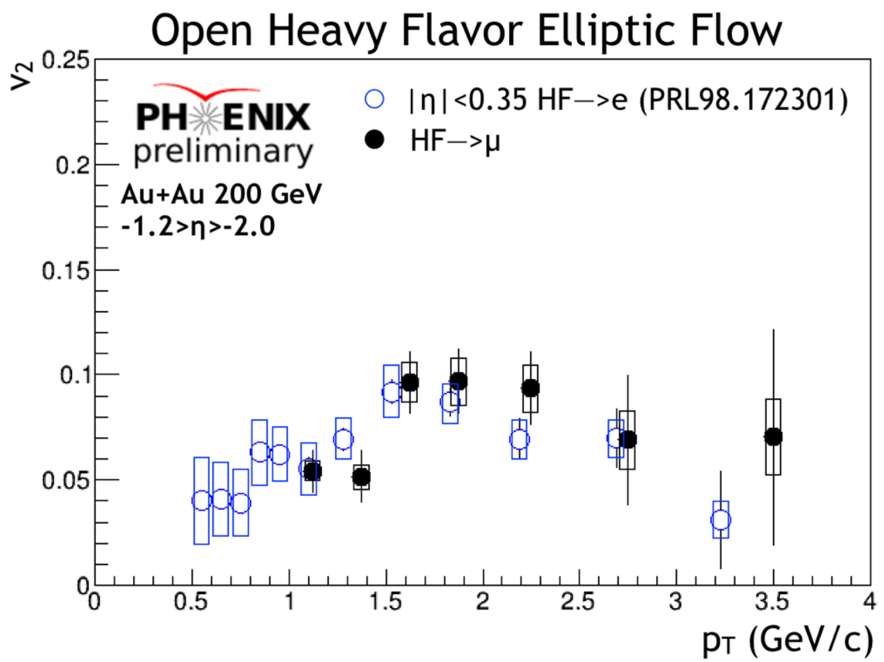
Characterizing the Jet structure in Au+Au and p+p collisions by the PHENIX experiment at RHIC

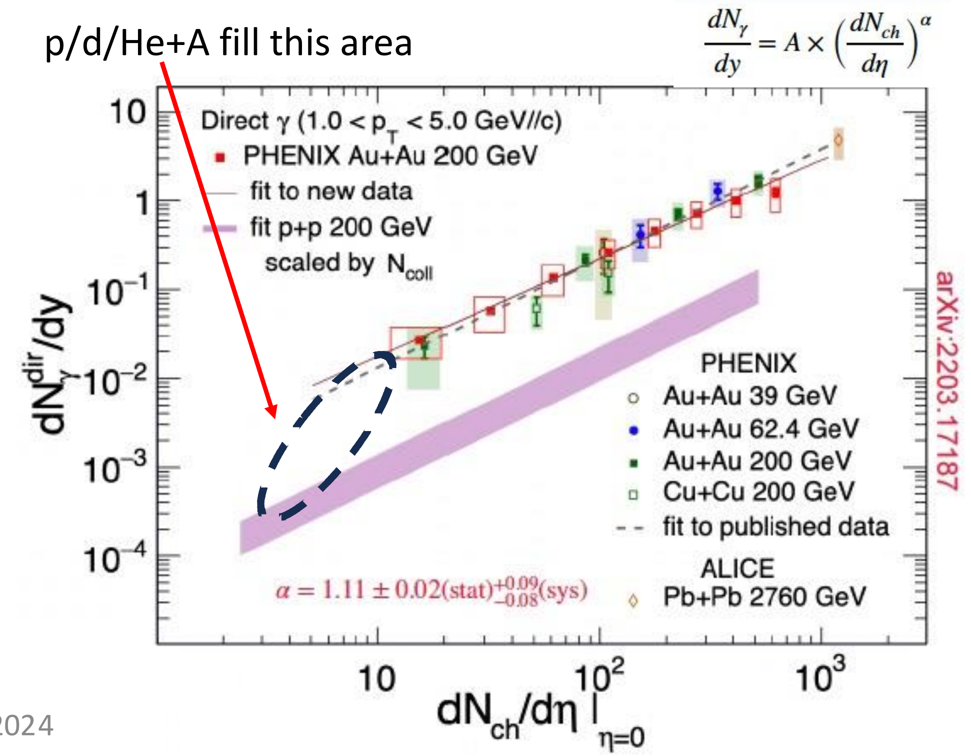
Takao Sakaguchi
(Brookhaven National Laboratory)
For the PHENIX collaboration

This presentation bases on results from:
PRC110, 044901(2024) and arXiv:2408.11144 (accepted for publication in Phys. Rev. D)

Hard/EM probes in QGP compared to p+p

- Heavy flavor: Flow of heavy quarks. Indication of "thermalization of heavy quarks" in the medium?
- Thermal photons: Systematic enhancement of the photon yield is seen in Au+Au
  - Onset of enhancement in p/d/He+A collisions
  - Obviously the "thermal" effect
- How about Jets? Do we see any "thermal" effect in jets?





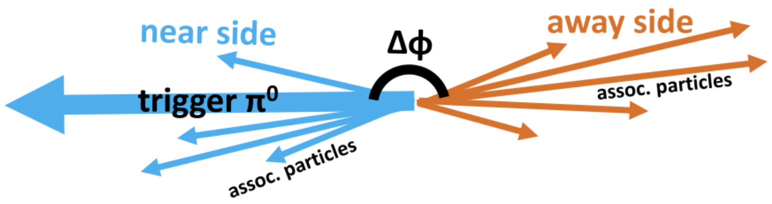
Comparing Au+Au and p+p jet cases

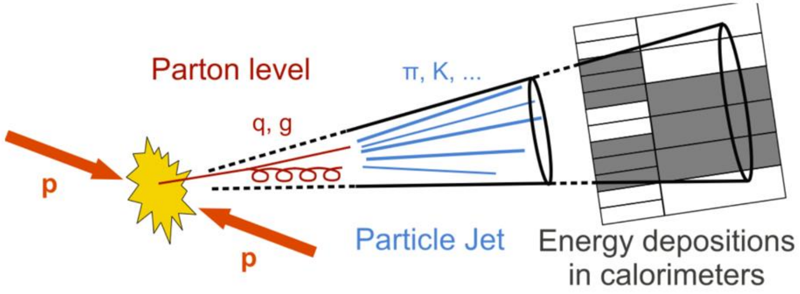
Au+Au

- Jets to probe the characteristics of nuclear medium (QGP) through its interaction with the medium
- Reconstruction of jets is great (to be done in sPHENIX) but hard at RHIC.
- Instead, use multi-particle correlation.
  - Effectively limiting the jet-cone radius (R) to be very small. → small R jets

p+p

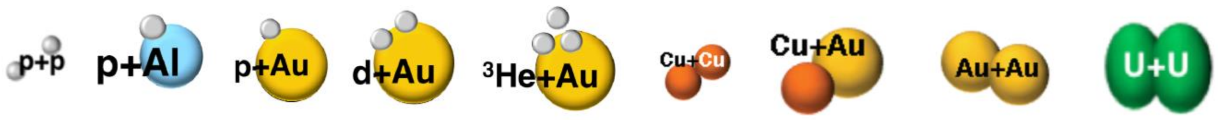
- Precise measurement of the “unmodified jets” is a baseline for Au+Au measurement
  - Cross-section, structure
  - Input to the model that run with QGP
- Model calculations at lower pT, small-R have difficulty matching data both at RHIC and LHC
- Full reconstruction is possible
  - Limited acceptance in PHENIX → small R jets





PHENIX experiment

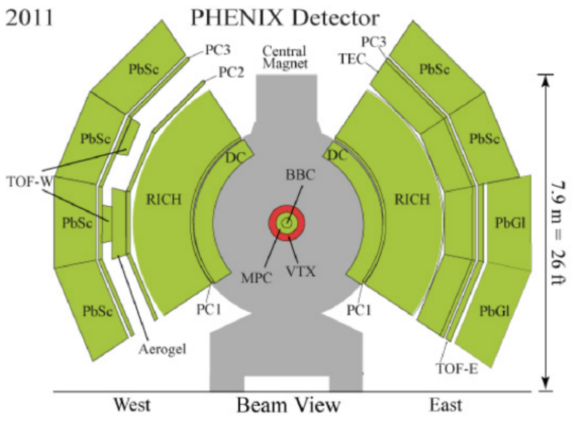
- Accomplished 16 years of operation with 9 collision species and 9 collision energies
  - Results from the recorded data are still coming out.



Hadrons, electron, photons

$|\eta|<0.35$ $\Delta\Phi = 2 \times \pi/2$

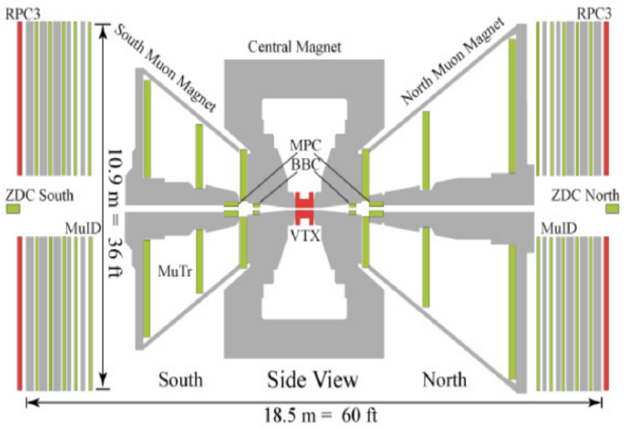
CENTRAL ARMS



Muons

$-2.2<\eta<-1.2$ $1.2<\eta<2.2$ $\Delta\Phi=2\pi$

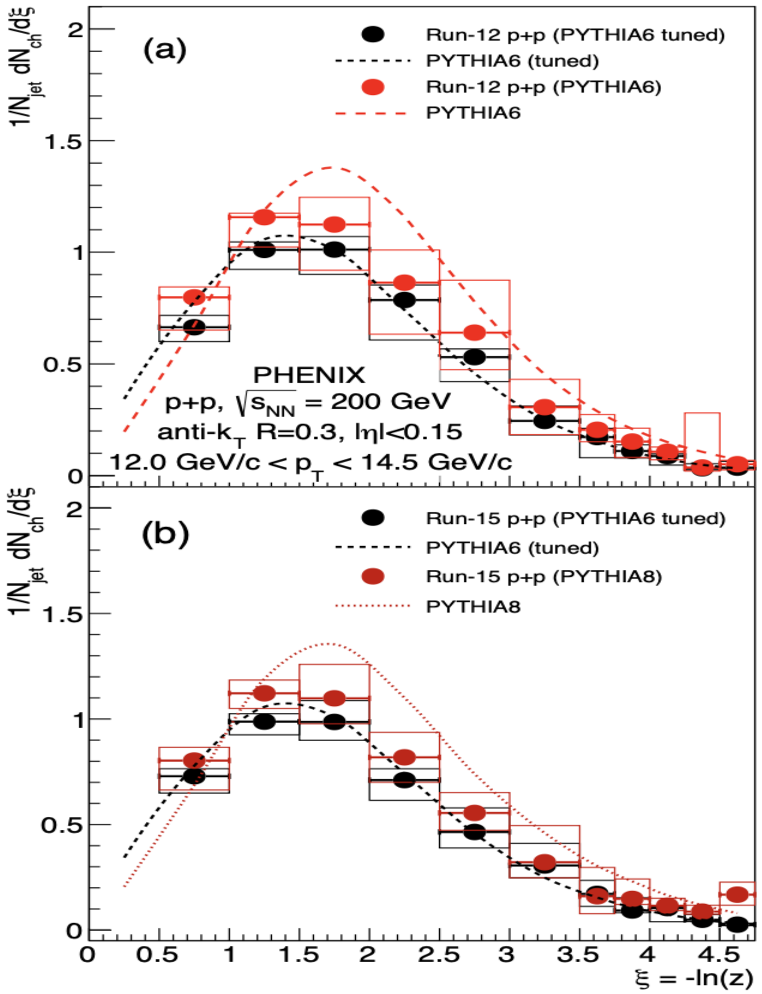
MUON ARMS



Run	Species	Energy $\sqrt{s_{NN}}$ (GeV)	Integrated Luminosity (mb^{-1})
1 (2000)	Au+Au	56	1.0E-6
2 (2001/2002)	Au+Au	200	2.4E-5
	p+p	200	1.5E+5
3 (2003)	d+Au	200	2.7E+3
	p+p	200	3.5E+5
4 (2004)	Au+Au	200	2.4E+2
	Au+Au	62.4	9.0E+0
5 (2005)	Cu+Cu	200	3.0E+3
	Cu+Cu	62.4	1.9E+2
	Cu+Cu	22.4	2.7E+3
	p+p	200	3.4E+6
6 (2006)	p+p	200	7.5E+6
	p+p	62.4	8.0E+4
7 (2007)	Au+Au	200	8.1E+2
8 (2008)	d+Au	200	8.0E+4
	p+p	200	5.2E+6
9 (2009)	p+p	500	1.4E+7
	p+p	200	1.6E+7
10 (2010)	Au+Au	200	1.5E+3
	Au+Au	62.4	1.1E+2
	Au+Au	39	4.0E+4
	Au+Au	7.7	3.0E+2
11 (2011)	p+p	500	1.8E+7
	Au+Au	19.6	2.0E+0
	Au+Au	200	1.7E+3
	Au+Au	27	7.0E+0
12 (2012)	p+p	200	1.0E+7
	p+p	510	3.2E+7
	U+U	193	2.0E+2
	Cu+Au	200	5.0E+3
13 (2013)	p+p	510	1.6E+8
14 (2014)	Au+Au	14.6	4.0E+0
	Au+Au	200	7.5E+3
	^{3}He+Au	200	2.4E+4
15 (2015)	p+p	200	6.0E+7
	p+Au	200	2.0E+5
	p+Al	200	5.0E+5
16 (2016)	Au+Au	200	7.0E+3
	d+Au	200	5.0E+4
	d+Au	62.4	5.0E+3
	d+Au	19.6	8.0E+1
	d+Au	39	2.0E+3

p+p

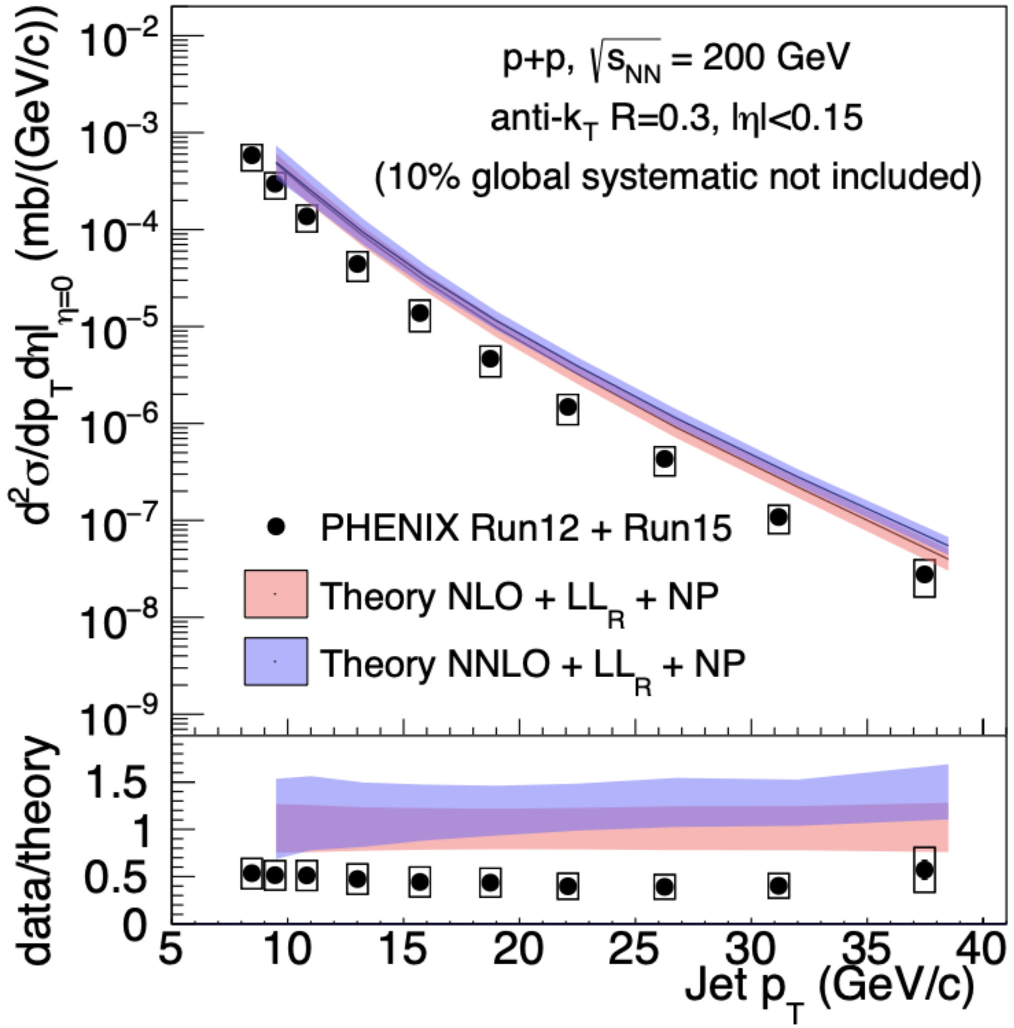
PYTHIA tuning for unfolding p_T spectra



- Initial unfolding showed that integrals of the jet substructure distributions (avg. number of jet constituents) are systematically larger in PYTHIA than in the data for all distributions.
  - Similar for both PYTHIA6 and PYTHIA8.
  - Produces biased and inconsistent unfolding results.
- "Tune" PYTHIA by randomly removing truth jet constituents until PYTHIA and data match in R distribution.
  - Rescale the momentum of the remaining constituents to account for the removed particles so that the overall jet cross-section shape doesn't change
- Does not affect jet cross-section.

arXiv:2408.11144 (accepted for publication in Phys. Rev. D)

Jets cross-section by PHENIX



- Both NLO and NNLO overpredicts data
- Same trend as STAR data comparison to NLO without LL_R at LHC
  - NLO predictions overestimate the jet cross section at small R, while the agreement is better at larger values of R.
- The difference indicates importance of non-perturbative corrections at low jet p_T and R.

Theory bands:
Private communication from G. Soyez based on:
Phys. Lett. **B378**, 287 (1996) ; Nucl. Phys. **B485**, 291 (1997); JHEP **04**, 039 (2015)

Obtained by matching the NLO and NNLO predictions to leading-logarithmic re-summation in the jet radius non-perturbative corrections from MC simulations averaging over several MC setups.

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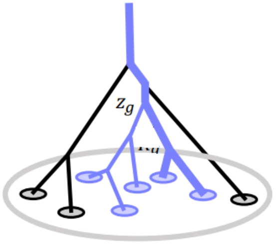
z_g distribution

$$z_g \stackrel{\text{def}}{=} \frac{\min(p_T^1, p_T^2)}{p_T^1 + p_T^2} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta_{SD}}$$

$$R_g \stackrel{\text{def}}{=} \Delta R_{12}$$



- SoftDrop groomed momentum fraction with z_{cut}=0.1 and b_{SD}
- Good agreement with STAR results from Phys. Lett. B 811, 135846 (2020)
  - Note different R for STAR (R=0.2,0.4) and PHENIX (R-0.3)
- Shift to lower z_g with increasing jet p_T
  - Higher asymmetric splitting at higher p_T

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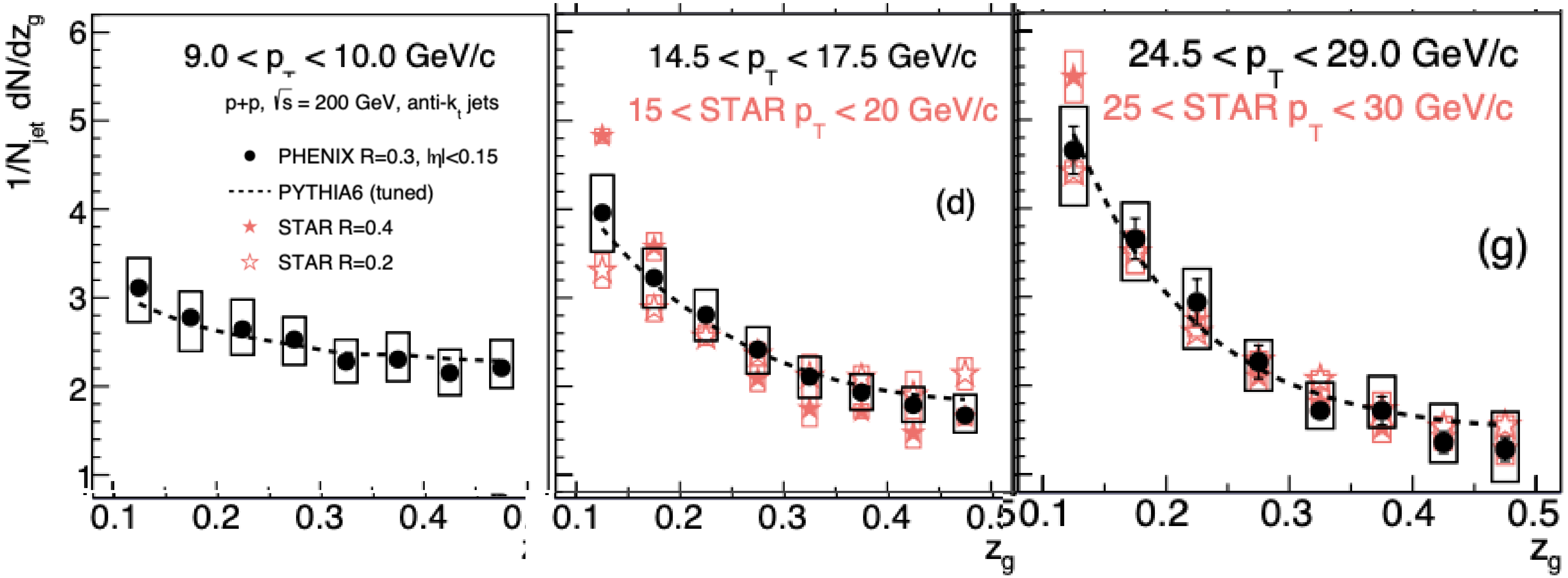
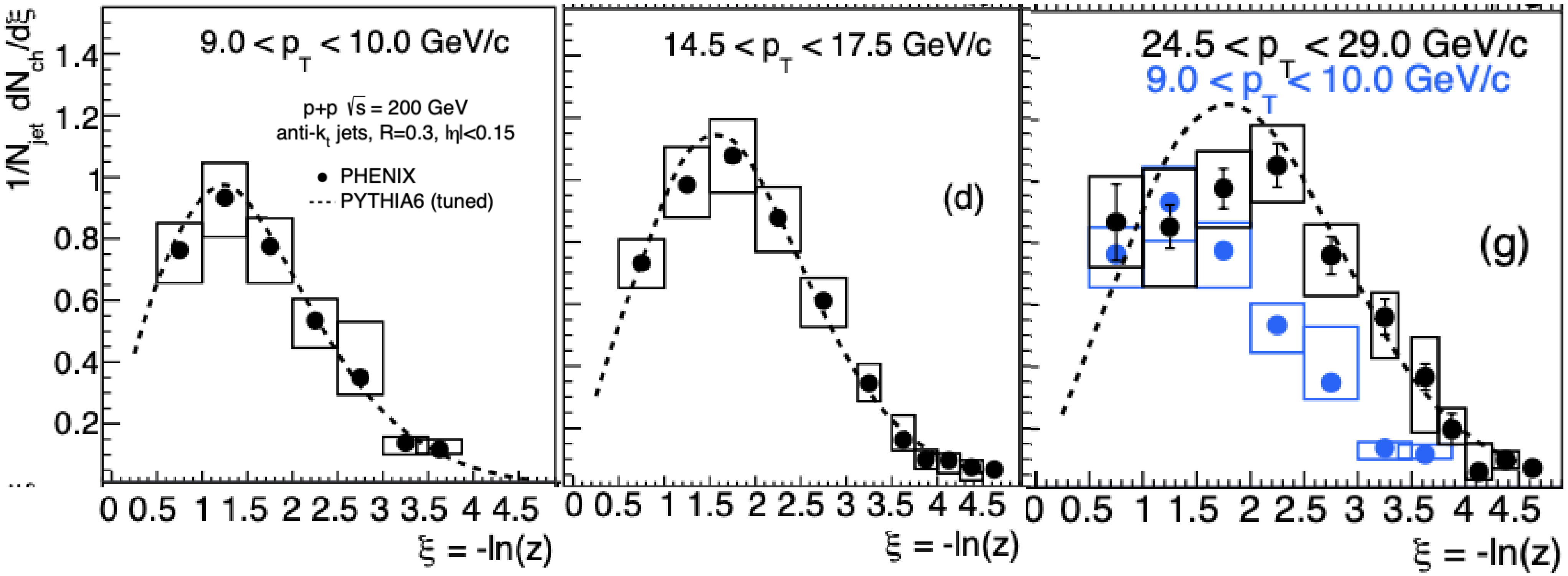


ξ distribution

$\xi = -\ln(z) = \ln(p_{T,jet}/p_{T,h})$

- ξ for charged particles, where z is the fraction of the jet pT carried by the charged particle.
- x distribution shifts toward lower z carried by a jet constituent with increasing jet p_T
  - The trend is similar to z_g but this is a “per constituent” variable.

arXiv:2408.11144 (accepted for publication in Phys. Rev. D)

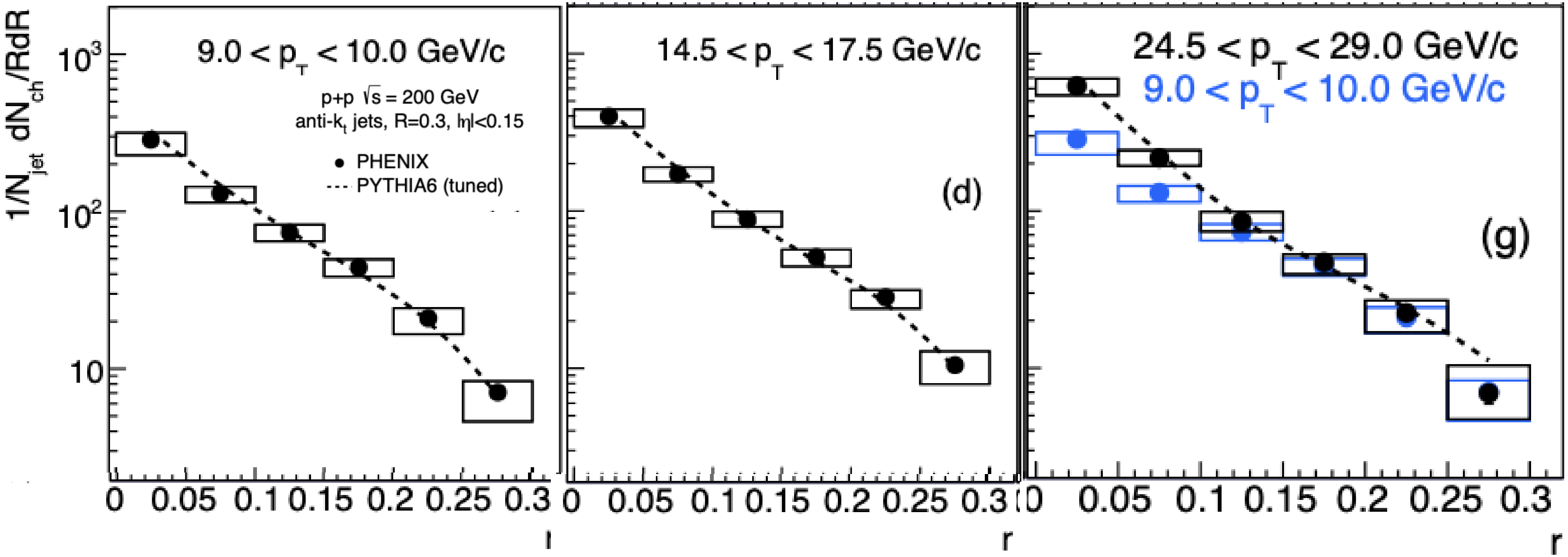


R distribution

$$R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$$

- Angular distribution of charged particles within jet with respect to the jet axis
- Significant increase at low R with increasing jet p_T
  - Higher particle density in the core of the jet at higher jet p_T
  - Consistent with increasing fraction of quark jets at higher jet p_T

arXiv:2408.11144 (accepted for publication in Phys. Rev. D)

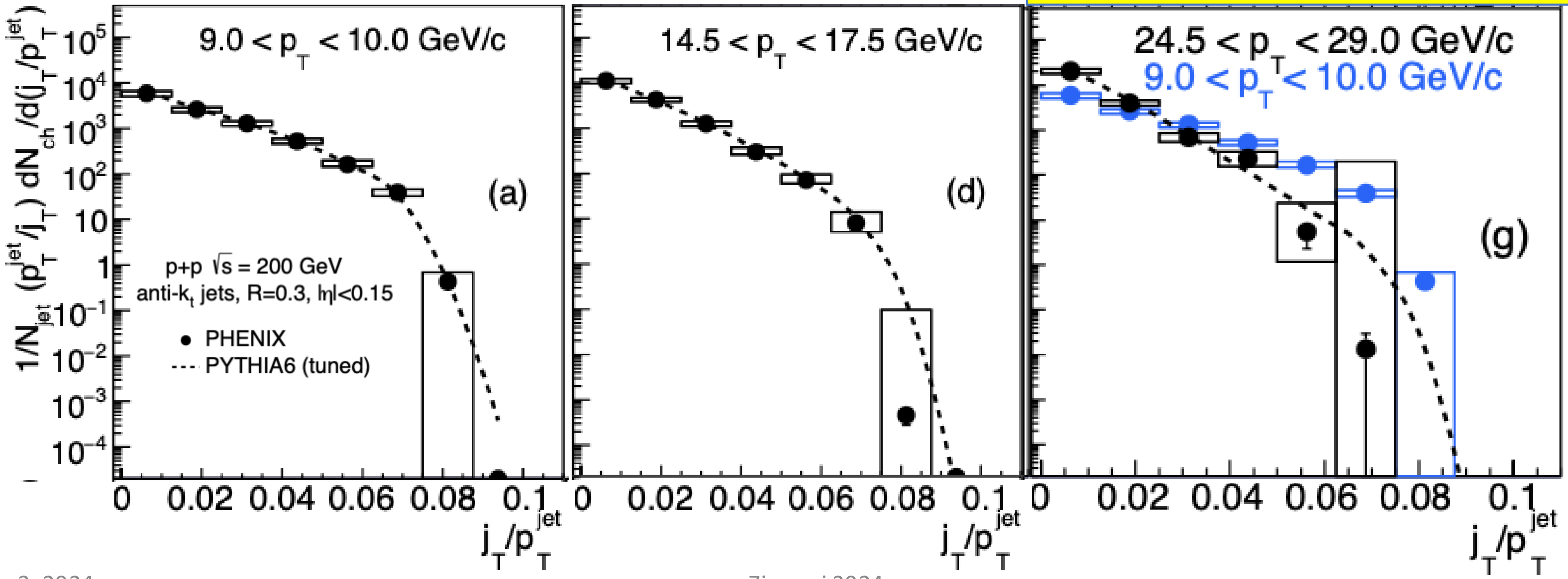


j_T/p_T^{jet} distribution

$j_T = |p_{jet} \times p_{track}| / |p_{jet}|$

- Charged particle transverse momentum j_T with respect to the jet axis normalized by jet p_T.
- Distribution gets steeper with less high j_T constituents as jet p_T increases.
  - Consistent with x and R distributions.
- Shows that j_T doesn't increase as much as p_T increases.

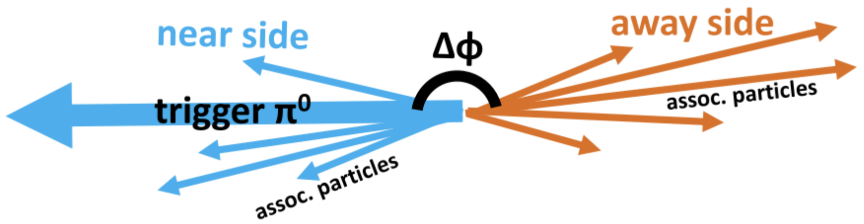
arXiv:2408.11144 (accepted for publication in Phys. Rev. D)



Au+Au

Quantifying jet modification in Au+Au

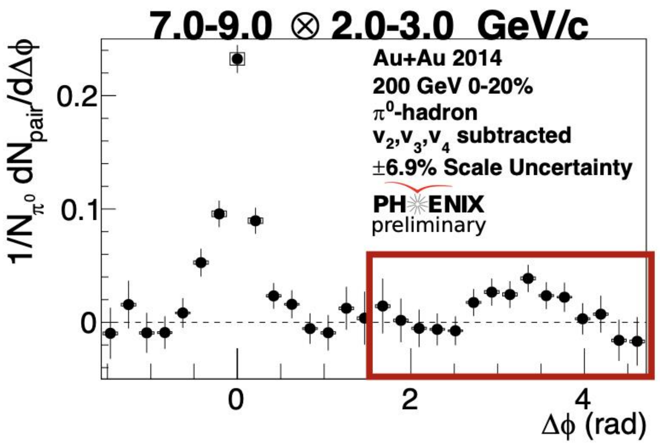
- We use two-particle correlation
  - Trigger on high p_T π^0 and look for the associated charged particles as a function p_T and $\Delta\phi$
- Flow estimation (v_2, v_3, v_4)
  - v_2 are from PHENIX π^0 measurement
  - v_3 and v_4 at high p_T are estimated using acoustic scaling: extrapolate $v_n/v_2^{n/2}$ ratios from low to high p_T.
- Background normalization (b_0):
  - Used ZYAM and absolute background normalization (ABS) to estimate systematic error on background normalization

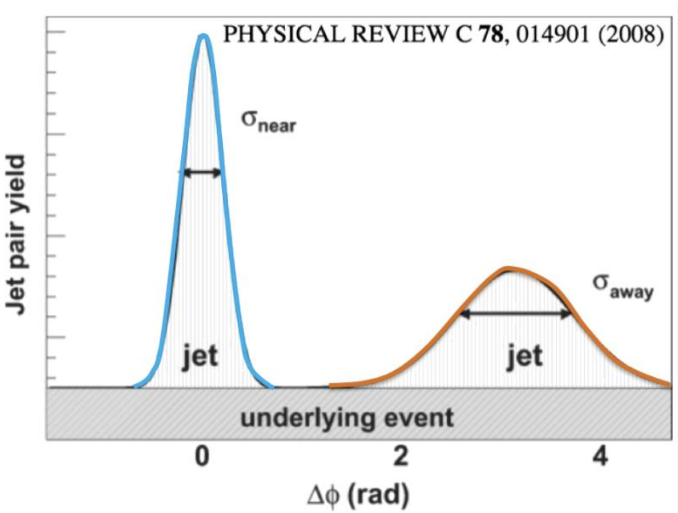


$$\frac{1}{N_{\pi^0}}\frac{dN_{\pi^0-h}}{d\Delta\phi} = \frac{1}{N_{\pi^0}}\frac{N_{\pi^0-h}}{\epsilon\int d\Delta\phi}\left\{\frac{dN^{\mathrm{same}}_{\pi^0-h}/d\Delta\phi}{dN^{\mathrm{mix}}_{\pi^0-h}/d\Delta\phi} - b_0\left[1+2\sum_{n=2}^{4}\langle v_n^{\pi^0} v_n^{h}\rangle\cos(n\cdot\Delta\phi)\right]\right\},$$

$$I_{AA}(\Delta\phi) = \frac{dN^{\mathrm{AuAu}}_{\pi^0-h}/d\Delta\phi}{dN^{pp}_{\pi^0-h}/d\Delta\phi}.$$

$$\Delta_{AA}(\Delta\phi) = \frac{dN^{\mathrm{AuAu}}_{\pi^0-h}}{d\Delta\phi} - \frac{dN^{pp}_{\pi^0-h}}{d\Delta\phi}.$$





Au+Au I_{AA} vs p_T

- Suppression is seen towards higher p_T
  - Consistently seen in 0-20 and 20-40% contralities.
- Difference between ZYAM and ABS will be a systematic error.

$$I_{AA}(p_{T,h}) = \frac{\int_{\pi/2}^{3\pi/2} \left[dN^{\mathrm{AuAu}}_{\pi^0-h}/d\Delta\phi\right] \cdot d\Delta\phi}{\int_{\pi/2}^{3\pi/2} \left[dN^{pp}_{\pi^0-h}/d\Delta\phi\right] \cdot d\Delta\phi}.$$

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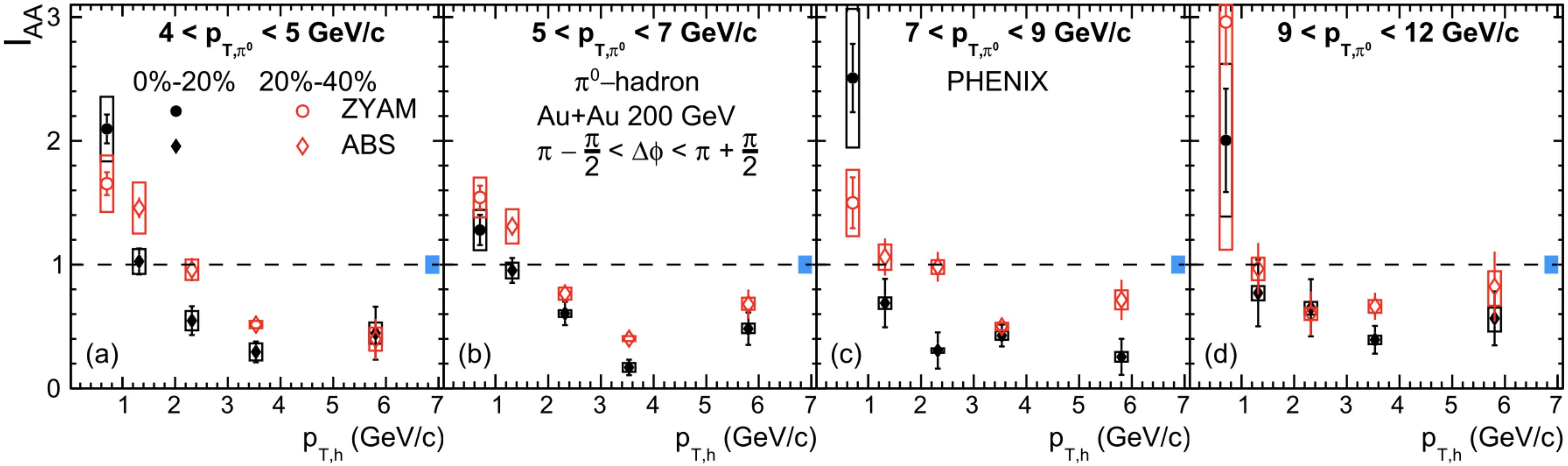

Au+Au I_{AA} vs $\Delta\phi$

- Suppression is seen towards higher $\Delta\phi$
- Particles with large angles with respect to the away-side direction are more prominently seen as going to lower p_T
  - Overall associated yields also increase.

$$I_{AA}(\Delta\phi) = \frac{dN^{\mathrm{AuAu}}_{\pi^0-h}/d\Delta\phi}{dN^{pp}_{\pi^0-h}/d\Delta\phi}.$$

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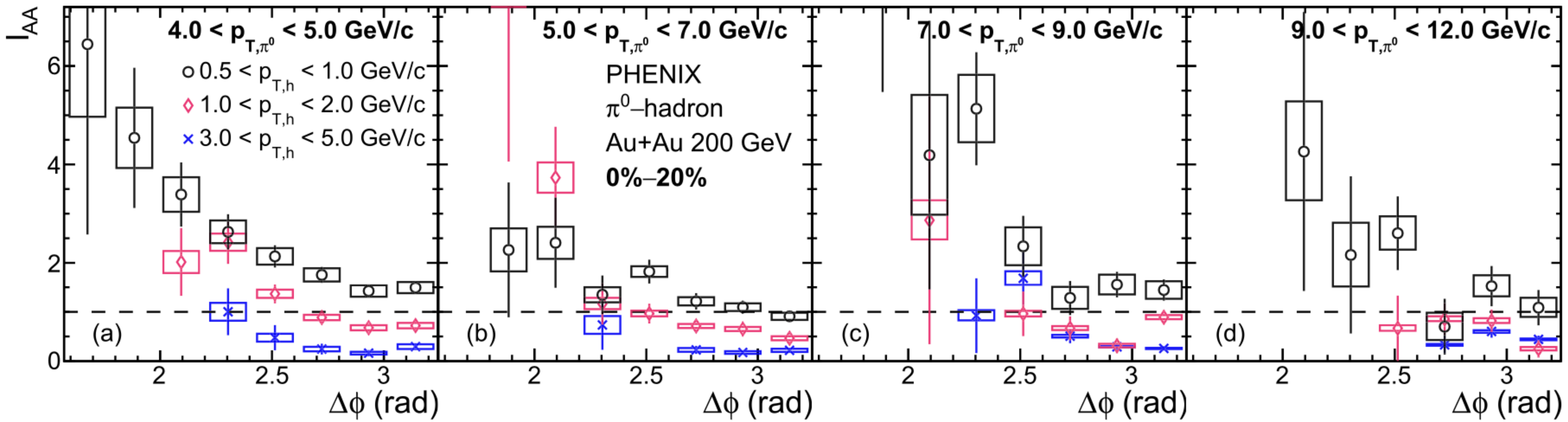
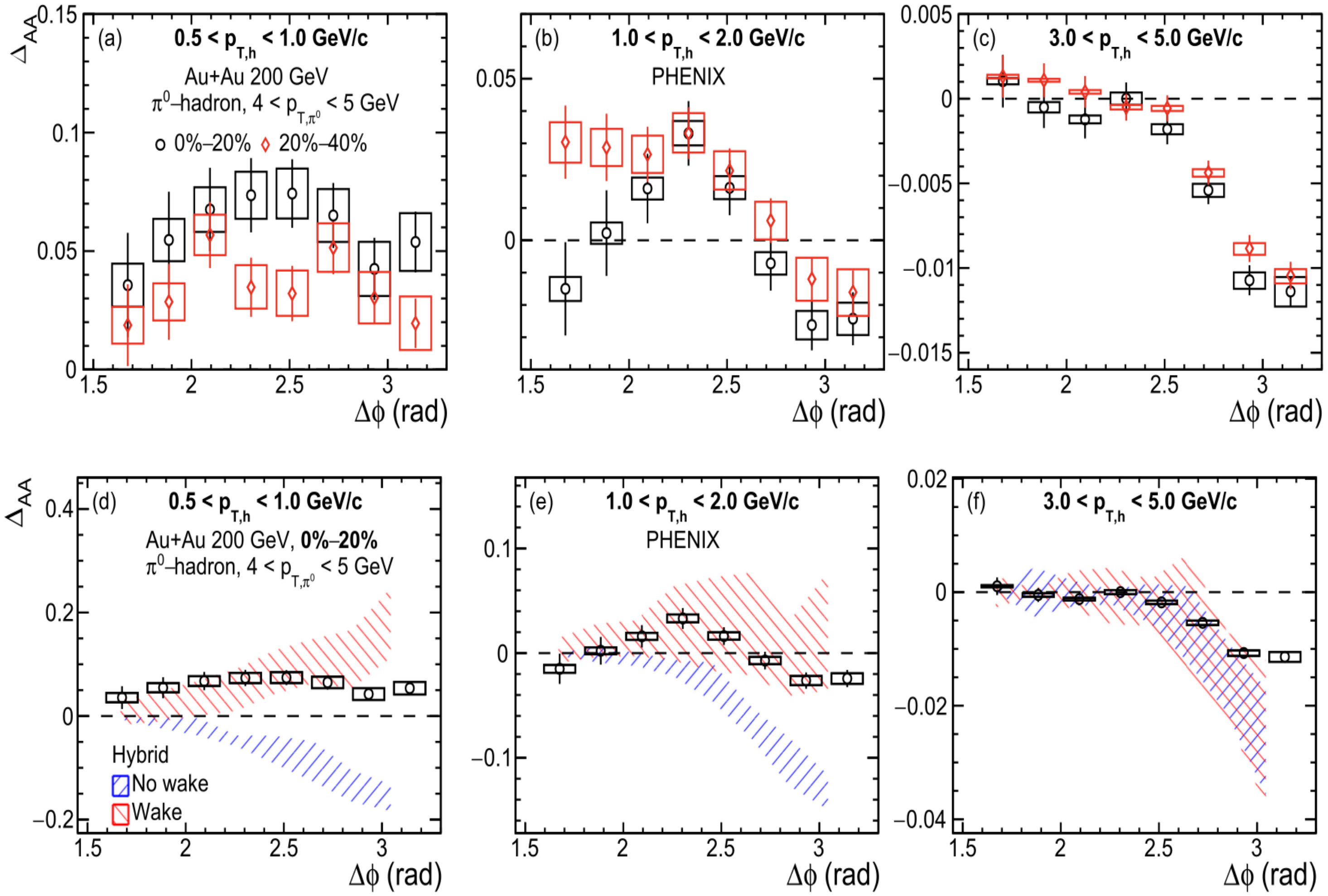


Au+Au D_{AA}

$$\Delta_{AA}(\Delta\phi) = \frac{dN^{\mathrm{AuAu}}_{\pi^0-h}}{d\Delta\phi} - \frac{dN^{pp}_{\pi^0-h}}{d\Delta\phi}.$$

PRC110, 044901(2024)

- A transition is seen from low p_T (enhancement) to high p_T (suppression) of the associated particles.
- Trend is reproduced by hybrid model with medium response
  - Wake: Hard scattered partons lost their energy which causes hydrodynamical "wake" of soft particles
- Centrality dependence? Change of p+p jet shape affects the model result?



[8] W. Chen, Z. Yang, Y. He, W. Ke, L. G. Pang, and X.-N. Wang, Search for the elusive jet-induced diffusion wake in Z/γ-jets with 2D jet tomography in high-energy heavy-ion collisions, Phys. Rev. Lett. **127**, 082301 (2021).
[9] J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos, and K. Rajagopal, A hybrid strong/weak coupling approach to jet quenching, J. High Energy Phys. 10 (2014) 019; 09 (2015) 175.

Conclusions

- Jets in p+p and Au+Au at cms energy of 200GeV are extensively studied in PHENIX at RHIC
  - Through full jet reconstruction in p+p and two particle correlation in Au+Au, respectively.

- PHENIX measured jet cross-section and substructure distributions in p+p
  - anti-k_T jets with R=0.3 and $8.0 < p_T^{jet} < 40.0$ GeV and $|\eta_{jet}| < 0.15$
  - NLO/NNLO predictions are higher than the measured cross-section
  - z_g agrees well with STAR and becomes steeper with jet p_T
  - x distribution shifts toward lower momentum fraction
  - R distribution shows increase at small R with increasing jet p_T
  - j_T/p_T^{jet} gets steeper, whose trend is consistent with x and R redistribution.

- PHENIX measured jet-modification through I_{AA}, D_{AA} in Au+Au
  - Clear suppression is seen towards high p_T and smaller $\Delta\phi$ with respect to away-side direction in I_{AA}
  - A transition is seen from low p_T (enhancement) to high p_T (suppression) of the associated particles in D_{AA}
  - Trend is reproduced by hybrid model with medium response with wake.
  - Change of p+p jet shape affects model calculation?

Backup

Jets as a QCD Probe

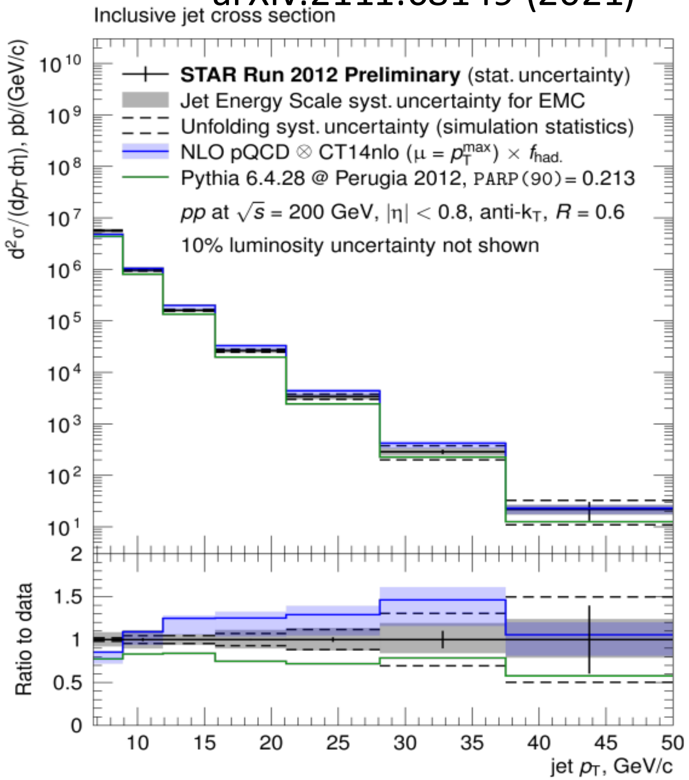
- High jet p_T and large R:
  - pQCD is broadly in good agreement with experiment.
- Lower jet p_T and small R:
  - need for good description of non-perturbative contributions, including pdf and hadronization process.
  - sensitive to UE, color reconnection, etc.
  - important for testing non-perturbative components of models of jet production.
- Study of energy distribution within jet (jet substructure):
  - single jet constituents – fragmentation function – hadronic level
  - groomed variables – subset of constituents – partonic level

Jets at RHIC energies give a good opportunity to study non-perturbative corrections.

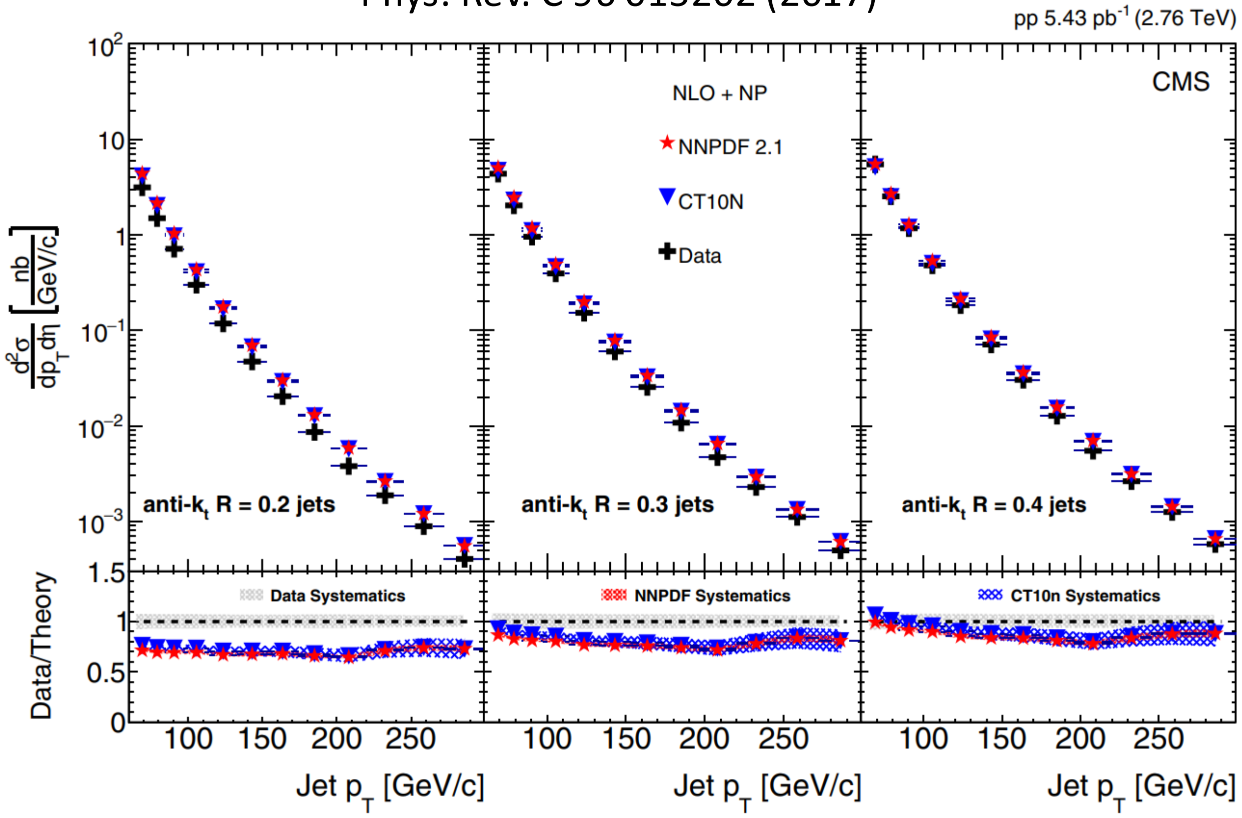
Jets in p+p collisions at RHIC and LHC

- Jet cross-section and substructure were studied in detail at LHC and RHIC(STAR)
  - Small R anti-k_T jet cross-sections *are systematically lower than NLO predictions*.
  - Large R generally agrees better with NLO.
- This seems to indicate that the distribution of particles in the jet is not accurately reproduced by NLO.

arXiv:2111.08149 (2021)



Phys. Rev. C 96 015202 (2017)



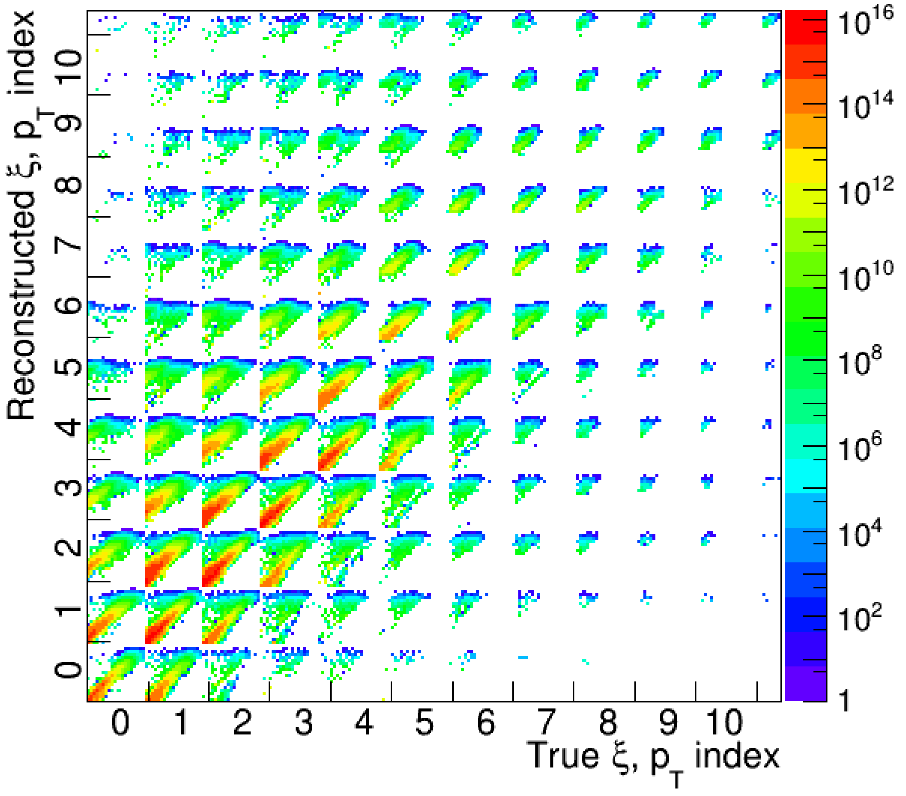
Jet reconstruction in PHENIX

- FastJet anti-k_T algorithm with small R (R = 0.2,0.3)
- Tracks with p_T > 0.5 GeV and EMCal clusters with E > 0.5 GeV
  - *Jet level cuts: $0.3 < c_f < 0.7$; $n_c > 2$; $p_T^{reco} > 5$ GeV*
- Bayesian unfolding takes into account missing energy, bin migration, etc.
  - *RooUnfold package used*
- Unfolding matrix:
  - PYTHIA6 tune A with extra tuning to match PHENIX data better
  - Detector response simulated by GEANT3
  - For jet substructure distribution unfolding is done in a more complicated way.

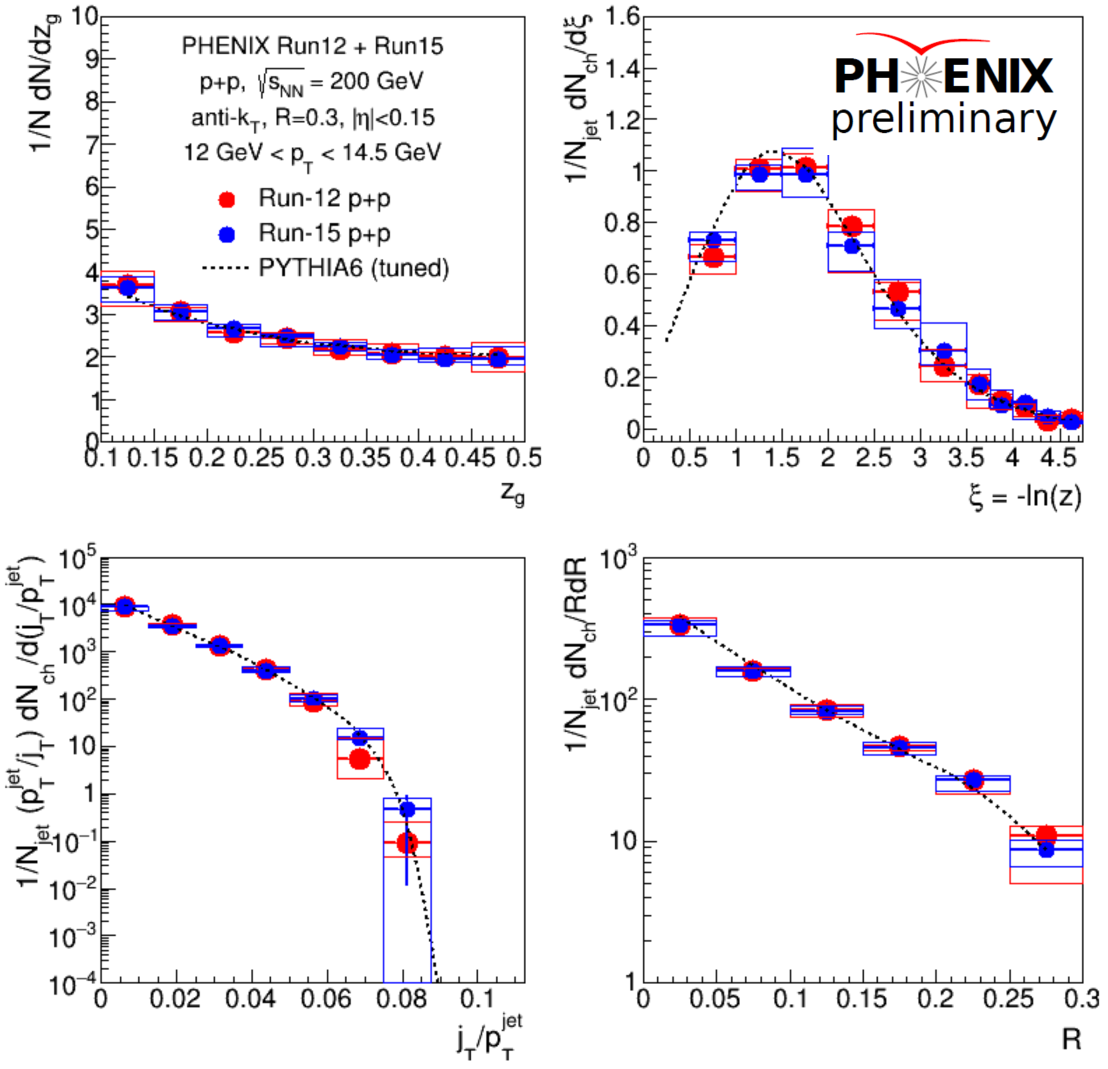
Example of 2D unfolding matrix for ξ distribution
(ξ = -ln(z) where z is the fraction of jet momentum carried by a jet constituent)

A set of one-dimensional unfolding matrices in jet p_T bins

Simultaneous unfolding in ξ and jet p_T

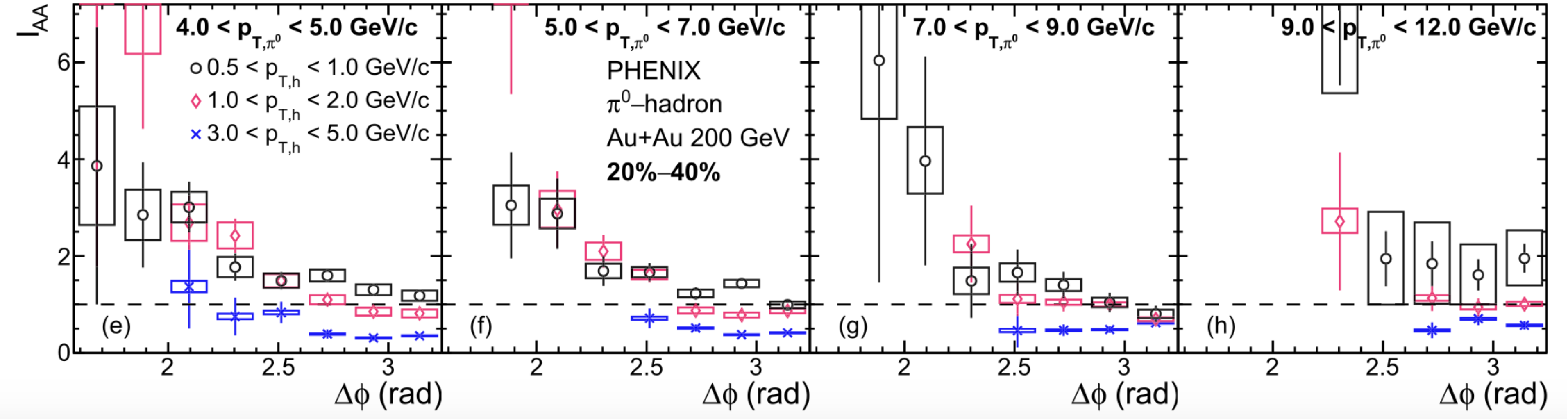


Run12 vs. Run15



Au+Au I_{AA}

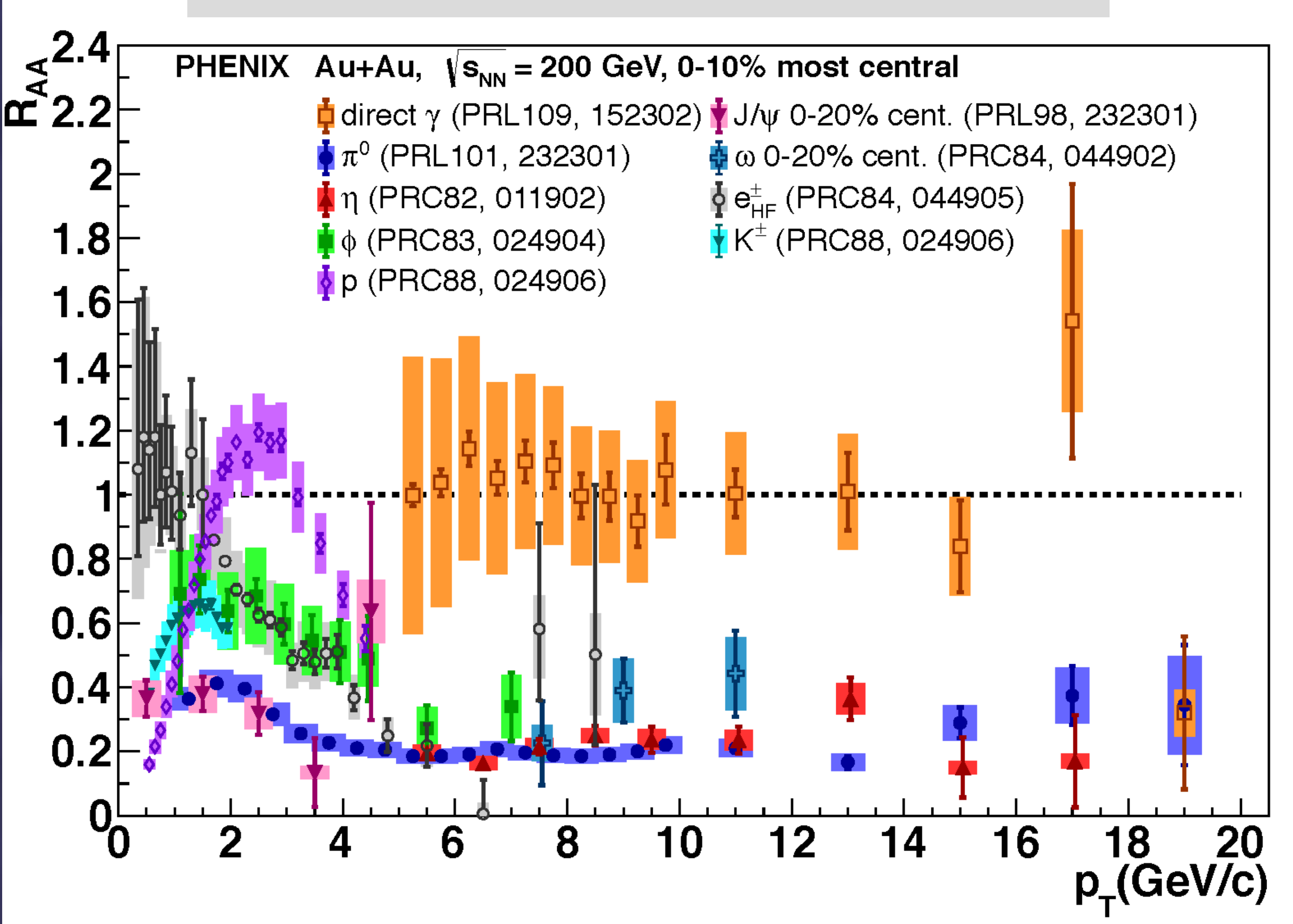
- 20-40%



The PHENIX T-shirt R_{AA} plot

Au+Au

Inclusive measurement of hadrons



$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{\frac{Ncoll}{\sigma_{inel}} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$