Photon-triggered jet reconstruction at the STAR experiment

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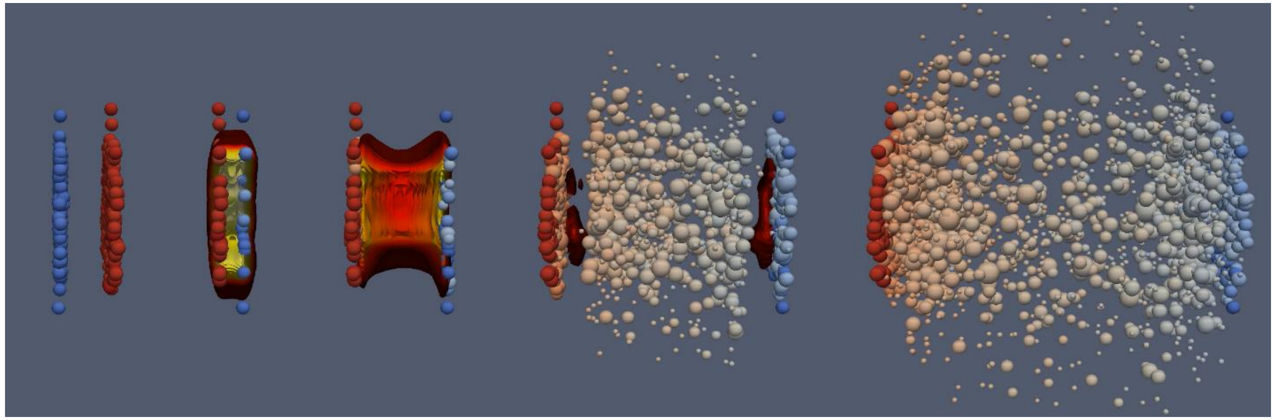
FOR THE STAR COLLABORATION

QGP & Jets

- The **Quark-Gluon Plasma** (QGP) –
  - Color charges confined to hadrons
  - Can be "deconfined" at high temperatures and density
- **RHIC** –
  - Au nuclei collided up to $\sqrt{s_{NN}} = 200$ GeV
  - Proton-proton collisions used as base line
- **Jets** –
  - Collimated sprays of hadrons
  - Produced early in collision by hard-scattered partons
  - Described perturbatively



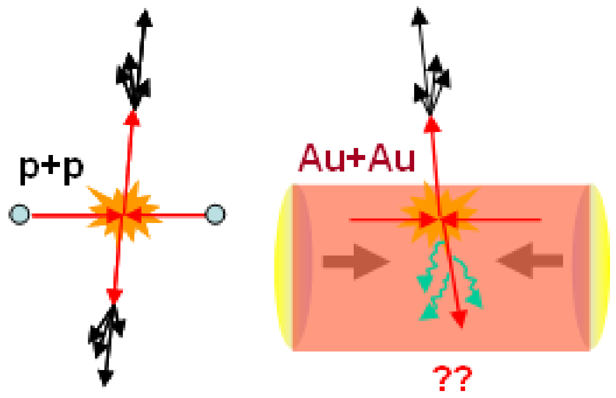
Picture credit: Jonah Bernhard

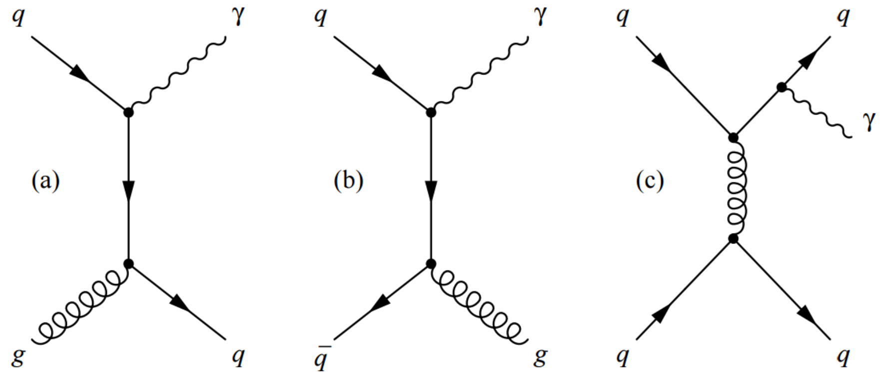
Photon Triggers

- **Jet Quenching** – elastic and inelastic energy loss by gluon radiation
  - » Parton will lose energy as it traverses medium
  - » Depends on initial energy, path length, color factor (C_A/C_F), coupling constant (α_s), etc…
- **Direct photon** (γ^{dir}) – photon scattered from energetic partons
  - » Doesn't strongly interact with medium so (to leading order)

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

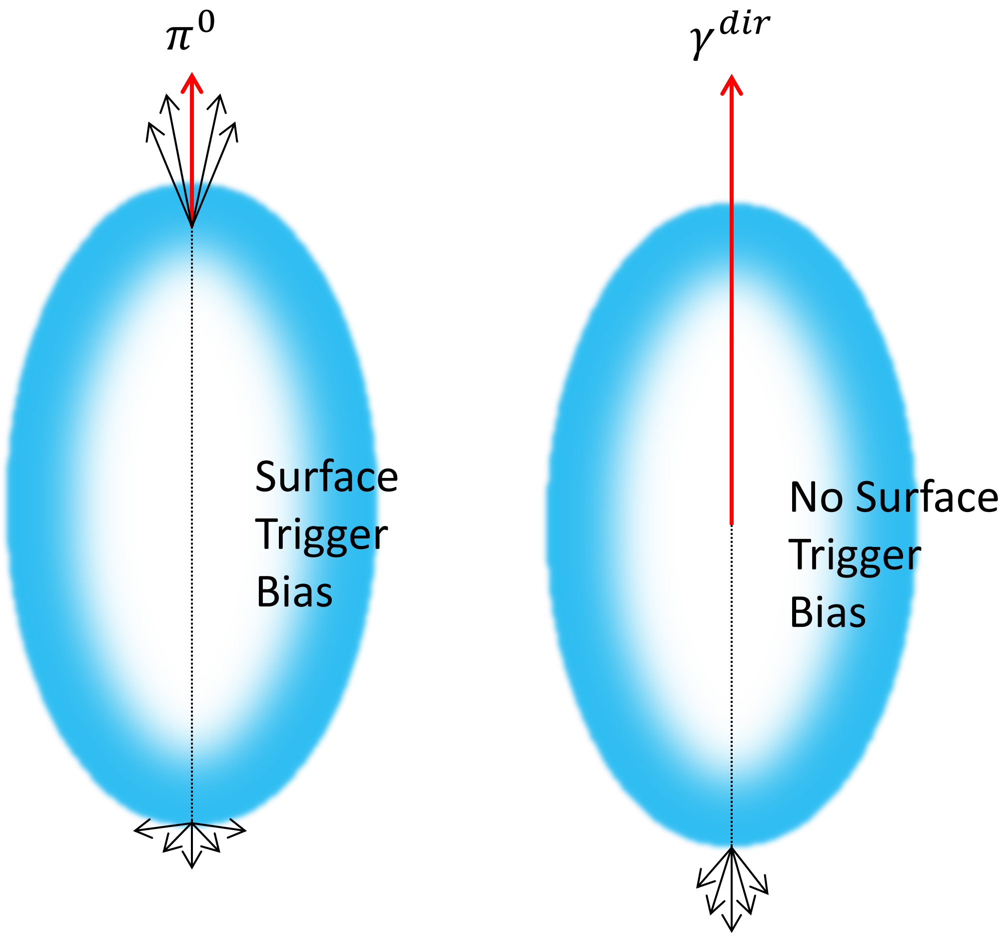
  - » Powerful way to measure energy loss
    - – PRL 77, 231 (1996)
- In experiment, we measure:
  - » γ^{dir}-hadron "jet-like" correlations
    - – PLB 760, 689 (2016)
  - » Reconstructed recoil jets in γ^{dir}-triggered events (ongoing)





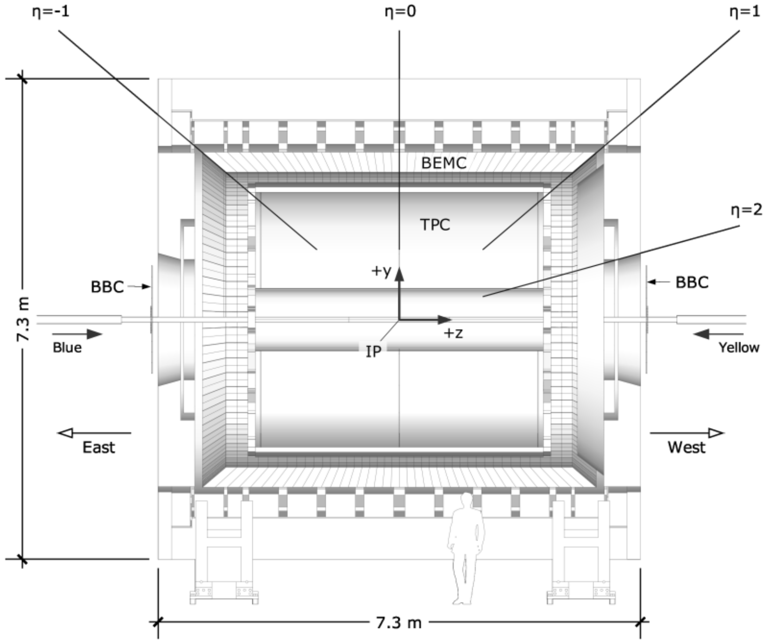
Photon vs. π^0 Triggers

- Compare quenching of jets opposite of γ^{dir}-triggers to those opposite energetic π^0-triggers...
  - Might illuminate path length and color factor dependence of energy loss.
- **Path Length** –
  - Energetic π^0 biased towards surface emission
    - Surface emission implies max path-length of medium for away-side
  - γ^{dir} has no such bias
    - More likely to come from volume of fireball than from surface
- **Color Factor** –
  - γ^{dir} mostly from quark-gluon Compton scattering
    - Mostly quark jets opposite γ^{dir} ($C_F = 4/3$)
  - π^0 from all QCD processes
    - Mostly gluon jets opposite π^0 ($C_A = 3$)
- On average, jets opposite γ^{dir}-triggers should **lose less energy** than those opposite π^0-triggers



The STAR Experiment

- Located at **RHIC** –
  - The Relativistic Heavy-Ion Collider
  - Built to study:
    - Partonic structure of nuclei and nucleons
    - And the **Quark-Gluon Plasma**



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

Neutral Triggers

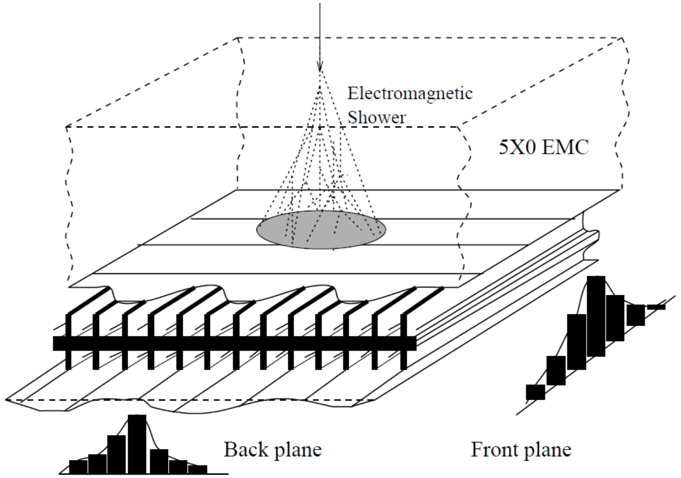
- **Barrel Shower Maximum Detector** (BSMD) – allows for spatial imaging in BEMC

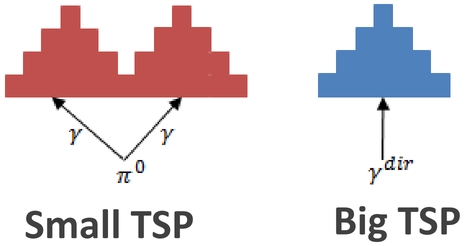
- Energetic π^0 and γ^{dir} discriminated via **Transverse Shower Profile** (TSP) –

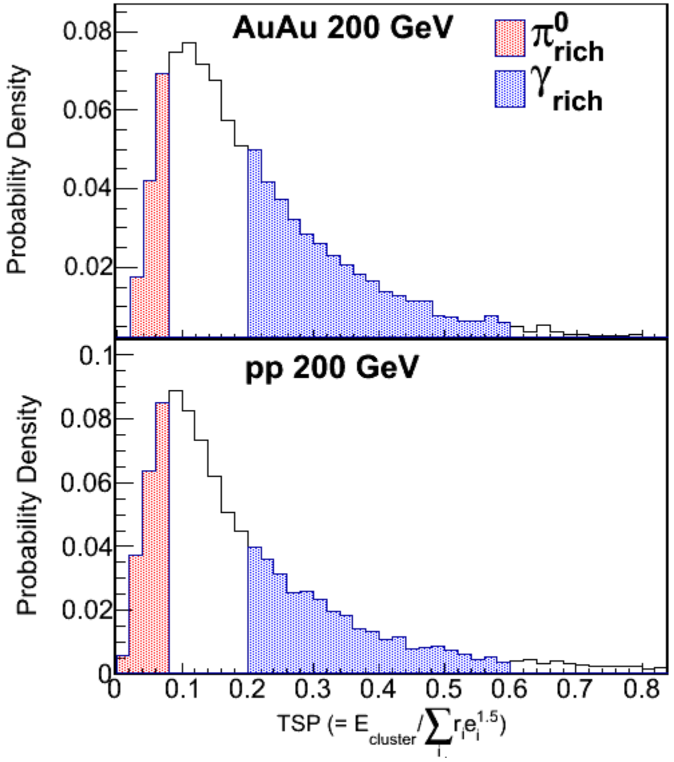
$$TSP = \frac{E_{cluster}}{\sum_i E_i^{strip} r_i^{1.5}}$$

  – $E_{cluster}$ is total energy of cluster
  – E_i^{strip} is energy of i^{th} 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}”)







arXiv:1512.08782v1 [nucl-ex]

γ^{dir}, π^0-Hadron Jet-Like Correlations

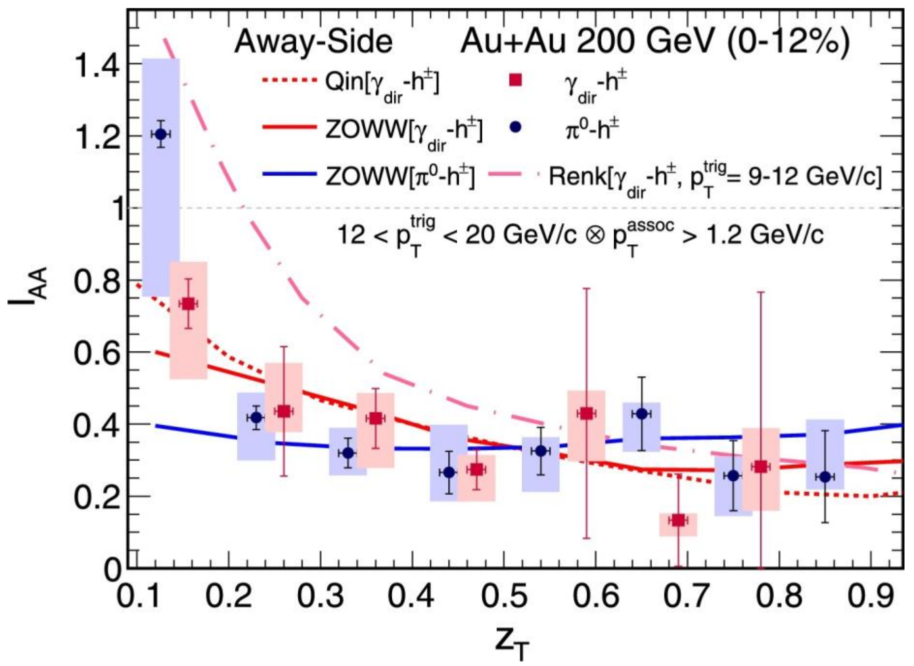
- Look for collisions with energetic γ^{dir}, π^0 and measure yield of charged hadrons on **away side** –

$$|\Delta\varphi - \pi| < 1.4$$

- **Nuclear Modification Factor** –

$$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$

- Comparing $I_{AA}^{\gamma^{dir}}$ to $I_{AA}^{\pi^0}$
  - » γ^{dir}-triggered recoil jets **should lose less energy** than π^0-triggered recoil jets
    - – Suppression should differ due to color factor ($C_F/C_A = 4/9$)
    - – Suppression should differ due to path length
  - » Within uncertainty, **NOT** observed in studied kinematic range



PLB 760, 689 (2016)

$$\Delta\varphi = \varphi_h - \varphi_{trig}$$

$$z_T = \frac{p_T^{assoc}}{p_T^{trig}}$$

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

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- **Nuclear Modification Factor** –

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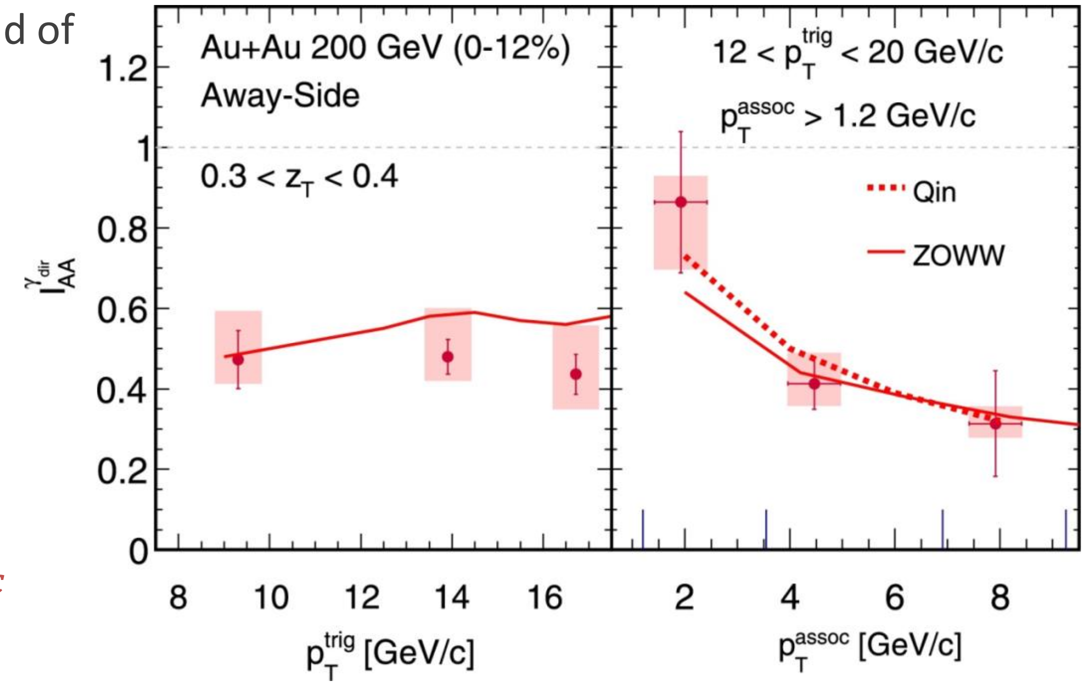
- For γ^{dir}-hadrons
  - Lower p_T^{assoc} less suppressed than higher p_T^{assoc}



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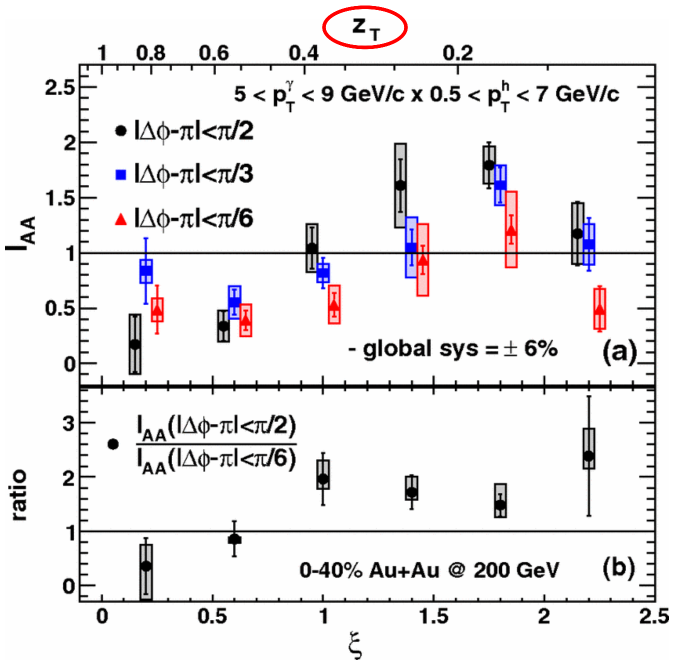
- PHENIX reported:
  - » $I_{AA}^{\gamma^{dir}} > 1$ for low z_T and large angles
  - » Expected if energy is redistributed in jet

- Comparing yields within $\pm 35°$ and $\pm 80°$ in STAR
  - » Low z_T and large angle enhancement seen **only** in π^0 trigger
  - » Possible that lost energy recovered at large angles for range of $p_T^{assoc} < 2$ GeV/c independent of p_T^{trig}

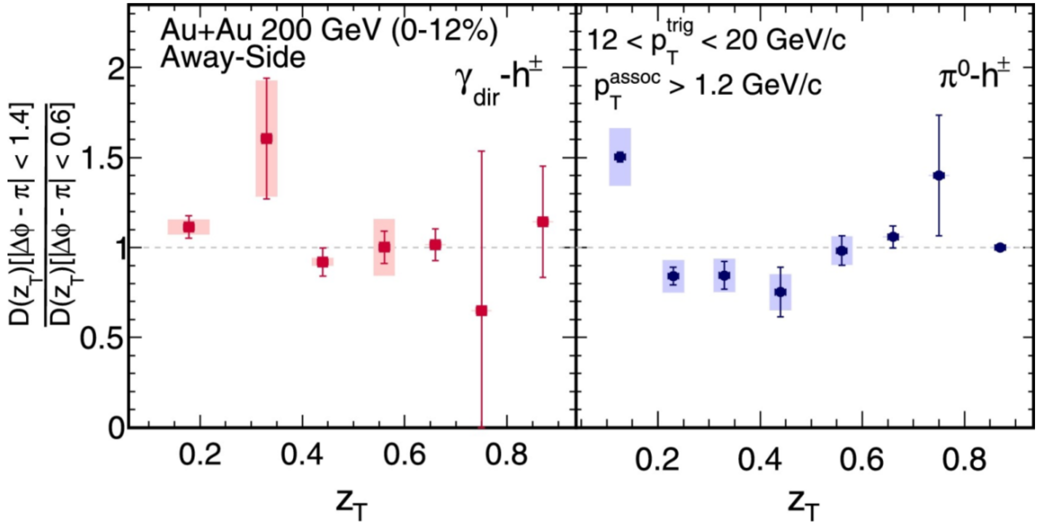
- For fixed $z_T \in (0.1, 0.4)$:
  - » **STAR:** $p_T^{trig} \in (12, 20) \Rightarrow p_T^{assoc} \in (1.2, 8)$
  - » **PHENIX:** $p_T^{trig} \in (5, 9) \Rightarrow p_T^{assoc} \in (0.5, 3.6)$

- Lost energy appears as soft particles emitted at large angles



PRL 111, 032301 (2013)

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



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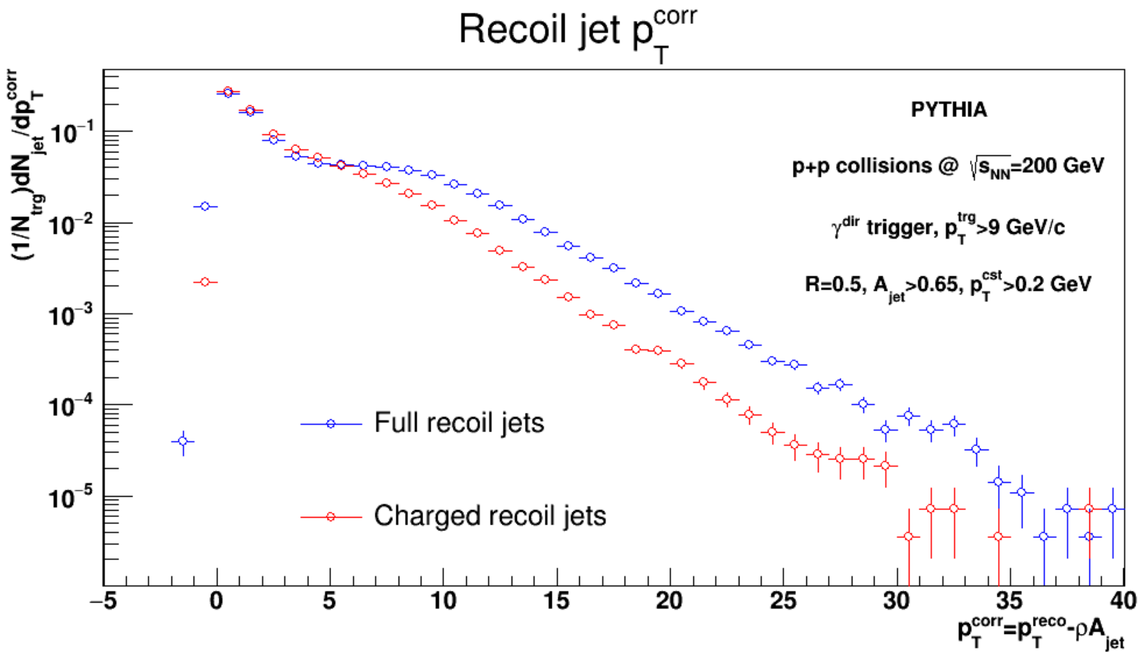
Photon-Triggered Jet Reconstruction

- Jet Reconstruction:
  - Particles clustered into jets via algorithm:
    - Cone, Cambridge-Aachen, k_T, **anti-k_T**
  - Pros:
    - Allows for study of correlations inside jets (jet sub-structure)
    - More sensitive to soft sector ($p_T^{cst} > 0.2$ GeV/c)
  - Cons:
    - **Very** sensitive to fluctuating background

- **Recoil Jets** – any jet satisfying:

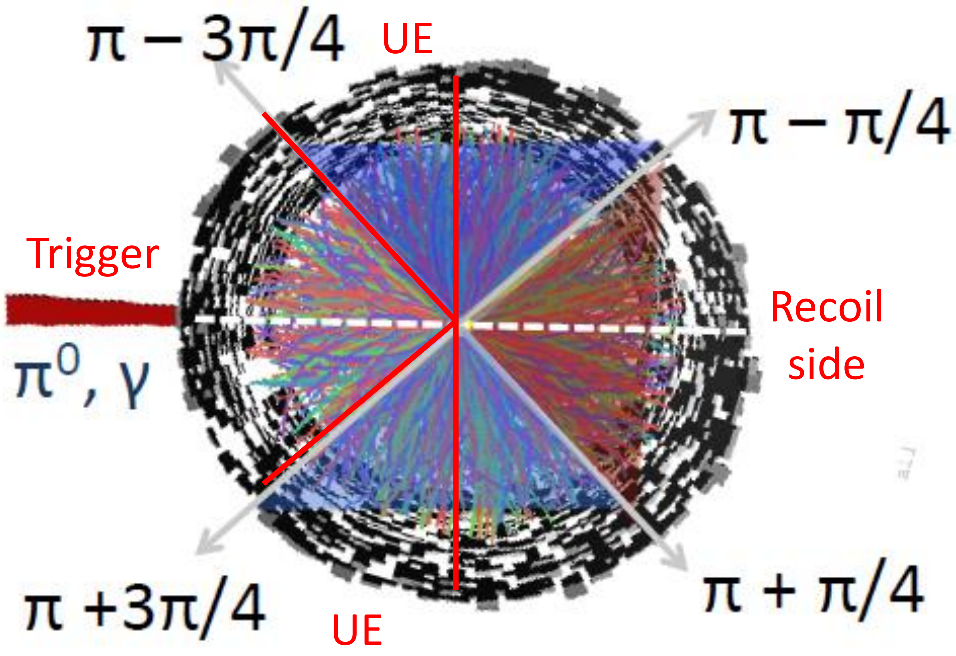
$$|\Delta\varphi - \pi| < \pi/4$$

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

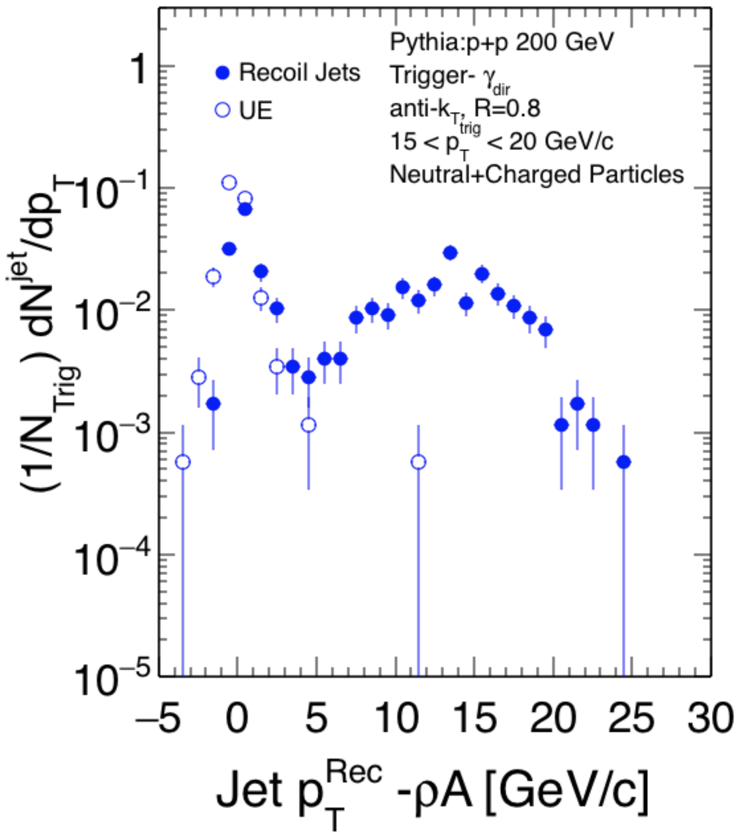


- **Above:**
  - PYTHIA generated recoil jet p_T^{corr} spectrum for **p+p collisions**
  - Illustrates difference between full and charged jets
  - Fastjet: arXiv:1111.6097v1 [hep-ph]

- Background sources in **p+p collisions:**
  - Jet finding
    - Split jets, Combinatorial Jets…
  - Underlying Event
    - Diffuse radiation not related to hard fragmentation
- Background sources in **Heavy Ion (HI) collisions:**
  - Jet finding
  - HI background
    - **Very** large fluctuations, flow, etc…
- Possible background techniques
  - Jet Finding
    - Mixed Event
  - Underlying Event
    - Different $\Delta\varphi$-regions (see left)
  - HI background
    - Unfolding



Preliminary study of γ^{dir}-triggered recoil jets using PYTHIA



- UE spectrum given by:

$$\left(\frac{1}{N_{trg}}\right)\frac{dN_{jet}(UE)}{dp_T}$$

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

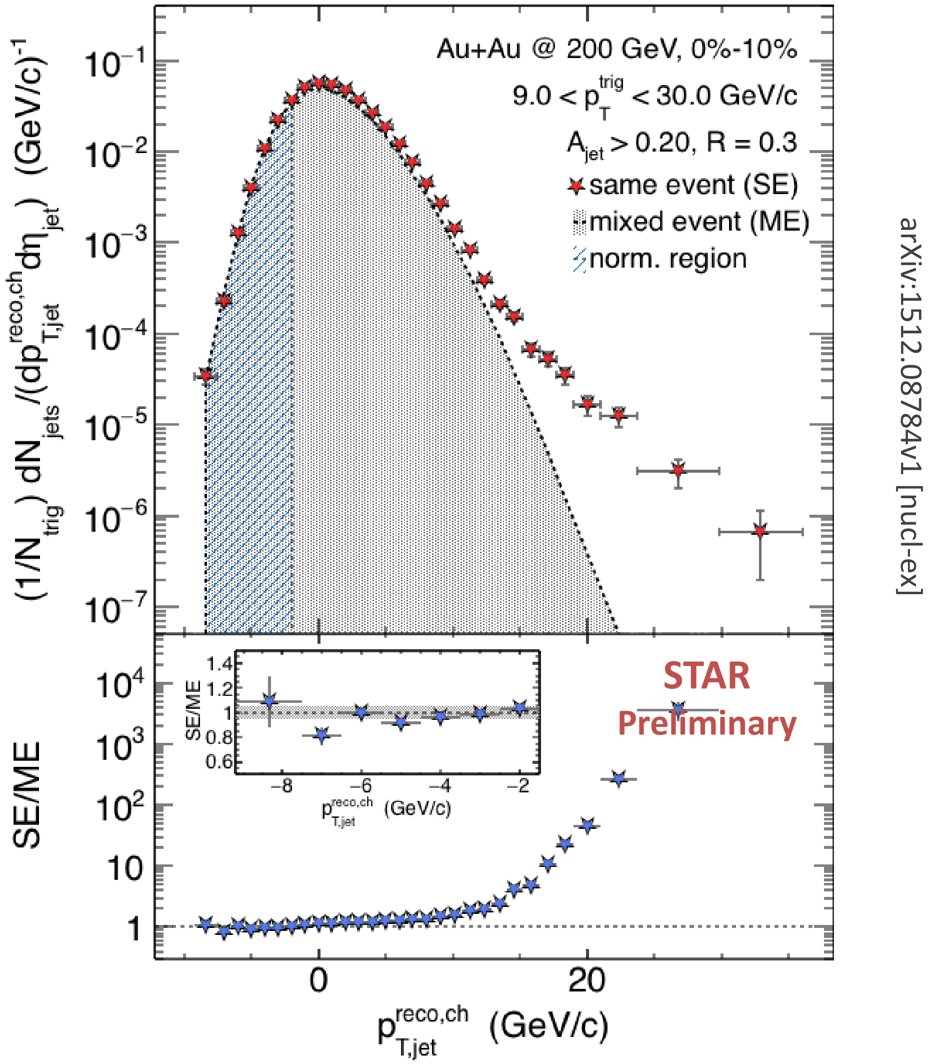
- **Unfolding –**
  - "True" spectrum distorted by background and detector
  - Create a "response matrix" that maps the true onto the measured spectrum.

$$M_j = R_{ij} T_i$$

  - True spectrum then obtained from

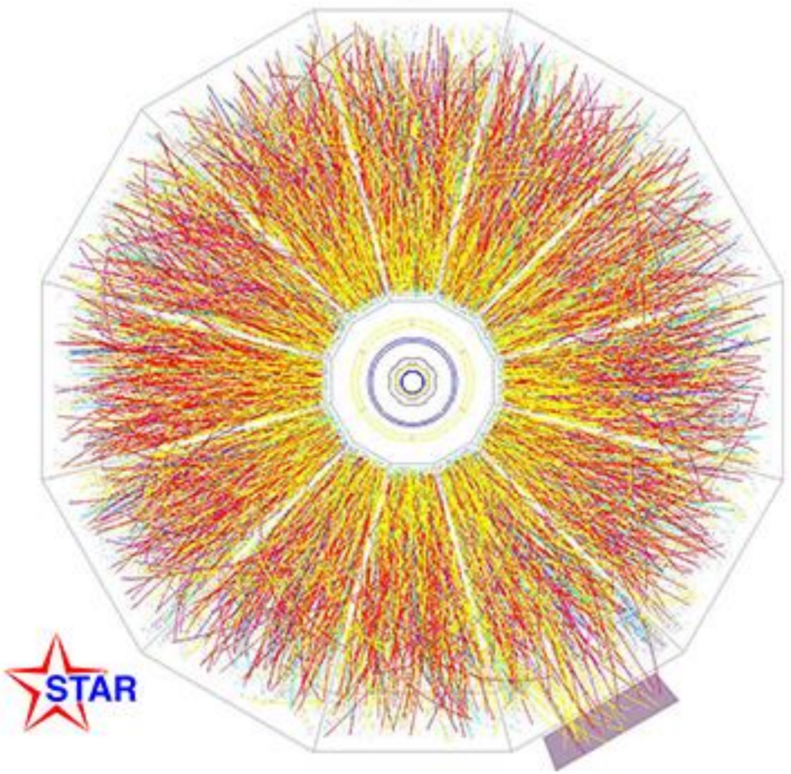
$$R_{ij}^{-1} M_j = T_i$$

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



Summary

- **Photon-Hadron Correlation** –
  - No observed difference due to color-factor or path-length (within uncertainties)
  - Less suppression at low p_t^{assoc}
  - Lost energy (possibly) escaping as soft radiation at wide angles
- **Photon-Jet Reconstruction** –
  - Currently ongoing
  - Still very early in analysis
    - Currently working on p+p baseline
    - “Testing the waters” in Au+Au
  - Stay tuned!



Thank you!

Extracted Yields

- **Per-Trigger Yields** – for a given trigger, total no. of associated hadrons divided by total no. of triggers
  - Near-side yields extracted within $|\Delta\varphi| \leq 1.4$
  - Away-side yields extracted within $|\Delta\varphi - \pi| \leq 1.4$

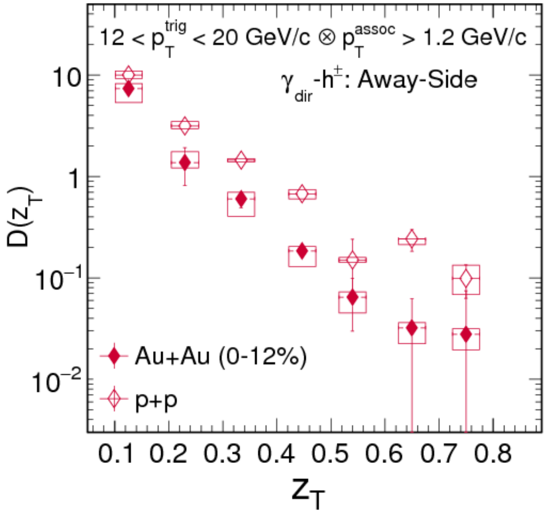
- Let $Y^{a(n)}_{\gamma^{rich}+h}$ and $Y^{a(n)}_{\pi^0+h}$ be the away-side (near-side) yields of hadrons associated with each trigger…

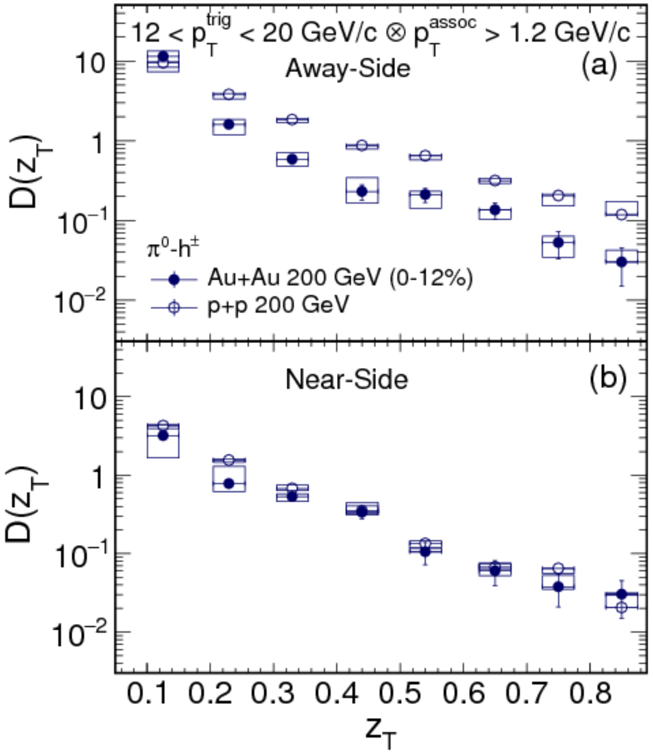
$$R \equiv \frac{Y^n_{\gamma^{rich}+h}}{Y^n_{\pi^0+h}} \Rightarrow 1 - R = \frac{N_{\gamma^{dir}}}{N_{\gamma^{rich}}}$$

  - Assumes $Y^n_{\gamma^{dir}+h} = 0$
  - 1-R ~ 40% for p+p
  - 1-R ~ 70% for Au+Au

- Then the away-side yield for γ^{dir}-triggers is given by:

$$Y^a_{\gamma^{dir}+h} = \frac{Y^a_{\gamma^{rich}+h} - RY^a_{\pi^0+h}}{1 - R}$$





PLB 760, 689 (2016)

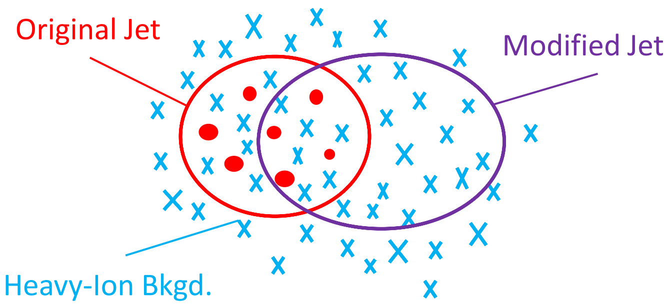
- Unfolding
  - True spectrum is distorted by background and detector
  - Create a response matrix to map true spectrum onto measured spectrum

$$M_j = R_{ij} T_i$$

    - R_{ij} calculated by:
      1) Simulate a “particle level” jet spectrum (e.g. Pythia)
      2) “Smear” spectrum with parameterization of detectors and background
      3) Match particle jets to detector jets
    - Effect of HI background determined by embedding Pythia events in Au+Au events
  - True spectrum then given by:

$$R_{ij}^{-1} M_j = T_i$$

- To correctly account for error bars and the steeply falling spectrum we must resort to “regularized” unfolding methods:
  - **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 performed using RooUnfold package: arXiv:1105.1160v1 [physics.data-an]



$$\delta p_T \equiv \left(p_T^{mod.} - \rho A\right) - p_T^{orig.}$$
$$\delta p_T = p_T^{corr} - p_T^{orig.}$$