Neutral pion production with respect to the reaction plane in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions at PHENIX

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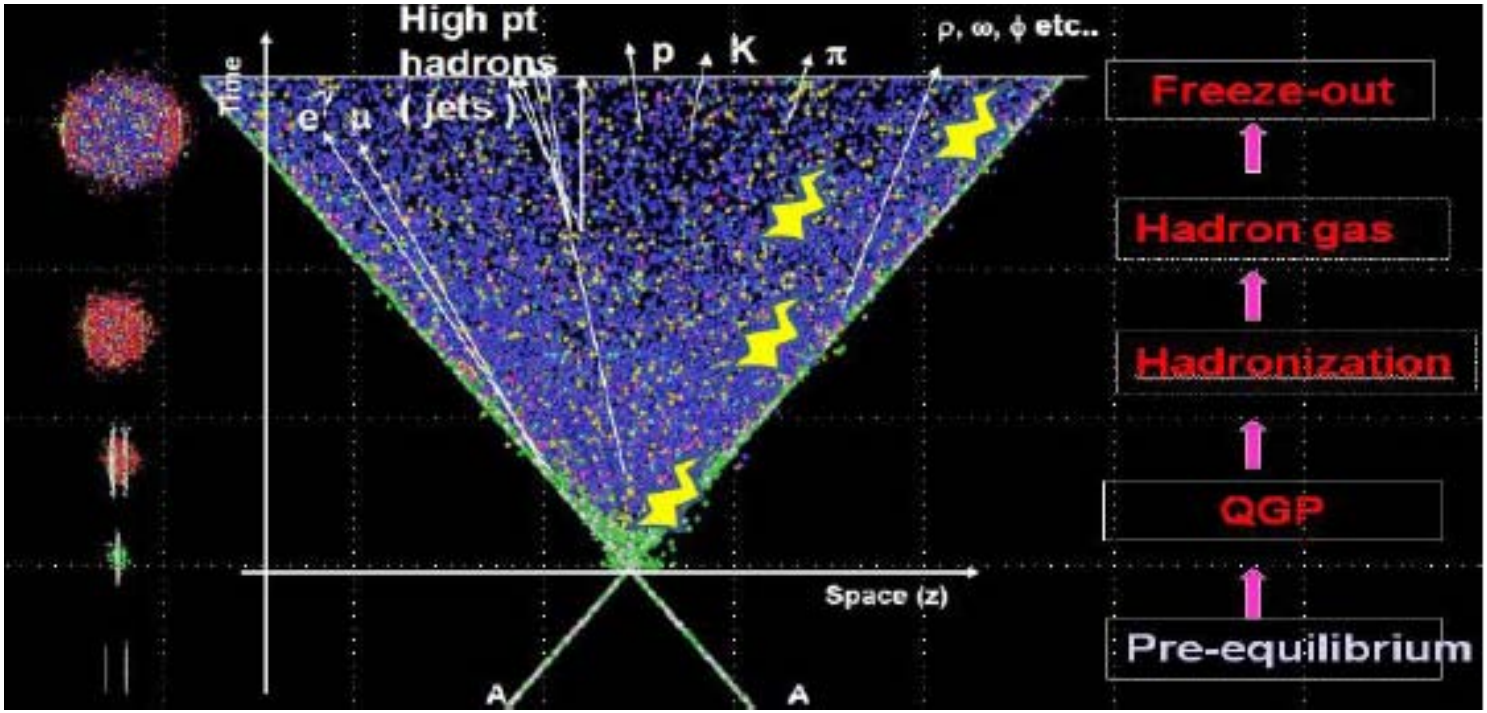
Good probe for studying the property of hot/dense matter



- **Hard scattered parton**
  - Hard scattered parton can penetrate the matter
  - Partons lose their energy in hot/dense matter
  - This probe is sensitive to the density of the matter and the path-length of the parton within it.

Physics Motivation

- (Path length integrated) yields suppression at high p_T (Factor of 5)
- Parton lose the energy with strong interaction
- Theoretical model (ex. GLV)
  - Only radiative process
- The quantity of the energy loss in GLV method if the medium is static,

$$\Delta E = \frac{9\pi C_R \alpha_s^3}{4} \int_0^L d\tau \ \rho_{eff}(\tau, x(\tau)) \ \tau \ln\left(\frac{1}{x_c}\right) \quad , \quad x_c = \frac{\mu^2 L}{2E}$$

- Theoretical energy loss in the matter
  - **Radiative process** $E_{loss} \propto L^2$
  - **Collisional process** $E_{loss} \propto L$
- Path length dependence of energy loss
  - **test the energy loss process by experiment**

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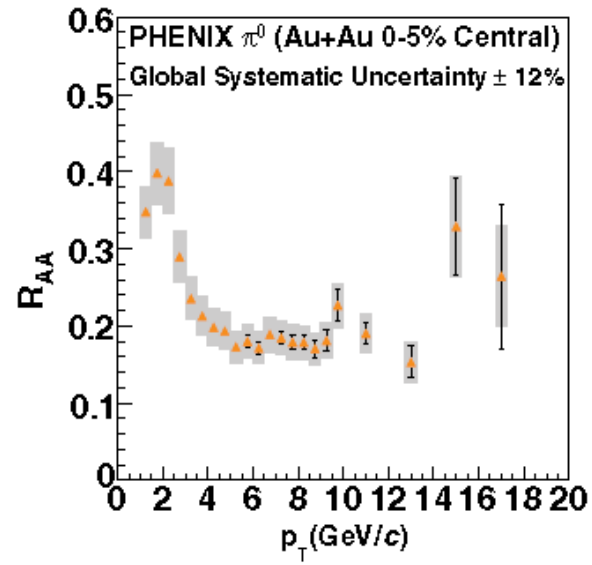
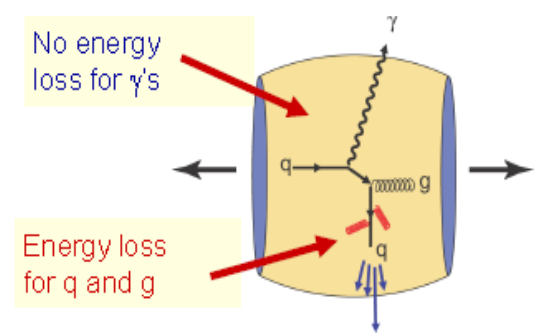


Nuclear modification factor

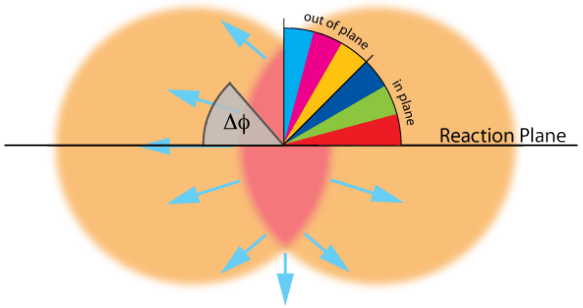
$$R_{AA}(p_T, cent) = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}(p_T, cent)/dp_T d\eta}{d^2 \sigma^{NN}/dp_T d\eta}$$



Measurement of $R_{AA}(p_T, L)$

☐ Correspondence relation

Path length (L) ↔ Azimuthal angle (Δϕ) and Centrality



$R_{AA}(p_T, L) \leftrightarrow R_{AA}(p_T, \text{centrality}, \Delta\phi)$

Light blue : long path length
Red : short path length

☐ Extraction of $R_{AA}(p_T,\Delta\phi)$

$$R_{AA}(p_T,\Delta\phi) \cong R_{AA}(p_T) \times \frac{N(p_T,\Delta\phi_i)}{\sum_{\phi_i} N(p_T,\Delta\phi_i)}$$

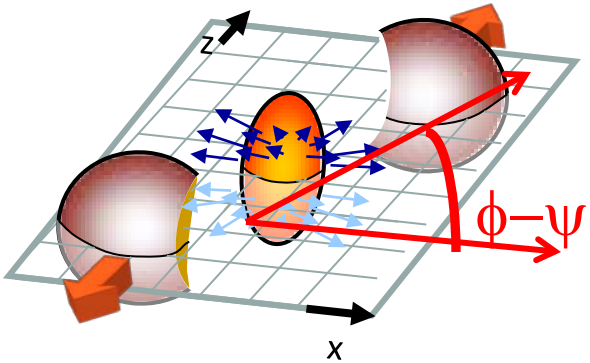
$$N(p_T,\Delta\phi_i) \cong N(1+2v_2\cos(2\Delta\phi_i))$$

☐ Anisotropy v_2 at high p_T

Spatial anisotropy in non-central collisions influences R_{AA} for each azimuthal angle

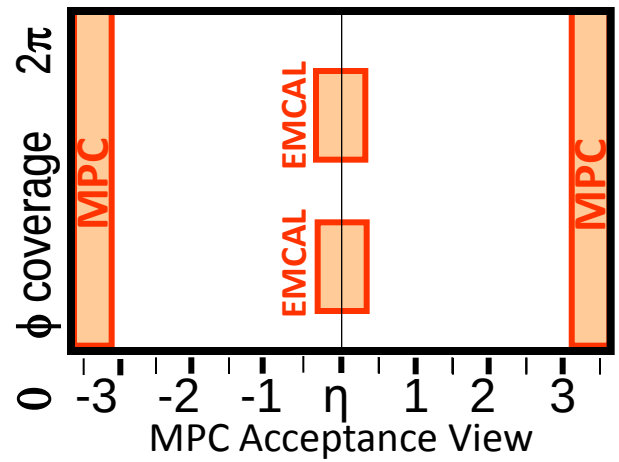
$$\frac{dN}{d(\phi-\Psi)} = N[1+\Sigma 2v_n \cos(n(\phi-\Psi))]$$

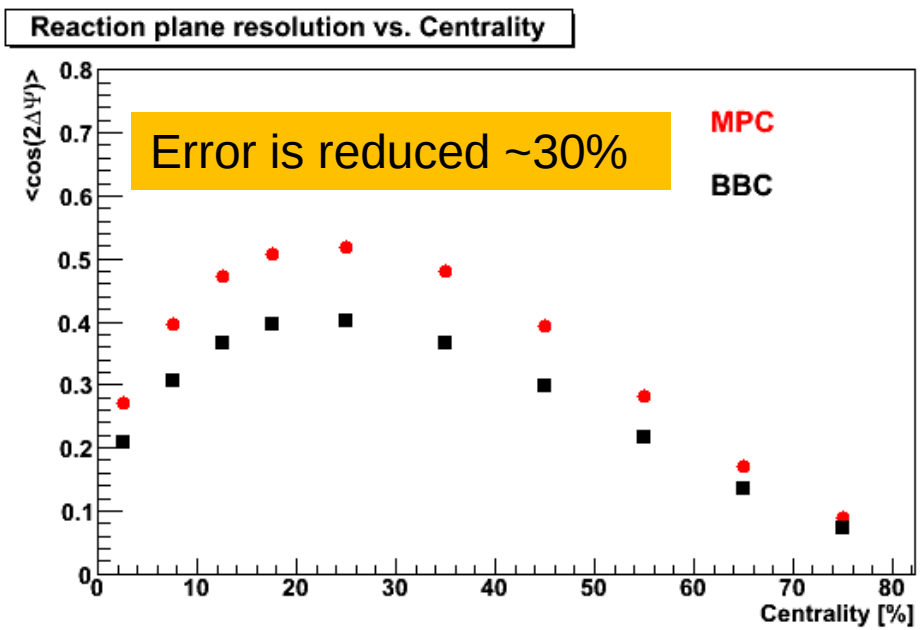
ϕ : Azimuthal angle of emitted particles
Ψ : Azimuthal angle from reaction plane



Detector for determination of reaction plane

- **Muon Piston Calorimeter (MPC)**
  - Rapidity coverage 3.1 < |η| < 3.7
  - PbWO4 Crystals + Avalanche Photodiodes





Reaction plane resolution

$$\sigma_{RP} = \langle \cos(2\Delta\phi) \rangle$$

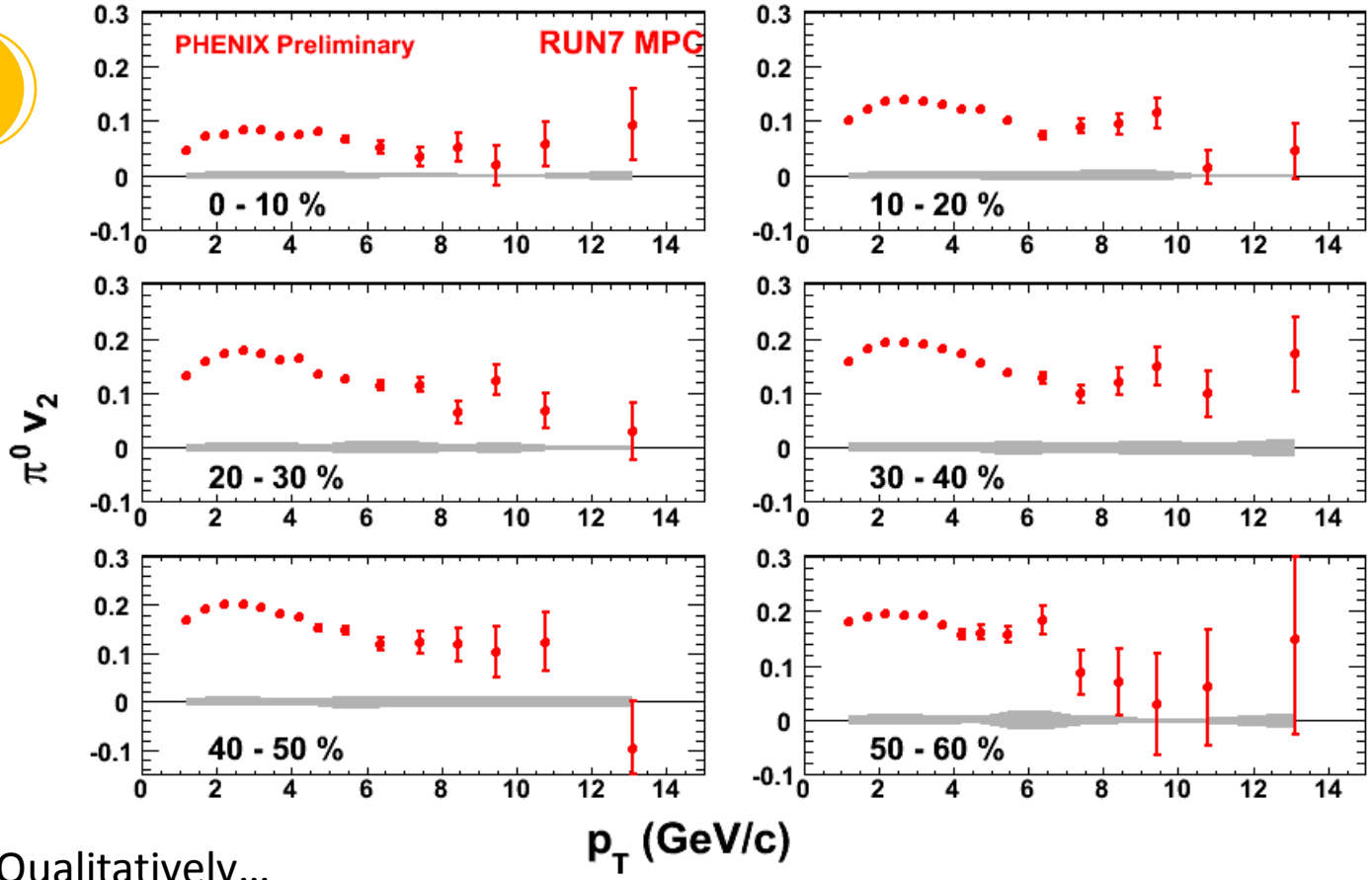
$$v_2^{corrected} = v_2^{measured} / \sigma_{RP}$$

Beam Beam Counter (BBC) :

Reaction plane detector before RHIC-Year 2007

Azimuthal anisotropy π^0 $v_2(p_T)$

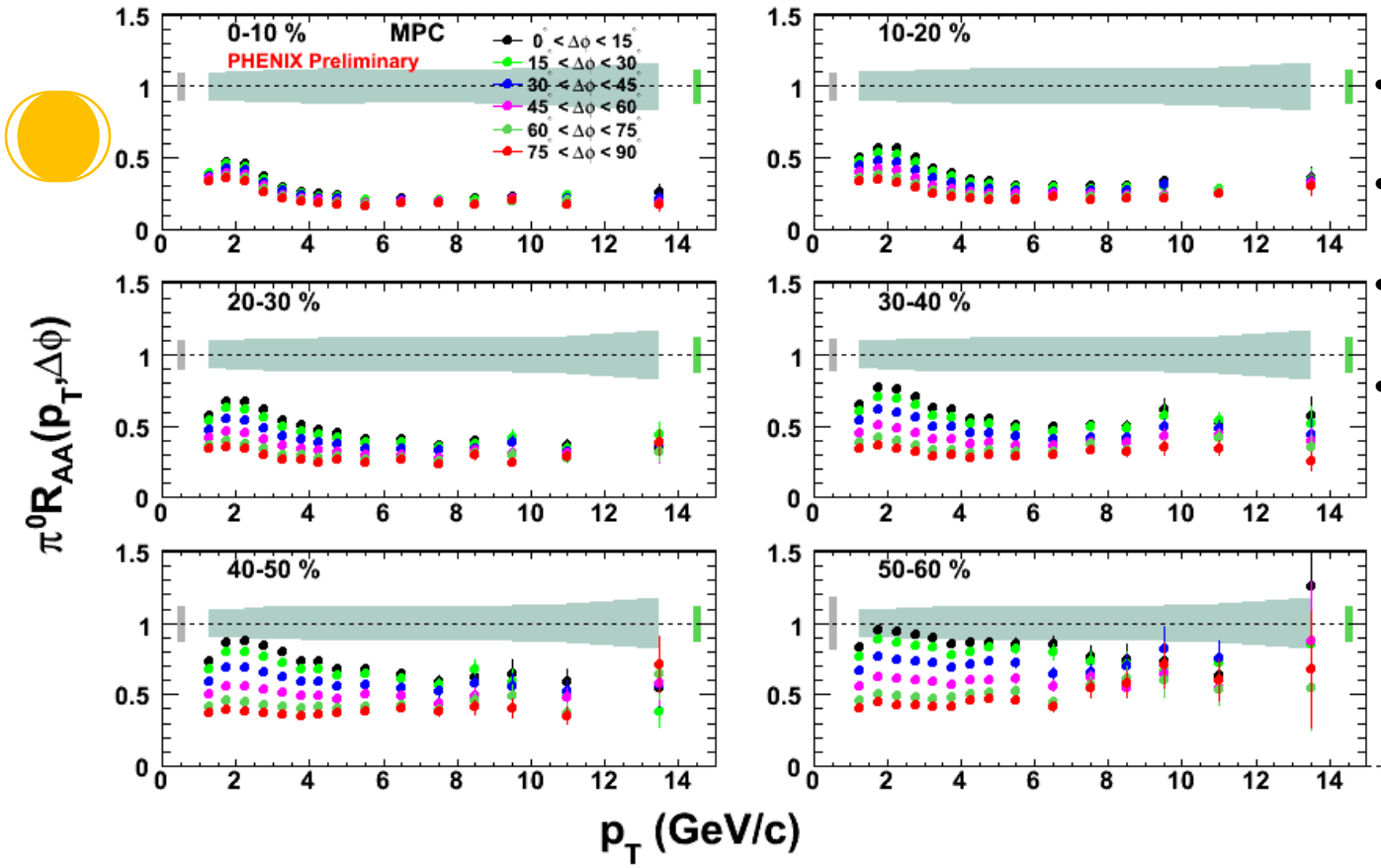
- π^0's are measured by mid-radrapidity (|y|<0.35)
- Reaction plane is determined by MPC



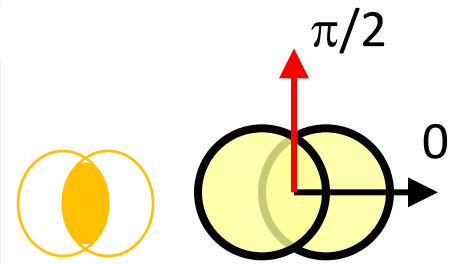
Qualitatively…

- ☐ Decrease at high pT (centrality20-30%)
- ☐ Keep finite values at high pT (other centrality classes)

Azimuthal angle dependence of $R_{AA}(p_T, \Delta\phi$, centrality)

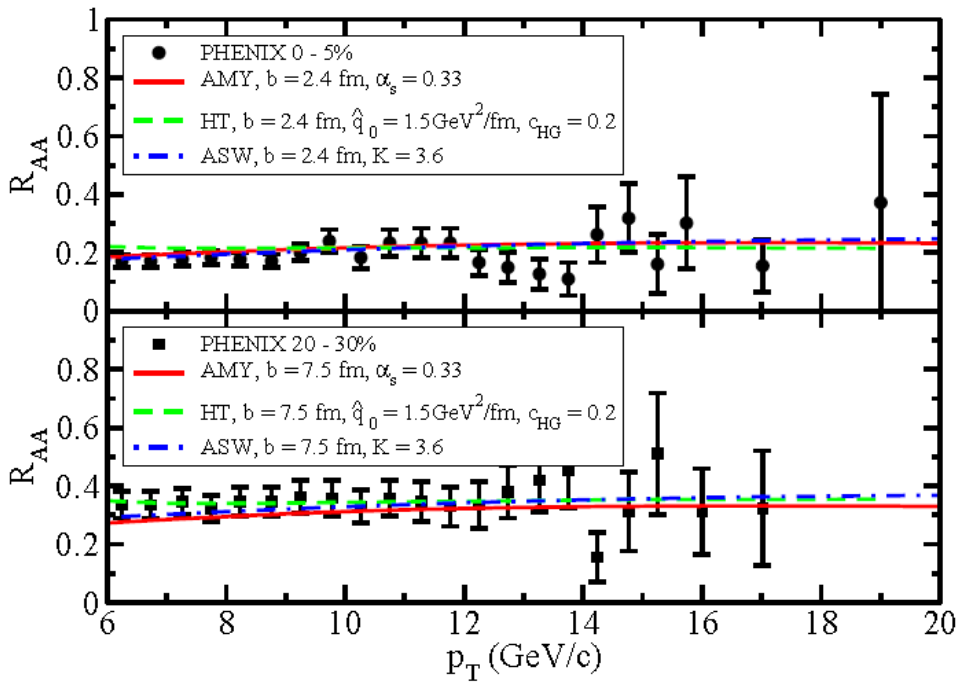


- **Dark gray band**: N_{col} systematic error
- **Green band**: p+p normalization error
- **Light gray band**: $R_{AA}(p_T,\Delta\phi)$ error
- **Error bar** : Statistical error



- **For pT increasing, azimuthal angle dependence of R_{AA} decrease.**
- **Azimuthal angle dependence of R_{AA} is small only in central collisions.**

Theorist's approach to the energy loss mechanism



- **AMY, Higher Twist (HT) and ASW**

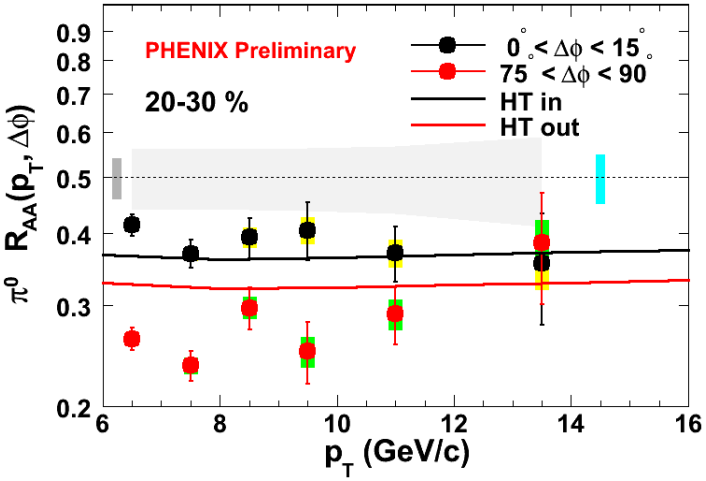
3-D hydrodynamic medium
+
Different parton energy loss scheme

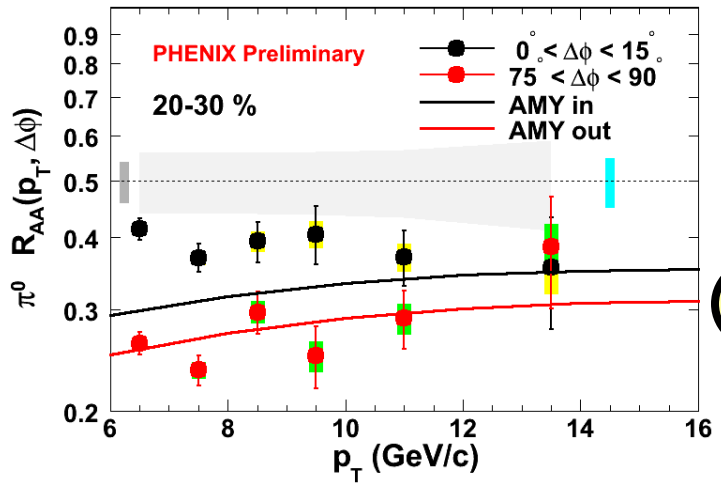
- **Fixed parameters at central collisions**
  - HT : q_0 = 1.5 (GeV^2/fm), c_{HG} = 0.2
  - AMY : α_s = 0.33
  - ASW : K = 3.5

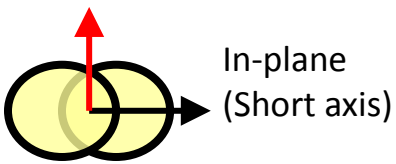
Detail of these model
→ *S.Bass et al. arXiv:0808.0908*

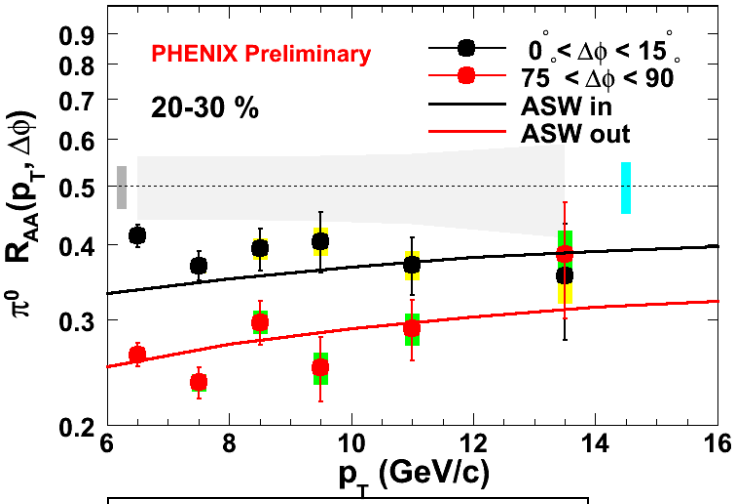
- These 3-D hydro + energy loss models can reproduce
  - **p_T dependence of azimuthal angle integrated R_{AA}**
  - **Centrality dependence of azimuthal angle integrated R_{AA}**

Comparison of In/out plane $R_{AA}(p_T, \Delta\phi, 20<cent<30)$









In-plane : **R_{AA} is almost flat**(~0.4)
: The data prefer ASW and HT

Out of plane : **Larger R_{AA} at high p_T(=small E-loss)**
: The data prefer ASW and AMY

Model calculation from S.Bass et al. arXiv:0808.0908

Summary and outlook

- Hard scattered parton
  - Good probe for studying the property of dense matter.
  - Sensitive to gluon density in the medium
- Azimuthal angle dependence of $R_{AA}(p_T, \Delta\phi)$
  - decrease as pT increase
  - In-plane R_{AA} become large at higher p_T for centrality 20-30%
  - Out of plane R_{AA} is flat for centrality 20-30%

- Measure R_{AA} for each averaged path length (<L>)
  - Ongoing work
- Constrain parameters for jet quenching models
  - Ongoing work

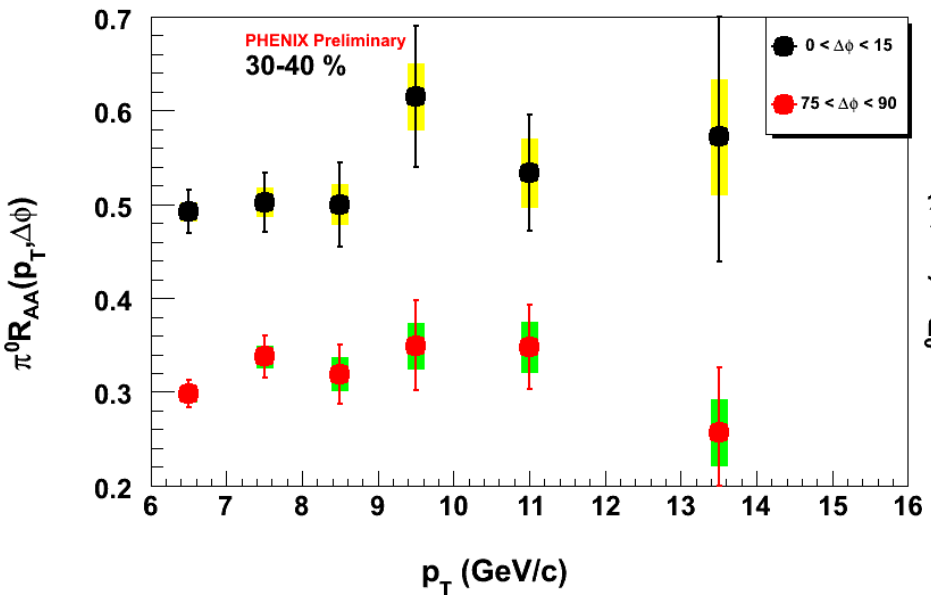
Backup

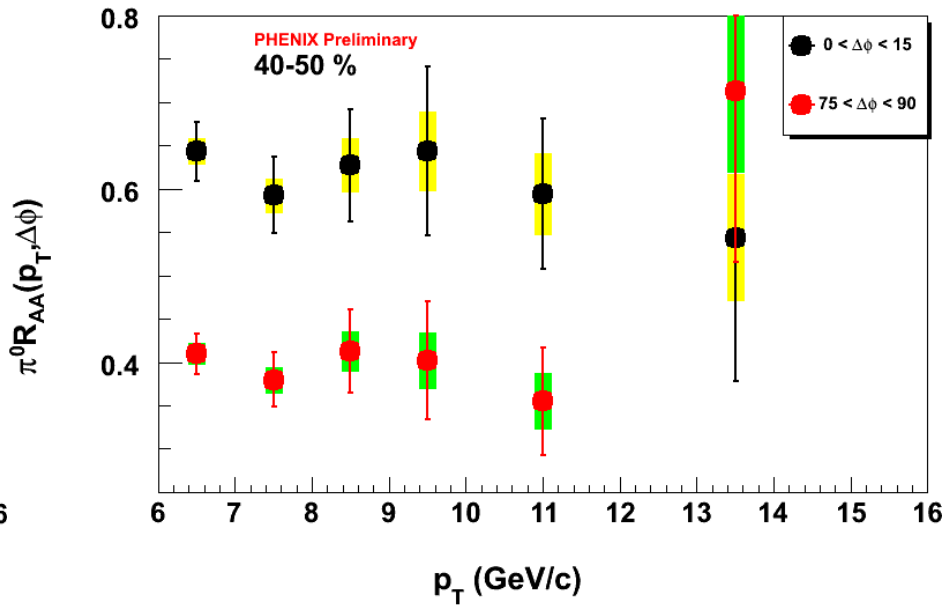
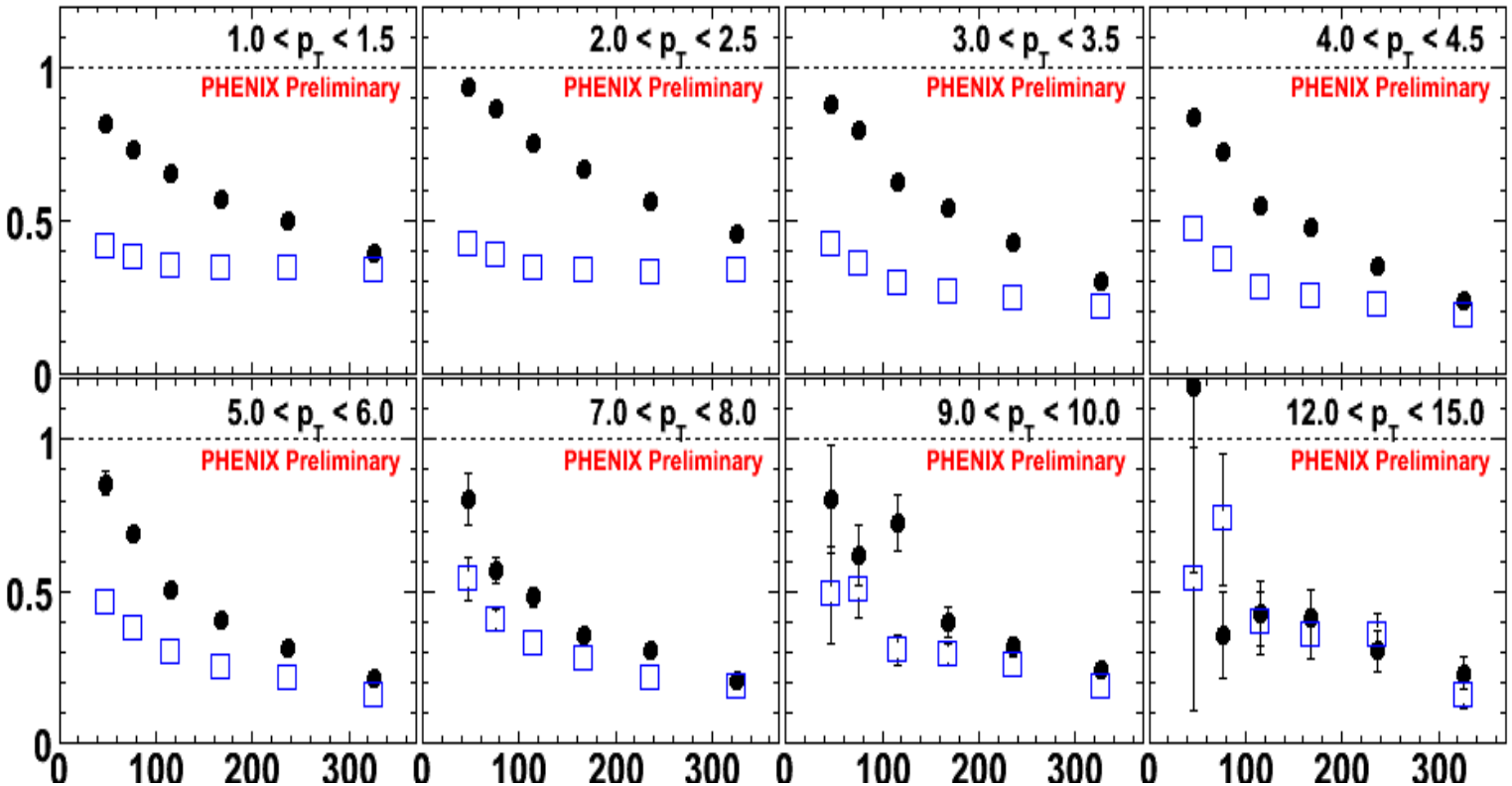
Systematic uncertainty source on integrated angle $R_{AA}(p_T)$

PRL **101**, 232301 (2008)

p_T (GeV/c)	2	6	10	16
uncertainty source		PbSc (PbGl)		
yield extraction (%)	3.0 (4.1)	3.0 (4.1)	3.0 (4.1)	3.0 (4.1)
PID efficiency (%)	3.5 (3.9)	3.5 (3.5)	3.5 (3.7)	3.5 (3.9)
Energy scale (%)	6.7 (9.0)	8.0 (9.2)	8.0 (8.2)	8.0 (12.3)
Acceptance (%)	1.5 (4.1)	1.5 (4.1)	1.5 (4.1)	1.5 (4.1)
π^0 merging (%)	··· (···)	··· (···)	4.4 (···)	28 (4.8)
Conversion (%)	3.0 (2.5)	3.0 (2.5)	3.0 (2.5)	3.0 (2.5)
off-vertex π^0 (%)	1.5 (1.5)	1.5 (1.5)	1.5 (1.5)	1.5 (1.5)
Total (%)	8.7 (12)	9.8 (11)	11 (11)	30 (15)
PbSc and PbGl combined: Total (%)	7.0	7.5	7.6	14

$R_{AA}(p_T, \Delta\Phi)$ for cent30-40 and 40-50%





In-plane and out of plane R_{AA}