

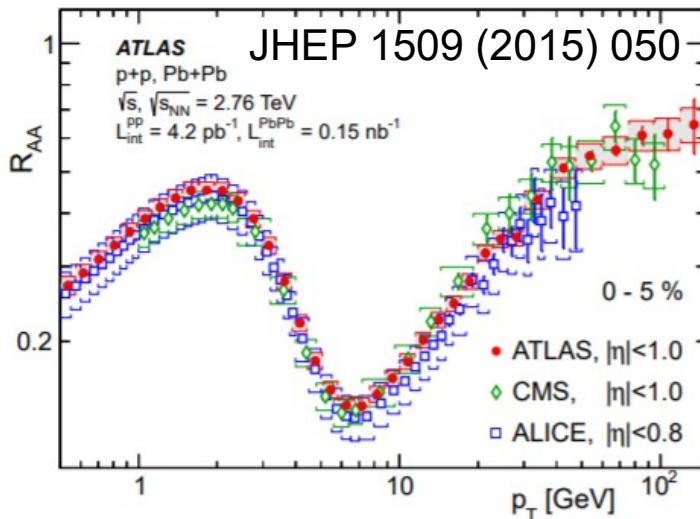
# Charged Particle Nuclear Modification Factors in pPb, PbPb, and XeXe Collisions with CMS

Austin Baty for the CMS Collaboration

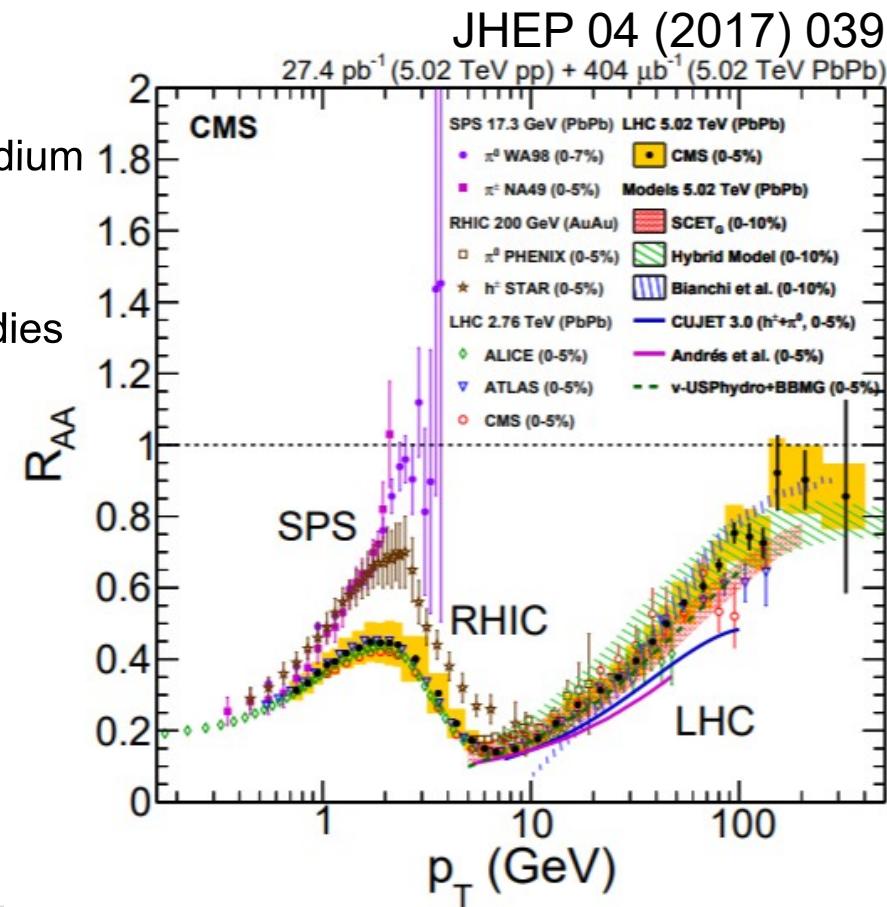
Quark Matter 2018  
Venice, Italy  
May 15, 2018

# Introduction

- Charged particle  $R_{AA}$  is a well-studied observable
- Sensitive to many effects:
  - nPDF effects
  - Cronin effect
  - Hydrodynamic flow
  - Parton energy loss
- Strong suppression indicates presence of hot medium
- Detailed understanding of particle spectra helps constrain models of the QGP
- Also useful as reference for flavor-dependent studies

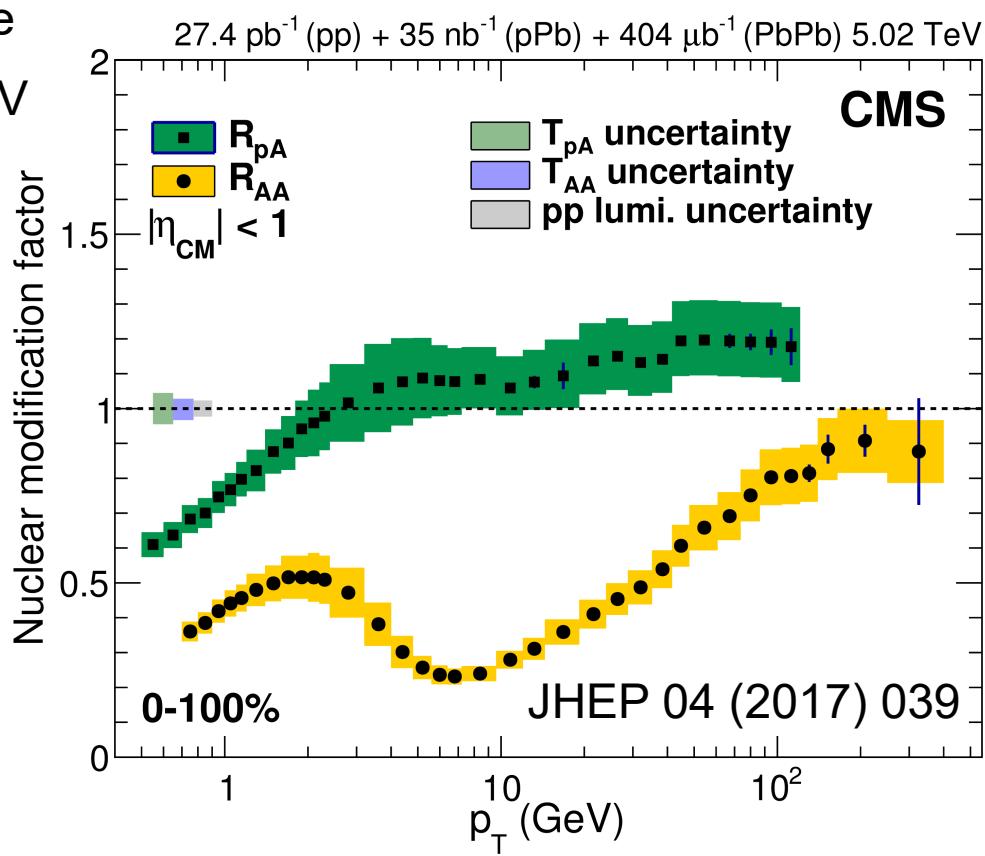


$$R_{AA}(p_T) = \frac{d^2 N^{AA}/dp_T d\eta}{T_{AA} d^2 \sigma^{NN}/dp_T d\eta'}$$



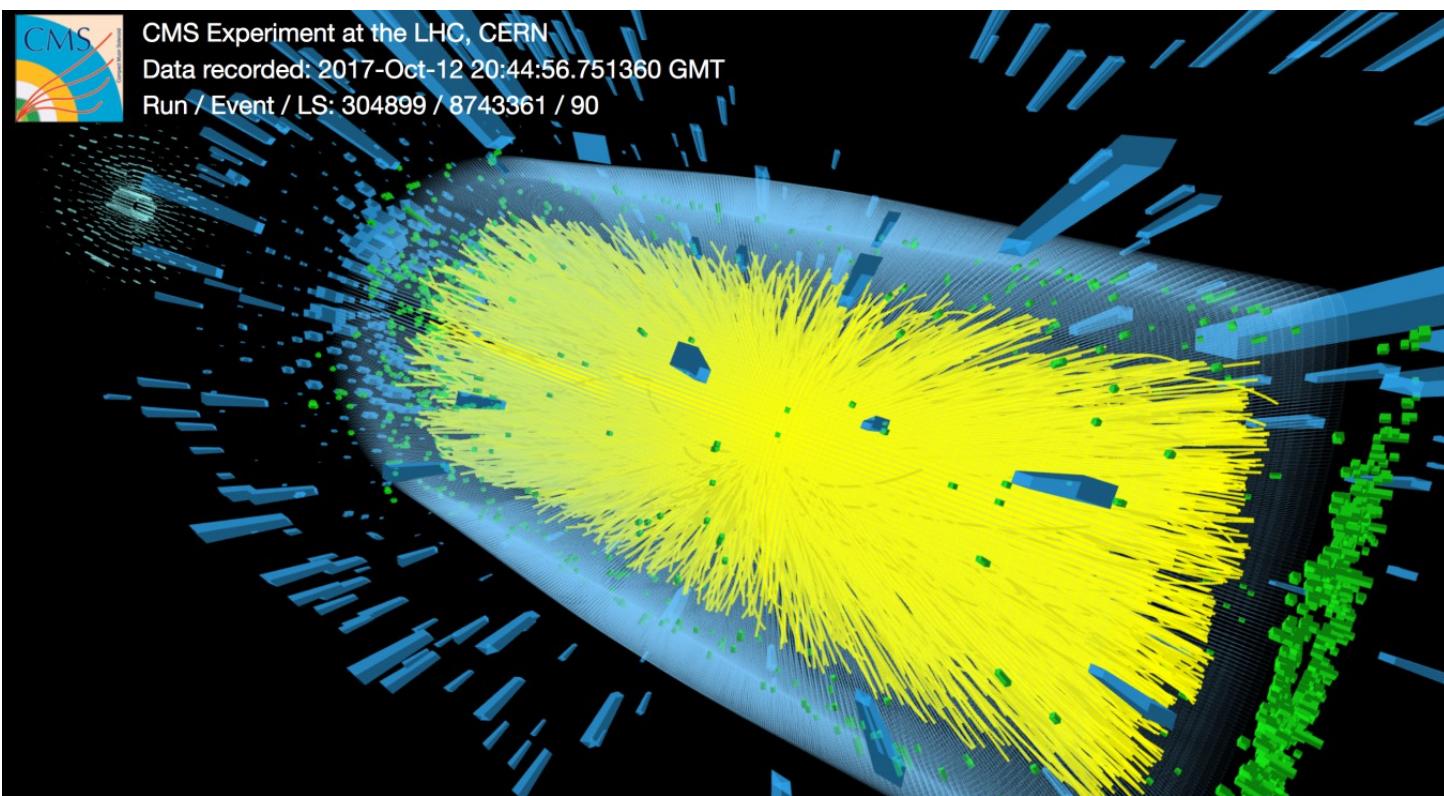
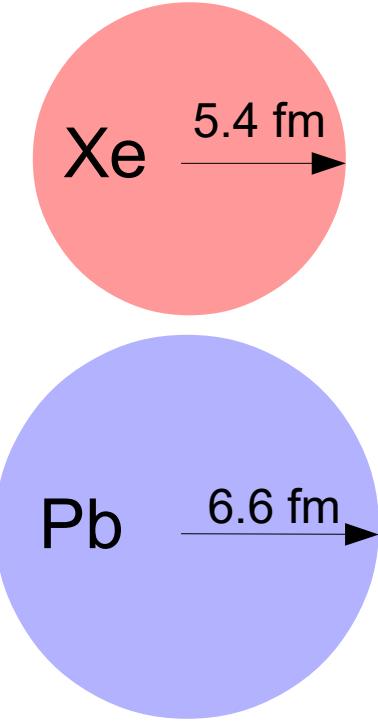
# 5.02 TeV PbPb $R_{AA}$ and $R_{pPb}$

- Measured  $R_{AA}$  up to 300 GeV with 5.02 TeV PbPb data
- Strong suppression similar to 2.76 TeV PbPb
  - Rising trend between 10 to 100 GeV
- $R_{pPb}$  updated with measured pp reference
- Shadowing effects significant at  $p_T < 2$  GeV
- Slight enhancement seen at higher- $p_T$ 
  - Radial flow ( $\sim 3$  GeV)
  - Cronin effect ( $\sim 3$  GeV)
  - Anti-shadowing ( $> 30$  GeV)
- Initial-state effects not responsible for suppression seen in  $R_{AA}$  above  $\sim 3$  GeV



# XeXe Collisions at 5.44 TeV

- CMS gathered 19M ( $3.42 \mu\text{b}^{-1}$ ) of  $^{129}\text{Xe}$  collisions in fall 2017
- Unique opportunity to study a mid-sized collision system at LHC
- Tests strength of suppression signal vs system size
- Probes path-length dependence of parton energy loss

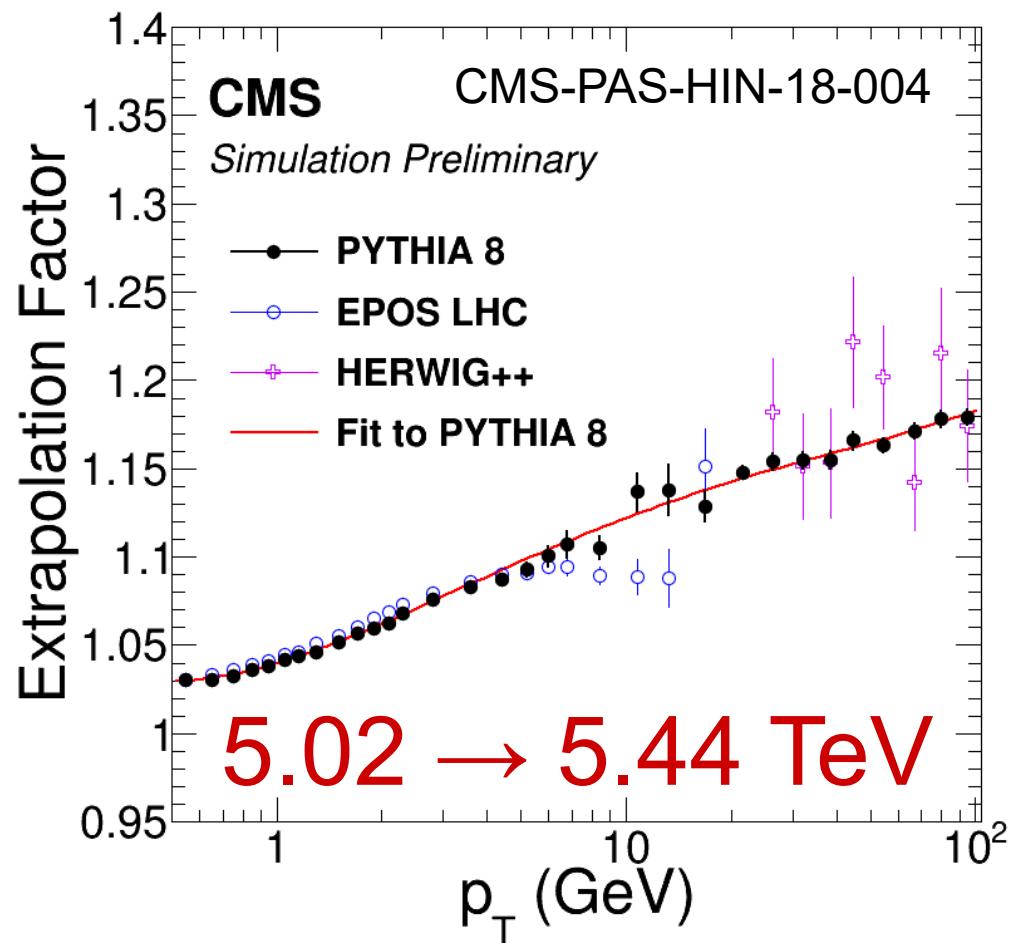


# 5.44 TeV pp reference



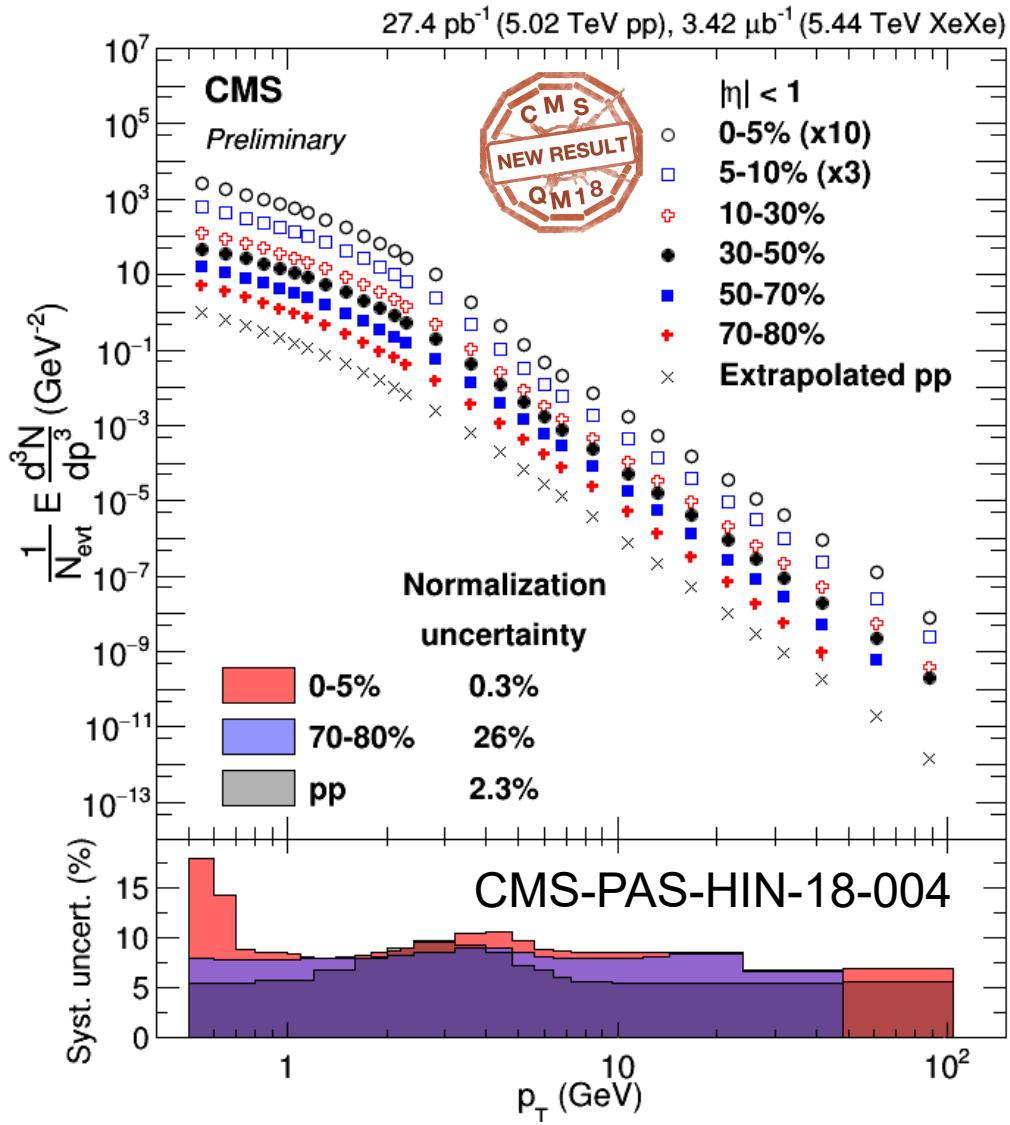
- No pp data at 5.44 TeV exists
- MC-based extrapolation of 5.02 TeV spectrum
- Extrapolation factor from 3-18%
- Cross-checked with:
  - EPOS LHC
  - Herwig++
  - Extrapolation from 7 TeV pp
  - 'relative placement' procedures
  - $x_T$  scaling procedures
- All methods found to be consistent within a few %

$$\left( \frac{d\sigma_{5.44}^{pp}}{dp_T} \right)_{\text{Extrap.}} = \left( \frac{d\sigma_{5.44}^{pp}}{dp_T} \right)_{\text{MC}} \left( \frac{d\sigma_{5.02}^{pp}}{dp_T} \right)_{\text{Data}}$$



# XeXe spectra

- XeXe spectra in 6 centrality bins
  - $p_T$ =0.5 to 100 GeV
- Similar power-law behavior as pp reference ( $p_T > 10$  GeV)
- Largest uncertainties at low- $p_T$  in central events from tracking
- Peripheral XeXe has large normalization uncertainty
  - Event selection efficiency
- pp reference uncertainty dominated by 5 TeV measurement

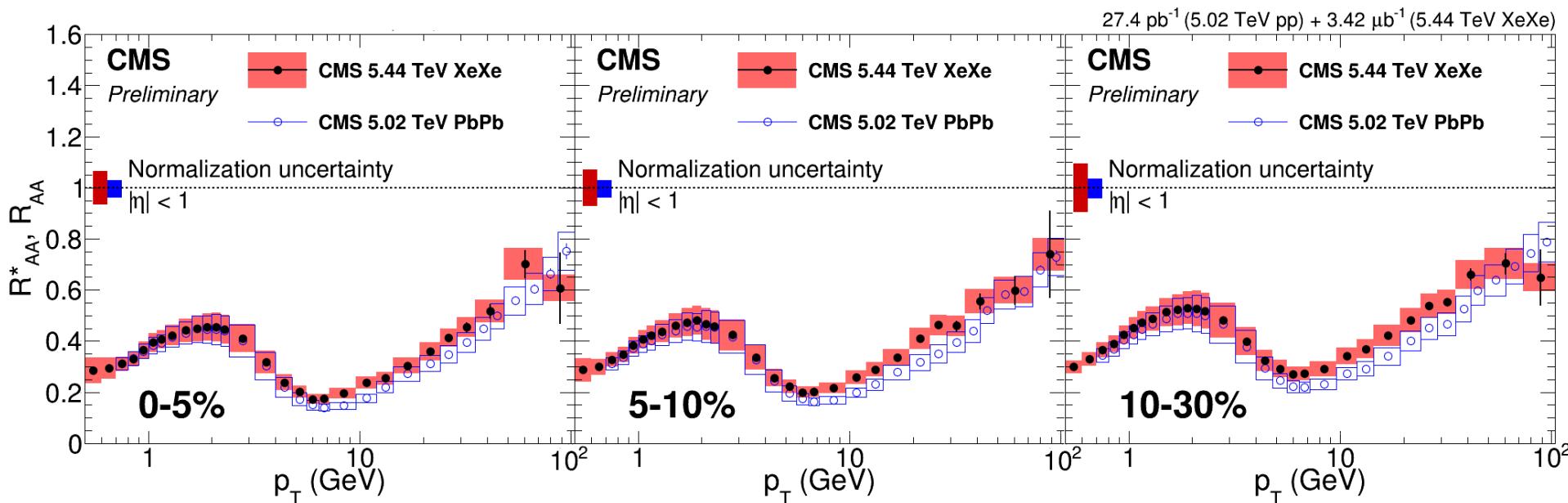


# $R_{AA}^*$ – central events

- $R_{AA}^*$  – asterisk denotes use of extrapolated reference
- XeXe  $R_{AA}^*$  compared with PbPb  $R_{AA}$
- Strong suppression in XeXe
  - Similar oscillatory shape as PbPb
- XeXe and PbPb agree well for  $p_T < 3$  GeV
- Indication of less suppression at higher  $p_T$



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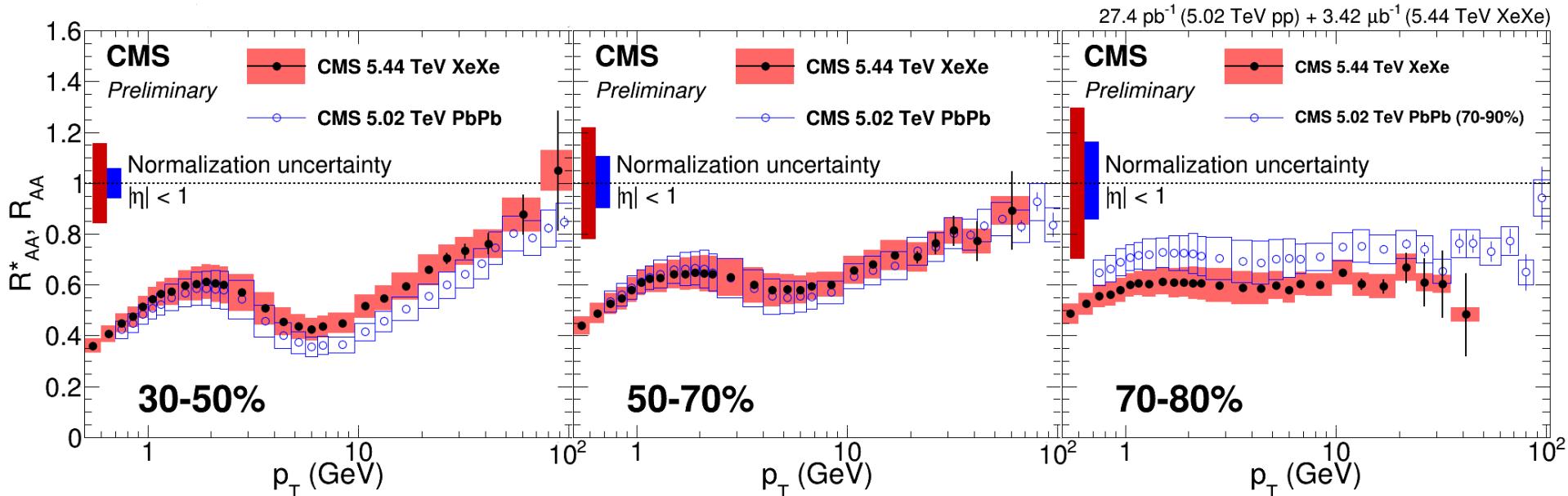


# $R^*_\text{AA}$ – peripheral events

- XeXe  $R^*_\text{AA}$  increases in more peripheral events until last centrality bin
- Flat trend in 70-80% XeXe
  - Larger suppression than 70-90% PbPb events
  - 30% normalization uncertainty ( $T_\text{AA}$  + event selection efficiency)
- Strong quenching not expected in peripheral events
  - Could also be affected by  $p_T$ -dependent event selection biases



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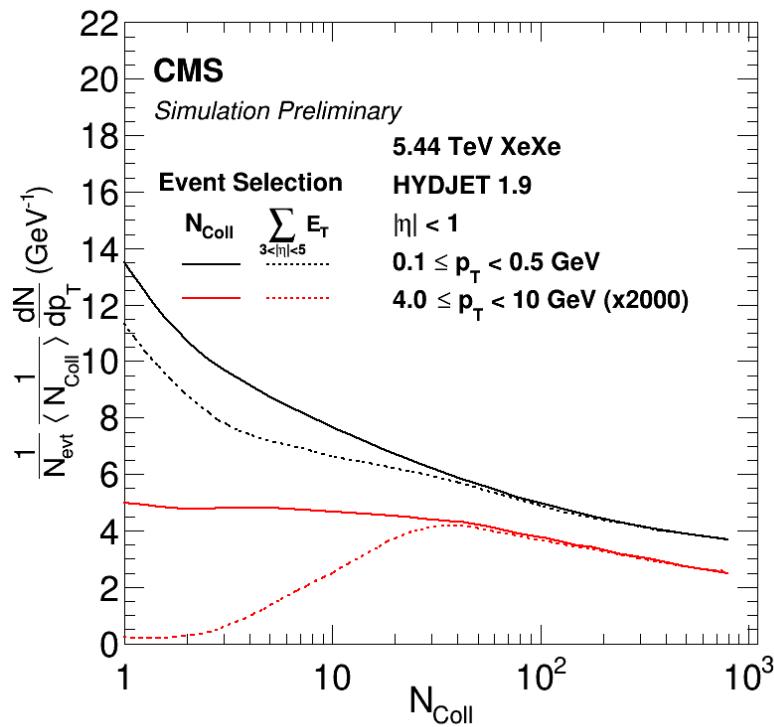


# Event Selection Bias

- Charged particle yields compared using  $N_{\text{coll}}$  vs forward  $E_T$  selection
- Depletion of particles for low  $N_{\text{coll}}$  events

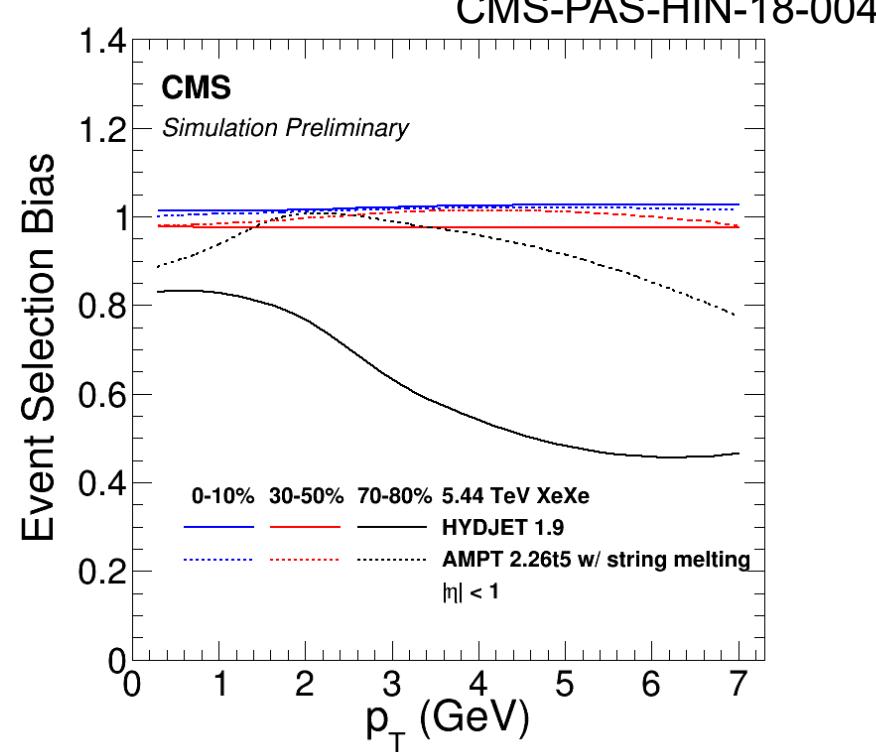
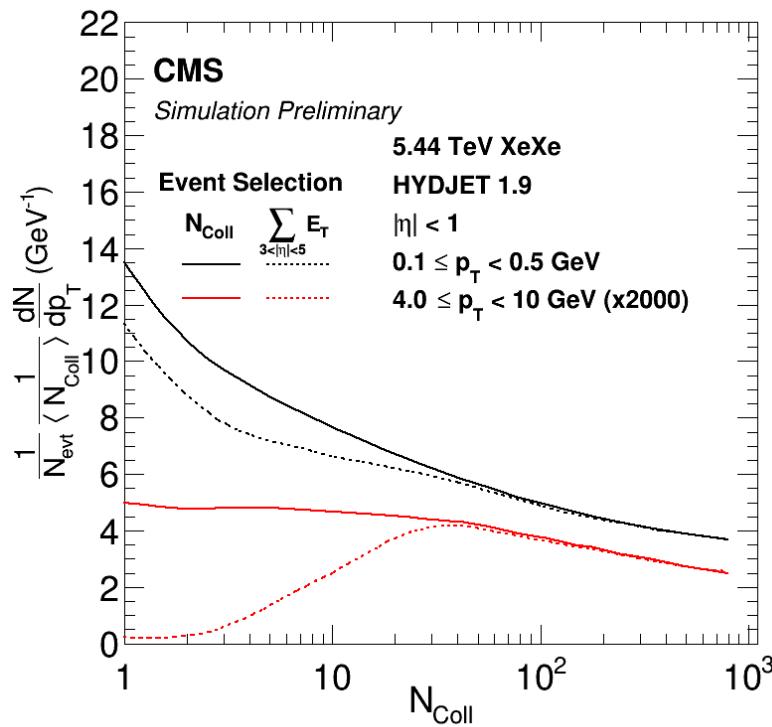


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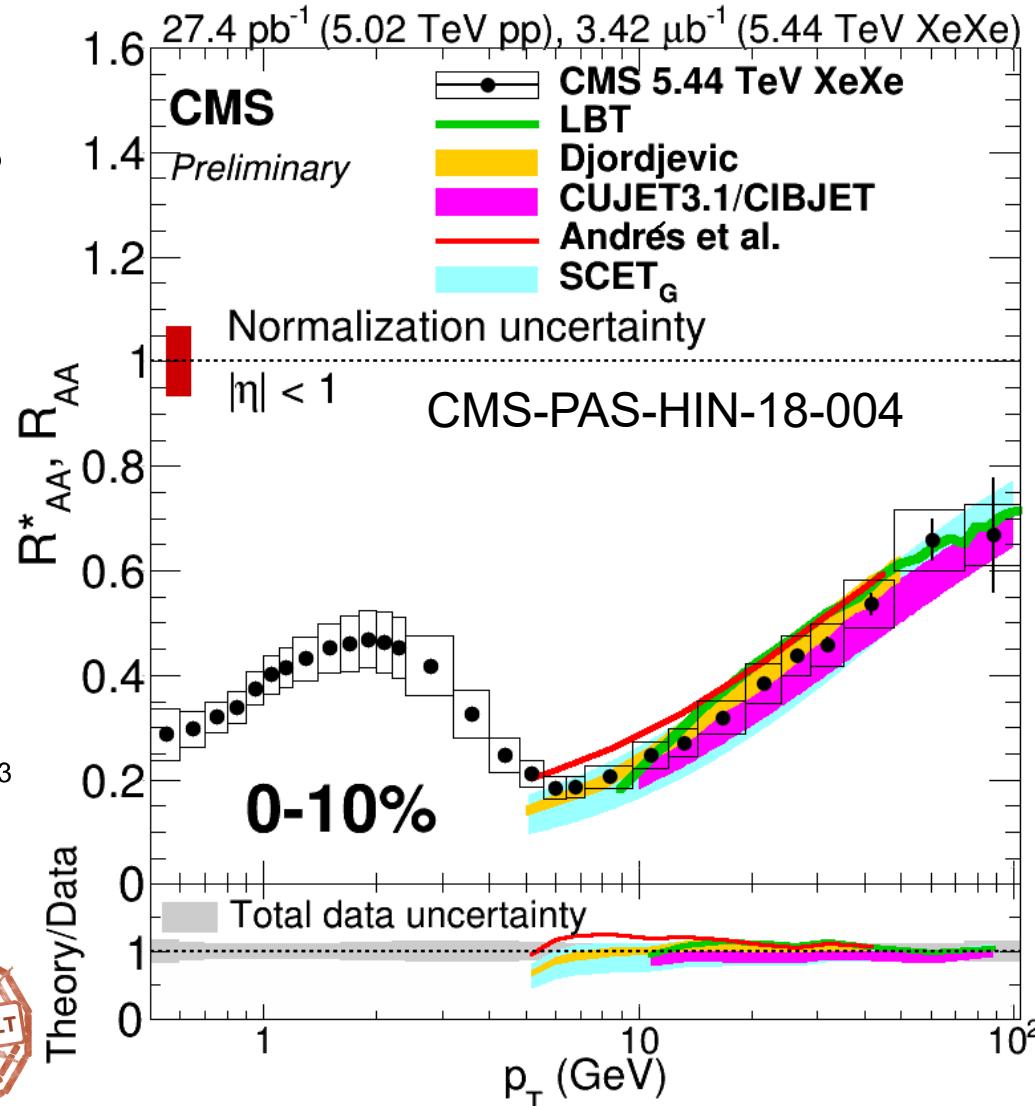
# Event Selection Bias

- Charged particle yields compared using  $N_{\text{coll}}$  vs forward  $E_T$  selection
  - Depletion of particles for low  $N_{\text{coll}}$  events
  - Leads to  $p_T$ -dependent event selection bias
  - Magnitude is highly model dependent
    - HYDJET predicts up to 50% suppression
    - AMPT with string melting: only 20%



# Theory Comparisons - 0-10%

- Linear Boltzmann Transport Model
  - CLV<sub>isc</sub> hydro medium expansion
  - Quadratic energy loss in static QGP
- Djordjevic Model
  - Bjorken expansion of medium
- CUJET3.1
  - CIBJET modeling of flow harmonics
- Andrés et al.
  - 'quenching weights' formalism
- SCET<sub>G</sub>
  - Medium evolution with IEBE hydro
  - Energy loss scales as roughly  $N_{\text{part}}^{2/3}$
- Models predict  $R_{AA}$  reasonably
- Similar agreement in 30-50%

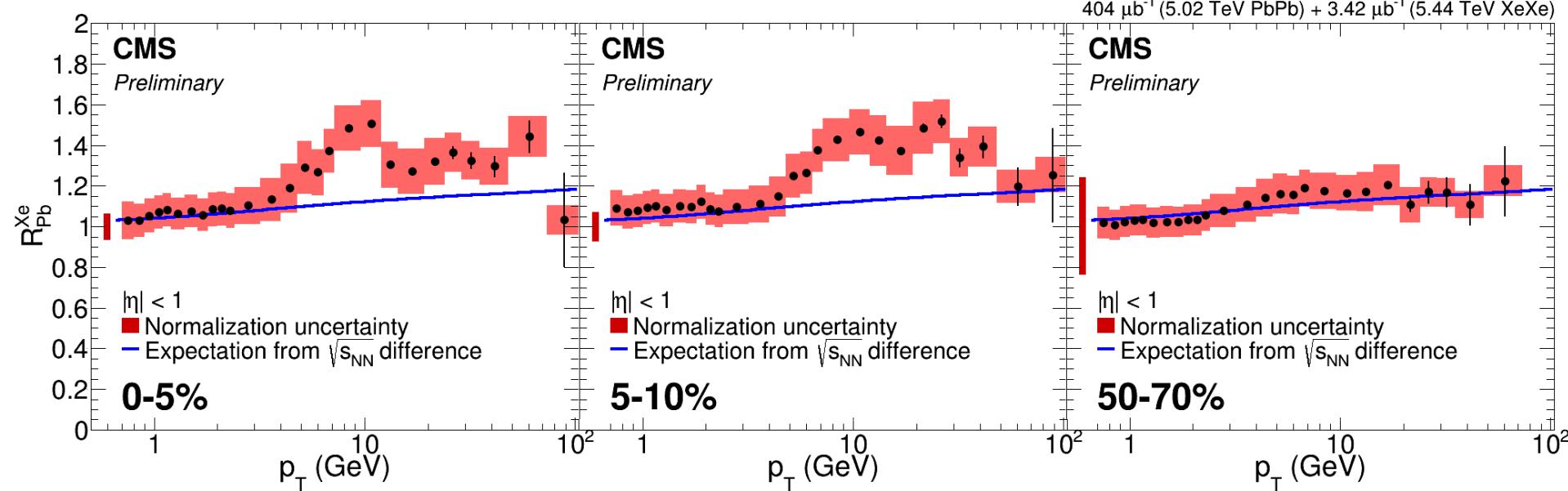


# $R_{\text{Pb}}^{\text{Xe}}$ – Ratio without reference

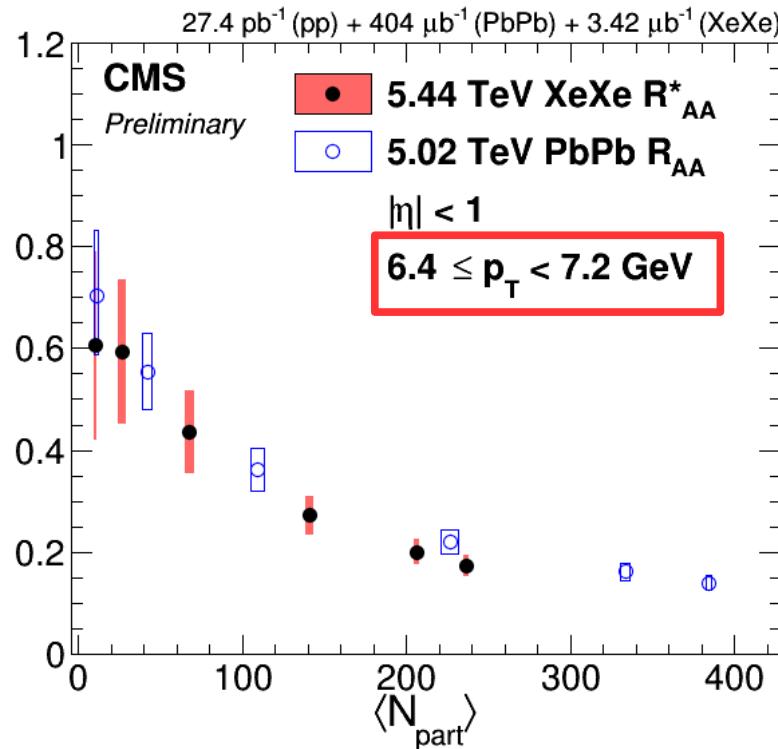
- $R_{\text{Pb}}^{\text{Xe}}$ : XeXe and PbPb spectra ratio without pp reference      
$$R_{\text{Pb}}^{\text{Xe}}(p_T) = \frac{dN^{\text{XeXe}}/dp_T}{dN^{\text{PbPb}}/dp_T} \frac{T_{\text{PbPb}}}{T_{\text{XeXe}}}.$$
- No correlated pp reference uncertainty
- Compare to expectation from **difference in center of mass energies**
  - 5.44/5.02 TeV PYTHIA (same as reference extrapolation factor)
- Rising structure around 6-10 GeV – interplay between flow and energy loss
- 50-70% compatible with center of mass energy difference



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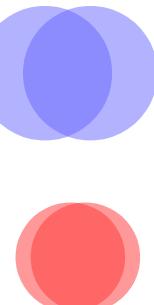
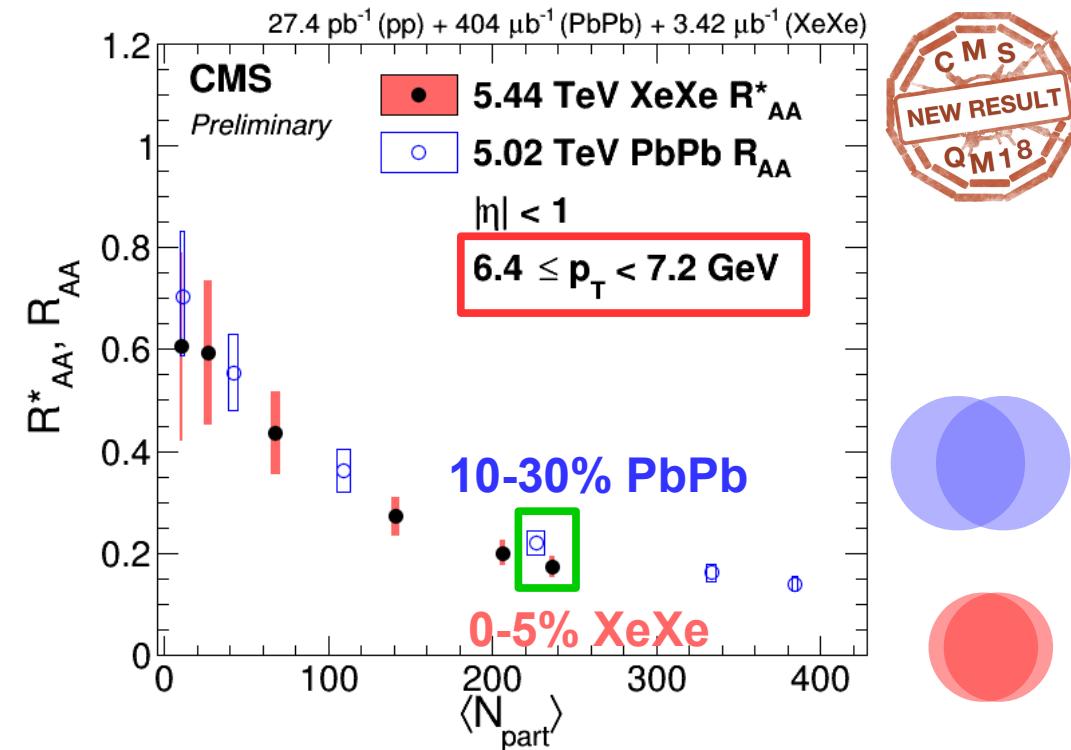
# $R_{AA}$ vs $N_{part}$



- XeXe and PbPb  $R_{AA}$  follow similar trends when comparing vs.  $\langle N_{part} \rangle$

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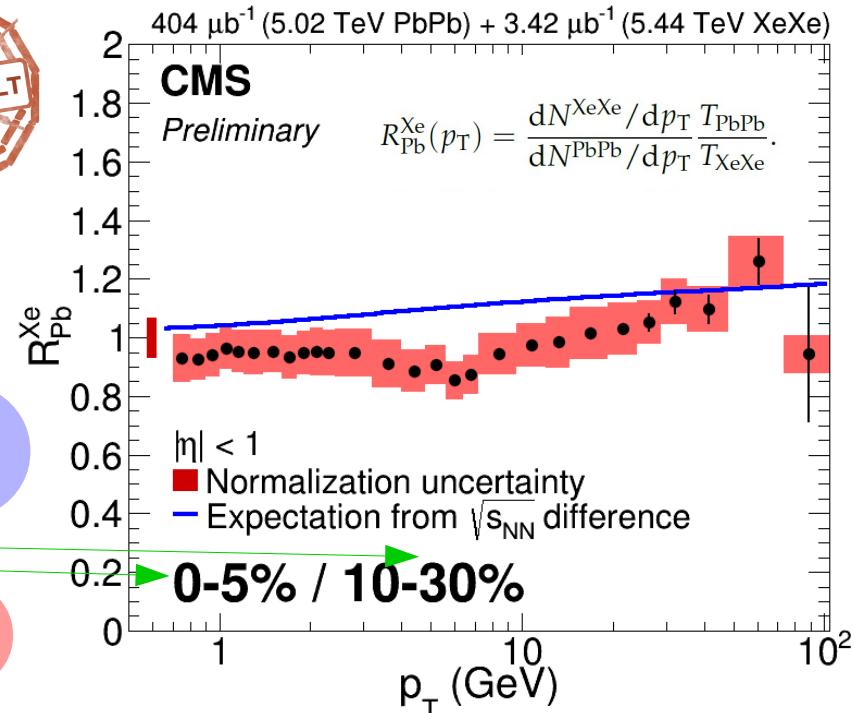
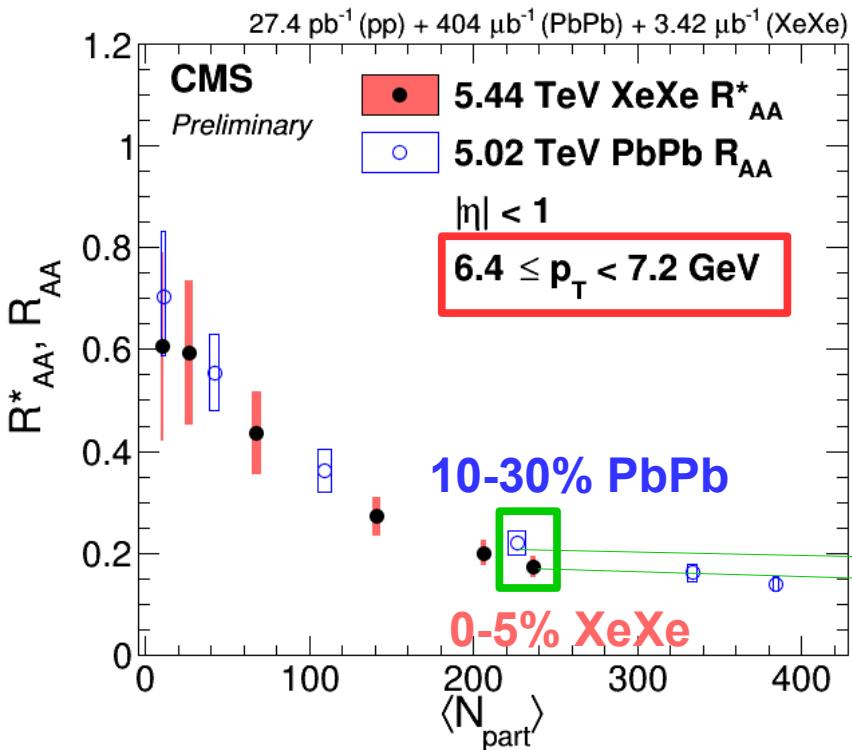
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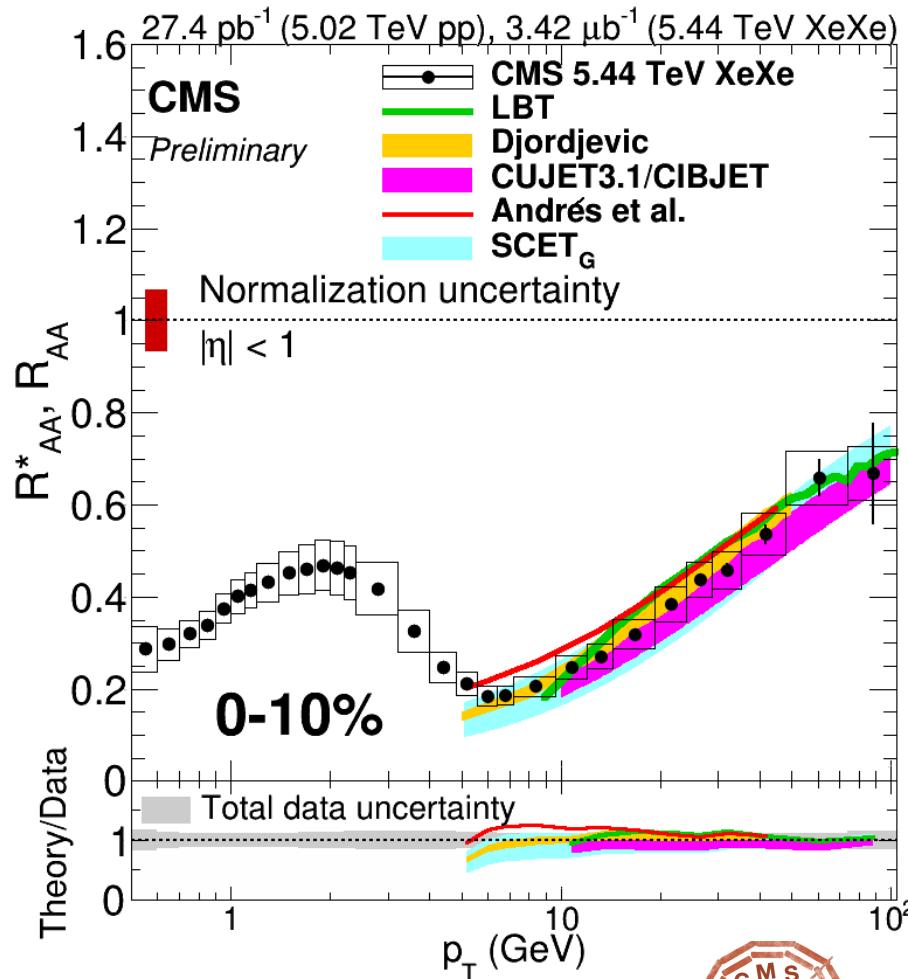


- XeXe and PbPb  $R_{AA}$  follow similar trends when comparing vs.  $\langle N_{part} \rangle$
- $R_{Pb}^{Xe}$ : comparison of XeXe and PbPb spectra for similar  $\langle N_{part} \rangle$
- XeXe more suppressed around 6 GeV than expected from energy difference

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# Summary

- Observe strong suppression of  $R_{AA}$  in central PbPb and XeXe collisions
- Peripheral  $R_{AA}$  suppression could be from event selection biases
- See high- $p_T$  differences comparing XeXe and PbPb events at same centrality
- Behavior is different when comparing similar  $\langle N_{part} \rangle$  instead of centrality
- Constrains path-length dependence of energy loss models



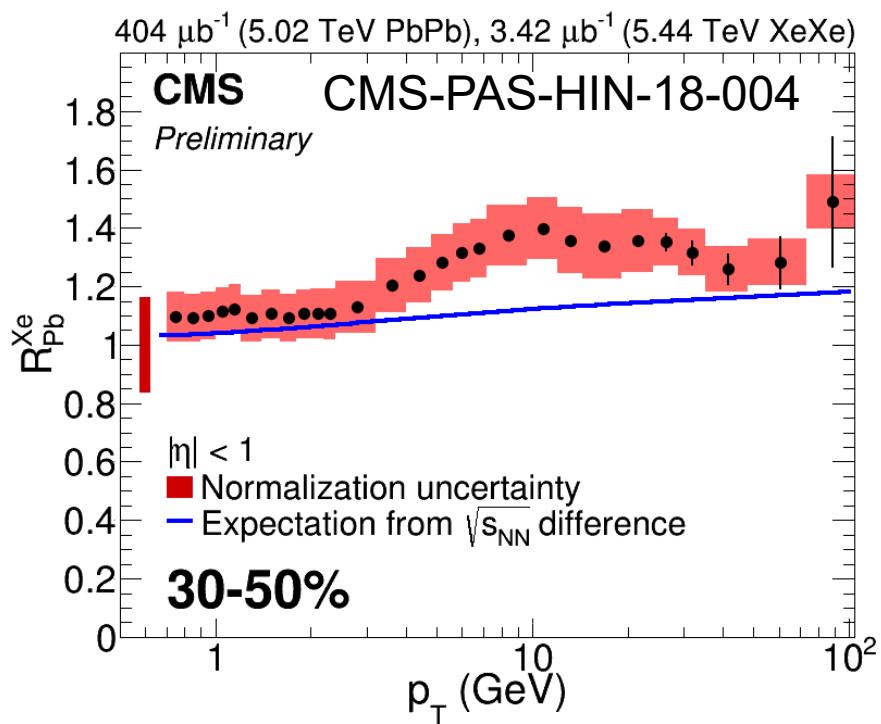
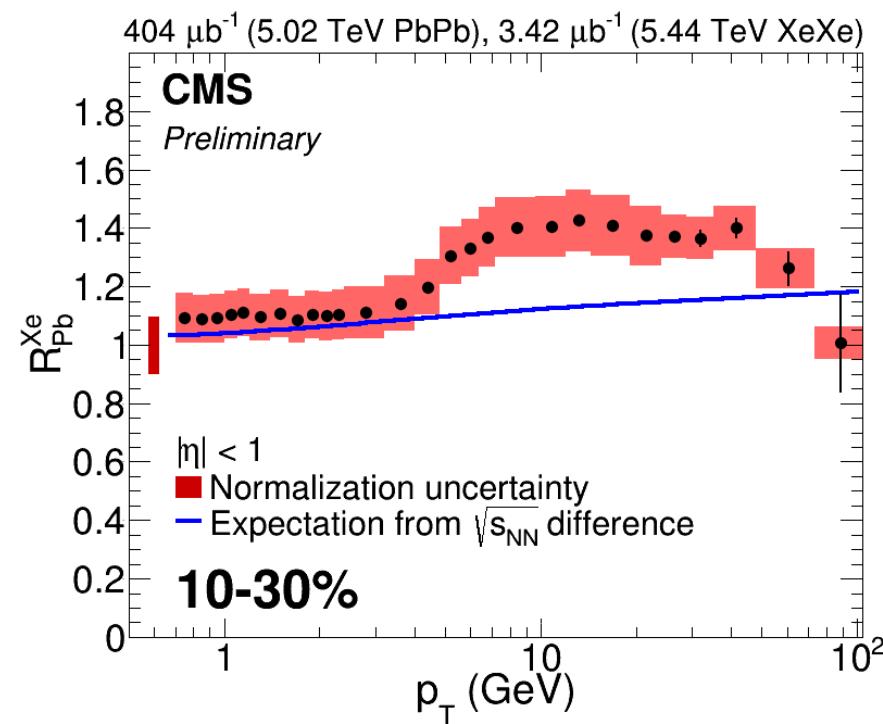
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# Backup

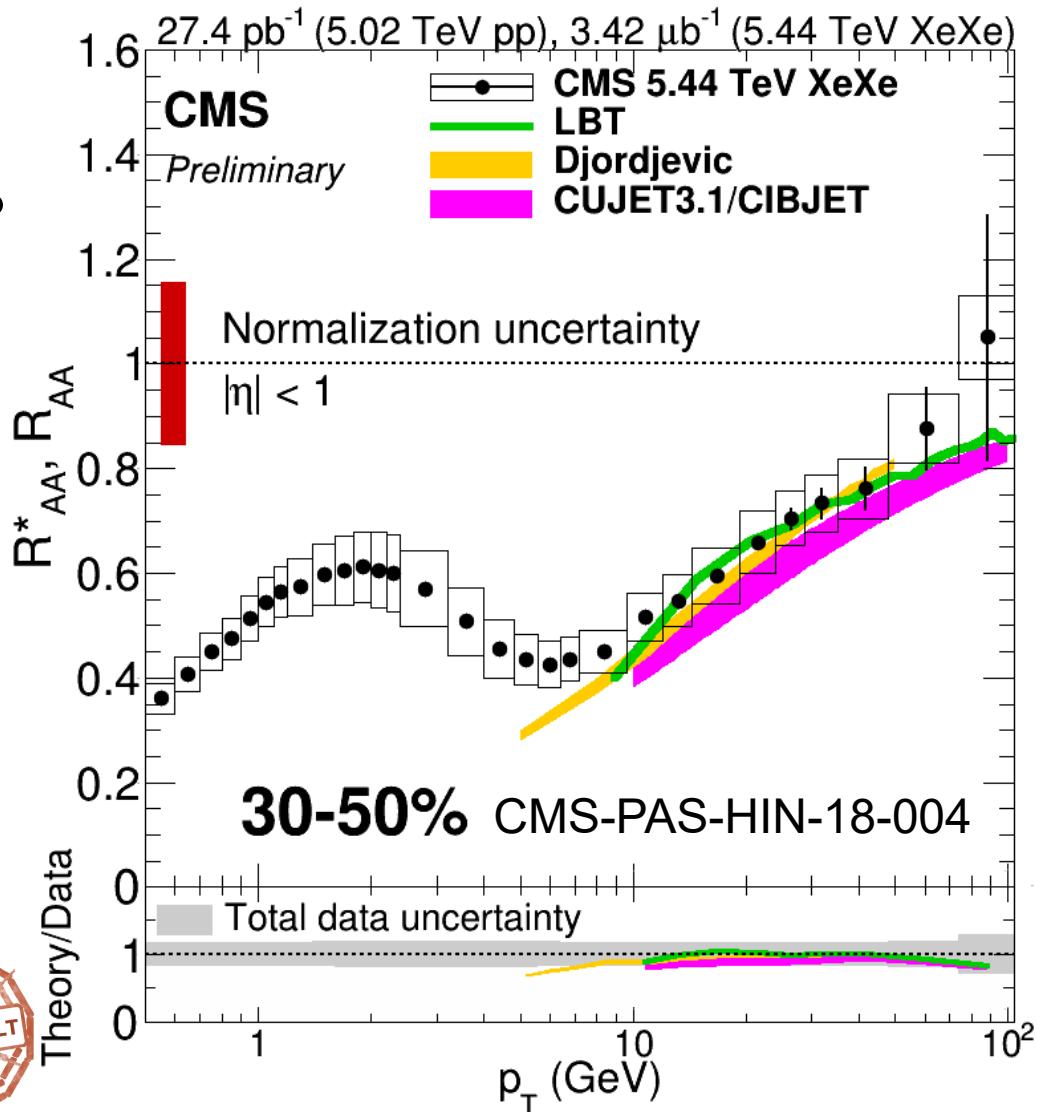
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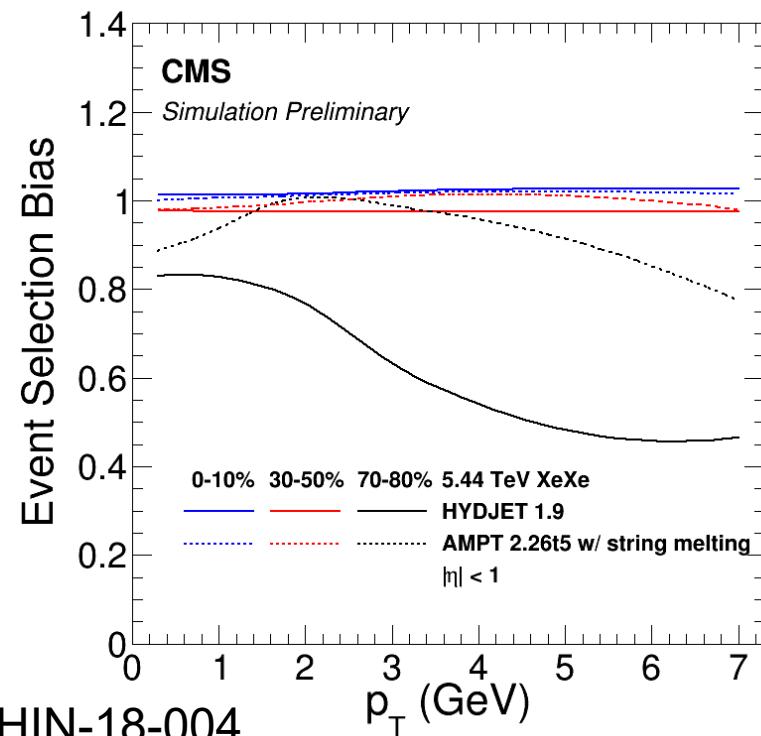
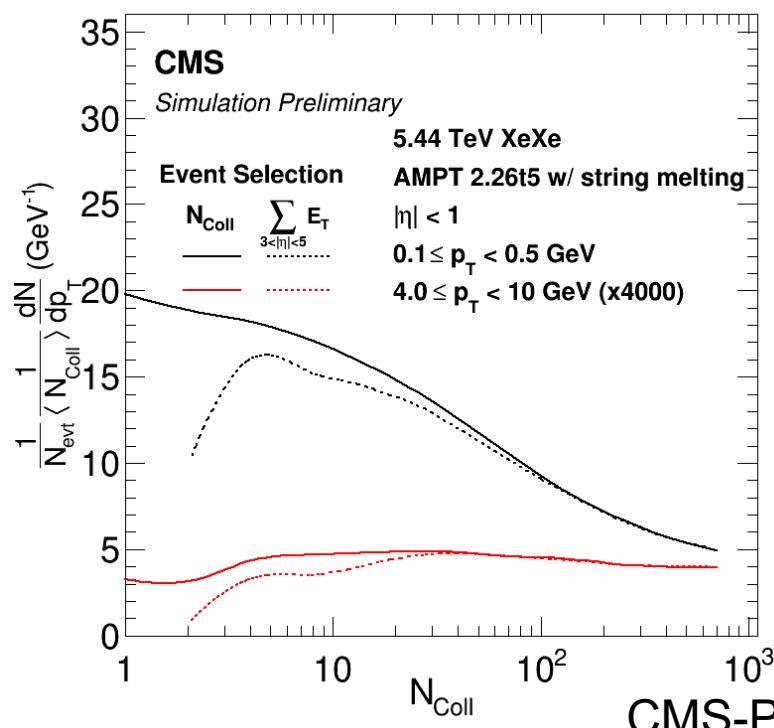
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- Djordjevic Model
  - Bjorken expansion of medium
- CUJET3.1
  - CIBJET modeling of flow harmonics
- Models predict  $R_{AA}$  reasonably



# Event Selection Bias - AMPT

- Similar study performed in AMPT with string melting
  - Smaller bias observed than in HYDJET
  - Depends on modeling of forward energies and high- $p_T$  yields in barrel

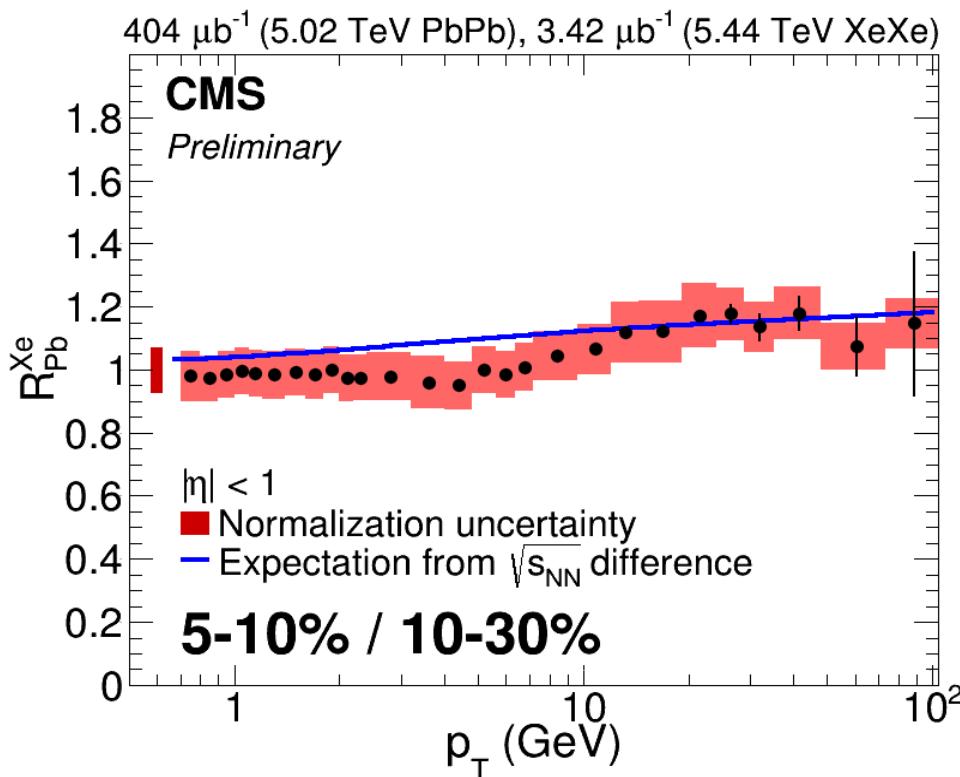


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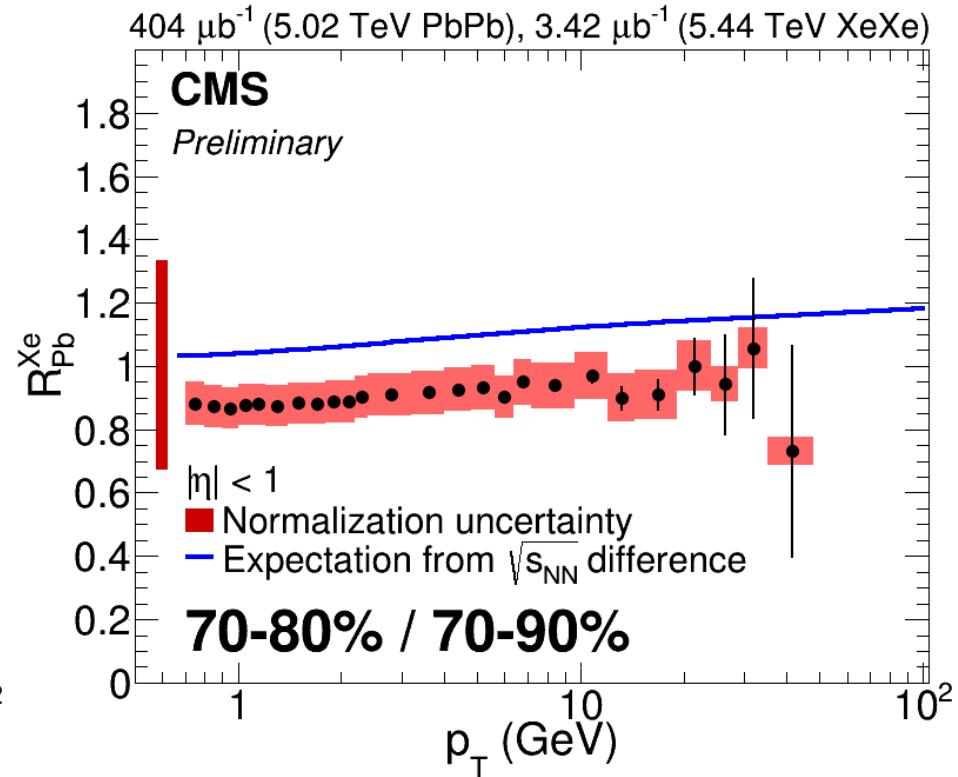
# Comparisons at similar N<sub>part</sub>

- 5-10% XeXe: N<sub>part</sub> = 207
- 10-30% PbPb: N<sub>part</sub> = 227
- Peripheral events: N<sub>part</sub> compatible within uncertainties

$$R_{\text{Pb}}^{\text{Xe}}(p_{\text{T}}) = \frac{dN^{\text{XeXe}}/dp_{\text{T}}}{dN^{\text{PbPb}}/dp_{\text{T}}} \frac{T_{\text{PbPb}}}{T_{\text{XeXe}}}.$$

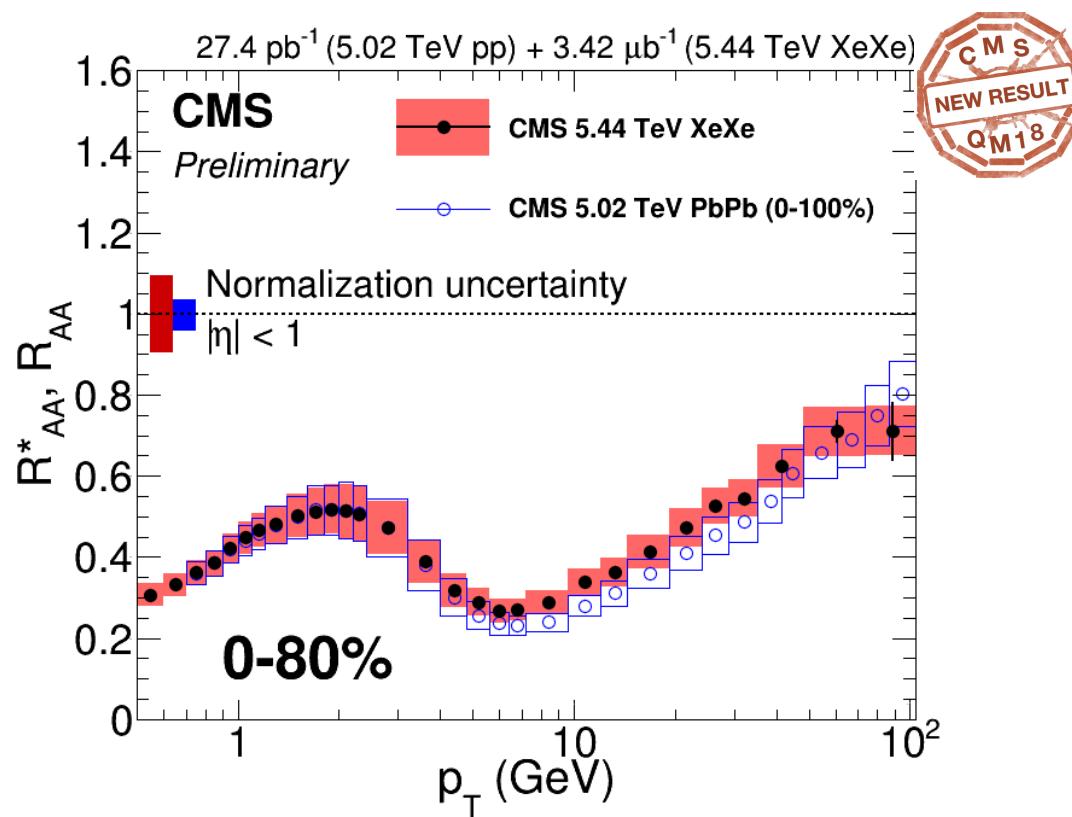


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# 0-80% $R_{AA}$

- Two systems agree at low- $p_T$
- XeXe slightly higher starting around  $\sim 6$  GeV



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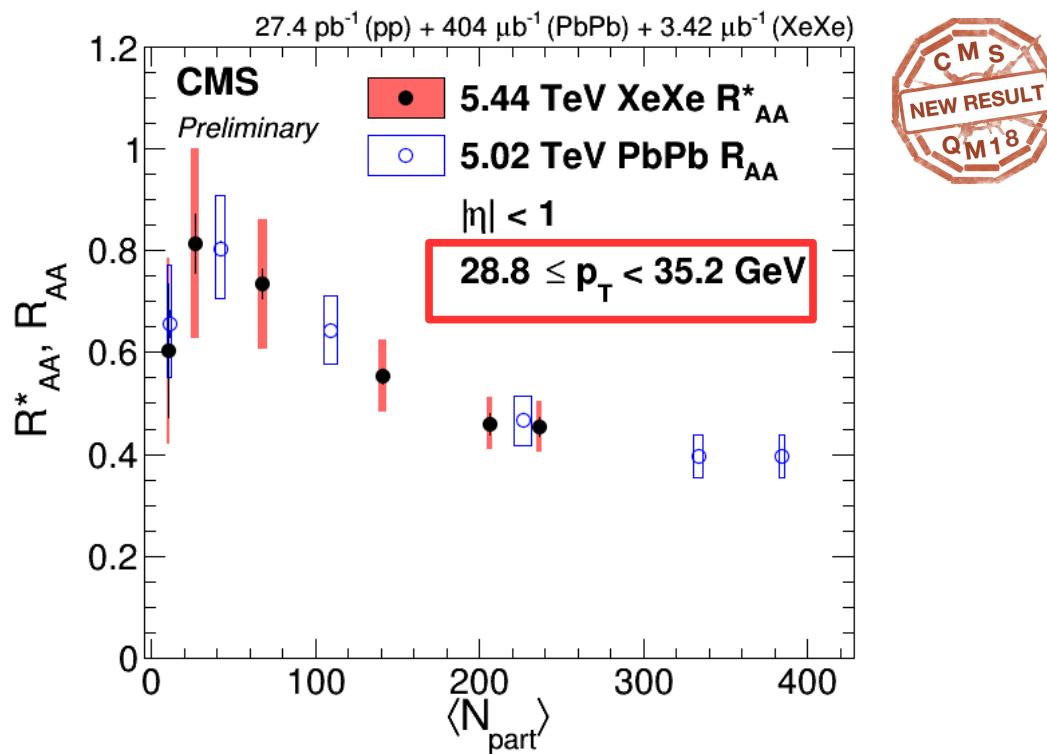
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# $R_{AA}$ vs $N_{part}$ – Higher $p_T$

- Agreement between PbPb and XeXe  $R_{AA}$  also observed at higher  $p_T$



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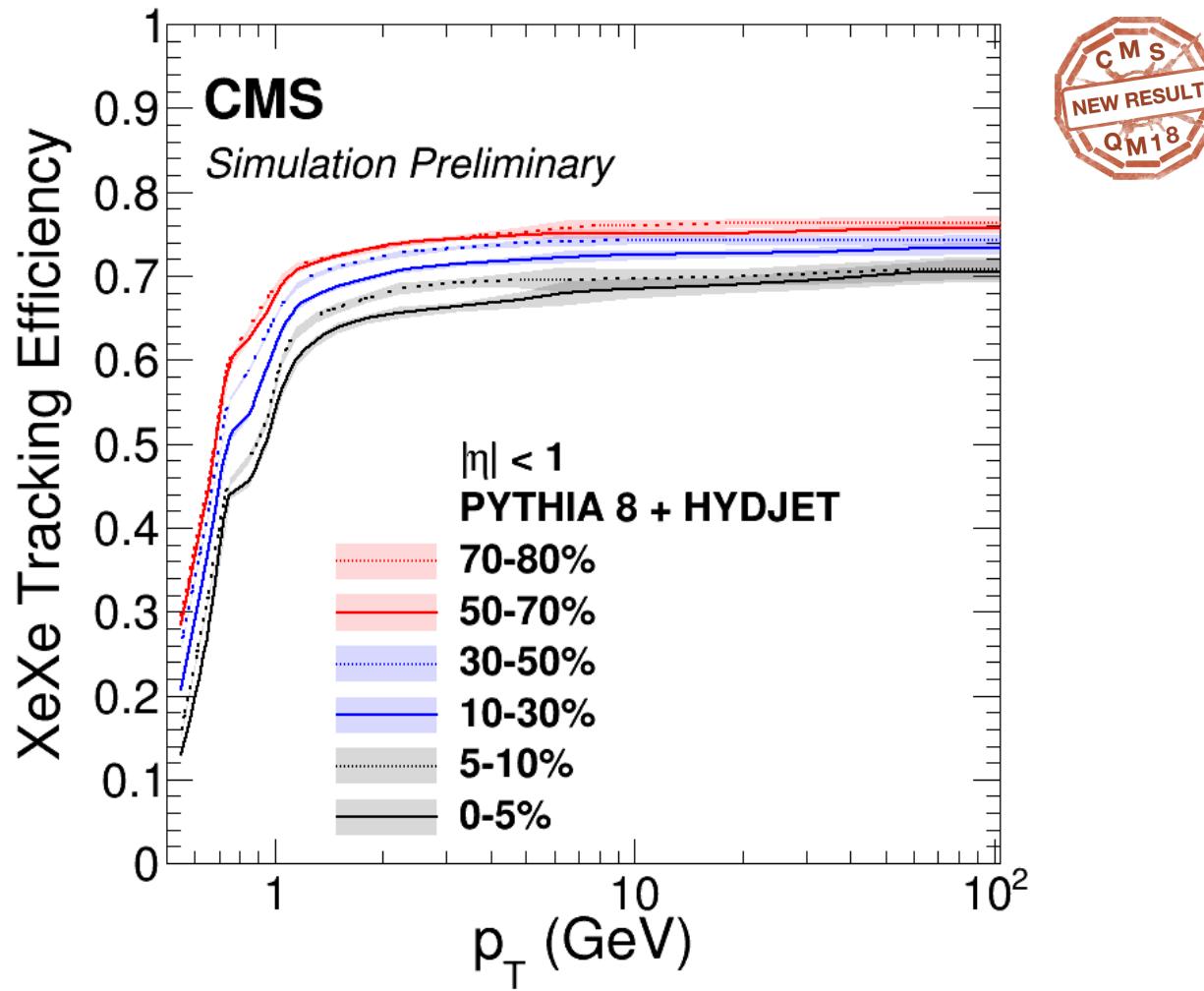


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# XeXe Tracking Efficiency



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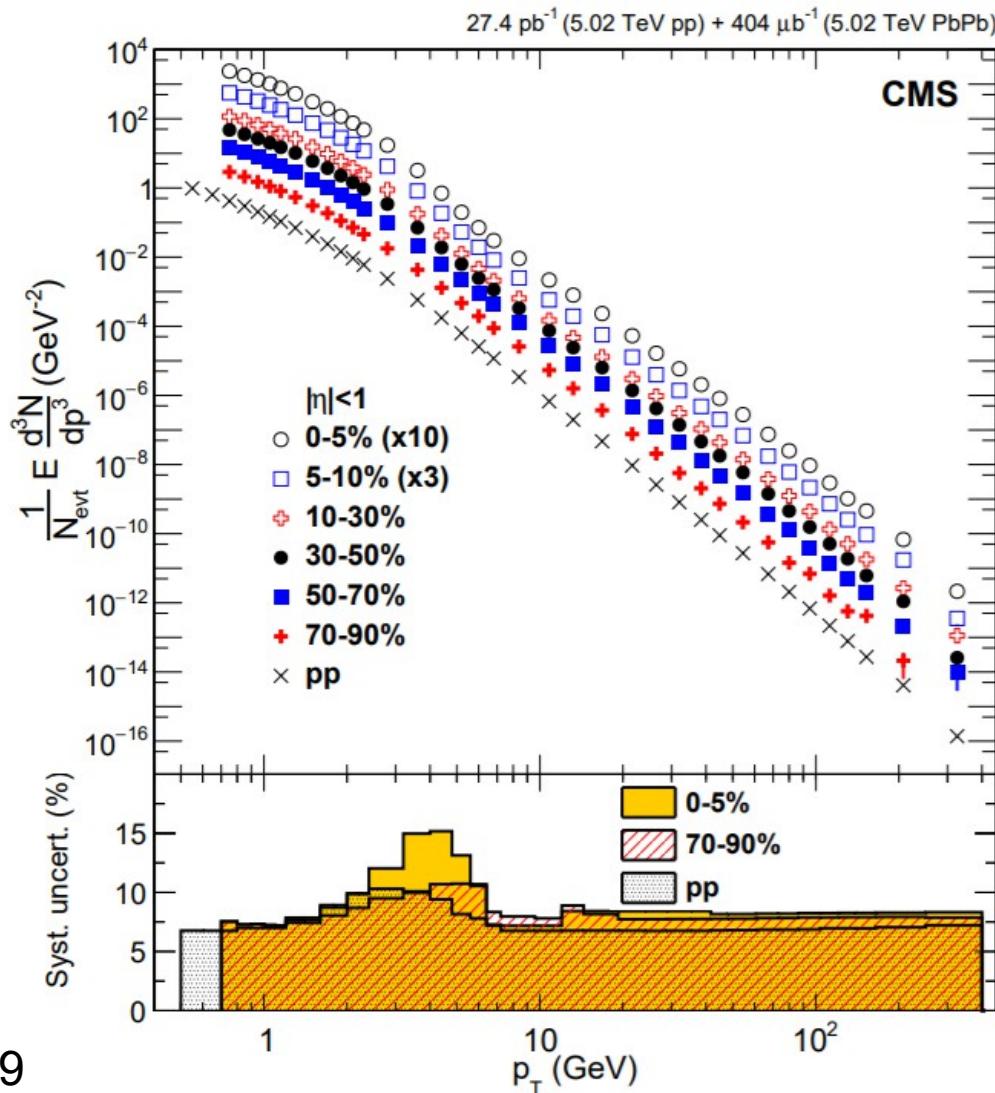


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# Input 5.02 TeV Spectra



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