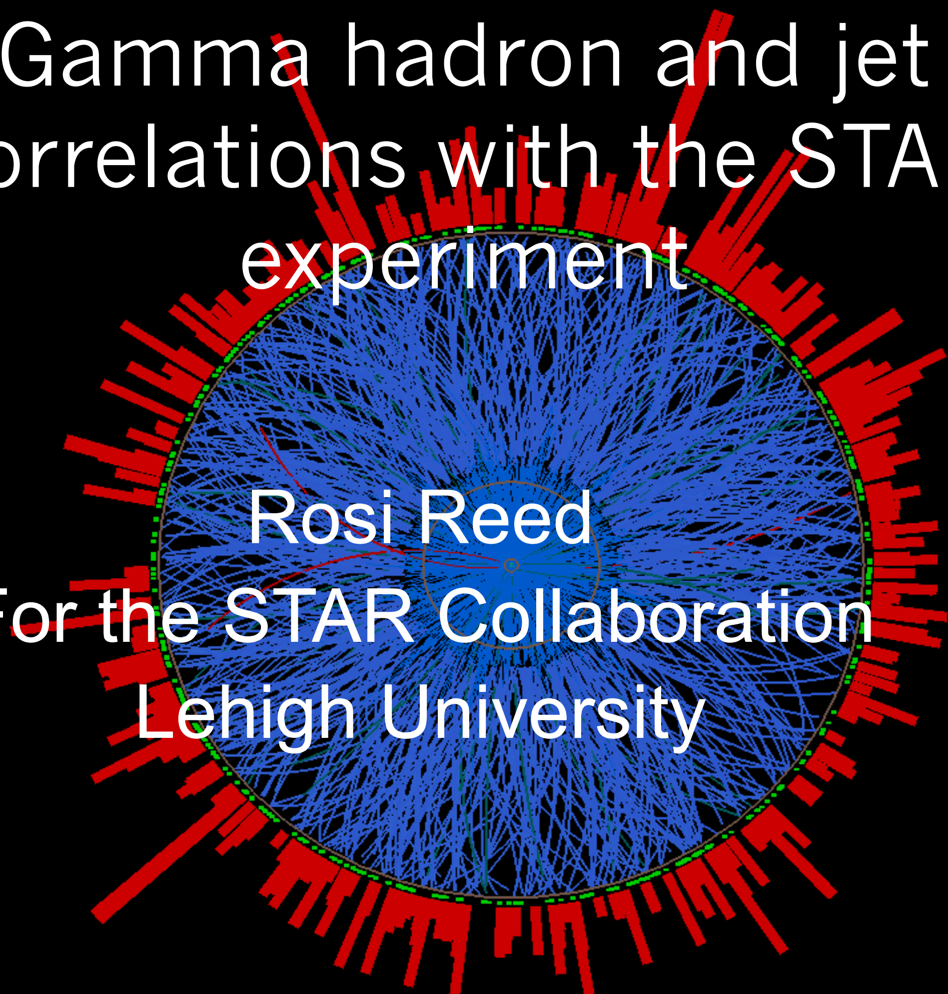
Gamma hadron and jet correlations with the STAR experiment



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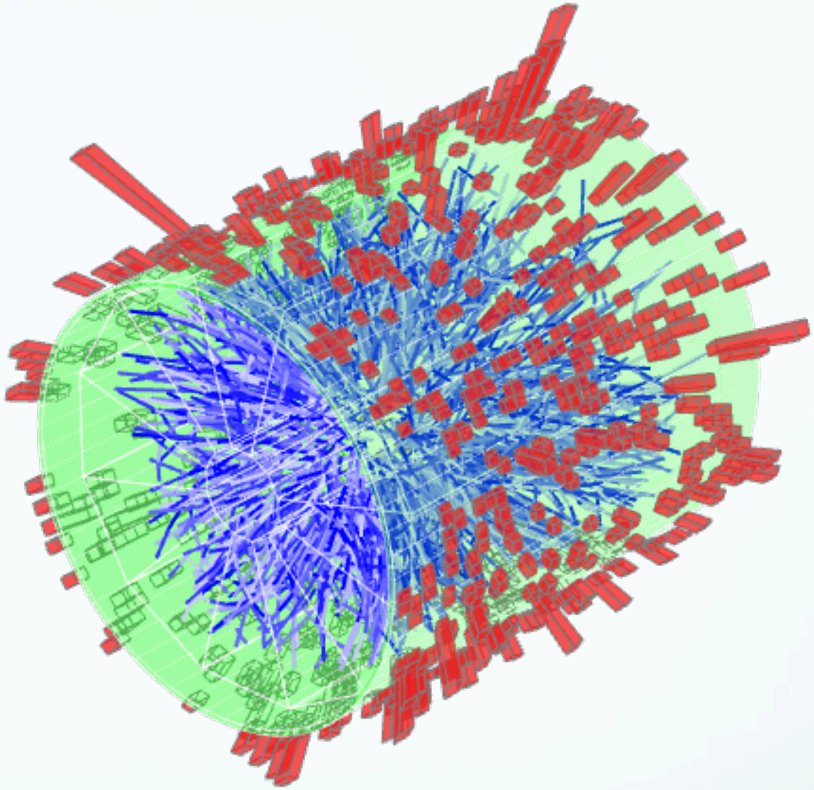
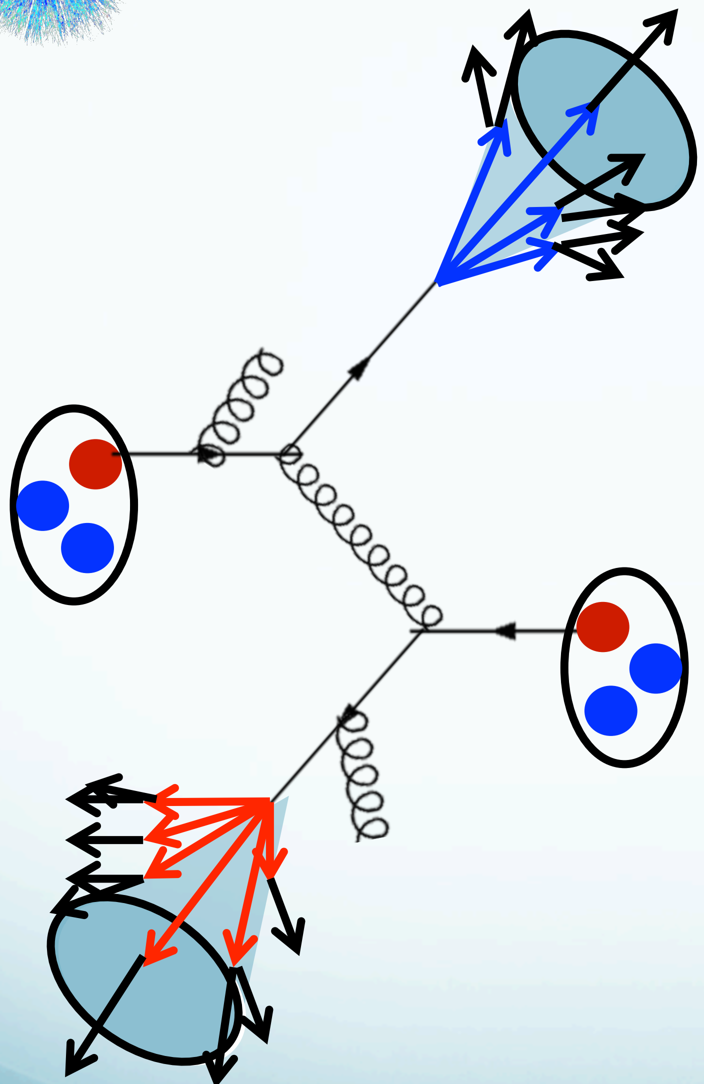
Outline

- Introduction
  - Jets and jet proxies
  - γ-jet and γ-h
- STAR detector
- γ_{rich}-$h^{\pm}$ and π^0-$h^{\pm}$ correlations
- Hadron-jet
- Conclusions



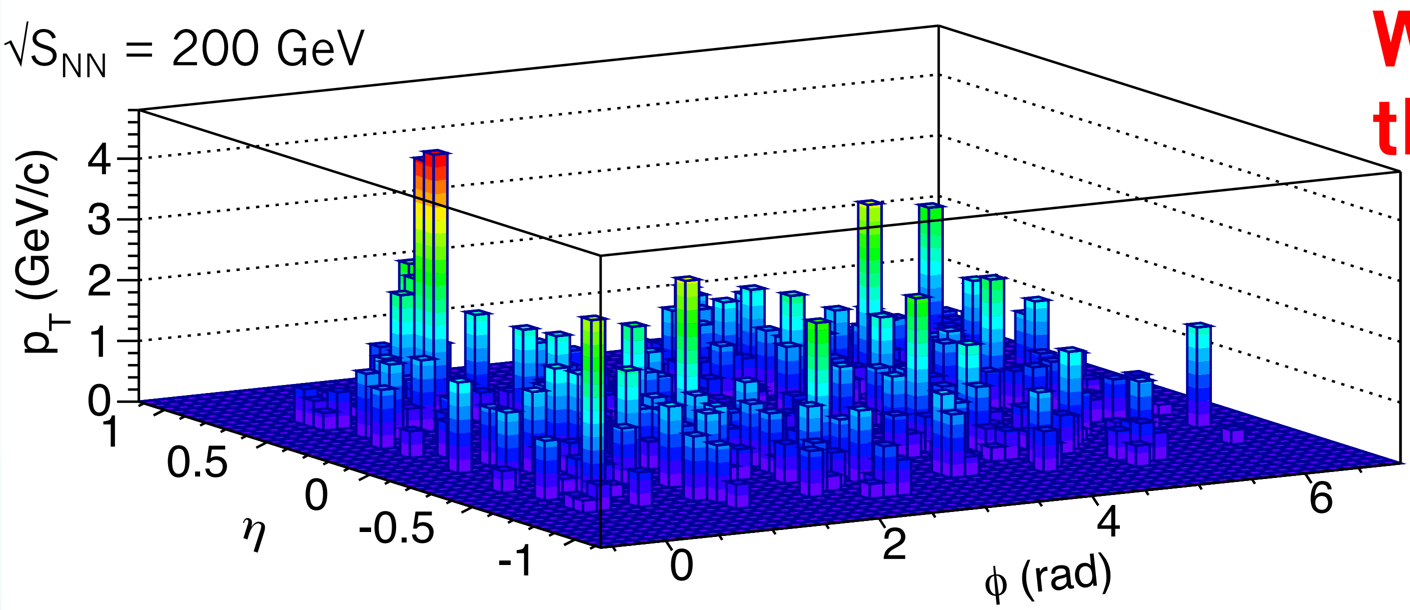
Jets in Heavy-Ion Collisions



- Colored partons undergo a hard scatter
  - Radiate soft gluons and quarks
  - Hadronize into a spray of particles
- Produced early prior to QGP formation
  - Interact and lose energy to the medium via radiation and collisions
- Expected to **reflect the kinematics and topology** of the hard scattered partons
  - Underlying background creates fake jets and smears the kinematics of "true" jets

There is no unambiguous definition of what a jet is!

Jets in Heavy-Ion Collisions
Complications: Background



Where are the jets?

0-10% central
STAR:
ρ_{ch} ~ 29 GeV
ALICE:
ρ_{ch} ~ 130 GeV

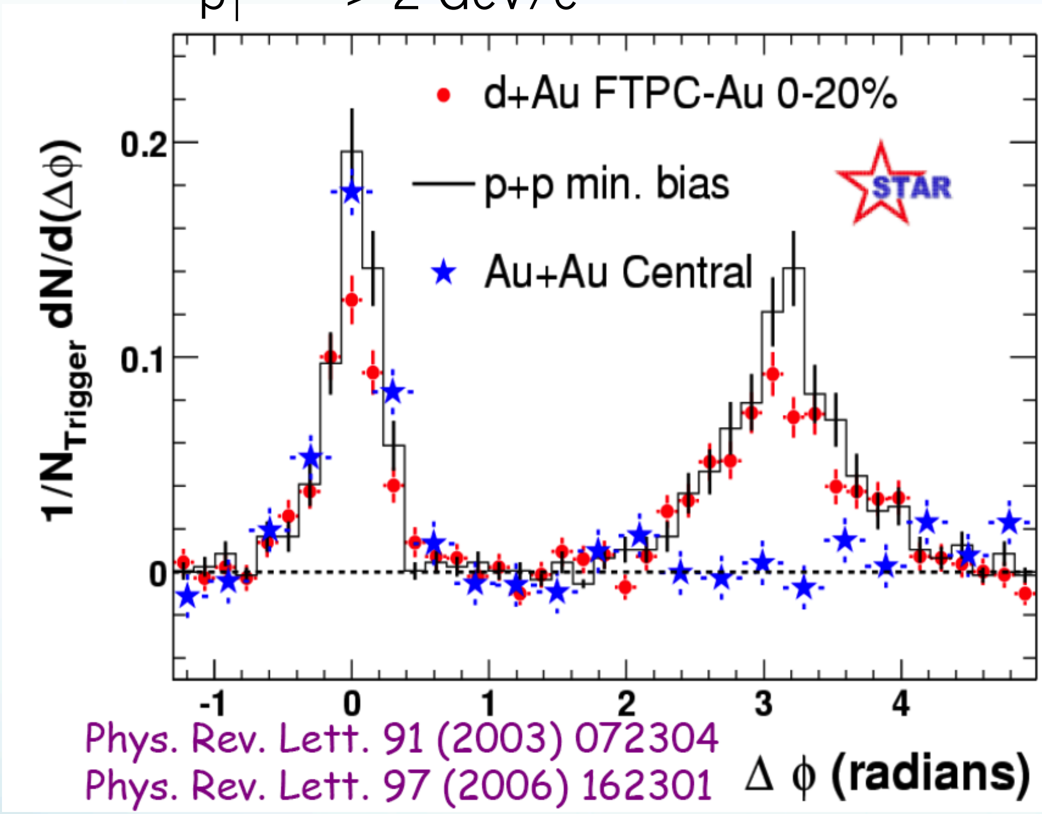
JHEP09(2015)170

- Unlike in pp collisions, the underlying event in AA collisions makes jet finding difficult
  - Fake jets → Jet finder clusters particles from bulk
  - Jet smearing → Background fluctuates underneath jet
- First "jet" results used high p_T hadrons as proxies

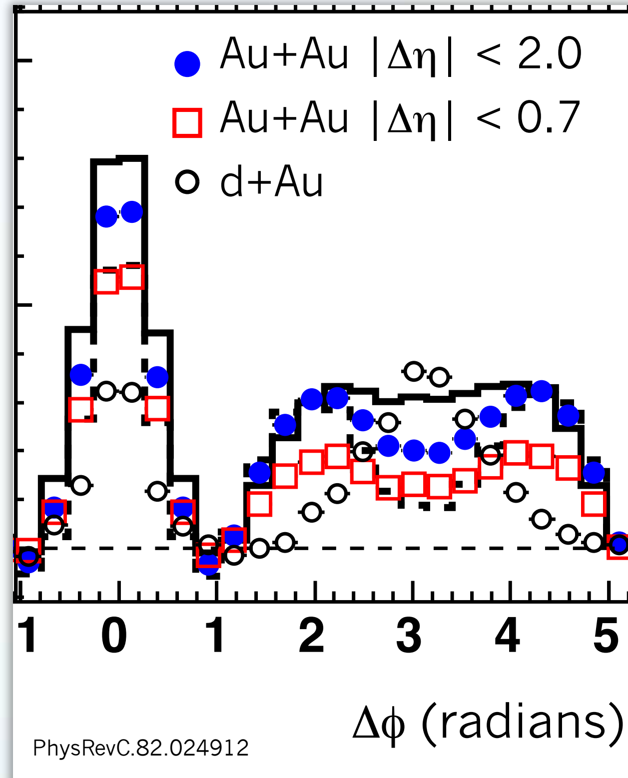
Di-hadron Correlations

A jet proxy

$4 < p_T^{trig} < 6$ GeV/c
$p_T^{assoc} > 2$ GeV/c



$4 < p_T^{trig} < 6$ GeV/c
$1 < p_T^{assoc} < 2.5$ GeV/c

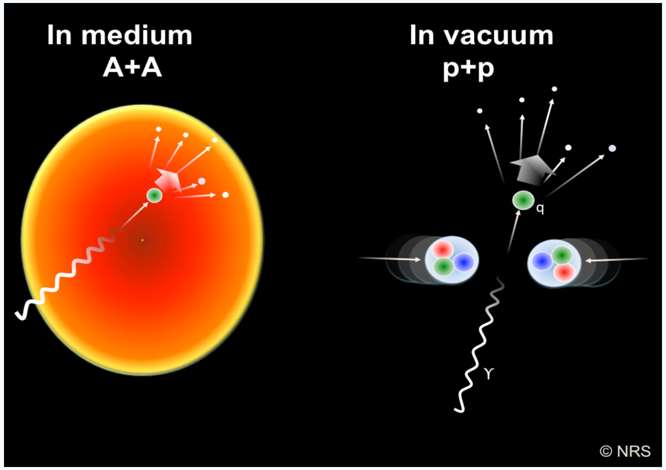


Strong modification of the recoil-jet indicated substantial partonic interaction with the QGP, d+Au results show not CNM

- Geometric “surface” bias
- What is the parton p_T and flavor?

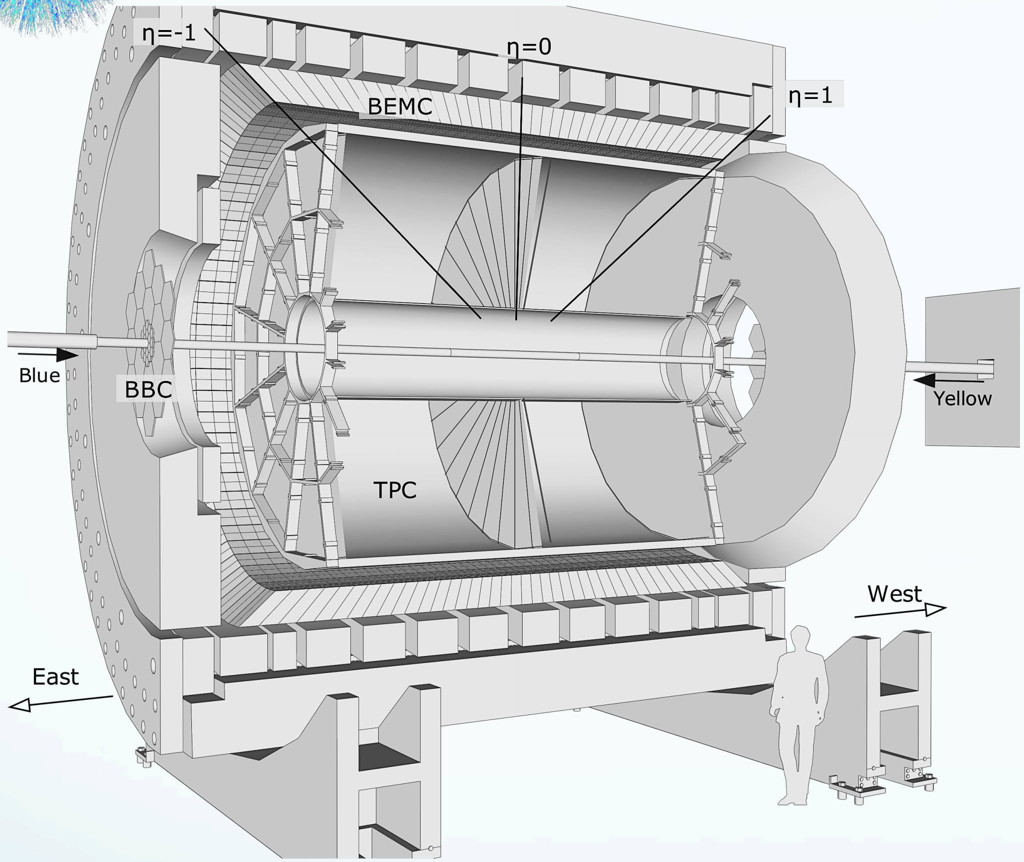
γ-jet: Golden Probe of the QGP

- Direct photon-jet analyses have many advantages
  - Photon is highly correlated with the parton kinematics
  - Process is dominated by Compton scattering ($qg \rightarrow q\gamma$)
    - Fixes flavor
  - Photon does not interact with the QGP
    - Reflects the initial parton kinematics
    - No geometric bias
    - Allows jet-medium tomography



- Disadvantages
  - Low cross-section
  - Still need to account for effect of underlying event
    - Common to all jet analyses
  - Use γ-$h^{\pm}$ as a jet proxy

STAR detector

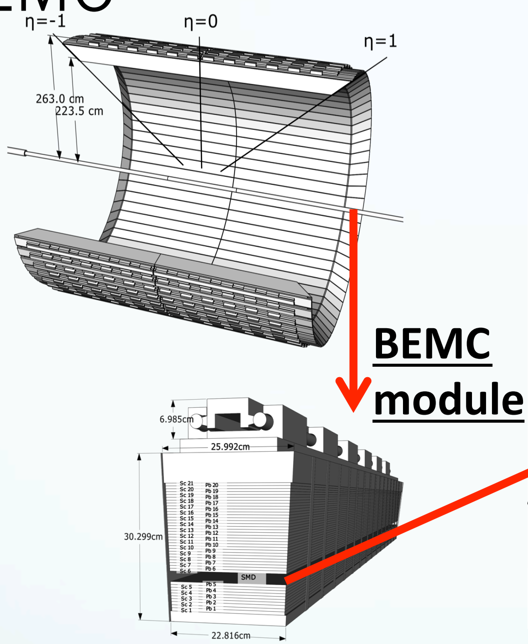


- Barrel Electromagnetic Calorimeter (BEMC) → measures EM clusters
  - High Tower Trigger
- Time Projection Chamber (TPC) → identifies charged hadron tracks
- Acceptance (BEMC + TPC):
  - 2π-azimuth
  - $|\eta| < 1.0$, both for BEMC and TPC
- Data sets:
  - Au+Au year-11: $\mathcal{L}_{int} = 2.8\ nb^{-1}$
  - pp year-9: $\mathcal{L}_{int} = 23\ pb^{-1}$

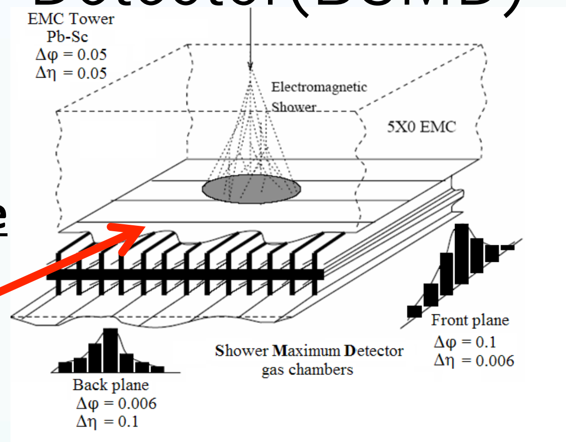
Transverse shower profile π^0/γ_{dir} discrimination

Main background comes from $\pi^0 \rightarrow \gamma\gamma$ decay

BEMC

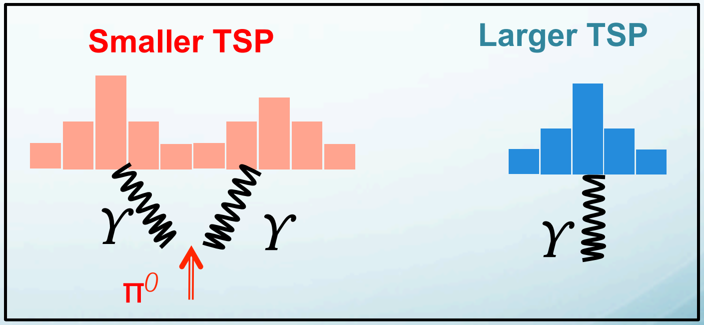


Shower Maximum Detector(BSMD)



$$\mathbf{TSP} = \frac{\mathbf{E_{cluster}}}{\sum_i \mathbf{e_i r_i^{1.5}}}$$

$E_{cluster}$: Cluster energy
e_i: BSMD strip energy
r_i: distance between strip and cluster center

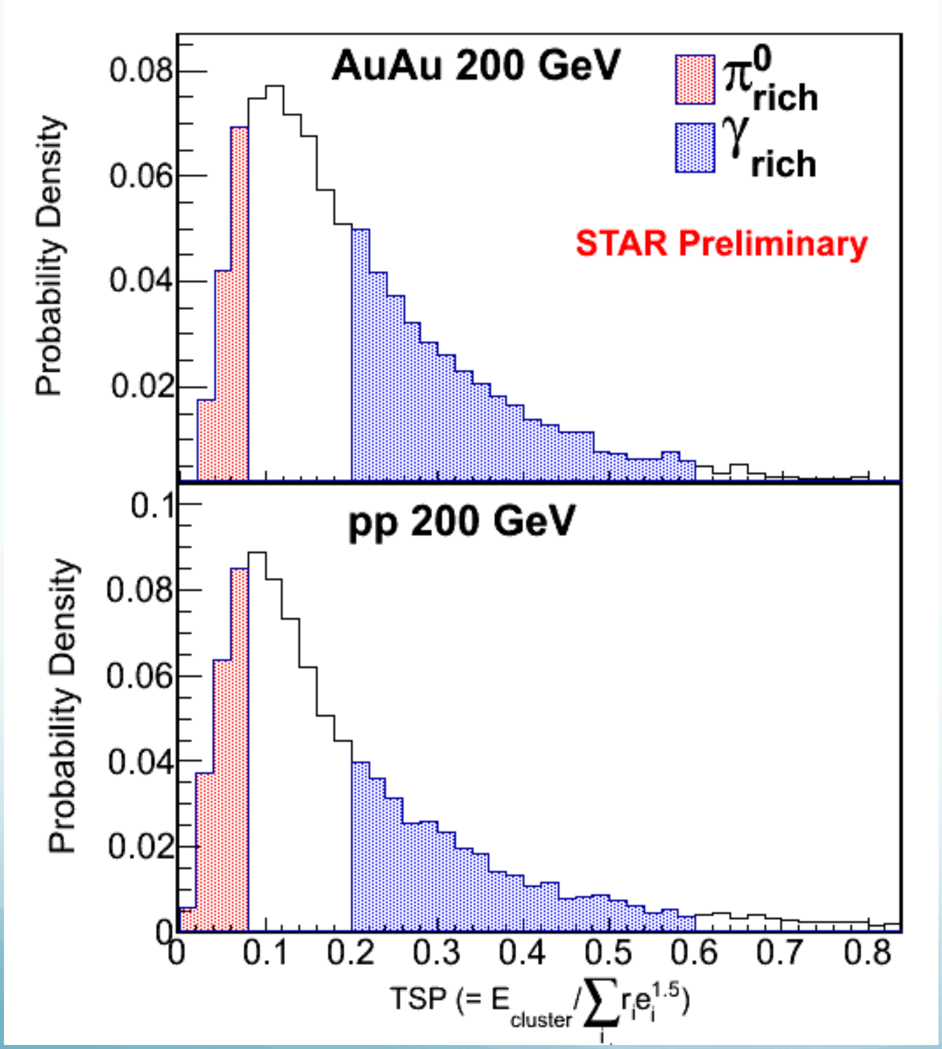


BSMD and BEMC tower used to determine Transverse Shower Profile (TSP)

- Nearly pure sample of π^0 (π^0_{rich})
- Sample with enhanced fraction of γ_{dir} (γ_{rich})

Transverse shower profile π^0/Υ_{dir} discrimination

Main background comes from $\pi^0 \rightarrow \gamma\gamma$ decay



$$\mathbf{TSP} = \frac{\mathbf{E_{cluster}}}{\sum_i \mathbf{e_i r_i^{1.5}}}$$

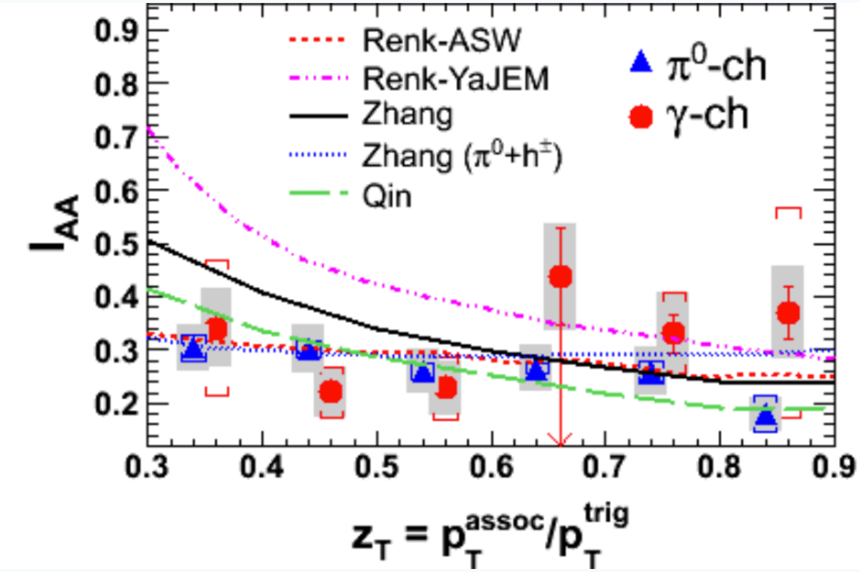
$E_{cluster}$: Cluster energy
e_i: BSMD strip energy
r_i: distance between strip and cluster center

Compare π^0_{rich} and γ_{rich} populations

- Path-length and color factor effects
- γ_{rich} away side should be less suppressed

I_{AA} vs z_T: Previous Results

(STAR Collab., PRC 82, 034909)



$8 < p_T^{trig} < 16$ GeV/c

$$I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}} \qquad z_T = \frac{p_T^{assoc}}{p_T^{trig}}$$

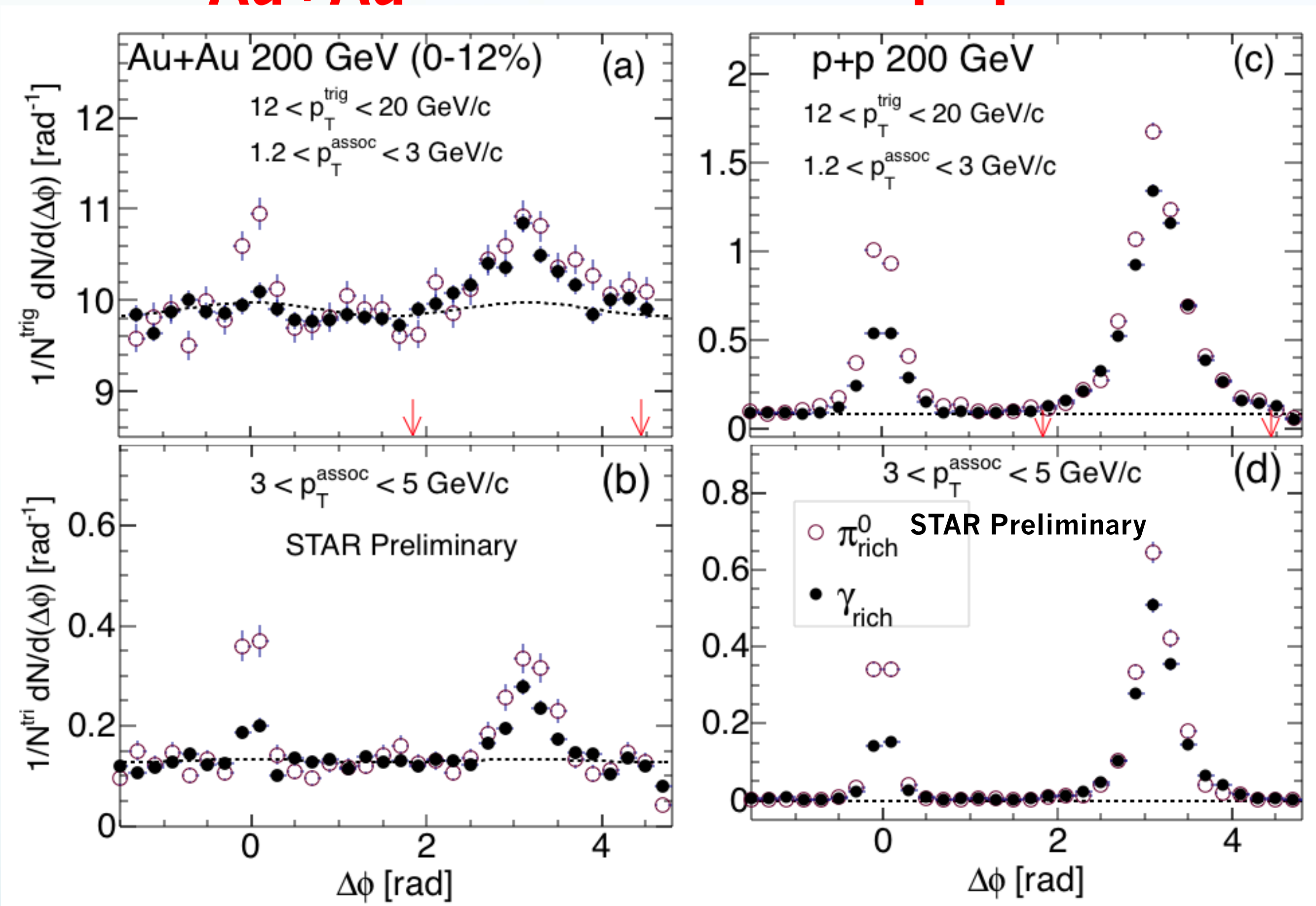
$D(z_T)_{XX}$: per trigger away-side yield for X+X collisions

- I_{AA} showed similar level of suppression for both samples
- Jet fragmentation function is enhanced at low p_T
  - Effect should be seen in z_T

How much energy is lost and where is it recovered? Needed to extend measure to lower z_T

Raw Correlation functions

Au+Au **p+p**



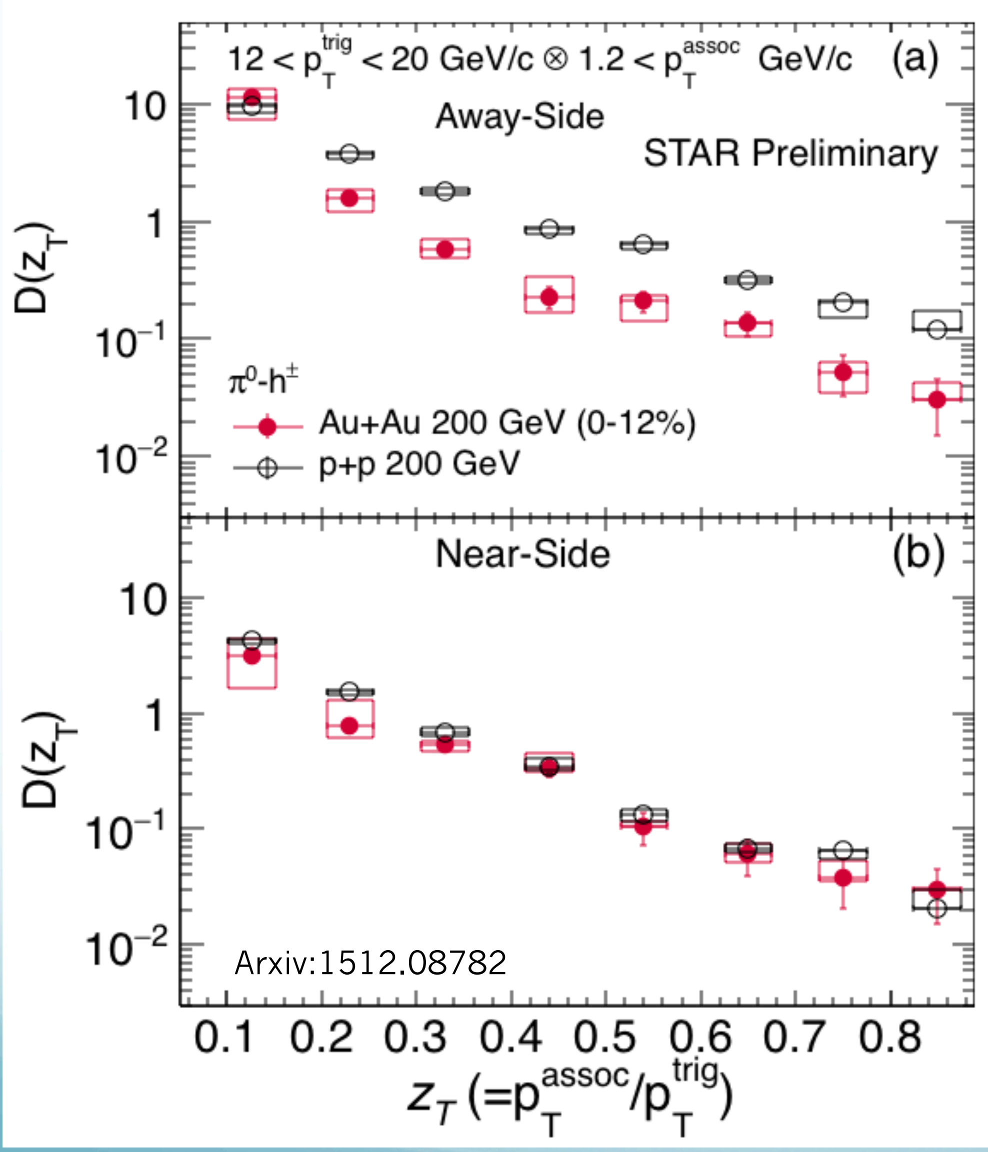
↓ Away-side integration window

...... background level

$|\eta| < 1.0$

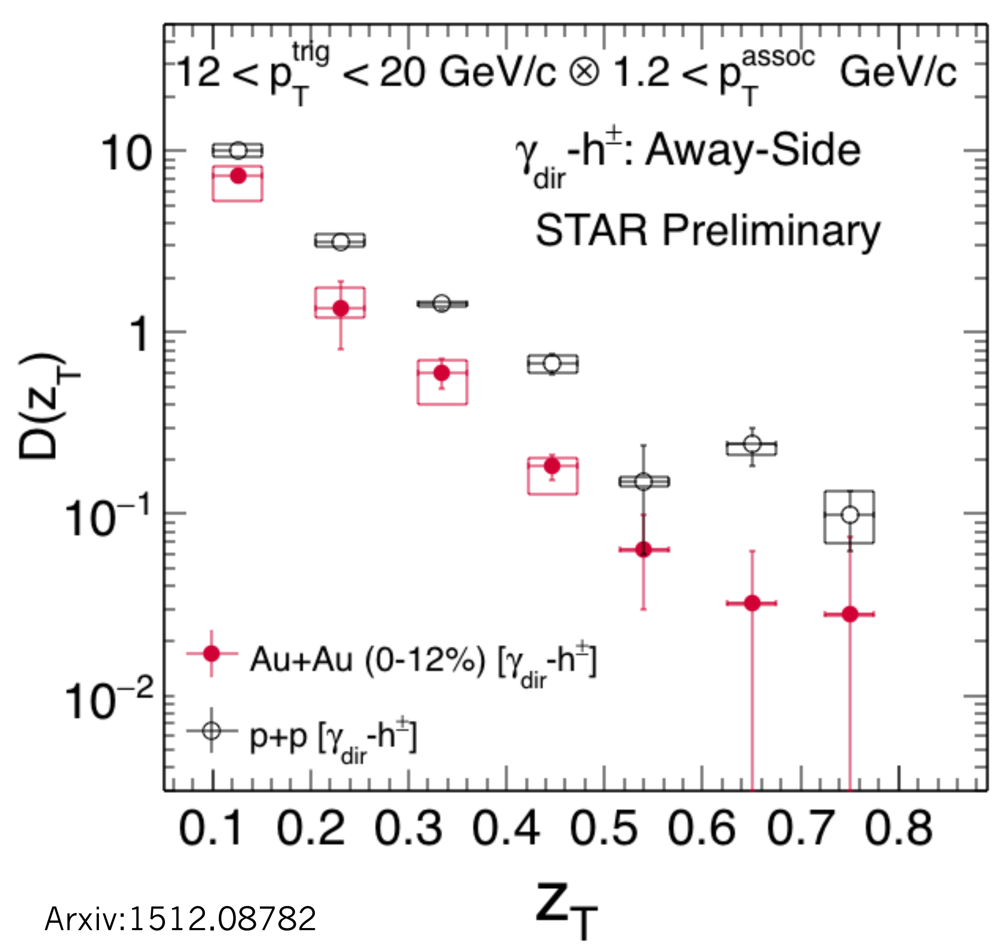
- Uncorrelated background is subtracted
- $\Delta\varphi$ acceptance is corrected using the mixed events (modulated with elliptic flow for Au+Au collisions)

Yield associated with π^0



- Near-side $|\Delta\varphi| \leq 1.4$
- Away-side $|\Delta\varphi - \pi| \leq 1.4$
- **Away-side yields suppressed in central (0-12%) Au+Au collisions**
- Near-side shows no significant suppression
- Integrating near-side yields
  - ~85(±3)% energy fraction carried by π^0 over "charged jet energy" (π^0 + charged hadrons) in pp 200 GeV
    - γ carries nearly all, z_T is not precisely the same

Yield associated with γ



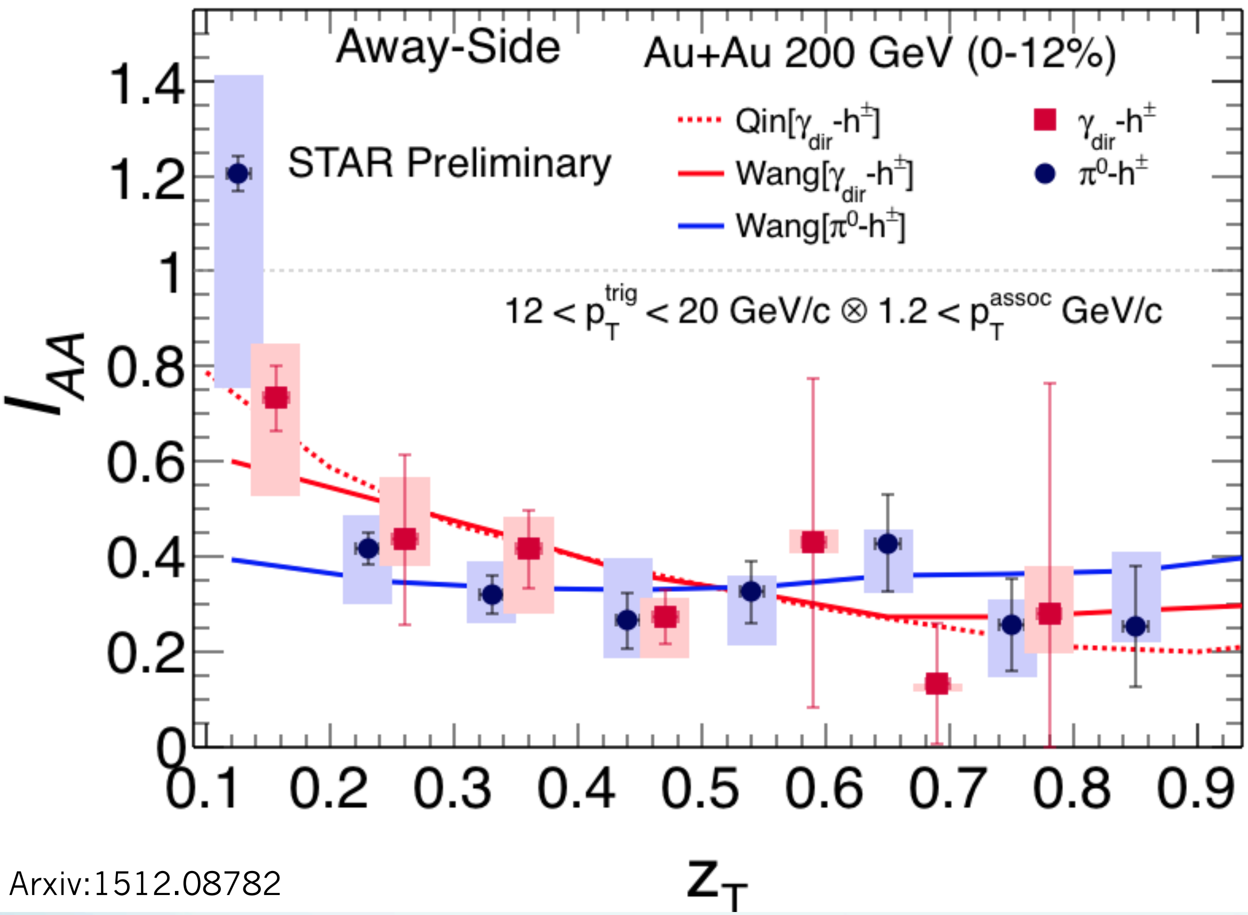
Arxiv:1512.08782

Away-side $|\Delta\varphi - \pi| \leq 1.4$

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

- Y^a: away-side yield
- Y^n: near-side yield
- Normalized per trigger
- Purity of γ_{dir} vs γ_{rich} sample:
  - $1 - R = \frac{N_{\gamma dir}}{N_{\gamma rich}}$
- 1-R =
  - Central Au+Au ~70%
  - pp ~40%
- **Away-side yields suppressed in central (0-12%) Au+Au collisions**

I_{AA} of γ_{dir} and π^0



Arxiv:1512.08782

$$I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}}$$

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

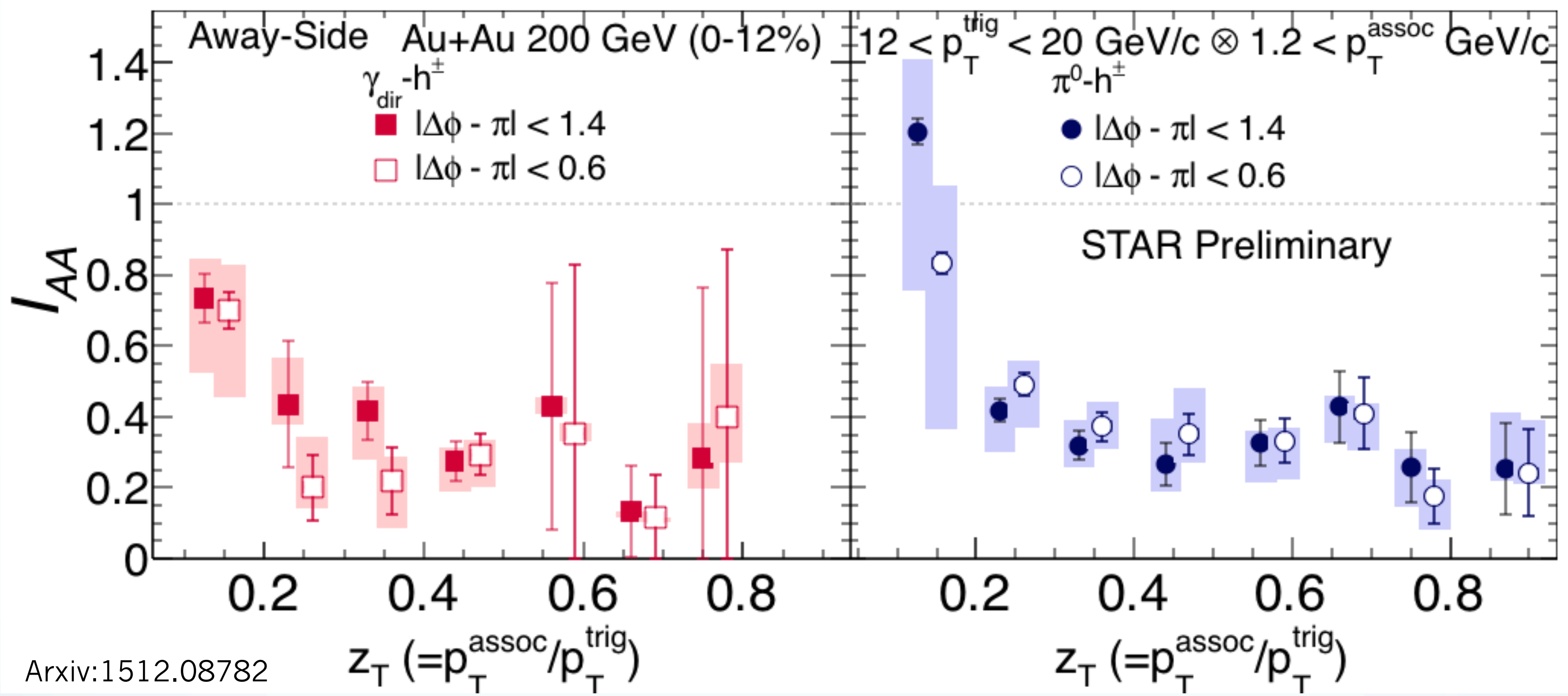
$I_{AA}^{\pi 0\text{-}h}$ and $I_{AA}^{\gamma dir\text{-}h}$ show similar strong suppression

- $I_{AA}^{\pi 0\text{-}h}$, $I_{AA}^{\gamma dir\text{-}h}$ less suppressed at $z_T<0.2$ than at high z_T
- Models don't include absorption and redistribution of lost energy in the medium

Qin: G.-Y Qin et al., PRC 80, 054909 (2009) (NLO pQCD + (3+1)hydro with jet-medium and fragmentation photon)

Wang: X. N. Wang et al., Phys. Rev. C 84, 034902 (2011) Phys. Rev. C 81, 064908 (2010) Phys. Rev. Lett. 103, 032302 (2009) (NLO pQCD + (3+1)hydro)

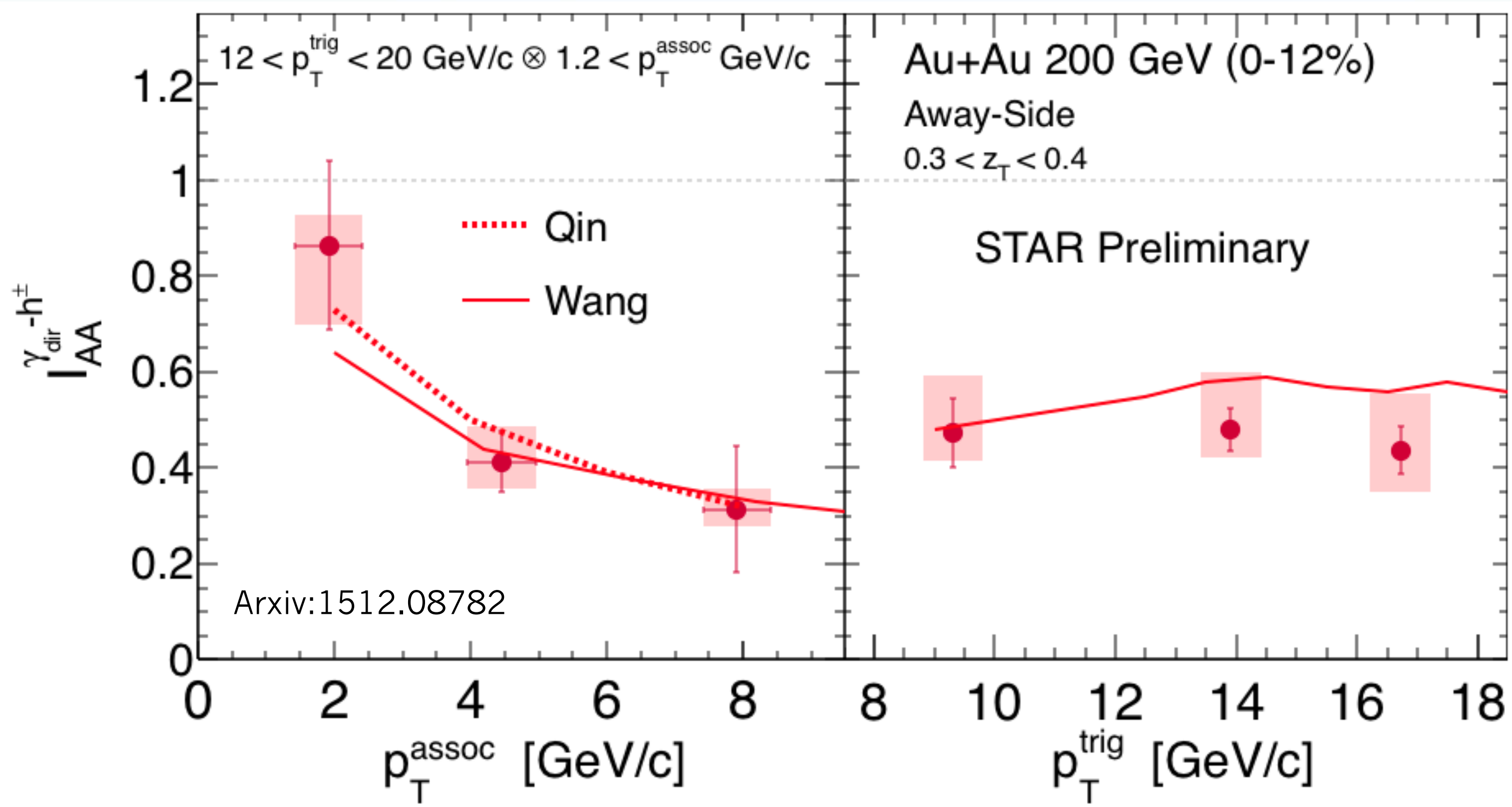
γ–h I_{AA} vs Integration window π^0–h



Arxiv:1512.08782

- Error bars are largely correlated
- **No significant dependence of suppression on integration window** is observed for Υ_{dir}-h$^{\pm}$ and π^0-h$^{\pm}$ I_{AA} results at high p_T^{Trig} ($12 < p_T^{Trig} < 20$ GeV/c)

I_{AA} vs p_T^{assoc} and p_T^{Trig}

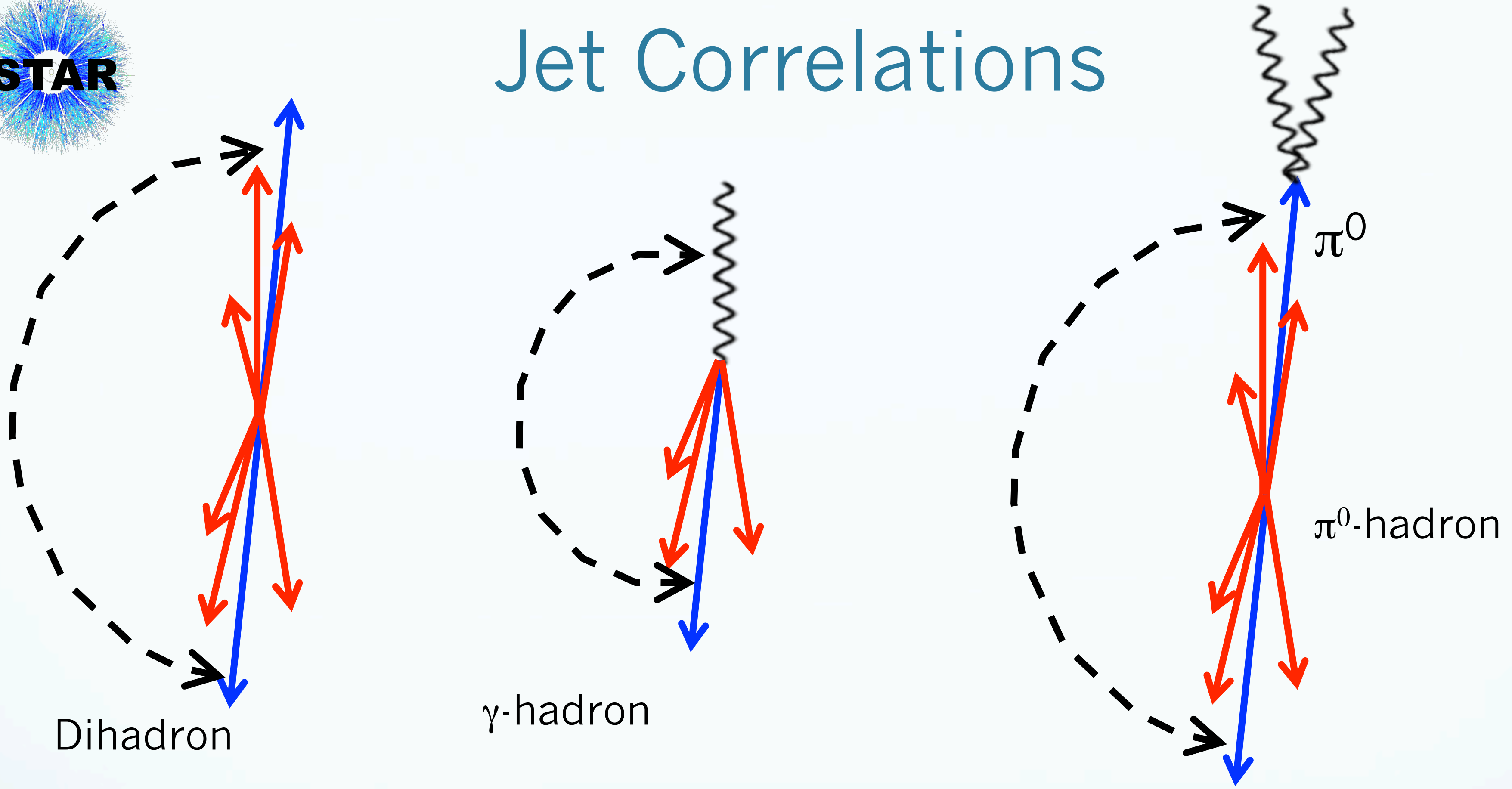


G.-Y Qin et al., PRC 80, 054909 (2009)

X. N. Wang et al., Phys. Rev. C 84, 034902 (2011)
Phys. Rev. C 81, 064908 (2010)
Phys. Rev. Lett. 103, 032302 (2009)

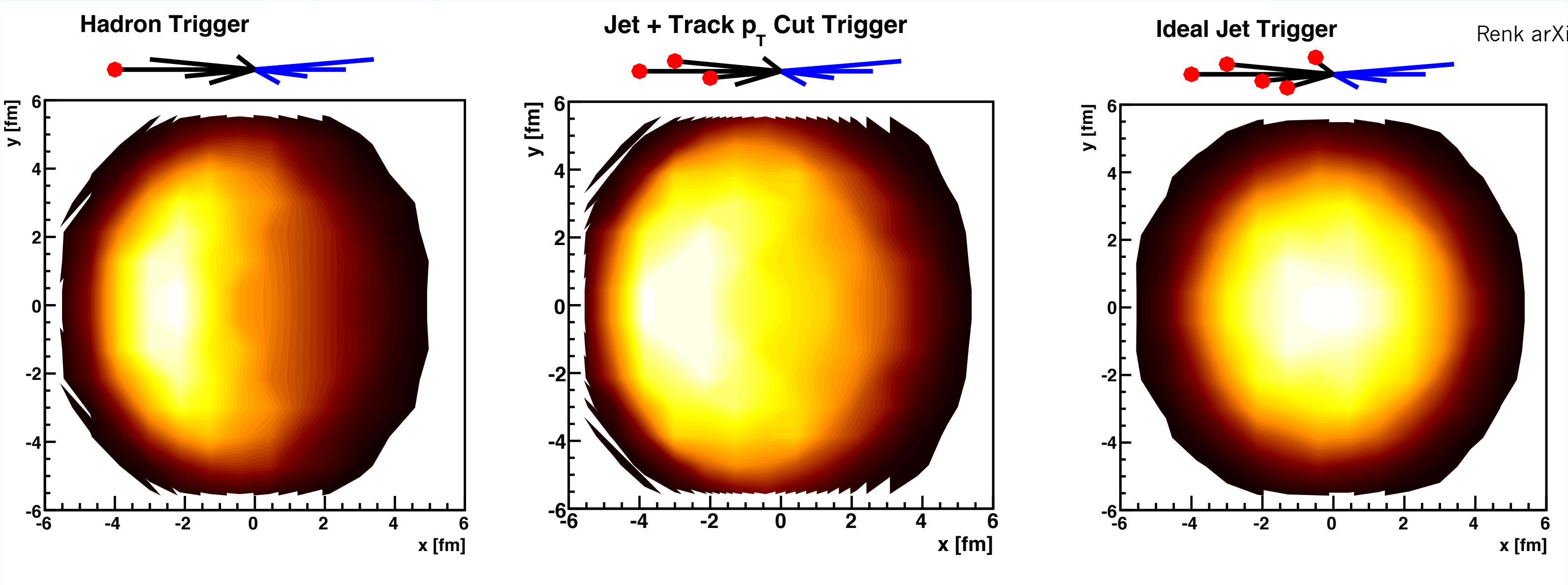
- Away-side suppression depends on p_T^{assoc}
- High-p_T suppression does not depend on direct photon trigger energy

Jet Correlations

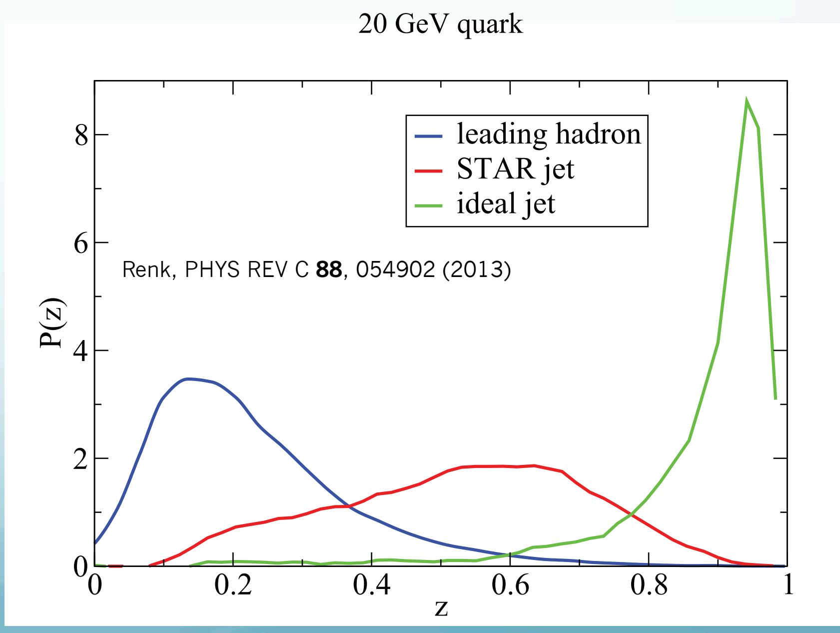


- Different biases→Jet Geometry Engineering
- Apply jet techniques developed at LHC/RHIC to RHIC jets!
  - Allows a measurement of the dijet or γ-jet energy imbalance
  - How much energy is still correlated with the initial parton? Need jet reconstruction!

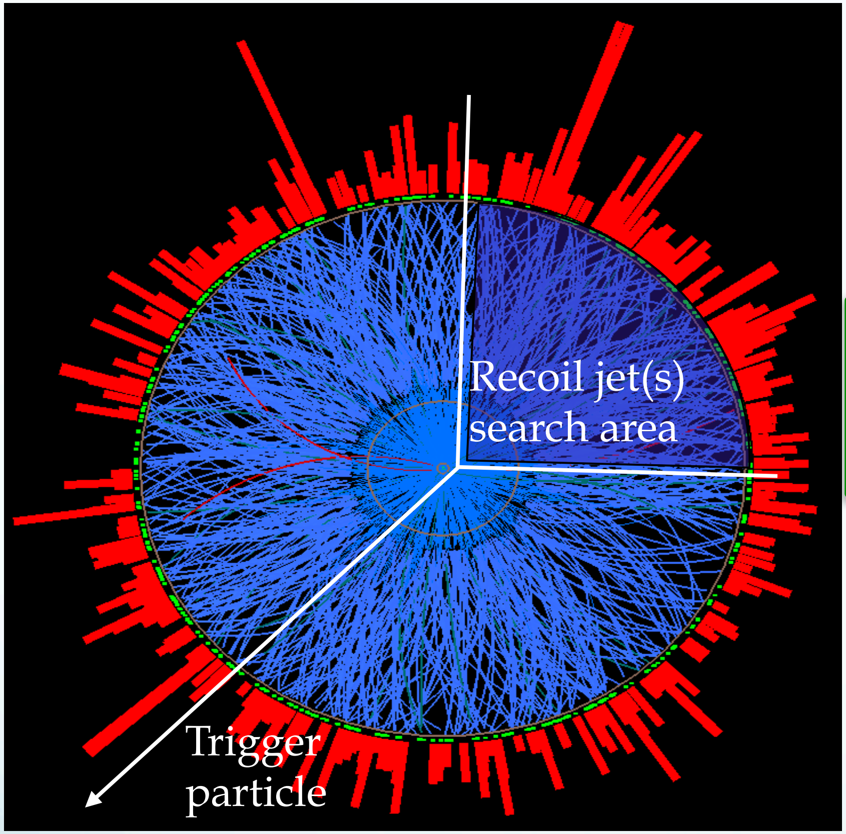
Reconstructed Jet Correlations



- **Biases for jets will be different than for π^0 or γ**
- Different biases→Jet Geometry Engineering
- New techniques and larger data samples allows jet-h+ h-jet correlations
- Probability density of $z = E_{obs}/E_{parton}$



h-Charged Jet correlations



Semi-inclusive yield of jets recoiling from a high p_T hadron trigger

$$\frac{1}{N^h_{trig}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{pp\to h+X}}\frac{d\sigma^{pp\to h+jet+X}}{dp_{T,jet}}$$

Measured — Calculable in pQCD

Trigger on high p_T hadron → Selection of a high p_T process

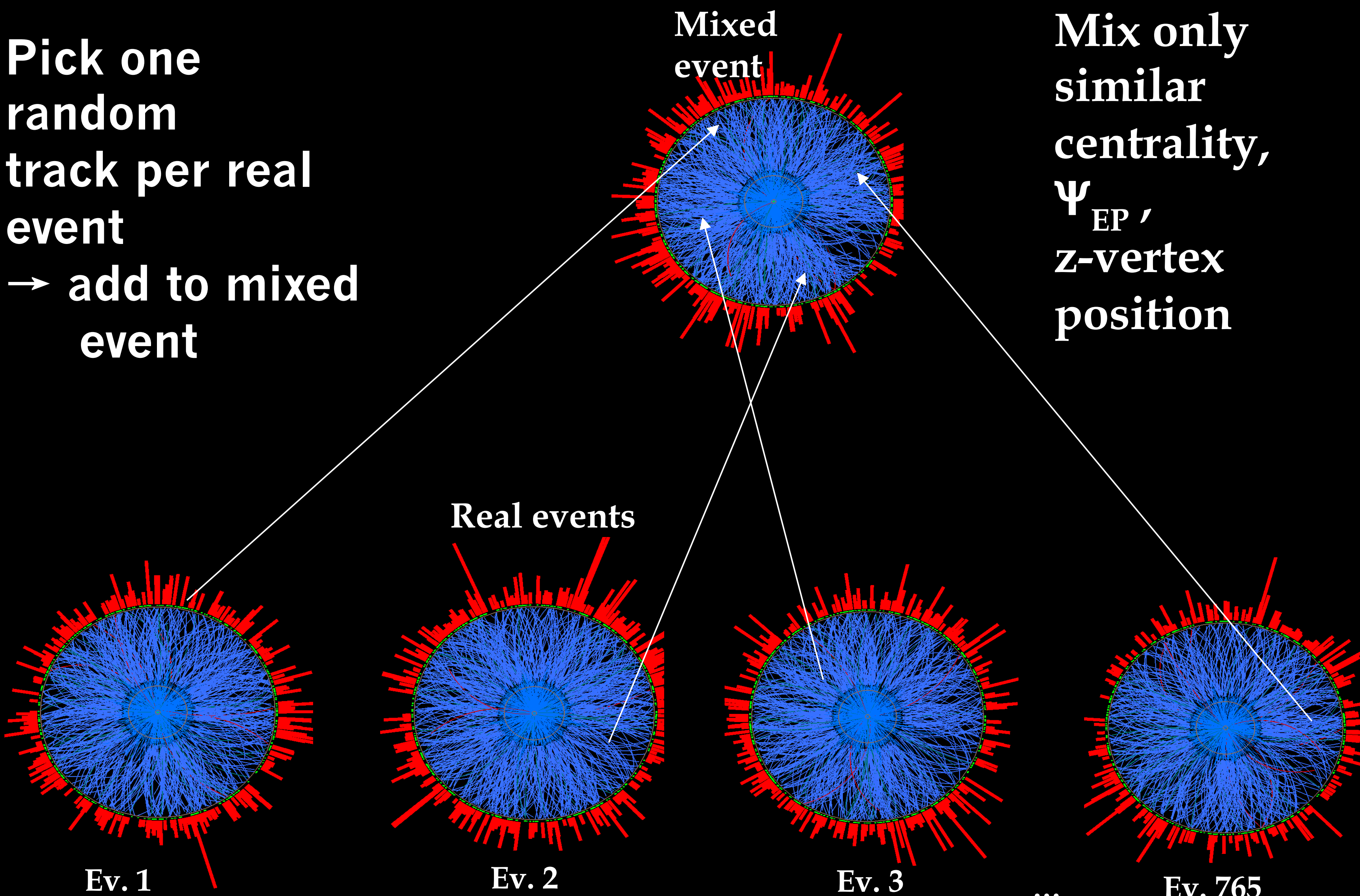
- Use all jet candidates on the other azimuthal hemisphere within +/- 45° → **no fragmentaion bias on recoil side**!

Combinatorial recoil jets? → Event mixing!

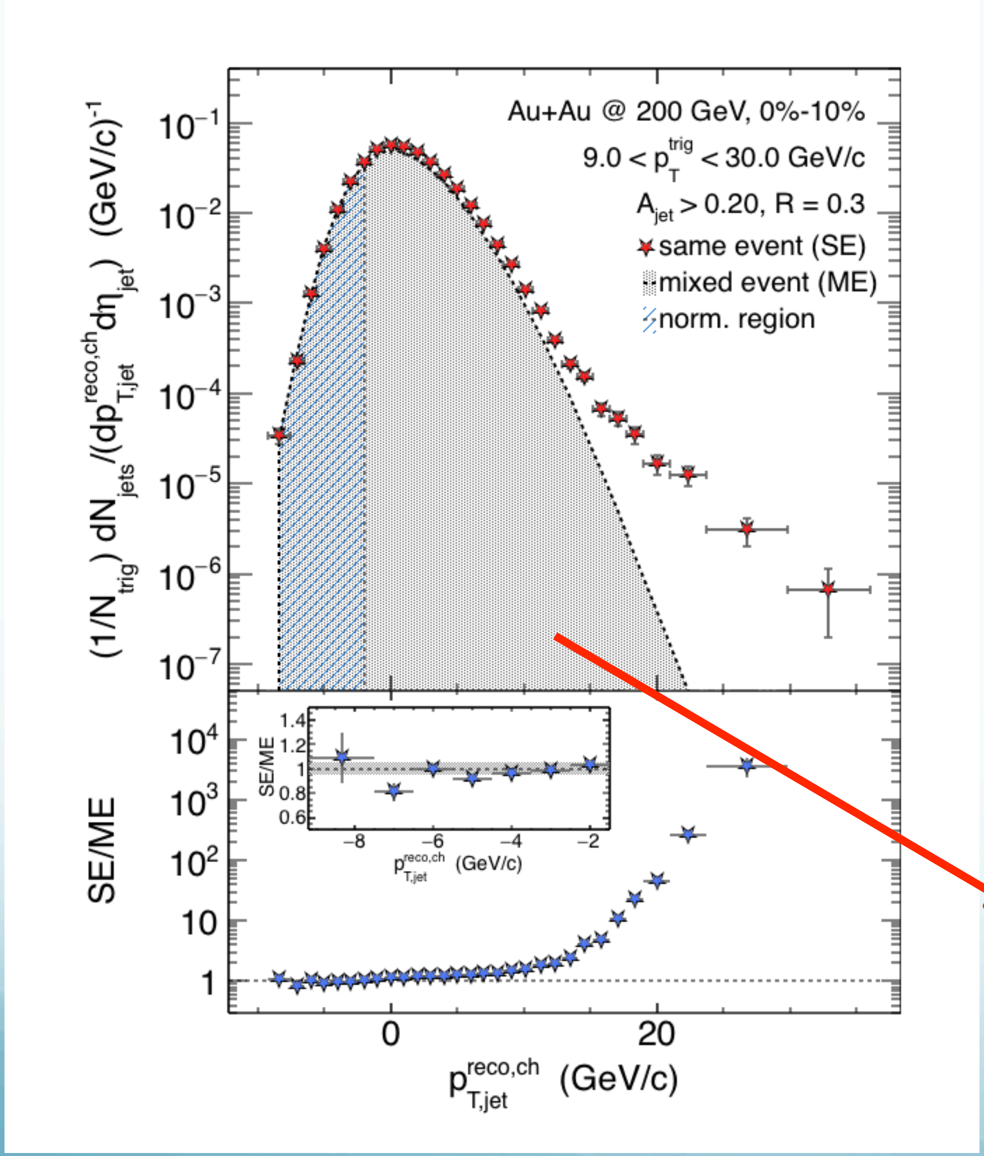
Mixed Event Generation for Jets

Pick one random track per real event
→ add to mixed event

Mix only similar centrality, Ψ_{EP}, z-vertex position



Charged Raw Recoil Jet Spectrum: Central

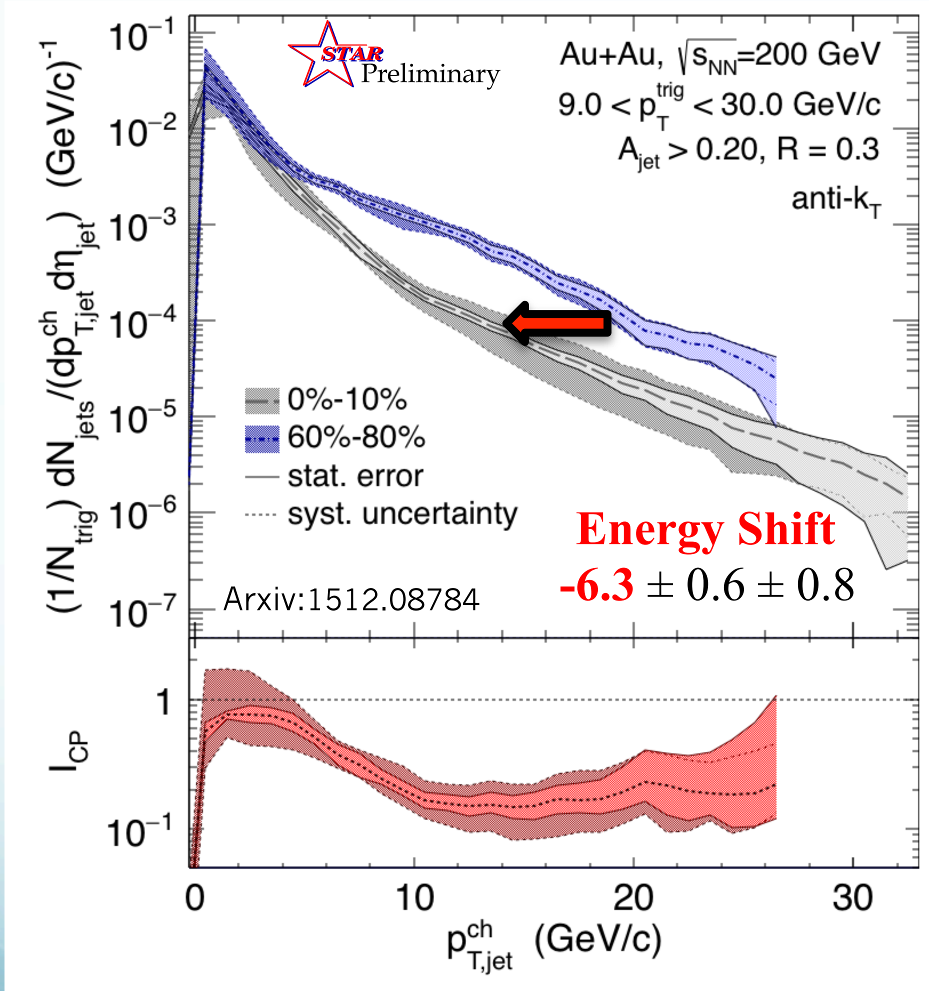


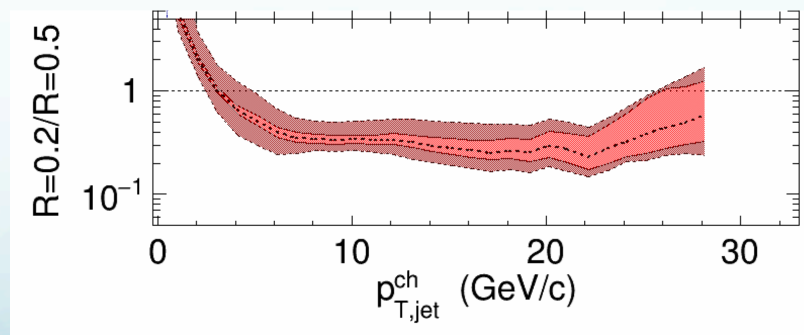
- Excellent description of low p_T SE spectrum with ME
- Normalization region varied systematically
- Significant jet signal at $p_T - \rho A > 10$ GeV/c

Combinatorial jet background
→ statistically described by mixed event technique

I_{CP} for h-jet correlations

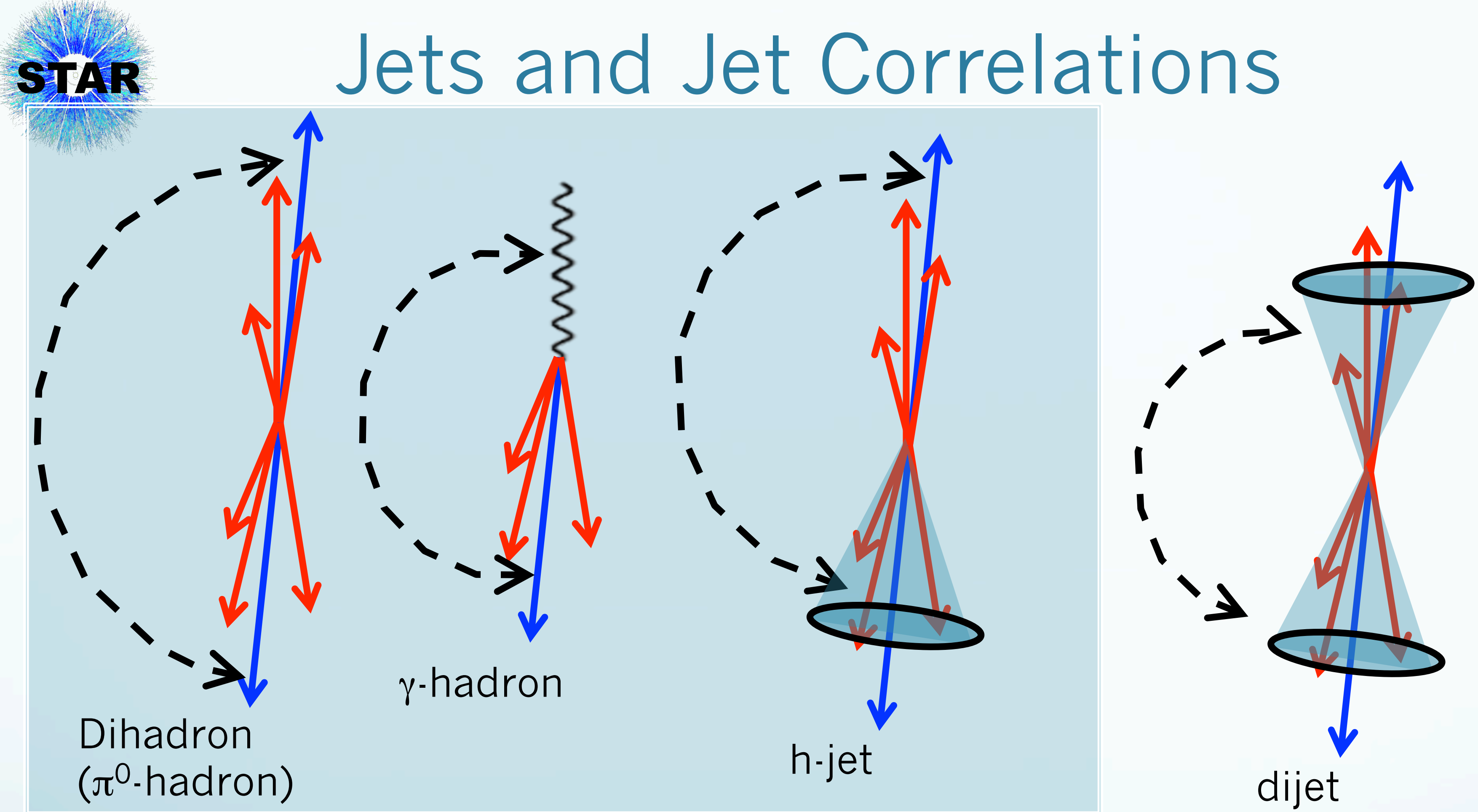
- Significant suppression (~0.2) at p_T > 10 GeV/c
  - γ-jet similar? (Geometry)
- Dijet Momentum Imbalance?
- Energy Shift
  - -6.3 (R=0.2) vs -3.8 (R=0.5)
- Ratio of cone size relatively flat for p_T > 10 GeV/c
- Compare RHIC and LHC → Need similar bias → Theory Calculation





Errors show combined systematics of unfolding and track reconstruction

Jets and Jet Correlations

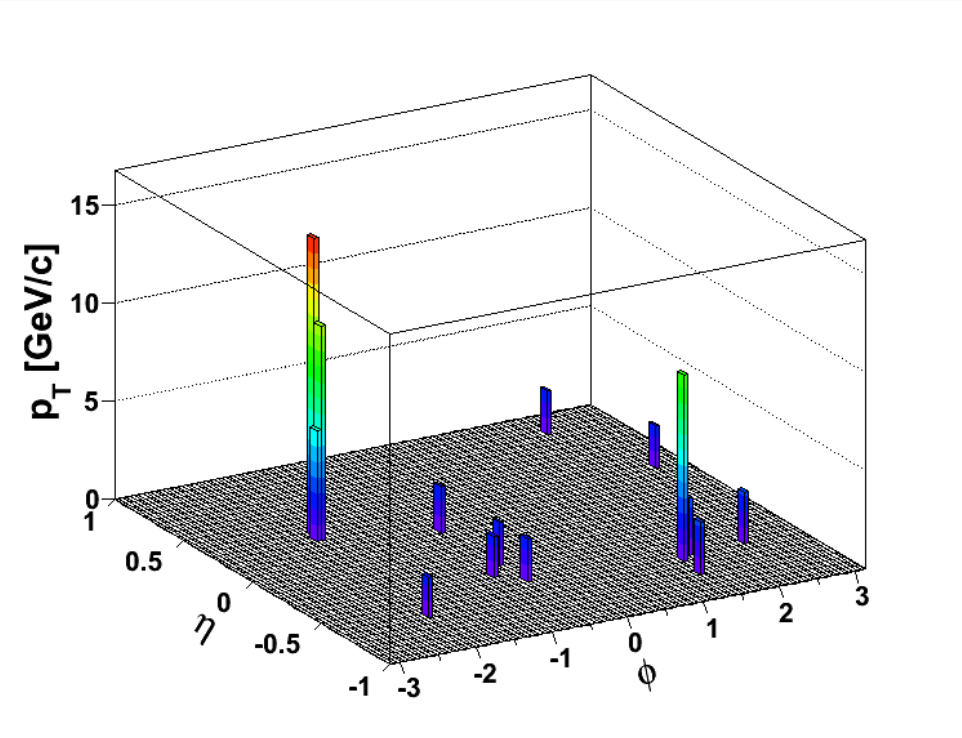


- Hadron triggered correlations do not allow a direct measure of the dijet momentum imbalance
- Experimentally we require a minimum p_T constituent cut
  - How does this effect the balance?

$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$

*ATLAS, PRL **105**, 252303*
*CMS, PRC **84**, 024906 (2011)*

(Biased) Di-Jet Selection



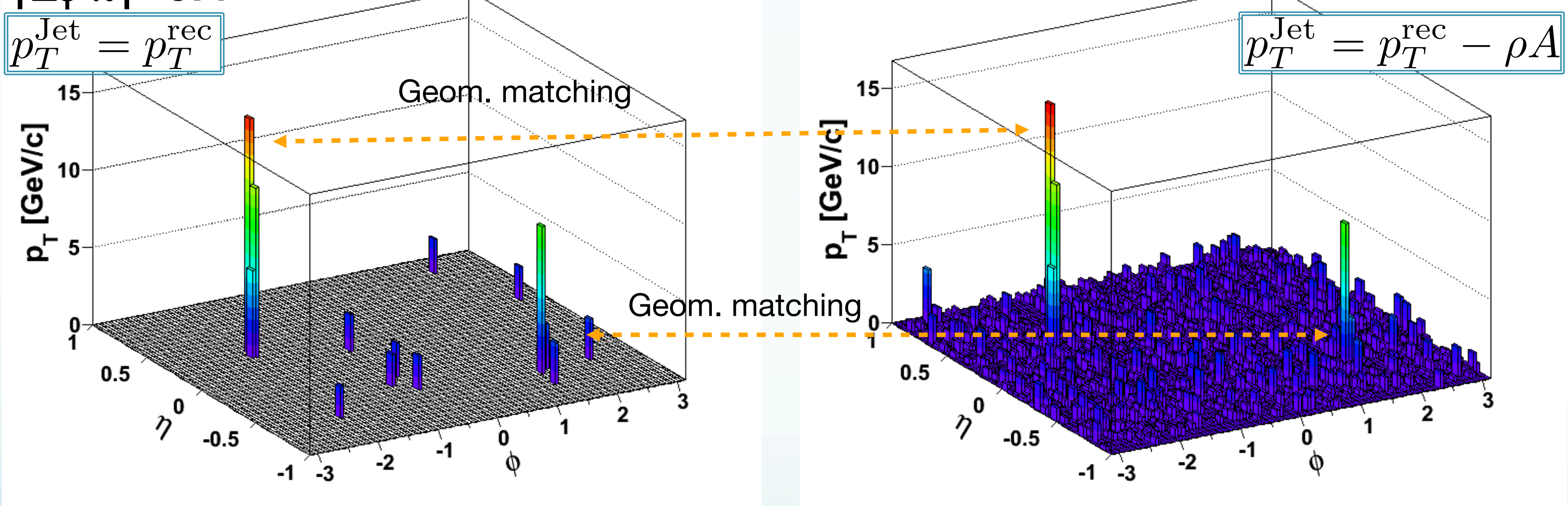
- Constituent p_T^{Cut} = 2 GeV/c
  - Reduce BG
  - Reduce combinatorial jets
- Di-jet Selection:
  - Jet p_T^{Lead}>20 GeV/c
  - Jet $p_T^{SubLead}$>10 GeV/c
  - $|\Delta\phi - \pi|<0.4$

Matched Di-jets w/o Constituent p_T Cut

p_T^{Cut}=2 GeV/c
p_T^{Lead}>20 GeV/c
$p_T^{SubLead}$>10 GeV/c
$|\Delta\phi-\pi|<0.4$

Rerun jet-finding algorithm anti-k_T on **these events** →

p_T^{Cut}=0.2 GeV/c
p_T^{Lead}>20 GeV/c (p_T^{Cut}=2 GeV/c)
$p_T^{SubLead}$>10 GeV/c (p_T^{Cut}=2 GeV/c)



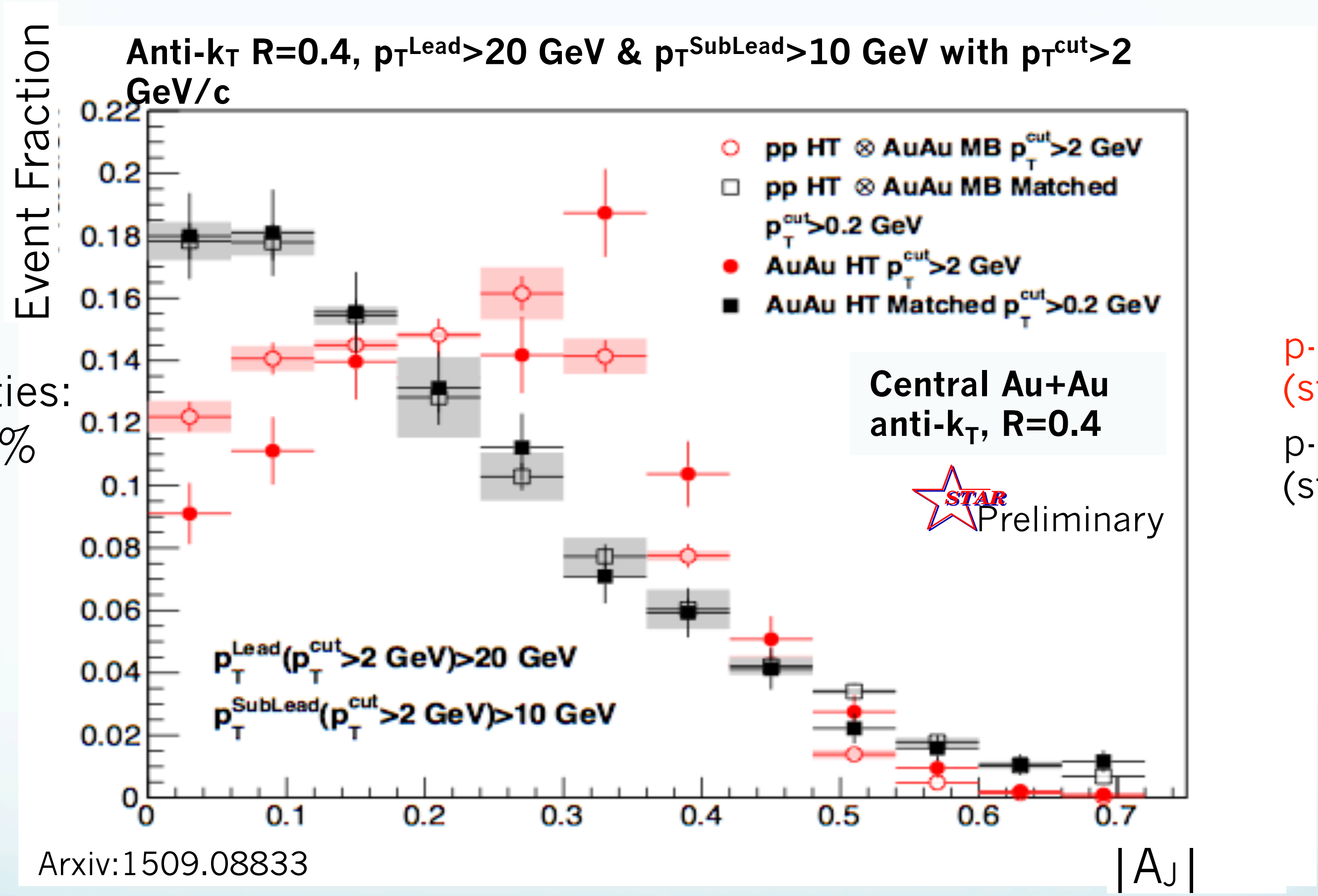
Keep this jet selection

Calculate "matched" $|A_J|$ with constituent $p_{T,cut}$>0.2 GeV/c.

Geom. matching: $\Delta R<0.4$

Di-Jet Imbalance A_J Central Au+Au, R=0.4

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



p-value < 10^{-4} (stat. error only)

p-value = 0.8 (stat. error only)

Au+Au di-jets more imbalanced than p+p for $p_T^{cut}>2$ GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

STAR Statistics

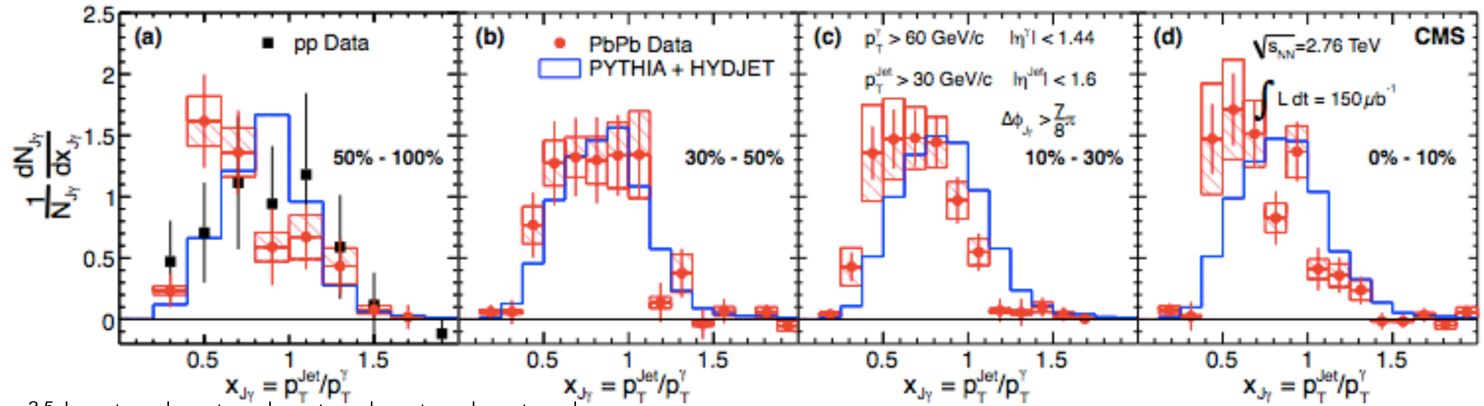
- Increased statistics recorded in 2011 will allow for γ_{rich}-jet correlations
  - Compare h-jet and γ_{rich}-jet
  - Path-length dependence
  - Energy loss

Year	Species	$\sqrt{s_{NN}}$	Integrated Luminosity
2006	pp	200 GeV	11 pb^{-1}
2007	Au+Au	200 GeV	535 μb^{-1}
2009	pp	200 GeV	23 pb^{-1}
2011	Au+Au	200 GeV	2.8 nb^{-1}
2014	Au+Au	200 GeV	43.9 $\mathrm{n}b^{-1}$
2015	pp	200 GeV	382 $\mathrm{p}b^{-1}$
2015	p+Au	200 GeV	1.27 $\mathrm{p}b^{-1}$
2016	Au+Au	200 GeV	To be recorded

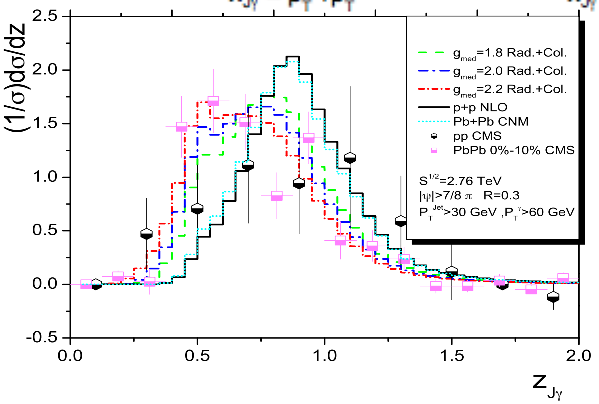
- Measuring the same observable at RHIC and the LHC with the same parton p_T and flavor will be key
  - Complementary to our understanding of QCD

Photon Jet Energy Fraction x_{Jg}

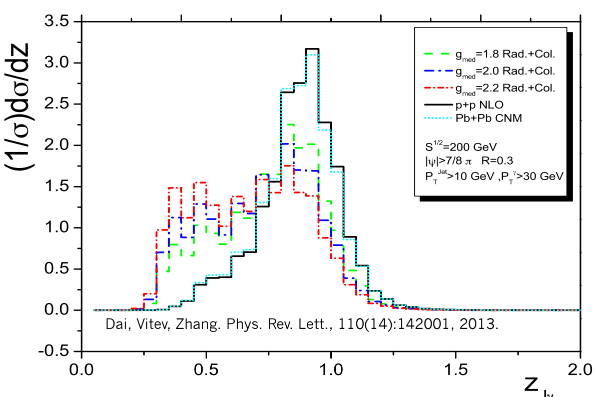
CMS: Phys. Lett., B718:773–794, 2013.



$$x_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$$



2.76 TeV



Dai, Vitev, Zhang. Phys. Rev. Lett., 110(14):142001, 2013.

200 GeV

- The steeper falling RHIC cross-sections
  - Narrow $x_{J\gamma}$ distribution in pp
  - Larger broadening shift in $\langle x_{J\gamma} \rangle$ in A+A collisions
    - Less energy per jet is dissipated on average
- Order of magnitude increase in statistics make this feasible!

Conclusions

- Away-side hadrons of triggered γ_{dir} and π^0 show similar suppression
  - **Expected result of $I_{AA}\pi^0$-h < $I_{AA}\gamma_{dir}$-h isn't observed in $0.1 < z_T < 0.9$ range, within uncertainties**
- Suppression at low z_T is less compared to high z_T
  - **Low p_T enhancement of jet fragmentation function**
- No direct photon trigger energy dependence of suppression is observed at high-p_T
- Clear away-side p_T^{assoc} dependence of suppression is observed for $I_{AA}\gamma_{dir}$-h
- I_{CP} of h-jet is ~0.2
  - **Energy shift is smaller for larger cone size**
- For biased dijets, the lost energy is recovered within R = 0.4, differs from LHC results
- Increased data will allow differential jet measurements at RHIC energies
  - Complementary with LHC results

Back-Up