$$

$$D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

GFIP event generator
MadGraph for hard parton creation
PYTHIA8 for parton shower
LDME

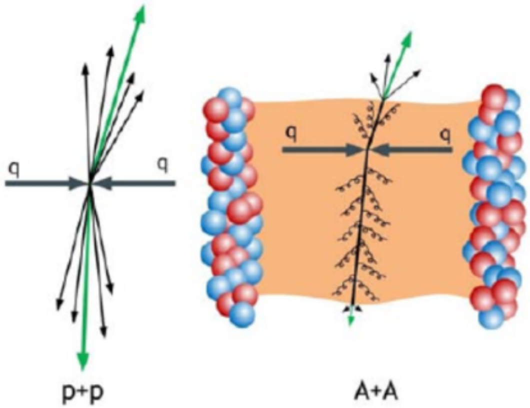
arXiv:1603.0698; 1405.0301; 1403.3612; 1311.7078; 1208.5301



[arXiv:2208.08323]

Dominant contributions from gluon fragmentation.

Raa in AA Collisions



Many frameworks exist.

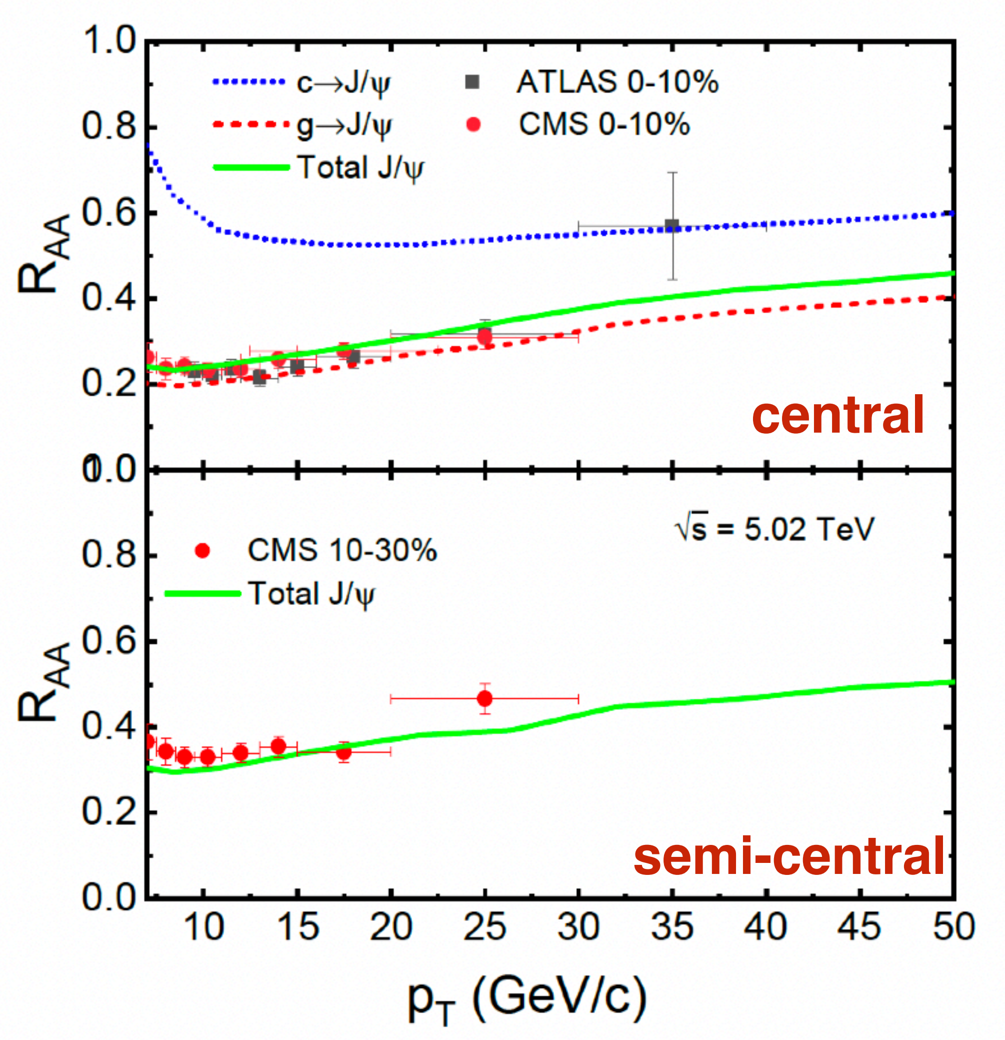
In this work we use the LBT (Linear Boltzmann Transport), a well-tested framework.

arXiv:1302.5874;1503.03313; 1605.06447;1703.00822

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

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

Raa at High pT in AA Collisions



The over J/Psi suppression at high pT is dominantly driven by the gluon energy loss.

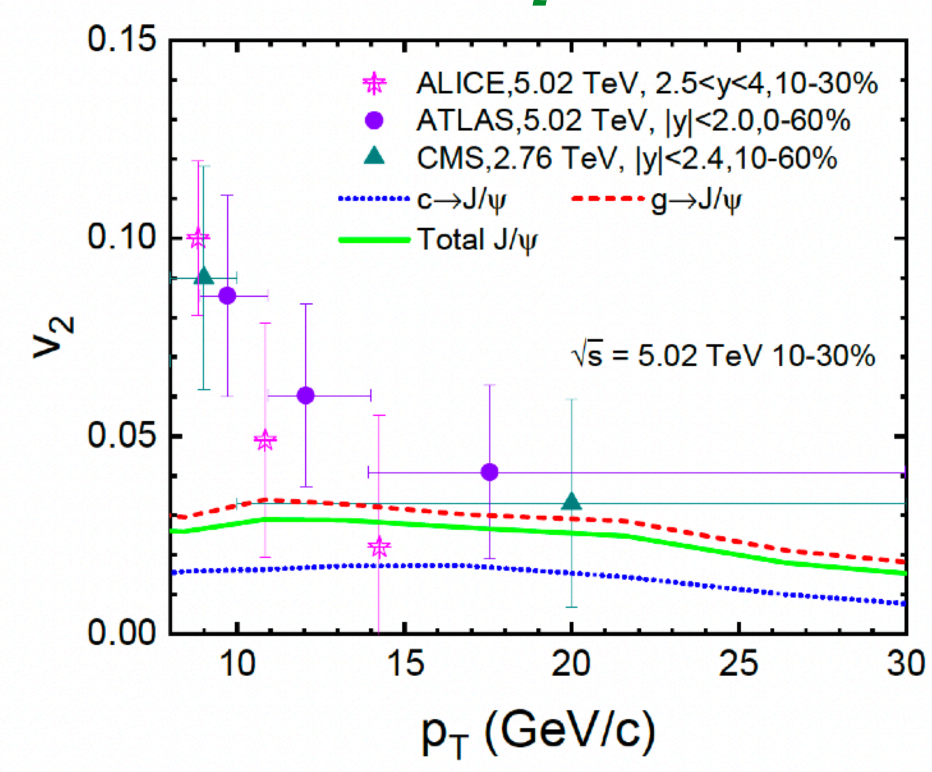
— gluon dominance in J/Psi production already shown in pp collisions

— stronger in-medium energy loss of gluons due to color factors

[arXiv:2208.08323]

Anisotropy v2 at High pT

[arXiv:2208.08323]



Reasonable agreement with data

[Note however: high pT v2 is a known persistent challenge, the solution of which may require non-perturbative medium q-hat, see e.g. CUJET3 line of work]

An Independent Bayesian Validation

Bayesian extraction of parton energy loss distributions *arXiv:1808.05310*

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

$$\langle \Delta p_T^i \rangle = \beta_i p_T^{\gamma_i} \log(p_T)$$

$$W^i(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)}$$

Energy loss distribution

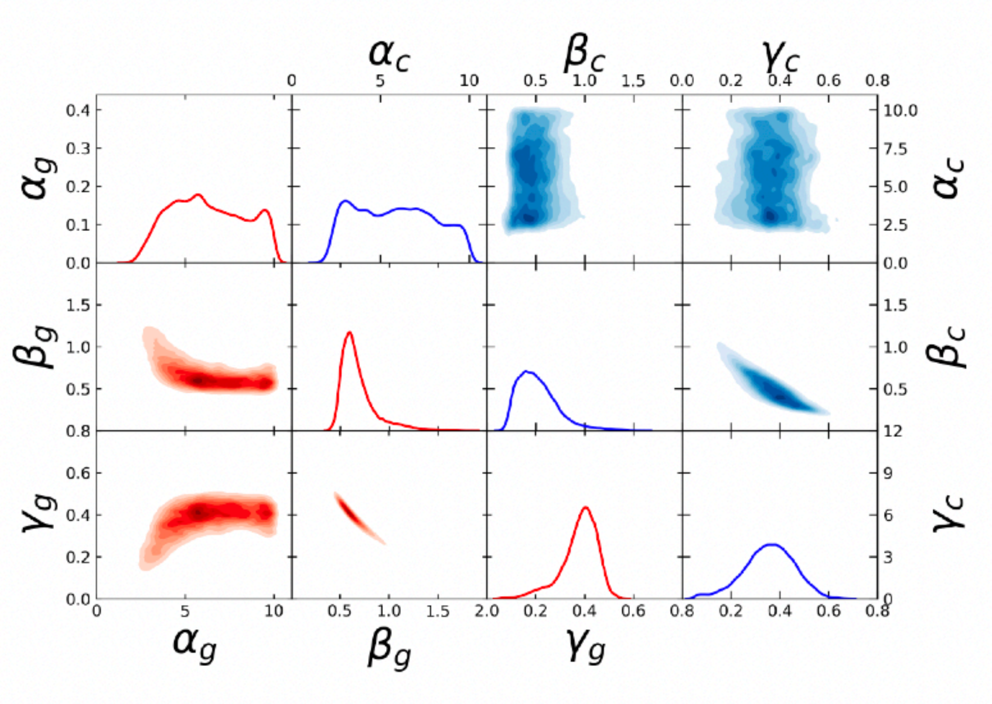
Three parameters in the above for each parton type: $[\alpha_i, \beta_i, \gamma_i]$

Bayesian analysis with exp. data (central J/Psi Raa at 5.02 TeV)

Flat prior distributions for $[\alpha_i, \beta_i, \gamma_i] \in [(0, 10), (0, 8), (0, 0.8)]$

10^6 MCMC steps for equilibration, then 10^6 steps for scanning around the parameter space

An Independent Bayesian Validation



One can see clearly a stronger sensitivity/ constraint for the gluon energy loss parameters

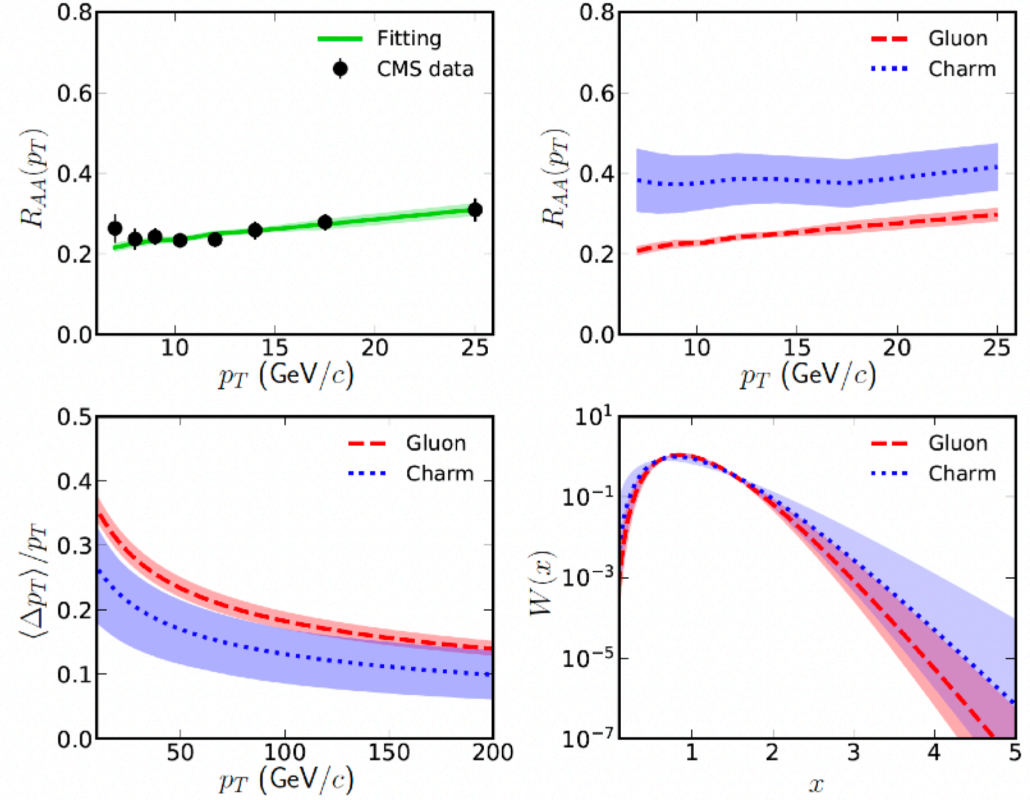
Extracted parameters for parton energy loss distributions

(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

[arXiv:2208.08323]

An Independent Bayesian Validation

The Bayesian optimized results agree perfectly with data, and again confirms the dominance of gluon energy loss in the high pT J/Psi suppression.



[arXiv:2208.08323]

In turn, this offers the unique opportunity for an accurate extraction of gluon in-medium energy loss distributions!

Conclusion

— High pT J/Psi production in pp collisions can be well described and is demonstrated to be dominated by gluon contributions

— High pT J/Psi suppression in AA collisions can also be well described and is shown to be mainly driven by the gluon in-medium energy loss

— An independent Bayesian analysis confirms the sensitivity of J/Psi Raa to gluons and allows a quantitative extraction of gluon energy loss distributions

— This finding offers a unique opportunity for testing the color dependence of hard probes with future high precision data and scaled-up numerical extractions of both gluon and quark in-medium energy loss.