Towards the full reconstruction of neutral-triggered recoil jets in Au+Au Collisions

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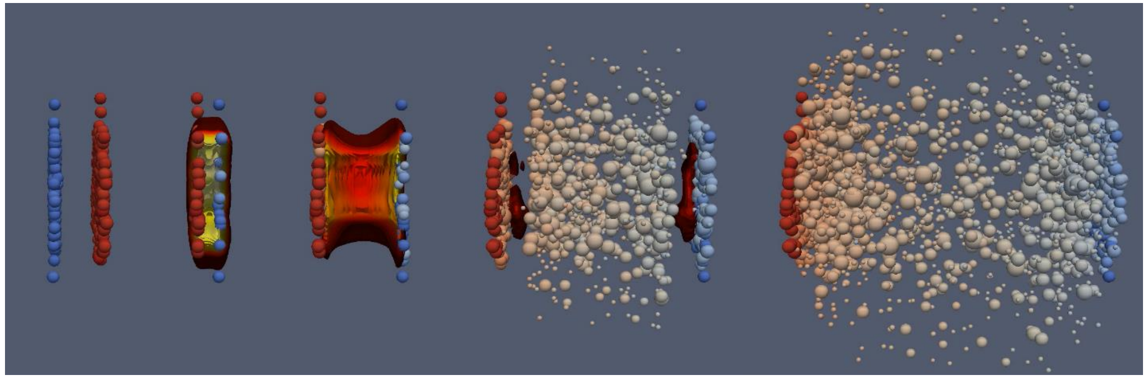
STAR

TEXAS A&M UNIVERSITY

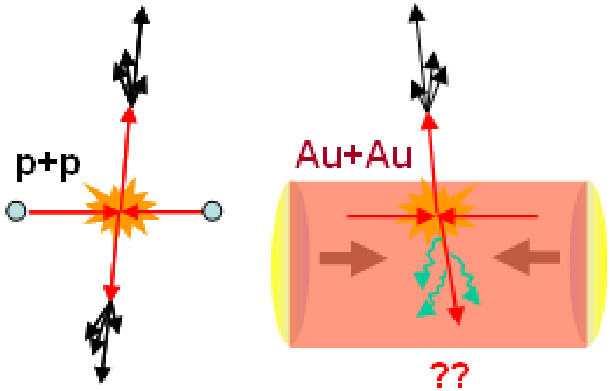
Energy-Loss and Neutral Triggers

- **Jets** are powerful probes of the hot dense medium of heavy ion collisions:
  - Produced early in collision by hard-scattered partons
  - Described perturbatively



Picture credit: Jonah Bernhard

- **Jet-Quenching:** energy loss by gluon radiation
  - Partons lose energy as they traverse QGP
  - Depends on E_0, L, C_A/C_F, $\hat{q}$, α_s, etc…
  - **Can measure by comparing AuAu-collisions to pp-collisions**



- In particular, jets opposite direct photons may provide a promising probe of energy loss

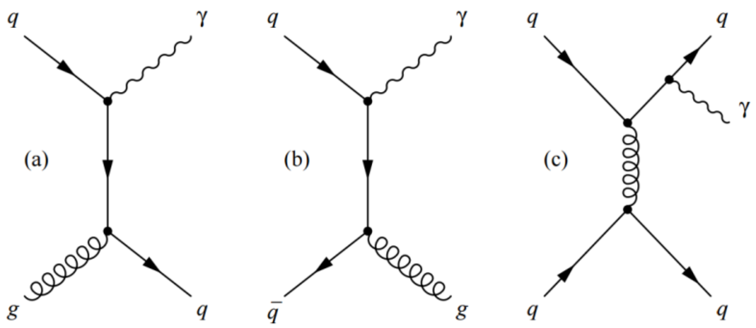
- **Direct photon (γ^{dir}):** photon scattered from energetic partons
  - » Doesn't strongly interact with medium so (to leading order)

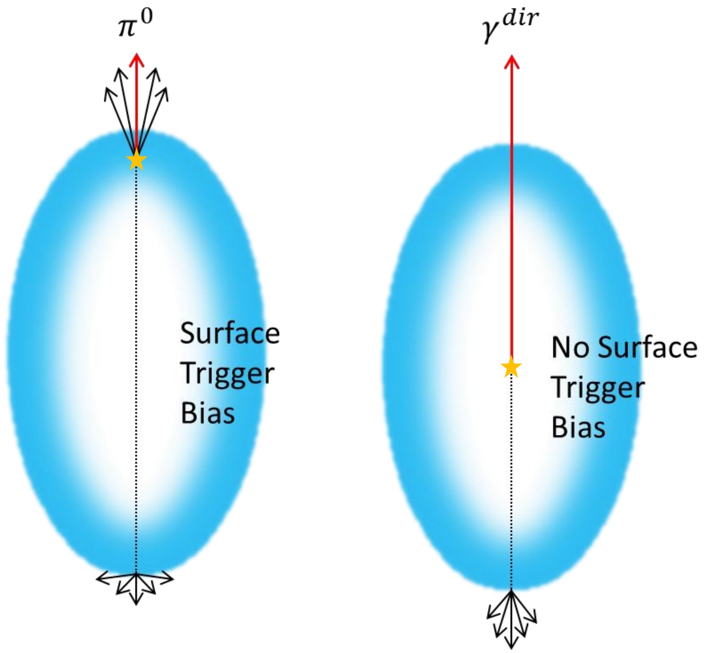
$$E_T^{\gamma} \approx E_T^{parton}(t_0)$$

  - » Powerful way to measure energy loss
    - – PRL 77, 231 (1996)

- Comparison of jets opposite γ^{dir} to those opposite energetic π^0 might illuminate path length and color factor dependence…
  - » **Path Length:**
    - – Energetic π^0 biased towards surface emission
    - – γ^{dir} has no such bias
  - » **Color Factor:**
    - – γ^{dir} mostly opposite quark jets $(C_F = 4/3)$
    - – π^0 mostly opposite gluon jets $(C_A = 3)$
      - › PRD 72, 014014 (2005)

- On average, jets opposite γ^{dir} should **lose less energy** than those opposite π^0

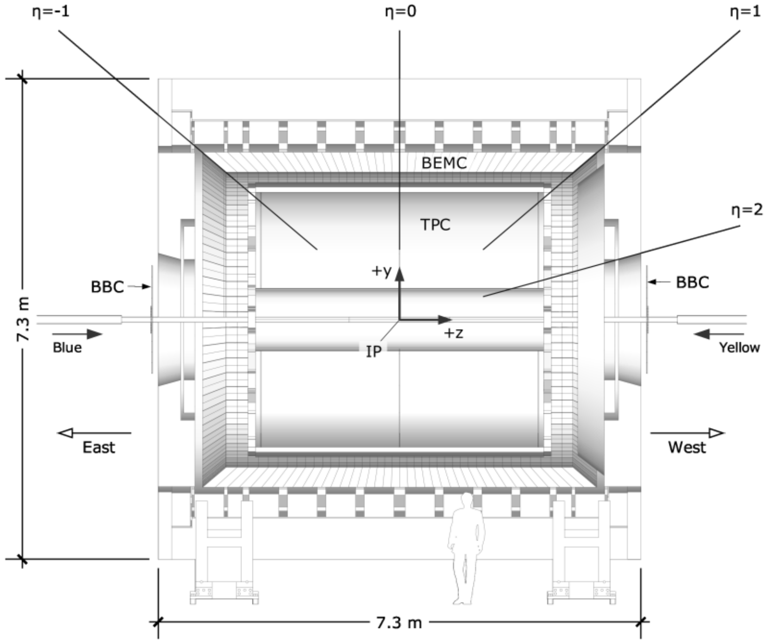




The STAR Experiment

- Located at the **Relativistic Heavy Ion Collider (RHIC):**
  - collides Au-nuclei up to $\sqrt{s_{NN}} = 200$ GeV
  - pp-collisions used as baseline

- As a jet detector:
  - **Time Projection Chamber (TPC)**
    - Measures charged particles
  - **Barrel Electro-Magnetic Calorimeter (BEMC)**
    - Identifies electromagnetic clusters (neutral particles)
  - Both cover $\varphi = 2\pi, \eta = \pm 1$



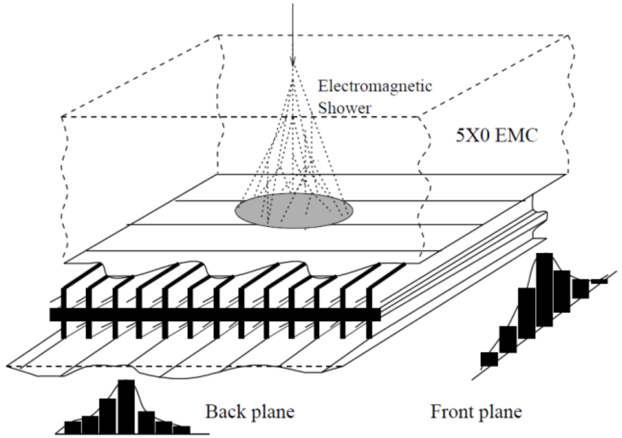
- **Barrel Shower Maximum Detector (BSMD):**
  - Allows for spatial imaging in BEMC

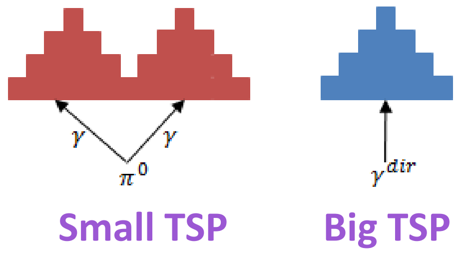
- Energetic π^0 and γ^{dir} discriminated via **Transverse Shower Profile (TSP):**

$$TSP = \frac{E_{cluster}}{\sum_i E_i^{strip} r_i^{1.5}}$$

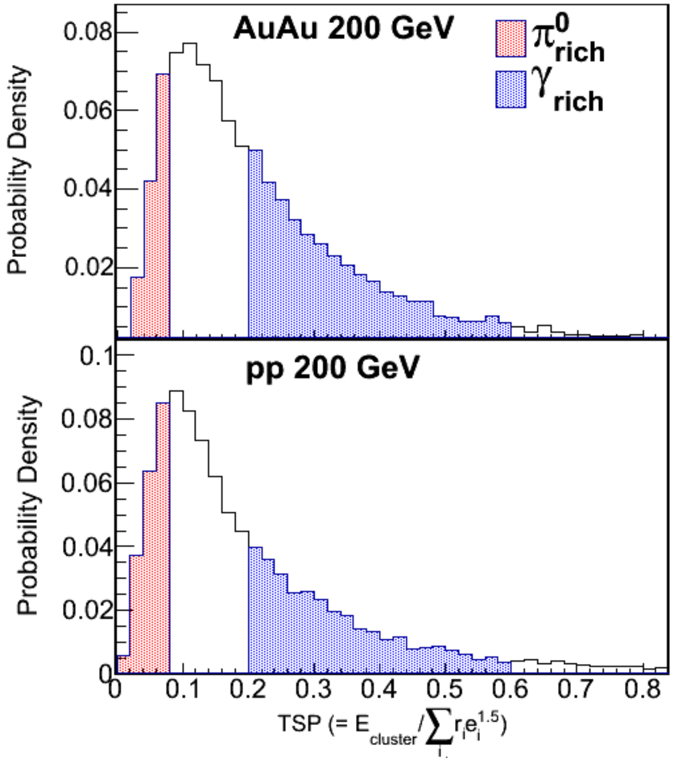
  - $E_{cluster}$ is total energy of cluster
  - E_i^{strip} is energy of ith strip
  - r_i is distance from strip to center of cluster

- Split triggers into a sample of nearly pure π^0 and a sample with enhanced fraction of γ^{dir} (γ^{rich})
  - $N^{\gamma^{dir}}/N^{\gamma^{rich}}$ ~40% (p+p)
  - $N^{\gamma^{dir}}/N^{\gamma^{rich}}$ ~70% (Au+Au)





arXiv:1512.08782v1 [nucl-ex]

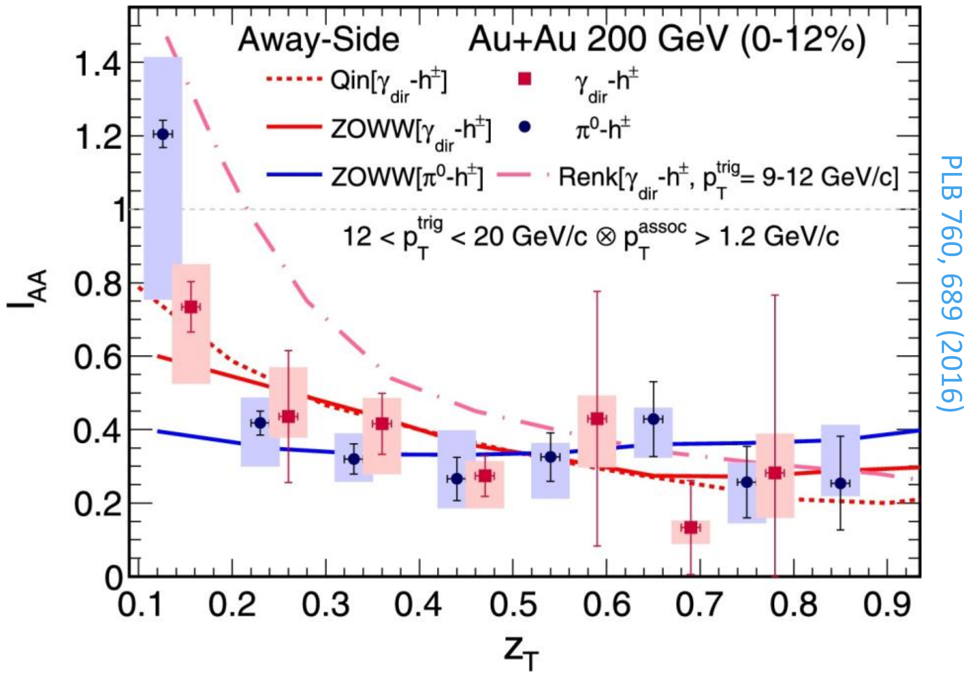


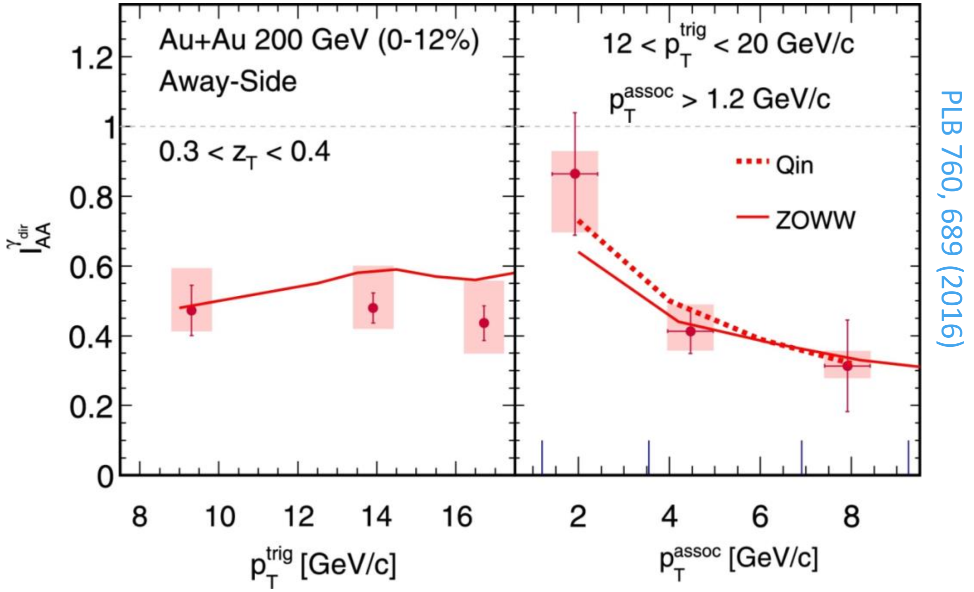
Recent STAR Results

- Recent γ^{dir}, π^0-hadron correlation measured by STAR:
  - » Look for collisions with energetic γ^{dir}, π^0 and measure yield of charged hadrons on **away side:** $$|\Delta\varphi - \pi| < 1.4$$
  - » **Nuclear Modification Factor**: $$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$
- Suppression expected to differ between γ^{dir}-hadrons and π^0-hadrons
  - » **NOT** seen within uncertainties
- For γ^{dir}-hadrons…
  - » **Lower p_T^{assoc} less suppressed than higher p_T^{assoc}**

$$\Delta\varphi = \varphi_{assoc} - \varphi_{trig}$$
$$z_T = \frac{p_T^{assoc}}{p_T^{trig}}$$

- Qin: PRC 80, 054909 (2009)
- ZOWW: PRL 103, 032302 (2009)

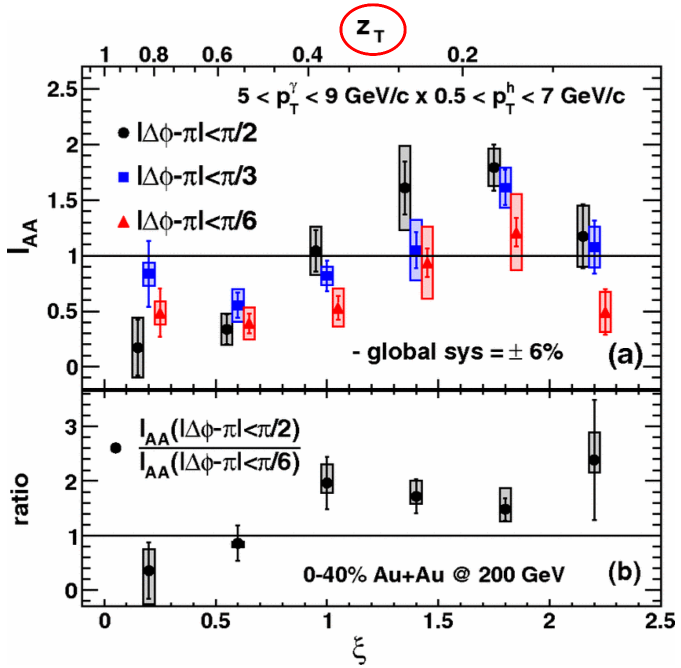




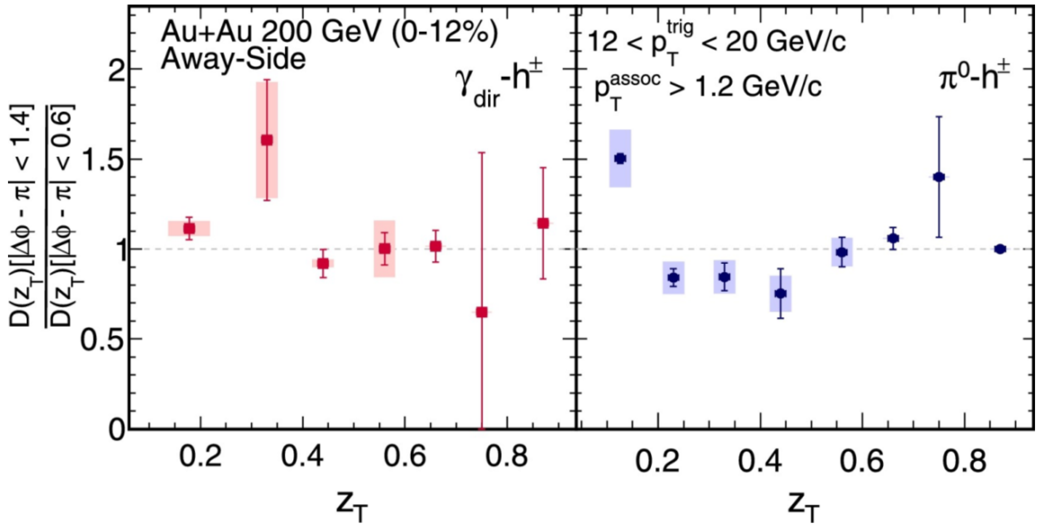
- PHENIX reported:
  - $I_{AA}^{\gamma^{dir}} > 1$ for low z_T and large angles
  - Expected if energy is redistributed in jet
- Comparing yields within $\pm 35°$ and $\pm 80°$ in STAR
  - Low z_T and large angle enhancement seen **only** in π^0 trigger
- For fixed $z_T \in (0.1, 0.4)$:
  - **STAR:** $p_T^{trig} \in (12, 20) \Rightarrow p_T^{assoc} \in (1.2, 8)$
  - **PHENIX:** $p_T^{trig} \in (5, 9) \Rightarrow p_T^{assoc} \in (0.5, 3.6)$

$\Rightarrow$ Both results consistent with picture of lost energy being recovered at low p_T (< 2 GeV/c) **independent of trigger p_T**

$$\xi \equiv \ln \frac{1}{z_T}$$

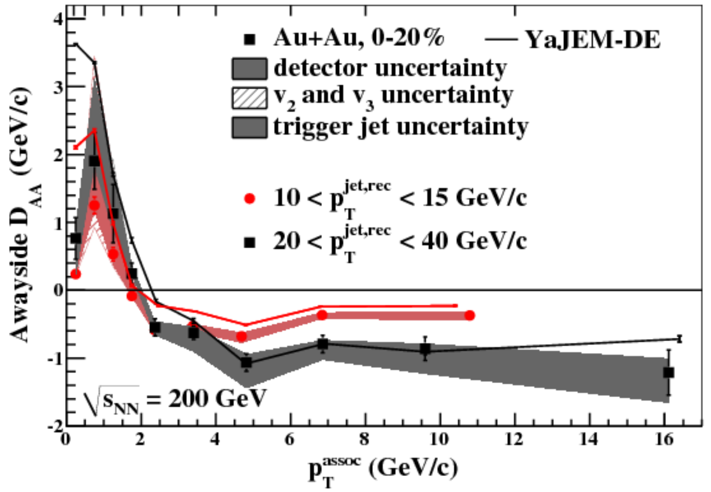


PRL 111, 032301 (2013)



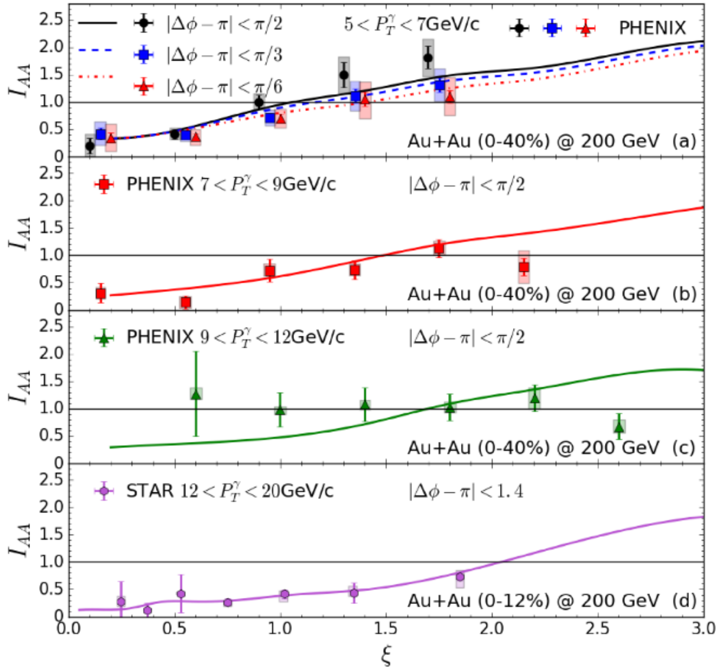
PLB 760, 689 (2016)

- Lost energy being recovered below **fixed p_T** rather than **fixed z_T** consistent with measurement of jet-hadron correlations by STAR
  - Observed enhancement in Au+Au of away-side particles with $p_T < 2$ GeV/c
  - PRL 112, 122301 (2014)



PRL 112, 122301 (2014)

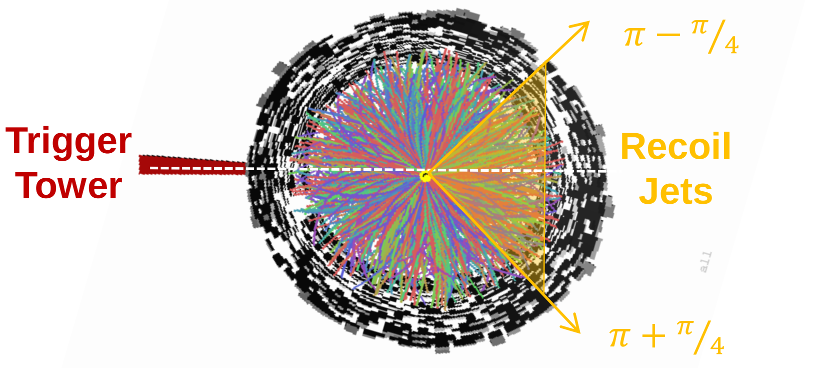
- There has been considerable theoretical activity following the γ^{dir}, π^0-hadron measurement
  - A recent paper by Chen et al attributes this effect to medium excitations
  - arXiv:1704.03648 [nucl-th]



arXiv:1704.03648 [nucl-th]

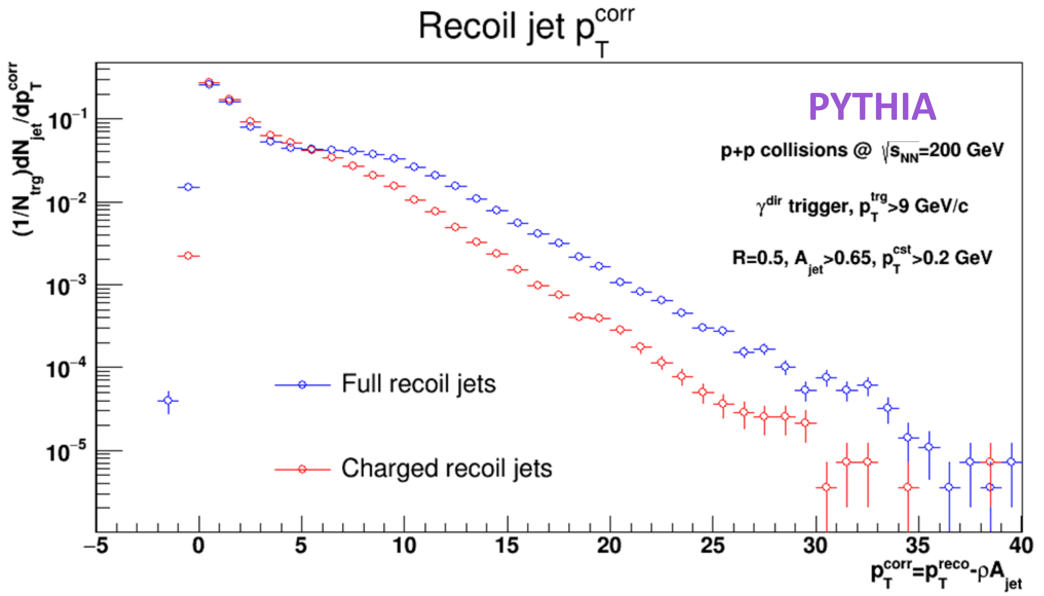
- However, the non-observation of the differences between γ^{dir} and π^0 suppressions demonstrates need for more precise methods

Jet Reconstruction



- Jets defined operationally:
  - » Particles clustered into jets via an algorithm
    - – anti-k_T
    - – R = 0.3, 0.5 (0.7?)
    - – $p_T^{cst} > 0.2$ GeV/c
  - » Clustering done with FastJet
    - – arXiv:1111.6097v1 [hep-ph]

- **Below:** Pythia generated recoil jets (γ^{dir} trigger)
  - » Difference between full and charged jets

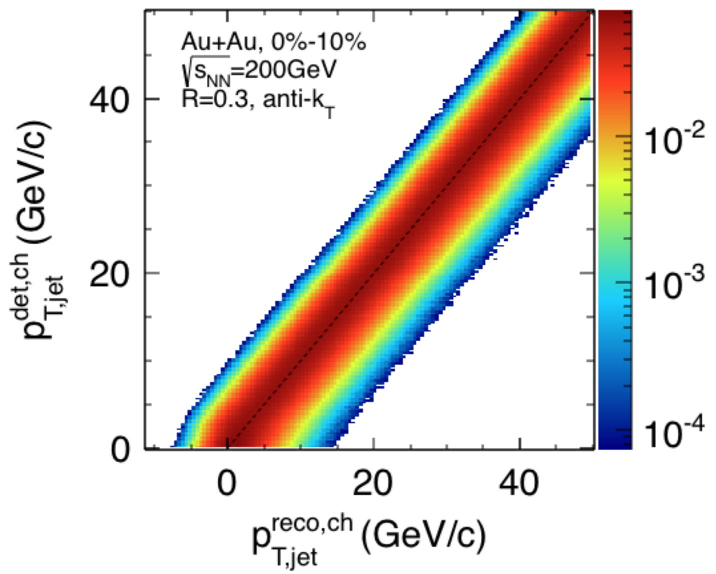


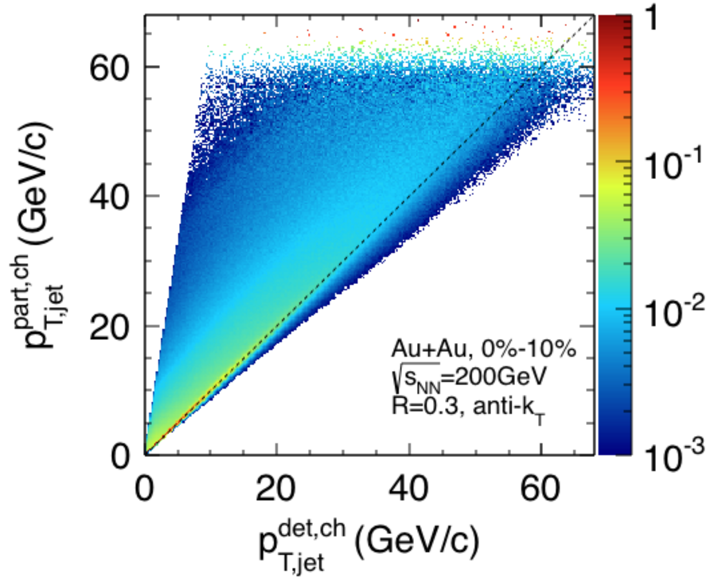
- **Recoil Jets:** any jet satisfying
$$\left|\Delta\varphi^{jet} - \pi\right| < \pi/4$$

- Semi-inclusively measure recoil jets:
  1) Select collisions with high energy γ^{dir} (or π^0)
  2) Cluster charged **and** neutral constituents into jets ("full" jets) using **anti-k_T**
     - – Gives much more precise measurement of E^{jet} than just charged constituents ("charged" jets)
  3) Count all recoil jets

- Numerous sources of background and distortion:
    a) Jet reconstruction
        – Split jets, combinatorial jets, etc.
    b) Underlying event
        – Diffuse radiation not related to the hard scatter
        – Beam remnants, multi-parton interactions, etc.
    c) Heavy-ion background
        – Collective flow, etc.
    d) Detector effects
        – Limited resolution, finite acceptance, etc.
- Similar measurement of semi-inclusive hadron-jet correlations by STAR utilizes these correction schemes:
    a) Regularized unfolding:
        – Detector effects
        – Heavy-ion background
        – Underlying event
    b) Mixed event:
        – Underlying event
        – Jet reconstruction
    » PRC 96, 024905 (2017)

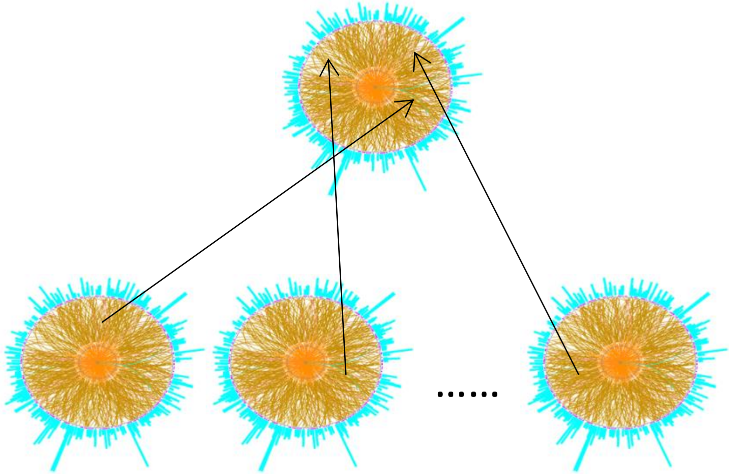
PRC 96, 024905 (2017)





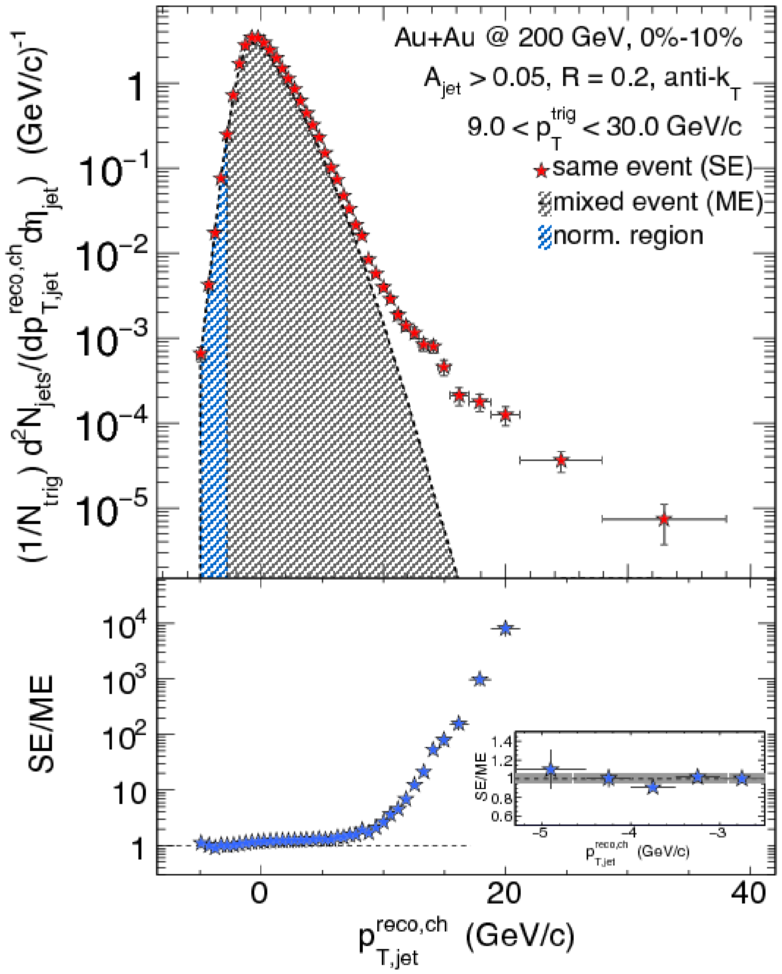
- **Mixed Event:**
  - » Create pseudo-event from randomly selected tracks
    - – Randomly select 1 track per real event
    - – Add it to the Mixed Event
    - – Use only events with same centrality, evt. plane, vtx. z-position
  - » Very good description of combinatorial background

Mixed Evt.



Evt. 1 Evt. 2 …… Evt. 711

Au+Au charged hadron-triggered jet spectrum compared to mixed-event spectrum



PRC 96, 024905 (2017)

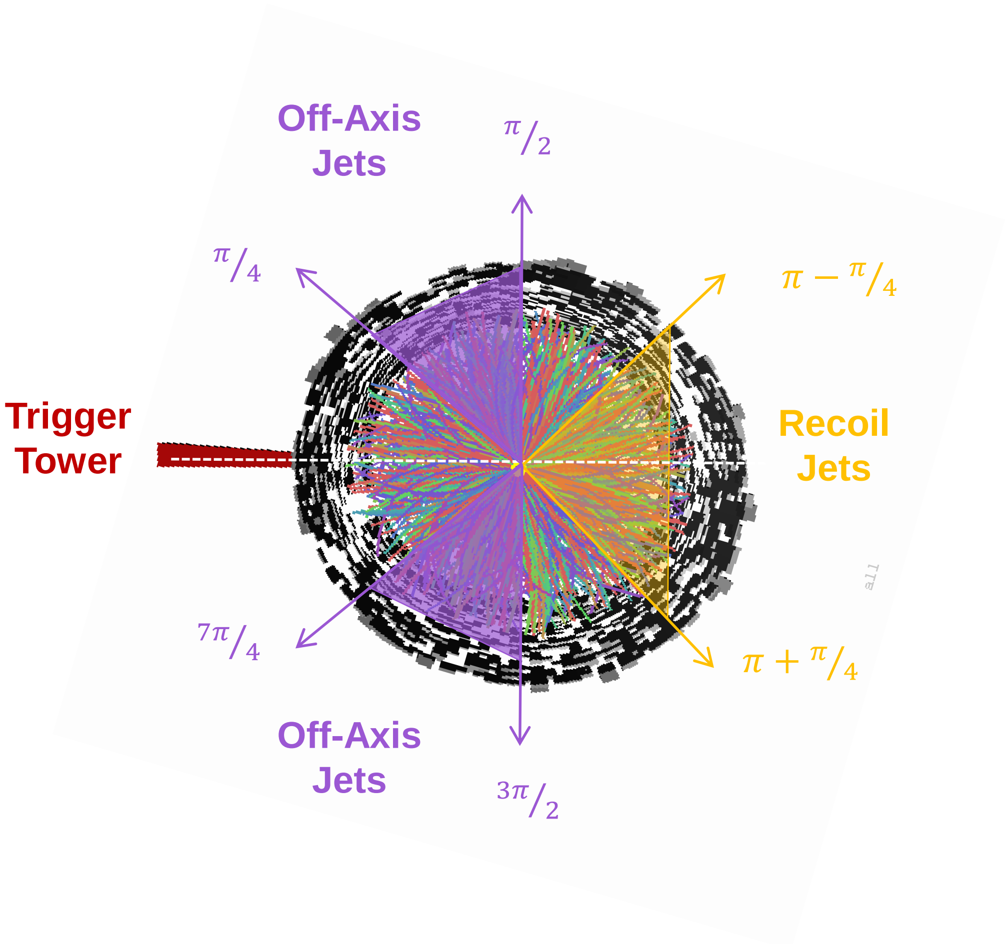
- **Off-axis cone:** interesting to compare to mixed event distribution
  - Select jets falling in these regions:
    $\Delta\varphi^{jet} \in (\pi/4, \pi/2)$
    $\Delta\varphi^{jet} \in (3\pi/2, 7\pi/4)$
  - Possible way to extract large-angle correlations…

- Off-axis yield normalized to:

$$\frac{\left\langle N_{OA}^{jet} \right\rangle - \left\langle N_{RE}^{jet} \right\rangle}{\left\langle N_{OA}^{jet} \right\rangle}$$

  - N_{OA}^{jet} is the no. of jets in off-axis region
  - N_{RE}^{jet} is the no. of recoil jets in acceptance

- Currently investigating…

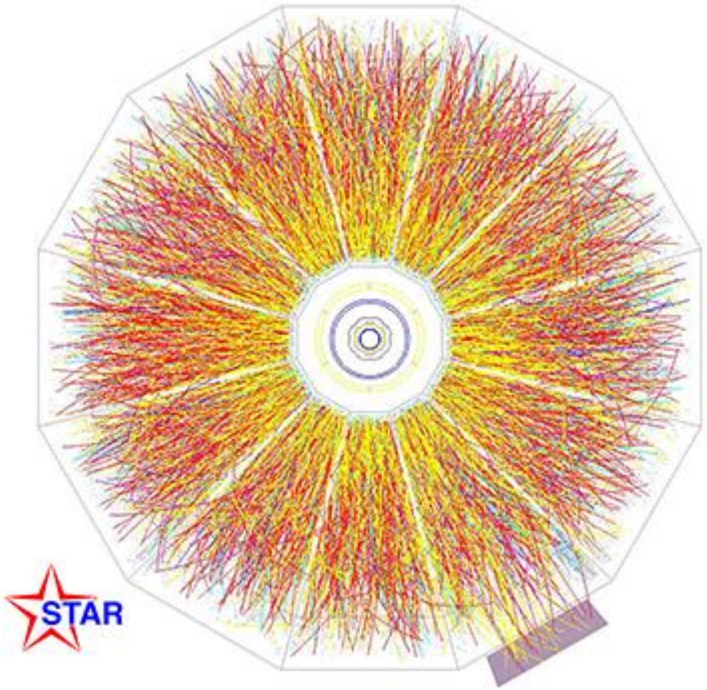


Summary

- Jets opposite neutral triggers may provide a powerful probe of in-medium energy loss
  - Comparison of jets opposite γ^{dir} to those opposite energetic π^0 may shed light on path-length and color factor dependence

- **No** difference in suppression observed **within kinematic range** between charged hadrons opposite γ^{dir} to those opposite energetic π^0
- Comparisons to PHENIX data and jet-hadron correlations point to energy being recovered at low momentum ($p_T^{assoc} < 2$ GeV/c)
  - Points to need for more precise techniques
  - e.g. full jet reconstruction

- Stay tuned!



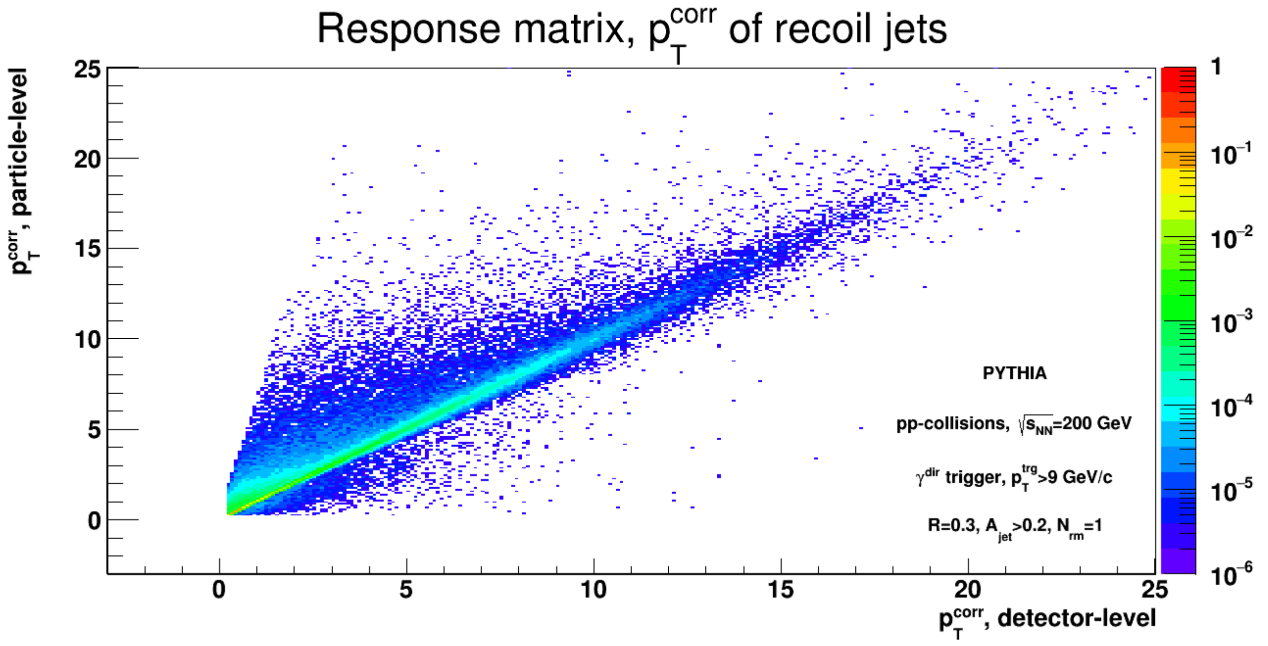
Thank You!

Backup

- **Unfolding:**
  - True spectrum is distorted by background and detector
  - Create a response matrix to map true spectrum onto measured spectrum
    $$M_j = R_{ij} T_i$$
  - R_{ij} calculated by:
    a) Simulate collisions (e.g. Pythia)
    b) Apply "smearing" (e.g. Geant and/or embedding into data)
    c) Match jets before smearing to corresponding jets after smearing
    – Effect of HI background determined by embedding Pythia events in Au+Au events
  - True spectrum then given by:
    $$R_{ij}^{-1} M_j = T_i$$

- Unfolding is "regularized" to account for error bars and the steeply falling spectrum…
  - **Bayesian Method:** R_{ij}^{-1} is guessed based on given prior using Baye's Theorem, and then iteratively tweaked.
    – Must specify no. of iterations
  - **SVD Method:** R_{ij}^{-1} computed indirectly via Singular-Value Decomposition.
    – Must specify no. of terms to keep during SVD

- Unfolding done with RooUnfold
  - arXiv:1105.1160v1 [physics.data-an]



- **Above:**
  - Example response matrix for charged jets