Dijet mass modification in heavy ion collisions

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Based on: arXiv:1810.10007
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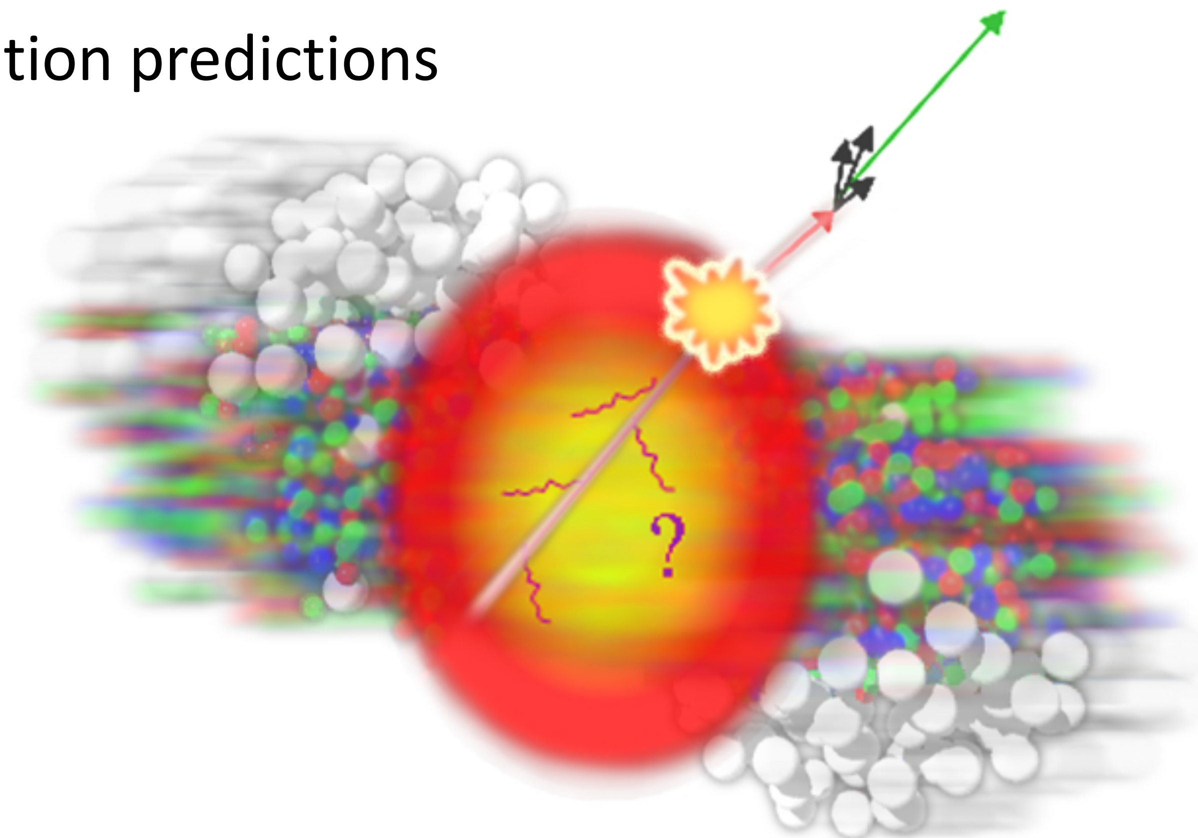
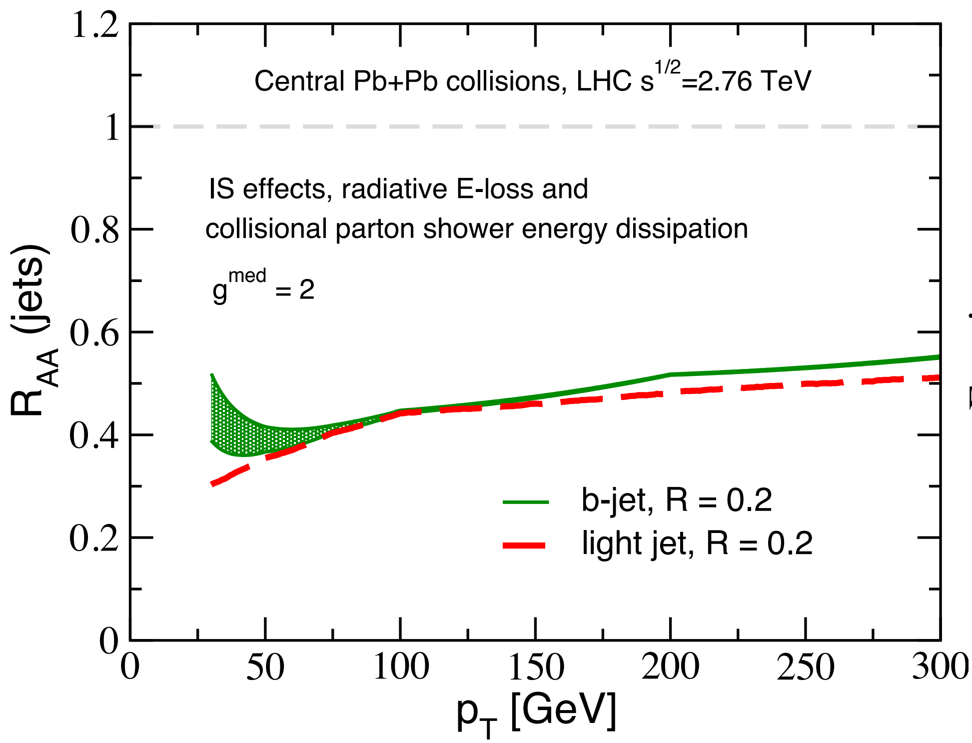
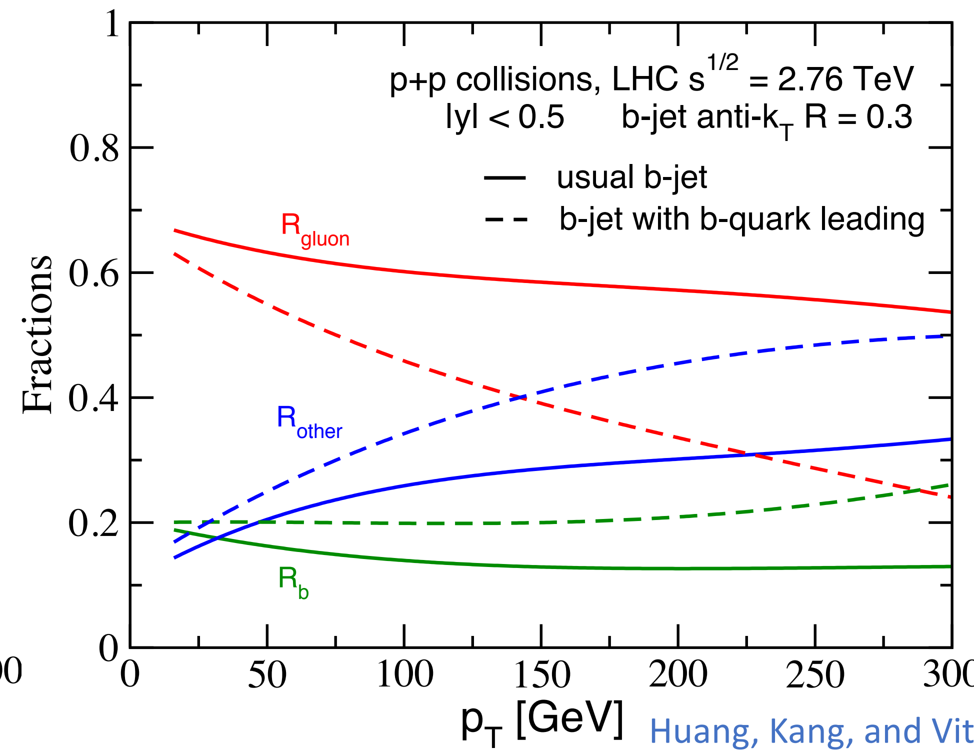
Outline

- Motivation
- Theoretical foundations
- Dijet mass modification predictions
- Summary



b-jets vs. light quark jets

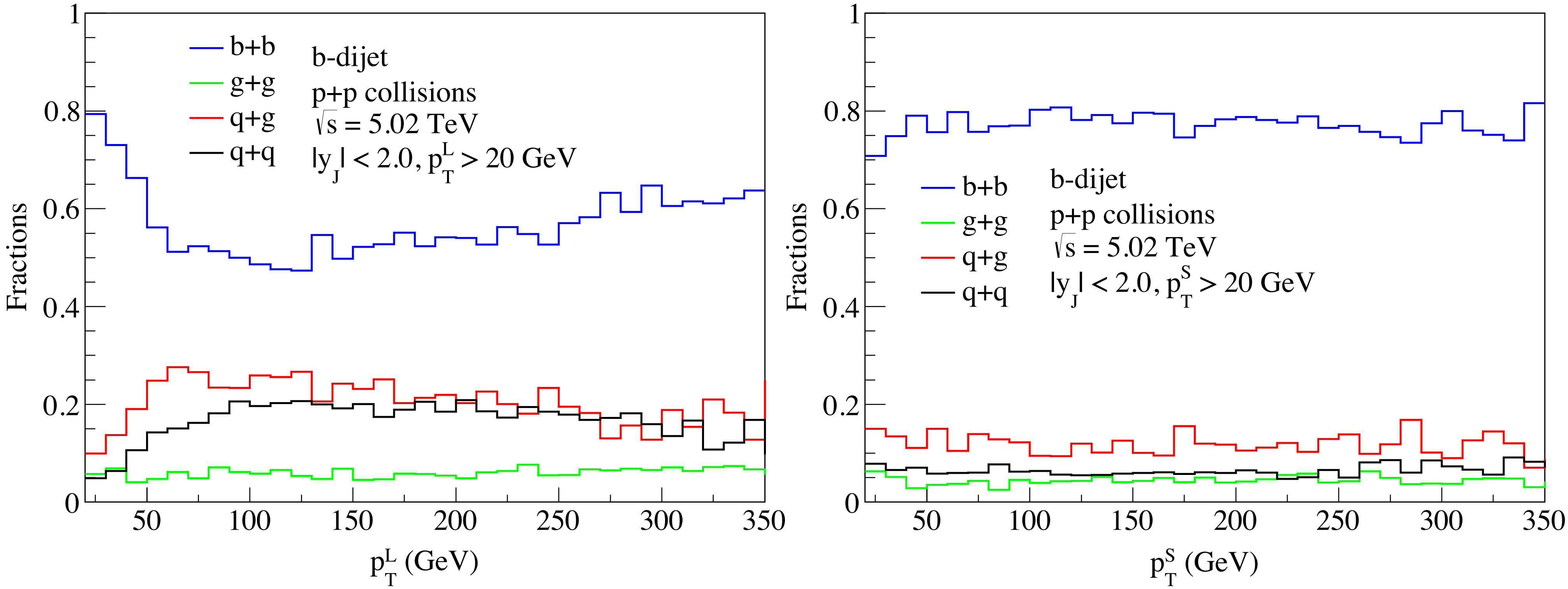




Huang, Kang, and Vitev
PLB 726, 251 (2013)

- Single b-jets do not shed light on heavy quark energy loss
- Fractional contributions of subprocesses and R_{AA} show single b-jets behave more like light quarks in QCD medium
- Gluon splitting to b-bbar contribution dominates, thus not a good observable for b-quark energy loss

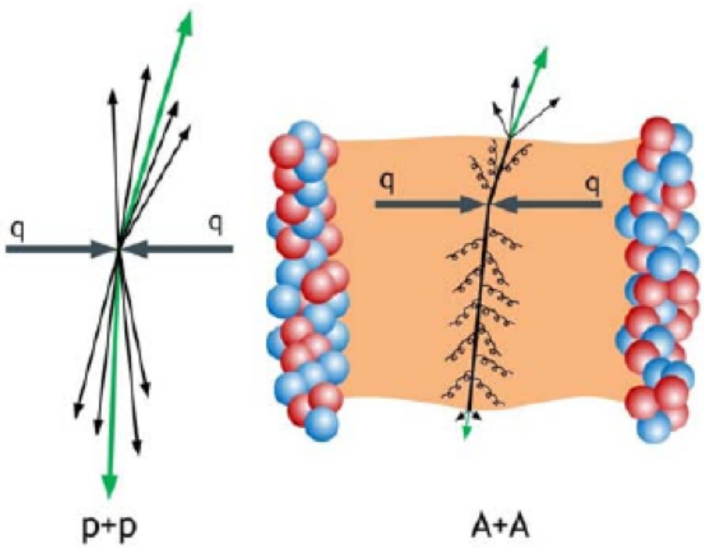
Flavor origins of b-dijets

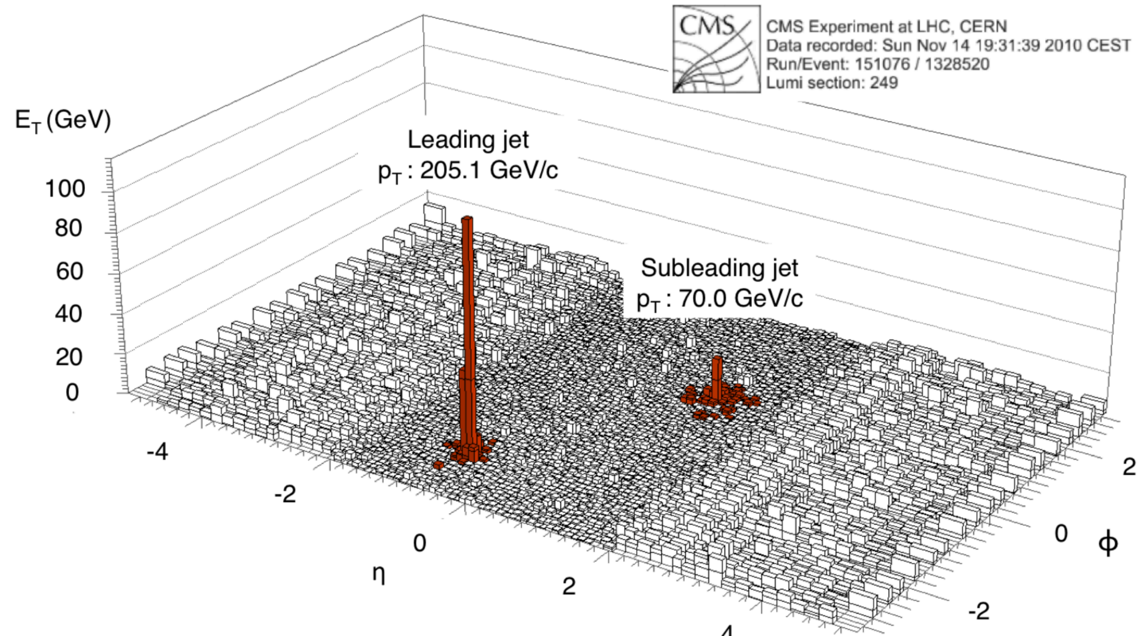


- b-dijet production dominated by b+b channel across entire pT range
- Most accurately reflects the energy loss of b-quarks

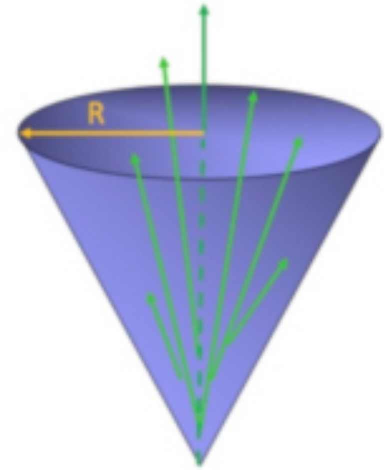
Why dijets?

- Flavor origins make dijets particularly well-suited to probe the heavy flavor dynamics in the QGP
- b quarks are expected to suffer the least amount of medium-induced radiative energy loss: $\Delta E_{\mathrm{rad}}(g) > \Delta E_{\mathrm{rad}}(q) > \Delta E_{\mathrm{rad}}(c) > \Delta E_{\mathrm{rad}}(b)$
- This motivates our study of b-tagged dijets





p+p baseline to A+A cross section



- p+p baseline simulated in Pythia 8 w/ FastJet and anti-kT algorithm
- Production cross section for n-jet events in the presence of the medium factorizes in the following way:

$$d\sigma^{\text{quenched}}_{n-\text{jet}}(\epsilon_1, \ldots, \epsilon_n) = P_1(\epsilon_1) \otimes \cdots \otimes P_n(\epsilon_n) \\ \otimes |J_1(\epsilon_1)| \cdots |J_n(\epsilon_n)| \, d\sigma^{pp}_{n-\text{jet}}(\epsilon_1, \ldots, \epsilon_n)$$

- Each $P_i(\epsilon_i)$ is the probability density for the parent parton to redistribute a fraction ϵ_i of its energy through medium-induced soft gluon bremsstrahlung
- Each $J_i(\epsilon_i)$ is a phase space Jacobian taking this energy loss into account
- It is this factorization that allows us to take:

$$d\sigma^{pp}_{\text{dijet}} \longrightarrow d\sigma^{AA}_{\text{dijet}}$$

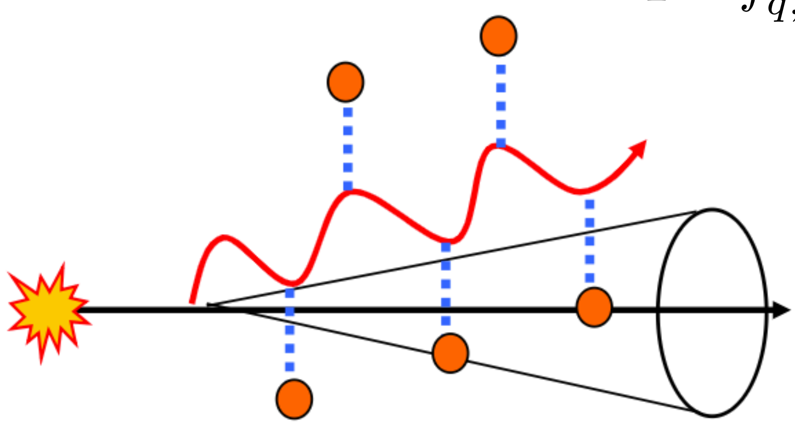
Jet energy loss in a nuclear medium

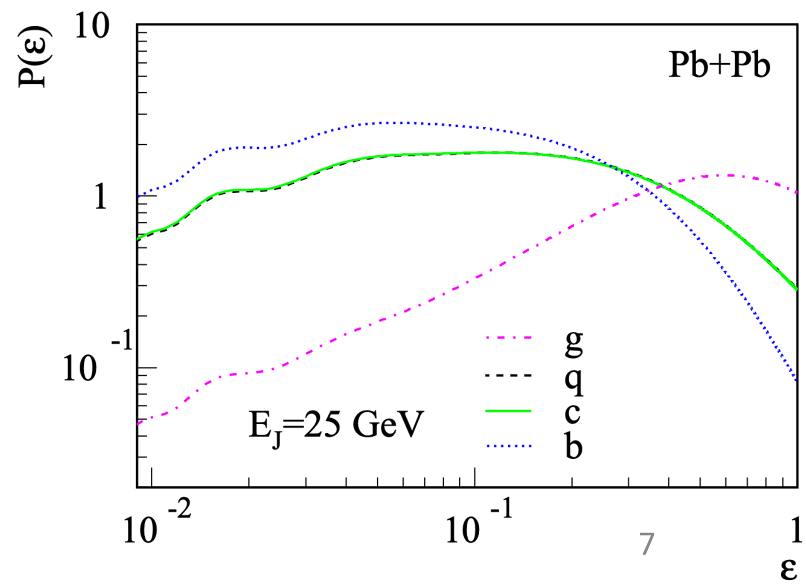
- Medium-modification of reconstructed jets captured by out-of-cone energy loss fraction:

$$f_{q,g}^{\text{loss}}(R;\text{rad}+\text{coll}) = 1 - \left(\int_0^R dr \int_{\omega_{\text{coll}}}^E d\omega \, \frac{dN_{q,g}^g(\omega,r)}{d\omega dr} \right) \Big/ \left(\int_0^{R_{\text{max}}} dr \int_0^E d\omega \, \frac{dN_{q,g}^g(\omega,r)}{d\omega dr} \right)$$

- Initial high energy jet is prepared to obtain final jet that is observed – this defines the phase space Jacobian

$$p'_T(\epsilon,R) = J(\epsilon,R)\cdot p_T = \frac{p_T}{1-f_{q,g}^{\text{loss}}(R)\cdot\epsilon}$$





Dijet mass

- Dijet mass is given by the standard formula:

$$m_{12}^2 = (p_1 + p_2)^2$$

- This can be expressed in terms of P_T after a few lines of algebra:

$$m_{12}^2 = m_1^2 + m_2^2 + 2\left[m_{1T}m_{2T}\cosh(\Delta\eta) - p_{1T}p_{2T}\cos(\Delta\phi)\right]$$

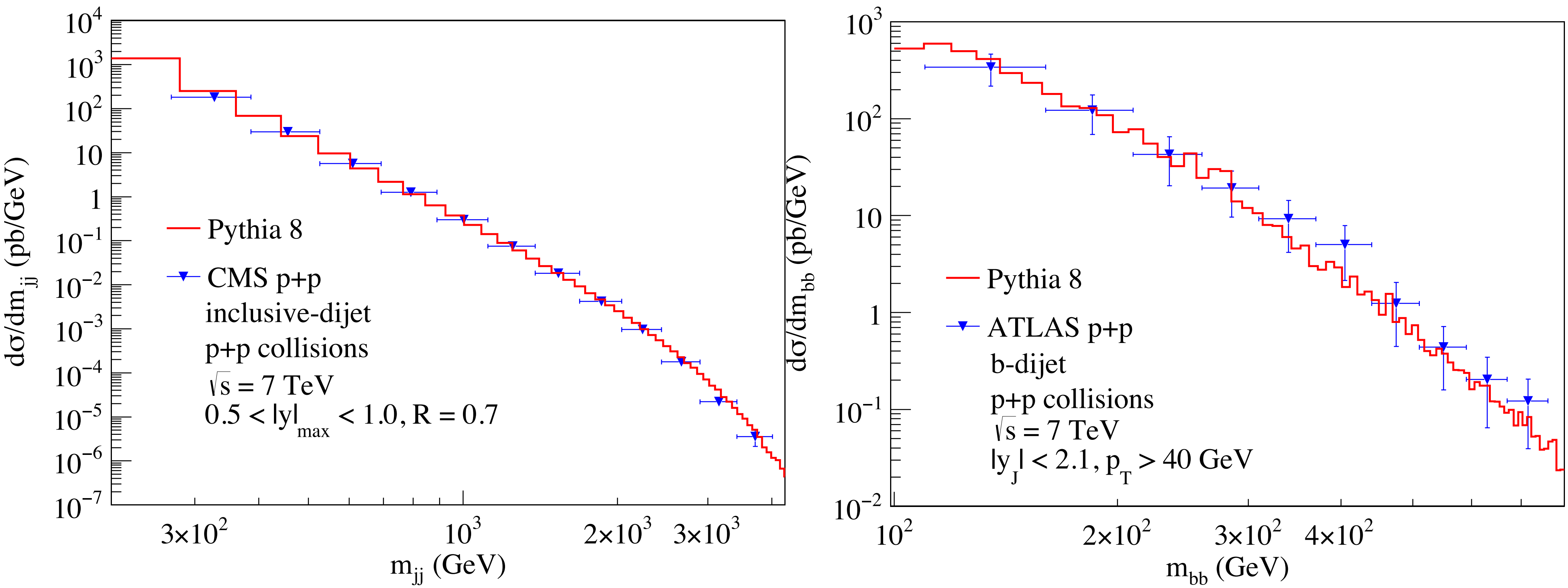
where $\Delta\eta = \eta_1 - \eta_2, \quad \Delta\phi = \phi_1 - \phi_2$ and $m_T = \sqrt{m^2 + p_T^2}$

- In the high P_T limit: $p_T \gg m \implies m_T \approx p_T$

- This gives us dijet mass in a form that is amenable to quenching

$$m_{12}^2 \approx m_1^2 + m_2^2 + 2p_{1T}p_{2T}\left[\cosh(\Delta\eta) - \cos(\Delta\phi)\right]$$

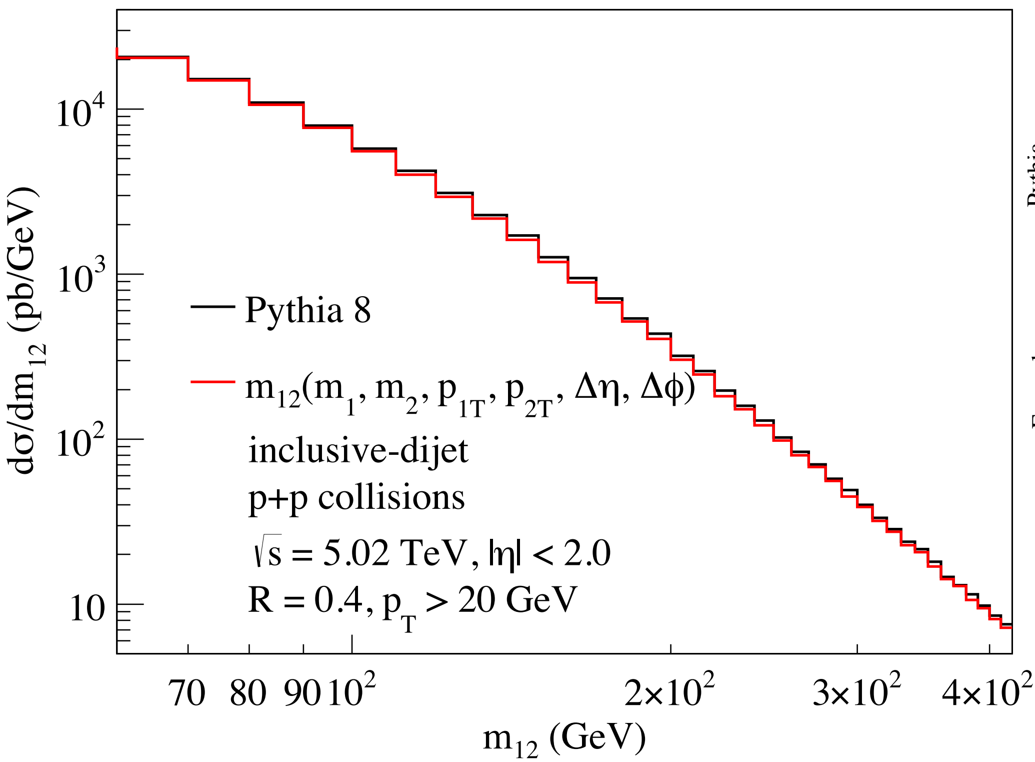
Previous LHC measurements of dijet mass

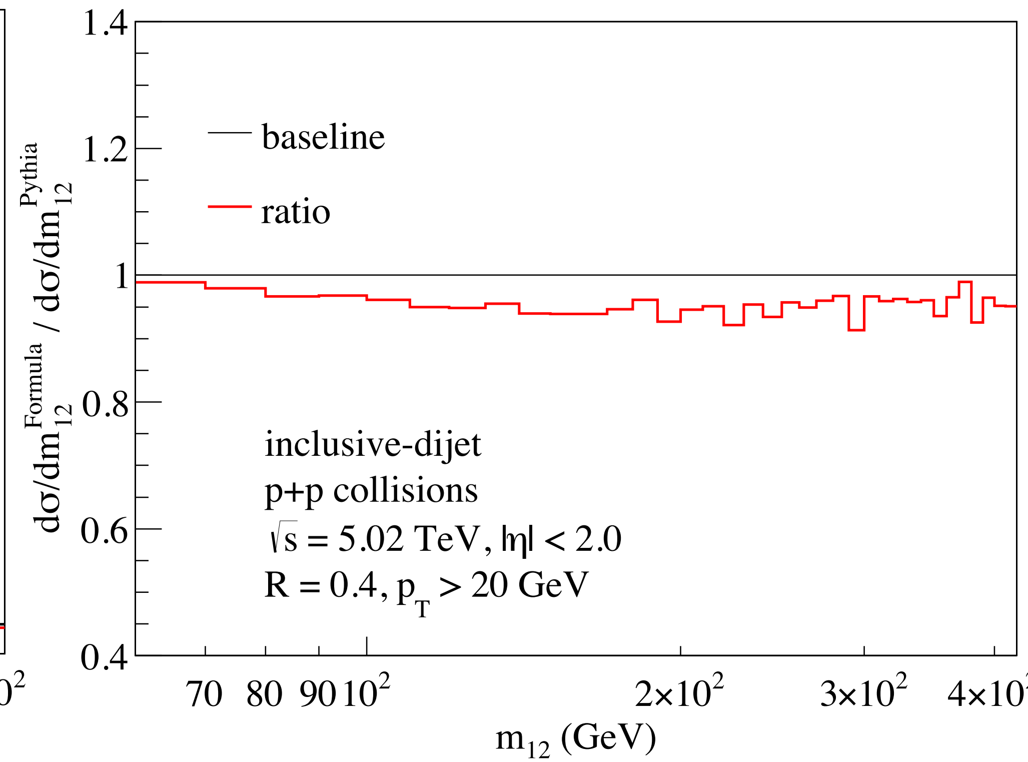


- Differential cross section vs. invariant mass of inclusive dijets measured by CMS (left) and b-tagged dijets measured by ATLAS (right)
- Simulations agree reasonably well with the experimental data

$$m_{12}^2 = (p_1 + p_2)^2$$

Comparison of dijet mass expressions





$$\frac{d\sigma^{pp}}{dm_{12}} = \int dp_{1T}\ dp_{2T}\ \frac{d\sigma^{pp}}{dp_{1T}dp_{2T}} \times \delta\left(m_{12} - \sqrt{\langle m_1^2\rangle + \langle m_2^2\rangle + 2p_{1T}p_{2T}\langle\cosh(\Delta\eta) - \cos(\Delta\phi)\rangle}\right)$$

Nuclear modification factor for dijet mass

- Previous factorization gives us cross section for dijet production in A+A:

$$\frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma^{AA}}{dp_{T1}dp_{T2}} = \sum_{q,g}\int_0^1 d\epsilon_1\ P_{1\ q,g}(\epsilon_1)\int_0^1 d\epsilon_2\ P_{2\ q,g}(\epsilon_2)$$
$$\times J_{1\ q,g}(\epsilon_1, R_1) J_{2\ q,g}(\epsilon_2, R_2)\frac{d\sigma^{pp}_{q,g}(p'_{T1}, p'_{T2})}{dp'_{T1}dp'_{T2}}$$

- Dijet mass cross section in A+A is then obtained via:

$$\frac{d\sigma^{AA}}{dm_{12}} = \int dp_{1T}\ dp_{2T}\ \frac{d\sigma^{AA}}{dp_{1T}dp_{2T}}$$
$$\times\ \delta\left(m_{12} - \sqrt{\langle m_1^2\rangle_{pp} + \langle m_2^2\rangle_{pp} + 2p_{1T}p_{2T}\langle \cosh(\Delta\eta) - \cos(\Delta\phi)\rangle_{pp}}\right)$$

- This then leads naturally to a new observable for heavy ion collisions

$$R_{AA}(m_{12}) = \frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma^{AA}/dm_{12}}{d\sigma^{pp}/dm_{12}}$$

Sensitivity to medium effects

- For medium modification, we must consider initial jet with increased P_T :

$$p'_T = J \cdot p_T \sim p_T + \Delta$$

- We can get a feel for the sensitivities of dijet observables by substituting this shifted P_T into their proton-proton definitions
- Traditional dijet observables include the dijet asymmetry A_J and the dijet imbalance z_J, both of which contain *ratios* P_T as opposed to *products*

$$A_J^{pp} = \frac{p_T^L - p_T^S}{p_T^L + p_T^S}$$

Dijet asymmetry

$$z_J^{pp} = \frac{p_T^S}{p_T^L}$$

Dijet imbalance

$$m_{pp}^2 = m_L^2 + m_S^2 + 2p_T^L p_T^S[\cosh(\Delta\eta) - \cos(\Delta\phi)]$$

Dijet mass

Sensitivity to medium effects

- The effects of medium-modification are *suppressed* with *ratios*

$$A_J^{AA} \approx A_J^{pp}\left\{1 - \frac{\Delta_L + \Delta_S}{p_T^L + p_T^S}\right\} + \frac{\Delta_L - \Delta_S}{p_T^L + p_T^S} + \dots$$

$$z_J^{AA} \approx z_J^{pp}\left\{1 + \frac{\Delta_S}{p_T^S} - \frac{\Delta_L}{p_T^L} + \dots\right\}$$

- And they are *enhanced* with *products*

$$m_{AA}^2 \approx m_{pp}^2 + \{p_T^L \Delta_S + p_T^S \Delta_L\}[\cosh(\Delta\eta) - \cos(\Delta\phi)] + \dots$$

Sensitivity to medium effects

- The effects of medium-modification are *suppressed* with *ratios*

$$A_J^{AA} \approx A_J^{pp}\left\{1 - \frac{\Delta_L + \Delta_S}{p_T^L + p_T^S}\right\} + \frac{\Delta_L - \Delta_S}{p_T^L + p_T^S} + \ldots$$

suppression

$$z_J^{AA} \approx z_J^{pp}\left\{1 + \frac{\Delta_S}{p_T^S} - \frac{\Delta_L}{p_T^L} + \ldots\right\}$$

enhancement

- And they are *enhanced* with *products*

$$m^2_{AA} \approx m^2_{pp} + \{p_T^L \Delta_S + p_T^S \Delta_L\}[\cosh(\Delta\eta) - \cos(\Delta\phi)] + \ldots$$

Sensitivity to medium effects

- The effects of medium-modification are *suppressed* with *ratios*

$$A_J^{AA} \approx A_J^{pp}\left\{1 - \frac{\Delta_L + \Delta_S}{p_T^L + p_T^S}\right\} + \frac{\Delta_L - \Delta_S}{p_T^L + p_T^S} + \ldots$$

$$z_J^{AA} \approx z_J^{pp}\left\{1 + \frac{\Delta_S}{p_T^S} - \frac{\Delta_L}{p_T^L} + \ldots\right\}$$

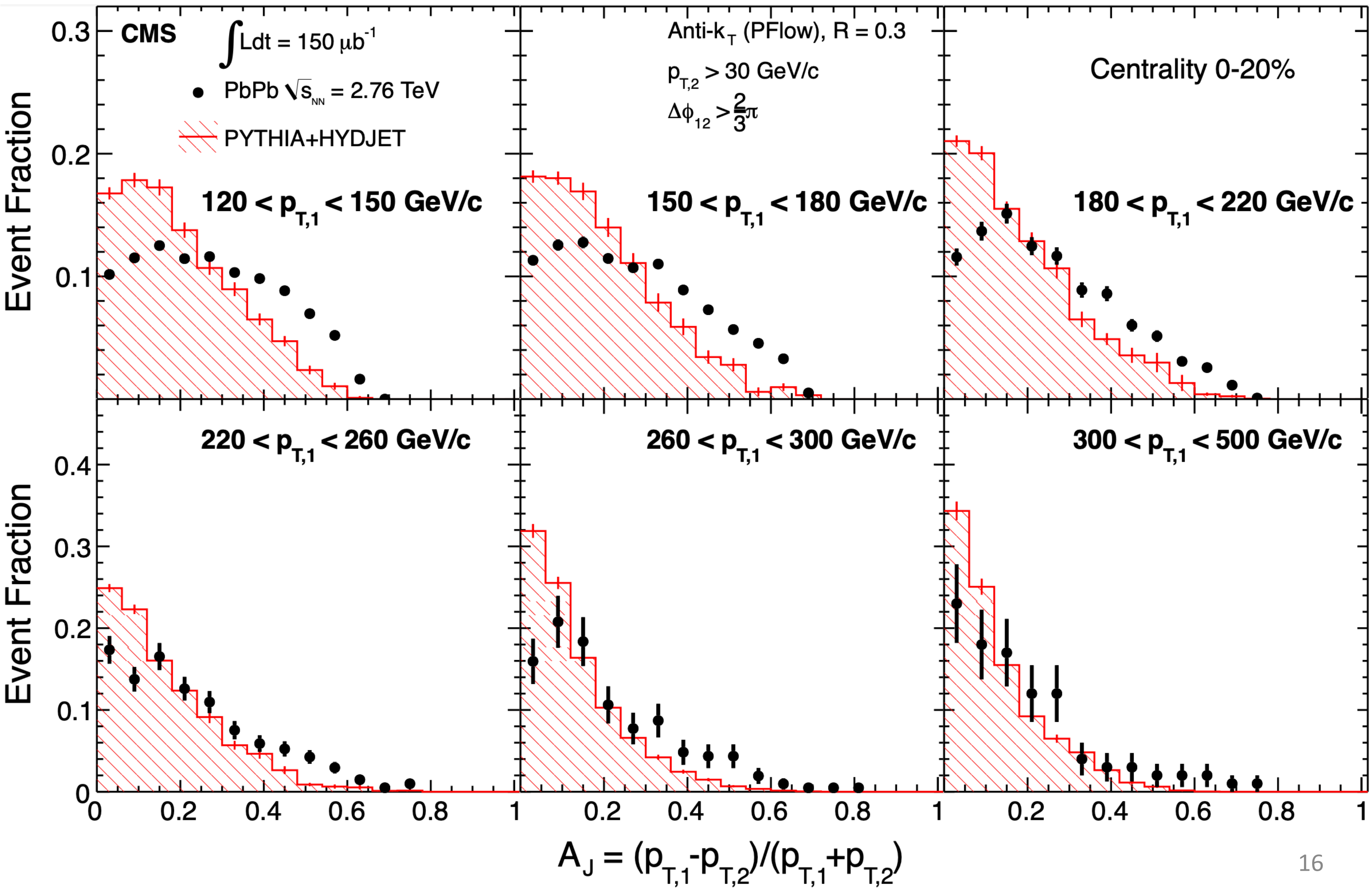
suppression

enhancement

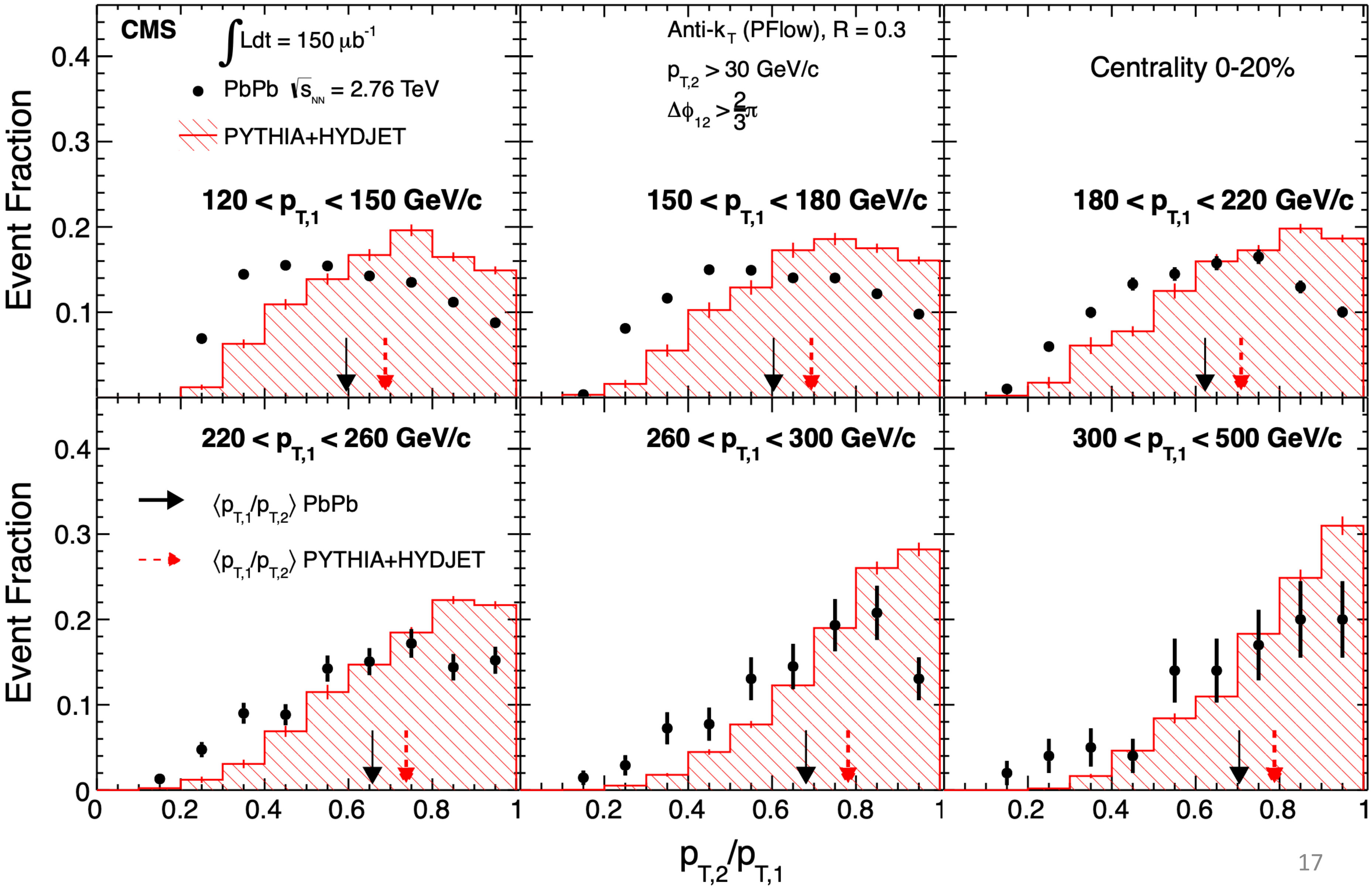
- And they are *enhanced* with *products*

$$m_{AA}^2 \approx m_{pp}^2 + \{p_T^L \Delta_S + p_T^S \Delta_L\}[\cosh(\Delta\eta) - \cos(\Delta\phi)] + \ldots$$

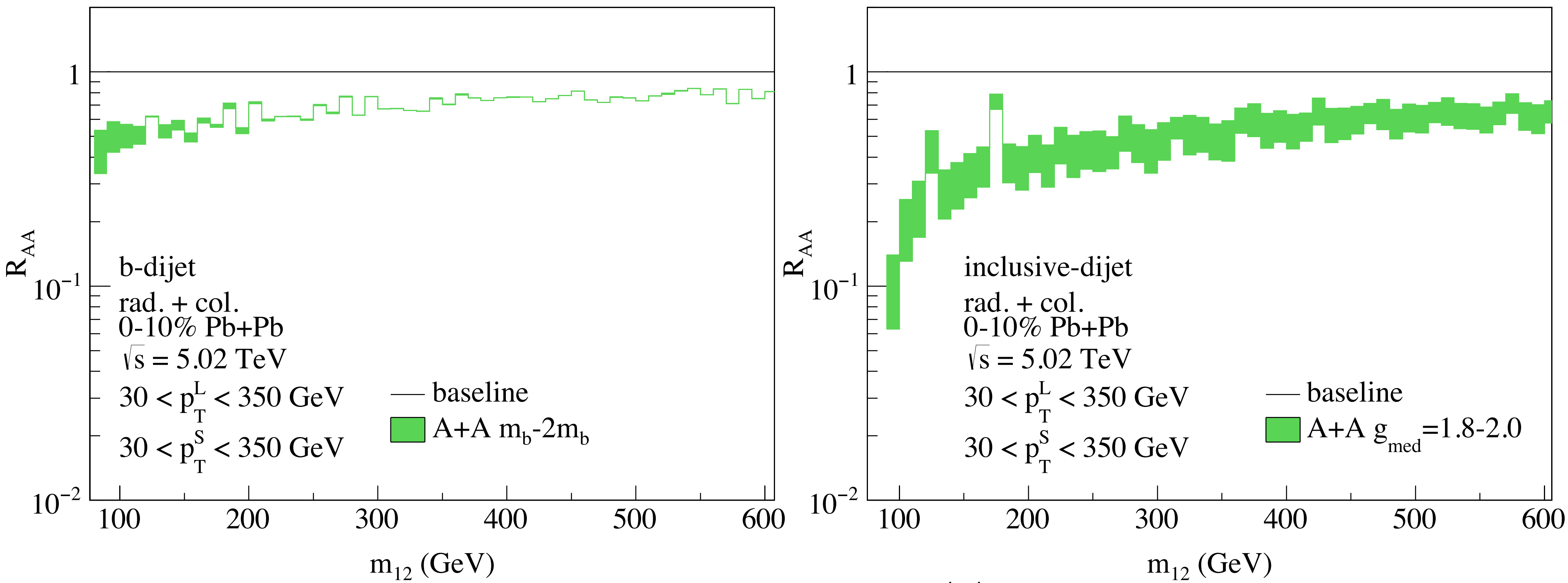
Dijet asymmetry at 2.76 TeV



Dijet imbalace at 2.76 TeV



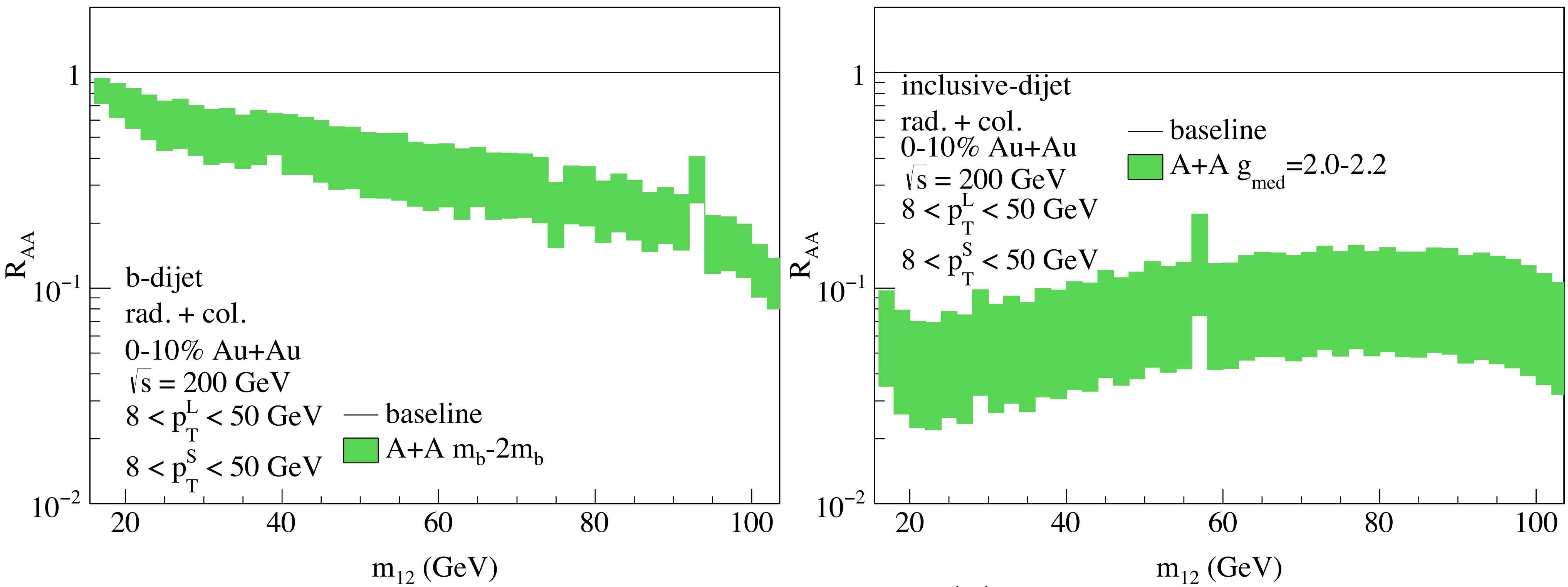
Dijet mass modification: CMS



$$R_{AA}(m_{12}) = \frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^{AA}/dm_{12}}{d\sigma^{pp}/dm_{12}}$$

- At lowest dijet mass we observe a nearly order-of-magnitude suppression in the production of inclusive dijets as compared to b-tagged dijets

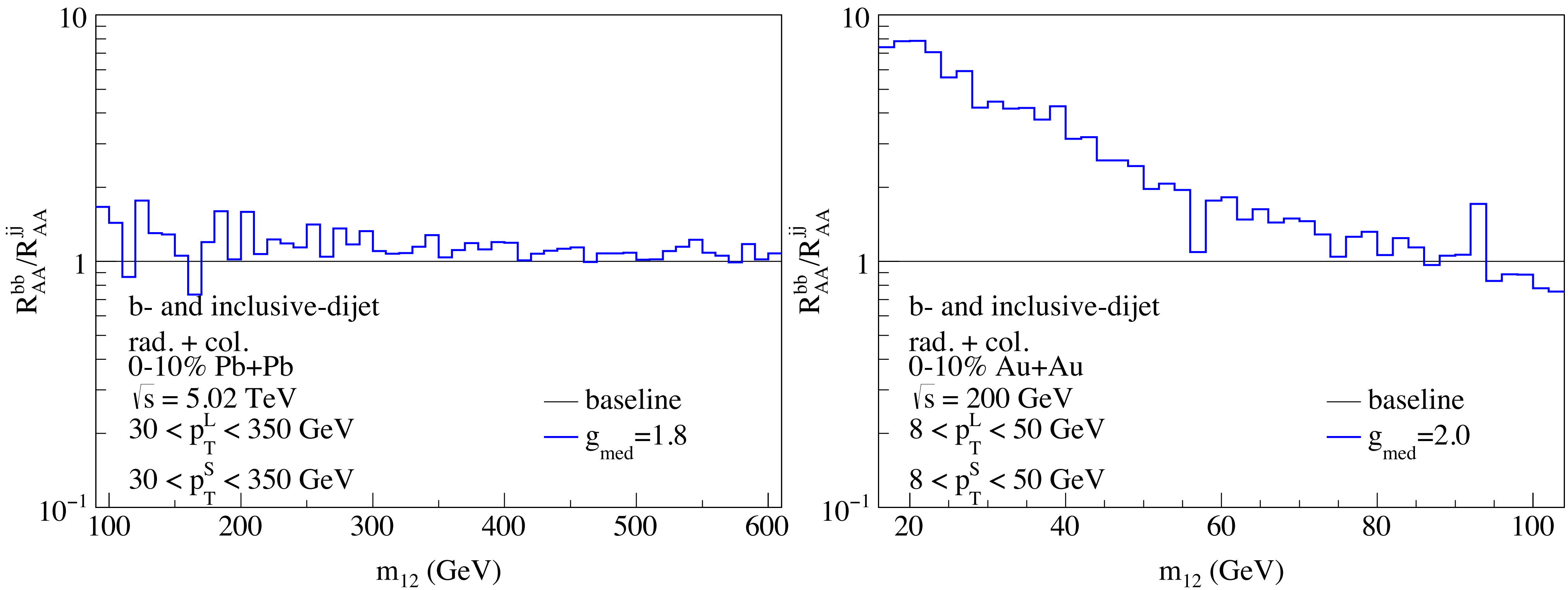
Dijet mass modification: sPHENIX



$$R_{AA}(m_{12}) = \frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma^{AA}/dm_{12}}{d\sigma^{pp}/dm_{12}}$$

- sPHENIX expected to see dramatic suppression of inclusive dijets relative to b-tagged across a majority of its kinematic range!

Relative magnitudes of mass modifications



- Alternatively, both experiments should expect to observe an abundance of b-tagged dijets upon analysis of dijet mass spectra
- sPHENIX is particularly well-suited to observe this dramatic effect

Summary

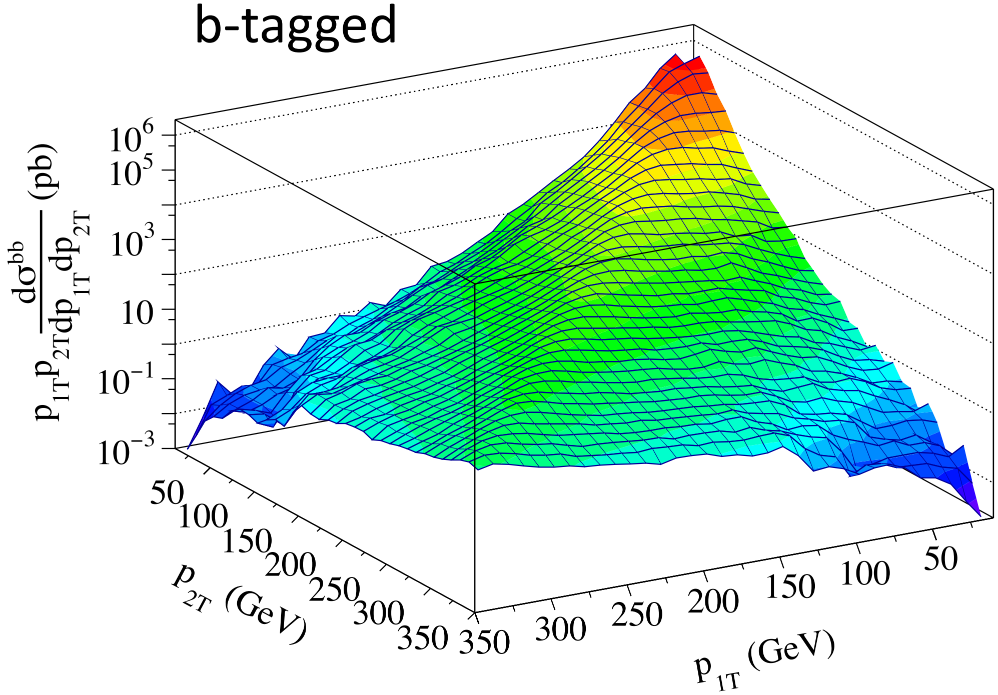
- We have evaluated the production of b-tagged and inclusive dijets for both CMS (Pb+Pb @ 5.02 TeV) and sPHENIX (Au+Au @ 200 GeV)
- We have proposed a new observable that reveals dramatic differences in the energy loss mechanisms of light and heavy flavor jets
- Dijet mass modification is a promising ingredient to understanding the in-medium dynamics of b-quarks
- The future sPHENIX experiment is particularly well-suited to unveil this novel effect

Thank you!

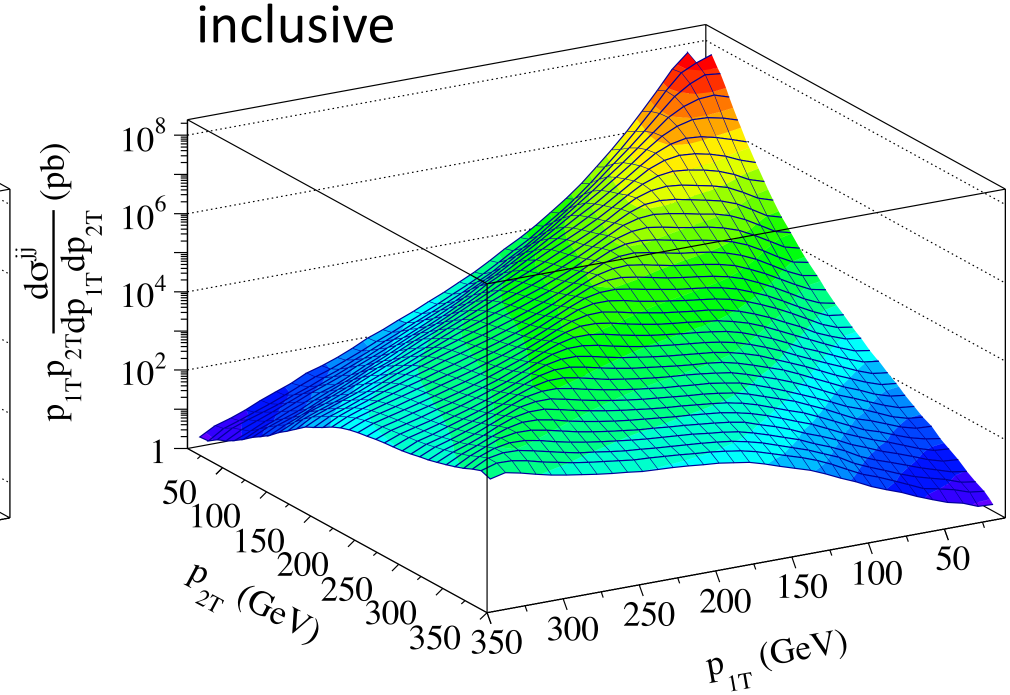
Backup Slides

Double differential cross sections: CMS

b-tagged



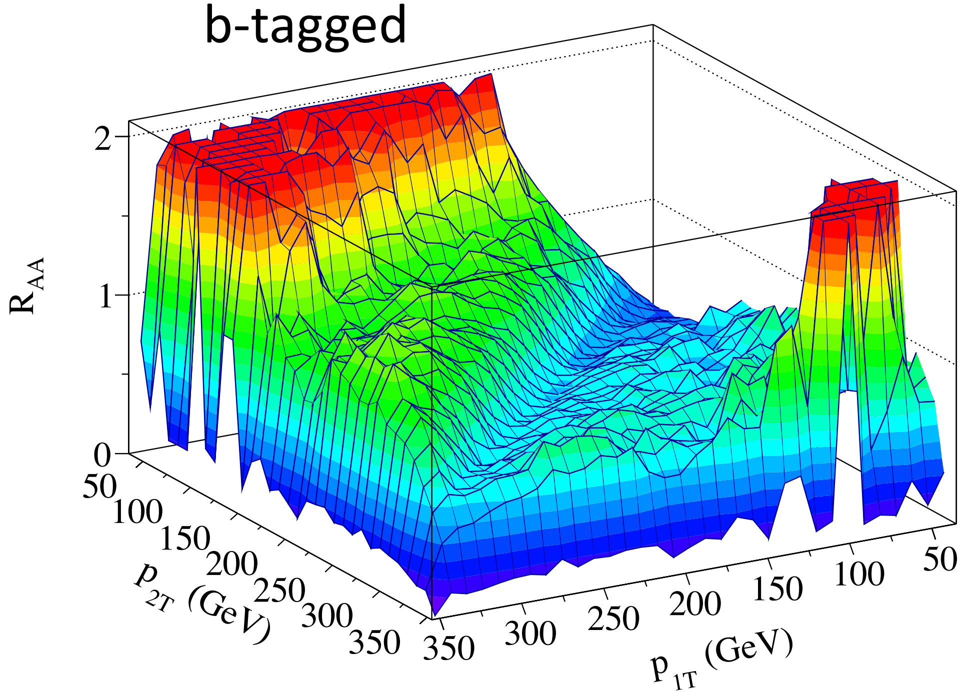
inclusive



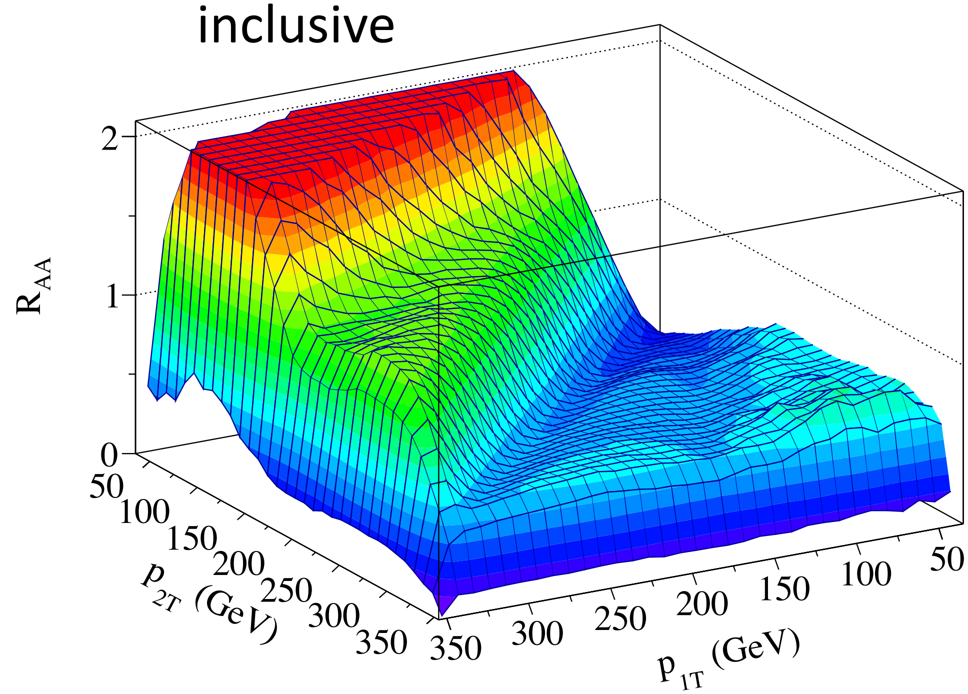
- Here we display the cross section in a more “symmetric manner,” i.e. we do not distinguish between “leading” and “subleading” jets
- This best illustrates the “ridge” along the diagonal, i.e. the kinematic preference for the production of back-to-back dijet pairs

Nuclear modification factors: CMS

b-tagged



inclusive

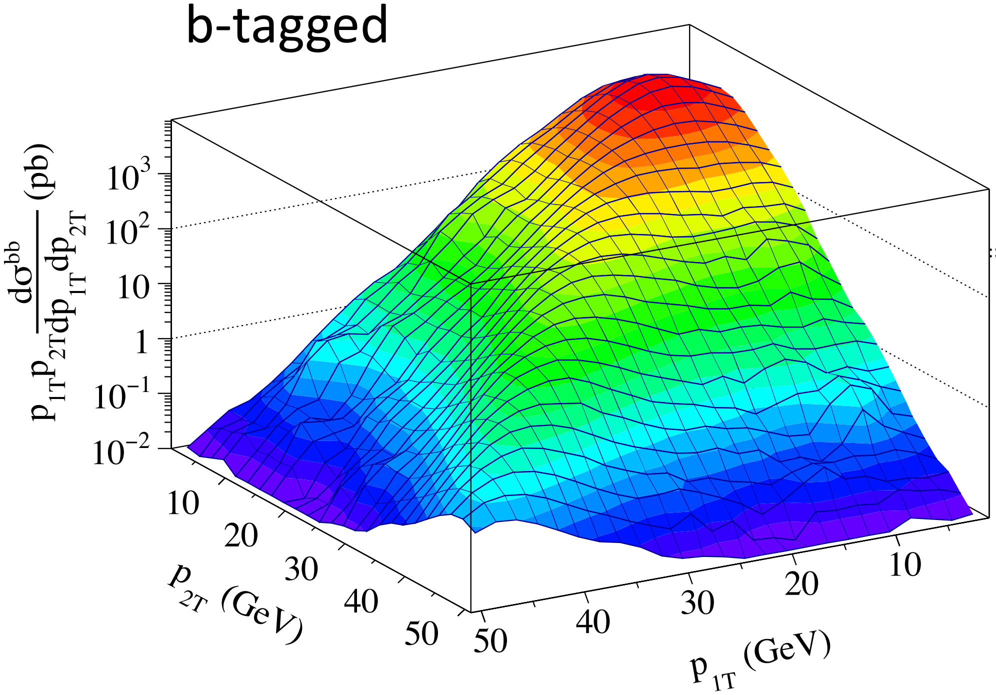


$$R_{AA}(p_{1T}, p_{2T}) = \frac{1}{\langle N_{\rm bin} \rangle} \frac{d\sigma^{AA}/dp_{1T}dp_{2T}}{d\sigma^{pp}/dp_{1T}dp_{2T}}$$

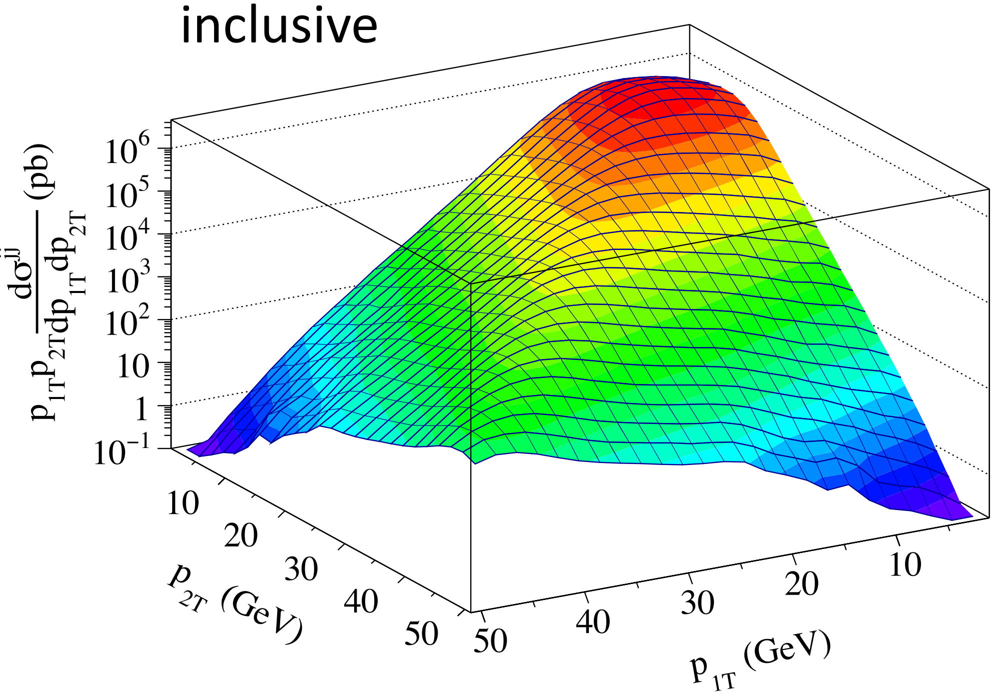
- Here, P_{1T} denotes the transverse momentum of the trigger/leading jet while P_{2T} denotes the recoil/subleading jet
- We observe the largest suppression along the main diagonal

Double differential cross sections: sPHENIX

b-tagged

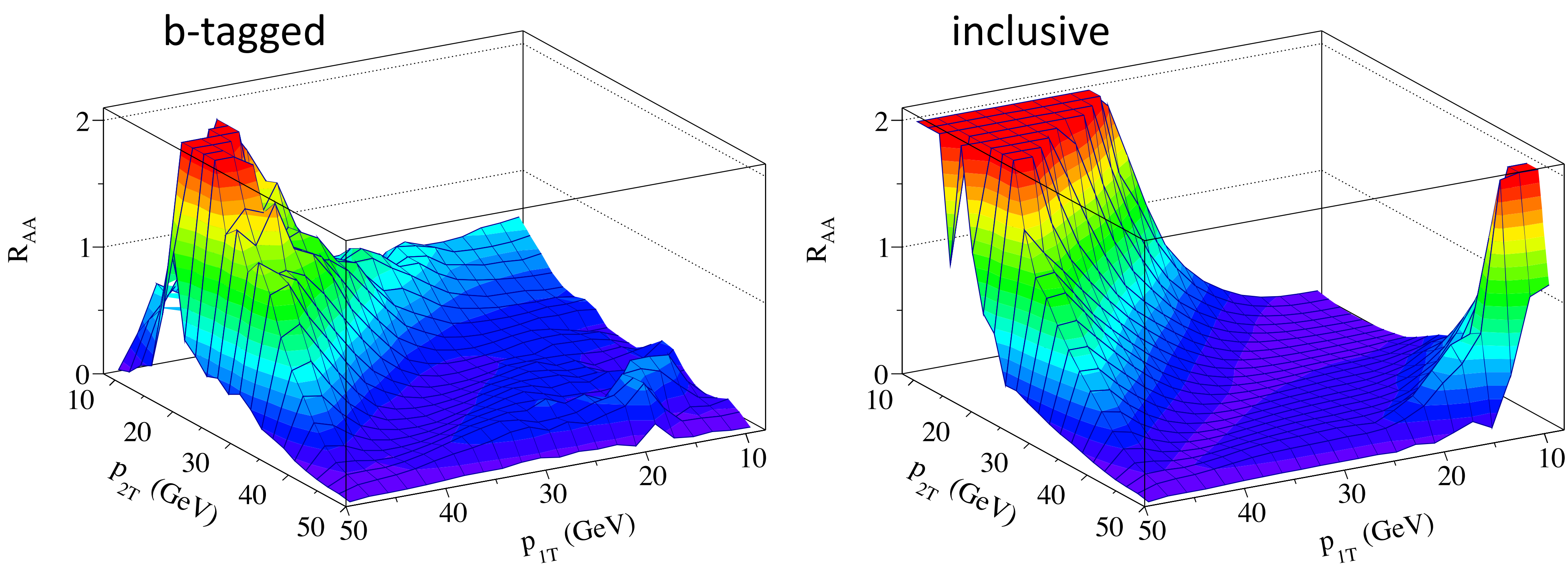


inclusive



- While kinematic range available for RHIC is far more limited than at of the LHC, we again observe the “ridge” along the diagonal, signaling proclivity for dijets to emerge back-to-back

Nuclear modification factors: sPHENIX



$$R_{AA}(p_{1T}, p_{2T}) = \frac{1}{\langle N_{\rm bin} \rangle} \frac{d\sigma^{AA}/dp_{1T}dp_{2T}}{d\sigma^{pp}/dp_{1T}dp_{2T}}$$

- Again, P_{1T} denotes the transverse momentum of the trigger/leading jet while P_{2T} denotes the recoil/subleading jet
- sPHENIX kinematics show an even stronger suppression along the main diagonal – revealing an amplification of jet-quenching effects relative to CMS