Jets and Jet Substructure in $\sqrt{s}$ =200 GeV p+p/p+Au/d+Au Collisions with PHENIX at RHIC

John Lajoie

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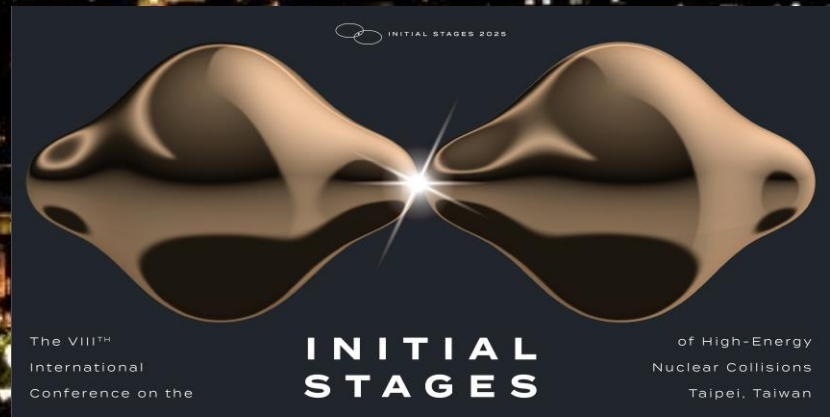
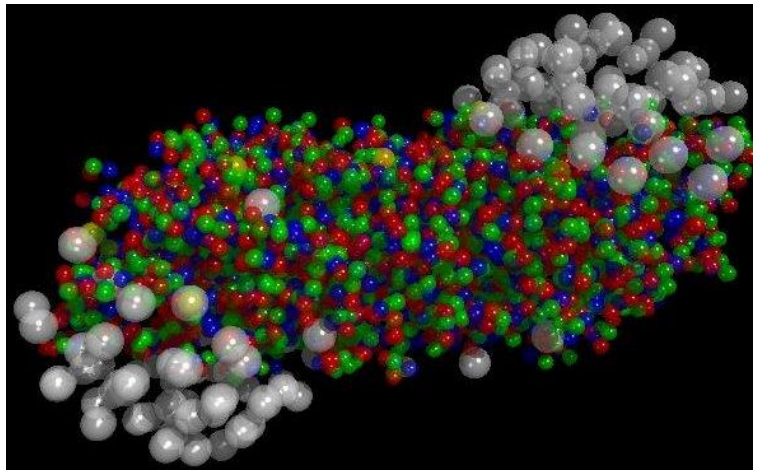


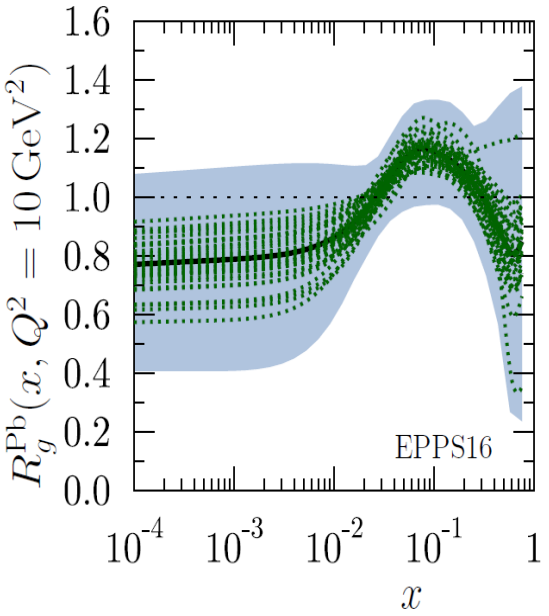
Jets as a QCD Probe at RHIC

How do collective, many-body phenomena arise from first-principles QCD?

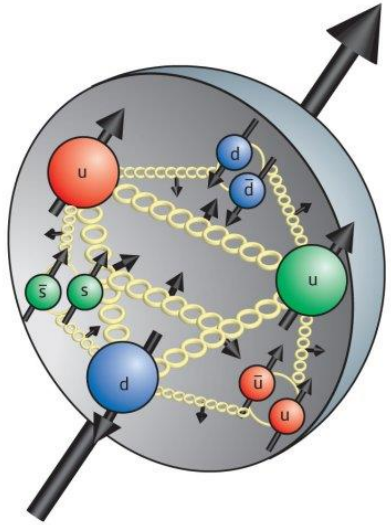
A+A Collisions



p+A (d+A) Collisions



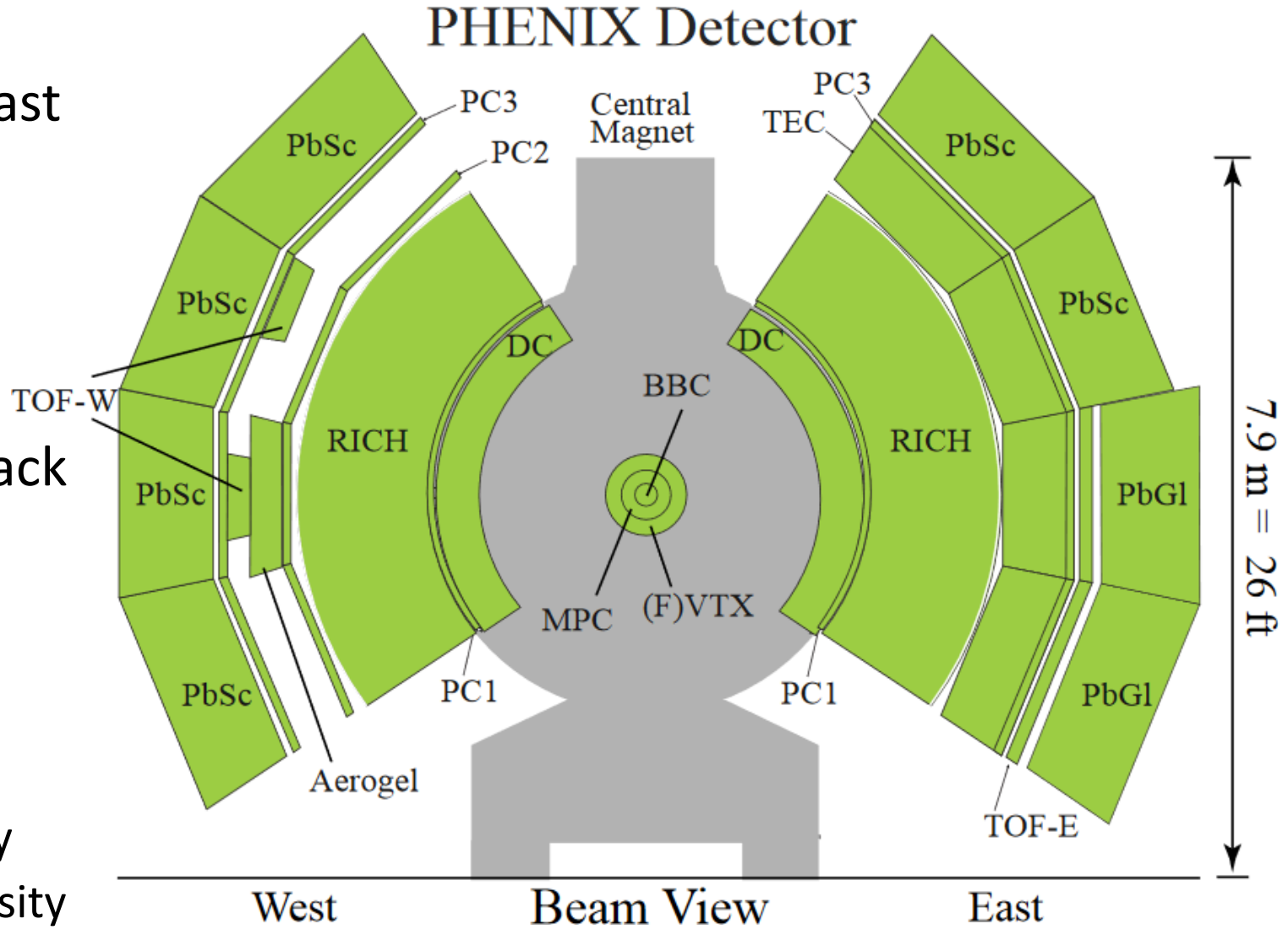
$p^{\uparrow} + p^{\uparrow}$ Collisions



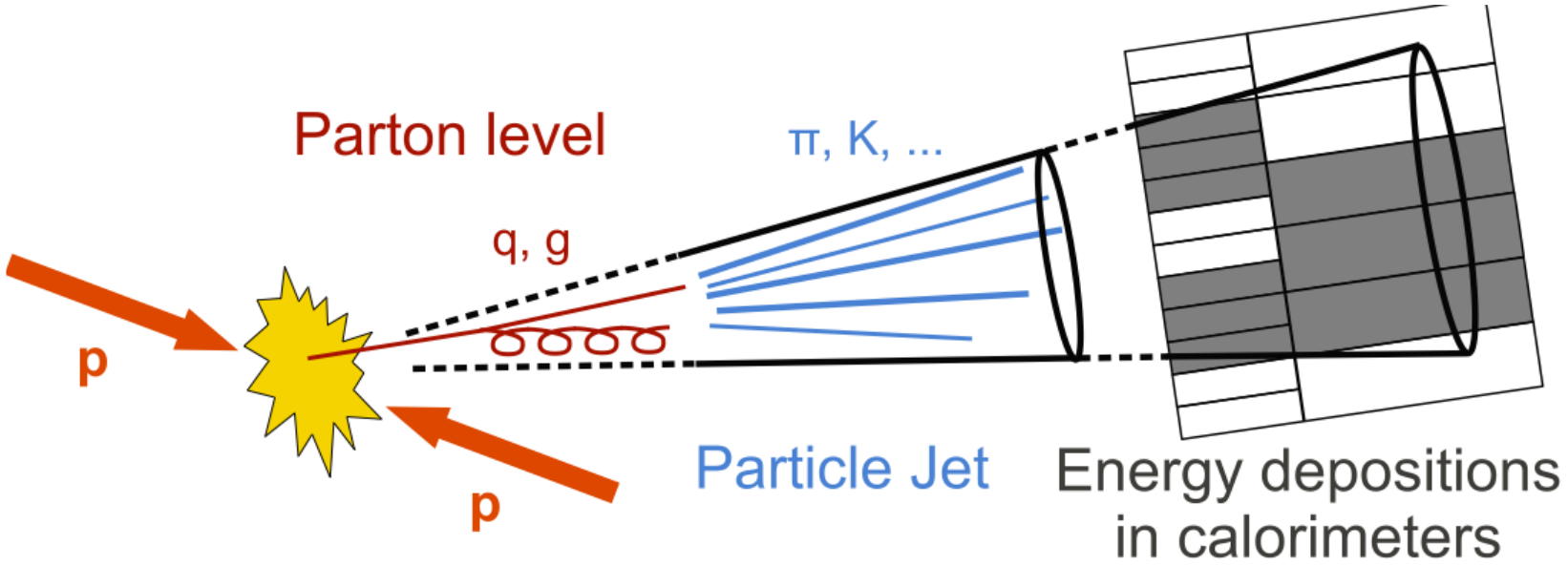
Baseline in p+p collisions;
p+A, d+A collisions to investigate CNM effects

The PHENIX Detector

- Two central detector arms (East and West)
- Acceptance:
  - $|\eta|<0.35$
  - $\phi \sim 90^{o}$
- Drift and Pad Chambers to track charged particles
- EMCal for EM energy
  - High tower jet trigger
- Run-15:
  - Sampled $60pb^{-1}$ p+p luminosity
  - Sampled $200nb^{-1}$ p+Au luminosity



Jet Reconstruction in PHENIX



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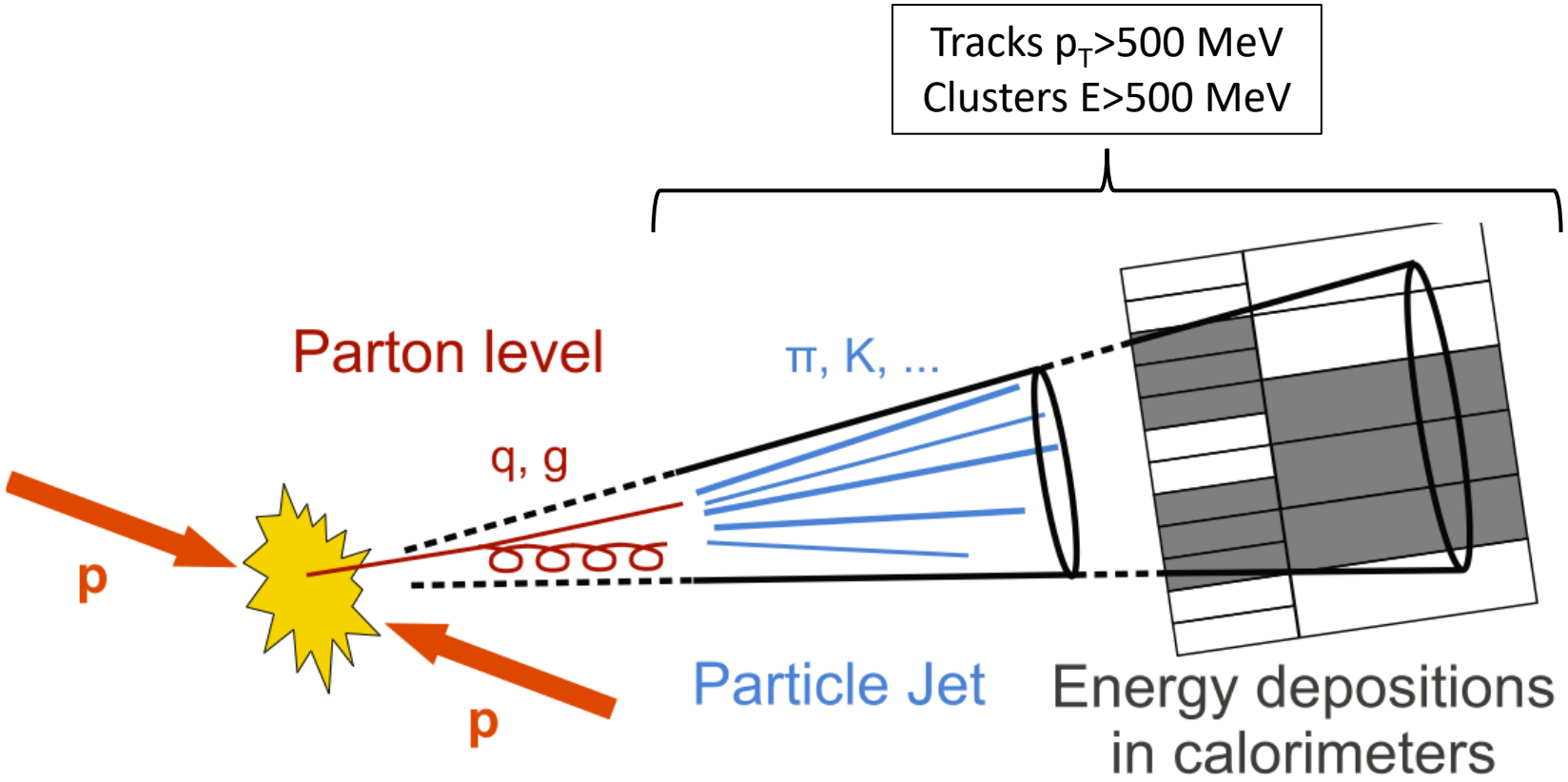
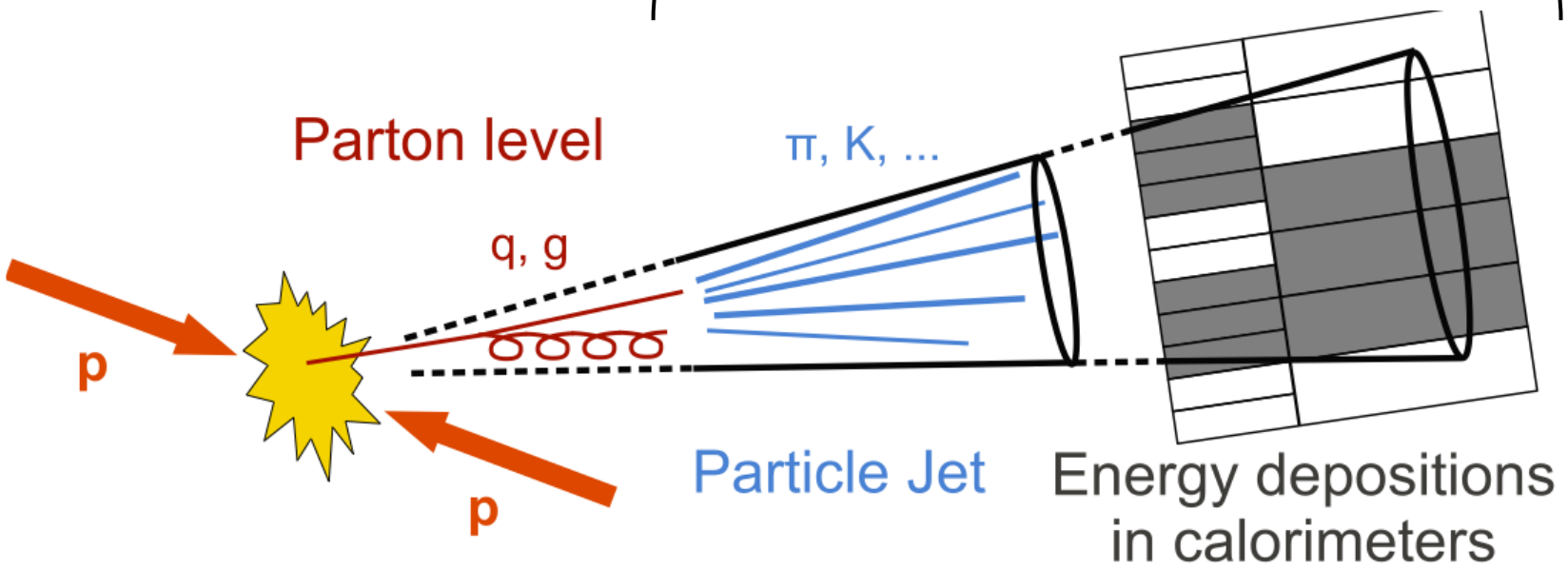


Jet Reconstruction in PHENIX

Tracks p_T>500 MeV
Clusters E>500 MeV

FastJet
anti-k_T algorithm
(R=0.3):

$$d_{ij} = min(\frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2})\frac{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}{R^2}$$



Reco jet-level cuts:
- $0.3 < c_f < 0.7$
- n_C>=3
- p_T^{reco}>5 GeV

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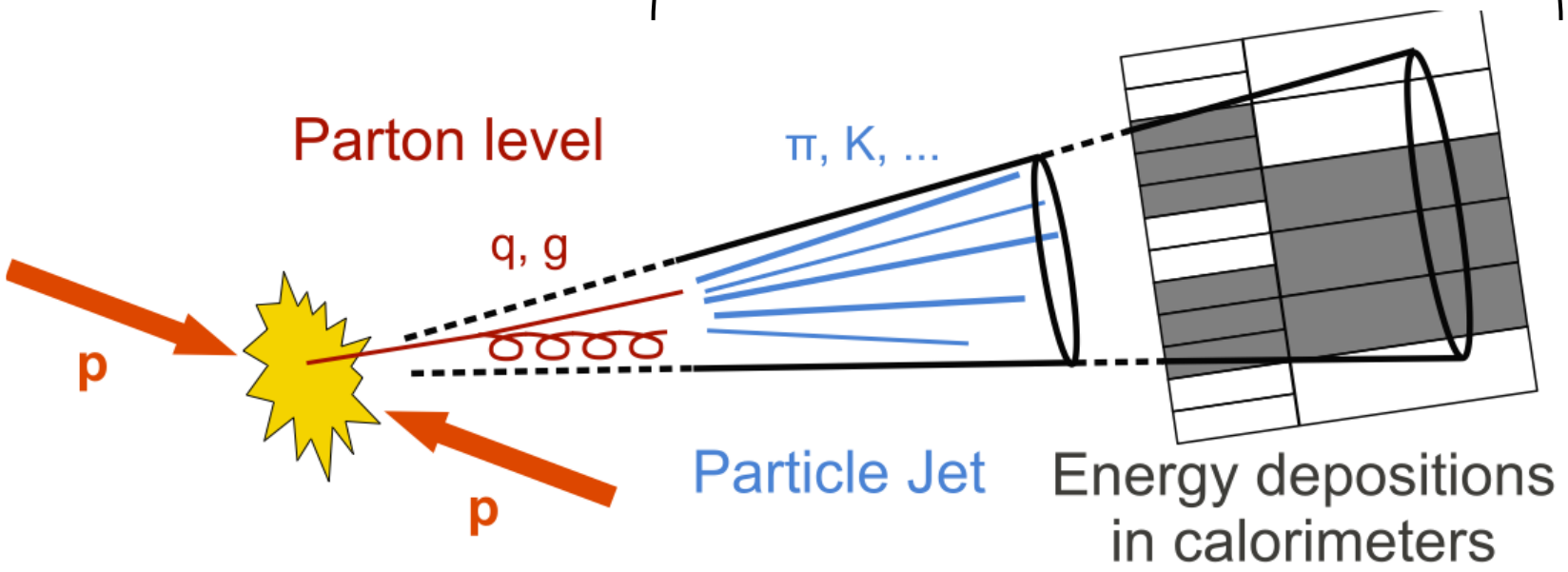

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Bayesian Unfolding:
- Missing energy
- Bin migration (resolution)
- Trigger Efficiency
- UE Subtraction (p,d+Au)

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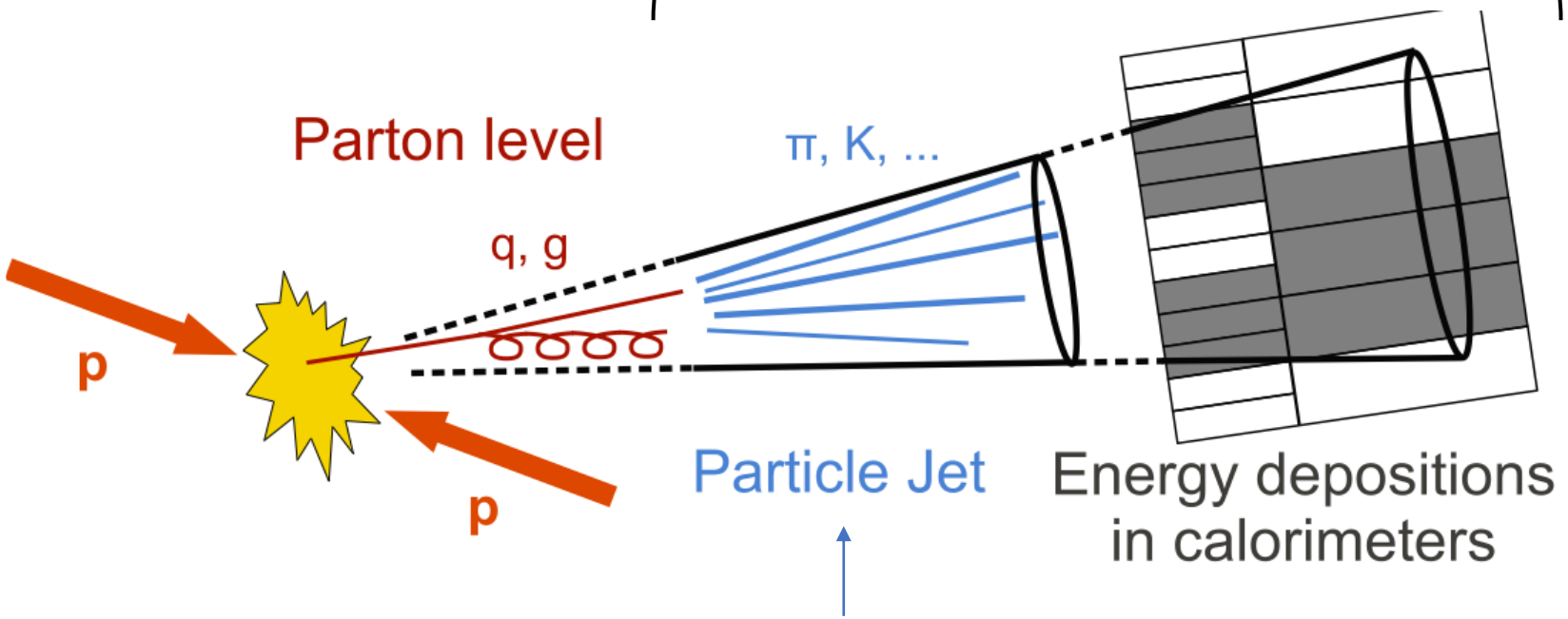

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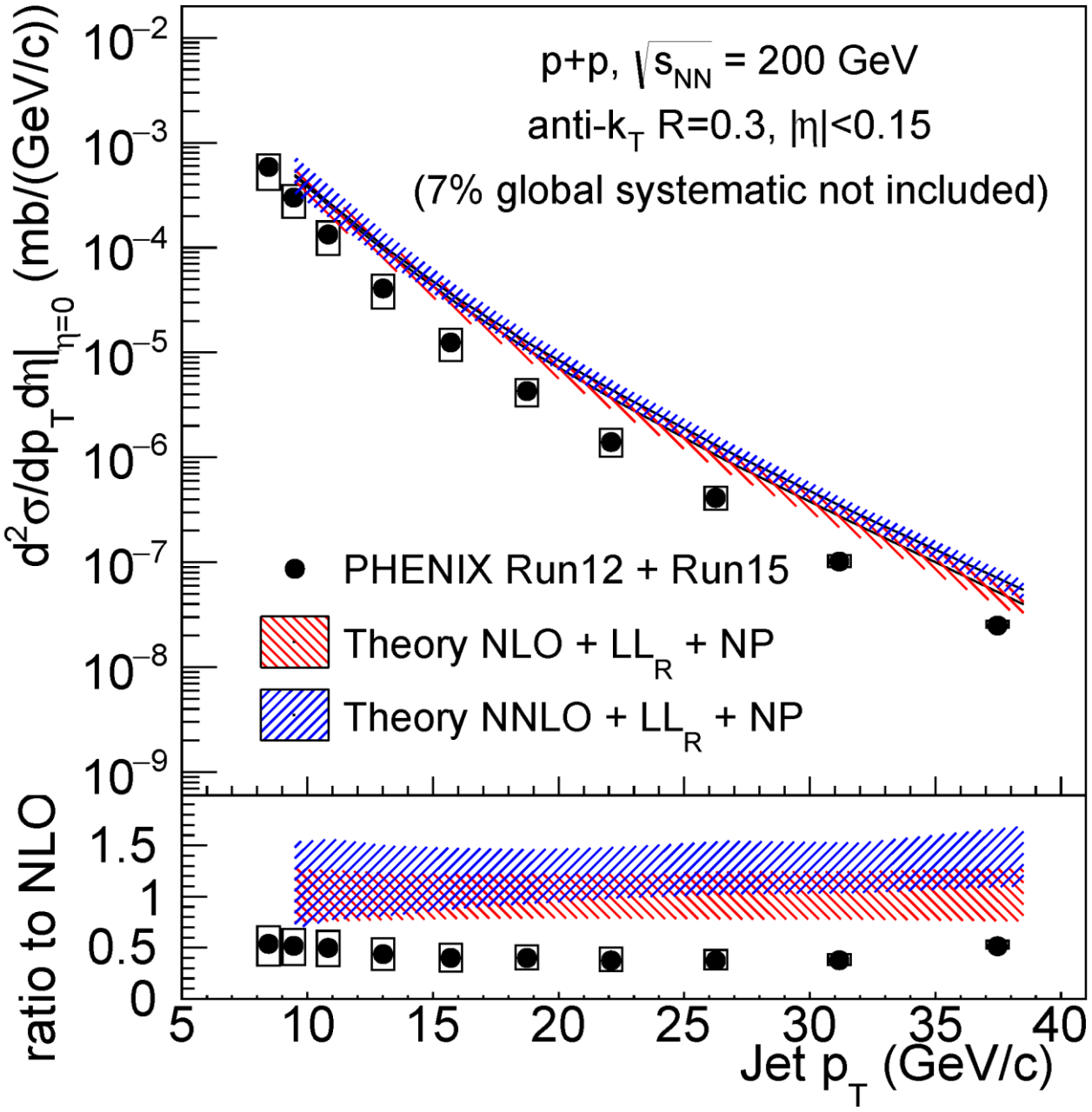
Unfold to hadron jet (1D)
and substructure (2D)
(Pythia prior)

Jet Production in 200 GeV p+p Collisions

Jet cross section at mid-rapidity in PHENIX.

Measured cross section is lower than NLO/NNLO predictions. This is not necessarily inconsistent with published results from STAR and CMS (for small R jets)

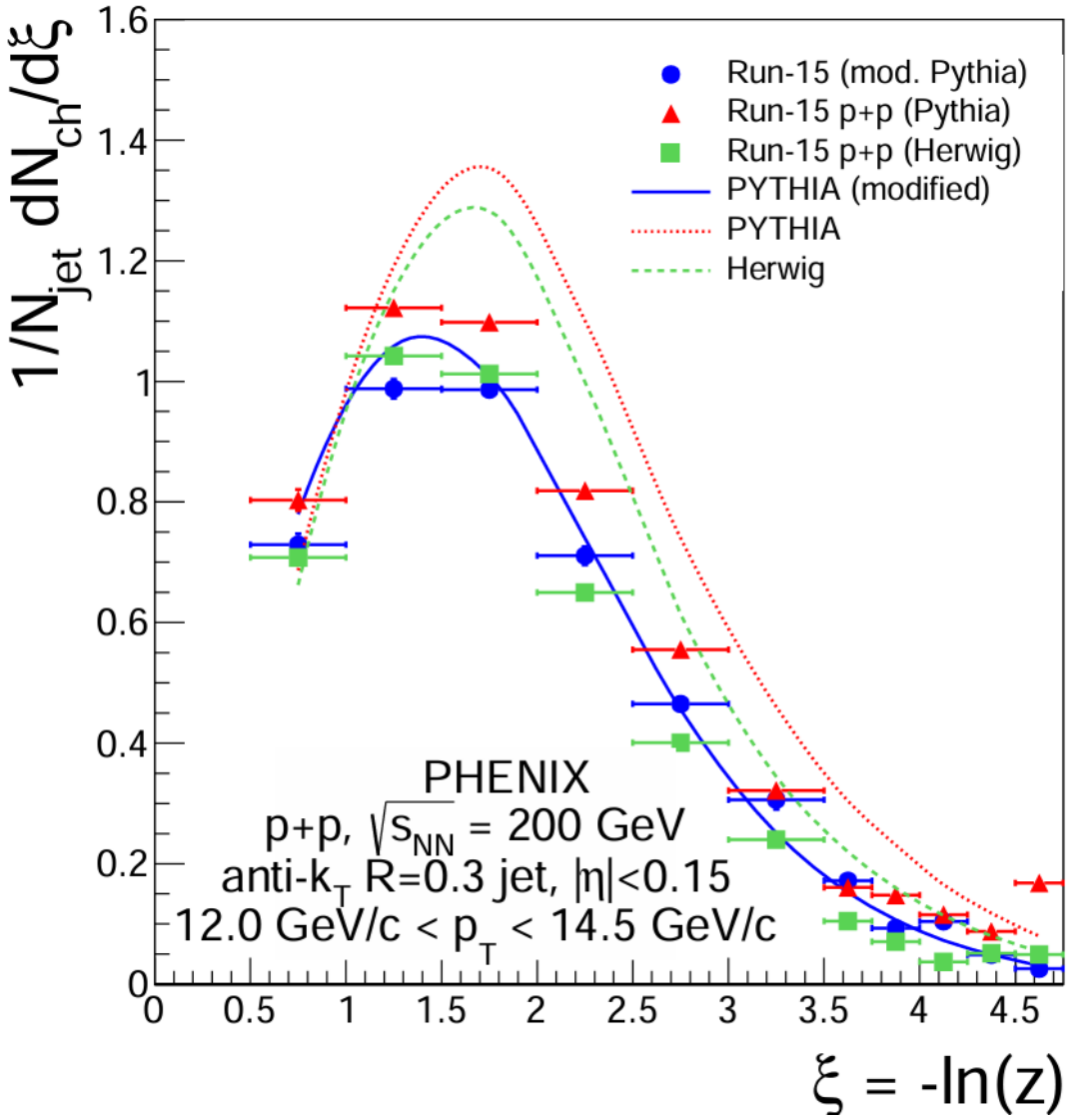


Phys. Rev. D 111, 112008 (2025)
https://doi.org/10.1103/hpm9-qfp6

2D Substructure Unfolding

MC models not well-tuned to RHIC energies, measured substructure distributions generally have a smaller number of constituents, indicating a harder fragmentation than seen in the models. This can bias the unfolding.

Developed a modified Pythia6 model by reweighting particles in the jet cone to match the observed fragmentation. This model was used in the unfolding.

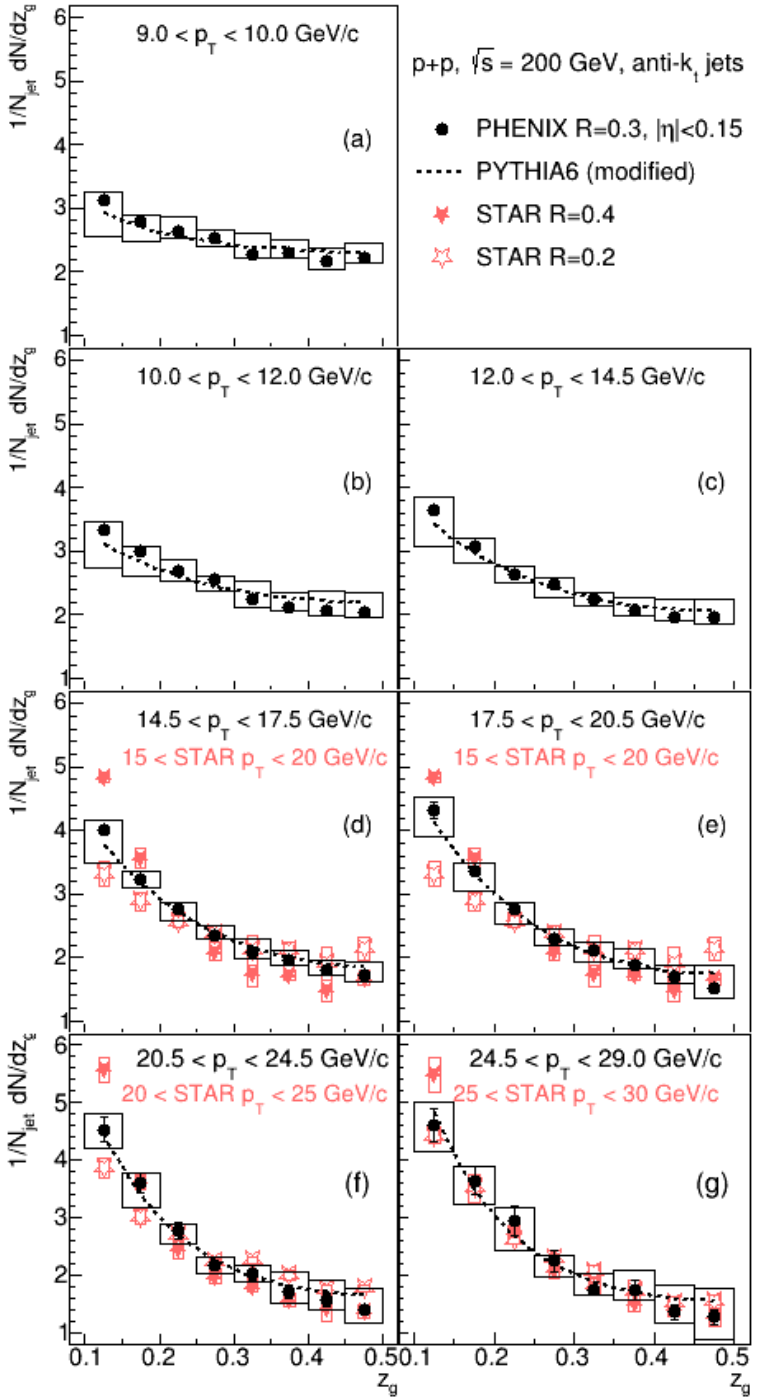


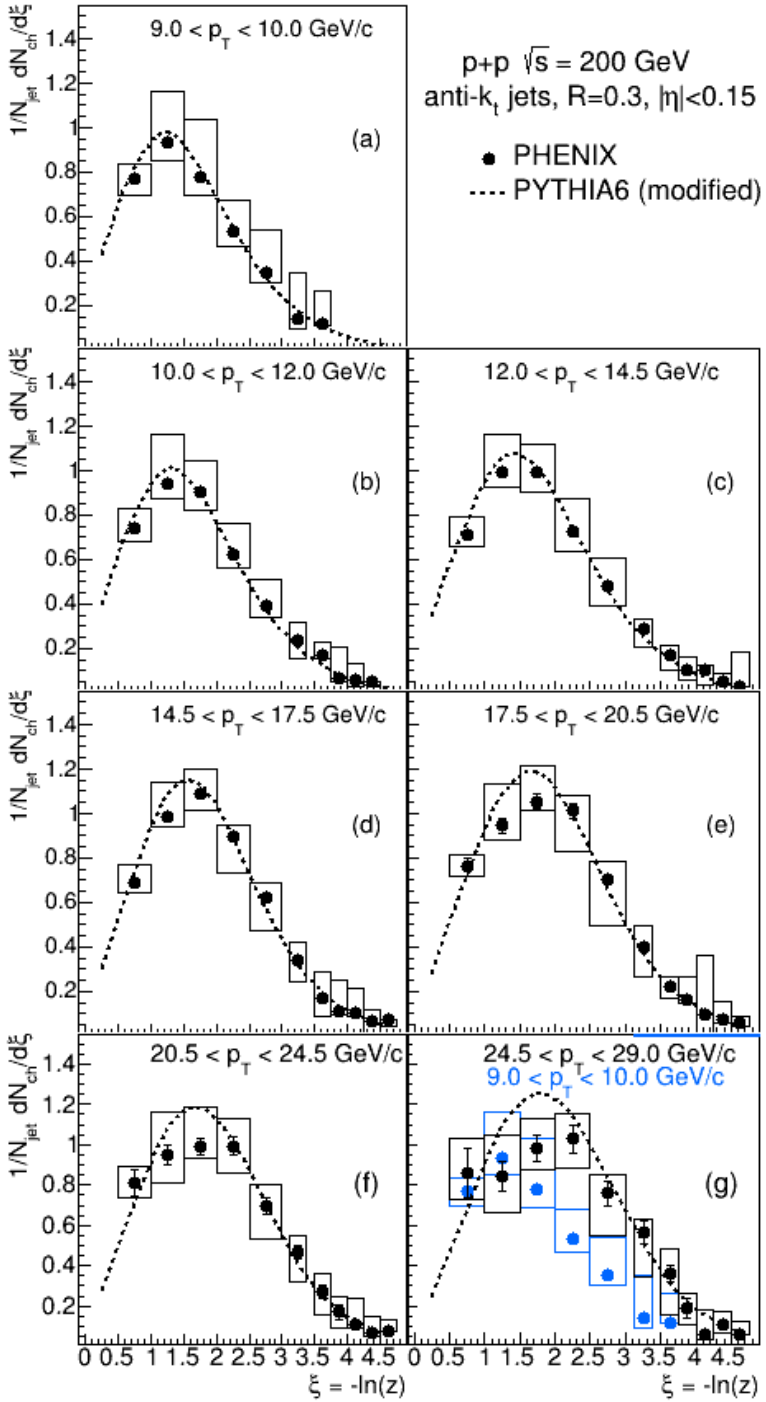
Substructure I

z_g distribution determined with all constituents, other distributions use charged tracks.

Groomed momentum fraction consistent with STAR results.

PHENIX results indicate a lower constituent multiplicity in jets compares to PYTHIA, HERWIG.





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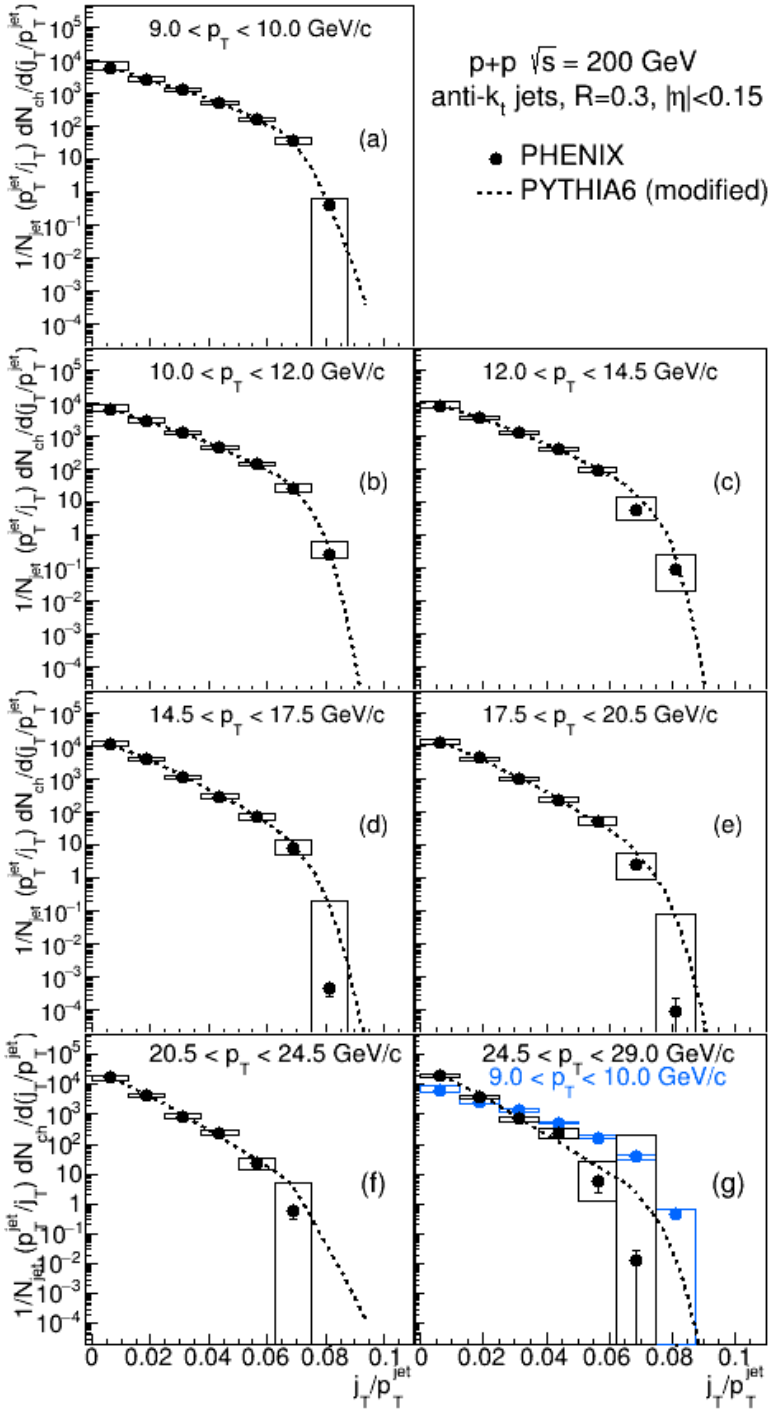
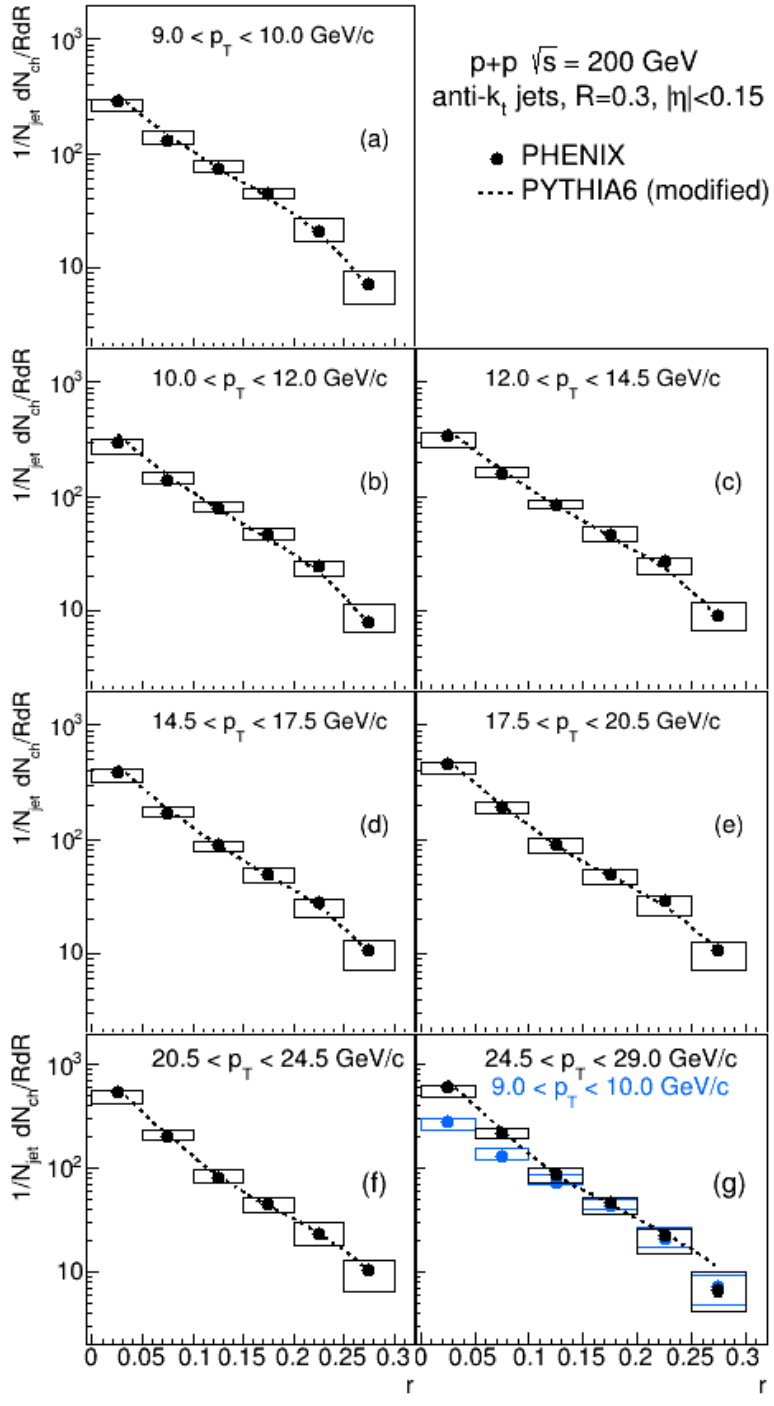
Substructure II

Constituent j_T/p_T^{jet} and distribution of particles from jet axis $\rho(r)$ determined using charged tracks.

Provide a baseline for further studies in p+A collisions.





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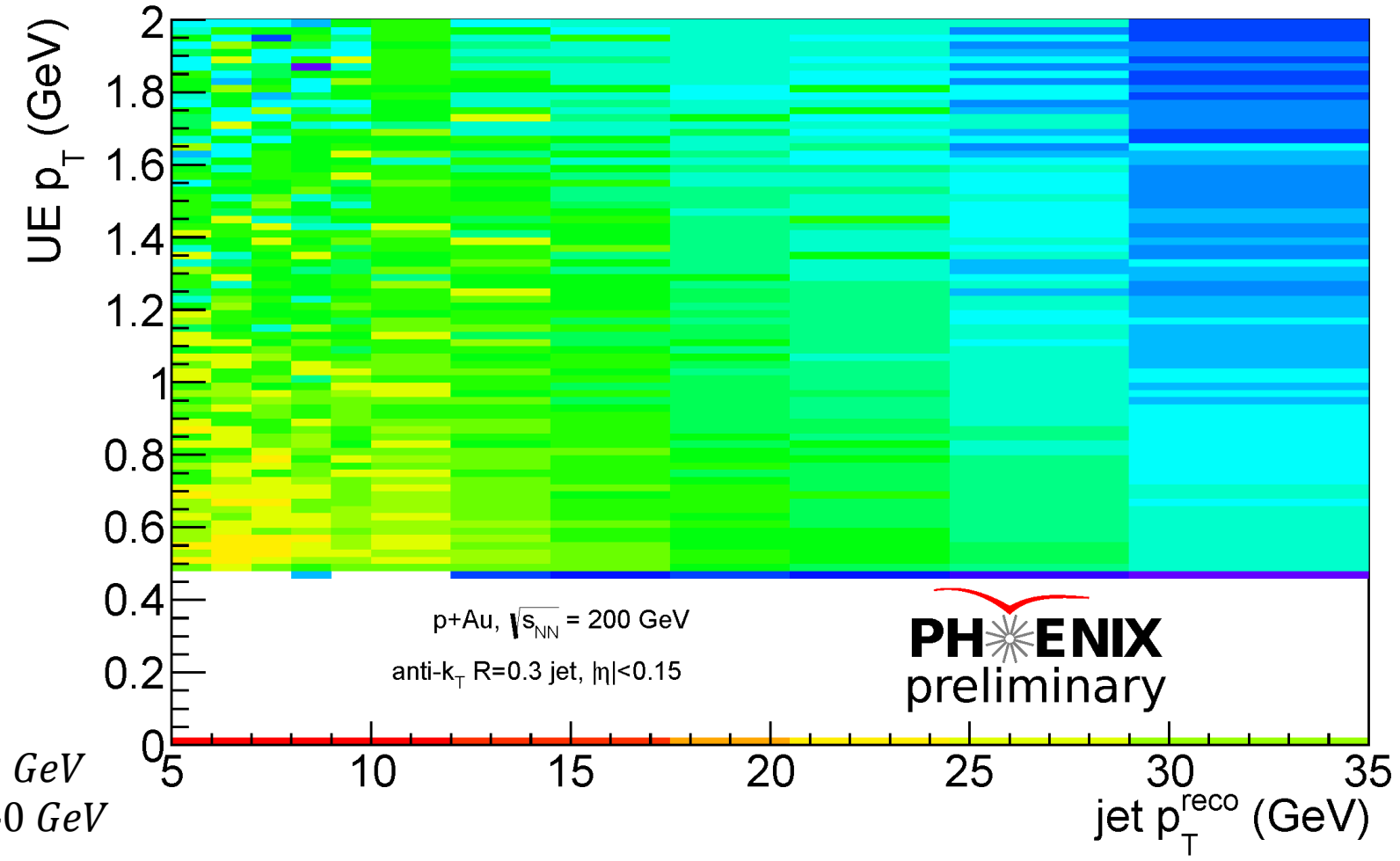
https://doi.org/10.1103/hpm9-qfp6

Underlying Event in p+Au

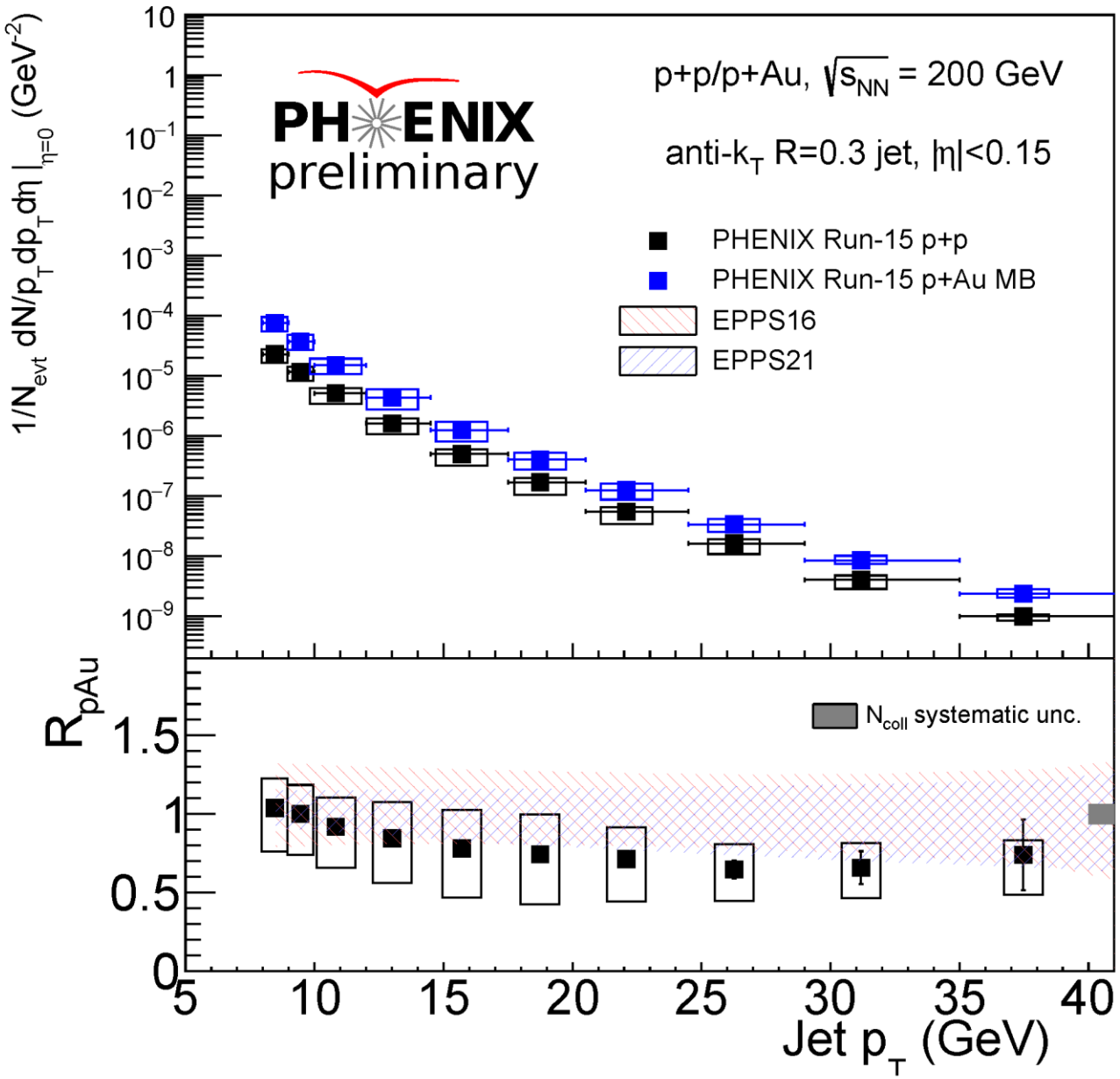
p_T from underlying event (PYTHIA6 embedded in p+Au MB events) – cross section weighted

~90% of jets don't have a UE contribution – when they do it is enhanced at low reco p_T by the trigger.



For the ~10% of jets that do have a UE contribution:

$$\langle UE\ p_T \rangle\ (10 - 12\ GeV\ jet\ p_T^{reco}) = 1.02\ GeV$$
$$\langle UE\ p_T \rangle\ (20 - 24.5\ GeV\ jet\ p_T^{reco}) = 0.840\ GeV$$



p+Au Jets

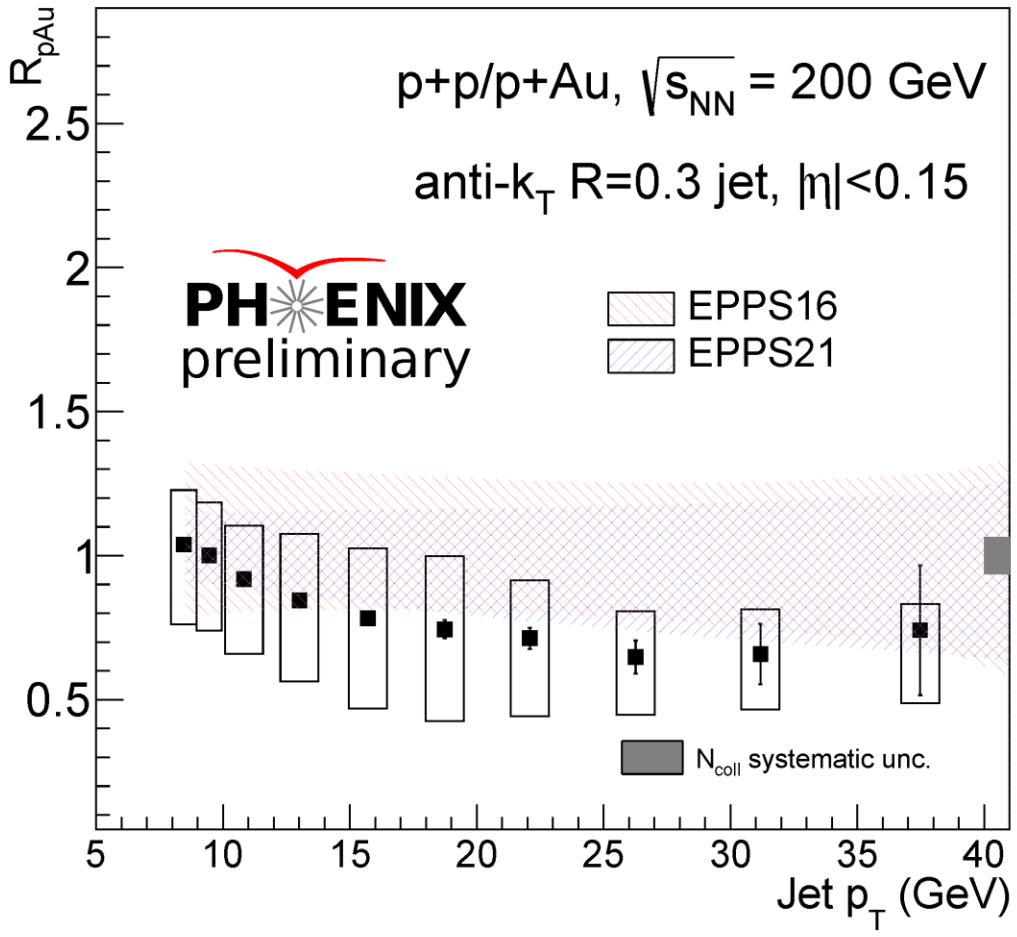
New Preliminary Result

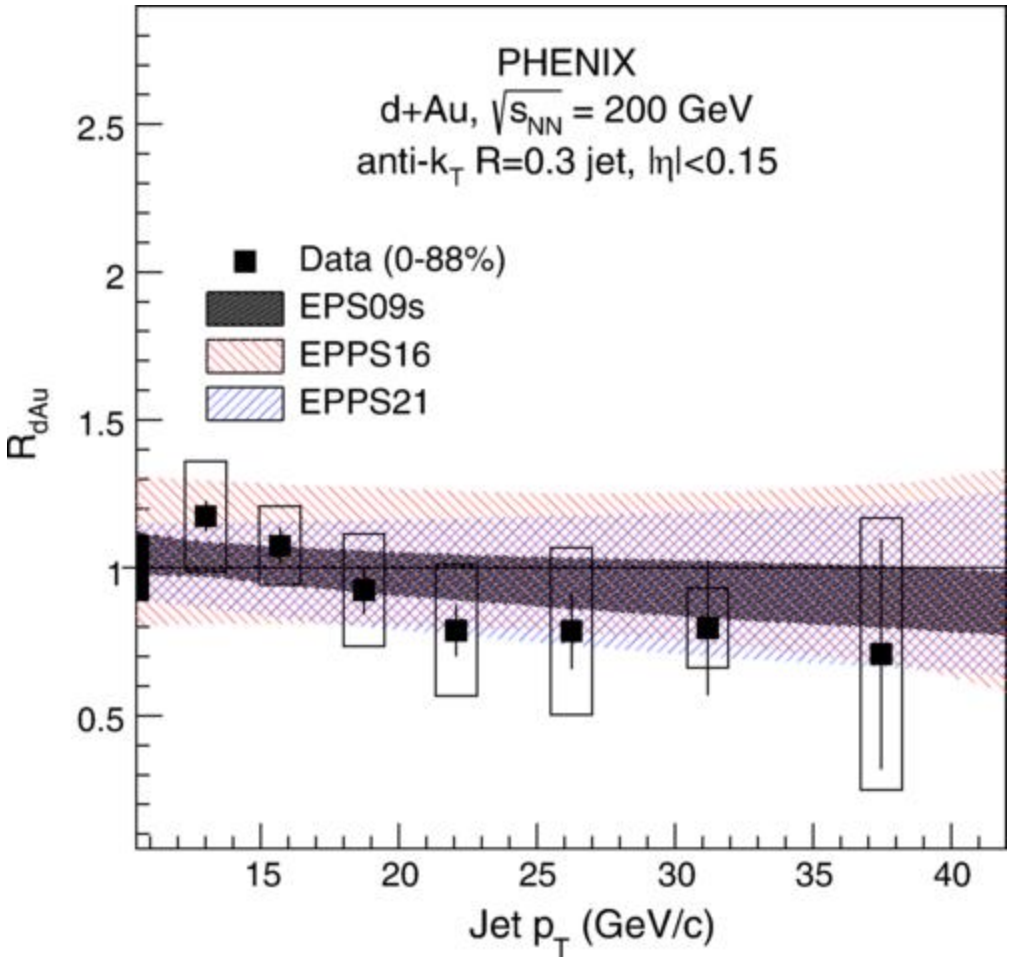
p+Au underlying event subtracted by embedding MC events in MB data events.

Invariant yield in Run-15 p+p/p+Au collisions.

Measured R_{pAu} is consistent with nPDF predictions, shows a dependence on jet p_T.

Comparison between p+Au and d+Au





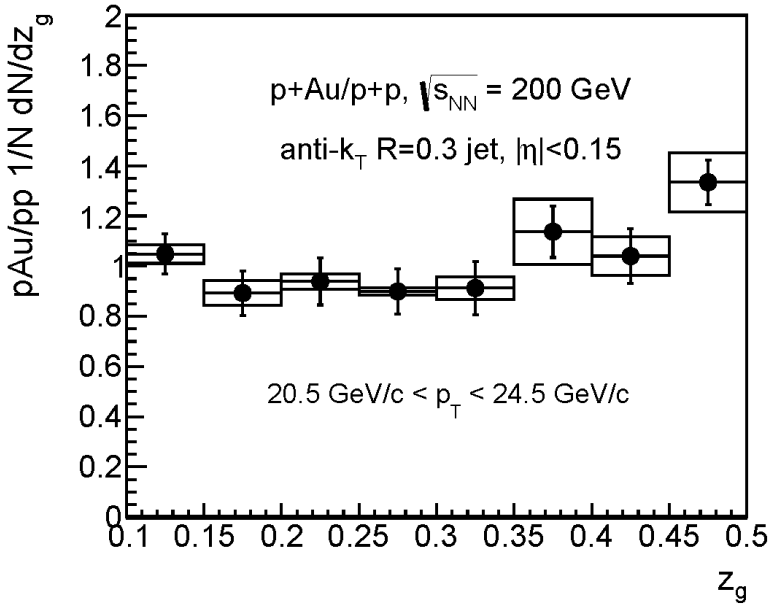
Phys. Rev. Lett. **134**, 099901
https://doi.org/10.1103/PhysRevLett.134.099901

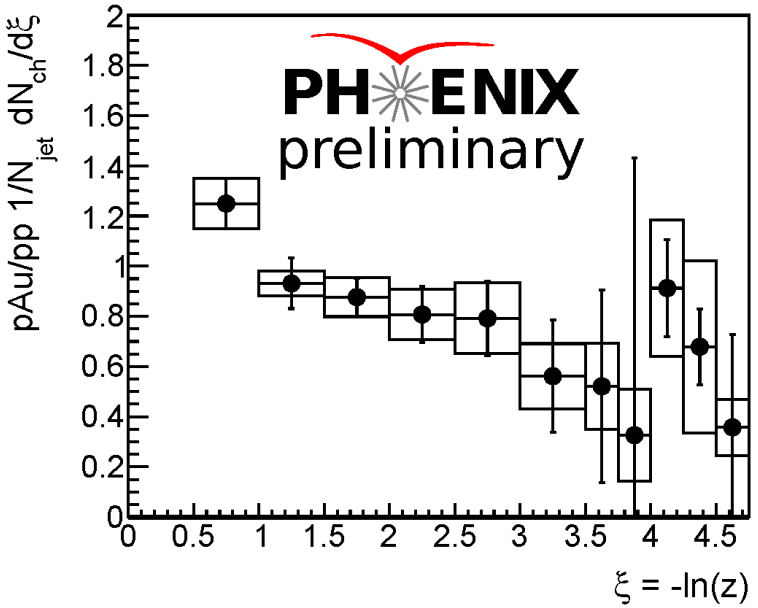
Jet Substructure in p+Au

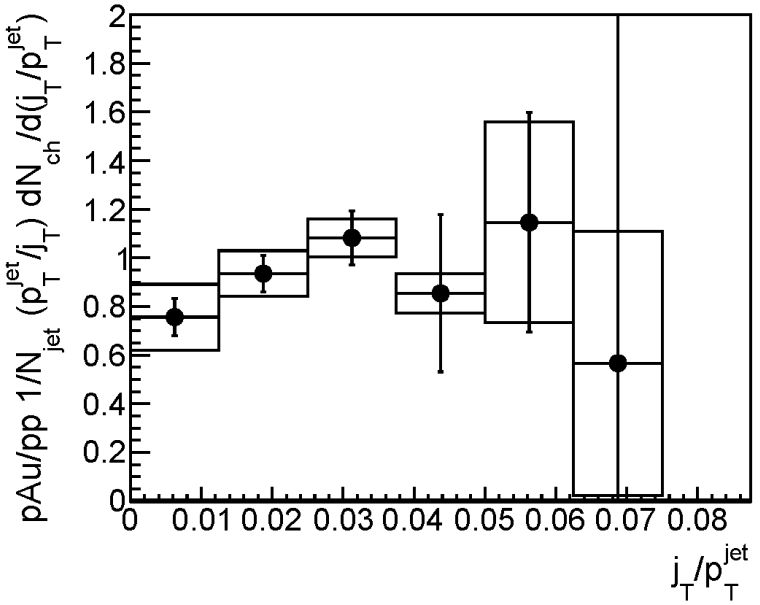
New Preliminary Result

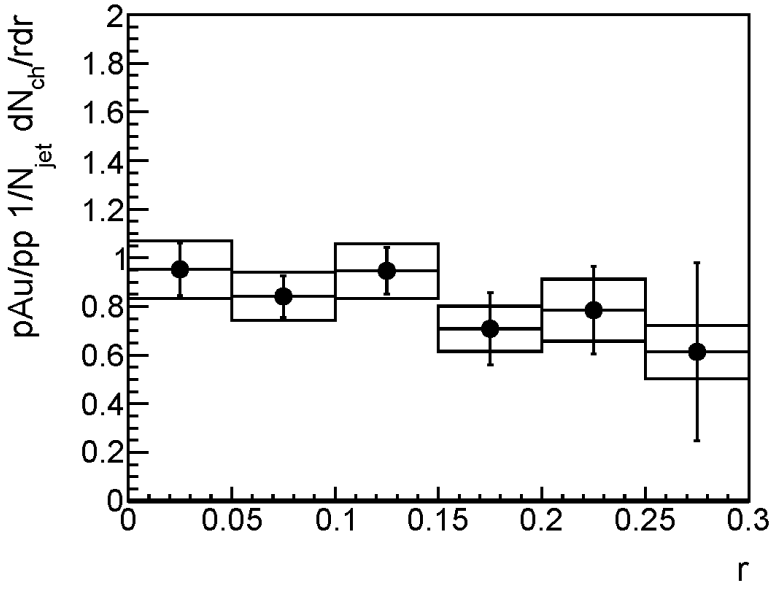
Substructure distribution ratios in Run-15 p+Au/p+p collisions.

- Bias towards more symmetric splittings in p+Au
- Suppression of soft part of fragmentation function
- Suppression at small j_T/p_T^{jet}
- Suppression of jet constituents at large distance from jet axis.









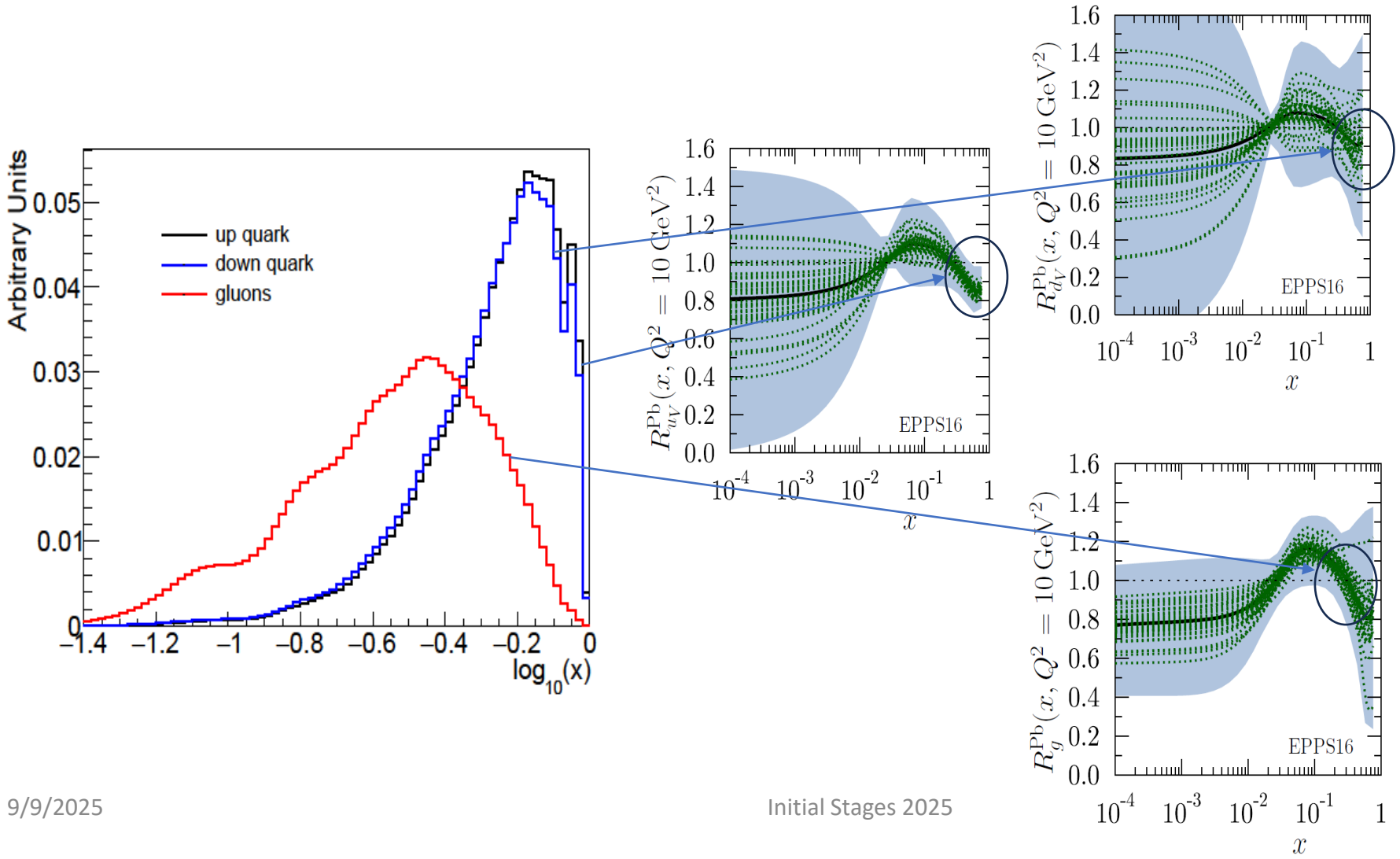
Conclusion

- ***Recently Published*** results for anti-k_T R=0.3
  jet cross section and substructure for p+p at $\sqrt{s} = 200$ GeV
  - Phys. Rev. D 111, 112008 (2025)
  - Measured cross sections lower than NLO/NNLO (and MC)
  - Jet substructure measured for z_g, ξ=-ln(z), j_T/p_T^{jet} and $\rho(r)$
- ***Recently Published*** revised results for anti-k_T R=0.3
  jet invariant yield for d+Au at $\sqrt{s}$ =200 GeV
  - Phys. Rev. Lett. 134, 099901 (2025)
  - Min-bias R_{dAu} consistent with nPDF's
- ***New Preliminary*** results anti-k_T R=0.3
  jet invariant yield and substructure for p+Au at $\sqrt{s} = 200$ GeV
  - Min-bias R_{pAu} consistent with nPDF's
  - Jet substructure modified compared to p+p at the same p_T^{jet}
  - *Jet substructure provides a new opportunity to understand the origin of CNM effects*

BACKUP

Jets Kinematics in PHENIX

EPPS16: https://doi.org/10.1140/epjc/s10052-017-4725-9



At |η|<0.15 in PHENIX, we predominantly see a suppression (EMC effect) of valence quarks and cross between the antishadowing/shadowing region for gluons.

2D Unfolding Method

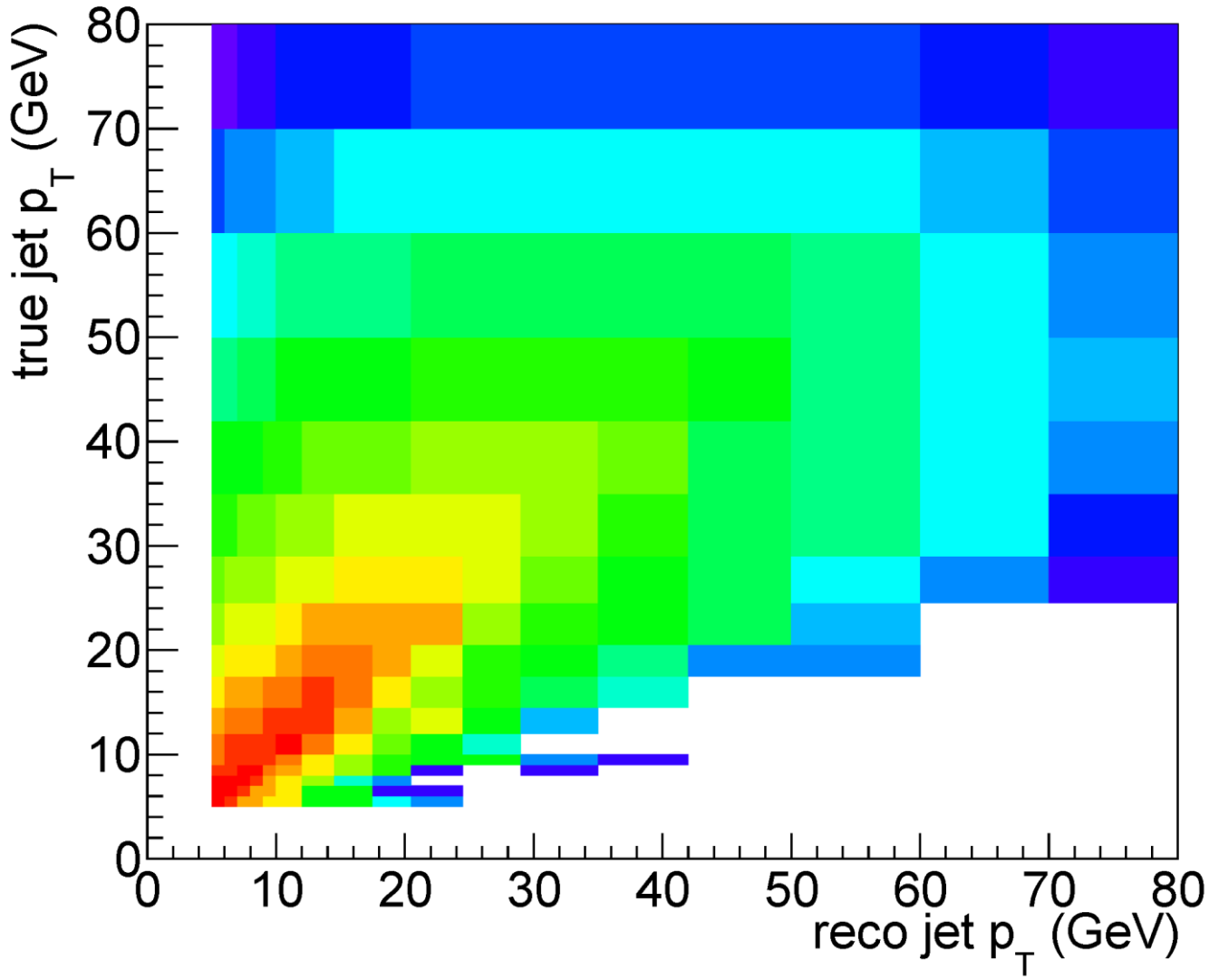
- Mathematically this is very similar to 1D unfolding:
  - 1D: unfold a distribution
  - 2D: unfold a distribution as a function of another variable.

- We unfold distributions in z_g, $(\xi, j_T, dR)_{charged}$ as a function of jet p_T
  - For the response matrix we now keep track of multiple quantities per jet
  - For z_g we just keep track of (z_g, p_T)
  - For $x = (\xi, j_T, dR)_{charged}$ we take a slightly different approach:
    - Every jet samples the distribution x multiple (N_{ch}) times
    - Fill the response matrix with the (x, p_T) for every charged particle.
    - Normalization of unfolded distribution maintains meaning – integral is N_{ch}

- Reminder – for p+Au, d+Au we embed Pythia in data events
  - Embedding is *done separately for each centrality range in d+Au*

p+p Response Matrix

Response matrix for Run-15 200 GeV p+p using modified Pythia6, jets with anti-k_T R=0.3



p+Au Response Matrix

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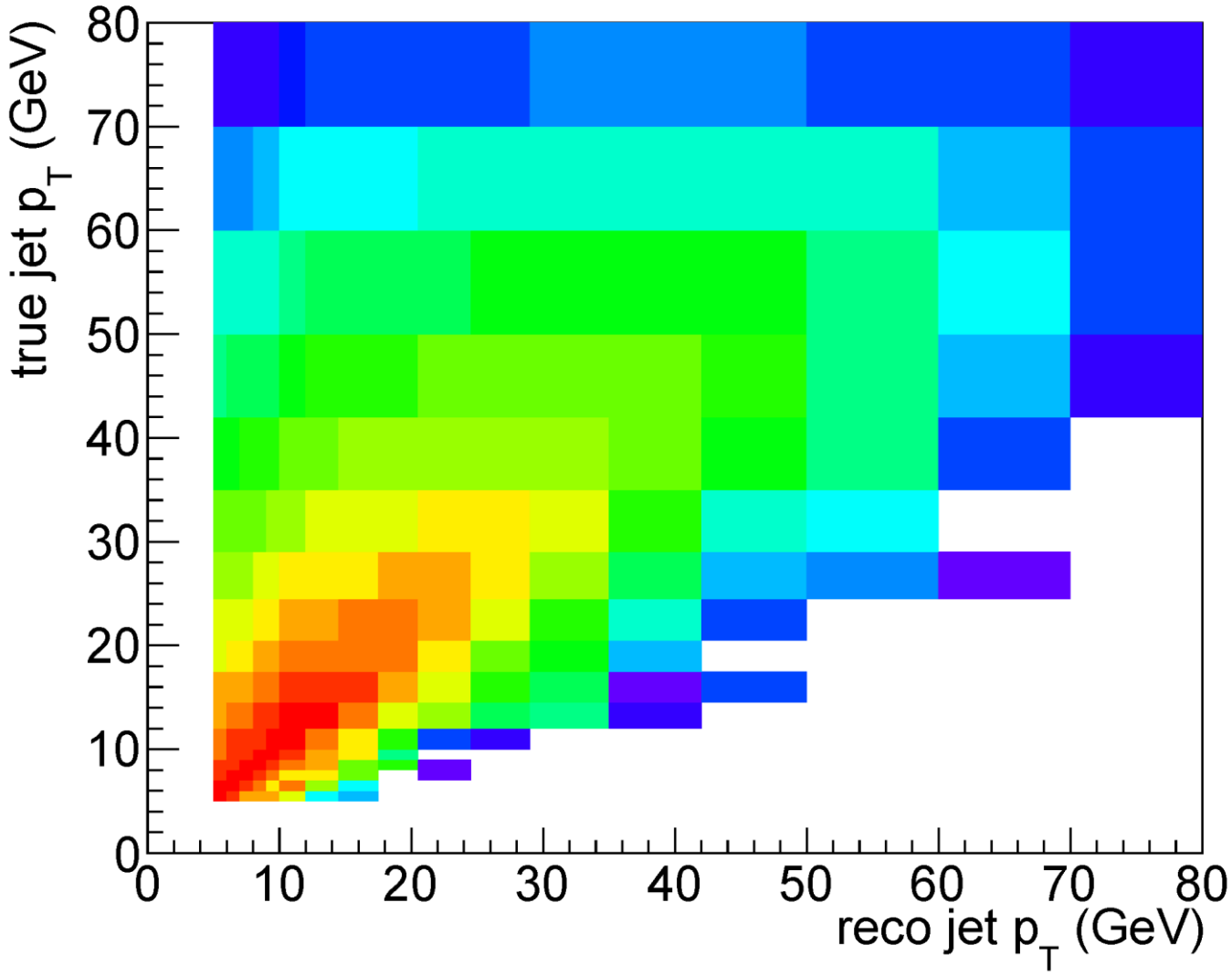
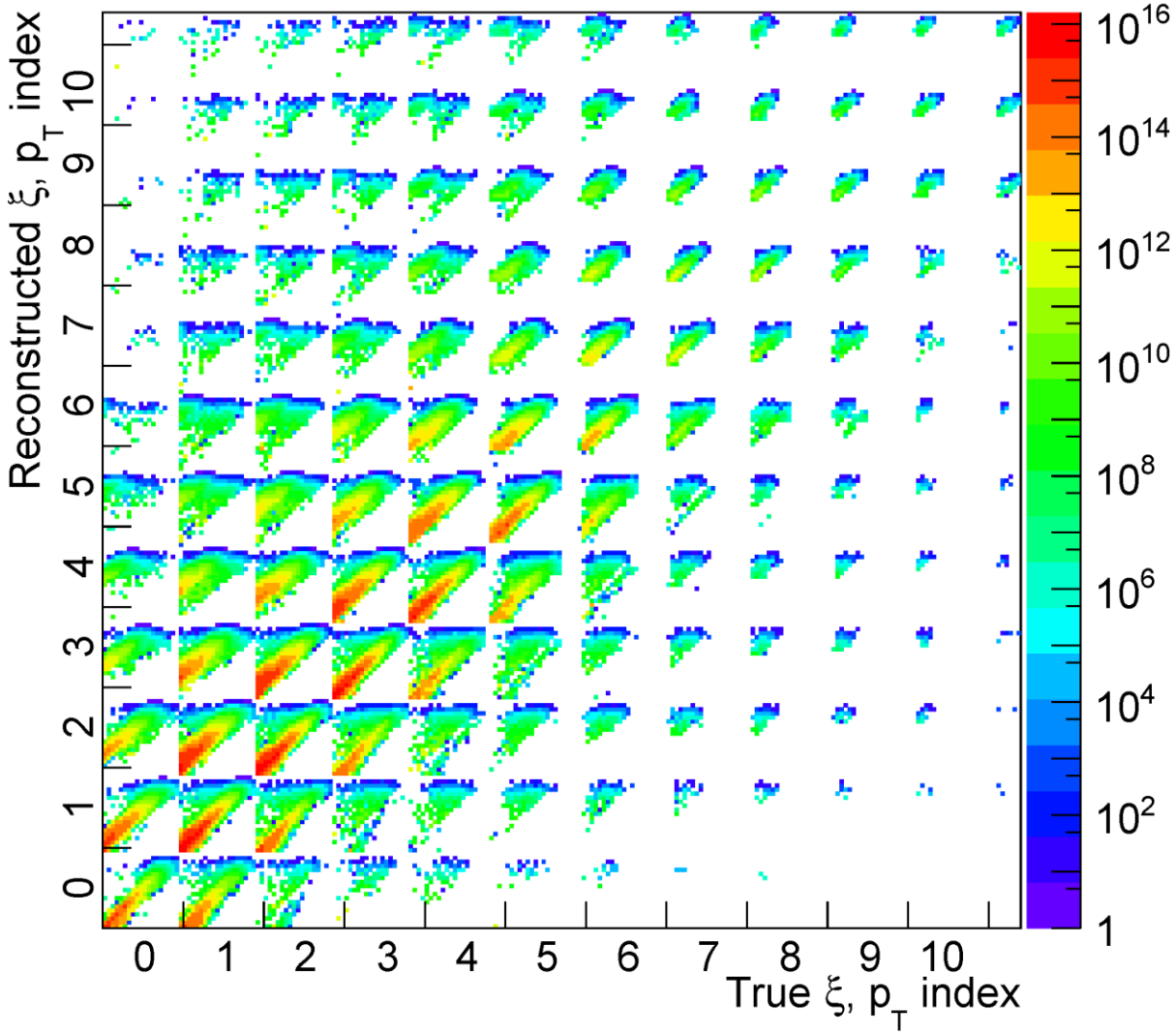


2D Unfolding Matrix

Response matrix for FF ξ unfolding (Run-15 p+p).

Index is:
$\xi^{bin}*(19) + p_T^{bin}$

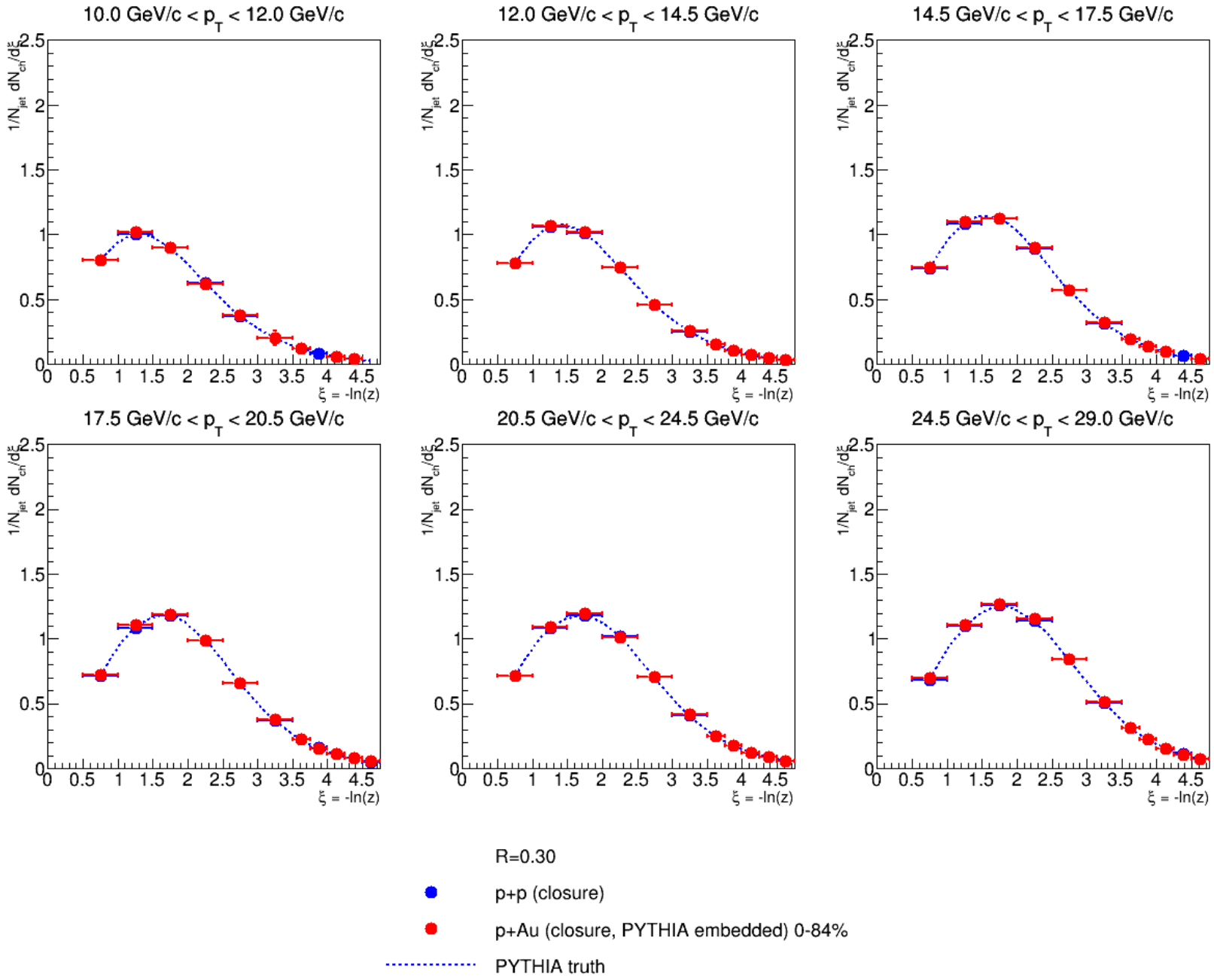
So each sub-plot is the $p_T^{reco} - p_T^{true}$ correlation in a bin of ξ.



Unfolding Closure Test

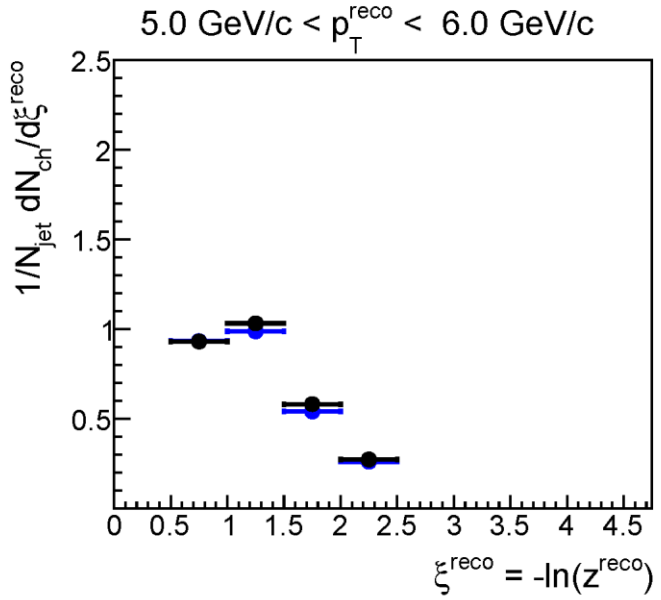
Closure test using the modified Pythia model.

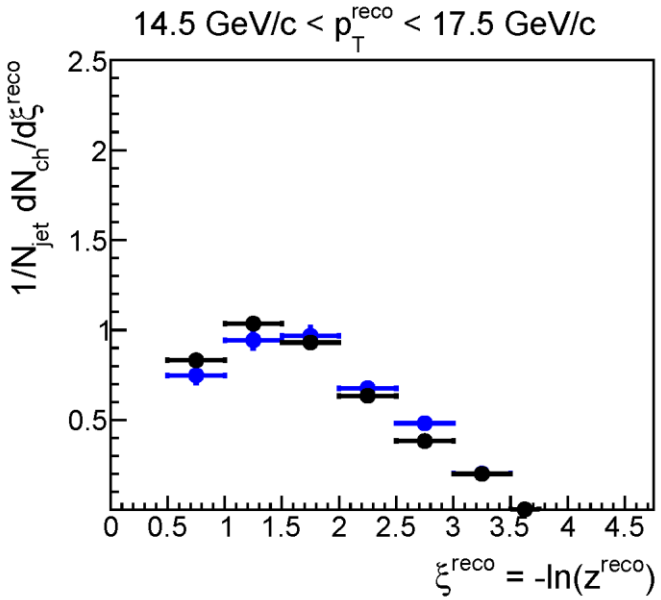
In both cases, the unfolded distributions from simulated data recover the truth input distributions.

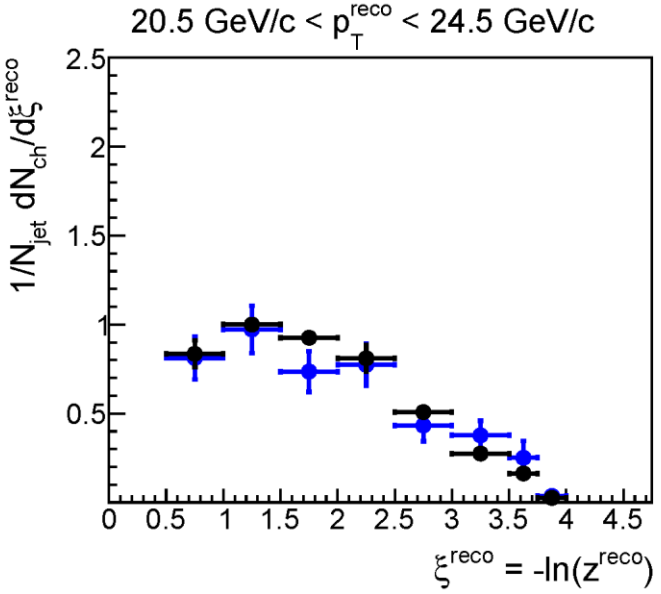


p+p Reco Level Distributions

Excellent agreement between simulation and reco distributions prior to unfolding.







p+p reco (data)

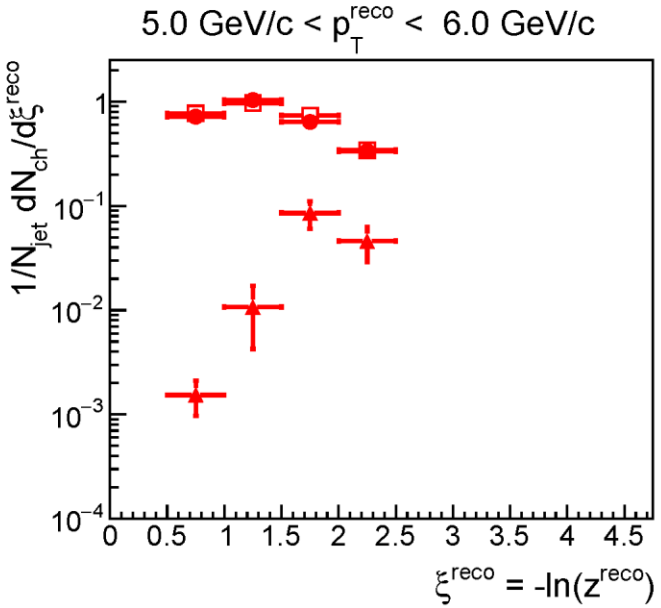
p+p reco (PYTHIA)

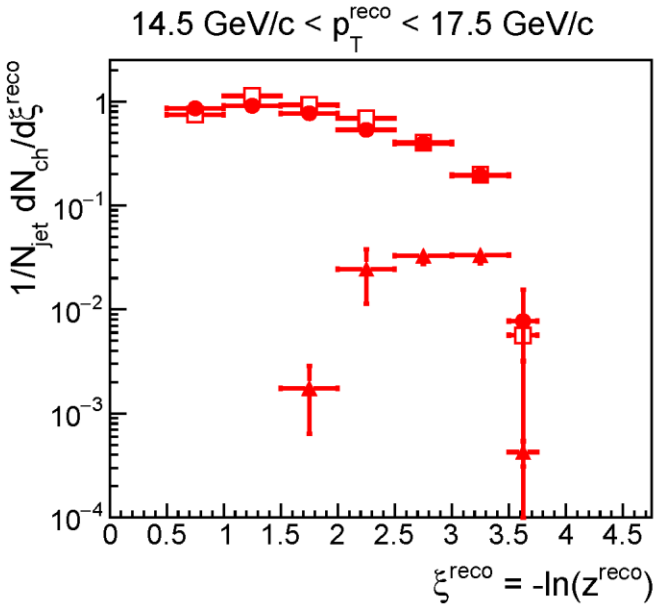
PHENIX preliminary

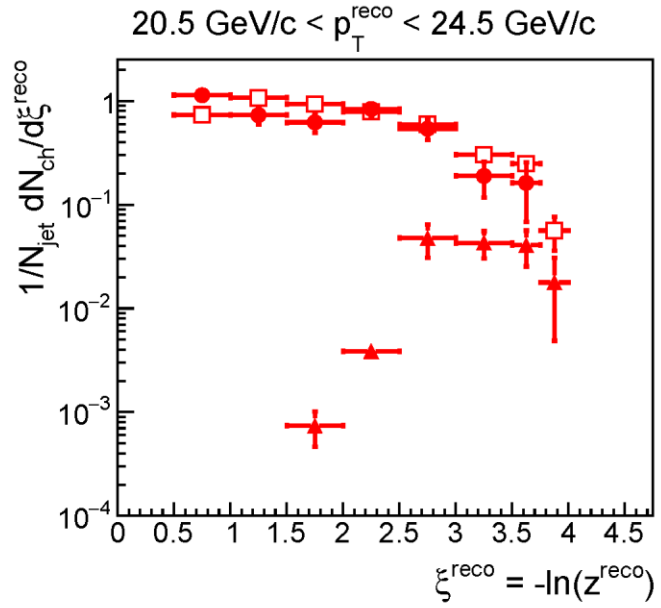
p+Au Reco Level Distributions

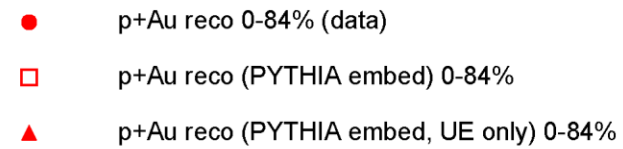
Excellent agreement between simulation and reco distributions prior to unfolding.

Effect of underlying event on reco level FF is also shown, typically small in most bins.





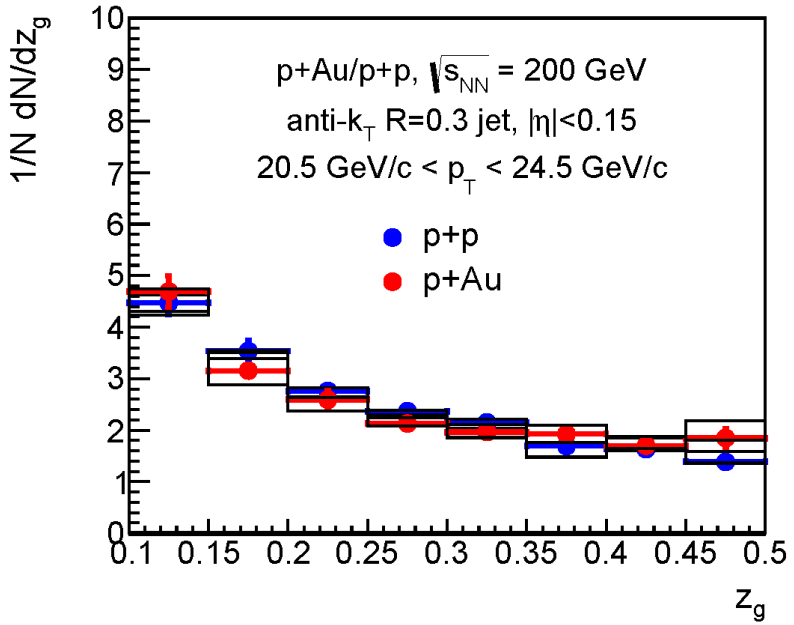


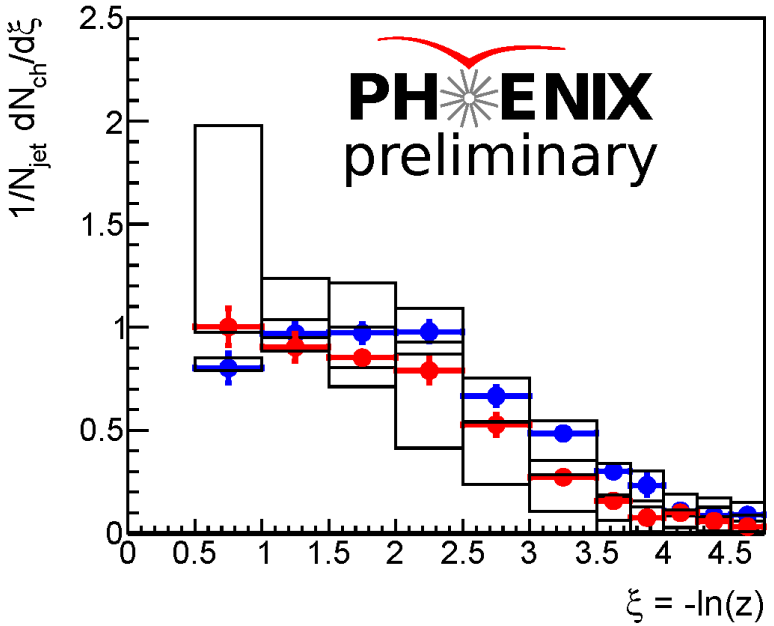


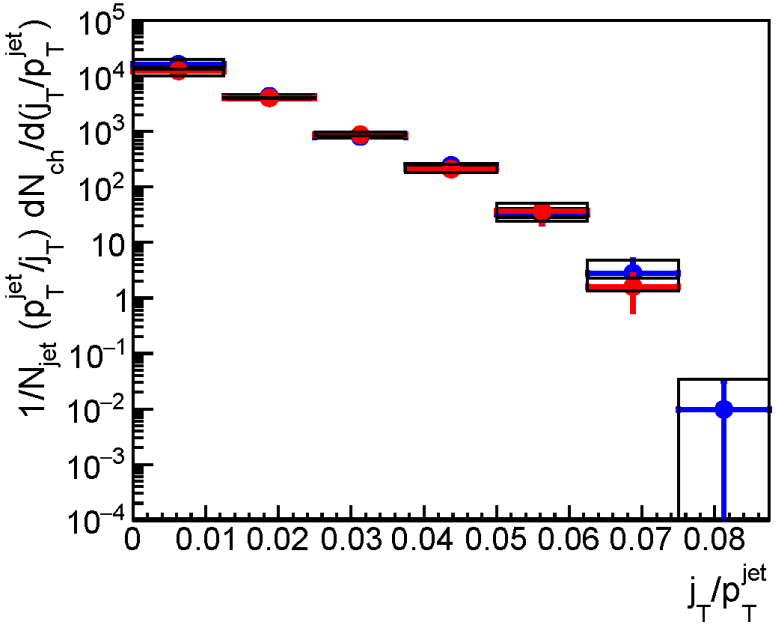
PHENIX
preliminary

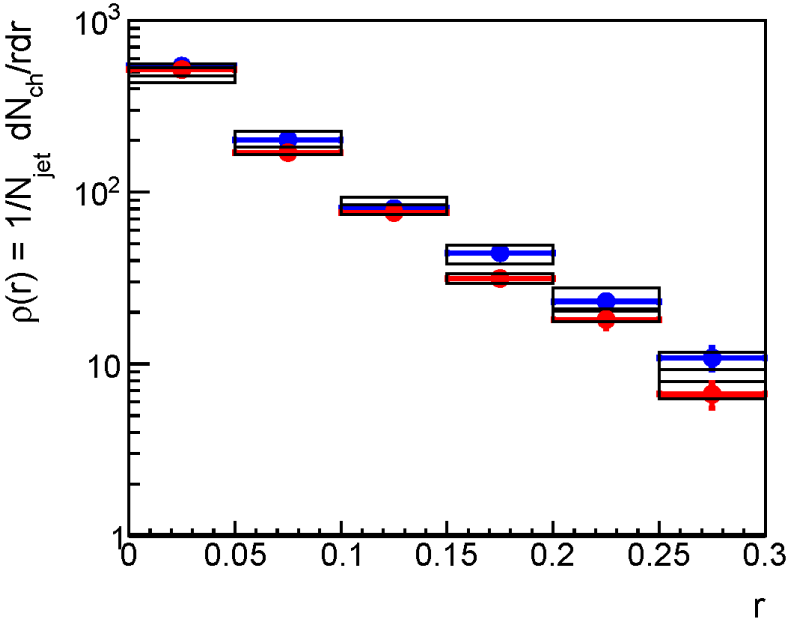
Direct comparison of p+Au and p+p substructure distributions.

Note that some systematic errors cancel between p+p and p+Au.



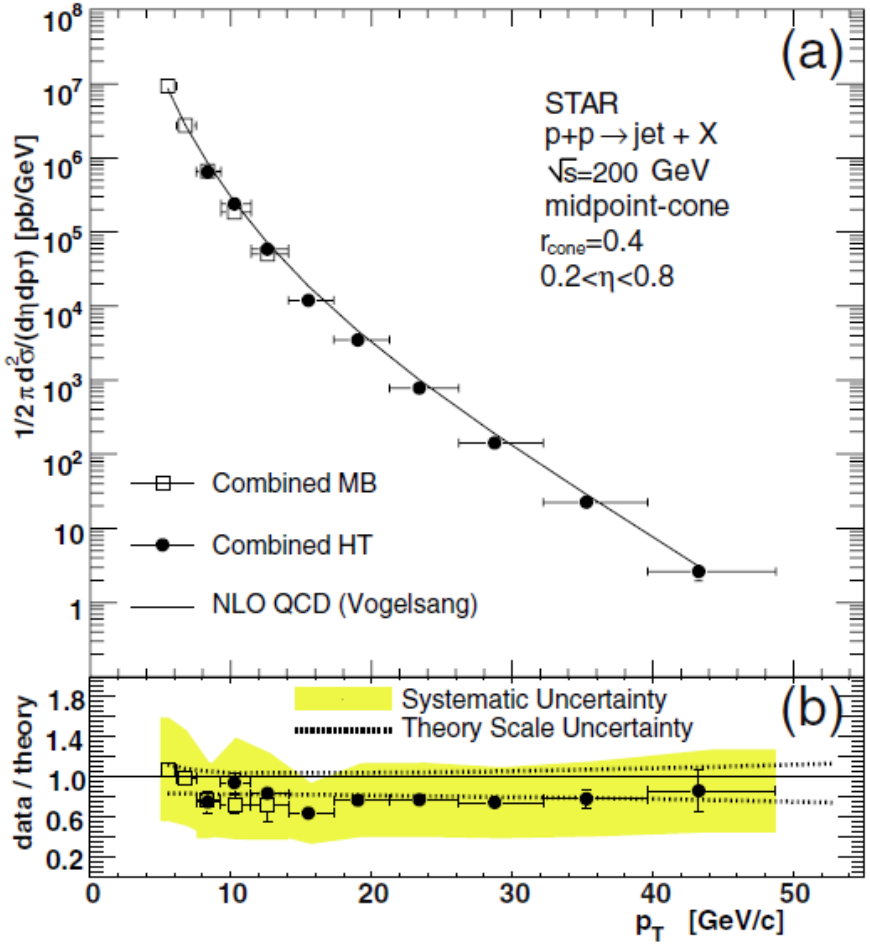


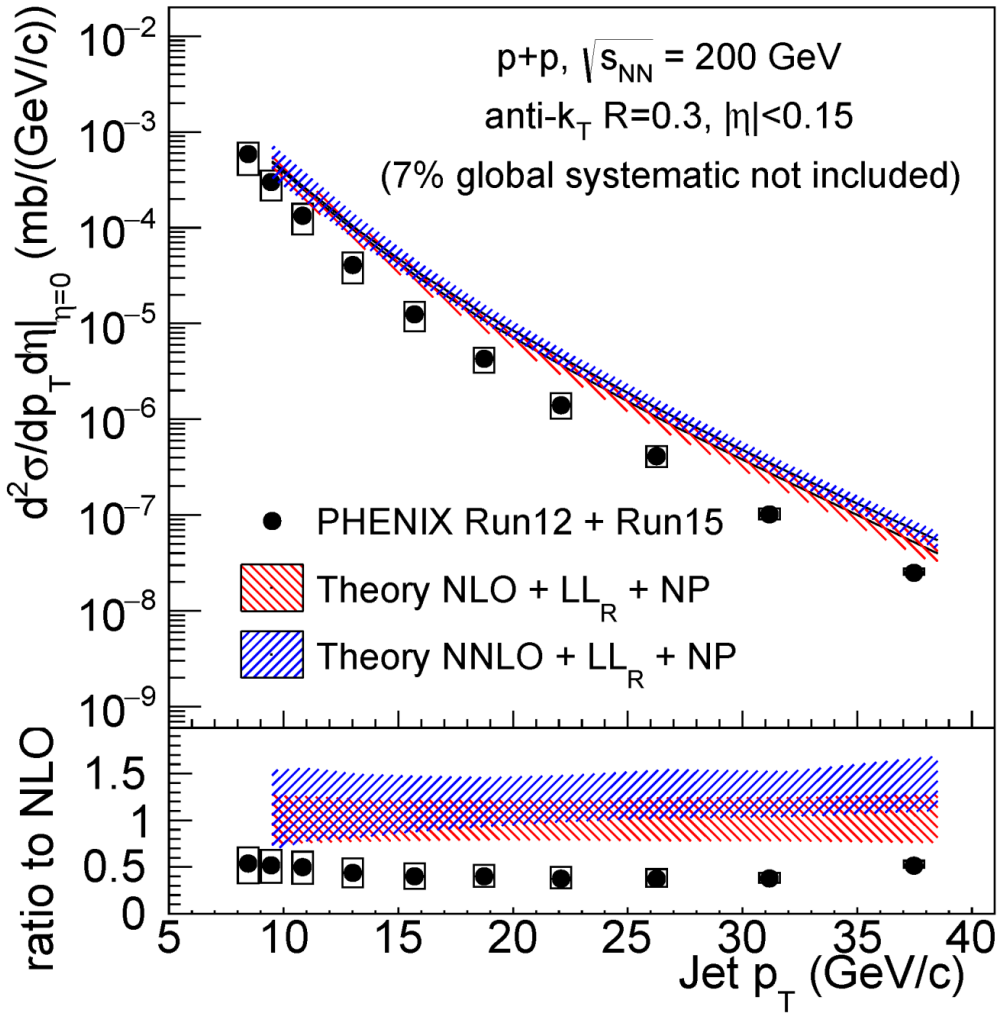




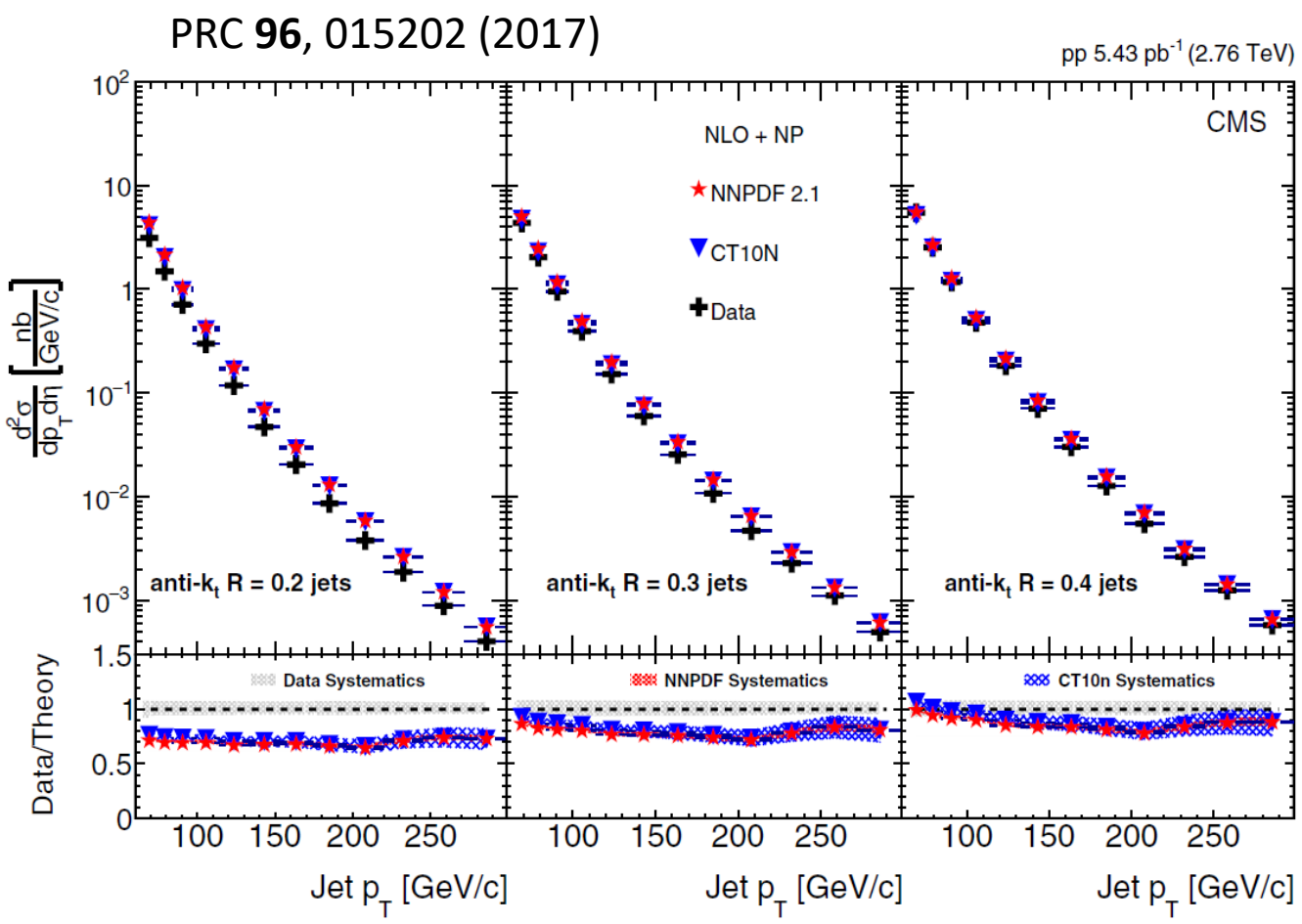
Comparison with STAR

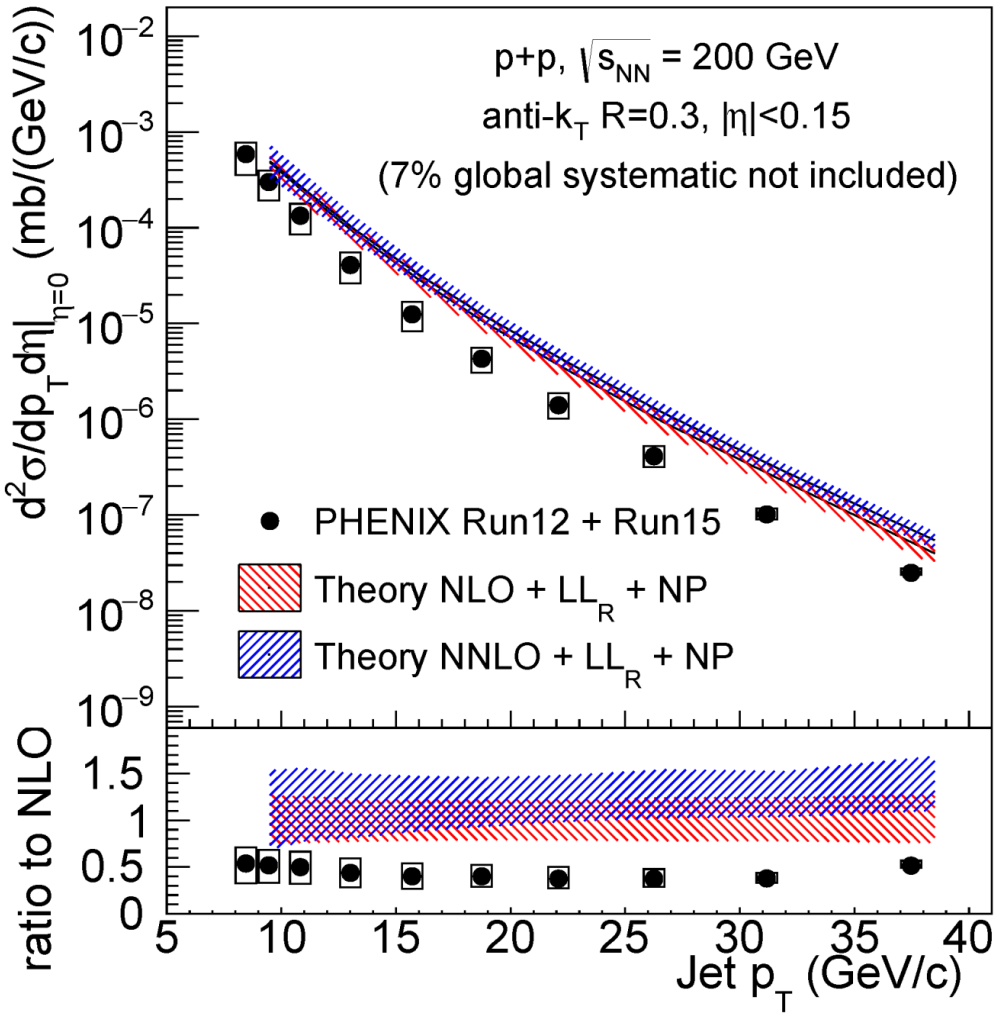
PRL **97,** 252001 (2006)



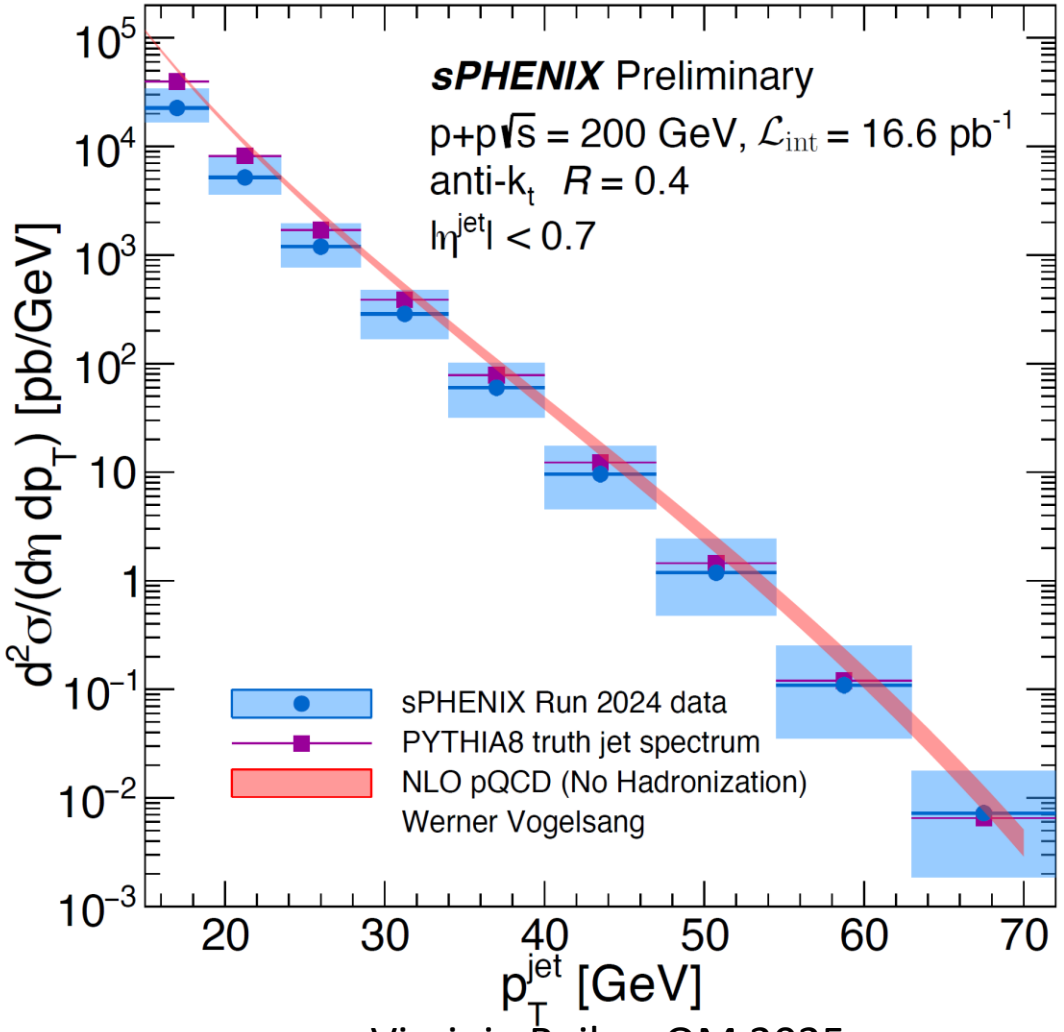


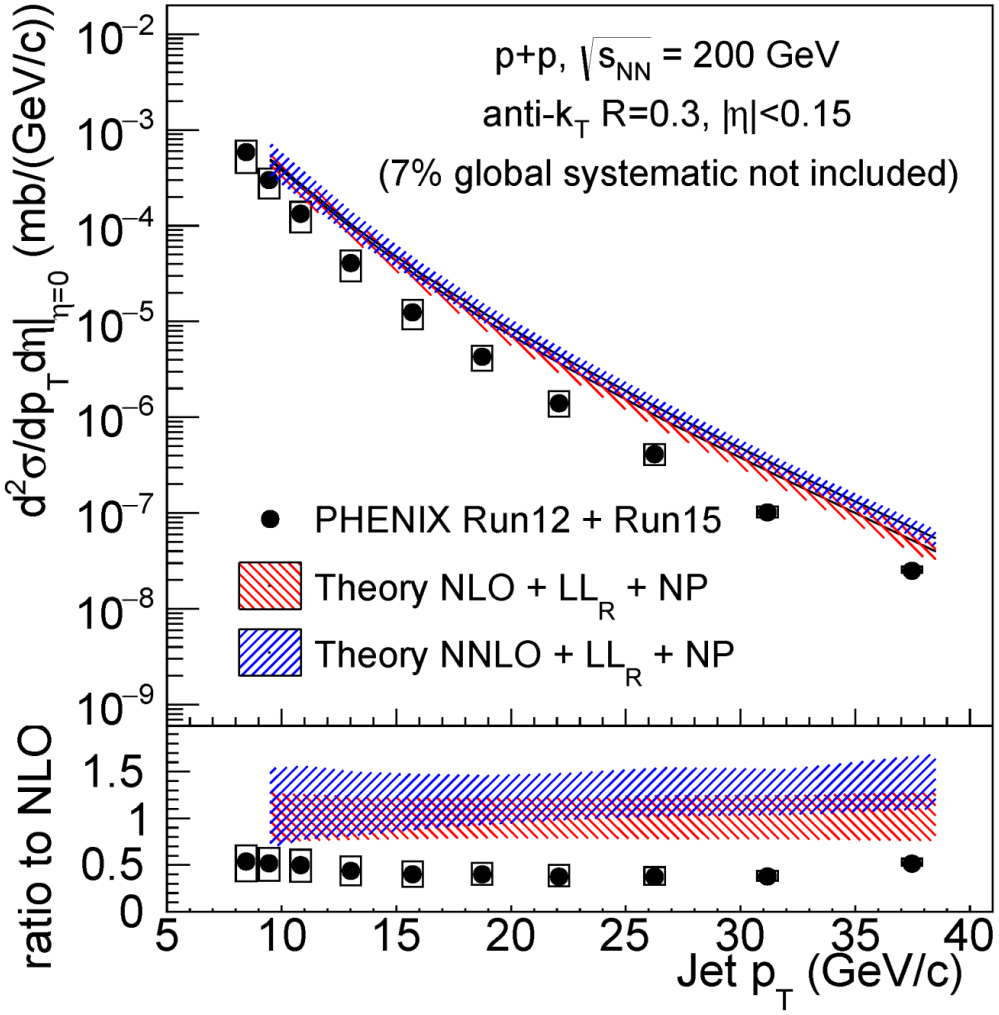
Comparison with CMS





Comparison with sPHENIX





Virginia Bailey, QM 2025

Subprocess Fractions p+p/p+Au