

Mapping the redistribution of jet energy in PbPb collisions using jets with various radius parameters with CMS

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for the CMS Collaboration

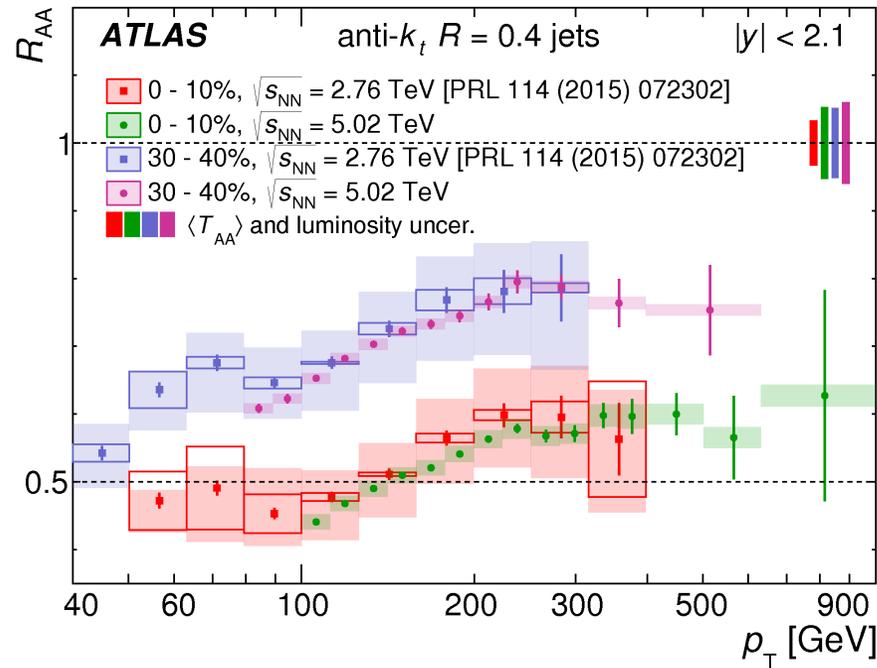
Quark Matter 2019, Wuhan, China

November 6, 2019

Introduction

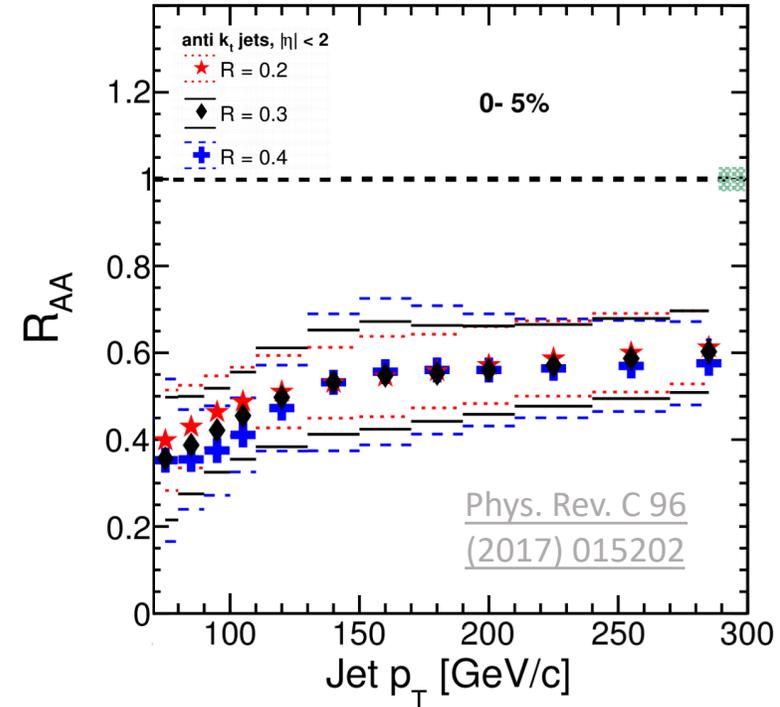
ATLAS 5.02 TeV, R = 0.4

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CMS 2.76 TeV R Scan

CMS pp 5.43 pb⁻¹ + PbPb 166 μb⁻¹ (2.76 TeV)



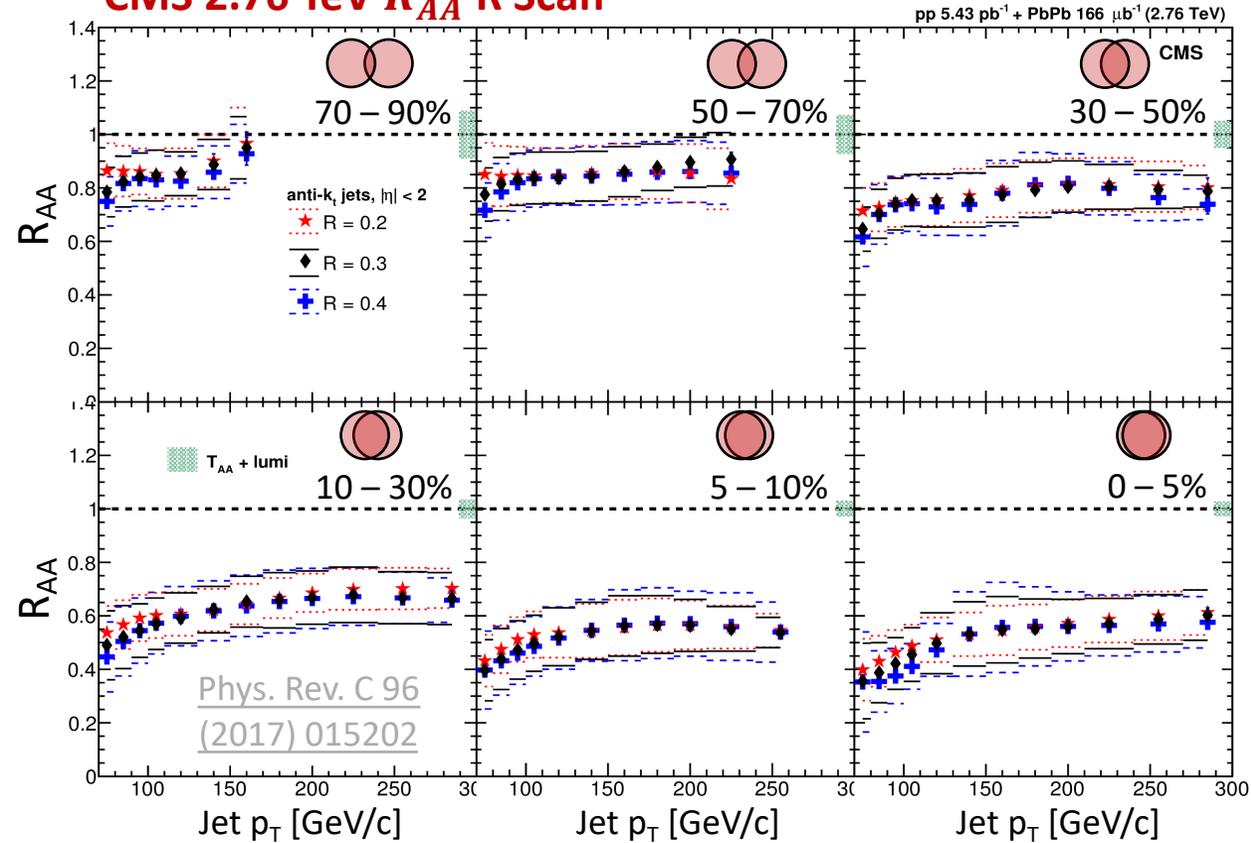
Partons lose energy in QGP = **jet quenching**

Jet quenching seen in R_{AA} modifications

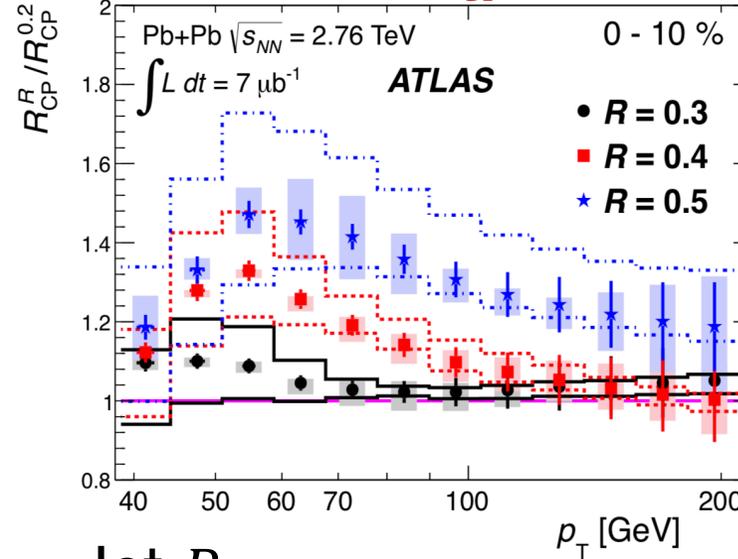
$$R_{AA}(p_T) = \frac{\text{PbPb jet yield}}{\text{scaled pp jet yield}}$$

Past Results

CMS 2.76 TeV R_{AA} R Scan



ATLAS 2.76 TeV R_{CP} R Scan

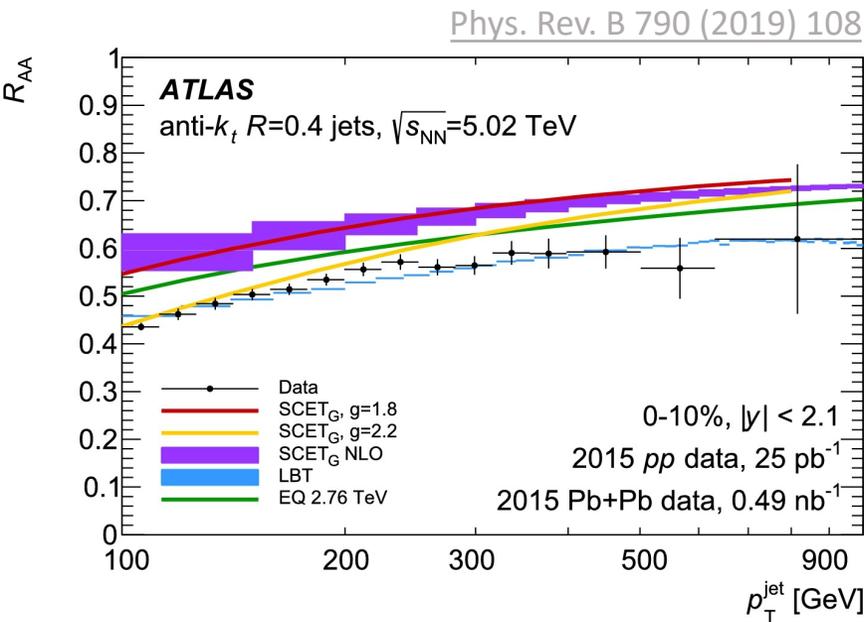


Jet R_{AA} ...

- increases weakly with jet p_T
- increases with impact parameter
- is independent of R for 0.2 - 0.4

However, ATLAS R_{CP} (central to peripheral ratio) shows significant dependence on R

Theory Predictions: Jet R_{AA}



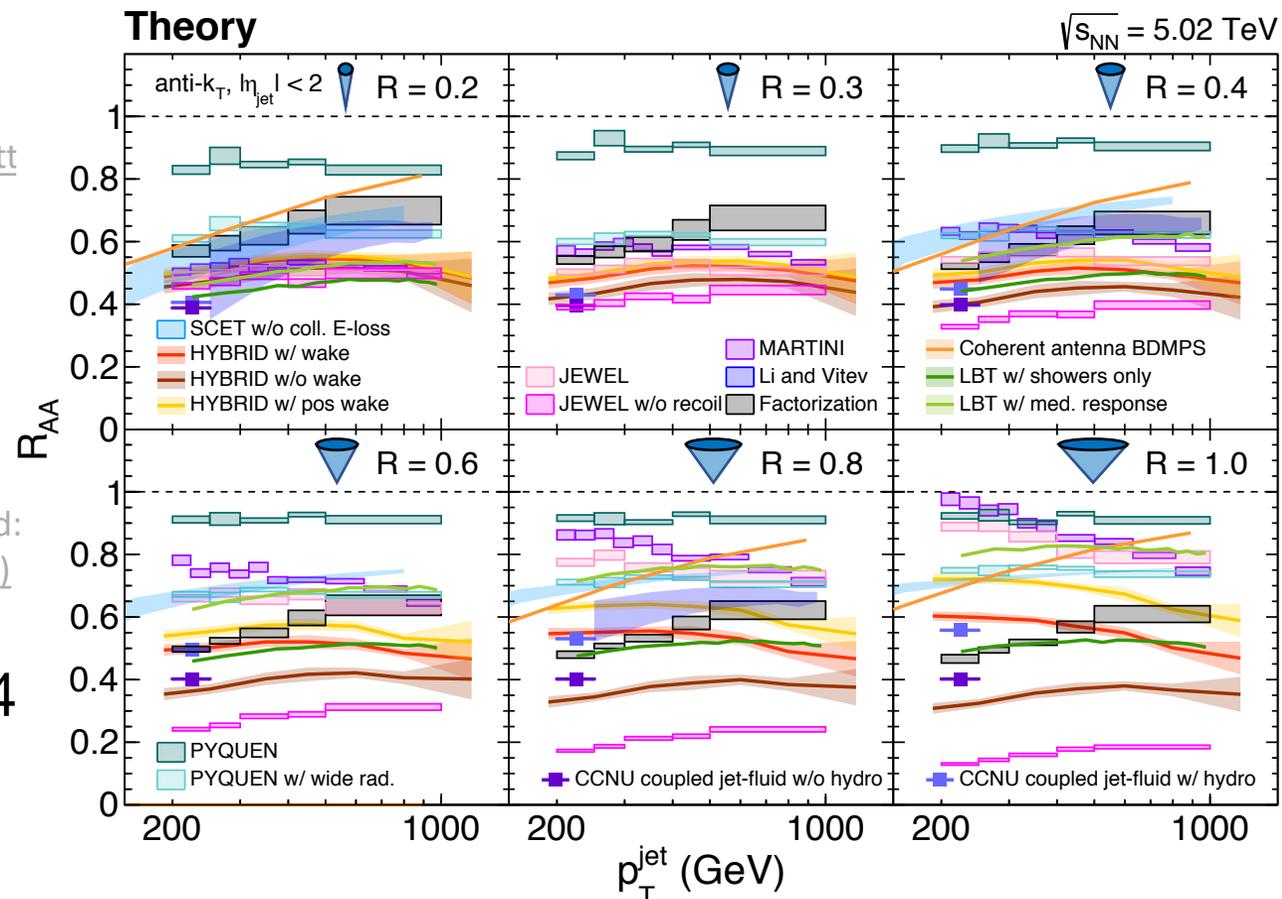
Jewel: [JHEP 1707 \(2017\) 141](#)

Factorization: [Phys. Lett 122 \(2019\) 252301](#)

Hybrid:
[arXiv:1907.12301](#) &
[JHEP03 \(2017\) 135](#)

LBT: [Phys. Rev. C 99 \(2019\) 054911](#)

CCNU coupled jet-fluid:
[Phys. Rev. C 94 \(2016\) no.2, 024902](#)



Theories follow general R_{AA} trend for $R = 0.4$

They yield very different predictions with increasing p_T and $R \rightarrow 1.0$

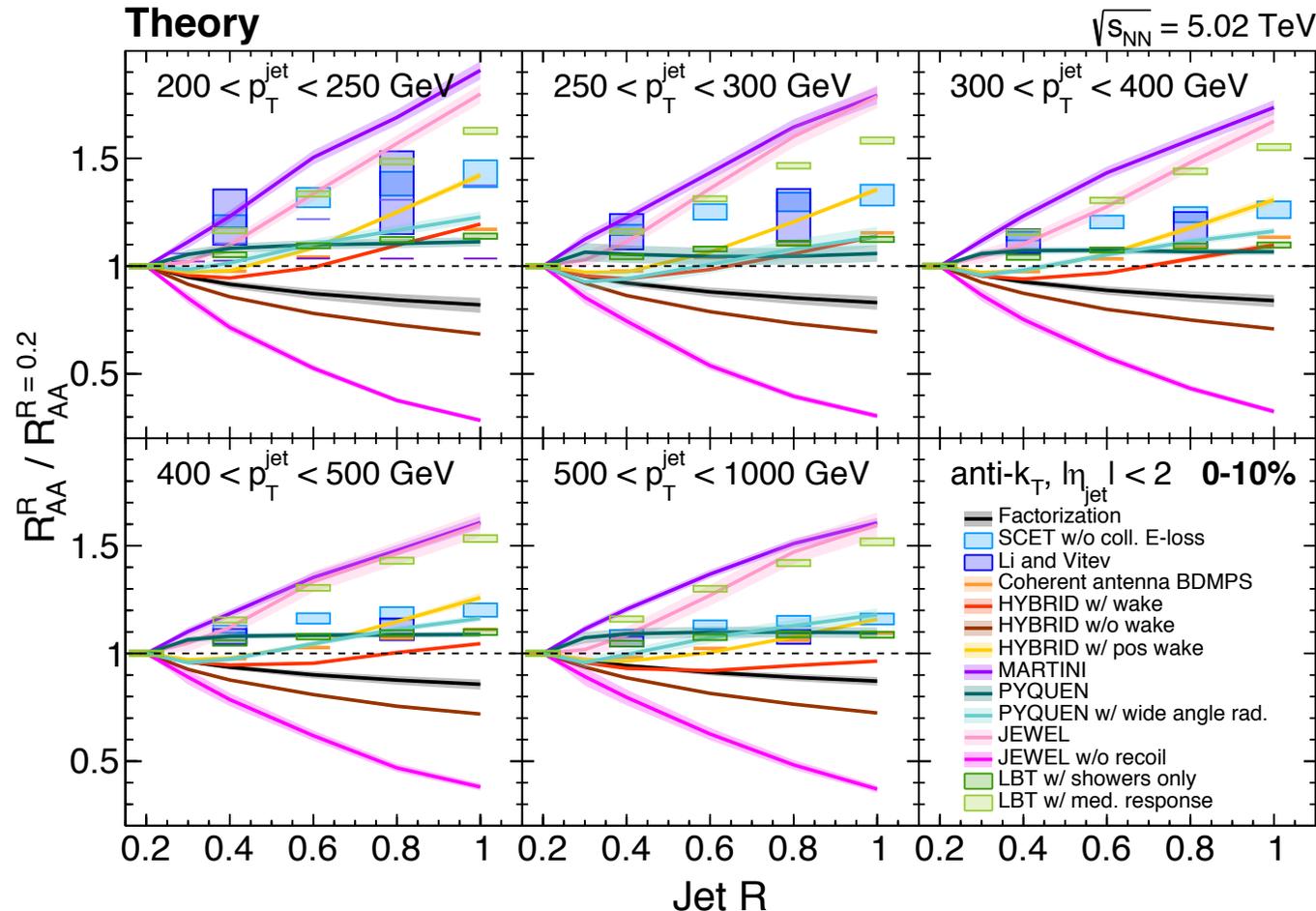
MARTINI: [Phys. Rev. C 80 \(2019\) 054913](#) Li and Vitev: [JHEP 1907 \(2019\) 148](#) & [Phys. Lett. B 795 \(2019\) 502-510](#)

SCET_G w/o coll. E-loss: [JHEP05 \(2016\) 023](#)

Pyquen: [Eur. Phys. J C16 \(2000\) 527-536](#) & [Eur. Phys. J C46 \(2006\) 211-217](#) & [SINP MSU 2004-14/753](#)

BDMPS: [Phys. Rev. D 98 \(2018\) no.5, 051501](#)

Theory Predictions: Jet $R_{AA}^R/R_{AA}^{0.2}$



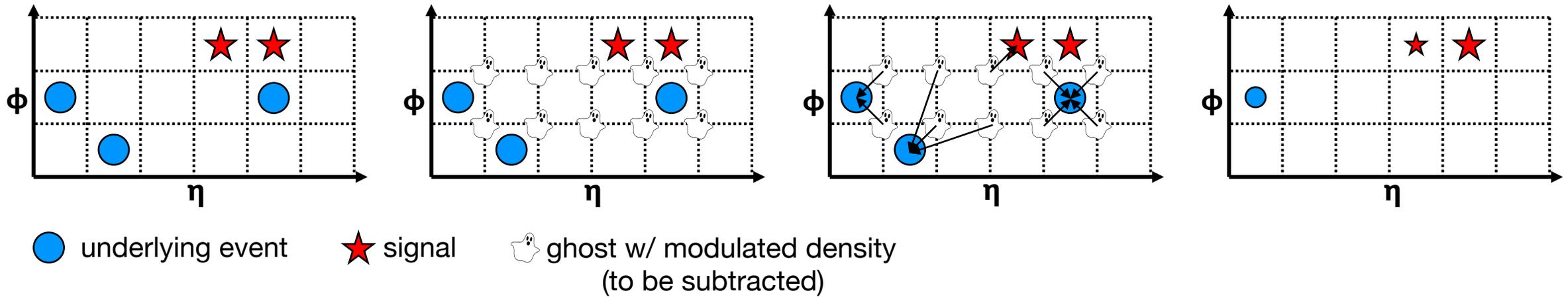
Effects as R increases:

- Energy more spread out
- Jet splitting emerging
- Gluon radiation and medium response recovered
- Quark vs. gluon contributions change

$R_{AA}^R/R_{AA}^{0.2}$ ratio will increase if PbPb recovers energy faster than pp with increasing R

Analysis Strategy

1. Reconstruct jets from particle-flow candidates with anti- k_t algorithm using $R = 0.2, 0.3, 0.4, 0.6, 0.8, 1.0$
2. Subtract underlying event using constituent subtraction and flow modulation



3. Apply jet energy correction
4. Unfold raw data with d'Agostini's algorithm to account for detector effects

Graphic credit: Chris McGinn

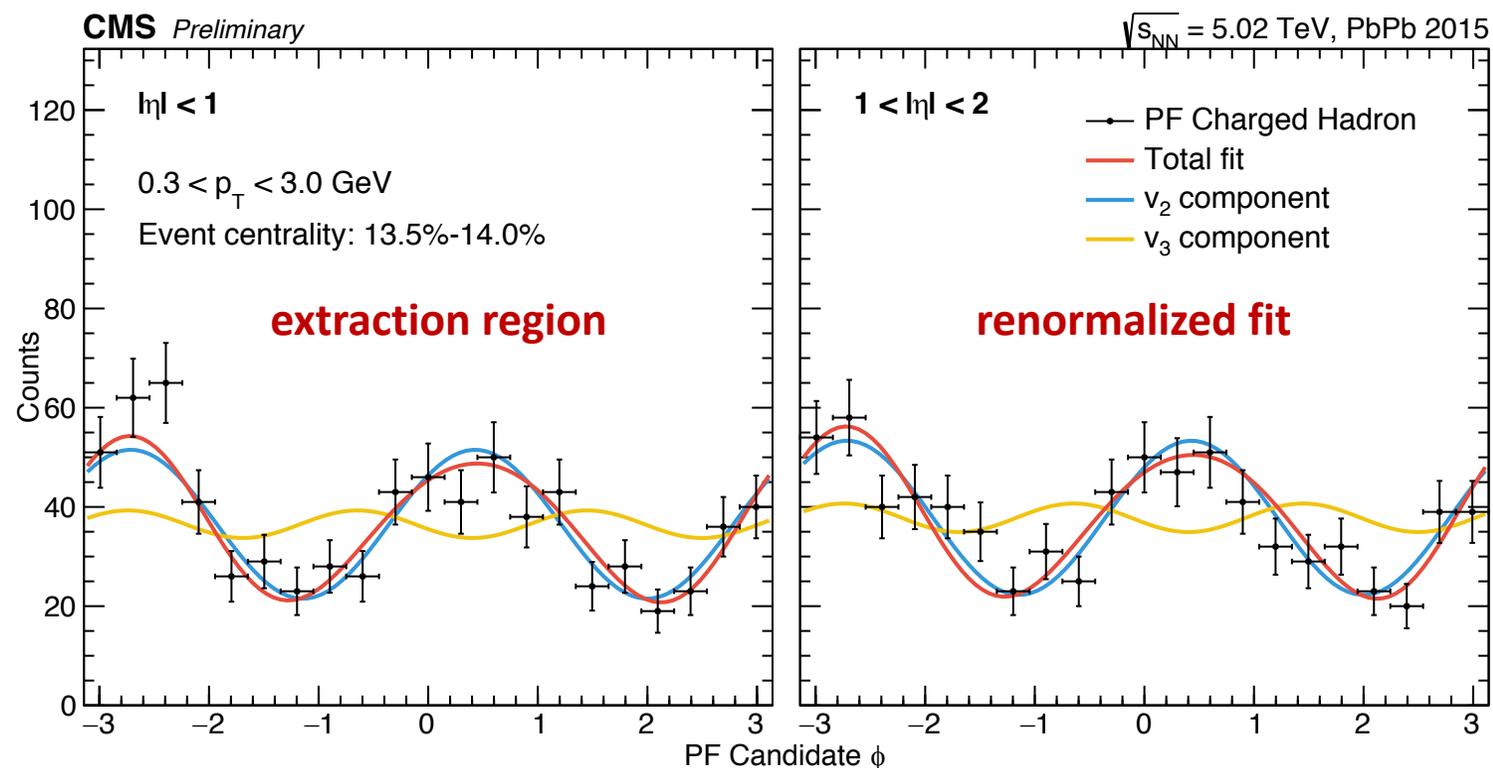
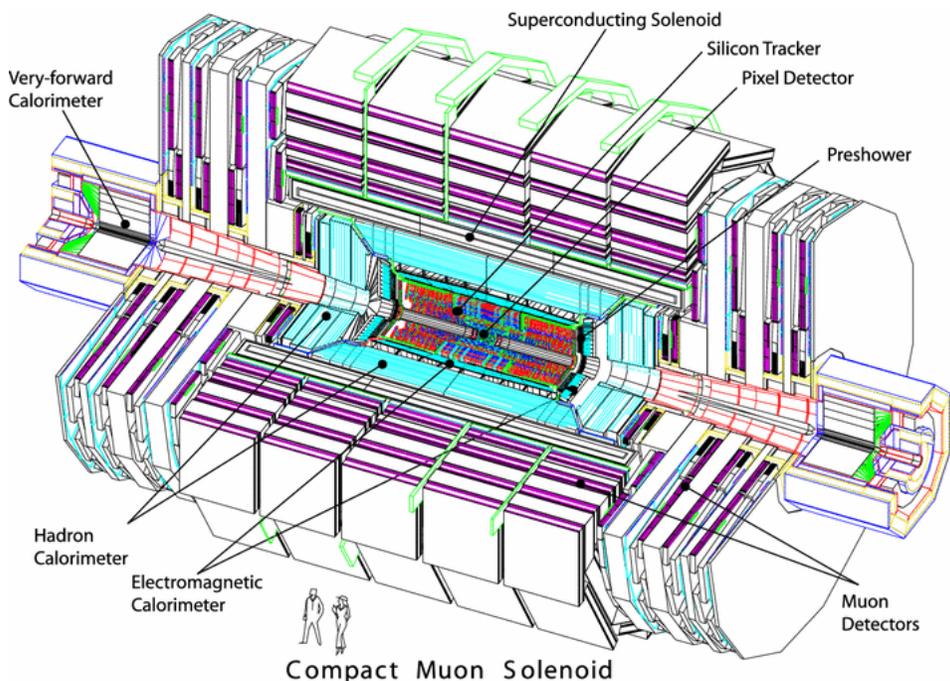
Background Subtraction

Use **constituent subtraction** with **flow-modulated ρ** to account for underlying event fluctuations from elliptic and triangular flow (v_2 and v_3):

JHEP06 (2014) 092

Phys. Lett. B 753
(2016) 424

$$\rho(\eta, \phi) = \rho(\eta) \times (1 + 2v_2 \cos(2[\phi - \Phi_{EP,2}]) + 2v_3 \cos(3[\phi - \Phi_{EP,3}]))$$

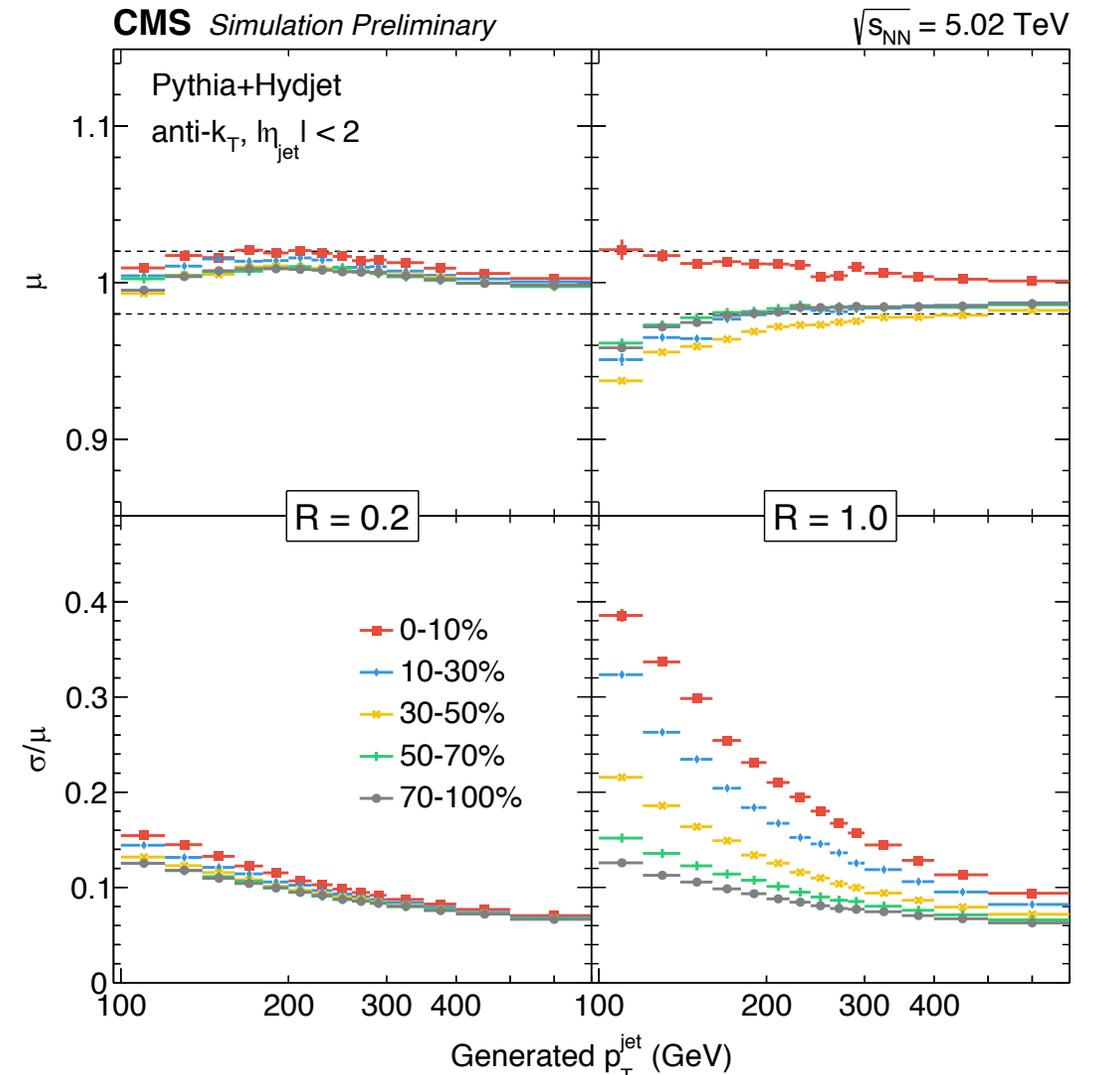


Jet Scale and Resolution

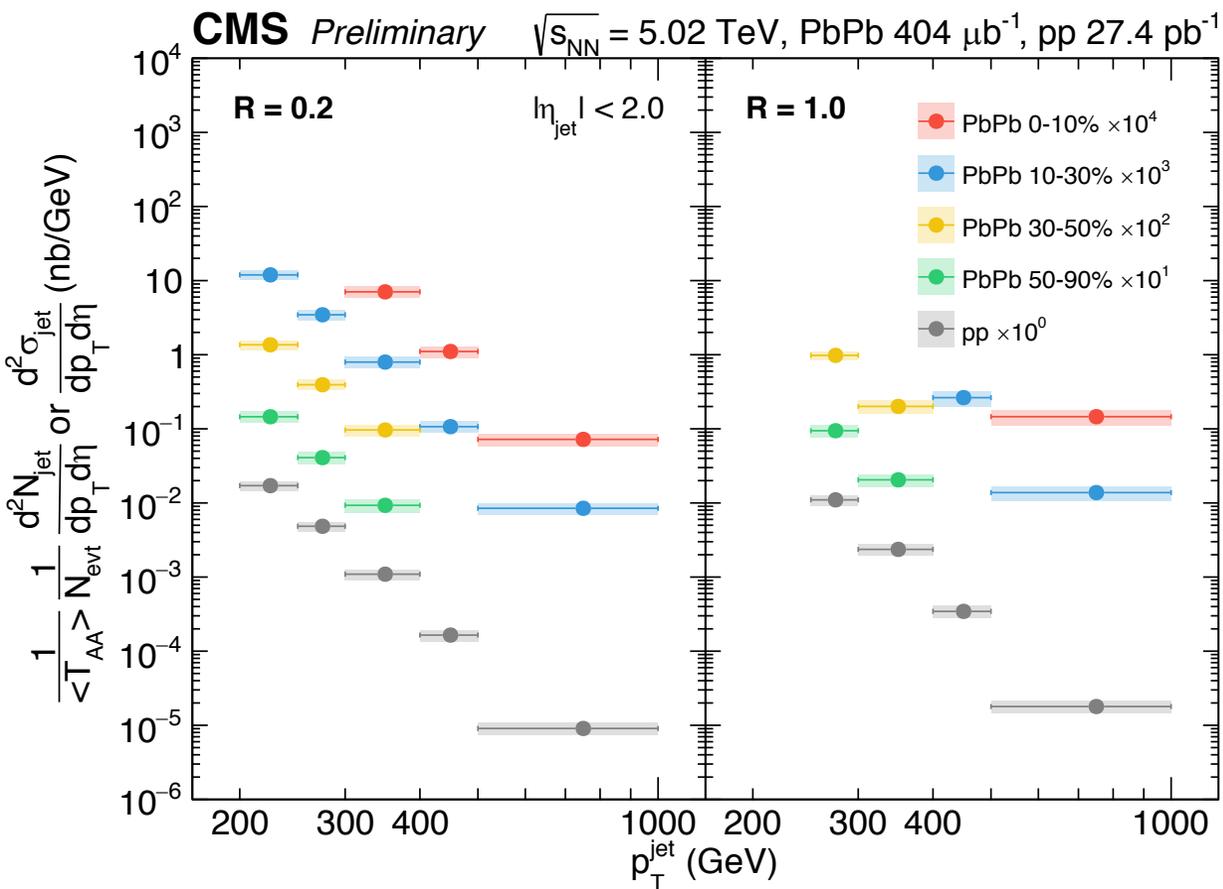
- Flow modulation reduces jet energy resolution $\sim 10\text{-}20\%$
- Evidence of over-subtraction for large R at low p_T since amount subtracted scales with area
- Jets can bias the flow modulation fit leading to additional nonclosure

$$\mu = \langle p_T^{\text{reconstructed}} / p_R^{\text{truth}} \rangle$$

$$\sigma = \sigma(p_T^{\text{reconstructed}} / p_R^{\text{truth}})$$

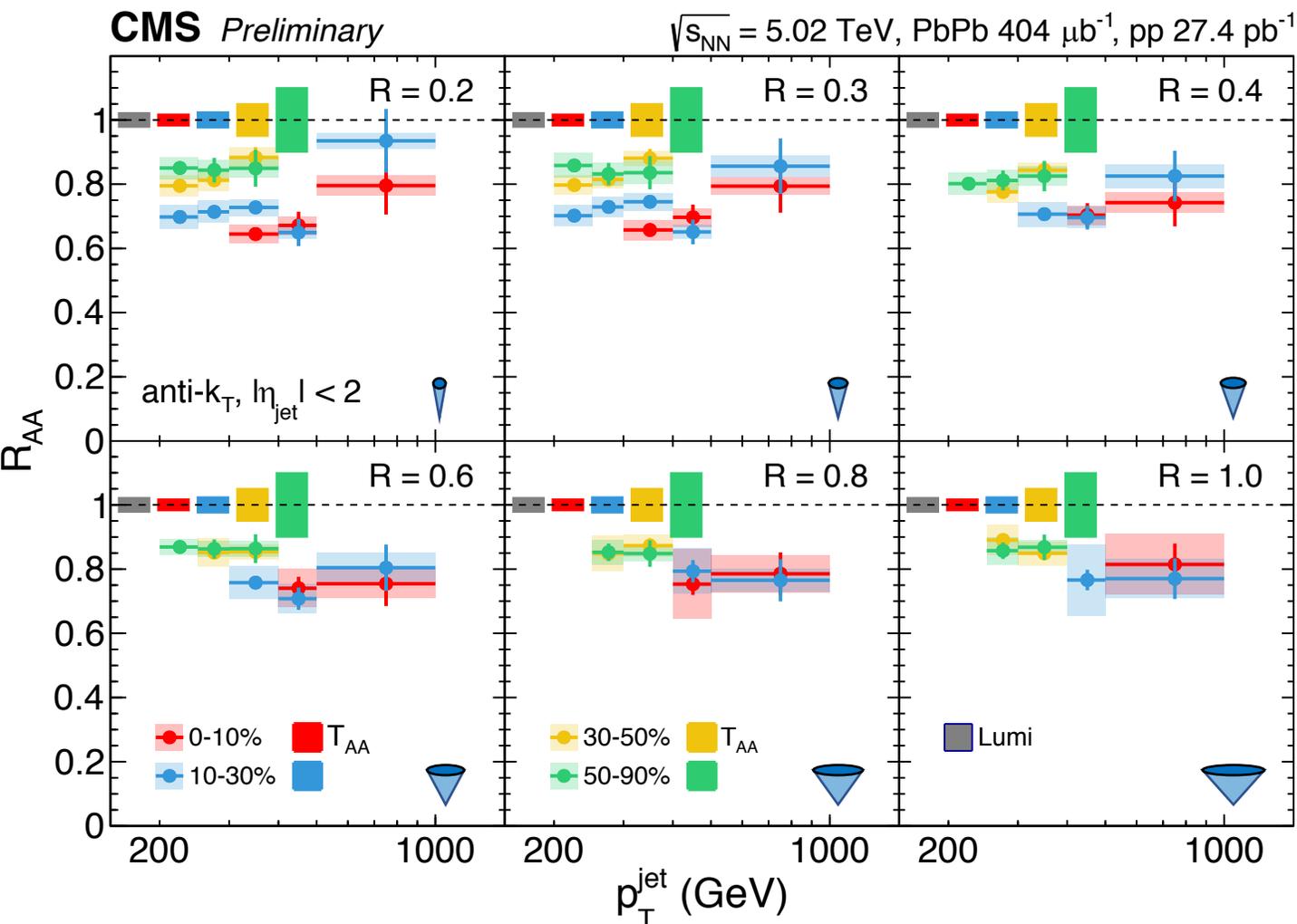


Results: Spectra



- Past results showed R_{AA} has a weak p_T dependence
- \Rightarrow Don't expect much modification in spectra shape, mostly in yield
- Production for $R = 1$ is increased as expected since more energy is included in the jet cone

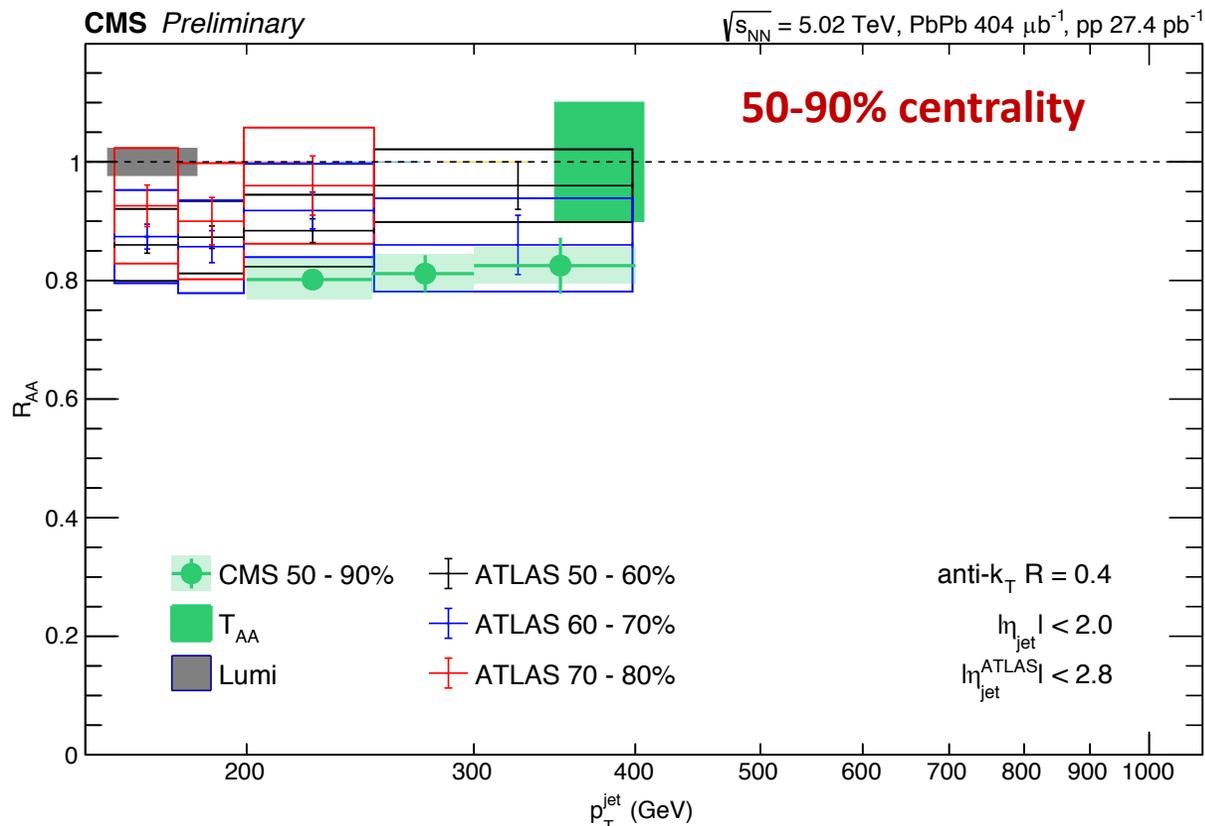
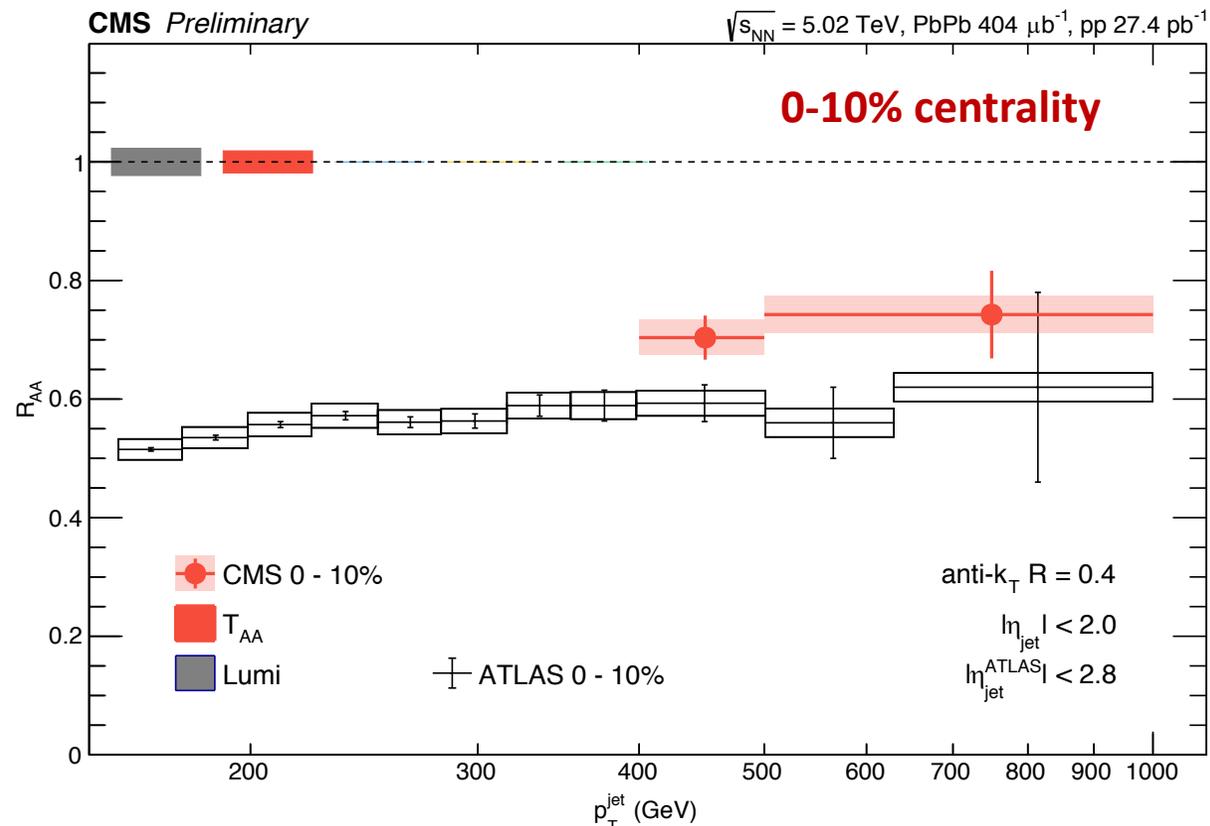
Results: Jet R_{AA}



$$R_{AA}(p_T) = \frac{\text{PbPb jet yield}}{\text{scaled pp jet yield}}$$

- Systematic uncertainties partially cancel
- Central collisions show **strong suppression** for all R
- Most peripheral collisions **consistent with unity**
- Hints of increasing R_{AA} with p_T

ATLAS Jet R_{AA} Comparisons

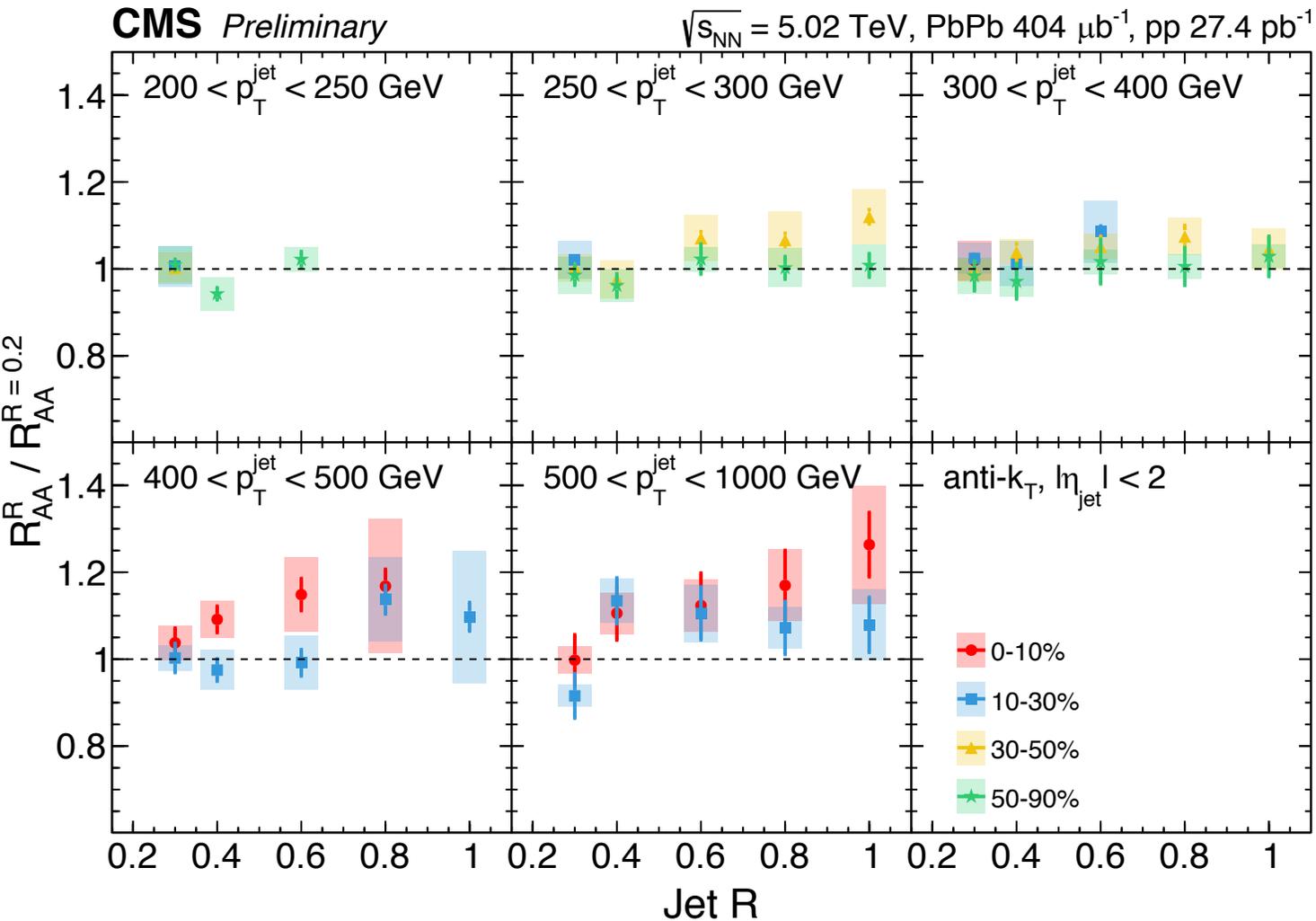


$\sim 1.5 \sigma$ deviation in central collisions

Good agreement for all other centrality classes

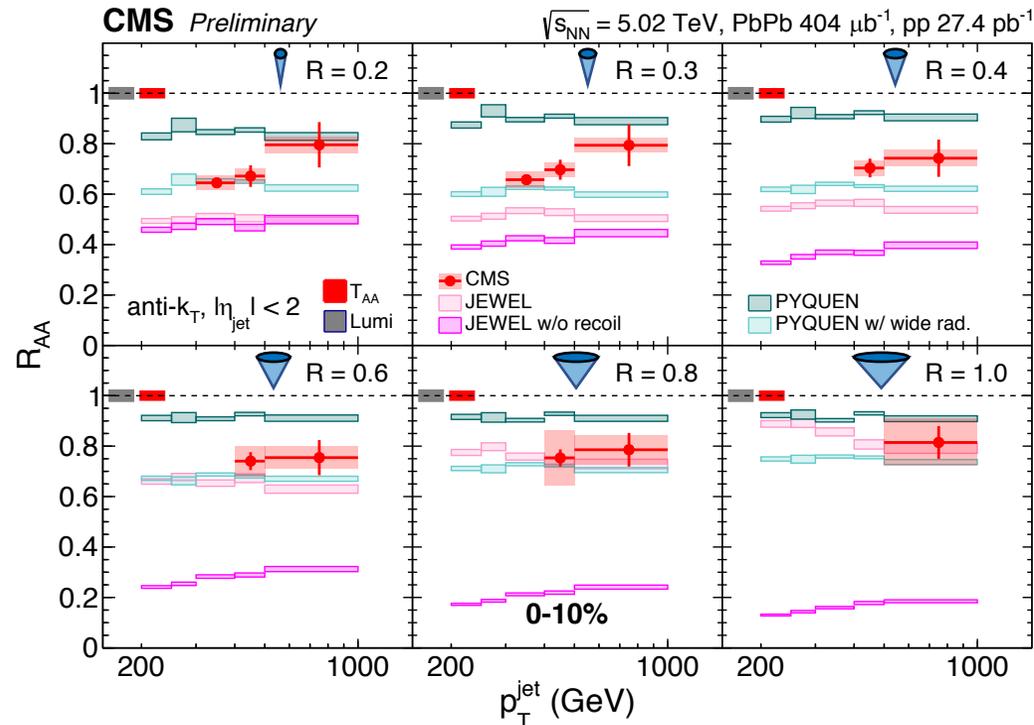
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Results: Jet $R_{AA}^R / R_{AA}^{R=0.2}$



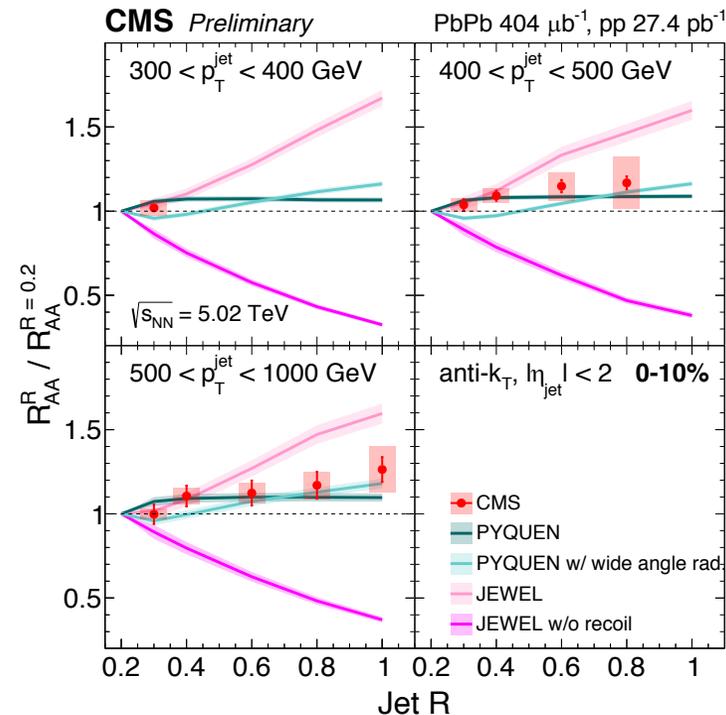
- Double ratio allows further cancellation of systematics
- **Increases if PbPb recovers energy faster than pp with increasing R**
- Central collisions show **light recovery** at high p_T
- Peripheral collisions **consistent with unity**

Theory Comparison: Event Generators



Jewel:

- Scattering and radiative energy loss for hard partons
- Recoiling medium that carries energy away
- Overestimates R dependence



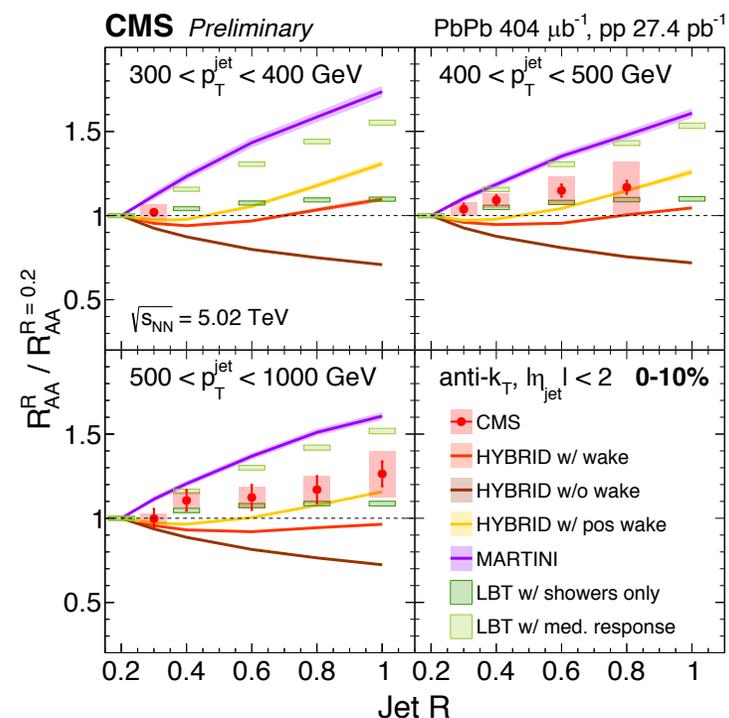
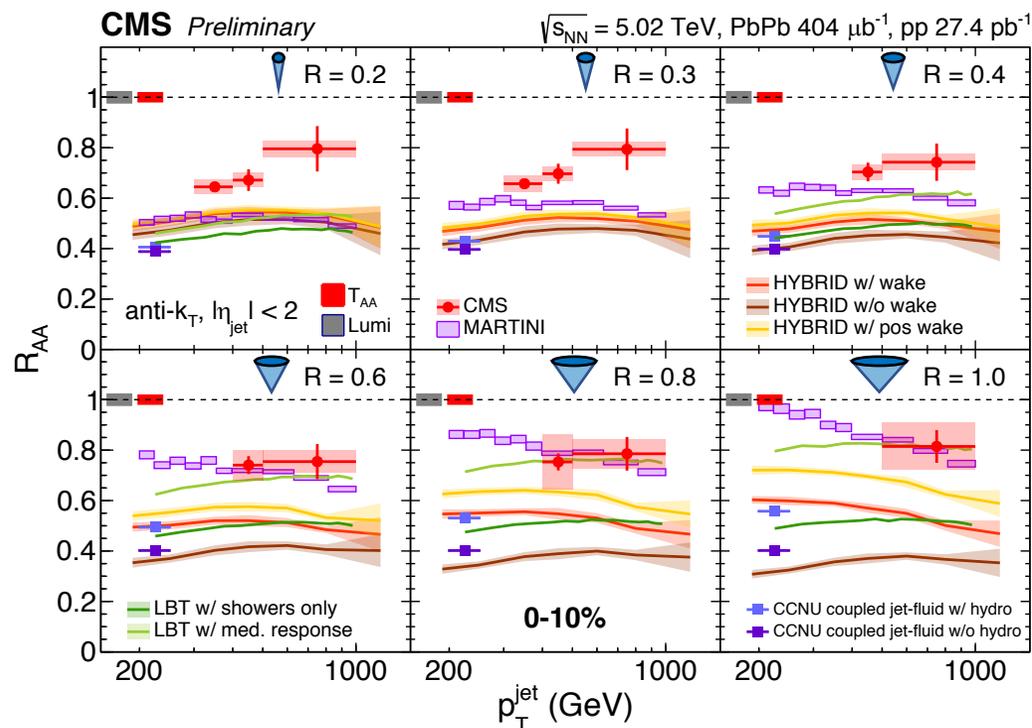
Pyquen:

- Superposition of soft hydro state and hard jets
- Rescattering and radiation for hard partons
- Decent description of R dependence

Jewel: [JHEP 1707 \(2017\) 141](#)

Pyquen: [Eur. Phys. J C16 \(2000\) 527-536](#) & [Eur. Phys. J C46 \(2006\) 211-217](#) & [SINP MSU 2004-14/753](#)

Theory Comparison: Monte Carlo



CCNU coupled jet-fluid: [Phys. Rev. C 94 \(2016\) no.2, 024902](#), [Phys.Rev. C 95 \(2017\) no.4, 044909](#), & [arXiv:1906.09562](#)

MARTINI: [Phys. Rev. C 80 \(2019\) 054913](#)

Hybrid: [arXiv:1907.12301](#) & [JHEP03 \(2017\) 135](#)

LBT: [Phys. Rev. C 99 \(2019\) 054911](#)

wake \Rightarrow full medium response

pos wake \Rightarrow only pos. contribution

no wake \Rightarrow no medium response

MARTINI:

- Hydrodynamic model
- Jets propagate in evolving med.
- Overestimates R dependence

LBT:

- Hydrodynamic medium
- pQCD jets and med. recoil
- Overestimates R dependence

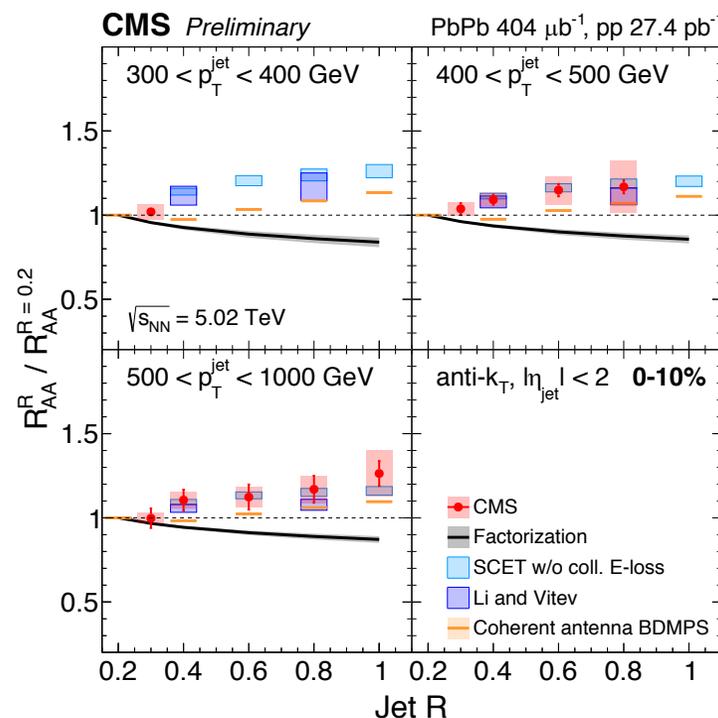
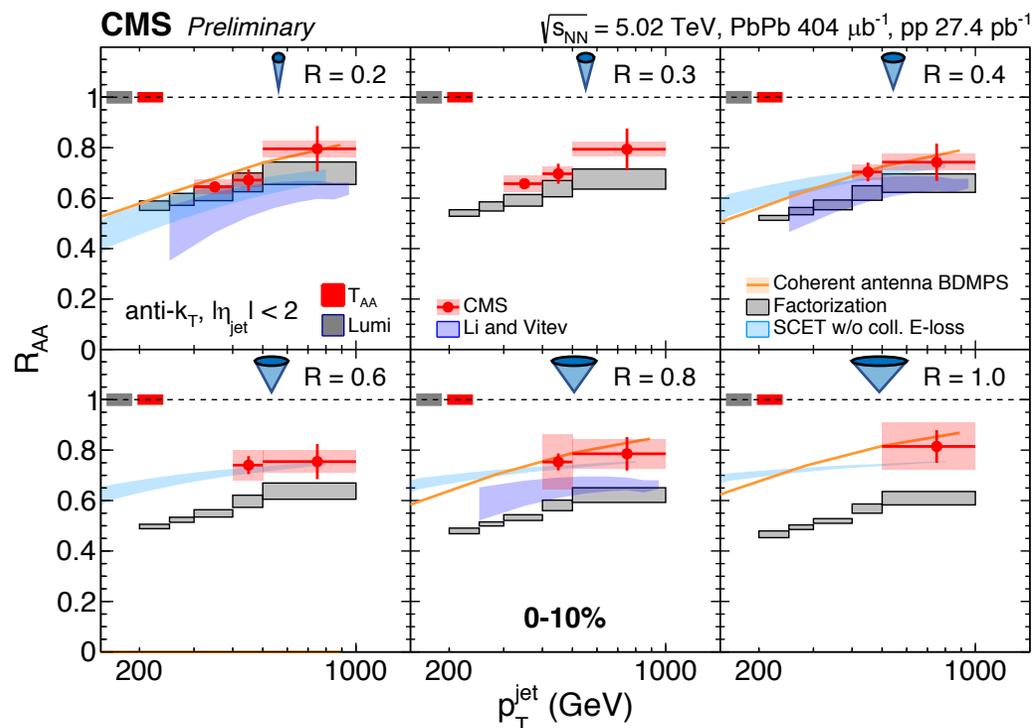
Hybrid:

- Soft contribution + pert. jets
- Wake = full medium response
- Overestimates suppression

CCNU coupled jet-fluid

- Collisions, splitting, p_T broad.
- Viscous hydro medium
- Sensitive to med. response

Theory Comparison: Calculations



Factorization: [Phys. Lett. 122 \(2019\) 252301](#)

Li and Vitev: [JHEP 1907 \(2019\) 148](#)
& [Phys. Lett. B 795 \(2019\) 502-510](#)

SCET_G w/o coll. E-loss: [JHEP05 \(2016\) 023](#)

Coherent antenna BDMPS: [Phys. Rev. D 98 \(2018\) no.5, 051501](#)

Factorization:

- Factorization of jet cross sections
- Jet func. extracted from small R
- Underestimates R dependence

SCET_G w/o coll. energy loss:

- SCET_G models interaction of hard partons with soft gluons
- Great agreement with data

Li and Vitev:

- Use SCET_G framework
- Coll. energy loss & CNM
- Great agreement with data

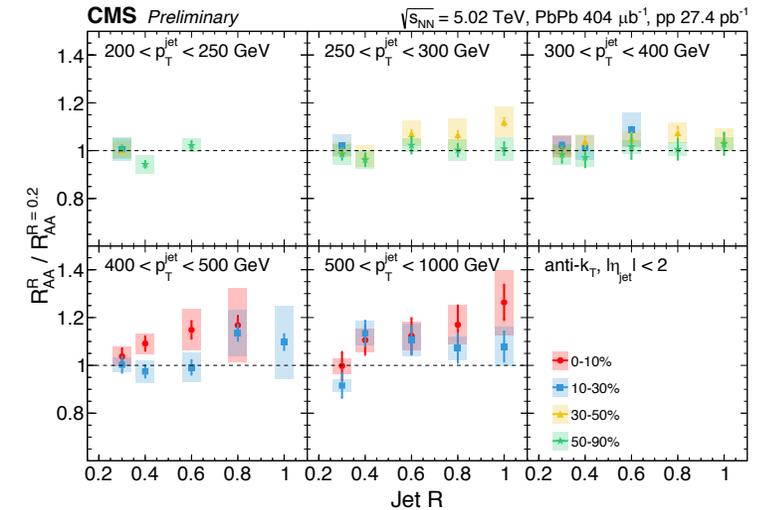
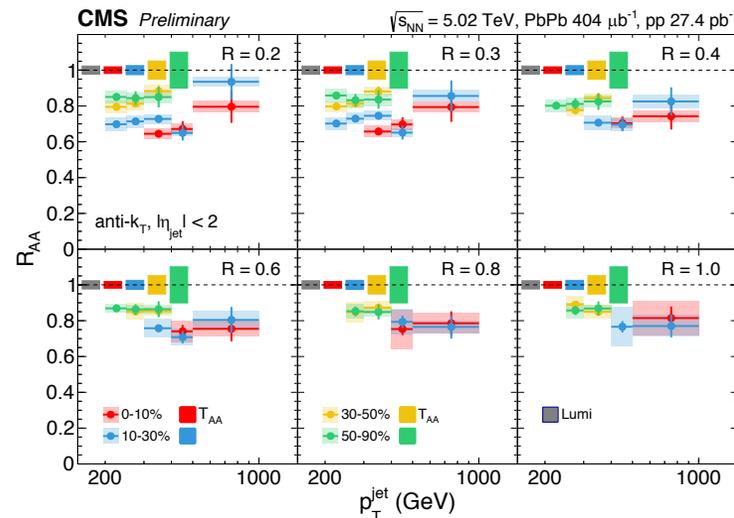
Coherent Antenna BDMPS:

- Quenching & Sudakov factors
- Suppresses large angle fluct.
- Slightly underestimates R dep.

Conclusions

- Measured nuclear modification factor R_{AA} for jets with $R = 0.2, 0.3, 0.4, 0.6, 0.8, 1.0$ based on pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Strong suppression of high p_T jets for all R
- Central collisions: observed recovery of energy faster than the pp reference
- Peripheral collisions: observed no apparent R dependence & little quenching

Measurements sensitive to jet quenching mechanism, medium response, wide angle radiations

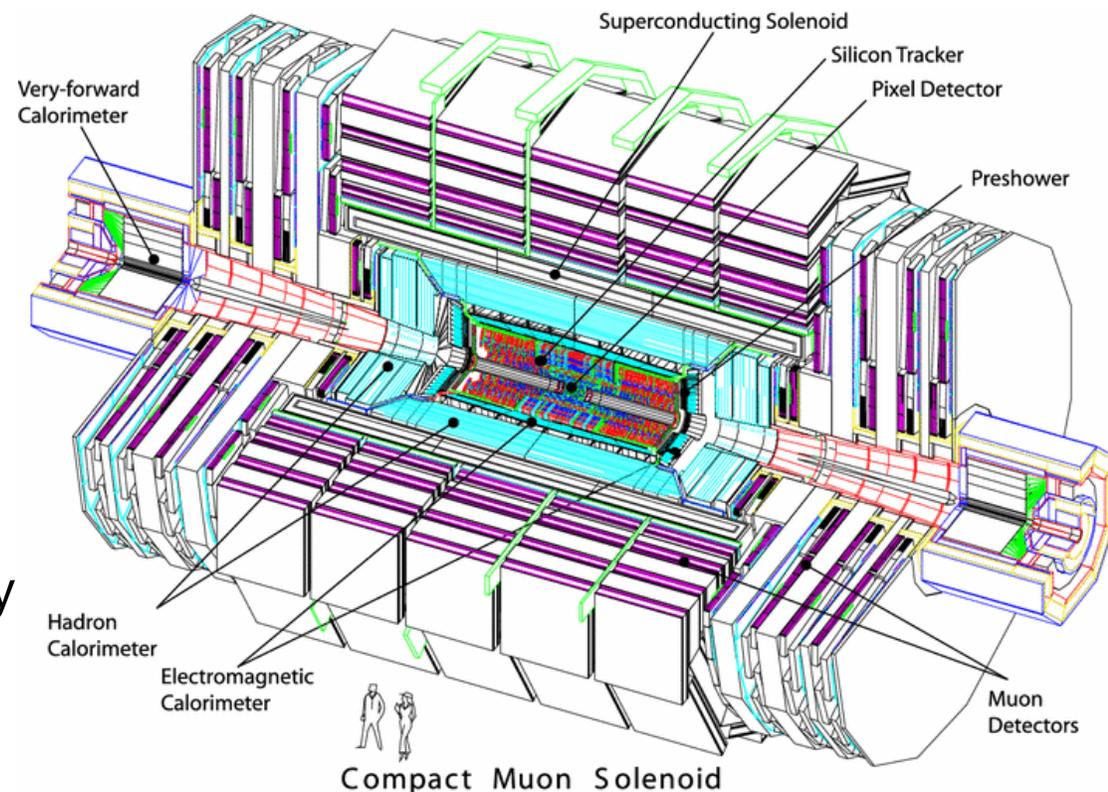


Acknowledgements: The MIT group's work was supported by US DOE-NP.

Backup

Object Selections

- Jet-triggered events with $p_T > 80$ GeV in pp (27.4 pb^{-1}) and PbPb ($404 \text{ } \mu\text{b}^{-1}$) collisions at $\sqrt{s_{NN}} = 5.02$ TeV
 - Selected high p_T jets ($p_T > 200$ GeV) with $|\eta| < 2$
 - To remove non-collision events require vertex $|z| < 15$ cm, 3 HF towers > 3 GeV, cluster shape compatibility
- Categorize by event centrality = degree of overlap of lead ions
 - 0% centrality corresponds to head-on collision
 - Centrality determined by the sum of transverse energy from HF calorimeter towers
 - Used centrality intervals 0–10%, 10–30%, 30–50%, and 50–90%
- Triggering is fully efficient in both pp and PbPb collisions for this selection



Background Subtraction

Need to remove the soft underlying event (UE)

Use **constituent subtraction (CS)** with estimated UE density ρ

- Add ghost particles on η - ϕ grid according to $p_T^{ghost} = A_{ghost} \cdot \rho$, $m_\delta^{ghost} = A_{ghost} \cdot \rho_m$ where A_{ghost} is the area of the ghost
- Choose ghosts and real particles to combine in order of decreasing

$$\Delta R_{i,k} = p_{Ti}^\alpha \cdot \sqrt{(y_i - y_k^{ghost})^2 + (\varphi_i - \varphi_k^{ghost})^2}$$

- Where ghost p_T exceeds real p_T , remove the real particle and reduce ghost p_T by real (and vice versa)
- Continue until all ghosts are gone

[JHEP06 \(2014\) 092](#)

Background Subtraction

Use constituent subtraction (CS) with **flow-modulated ρ** to account for UE variations from triangular and elliptic flow (v_2 and v_3):

$$(1) \quad N(\phi) = N_0(1 + 2v_2 \cos(2[\phi - \Phi_{EP,2}]) + 2v_3 \cos(3[\phi - \Phi_{EP,3}]))$$

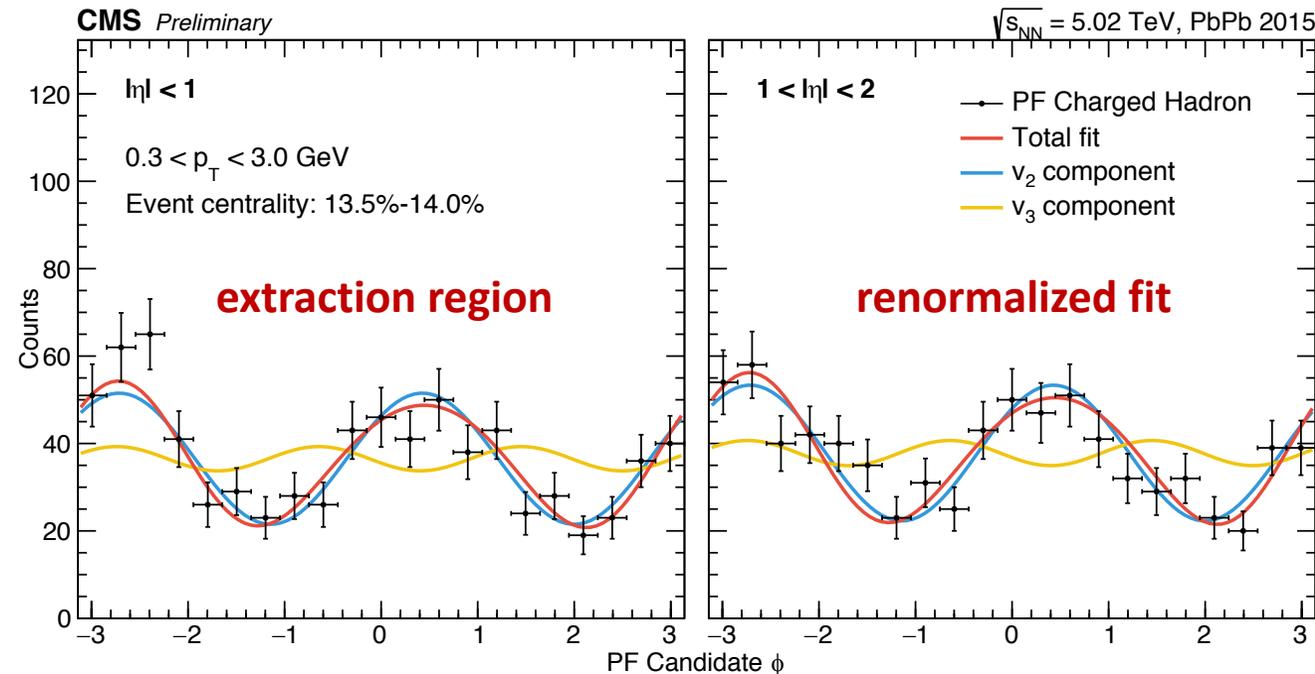
$$(2) \quad \rho(\eta, \phi) = \rho(\eta) \times (1 + 2v_2 \cos(2[\phi - \Phi_{EP,2}]) + 2v_3 \cos(3[\phi - \Phi_{EP,3}]))$$

Phys. Lett. B 753
(2016) 424

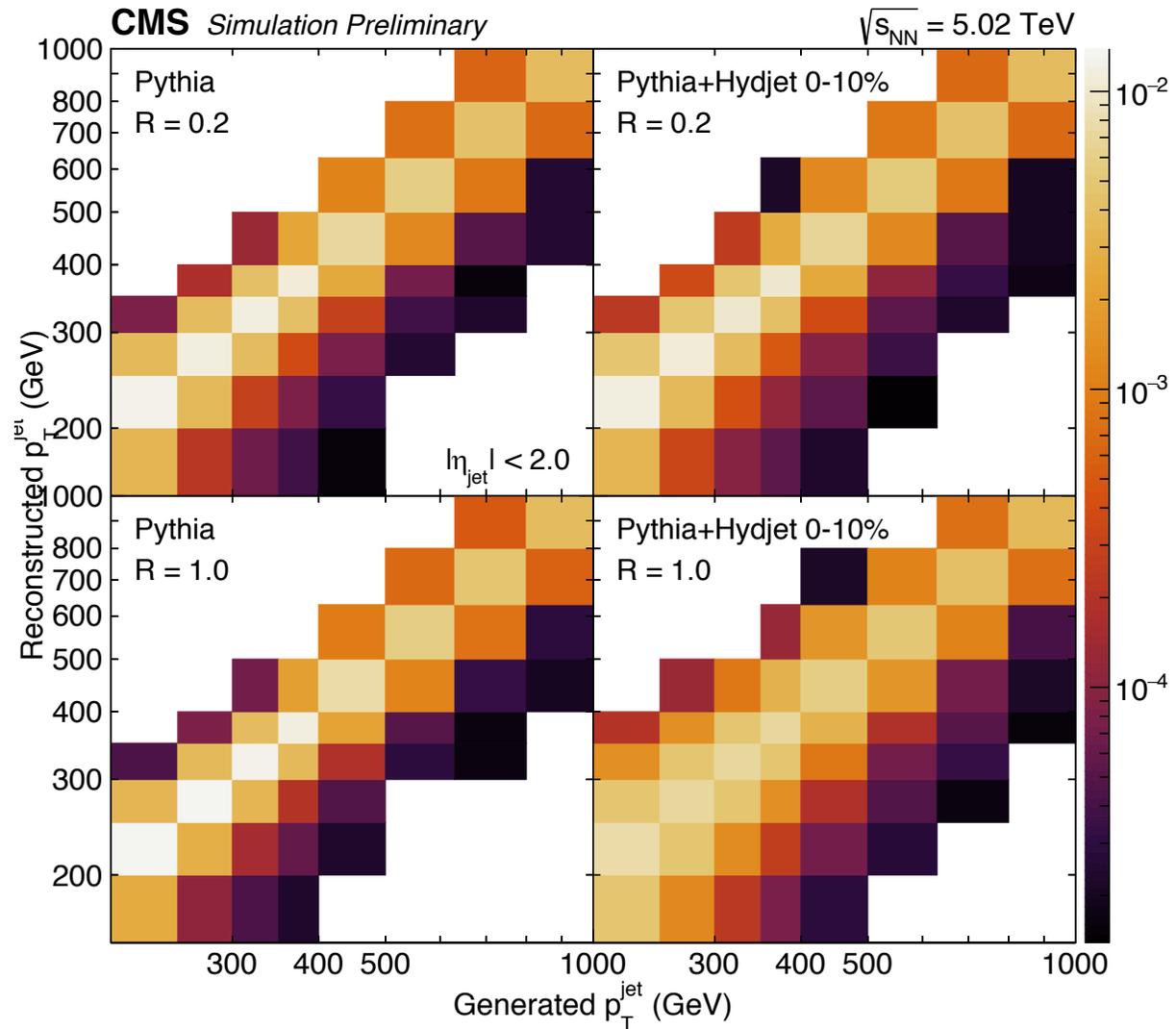
Step 1: Find event plane angles for v_2 and v_3 : $\Phi_{EP,2}$ and $\Phi_{EP,3}$ using HF calorimeters ($3 < |\eta| < 5$)

Step 2: Fit PF candidates with $0.3 < p_T < 3.0$ GeV and $|\eta| < 1$ using Eqn. 1 to get N_0 , v_2 , and $v_3 \Rightarrow \rho(\eta, \phi)$ (Eqn. 2)

Discard if bad fit or insufficient statistics $\Rightarrow \rho(\eta, \phi)$ estimated to be flat

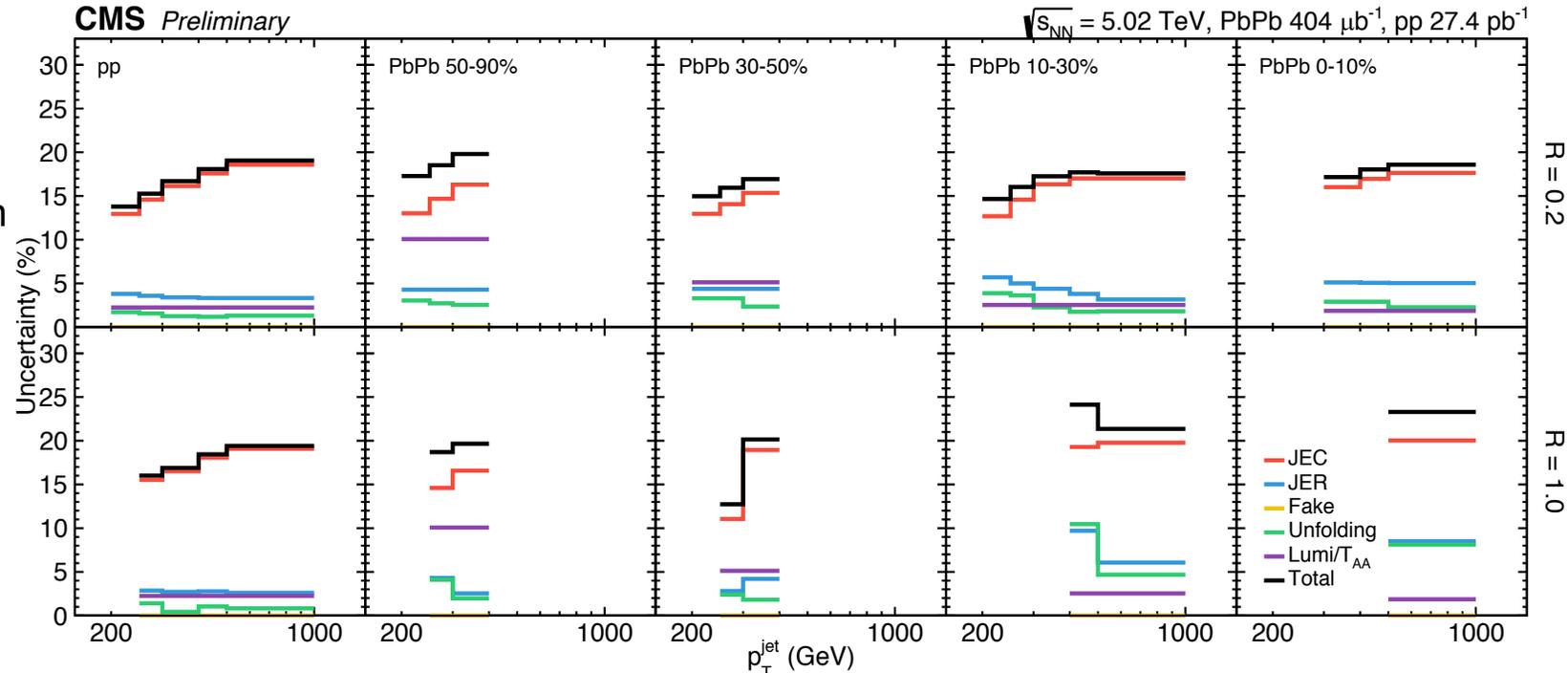


Response Matrices



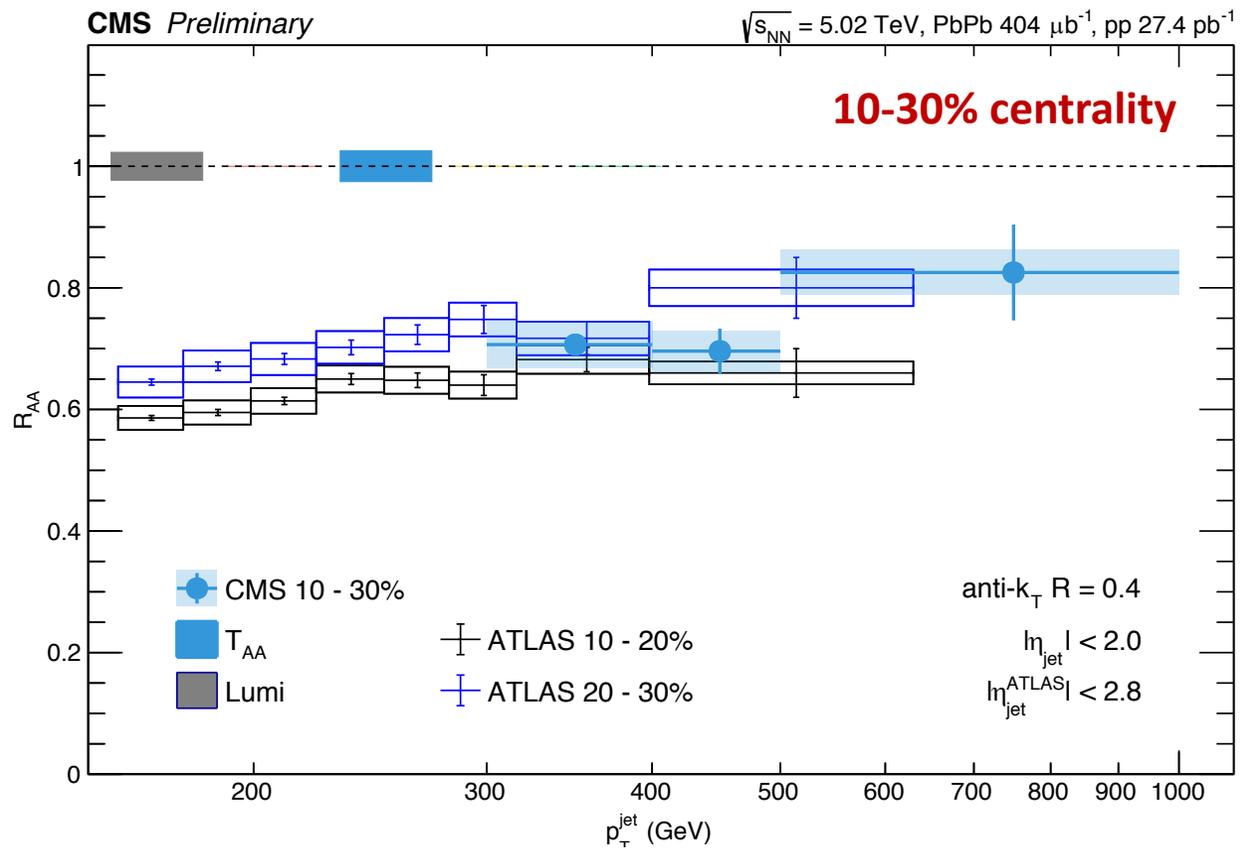
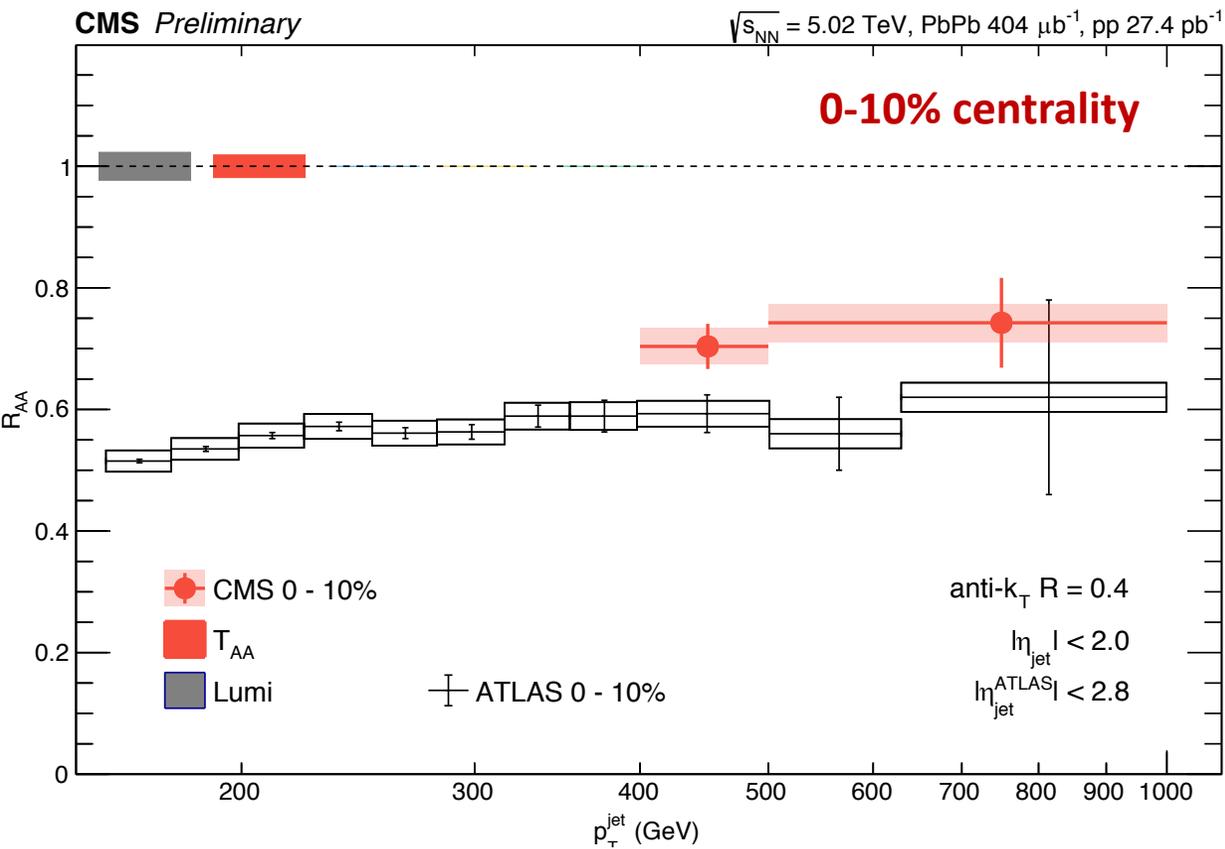
Systematics

- Jet energy scale (JES) uncertainty ranges from 15-20%
 - Nonclosure from simulation
 - Data/simulation differences
 - UE difference between data/simulation (cancels in R_{AA} ratios but not R_{AA})
- Jet energy resolution (JER)
 - Uncertainty from simulation (does not cancel in R_{AA})
 - Data/simulation differences (partial cancellation in R_{AA})
- Fake jets contamination evaluated from simulation (negligible)
- Unfolding uncertainty is 5-10%
 - Choice of prior
 - Unfolding algorithm: Bayesian vs SVD



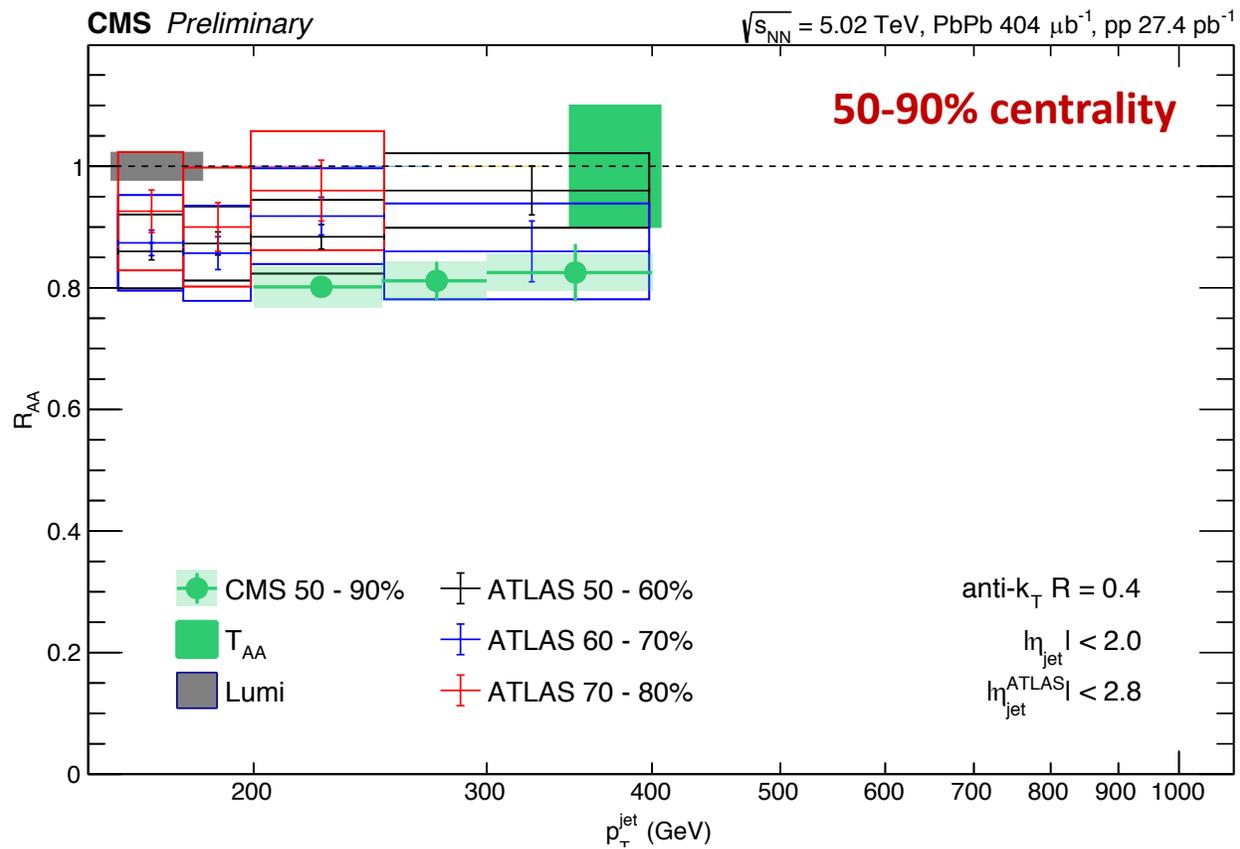
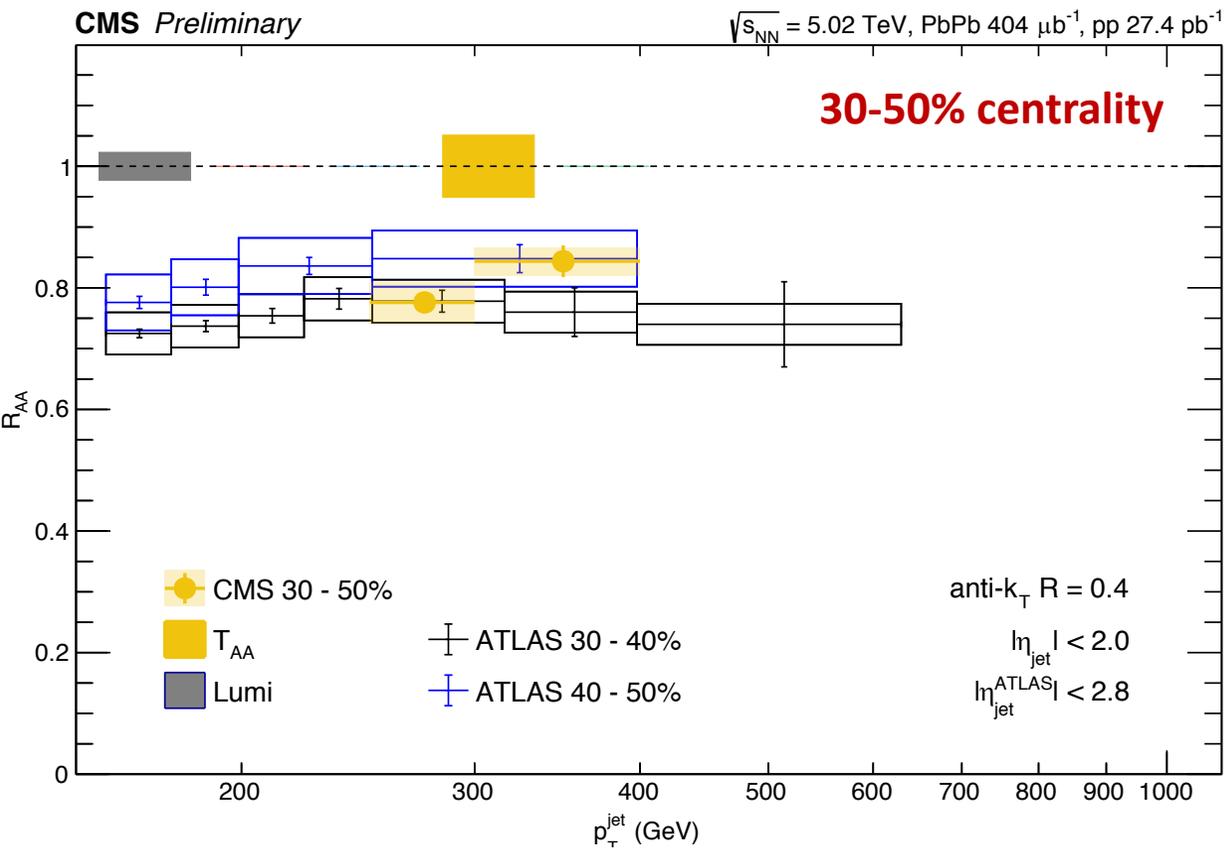
- Luminosity / T_{AA}
 - pp integrated luminosity uncertainty is 2.3%
 - T_{AA} relative uncertainty is 3-11% from central to peripheral

ATLAS Jet R_{AA} Comparisons



[Phys. Rev. B 790 \(2019\) 108](#)

ATLAS Jet R_{AA} Comparisons



[Phys. Rev. B 790 \(2019\) 108](#)

Results: Spectra Ratio

