Azimuthal distributions of high-pt direct γ and π^0 w.r.t reaction plane at STAR

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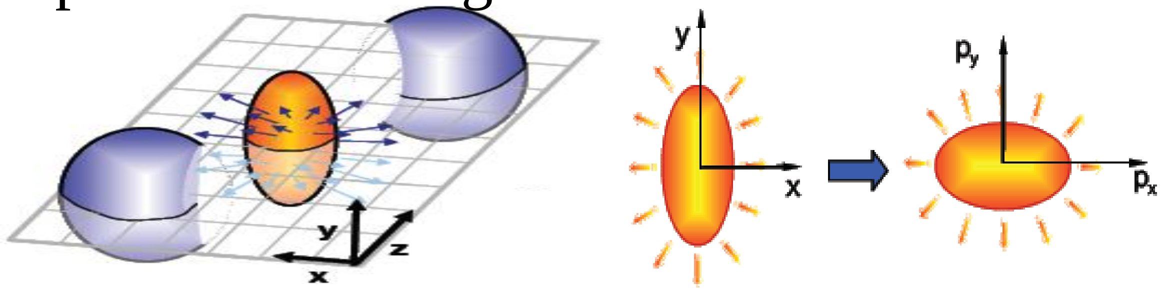
Elliptic flow at low pt

➢ The azimuthal distributions of the produced particles in heavy-ion collisions are considered to be sensitive to the initial geometric overlap of the colliding nuclei.

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



$$dN/d\phi \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_{RP})$$

➢ Eccentricity in spatial coordinate is preserved and mapped into the momentum coordinates **if the produced particles are not freely streaming.**

➢ At low p_T the produced particles are not freely streaming and the collectivity is built even before hadronization.

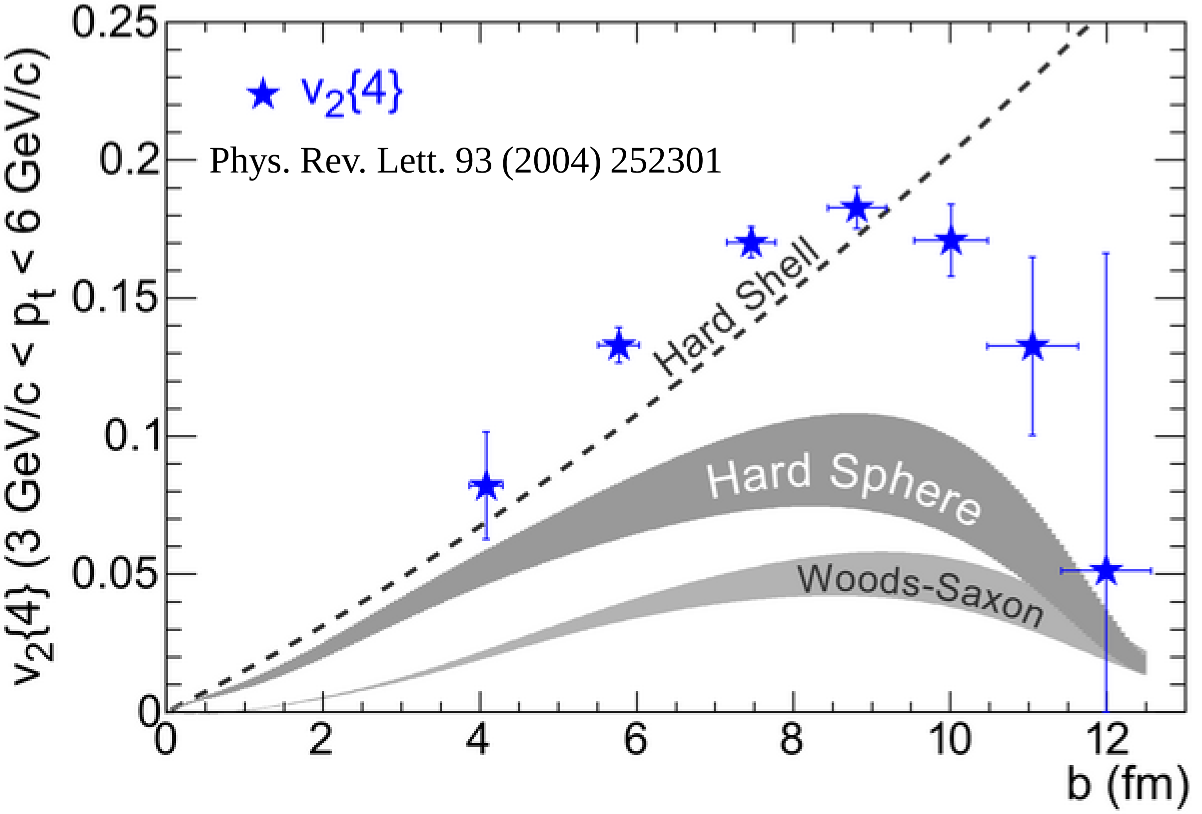
Non-flow

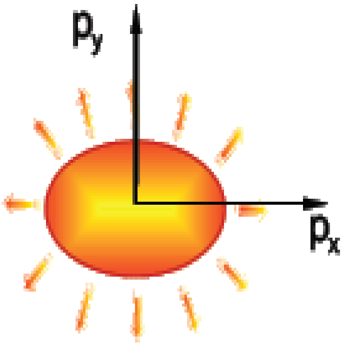
$$\langle \sum_i \cos 2(\phi_{p_t} - \phi_i) \rangle = M\, v_2(p_t)\, \bar{v}_2 + \{\text{non-flow}\}$$

Elliptic flow at high pt

V_2 at high p_T is finite positive!

Jet quenching : energy loss dependence of path length





- Azimuthal anisotropy at large p_T seem to be too large for a pure "jet quenching" Phys. Rev. C. 66, 027902 (2002)
- Surface emission is not consistent with the measured value of elliptic flow at high p_T Phys. Rev. Lett. 93 (2004) 252301

Why elliptic flow of direct photons?

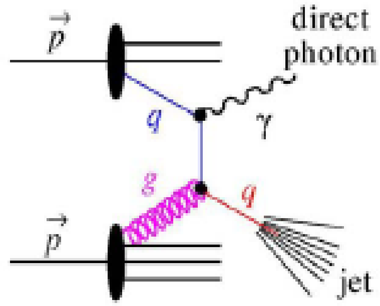
- v_2 of electromagnetically interacting particles.
- v_2 measurements at higher p_T.
- Production mechanisms of photons

Jet-medium photons

Phys.Rev. Lett. 90,132301 (2003)

$v_2 < 0$

Compton scattering

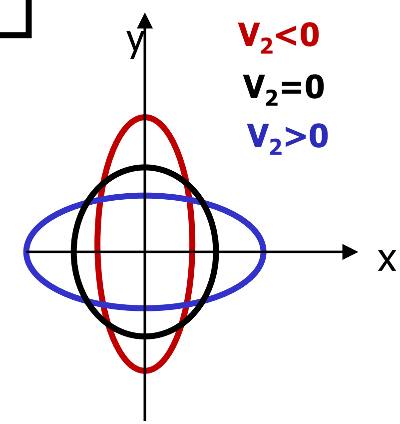


$v_2 = 0$

Frag. photons

JETP Lett. 80, 1 (2004)

$v_2 > 0$



- Path length dependence of parton energy loss.

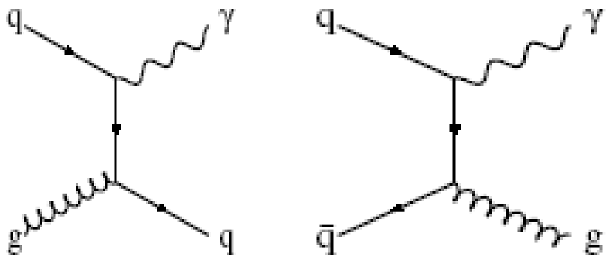
$V_2 < 0$: Particles preferred to traverse through the longer path "out-of-plane"

$V_2 = 0$: No preferred direction w.r.t. reaction plane

$V_2 > 0$: Particles preferred to traverse through the shorter path "in-plane"

LO production of direct γ and fragmentation γ

Direct photons



Compton Scattering Annihilation

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

$\rightarrow \quad \gamma/\pi^0 > \alpha_{em}$

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 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)

Methods of γ^{dir} measurements

✓ Standard Method

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

PHENIX is well-adapted for this method due to the calorimeter granularity and the distance between the calorimeter to the interaction point $\rightarrow \pi^0$ reconstruction in central Au+Au up to $p_T \sim 20$ 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 $\rightarrow \gamma/\pi^0$ discrimination up to $p_T \sim 26$ 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

Analysis technique

1. Electromagnetic neutral cluster (π^0, η, ρ^0,ω,…,γ^{frag},γ^{dir})

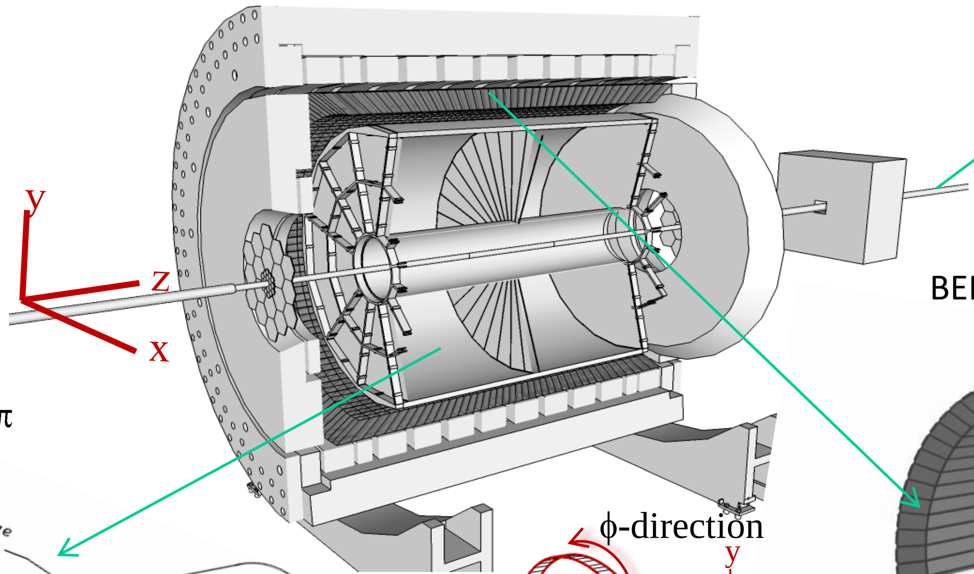
2. Reaction plane measurements

3. v_2 neutral cluster vs. v_2 charged particles

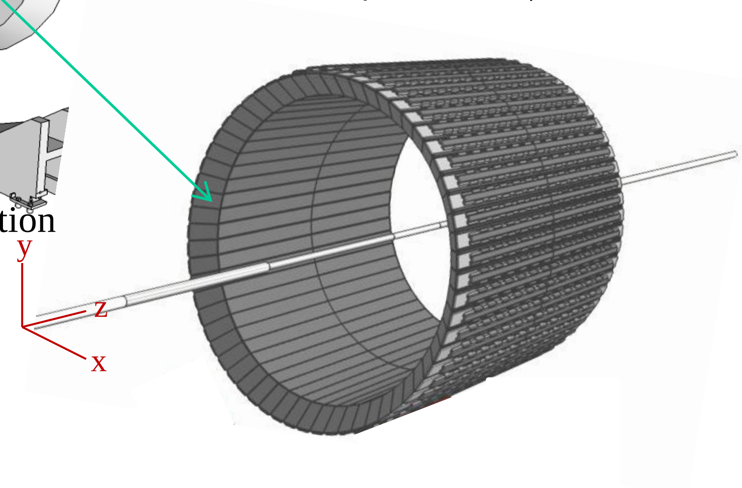
4. Transverse shower profile to obtain sample rich/free of γ^{dir}

5. Obtain v_2 of γ^{dir}

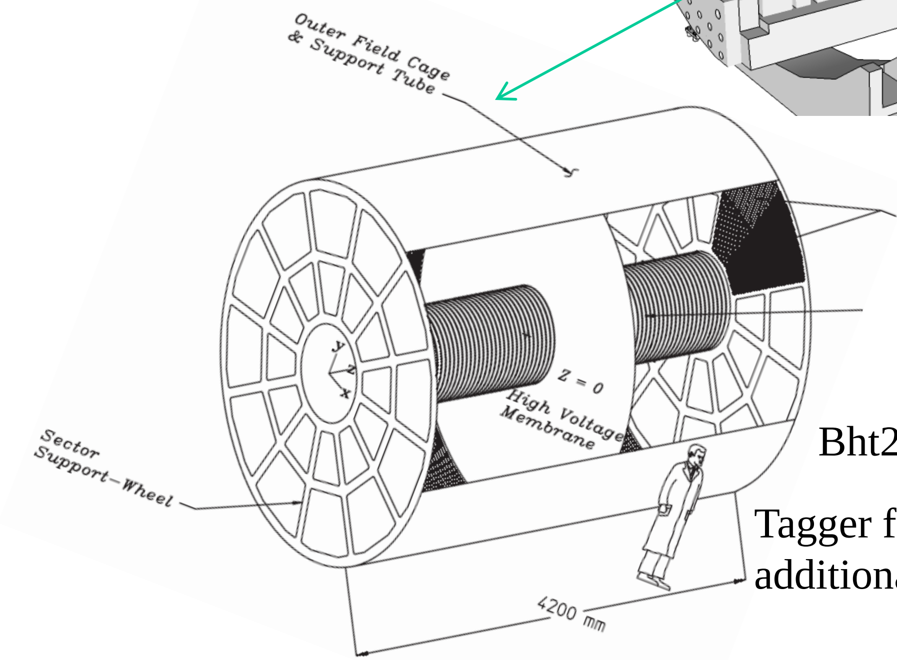
STAR detector and on-line γ-rich event selections

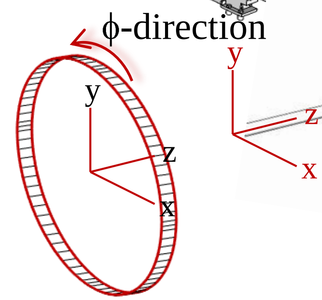


BEMC: $|\eta| < 1,\ 0 < \phi < 2\pi$



TPC: $|\eta| < 1,\ 0 < \phi < 2\pi$





L2gamma trigger in AuAu (2007)

Bht2-mb: ZDC coincidence, and $E_{T(tower)} > 5.76$ GeV

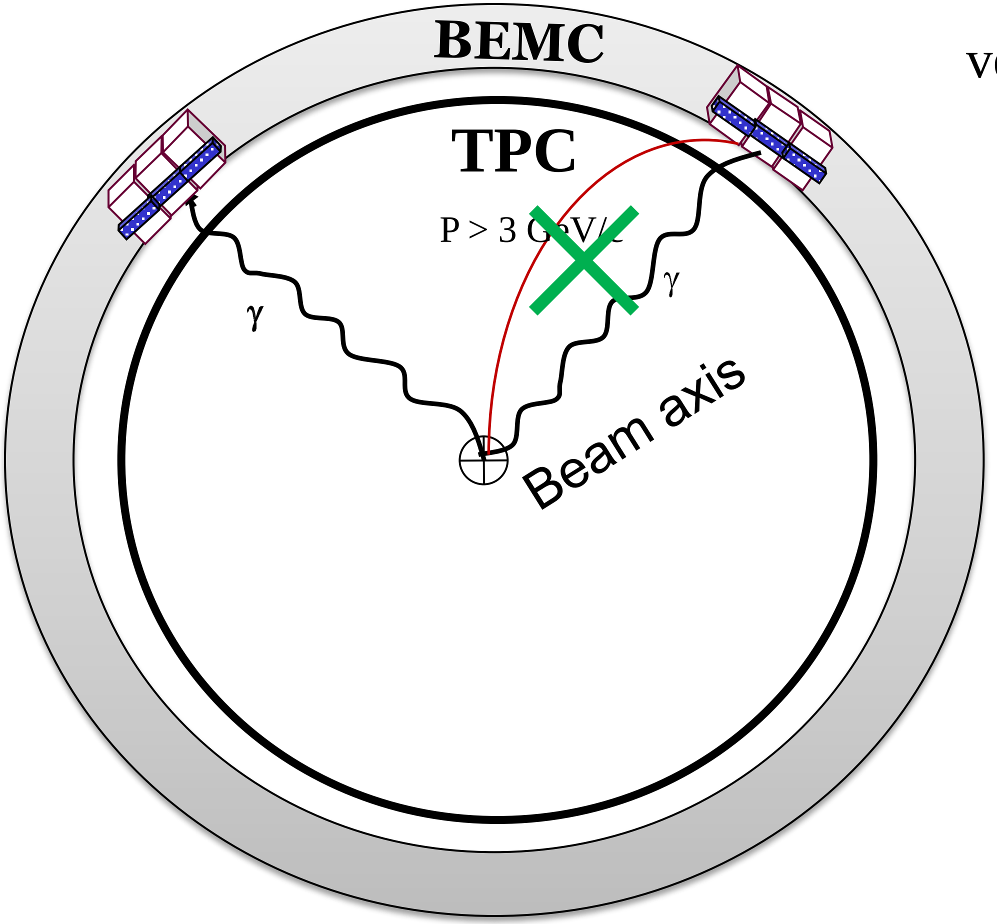
Tagger for express stream: Based on bht2-mb, with additional higher $E_{T\ (cluster)} > 7.44$ GeV . "Cluster_size ≤ 2 towers"

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

6k events of minimum bias trigger

STAR detector and off-line neutral cluster selections

✓ Select neutral clusters "triggers" (BEMC-BSMD) using charged-particle veto (TPC)



vertex within ±55 cm of the center of TPC.

At least one cluster with $E_T > 8$ GeV, Esmdη > 0.5 GeV, Esmdϕ > 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.

Reaction plane measurements and v2

Event plane from TPC

$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{\sum_i sin(2\delta_i)}{\sum_i cos(2\delta_i)}\right)$$

Shift method for event plane flattening

$$\Psi' = \Psi + \sum_n \frac{1}{n}[-\langle\sin(2n\Psi)\rangle\cos(2n\Psi) + \langle\cos(2n\Psi)\rangle\sin(2n\Psi)]$$

Sub-event method for reaction plane resolution

$$\sigma_{\mathrm{RP}} = C\sqrt{< \cos[2(\psi^A - \psi^B)] >}, C = \sqrt{2}$$

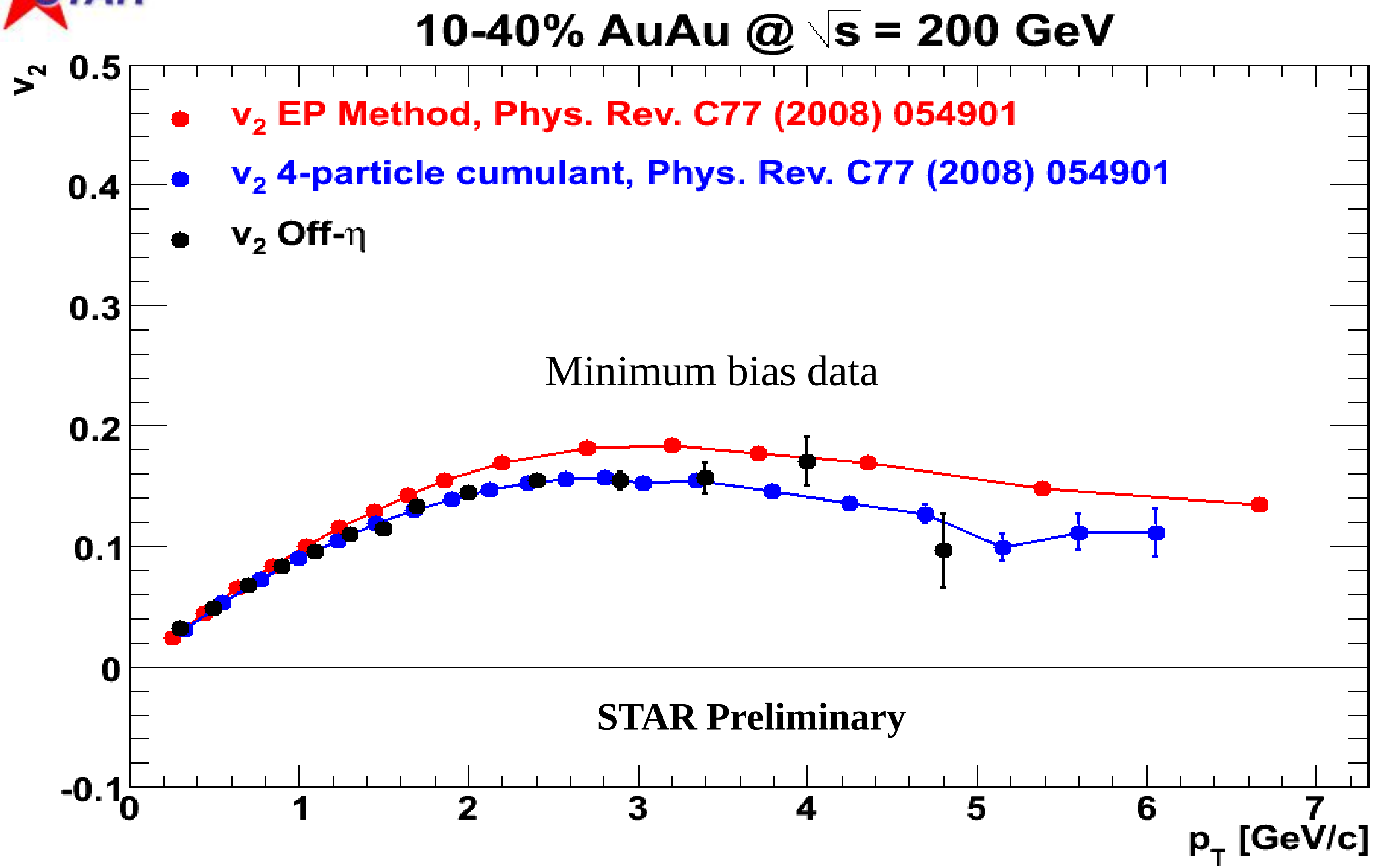
v_2 of charged and neutral particles

$$v_2^{track,obs} = < \cos(2\phi_{track} - 2\psi) >$$

$$v_2^{neutral,obs} = < \cos(2\phi_{tower} - 2\psi) >$$

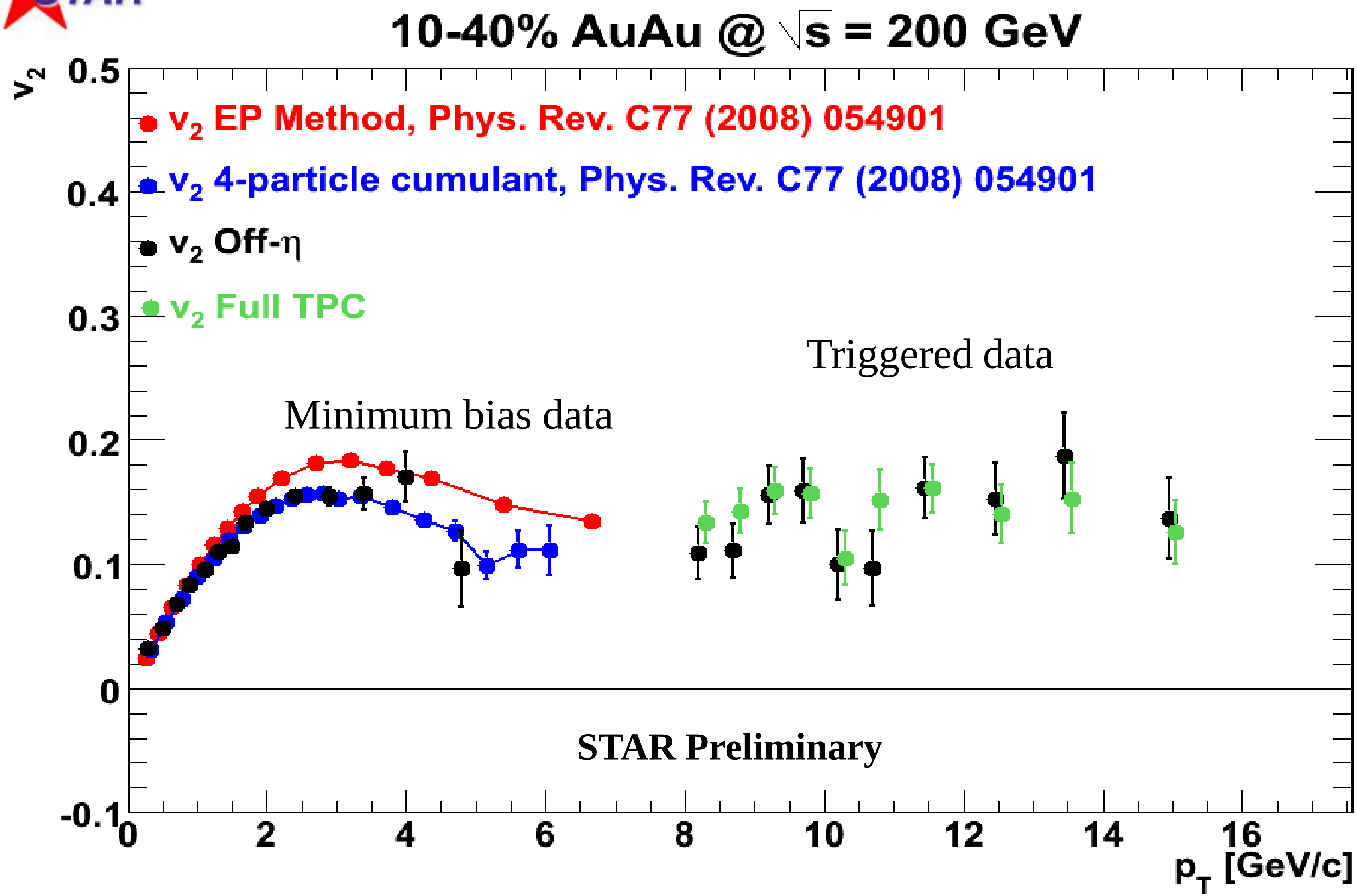
$$v_2 = \frac{v_2^{obs}}{\sigma_{\mathrm{RP}}}$$

Elliptic flow of charged particles at low pt



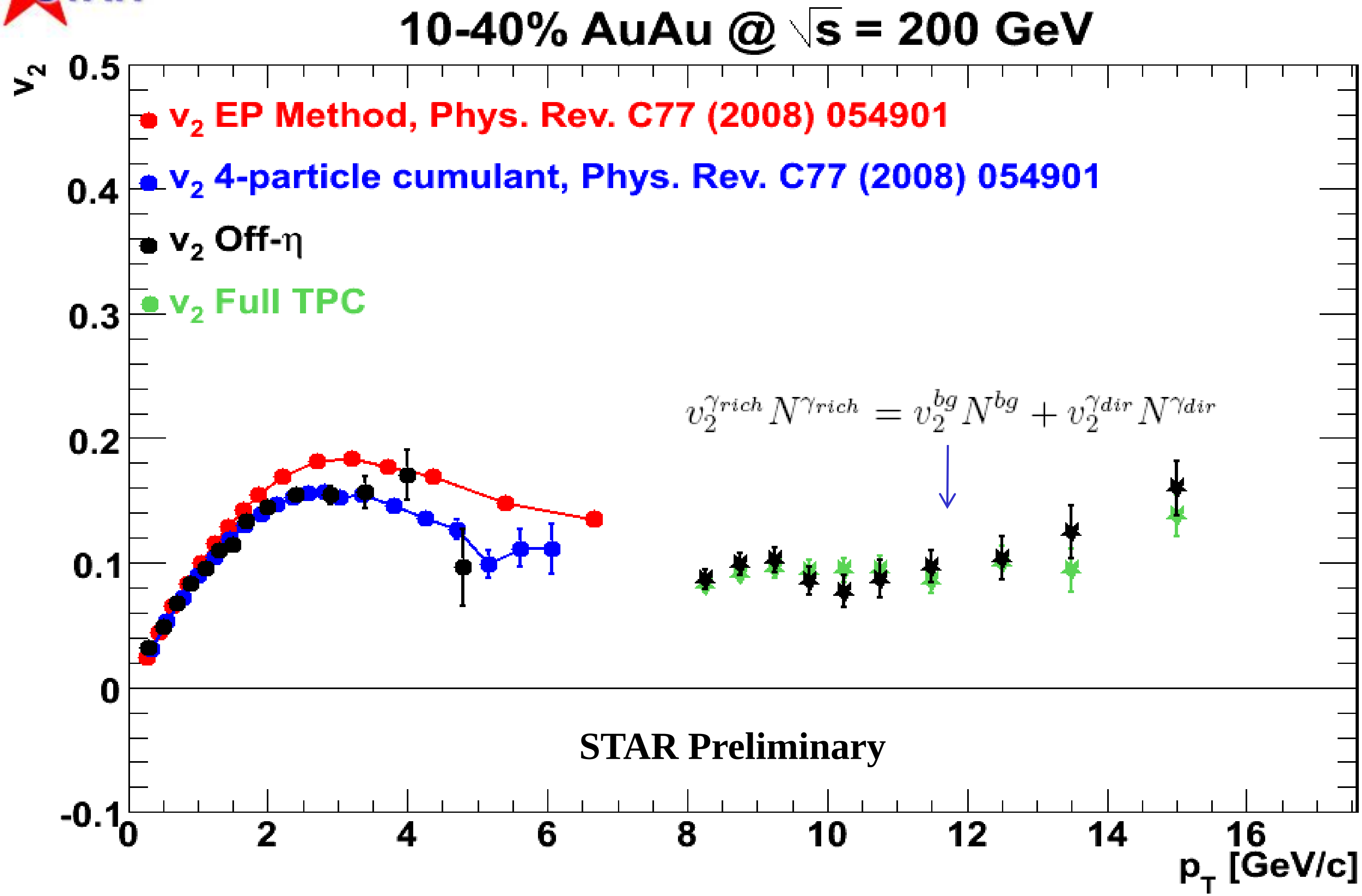
v_2(EP off-η) reproduces the v2{4} quite well

Elliptic flow of charged particles at high pt



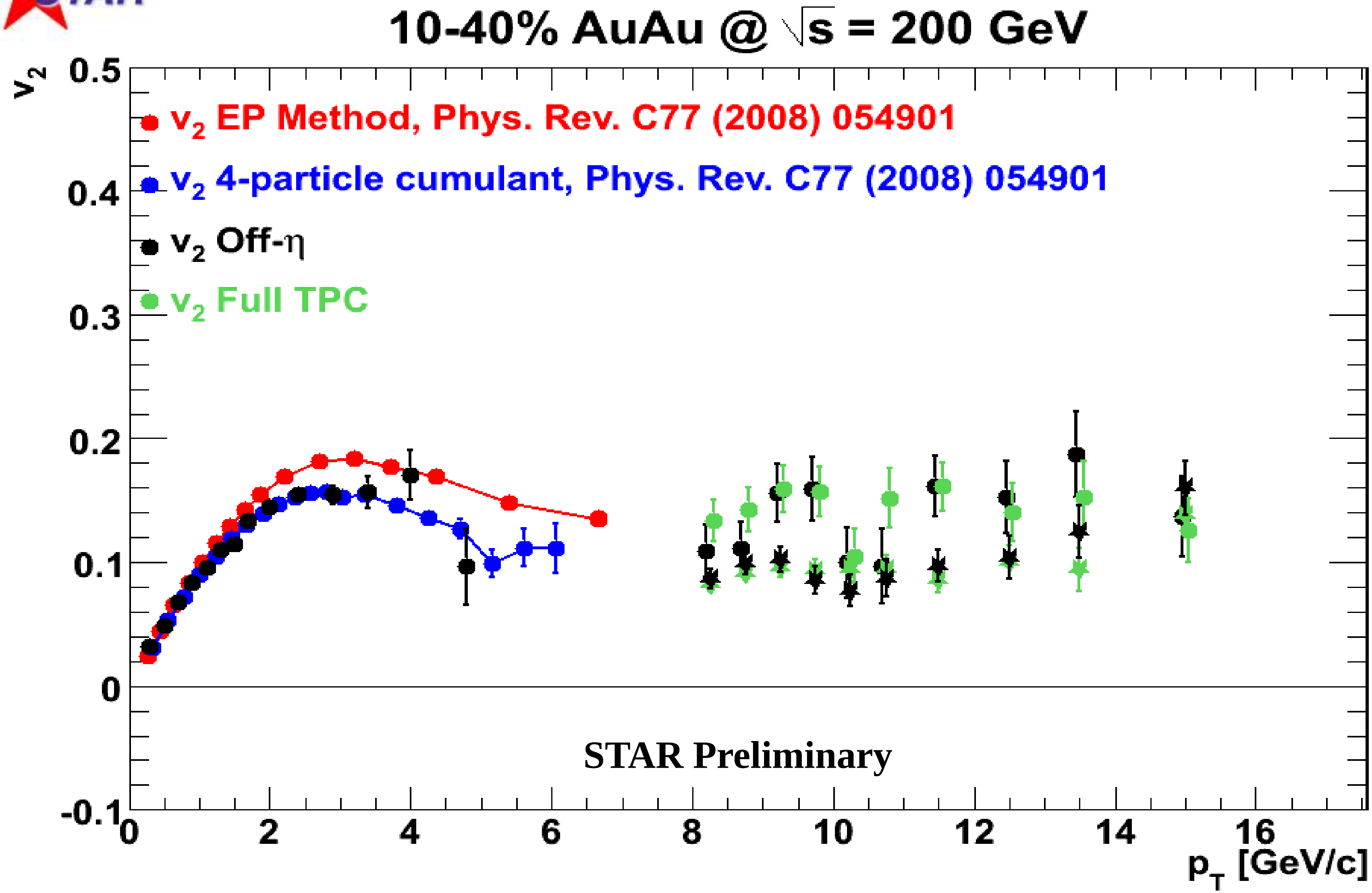
v_2 of charged particles is ~ 15% in 10-40% (AuAu@200GeV) and constant in pt (8-16GeV/c)

Elliptic flow of neutral particles at high pt



v_2 of neutral particles is ~ 10% in 10-40% (AuAu@200GeV) and constant in pt (8-16GeV/c)

Elliptic flow of neutral/charged particles at high pt

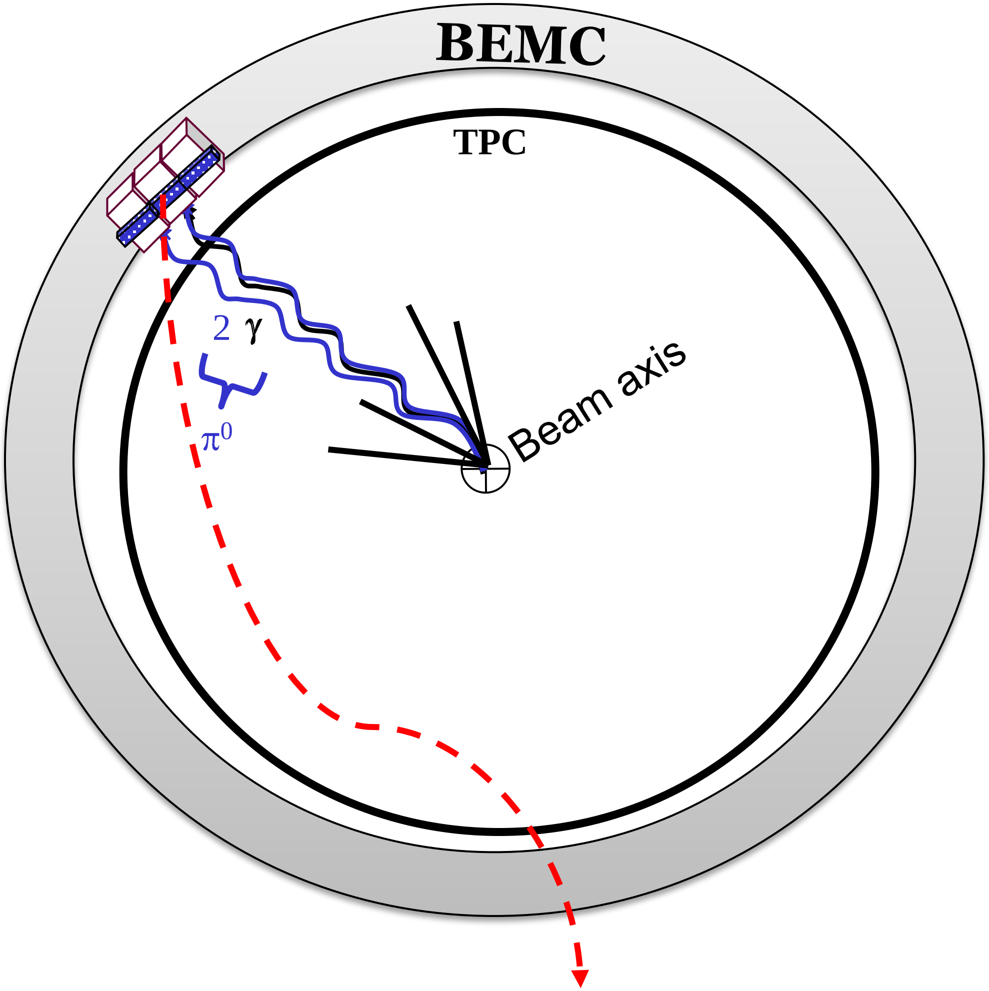


v_2 of neutral particles is less than v_2 of charged particles due to direct photons contributions

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

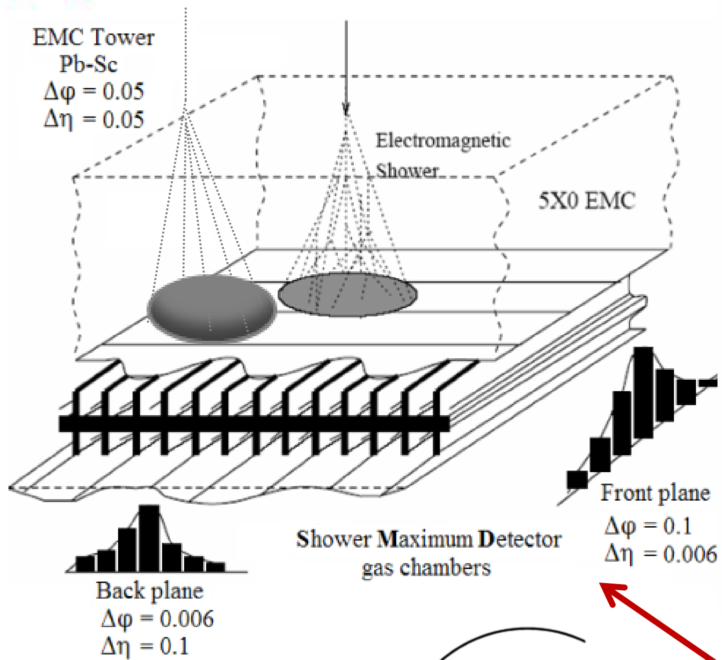
~10% of all π^0 (8-16GeV/c) decay asymmetrically with one gamma has p_T > 8 GeV/c within STAR-BEMC acceptance.

η causes similar level of background as asymmetric π^0.

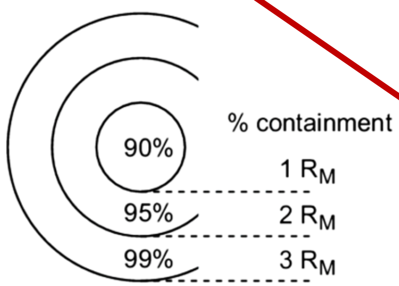


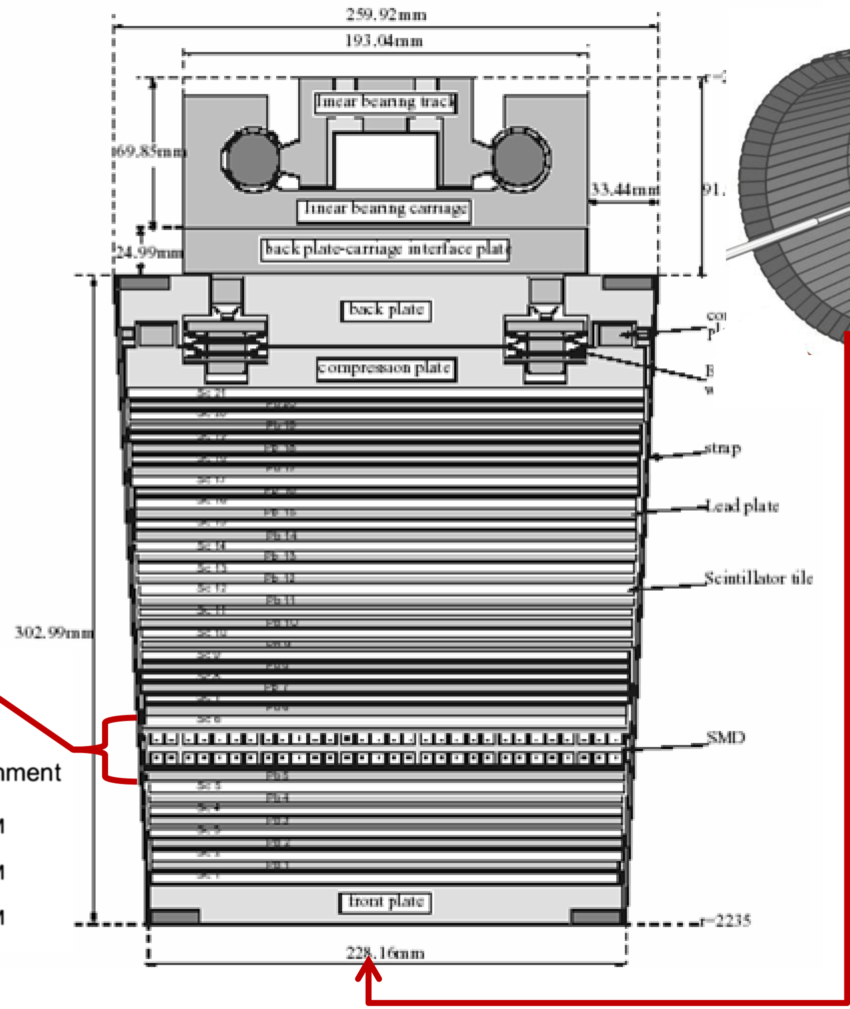
Either to reconstruct π^0 or to use the transverse shower shape analysis to distinguish between π^0 and γ^{dir}

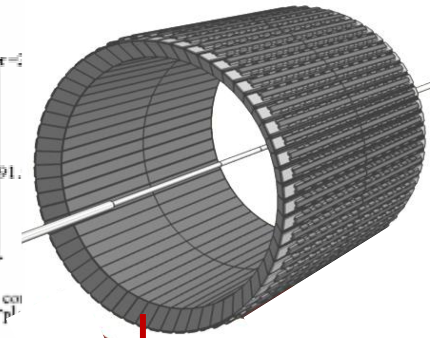
STAR BEMC and BSMD



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



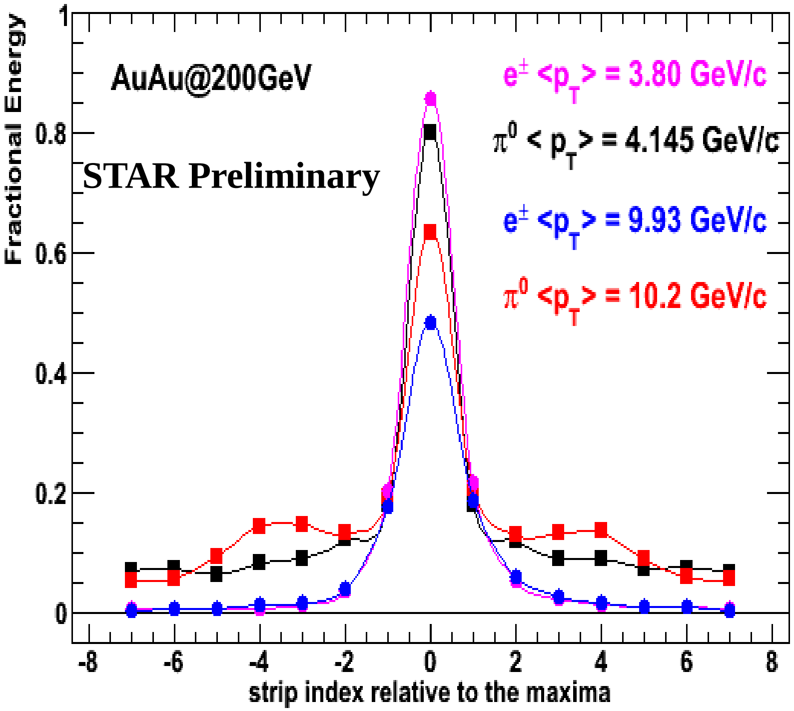


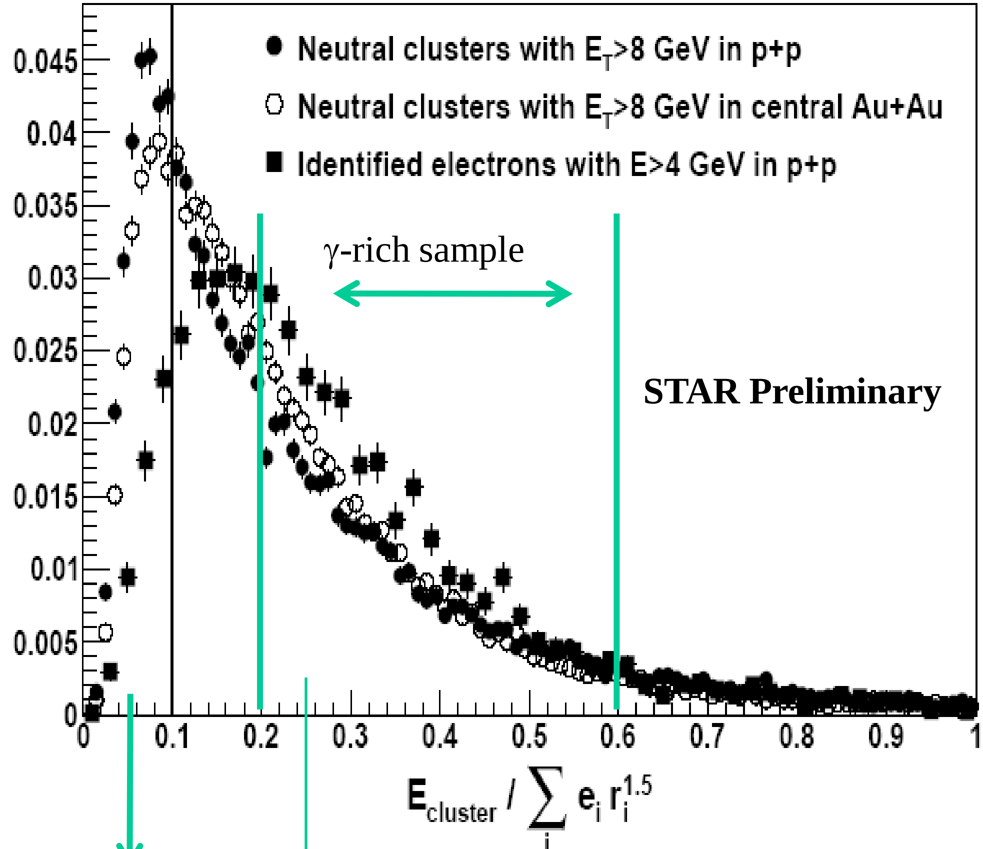


The two photons originated from π^0 hit the same tower at p_T>8GeV/c

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.

Shower Profile of single γ vs. two close γs





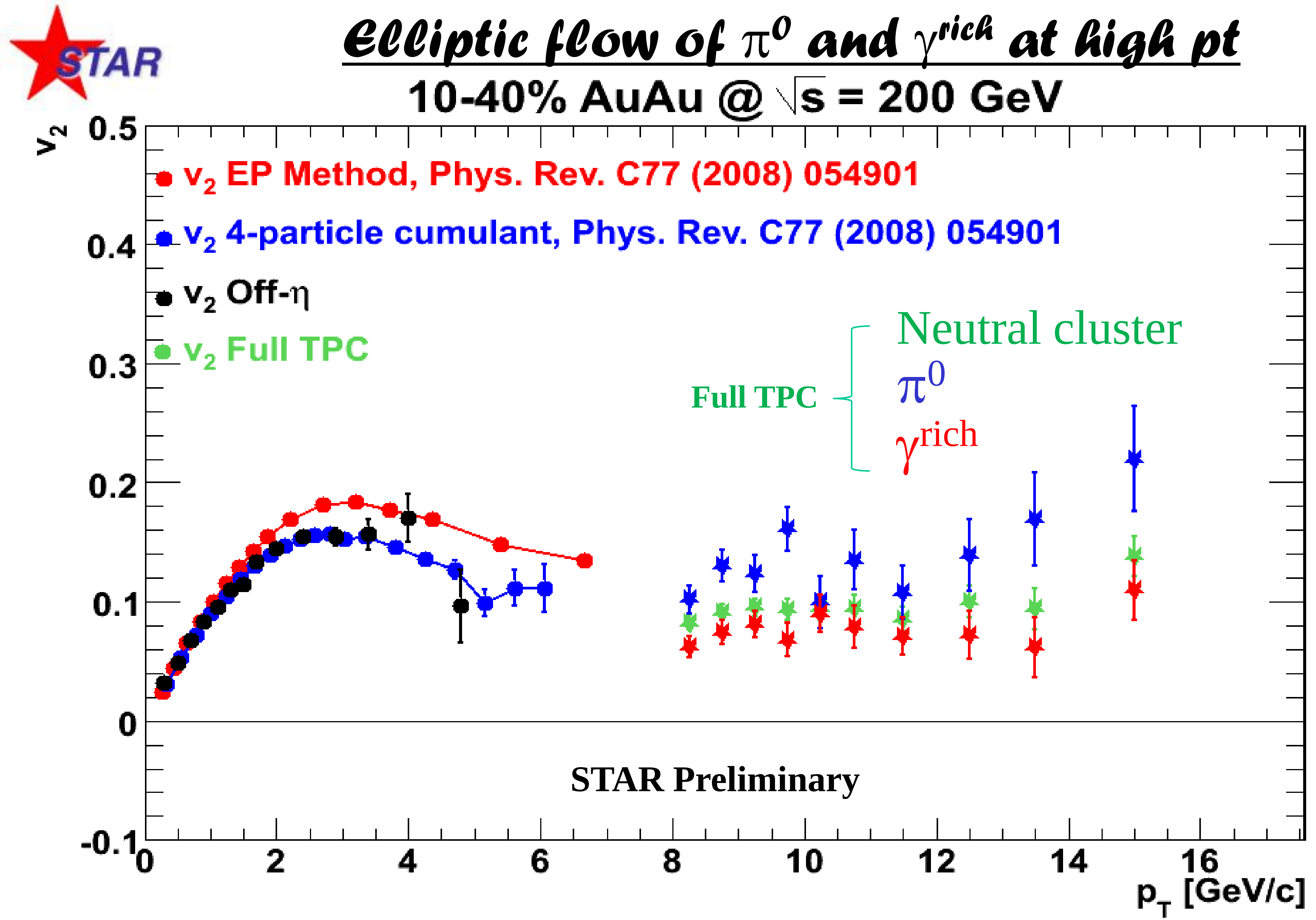
direct γ free (π^0-rich) sample

$$N^{\gamma_{rich}} = N^{bg} + N^{\gamma_{dir}}$$

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

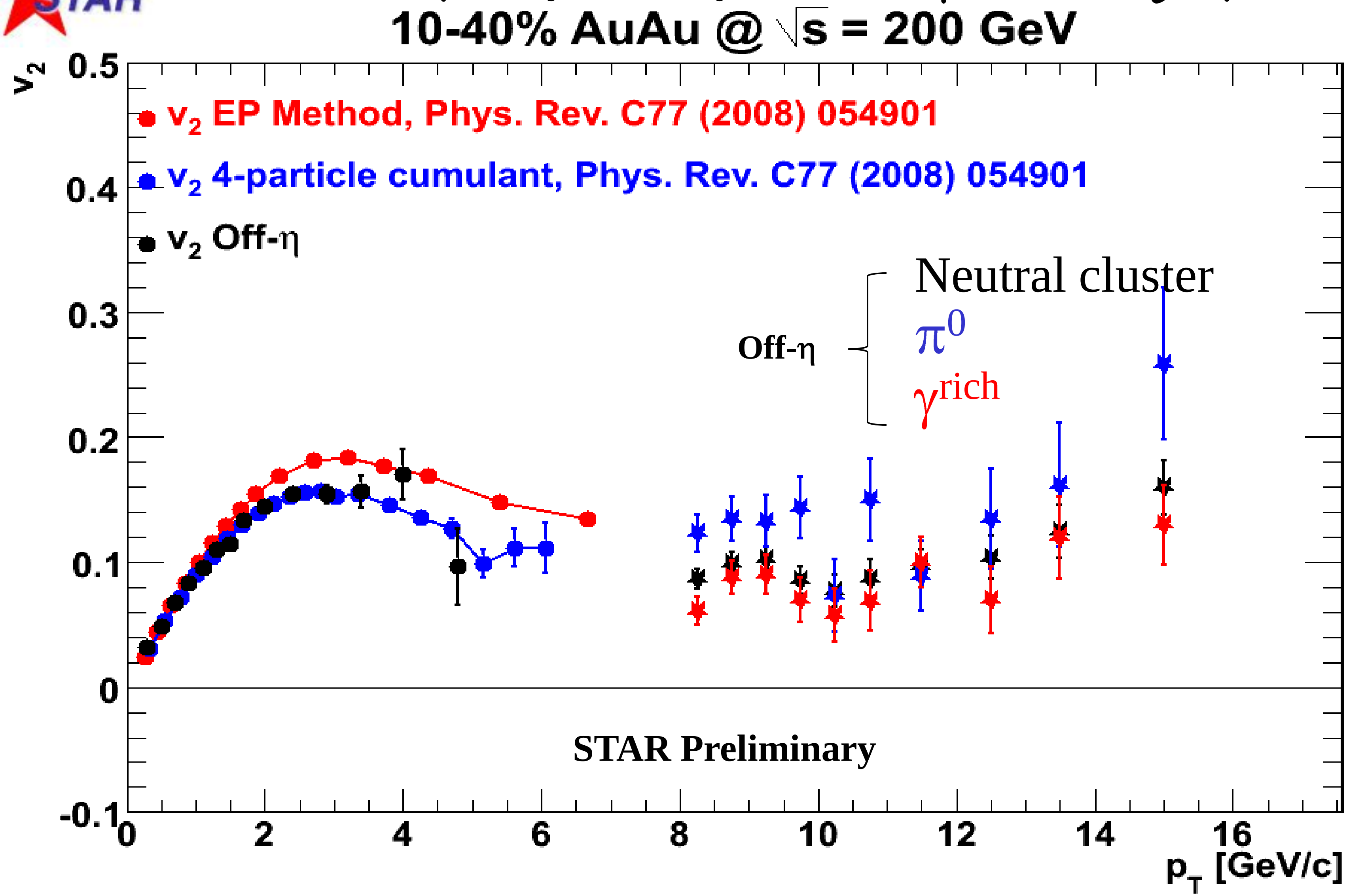
The rejection power of direct photons is ~ 90%

Elliptic flow of π^0 and γ^{rich} at high pt



v_2 of γ^{rich} < v_2 of π^0 as expected

Elliptic flow of π^0 and γ^{rich} at high pt



v_2 of γ^{rich} < v_2 of π^0 as expected

Obtain v2 of direct photons

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

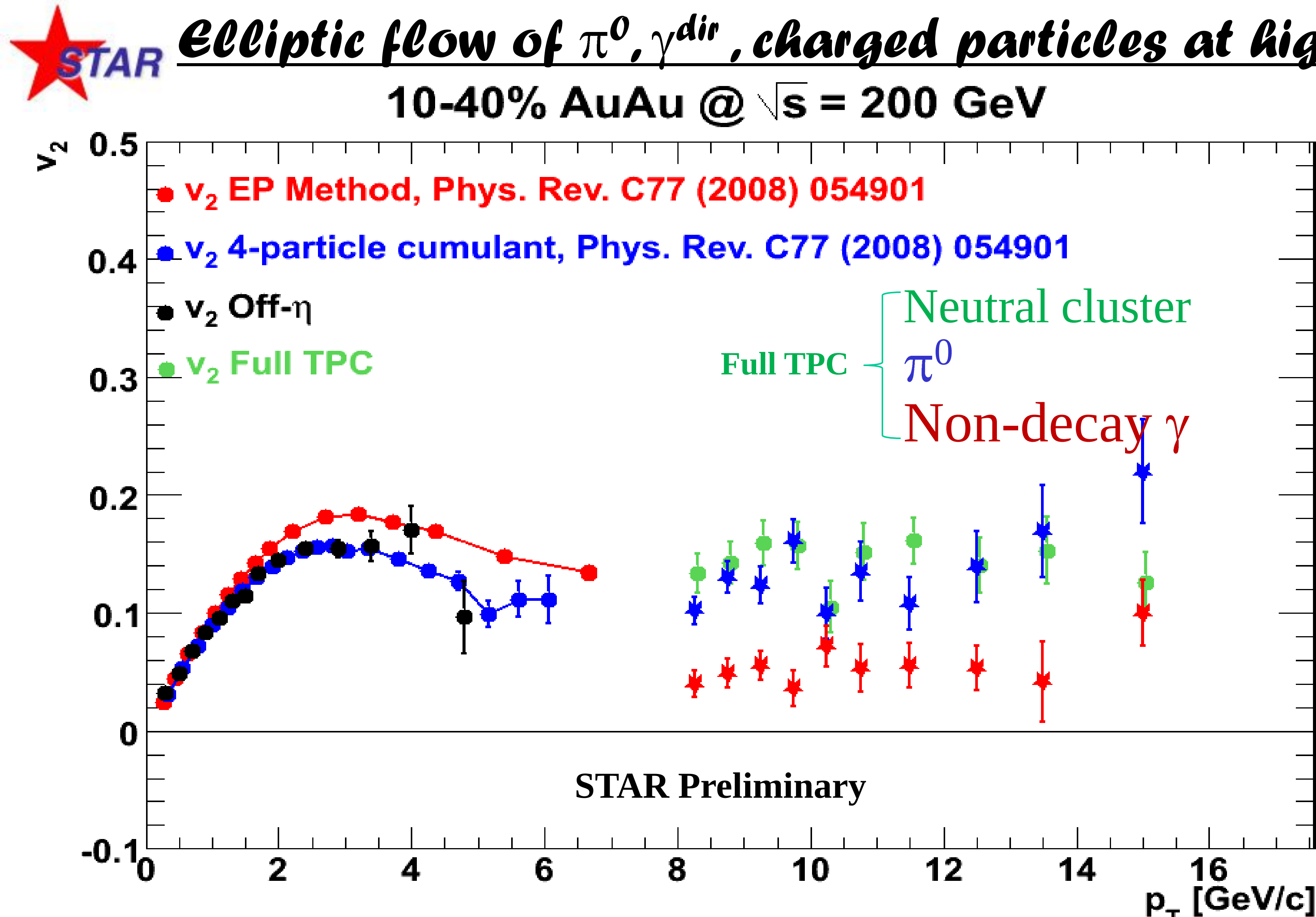
$$v_2^{\gamma rich} N^{\gamma rich} = v_2^{bg} N^{bg} + v_2^{\gamma dir} N^{\gamma dir}$$

$$\mathcal{R} = \frac{N^{bg}}{N^{\gamma rich}} \simeq \frac{N^{\pi^0}}{N^{\gamma rich}}$$

$$v_2^{\gamma direct} = \frac{v_2^{\gamma rich} - v_2^{bg}\mathcal{R}}{1-\mathcal{R}}$$

$$v_2^{\gamma direct} = \frac{v_2^{\gamma rich} - v_2^{\pi^0}\mathcal{R}}{1-\mathcal{R}}$$

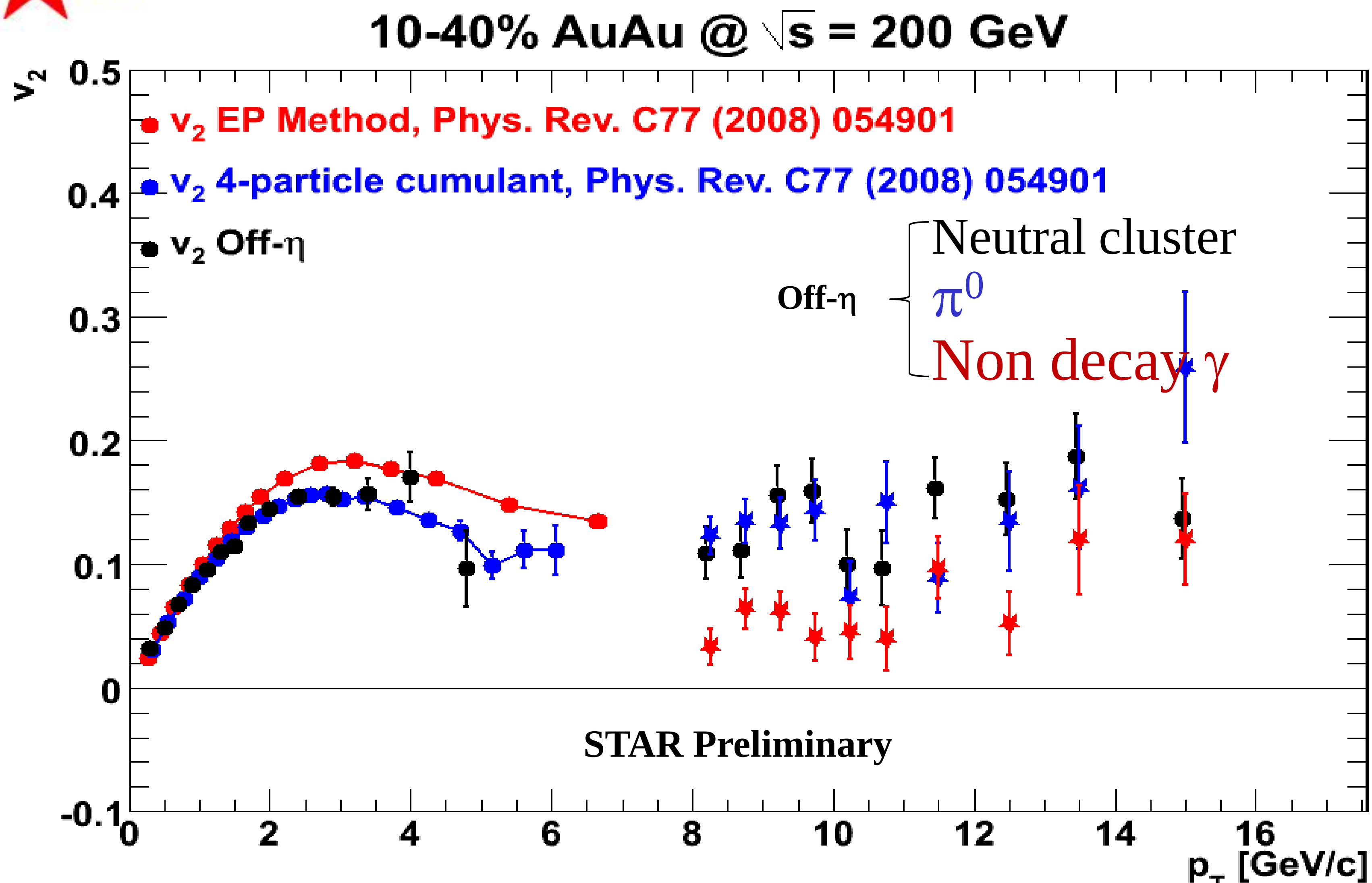
Elliptic flow of π^0, γ^{dir}, charged particles at high pt



v_2 of non decay γ is ~1/3 of v_2 of π^0 and charged particles

v_2 of non decay γ is not zero and not negative

Elliptic flow of π^0, γ^{dir}, charged particles at high pt



v_2 of non decay γ is ~1/3 of v_2 of π^0 and charged particles

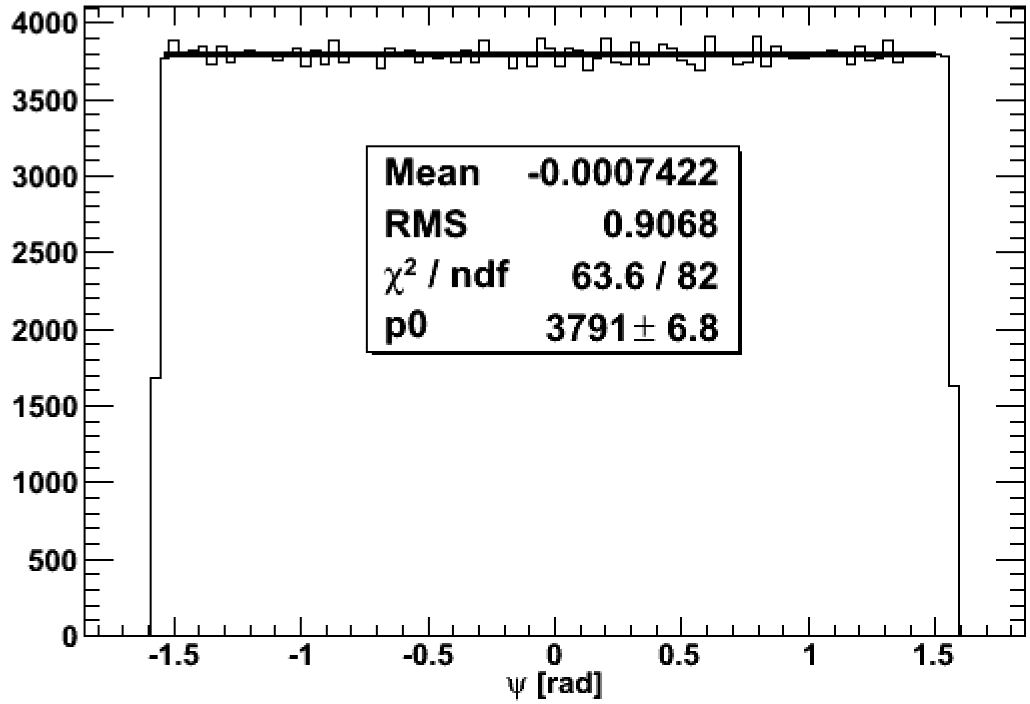
v_2 of non decay γ is not zero and not negative

Summary

- The geometrical effect of the medium can be probed by the elliptic flow measurement
- Finite and +ve value of v_2 persist up to pt=16 GeV/c for charged and neutral particles
- STAR has reported the first "preliminary" results of non decay photons elliptic flow at high pt at RHIC
- No sign of negative v_2 of non decay photons
- Statistically significant value of +ve v_2 of non decay photons
- The v_2 at high pt can not be interpreted as path length dependence of energy loss

Backup slides

Reaction plane



Only shift method is used to flatten the RP up to the 20th harmonic:

$$\Psi' = \Psi + \sum_n \frac{1}{n}[-\langle\sin(2n\Psi)\rangle\cos(2n\Psi) + \langle\cos(2n\Psi)\rangle\sin(2n\Psi)]$$

Reaction plane is flat "cos and sin ~ 0"

Previous measurements of v2(γ^{dir}) at RHIC Phys. Rev. Lett96 (2006) 032302

$$v_2^{inclusive\ \gamma} = \frac{v_2^{direct\ \gamma} N_{direct\ \gamma} + v_2^{b.g.} N_{b.g.}}{N_{direct\ \gamma} + N_{b.g.}}$$

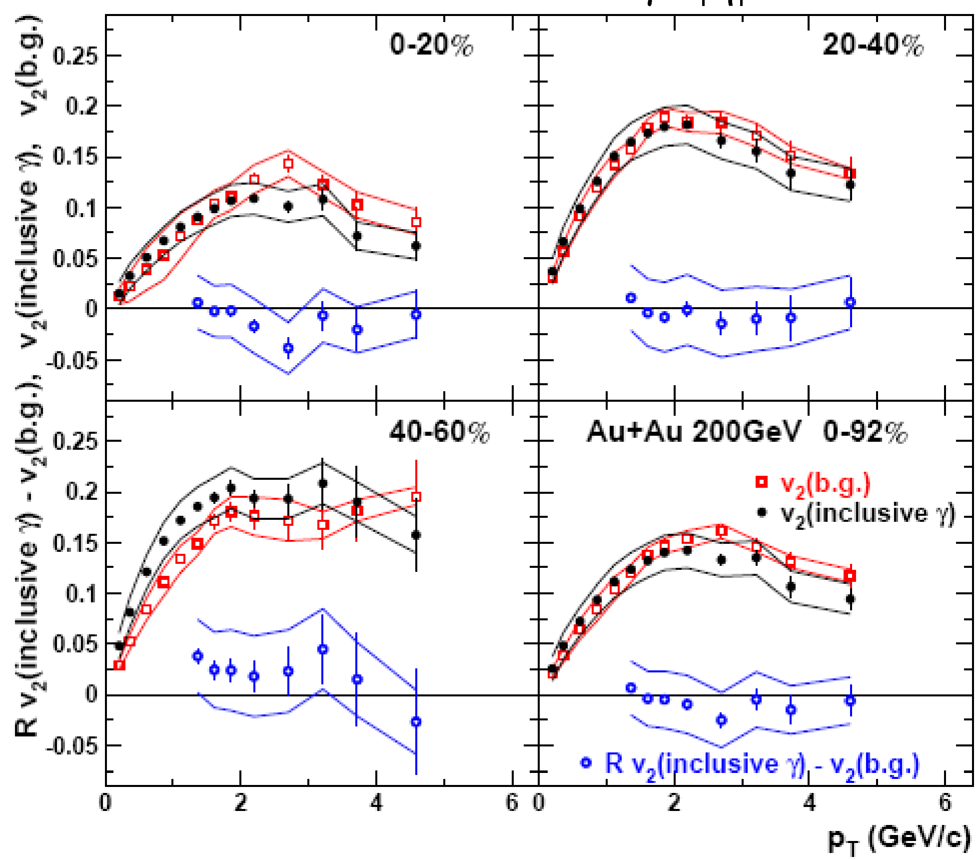
$$\sigma_{\rm RP} = \langle \cos(2(\Phi_{\rm measured} - \Phi_{\rm RP})) \rangle \text{ is } 0.3$$

PHENIX BBC: $3.1 < |\eta| < 3.9$

$$R = (N_{direct\ \gamma} + N_{b.g.})/N_{b.g.}$$

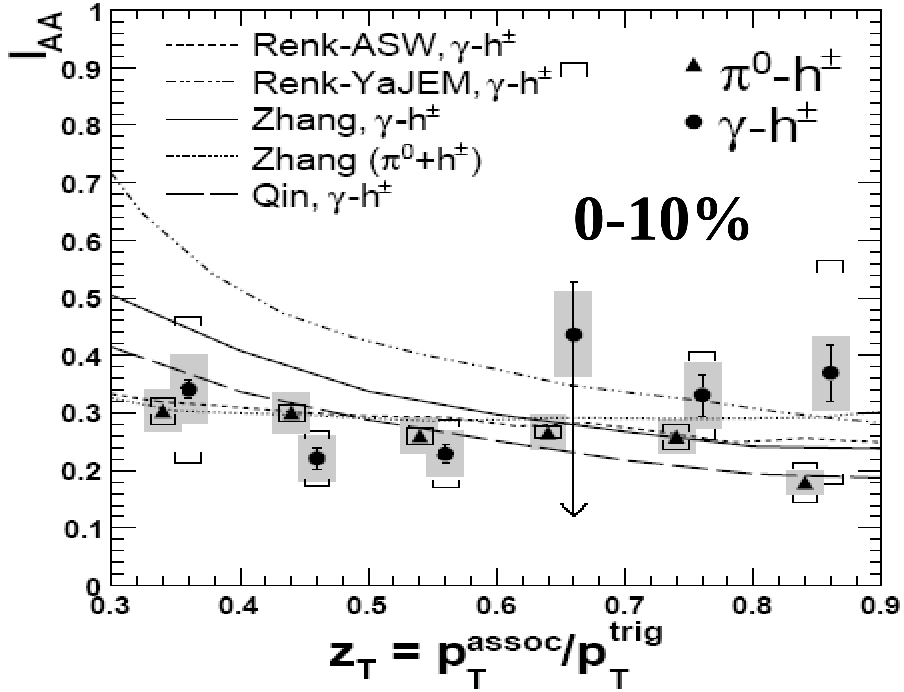
Measured π^0 and inclusive γ : $|\eta| < 0.35$

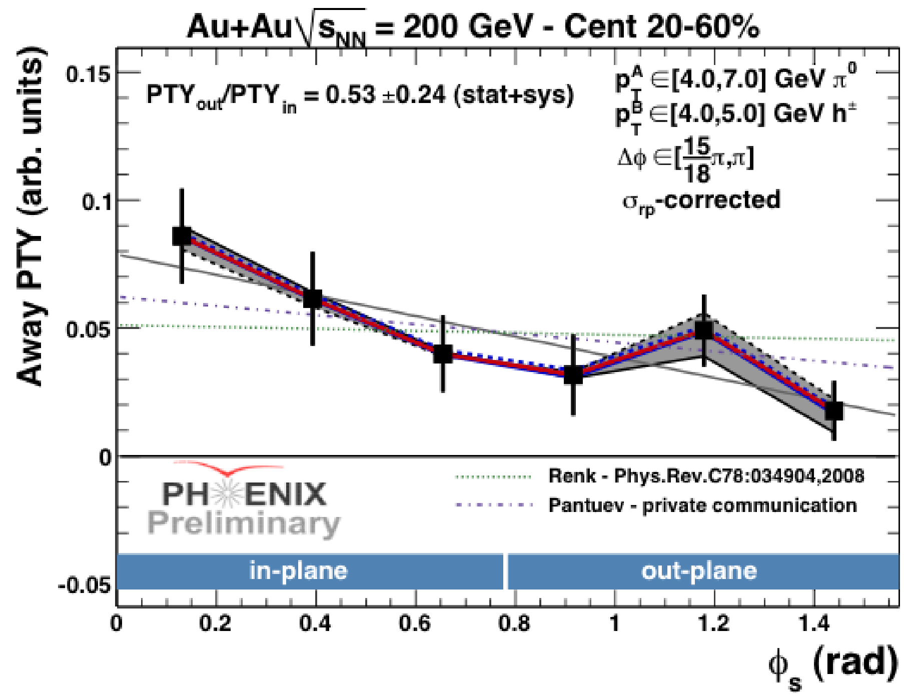
$$v_2^{direct\ \gamma} = \frac{R v_2^{inclusive\ \gamma} - v_2^{b.g.}}{R-1}.$$

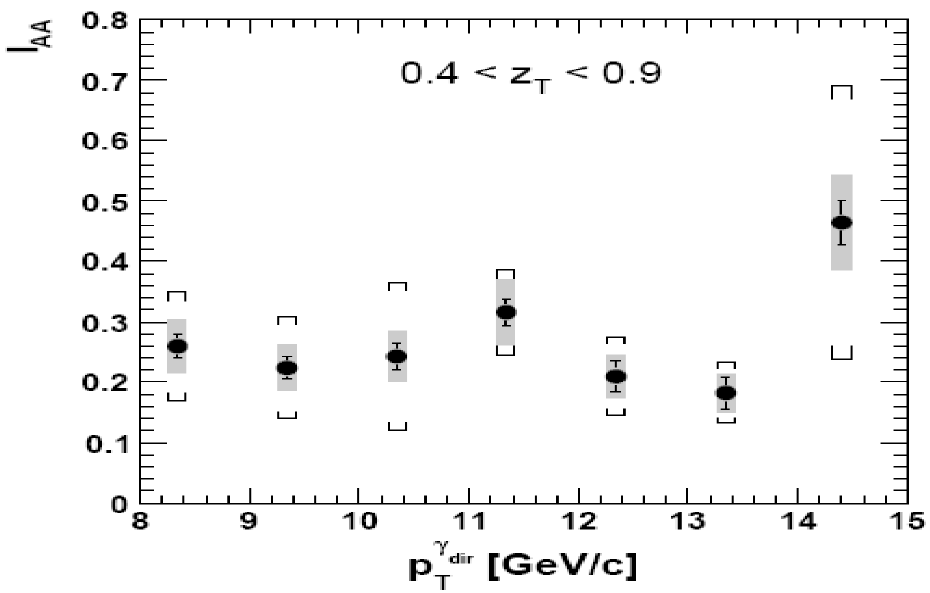


This measurements implies that v_2 of direct photons is ~ 0

Path length dependence of energy loss

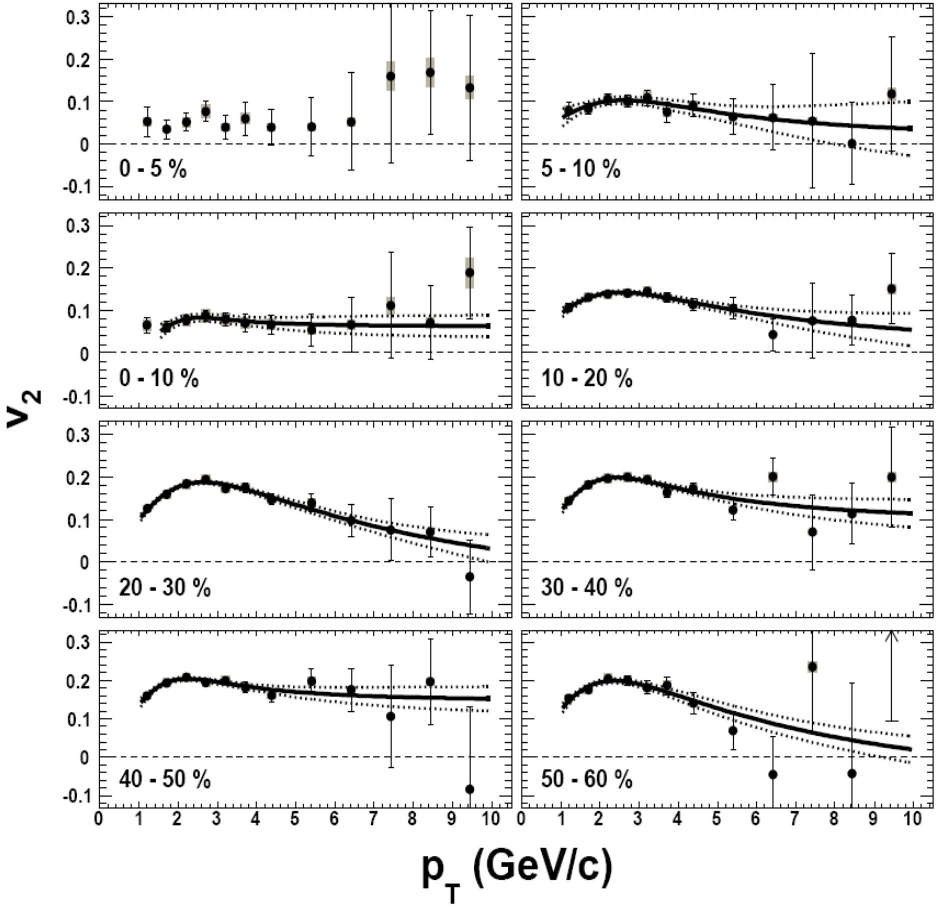


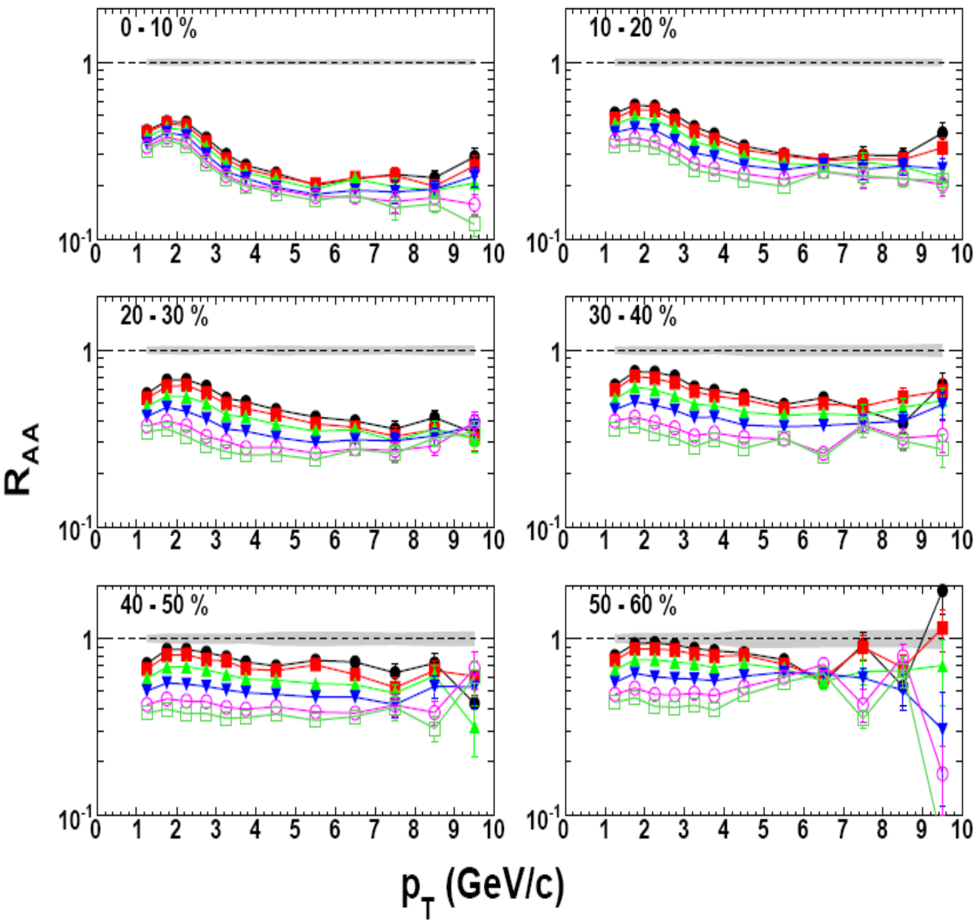




- **STAR measurement does not show path-length dependence.**
- **PHENIX measurement show path-length dependence.**

Path length dependence of energy loss





- π^0 v_2 (pt) and $R_{AA}(\Delta\phi)$ show statistically significant dependence on the path length particularly at pt < 6GeV