Measurement of medium-induced modification of $\gamma_{\text{dir}}+\text{jet}$ and $\pi^0+\text{jet}$ yield and acoplanarity in $p+p$ and central Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV by STAR
$\gamma_{\text{dir}}/\pi^0 + \text{jet}$ as probes of the QGP

- Jets coincident with direct photons ($\gamma_{\text{dir}}$) are valuable probe to study in-medium modification (jet quenching)
  - $\gamma_{\text{dir}}$ constrains kinematics of recoil jet

- Comparing $\gamma_{\text{dir}}/\pi^0$ triggers:
  - Different q/g fractions
  - Different recoil path length distributions

Adapted from Renk, PRC 88, 054902 (2013)
$\gamma_{\text{dir}}/\pi^0$ + jet as probes of the QGP

- **Medium-induced energy loss**
  - $\Rightarrow$ Energy transported outside jet cone

- **Acoplanarity**: recoil jet deflected from $\gamma_{\text{dir}}/\pi^0$ 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
STAR $\gamma_{\text{dir}} + h^\pm$ and semi-inclusive $h^\pm +$jet measurements

- STAR identified $\gamma_{\text{dir}}/\pi^0$ to measure quenching of correlated $h^\pm$
  - Did not reconstruct jets
  - $\gamma_{\text{dir}}/\pi^0$ axis provides reference for broadening

- STAR also measured semi-inclusive yields of recoil jets correlated with $h^\pm$ triggers to search for medium modification
  - $\gamma_{\text{dir}}$ triggers were not used

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

- **Time Projection Chamber (TPC)**
  - charged particles ($|\eta| < 1$, full azimuth)

- **Barrel Electromagnetic Calorimeter (BEMC):**
  - trigger on energetic $\gamma_{\text{dir}}$ or $\pi^0$

- **Barrel Shower Maximum Detector (BSMD):**
  - discriminates $\gamma_{\text{dir}}/\pi^0$ based on transverse shower profile

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

In memoriam, Tom Cormier
Candidate $\pi^0/\gamma_{\text{dir}}$ triggers are clusters made of:
- 1 or 2 BEMC towers, and
- 15 $\eta$ and 15 $\phi$ BSMD strips

$\gamma^0/\gamma_{\text{dir}}$ identified via Transverse Shower Profile (TSP):

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

TSP used to split data into two samples:

i. 95% pure sample of $\pi^0$

ii. Sample with an enhanced fraction of $\gamma_{\text{dir}}$ ($\gamma_{\text{rich}}$)

$\gamma_{\text{rich}}$ background levels ($B$)

- 33% ~ 16% (Au+Au)
- 57% ~ 47% (p+p)

Decay background in $\gamma_{\text{rich}}$ removed via statistical subtraction

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

- Measured via near-side $h^\pm$ yields
- Includes some fragmentation photons

> STAR, PRC 82, 034909 (2010)
Raw jet distributions

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

- Trigger-jet azimuthal separation:
  \[ \Delta \phi = \phi_{\text{trig}} - \phi_{\text{recoil jet}} \]

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

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

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

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

Raw semi-inclusive $\gamma_{rich}^{jet}$ distributions in Au+Au collisions
Recoil $p_{T,\text{jet}}^{\text{ch}}$ yield corrections

- $p_{T,\text{jet}}^{\text{ch}}$ shifted and smeared by:
  1. Presence of HI background (Au+Au only)
  2. 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 $p_{T,\text{jet}}^{\text{ch}}$ and $\Delta \phi$ smearing
  - Response matrix factorized into:
    1. $p_{T,\text{jet}}^{\text{ch}}$-smearing piece
    2. $\Delta \phi$-smearing piece

≈ Nihar Sahoo poster [Wed T04_1]

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Corrected recoil jet distributions

- Semi-inclusive recoil jet $p_{T,jet}^{ch}$ distributions
  - $E_T^{\text{trig}} (\pi^0)$: [9, 11], [11, 15] GeV
  - $E_T^{\text{trig}} (\gamma_{\text{dir}})$: [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)
  - $E_T^{\text{trig}}$ shifted and smeared to account for trigger energy scale/resolution
### Comparison to $h^{±}$+jet measurement

[STAR, PRC 96, 024905 (2017)]

- **$I_{AA}$**: yield ratio Au+Au/$p+p$ for **same $R$**
  \[ I_{AA} \equiv Y_{AuAu}/Y_{pp} \]

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

- **$R^{0.2/0.5}$**: yield ratio $R = 0.2/0.5$ ratio for **same system**
  \[ R^{0.2/0.5} \equiv Y_{0.2}/Y_{0.5} \]

- This analysis consistent with published $h^{±}$+jet
  - **Note**: different $E_T^{\text{trig}}$ range

- Comparison to PYTHIA-8:
  - Smaller uncertainties in this analysis enable discrimination
  - Measured $R^{0.2/0.5}$ less than PYTHIA-8
Comparison to $h^{\pm}\text{+jet}$ measurement

[STAR, PRC 96, 024905 (2017)]

- $I_{AA}$: yield ratio $\text{Au+Au}/p+p$ for same $R$
  \[ I_{AA} \equiv \frac{Y_{\text{AuAu}}}{Y_{pp}} \]
- $I_{CP}$: yield ratio $\text{Au+Au}$ central/peripheral for same $R$
  \[ I_{CP} \equiv \frac{Y_{\text{cent}}}{Y_{\text{per}}} \]
  - $h^{\pm}\text{+jet}$: central = 0 – 10%, peripheral = 60 – 80%
- \( \mathcal{R}^{0.2/0.5} \): yield ratio $R = 0.2/0.5$ ratio for same system
  \[ \mathcal{R}^{0.2/0.5} \equiv \frac{Y_{0.2}}{Y_{0.5}} \]

- This analysis consistent with published $h^{\pm}\text{+jet}$
  - **Note:** different $E_T^{\text{trig}}$ range

- Comparison to PYTHIA-8:
  - Smaller uncertainties in this analysis enable discrimination
  - **Measured** $\mathcal{R}^{0.2/0.5}$ less than PYTHIA-8
R dependence of $I_{AA}$

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

- $\pi^0$ and $\gamma_{\text{dir}} I_{AA}$ consistent
  ⇒ Different q/g fractions, path length distribution
  - $\gamma_{\text{dir}} + \text{jet recoil spectrum steeper}$
    ⊳ Same suppression from smaller energy loss?

New: Baseline is measured $p+p$ distribution
Comparison of $I_{AA}$ to theory

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

- **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)
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

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

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

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

- Corrected $\Delta \phi$ spectra in $p+p$ compared against $E_T^{\text{trig}}$ smeared PYTHIA-8
  - PYTHIA-8 consistent with Data
  
- PYTHIA-8 only LO+LL
  
\[ R = 0.2 \]

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

\[ R = 0.5 \]

\[ \pi^0 \]
Corrected $\Delta\phi$ distributions in Au+Au collisions

- **$R = 0.2$**
  - Corrected $\Delta\phi$ spectra in Au+Au compared against smeared PYTHIA-8
    - $\Rightarrow$ PYTHIA-8 validated against $\pi^0$+jet $p+p$ data
  - **Note:** $\Delta\phi$ integrated yield is $I_{AA}$

- **$R = 0.5$**
  - 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

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Summary

- $I_{AA}$ consistent between $\pi^0$+jet and $\gamma_{\text{dir}}$+jet
  - Different q/g fractions, different recoil path length distributions, different spectra shapes
  - Tension with theoretical predictions...

- $I_{AA}$ and $\eta^{0.2/0.5}$ 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
Thank you!

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

- $R = 0.2$ (left) and 0.5 (right) semi-inclusive $\pi^0$+jet and $\gamma_{\text{dir}}$+jet spectra in PYTHIA-8

- **Notice:** $\gamma_{\text{dir}}$+jet spectra are significantly steeper than $\pi^0$+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, $v_2$, event plane, etc. distributions
    - Event-wise shift in energy applied to MEs to match $\rho$ of SEs
- MEs reproduce ensemble-averaged features of real events
  - But any multi-hadron correlations are destroyed

**Figures:** MB AuAu $\rho$ distributions (left) for SEs vs. MEs before and after shift, and MB AuAu track ($\eta, \phi$) distributions (right) for SE vs. MEs.
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 $p_{T,\text{trg}}$
♡ MPI rate in Au+Au small at RHIC. Will be even smaller in $p+p$!

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

- Relative fraction of quarks recoiling from $\pi^0/\gamma_{\text{dir}}$ triggers calculated in PYTHIA-6 (STAR tune) as:
  \[ q/(q+g) \]
  - $q$: no. of events w/ quarks as recoil partons
  - $(q+g)$: total no. of events

- Recoil partons selected by
  1) Identifying immediate product of hard scatter responsible for $\pi^0$ trigger via distance cut in $(\eta, \phi)$ space
     - Distance cut not necessary for $\gamma_{\text{dir}}$ triggers
  2) Recoil parton is then the other parton
     - Recoil partons required to have $|\eta| < 1$
Extracting $\gamma_{\text{dir}}$ from $\gamma_{\text{rich}}$

- Background level of $\gamma_{\text{rich}}$ measured by taking ratio of Near-Side per-trigger yields: 
  \[ B = \frac{Y_{pp}^{\gamma_{\text{rich}}}}{Y_{pp}^{\gamma_{\text{rich}}} / Y_{pp}^{\pi^0}} \]
  - Decay component subtracted from $\gamma_{\text{rich}}$ via:
    \[ Y_{pp}^{\gamma_{\text{dir}}} = \frac{Y_{pp}^{\gamma_{\text{rich}}} - B \cdot Y_{pp}^{\pi^0}}{1 - B} \]

- For $E_T^{\text{trig}} \in (9,11)$ GeV in $p+p$ collisions, $B$ is measured to be: 
  \[ B \approx 0.57 \pm 0.05 \]

- Assumptions:
  I. $\gamma_{\text{dir}}$ have zero NS correlated yield.
  II. NS correlated yields for decay photons from asymmetric decays have same functional shape as measured $\pi^0$ NS correlated yield.

Figure: Per-trigger azimuthal yields of correlated hadrons for $\pi^0_{\text{rich}}$ and $\gamma_{\text{rich}}$ triggers in 40 – 80% (left) and 0 – 10% (right) central Au+Au collisions.
Trigger energy scale

- Energy of trigger $\pi^0/\gamma_{\text{dir}}$ 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 $\sim97\%$ for $\gamma$ across $E_{T,\text{trg}}$
  b) TES is $92\% \sim 97\%$ for $\pi^0$ with increasing $E_{T,\text{trg}}$
  c) TER is $\sim8\%$ for both $\gamma$ and $\pi^0$ across $E_{T,\text{trg}}$

Figure: impact of TES/R smearing on PYTHIA-6 (STAR tune) $\gamma_{\text{dir}}$-triggered recoil jets
Δϕ calculation and correction procedure

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

- **Corrected Δϕ yields obtained by**
  1) Each $(Δϕ, p_{T, \text{jet}}^{\text{reco, ch}})$ distribution unfolded to correct for $p_{T, \text{jet}}^{\text{reco, ch}}$ smearing
  2) Unfolded $p_{T, \text{jet}}^{\text{reco, ch}}$ distributions integrated to give corrected Δϕ yields
  3) Correction for Δϕ smearing applied
O Jets reconstructed by clustering TPC tracks
  - Clustered using anti-$k_T$ algorithm
  - With $R = 0.2, 0.5$

O Jet $p_T$ adjusted for background energy density via

\[ p_{T,\text{jet}}^{\text{reco},\text{ch}} = p_{T,\text{jet}}^{\text{raw},\text{ch}} - \rho \cdot A_{\text{jet}} \]

O Substantial heavy-ion combinatoric background corrected with Mixed-Event (ME) Technique
  - Shaded regions indicate jets from mixed events
Jet $p_T$ adjusted for background energy density via

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

- Jets reconstructed by clustering TPC tracks
  - Clustered using anti-$k_T$ algorithm
  - With $R = 0.2, 0.5$
- 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
    - $\sim 18,000 \pi^0$-triggers
    - $\sim 24,000 \gamma$-rich-triggers
  - No. of AuAu triggered events
    - $\sim 52,000 \pi^0$-triggers
    - $\sim 127,000 \gamma$-rich-triggers
  - $\pi^0$ and $\gamma$-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:
    - TSP $< 0.08$ for $\pi^0$
    - TSP $\in (0.2, 0.6)$ for $\gamma$-rich
  - Additional QA cuts:
    - $\sum p_{\text{match}}^{\text{match}} < 3$ GeV/c
    - $e_\eta^{\text{strip}}, e_\phi^{\text{strip}} \geq 0.5$ GeV

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

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

- **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: $\exists$ tower in the event which contains $>4.3$ GeV
  - $\exists$ a 3x3 cluster of EMC towers whose 2 most energetic towers contains a sum total of $>7.44$ GeV

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\[ \gamma_{\text{dir}}/\pi^0 \text{+jet as probes of jet quenching} \]

- **Prompt photon** \( (\gamma_{\text{dir}}) \): photon scattered from energetic partons
  - Doesn’t strongly interact with medium so \( E_T^{\gamma} \approx E_T^{\text{parton}}(t_0) \)
  - Recoiling parton provides well-calibrated probe of partonic energy loss...
    - Wang et al, PRL 77, 231 (1996)
- Comparing \( \gamma_{\text{dir}} \) to \( \pi^0 \) triggers:
  a) Different recoil path lengths on average
  b) Different q/g fractions between recoil populations
  c) Different recoil spectrum shape
  \( \Rightarrow \text{Suppression experienced by recoil jets should differ} \)

Adapted from T. Renk, PRC 88, 054902 (2013)
Previous $\gamma_{\text{dir}}/\pi^0$ quenching measurements

- STAR measured jet quenching using $h^\pm$ correlated with $\gamma_{\text{dir}}/\pi^0$
  - Data cannot resolve differences in quenching between $\gamma_{\text{dir}}/\pi^0$ 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
  - $\gamma_{\text{dir}}+\text{jet}$ 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 $p_T$)
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 ($h^\pm$, $\pi^0$, $\gamma_{\text{dir}}$) 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