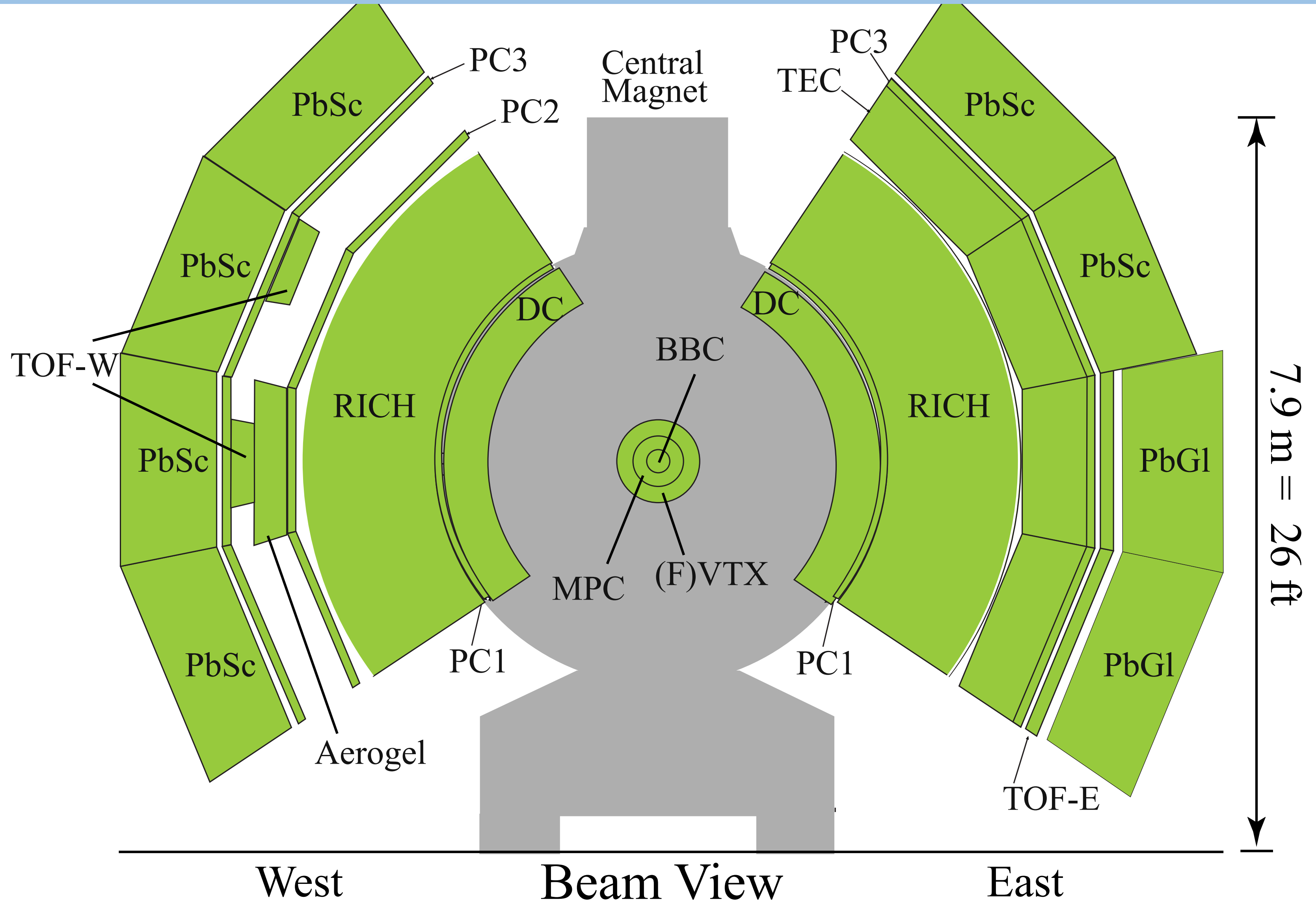
# *Recent Jet, Heavy-Flavor, and High-$p_T$ results from PHENIX*

Dan Richford for the PHENIX Collaboration

2023 AGS/RHIC Users Meeting

2:10 p.m., Wednesday, August 2, 2023

# Detector


PbSc
PC3
PC2
Central Magnet
PC3
TEC
PbSc
PbSc
PbSc
DC
DC
BBC
TOF-W
RICH
RICH
PbSc
PbGl
MPC
(F)VTX
PC1
PC1
PbSc
PbGl
Aerogel
TOF-E
7.9 m = 26 ft
West
Beam View
East

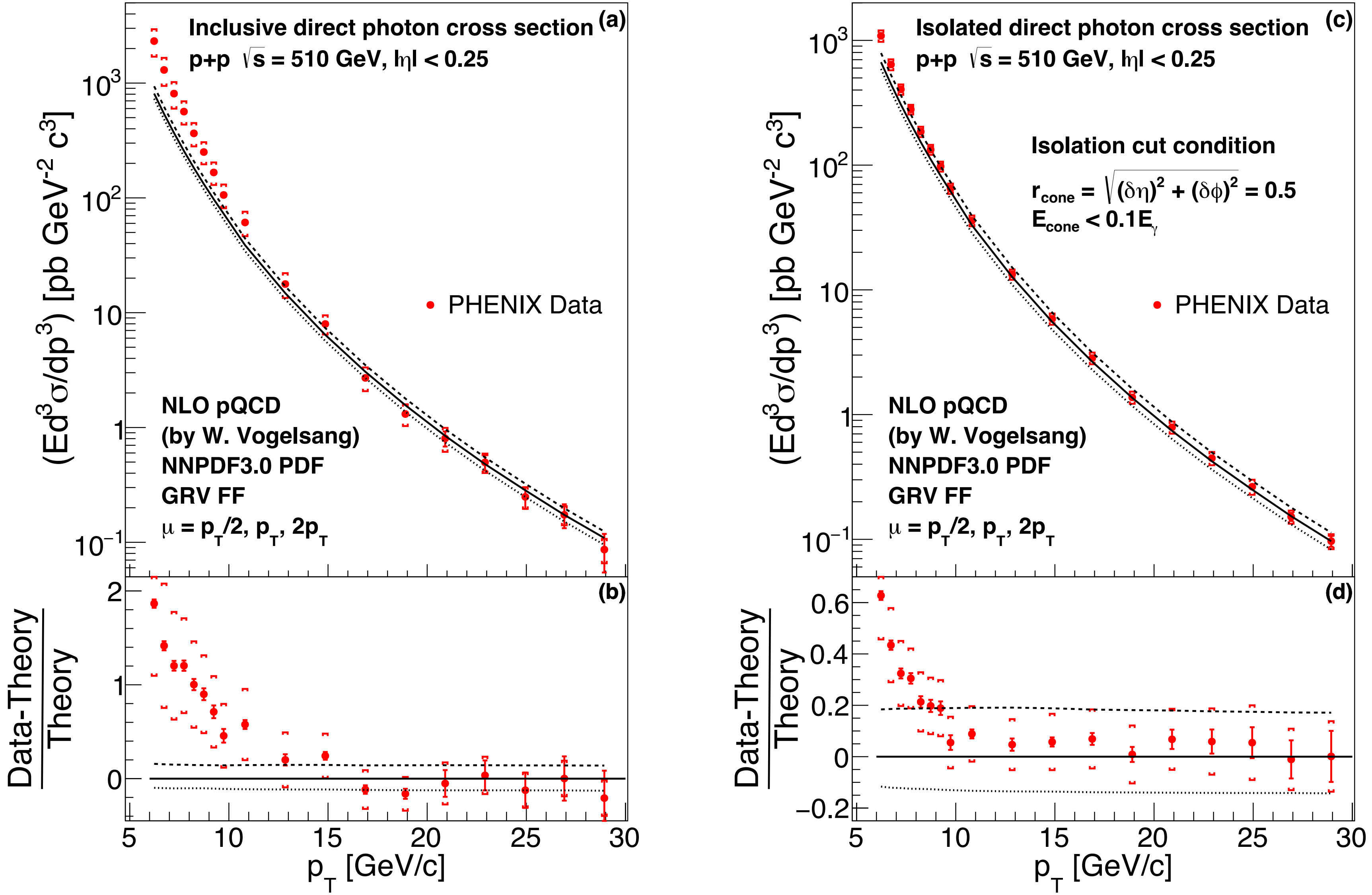
# Results

*High $p_T$*

# Direct photon cross-section ($p + p$)

Phys. Rev. Lett. 130, 251901 (2023)
https://arxiv.org/abs/2202.08158

- Agreement with NLOpQCD @ $p_T \gtrsim 12$ GeV/c
  - Consistent with prior results (PRD 86, 072008: Fig 10)
- Underestimates @ $p_T \lesssim 12$ GeV/c



# Direct photon $A_{LL}$ $(p + p)$

PHENIX

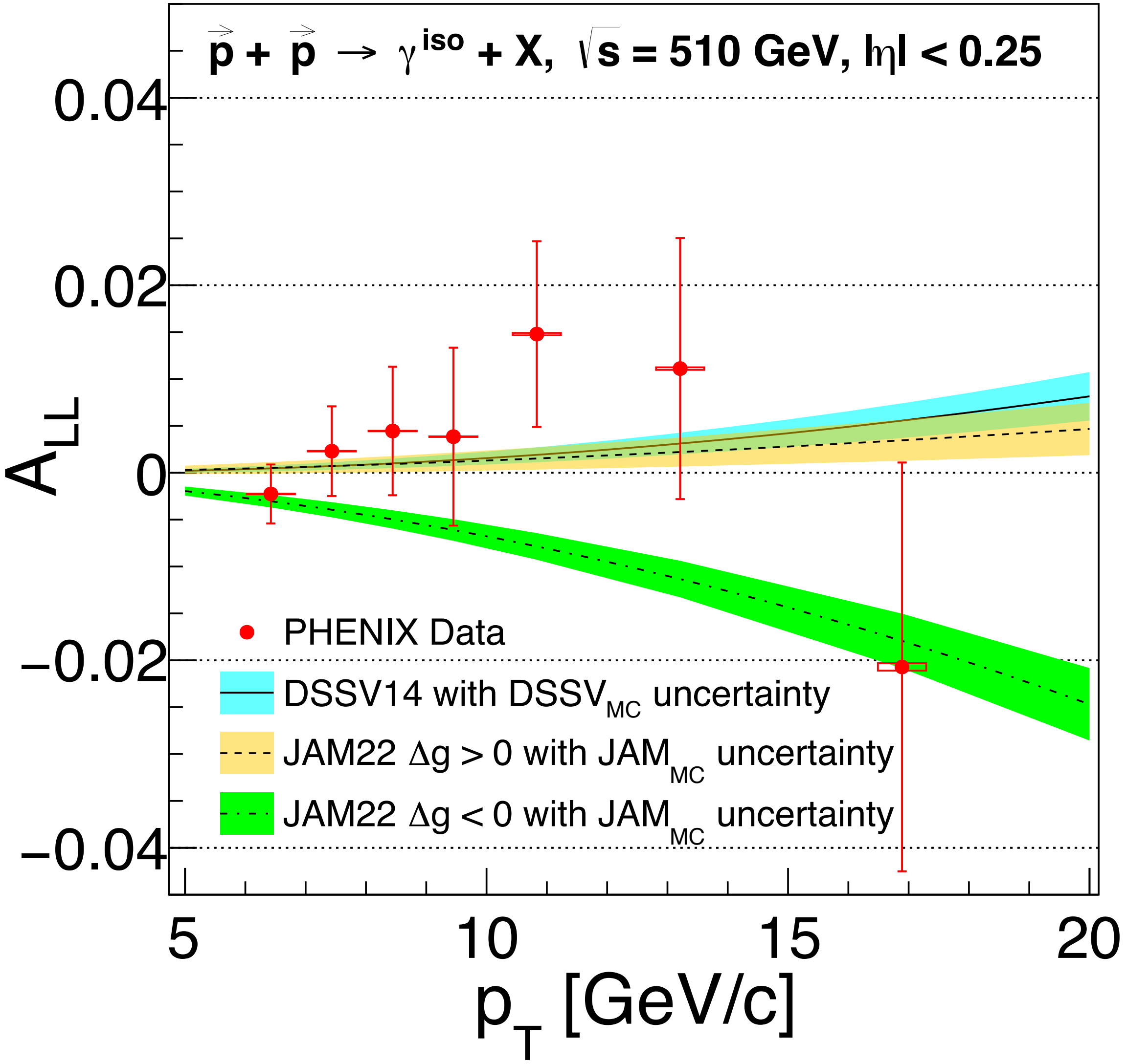
Phys. Rev. Lett. 130, 251901 (2023)
https://arxiv.org/abs/2202.08158
https://www.bnl.gov/newsroom/news.php?a=121250

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

$A_{LL}$ (double helicity asymmetry) for direct photons isolates the gluon contribution because $q + g \rightarrow q + \gamma$ dominates at RHIC at $pT > 5$ GeV/c

PHENIX data follows the
$\Delta g > 0$ polarized gluon PDF

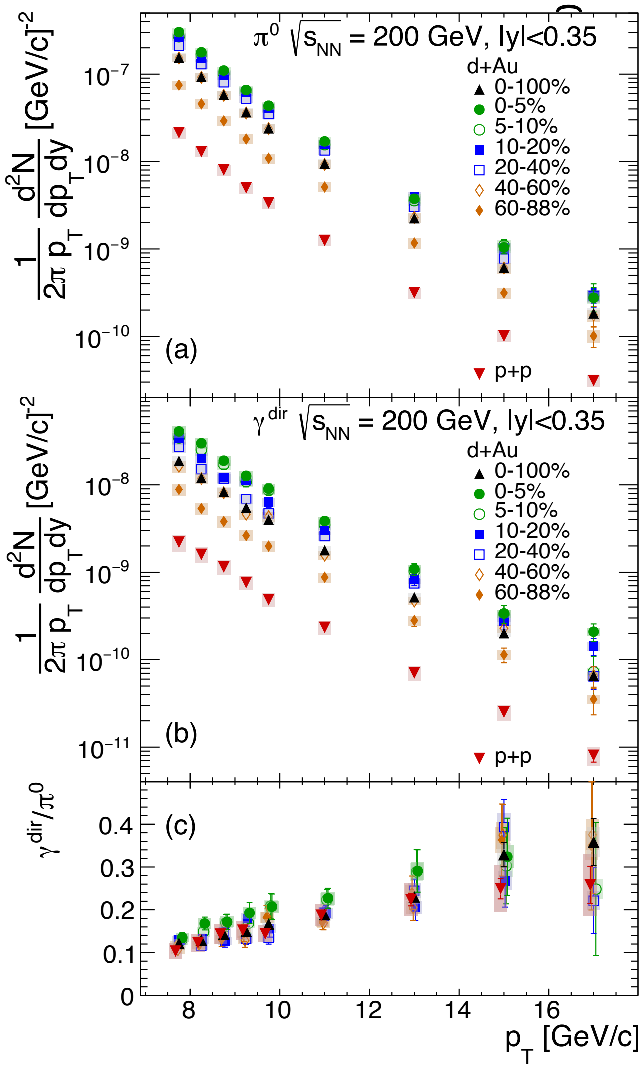
- Gluon spins aligned with proton spin

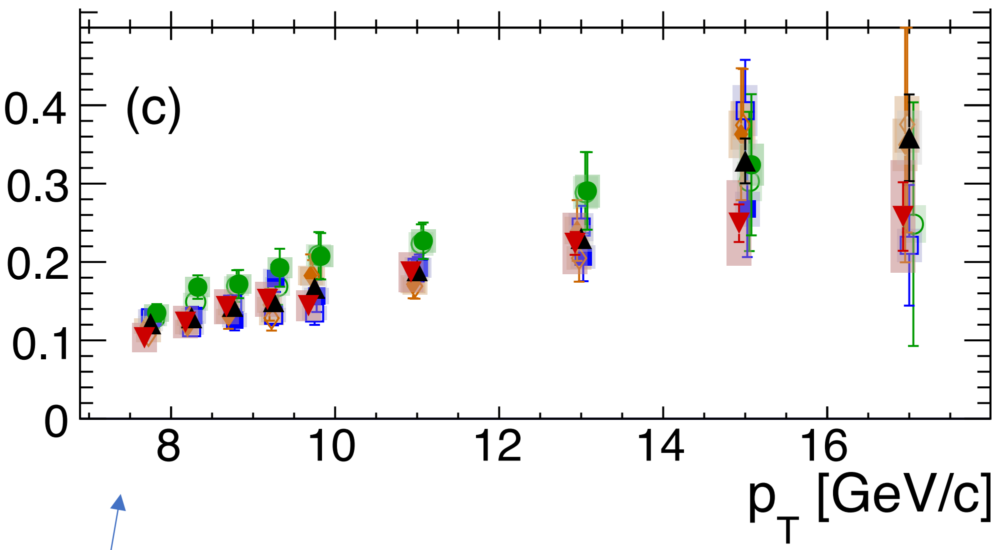


# PHENIX $N_{Coll}$ from direct photons (d + Au) (1/4)

http://arxiv.org/abs/2303.12899

- Purpose: Demonstrate alternative way to calculate $N_{coll}$
  - Glauber model (forward rapidity)
  - Measured direct photons (midrapidity)
- Motivation
  - For small systems, a high-pT particle at mid-rapidity is not available to hit forward detectors




Direct Photon $N_{coll}^{EXP}$:

$$N_{coll}^{\mathrm{EXP}} = \frac{Y_{d+Au}^{\gamma^{dir}}}{Y_{p+p}^{\gamma^{dir}}}$$

… because yield of direct photons in p + p scales with $N_{coll}$

# $N_{coll}$ from Direct Photons (d+Au) (2/4)

http://arxiv.org/abs/2303.12899

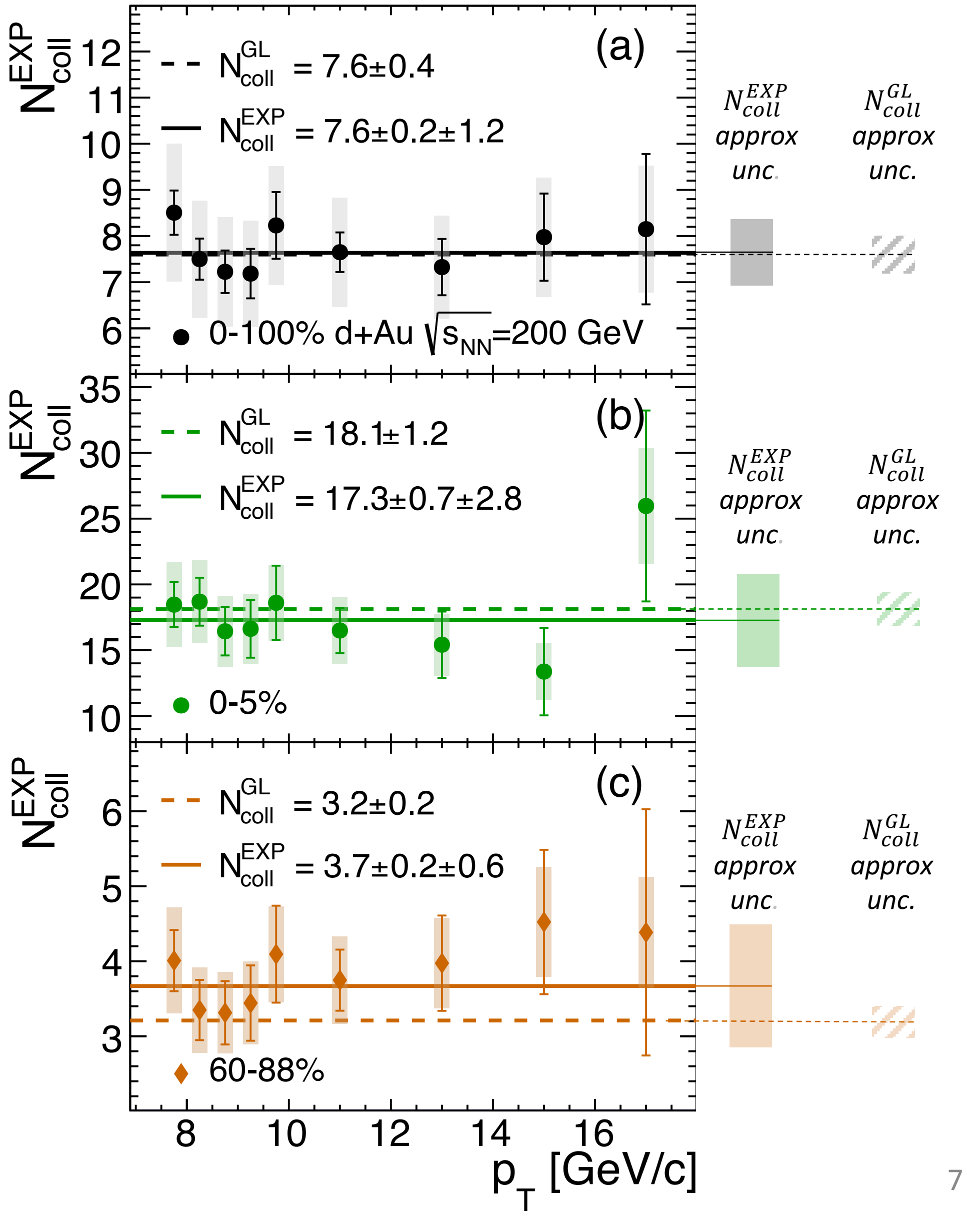
$$N_{coll}^{\mathrm{EXP}} = \frac{Y_{d+Au}^{\gamma^{dir}}}{Y_{p+p}^{\gamma^{dir}}}$$

Comparing:

Glauber-model $N_{coll}^{GL}$

PHENIX-measured (mid-$\eta$) $N_{coll}^{EXP}$

vs. $p_T$



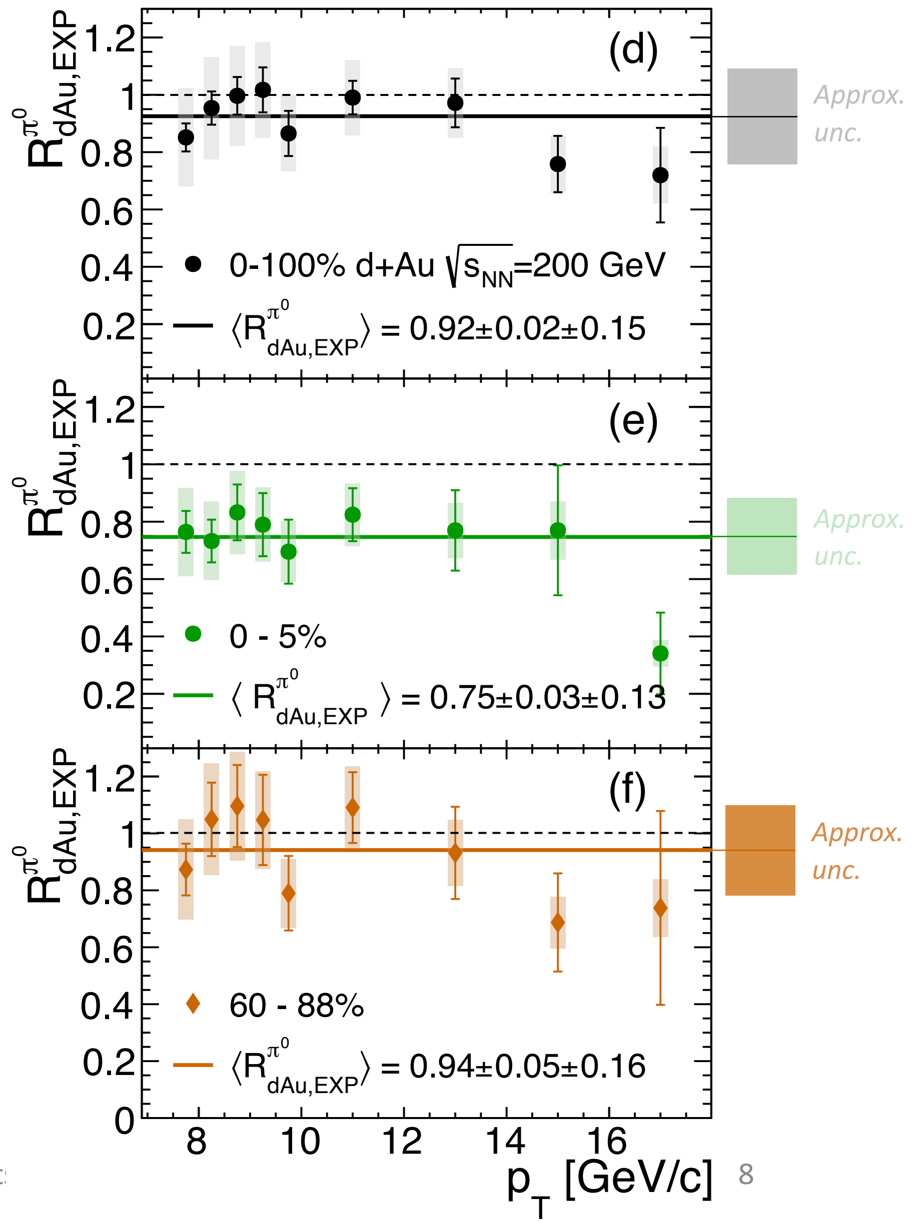
# $N_{Coll}$ from Direct Photons (3/4)

http://arxiv.org/abs/2303.12899

$R_{dAu}{}^{\pi 0}$ vs. $p_T$

$$R_{dAu}^{\pi^0\ \ EXP} = \frac{Y_{dAu}^{\pi^0}}{N_{coll}^{EXP} Y_{pp}^{\pi^0}}$$

- Suppression in central events using the direct-photon $N_{coll}{}^{EXP}$

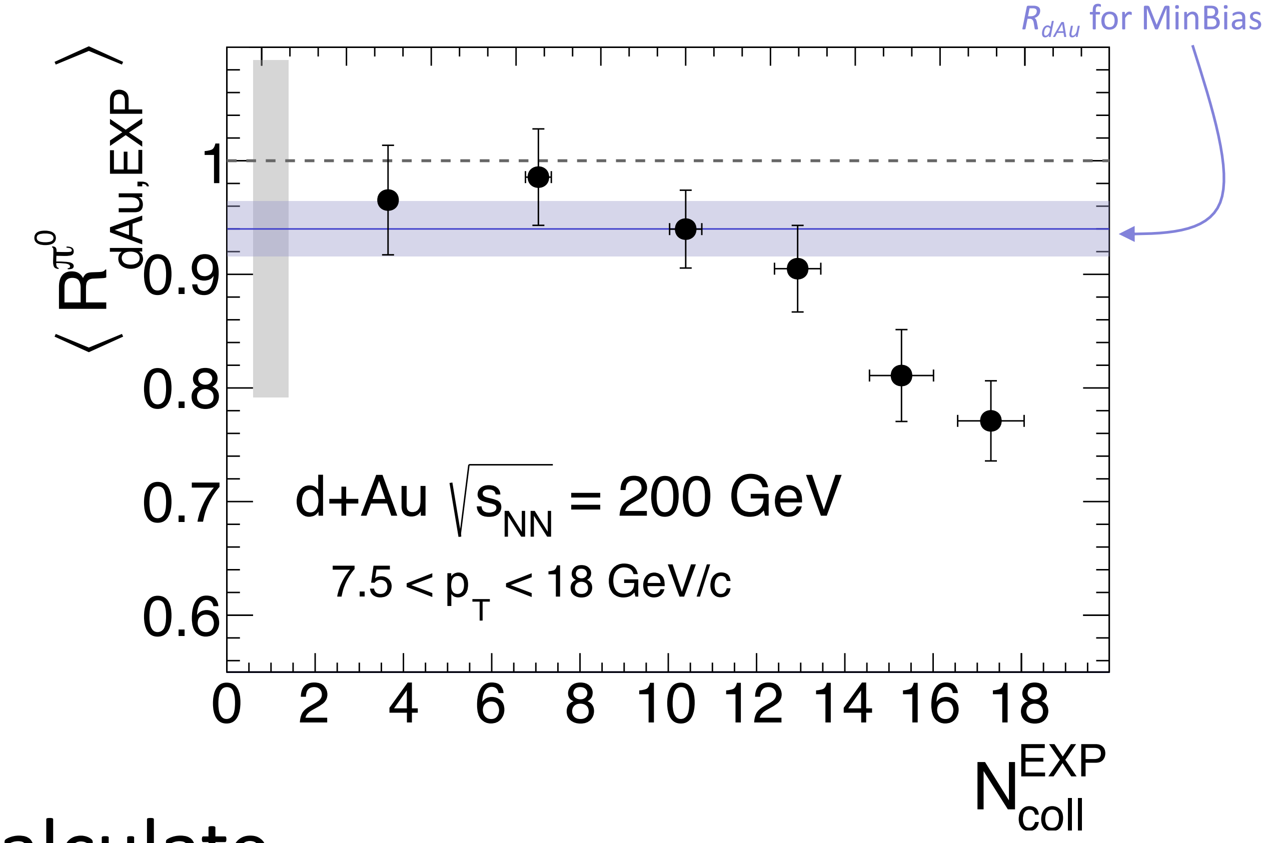


# $N_{Coll}$ from Direct Photons (4/4)

http://arxiv.org/abs/2303.12899

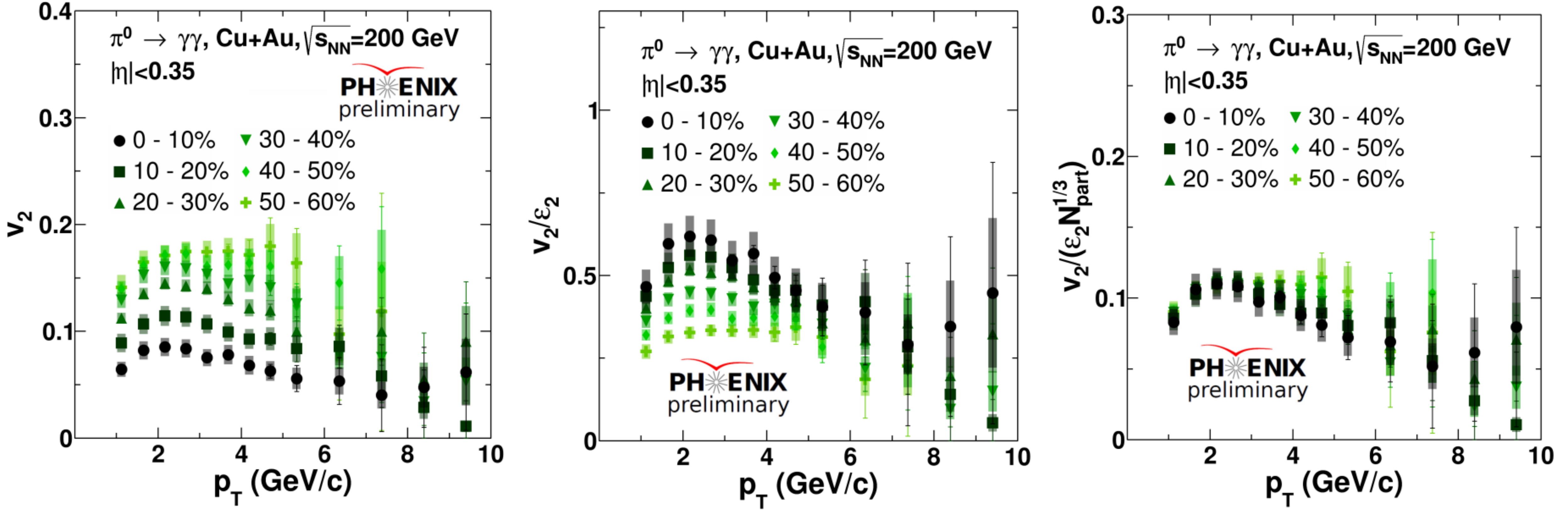
$p_T$-integrated $R_{dAu}$ vs $N_{coll}^{EXP}$

- Scale uncertainty common to all points
    - ≈ 20% suppression for most central events




- Overall: Using direct-photons to calculate $N_{coll}$ is consistent with past measurement (PRC 105, 064902, Fig. 9)

# $v_2, v_2/\varepsilon_2, v_2/\varepsilon_2 N_{part}^{1/3}$ (Cu + Au)

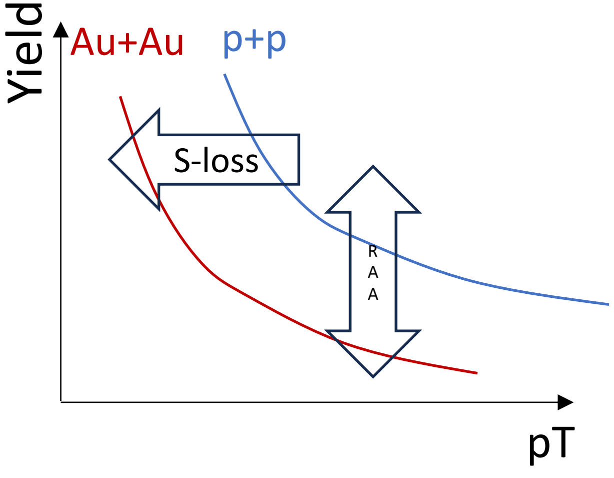



$v_2$ measurement at high $p_T$; scales with eccentricity ($\varepsilon$), "linear" system size ($N_{part}$): $\varepsilon_2 \times N_{part}^{1/3}$

Consistent with prior *Au* + *Au* result ($v_2$: PRC 88,064910; $\varepsilon_2$, $N_{part}$: PRC 94, 054910)

# $S_{loss}$ for charged hadrons vs $\pi^0$ (*Au + Au*) (1/3)

Hadron fractional momentum loss ("Left-shift" as opposed to "down-shift")

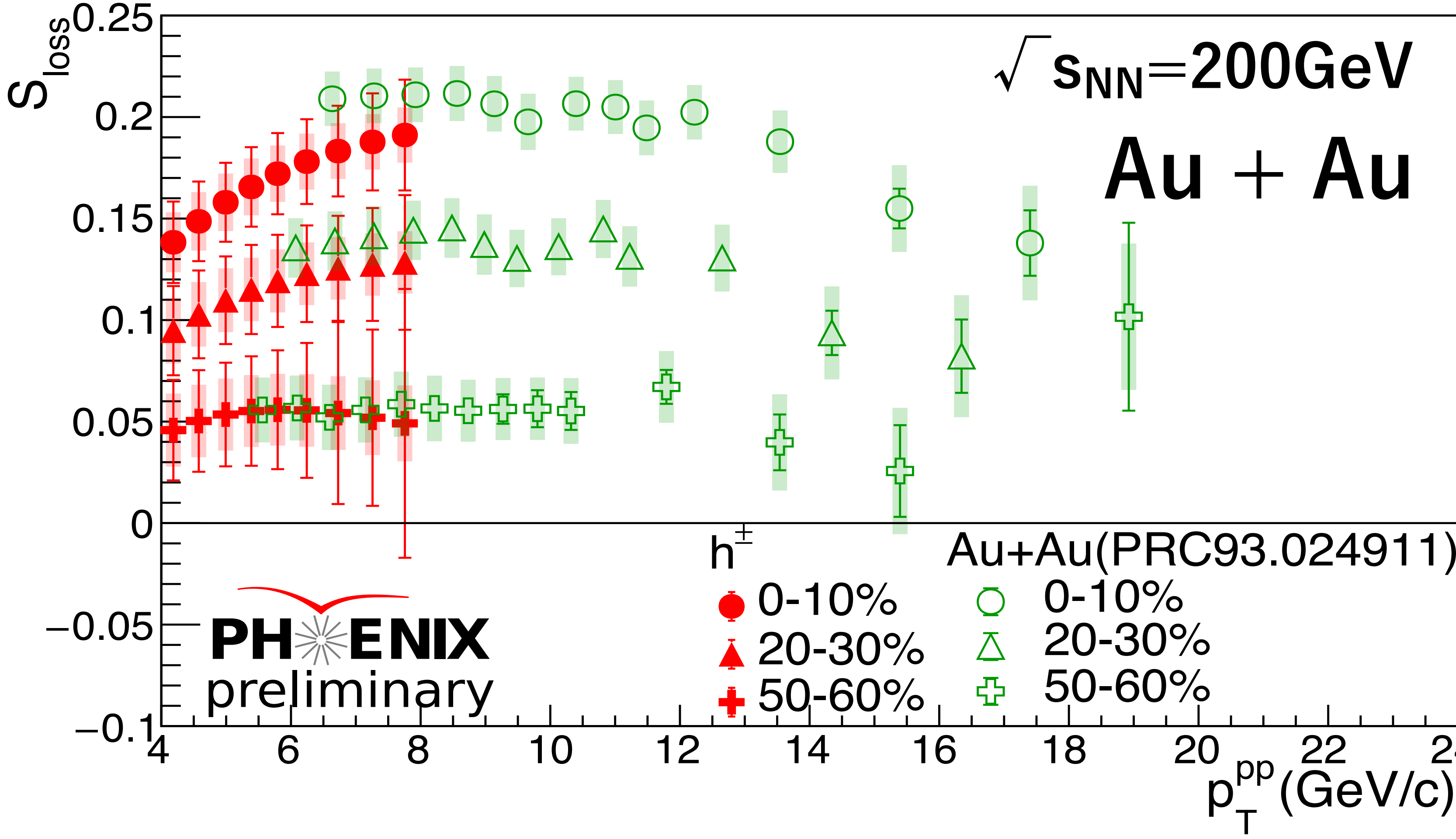



$$S_{loss} = \frac{p_T^{p+p} - p_T^{Au+Au}}{p_T^{p+p}}$$

**Red**: Charged hadron $S_{loss}$

**Green**: $\pi^0$ $S_{loss}$

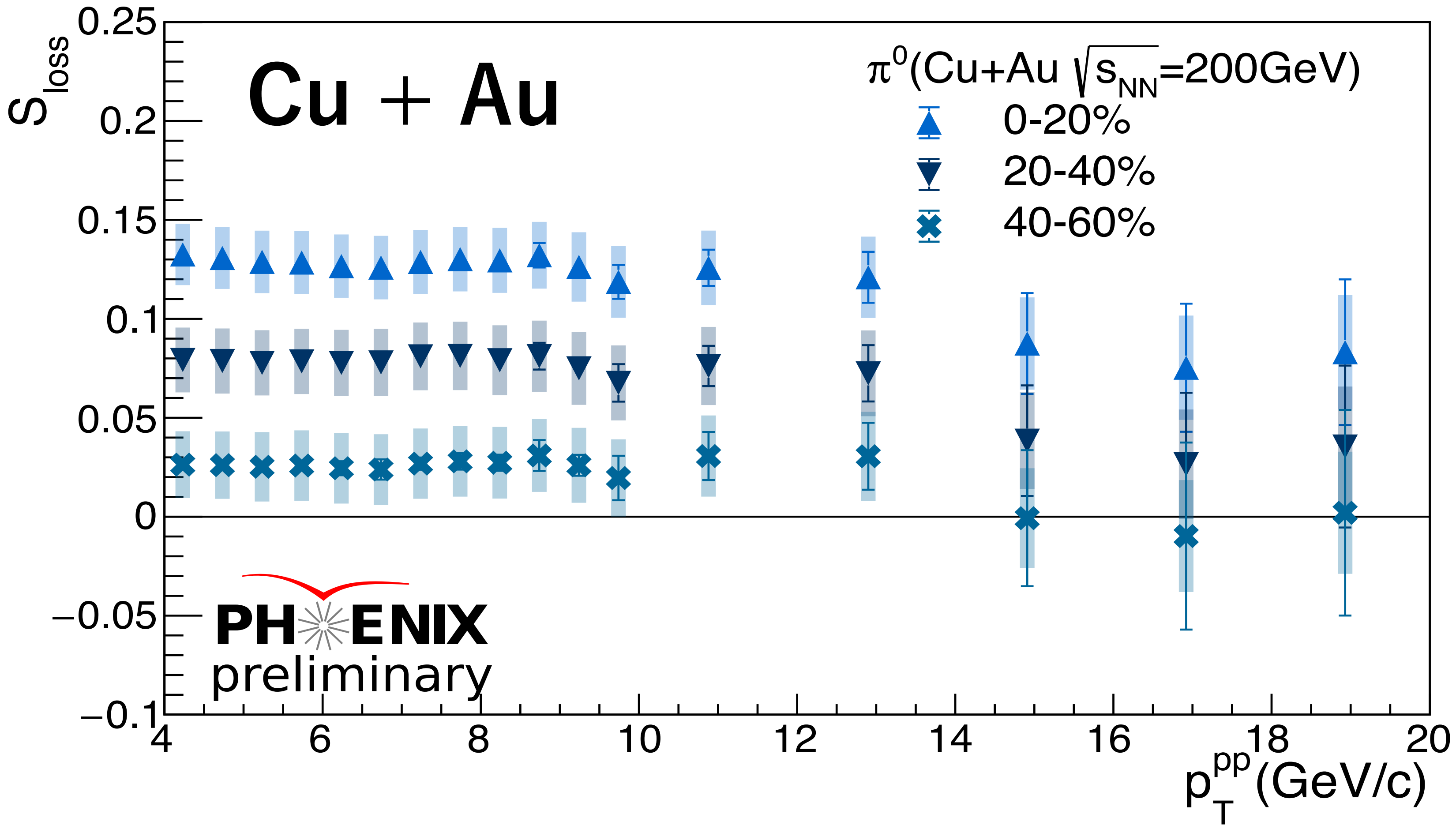
(Plot integrated over all $\varphi$)



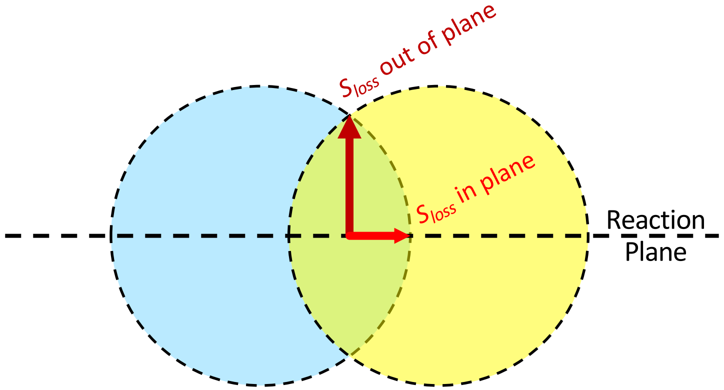
# $S_{loss}$ for $\pi^0$ ($Cu + Au$) (2/3)

$\pi^0$ fractional momentum loss vs $p_T$
(integrated over all $\varphi$)

$$S_{loss} = \frac{p_T^{p+p} - p_T^{Cu+Au}}{p_T^{p+p}}$$

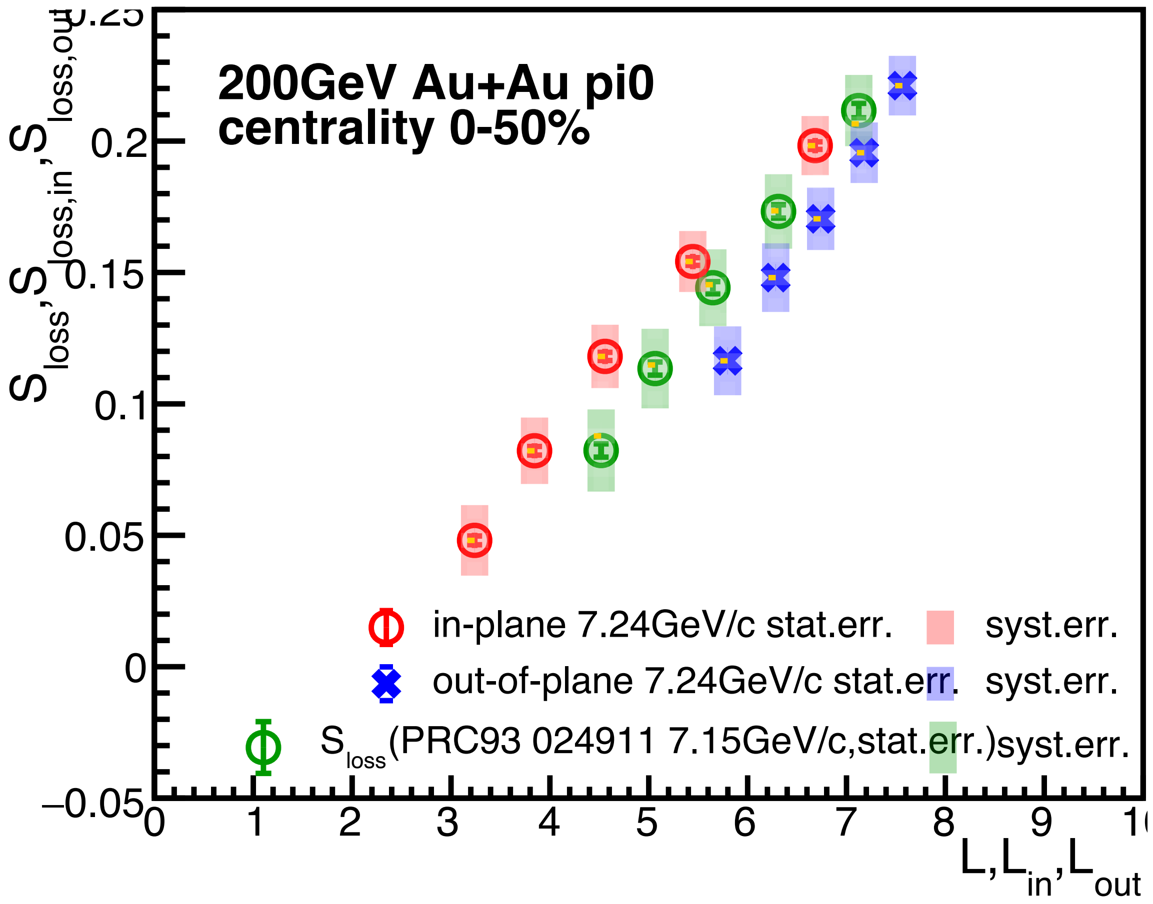


# $S_{loss}$ w.r.t. azimuth ($Cu + Au$) (3/3)




$S_{loss}$ vs. path-length

Can see two clear trends for in- and out-of-plane $S_{loss}$




$4 \leq p_T \leq 10$ GeV/c

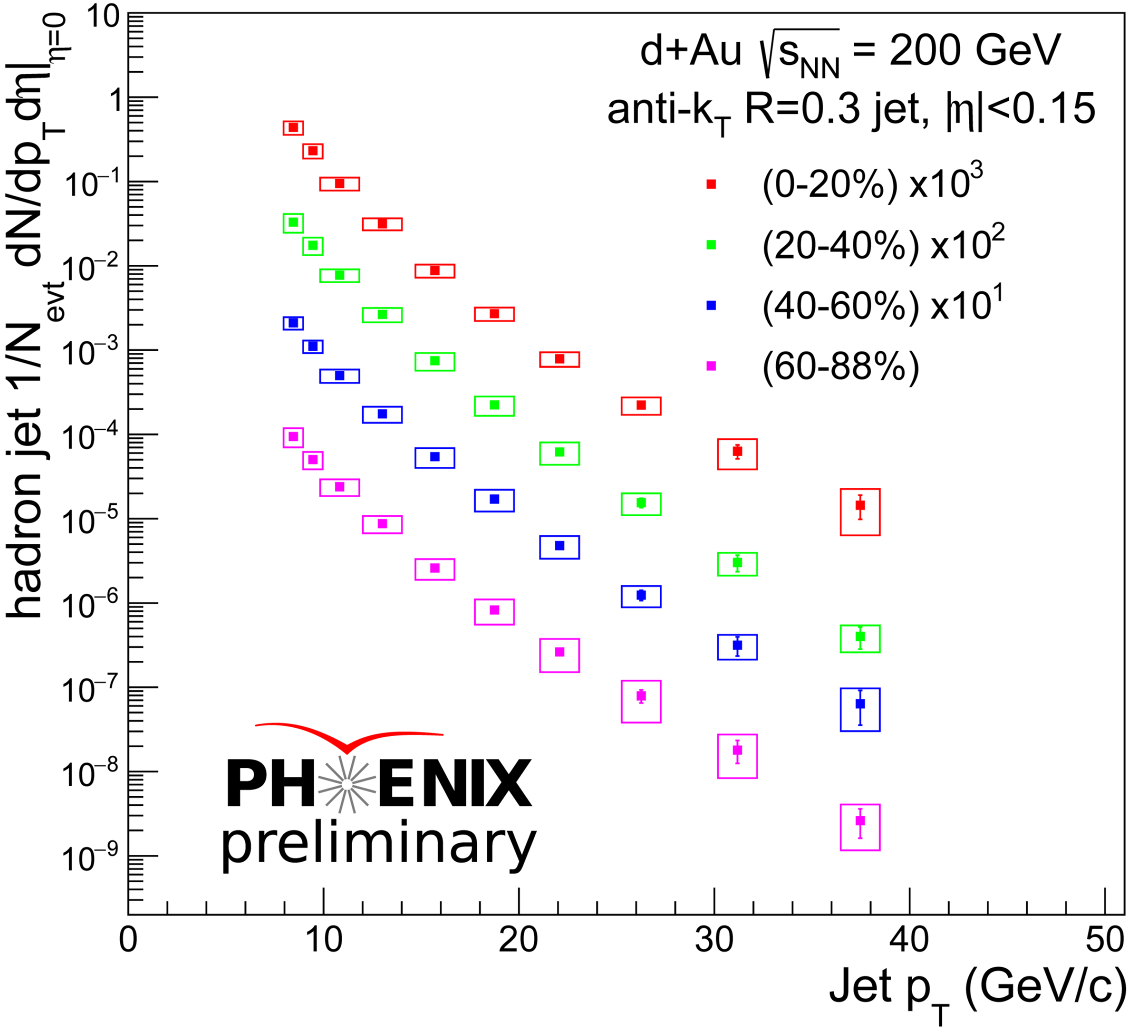
*Jets*

# Jet Yield vs. Centrality (*d + Au*)

*Jet Yield vs Centrality*

very consistent across centrality classes

also consistent with recent p + Au results

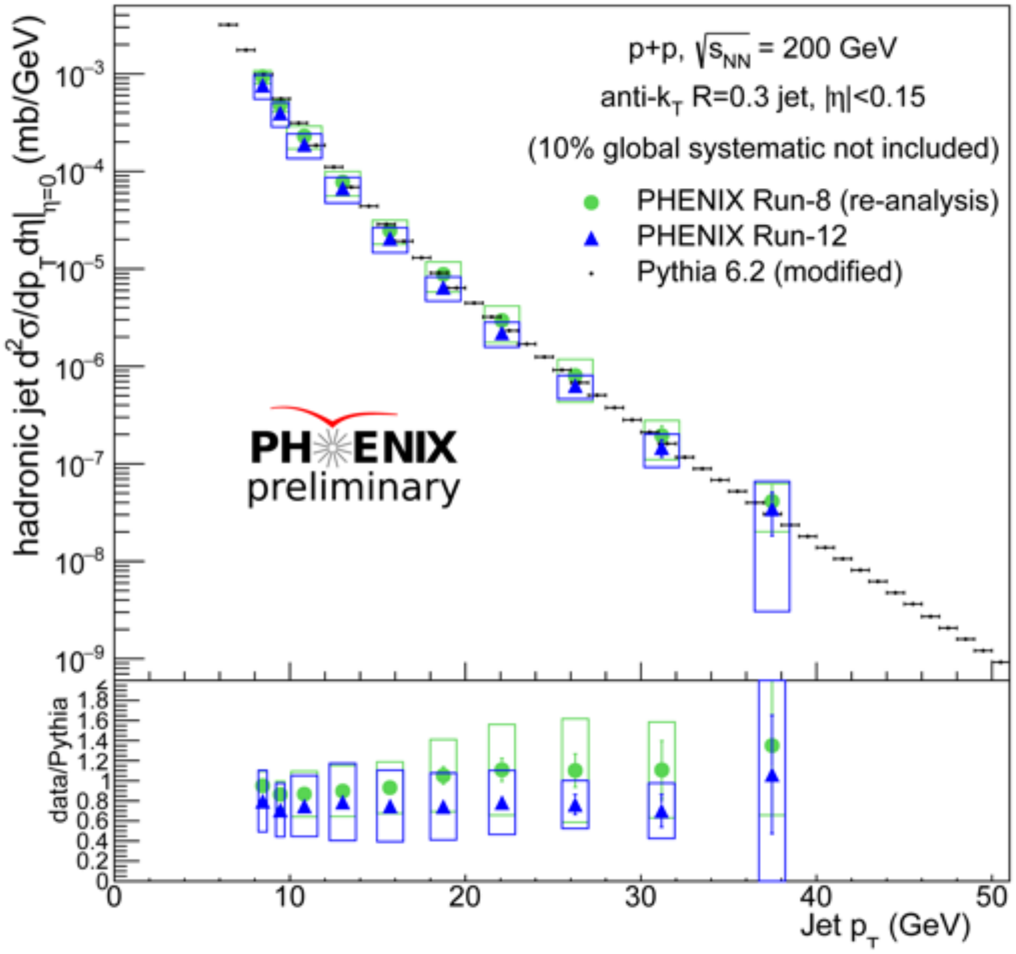


# PHENIX Jet cross-section, structure ($p + p$) (1/5)

Purpose: p + p baseline

Additional: modify simulation to better follow the data

- Found that Pythia prefers more charged particles in its jets than are present in data
  - Can affect unfolding for structure quantities & uncertainty
- Method:
  1. Find ratio of data/unmodified-Pythia for the distribution of charged particles w.r.t. the jet axis
  2. Randomly remove constituent particles from the jets (charged and neutral) according to that distribution
  3. Re-scale for the lost momentum
- Plot: cross-section unfolding with corrected/tuned simulation

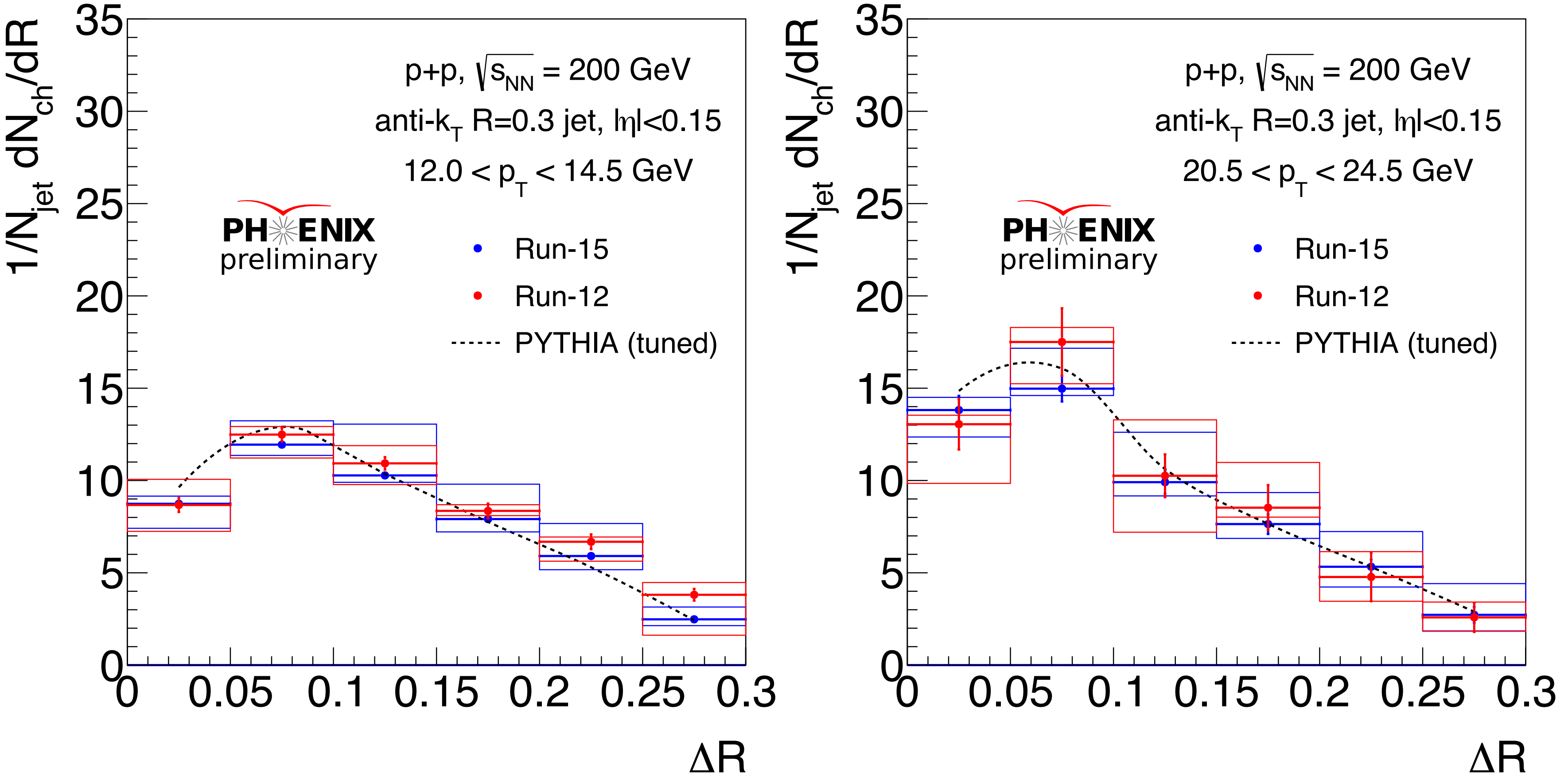


# Jet cross-section, structure ($p+p$) (2/5)

Distribution of particles w.r.t. the jet axis:

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

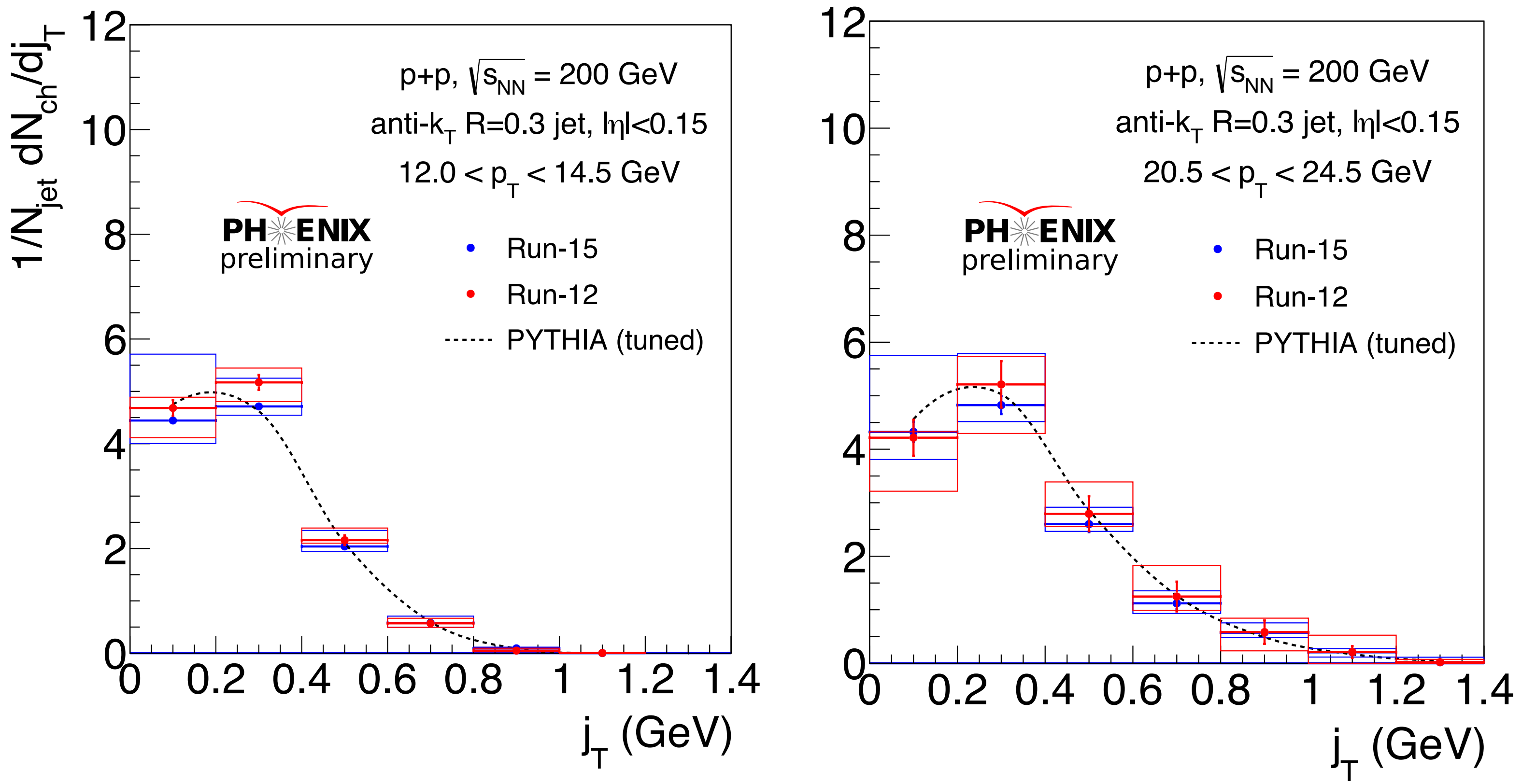
This is the variable used to modify the Pythia-generated prior.



# Jet cross-section, structure ($p + p$) (3/5)

$$j_T = \frac{|\vec{p}_{\rm jet} \times \vec{p}_{\rm track}|}{|\vec{p}_{\rm jet}|}$$

Distribution of charged particle transverse momentum w.r.t. the jet axis (transverse fragmentation)

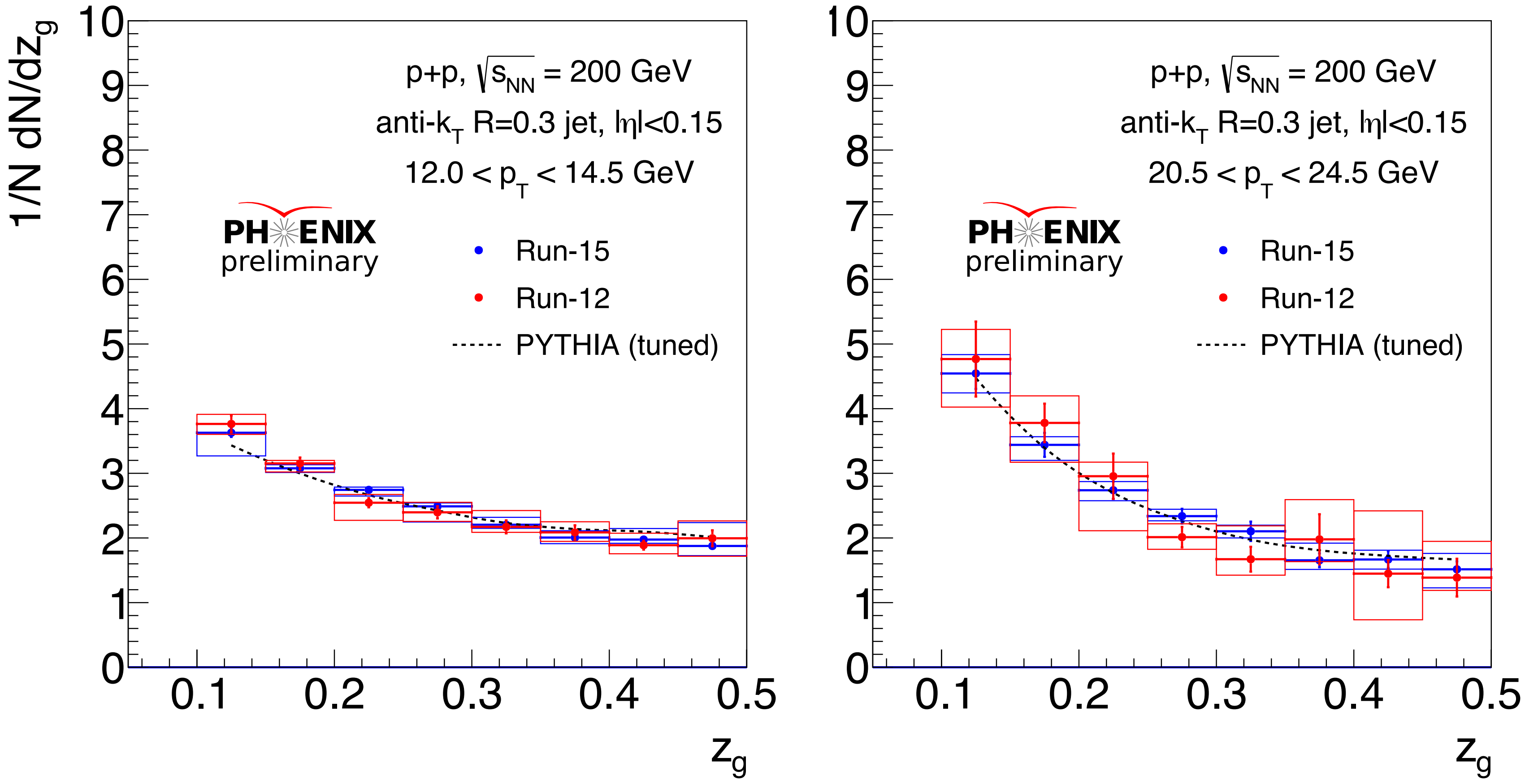


# Jet cross-section, structure ($p + p$) (4/5)

Momentum sharing fraction: direct probe of QCD splitting functions

$$z_g = \frac{\min(p_{T_1}, p_{T_2})}{p_{T_1} + p_{T_2}}$$

(Calculated for all constituent particles, not just charged)

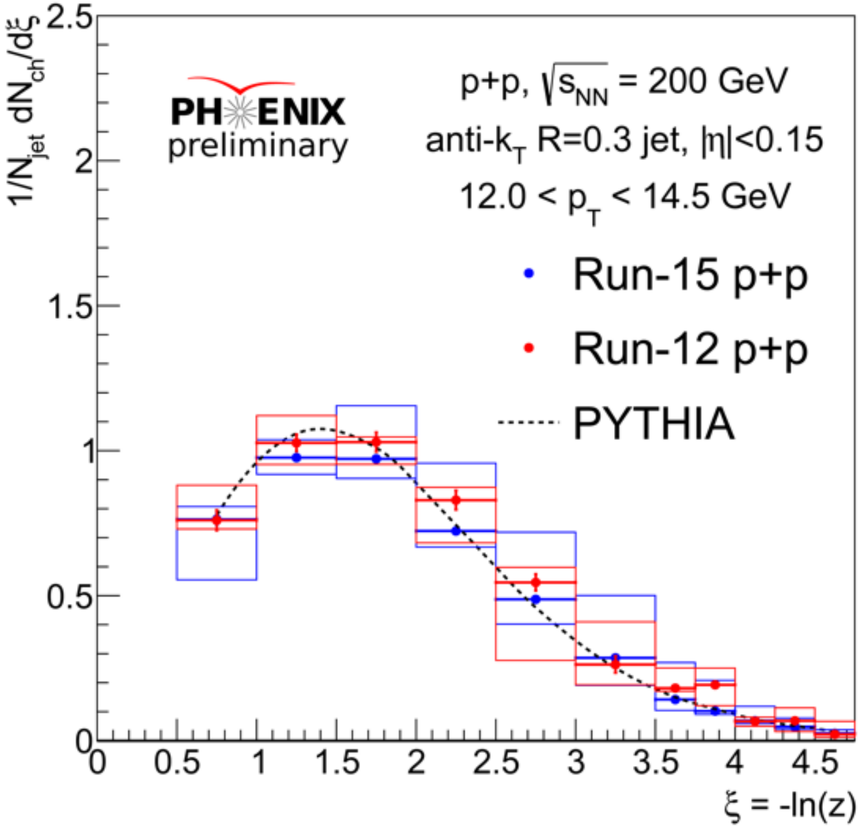


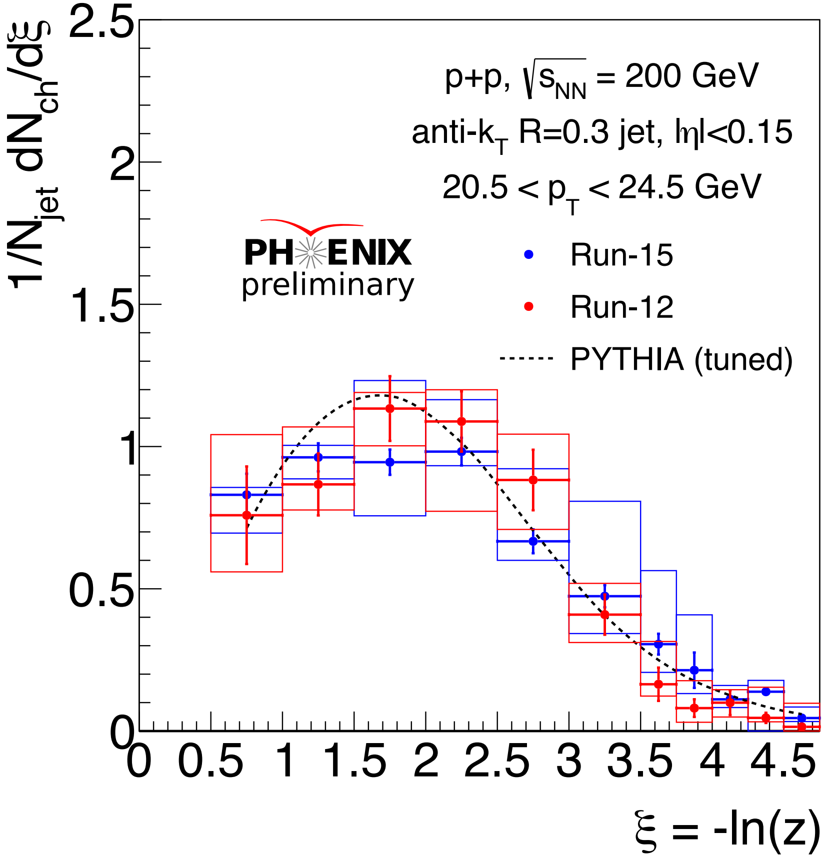
# Jet cross-section, structure ($p + p$) (5/5)

…

Fraction of jet momentum carried by charged particle (fragmentation function):

$$\xi = -\ln z$$
$$= -\ln\left(\frac{\vec{p}\cdot\overrightarrow{p_{jet}}}{p\,p_{jet}}\right)$$

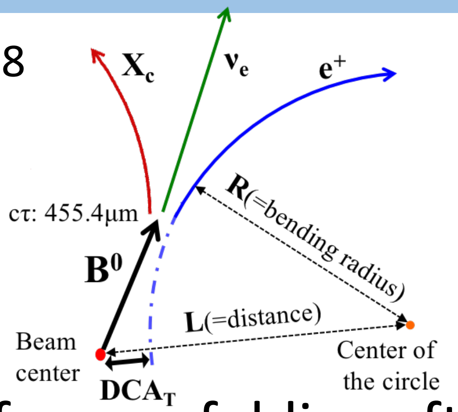


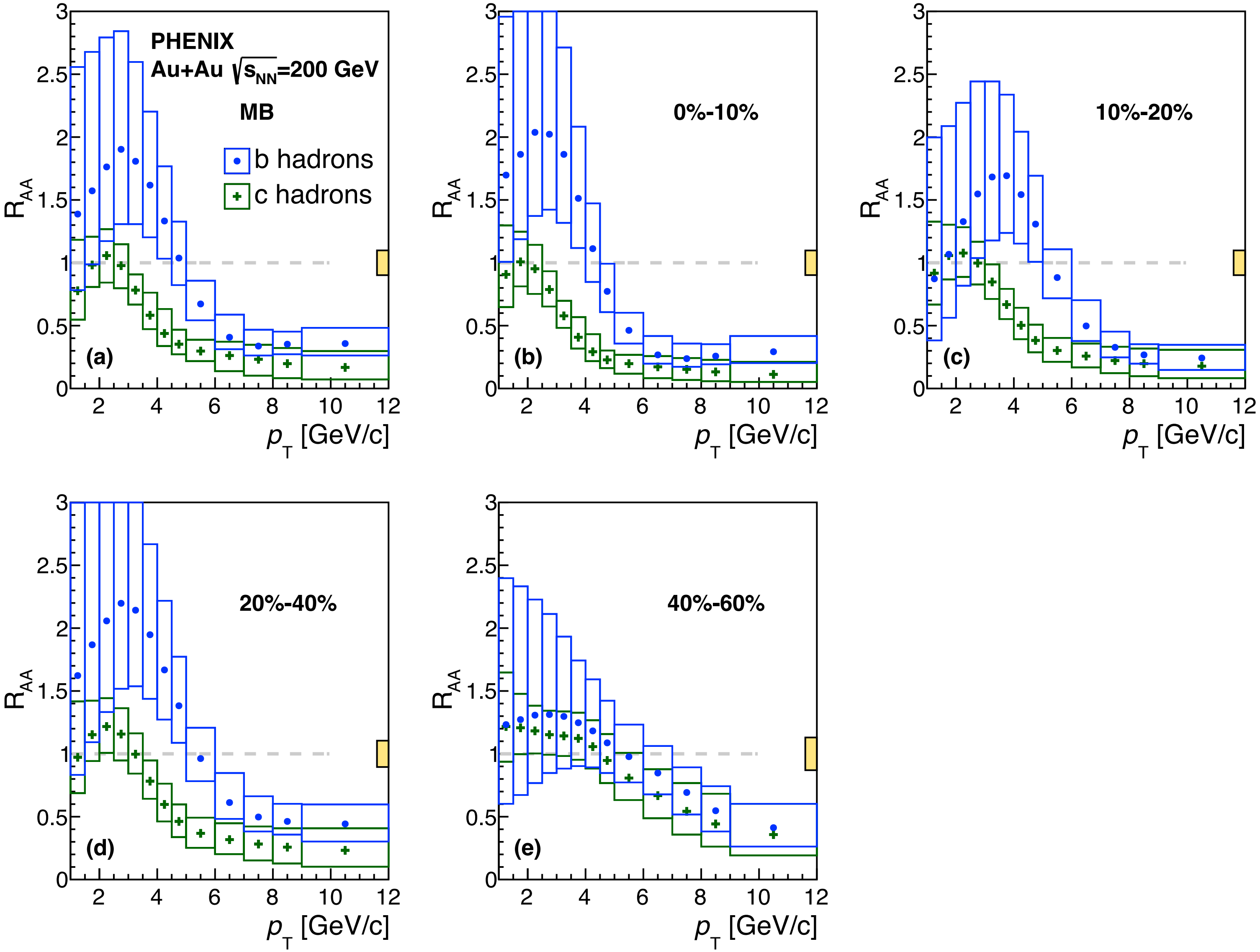
# *Heavy Flavor*

# Heavy-flavor $R_{AuAu}$ ($Au + Au$) (1/2)

arxiv:2203.17058




- Results from unfolding after removing all non-HF electrons/positrons (consistent with STAR: Eur Phys J C 82:1150, Fig 9b).
- All centralities show suppression of both charm and bottom at pT > 5 GeV/c
- Charm is suppressed more strongly

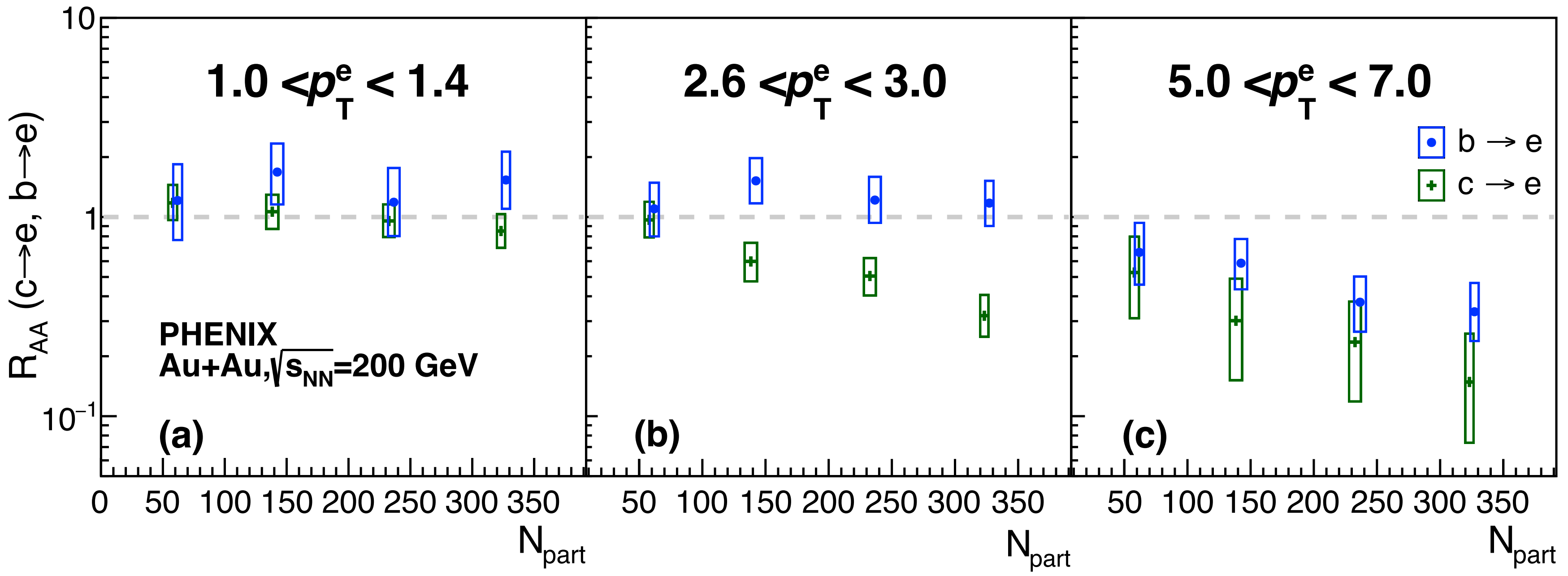


# Heavy-flavor $R_{AuAu}$ ($Au + Au$) (2/2)

arxiv:2203.17058

$R_{AuAu}$ ($p_T$ integrated)
vs $N_{part}$

- Charm $p_T$ dependence
  - $p_T < 1.4$ GeV/c: $R_{AuAu} \approx 1$
  - $2.6 < p_T < 3$ GeV/c: charm suppressed
  - $p_T > 5$ GeV/c: both suppressed
- Mass-ordering
  - charm loses more energy in the QGP



# Summary (the end)

**PHENIX Jet/HF/high-pT physics remain a vibrant area of data analysis!**

High-pT

*p+p @ 510 GeV cross-section and $p_T$ < 12 GeV/c underestimation by theory*

*p+p $A_{LL}$ consistent with positive spin-contribution from gluons*

*New way to measure $N_{coll}$ with midrapidity direct photons*

*Decay-product species' azimuth-integrated $S_{loss}$ consistent in Au + Au*

*Cu + Au azimuth-integrated $S_{loss}$ vs $p_T$ behaves like Au + Au*

*In-plane/Out-of-plane $S_{loss}$ shows clear difference w.r.t. path length*

Jets

*Tuning Pythia to fit data using that program's excess of charged particles in jets*

*p + p baseline for jet structure quantities*

Heavy Flavor

*Au + Au charm- and beauty-derived $R_{AuAu}$*

*$R_{AuAu}$ vs $N_{part}$ shows mass-ordering in QGP interactions*

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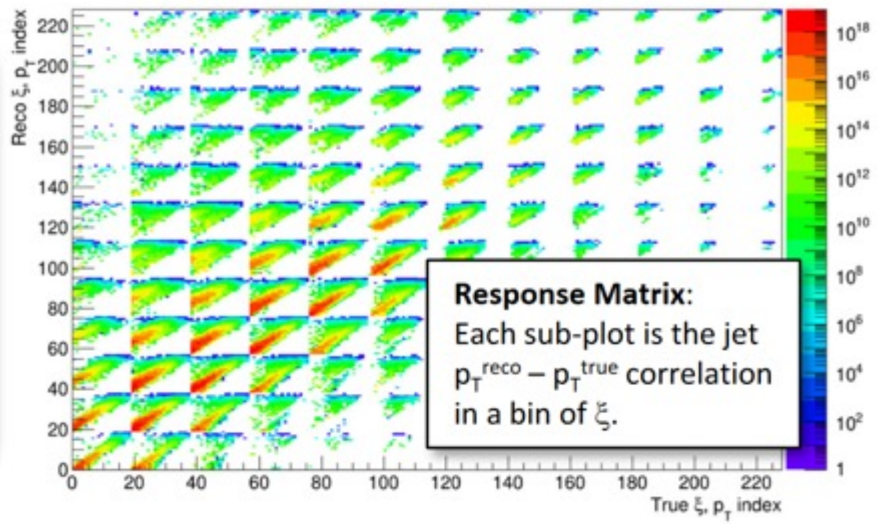
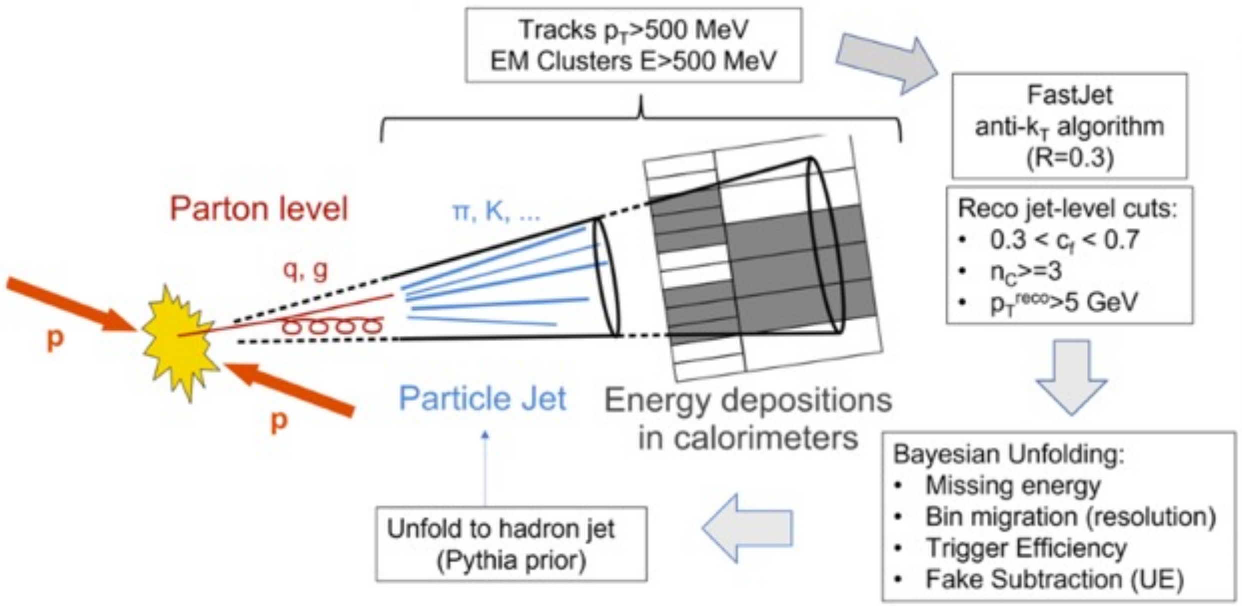
# Index

*Backup Slides*

# Jet reconstruction

- Clusters and tracks are combined using an anti-$k_T$ algorithm
  - Get R = 0.3 jets
- Make cuts
- Unfolding to account for detector effects (see diagram)




- For sub-structure, unfolding is done between jet-$p_T$ and a particular sub-structure quantity
- **Pythia prior probability used to match the mean number of charged particles in jet vs $p_T$**
  - **Tuned iteratively**