Probing the Properties of the Matter Created at RHIC

Helen Caines - Yale

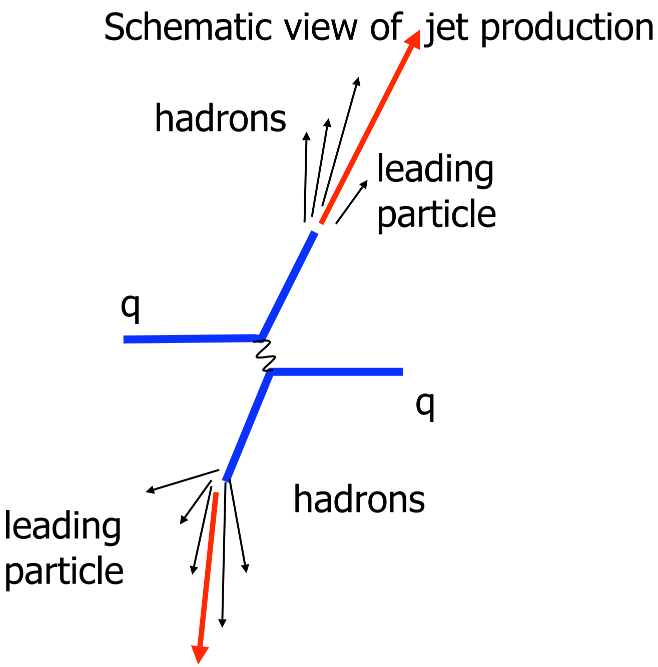
ISMD: Hamburg, Germany

Sept. 2008

Probing the medium - Jet production

Early production in parton-parton scatterings with large Q^2.

Direct interaction with partonic phases of the reaction



Probing the medium - Jet production

Early production in parton-parton scatterings with large Q^2.

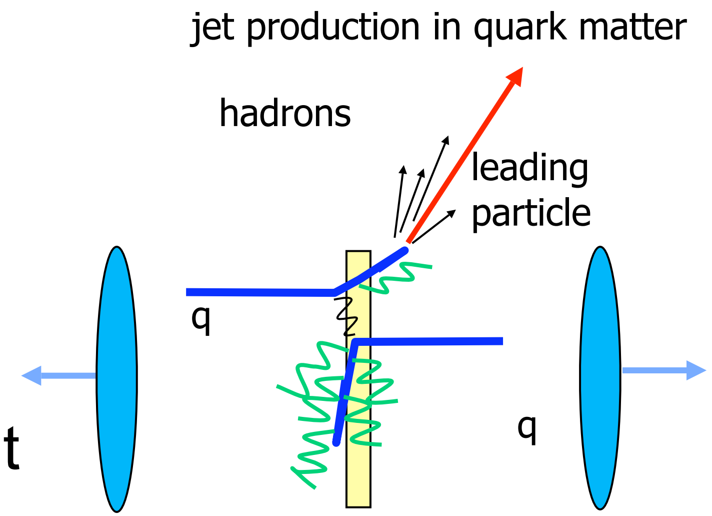
Direct interaction with partonic phases of the reaction

Use “jets” as probes at RHIC

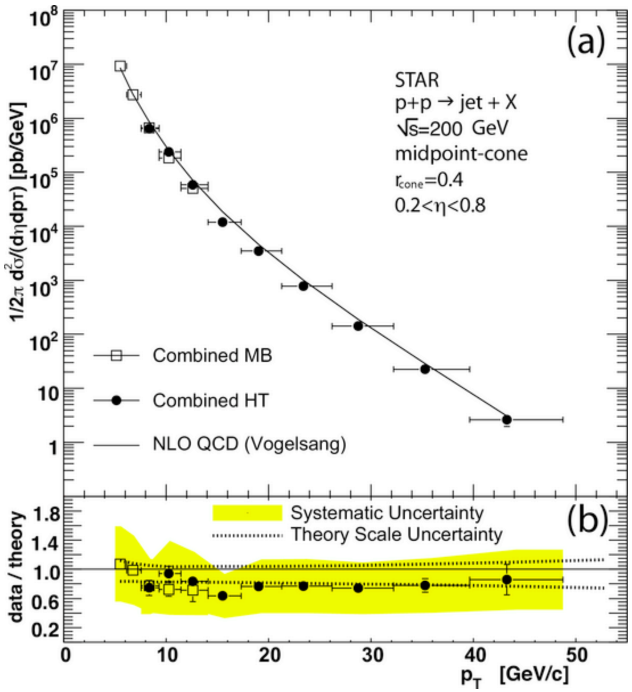
From p+p

- Have a known jet rate
- Have a known energy

Use suppression pattern to learn about medium



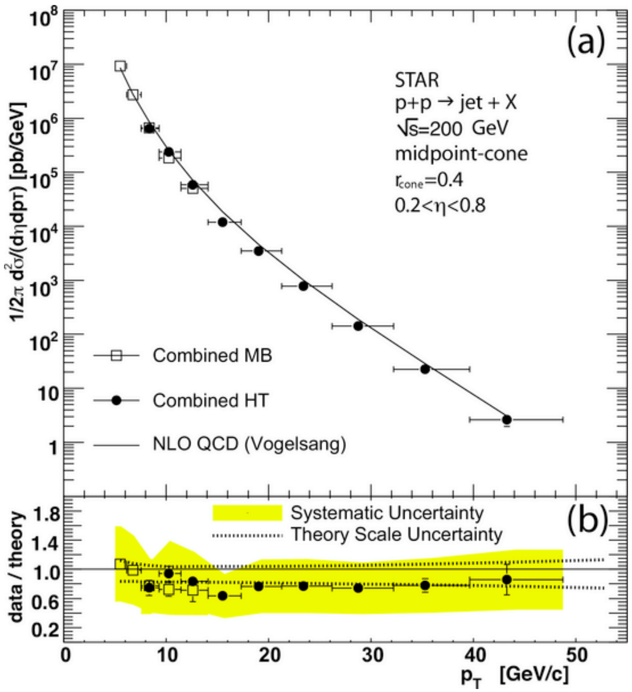
Jets – a calibrated probe?



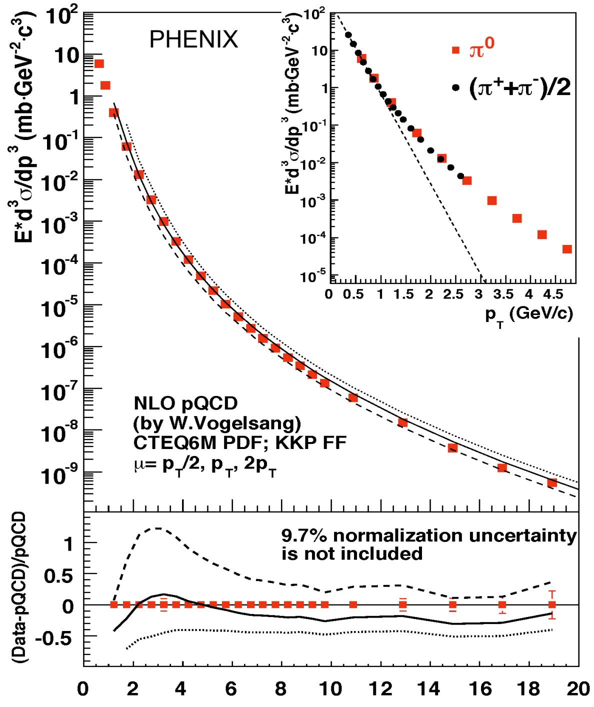
STAR : PRL 97 (2006) 252001

Jet production in p+p understood in pQCD framework

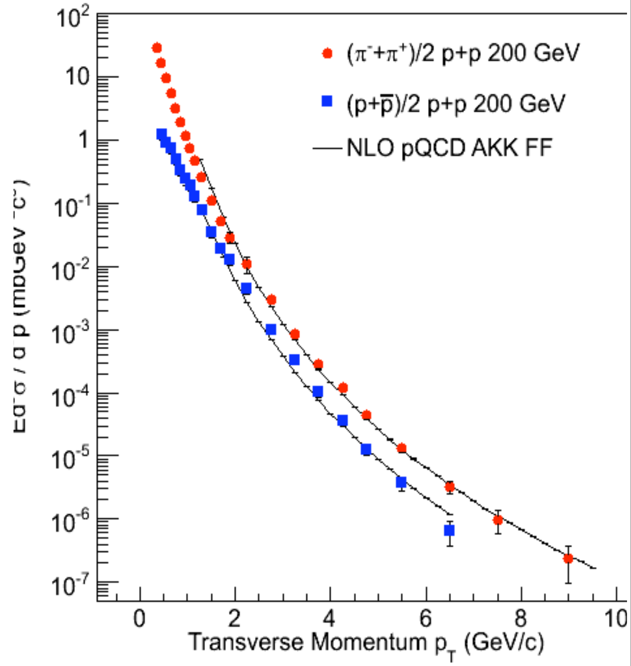
Jets – a calibrated probe?



STAR : PRL 97 (2006) 252001



K.Reygers QM2008



STAR : PLB 637 (2006) 161

S. Albino et al, NPB 725 (2005) 181

Jet production in p+p understood in pQCD framework

Particle production in p+p also well modeled.

Seems we have a reasonably calibrated probe

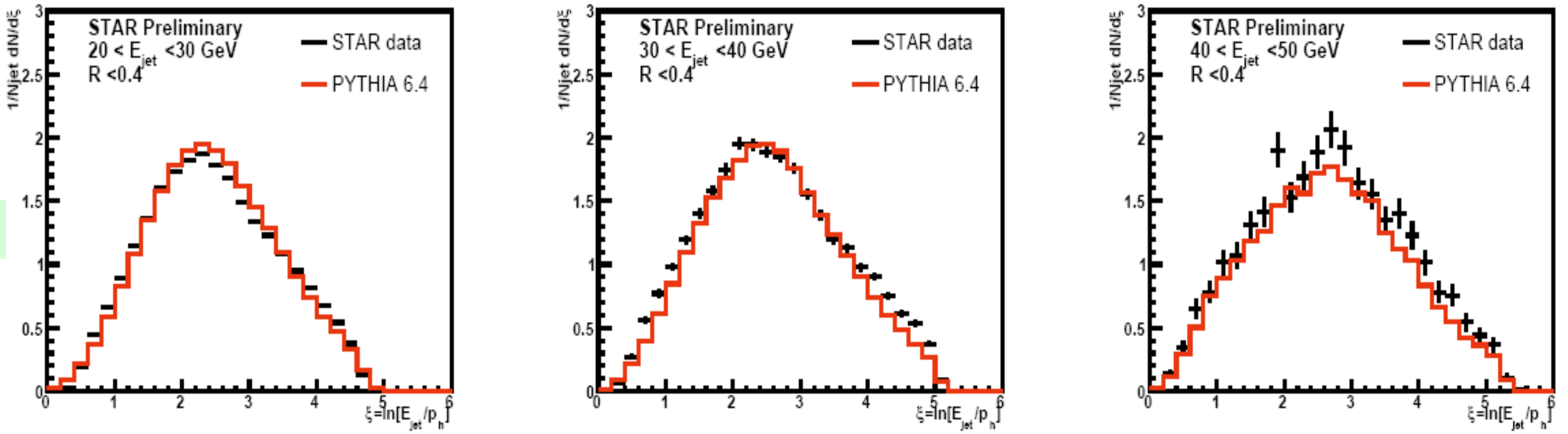
Charged hadron ξ in p+p 200 GeV

20<E^{reco}<30 GeV

30<E^{reco}<40 GeV

40<E^{reco}<50 GeV

R<0.4



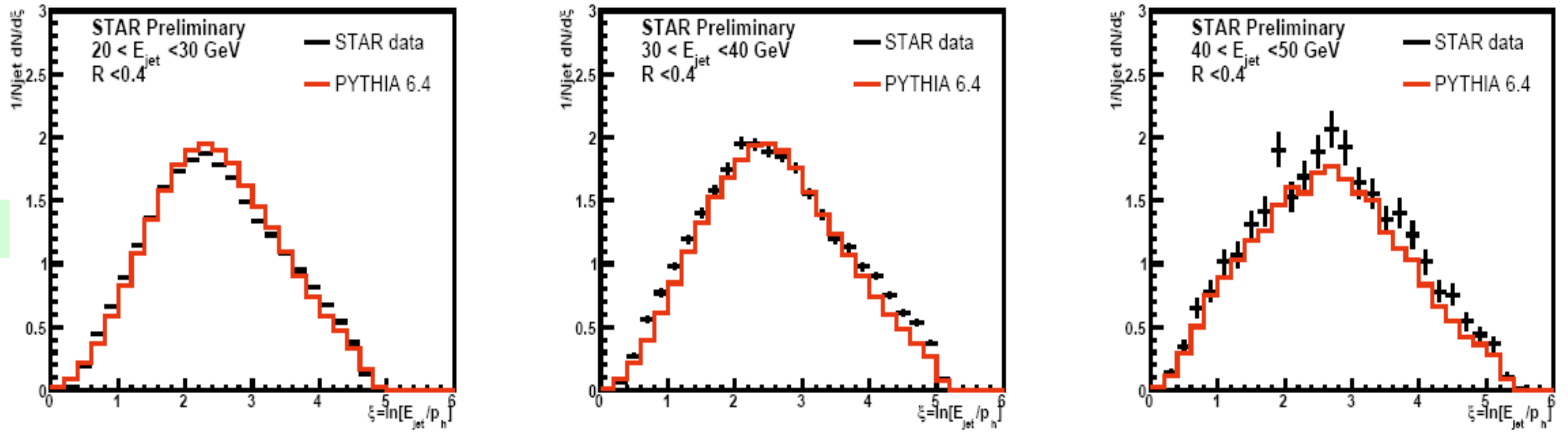
M. Heinz
Hard Probes 2008

Reasonable agreement between Pythia and data

Charged hadron ξ in p+p 200 GeV

20<E^reco<30 GeV | 30<E^reco<40 GeV | 40<E^reco<50 GeV

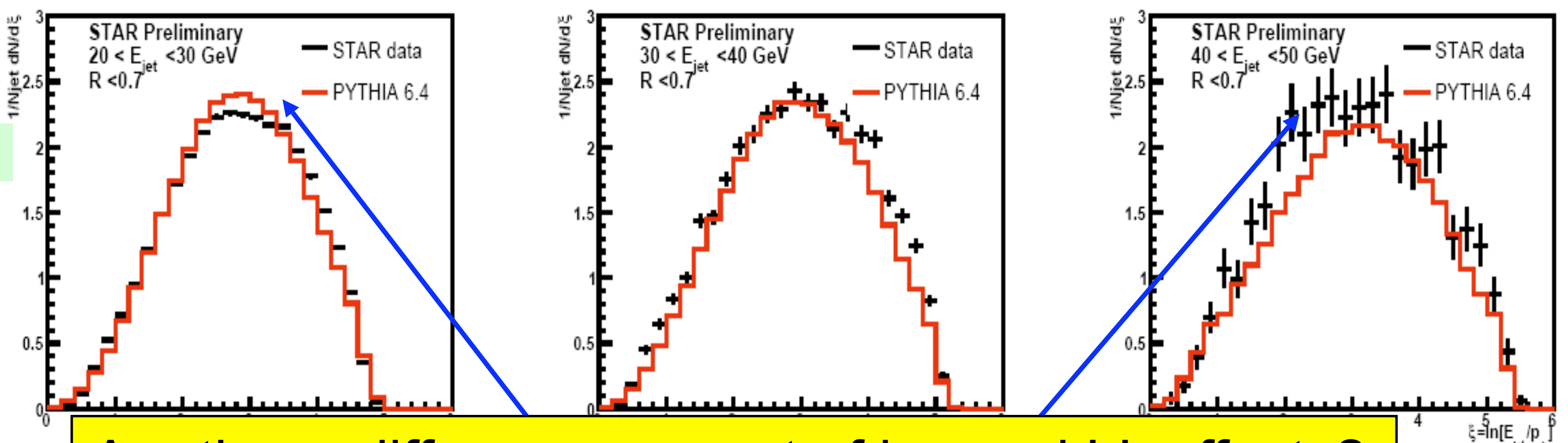
R<0.4



M. Heinz
Hard Probes 2008

Reasonable agreement between Pythia and data

R<0.7



Are these differences onset of beyond LL effects?

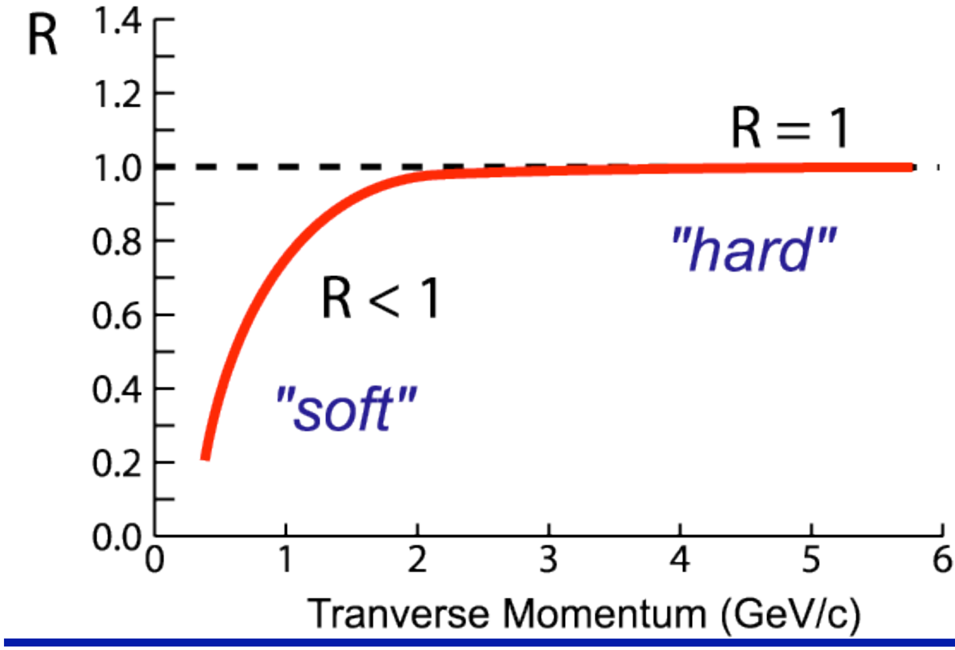
First attempt - use single particle spectra

Compare Au+Au with p+p Collisions ⇒ R_{AA}

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

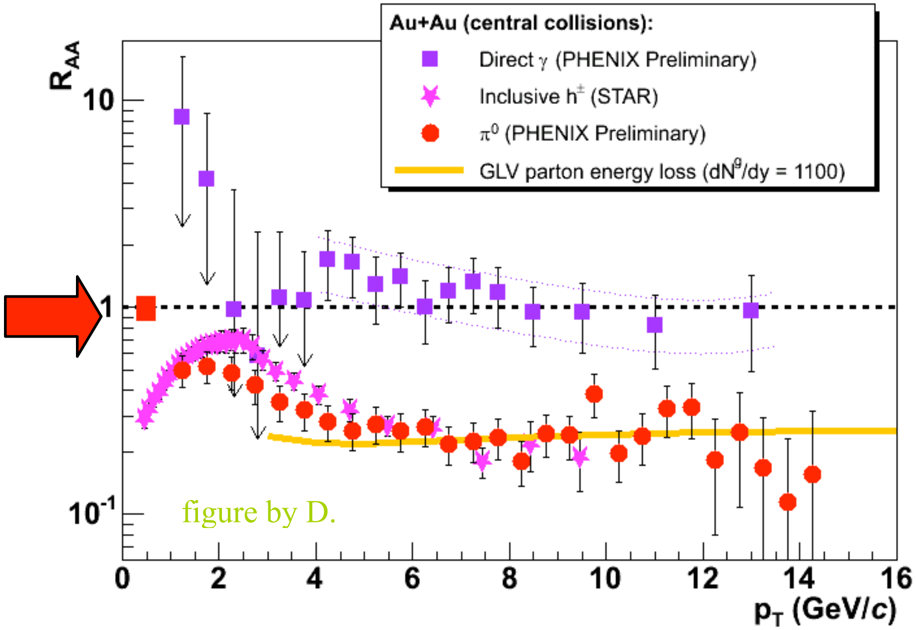
Average number of NN collision in an AA collision



No "Effect":
- R < 1 at small momenta
- R = 1 at higher momenta where hard processes dominate

Suppression: R < 1

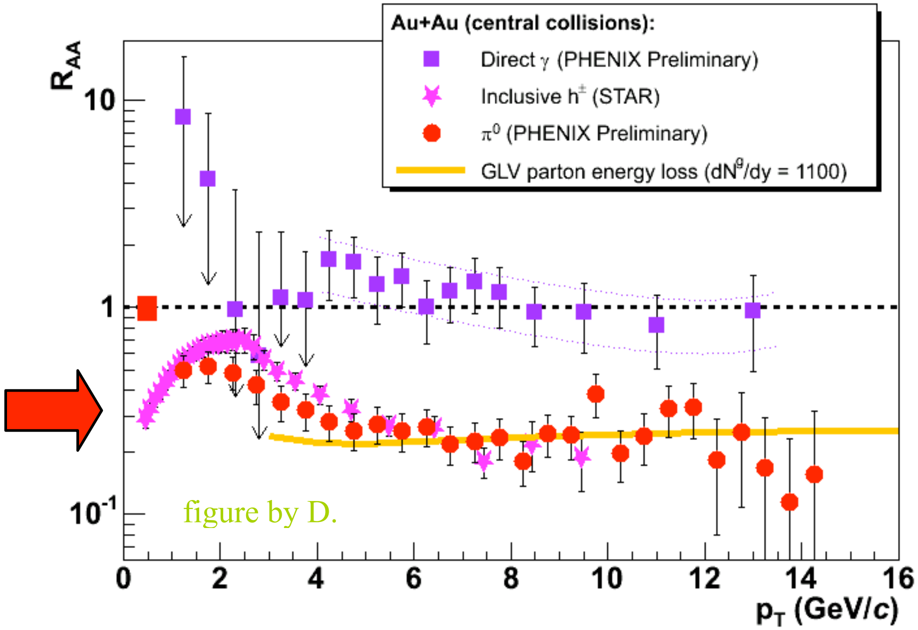
High-p_T suppression



Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works

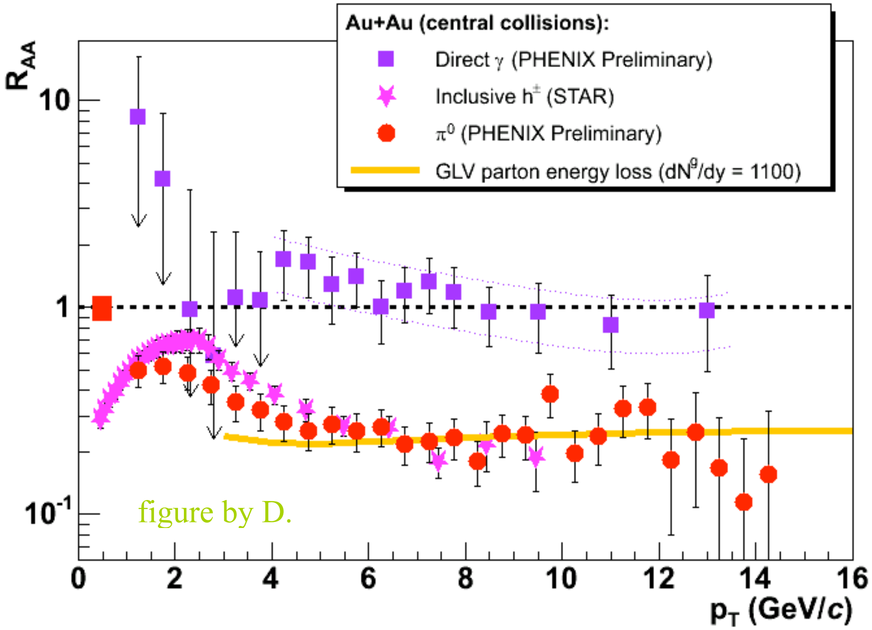
High-p_T suppression

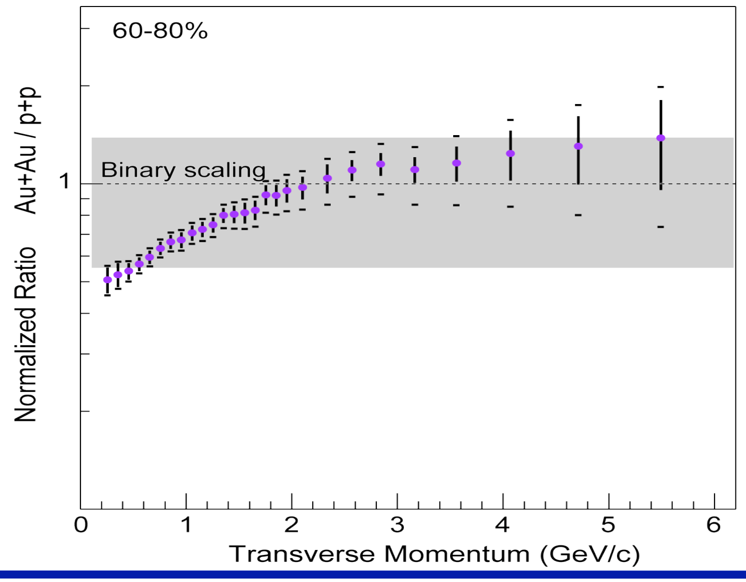


Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works
2. Hadrons are suppressed in central collisions
   - Huge: factor 5

High-p_T suppression



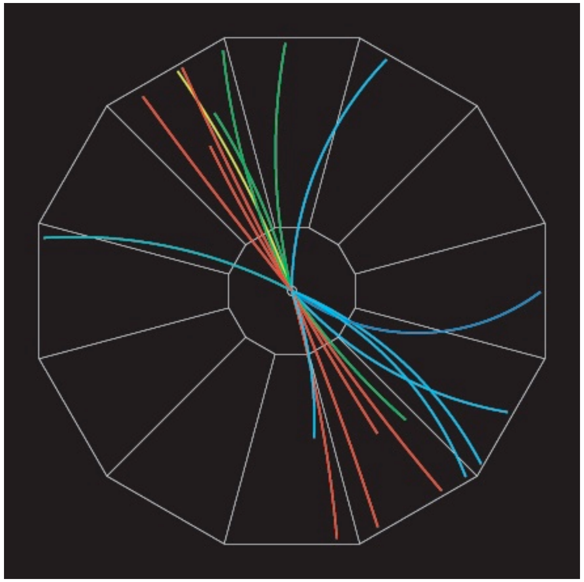


Observations at RHIC:

1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works
2. Hadrons are suppressed in central collisions
   - Huge: factor 5
3. Hadrons are not suppressed in peripheral collisions
   - Good! medium not dense

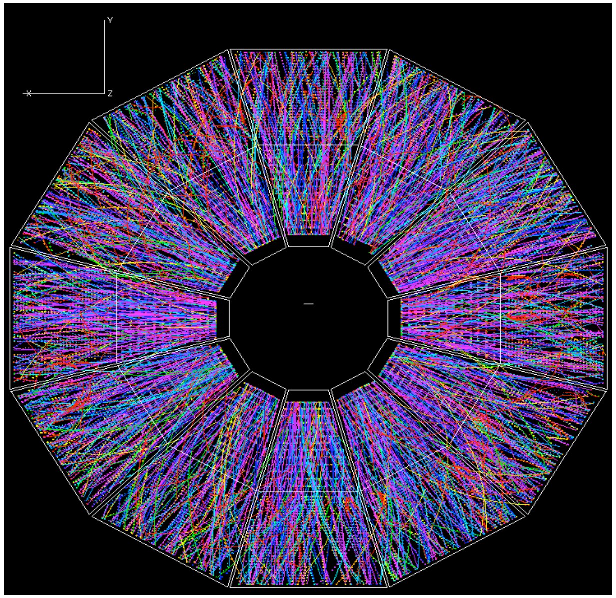
Jet correlations in heavy-ion collisions

- Full jet reconstruction very challenging
  background from bulk similar to signal for jet p_T<~30 GeV



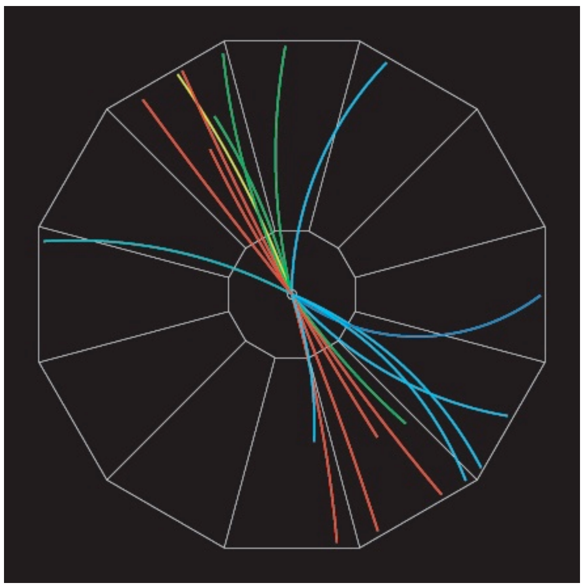
p+p collisions

Au+Au collisions



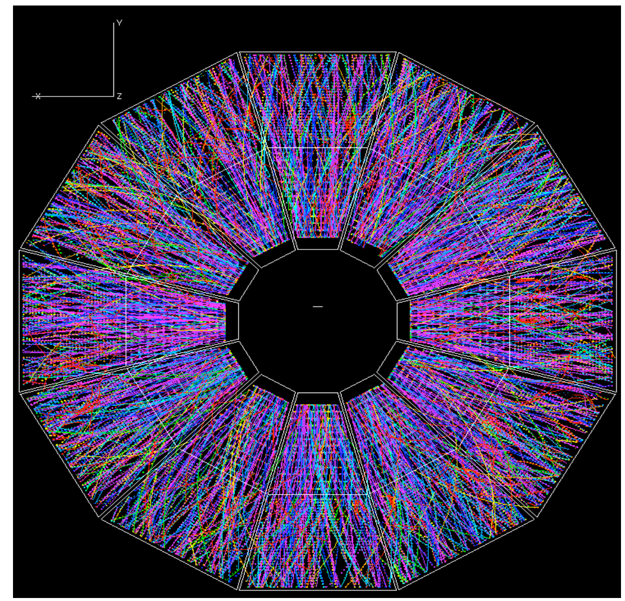
Jet correlations in heavy-ion collisions

- Full jet reconstruction very challenging
  background from bulk similar to signal for jet p_T<~30 GeV



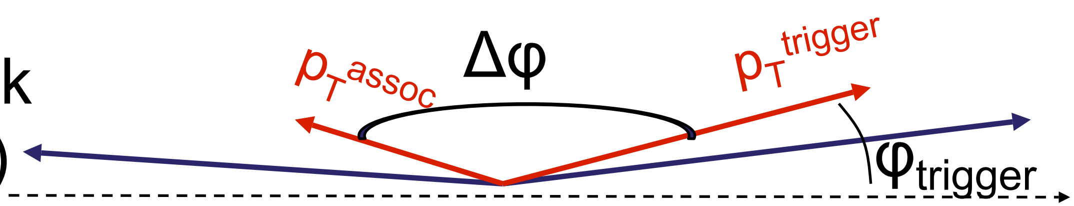
p+p collisions

Au+Au collisions



Use di-hadron correlations

Back-to-back (away side) jet



Trigger (near side) jet

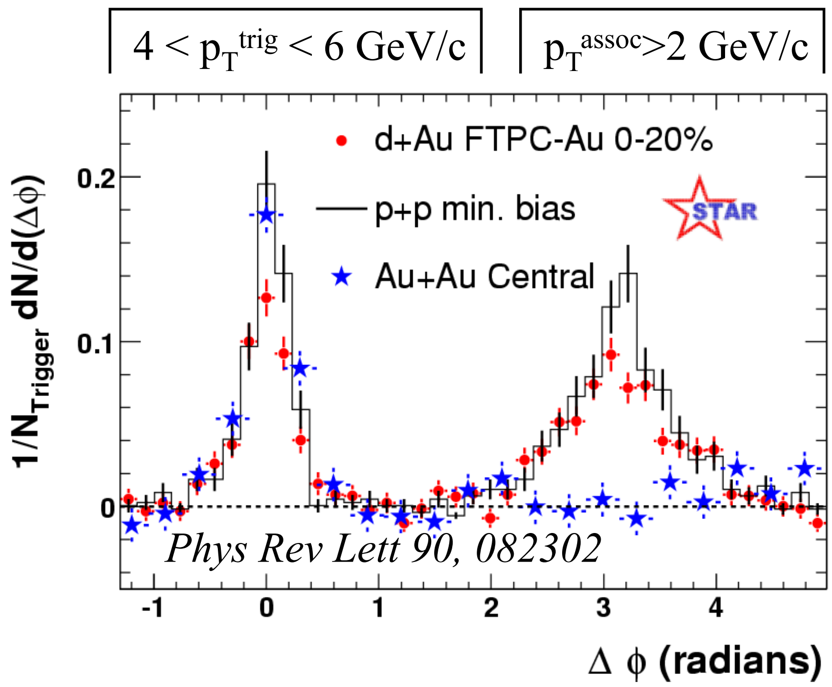
RHIC seminal di-hadron results

"The disappearance of the away-side jet"

d+Au results similar to p+p

→ final state interaction

→ d+Au can be used as the reference measurement instead of p+p



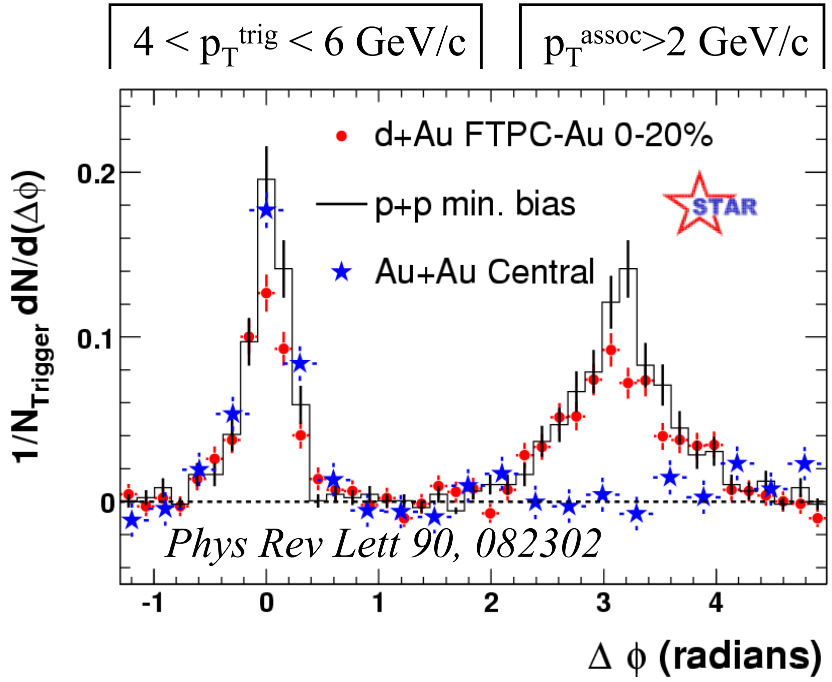
RHIC seminal di-hadron results

"The disappearance of the away-side jet"

d+Au results similar to p+p

→ final state interaction

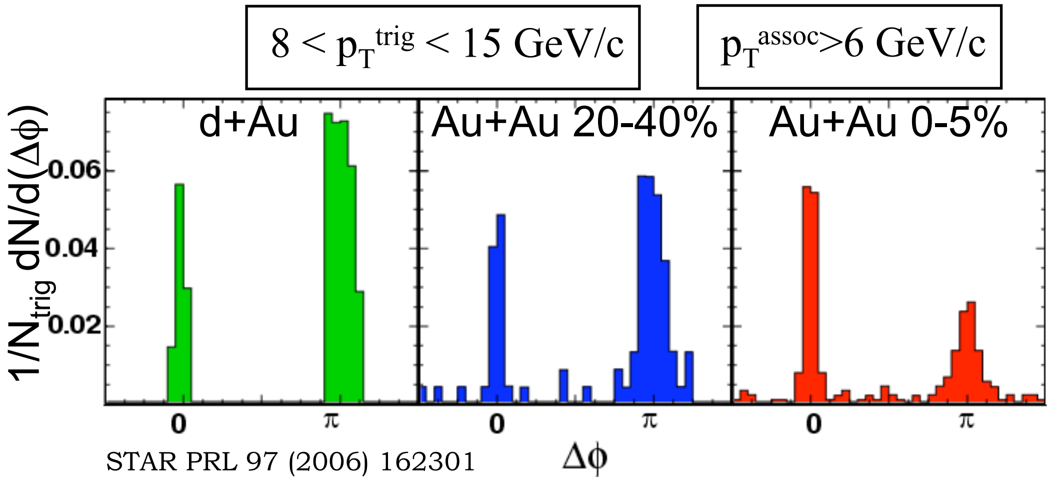
→ d+Au can be used as the reference measurement instead of p+p



"High p_T Punch-through"

Away side correlation reappears for high p_T correlations

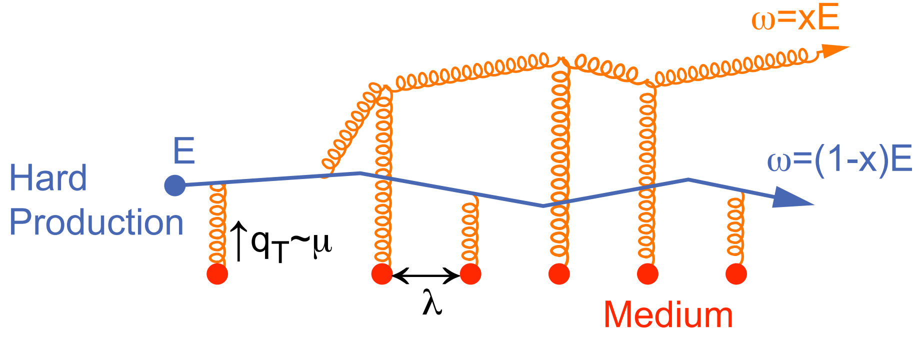
→ yield reduced compared to d+Au



STAR PRL 97 (2006) 162301

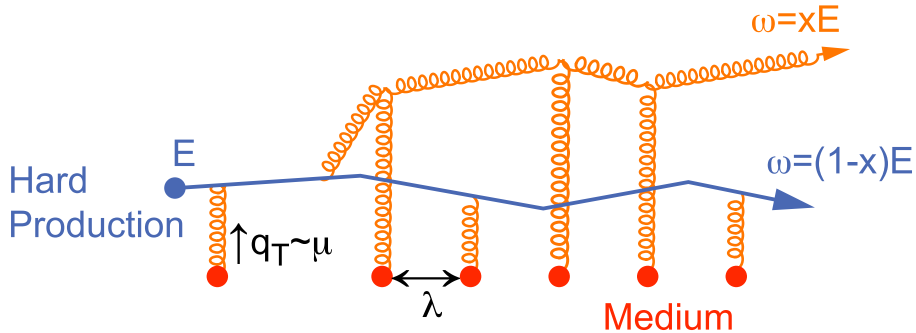
Interpretation

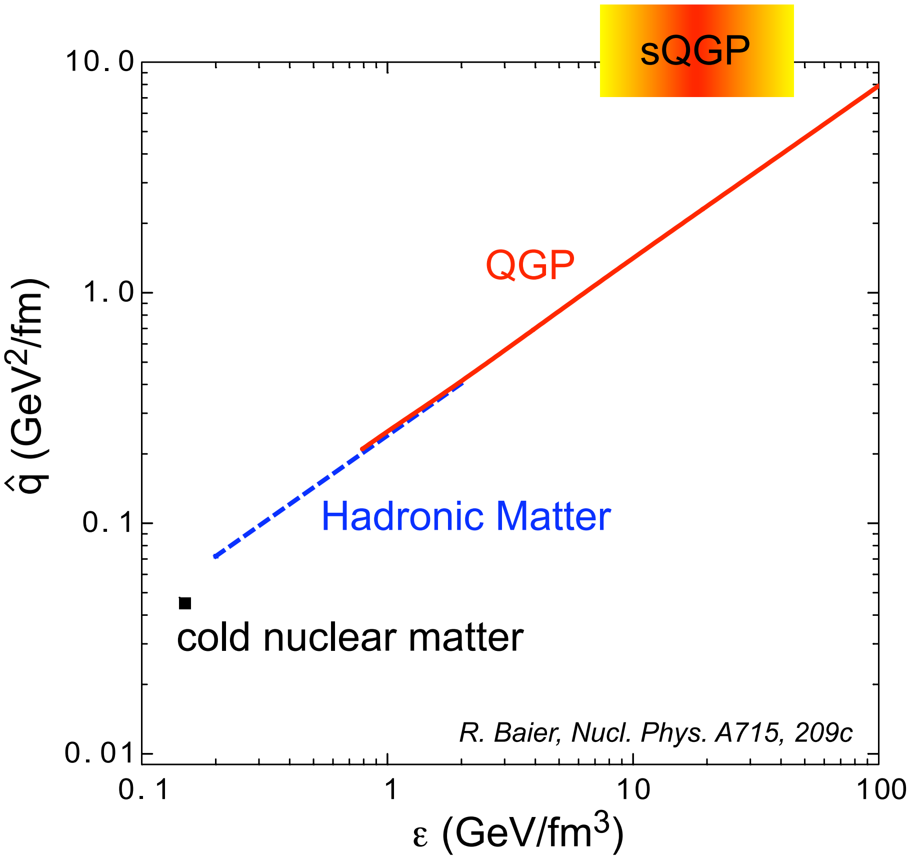
Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium



Interpretation

Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium





- Mean parton energy loss ∝ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - Coherence among radiated gluons
    - $\Delta E_{loss} \sim \Delta L^2$ (medium length)

      $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$

  is $\langle k_T^2 \rangle$ transferred per unit path length

$$\hat{q} = \frac{\langle k_T^2 \rangle}{L} \approx \frac{\mu^2}{\lambda} \qquad \hat{q} = \hat{q}(\vec{r}, \tau)$$

  - gluon density dN_g/dy

The model landscape (not exhaustive)

PQM (Parton Quench model)

Implementation of BDMPS (calc. E loss via coherent gluon radiation - many soft scattering approx.

☺ Realistic geometry

☹ Static medium, q time average (i.e. depends on initial density, scheme evolution dependent)

☹ No initial state multiple scatterings

☹ No modified PDFs

GLV

Implementation of GLV formalism (calc. E loss via gluon brehmsstralung -few hard scatterings.)

☺ Realistic geometry

☺ Bjorken expanding medium - Calc. a priori (w/o E loss) average path length - use to calc. partonic E loss

WHDG

Implementation of GLV formalism (calc. E loss via gluon brehmsstralung -few hard scatterings) + collisional energy loss.

☺ Realistic geometry - integral over all paths

☺ Expanding medium

☹ No initial state multiple scatterings

ZOWW

Modified fragmentation model (radiative gluon E loss incorporated into effective medium modified FF)

☹ Hard sphere geometry

☺ Expanding medium

Constraining $\hat{q}$

Model	Opacity Parameter	
PQM	$\langle \bar{q} \rangle$ = 13.2 (+ 2.1 - 3.2)	
GLV	dN_g/dy = 1400 (+270 -150)	($\langle \bar{q} \rangle$~7)
WHDG	dN_g/dy = 1400 (+200 -375)	
ZOWW	ε_0 = 1.9 (+0.2 - 0.5)	($\langle \bar{q} \rangle$~1)

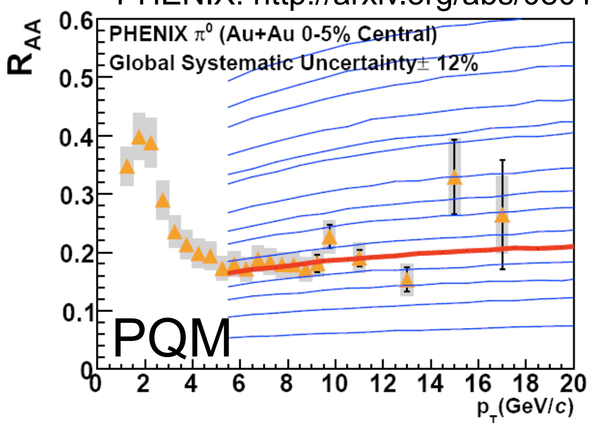
PQM: A. Dainese, C. Loizides, G. Paic, Eur. Phys. J C38: 461 (2005). C. Loizides, Eur. Phys. J.C49, 339 (2007).

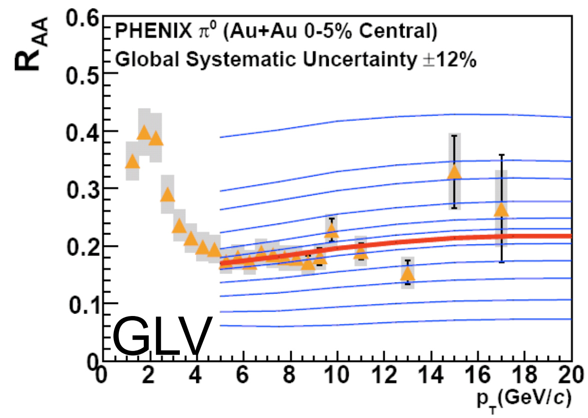
GLV: I. Vitev, Phys. Lett. B639, 38 (2006). M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B571, 197 (2000).

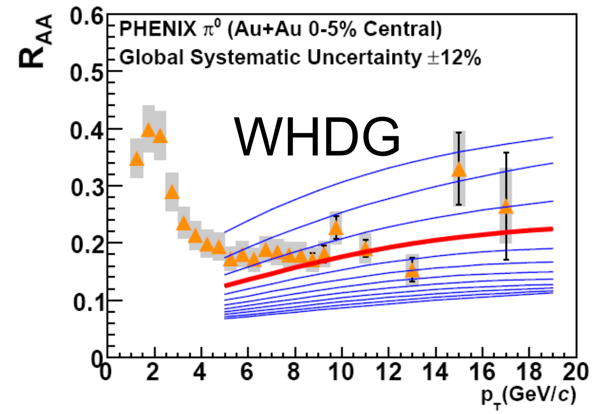
WHDG: W.A. Horowitz, S. Wicks, M. Djordjevic, M. Gyulassy,in preparation; S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, Nucl. Phys. A 783, 493 (2007); S. Wicks, W. Horowitz, M. Djordjevic,M. Gyulassy, Nucl. Phys. A 784, 426 (2007).

ZOWW: H. Zhang, J.F. Owens, E. Wang, X-N Wang, Phys Rev. Lett. 98: 212301 (2007).

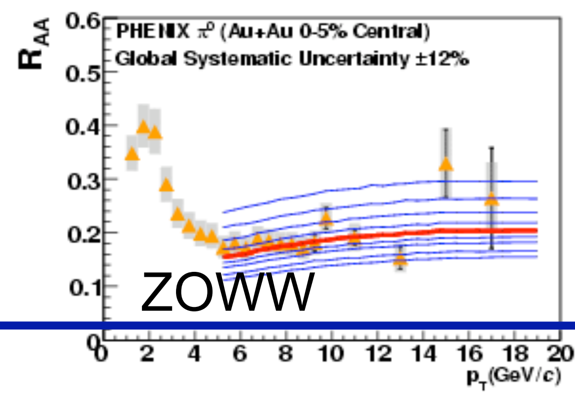
PHENIX: http://arxiv.org/abs/0801.1665







$\langle \bar{q} \rangle$ only the natural unit in PQM



Need other observables to dis-entangle all the possible effects

Two particles are better than one

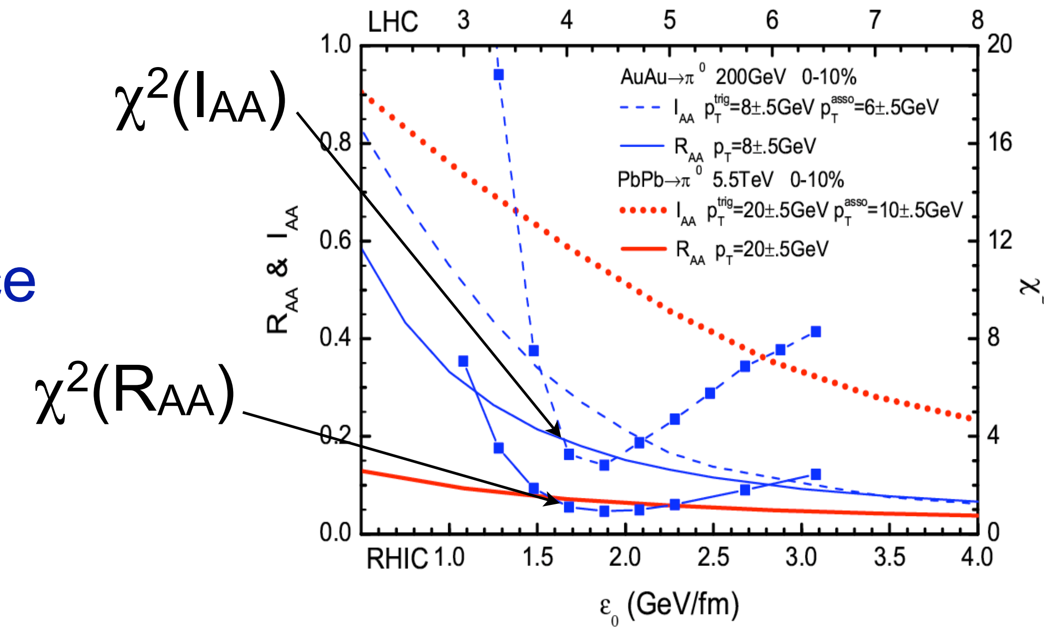
Compare fits to R_{AA} and I_{AA}

H. Zhang, J.F. Owens, E. Wang, X.N. Wang

Phys. Rev. Lett. 98: 212301 (2007)

- Minima of data in same place
- Sharper for di-hadrons

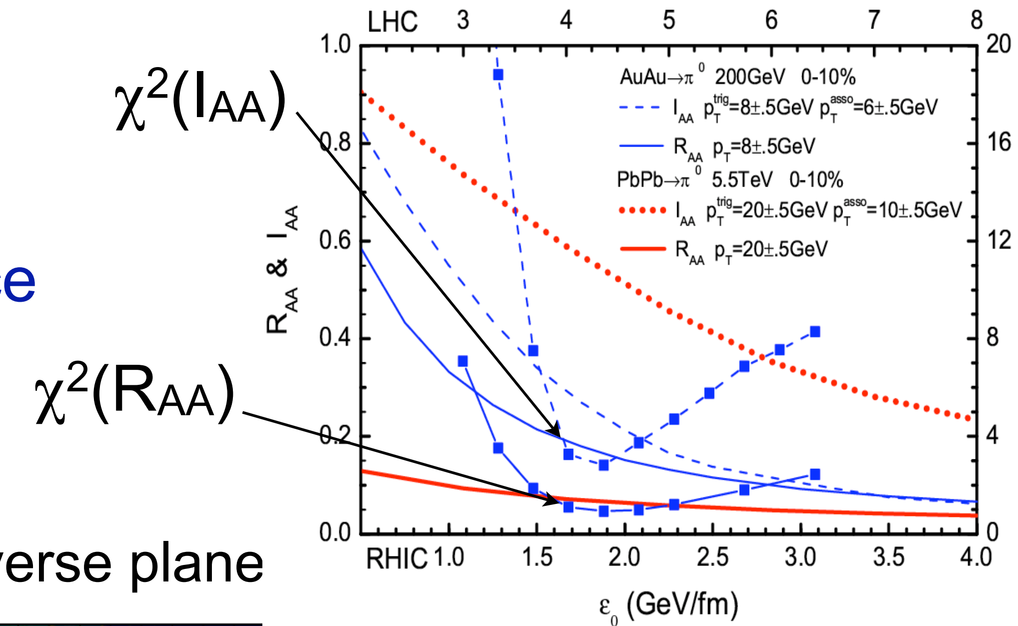
$q_0\tau_0 \sim \hat{q} = 2.8 \pm 0.3$ GeV^2/fm



Two particles are better than one

Compare fits to R_{AA} and I_{AA}

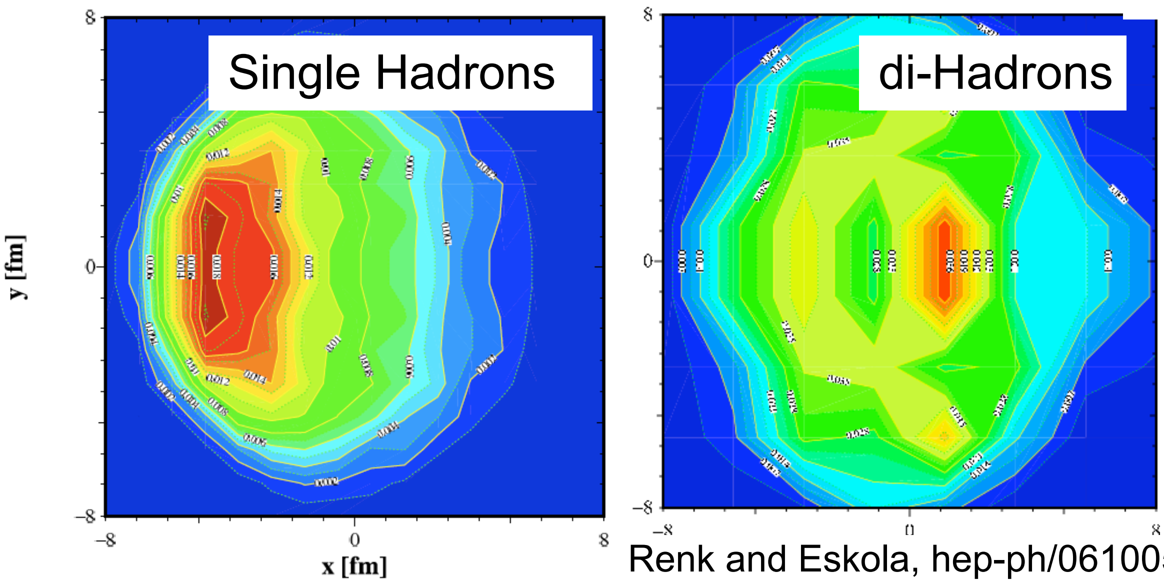
H. Zhang, J.F. Owens, E. Wang, X.N. Wang
Phys. Rev. Lett. 98: 212301 (2007)



- Minima of data in same place
- Sharper for di-hadrons

$q_0\tau_0 \sim \hat{q} = 2.8 \pm 0.3\ \mathrm{GeV^2/fm}$

Parton production points in transverse plane



Renk and Eskola, hep-ph/0610059

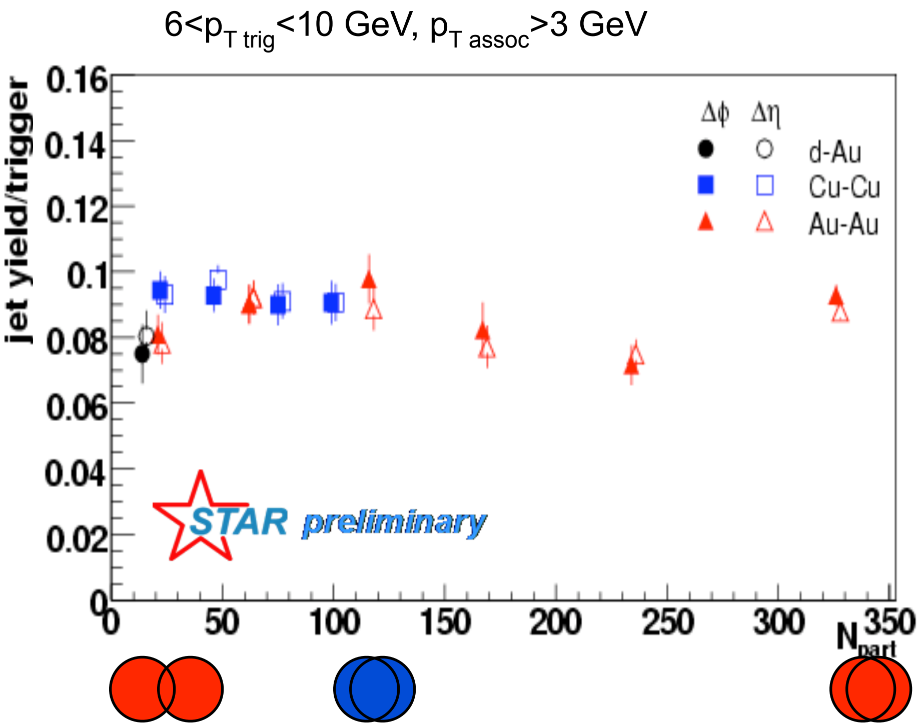
- Surface bias effectively leads to saturation of R_{AA} with density

minimize bias:
di-hadron correlations
full jets

Di-hadron near- and away-side yields

"jet yield" = No. of associated particles in jet "cone"/trigger

O Catu QM2008



Near-side jet yield:

Consistent for same N_{part}

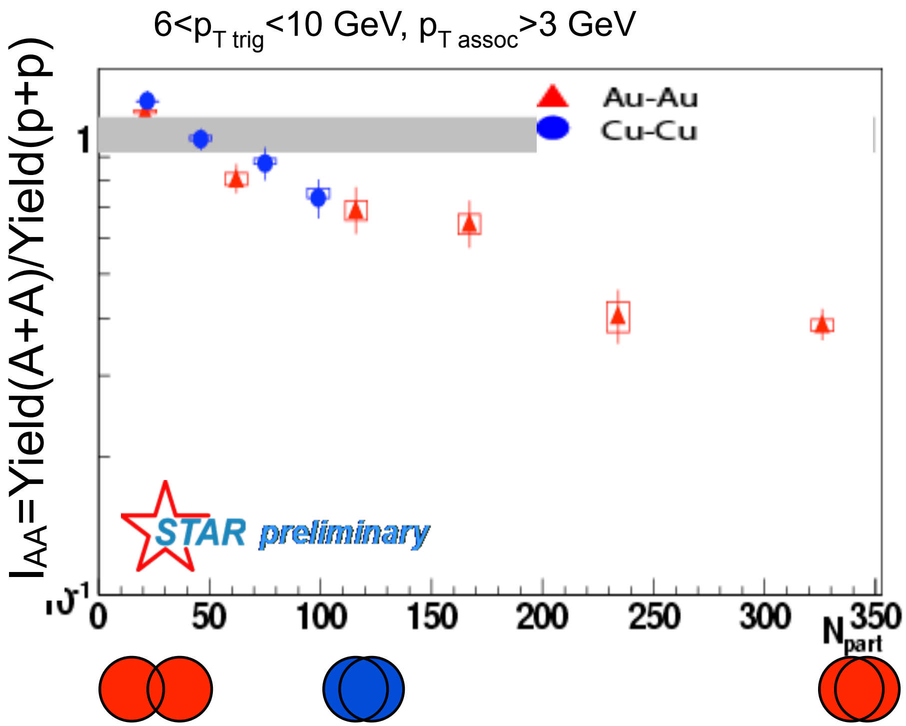
Independent of N_{part}

Unmodified vacuum frag?

Di-hadron near- and away-side yields

“jet yield” = No. of associated particles in jet “cone”/trigger

O Catu QM2008



Near-side jet yield:

Consistent for same N_{part}

Independent of N_{part}

Unmodified vacuum frag?

Away-side jet yield:

Consistent for same N_{part}

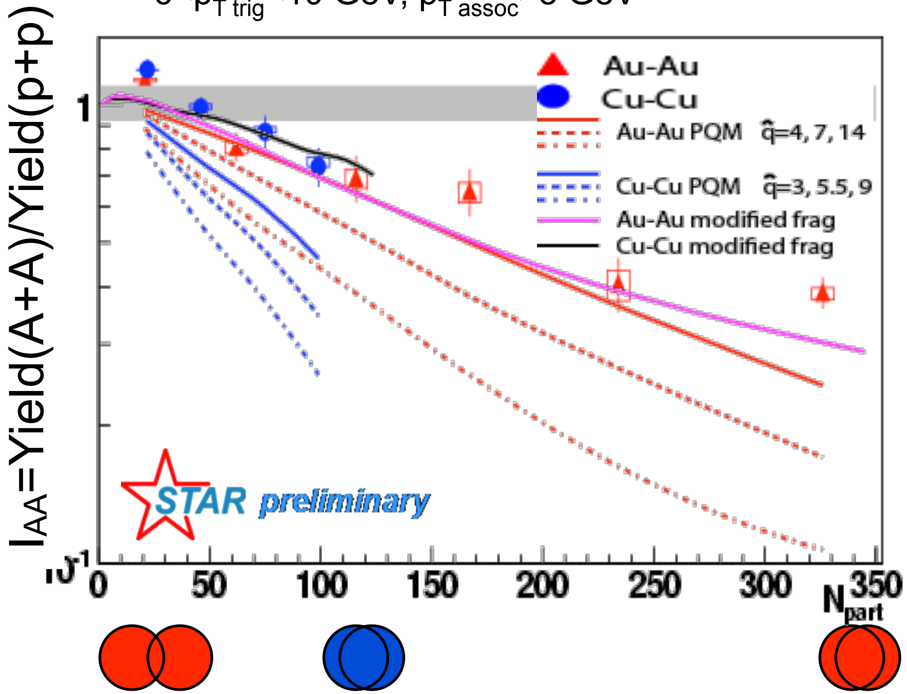
Strongly dependent on N_{part}

Di-hadron near- and away-side yields

"jet yield" = No. of associated particles in jet "cone"/trigger

O Catu QM2008

$6<p_{T\,trig}<10$ GeV, $p_{T\,assoc}>3$ GeV



ZOWW,Modified frag: nucl-th/0701045 - H.Zhang, J.F. Owens, E. Wang, X.N. Wang

PQM: C. Loizides, Eur. Phys. J. C 49, 339-345 (2007)

Near-side jet yield:

Consistent for same N_{part}

Independent of N_{part}

Unmodified vacuum frag?

Away-side jet yield:

Consistent for same N_{part}

Strongly dependent on N_{part}

Models:

Neither describe low N_{part} shape

PQM:

Misses Au-Au to Cu-Cu evolution

ZOWW:

Gets Au-Au to Cu-Cu evolution

Di-hadron “fragmentation functions”

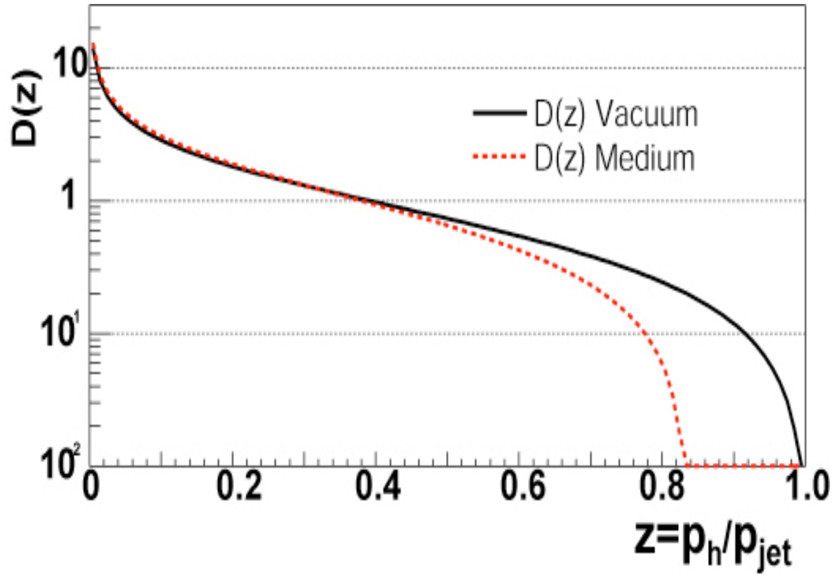
Sensitive measure of medium properties

→ medium-induced energy loss causes modification of frag. function

Without full jet reconstruction, jet/ parton energy not measurable

→ z not measured

→ $z_T = p_{Tassoc}/p_{Ttrig}$



Di-hadron “fragmentation functions”

Sensitive measure of medium properties

→ medium-induced energy loss causes modification of frag. function

Without full jet reconstruction, jet/ parton energy not measurable

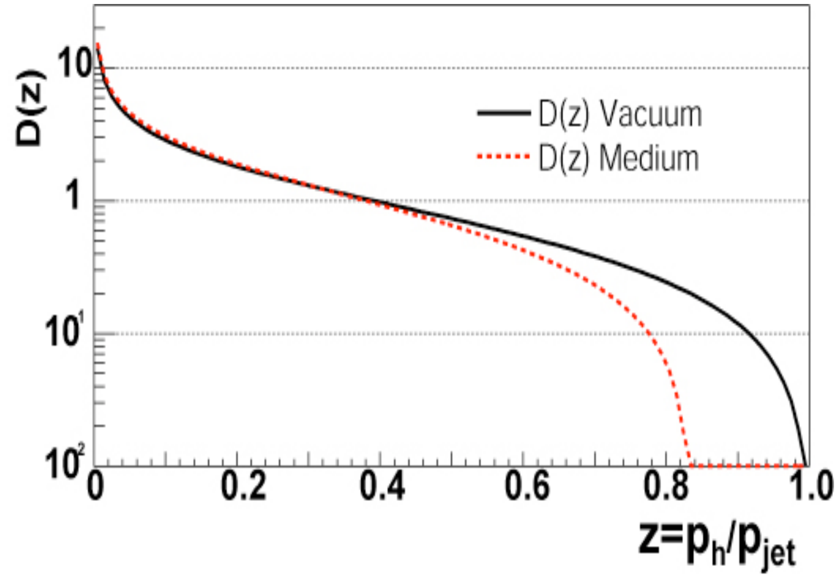
→ z not measured

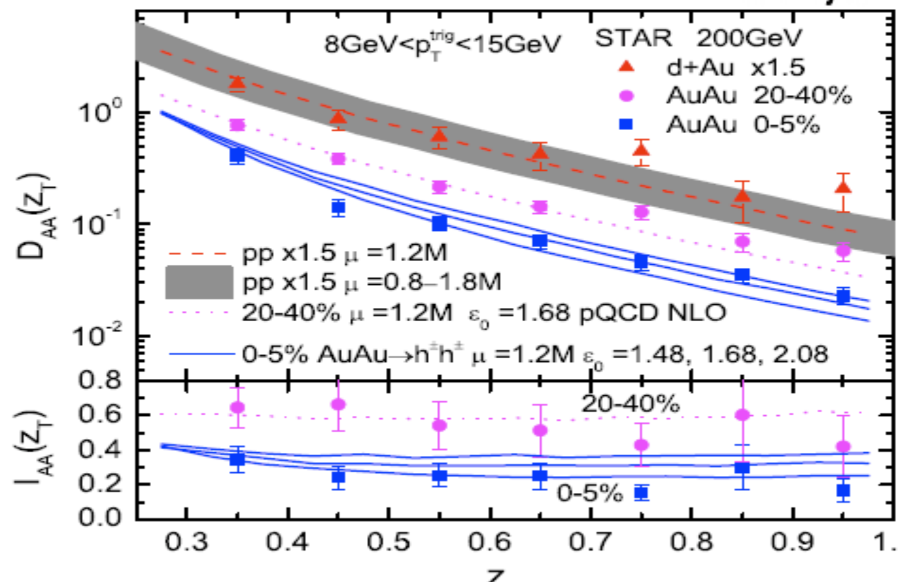
→ $z_T = p_{Tassoc}/p_{Ttrig}$

Di-hadron fragmentation function ($D_{AA}(Z_T)$)

ratio of di-hadron jet-like correlated yield to single hadron yield

$$D^{h_1h_2}(z_T, p_T^{\rm trig}) = p_T^{\rm trig} \frac{d\sigma_{AA}^{h_1h_2}/dp_T^{\rm trig}dp_T}{d\sigma_{AA}^{h_1}/dp_T^{\rm trig}}$$



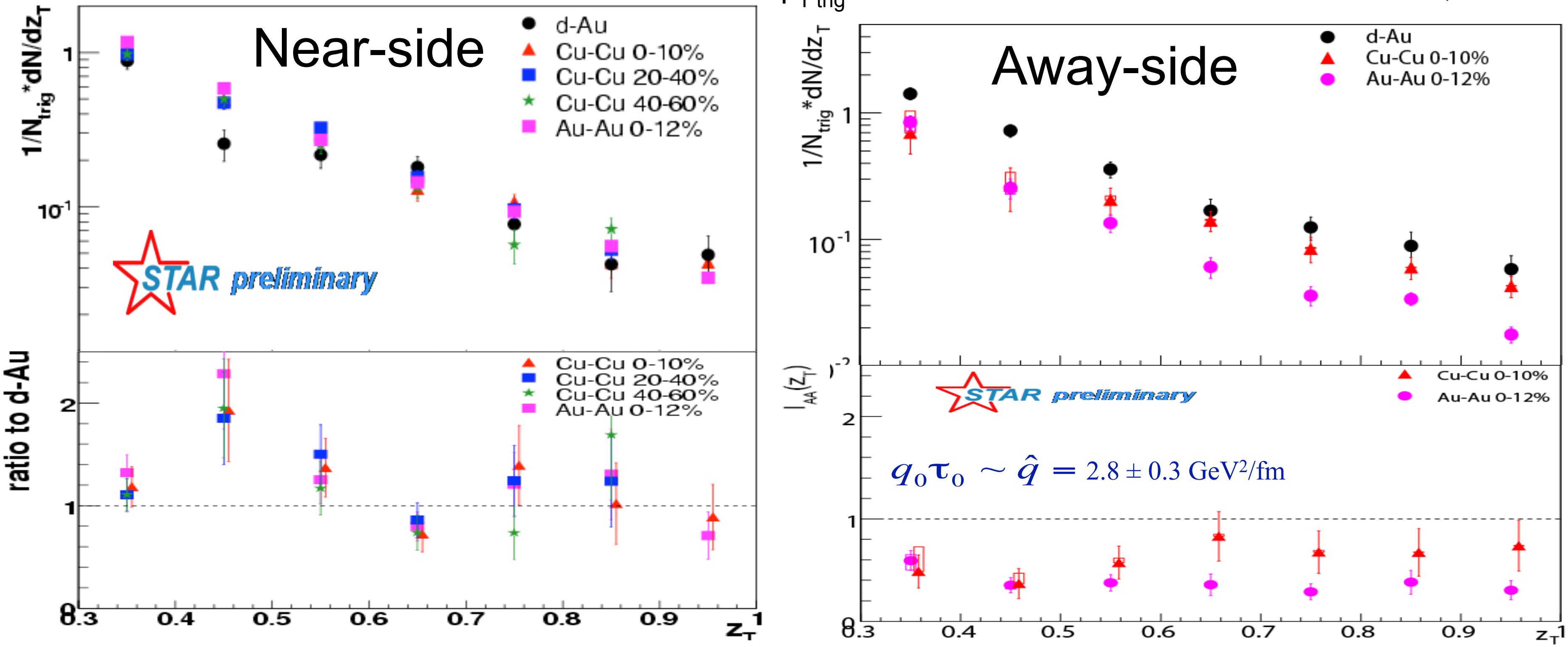


ZOWW: H.Zhang, J.F. Owens, E. Wang, X.N. Wang - Phys. Rev. Lett. 98: 212301 (2007)

Fragmentation functions Cu-Cu & Au-Au

$6 < p_{T\,trig} < 10$ GeV

O. Catu QM2008



Near-side: Unmodified

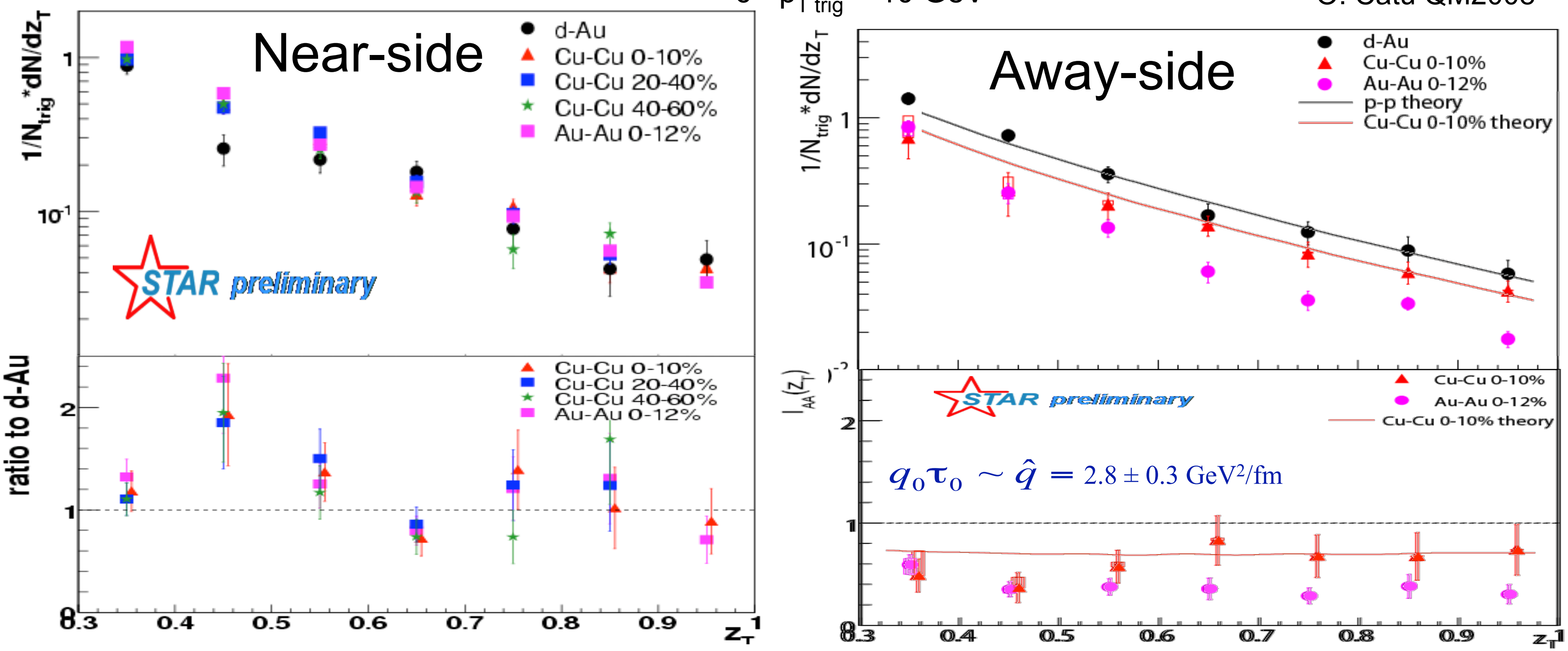
Away-side: Suppressed but shape not modified (in considered z_T range)

Less suppressed for central Cu-Cu than Au-Au

Fragmentation functions Cu-Cu & Au-Au

6< $p_{T\,trig}$ < 10 GeV

O. Catu QM2008



Theory - X.N.Wang private communication

H.Zhang, J.F. Owens, E. Wang, X.N. Wang - Phys. Rev. Lett. 98: 212301 (2007)

Near-side: Unmodified

Away-side: Suppressed but shape not modified (in considered z_T range)

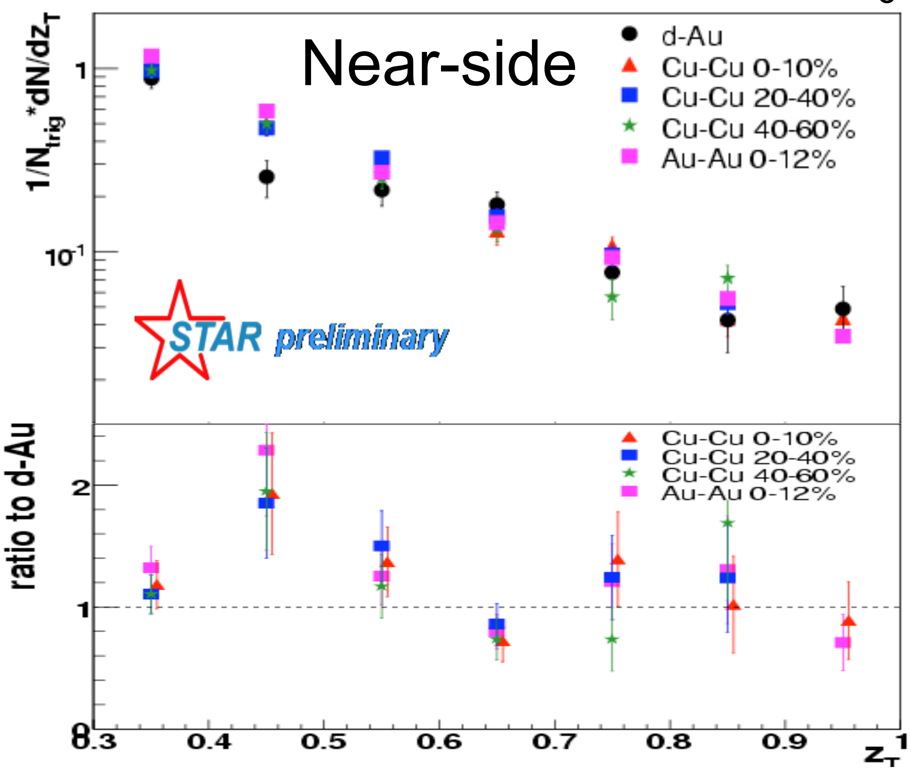
Less suppressed for central Cu-Cu than Au-Au

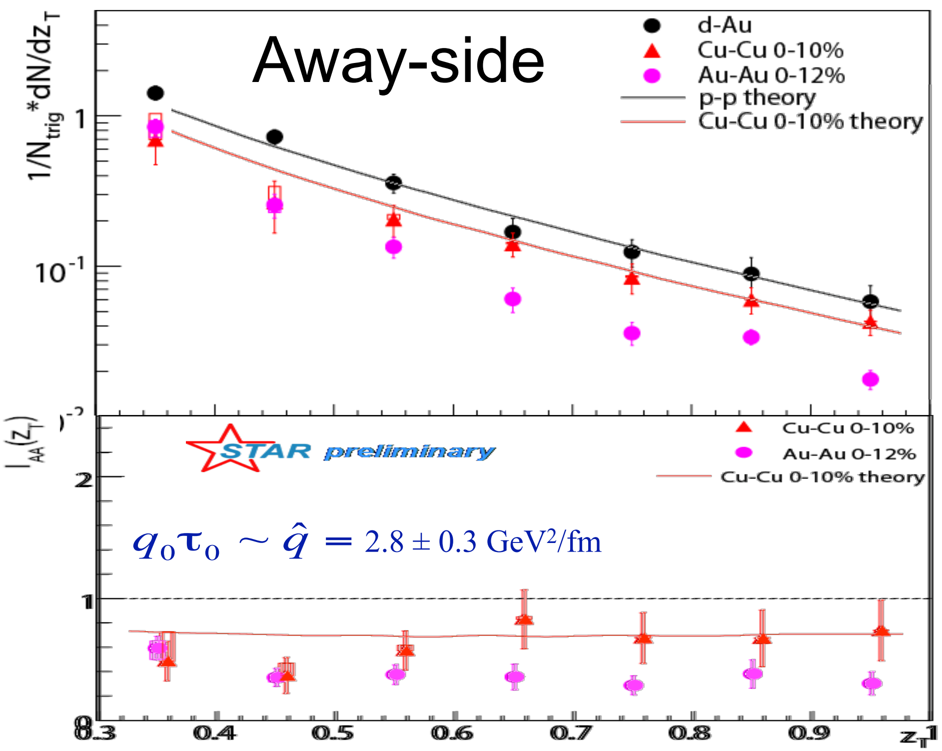
Parameters from Au-Au evolve to Cu-Cu

Fragmentation functions Cu-Cu & Au-Au

$6 < p_{T\,trig} < 10$ GeV

O. Catu QM2008





Theory - X.N.Wang private communication

H.Zhang, J.F. Owens, E. Wang, X.N. Wang - Phys. Rev. Lett. 98: 212301 (2007)

Near-side: Unmodified

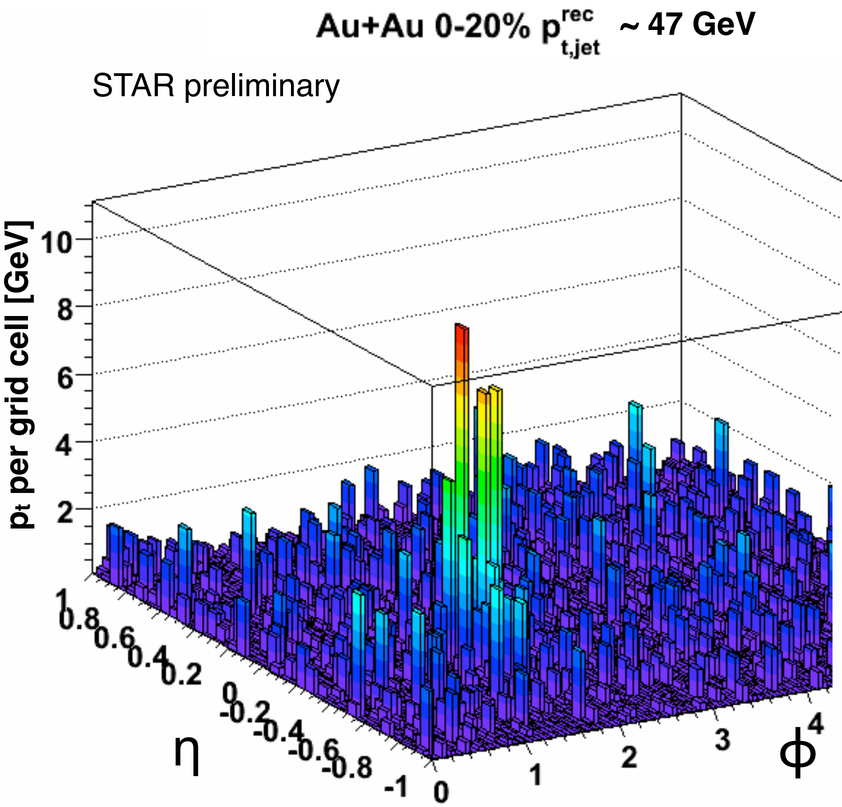
Away-side: Suppressed but shape not modified (in considered z_T range)

Less suppressed for central Cu-Cu than Au-Au

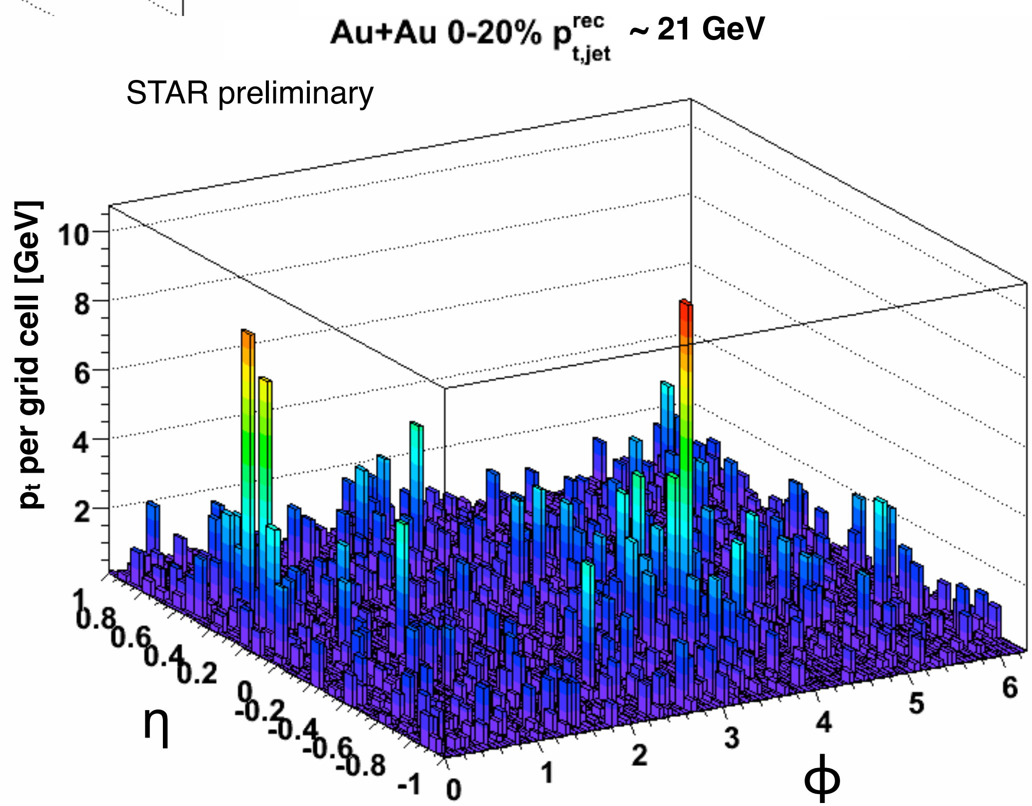
Parameters from Au-Au evolve to Cu-Cu

Consistent with vacuum fragmentation after energy loss!

Jets @ RHIC in Au-Au collisions



Clearly visible in central events on E-by-E basis

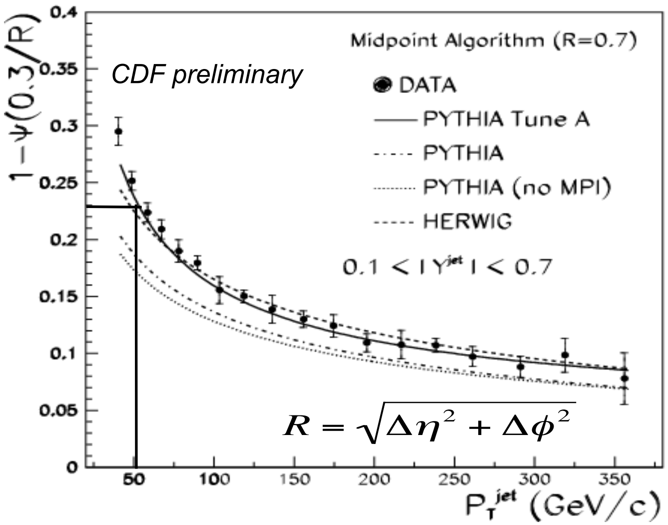


Energies as low as 20 GeV resolvable

J. Putschke Hard Probes 2008

Jet-finding strategies in heavy-ion

Jet energy fraction outside cone

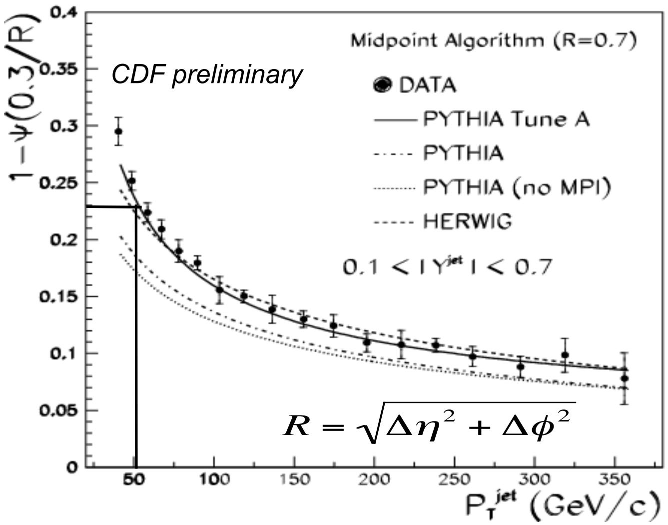


- Unmodified (p+p) jets:
  ~ 80% of energy within R~0.3
- Need to suppress heavy-ion background:
  small jet cones areas
  R~0.3-0.4
  remove underlying event
  $p_{t,track}$,$E_{t,tower}$ >1-2 GeV

J. Putschke Hard Probes 2008

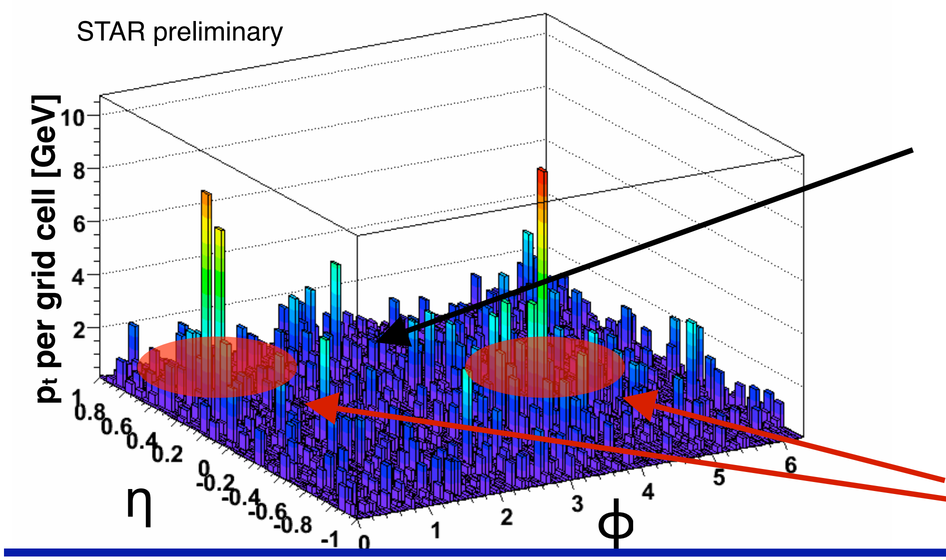
Jet-finding strategies in heavy-ion

Jet energy fraction outside cone



- Unmodified (p+p) jets:
  ~ 80% of energy within R~0.3
- Need to suppress heavy-ion background:
  small jet cones areas
  R~0.3-0.4
  remove underlying event
  $p_{t,track}$,$E_{t,tower}$ >1-2 GeV

Estimate background E-by-E by sampling Out-of-Cone area:

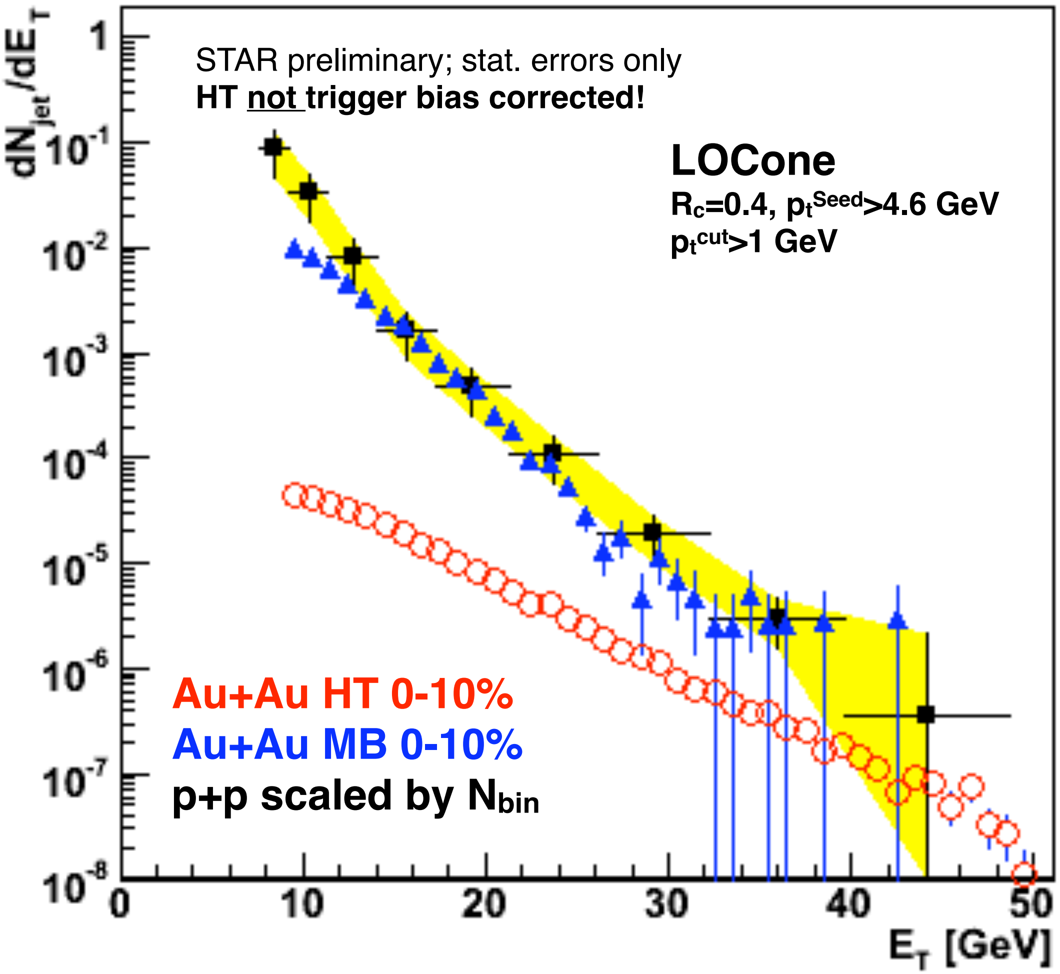


Out-of-Cone area:
used to estimate mean background energy and “mean background FF function”

Caveat: Precision depends on acceptance, event-by-event fluctuations and elliptic flow (small effect for central heavy-ion collisions) …

J. Putschke Hard Probes 2008

Jet spectrum in Au+Au collisions



MB-Trig: Good agreement with N_{bin} scaled p+p collisions

HT-Trig: Large trigger bias how far up does it persist? (in p+p at least to 30 GeV)

Relative normalization systematic uncertainty: ~50%.

Further statistics of MB is needed to assess the bias in HT Trigger.

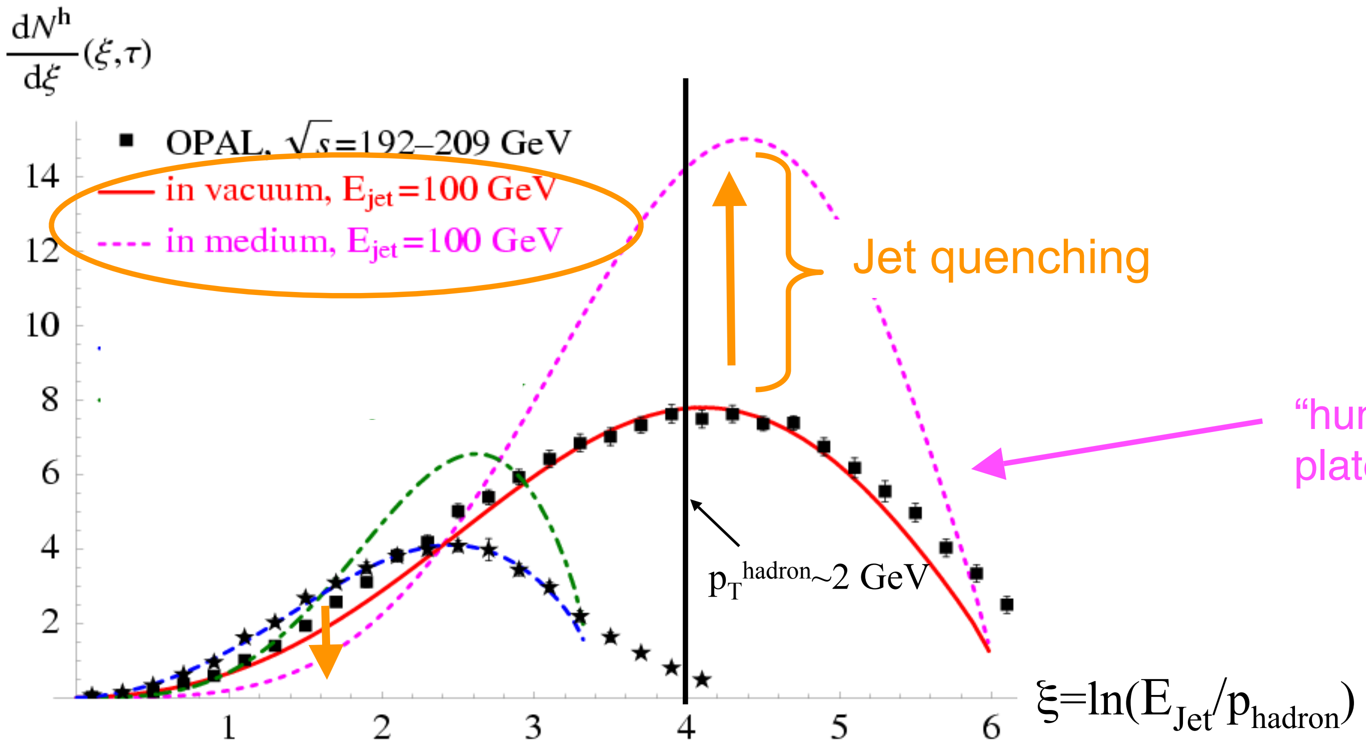
First reconstructed jets in central heavy ion collisions.

black points: p+p mid-cone corrected to particle level (scaled by N_{bin})
blue solid points: Au+Au minbias corrected for p_t^{cut} and eff. using Pythia
red open points: Au+Au HT trigger not corrected for p_t^{cut} and eff. using Pythia

S. Salur Hard Probes 2008

A closer look at Au-Au fragmentation

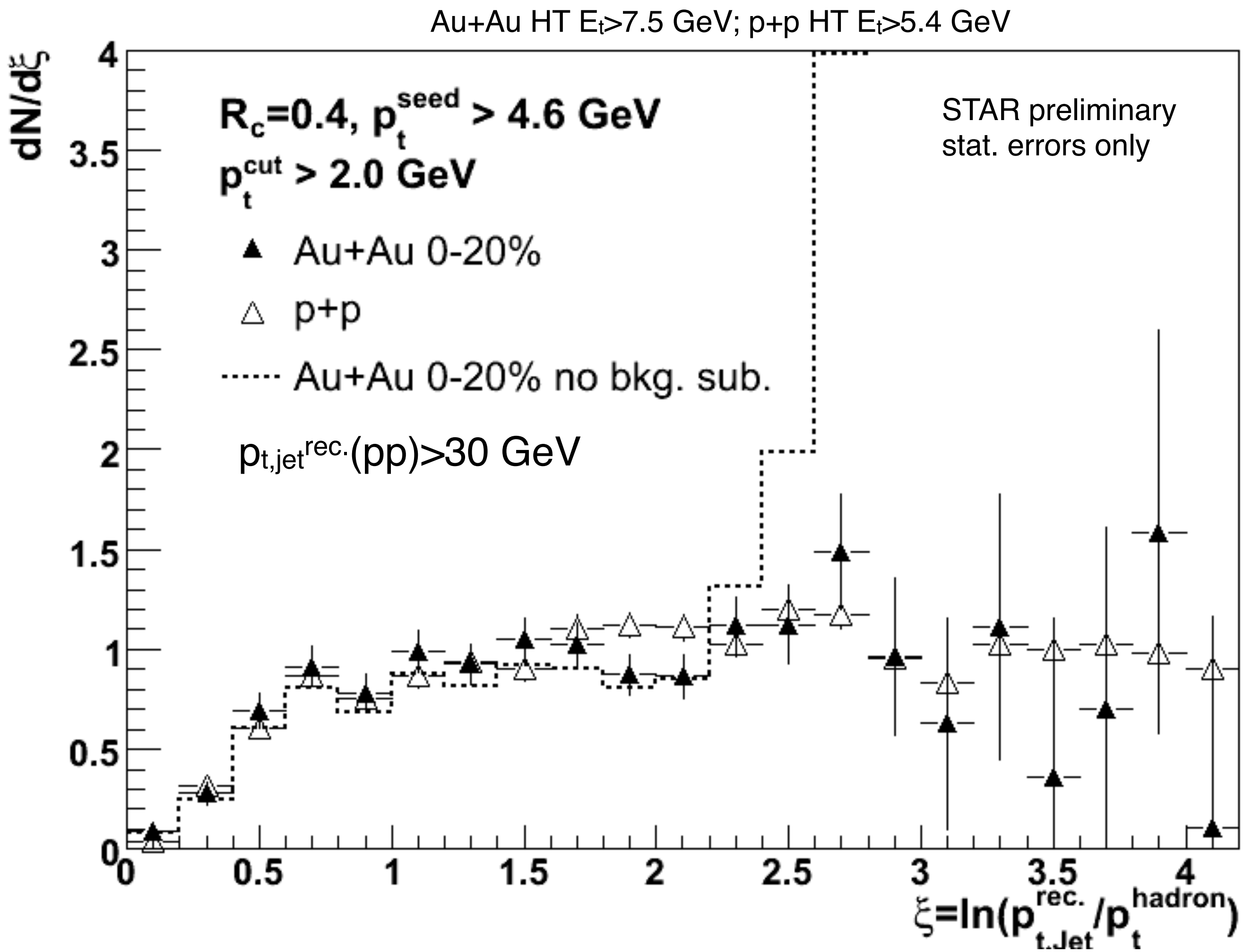
- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*



Jet quenching ⇒ fragmentation should be strongly modified at p_T^{hadron}~1-5 GeV

Do we measure this at RHIC?

Fragmentation function ratio Au+Au



$p_{t,jet}^{rec.}$(pp)>30 GeV

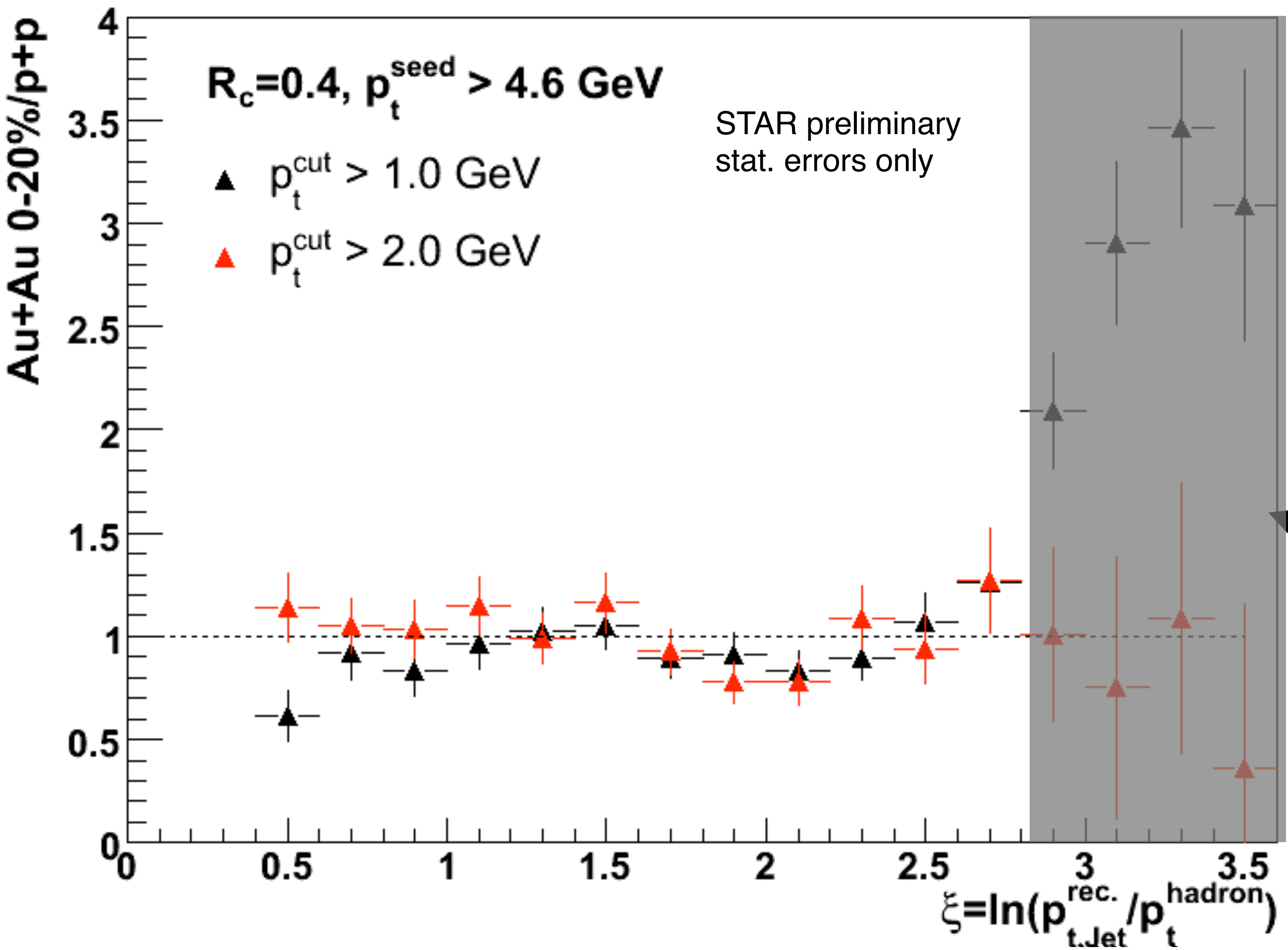
To select corresponding p+p jet-population in 0-20% Au+Au based on Pythia simulations:

$p_{t,jet}^{rec.}$(Au+Au)>31 GeV for p_t^{cut}>2 GeV

$p_{t,jet}^{rec.}$(Au+Au)>35 GeV for p_t^{cut}>1 GeV

J. Putschke Hard Probes 2008

Fragmentation function ratio Au+Au



$p_{t,jet}^{rec.}$(pp)>30 GeV

To select corresponding p+p jet-population in 0-20% Au+Au based on Pythia simulations:

$p_{t,jet}^{rec.}$(Au+Au)>31 GeV for p_t^{cut}>2 GeV

$p_{t,jet}^{rec.}$(Au+Au)>35 GeV for p_t^{cut}>1 GeV

dominated by uncertainties due to background subtraction for p_t^{hadron}<2 GeV

No apparent modification of frag. function compared to p+p !?

Caveat: ξ not corrected for jet energy shift due to quenching. Need MC quenching models !

J. Putschke Hard Probes 2008

Summary

At RHIC we are past the discovery stage ⇒ quantitative

- What are the properties of this strongly coupled medium?
  - i.e. transport coefficients

Di-hadron correlations suggest

- Large e-loss occurs in the medium followed by vacuum fragmentation
- many models seem to be an OK job, need more selective data

First full jet reconstruction in heavy-ion collisions

- Leading jet energy spectrum shows no strong suppression
- Leading jet fragmentation spectrum shows no shape change (where measured)
- Use in combination with previous data and new results on γ-jet (not shown) to further constrain E-loss models

Next steps

- Ongoing upgrades to STAR and PHENIX
  - Vertex detectors, increased coverage and PID, improved triggering capabilities ⇒ rare probes, heavy flavor, γ-jet, ...
- Electron Beam Ion Source (EBIS) to extend ranges of species (U+U)
- RHIC-II: increase luminosity by factor 5 using stochastic cooling
- LHC - next energy frontier, unique opportunity to study QGP