Measurement of medium-induced modification of γ_{dir}+jet and π^0+jet yield and acoplanarity in p+p and central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV by STAR

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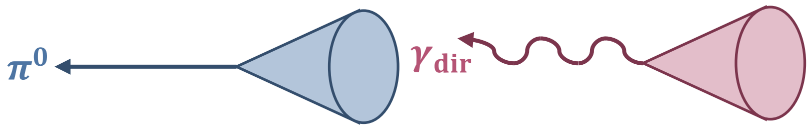
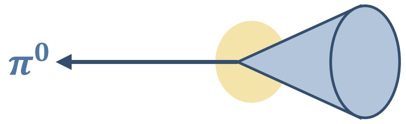
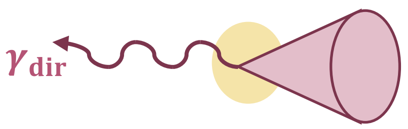
U.S. DEPARTMENT OF ENERGY | Office of Science

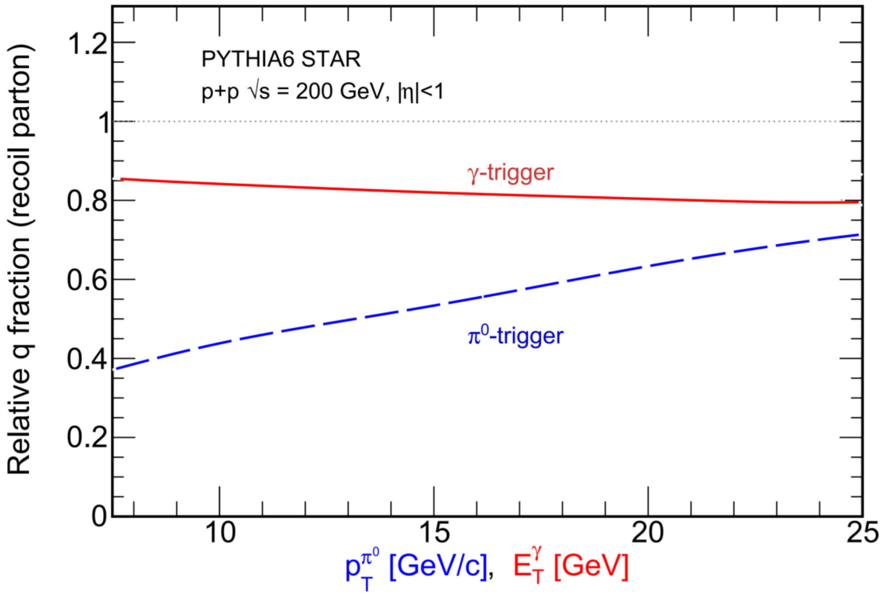
Derek Anderson
Texas A&M University
For the STAR Collaboration

$\gamma_{\mathrm{dir}}/\pi^0$+jet as probes of the QGP

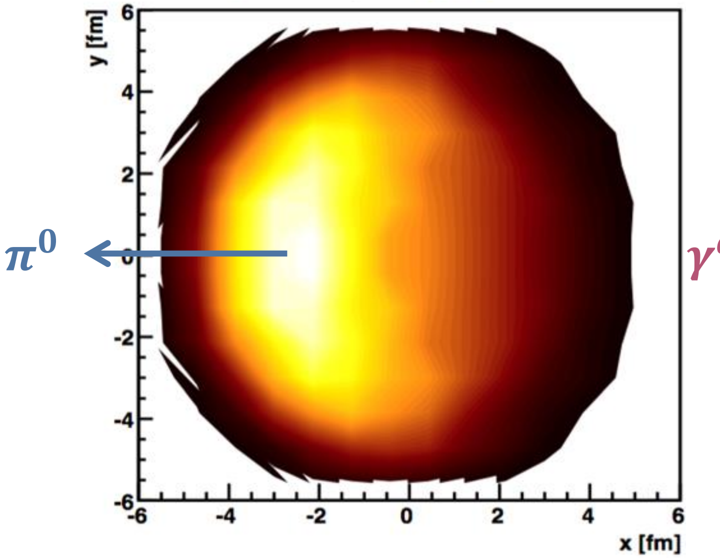




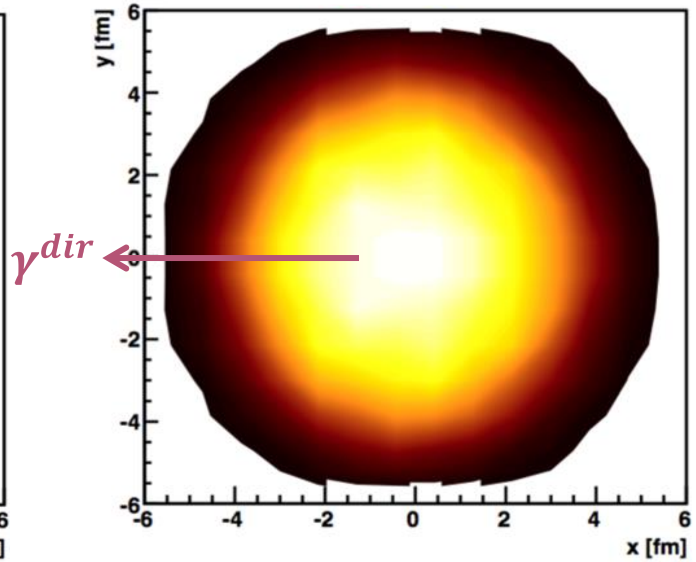




Hadron Trigger



γ_{dir} Trigger

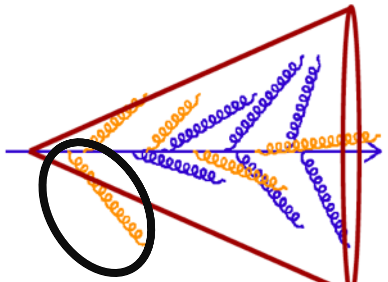


Adapted from
Renk, PRC **88**, 054902 (2013)

- Jets coincident with direct photons (**γ_{dir}**) are valuable probe to study in-medium modification **(jet quenching)**
  - γ_{dir} constrains kinematics of recoil jet
- Comparing $\gamma_{\mathrm{dir}}/\pi^0$ triggers:
  - ☞ **Different q/g fractions**
  - ☞ **Different recoil path length distributions**

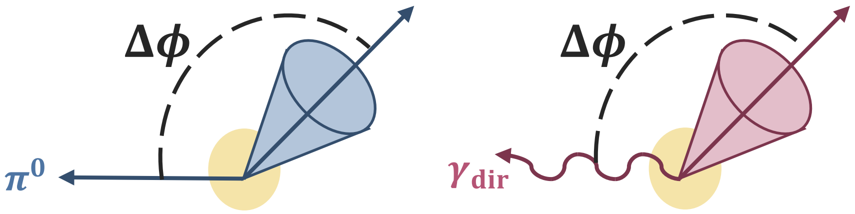
$\gamma_{\mathrm{dir}}/\pi^0$+jet as probes of the QGP

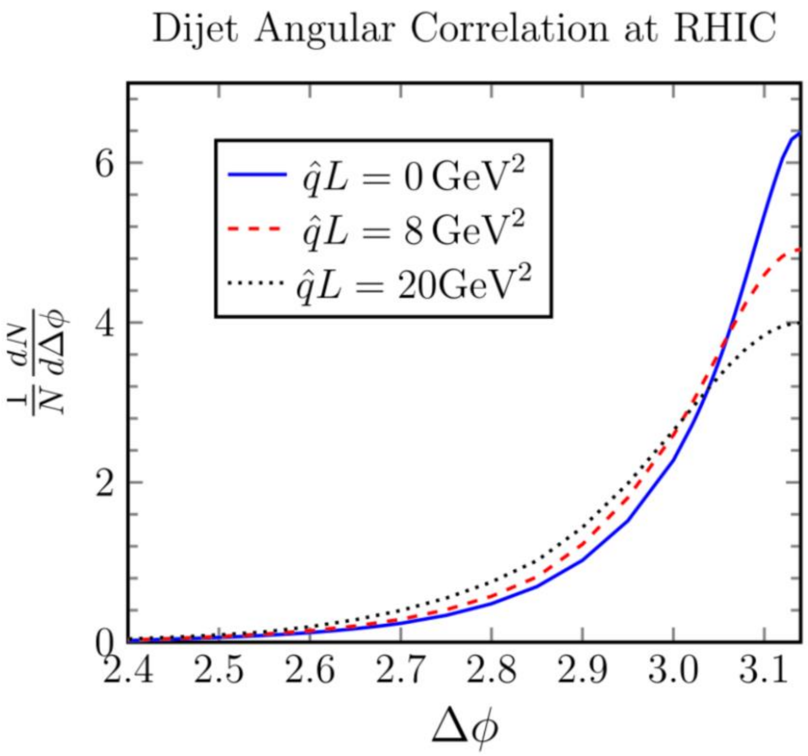
- **Medium-induced energy loss**
  - ⇒ Energy transported outside jet cone



- **Acoplanarity:** recoil jet deflected from $\gamma_{\mathrm{dir}}/\pi^0$ axis
  - ∵ Vacuum Sudakov radiation
  - ∵ **Medium effects:**
    - a) Scattering off QGP quasi-particles
    - b) Multiple soft scatters in medium

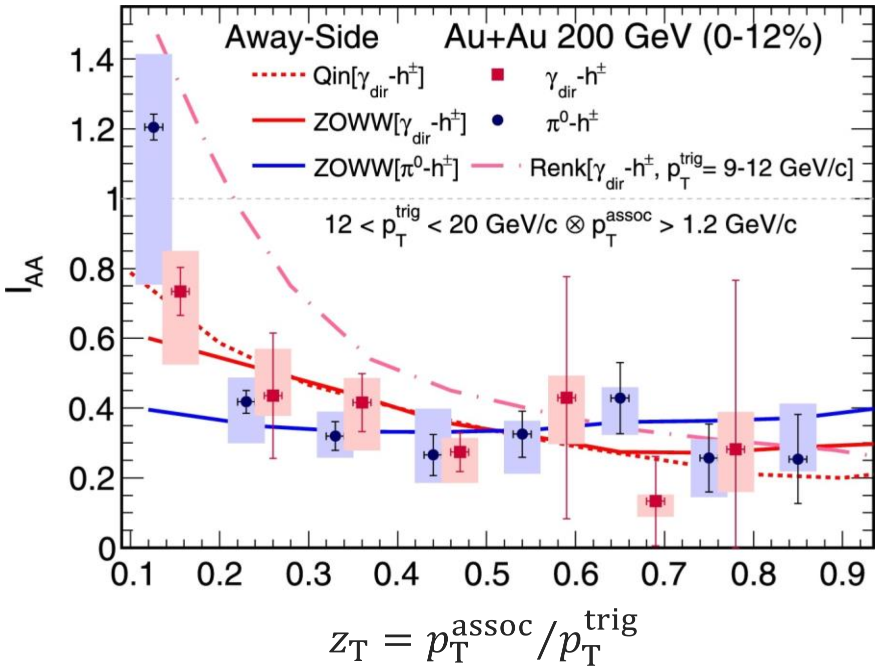
∴ **Measurement of jet acoplanarity probes micro-structure of QGP**





Mueller et al, PLB **763**, 208 (2016)

STAR γ_{dir}+$h^{\pm}$ and semi-inclusive $h^{\pm}$+jet measurements



STAR, PLB **760**, 689 (2016)

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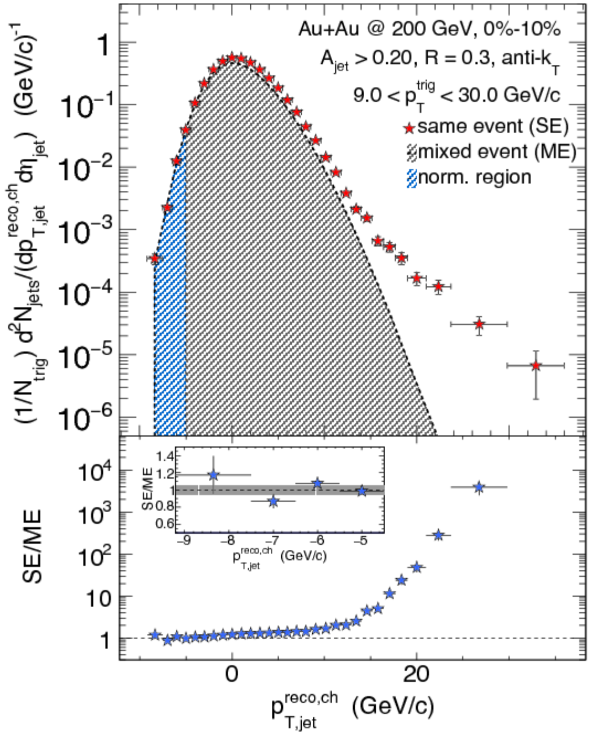


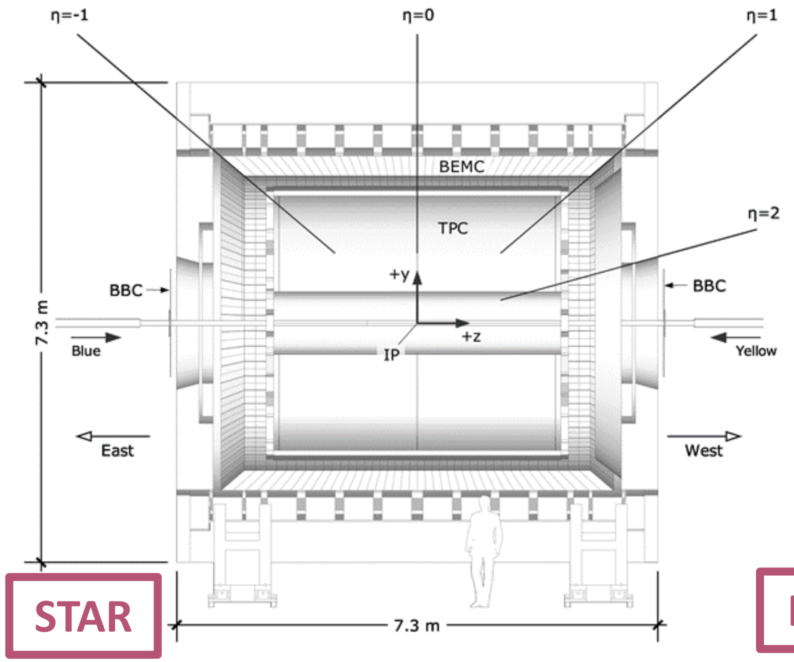
STAR, PRC **96**, 024905 (2017)

- STAR identified $\gamma_{\mathrm{dir}}/\pi^0$ to measure quenching of correlated $h^{\pm}$
  - ☞ **Did not reconstruct jets**
  - ☞ $\gamma_{\mathrm{dir}}/\pi^0$ axis provides reference for broadening
- STAR also measured semi-inclusive yields of recoil jets correlated with $h^{\pm}$ triggers to search for medium modification
  - ☞ $\boldsymbol{\gamma_{\mathrm{dir}}}$ **triggers were not used**

Here we combine the two approaches to measure semi-inclusive charged jets recoiling from $\gamma_{\mathrm{dir}}/\pi^0$ triggers in p+p and Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV

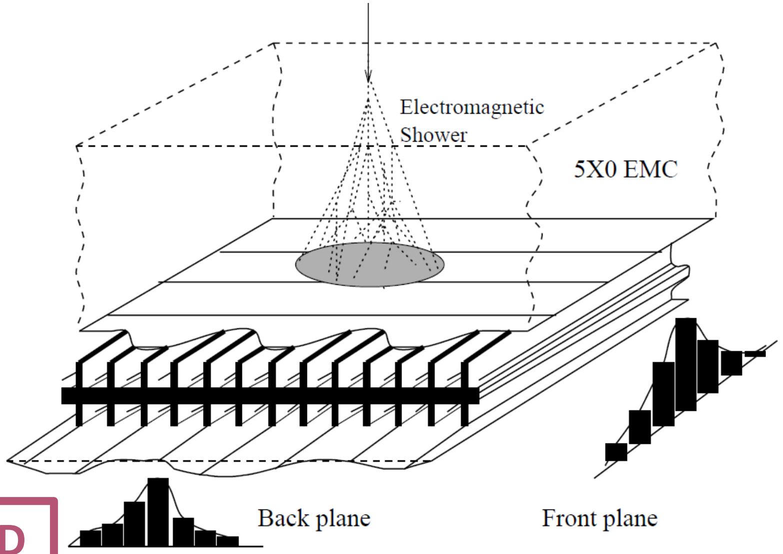
STAR subsystems and datasets

STAR, PRD **86**, 032006 (2012)



STAR

Beddo et al, NIM **A499**, 725 (2003)



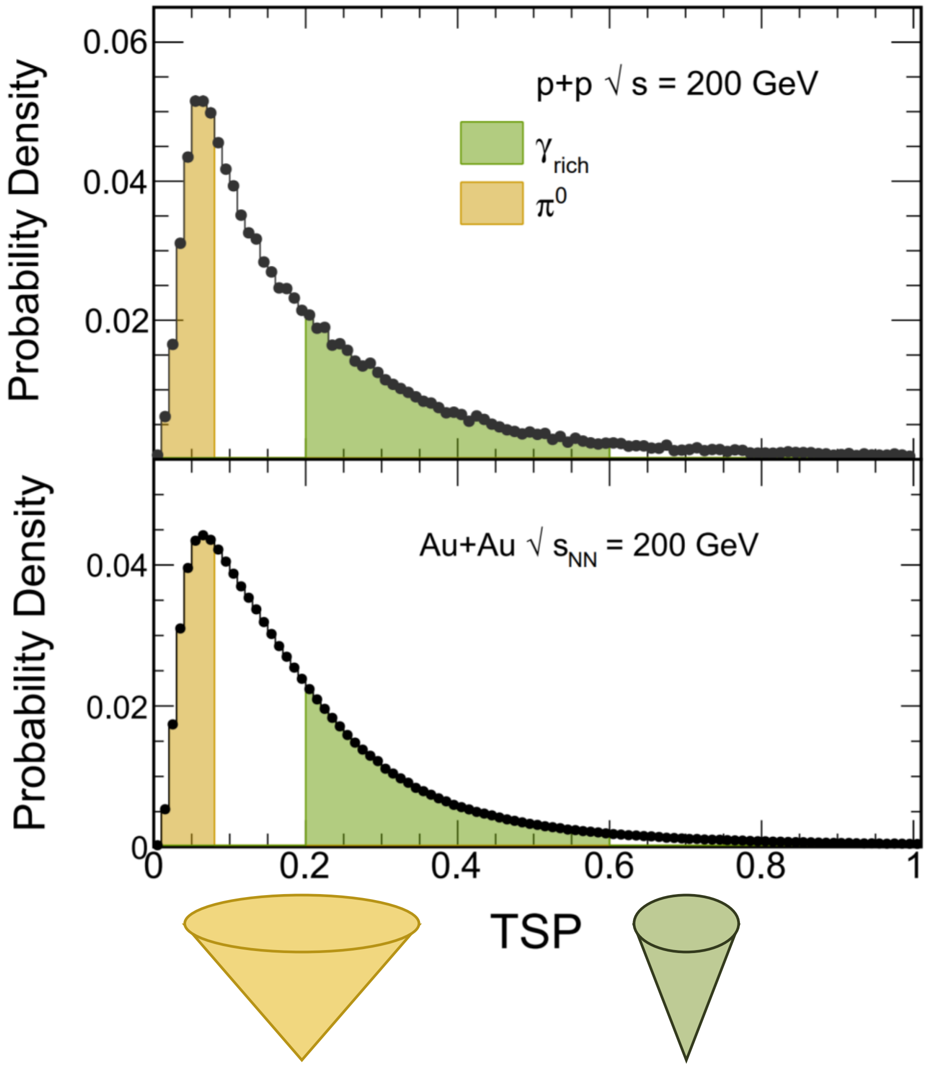
BSMD

In memoriam,
Tom Cormier

- **Time Projection Chamber (TPC)**
  - charged particles ($|\eta| < 1$, full azimuth)
- **Barrel Electromagnetic Calorimeter (BEMC):**
  - trigger on energetic γ_{dir} or π^0
- **Barrel Shower Maximum Detector (BSMD):**
  - discriminates $\gamma_{\text{dir}}/\pi^0$ based on transverse shower profile

- **This analysis**
  - BEMC trigger ($E_{\text{T}}^{\text{tower}} \gtrsim$ 6 GeV)
  - **Au+Au:** 13 nb^{-1} (2014)
  - ***p+p*:** 23 pb^{-1} (2009)

$\gamma_{\text{dir}}/\pi^0$ identification



- Candidate $\pi^0/\gamma_{\text{dir}}$ triggers are clusters made of:
  - **1 or 2 BEMC towers**, and
  - **15 η and 15 ϕ BSMD strips**
- $\pi^0/\gamma_{\text{dir}}$ identified via **Transverse Shower Profile (TSP):**

$$\text{TSP} \equiv \frac{E_{cluster}}{\sum_i e_i r_i^{1.5}}$$

- TSP used to split data into two samples:
  1. 95% pure sample of π^0
  2. Sample with an enhanced fraction of γ_{dir} (γ_{rich})

☞ γ_{rich} background levels (B)
  - 33% ~ 16% **(Au+Au)**
  - 57% ~ 47% $(p+p)$

☞ Measured via near-side $h^{\pm}$ yields

☞ Includes some fragmentation photons

› STAR, PRC **82**, 034909 (2010)

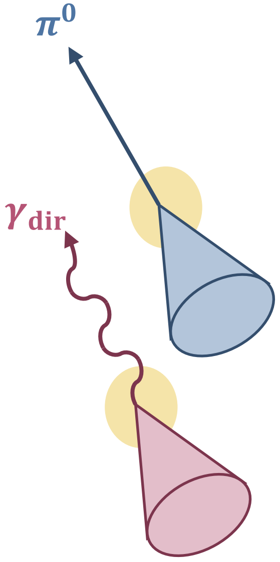
- Decay background in γ_{rich} removed via statistical subtraction

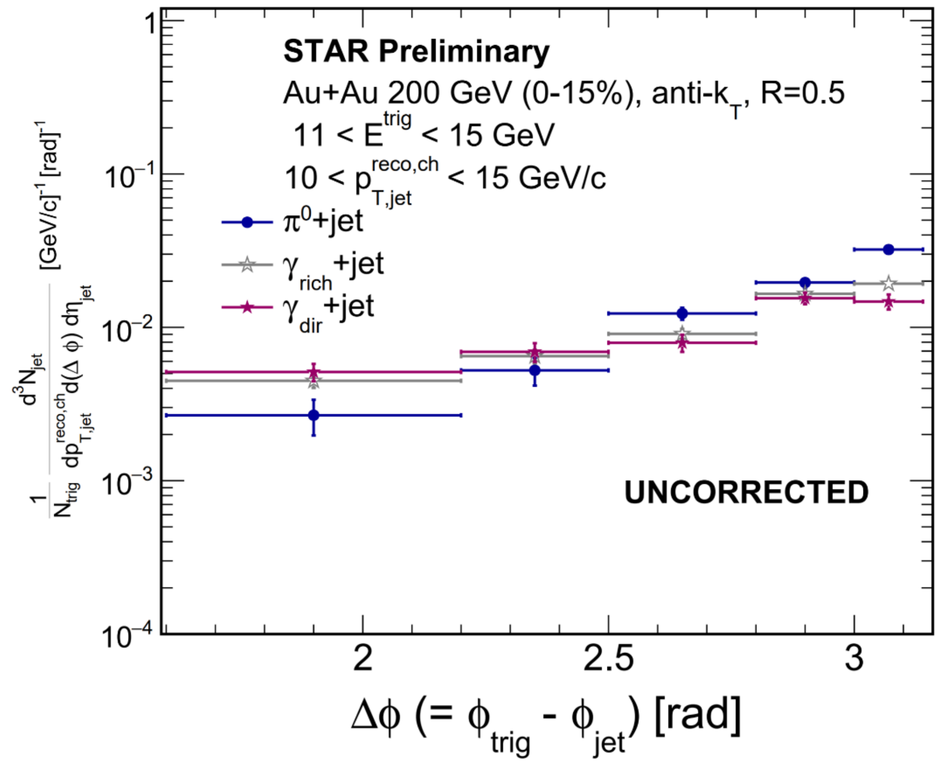
$$Y_{\text{pp}}^{\gamma_{\text{dir}}} = \frac{Y_{\text{pp}}^{\gamma_{\text{rich}}} - B \cdot Y_{\text{pp}}^{\pi^0}}{1 - B}$$

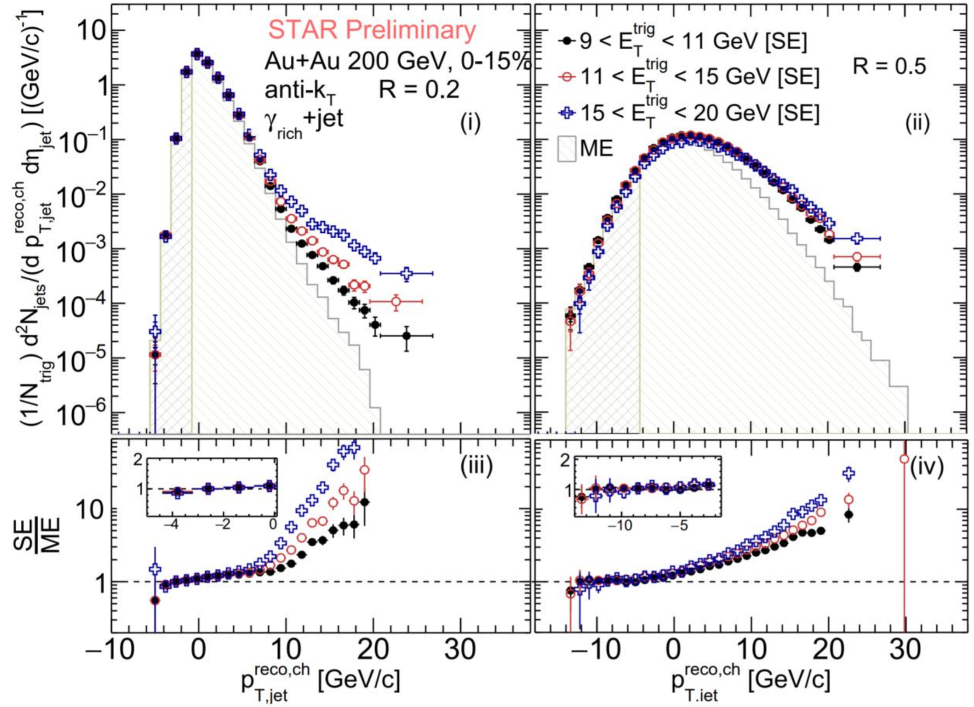
Raw jet distributions

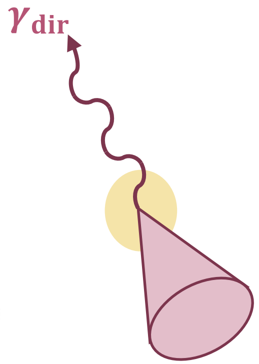
Nihar Sahoo poster [Wed T04_1]

$\Delta\phi \in (3\pi/4\,, 5\pi/4)$







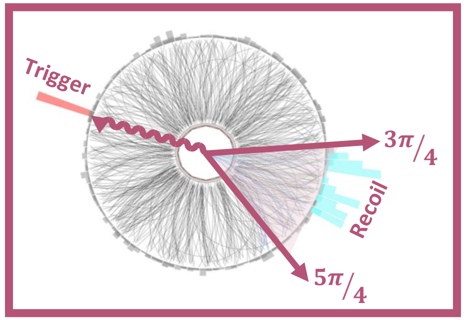


- Jets reconstructed by clustering TPC tracks
  - anti-k_T ($R = 0.2, 0.5$)
    - › Cacciari et al, JHEP **04**, 063 (2008)
  - $|\eta_{jet}| < 1 - R$

- **Trigger-jet azimuthal separation:**

$$\Delta\phi = \phi_{\text{trig}} - \phi_{\text{recoil jet}}$$

- Measured projections of 2D distribution in $(\Delta\phi, p_{\text{T,jet}})$



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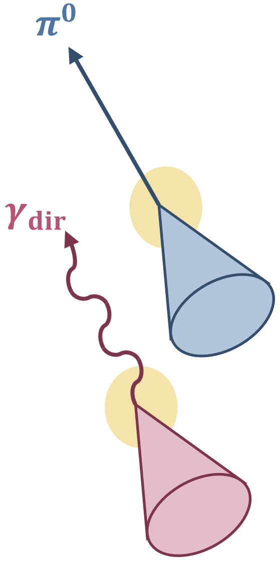

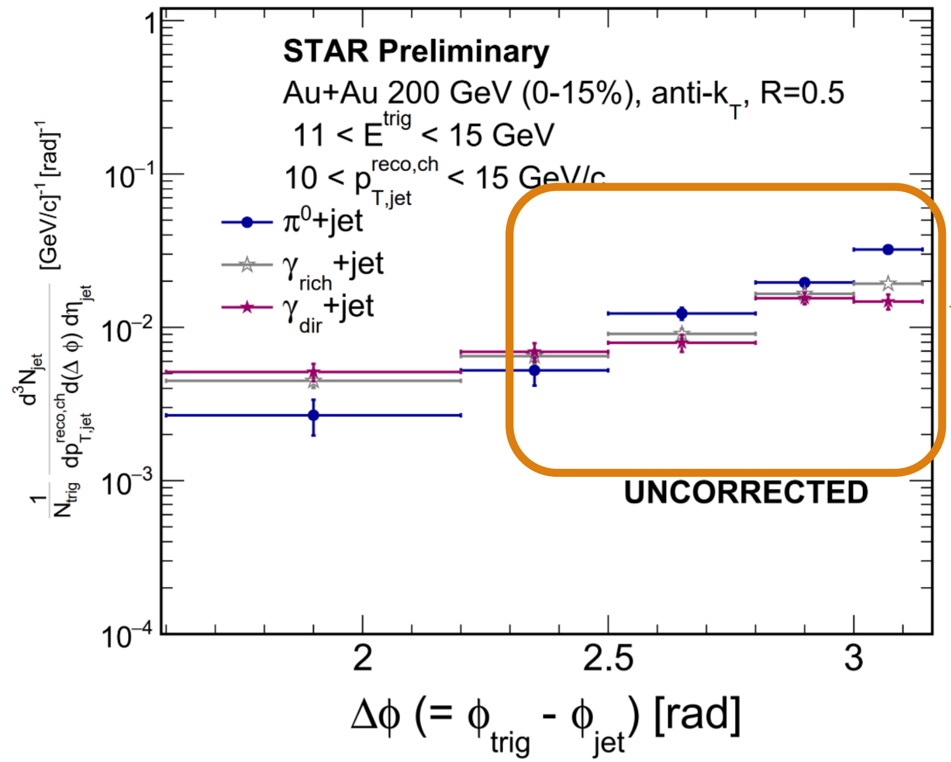

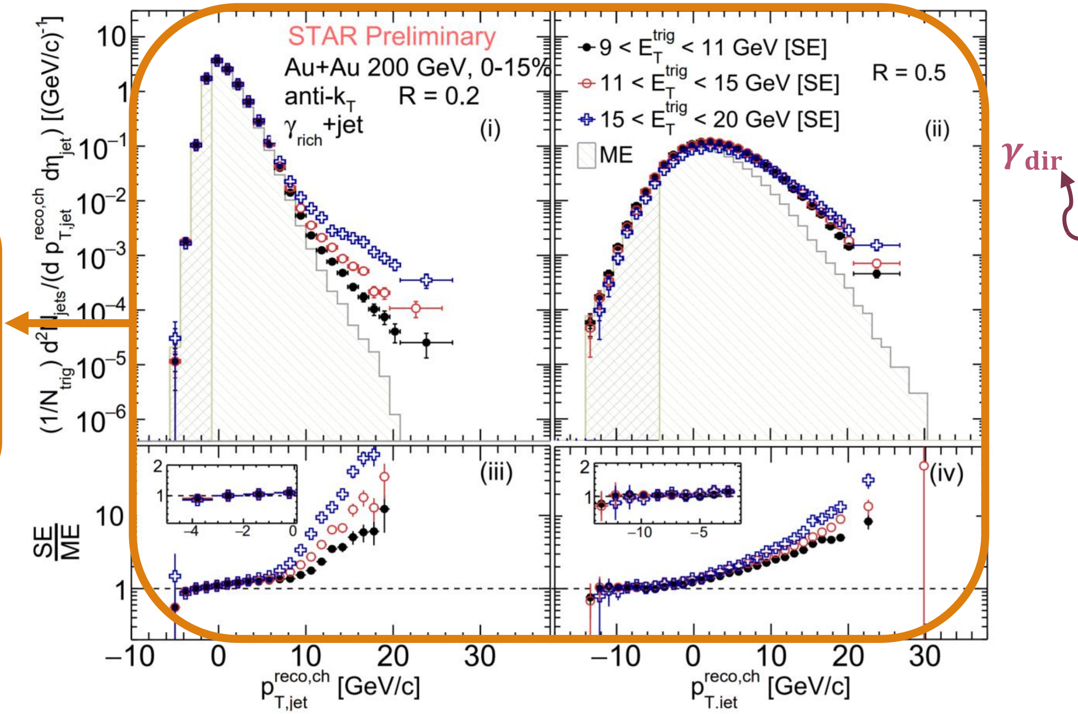

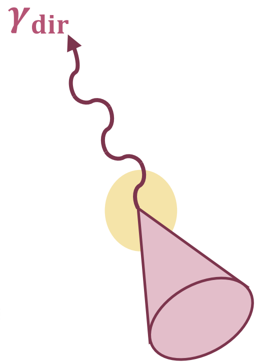

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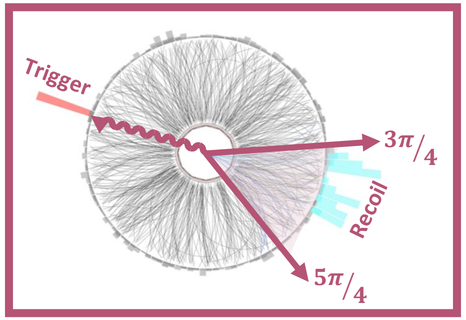
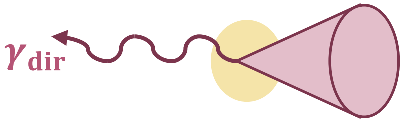


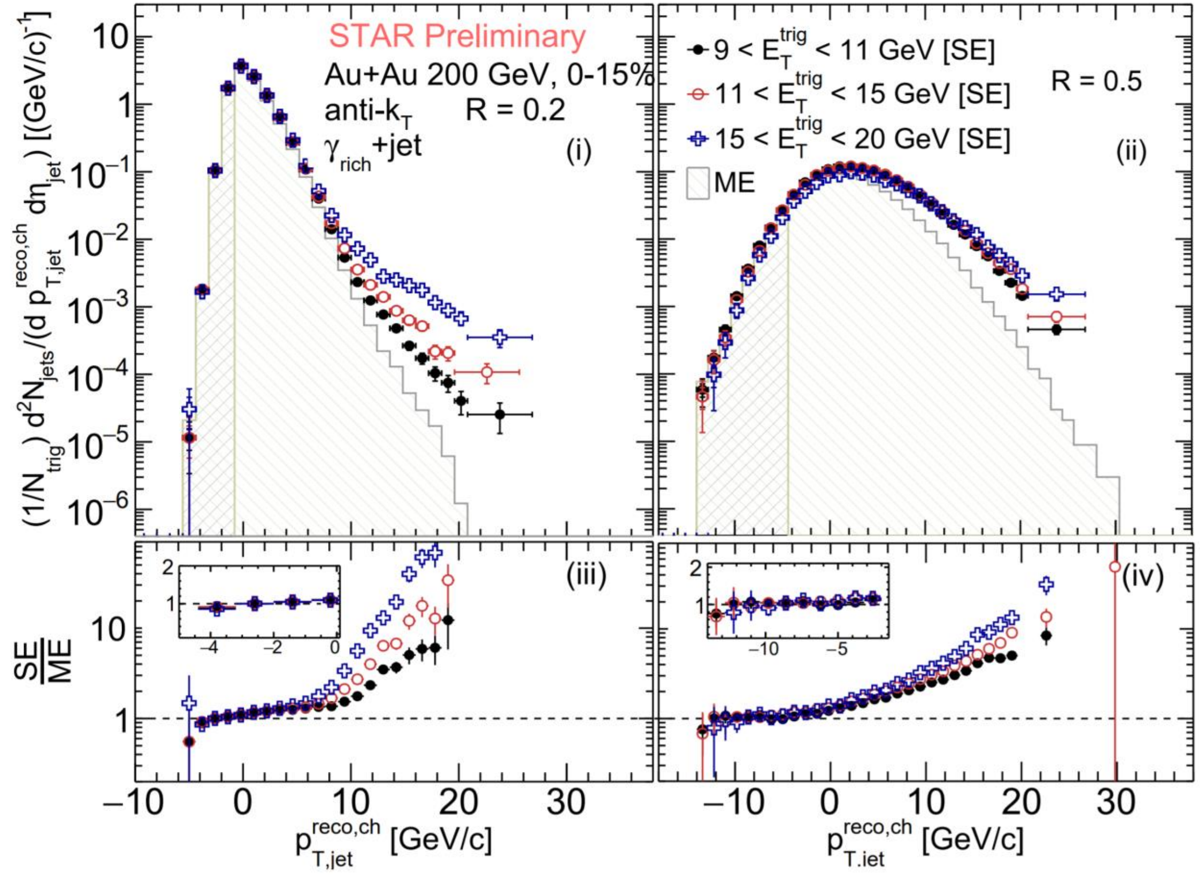
Raw jet distributions: corrections

- **Au+Au:** large uncorrelated background yield corrected via Mixed-Events [ME] **(shaded regions)**
  - › STAR, PRC **96**, 024905 (2017)

- $p+p$**:** Underlying Event [UE] effects are small
  - ∴ No ME subtraction applied

- $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ smearing and shifting corrected in 2 steps
  1) Event-wise adjustment:
     $$p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \cdot A_{\mathrm{jet}}$$
  2) Residual fluctuations corrected with regularized unfolding

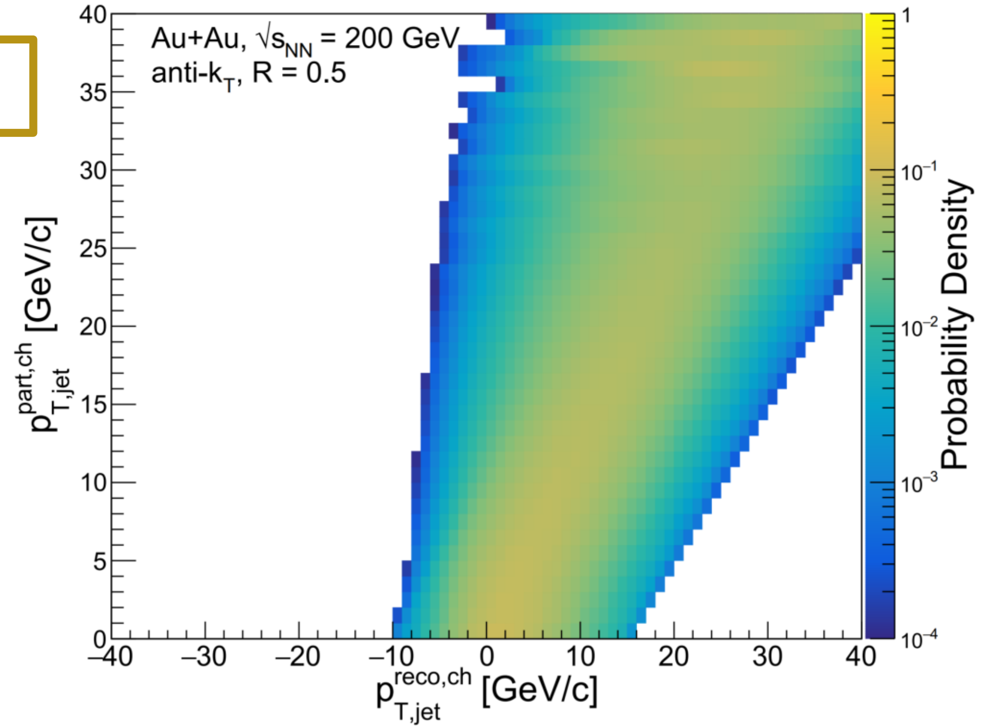


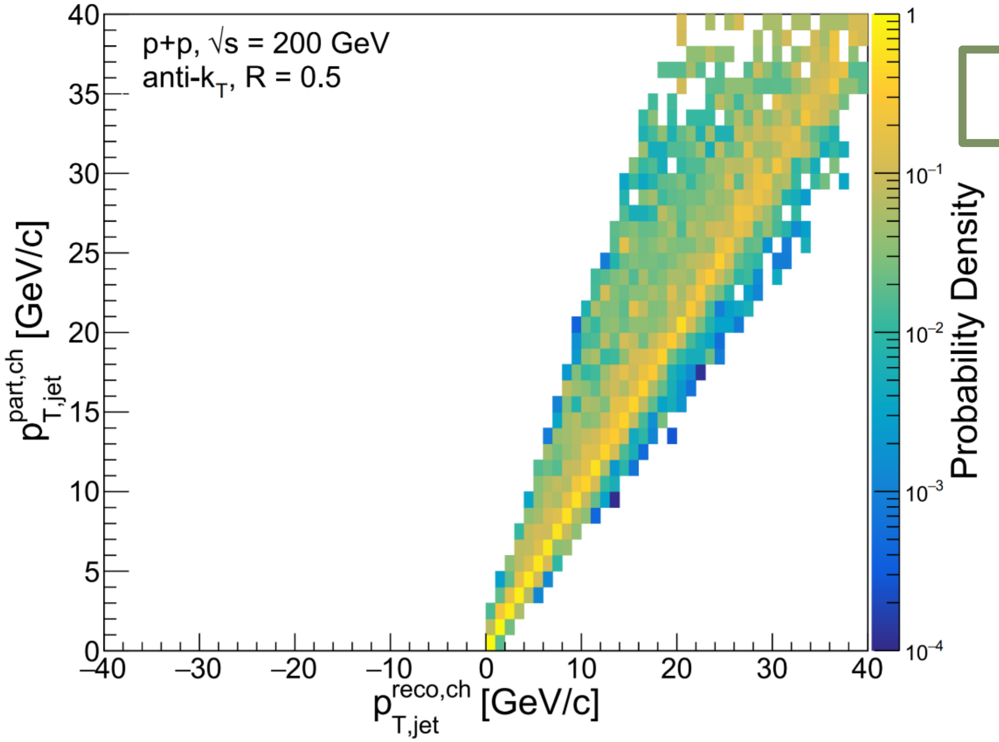


👆 Raw semi-inclusive γ_{rich}+jet distributions in Au+Au collisions

Recoil $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ yield corrections

Au+Au





p+p

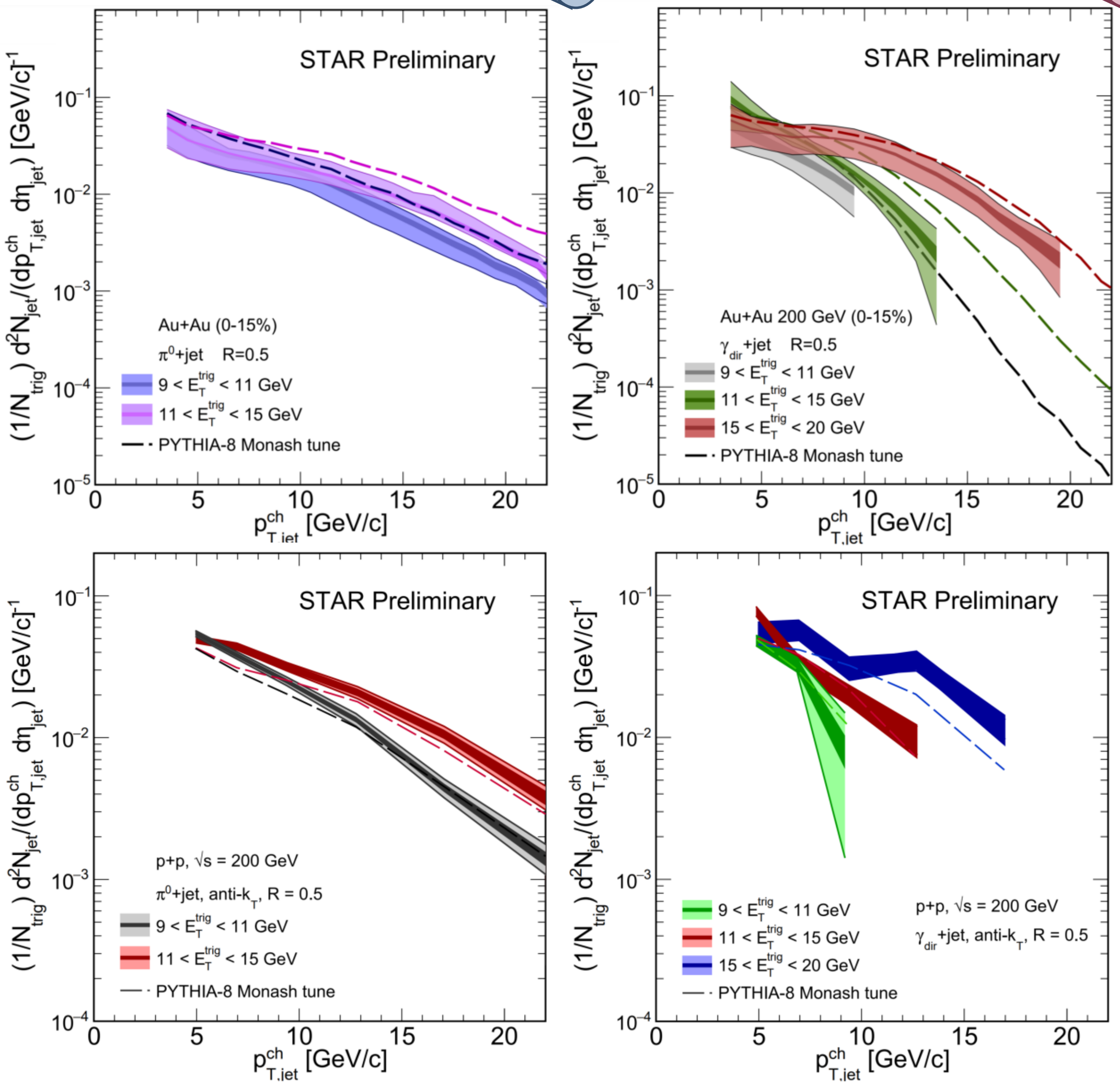
- $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ shifted and smeared by:
  - a) **Presence of HI background** (Au+Au only)
  - b) **Detector effects** (p+p and Au+Au)
- Corrected using regularized unfolding
  - – Bayesian and SVD algorithms
    - › STAR, PRC **96**, 024905 (2017)

- $\Delta\phi$ distributions must account for **$p_{\mathrm{T,jet}}^{\mathrm{ch}}$ and $\Delta\phi$ smearing**
  - – Response matrix factorized into:
    - a) $p_{\mathrm{T,jet}}^{\mathrm{ch}}$-smearing piece
    - b) $\Delta\phi$-smearing piece
  - ☞ **Nihar Sahoo poster [Wed T04_1]**

Corrected recoil jet distributions

Au+Au

p+p



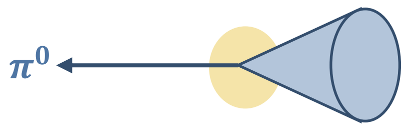
- Semi-inclusive recoil jet $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ distributions
  - $E_{\mathrm{T}}^{\mathrm{trig}}(\pi^0)$: [9, 11], [11, 15] GeV
  - $E_{\mathrm{T}}^{\mathrm{trig}}(\gamma_{\mathrm{dir}})$: [9, 11], [11, 15], [15, 20] GeV
- **Dark band:** statistical errors
  Light band: systematic uncertainties
- **Dominant systematic uncertainties:**
  - Tracking efficiency
  - Unfolding procedure
  - Purity (hadronic background subtraction)
- **Dashed line:** PYTHIA-8 (MONASH tune)
  - $E_{\mathrm{T}}^{\mathrm{trig}}$ shifted and smeared to account for trigger energy scale/resolution

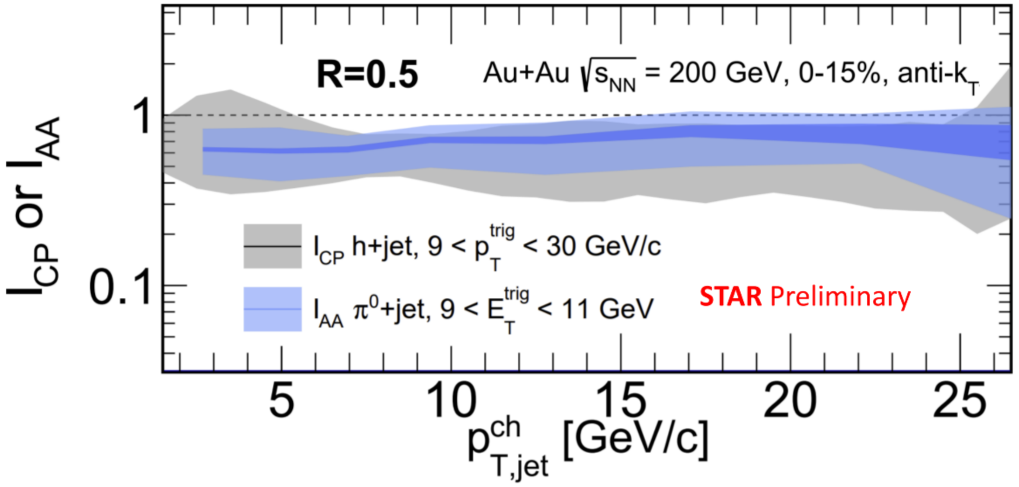
Comparison to $h^{\pm}$+jet measurement

[STAR, PRC **96**, 024905 (2017)]

- I_{AA}: yield ratio Au+Au/p+p for **same R**
  $$I_{\mathrm{AA}} \equiv Y_{\mathrm{AuAu}}/Y_{\mathrm{pp}}$$
- I_{CP}: yield ratio Au+Au central/peripheral for **same R**
  $$I_{\mathrm{CP}} \equiv Y_{\mathrm{cent}}/Y_{\mathrm{per}}$$
  - $h^{\pm}$+jet: central = 0 – 10%, peripheral = 60 – 80%
- $\mathfrak{N}^{0.2/0.5}$: yield ratio $R = 0.2/0.5$ ratio for **same system**
  $$\mathfrak{N}^{0.2/0.5} \equiv Y_{0.2}/Y_{0.5}$$

- This analysis consistent with published $h^{\pm}$+jet
  - **Note:** different $E_{\mathrm{T}}^{\mathrm{trig}}$ range
- Comparison to PYTHIA-8:
  - Smaller uncertainties in this analysis enable discrimination
  - ☞ **Measured $\mathfrak{N}^{0.2/0.5}$ less than PYTHIA-8**





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- I_{CP}: yield ratio Au+Au central/peripheral for **same R**
  $$I_{CP} \equiv Y_{cent}/Y_{per}$$
  - $h^{\pm}$+jet: central = 0 – 10%, peripheral = 60 – 80%
- $\mathfrak{R}^{0.2/0.5}$: yield ratio $R = 0.2/0.5$ ratio for **same system**
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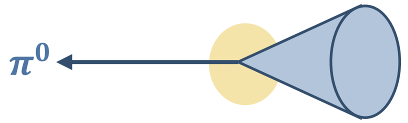
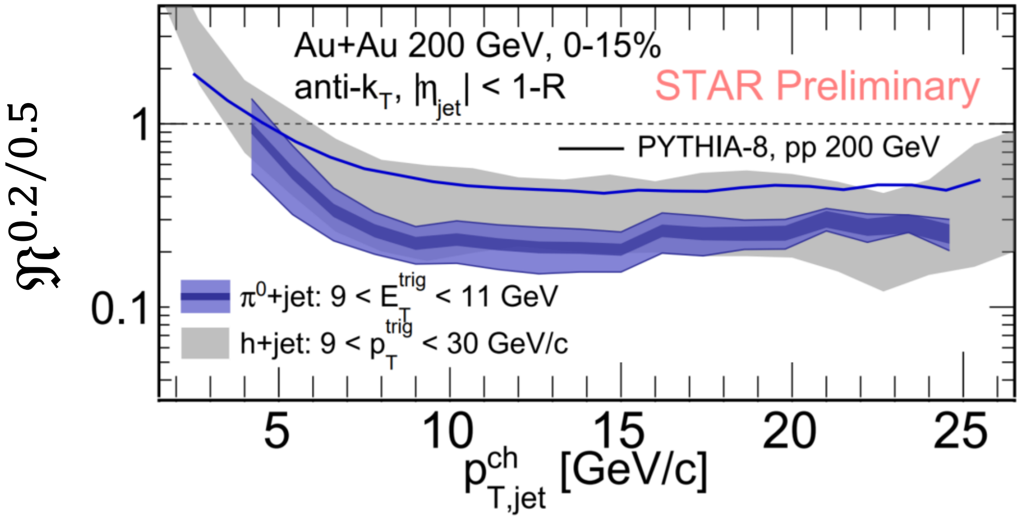
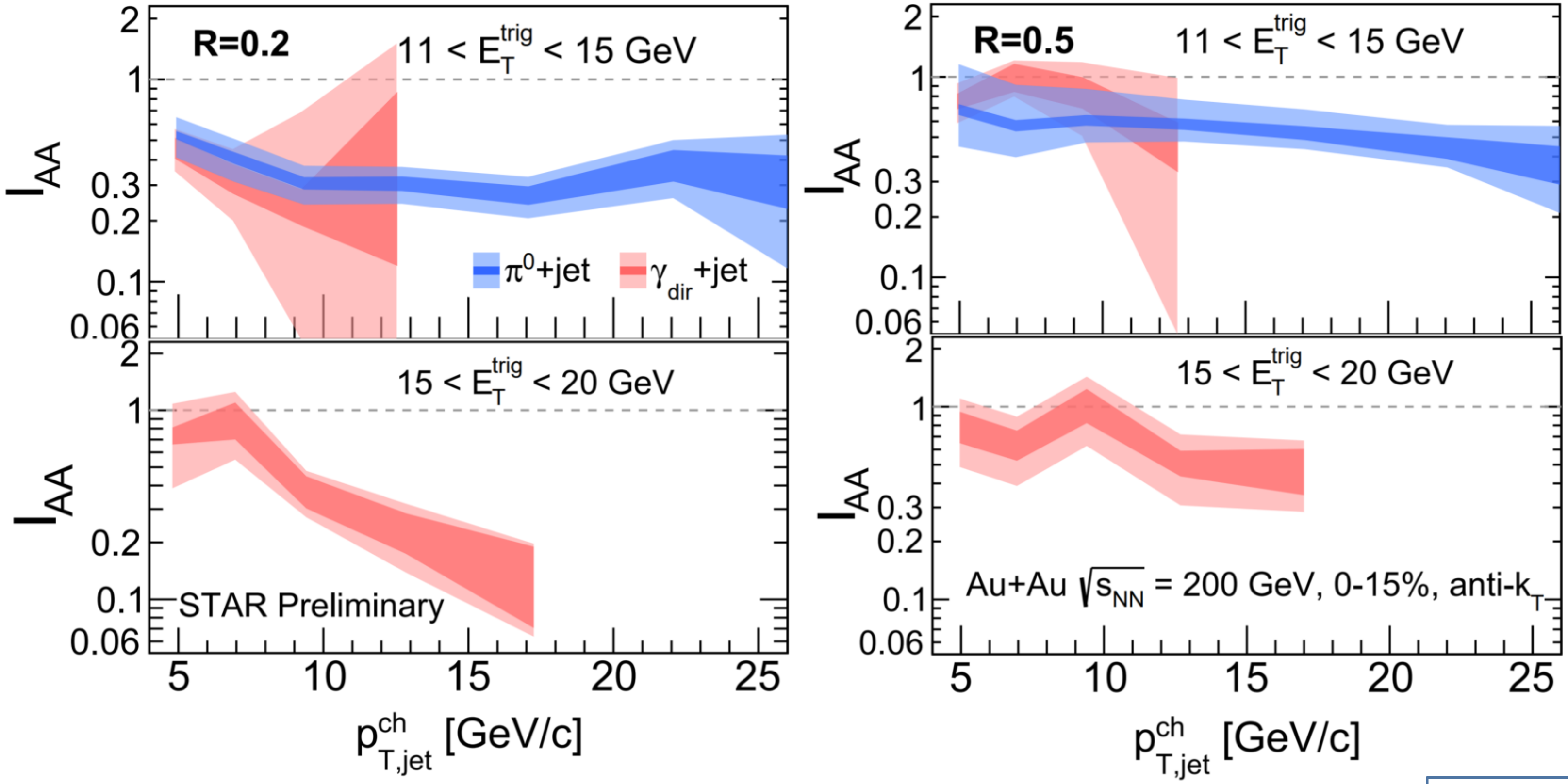
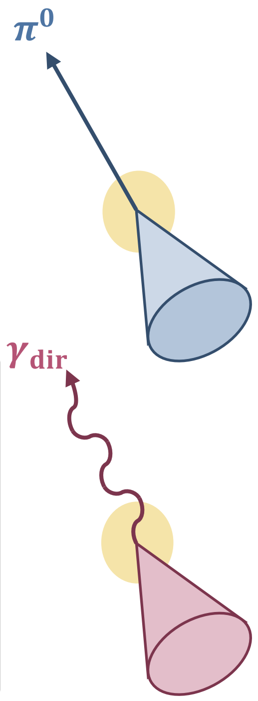




R dependence of I_{AA}

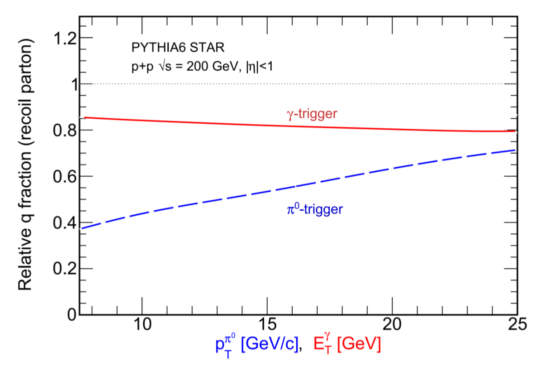




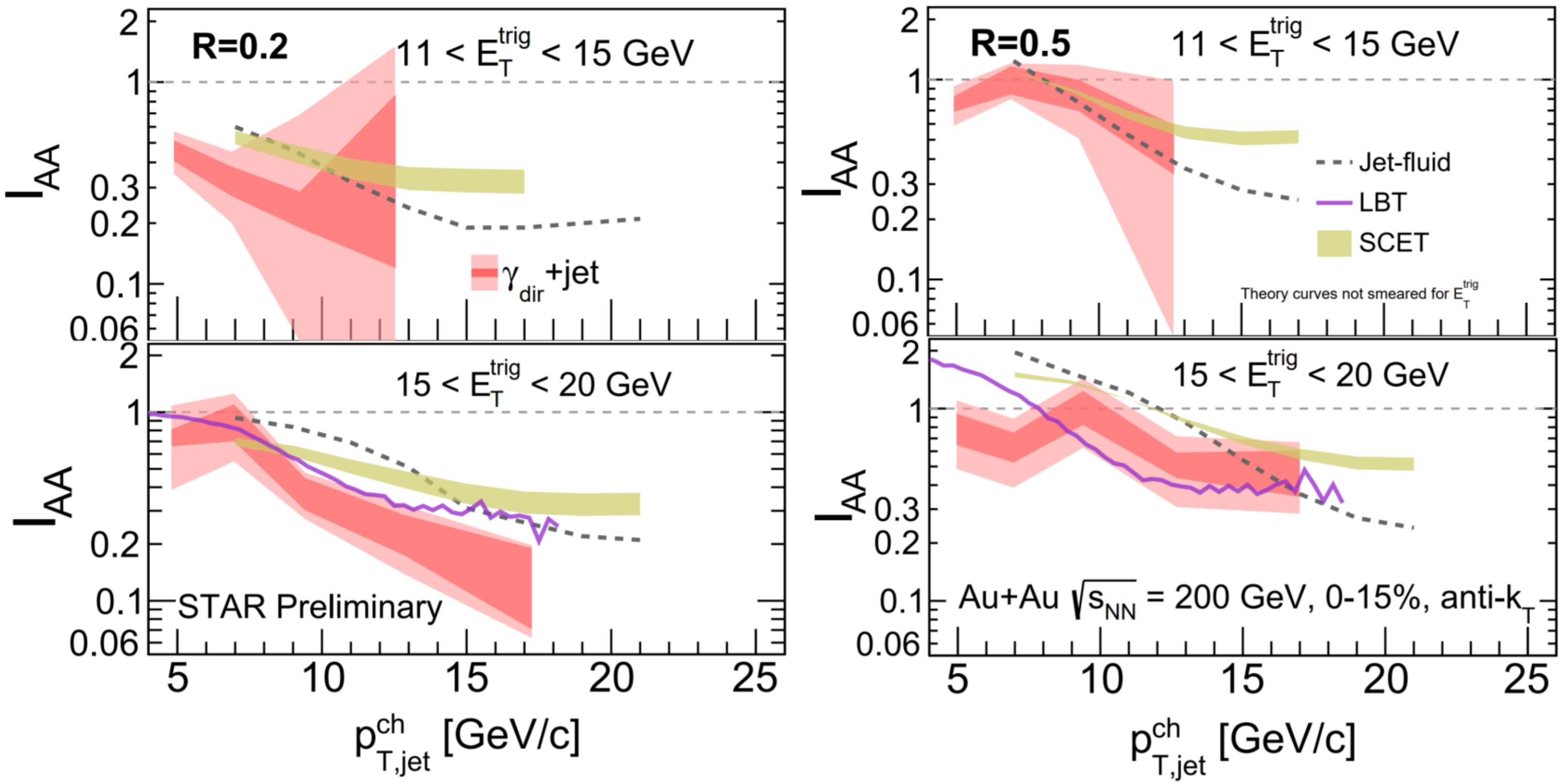
- $R = 0.2$ **more suppressed than 0.5**
  - ⇒ Indication of energy redistributed to wide angles

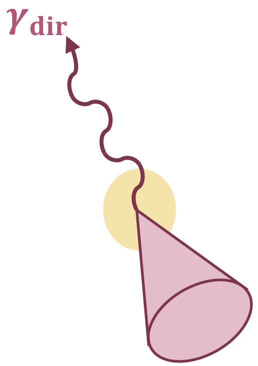
New: Baseline is measured p+p distribution

- π^0 **and** γ_{dir} I_{AA} **consistent**
  - ⇒ Different q/g fractions, path length distribution
  - – γ_{dir}**+jet recoil spectrum steeper**
    - ∴ Same suppression from smaller energy loss?



Comparison of I_{AA} to theory

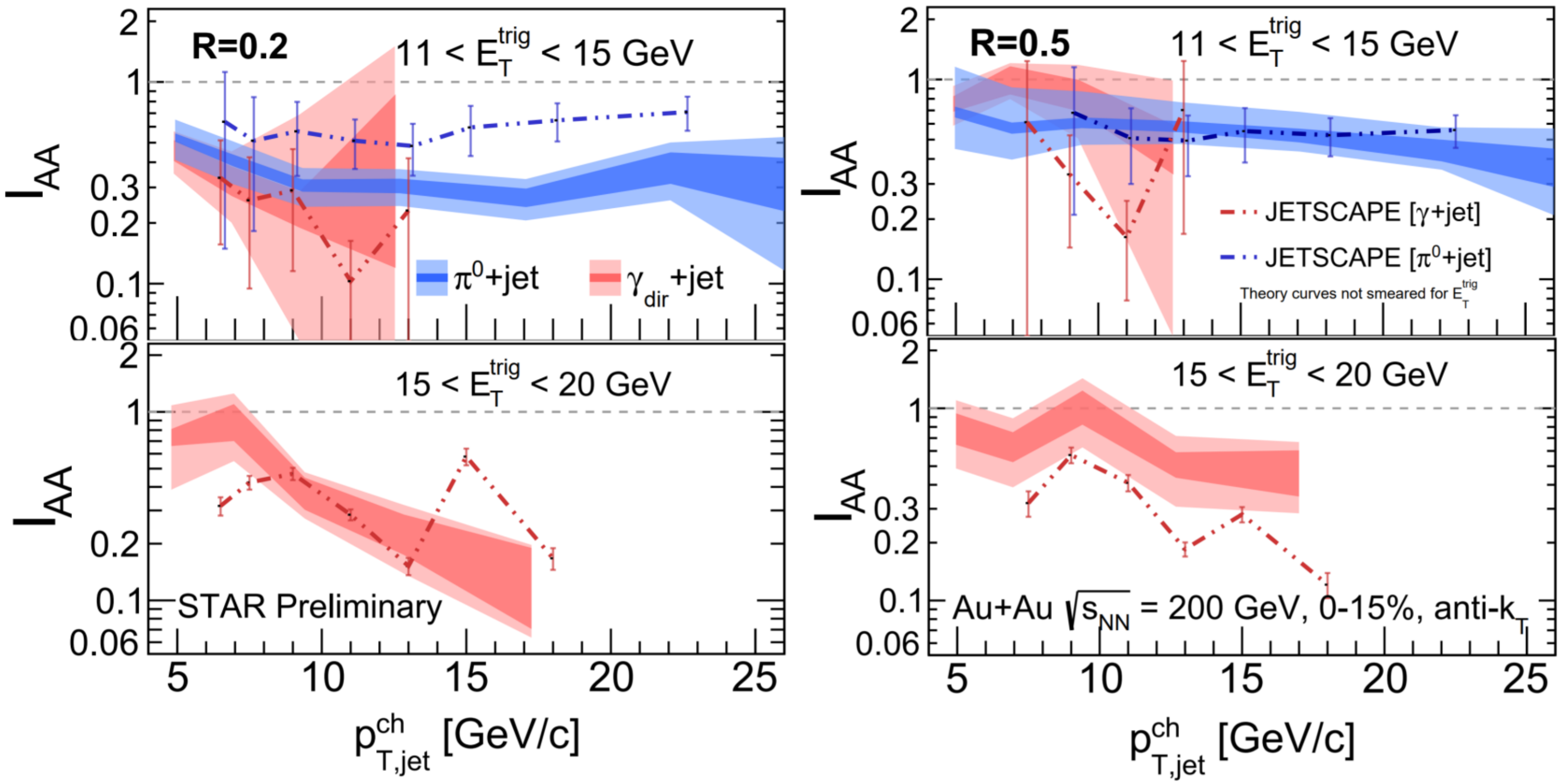


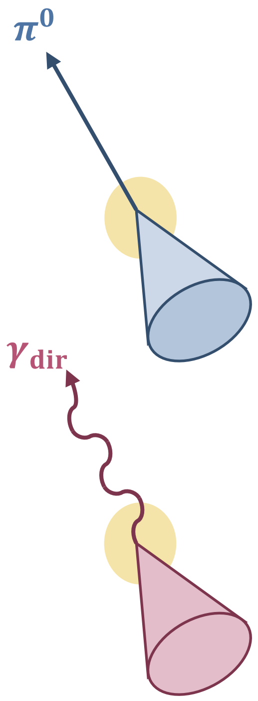


- **Theory calculations:**
  - **[Jet-Fluid]** N.-B. Chang, G.-Y. Qin, PRC **94**, 024902 (2016)
  - **[LBT]** T. Luo, S. Cao, Y. He, X.-N. Wang, PLB **782**, 707 (2018)
  - **[SCET]** M. D. Sievert, I. Vitev, and B. Yoon, PLB **795**, 502 (2019)

- Theoretical predictions:
  - ☞ **$p_{T,jet}^{ch}$ dependence?**
    Consistent
  - ☞ **Suppression magnitude?**
    Some tension…

Comparison of I_{AA} to theory





- **JETSCAPE calculation:**
  - Dotted-dashed lines
  - Bars are statistical errors

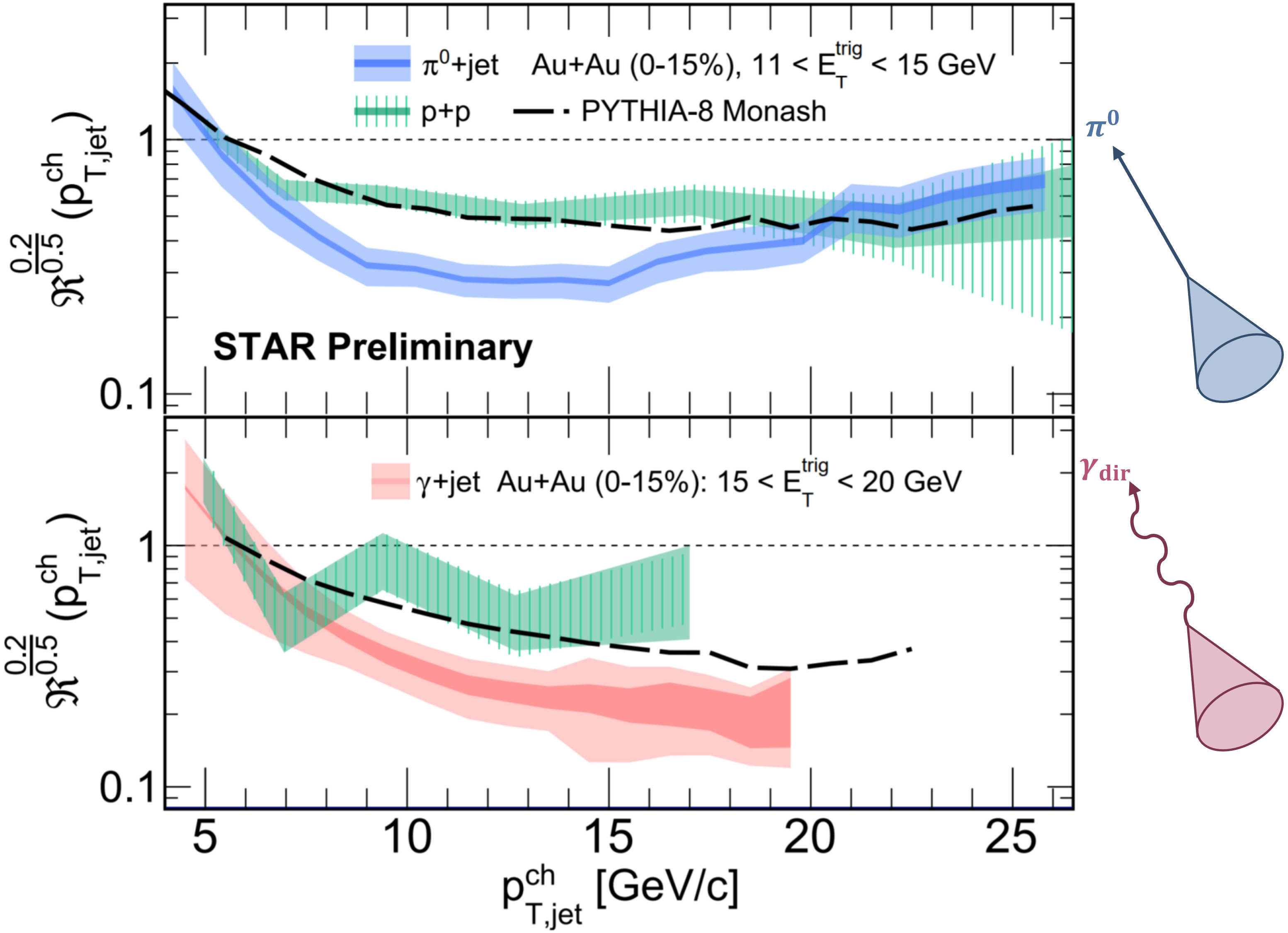
☞ **Chathuranga Sirimanna (JETSCAPE) poster [Wed T13]**

- JETSCAPE predictions:
  - ☞ **$p_{T,jet}^{ch}$ dependence?**
    Consistent
  - ☞ **Suppression magnitude?**
    Some tension…

R dependence of recoil yields

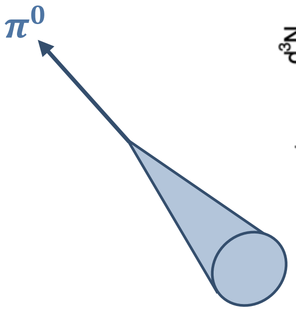
$$\mathfrak{R}^{0.2/0.5} \equiv Y_{0.2}/Y_{0.5}$$

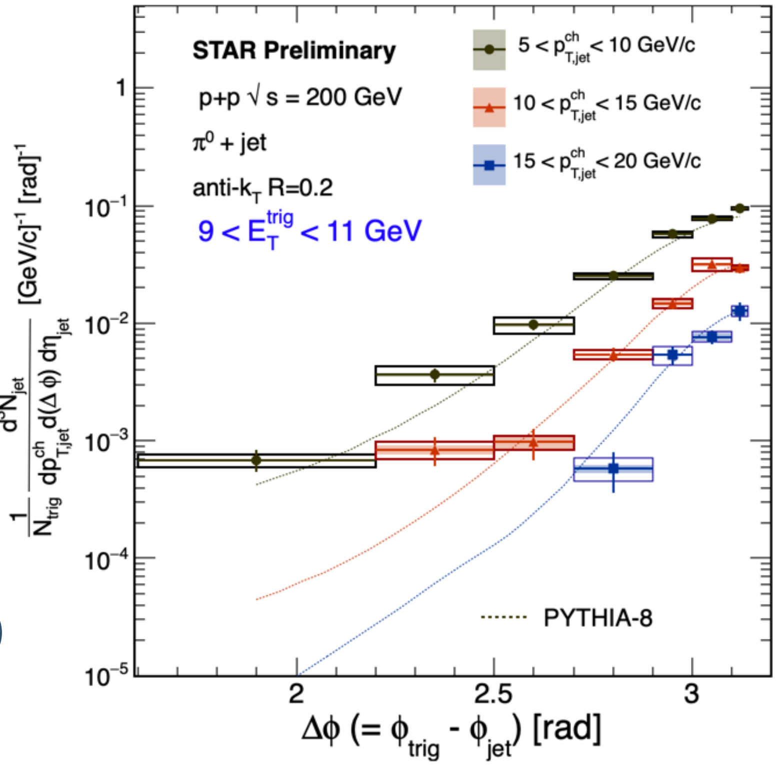
- $\mathfrak{R}^{0.2/0.5} < 1$ in p+p **due to jet shape in vacuum**
  - PYTHIA−8 agrees with p+p data
- Au+Au suppressed relative to p+p
  - $\Rightarrow$ **Observation of medium-induced intra-jet broadening**
- **Note:** $E_{\mathrm{T}}^{\mathrm{trig}}$ and trigger type differ between panels
  - **Upper:** 11 – 15 GeV π^0
  - **Lower:** 15 – 20 GeV γ_{dir}
- p+p style different
  - **Hatched band:** systematic uncertainty



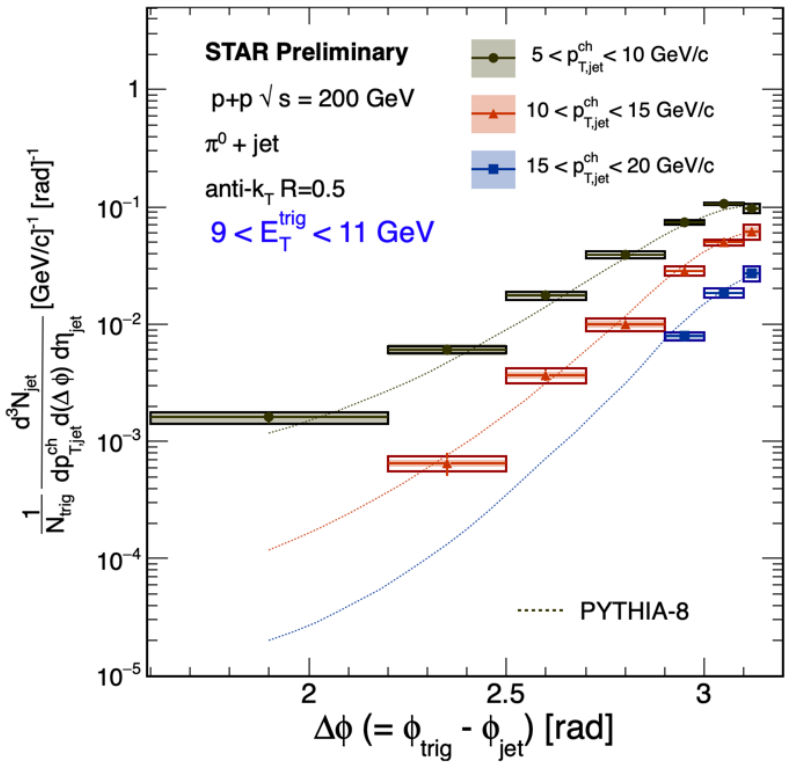
Corrected $\Delta\phi$ distributions in p+p collisions

$R = 0.2$



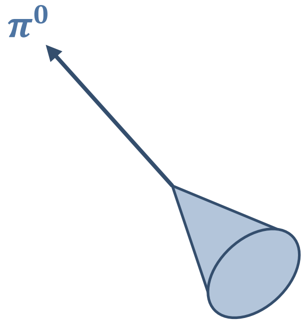


Nihar Sahoo poster [Wed T04_1]



$E_T^{trig} = [9, 11]$ GeV

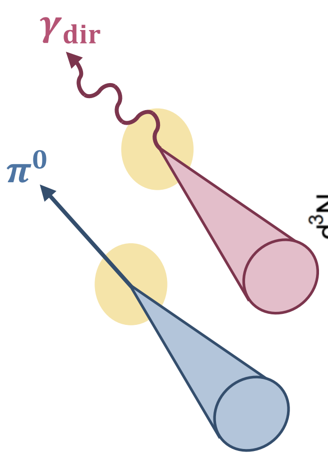
$R = 0.5$



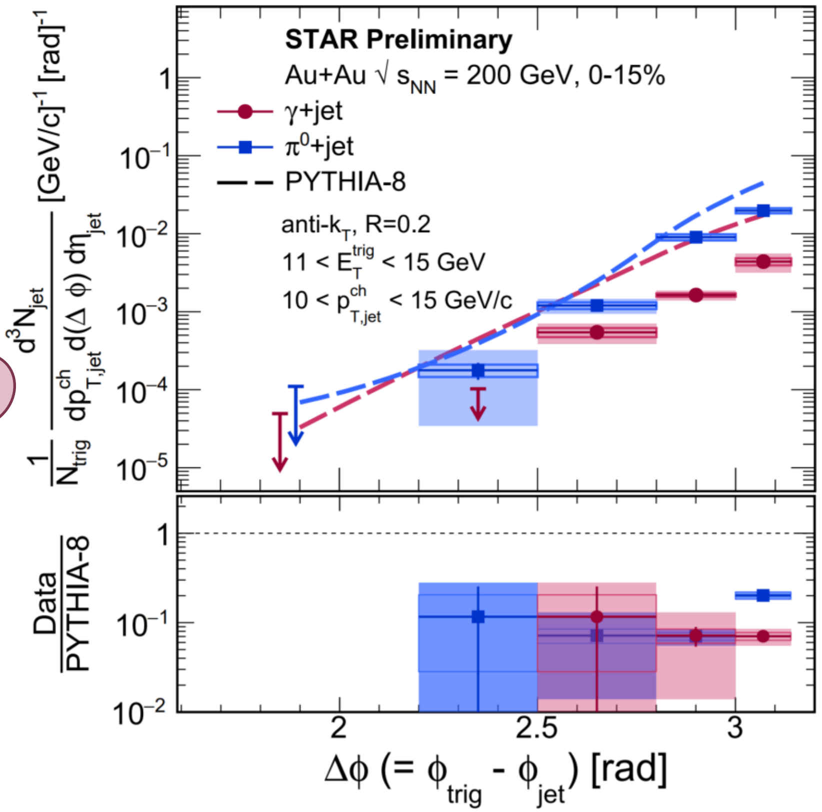
- Corrected $\Delta\phi$ spectra in p+p compared against E_T^{trig} smeared PYTHIA-8
  - **PYTHIA-8 consistent with Data**
- PYTHIA-8 only LO+LL
  - ∴ **NLO calculations needed**

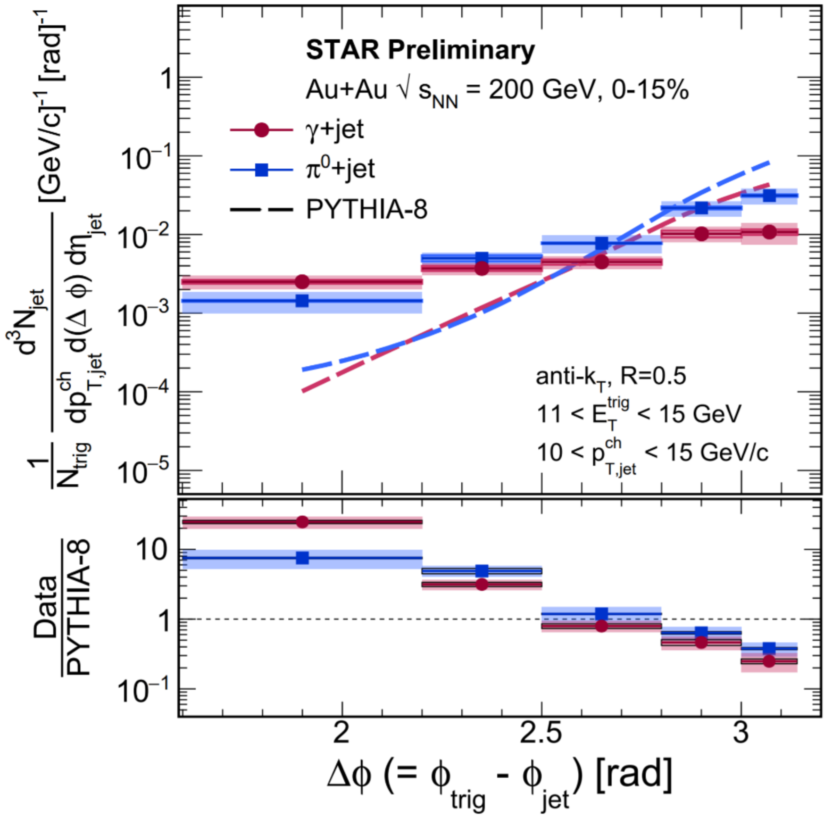
Corrected $\Delta\phi$ distributions in Au+Au collisions

$R = 0.2$

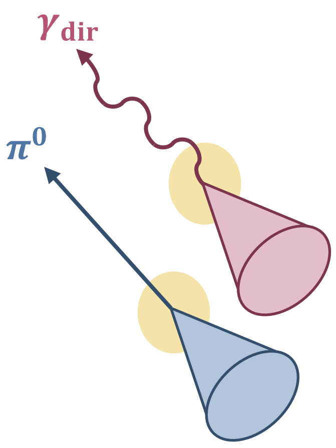


Nihar Sahoo poster
[Wed T04_1]





$R = 0.5$



$E_T^{\text{trig}} = [11, 15]$ GeV

- Corrected $\Delta\phi$ spectra in Au+Au compared **against smeared PYTHIA-8**
  - $\Rightarrow$ PYTHIA-8 validated against π^0+jet p+p data
- **Note:** $\Delta\phi$ integrated yield is I_{AA}

- **Highly significant medium-induced broadening of acoplanarity for $R = 0.5$**

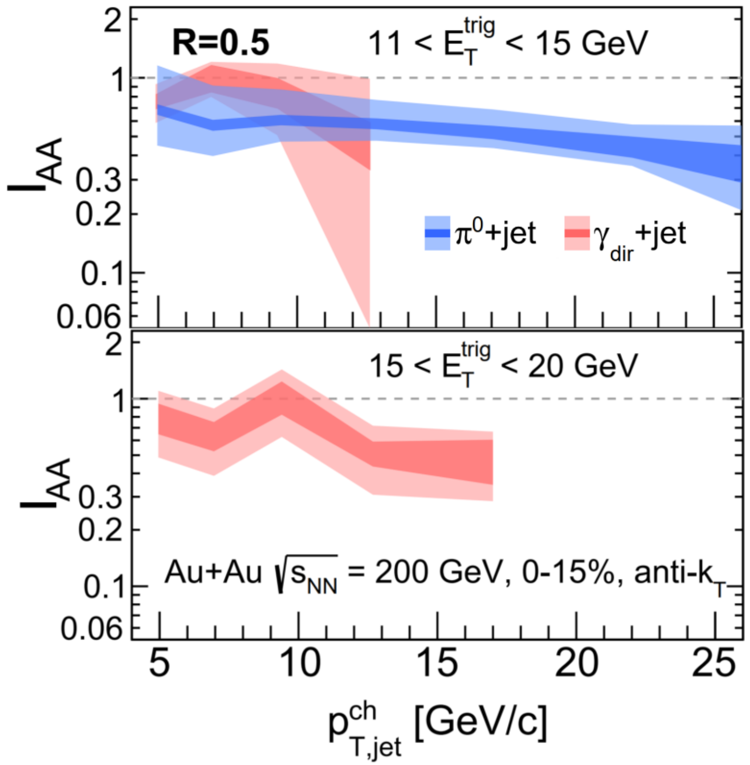
$\Rightarrow$ Medium effects include

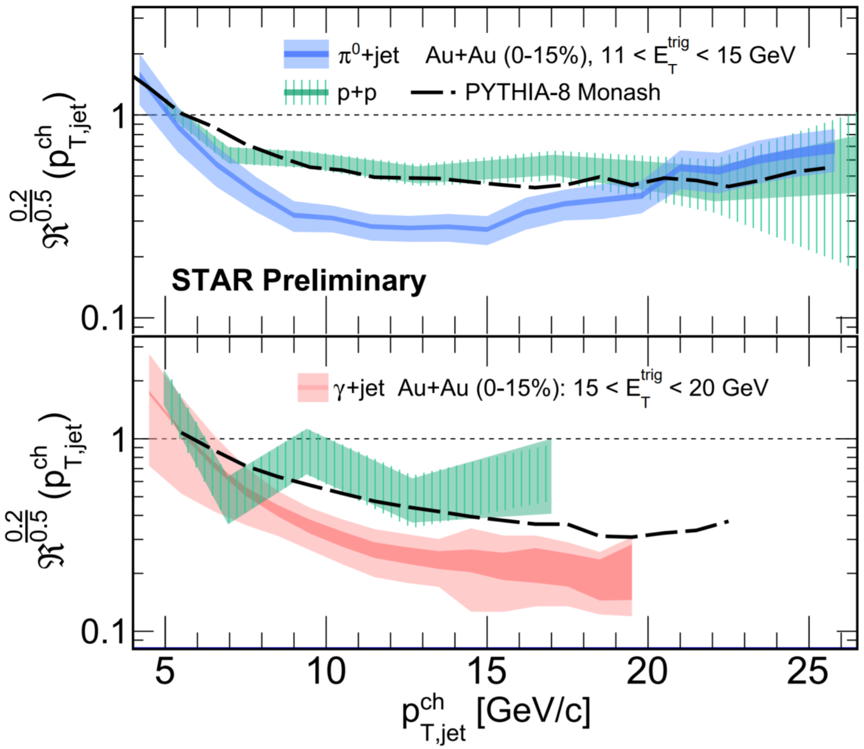
a) Scattering off QGP quasi-particles

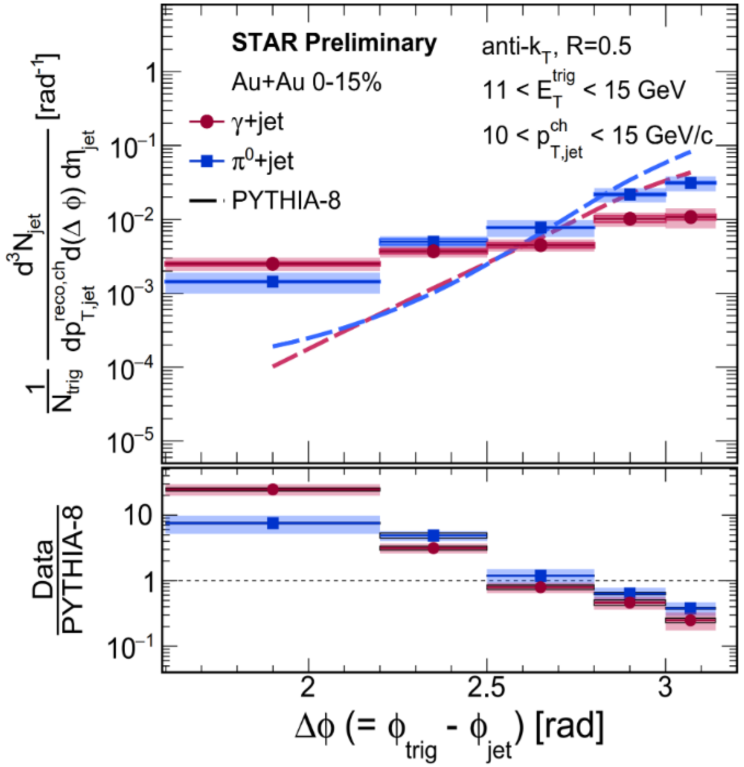
b) Multiple soft scatters

Summary

Nihar Sahoo poster [Wed T04_1]







- **I_{AA} consistent between π^0+jet and γ_{dir}+jet**
  - Different q/g fractions, different recoil path length distributions, different spectra shapes
  - Tension with theoretical predictions…
- **I_{AA} and $\mathfrak{R}^{0.2/0.5}$ demonstrate intra-jet broadening**
- **$\Delta\phi$ distributions for $R = 0.5$ jets in Au+Au suggest medium-induced broadening of acoplanarity**
  - Recall mechanisms:
    - a) Hard scattering off QGP quasi-particles
    - b) Multiple soft scatters in medium

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STAR

Thank you!

Supported in part by:

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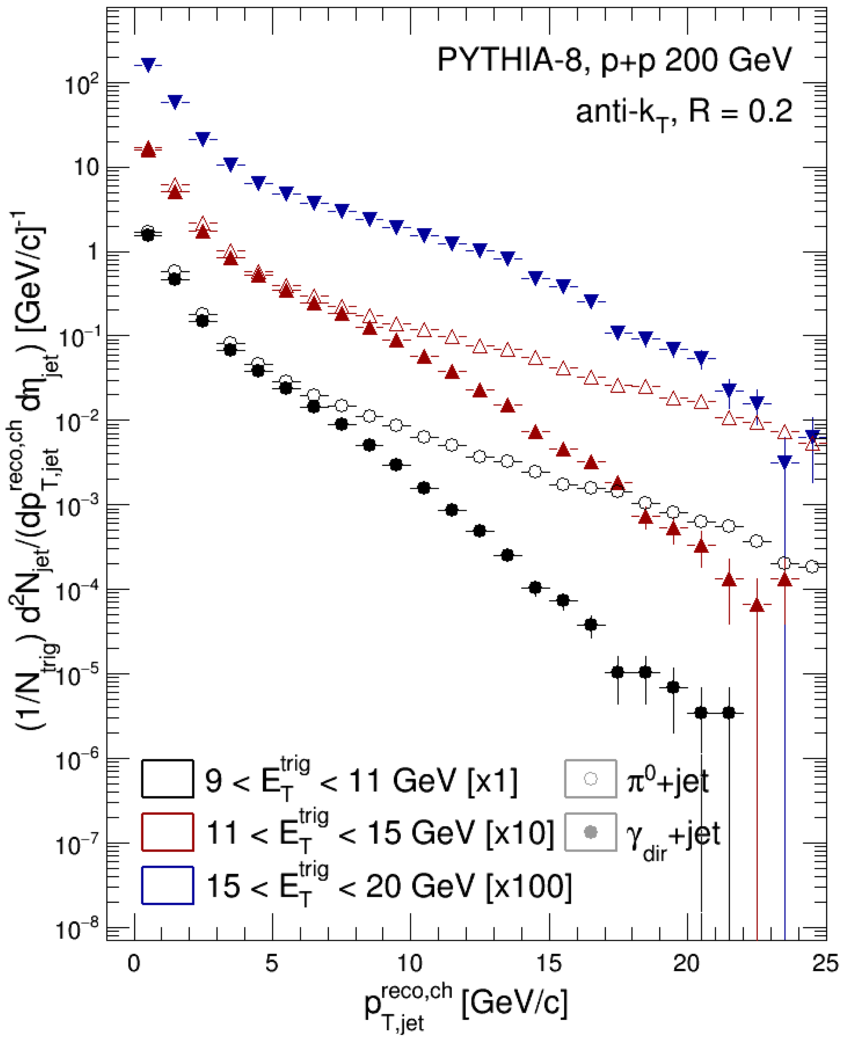
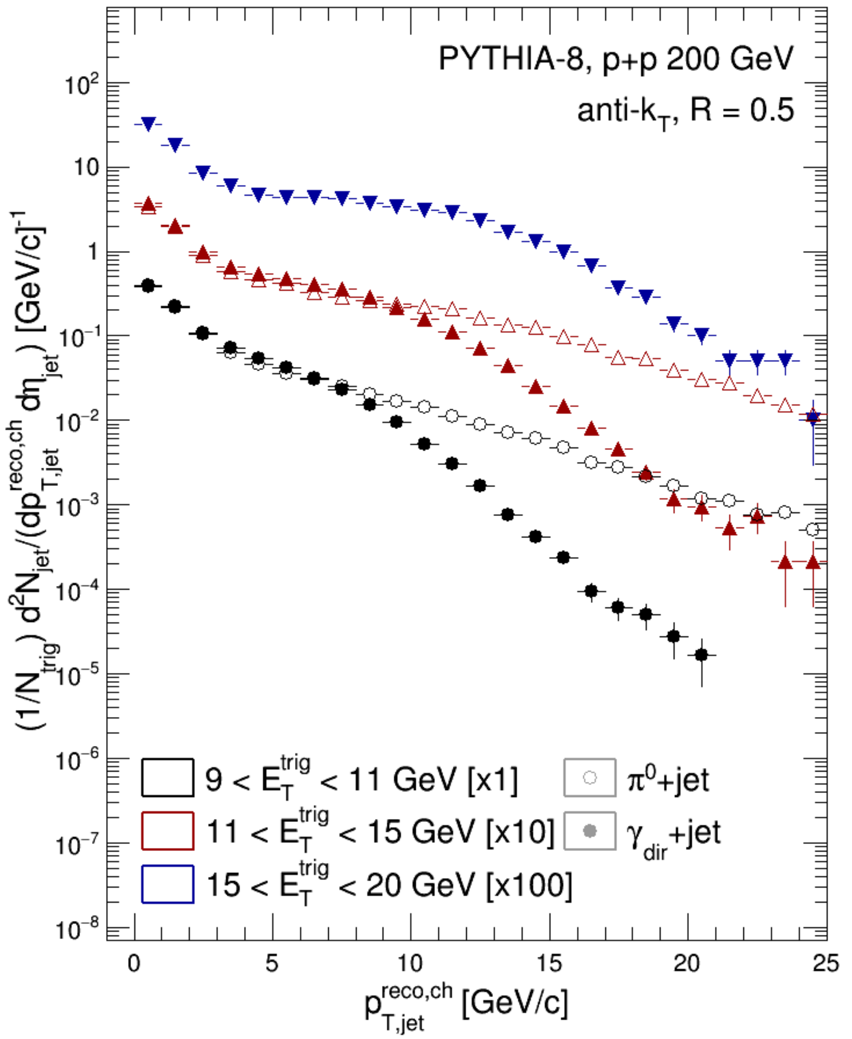
Shape of $\pi^0/\gamma_{\mathrm{dir}}$+jet in PYTHIA-8

- $R = 0.2$ **(left)** and 0.5 **(right)** semi-inclusive π^0+jet and γ_{dir}+jet spectra in PYTHIA-8
- **Notice:** γ_{dir}+jet spectra are significantly steeper than π^0+jet spectra

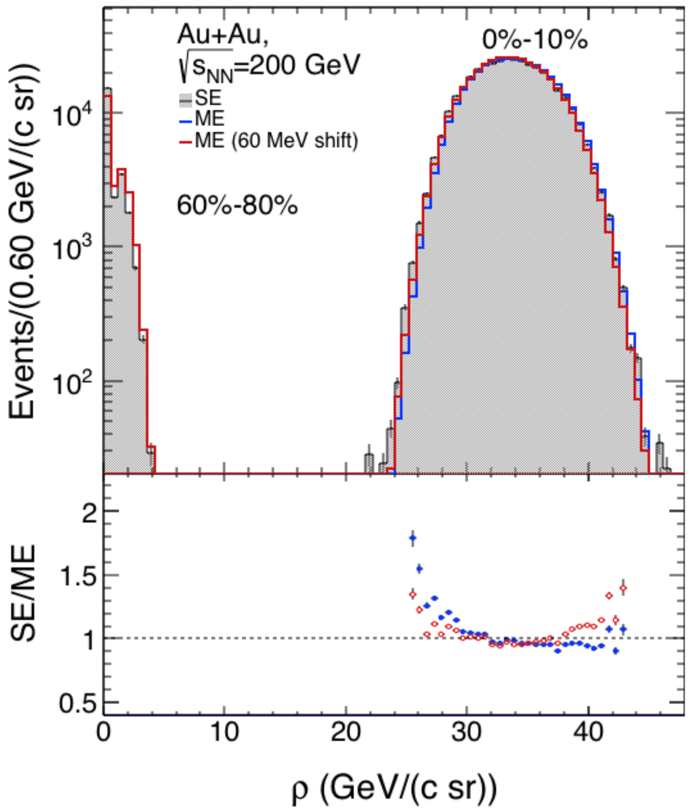


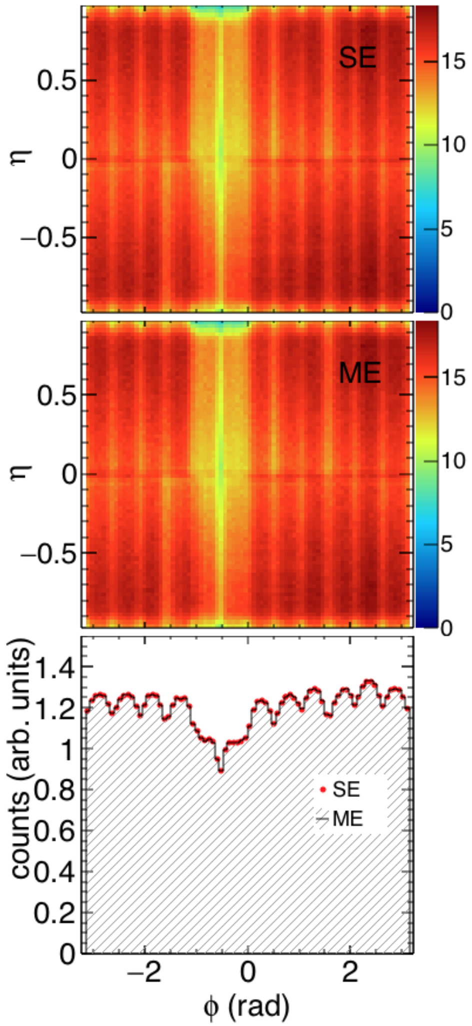


Mixed Event Technique

- **Mixed Event (ME) Technique:**
  - Developed in STAR, PRC **96**, 024905 (2017)
    - Synthetic events **(MEs)** formed from tracks from real MB events **(SEs)**
    - Tracks sampled such that:
      a) No tracks in a given ME come from same SE
      b) MEs have realistic multiplicity, v_z, event plane, etc. distributions
  - ☞ **Event-wise shift in energy applied to MEs to match ρ of SEs**
- MEs reproduce ensemble-averaged features of real events
  - **But any multi-hadron correlations are destroyed**

STAR, PRC **96**, 024905 (2017)





STAR, PRC **96**, 024905 (2017)

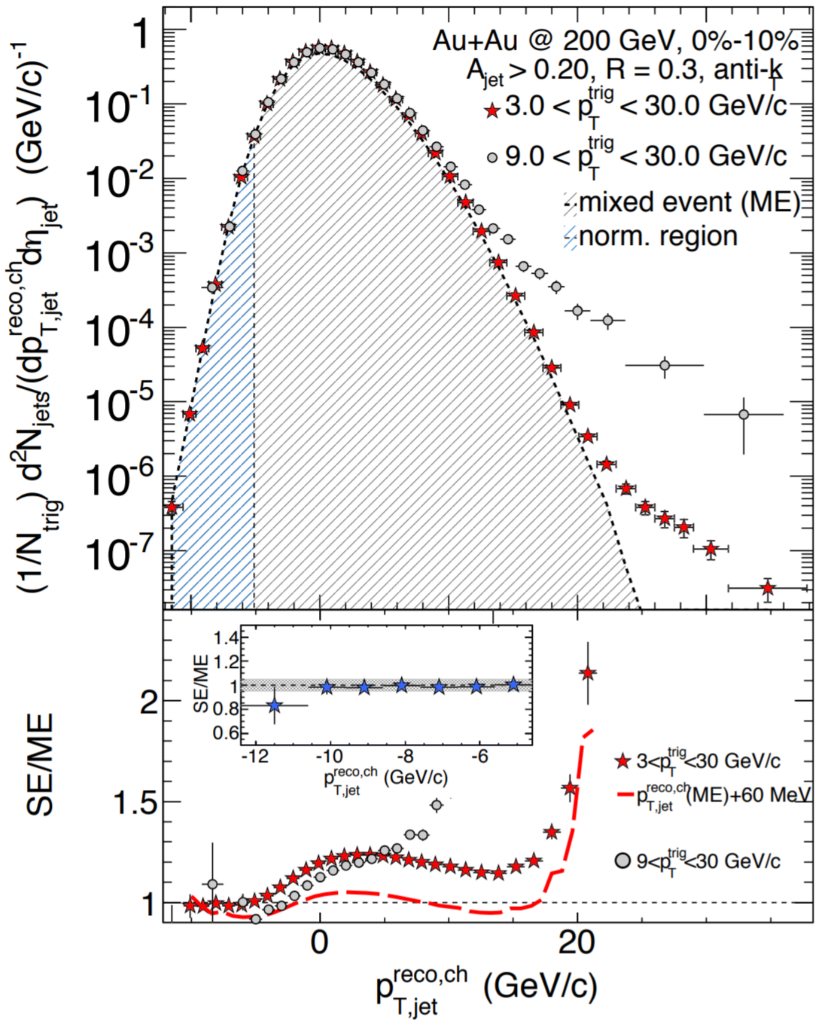
Figures: MB AuAu ρ distributions **(left)** for SEs vs. MEs before and after shift, and MB AuAu track (η, ϕ) distributions **(right)** for SE vs. MEs.

MPIs at RHIC

- ME technique destroys any correlations between QCD radiation
  - ⇒ **Including those due to MPIs**
  - ∴ Difference between SE and ME due to signal (hard scatter) and MPIs

- STAR estimated MPI rate at RHIC using the ME technique in 2017
  - – Lower bound of trigger p_{T} was dropped to 3 GeV/c
  - ⇒ Semi-inclusive spectrum **(red stars)** should approach combinatoric background (ME) + MPIs
  - › STAR, PRC **96**, 024905 (2017)

- Small differences observed between ME and spectrum with lower $p_{\mathrm{T,trg}}$
  - ∴ **MPI rate in Au+Au small at RHIC. Will be even smaller in p+p!**



STAR, PRC **96**, 024905 (2017)

Figure: raw semi-inclusive yields of $h^{\pm}$-triggered jets for two ranges of $p_{\mathrm{T,trg}}$

Quark Fractions

- Relative fraction of quarks recoiling from $\pi^0/\gamma_{\text{dir}}$ triggers calculated in PYTHIA-6 (STAR tune) as:

$$\boldsymbol{q}/(\boldsymbol{q}+\boldsymbol{g})$$

  - $\boldsymbol{q}$: no. of events w/ quarks as recoil partons
  - $(\boldsymbol{q}+\boldsymbol{g})$: total no. of events

- **Recoil partons selected by**
  1) Identifying immediate product of hard scatter responsible for π^0 trigger via distance cut in (η, ϕ) space
     - ☞ Distance cut not necessary for γ_{dir} triggers
  2) **Recoil parton is then the other parton**
     - ☞ Recoil partons required to have $|\eta| < 1$

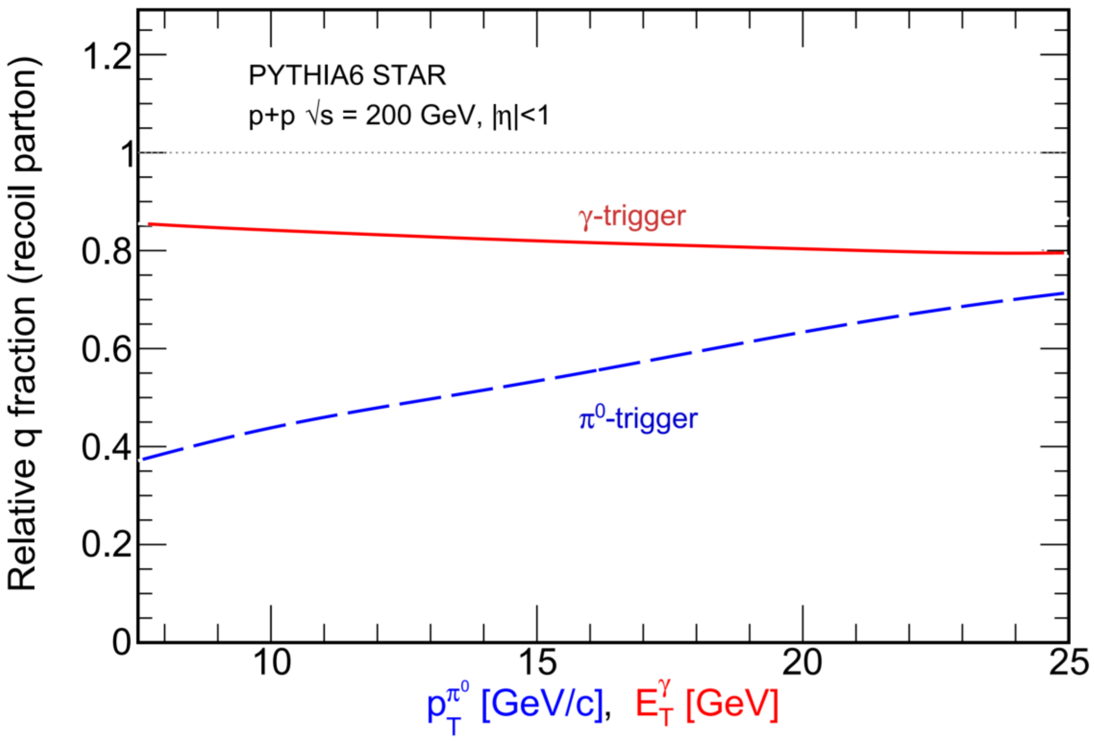


Figure: Relative recoil quark fraction for $\pi^0/\gamma_{\text{dir}}$ triggers in PYTHIA-6 (STAR tune).

Extracting γ_{dir} from γ_{rich}

- Background level of γ_{rich} measured by taking ratio of Near-Side per-trigger yields:
  $$B = Y_{\mathrm{pp}}^{\mathrm{NS}}(\gamma_{\mathrm{rich}})/Y_{\mathrm{pp}}^{\mathrm{NS}}(\pi^0)$$
  - Decay component subtracted from γ_{rich} via:
    $$Y_{\mathrm{pp}}^{\gamma_{\mathrm{dir}}} = \frac{Y_{\mathrm{pp}}^{\gamma_{\mathrm{rich}}} - B \cdot Y_{\mathrm{pp}}^{\pi^0}}{1 - B}$$
- For $E_{\mathrm{T}}^{\mathrm{trig}} \in (9,11)$ GeV in p+p collisions, B is measured to be:
  $$\boldsymbol{B \approx 0.57 \pm 0.05}$$
- **Assumptions:**
  I. γ_{dir} have zero NS correlated yield.
  II. NS correlated yields for *decay photons* from asymmetric decays have same functional shape as measured π^0 NS correlated yield.

STAR, PRC **82**, 034909 (2010)

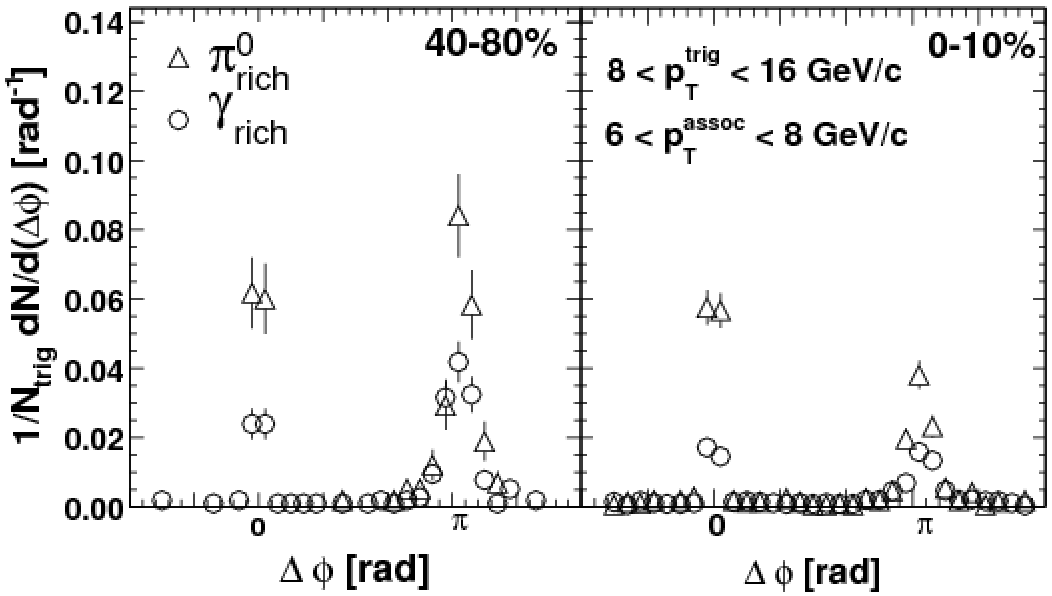


Figure: Per-trigger azimuthal yields of correlated hadrons for π^0_{rich} and γ_{rich} triggers in 40 – 80% **(left)** and 0 – 10% **(right)** central Au+Au collisions.

Trigger energy scale

- Energy of trigger $\pi^0/\gamma_{\mathrm{dir}}$ smeared by detector effects
  - **Trigger Energy Scale (TES):** overall shift in measured trigger E_{T} relative to actual E_{T}
  - **Trigger Energy Resolution (TER):** fluctuations of measured trigger E_{T} about the TES

- TES/R assessed using fast simulation:
  a) **TES is ~97%** for γ across $E_{\mathrm{T,trg}}$
  b) **TES is 92% ~ 97%** for π^0 with increasing $E_{\mathrm{T,trg}}$
  c) **TER is ~8%** for both γ and π^0 across $E_{\mathrm{T,trg}}$

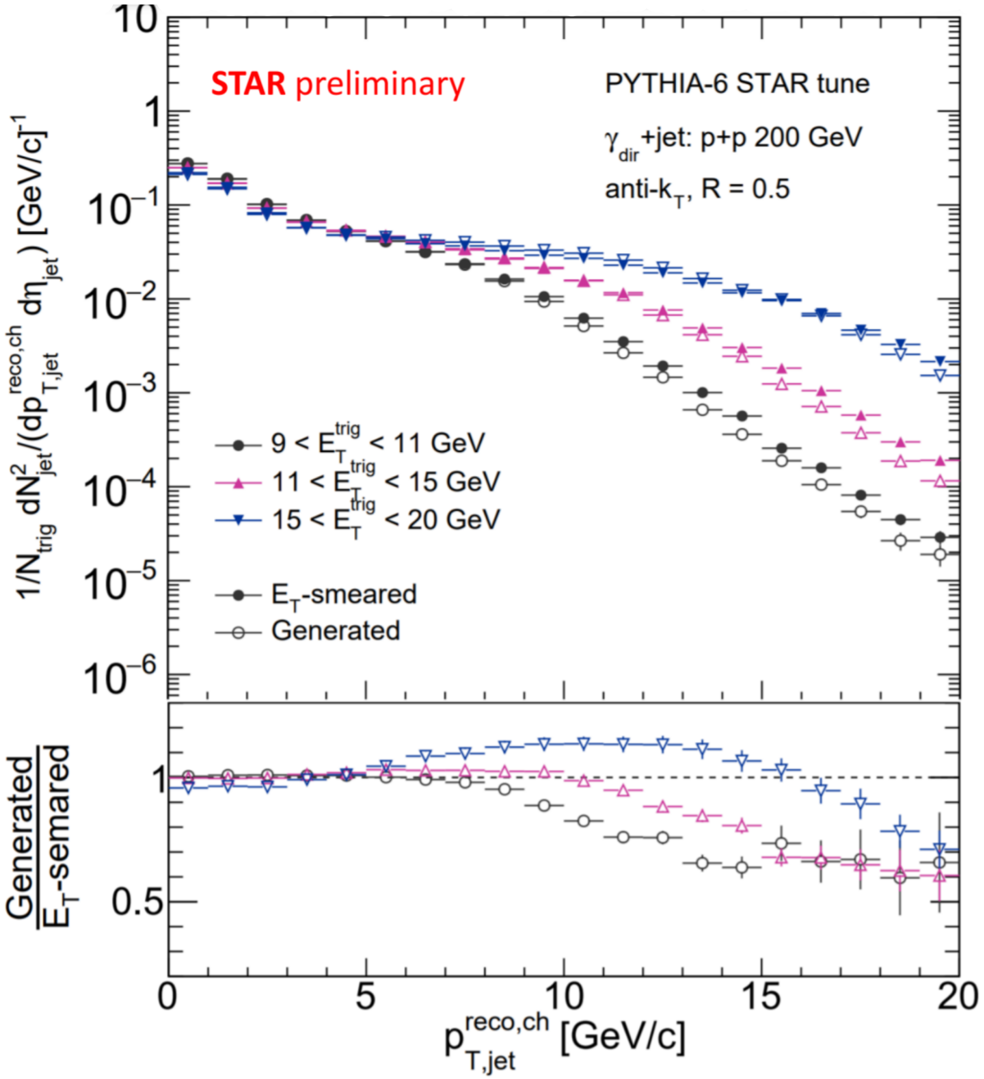
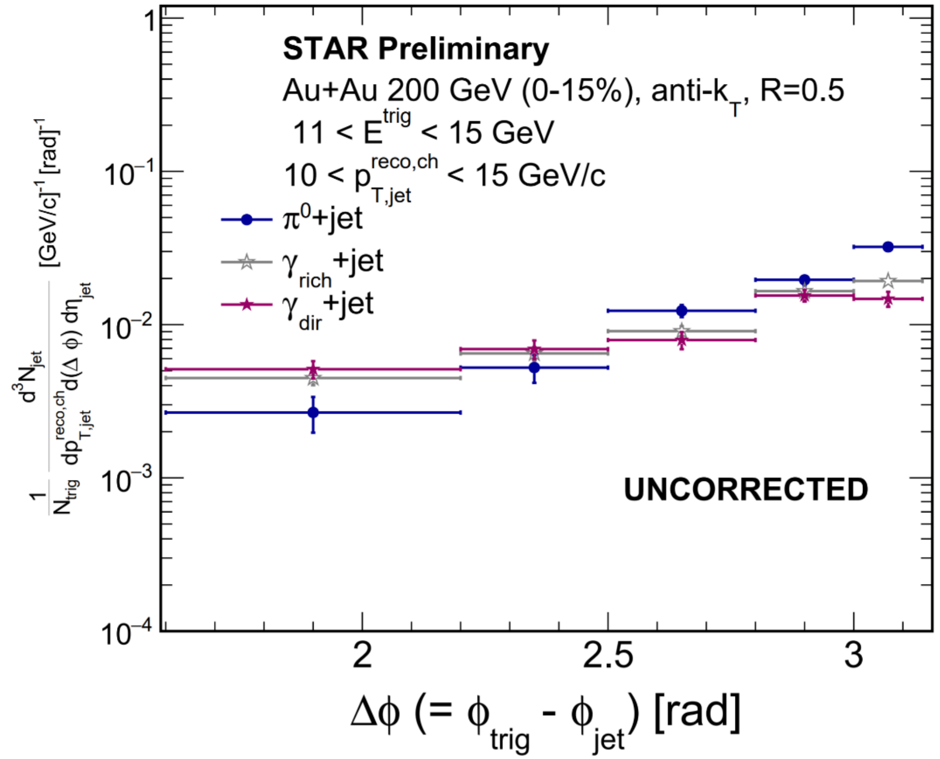
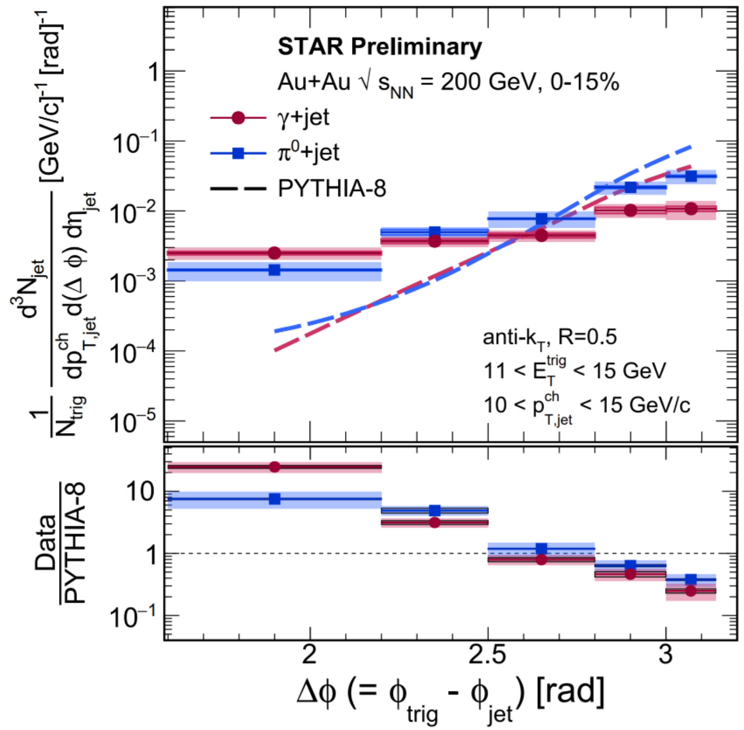


Figure: impact of TES/R smearing on PYTHIA-6 (STAR tune) γ_{dir}-triggered recoil jets

$\Delta\phi$ calculation and correction procedure

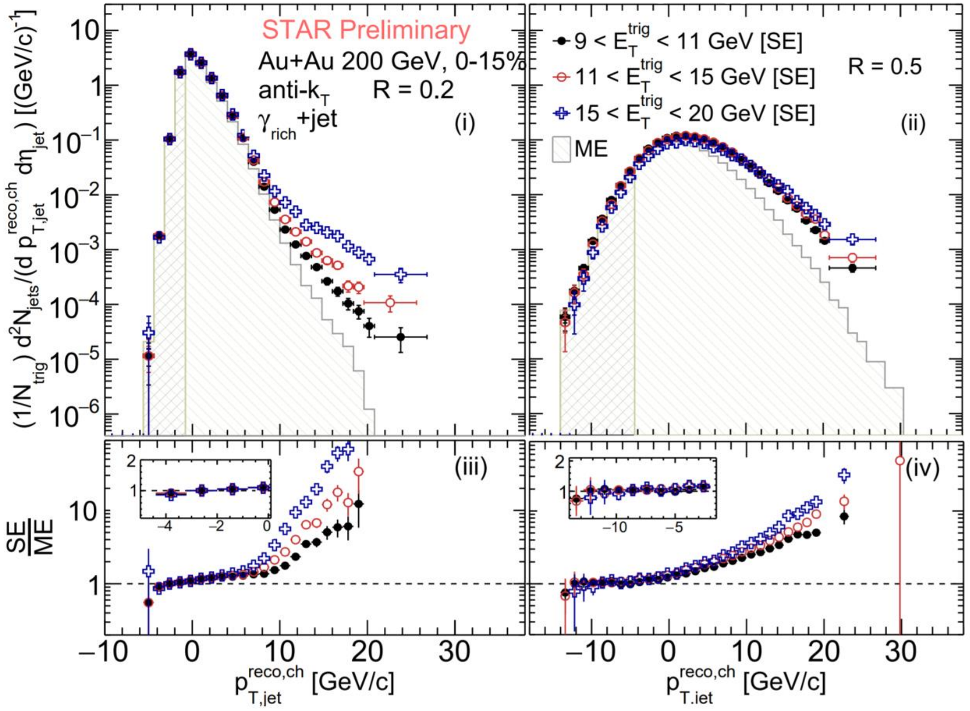


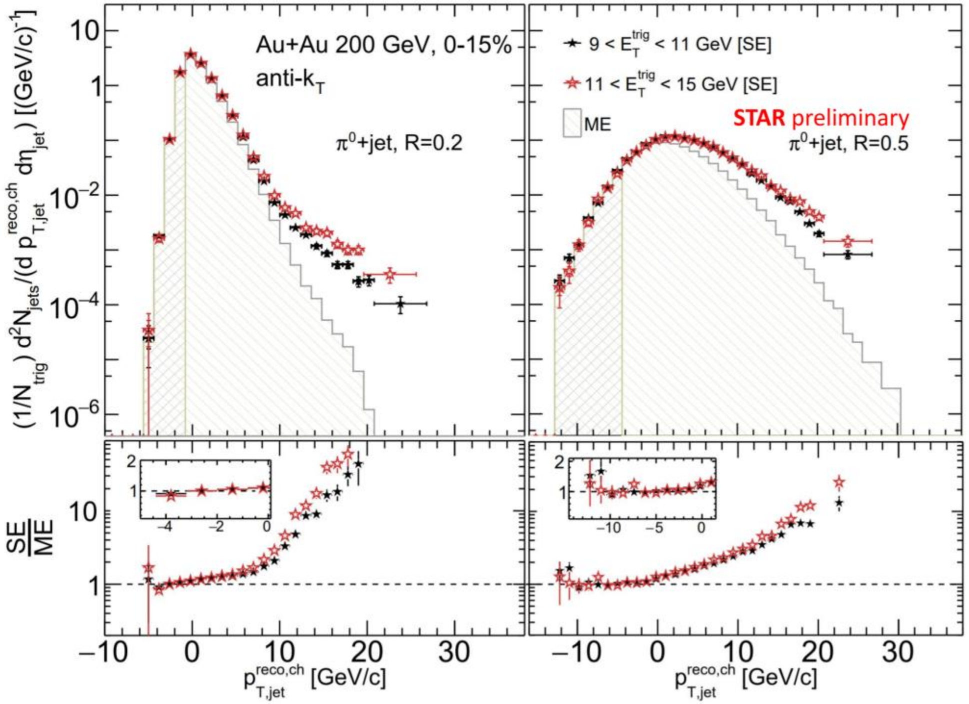


- **Raw $\Delta\phi$ yields obtained by**
  1) Bin jets according to $\Delta\phi$ and $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$
  2) Each ($\Delta\phi$, $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$) bin corrected with ME subtraction
  3) Yield for a $\Delta\phi$ bin is integral over ME-subtracted $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$ distribution

- **Corrected $\Delta\phi$ yields obtained by**
  1) Each ($\Delta\phi$, $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$) distribution unfolded to correct for $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$ smearing
  2) Unfolded $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$ distributions integrated to give corrected $\Delta\phi$ yields
  3) Correction for $\Delta\phi$ smearing applied

Raw $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$ distributions in Au+Au



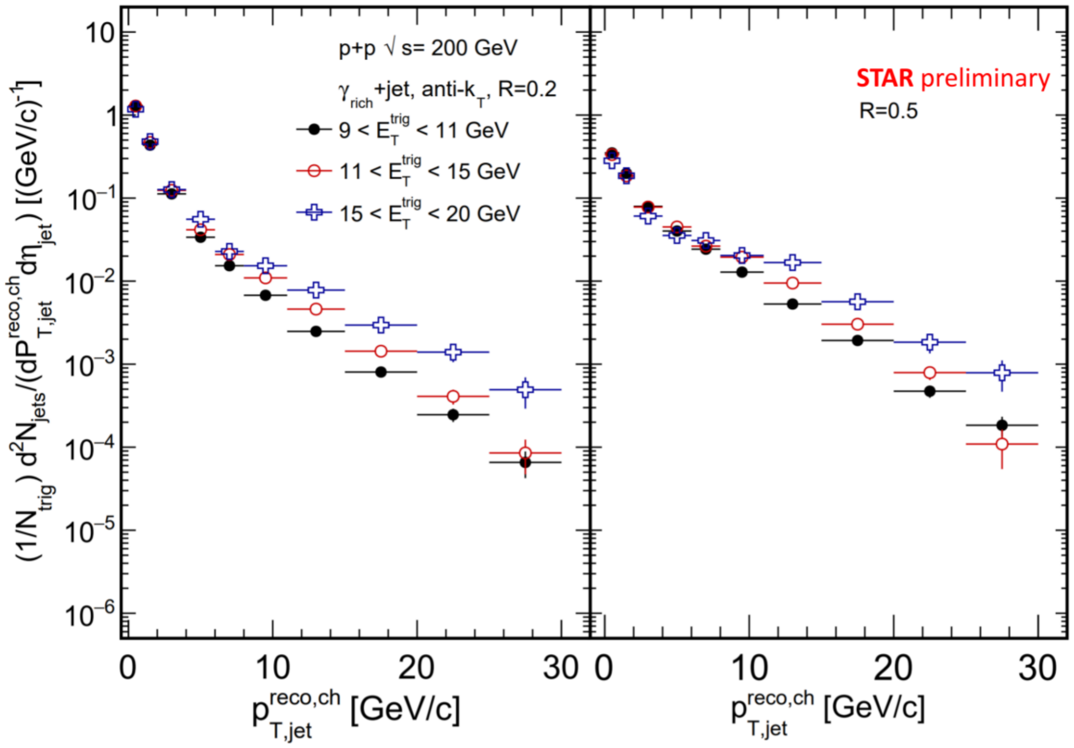


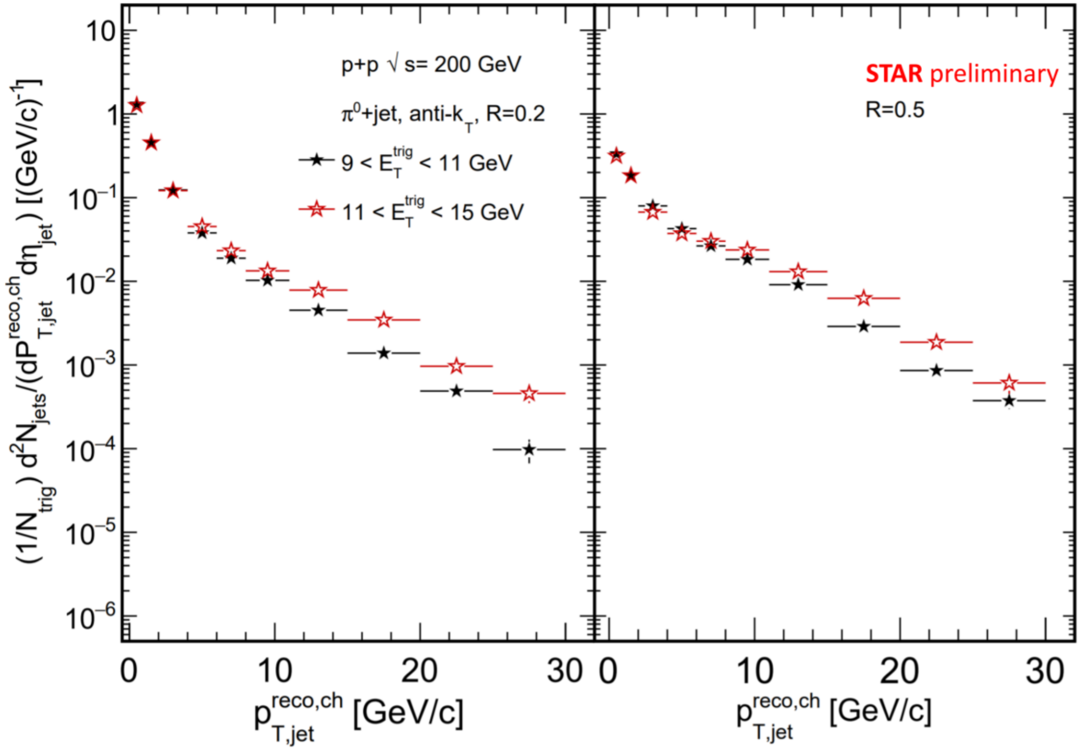
- Jets reconstructed by clustering TPC tracks
  - Clustered using anti-k_T algorithm
  - With $\boldsymbol{R} = \mathbf{0.2, 0.5}$
- Jet p_T adjusted for background energy density via

$$\boldsymbol{p}_{\mathbf{T,jet}}^{\mathbf{reco,ch}} = \boldsymbol{p}_{\mathbf{T,jet}}^{\mathbf{raw,ch}} - \boldsymbol{\rho} \cdot \boldsymbol{A}_{\mathbf{jet}}$$

- Substantial heavy-ion combinatoric background corrected with **Mixed-Event (ME) Technique**
  - Shaded regions indicate jets from mixed events

Raw $p_{\mathrm{T,jet}}^{\mathrm{reco,ch}}$ distributions in $p+p$





- Jets reconstructed by clustering TPC tracks
  - Clustered using anti-k_T algorithm
  - With $\boldsymbol{R = 0.2, 0.5}$
- Jet p_T adjusted for background energy density via

$$\boldsymbol{p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho \cdot A_{\mathrm{jet}}}$$

- Only underlying event correction applied to pp jet distributions is the background energy density correction

Analysis details

- **Data used:**
  - Run 14, 200 GeV AuAu collisions ($\mathcal{L}\sim 3.9$ nb^{-1})
  - Run 9, 200 GeV pp collisions ($\mathcal{L}\sim 14$ pb^{-1})
  - L2gamma Stream
  - No. of pp triggered events
    - ~18,000 π^0-triggers
    - ~24,000 γ_{rich}-triggers
  - No. of AuAu triggered events
    - ~52,000 π^0-triggers
    - ~127,000 γ_{rich}-triggers
  - π^0 and γ_{rich} identified using Transverse Shower Profile (TSP) cuts

- **Trigger definition:**
  - $E_{\text{T}}^{\text{trg}} \in (9,20)$ GeV, $|\eta_{\text{trg}}| < 0.9$
    - Split into bins of 9 – 11, 11 – 15, and 15 – 20 GeV
  - TSP cuts:
    - $\text{TSP} < 0.08$ for π^0
    - $\text{TSP} \in (0.2, 0.6)$ for γ_{rich}
  - Additional QA cuts:
    - $\sum p^{\text{match}} < 3$ GeV/c
    - $e_{\eta}^{\text{strip}}, e_{\phi}^{\text{strip}} \geq 0.5$ GeV

- **Track requirements:**
  - $p_{\text{T}}^{\text{trk}} \in (0.2, 30)$ GeV/c
  - $|\eta_{\text{trk}}| < 1$
  - Additional QA cuts:
    - $N_{\text{fit}} \geq 15$, $N_{\text{fit}}/N_{\text{poss}} \geq 0.52$
    - dca < 1 cm (global)

- **Jet details:**
  - Clustered with FastJet 3.0.6
  - Anti-k_{T} algorithm
  - $R = 0.2$ and 0.5
  - $|\eta_{\text{jet}}| < 1 - R$
  - $p_{\text{T,jet}}^{\text{raw,ch}} \in (0.2, 30)$ GeV/c
  - $p_{\text{T,jet}}^{\text{reco,ch}} = p_{\text{T,jet}}^{\text{raw,ch}} - (\rho \cdot A_{\text{jet}})$
    - $\rho \equiv \text{median}\{p_{\text{T,jet}}^{\text{raw,ch}}/A_{\text{jet}}\}$, excluding hardest jet
  - $A_{\text{jet}} > 0.05, 0.65$ (for $R = 0.2, 0.5$)
  - Recoil jets is any jet with $|\Delta\varphi - \pi| < \pi/4$

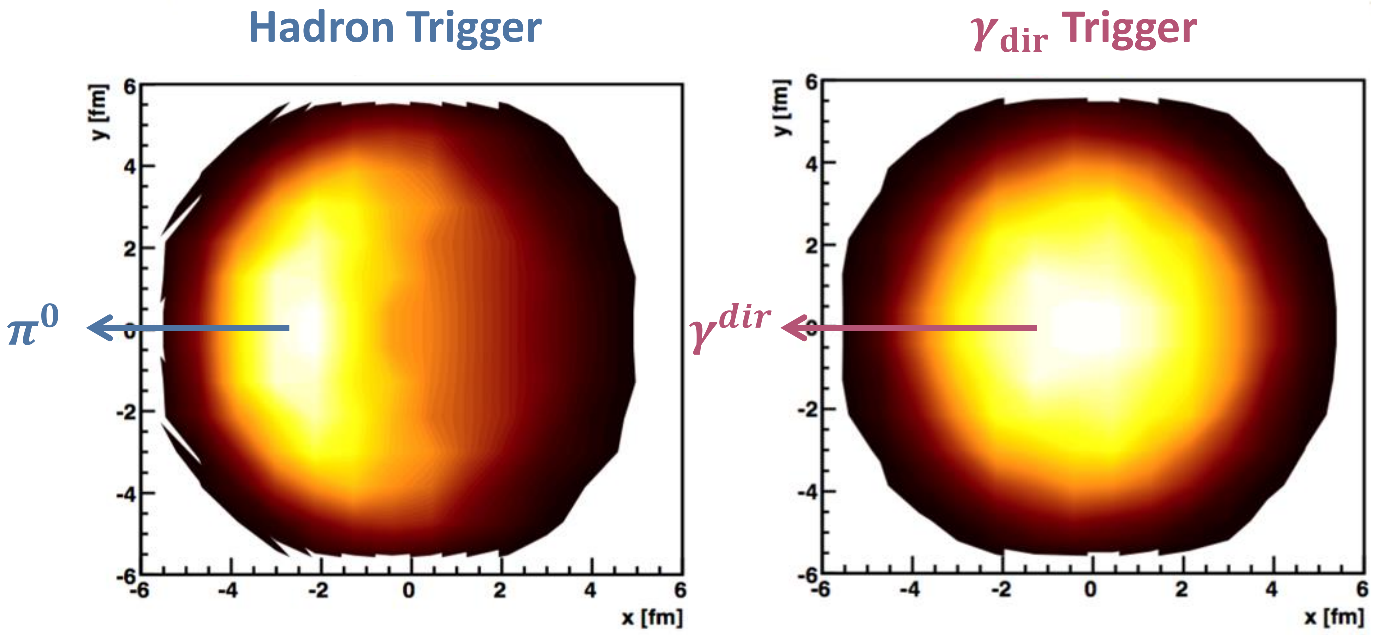
- **Unfolding details:**
  - Bayesian algorithm (via RooUnfold)
  - $n_{\text{iter}} = 4, 3$ (for $R = 0.2, 0.5$) used as default

- **L2gamma definition:**
  - Satisfies VPDMB and BHT2 triggers
    - **VPDMB Trigger:** coincident activity in east and west VPD detectors
    - **BHT2 Trigger:** ∃ tower in the event which contains >4.3 GeV
  - ∃ a 3x3 cluster of EMC towers whose 2 most energetic towers contains a sum total of >7.44 GeV

$\gamma_{\mathrm{dir}}/\pi^0$+jet as probes of jet quenching

- **Prompt photon (γ_{dir}):** photon scattered from energetic partons
  - Doesn't strongly interact with medium so
    $$E_{\mathrm{T}}^{\gamma} \approx E_{\mathrm{T}}^{\mathrm{parton}}(t_0)$$
  - ∴ Recoiling parton provides well-calibrated probe of partonic energy loss…
    - Wang et al, PRL **77**, 231 (1996)

- Comparing γ_{dir} to π^0 triggers:
  a) Different recoil path lengths on average
  b) Different q/g fractions between recoil populations
  c) Different recoil spectrum shape
  ⇒ **Suppression experienced by recoil jets should differ**

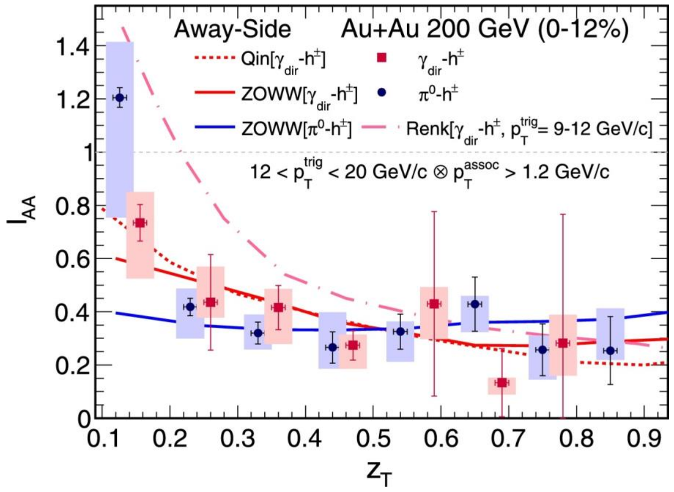


Adapted from
T. Renk, PRC **88**, 054902 (2013)

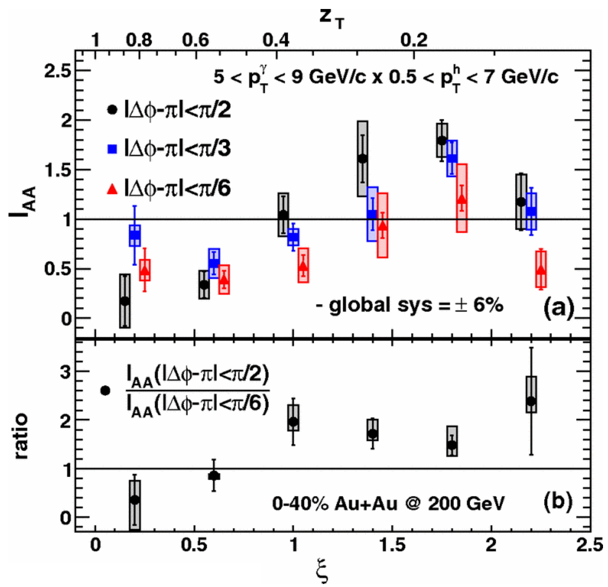
Previous $\gamma_{\mathrm{dir}}/\pi^0$ quenching measurements

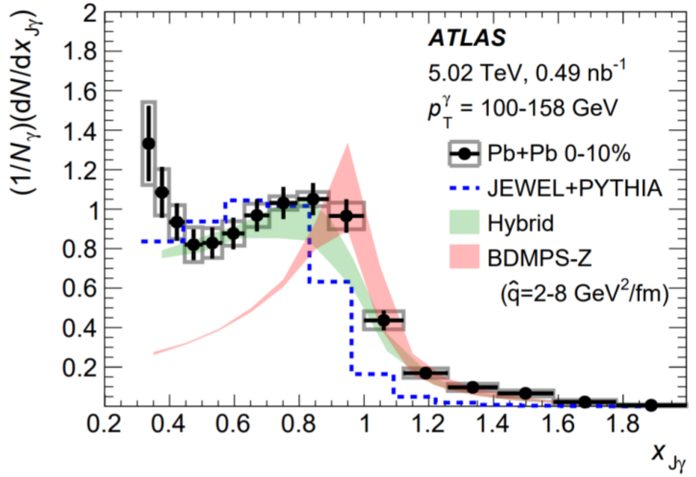
- STAR measured jet quenching using $h^{\pm}$ correlated with $\gamma_{\mathrm{dir}}/\pi^0$
  - ☞ Data cannot resolve differences in quenching between $\gamma_{\mathrm{dir}}/\pi^0$ triggers predicted by models
- Comparisons to other measurements:
  - – suggest lost energy redistributed into medium beneath **fixed p_{T}** rather than z_{T}…
- **Reconstructed jets** can be used to investigate low p_{T} region and search for jet broadening
  - – γ_{dir}+jet measurements have been done at the LHC, but not at RHIC
- How is jet energy redistributed in medium?
  - ☞ **Full picture requires measurement of jets over full phase space**
  - ☞ (including larger R and lower p_{T})

STAR, PLB **760**, 689 (2016)



PHENIX, PRL **111**, 032301 (2013)

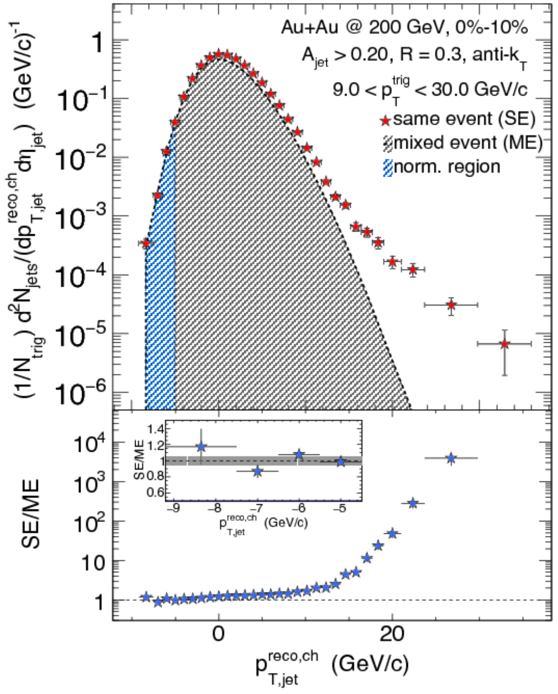




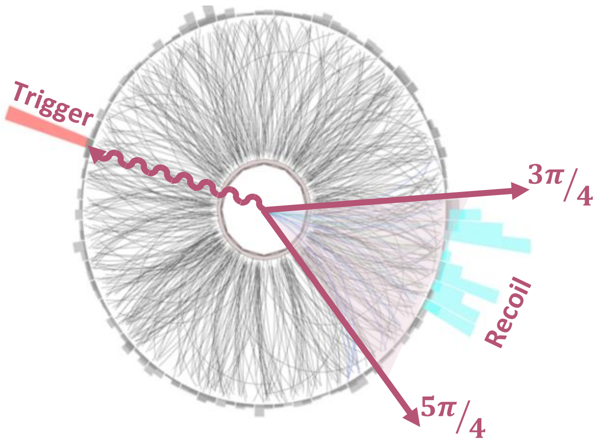
ATLAS, PLB **789**, 167 (2019)

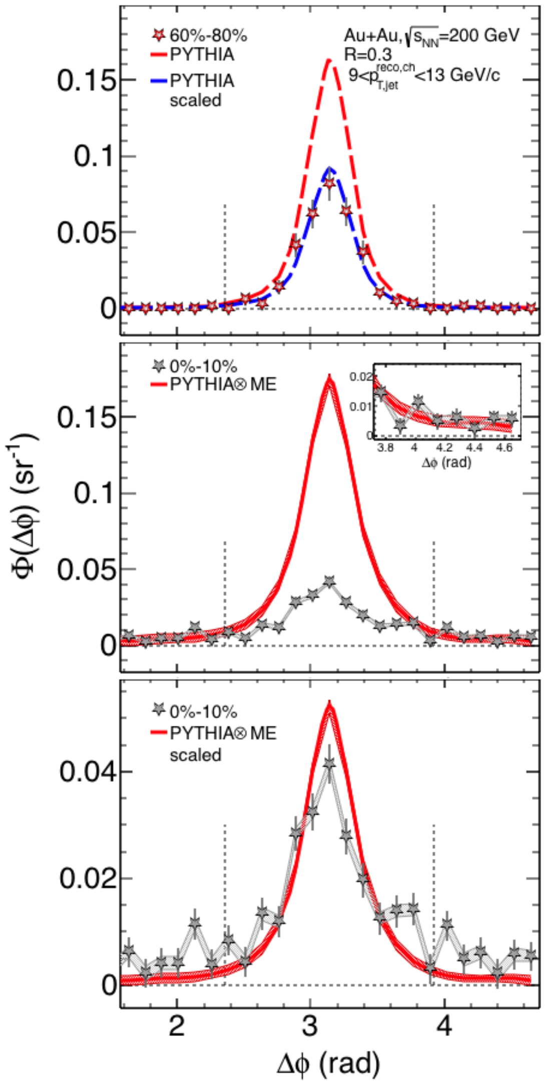
Semi-inclusive jet measurements

- Semi-inclusive approach to jet-quenching offers effective method to measure jets over full phase space
  - › ALICE, JHEP **09**, 170 (2015)
  - › STAR, PRC **96**, 024905 (2017)
- **The approach:**
  - Collisions containing energetic triggers ($h^{\pm}, \pi^0, \gamma_{\mathrm{dir}}$) selected exclusively, and then **recoil jets** measured inclusively
  - Corrections carried at an ensemble-average level
- **Approach used to measure medium modification (quenching, broadening, and acoplanarity) at RHIC**



STAR, PRC **96**, 024905 (2017)





STAR, PRC **96**, 024905 (2017)