Azimuthal Correlation of direct γ and π^0 with charged hadrons at STAR

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For the STAR Collaboration

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How many bodies are required before we have a problem?

G. E. Brown: History carries the answer

In eighteenth-century Newtonian mechanics, the three-body problem was **insoluble**.

With the birth of relativity and QED, the two- and one-body problems became **insoluble**.

And within modern QFT, the problem of zero bodies (vacuum) is **insoluble**.

So, if we are out after **exact solutions**, no bodies at all is already too many!

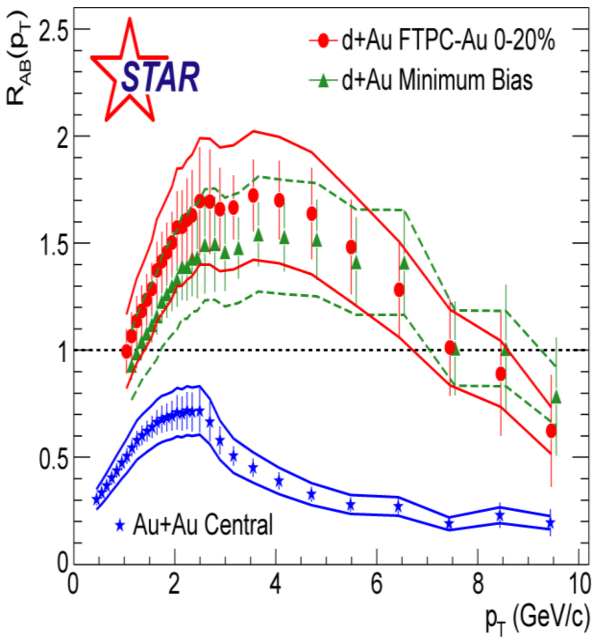
R. D. Mattuck

Table of contents

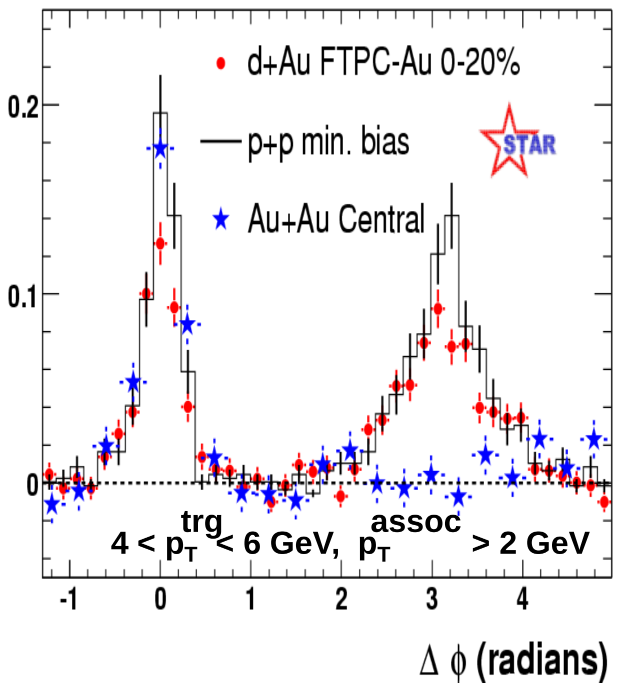
Evolution of jet suppression picture at RHIC

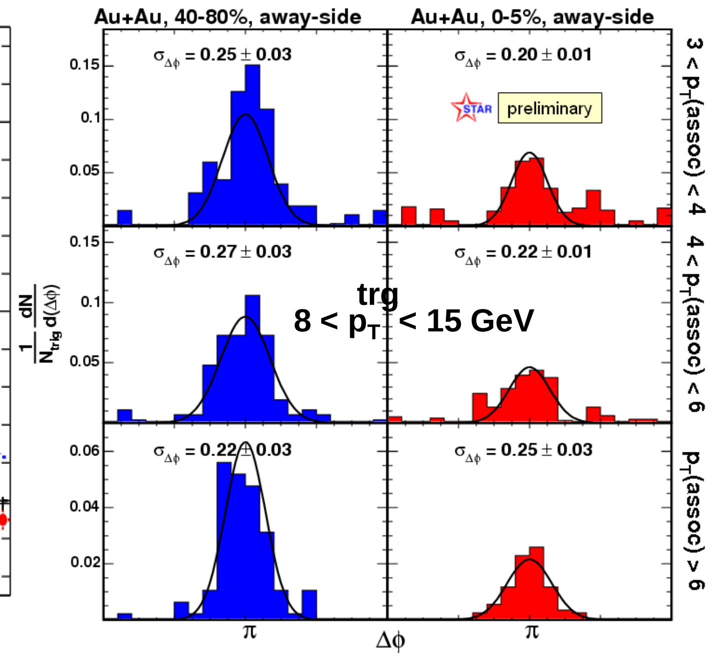
Hadrons suppression in central Au+Au is:

PRL. 91 072304 (2003)



PRL 91 072304 (2003)





final-state effect → surface-biased → tangential-biased and/or punch-through Non interacting jets

Medium needs more penetrating probes

- Direct γ
  this talk
- Full jet reconstruction
  Andrew Adare`s talk
  Elena Bruna's talk
- 2+1 correlations
  Hua Pei's talk

Azimuthal correlation of direct γ/π^0-charged hadrons

1. Direct γ-charged hadrons

- High-p_T γ^{dir} balances the p_T of the other outgoing parton

k_T effect (several hundred MeV "theoretically" and ~3GeV reported by PHENIX).

Energy loss dependence on parton initial energy

2. Direct γ-charged hadrons vs. π^0-charged-hadrons

- $\lambda_{\gamma dir}$ is large enough that its momentum is preserved, and also samples uniform spatial distribution of the hard scattering vertex inside the medium $\rightarrow$ "no surface and no tangential biases"

Energy loss dependence on path length

- If Compton scattering is the dominant process for γ^{dir} productions

Energy loss dependence on color factor

At same trigger (γ/π^0) energy, the outgoing parton of π^0-h coincidence is more energetic than that of γ^{dir} –h coincidence.

Expectation on the away-side of γ^{dir} and π^0

Conjecture of energy loss functional form for particular medium

$$P(\Delta E) \propto F(E, L, C_R, f)$$

"independent variables" (E, L, C_R, f)

1. F(L) : The recoiling jet from π^0 travel on average longer distance within the medium than that of γ^{dir}

2. F(C_R): If the Compton scattering is the dominance channel for γ^{dir} productions, then recoiling jet of π^0 is a mix of q/g while for γ^{dir} the dominance is q.

▶ These two factors cause the recoil jet from π^0 to lose more energy than that of γ^{dir}

3. F(E) : The energy of the recoiling jet from π^0 is greater than that of γ^{dir}.

✓ This factor needs to be measured

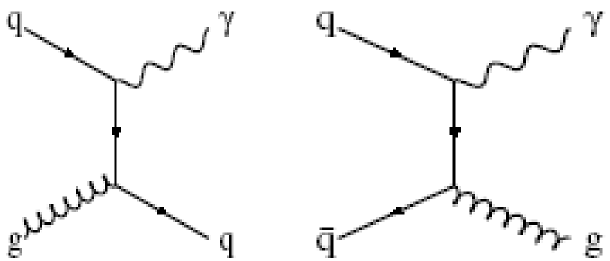
According to theoretical models:

Relative phase: $dE_{rad}/dz \propto C_R\, \alpha_s\, E \langle q_\perp^2 \rangle$ $\quad dE_{rad}/dz \propto C_R\, \alpha_s \ln(E) \langle q_\perp^2 \rangle$

Static Medium: $dE_{rad}/dz \propto L^2$ $\quad$ Dynamic Medium: $dE_{rad}/dz \propto L$

Notice : We don't measure energy loss but I_{AA}, how I_{AA} is related to ΔE?

LO production of direct γ and backgrounds



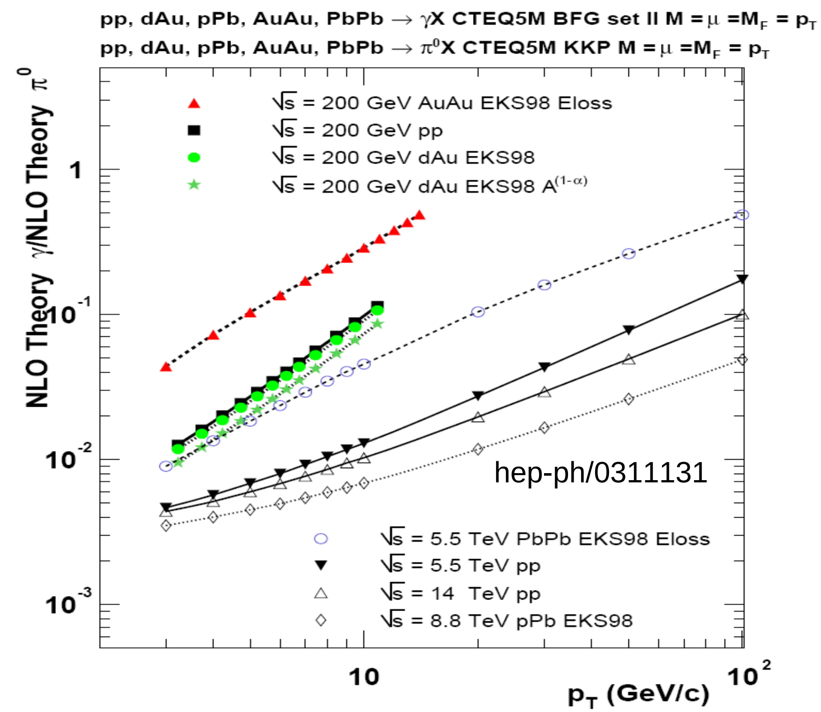
Compton Scattering   Annihilation

Very challenging measurements due to the S/B ratio, π^0 is the major source of bg.

The Compton-scattering process $\rightarrow \gamma/\pi^0 > \alpha_{em}$

$\rightarrow$ High-pt direct photons are produced at a rate comparable to that of single particles.

S/bg at $\sqrt{S}$=200 GeV at mid-rapidity at p_T > 8 GeV/c	p+p	Au+Au (central)
γ^{dir}/π^0	~1:5	~1:1
γ^{dir}/η	~1:1.25	~1:0.25
$\gamma^{dir}/\gamma^{frag}$	~1:0.4	?



Fragmentation photons

Fragmentation photons γ^{frag}

Example of Bremsstrahlung diagrams

γ^{frag} seems to be accompanied by additional hadrons.

$$zD_{\gamma/q}(z,Q^2)=e_q^2\frac{\alpha}{2\pi}[1+(1-z)^2]\ln(Q^2/\Lambda^2) \sim \alpha_{em}/\alpha_s$$

$$zD_{\gamma/g}(z,Q^2)=0$$

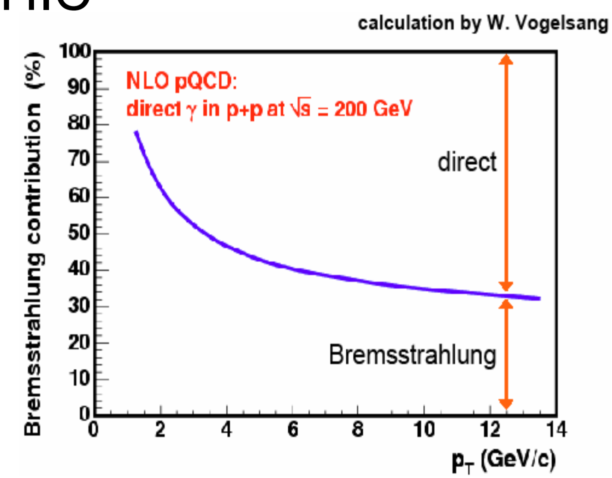
- The sub-process of γ^{frag} is of order of $O(\alpha_s^2)$ but its yield is comparable to γ^{dir} LO process $O(\alpha_s\alpha_{em})$.

- The relative contributions of γ^{dir} and γ^{frag} are strongly depend on the region explored in the PDF$\rightarrow$ collider energy and kinematics.

"more problematic at LHC than at RHIC"

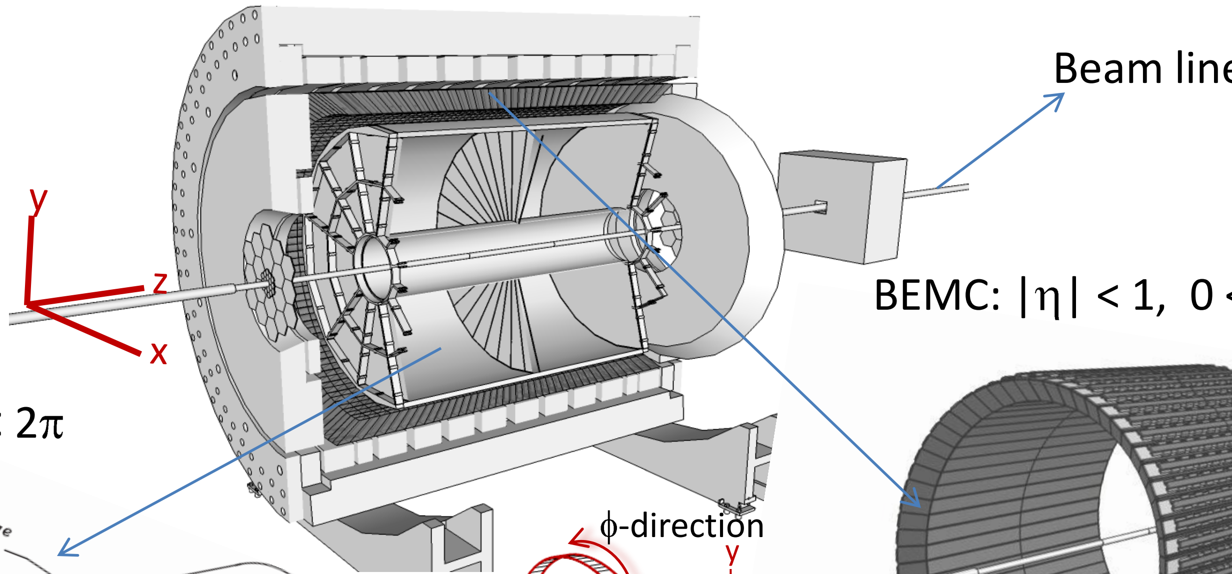
- The γ^{frag} contribution is expected to fall off more rapidly in x_T than the other lowest order of γ^{dir}. (G. Sterman et al. Rev. Mod. Phys. 67, 157 (1995))

- γ^{frag} / γ^{dir} ~30-40% at $p^{\gamma}_T > 8$ GeV/c at mid-rapidity at RHIC energy. D. De Florian and W, Vogelsang, Phys. Rev. D72, 014014 (2005)



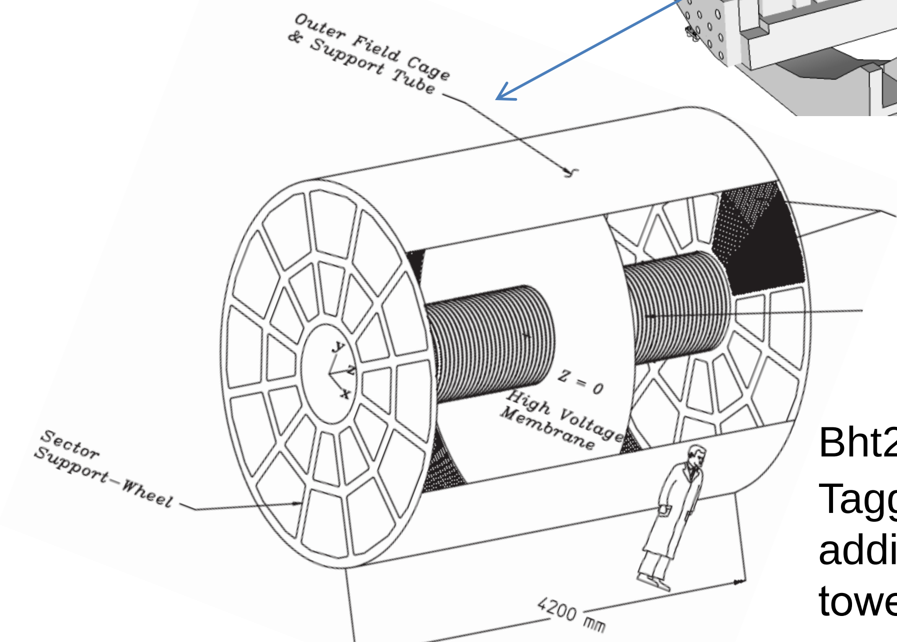
STAR detector and on-line γ-rich event selections

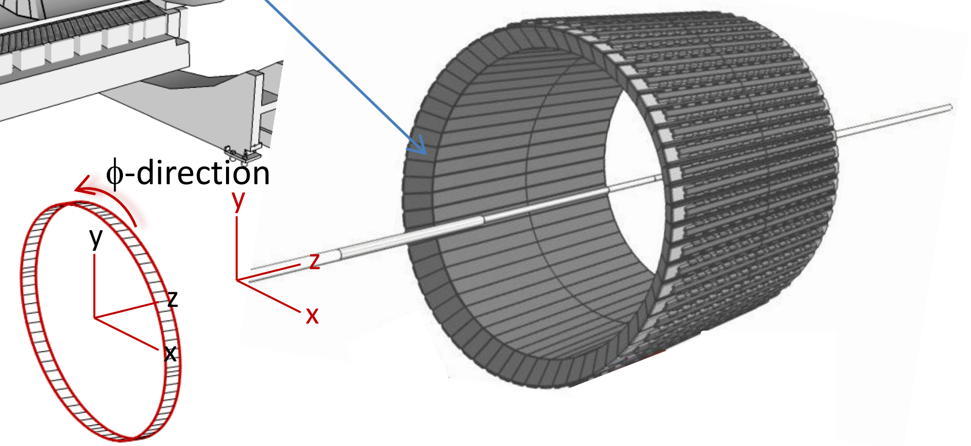
➢ **STAR is well-suited detector for correlation measurements**



BEMC: |η| < 1, 0 < ϕ < 2π

TPC: |η| < 1, 0 < ϕ < 2π





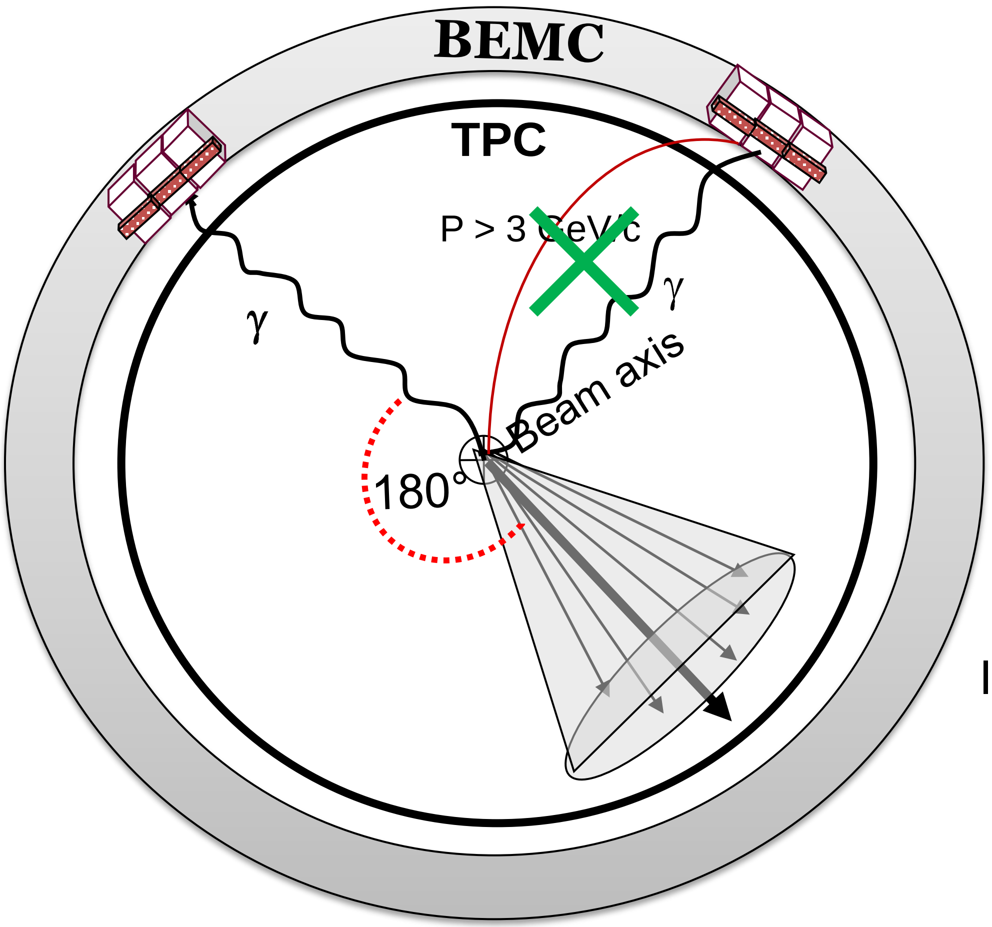
L2gamma trigger in AuAu (2007)

Bht2-mb: ZDC coincidence, and $E_{T(tower)} > 5.76$ GeV
Tagger for express stream: Based on bht2-mb, with additional higher $E_{T\ (cluster)} > 7.44$ GeV . "Cluster_size ≤ 2 towers"

1 γ-triggered event each 5k minbias event → ~ 500 μb^{-1} of AuAu 2007 @ 200GeV
~ 11 pb^{-1} of pp 2006 @ 200GeV

STAR detector and off-line γ-rich event selections

✓Correlate neutral clusters "triggers" (BEMC-BSMD) with tracks (TPC)



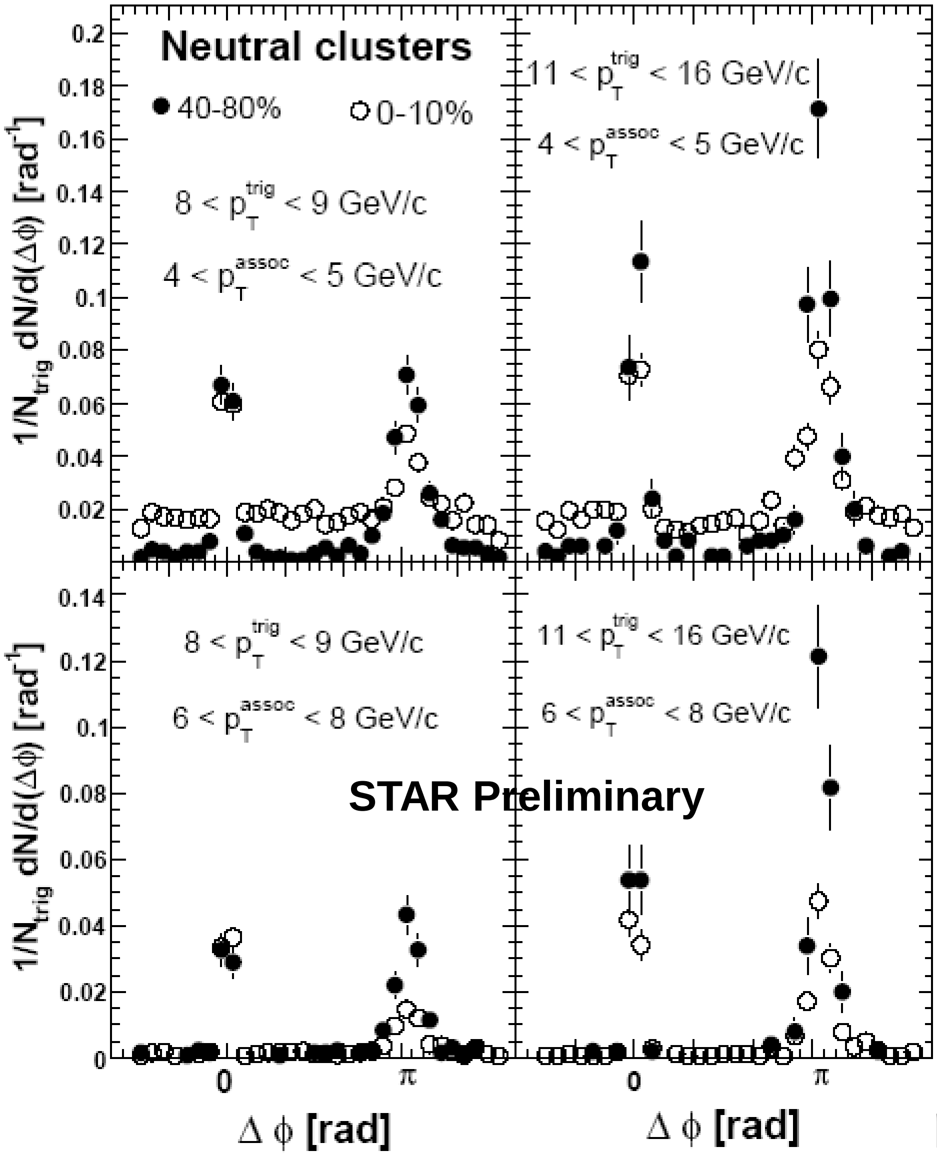
Offline: event selection and analysis

vertex within ±55 cm of the center of TPC.

at least one cluster with $E_T > 8$ GeV, $Esmd\eta > 0.5$ GeV, $Esmd\phi > 0.5$ GeV, and no track with $p > 3$ GeV/c pointing to that cluster.

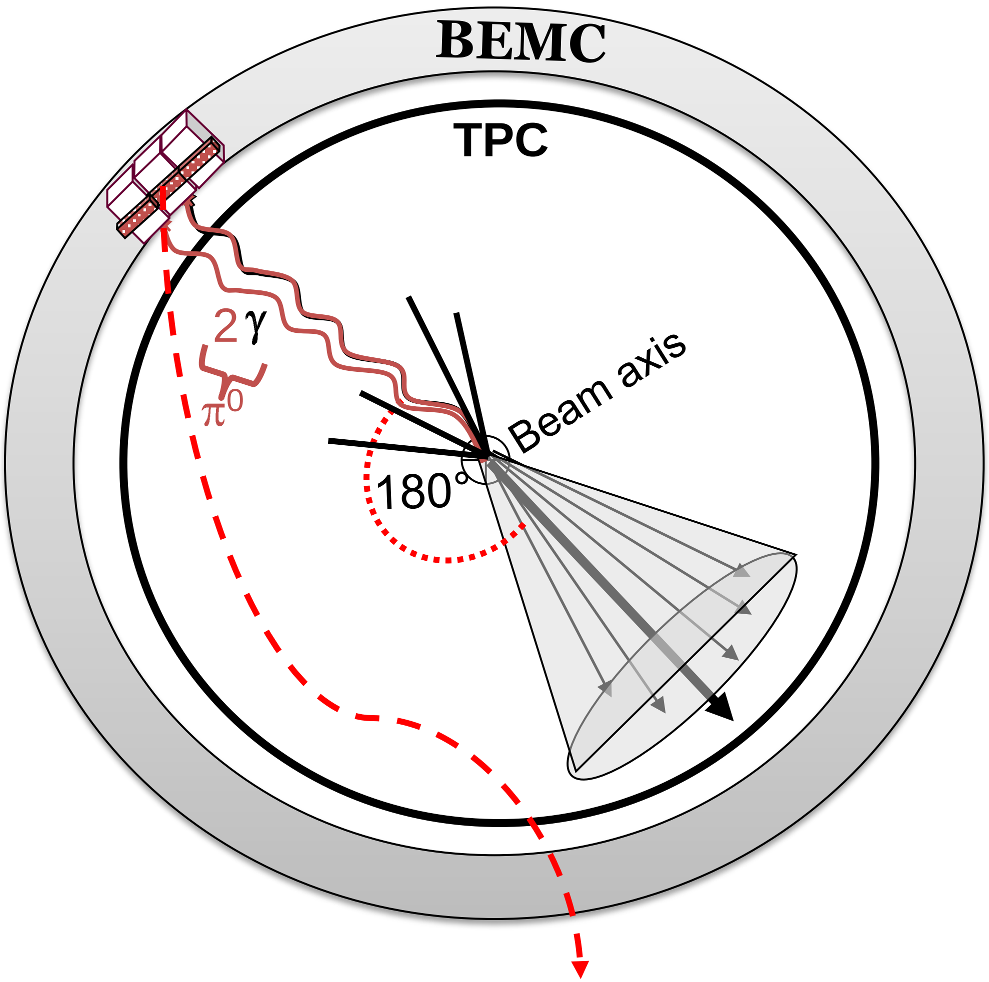
In Au+Au: 28% of the integrated luminosity has $E_T > 8$ GeV of which 96.5% left at least 0.5 GeV on each planes of SMD of which 93% has no track with $p > 3$ GeV/c pointing to it.

Azimuthal correlation functions of neutral clusters



- Both near and away-side yields increase with trigger energy
- The increase on the away side is larger due to the trigger bias.
  - Final-state medium effects cause the away-side to be increasingly suppressed with centrality, without significant broadening.
- The suppression of the near-side yield in central relative to peripheral is consistent with the expected increase of the γ/π^0 ratio with centrality at high energy.

How to separate γ^{dir} from neutral bg.



Either to reconstruct π^0 or to use the transverse shower shape analysis to distinguish between π^0 and γ^{dir}

Methods of γ^{dir} extraction

✓ Standard Method

1. Measure inclusive photons.
2. Reconstruct other sources of photons "hadrons"!
3. Subtract photons from decay of π^0, η etc.

B. I. Abelev et al., hep-ex: 0912.3838

PHENIX is well-adapted for this method due to the calorimeter granularity and the distance between the calorimeter to the interaction point $\rightarrow$ π^0 reconstruction in central Au+Au up to p_T ~ 20 GeV/c

➢ Limited at very high p_T, effective method for both symmetric and asymmetric hadron decays

✓ Transverse Shower Profile Method

STAR is well-suited for the transverse shower shape analysis due to the Shower Maximum Detector $\rightarrow$ γ/π^0 discrimination up to p_T ~ 26 GeV/c. M. Beddo et al., Nucl. Instrum. Meth. A499, 725 (2003)

➢ Effective at very high p_T, but limited only for the symmetric hadron decays

Novel Method

Statistical measurement of γ-jet yields

- Use the transverse shower shape to select γ^{dir} free (π^0-rich) sample and γ^{rich} sample from the neutral clusters.

- Impose the condition of zero-near side yield associated with γ^{dir}

$$Y^{\gamma_{dir}+h} = \frac{\left(Y^{\gamma_{rich}+h} - \mathcal{R} Y^{bgd+h}\right)}{1-\mathcal{R}} \qquad \mathcal{R} = \frac{N^{bgd}}{N^{\gamma_{rich}}}$$

(a measure of bg in the γ_{rich} sample)

- Shower shape analysis doesn't measure all bg, it measures only the π^0 in its symmetric decay mode.

All sources of bg are approximated to the measured π^0

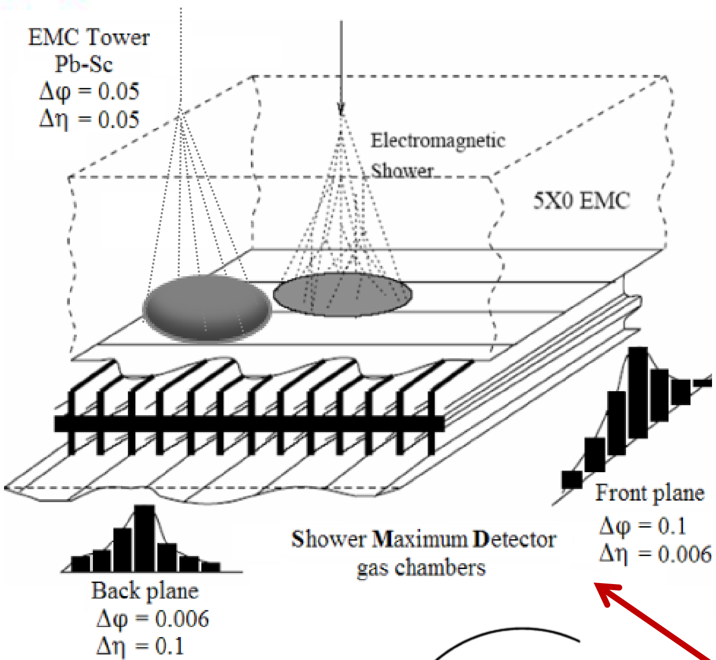
$$Y^{\gamma_{dir}+h} = \frac{\left(Y^{\gamma_{rich}+h} - \mathcal{R} Y^{\pi^0+h}\right)}{1-\mathcal{R}} \qquad \mathcal{R} \simeq \frac{N^{\pi^0}}{N^{\gamma_{rich}}} = \frac{Y_{NS}^{\gamma_{rich}+h}}{Y_{NS}^{\pi^0+h}}$$

Are $\mathcal{R}$ values reasonable?

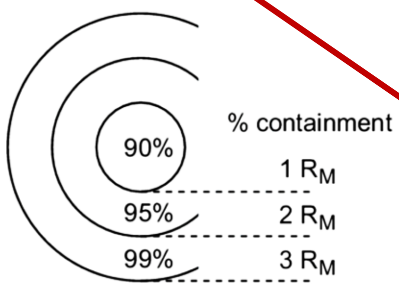
Do the other sources of bg have similar correlations with charged hadrons as that of the measured π^0?

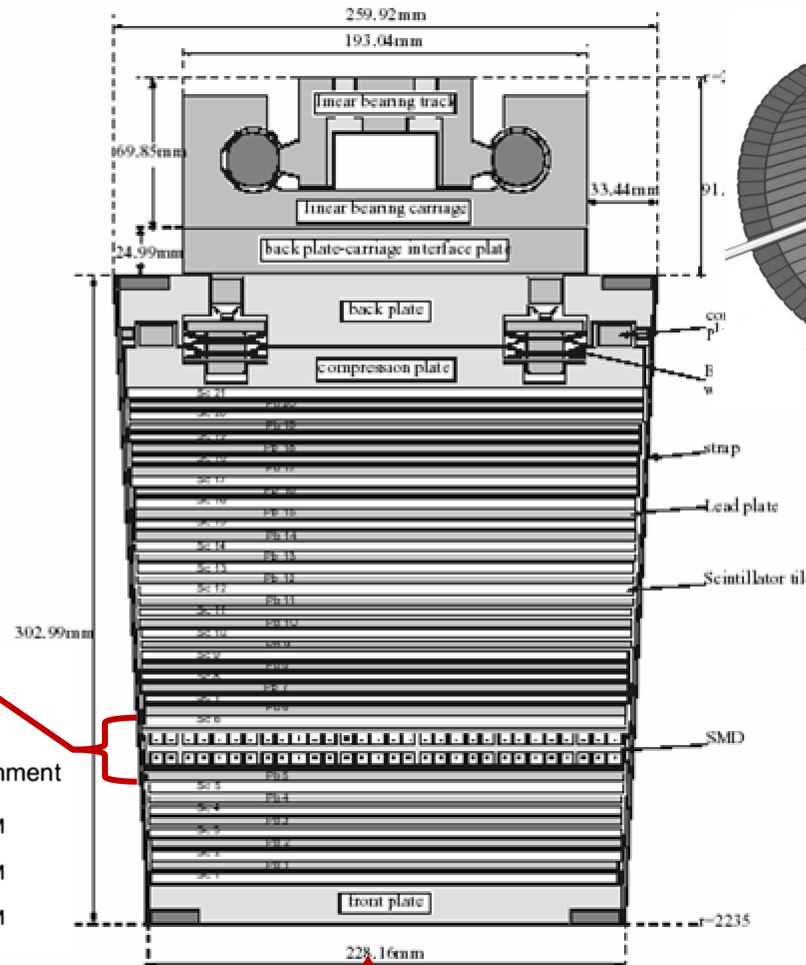
Note : ~10% of all π^0 (8-16GeV/c) decay asymmetrically with one gamma has p_T > 8 GeV/c within STAR-BEMC acceptance. η causes similar level of background as asymmetric π^0.

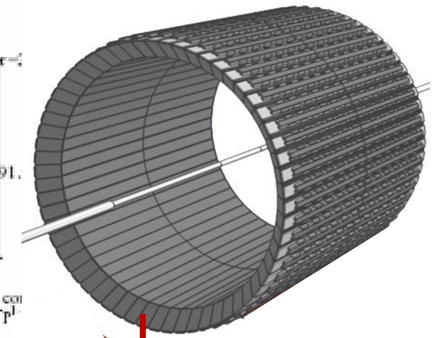
STAR BEMC and BSMD



$$E_{cluster} / \sum_i e_i r_i^{1.5}$$







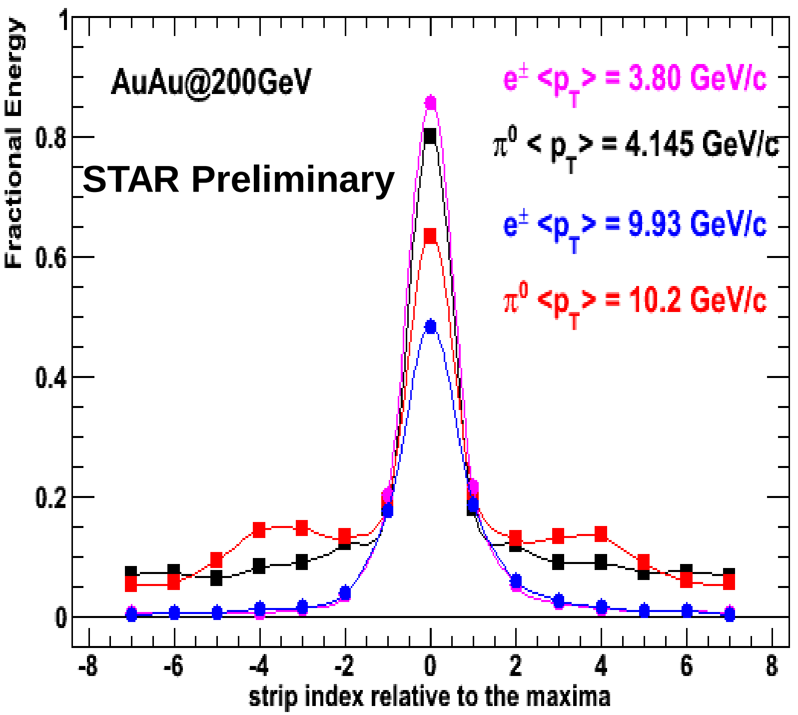
Cross section in ϕ

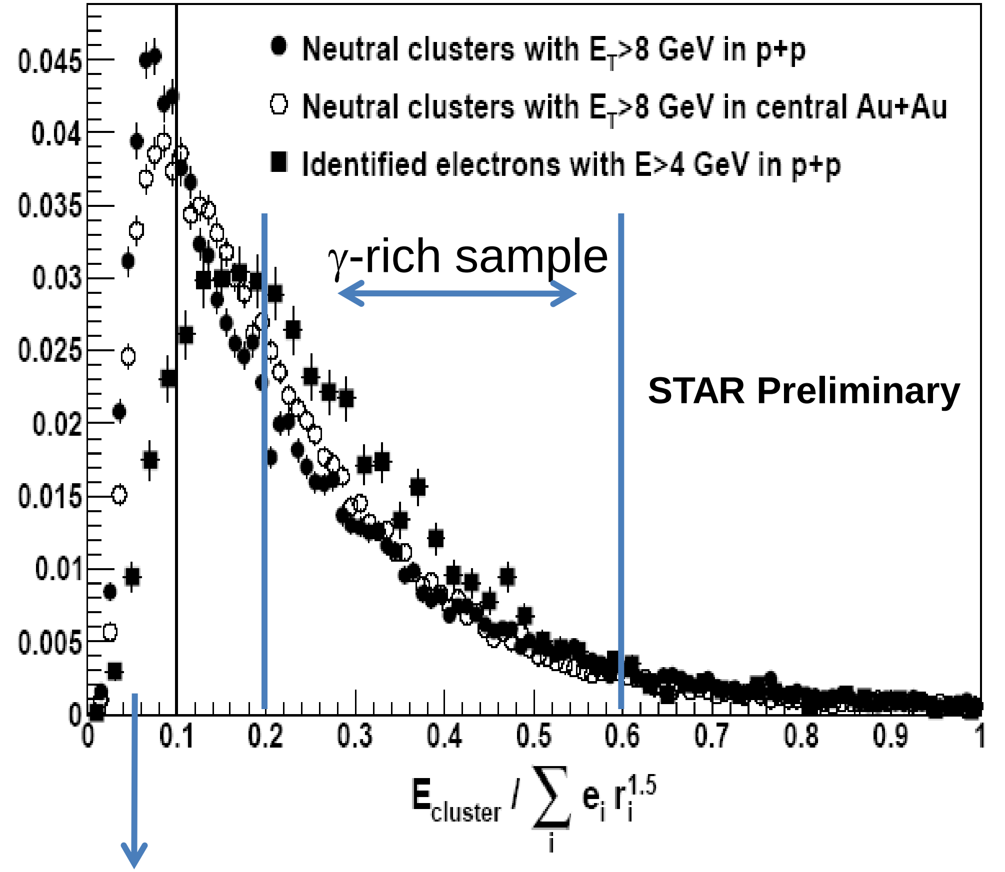
The two photons originated from π^0 hit the same tower at p_T>8GeV/c

The shower shape is quantified with the cluster energy, measured by the BEMC, Normalized by the position-dependent energy moment, measured by the BSMD strips.

Transverse Shower Profile Results

Shower Profile of single γ vs. two close γs



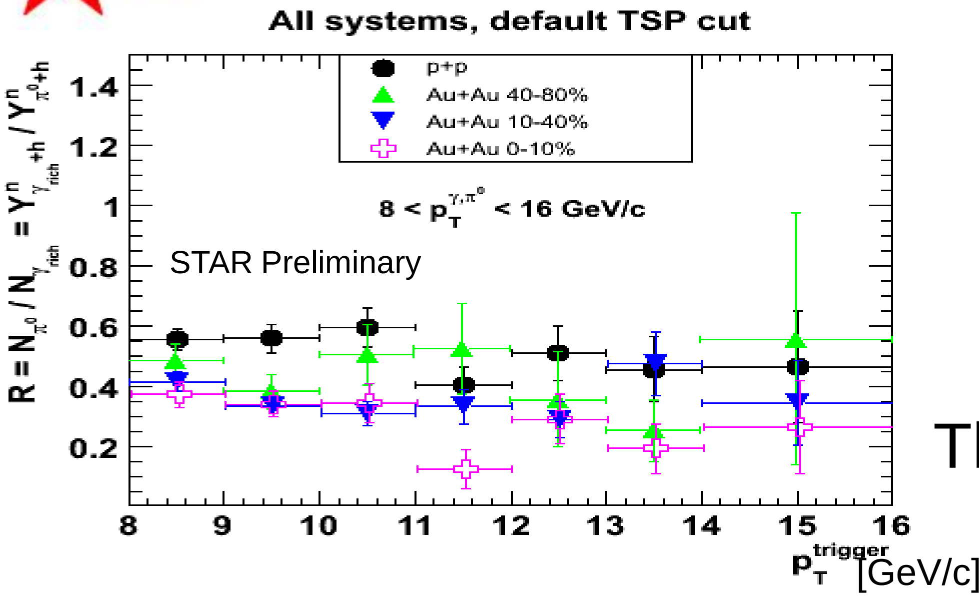


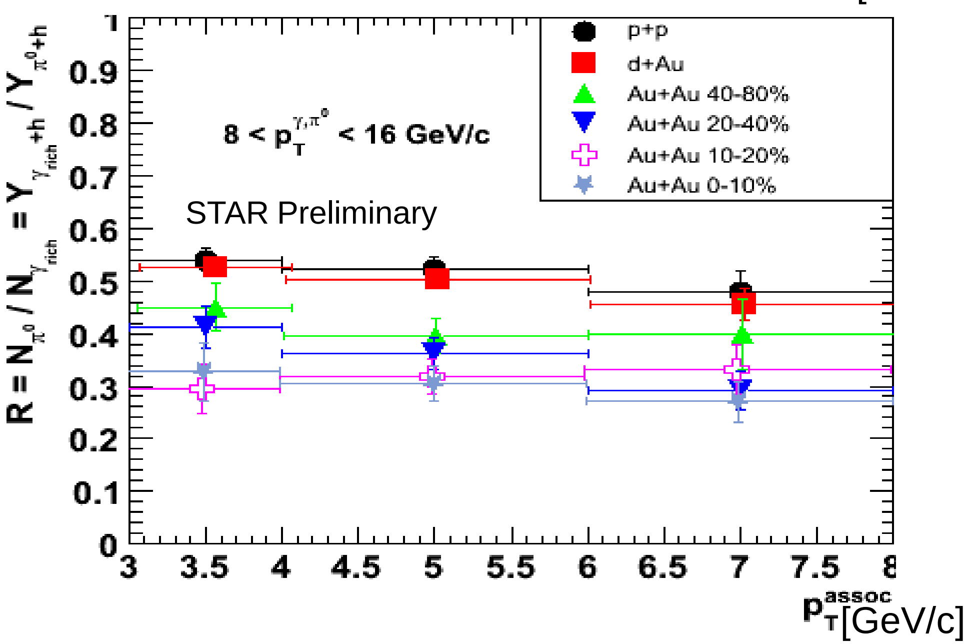
direct γ free (π^0-rich) sample

The probability distribution is peaked at smaller value in AuAu than in pp due to the larger relative fraction of γ^{dir}.

The rejection power of direct photons is ~ 90%

1. R values

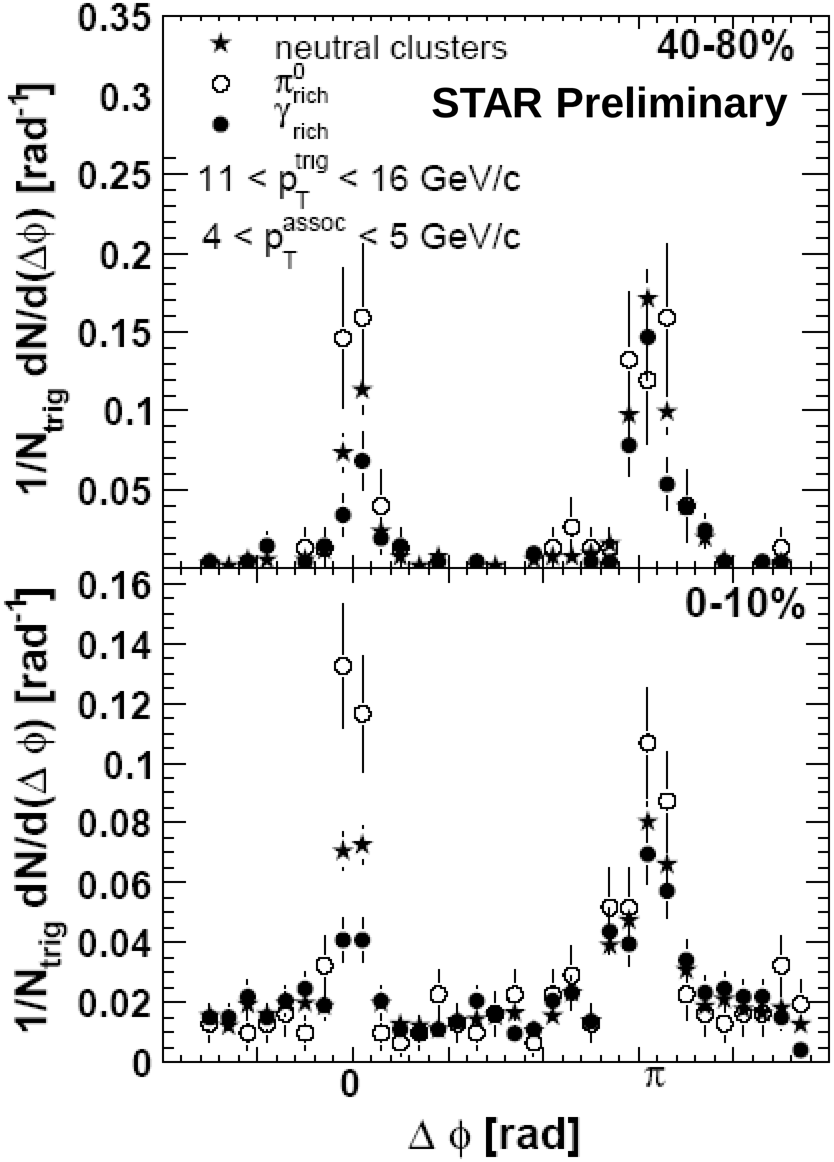




$$\mathcal{R} \simeq \frac{N^{\pi^0}}{N^{\gamma_{rich}}} = \frac{Y_{NS}^{\gamma_{rich}+h}}{Y_{NS}^{\pi^0+h}}$$

The level of bg in the γ_{rich} sample: ~55-30% from pp to central Au+Au, and doesn't show strong dependence neither on p_T trig nor on p_T assoc.

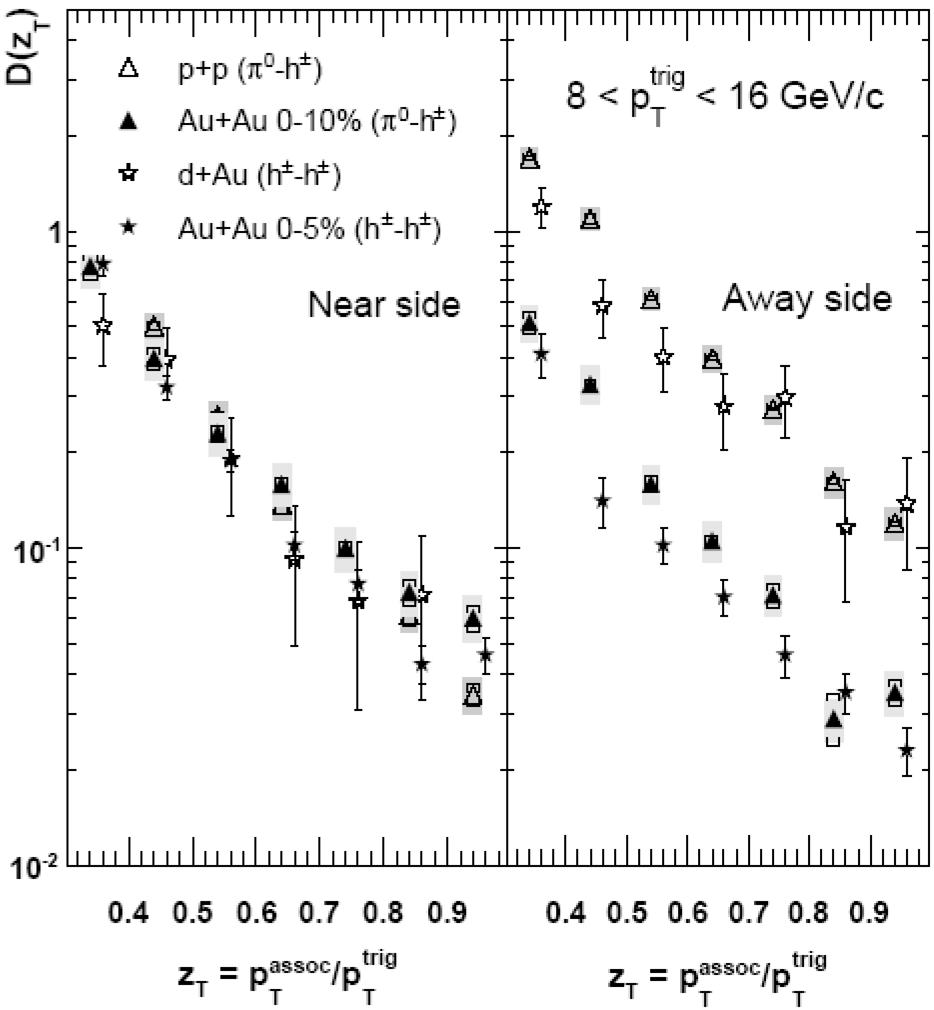
2. Correlation functions of neutral clusters, $\pi^0(\gamma^{dir}$ free), and γ^{rich} samples



- γ^{rich} sample has lower near-side yields compared to those of the π^0 rich, but not zero!
- Shower-shape analysis is only effective for rejecting two close γ showers, leaving background γ From asymmetric decays of π^0, η, γ^{frag}.
- The level of uncorrelated bg is dramatically suppressed relative to the signal over the measured range of p_T ^{assoc} $\rightarrow$"negligible v2 contribution".

3. z_T dependence of π^0-$h^{\pm}$ and $h^{\pm}$-$h^{\pm}$ near and away-side yields.

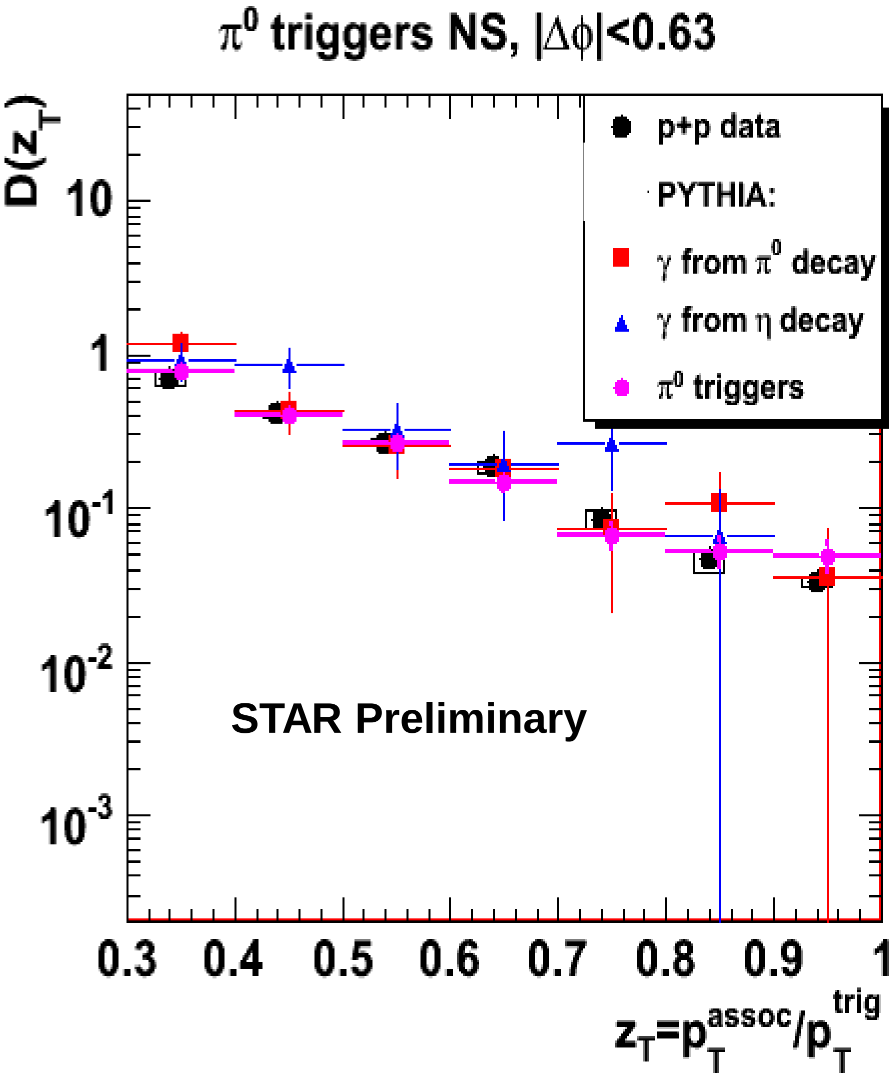
arXiv:0912.1871



- For π^0-$h^{\pm}$: Correlated systematic ~7-13% and point-to-point uncertainties are less than 5%
- A general agreement of ~ 20-30% b/w the results from π^0-$h^{\pm}$ and $h^{\pm}$-$h^{\pm}$ is clearly seen in both near and away-side yields $\rightarrow$ the π^0-rich sample is free of γ^{dir}.

Assumption Justifications

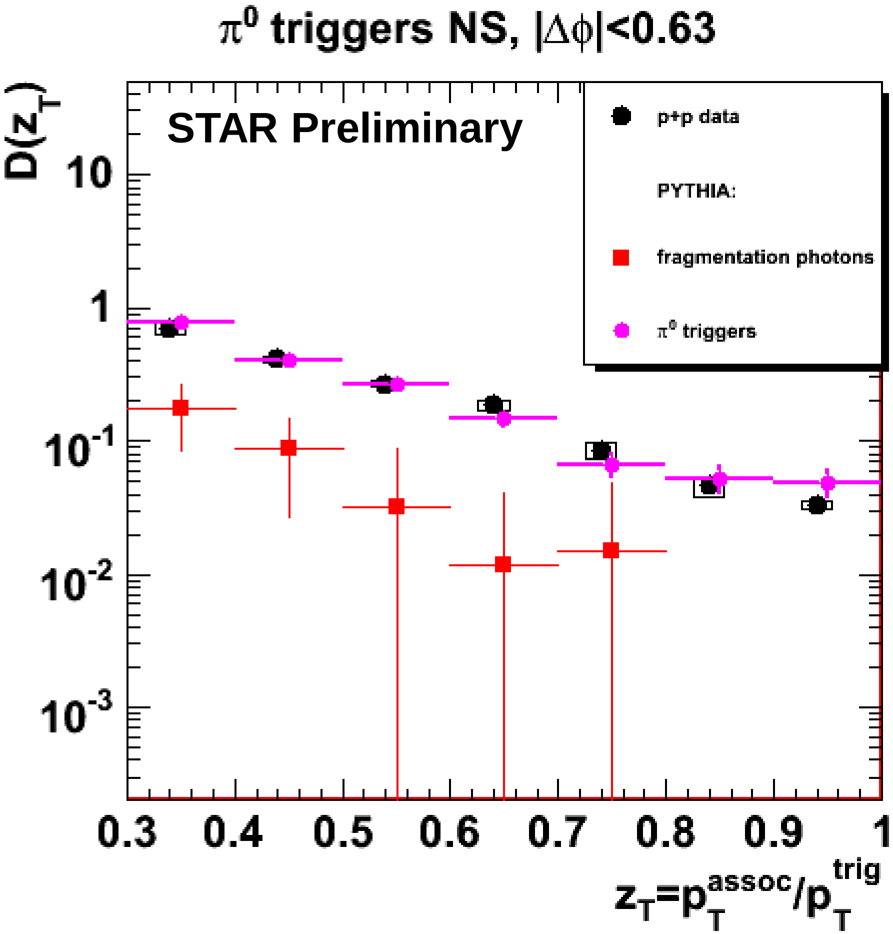
1. Do other sources of bg. have similar correlations with $h^{\pm}$ as the measured π^0?



PYTHIA simulation indicates, within ~10% at the same p_T trig, that the correlations of γ triggers From asymmetric hadron decays are

- ✓ Similar to those of symmetrically decaying π^0 triggers.
- ✓ Similar to the measured correlations of π^0-rich triggers.

2. Do other sources of bg. have similar correlations with $h^{\pm}$ as the measured π^0?



- γ^{frag} has different correlation with the charged particle compared to that of π^0 with insensitivity to the charged rejection cut..

2 classes of consideration for γ^{frag}:

1. The γ^{frag} which has near side yield are estimated using the χ^2 analysis, by comparing the shape of the near-side correlation of γ^{rich} to π^0 rich triggers, and is taken into account in the systematic errors.

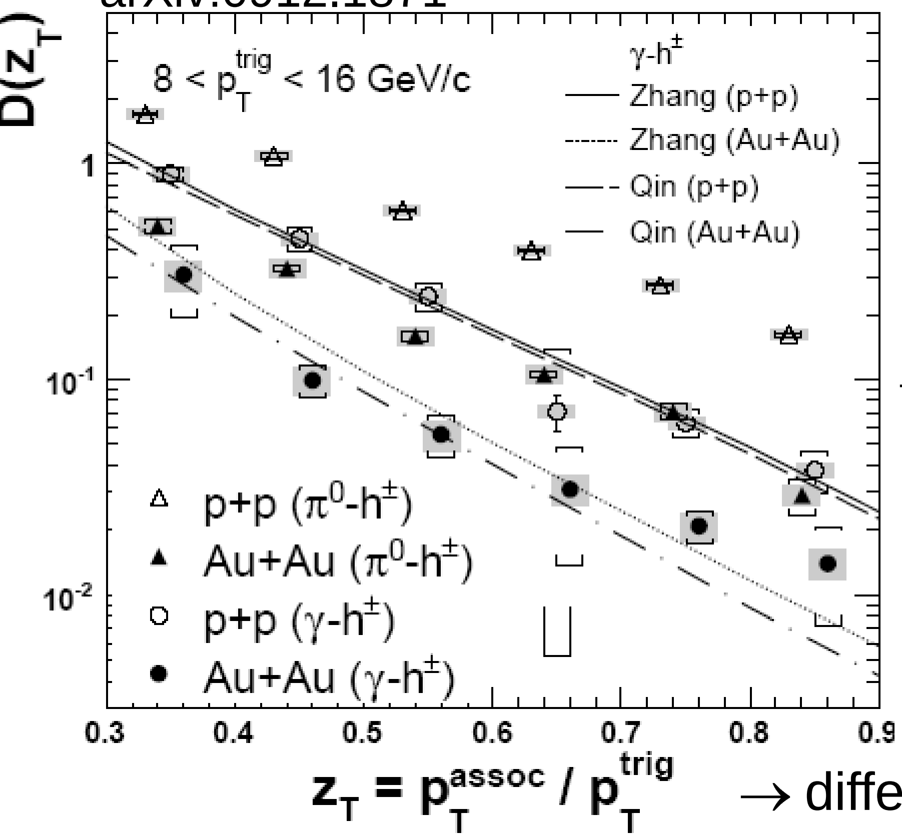
2. The γ^{frag} which has no near side yield within the integrated region "$|\Delta\phi| \leq 0.63$ rad" remains in the γ^{dir} measurements, but was studied by varying the PID cuts and included in final syst. Errors.

Extraction of the associated yields with γ^{dir}

$$Y^{\gamma_{dir}+h} = \frac{\left(Y^{\gamma_{rich}+h} - \mathcal{R} Y^{\pi^0+h}\right)}{1-\mathcal{R}}$$

z_T dependence of away-side associated-particle yields for π^0 triggers and γ^{dir} triggers.

arXiv:0912.1871



Data: γ^{dir} vs. π^0

- At given z_T, the away-side yield per π^0 trigger is significantly larger than that per γ^{dir} trigger.

p+p

→ γ^{dir} carries the total scattered constituent momentum while π^0 carries only a fraction of it.

→ different proportions of q and g recoiling from γ^{dir} and π^0 triggers.

Au+Au

→ different path length for the recoiling jet from π^0 trigger and γ^{dir} trigger.

→ color factor effect on energy loss.

Data vs. theory

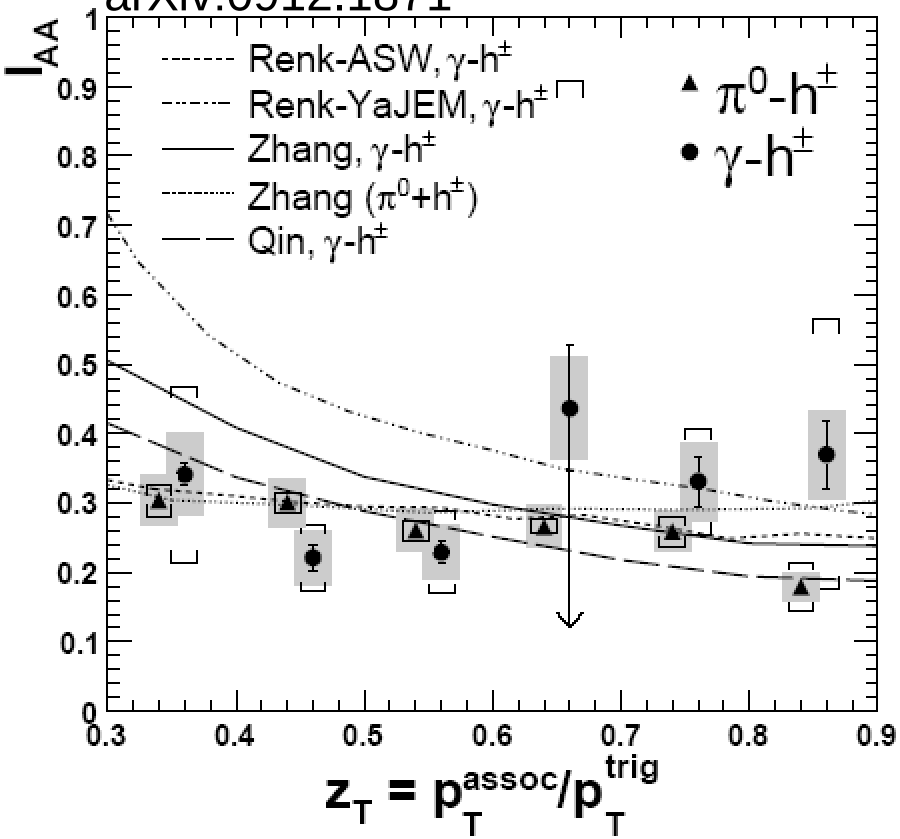
- The yields in p+p and Au+Au are well described by theoretical models:

1. Zhang et al., no γ^{frag} contributions.
2. Qin et al., significant contribution of γ^{frag}.

Medium effect as a function of z_T

$I_{AA}=D(z_T)_{pp}/D(z_T)_{AuAu(0-10\%)}$ for the recoiling jet of π^0 and γ^{dir} triggers:

arXiv:0912.1871



I_{AA} of π^0 vs. theory

→ agrees with Zhang et al. within the current uncertainties.

I_{AA} of γ^{dir} vs. theory

→ disfavors Renk-YaJEM→ lost energy is distributed to very low pt and large angle.

→ agrees with Renk-ASW, Qin et al., and Zhang et al. within current uncertainties.

→ shows no strong rise at low z_T.

Data: I_{AA} of π^0 vs. I_{AA} of γ^{dir}

→ similar level and pattern of suppression for I_{AA} of π^0 and γ^{dir} triggers and both are z_T-independent → effect of fluctuations in energy loss dominates over the effect of geometry !!! (Phys. Rev. C80, 014901 (2009)).

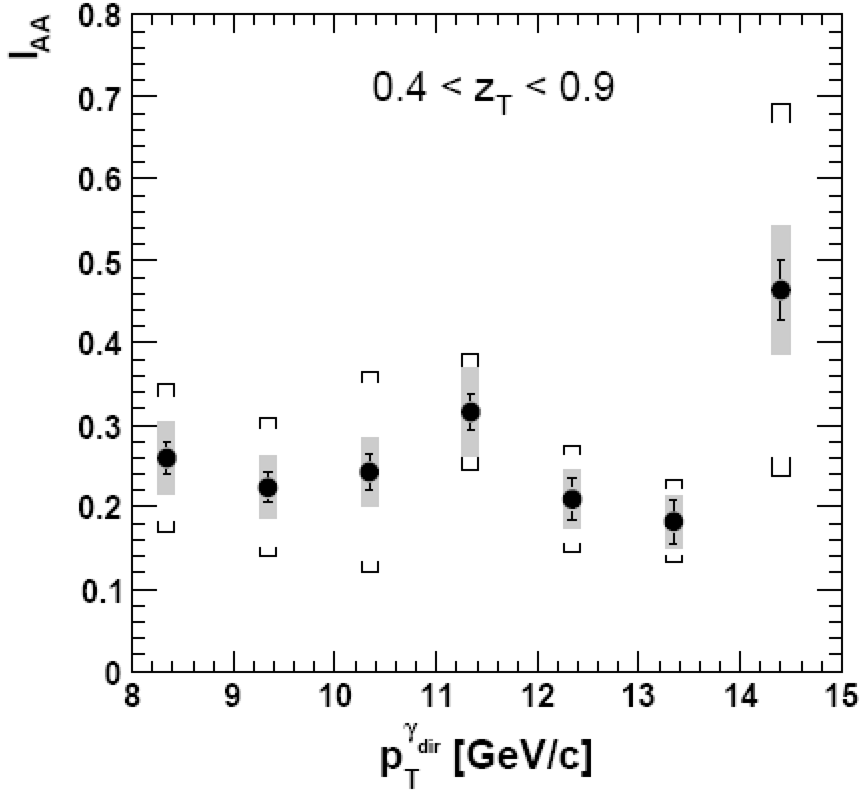
Energy loss dependence of parton initial energy

Why I_{AA} of γ^{dir} = I_{AA} of π^0 ?

Recall, we expect the recoil parton of π^0 to lose more energy than that of γ^{dir} due to the longer path length and color factor.

$P(\Delta E) \propto F(E, L, C_R, f)$

arXiv:0912.1871



Is it compensated with $P(\Delta E) \propto F(E)$?

- I_{AA} of γ^{dir} shows no strong dependence on E.

Then

- **The energy loss dependence on:**
1. Path length 2. Color factor
is not observed within the covered kinematics region

Summary

1. STAR, due to its acceptance, is capable of multi-analysis for more penetrating probes.

2. Direct photon-charged hadron coincidence measurement is clean probe for the energy loss dependence of parton initial energy.

3. Comparison of direct photon-charged hadron coincidence measurement with the neutral pion-charged hadron coincidence measurement provides tool for the energy loss dependence of path length and color factor.

4. STAR reported a novel method utilizing the transverse Shower Shape analysis for direct photon-charged hadrons coincidence measurements.

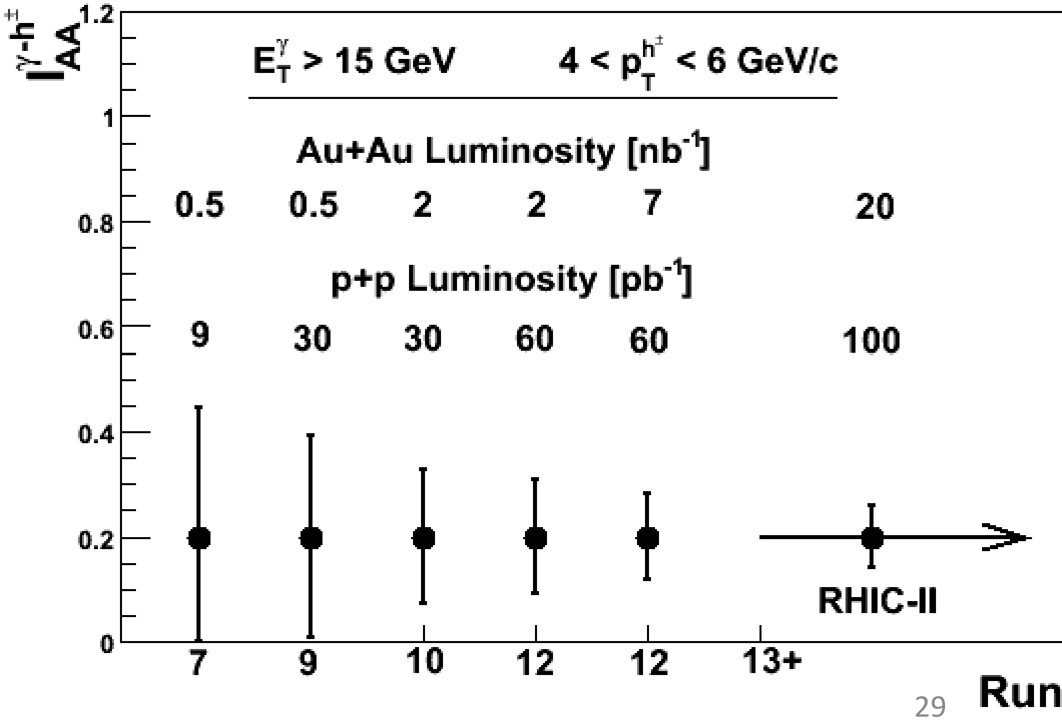
5. Within the covered kinematic range, the energy loss shows no dependence on parton initial energy, path length through the medium, and color factor.

6. Although different theoretical models assume energy loss dependence on path length, and parton initial energy; the theoretical predictions do not show significant difference between direct phtons and neutral pions away-side suppression within the covered kinematic ranges!!!

BOTH THEORY AND EXPERIMENT DON'T SUPPORT THE EXPECTATION
"within the covered kinematics range",
IS THE EXPECTATION WRONG? OR IS THE CURRENT PICTURE WRONG?

Outlook

- Probe the low z_T region.
- Comparison between the direct γ-triggered and π^0-triggered azimuthal correlations with charged hadrons and fully reconstructed jets in different collision systems.
- Performance of the same azimuthal correlation measurements with respect to the reaction plane.
- Measurement of v_2 of direct γ and π^0 at high p_T.
- Measurement of direct γ ridge.
- Study of LPV using direct γ and π^0.



If a model fit data, it is really great!

"No amount of experimentation can ever prove me right; a single experiment can prove me wrong"

Albert Einstein

RHIC enjoys a plenty of beautiful data for very difficult problem in which vacuum means too many bodies, so careful and very critical interpretations are required.