Direct Photon–Tagged Jets at RHIC

Anthony Hodges

Jet Physics: From RHIC/LHC to the EIC

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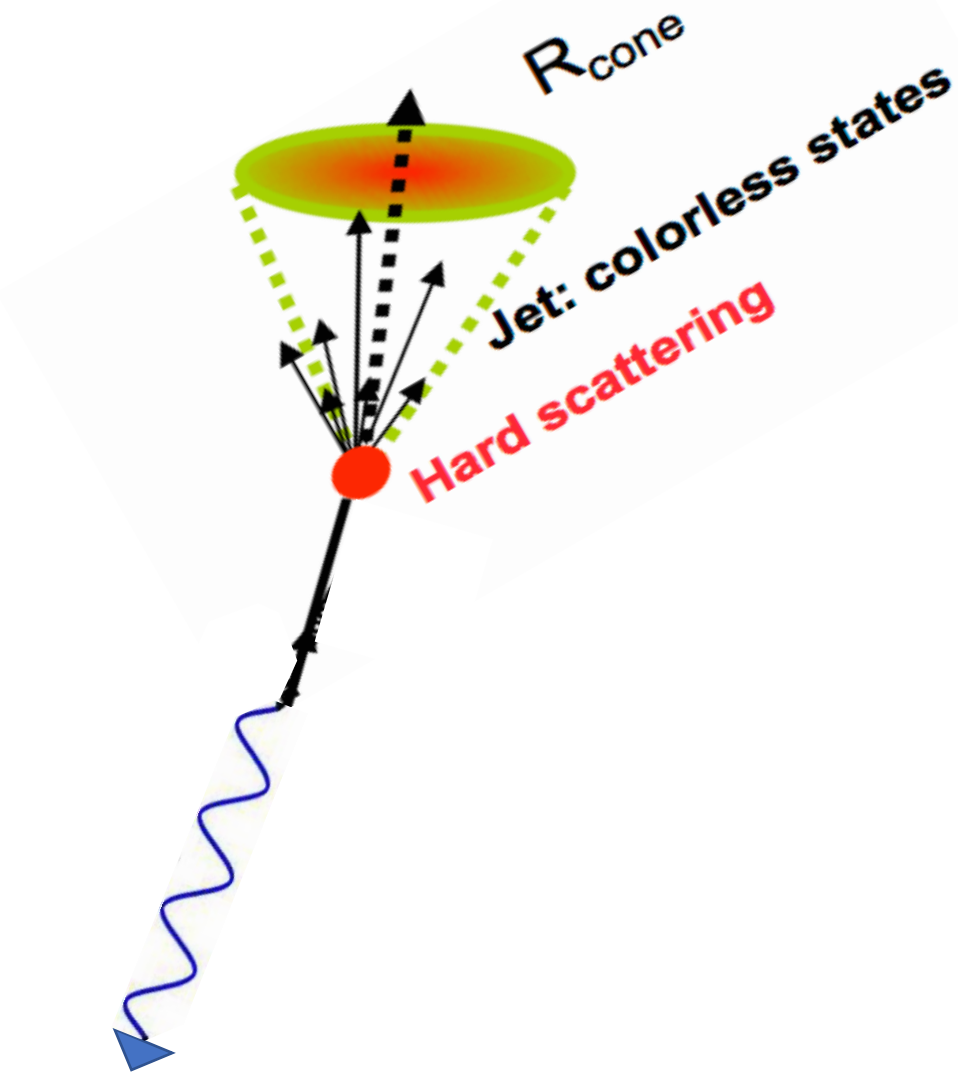
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Why Direct Photon-Tagged Jets?

- Jets
  - Perturbatively calculable
  - Excellent proxy for parent parton kinematics
- Direct photons
  - Preserves information about initial hard scatterings
  - Well-calibrated probe in heavy-ion collisions

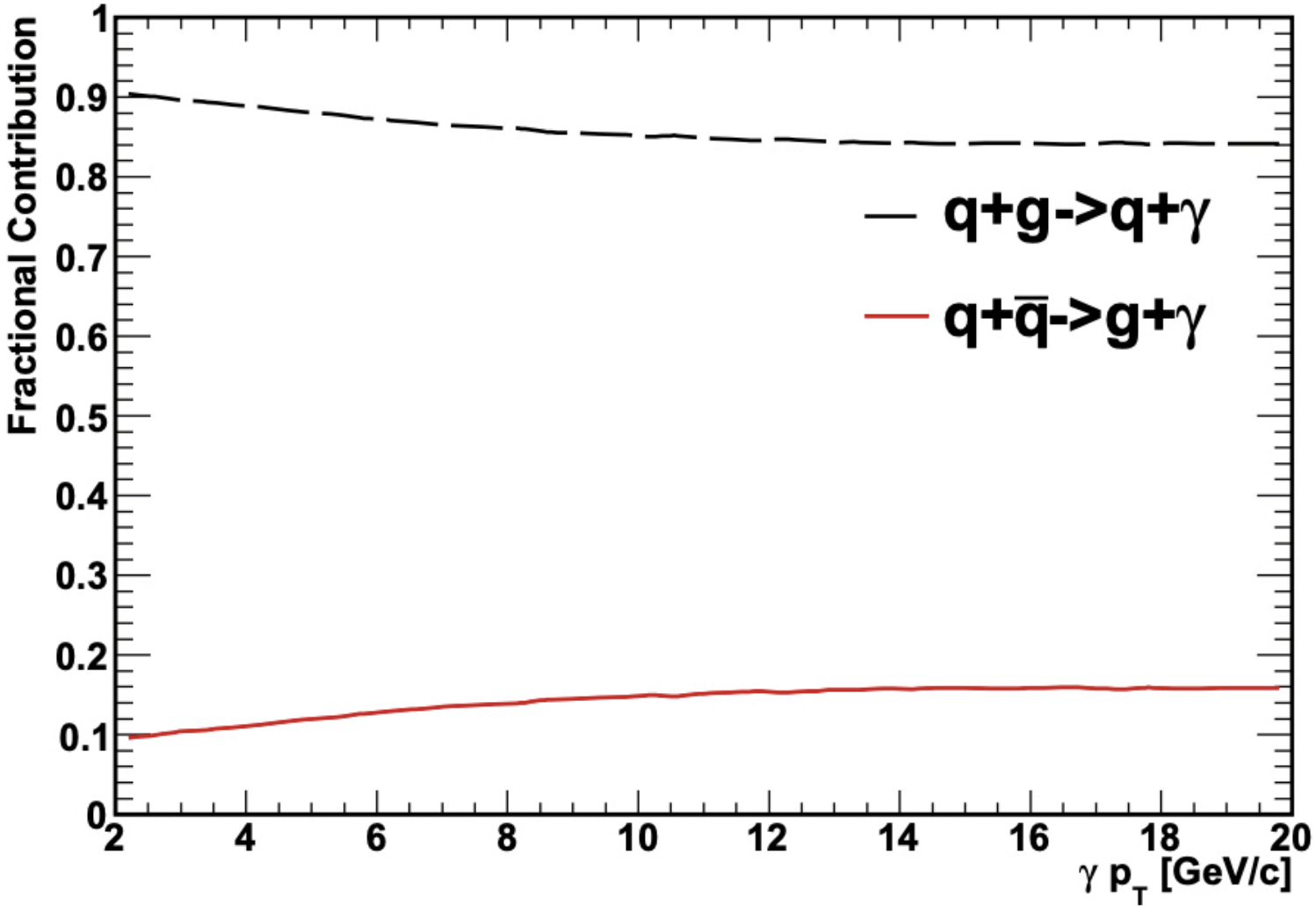


Why Direct Photon-Tagged Jets?

- Primary production via QCD Compton scattering

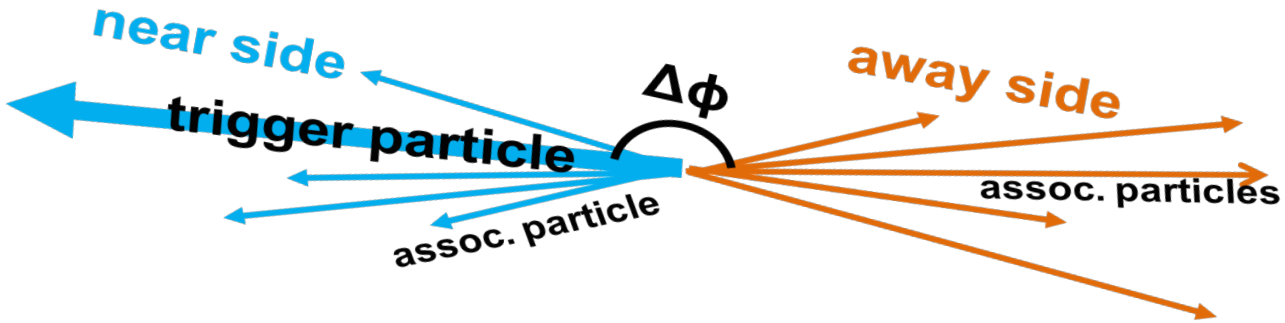
→ Biases recoil parton sample towards quarks

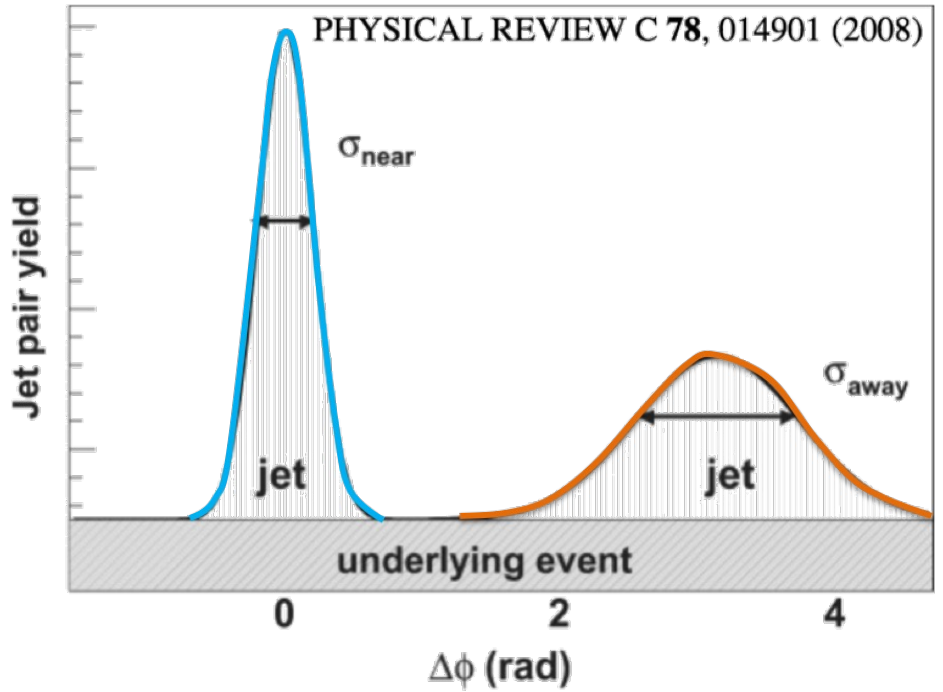
PHENIX – 1006.1347



Two-Particle Correlations

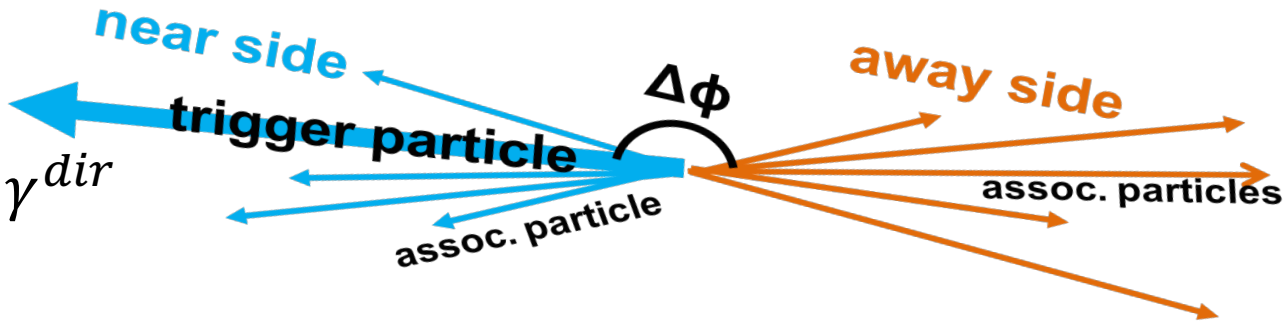
- Measure spatial correlation between high p_T jet proxy and jet fragments
- Extract $Y(x)$, per-trigger yield

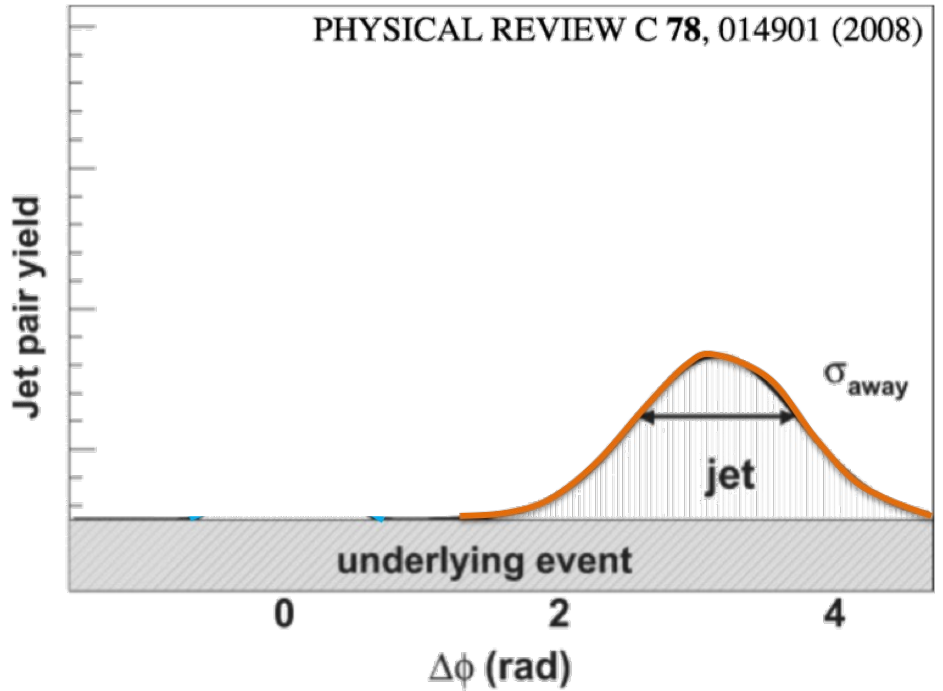




Two-Particle Correlations

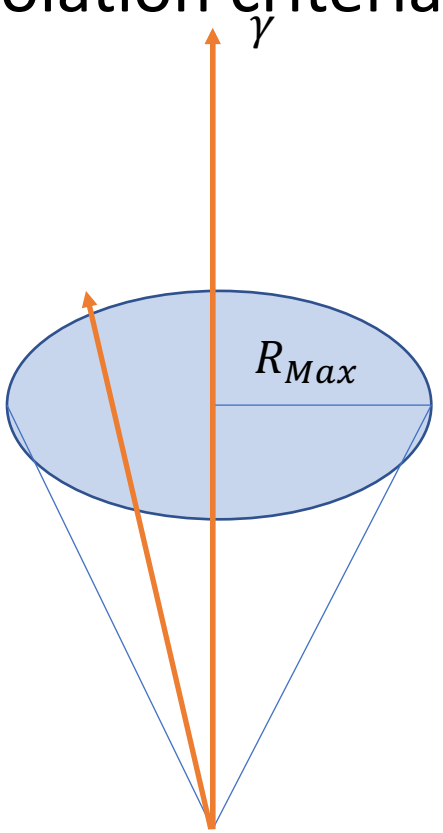
- Measure spatial correlation between high p_T jet proxy and jet fragments
- Extract $Y(x)$, per-trigger yield
- For γ^{dir} triggered correlations, near side yield ≈ 0



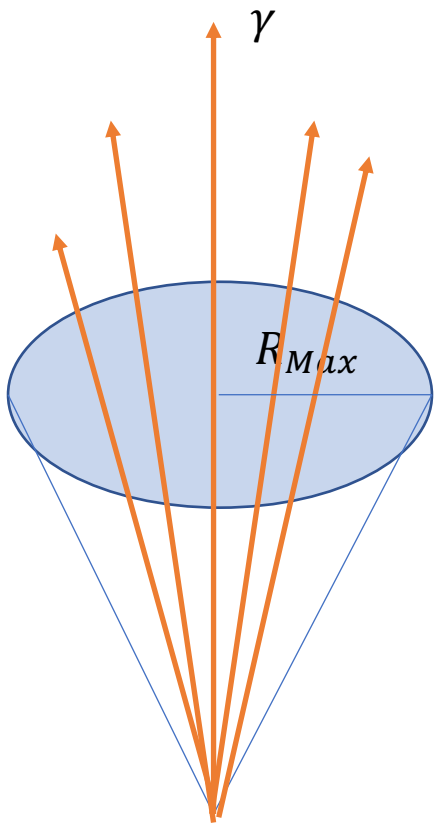


Direct Photon Extraction

- In $p + p$, $d + Au$: isolation criteria



Keep

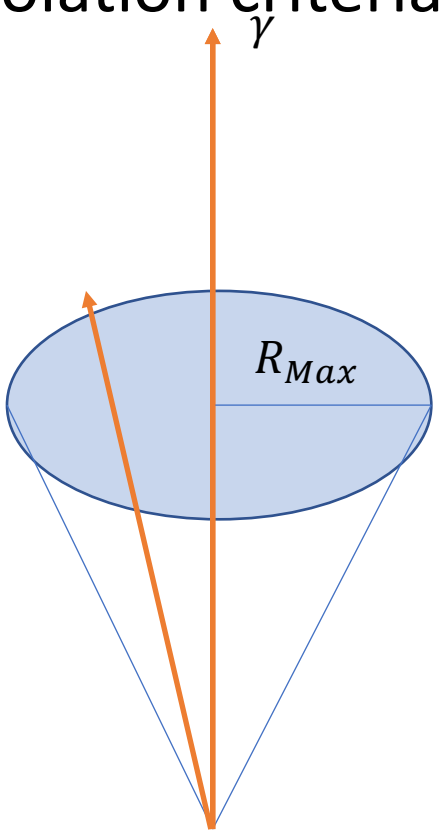


Reject

Requirement: $\sum_{\Delta R < R_{Max}} E < (E_\gamma * 0.1)$

Direct Photon Extraction

- In $p+p$, $d+Au$: isolation criteria



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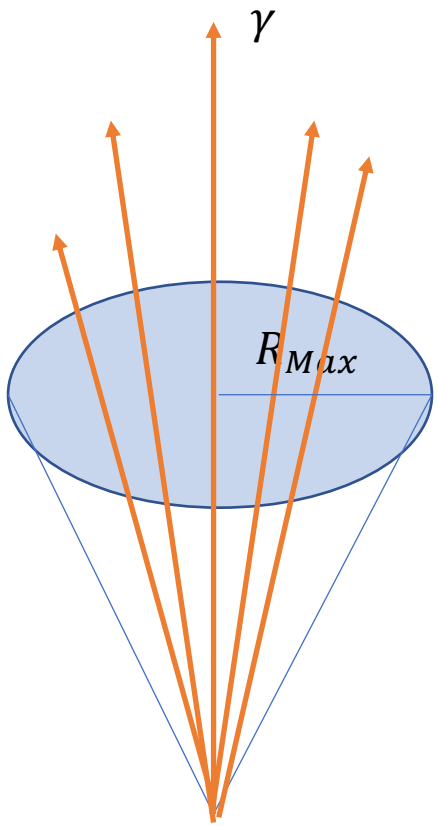
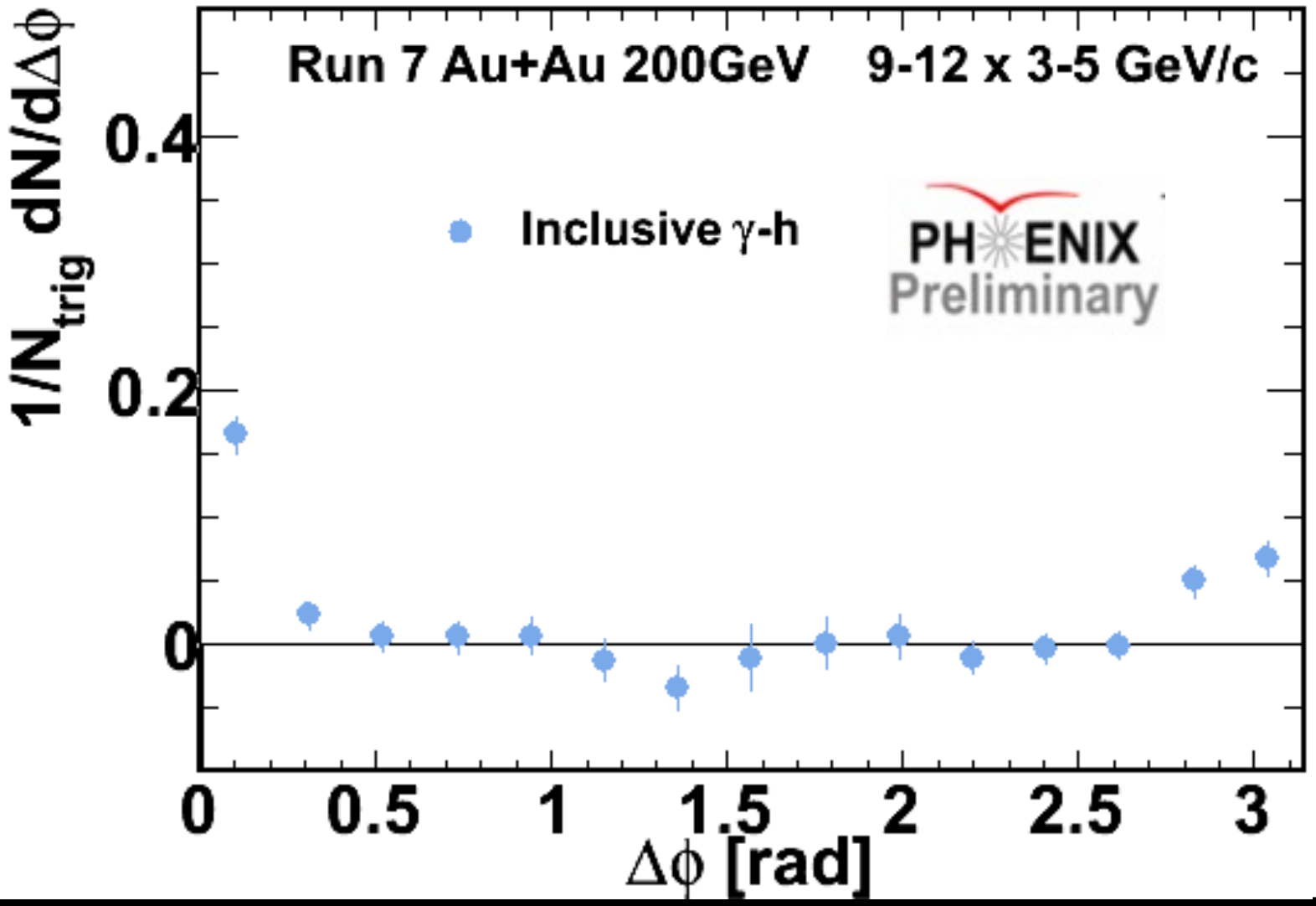


Reject

Requirement: $\sum_{\Delta R<R_{Max}} E < (E_\gamma * 0.1) + \langle E_{bg} \rangle$

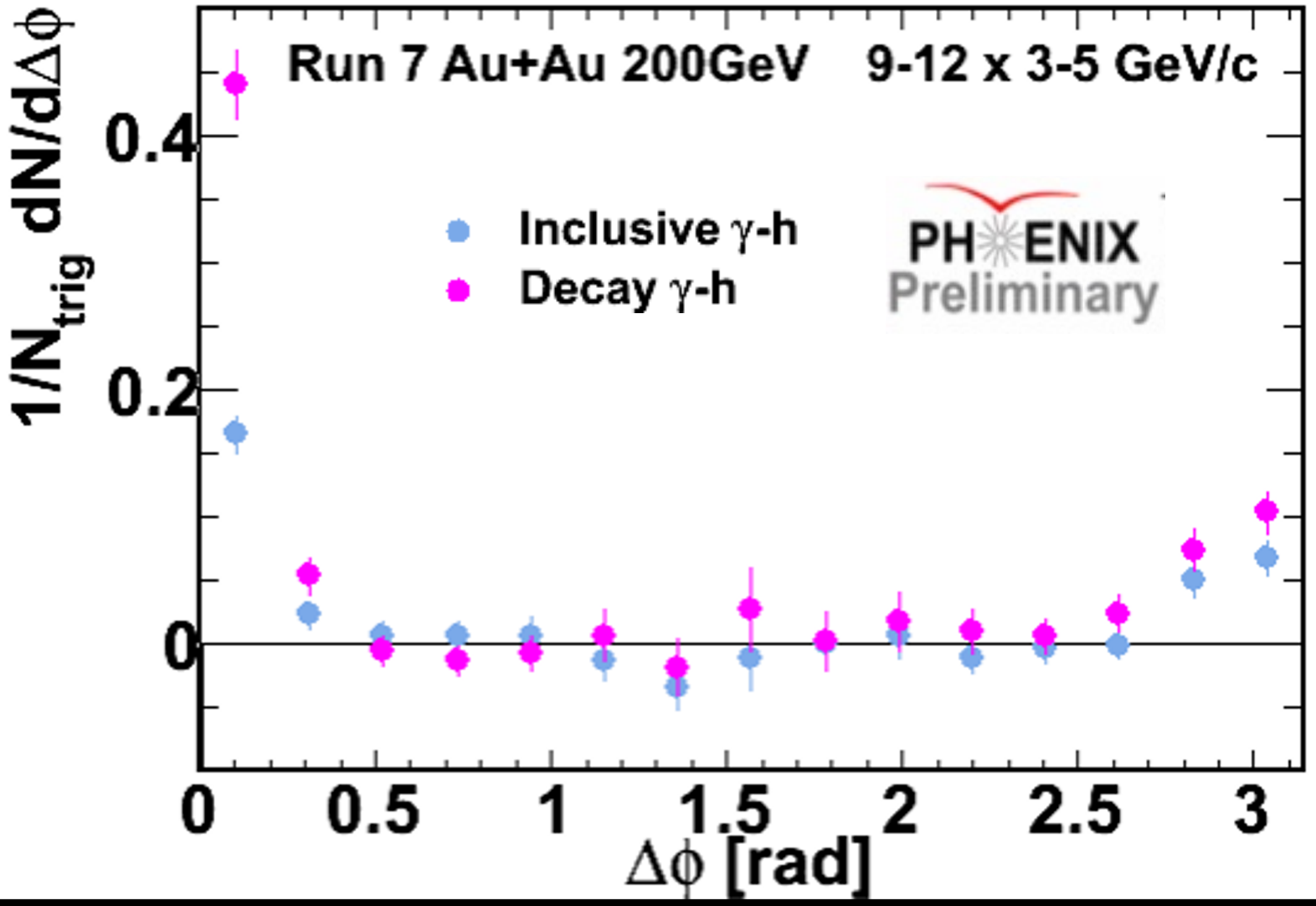
Statistical Subtraction

- Measure inclusive $\gamma - h^{\pm}$



Statistical Subtraction

- Measure inclusive $\gamma - h^{\pm}$
- Estimate decay $\gamma - h^{\pm}$ from $\pi^0 - h^{\pm}$

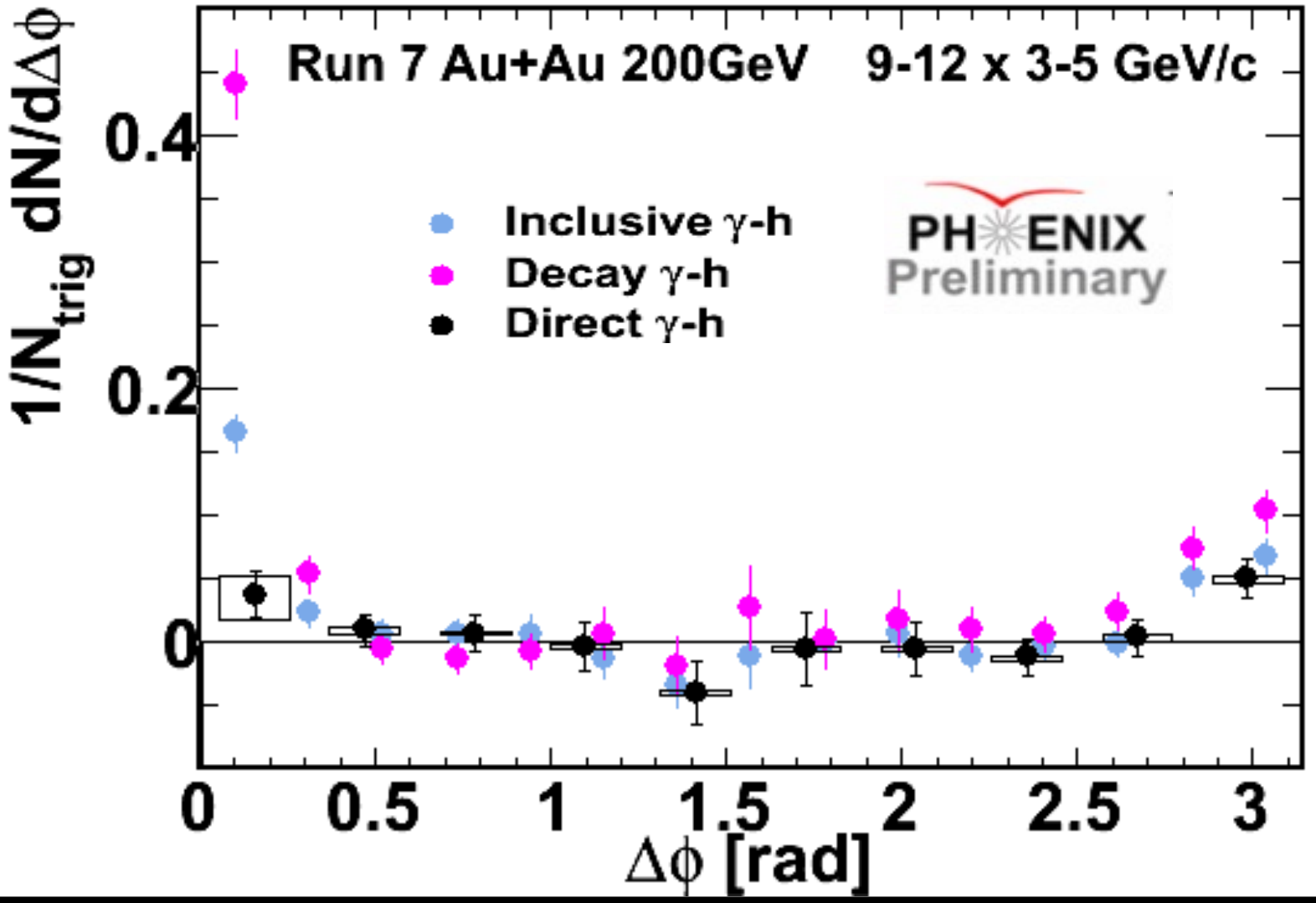


Statistical Subtraction

- Measure inclusive $\gamma - h^{\pm}$
- Estimate decay $\gamma - h^{\pm}$ from $\pi^0 - h^{\pm}$

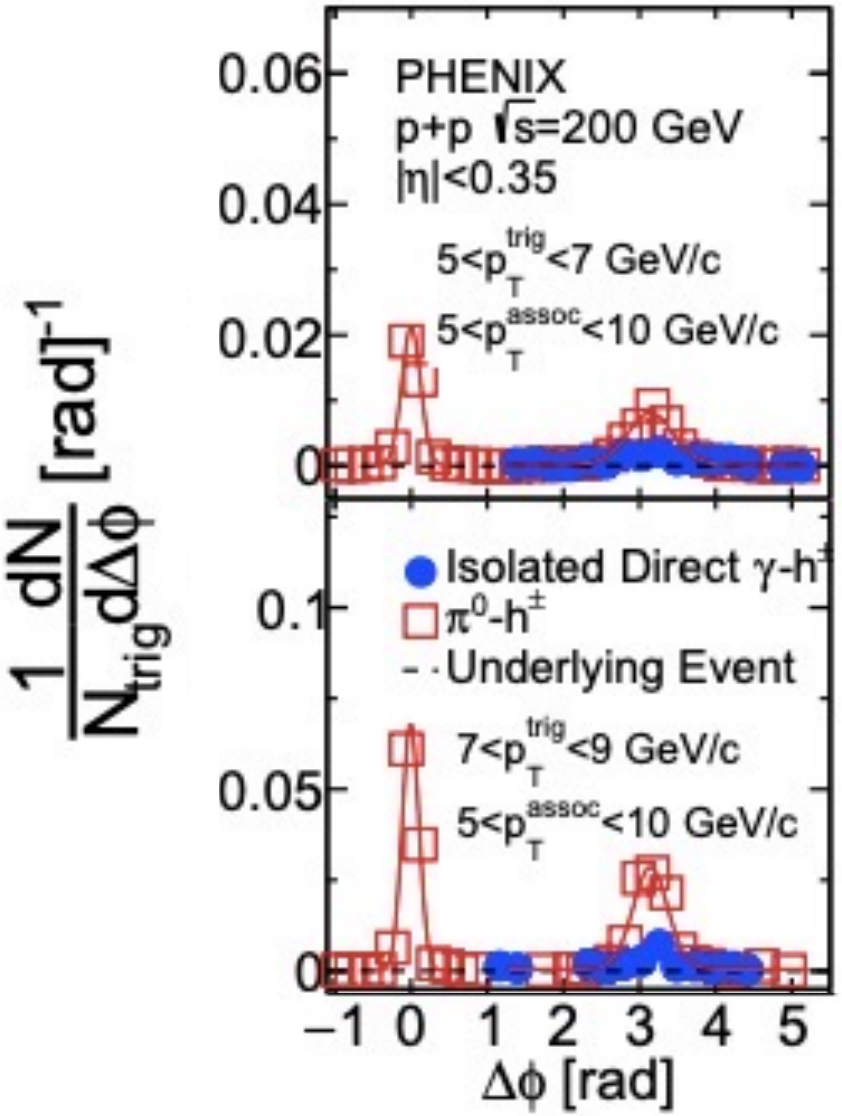
$$Y_{Direct} = \frac{R_\gamma Y_{Inclusive} - Y_{Decay}}{R_\gamma - 1}$$

$$R_\gamma = \frac{N_{Inclusive}}{N_{Decay}}$$

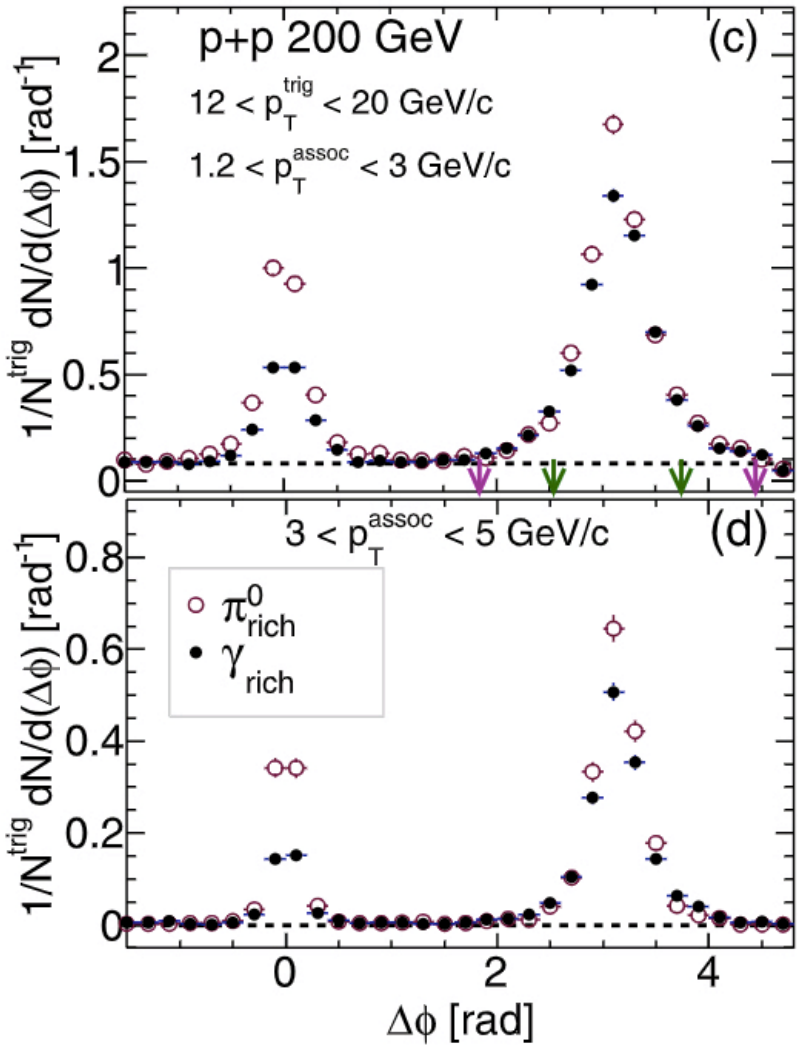


γ^{dir} and π^0– Hadron Correlations

PHENIX – 1805.02450



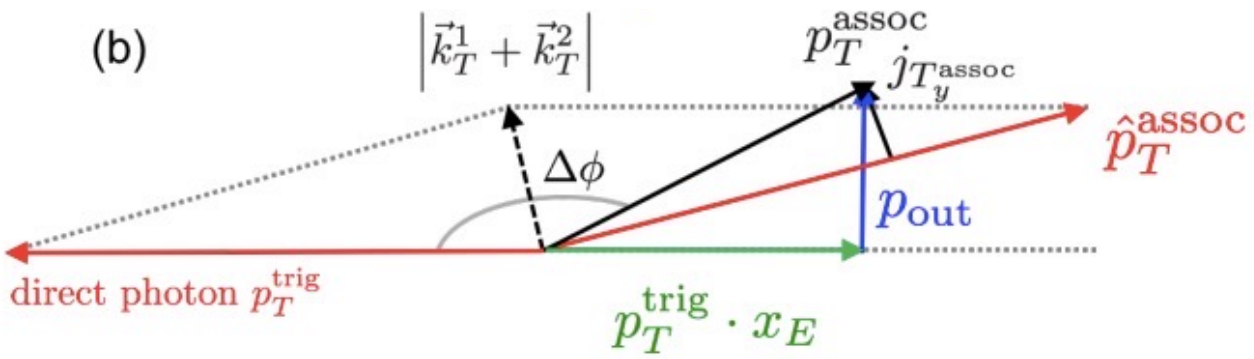
STAR – 1604.01117



- PHENIX → iso cone, no yields at $\Delta\phi \approx 0$
- STAR → photon rich sample, residual decay correlation
- $Y_{\pi^0} > Y_{\gamma^{dir}} \rightarrow \pi^0 - h^{\pm}$ probes larger Q^2

Broadening in $p + p$ Collisions

- p_{out} → hadron momentum transverse to jet axis
- γ^{dir} trigger constrains kinematics
- Broadening seen in baseline $p + p$ measurements



$$p_{out} = |p_T^{Assoc}| \sin \Delta\phi \qquad x_E = -\left|\frac{p_T^{Assoc}}{p_T^{Trig}}\right| \cos\Delta\phi$$

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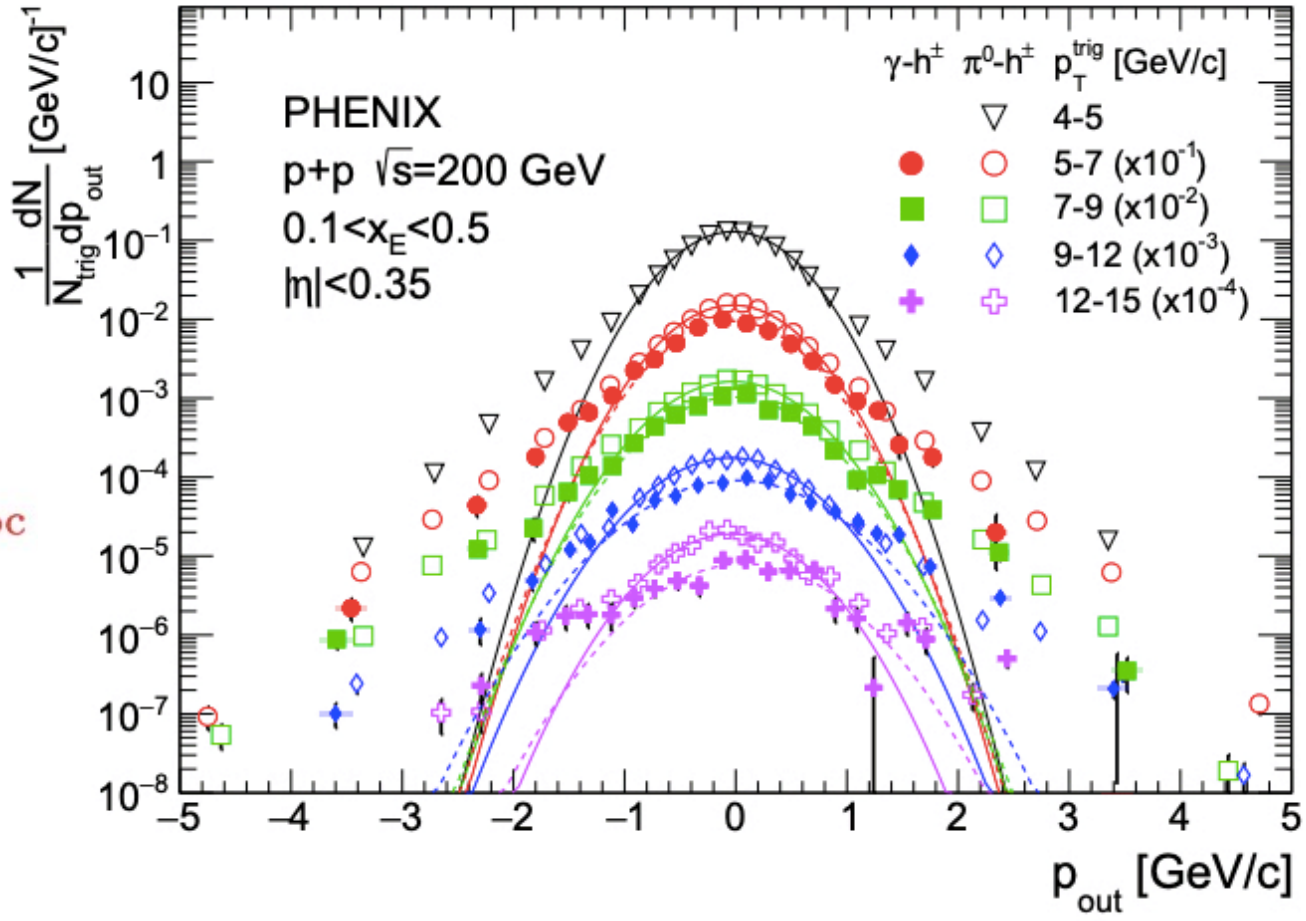
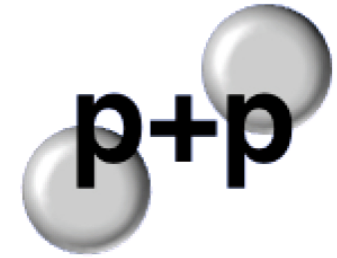


Broadening in $p + p$ Collisions



- Larger Gaussian widths with increasing p_T
- Avenue for testing QCD factorization?

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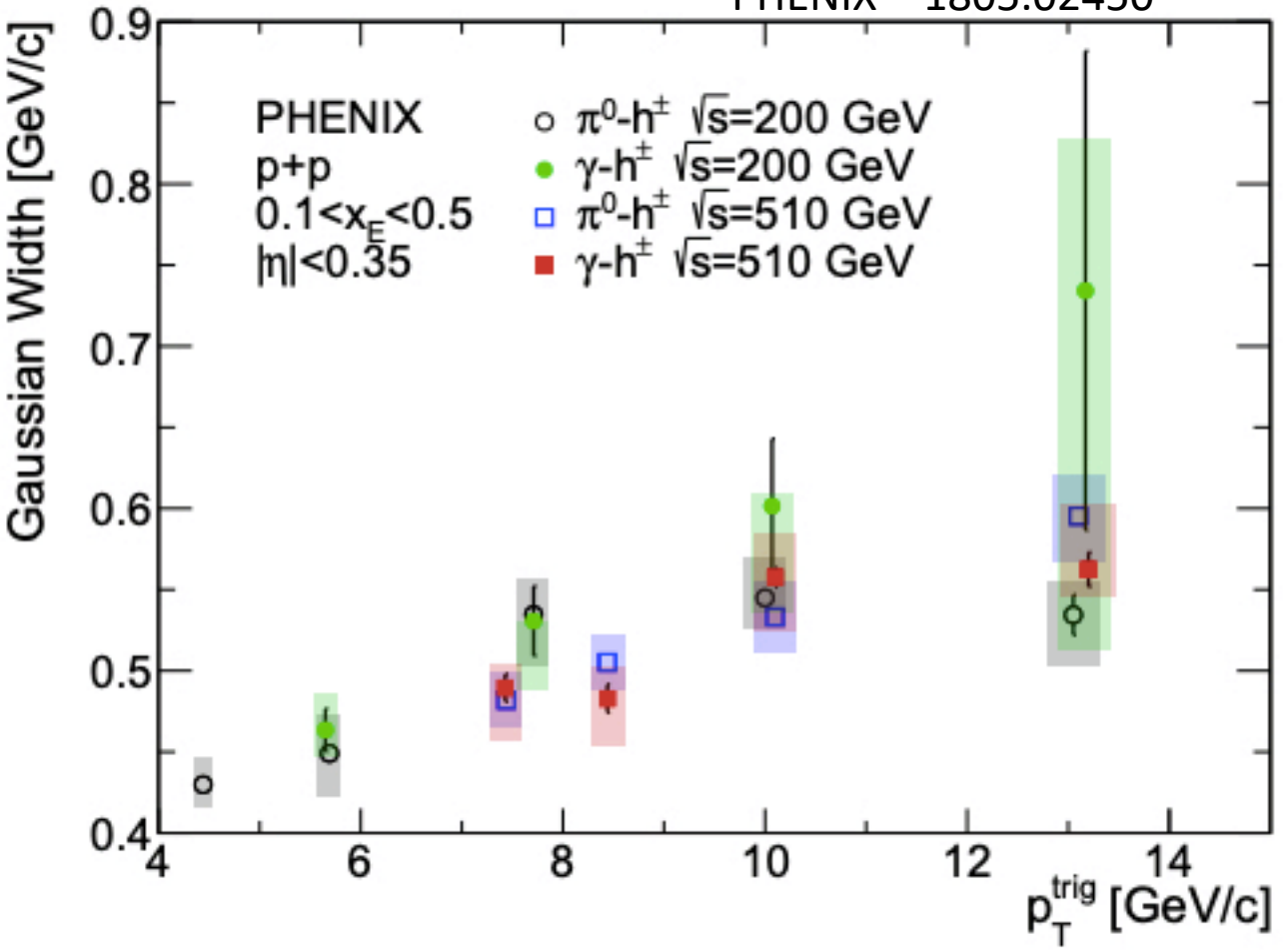
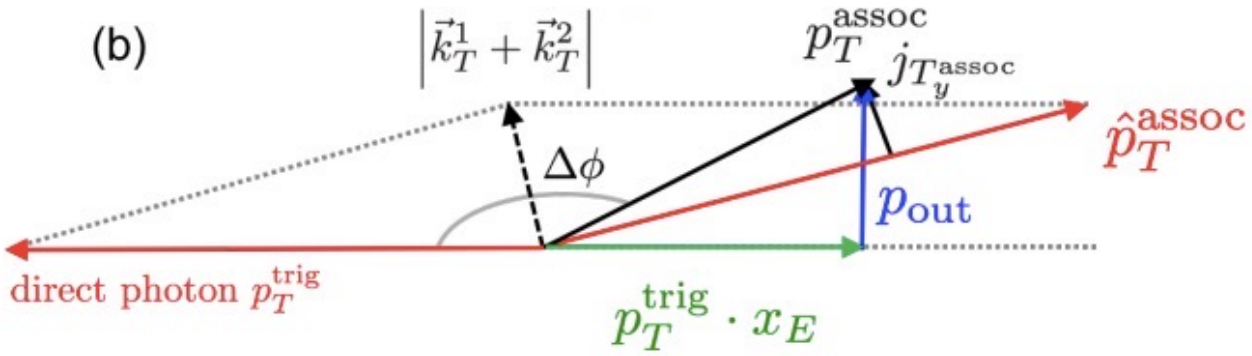




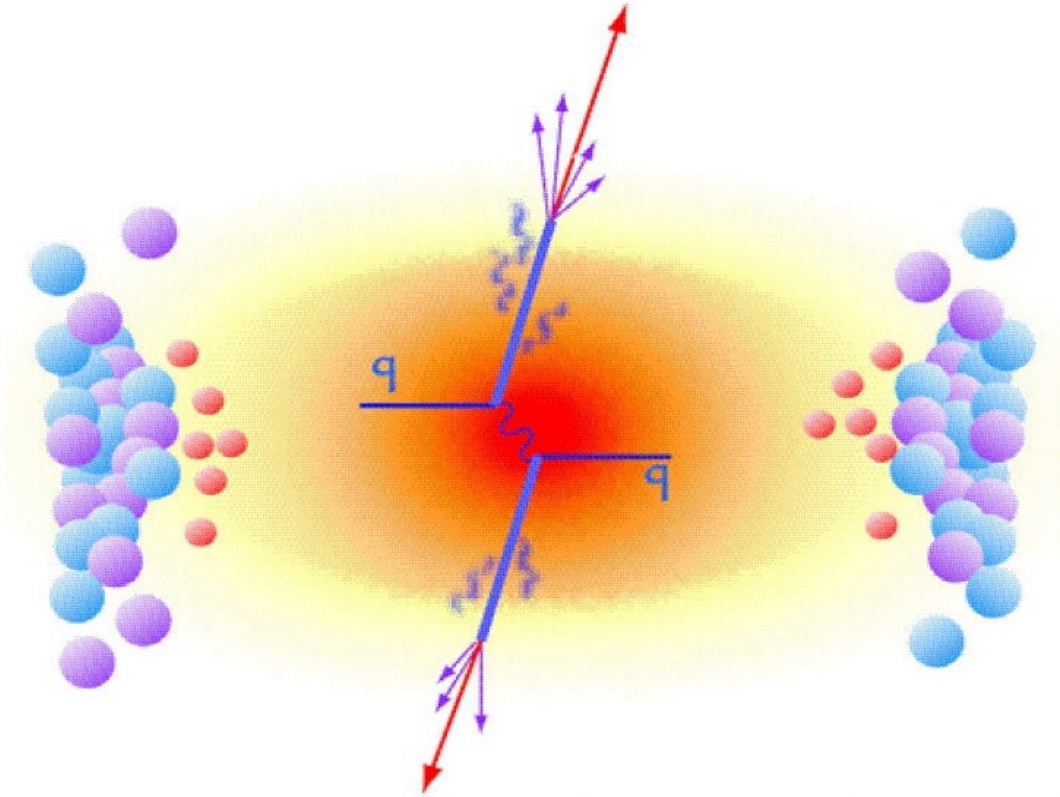
$$p_{out} = |p_T^{Assoc}| \sin \Delta\phi \qquad x_E = -\left|\frac{p_T^{Assoc}}{p_T^{Trig}}\right| \cos\Delta\phi$$

Quantifying Jet Modification in $A + A$ Collisions

- Jets in $A + A$ collisions are modified relative to $p + p$ baseline
  - Shape + Yield
- Yield modification: $I_{AA} = \frac{Y_{AA}(x)}{Y_{pp}(x)} \approx \frac{D_{AA}(x)}{D_{pp}(x)}$

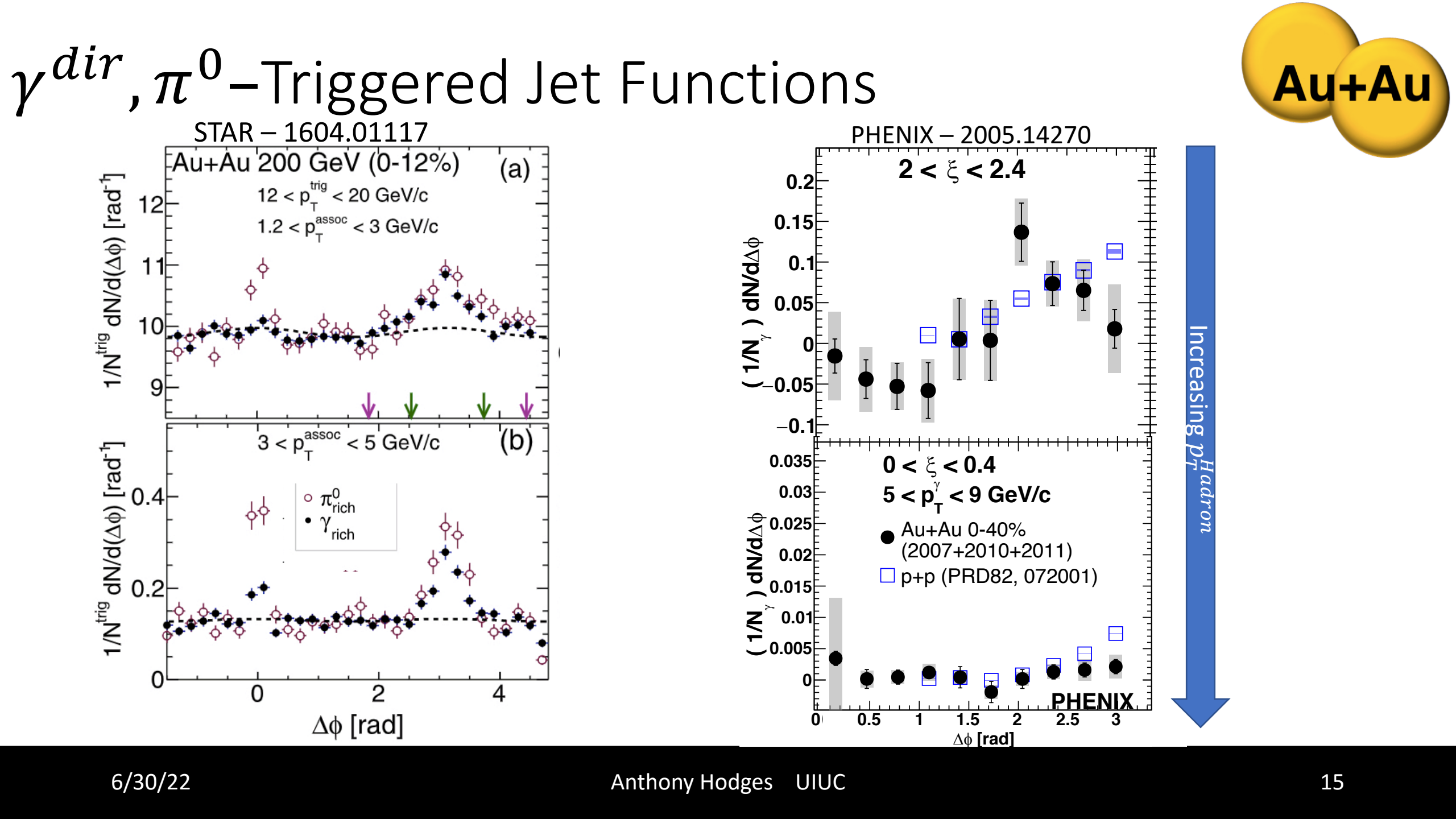
- $Y \rightarrow$ conditional yield of hadrons
- $x \rightarrow$ fragmentation variable (z_T, ξ) or p_T^h

$$z_T = \frac{p_T^h}{p_T^\gamma} \qquad \xi = \ln\left(\frac{1}{z_T}\right)$$



Heavy Ion Collision

γ^{dir}, π^0–Triggered Jet Functions



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PHENIX – 2005.14270

Per-Trigger Yield Modification

- Enhancement ($I_{AA} > 1$) of low p_T hadrons
- Suppression ($I_{AA} < 1$) of high p_T hadrons
- Good agreement with LBT+Hydro and MLLA
  - Encoded medium response/redistribution of energy lost from partons

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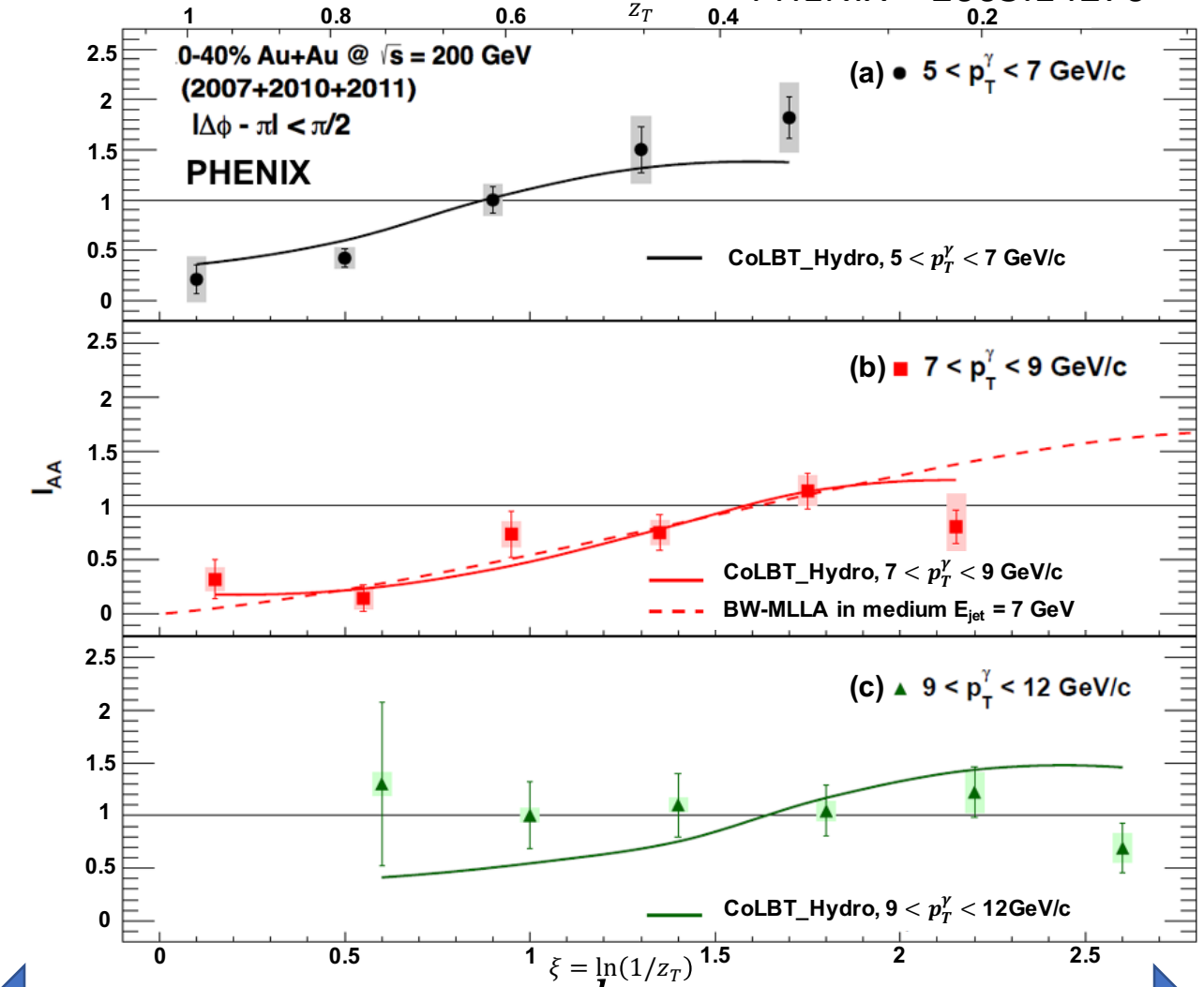

Per-Trigger Yield Modification

- No trigger flavor dependence of I_{AA} measured by STAR
- Lack of enhancement explained by 1.2GeV/c p_T^h cutoff
- ZOWW, QIN models describe data for $z_T > 0.2$

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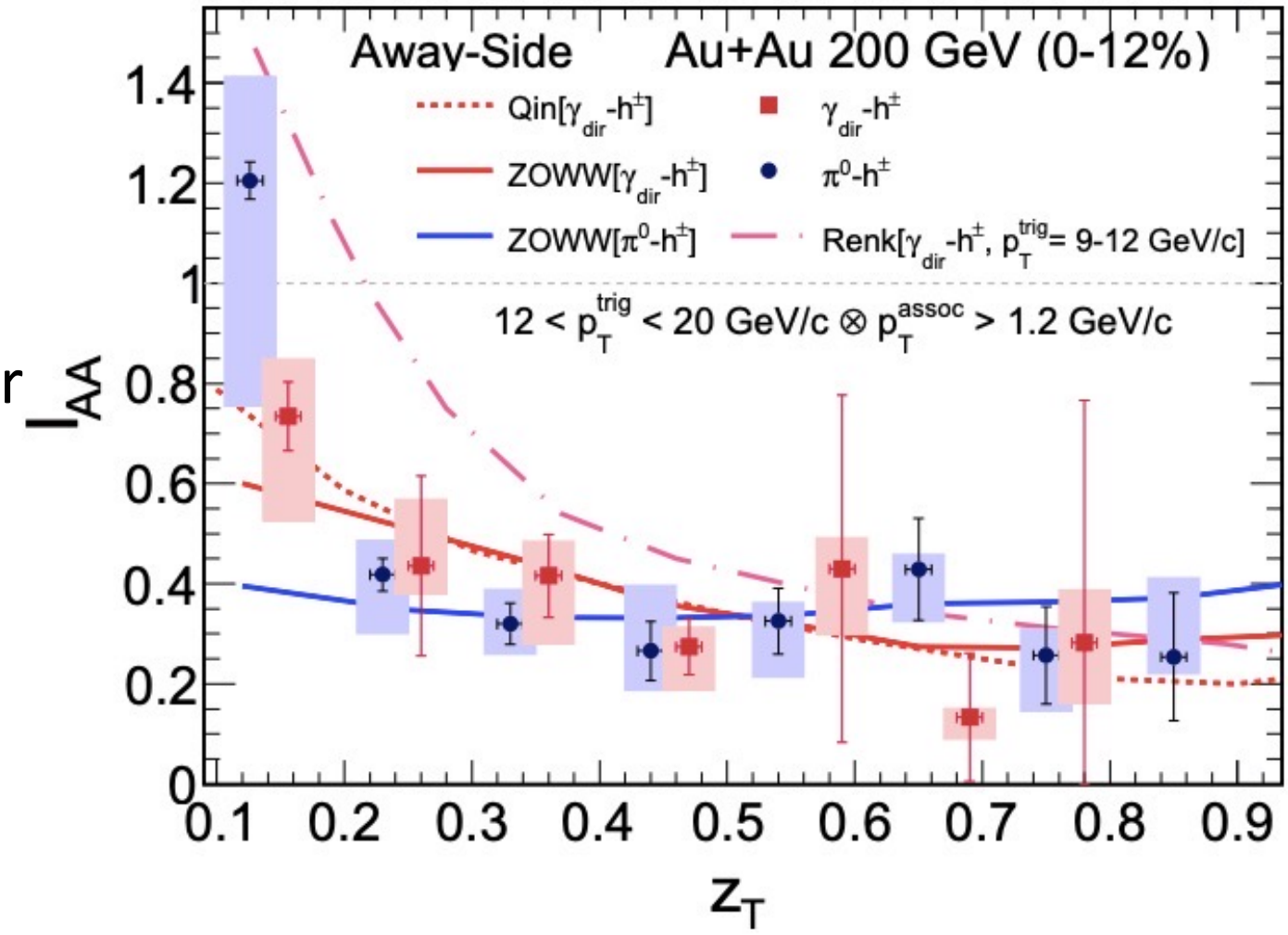
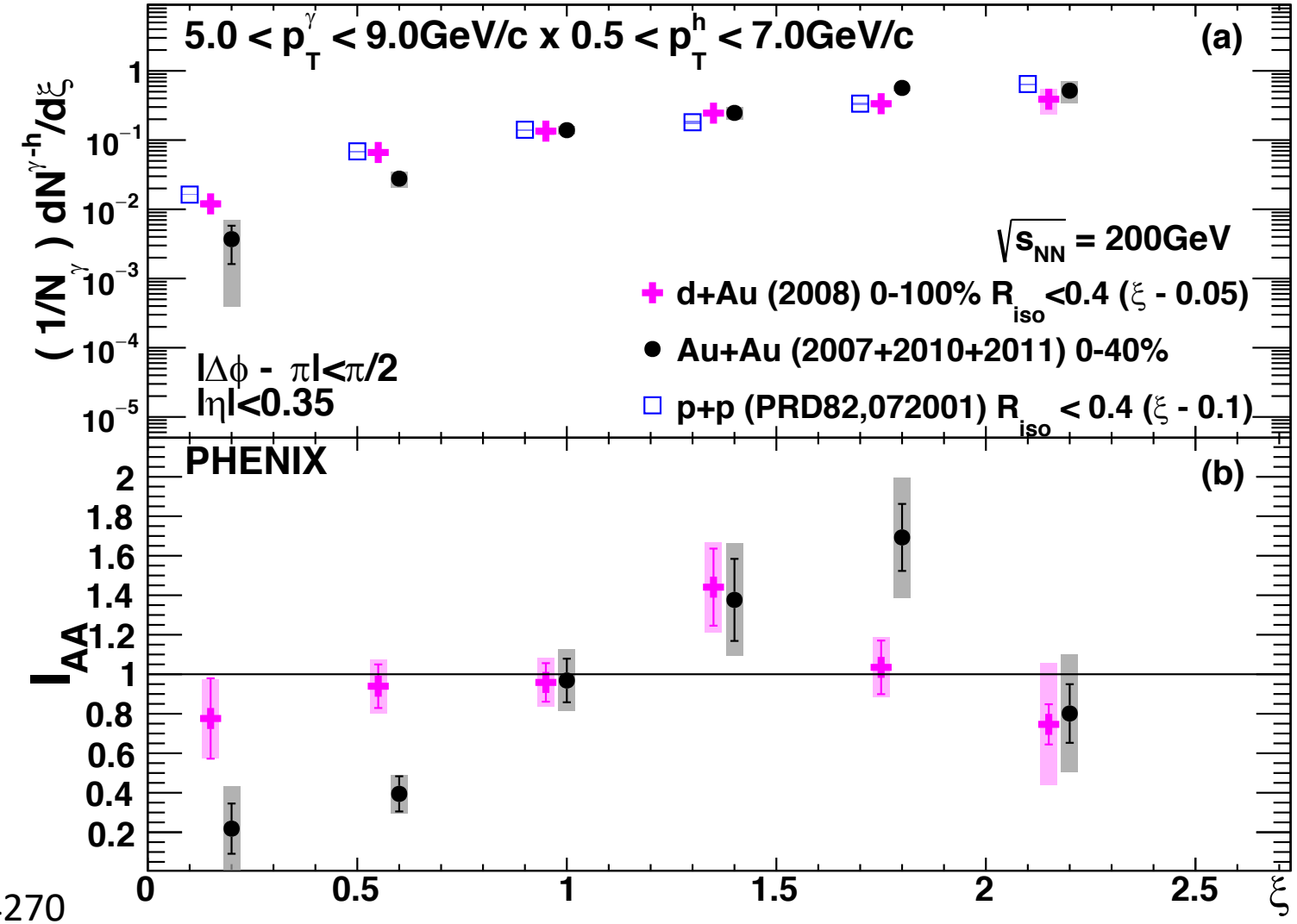


Probing Jet Modification in Small Systems

- I_{dA} from γ^{dir} correlations in $d + Au$ collisions more consistent with no modification



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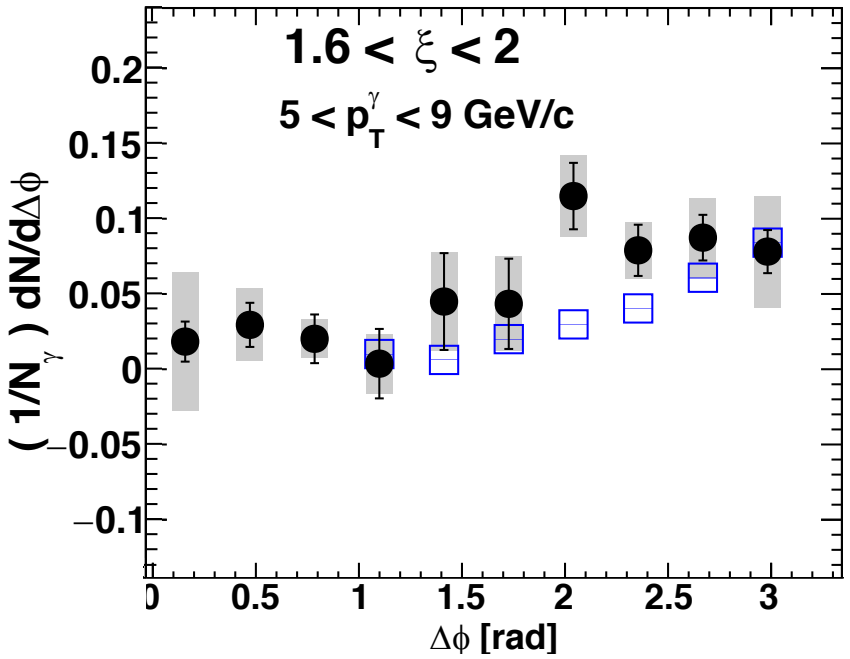
Angular Dependence of I_{AA}

- I_{AA} measured with different integration windows



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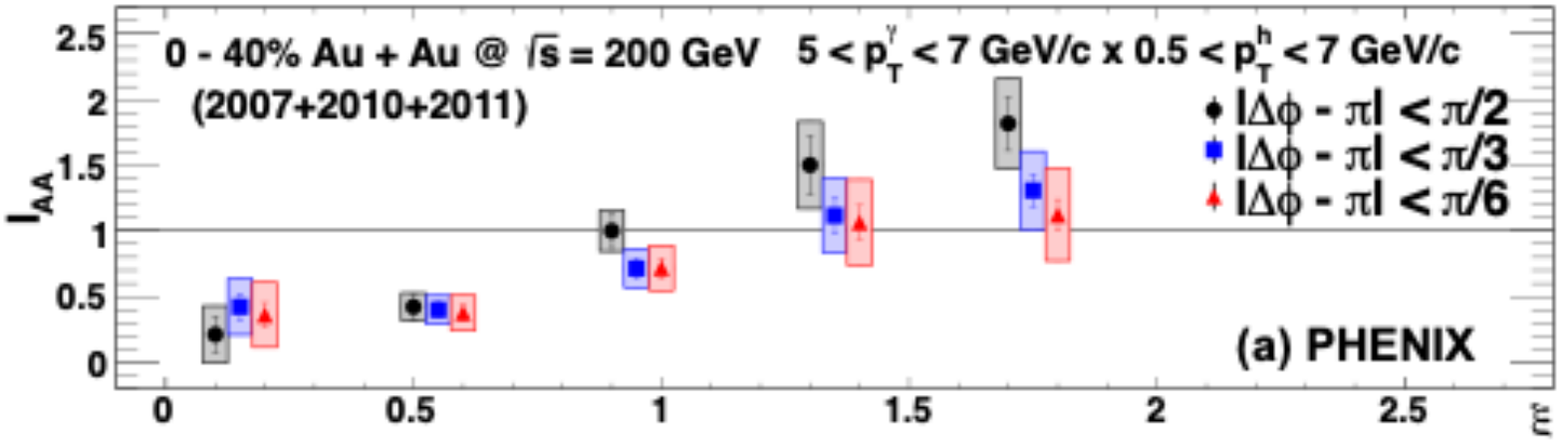
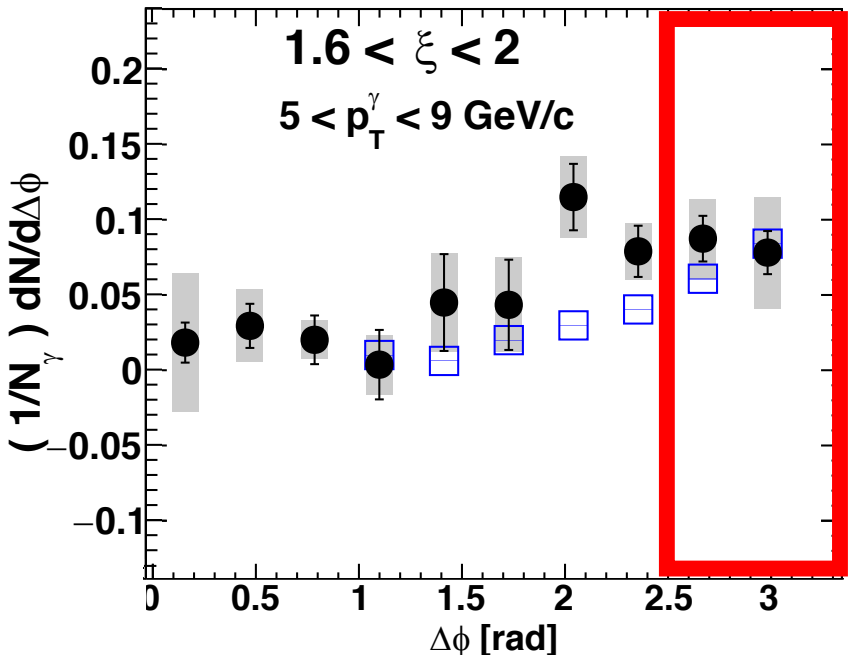


Angular Dependence of I_{AA}

- I_{AA} measured with different integration windows
- Least enhancement for narrow integration range

$|\Delta\phi - \pi| < \pi/6$,



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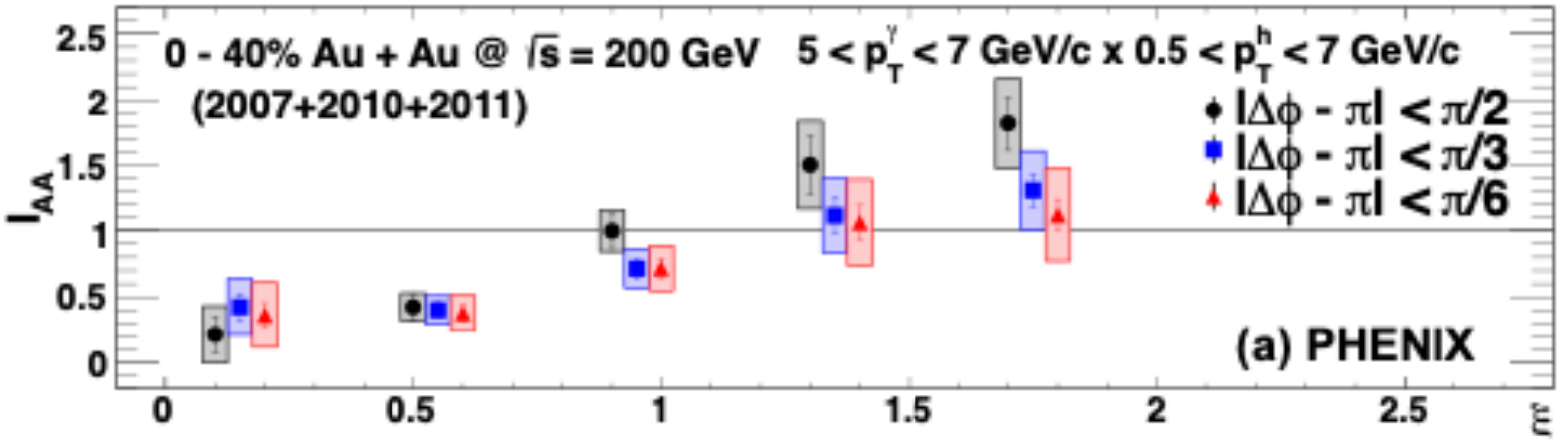
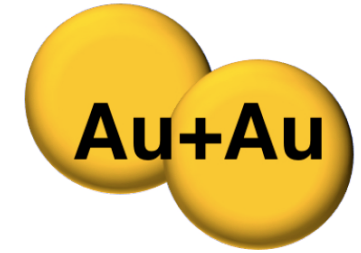
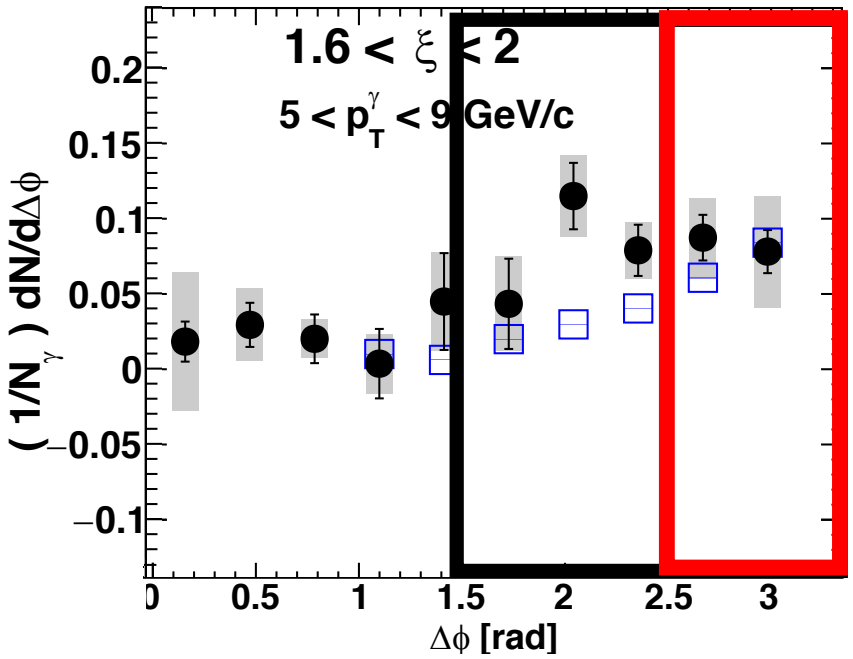


Angular Dependence of I_{AA}



- I_{AA} measured with different integration windows
- Biggest enhancement for **largest integration range**

$|\Delta\phi - \pi| < \pi/6, \pi/2$



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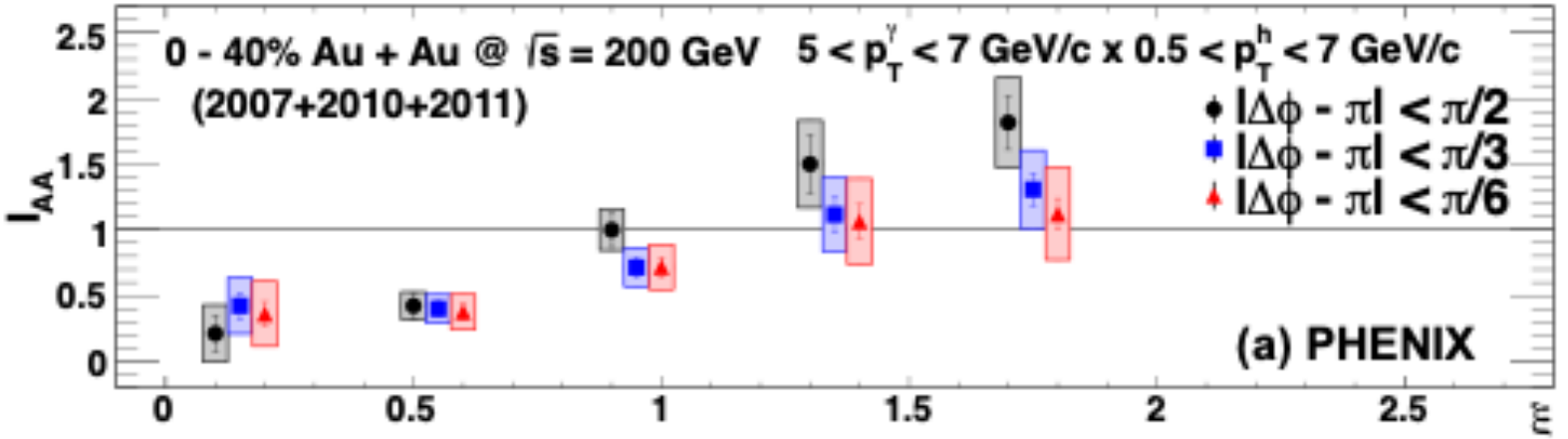
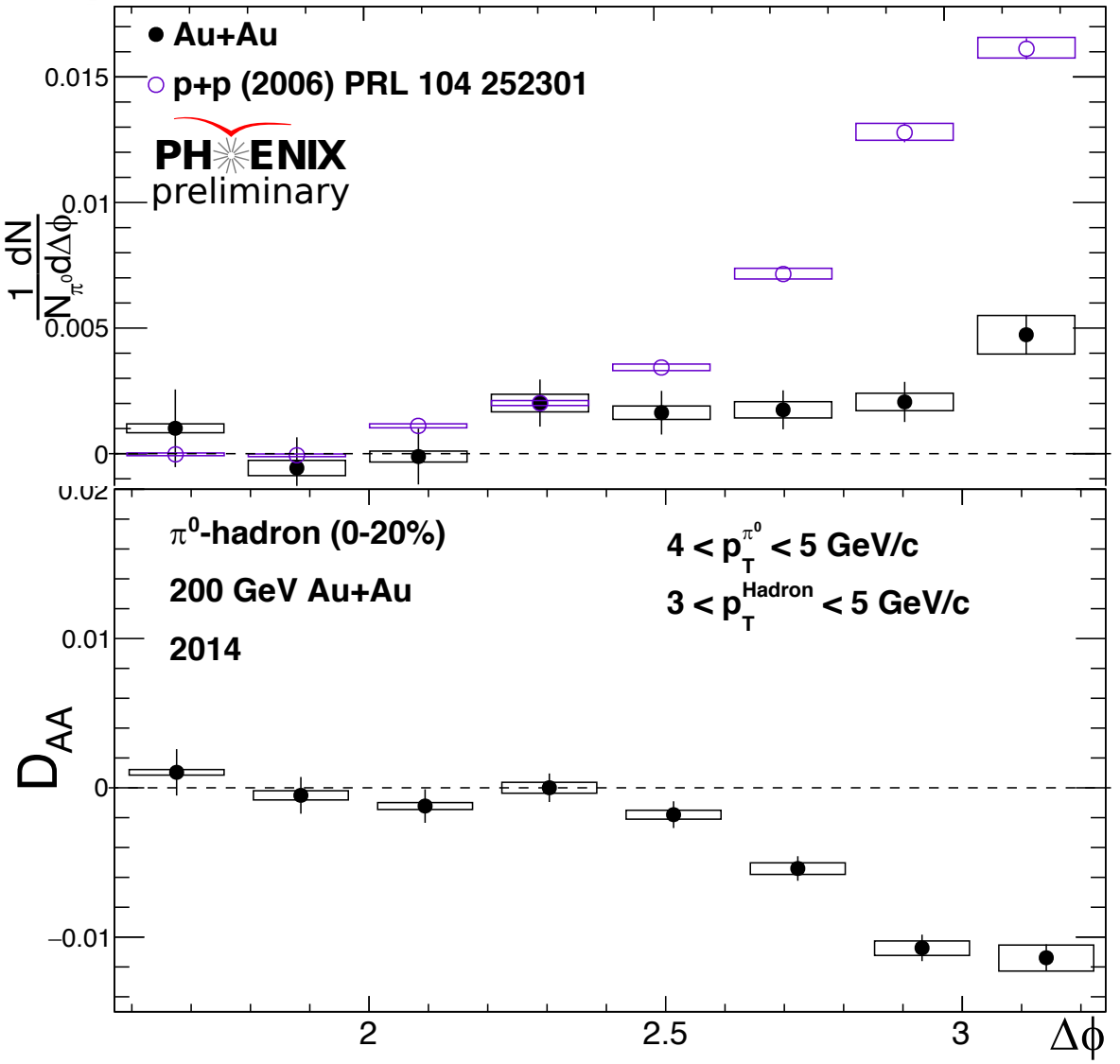


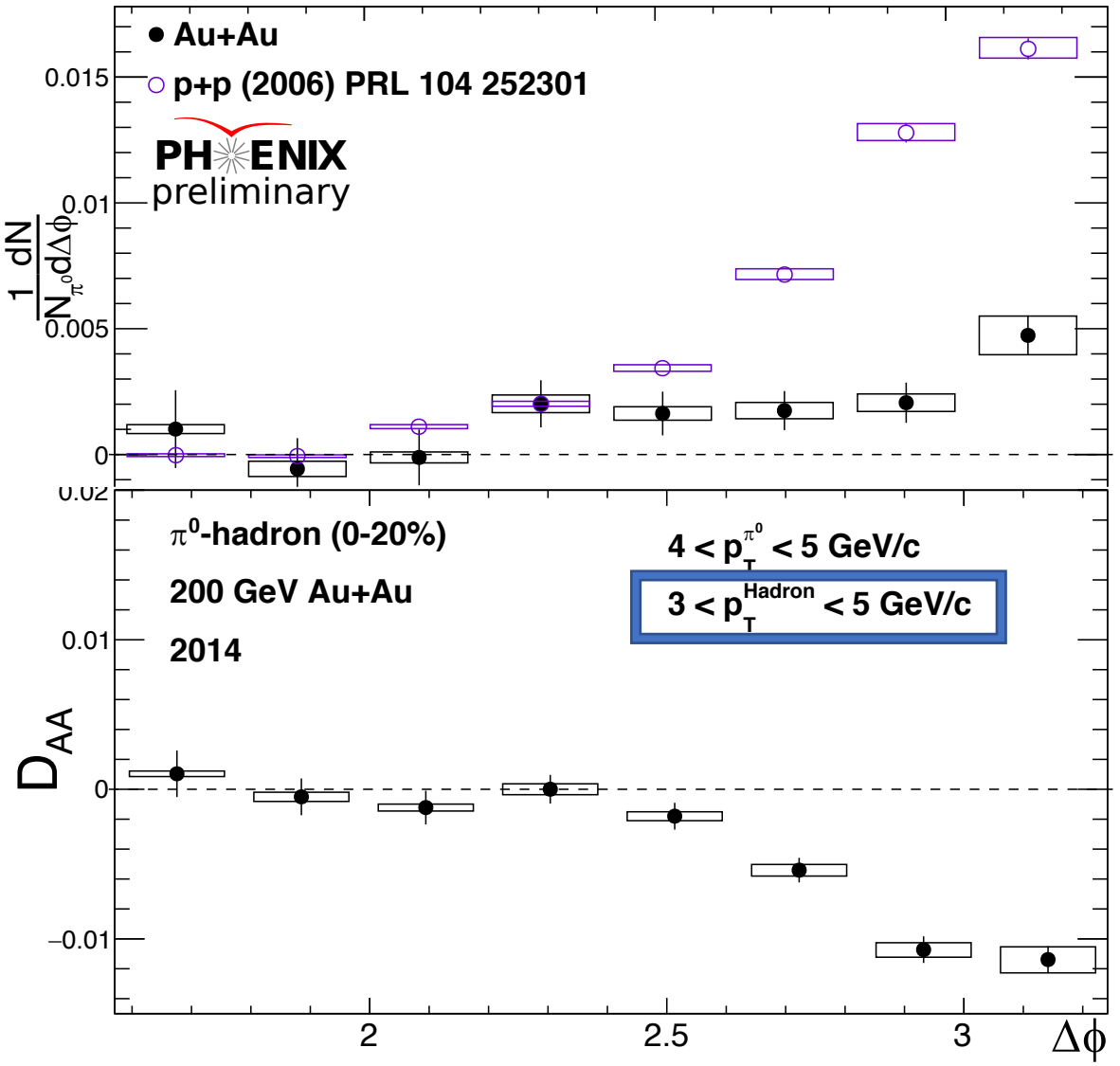
A Look at Structure with 2PC, $\pi^0 - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$



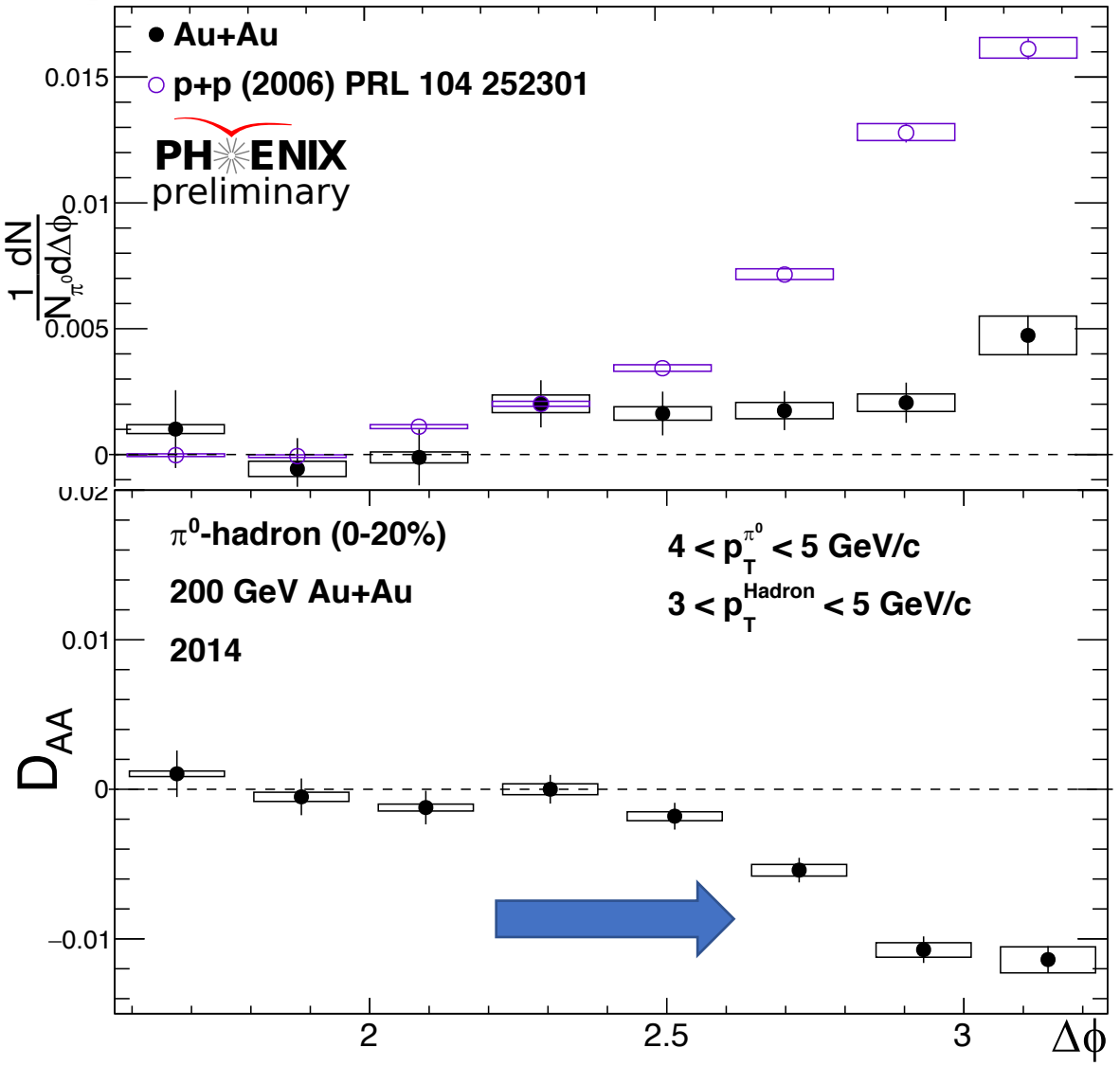
A Look at Structure with 2PC, $\pi^0 - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$
- $D_{AA} < 0 \rightarrow$ Suppression for high p_T associate hadrons



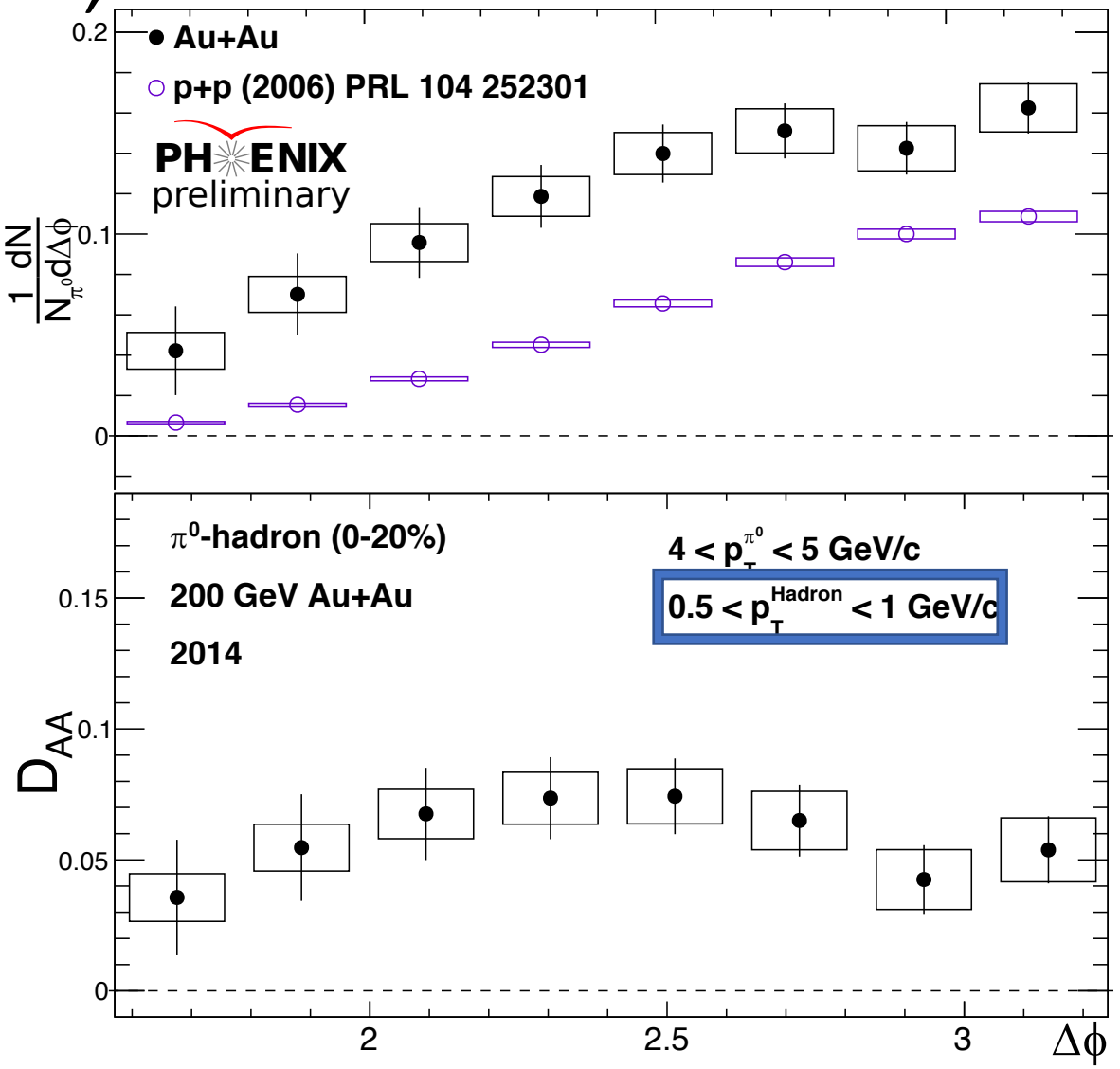
A Look at Structure with 2PC, $\pi^0 - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$
- $D_{AA} < 0 \rightarrow$ Suppression for high p_T associate hadrons
- Suppression most severe near jet core



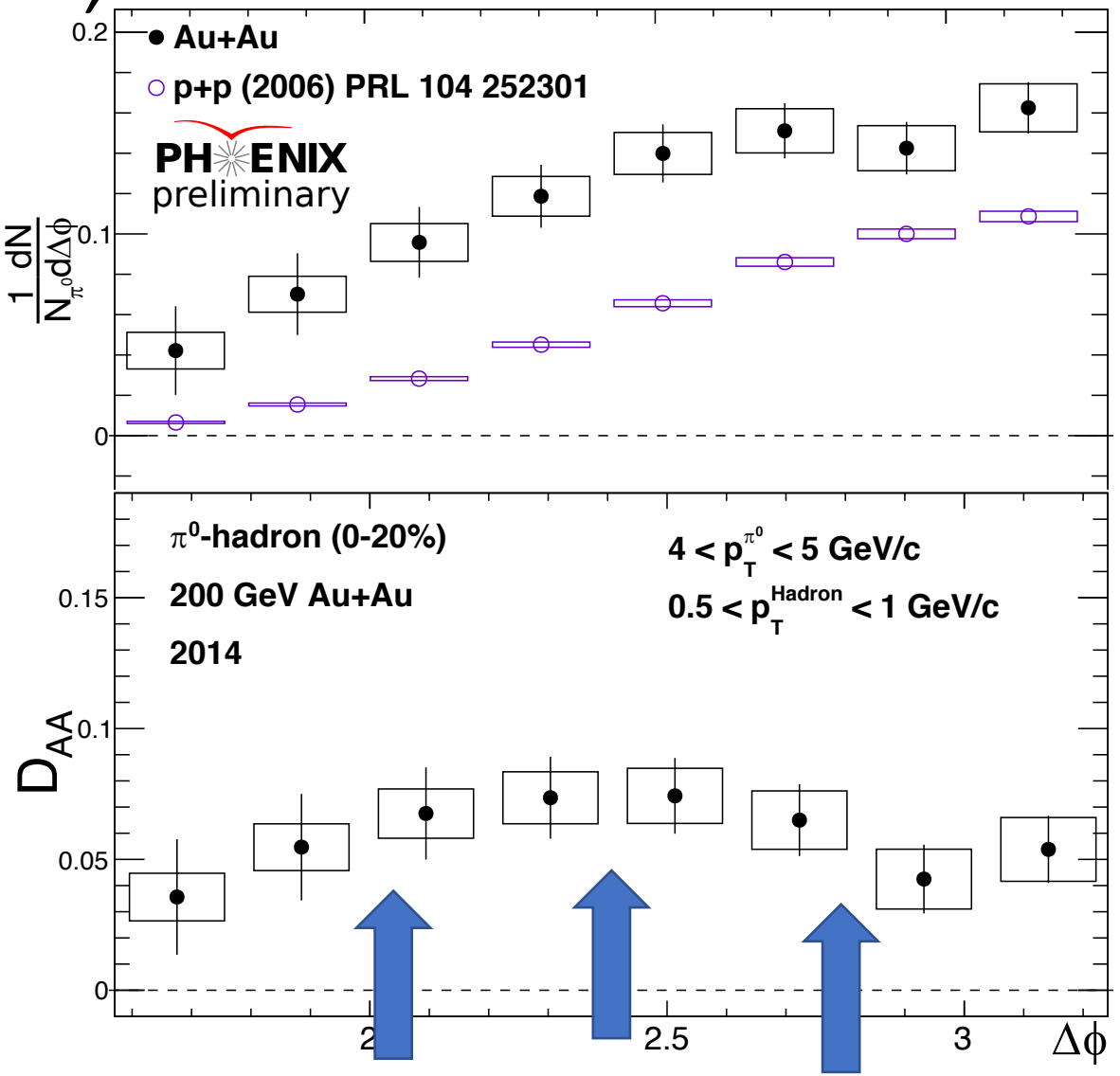
A Look at Structure with 2PC, $\pi^0 - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$
- $D_{AA} > 0 \rightarrow$ Enhancement of low p_T associate hadrons



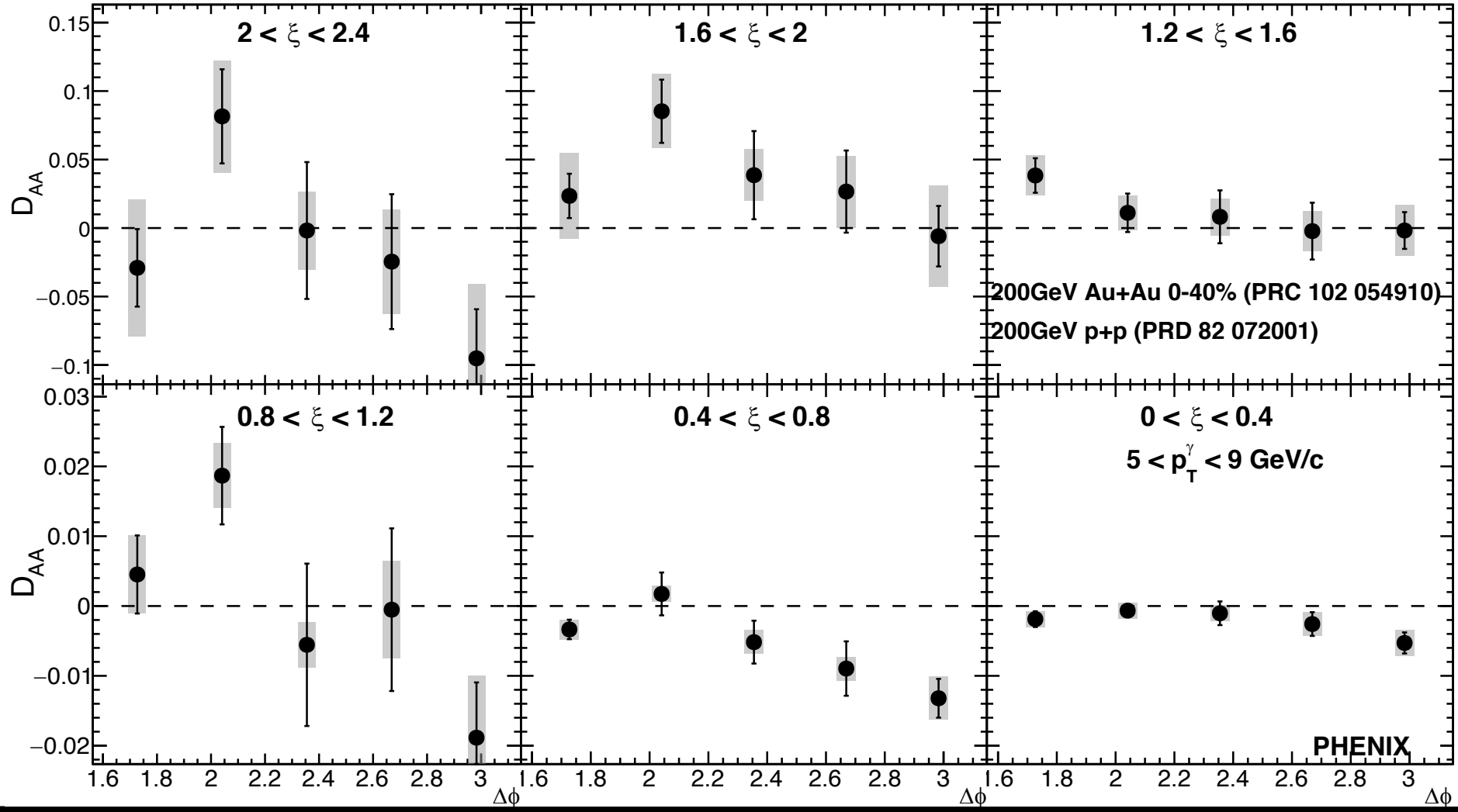
A Look at Structure with 2PC, $\pi^0 - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$
- $D_{AA} > 0 \rightarrow$ Enhancement of low p_T associate hadrons
- Enhancement seen at wide angles



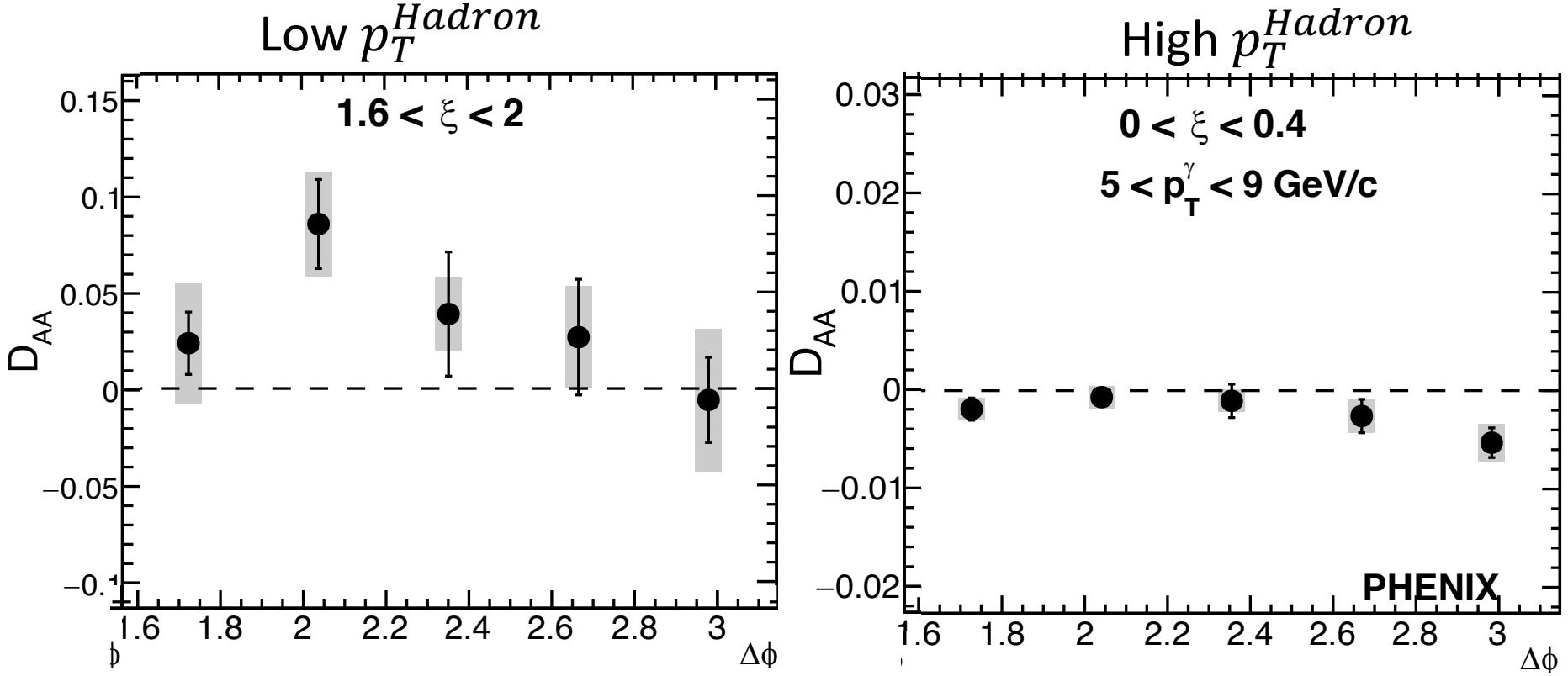
A Look at Structure with 2PC, $\gamma^{dir} - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$ from published data



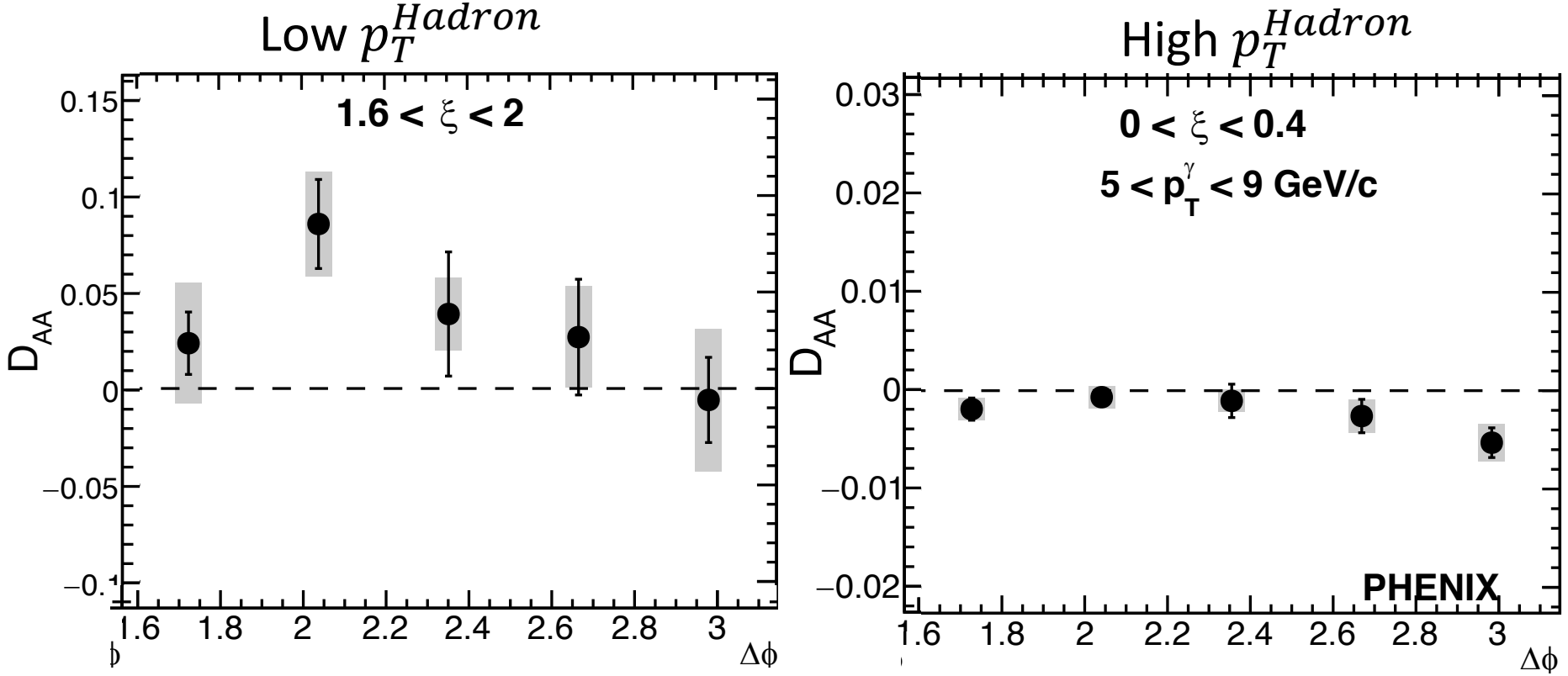
A Look at Structure with 2PC, $\gamma^{dir} - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$ from published data
- Similar trend as with $\pi^0 - h^{\pm}$



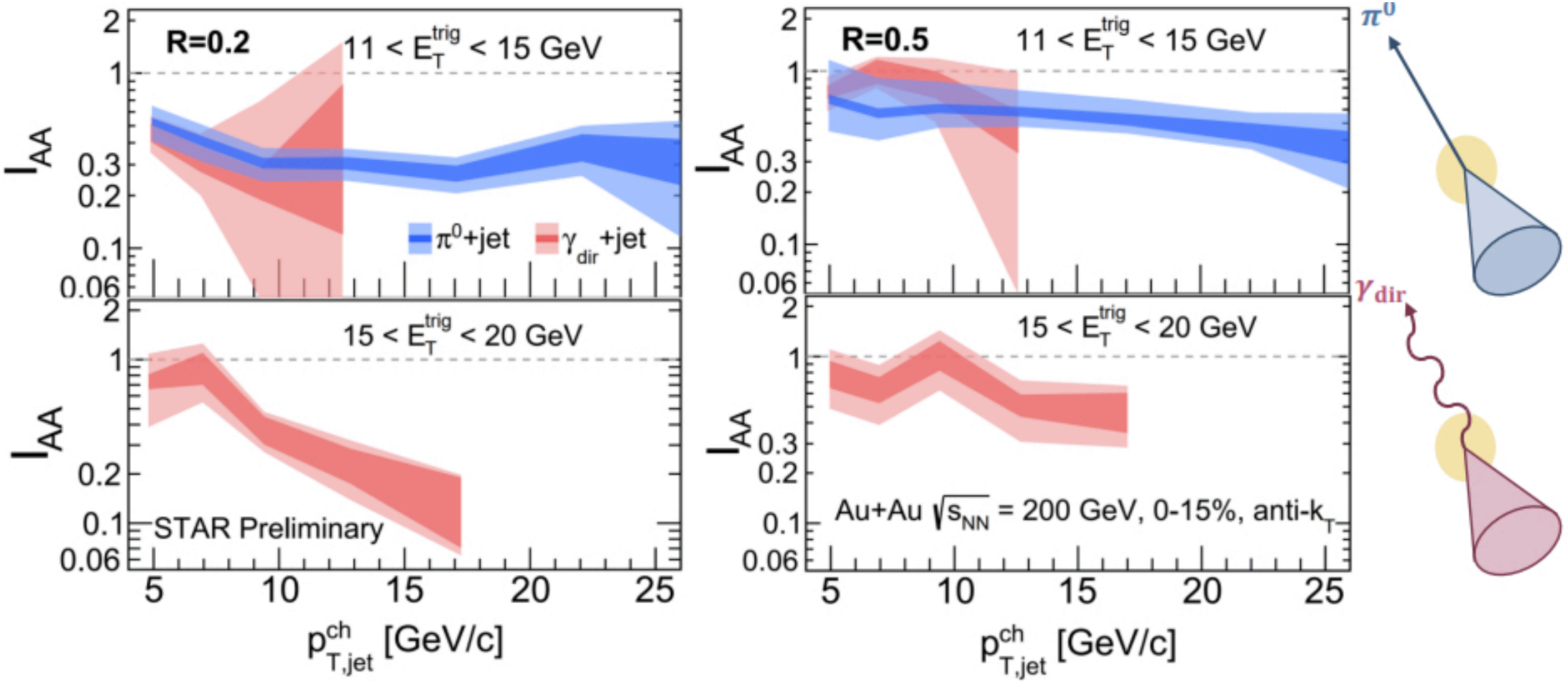
A Look at Structure with 2PC, $\gamma^{dir} - h^{\pm}$

- $D_{AA} = Y_{AA} - Y_{pp}$ from published data
- Similar trend as with $\pi^0 - h^{\pm}$
- Increased precision with later PHENIX data sets



Preliminary Jet Measurements from STAR

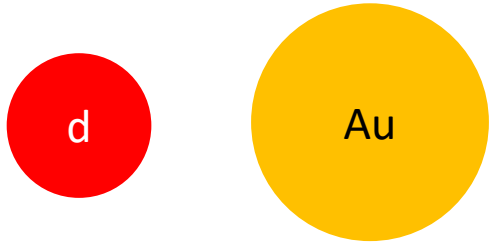
- $I_{AA}(p_T)$ similar for π^0 and γ^{dir} triggered correlations



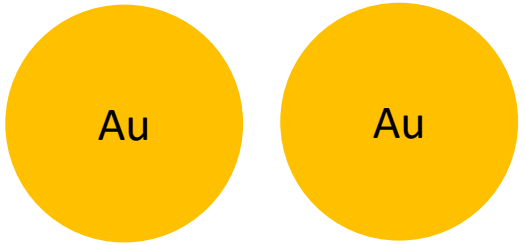
The Story So Far

- Highly differential results can help probe fundamental QCD phenomena

- I_{AA} in $d + Au$ collisions shows no significant modification

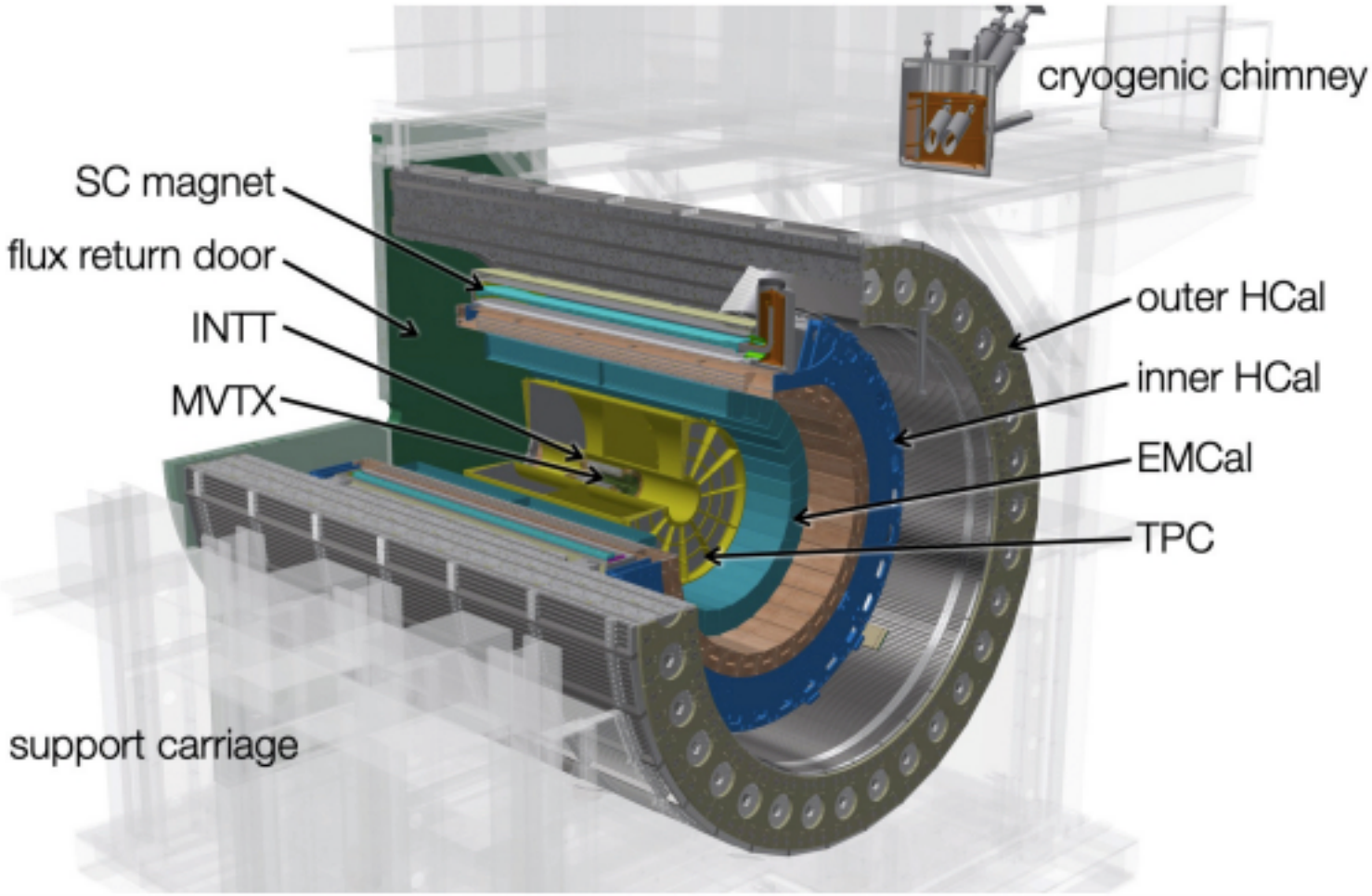


- I_{AA} from γ^{dir} and π^0-triggered correlations show enhancement of soft particles stemming from partonic energy loss
- Soft particles appear at wide angles relative to away-side peak
- No measurable difference between I_{AA}'s of different trigger types



The (Very Near!) Future: sPHENIX

- Next generation jet and upsilon detector at RHIC
- Jet measurements up to 70 GeV
- Direct photons up to 40 GeV
- First data taking run February 2023!



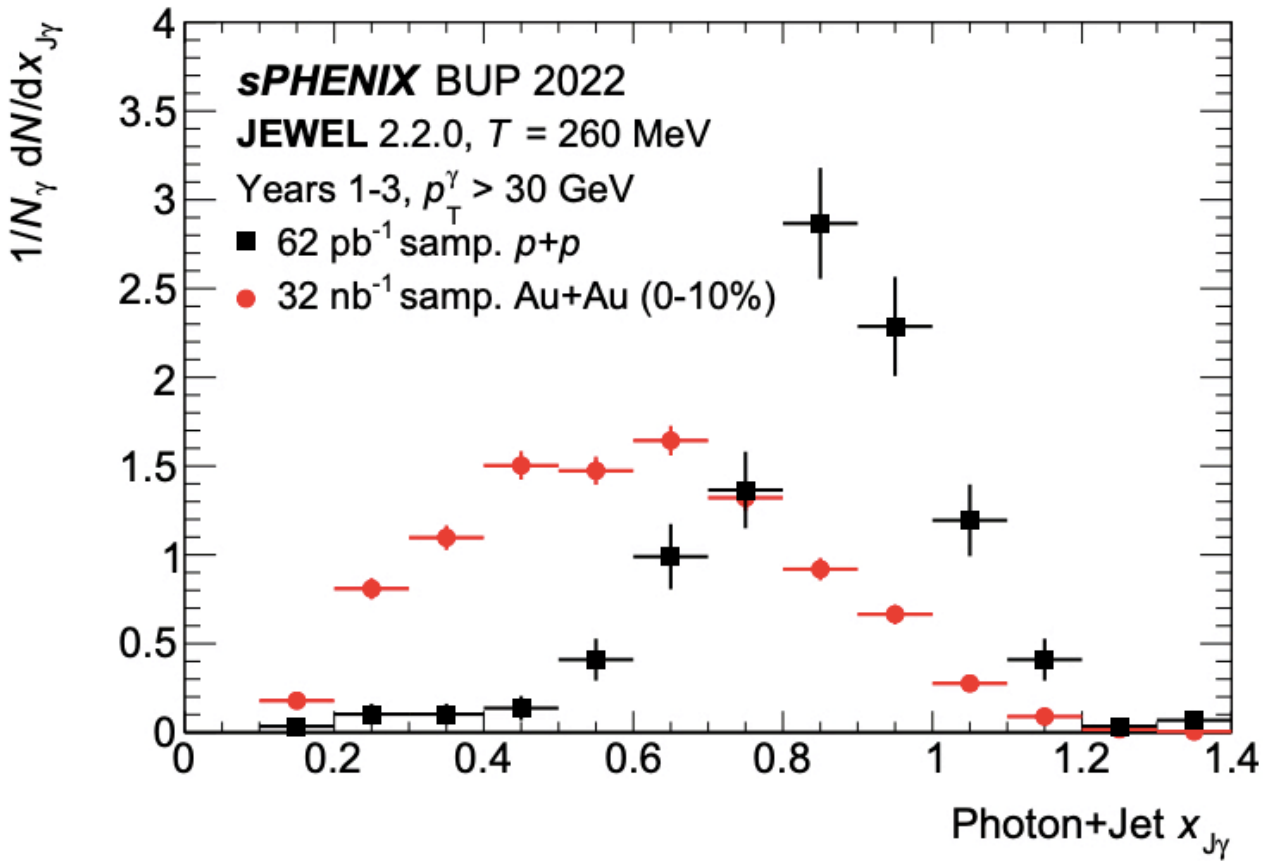
The (Very Near!) Future: sPHENIX

The sPHENIX Run Plan

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Photon Jet Measurements at sPHENIX

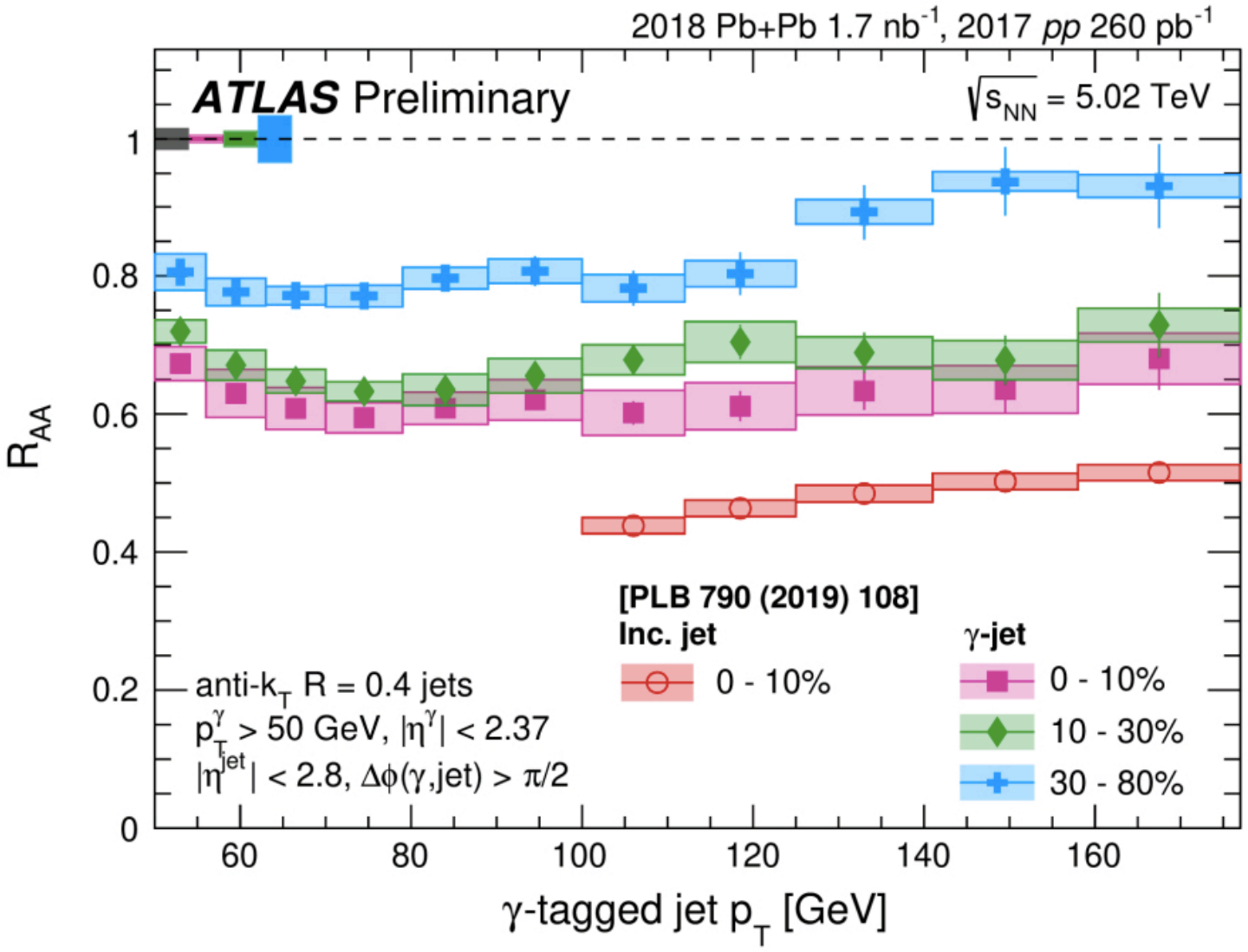
- Highly precise measurement of $x_{J\gamma}$
- $x_{J\gamma} = p_T^{Jet}/p_T^{\gamma}$
- Statistics across all three years will allow for highly differential measurements



Recent ATLAS Results

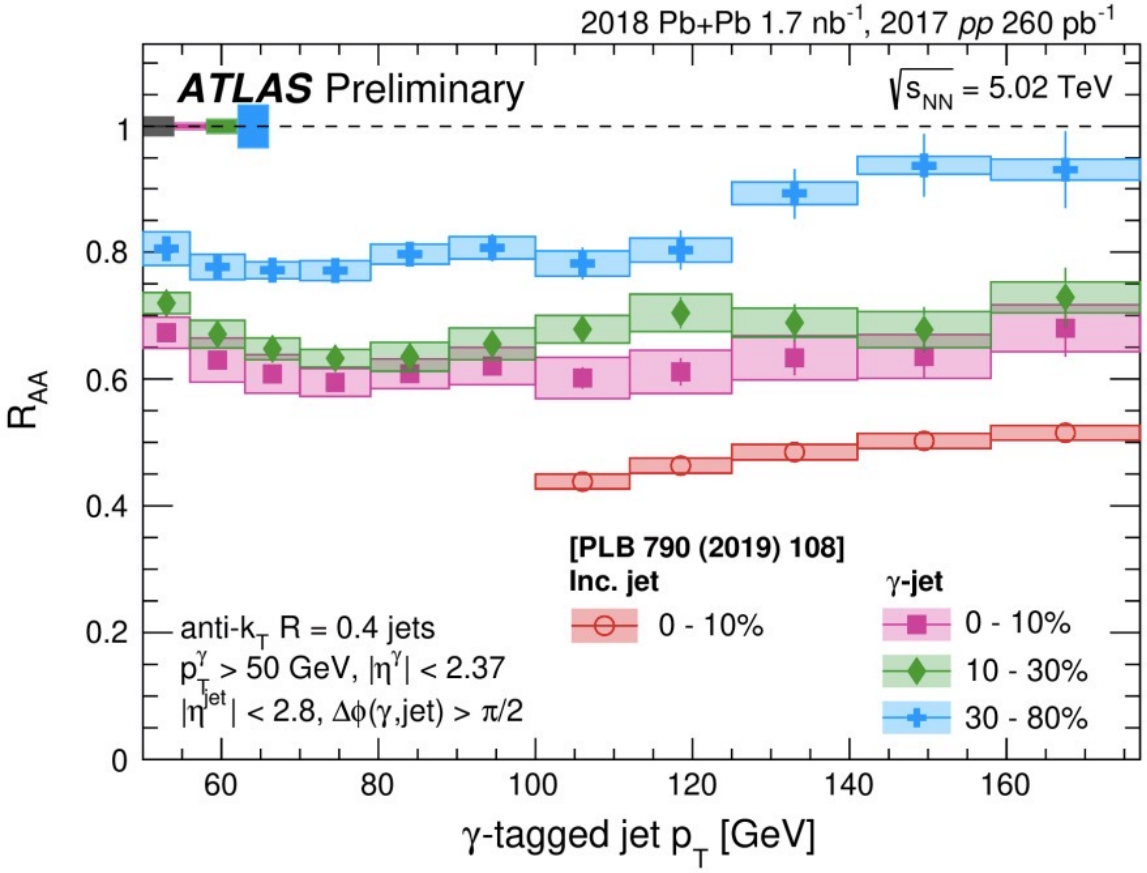
- γ^{dir} tagged jet R_{AA} less suppressed then inclusive

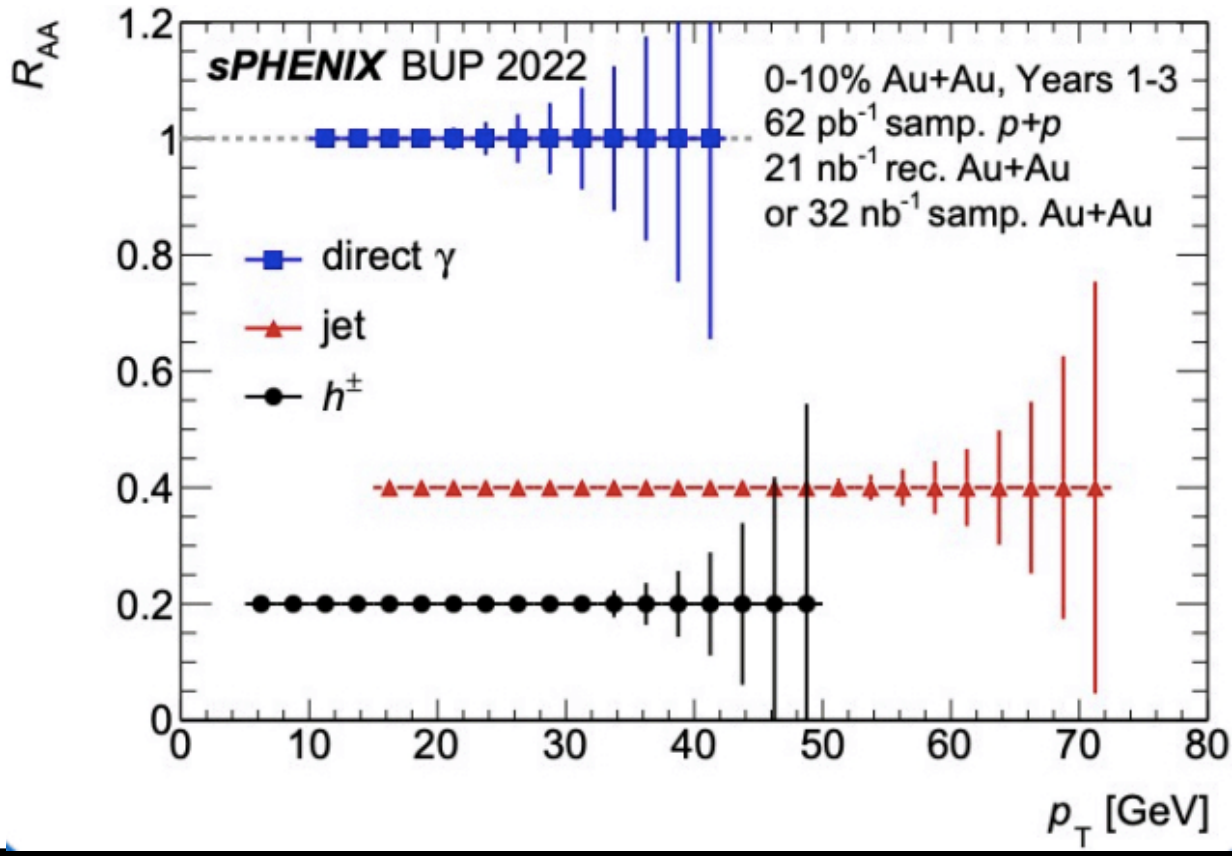
→ quark/gluon color charge



Photon Jet Measurements at sPHENIX

- sPHENIX kinematics will offer complimentarity to LHC measurements





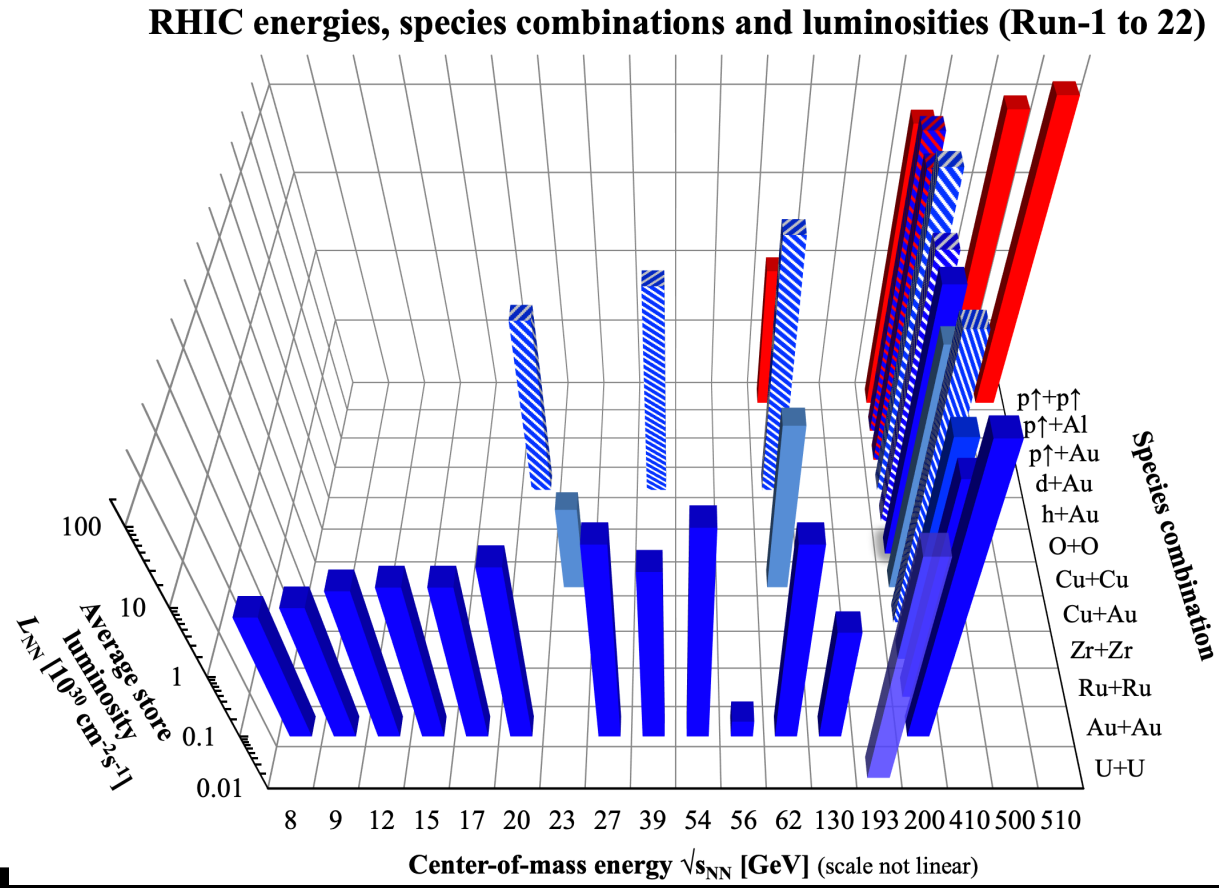
Summary and Outlook

- RHIC has a rich history of direct photon-tagged jet measurements from PHENIX and STAR
- STAR undergoing forward upgrade and has remaining datasets left to extract measurements
- Though PHENIX accomplished its data taking mission in 2016, it, too, still has promising measurements waiting in its 2014 and 2016 200GeV Au+Au datasets
- sPHENIX, a new jet detector at RHIC, will begin taking data in less than 1 year, promising precision photon-jet measurements

Back-up

The Relativistic Heavy-Ion Collider

Relativistic Heavy Ion Collider

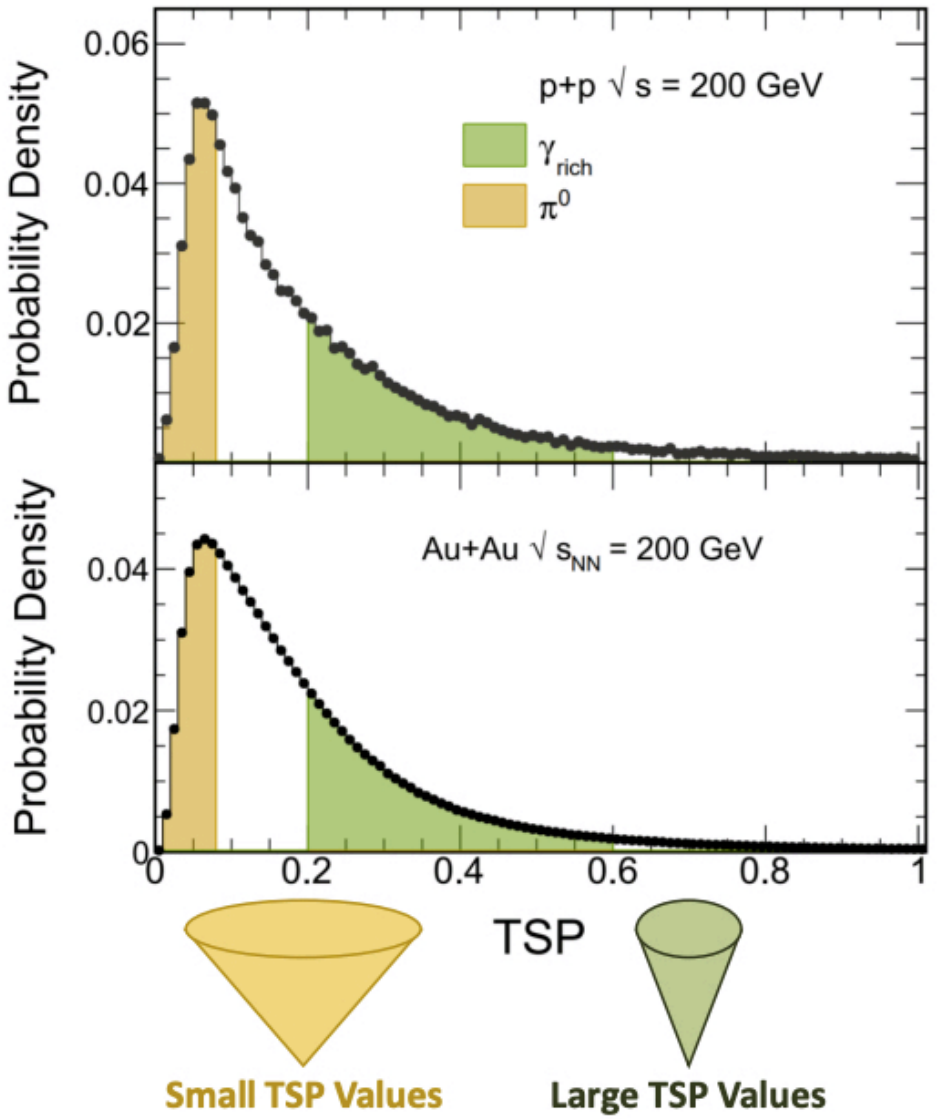


Direct Photon Extraction – STAR

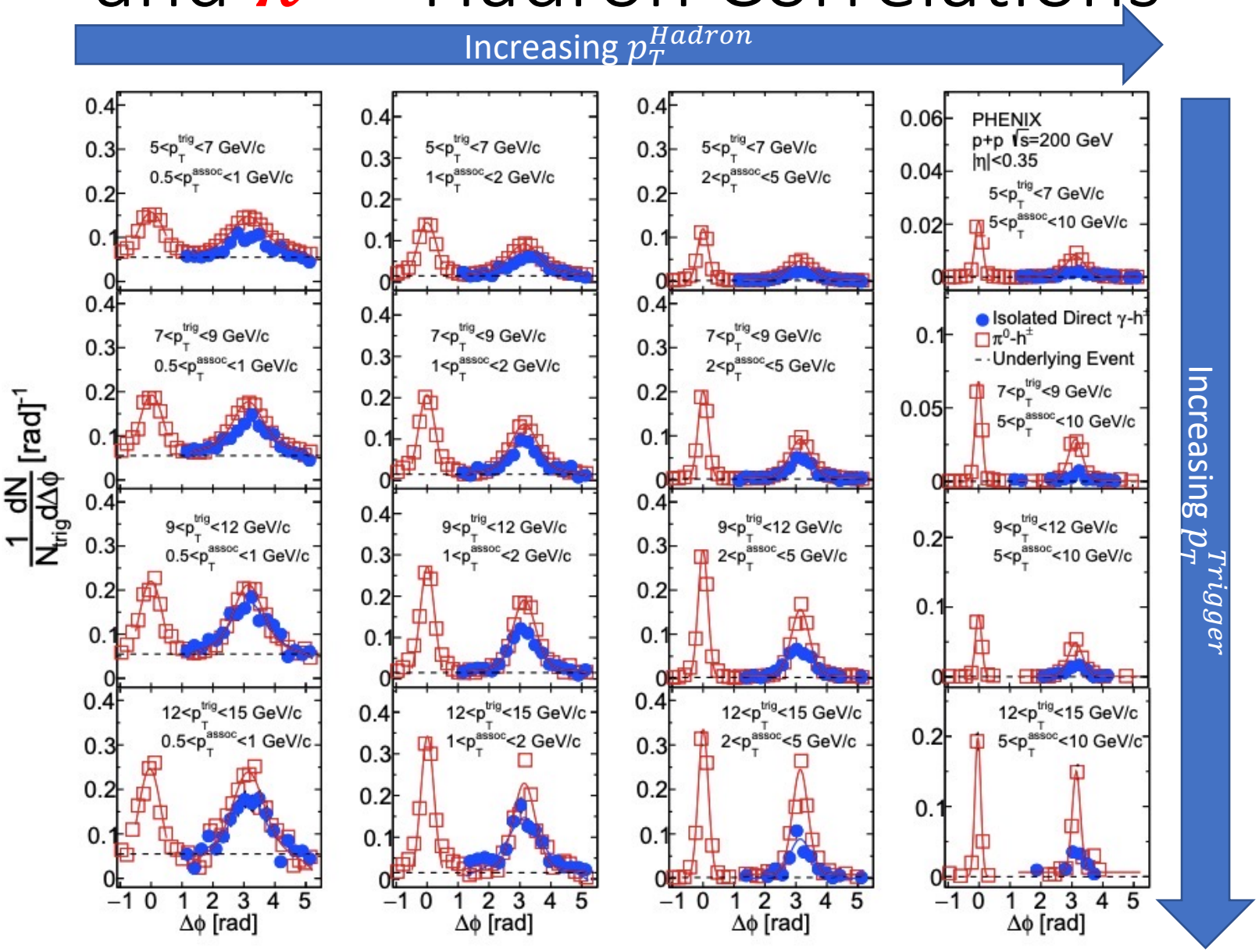
- Use shower shape to discriminate γ^{dir} from meson decays
- Transverse Shower Profile (TSP):

$$\mathrm{TSP} = \frac{\mathrm{E_{Cluster}}}{\sum e_i r_i}$$

- High TSP → High fraction of direct photons
- Low TSP → More likely from meson decays



γ^{dir} and π^0 – Hadron Correlations

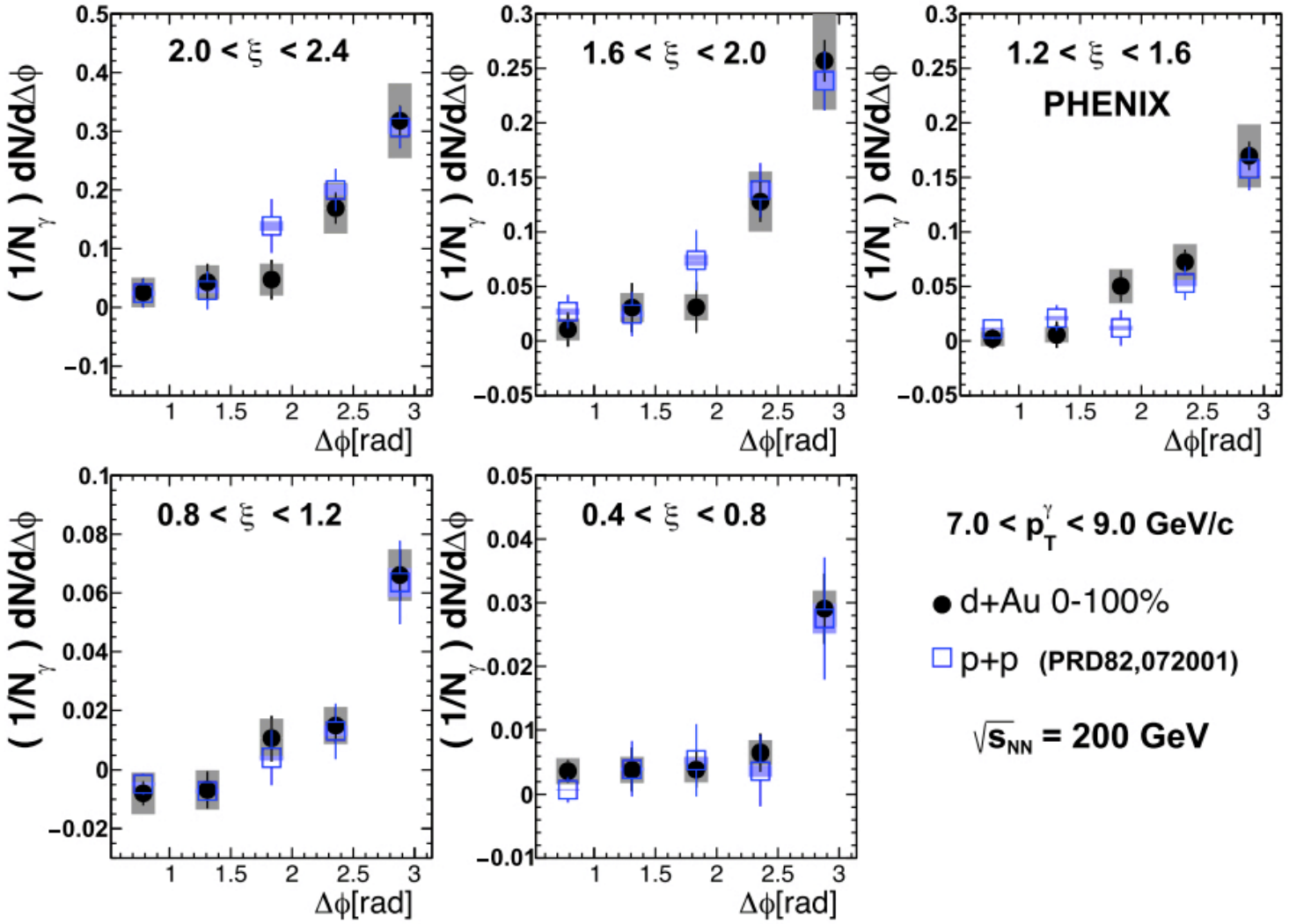


p+p

- Highly differential results from PHENIX in $p+p$

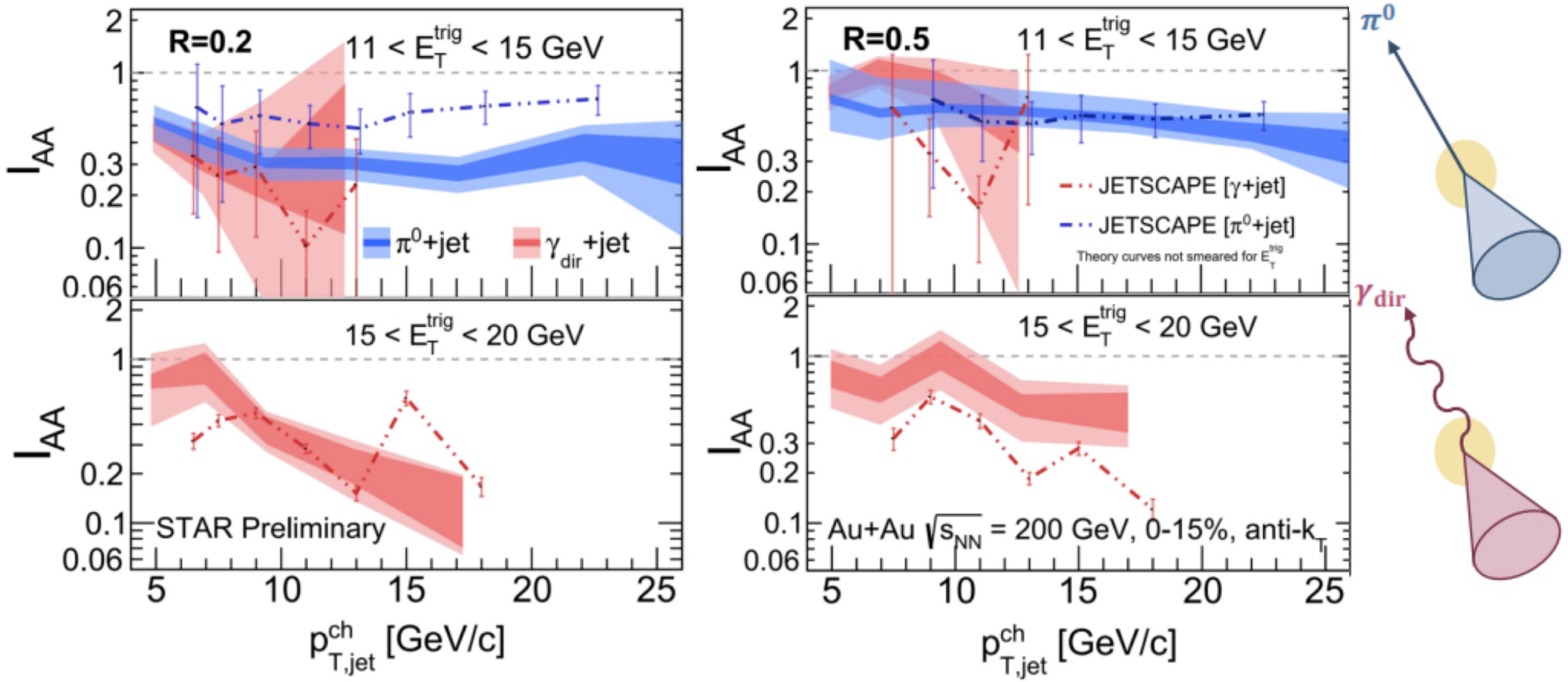
PHENIX – 1805.02450

$d + Au\ \gamma^{dir} - h^{\pm}$ Correlation Functions



γ^{dir} — Jet Measurements

- JETSCAPE → captures p_T dependence
-



γ^{dir} – Jet Measurements

- SCET, LBT, and Jet-fluid also show consistent p_T dependent
- Overall suppression magnitude remains elusive