Energy Loss in Heavy Ion Collisions

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Outline:

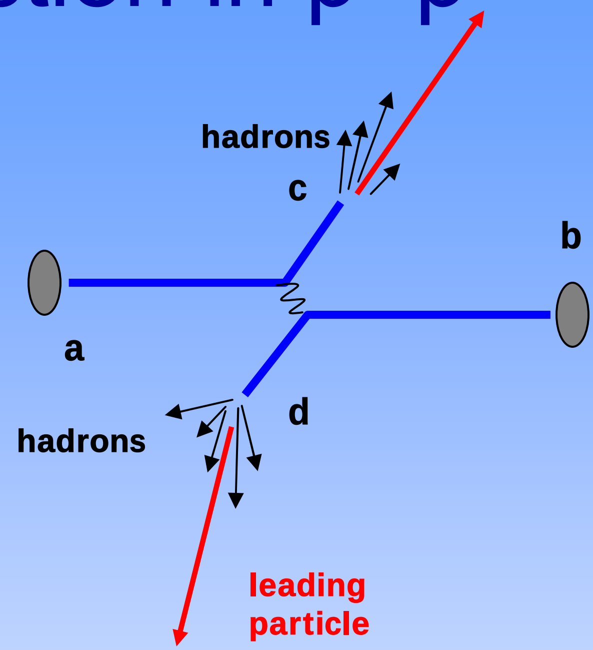
- introduction to energy loss
- p+p reference data vs pQCD
- gluon/light quark energy loss
- heavy-flavor energy loss
- direct photons

Observables: R_{AA}, particle ratios, two-particle correlations

vs system size, energy, rapidity

High-p_T particle production in p+p

- scattering of partons followed by fragmentation → jet
- can be calculated in perturbative QCD
- collinear factorization



$$\frac{d\sigma_{pp}^{h}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) \frac{D_{h/c}^{0}}{\pi z_c}$$

Parton distribution function	Matrix element	Fragmentation function
Measured in DIS	pQCD	e^+e^-

Parton energy loss in A+A ("jet quenching")

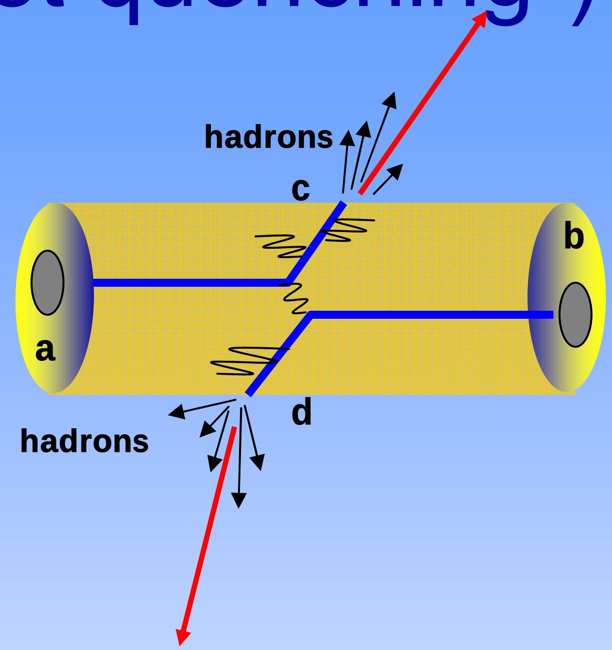
A+A collisions:

- initial state: similar to p+p

- final state: hard partons traverse medium and lose energy
  - gluon radiation
  - elastic collisions with surrounding partons

→ softening of particle spectra at high p_T

- energy loss different for gluon, light and heavy quarks (color factor, dead cone effect)



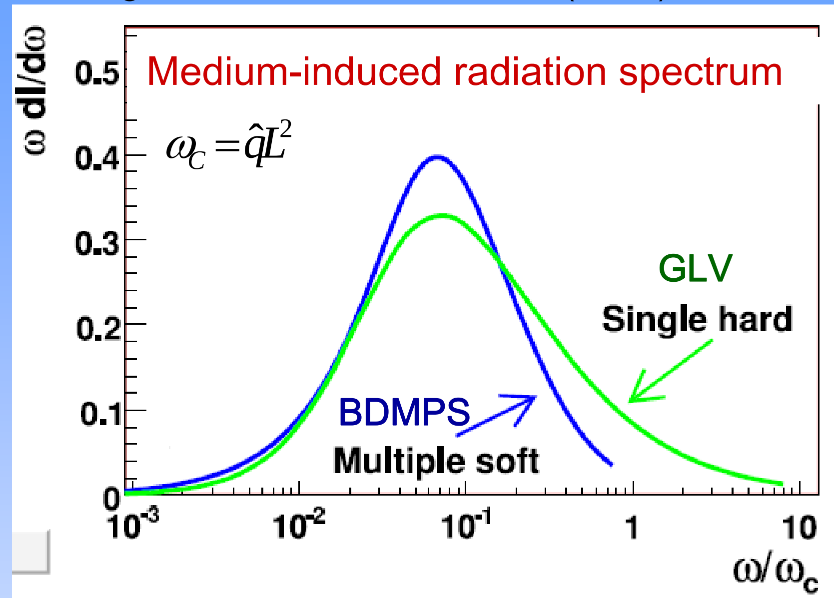
Goal: Use in-medium energy loss to measure medium properties

Radiative energy loss in QCD

Salgado, Wiedemann PRD68 (2003) 014008

4 jet quenching schemes:

- higher twist expansion
  Qiu, Sterman, Wang, Wang, Zhang, Majumder,…
- finite temperature field theory
  Arnold, Moore, Yaffe (AMY)
- opacity expansion:
  - thin medium/single hard scattering
    Gyulassy, Levai, Vitev, Djordjevic,… (GLV)
  - thick medium/multiple soft scatterings
    Baier, Dokshitzer, Mueller, Peigne, Schiff (BDMPS)
    Armesto, Salgado, Wiedemann (ASW)



$$\frac{d\sigma^{h_1}}{dy\,dp_{T_1}} \sim \int dx_a dx_b G(x_a) G(x_b) \frac{d\hat{\sigma}}{d\hat{t}} D_q^{h_1}(z_1)$$

energy loss

- medium properties can be characterized by a single constant:

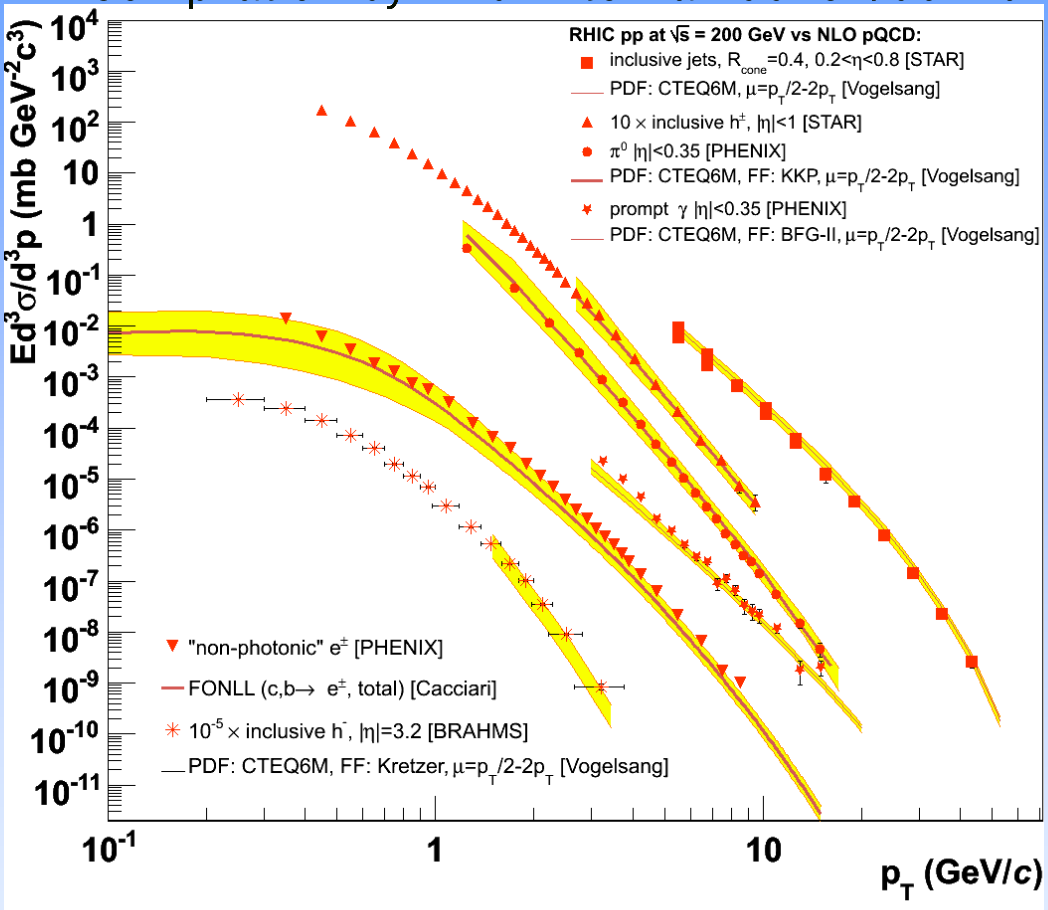
e.g. transport coefficient $\hat{q} \equiv \frac{\mu^2}{\lambda}$ 'average k_T-kick per mean-free-path'

- static medium: $\Delta E \propto L^2$ due to interference effects, expanding medium: $\Delta E \propto L$

p+p reference data

p+p reference @ 200 GeV vs pQCD

Compilation by D. d'Enterria nucl-ex/0611012



p_T-differential cross section:
- jets
- charged hadrons
- π^0
- direct photons
- D,B (non-photonic e^-)

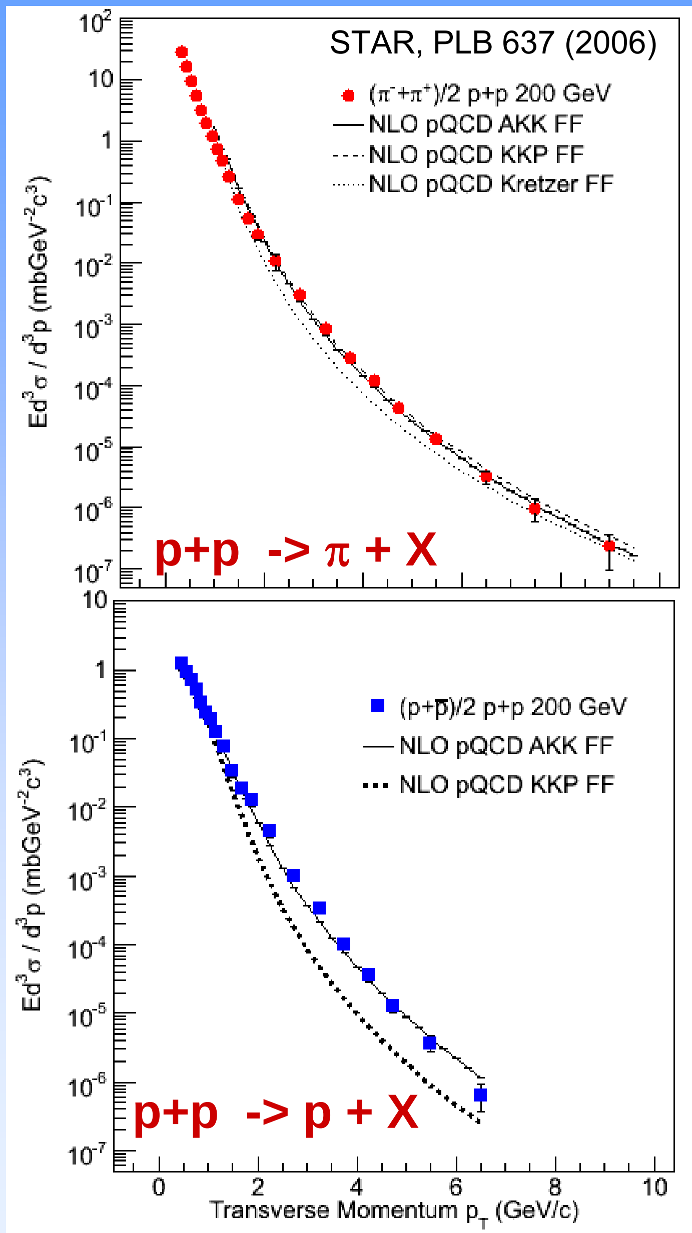
} $\eta\sim0$

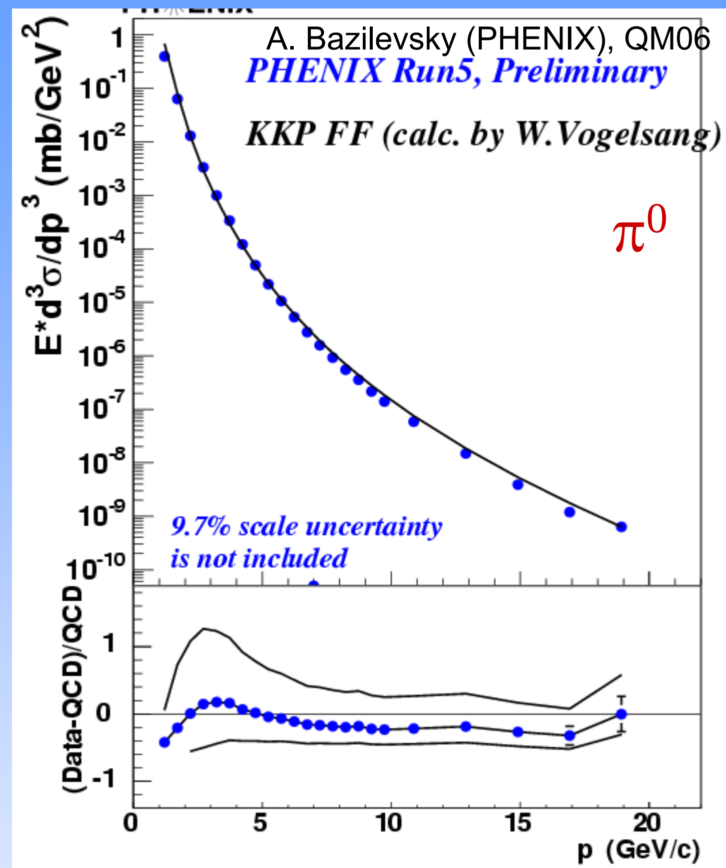
- negative charged hadrons $\eta=3.2$

• 9 orders of magnitude (10mb-10pb) broad range in p_T

Good agreement with theory

Proton and pion production in p+p



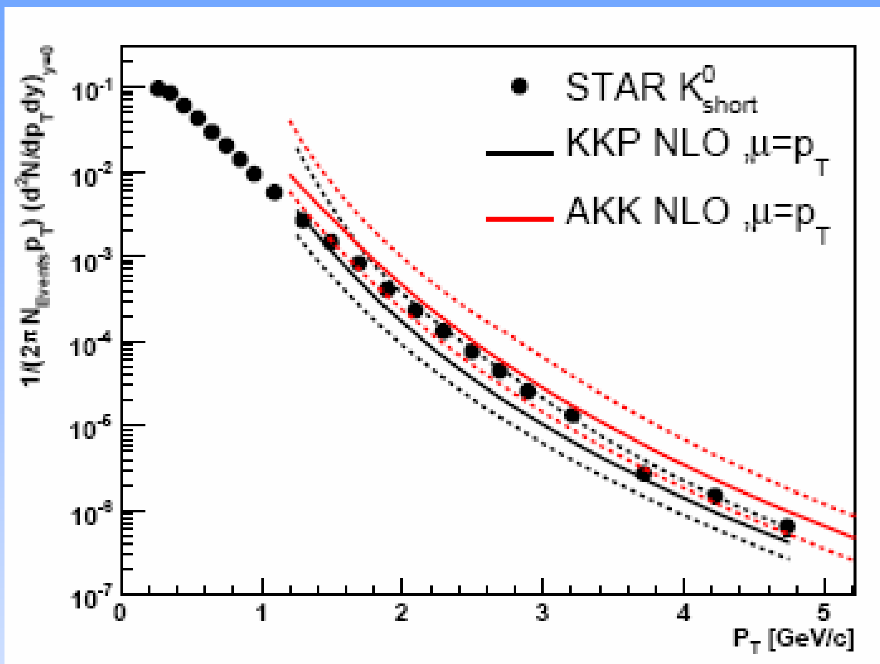


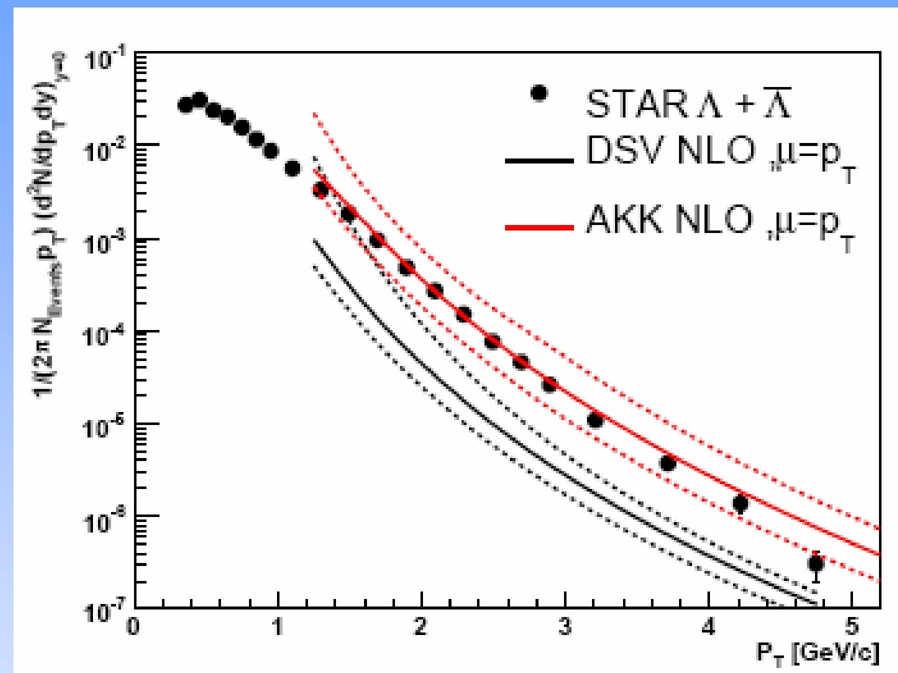
Pion and proton spectra agree with NLO pQCD using the latest AKK fragmentation functions

(Note: p is more sensitive to gluon fragmentation – KKP does not work!)

Strange particle production in p+p

STAR, PRC 75 (2007)





- STAR measurement of strange particles in p+p constrained AKK FF

AKK fragmentation functions agree well with both mesons and baryons at mid-rapidity.

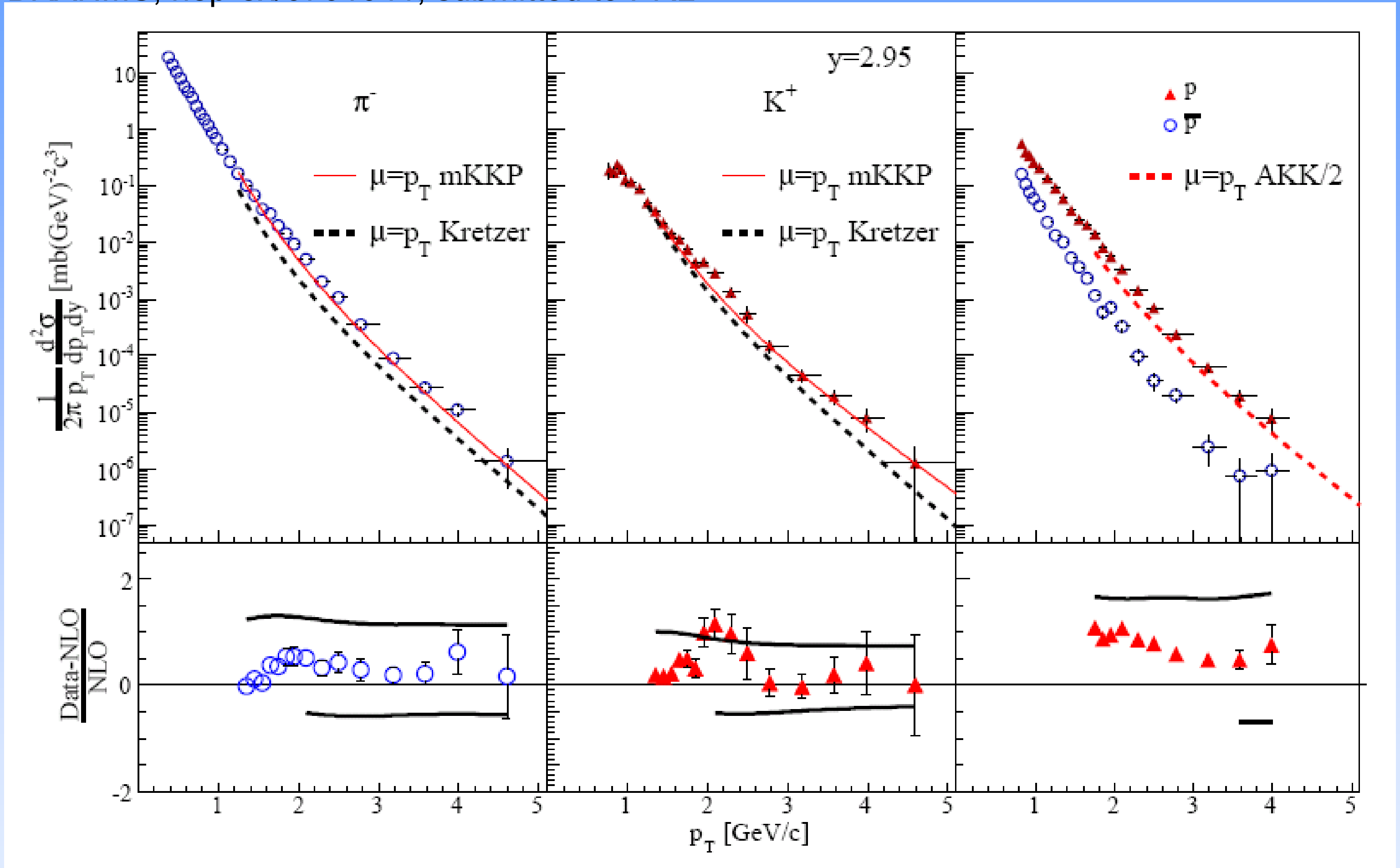
KKP (Kniehl-Kramer-Potter): NPB 582 (200)

AKK (Albino-Kniehl-Kramer): NPB 734, 50 (2006)

DSV (DeFlorian-Stratmann-Vogelsang): PRD57, 58111 (1998)

Hadron production in p+p at y~3

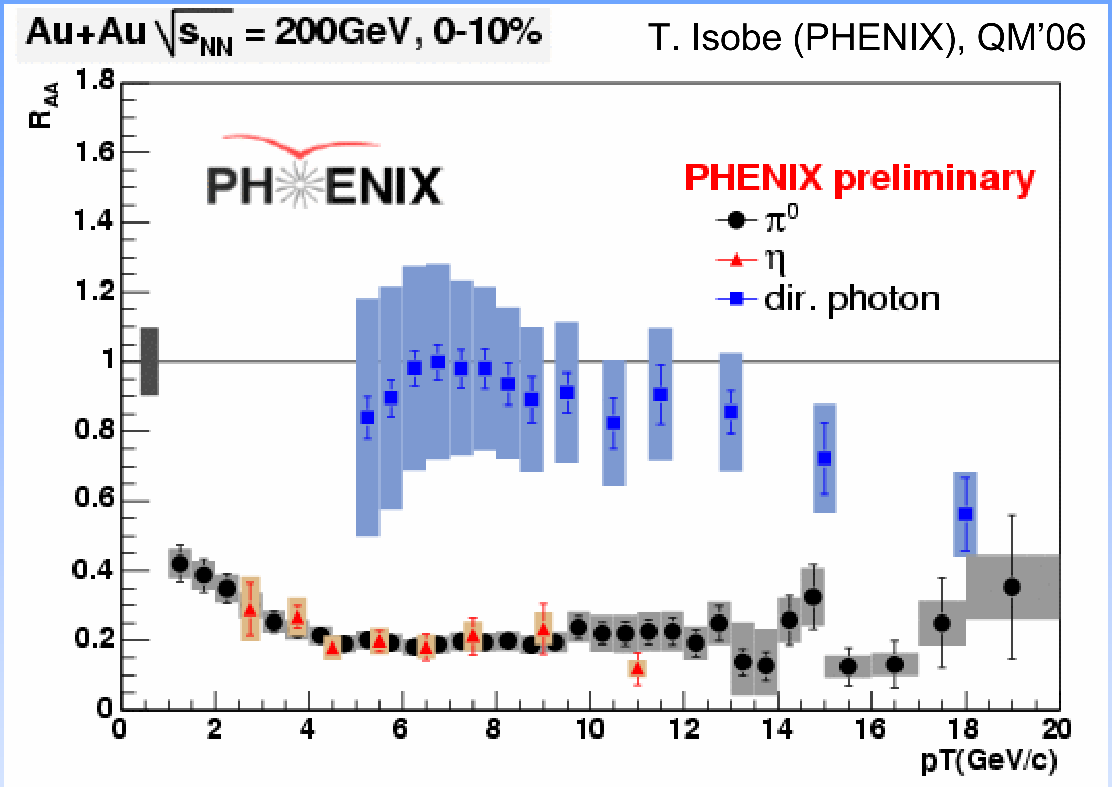
BRAHMS, hep-ex/0701041, submitted to PRL



NLO pQCD describes production of pions and kaons well at y~3, but fails to account for large proton yields and small $\bar{p}$/p ratio even with AKK FF.

Nuclear modification factors
Particle ratios

R_{AA} in Au+Au @ 200 GeV



Direct photons:

- measured p+p reference
- $R_{AA}(\gamma) < 1$ for $p_T > 12$ GeV/c

Isospin effect seen?
Ongoing study at $\sqrt{s_{NN}}$=62 GeV

π^0 and η:

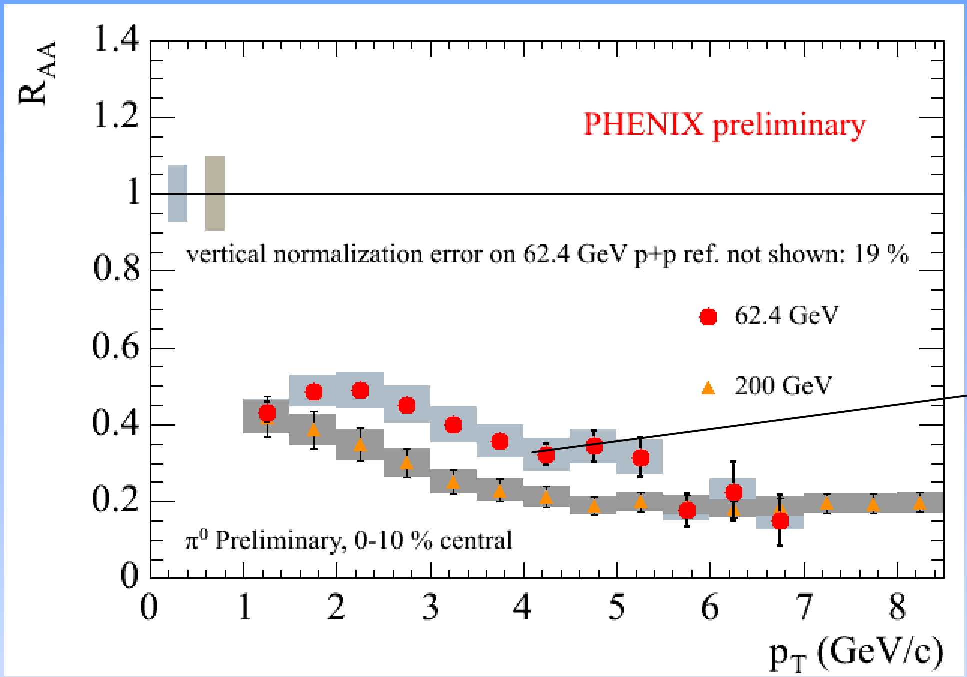
- Run 5: extended reach in p_T out to 20 GeV/c for π^0 and 15 GeV/c for η
- both have a common R_{AA}~0.2

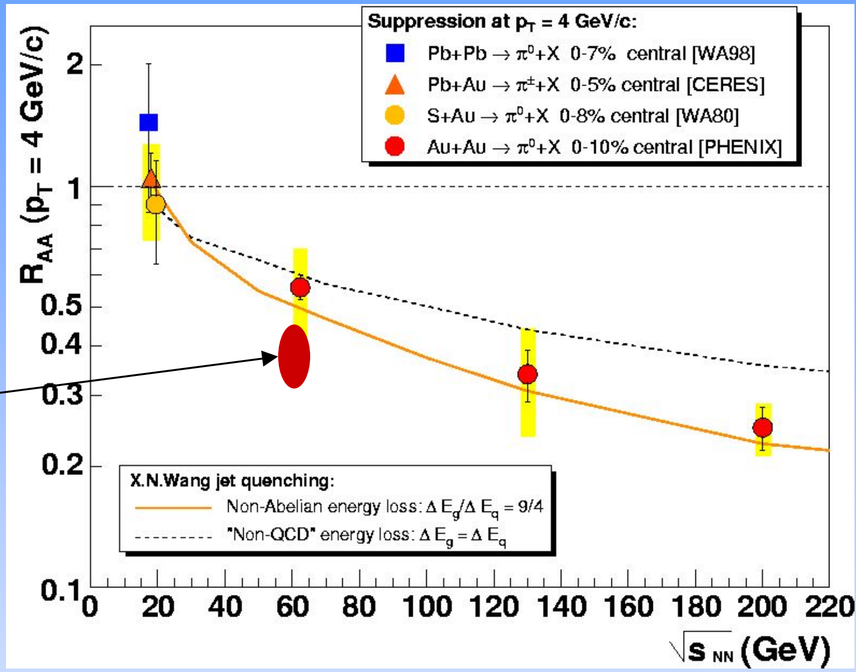
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

binary collision scaling

p+p reference

Energy dependence of R_{AA}





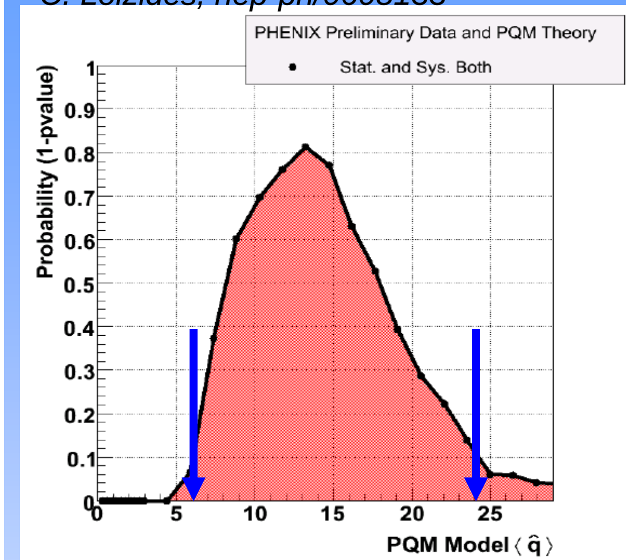
New!

Measured p+p reference at $\sqrt{s_{NN}}$ = 62 GeV instead of previously used ISR data

→ R_{AA} at $\sqrt{s_{NN}}$=62 GeV is now very close to $\sqrt{s_{NN}}$=200 GeV !

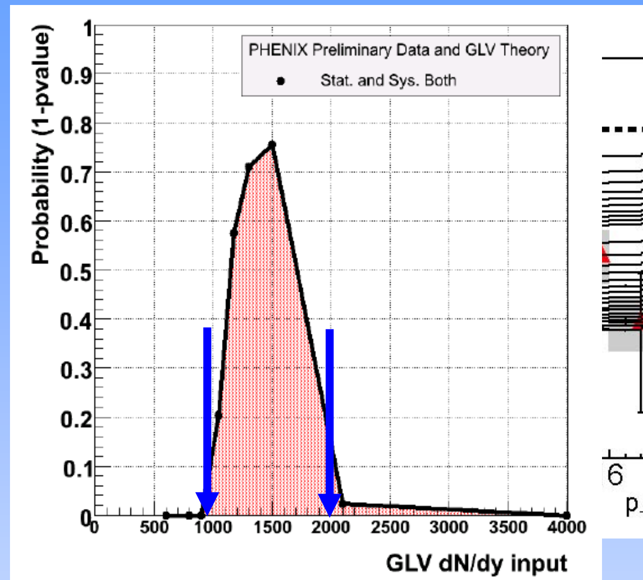
Comparing $R_{AA}(\pi^0)$ to models

C. Loizides, hep-ph/0608133



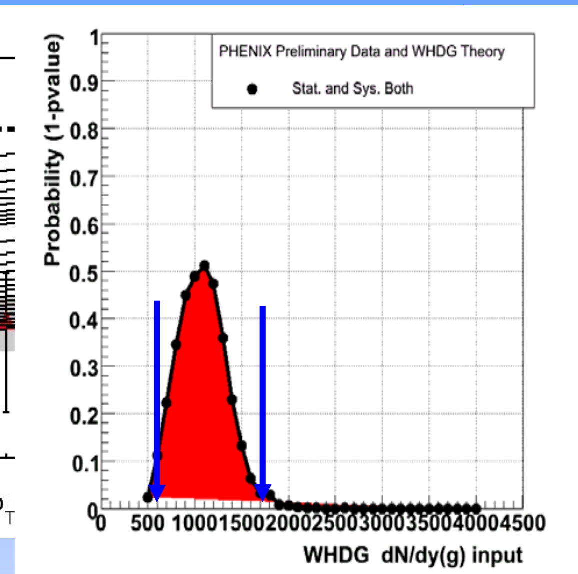
$6 \le \langle \hat{q} \rangle \le 24$ GeV^2/fm

I. Vitev



$1000 \le dN_g / dy \le 2000$

W. Horowitz



$600 \le dN_g / dy \le 1600$

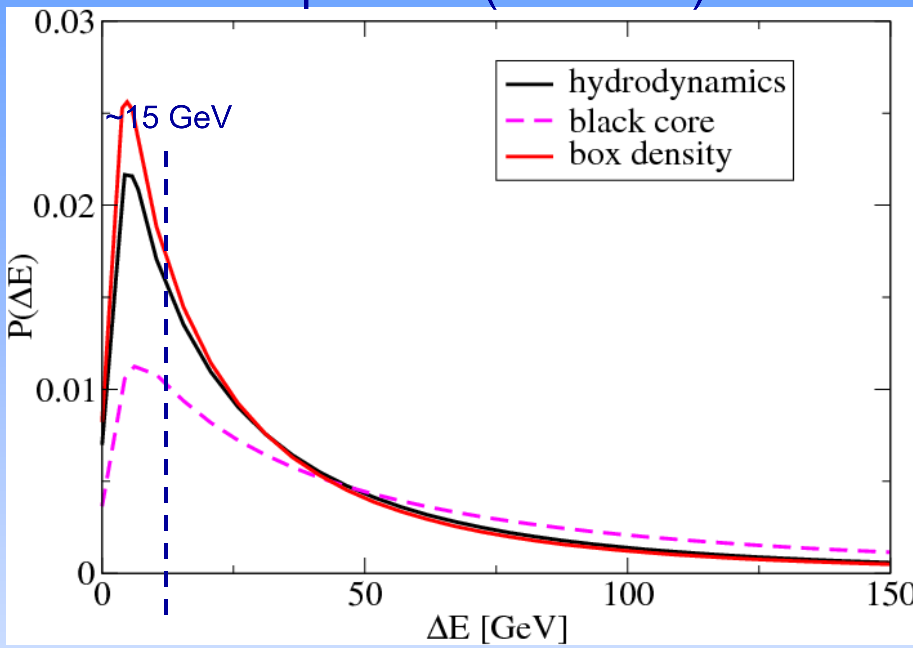
- χ^2 minimization fit to obtain the probability of a given parameter
- values given for probability > 10%

R_{AA} shows only a small sensitivity to model parameters

B. Sahlmueller (PHENIX), QM'06

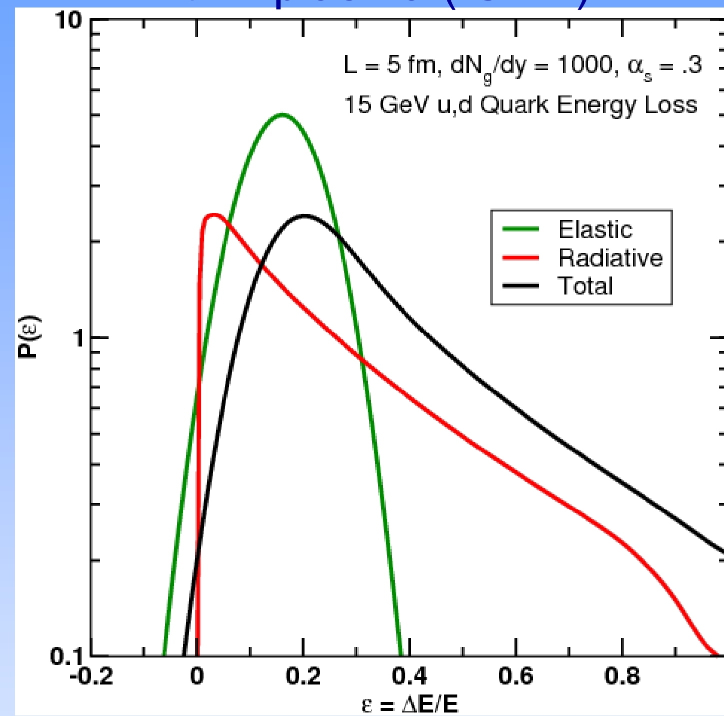
What do we learn from R_{AA}?

thick plasma ('BDMPS')



Renk, Eskola, PRC 75, 054910 (2007)

thin plasma ('GLV')



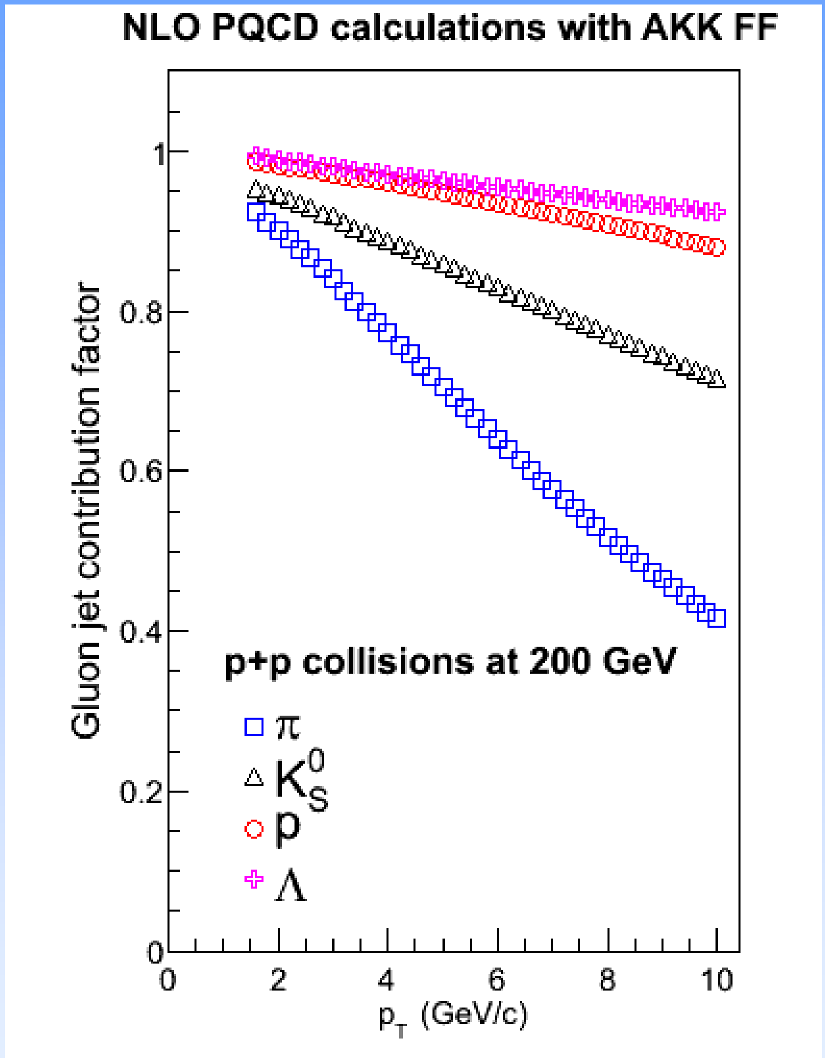
Wicks,Horowitz,Djordjevic,Gyulassy
NPA 784, 426 (2007)

Energy loss distributions very different for BDMPS and GLV formalisms

BUT! R_{AA} is similar

More differential probes needed!

Gluon vs quark energy loss



AKK = particle + anti-particle

AKK (Albino-Kniehl-Kramer): NPB 734, 50 (2006)

Gluon jet contribution factor increases from π, K, p towards Λ:

e.g. p_T = 8 GeV/c: 50% for π
90% for p

If $\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$

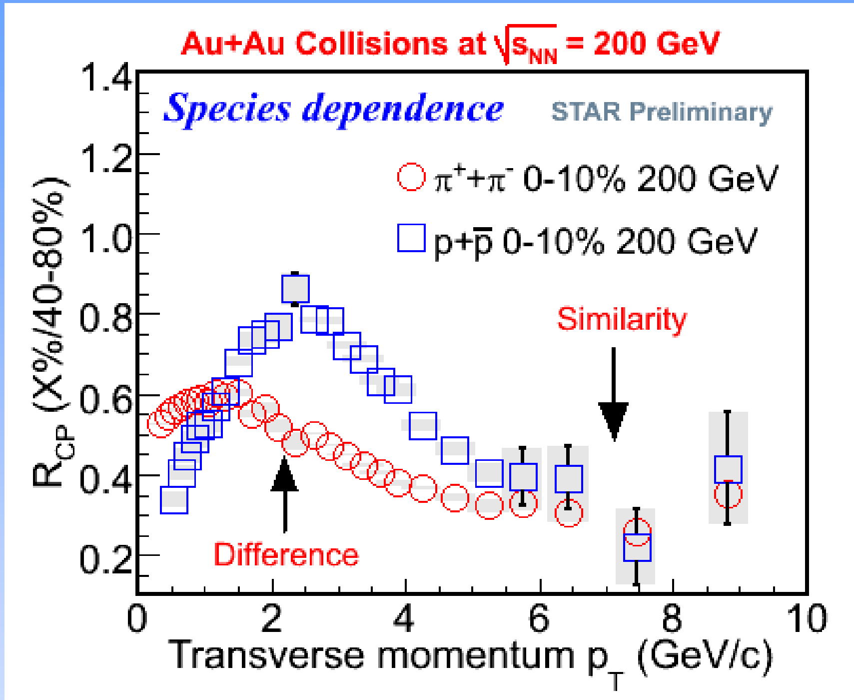
and $\frac{\Delta E_g}{\Delta E_q} \sim \frac{9}{4}$

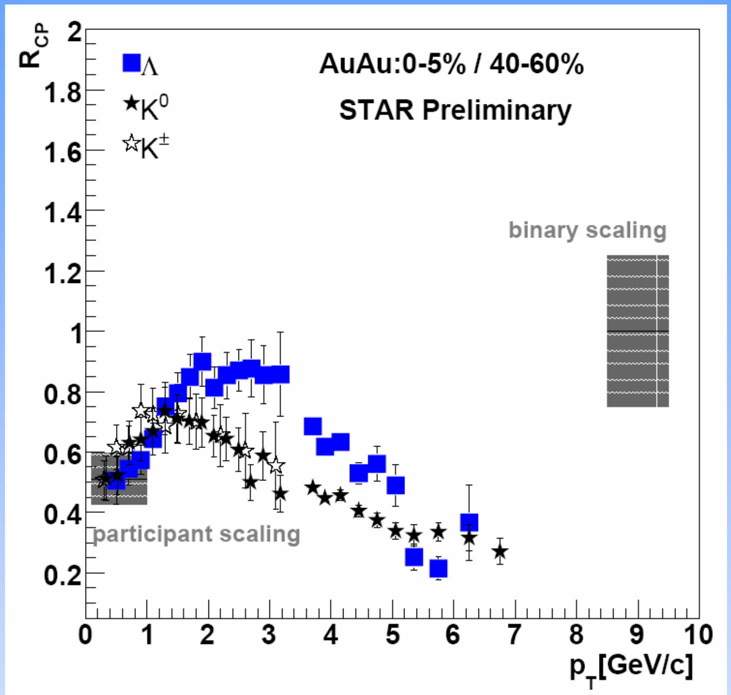
At high p_T for same beam energy, system and centrality:

$R_{CP}(\pi) > R_{CP}(p)$
$R_{CP}(K) > R_{CP}(\Lambda)$

R_{CP} of identified particles

STAR, PRL 97, 152301 (2006)





Intermediate-p_T (p_T =2-5 GeV/c): baryon/meson splitting

R_{CP}(meson)<R_{CP}(baryon)

High-p_T (p_T > 5 GeV/c):

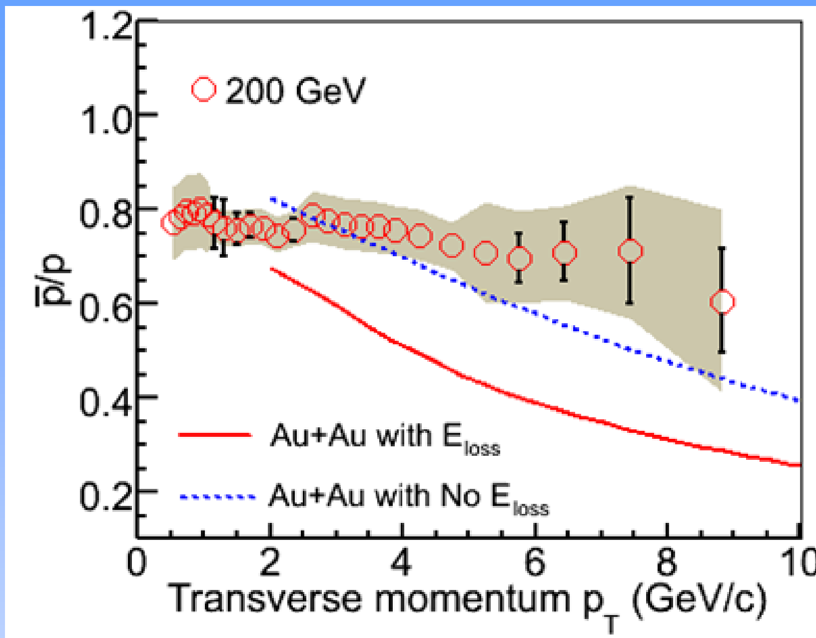
$R_{CP}(\pi)$~$R_{CP}(p)$

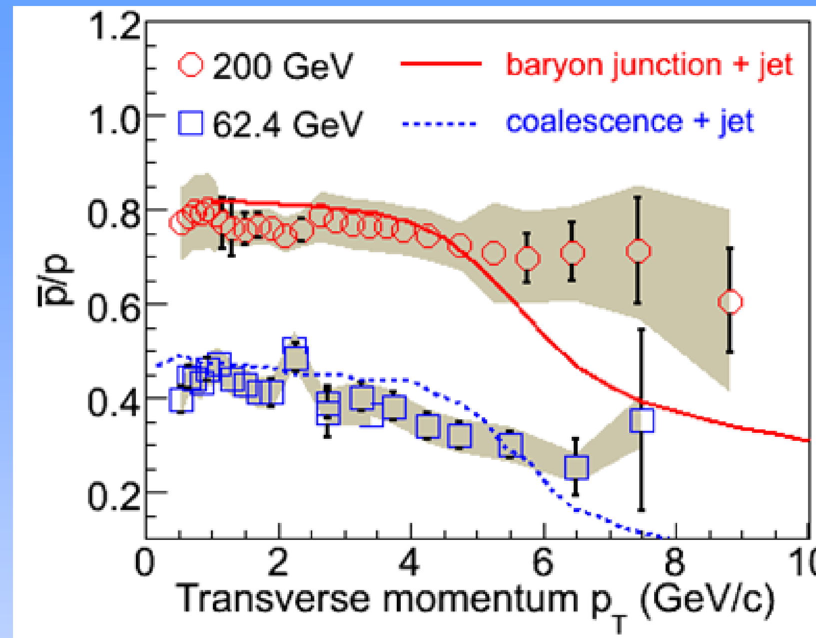
$R_{CP}(K)$~$R_{CP}(\Lambda)$

Does it mean similar energy loss of quarks and gluons ?

Energy dependence: anti-particle/particle ratios

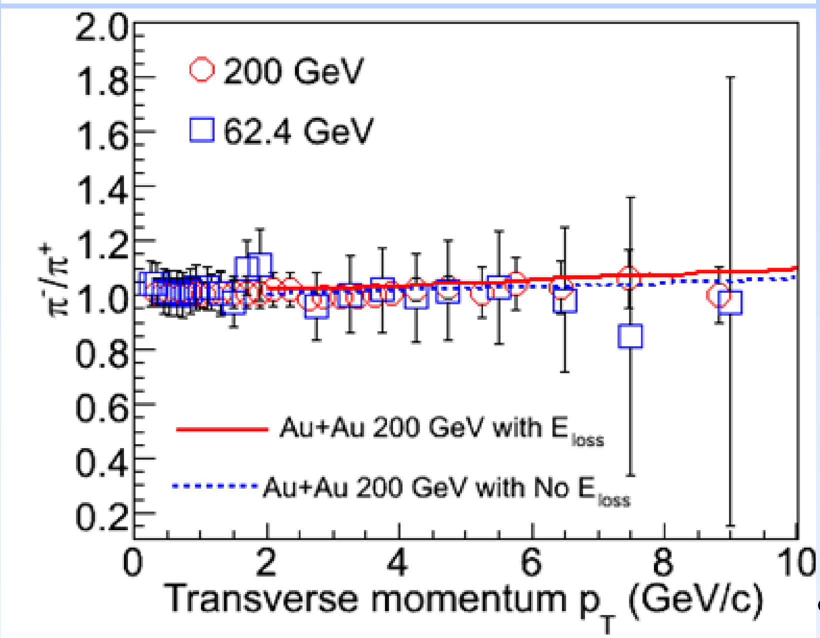
STAR, PRL 97, 152301 (2006)





STAR, nucl-ex/0703040

STAR, nucl-ex/0703040



π^-/π^+: independent of p_T

$\bar{p}/p$: model calculations with/without E_{loss} do not describe data

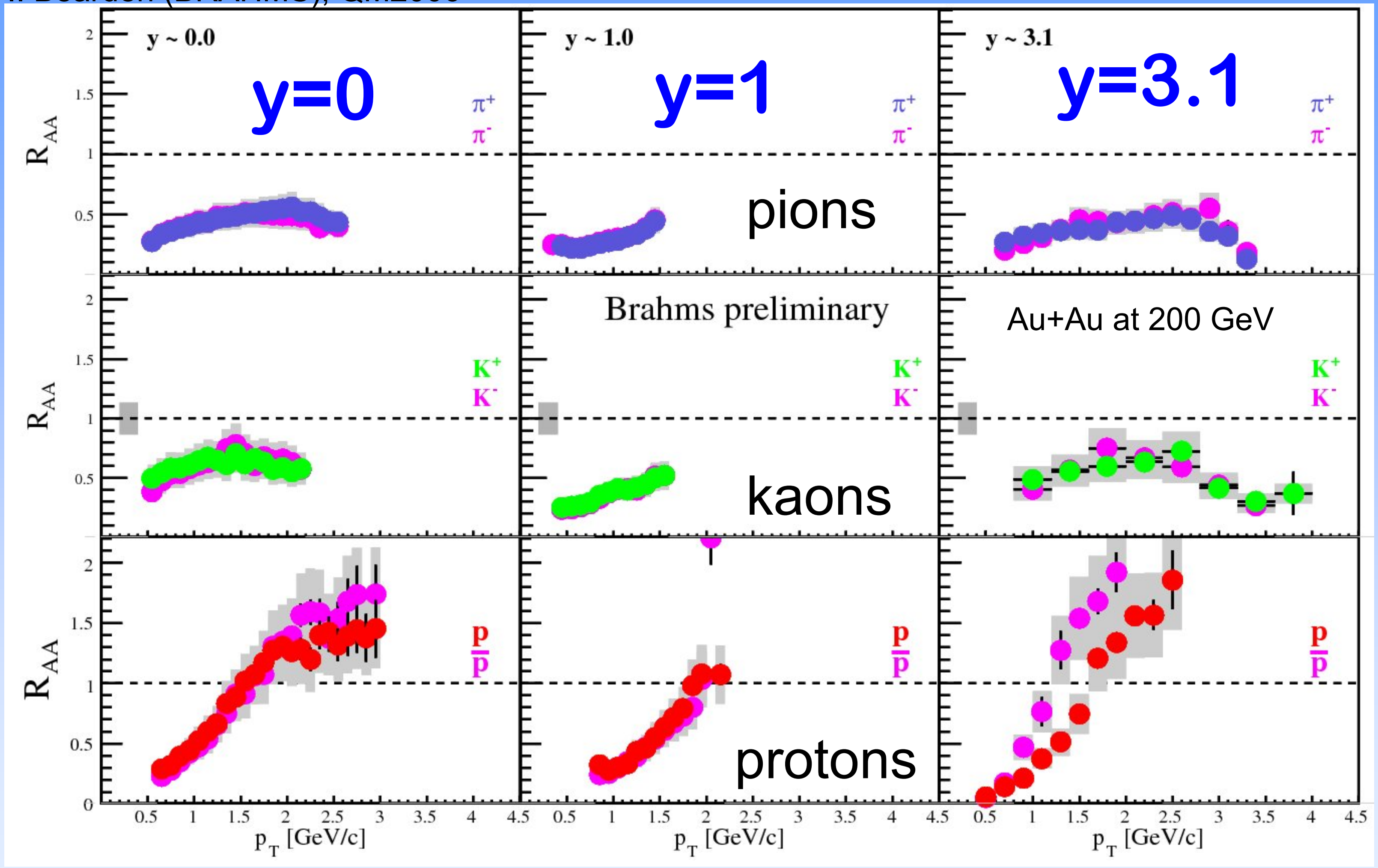
X.-N. Wang et al., PRC 70 (2004) – E_{loss}

Baryon junction and coalescence models describe data at intermediate p_T

I. Vitev et al.. NPA 715 (2003) - baryon junction
V. Greco et al., PRC 71 (2005) - coalescence

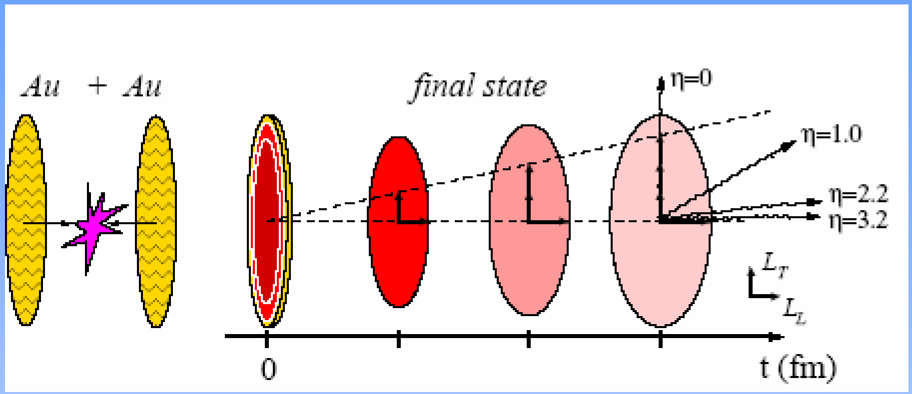
Rapidity dependence of R_{AA}

I. Bearden (BRAHMS), QM2006

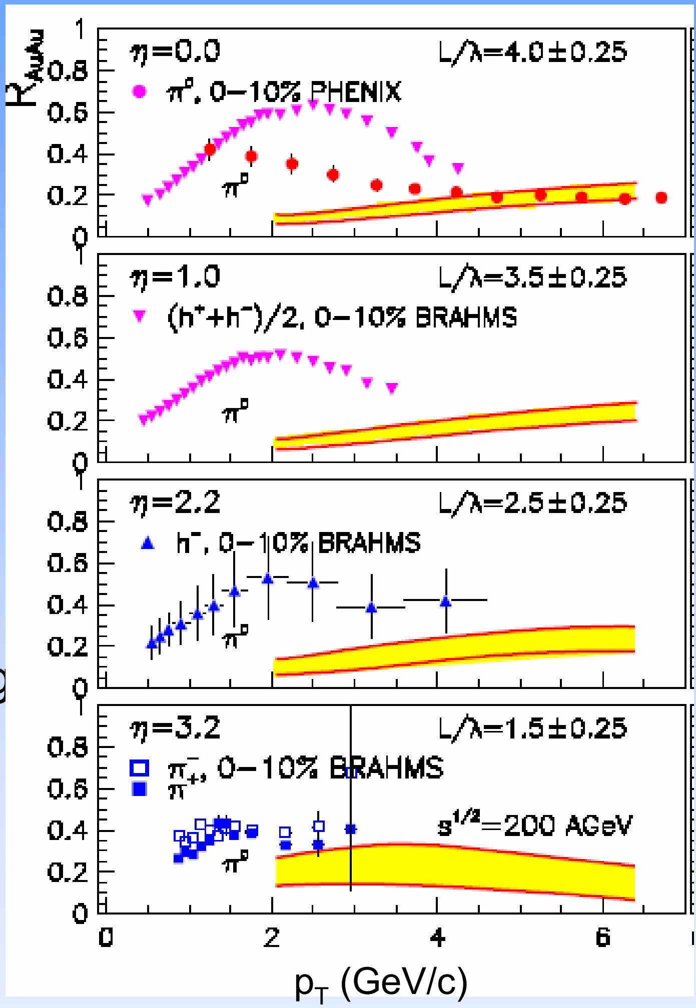


R_{AA} independent of rapidity for produced mesons

Why is R_{AA} independent of rapidity?



Barnafoldi, Levai, Papp, Fai, EJP C49 (2007)



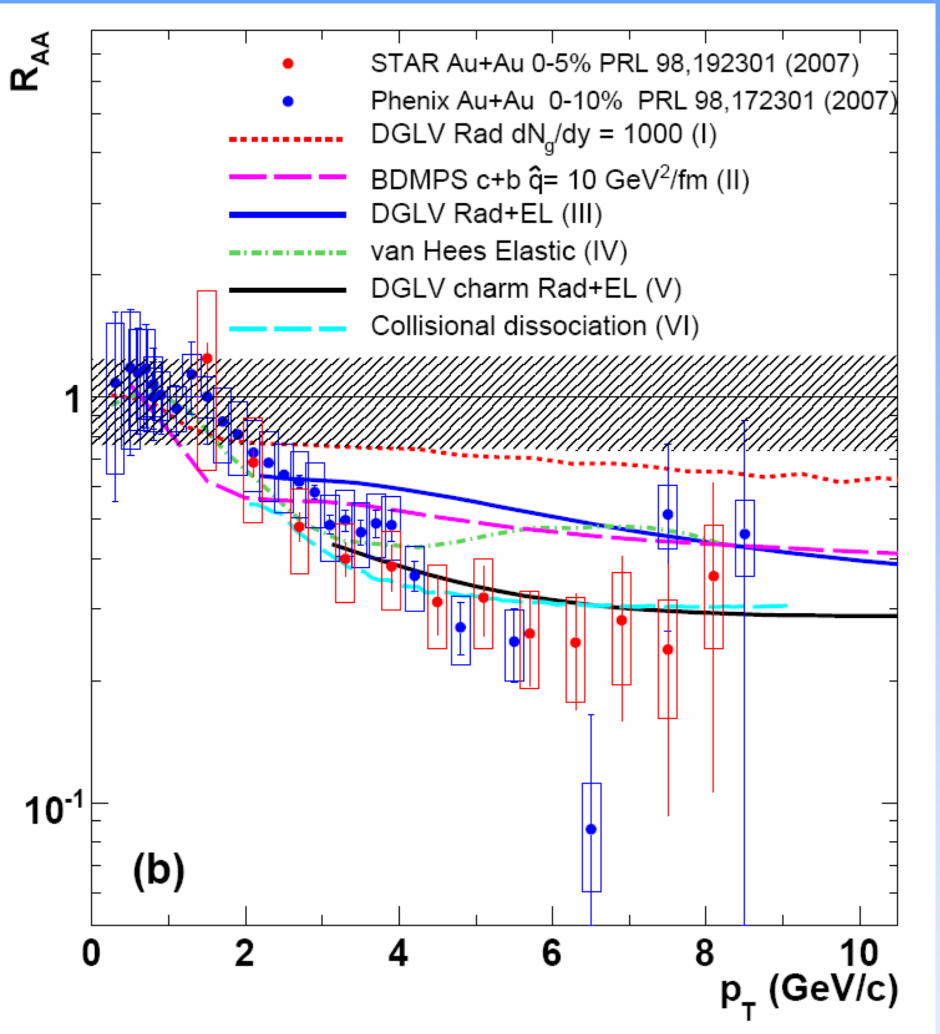
L/λ = opacity

- forward y = a unique information about medium in the longitudinal direction in the early stage

- competing effects: shadowing, multiple scattering, energy loss (GLV), geometry
- opacity decreases ~ linearly with y

  BUT!
- shadowing stronger at forward y
  - → effects compensate each other
  - → R_{AA} independent of y

R_{AA} of non-photonic electrons



Models have difficulties to describe the measured R_{AA}:

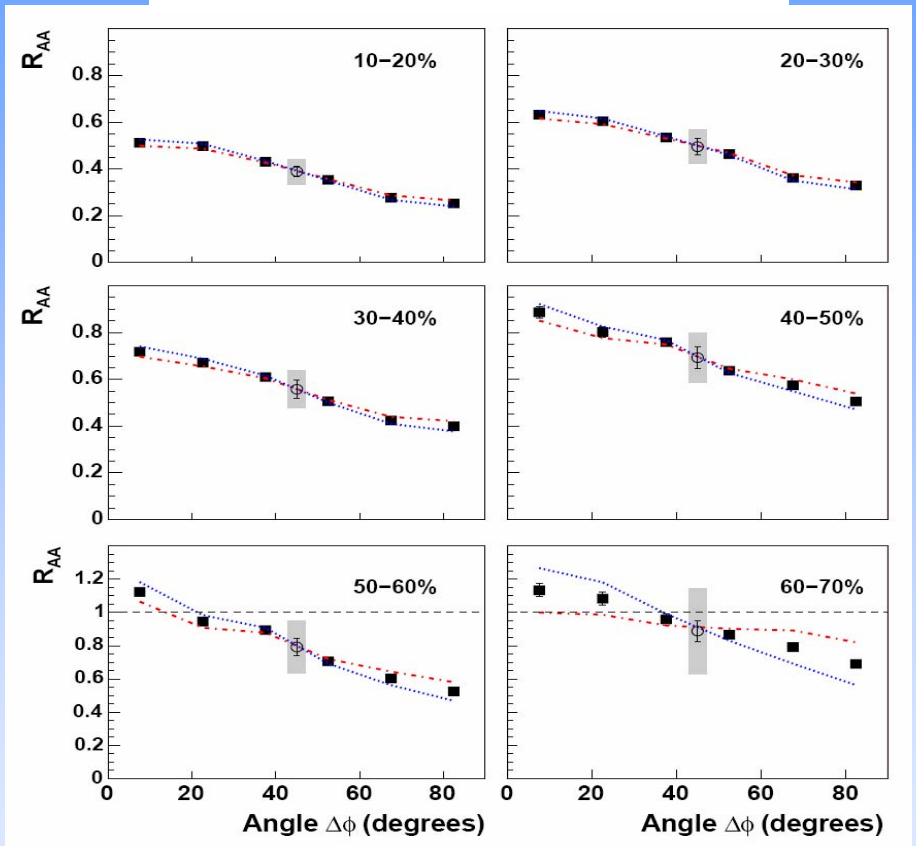
- radiative energy loss with typical gluon densities is not enough (I)
  M. Djordjevic et al., PLB 632 (2006) 81
- models involving a very opaque medium agree better (II)
  N. Armesto et al., PLB 637 (2006) 362
- collisional energy loss/resonant elastic scattering (III,IV,V)
  S. Wicks et al., NPA 784, (2007) 426
  H. v. Hees, R. Rapp, PRC 73 (2006) 034913
- heavy quark fragmentation and dissociation in medium → strong suppression for c and b (VI)
  A. Adil, I. Vitev, PLB 649, (2007) 139

Note: ~ agreement between STAR and PHENIX
(disagreement is common to p+p/Au+Au and cancels out in R_{AA})

Towards more differential probes …

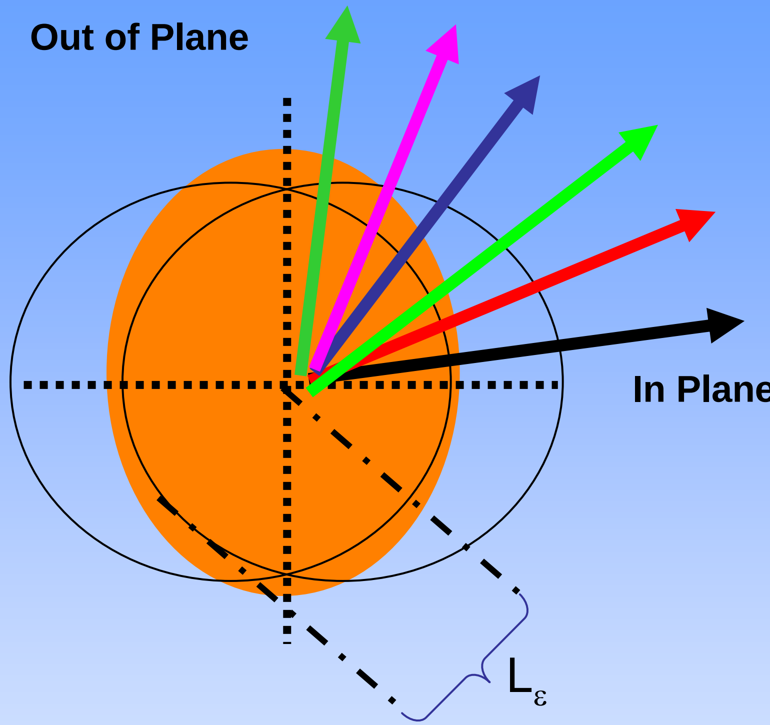
R_{AA} vs reaction plane

Au+Au collisions at 200GeV



3<p_T<5 GeV/c

PHENIX, nucl-ex/0611007, submitted to PRC

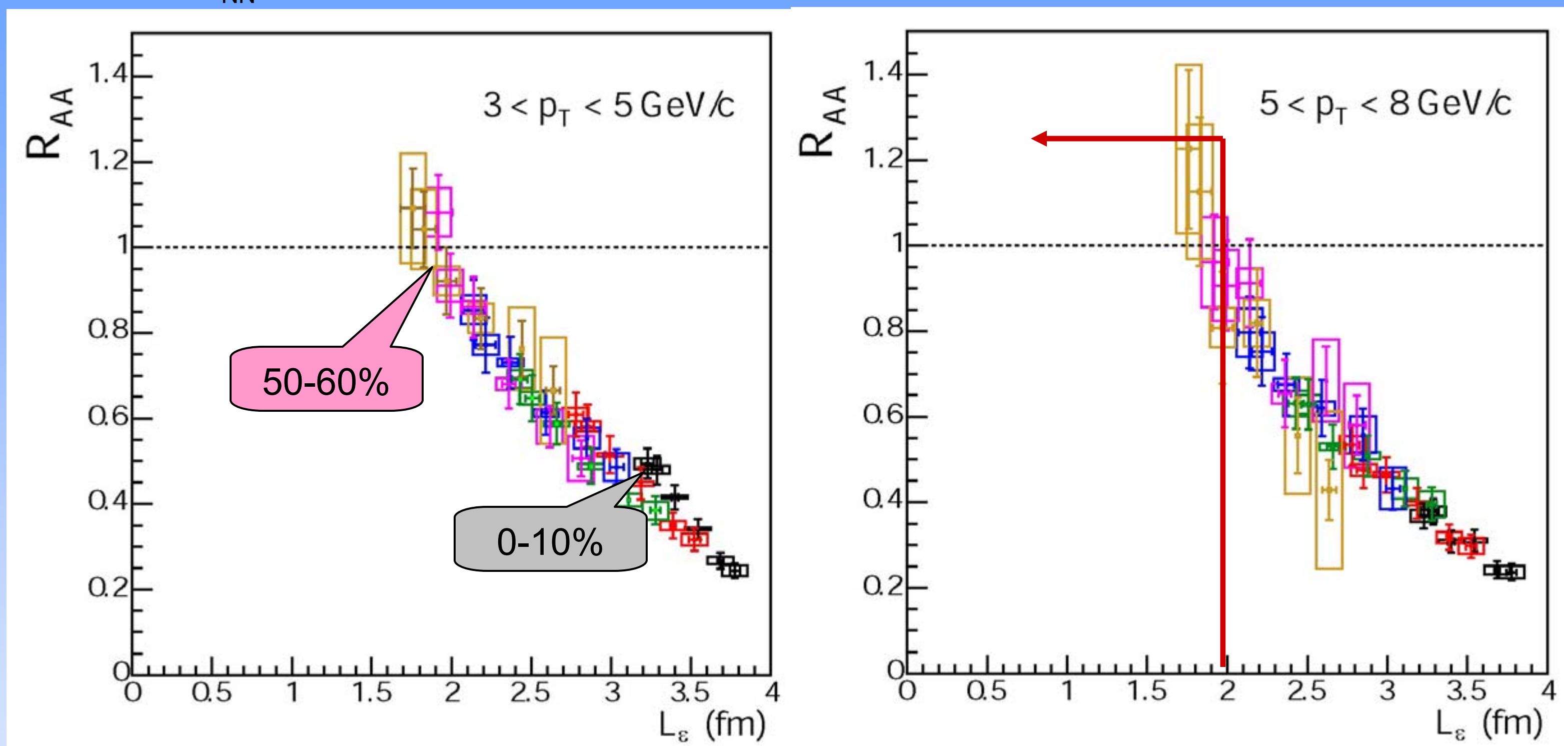


- factor 2 suppression out-of-plane than in-plane
- in plane emission shows no energy loss in peripheral bins.

Path length dependence of energy loss

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

PHENIX, nucl-ex/0611007, submitted to PRC



L_ε = matter thickness calculated in Glauber model

- R_{AA} is universal function of L_ε for all centrality classes and both p_T ranges
- Little/no energy loss for L_ε < 2 fm

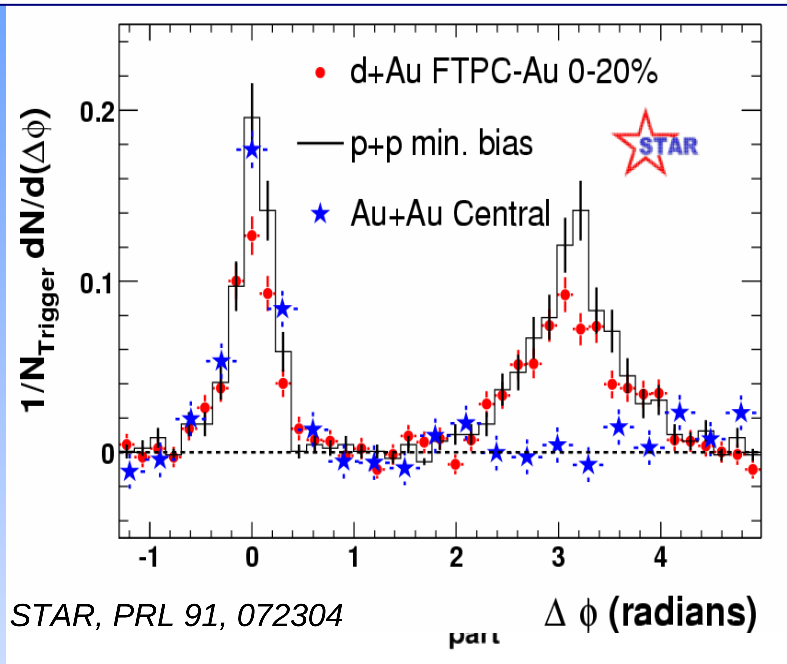
  Formation time effect? Surface emission zone? v_2?

Pantuev, hep-ph/0506095,
Shuryak+Zahed, hep-ph/0307267

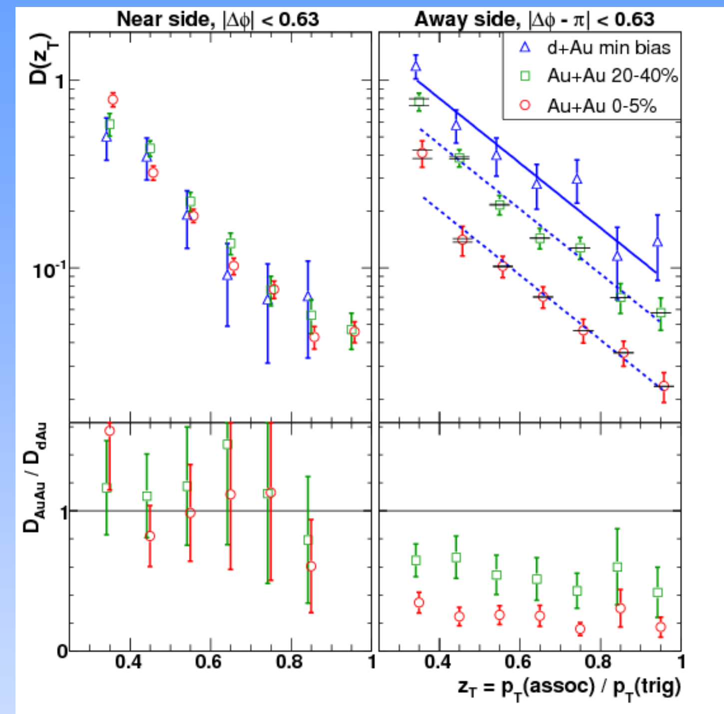
Jet-like correlations at high-p_T

STAR, Phys. Rev. Lett. 97 (2006) 162301

4 <p_T(trig)<6 GeV/c, 2 GeV/c <p_T(assoc)<p_T(trig)



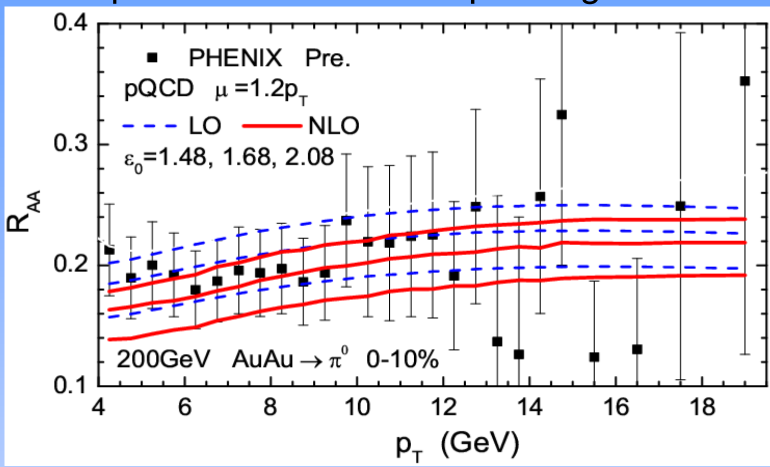
increasing p_T(assoc)

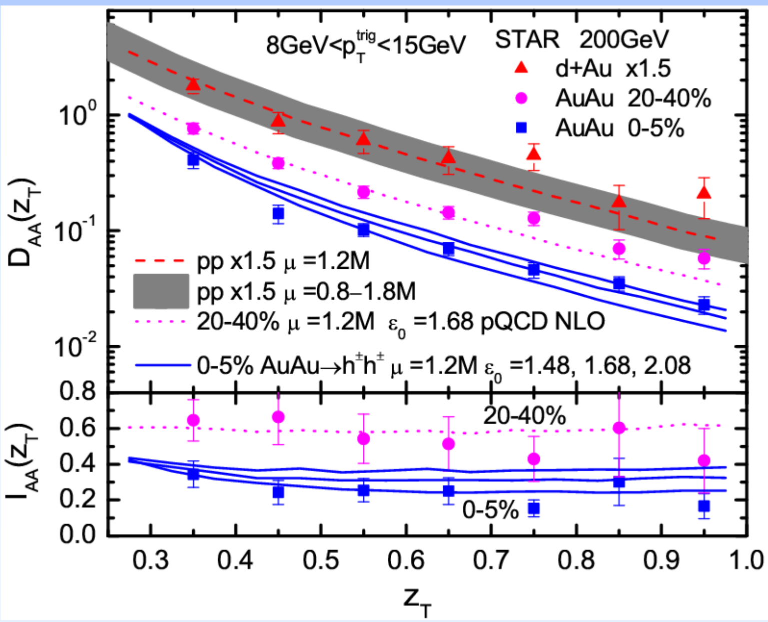


- disappearance of away-side correlations observed at intermediate p_T in central Au+Au collisions
- Run 4 statistics: a punch through observed at high p_T
  - away-side yield is suppressed: $R_{AA} \sim I_{AA}$
  - suppression without angular broadening or medium modification
  - $R_{AA} \sim I_{AA}$ in Cu+Cu as well

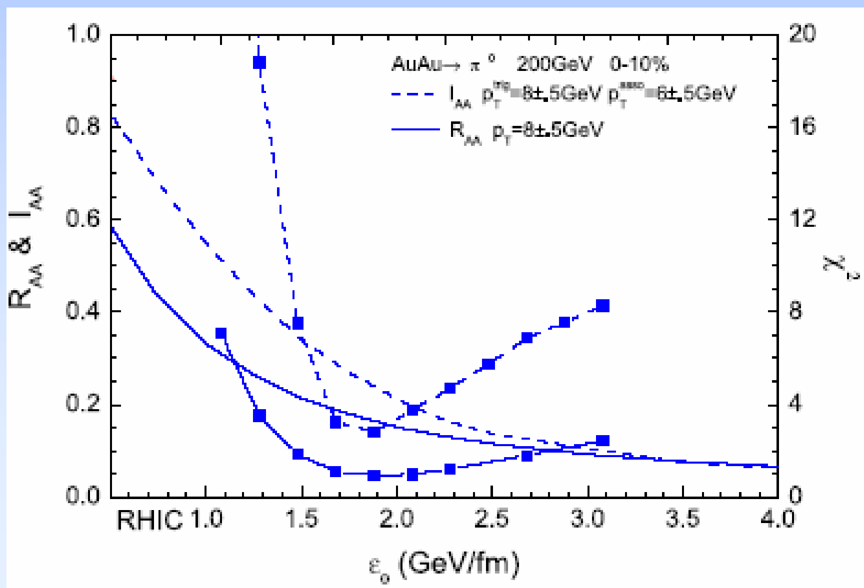
Away-side di-hadron suppression at high p_T

Zhang,Owens,Wang,Wang, nucl-th/0701045
NLO pQCD + KKP FF + expanding medium





- di-hadrons have a smaller surface bias
  → a "better" differential probe
- χ^2-minimum narrower for di-hadrons
  → stronger constraint on density
- extracted medium properties:
  ε_0 = 1.68 GeV/fm
  $\hat{q}$ = 2.8±0.3 GeV^2/fm



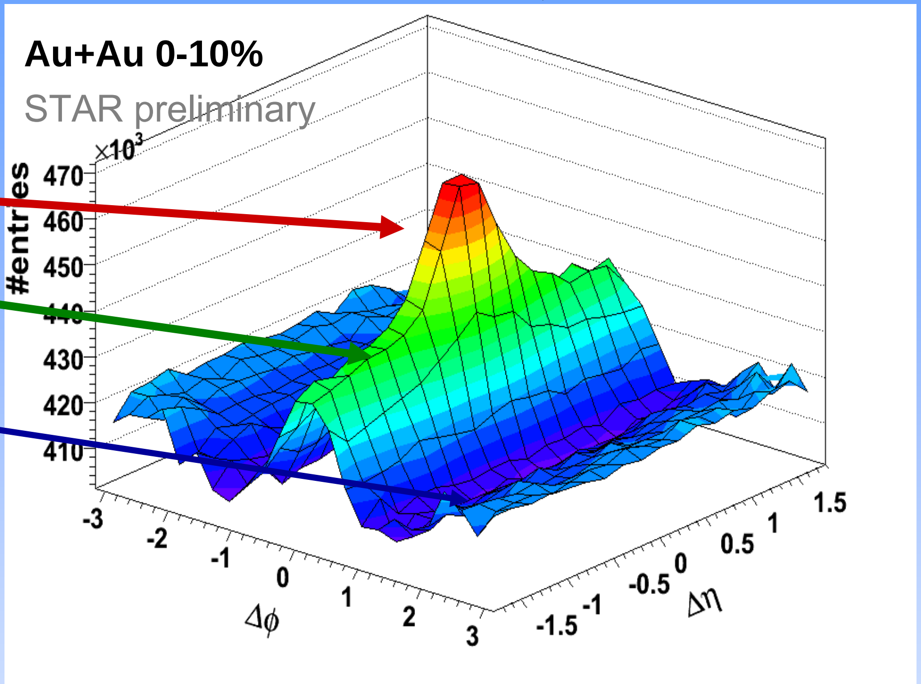
Di-hadron correlations: near-side peak

3 GeV/c < $p_T^{trigger}$ < 4 GeV/c, $p_{T,}^{assoc}$ > 2 GeV/c

Near-side jet peak

Near-side 'ridge'

Modified away-side (+ v_2)



J. Putschke (STAR), HP2006, QM2006

The near-side jet interacts with the medium!

What is the ridge?

1) Medium heating and parton recombination

Chiu & Hwa PRC 72, (034903) 2005

2) Radial flow + high-p_T trigger particle

Voloshin, nucl-th/0312065 NPA 749, 287 (2005)

3) Parton radiation and its coupling to the longitudinal flow

Armesto et al, PRL 93 (2004)

4) Momentum broadening in an anisotropic QGP

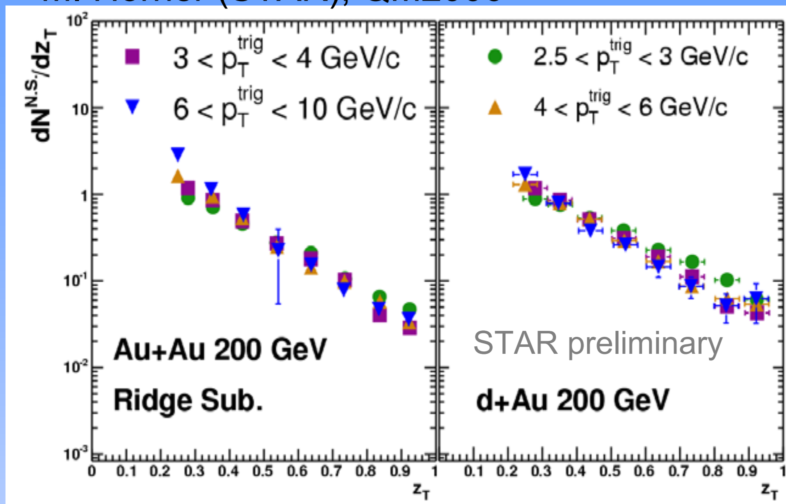
Romatschke, PRC 75, 014901 (2007)

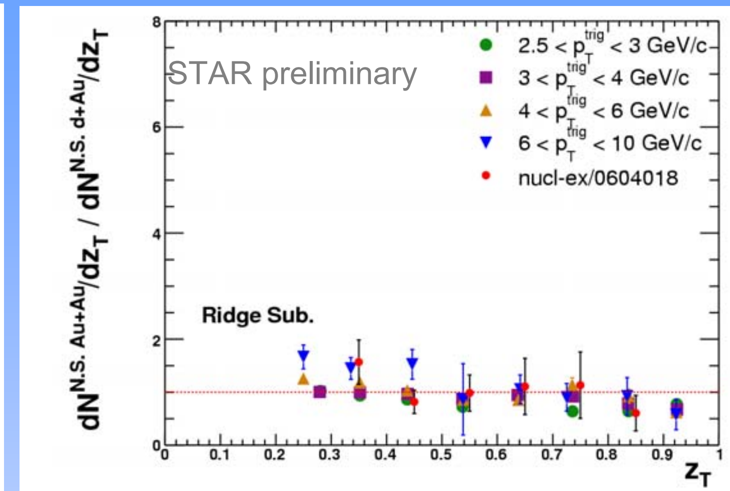
5) Longitudinal broadening of quenched jets in turbulent color fields

Majumder, Mueller, Bass, hep-ph/0611135

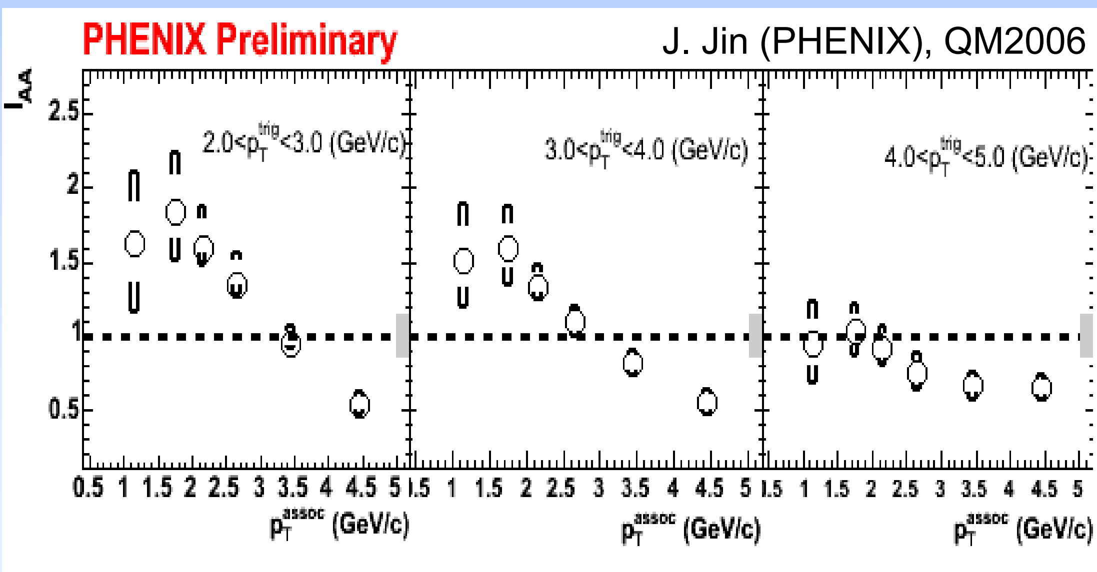
Near-side yields

M. Horner (STAR), QM2006



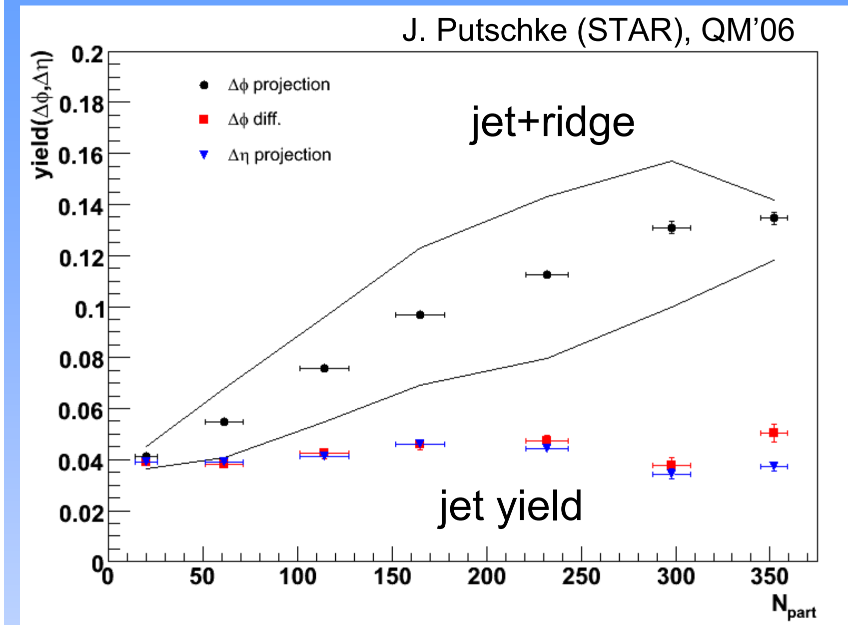


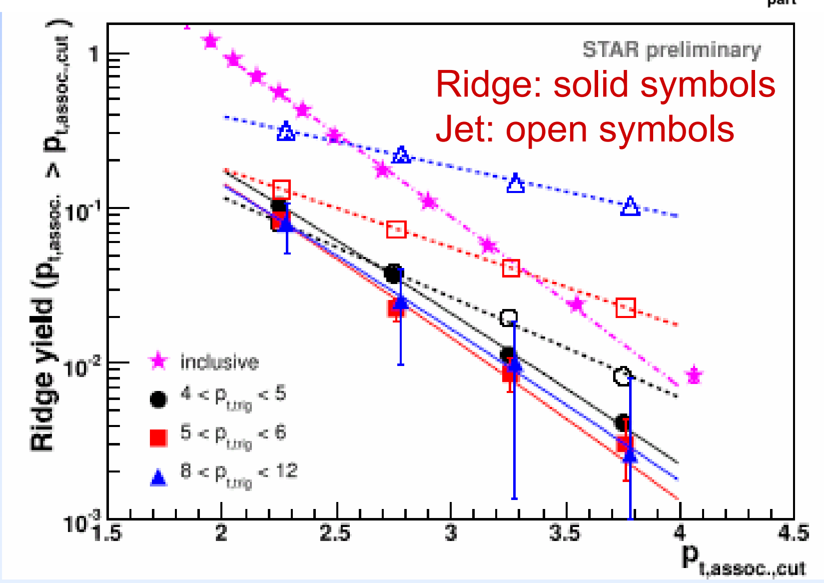
$z_T = p_{T,assoc}/p_{T,trig}$



- increase of near-side yield at low p_T^{assoc} (z_T) observed by STAR and PHENIX
- subtraction of $\Delta\eta$-independent 'ridge-yield' recovers centrality-independent jet yield

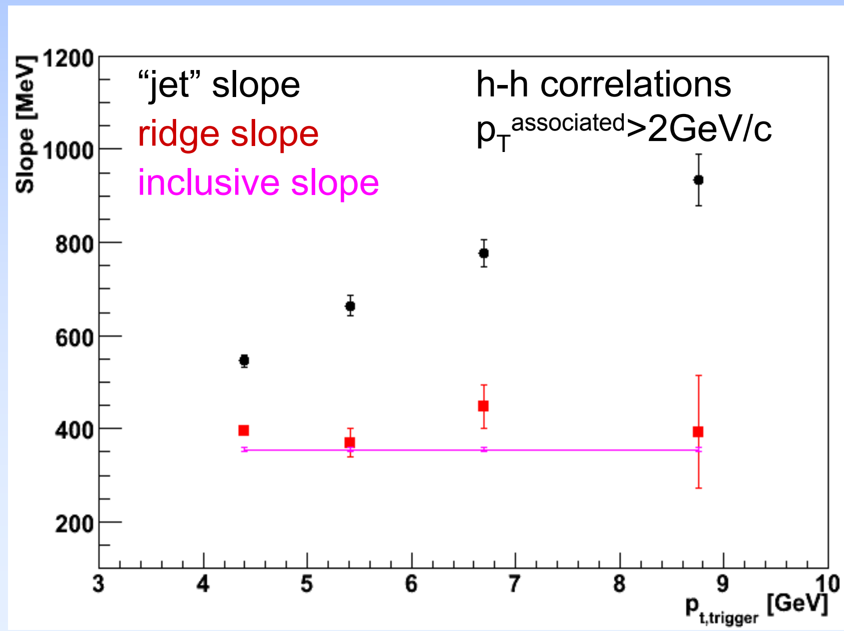
Ridge properties



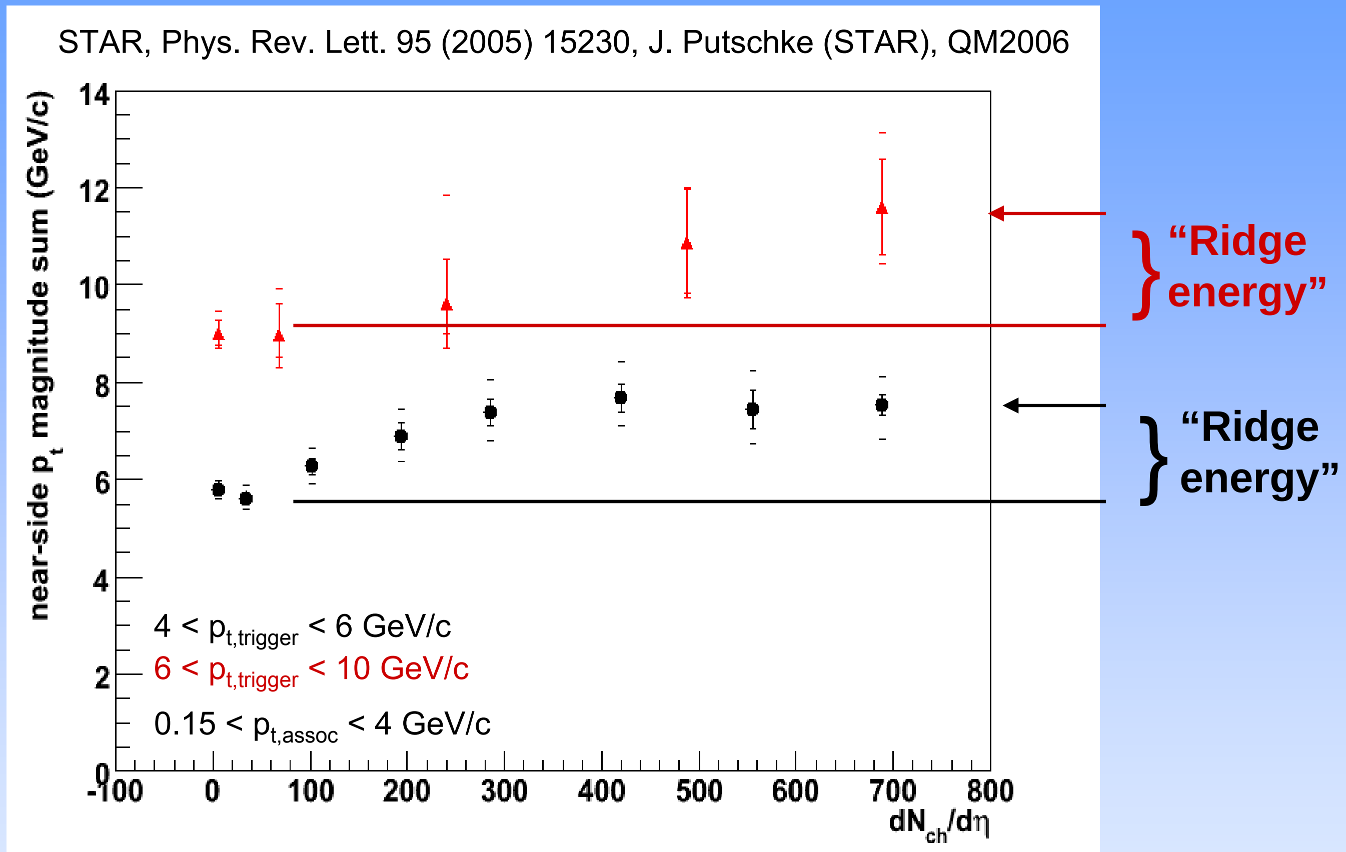


Ridge yield:

- increases with centrality
- ~ independent of $p_T^{trigger}$
- p_T -spectra are 'bulk-like'
- particle composition in the ridge → see talk of M. Daugherity

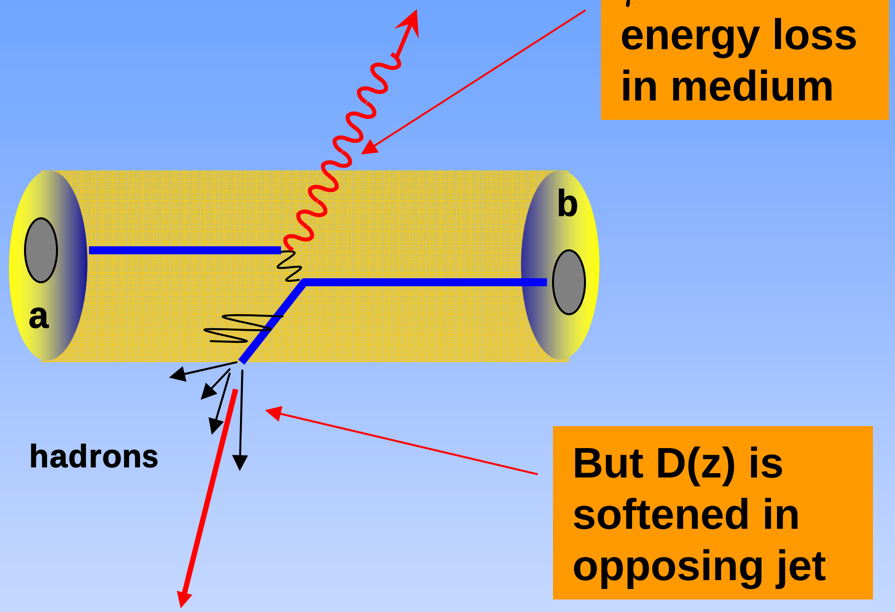


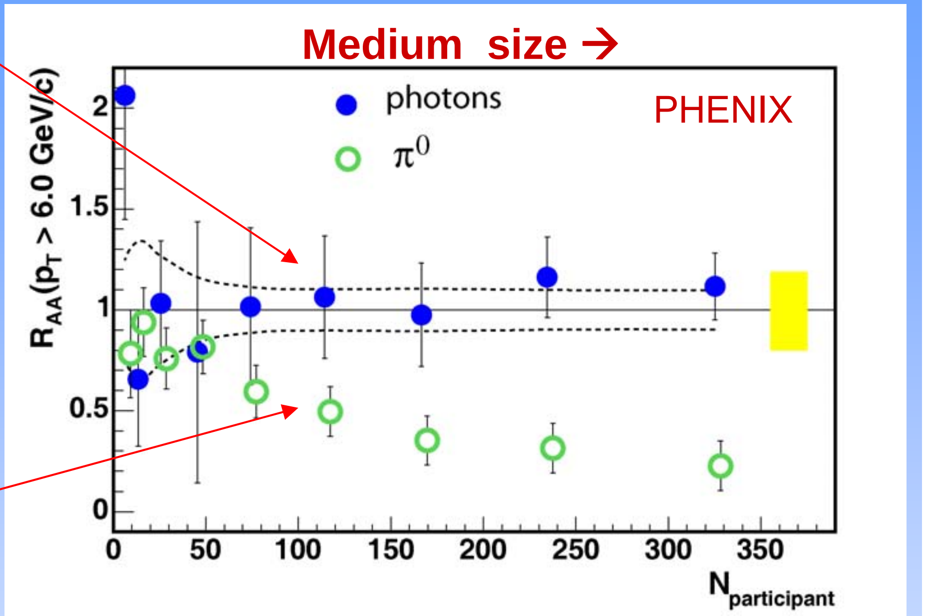
Energy content of the ridge



- near-side modification in published results also due to ridge
- energy content deposited in the ridge is few GeV

The golden channel: γ-jet



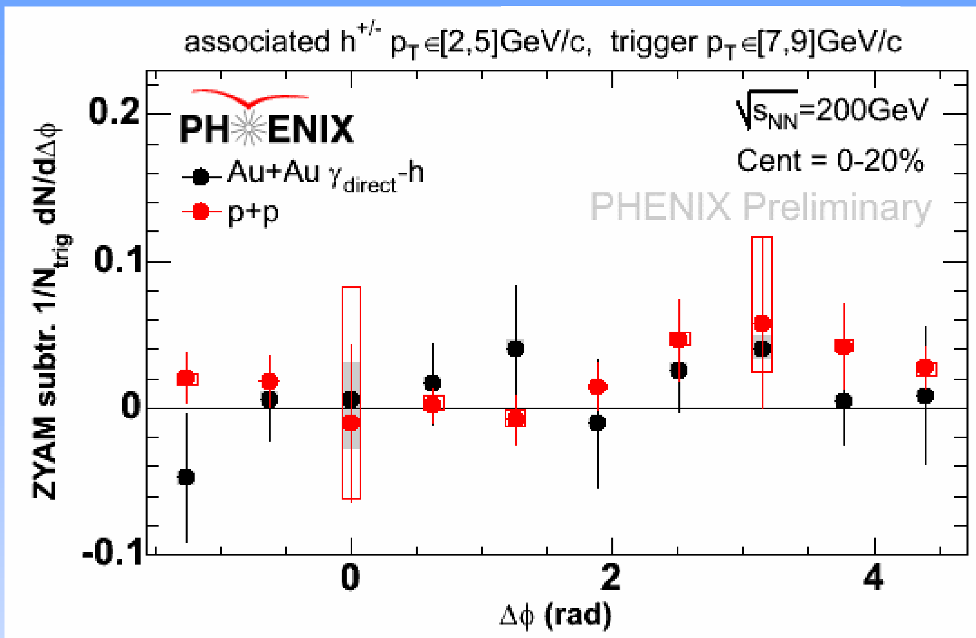


- hard process: pQCD calculations describe well measured data
- no surface bias
- calibrated probe: $E_{T,\gamma}$ = pre-quenched $E_{T,jet}$
- monochromatic source → differential measurement of jet-quenching

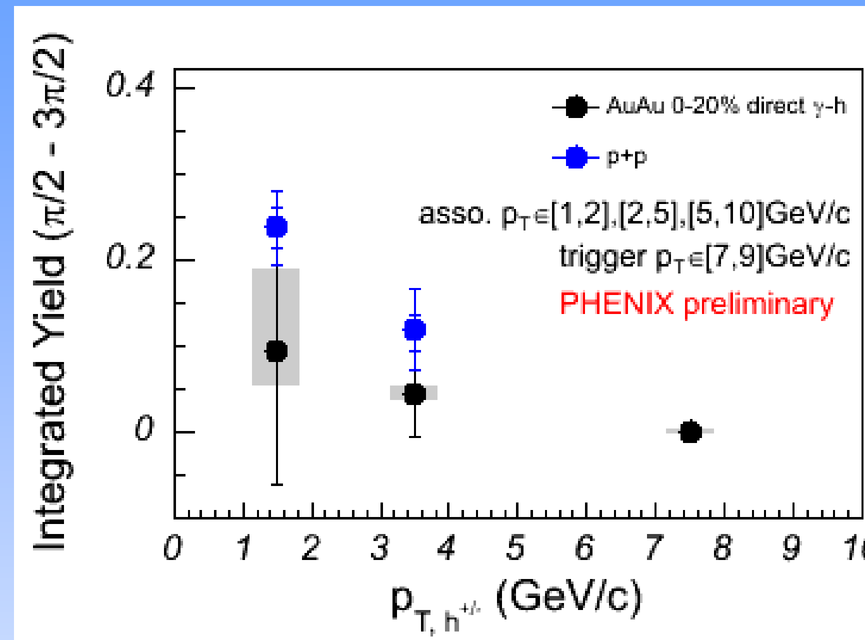
X.-N. Wang, Z. Huang, PRC 55, 3047, F. Arleo et al JEHP 0411, 009, T. Renk, PRC 71, 034906

First results on γ-hadron correlations

J. Jin, M. Nguyen, N.Grau (PHENIX), QM06



S. Chattopadhyay, F. Benedosso (STAR), QM06



- p+p: yields consistent with expectations from Pythia/HIJING
- Au+Au: a hint of away-side modification (?)
- ongoing studies in Cu+Cu (STAR/PHENIX)

- statistical and systematic uncertainties are large
- We have the tools, we just need more statistics ☺

Summary

• high-statistics Run4/Run5 enable exploration of in-medium energy loss in detail:

integrated (R_{AA}) → differential (R_{AA} vs reaction plane, correlations)

hadrons → identified particles (non-strange, strange, heavy-flavor)

'the golden channel' – γ-jet is emerging

• data trigger lots of interest in theoretical community

• upgrades to PHENIX and STAR will bring us even more exciting results

THANKS to BRAHMS, PHENIX and STAR for their input to this talk !!!