Measurement of high-pT hadrons at RHIC-PHENIX

Tadaaki Isobe

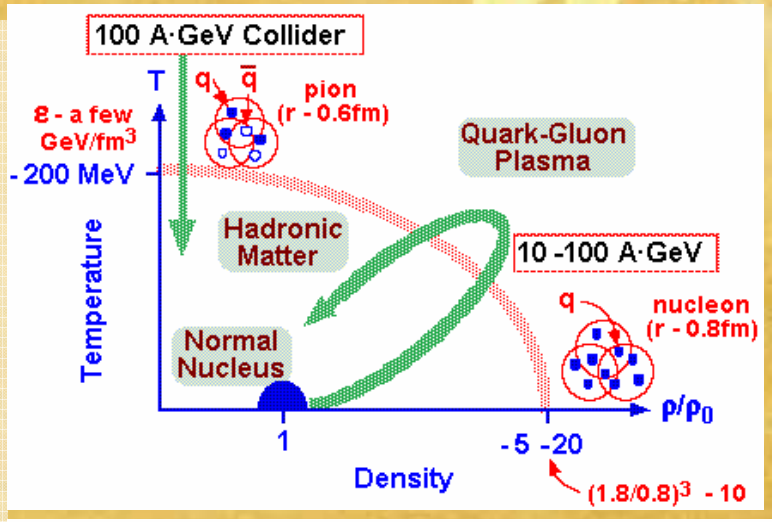
for the PHENIX collaboration

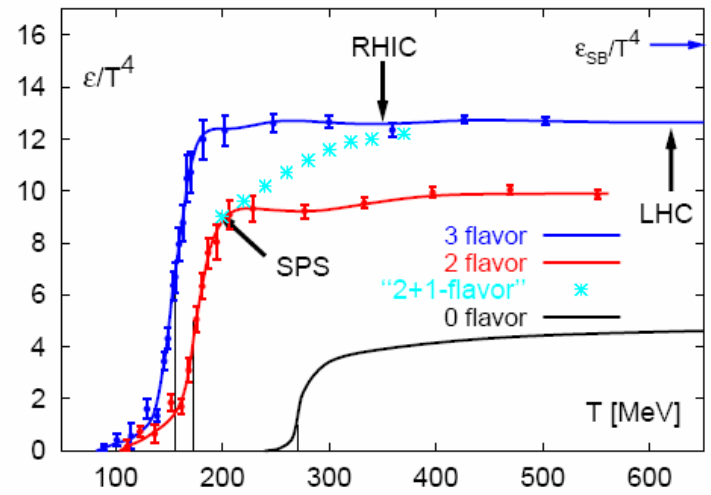
東京大学大学院理学系研究科附属
原子核科学研究センター
Center for Nuclear Study (CNS)

CNS, Univ. of Tokyo

Motivation for Relativistic Heavy Ion Collisions

- Quark Gluon Plasma (QGP)
  - Expected to be created with RHIC
  - It existed in the early universe
- QGP is a phase where bare strong interaction plays significant role
  - Quarks and gluons are deconfined and free from QCD binding
  - Study dynamical behavior of strongly interacting system
- Transition Point (Lattice QCD)
  - T ~ 170 MeV
  - E ~ 1.0 GeV/fm^3





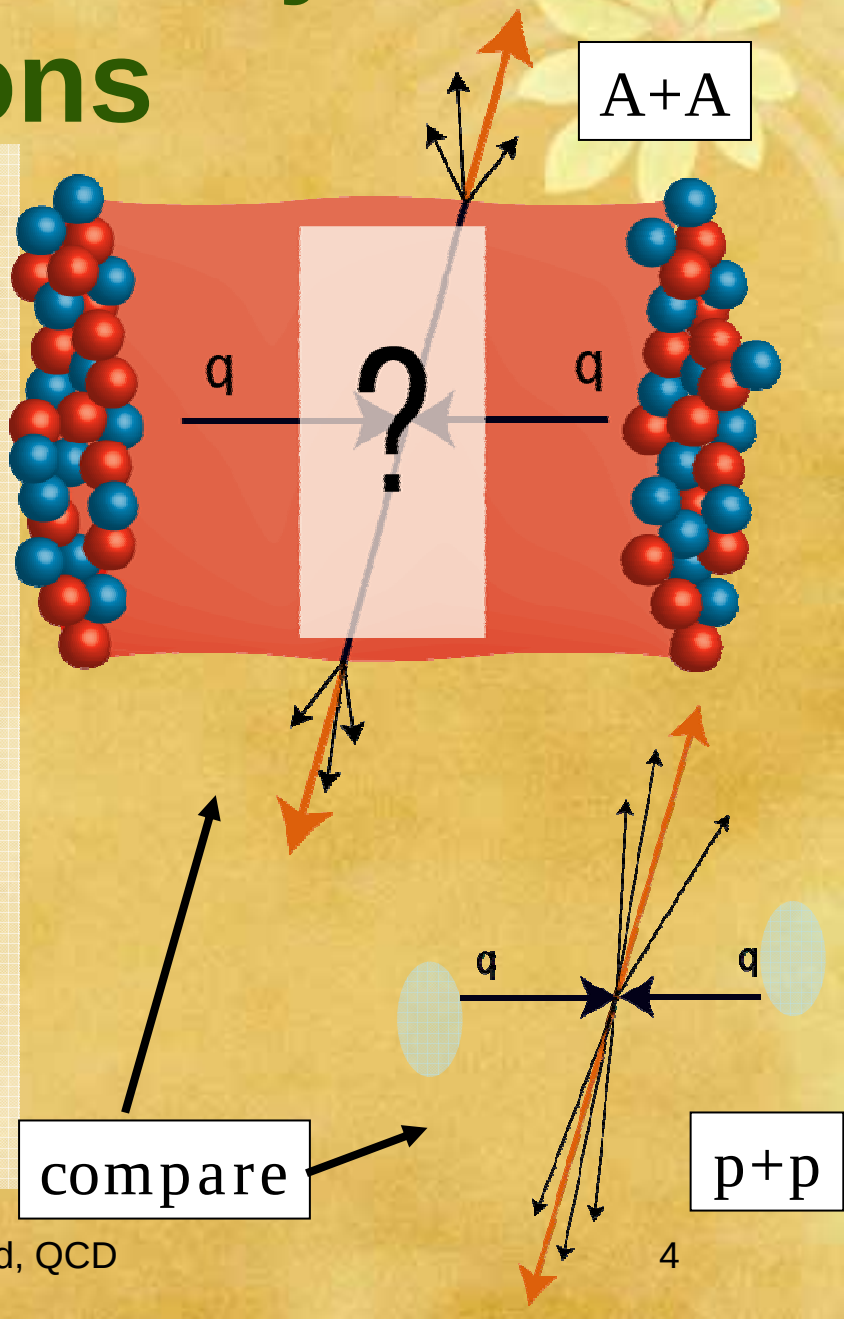
F. Karsch, Prog. Theor. Phys. Suppl. 153, 106 (2004)

Outline

- Measurement of high-pT hadrons
  - Hard scattering as probe of heavy ion collision
  - Nuclear modification factor. (R_{AA})
- Systematic study of Jet-quenching
  - System size dependence
  - Dependence on particle species
- Jet correlation in dense matter.
  - Evolution of jet shape.
- Summary

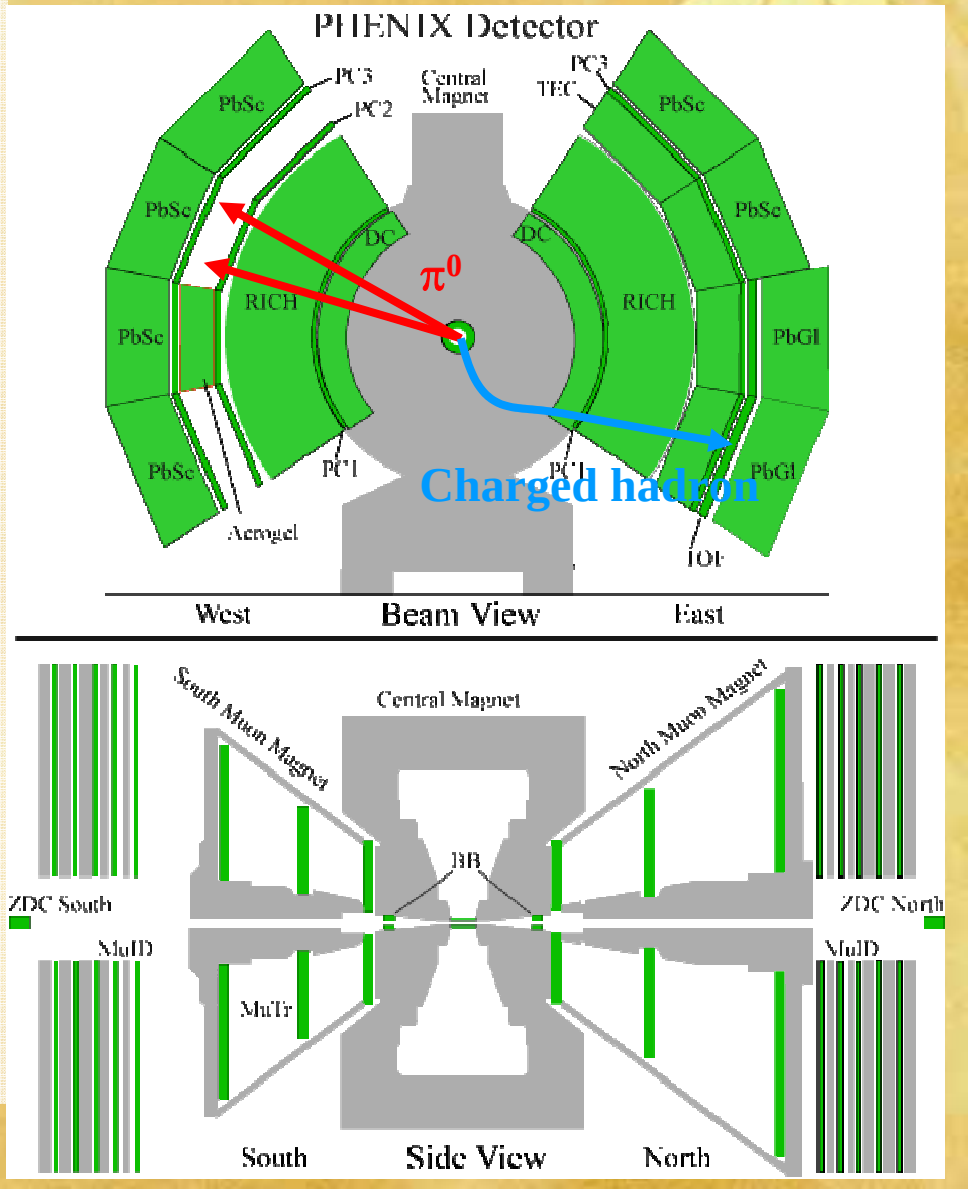
Hard probe in heavy ion collisions

- **Unique Signature at high energy: Hard scattering cross-section is large**
- **Initial yield and pT distributions in HIC can be predicted by p+p measurement + pQCD + collision geometry + cold nuclear effect.**
  - But it's impossible to reconstruct jets due to the large BG (dN_{ch}/dy = 700).
  - Measure high-pT particles as leading particle of the jets
- **Observed deviations are attributed to the medium.**



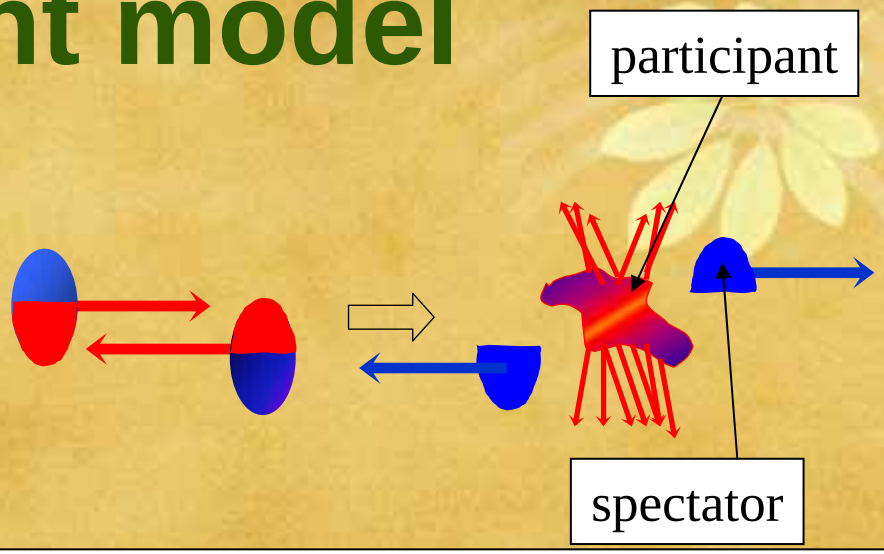
High-pT measurement at RHIC-PHENIX

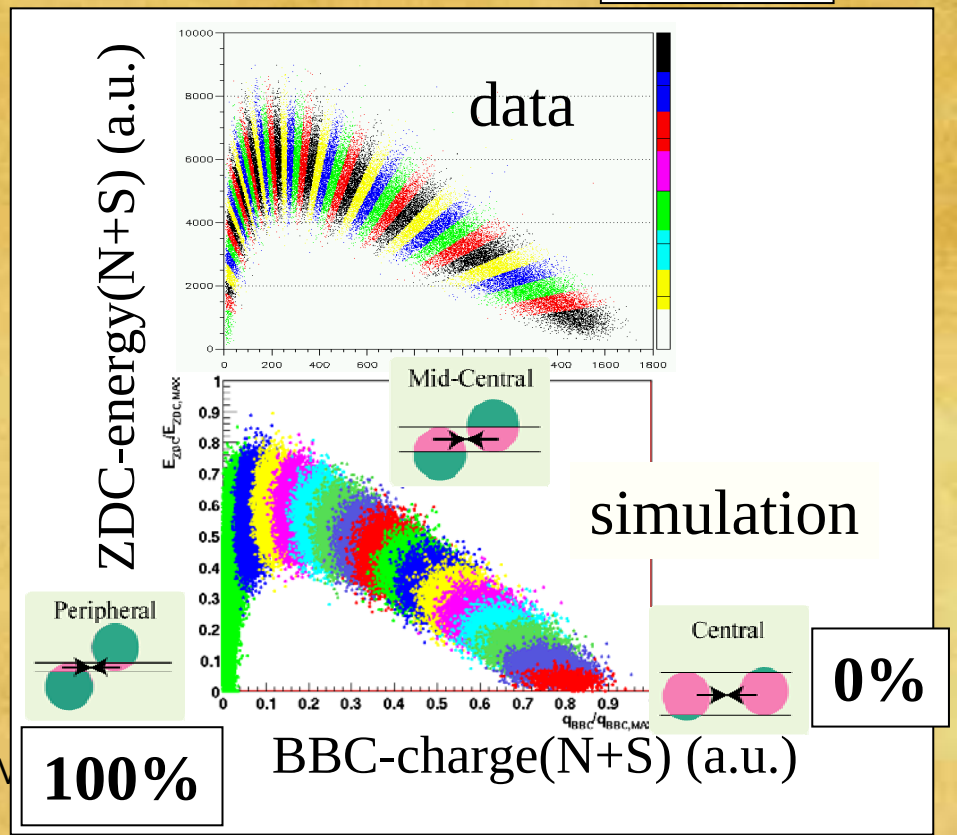
- $\pi^0/\eta \rightarrow 2\gamma$
- Photon measurement using EMCal
  - Distance from vertex point: 5m
    - $|\eta|<0.35$ $\phi = 2*90°$
  - 2 arm × 4 sectors
    - Lead Scintillator Type (PbSc)
    - Lead Glass Type (PbGl)
  - Fine granularity
    - Possible to measure π^0 up to 30GeV/c
- **Charged hadron →tracking and matching**
- Momentum measurement with DC
  - Measurement up to 10 GeV/c



Participant model

- **Participant and spectator**
  - *N*part: number of participant nucleons in collision
  - *N*coll: number of binary N-N collision
- **Centrality**
  - Determined with BBC and ZDC correlation
  - *N*part, *N*coll is obtained from MC with Galuber model.
  - 0%: central, 100%: peripheral collision

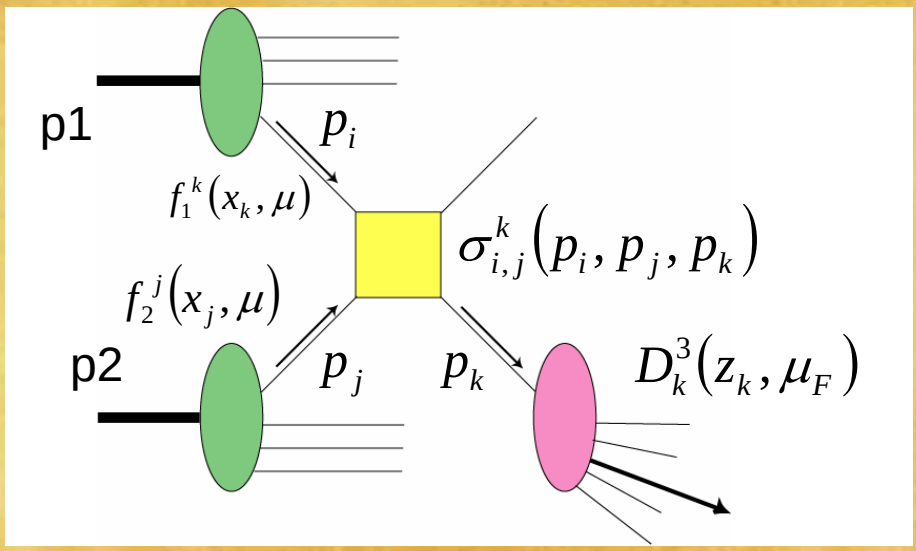




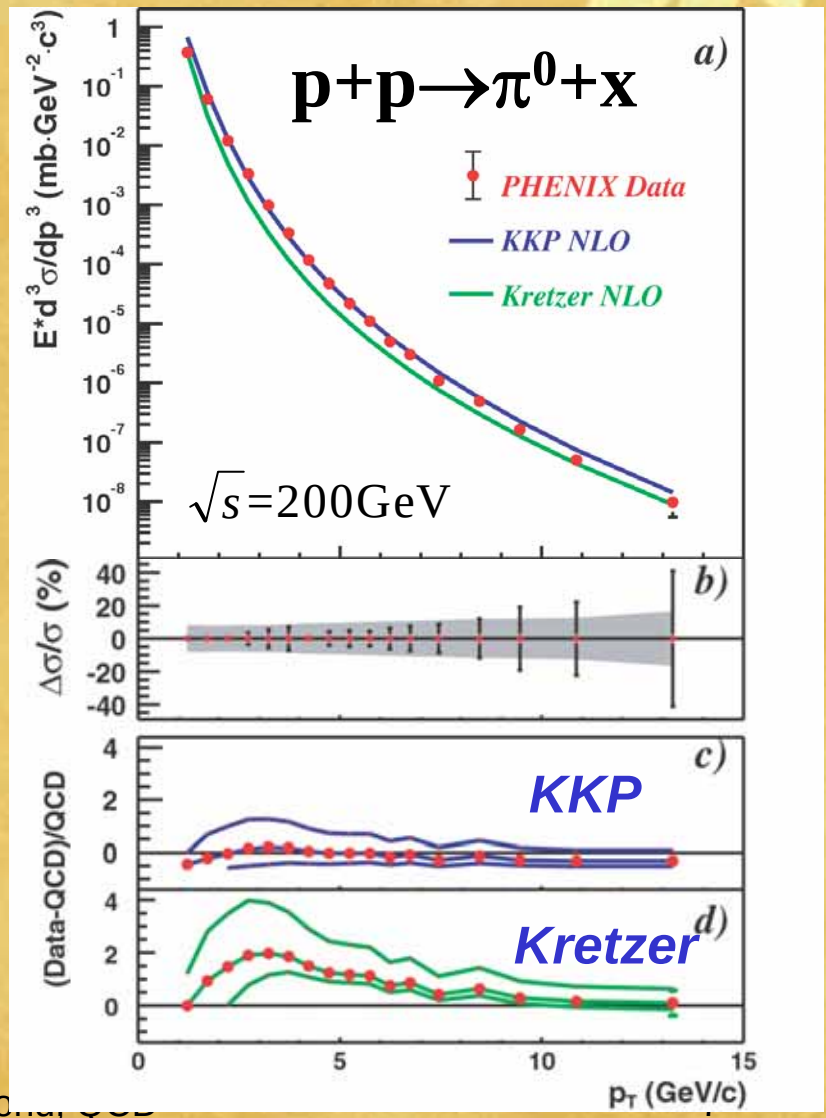
Hard scattering in p+p collisions

- **Hard scattering process well described by NLO pQCD calculation at high Q^2**

$$\sigma^3_{1+2} = \sum_{i,j,k} \int dx_i dx_j dx_k \times f_1^k(x_k,\mu) \cdot f_2^j(x_j,\mu) \times \sigma^k_{i,j}\left(p_i, p_j, p_k, \alpha_s(\mu_R), Q^2/\mu_F, Q^2/\mu_F\right) \times D^3_k(z_k,\mu_F)$$

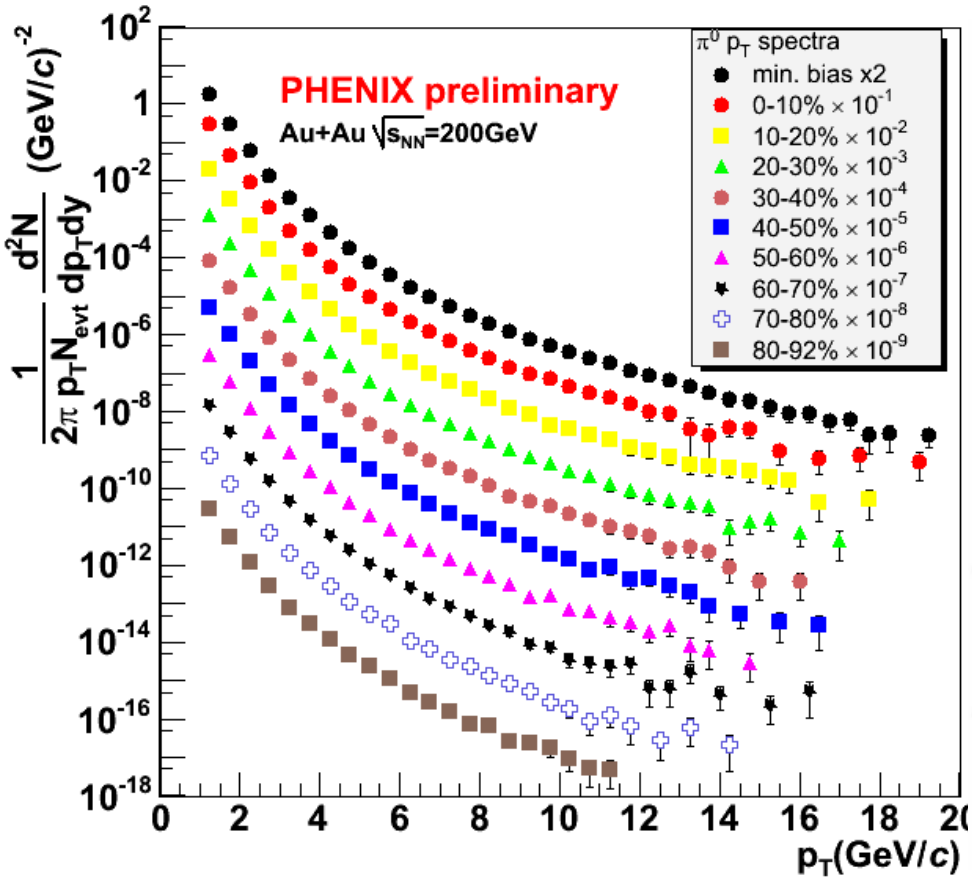


Phys. Rev. Lett. 91, 241803 (2003)

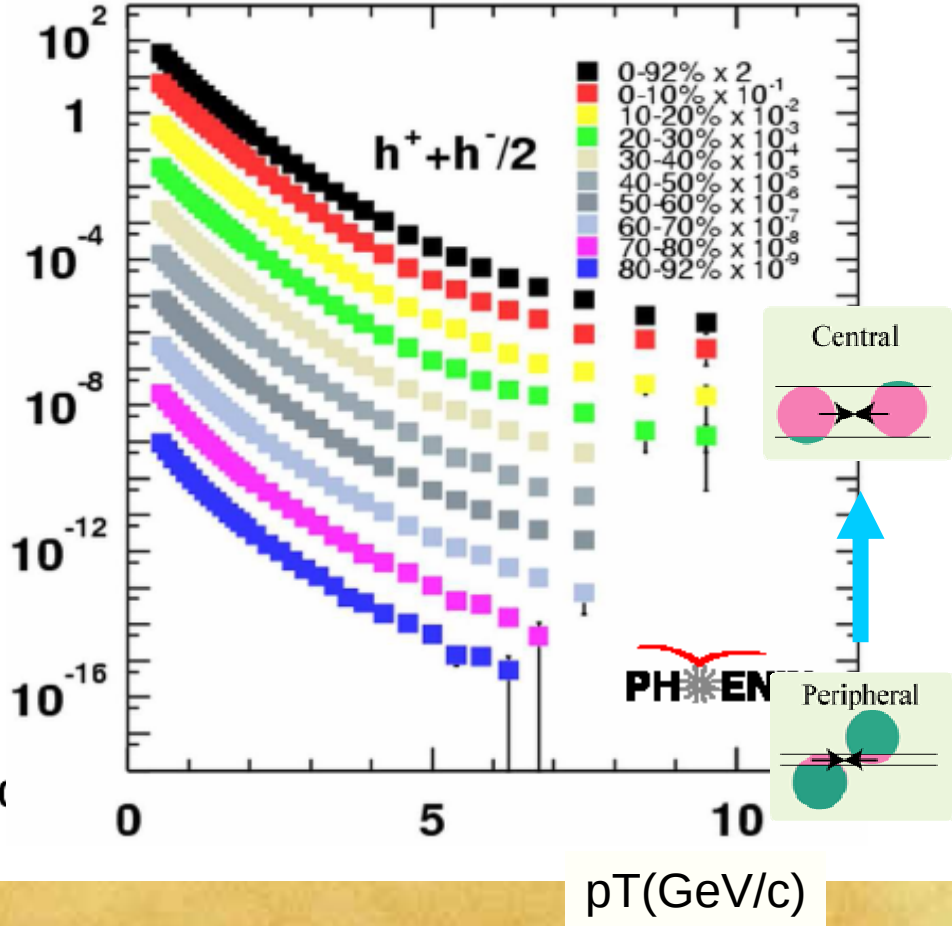


pT spectra in $\sqrt{s_{NN}}$ =200GeV Au+Au

Neutral Pion



Charged Hadron

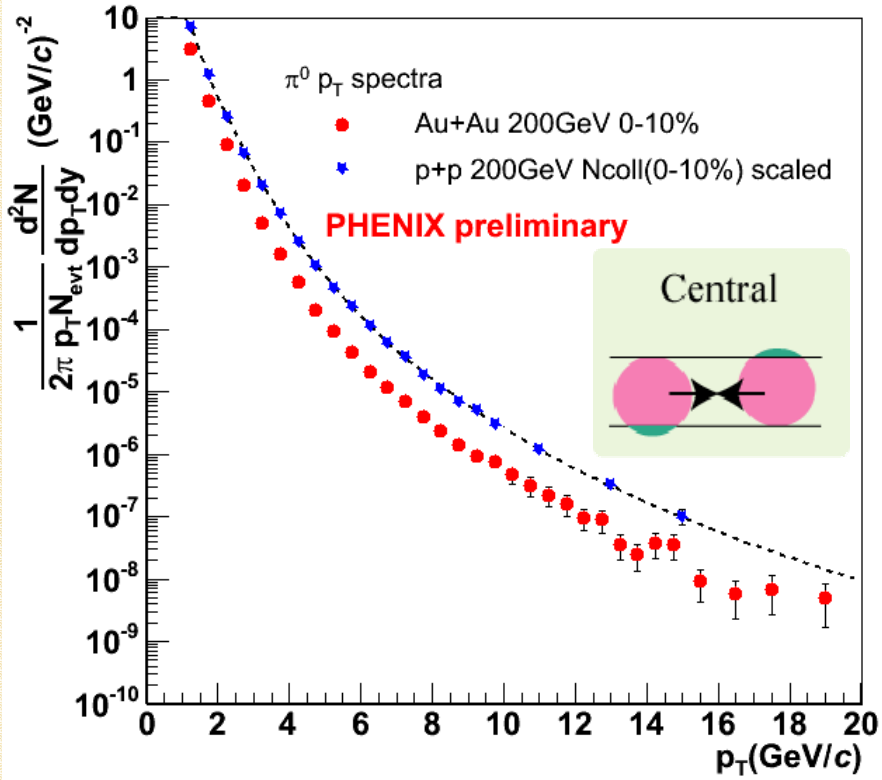


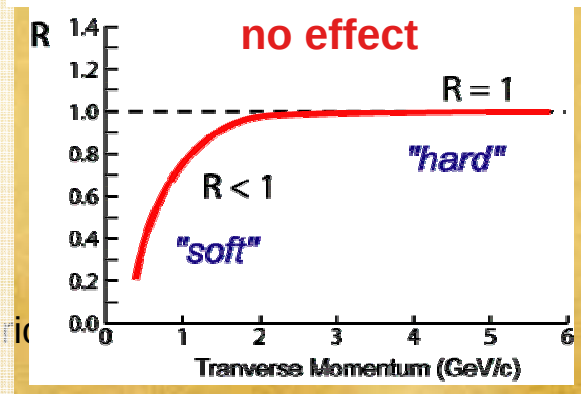
N_{coll} scaling and R_{AA}

- Yield from hard processes can be scaled with N_{coll}(# of collision)
- Suppression of π^0 at high pT in central Au+Au collisions
  - Jet-quenching
- Nuclear modification factor
  - divided by expected (binary scaled) yield from p+p data

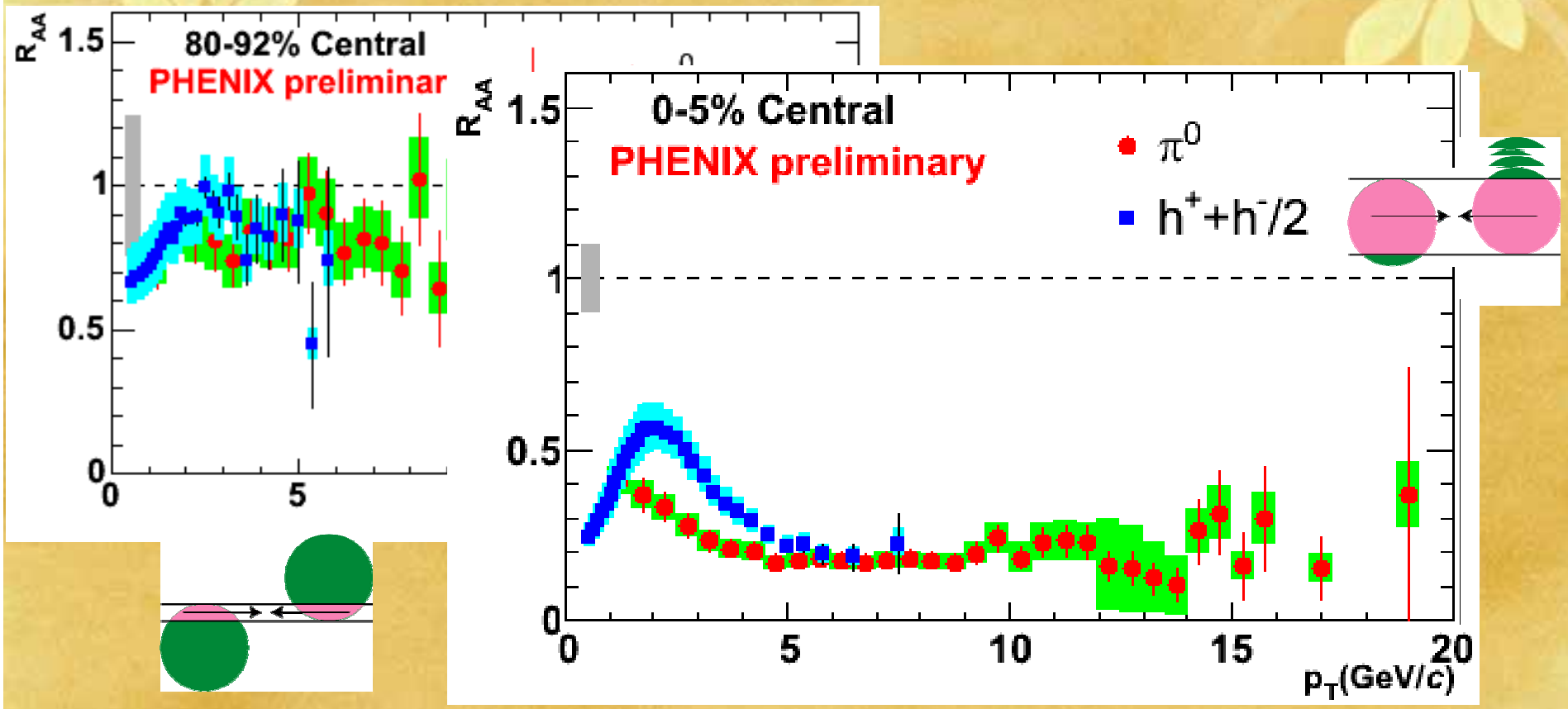
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

  - absence of nuclear effects: $R_{AA}=1$





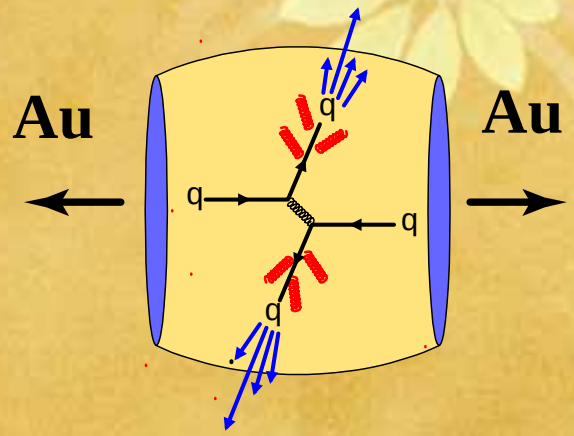
R_{AA} in $\sqrt{s_{NN}}$ =200GeV Au+Au



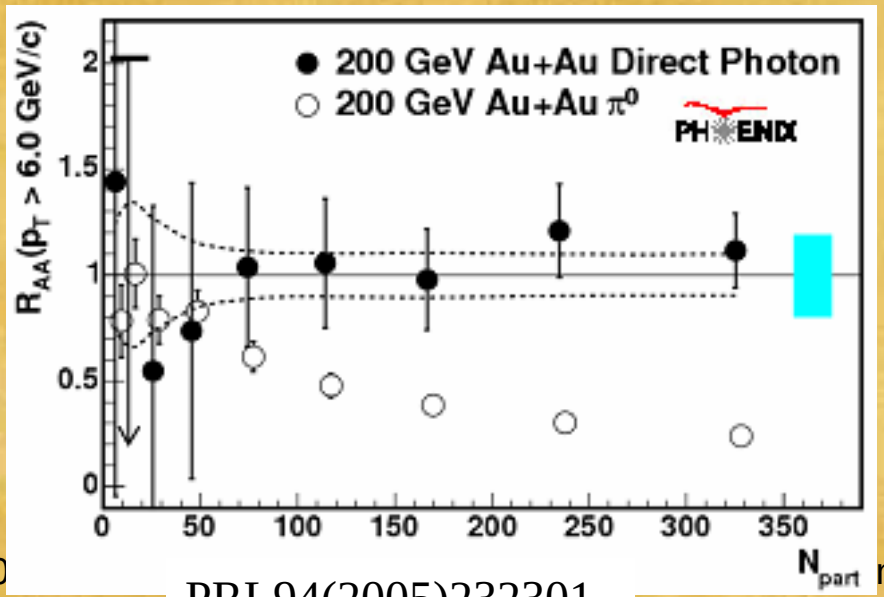
- Strong suppression is seen even at high pT. (~ 0.2)
- Constancy for pT>4GeV/*c* for all centralities

Jet-quenching is final state effect

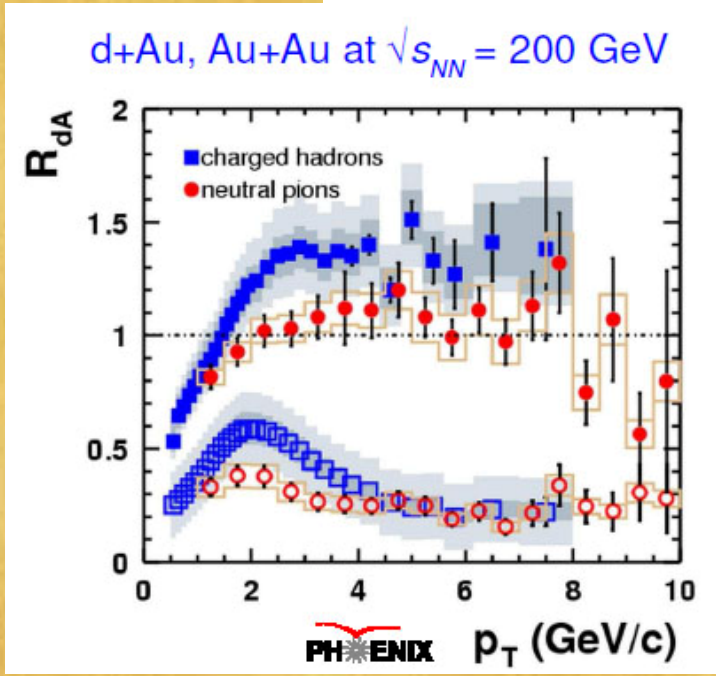
- Suppression of π^0 at high-pT in central Au+Au collisions
  - **Interpreted as energy loss of hard scattered partons in hot and dense matter**
- Non-suppression in *d*+Au
- Non-suppression of direct photons in Au+Au



PRL91(2003)072303



PRL94(2005)232301

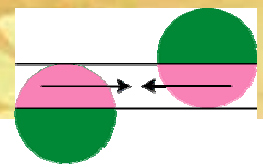


Systematic study of Jet-quenching effect

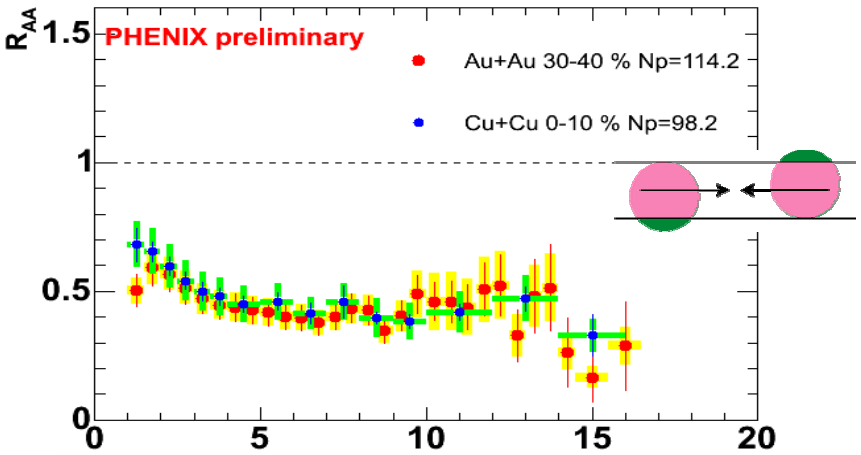
System size dependence

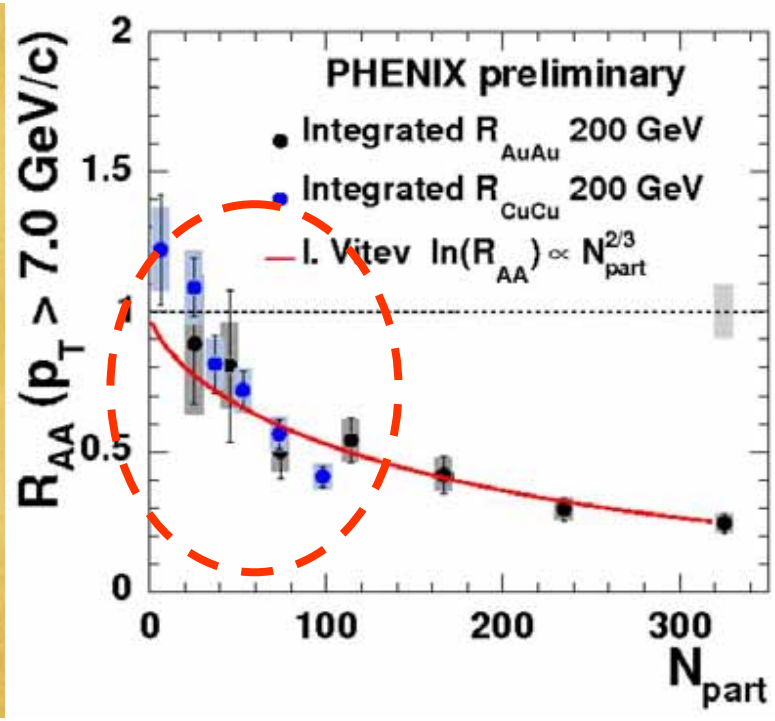
Particle mass dependence

System size dependence

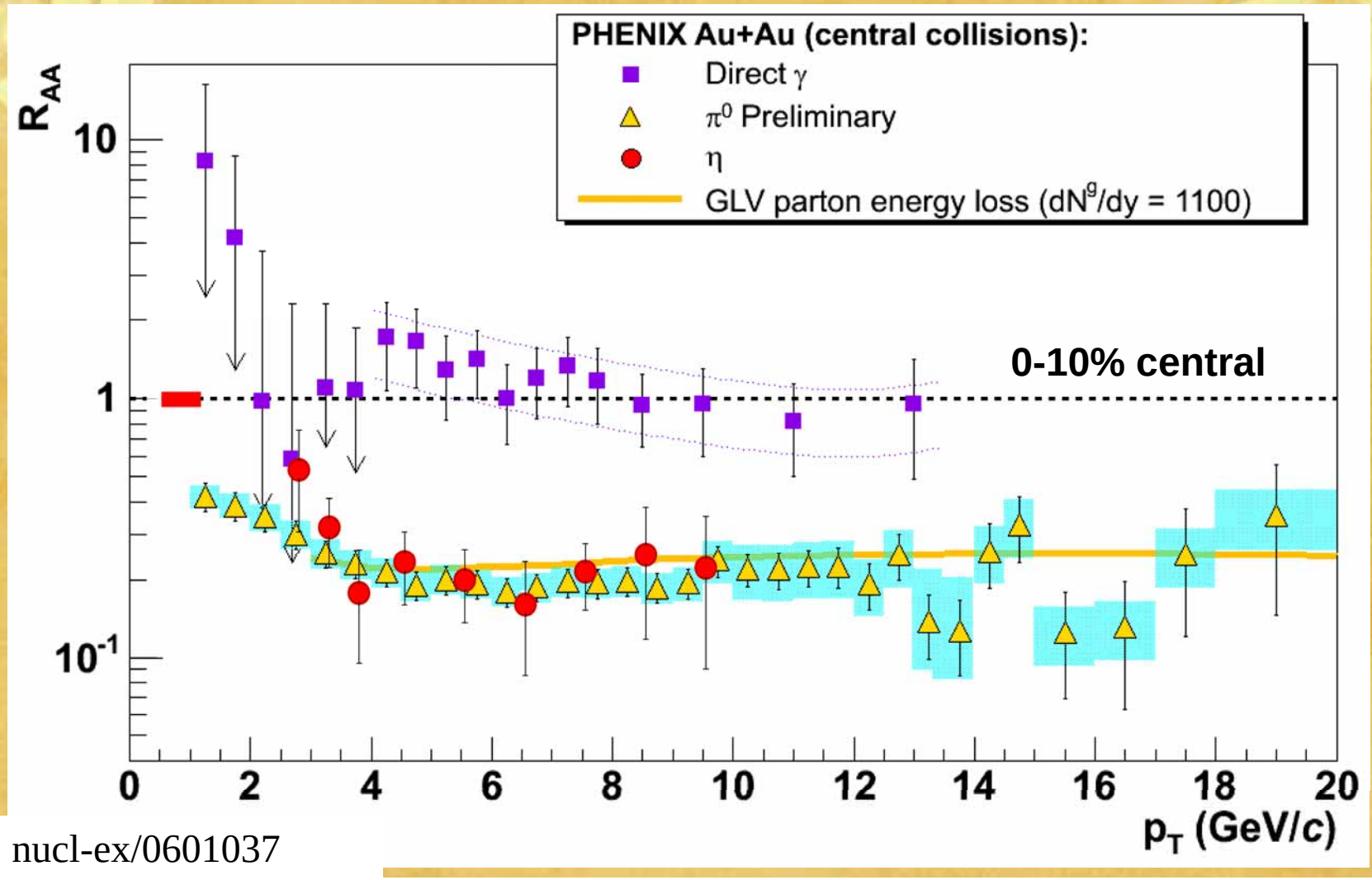


- **Cu+Cu measurement enable to measure the number of participant(*N*part) precisely**
- **π^0 R_{AA} at Cu+Cu 200GeV**
  - R_{AA} ~ 0.4 in most central collisions
  - Strong jet-quenching effects even in lighter colliding system
- **Similar behavior between Au+Au and Cu+Cu for same *N*part**
  - Consistent with pure density and path-length dependence





Dependence on particle species



nucl-ex/0601037

✓ η suppression is similar to π^0 (indicates partonic level)

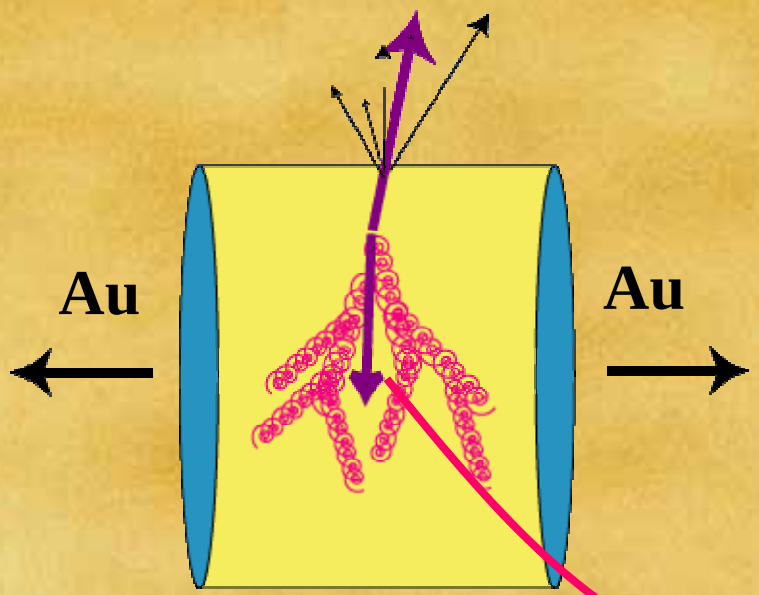
✓ support the model where $dN^g/dy=1100$ ($15 GeV/fm^3$)

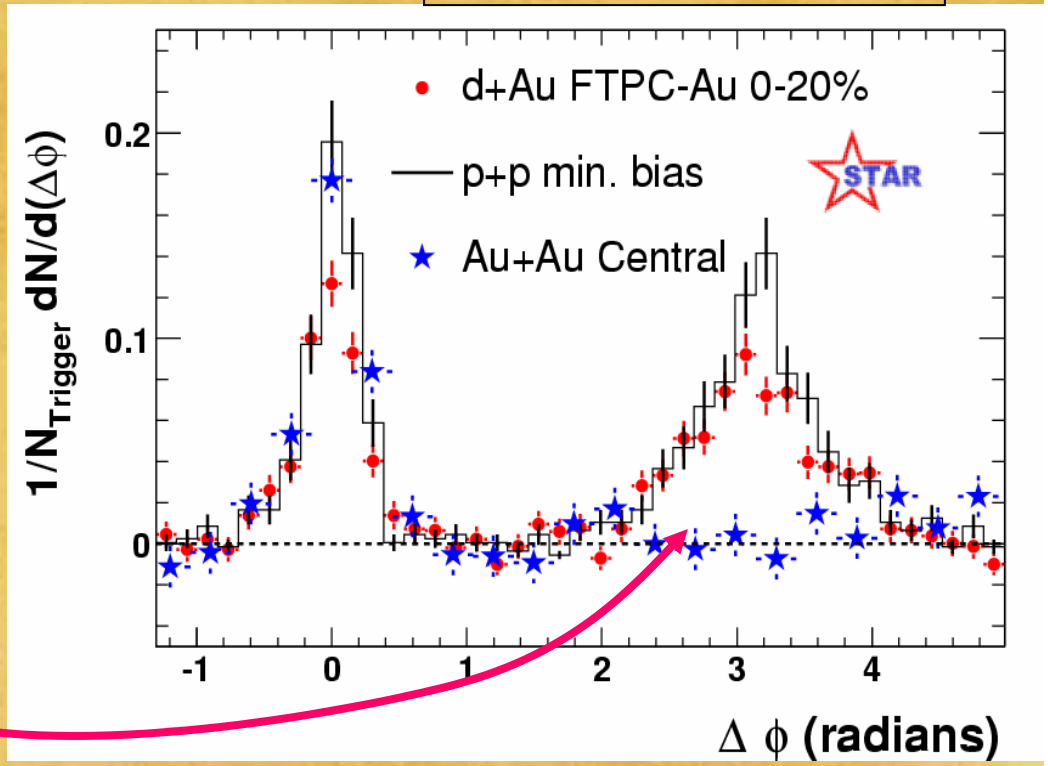
Jet correlation

Suppression of away side jet

- Only one "jet" is seen at a time in Au+Au central collisions.
- Disappearance of away side jet.
- Signal of jet-quenching

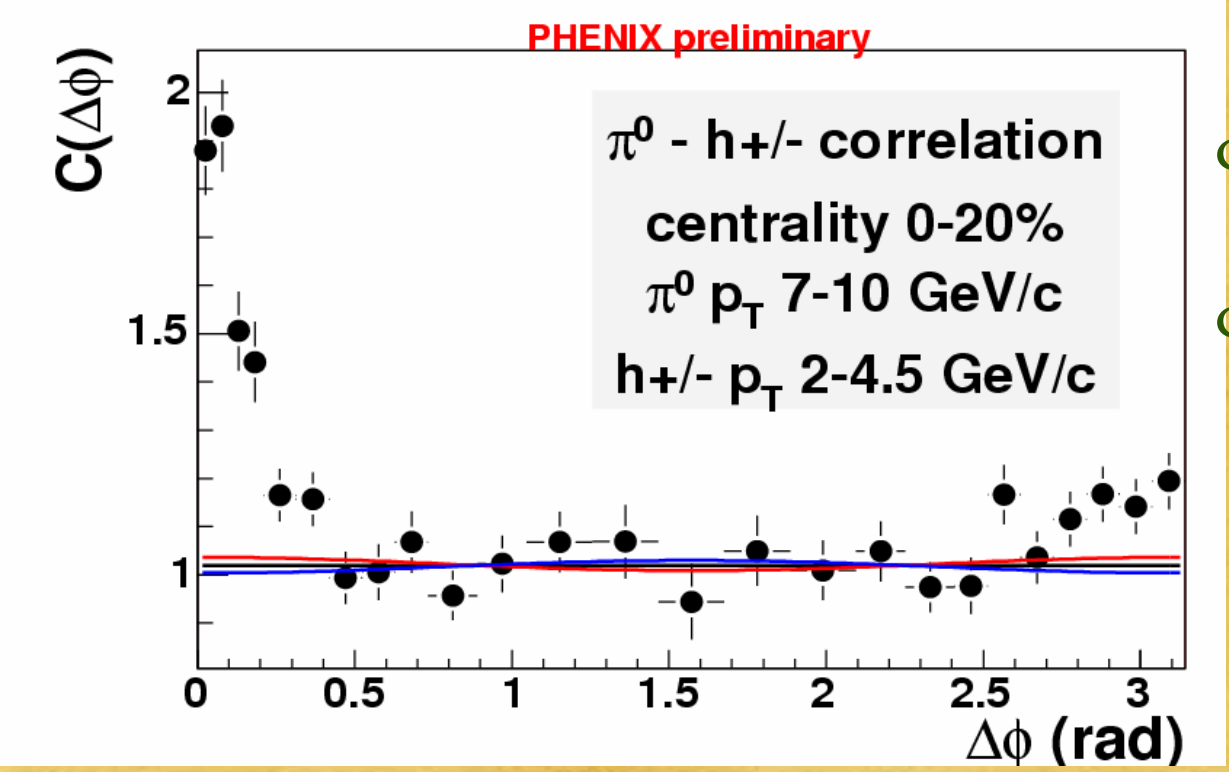
4 < pT(trig) < 6 GeV/c
pT(assoc) > 2 GeV/c





Jet-quenching

Emergence of away side Jet

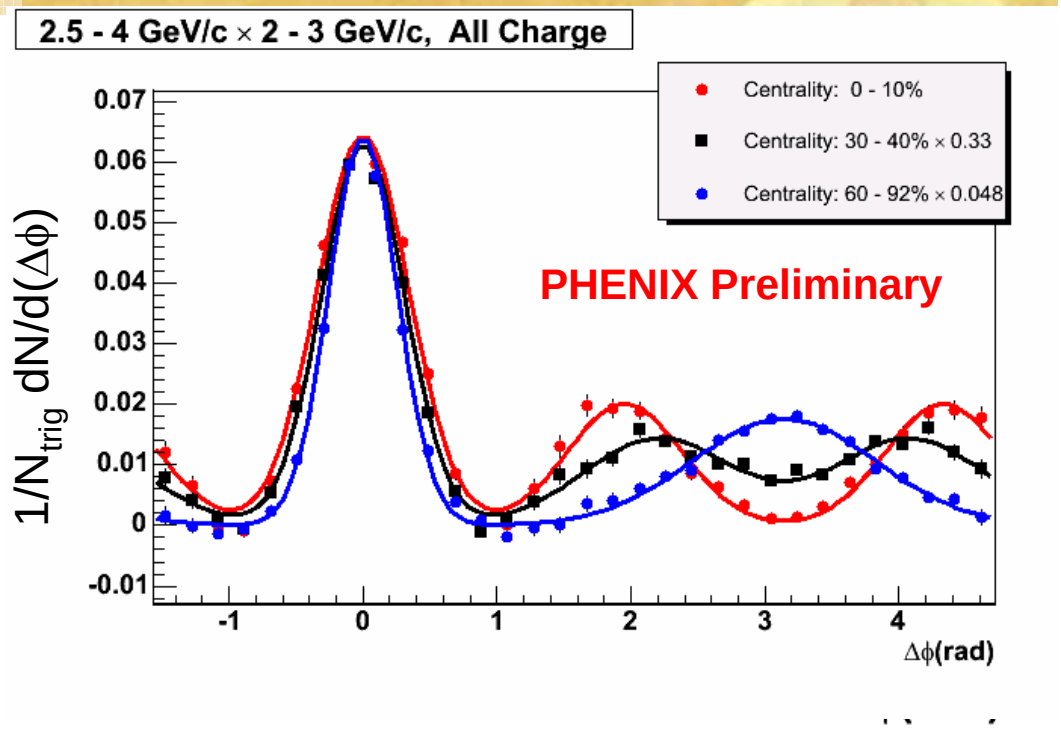


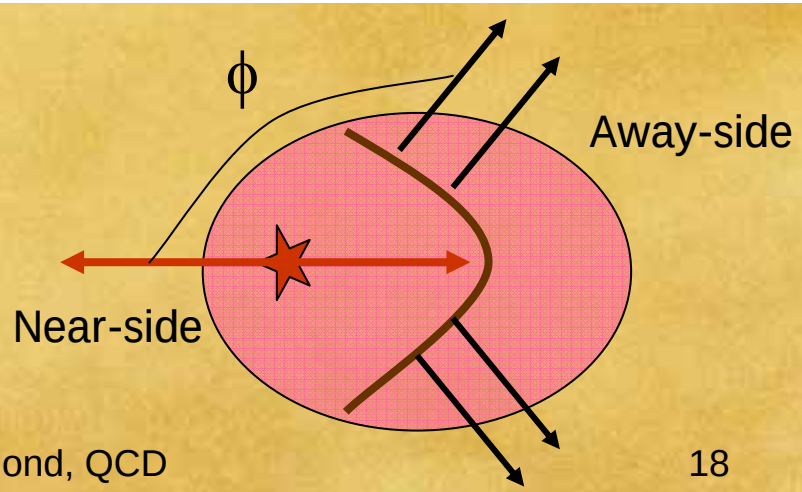
- C(Δφ) strength ~ S/B of jets
- Red and blue lines are the uncertainty in v_2.

- **Jets emerge for trigger >5 GeV and associated >2 GeV**
- Hint of narrow back-to-back peak for higher p_T(trig)?
  - Higher p_T(trig) reflects higher-Q^2 hard scattering

Jet modification

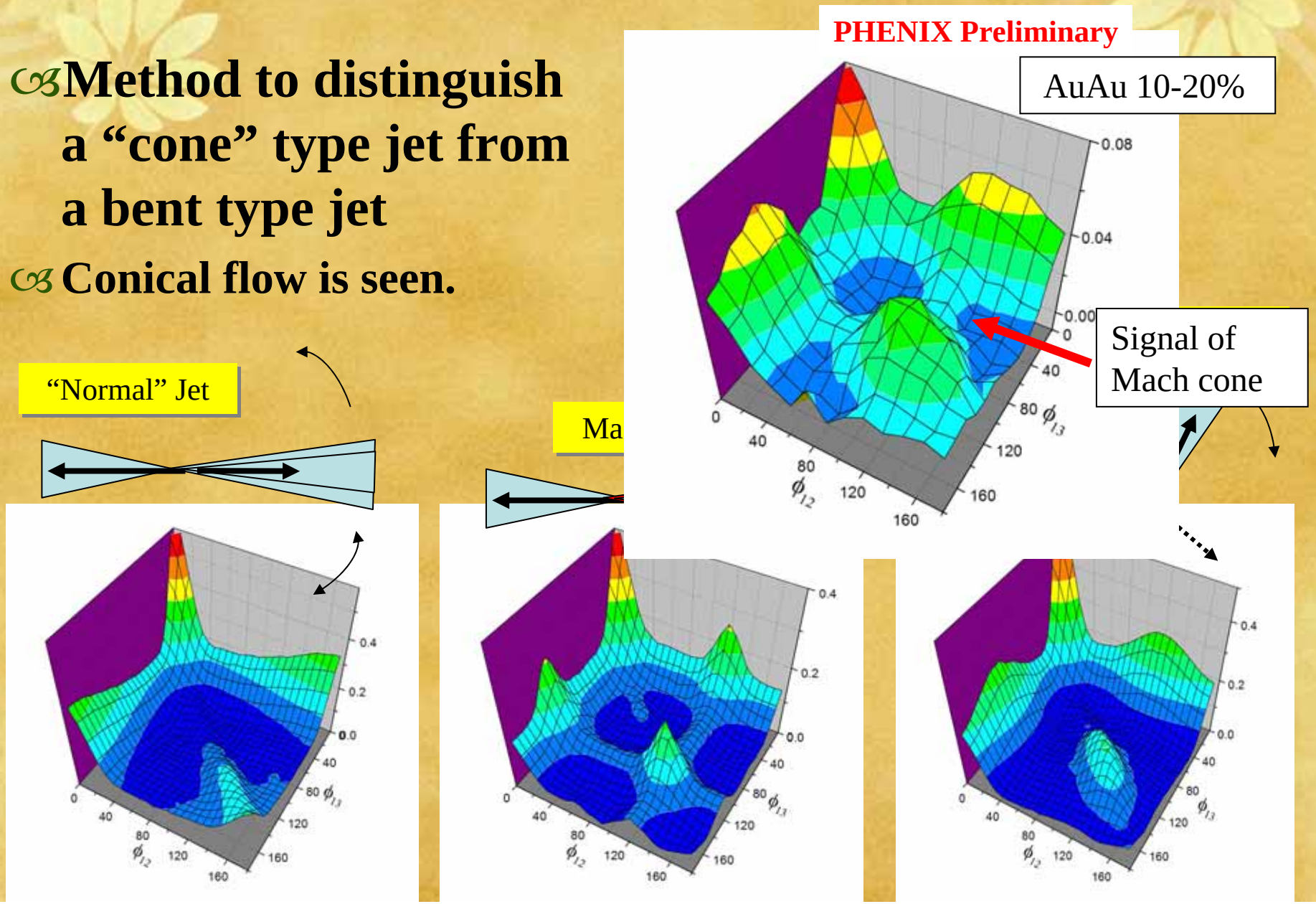
- **Two-particle correlation in the intermediate pT range**
  - Flow effect is subtracted.
- The shape of associated jet is cone like.
- large angle gluon radiation from LPM interference:
  - I. Vitev
- conical flow:
  - H. Stoecker, E. Shuryak, B. Muller
- Cherenkov like radiation:
  - I. Dremin, X.N. Wang





3-particle correlation

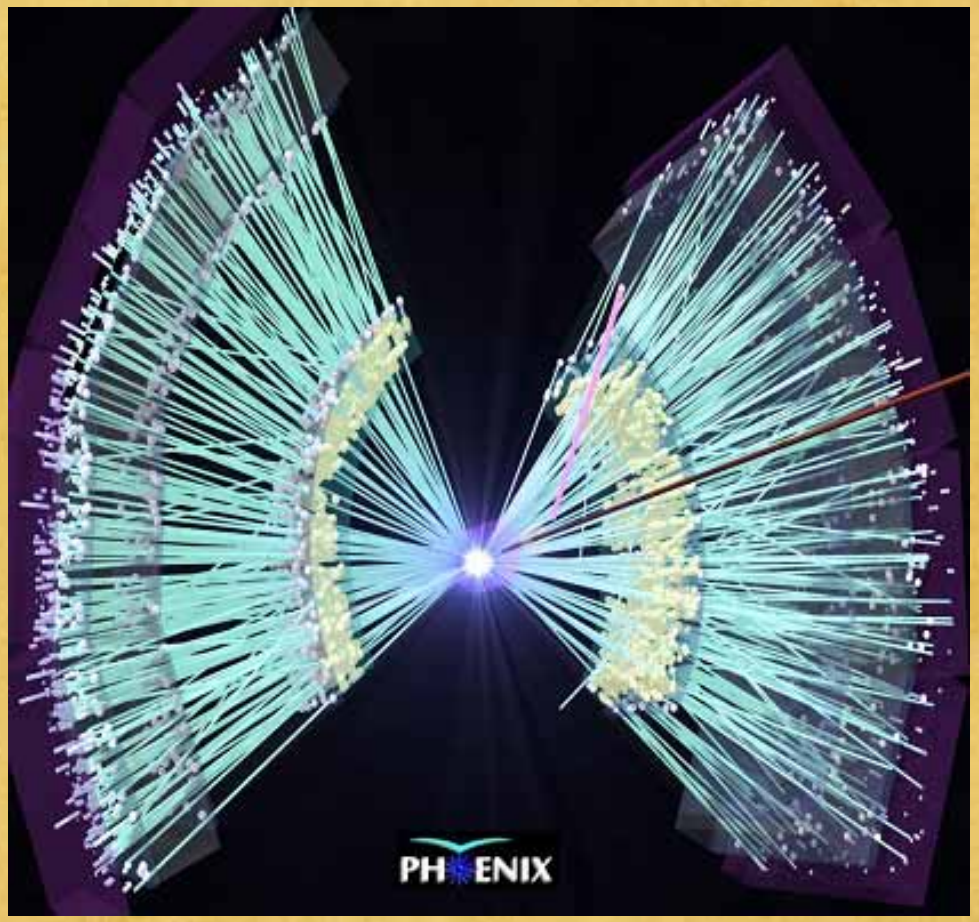
- Method to distinguish a “cone” type jet from a bent type jet
- Conical flow is seen.



Summary

- High-pT hadron suppression in central heavy ion collisions
  - dNg/dy ~ 1100 in 200GeV Au+Au (15GeV/fm^3)
- Systematic study of jet-quenching
  - System size dependence (Au+Au, Cu+Cu)
    - Similar behavior between Au+Au and Cu+Cu for same *N*part
  - η has a similar suppression pattern as π^0
- Evolution of jet shape
  - Tomography of dense matter
    - Cone like shape is observed
  - A qualitative picture to explain jet-modification is required

Backup slides



RHIC at BNL

Long Island, New York, USA

PHENIX

- First Heavy Ion collider
- 3.83 km circumference
- 106 ns bunch crossing
- Top Energy:
  - 500 GeV for p+p
  - 200 GeV for Au+Au
- Luminosity
  - Au+Au: 2×10^{26} cm^{-2} s^{-1}
  - p+p : 2×10^{32} cm^{-2} s^{-1} (*polarized*)

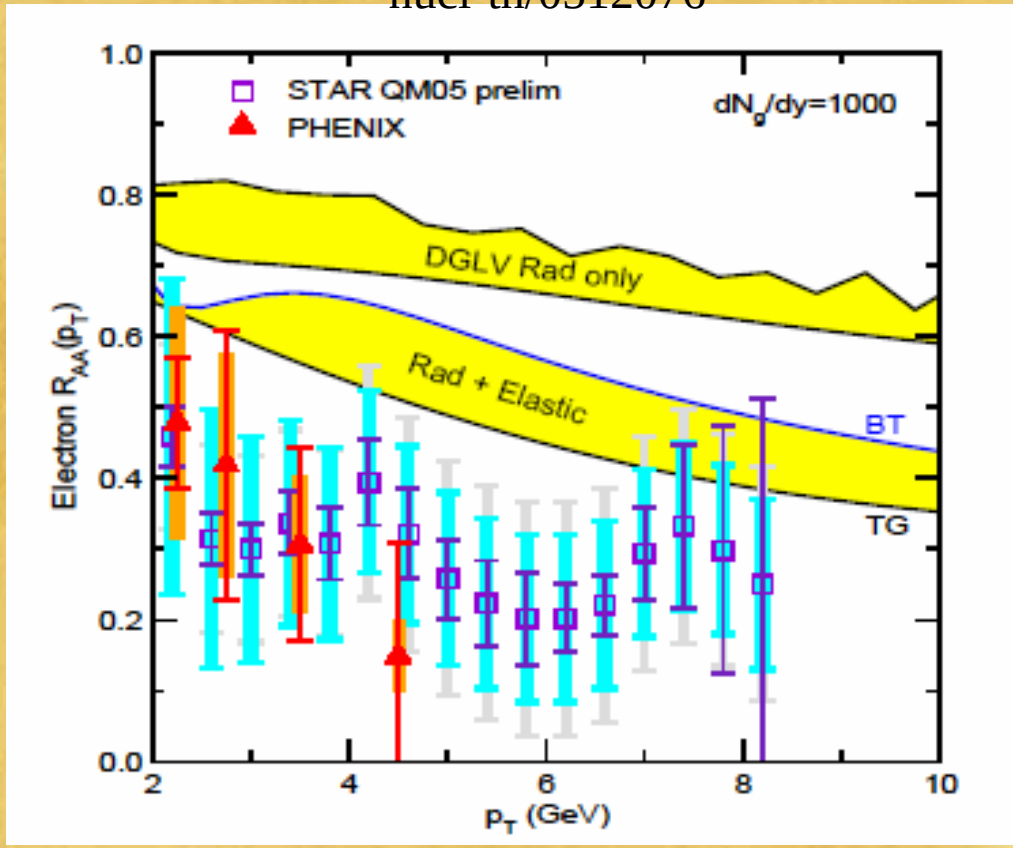
PHENIX Run-1 to Run-5 History

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{Tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	3 nb^{-1}	8.6G	11.9 pb^{-1}	173 TB
		Cu+Cu	62	0.19 nb^{-1}	0.4G	0.8 pb^{-1}	48 TB
		Cu+Cu	22.5	2.7 μb^{-1}	9M	0.01 pb^{-1}	1 TB
		p+p	200	3.8 pb^{-1}	85B	3.8 pb^{-1}	262 TB

Consistent with heavy flavor quenching?

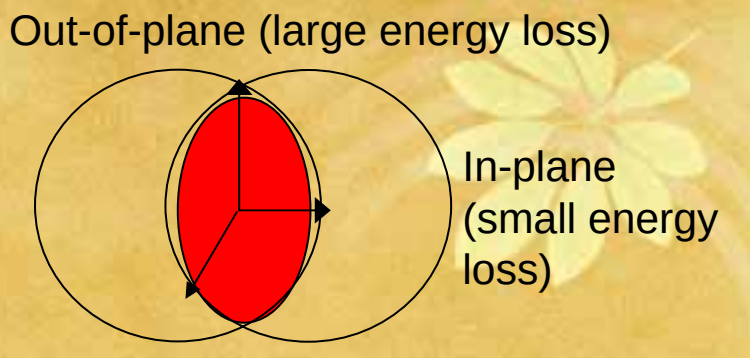
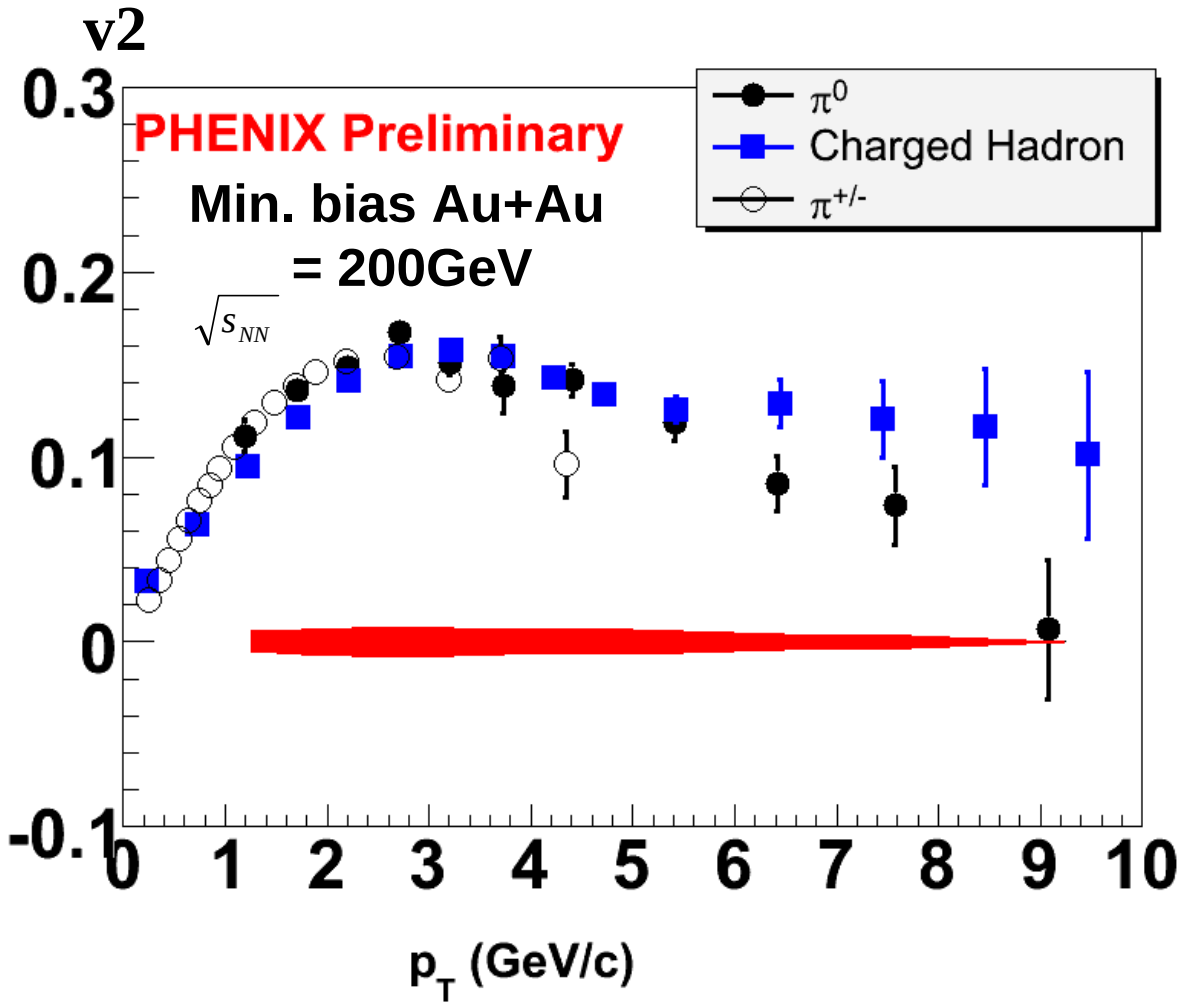
- Single electron R_{AA} dose not support dNg/dy=1000
- S. Wicks et. al explain the deviation with new calculation.
  - Radiative energy loss
  - Elastic energy loss
  - Jet pass length fluctuation

nucl-th/0512076



Single electron R_{AA} in $\sqrt{s_{NN}}$=200GeV Au+Au top 10% collision.

π^0/charged hadron v2



- v2 at high pT
  - azimuthal variation in energy loss
- Observation of v2 peak at pT = 2-3GeV/c and decreasing v_2 at high p_T