HP2024
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# $J/\psi$ production within jets in high-energy proton-proton and nucleus-nucleus collisions

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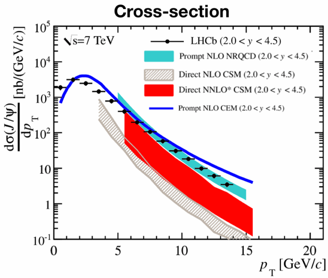
Shan-Liang Zhang, H. Xing,arXiv:2403.12704

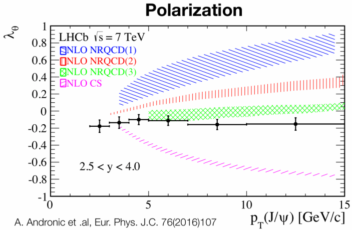
# Outline

1. Introduction
2. $J/\psi$ Production in pp Collisions
   - LP NRQCD for $J/\psi$ Production
   - Phenomenology at RHIC and the LHC energies
3. $J/\psi$ prouction in AA Collisions
   - The Linear Boltzmann transport model (LBT)
   - Nuclear modification on $J/\psi$ distributions
4. Summary

# $J/\psi$ in pp Collisions

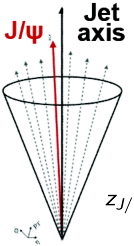
- $J/\psi$: bound states of $c\bar{c}$ pairs.
- Production mechanism merges:
  - Fixed-order perturbative QCD: quark-antiquark pairs
  - Non-perturbative long-distance matrix elements (LDME) for hadronization.
- Different models differ in the treatment of the hadronization.
- No consistent descriptions of cross section and polarization.




A. Andronic et .al, Eur. Phys. J.C. 76(2016)107
LHCb, Eur. Phys. J. C 73(2013)2631
LHCb, Eur. Phys. J. C 71(2011)1654

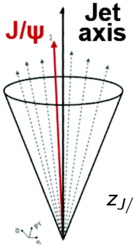
# $J/\psi$ Production in Jets in pp




$$z_{J/\psi} = \frac{p_T^{J/\psi}}{p_T^{Jet}}$$

- Fragmentation pattern is sensitive to production mechanism.PRL119(2017)032001

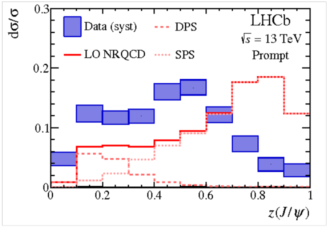
# $J/\psi$ Production in Jets in pp




$$z_{J/\psi} = \frac{p_T^{J/\psi}}{p_T^{Jet}}$$

- Fragmentation pattern is sensitive to production mechanism. PRL119(2017)032001
- $J/\psi$ is less isolated than expected by LO NRQCD in PYTHIA.
- Parton-parton scattering is not enough to describe $J/\psi$.

PRL.118.192001

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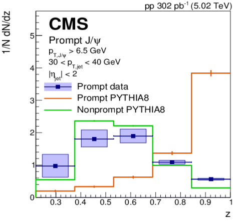


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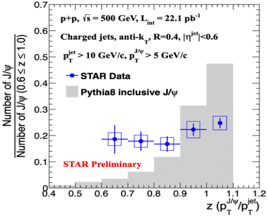
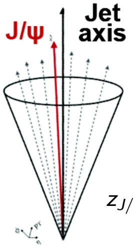


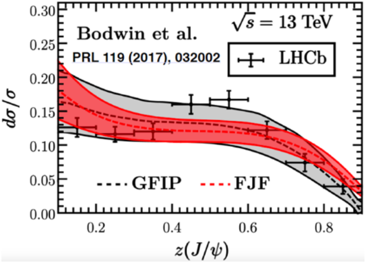
# Gluon Fragmentation Improved PYTHIA (GFIP)




$$z_{J/\psi} = \frac{p_T^{J/\psi}}{p_T^{\text{Jet}}}$$

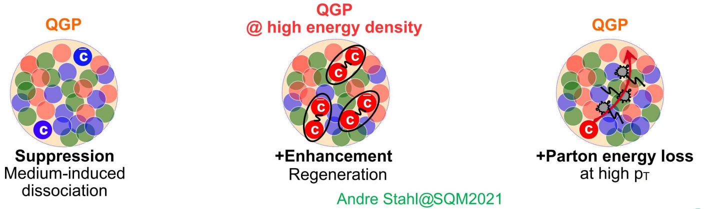
- Parton-parton scattering is not enough to describe $J/\psi$.
- Produced in parton shower: GFIP


- Model including $J/\psi$ produced in parton showers successfully describe LHCb data PRL 119, 032002 (2017)
- $J/\psi$ could be produced in parton showers(PS) PRL 119, 032002 (2017)
- We utilize a theoretical framework analogous to GFIP.



# $J/\psi$ Production in AA

- QGP (deconfined color medium) created in heavy-ion collisions.
- Regarded as a signature of color deconfinement. T. Matsui and H. Satz, PLB 178, 416 (1986).
- QGP is expected to modify the quarkonium production.



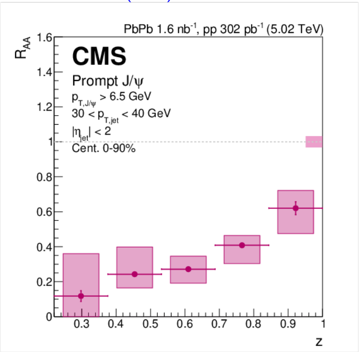

- Dissociation and regeneration well explain low-$p_{\mathrm{T}}$ $J/\psi$ suppression in AA PhysRevC.89.054911,PhysRevLett.128.162301
- In $p_{\mathrm{T}}^{J/\psi} \gg m_{J/\psi}$, almost no recombination, energy loss could play a dominant role for the $J/\psi$ $R_{\mathrm{AA}}$. Phys.Lett.B 767 (2017) 10-15,Sci.Bull. 68 (2023) 2003-2009

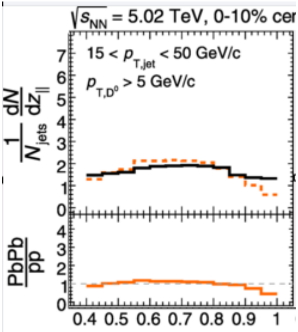
# Measurements of $J/\psi$ Production in Jets in AA

- If $J/\psi$ is generated in PS, thus the medium will modify PS and $z_{J/\psi}$.

PLB 825(2022) 136842

PRC.108.024905 .




- Significantly suppressed and could be explained by parton energy loss.
- Rising trend with increasing $z_{J/\psi}$, while $D_0$ in jets show downward trend.

# GFIP for $J/\psi$ Production

$$\frac{d\sigma^{J/\psi}}{dz^{J/\psi}dp_T^{jet}} = \sum_i \int \frac{dz}{z} \frac{d\sigma^i}{dz_i dp_T^{jet}} \otimes D_{i\to c\bar{c}(n)}(z)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

- $z_i = p_T^i/p_T^{jet}$ energy fraction carried by $i$
- $d\sigma^i/dp_T^{jet}dz_i$ CS of jet with $i$ carrying $z_i$
- $\hat{d}_{i\to[Q\bar{Q}(n)]}$ FF for $i$ to fragment into $Q\bar{Q}(n)$ at $\mu \sim 2m_c$,
  Y.Q.Ma et al. PhysRevD.89.094029
  G. T. Bodwin et al. JHEP11(2012)020
- $\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$ LDME: non-perturbative
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  K.T. Chao et al. PhysRevLett.108.24200,

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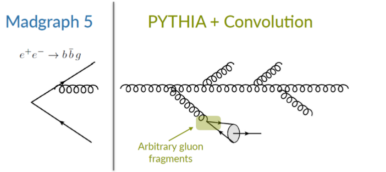
**Gluon Fragmentation Improved PYTHIA (GFIP)**




2. PYTHIA ⟶ No hadronization, adjust shower pT cutoff
3. Convolve NRQCD FFs w/ random final state gluon

Bain et. al., arXiv:1603.06981

# GFIP for $J/\psi$ Production

$$\frac{d\sigma^{J/\psi}}{dz^{J/\psi}\,dp_T^{\rm jet}} = \sum_i \int \frac{dz}{z} \frac{d\sigma^i}{dz_i dp_T^{\rm jet}} \otimes D_{i\to c\bar{c}(n)}(z)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

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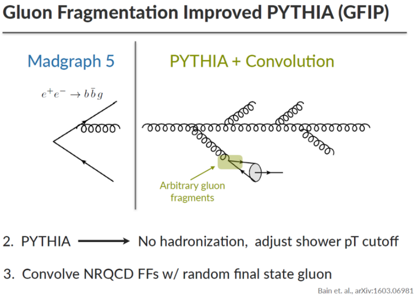
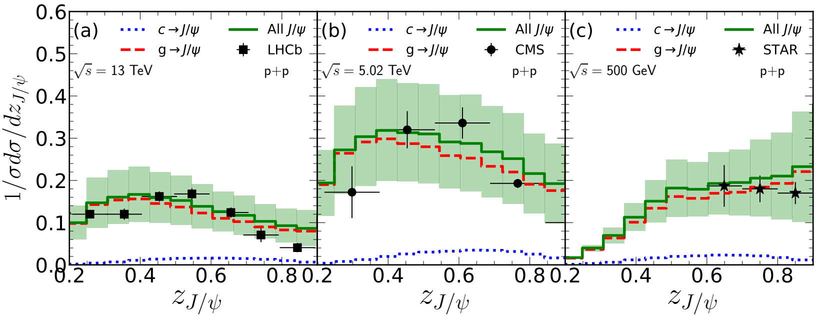


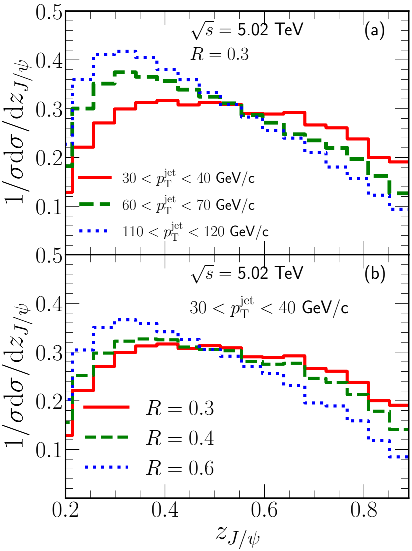

- LDMEs taken from Bodwin PRL.113,no.2,022001(2014).
- We restrict our discussion in the high $p_T$ region.

# $J/\psi$ Production within Jet in pp




- GFIP well describe the experimental data. [arXiv:2403.12704]
- **Gluon fragmentation dominates ($> 85\%$) the high-$p_T$ $J/\psi$ production.**
- Large band $\rightarrow$ further constrain LDMEs.
- The peak of $z_{J/\psi}$ shifts to smaller values from RHIC to LHC.

# $z_{J/\psi}$ vs $p_T^{jet}$ and Jet Cone $R$




arXiv:2403.12704

$z_{J/\psi}$ is shifted to softer regions with larger $p_T^{jet}$: larger $p_T^{jet}$, more showered gluons.

**$z_{J/\psi}$ distribution shifts to smaller value with larger jet cone $R$** : larger $R$, larger $p_T^{jet}$, smaller $z$.

# Energy loss model-LBT

Linear Boltzmann equation

$$p_a \cdot \partial f_a(x,p) = E_a(\mathcal{C}_{\rm el} + \mathcal{C}_{\rm inel}),$$

$\mathcal{C}_{\rm el}$ and $\mathcal{C}_{\rm inel}$ are the collision integrals for elastic and inelastic scatterings.

Elastic scattering PRC.91.054908, PRC.94.014909

$$\Gamma^a_{el}(E_a,T) = \frac{\gamma_2}{2E_a}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\int \frac{d^3p_3}{(2\pi)^3 2E_3}\int \frac{d^3p_4}{(2\pi)^3 2E_4} \times \frac{1}{2}\sum_{b(c,d)}[f_a(p_1)f_b(p_2) - f_c(p_3)f_d(p_4)]|M_{ab\to cd}|^2 \times S_2(s,t,u)(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)$$

Inelastic scattering PhysRevLett.85.3591;PhysRevLett.93.072301;PhysRevD.85.014023.

$$\Gamma^a_{\rm inel}(E_a,T,t) = \int dx dk_\perp^2 \frac{dN^a_g}{dx dk_\perp^2\, dt}, \quad \frac{dN_g}{dx dk_\perp^2\, dt} = \frac{2\alpha_s C_A P(x) k_\perp^4}{\pi(k_\perp^2 + x^2M^2)^4}\hat{q}\sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

The total scattering probability

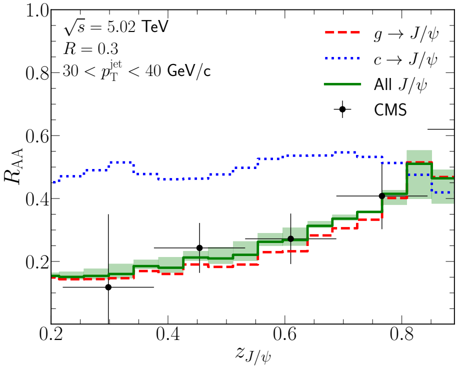
$$P^a_{\rm tot} = 1 - e^{-\Gamma_{\rm tot}\Delta t} = P^a_{\rm el} + P^a_{\rm inel} - P^a_{\rm el}P^a_{\rm inel}, \begin{cases} P^a_{\rm el} = 1 - e^{-\Gamma^a_{\rm el}\Delta t} \\ P^a_{\rm inel} = 1 - e^{-\Gamma^a_{\rm inel}\Delta t} \end{cases}$$

CLVisc3+1D Ideal hydrodynamatics Phys.Rev.C 86,024911 (2012).

LBT: light/heavy flavor hadron, inclusive jet, Z/$\gamma$-hadron/jet.

Phys.Lett.B **782**, 707-716 (2018), Phys.Lett.B 777, 86(2018);Phys.Rev.C 94, no.1, 014909 (2016). .

# $J/\psi$ Production within Jet in AA




[arXiv:2403.12704]

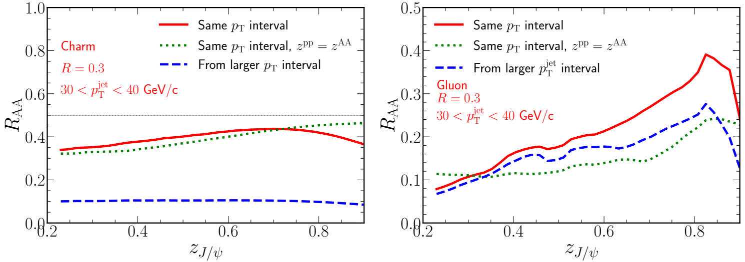
- GFIP well describe the experimental data.
- Gluon energy loss is the driving force for the $z_{J/\psi}$ suppression .
- Charm quark show much weaker dependence on $z_{J/\psi}$.

- Combined result of both $J/\psi$/jet yields reduction and the changes of the $z_{J/\psi}$ due energy loss.

# Effect of selection bias on $R_{AA}(z_{J/\psi})$

A quenched $J/\psi$-tagged jet within [30,40] GeV/$c$ may be originated from :

- Unquenched jet in the Same $p_T$ interval: $p_T^{BQ} \in [30, 40]$ GeV/$c$
- From larger $p_T$ interval: $p_T^{BQ} > 40$ GeV/$c$

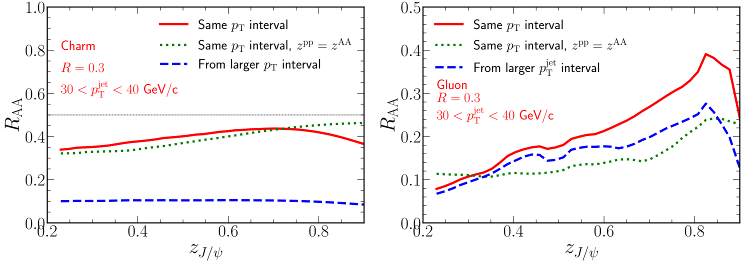



- Case 1 gives more than 80% contributions to charm jet $R_{AA}$
- Both case give comparable contributions to gluon jet.

# Effect of the shift of $z_{J/\psi}$ on $R_{AA}(z_{J/\psi})$

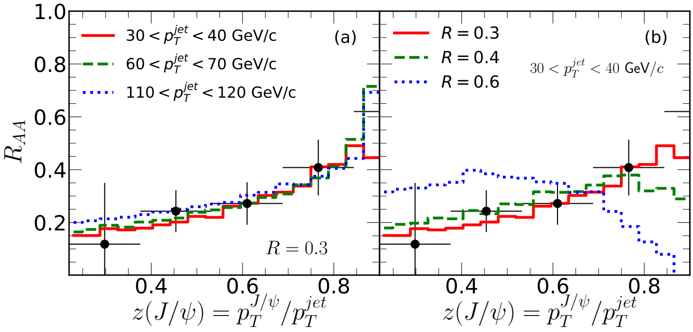
A quenched $J/\psi$-tagged jet within [30,40] GeV/$c$ may be originated from:

- Same $p_T$ interval: $p_T^{BQ} \in [30, 40]$ GeV/$c$
- $R_{AA}^{ref}$: $z^{J/\psi}$ is unmodified, $z^{AA} = (1 - f^{J/\psi})/(1 - f^{jet})z^{pp}$




- Shift of $J/\psi$ or jet out of the kinematic thresholds lead to the overall suppression of $R_{AA}$
- The shift of $z^{pp}$ to $z^{AA}$ dominate the $z_{J/\psi}$ dependence of $R_{AA}$ in large z region for both charm and gluon jet

# $R_{AA}(z_{J/\psi})$ vs $p_T^{\text{jet}}$ and Jet Cone $R$



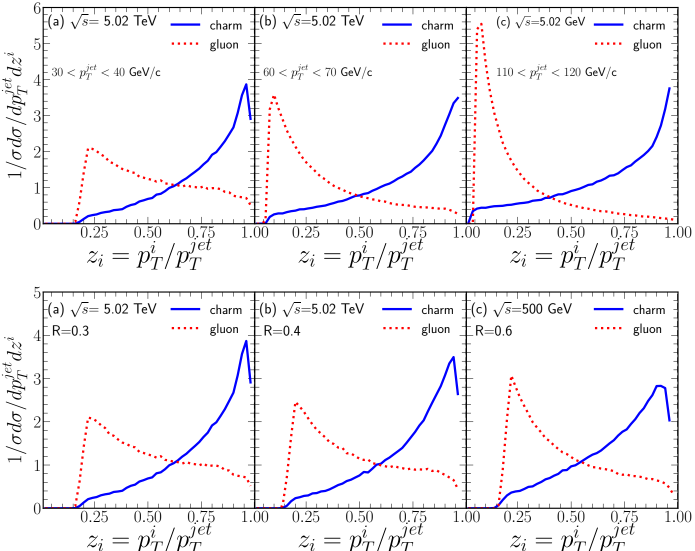

- Mild dependence of $R_{\text{AA}}(z_{J/\psi})$ on $p_T^{\text{jet}}$. [arXiv:2403.12704 ]
  - Both $J/\psi$ and jet loss energy, and have similar tendency.
- $R_{\text{AA}}(z_{J/\psi})$ is significantly modified with increasing jet radius.
  - Larger $R$, larger radiated gluons restored, less jet energy loss.

# Summary

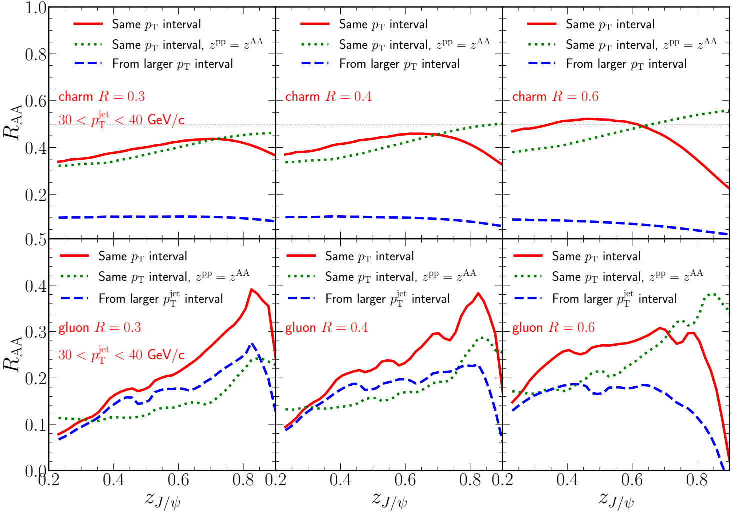
- High $p_T$ $J/\psi$ production in pp collisions can be well described and is demonstrated to be dominated by gluon contributions.
- $z_{J/\psi}$ is shifted to softer regions with larger $p_{\mathrm{T}}^{\mathrm{jet}}$ and $R$
- High $p_T$ $J/\psi$ suppression in AA collisions can also be well described and is shown to be mainly driven by the gluon in-medium energy loss.
- We expect mild $p_{\mathrm{T}}^{\mathrm{jet}}$ dependence and strong jet radius $R$ dependence of $R_{\mathrm{AA}}(z_{J/\psi})$.

# *Backup*

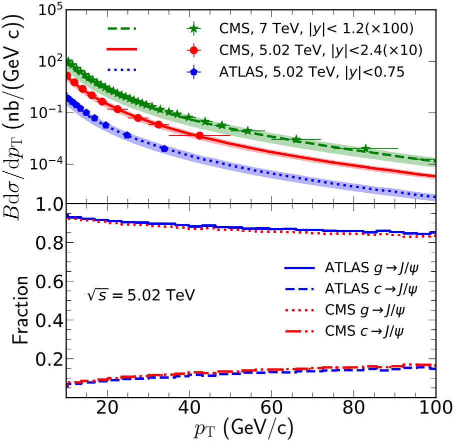
# $p_T^{jet}$ and R dependent $z_i$ distribution of gluon and charm



# Underlying mechanism for R dependent $R_{AA}(z_{J/\psi})$



# Results of $J/\psi$ Production in pp

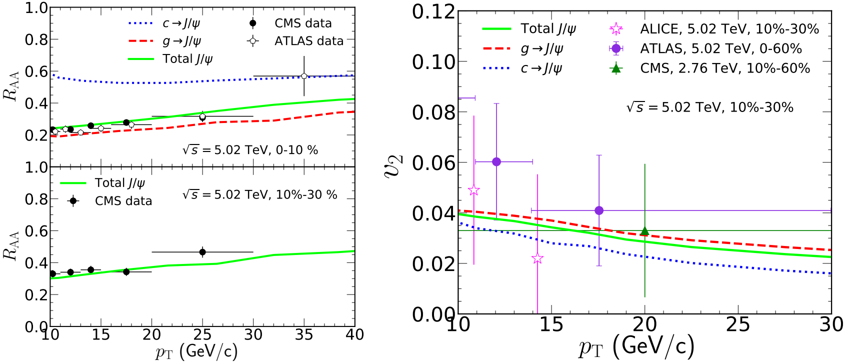



[arXiv:2208.08323]

GFIP well describe the experimental data.

**Gluon fragmentation dominates ($> 85\%$) the high-$p_\mathrm{T}$ $J/\psi$ production.**

# Inclusive $J/\psi$ production in AA




- Reasonable agreement with data.
- Gluon energy loss dominate large $p_T$ $J/\psi$ $R_{AA}$ and elliptic flow $v_2$.

# An Independent Bayesian Validation

Bayesian extraction of parton energy loss distributions.

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

Energy loss distributions PhysRevLett.122.252302

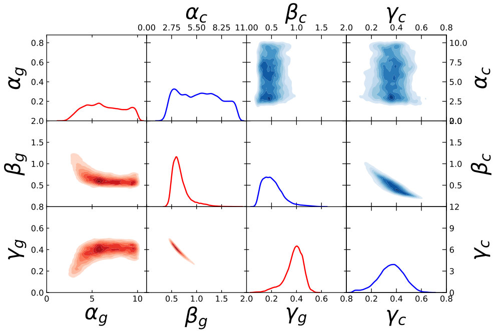
$$W^i(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)}, \begin{cases} x = \Delta p_T^i / \langle \Delta p_T^i \rangle \\ \langle \Delta p_\mathrm{T}^i \rangle = \beta_i (p_\mathrm{T}/p_\mathrm{T}^0)^{\gamma_i} \log(p_\mathrm{T}/p_\mathrm{T}^0) \end{cases}$$

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

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

1M MCMC steps for equilibration, then 1M steps for scanning around the parameter space

# Gluon and Charm Quark Energy Loss in Pb+Pb



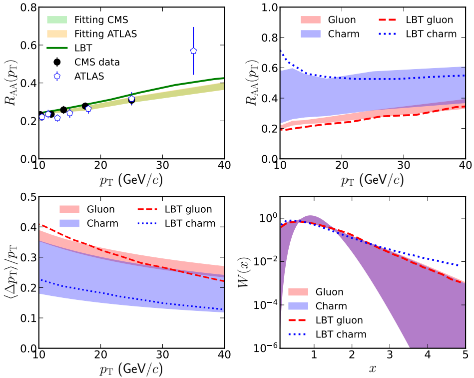

[arXiv:2208.08323]

One can see clearly a stronger sensitivity and constraint for gluon energy energy lose.

Extracted parameters for parton energy loss distributions

| $(0-10\%)$5.02 TeV | | | |
|---|---|---|---|
| | $\alpha$ | $\beta$ | $\gamma$ |
| Gluon | 5.25±1.09 | 0.7±0.07 | 0.37±0.03 |
| Charm | 6.33±2.06 | 0.53±0.19 | 0.36±0.09 |

# Gluon and Charm Quark Energy Loss in Pb+Pb




[arXiv:2208.08323]

The optimized results agree perfectly with data, and confirms the dominance of gluon energy loss for high $p_T$ $J/\psi$ suppression.

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

ALICE, JHEP 10, 141 (2020),
ATLAS, Eur. Phys. J. C 78, 784 (2018 ),
CMS, Eur. Phys. J. C 77, 252 (2017).