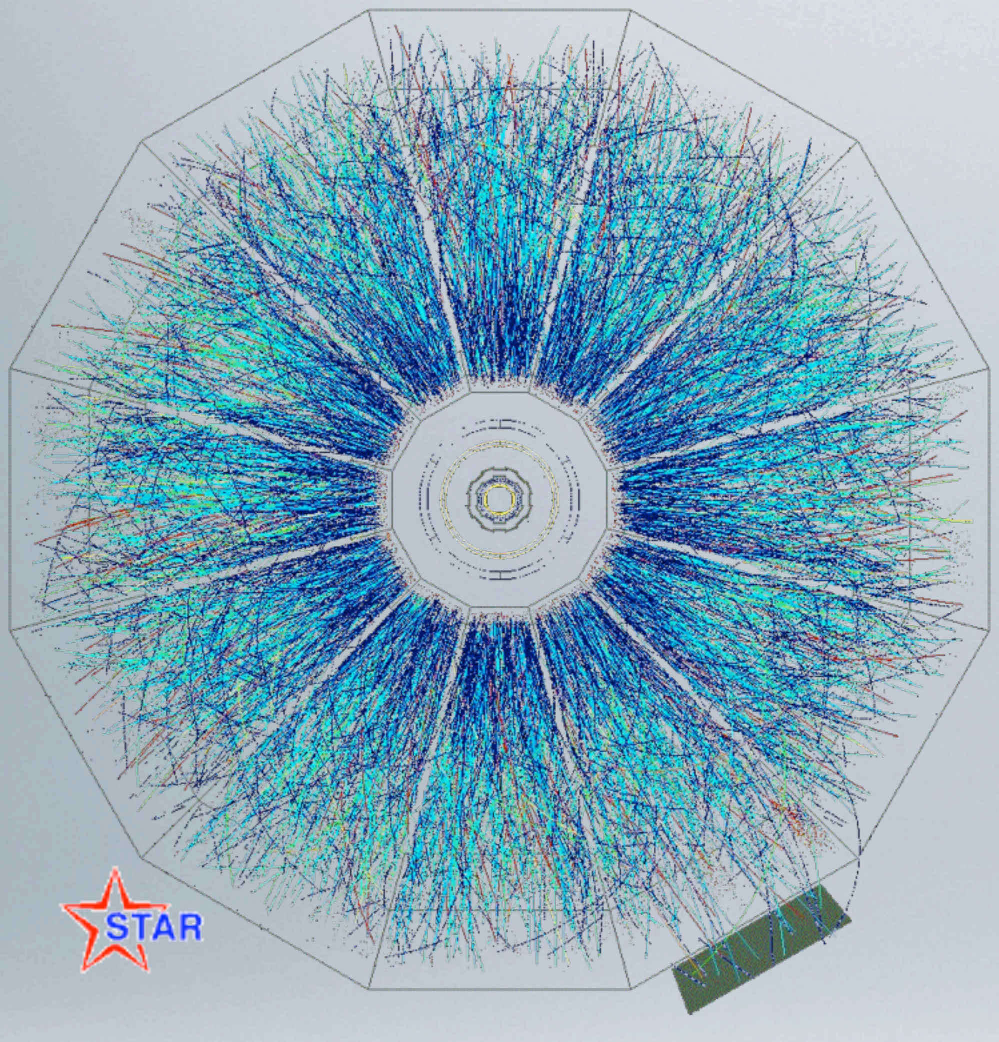
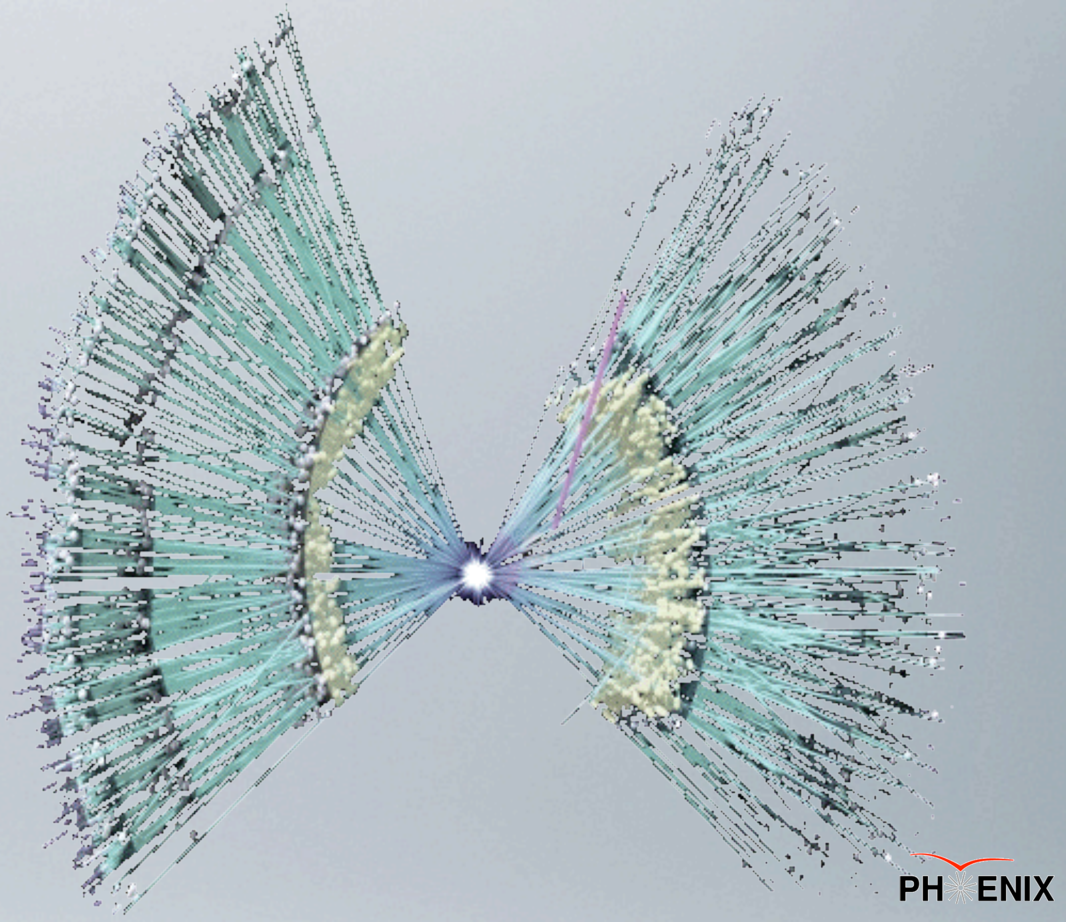




RECENT RESULTS FROM RHIC

T. Peitzmann
Utrecht University

Lepton Photon 2009, Hamburg

Universiteit Utrecht

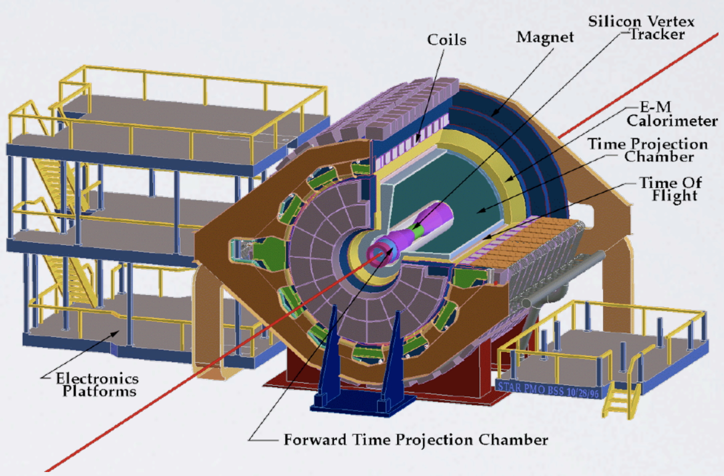
NIKHEF

THE RHIC PROGRAM

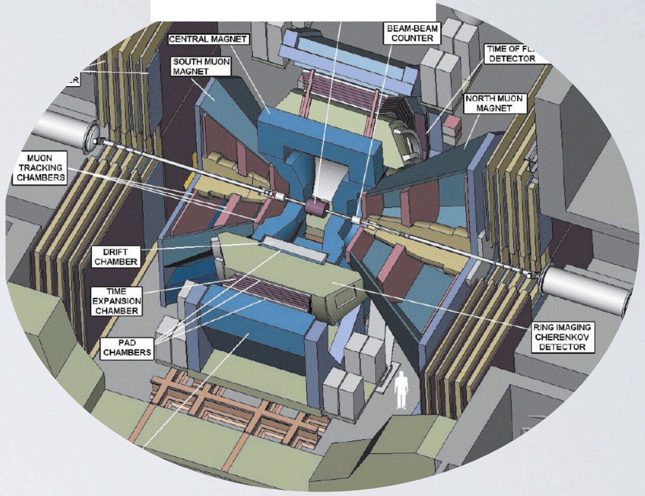
- BNL accelerator complex delivering beams since 2000
  - p+p at 62, 200, 500 GeV
    - polarized beams for spin program
    - reference for heavy ions
  - Au+Au at 9.2, 19.6, 62.4, 130, 200 GeV
  - Cu+Cu at 22.4, 62.4, 200 GeV

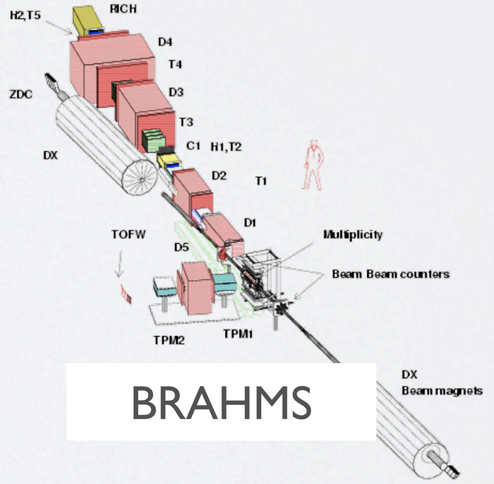
- four experiments

STAR

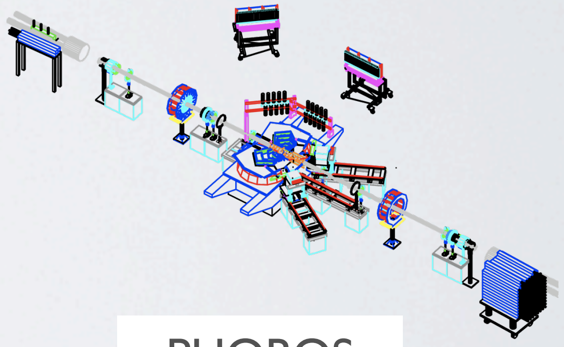


PHENIX





BRAHMS



PHOBOS

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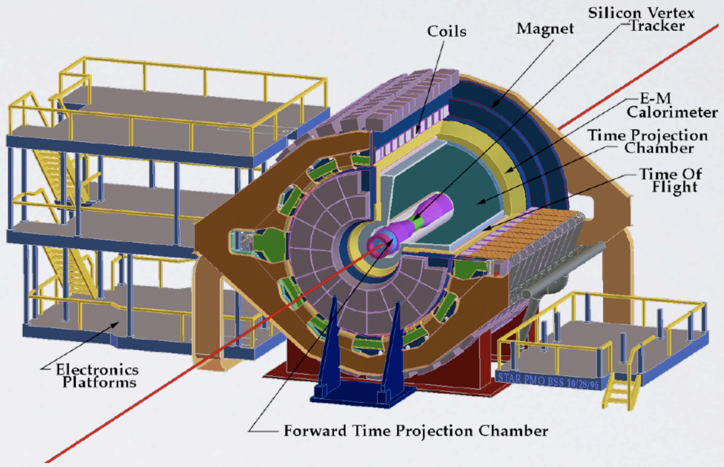

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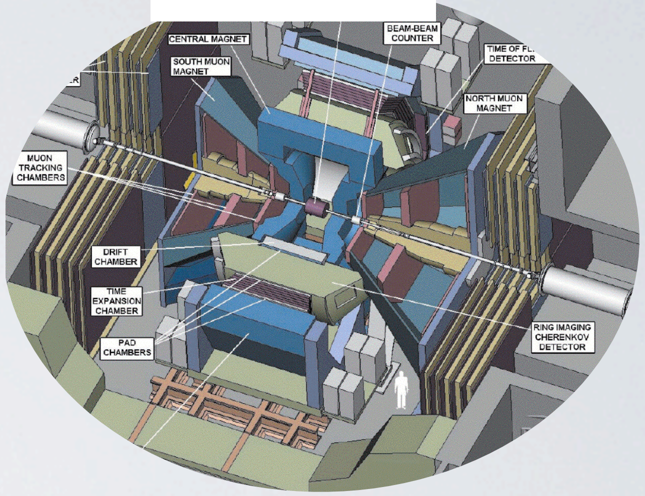
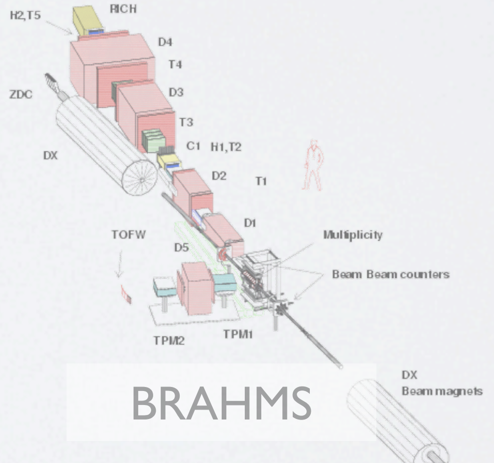


being upgraded



BRAHMS

PHOBOS

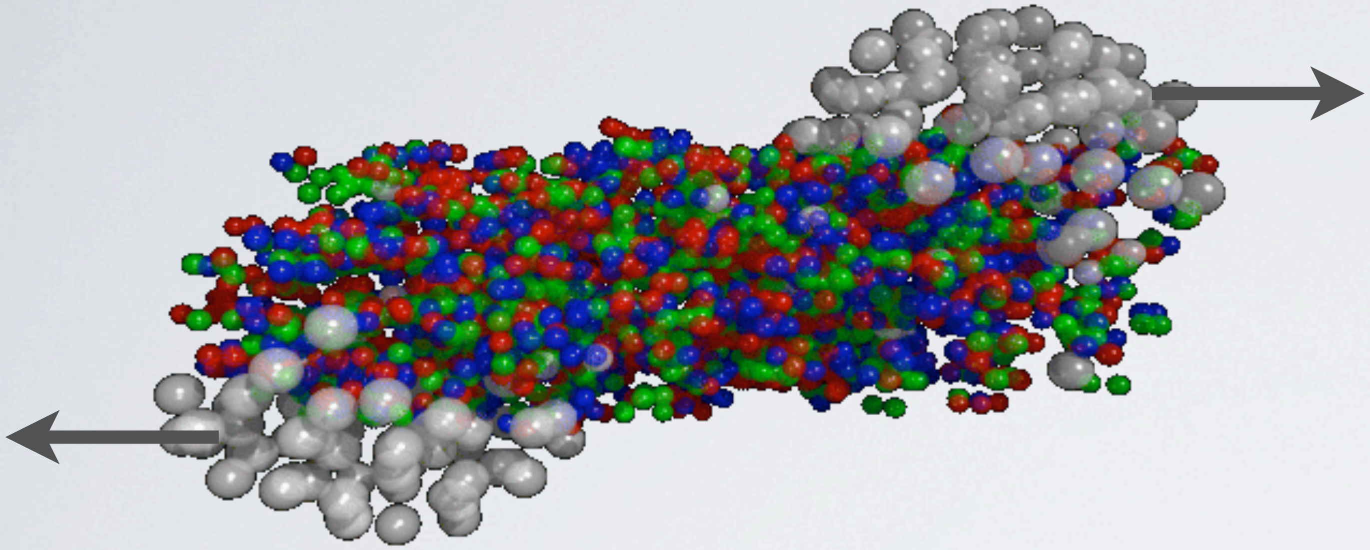
finished data taking in 2006

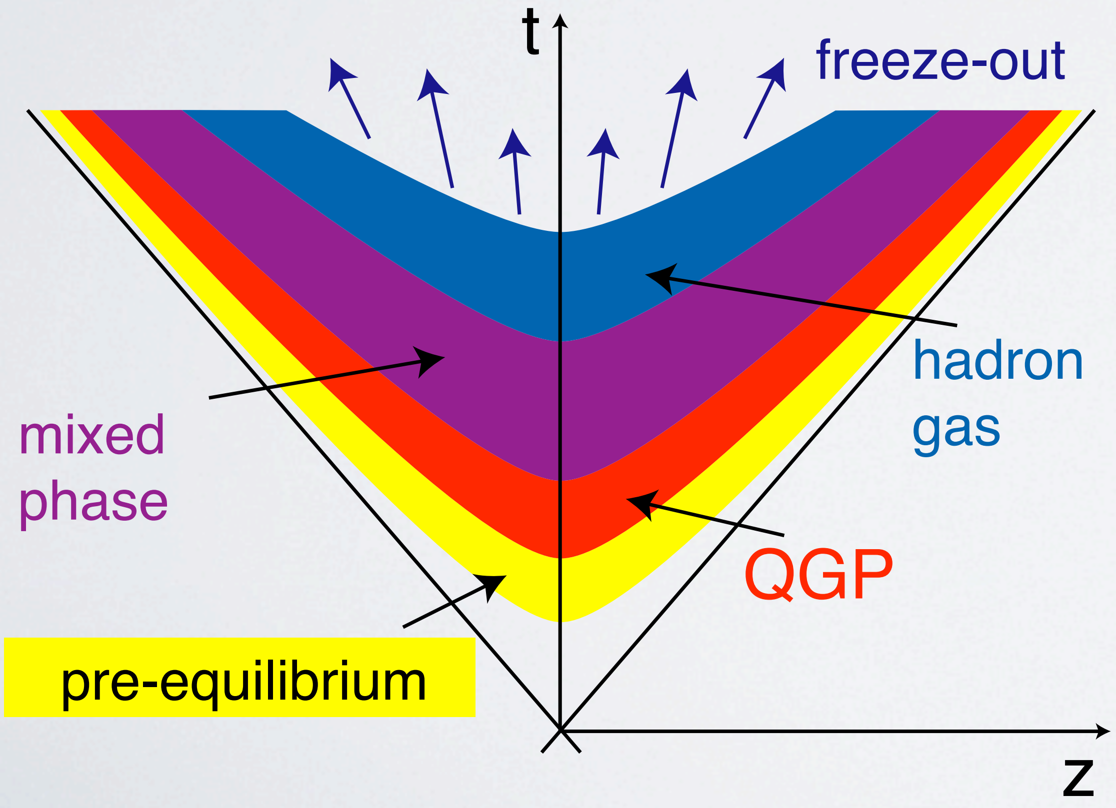
OUTLINE

- the initial state: gluon saturation
- elliptic flow: equilibration and viscosity
- *interlude: taking equilibration serious*
- parton energy loss: jet quenching and medium response
- heavy flavor
- thermal photons

- caveat: many results I can not cover here!

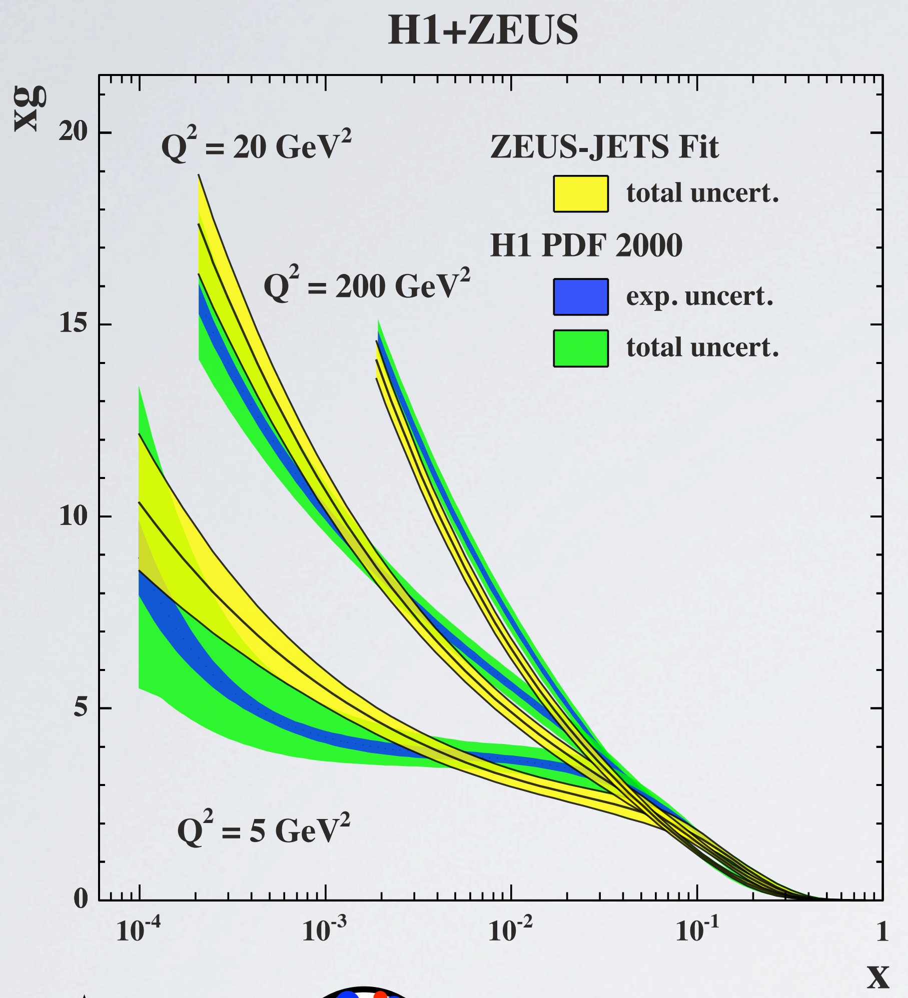
HEAVY-ION COLLISIONS

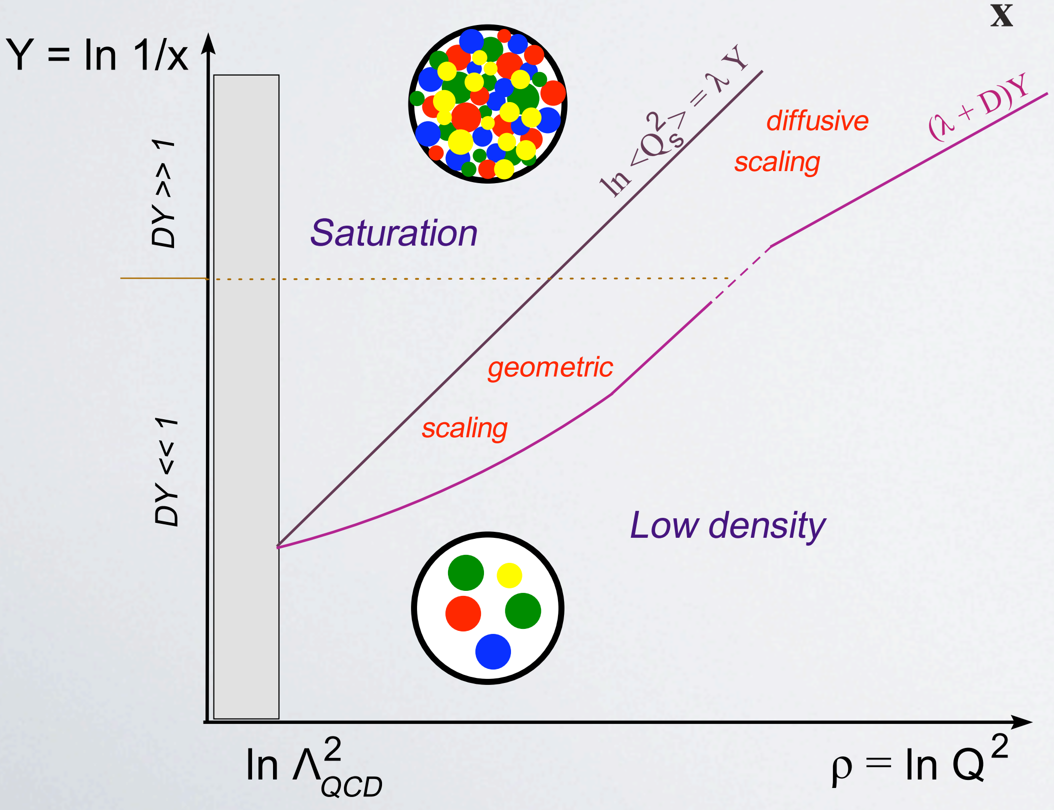




- want to study dense, equilibrated partonic system
    - equilibration achievable? (see later)
- for any description of the evolution of the system need knowledge of **initial state**
- 0. order assumption: independent superposition of nucleons
    - use PDFs to get parton densities

GLUON SATURATION

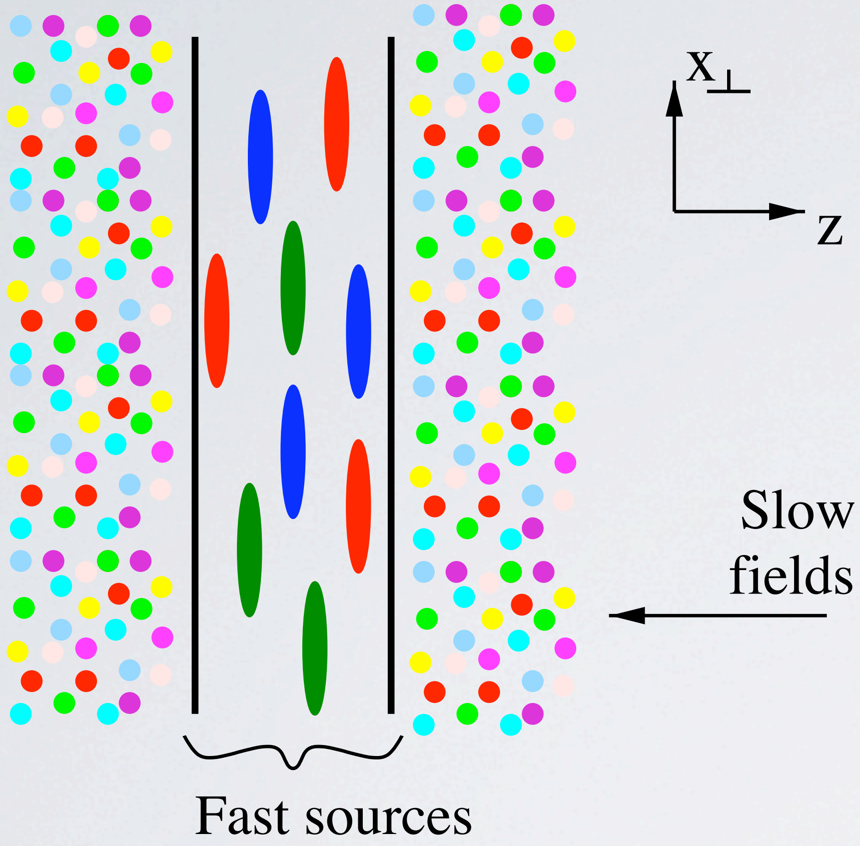


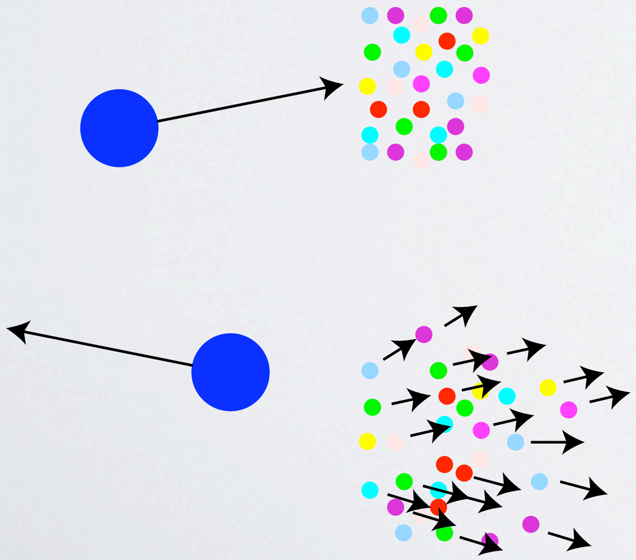


- from evolution equations (DGLAP, BFKL):
- gluon density increases with Q^2 and 1/x
  - leads to very high gluon density
  - problems with unitarity
- for high density non-linear processes become important
- gluon saturation below saturation scale

$$Q_s^2(x) \approx \frac{\alpha_S}{\pi R^2} xG(x, Q^2) \propto A^{1/3} \cdot x^{-\lambda}$$

COLOR GLASS CONDENSATE



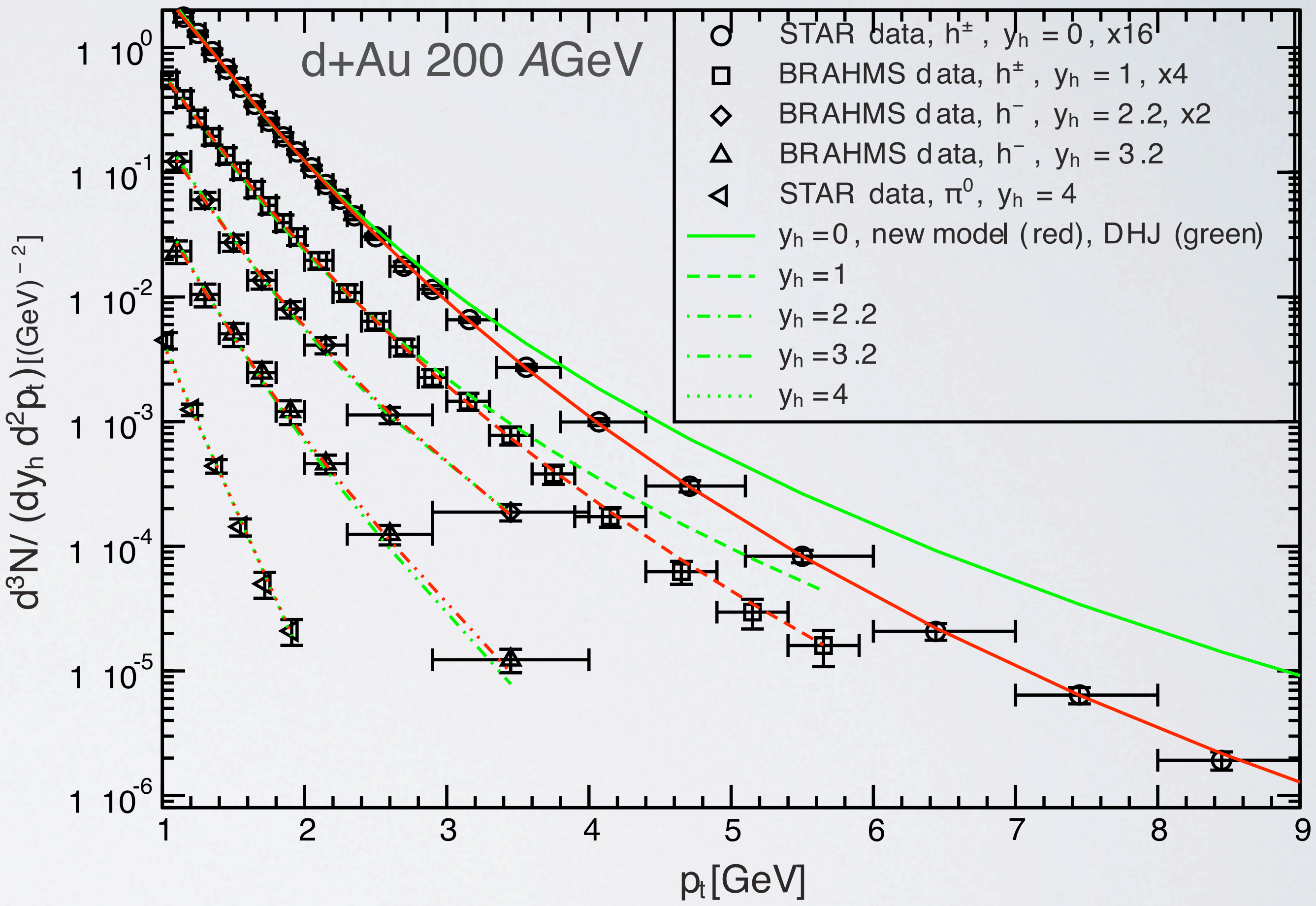


- model for high density limit:
  - condensate - classical color field
  - glass - slowly varying
- gluon saturation predicts:
  - reduction of gluon density compared to DGLAP and BFKL
  - geometric scaling
  - "hard" scatterings off coherent multi-gluon state
    - no recoil jet!
- stronger effects in nuclei!

HADRON SPECTRA AT RHIC

- RHIC data compatible with geometric scaling (red)
- model with scaling violation deviates only at high p_T
  - DGLAP regime?
- region of low x is very low p_T
  - reference (pQCD) not applicable?

D. Boer et al., arXiv:0810.0113



discriminating power at RHIC for details of saturation limited

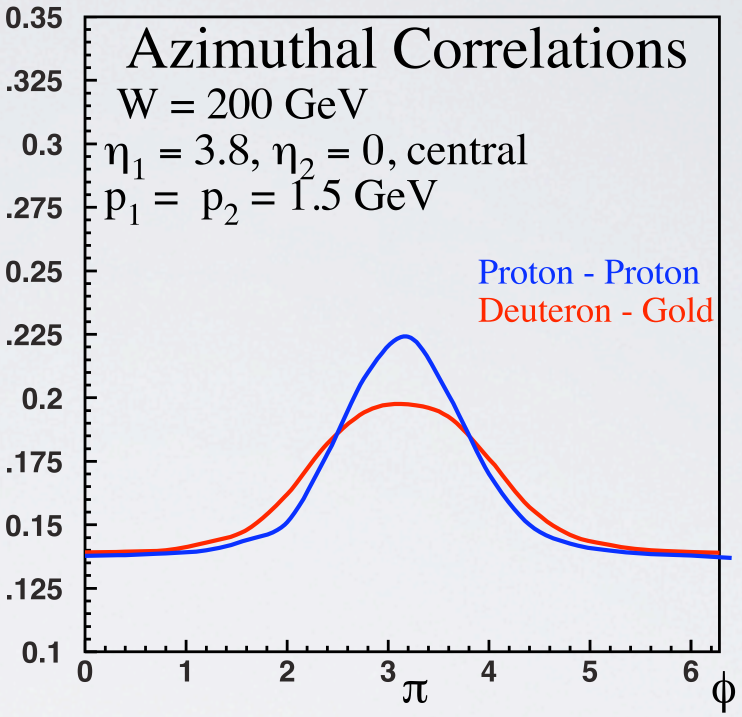
SINGLE VS DI-HADRON STUDIES

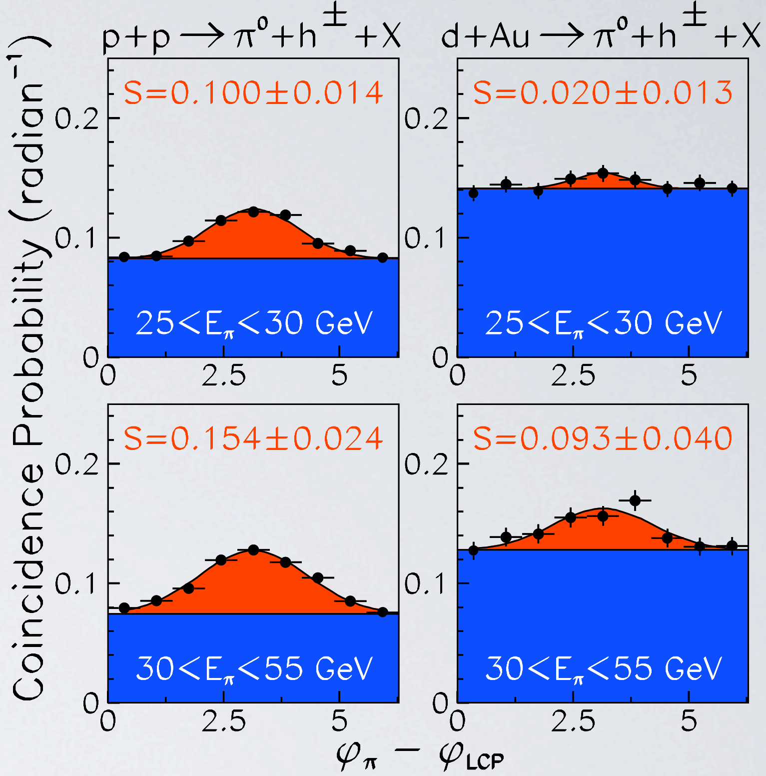
- stronger constraints in x-values for di-hadrons
- normalization issues
  - inclusive yield (pp reference for dA) depends on cross-section normalization (K-factors etc.)
  - triggered correlations: absolute cross-section taken out

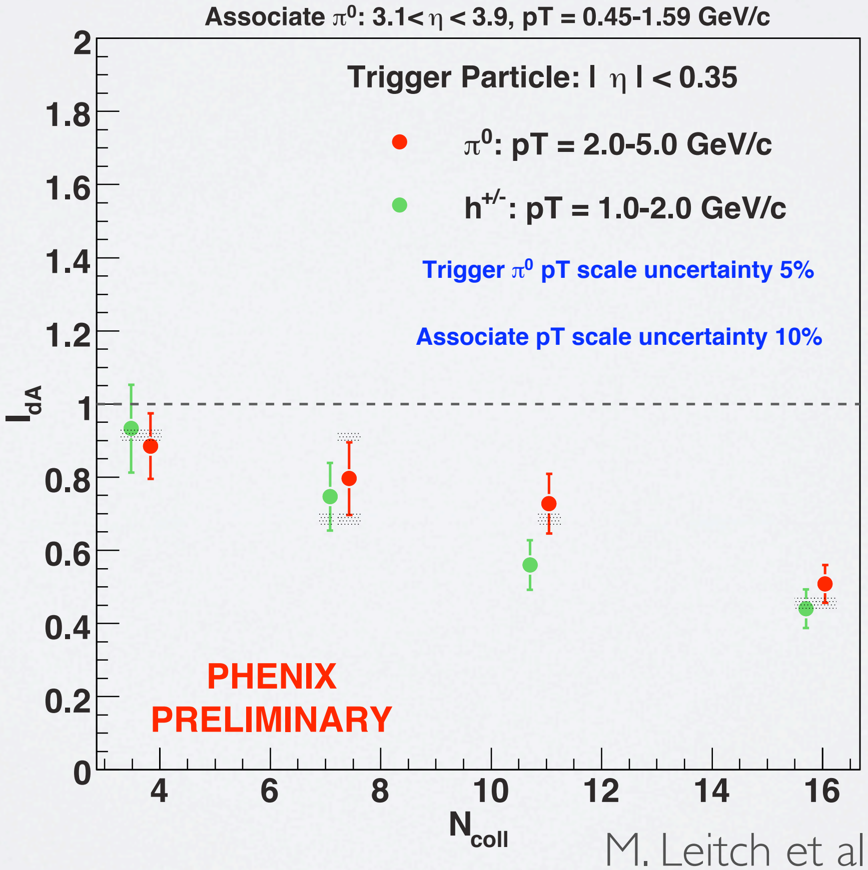
hard scattering occurs, but scattering partner is not a single parton
⇒back-side correlation disappears

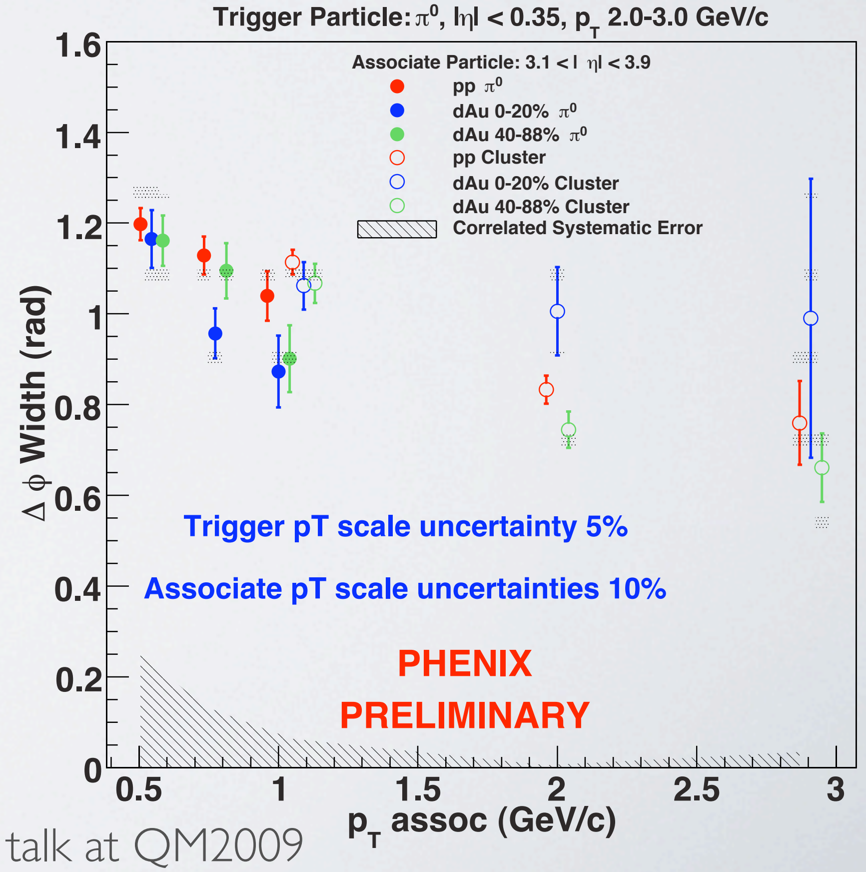
DIHADRON CORRELATIONS

- saturation models predict suppression of di-jet correlation in d+Au
  - qualitatively observed, but data not yet conclusive
  - model calculations not directly comparable to data
  - stay tuned for higher statistics


D. Kharzeev et al., hep-ph/0403271

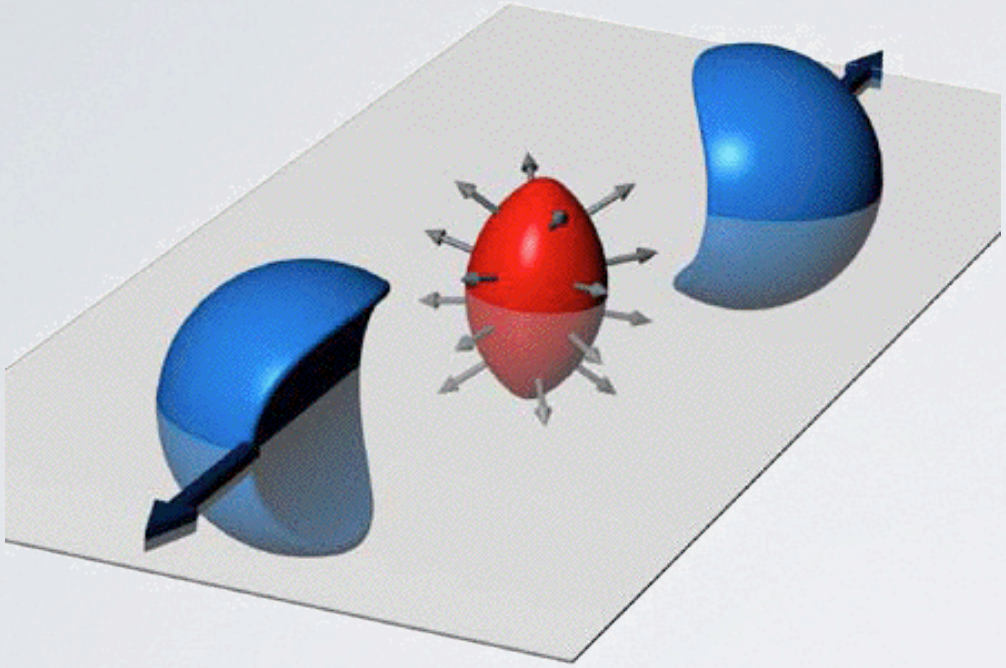

STAR, PRL 97 (2006) 152302



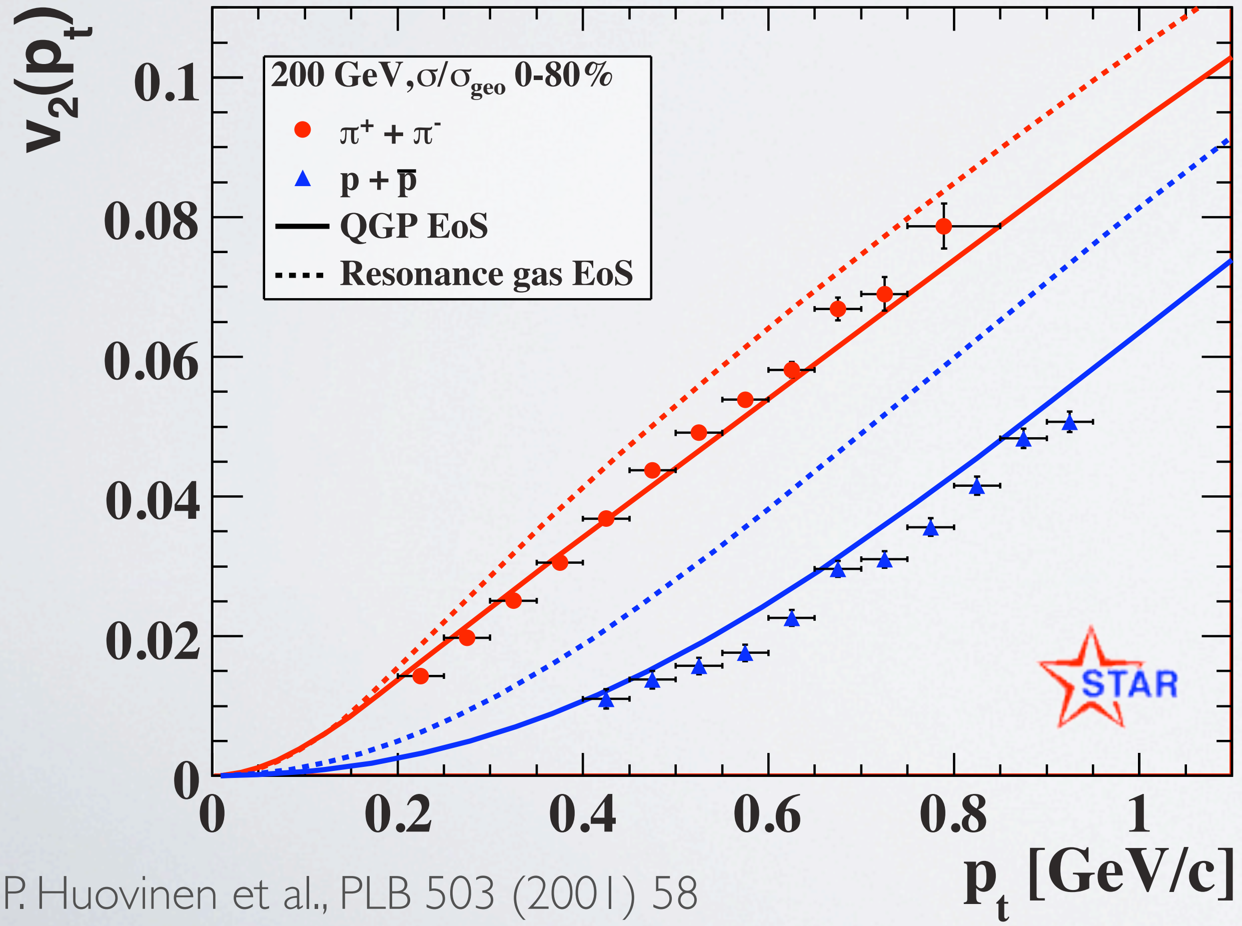


M. Leitch et al, talk at QM2009

ELLIPTIC FLOW



STAR Collaboration, PRL 87 (2001) 182301



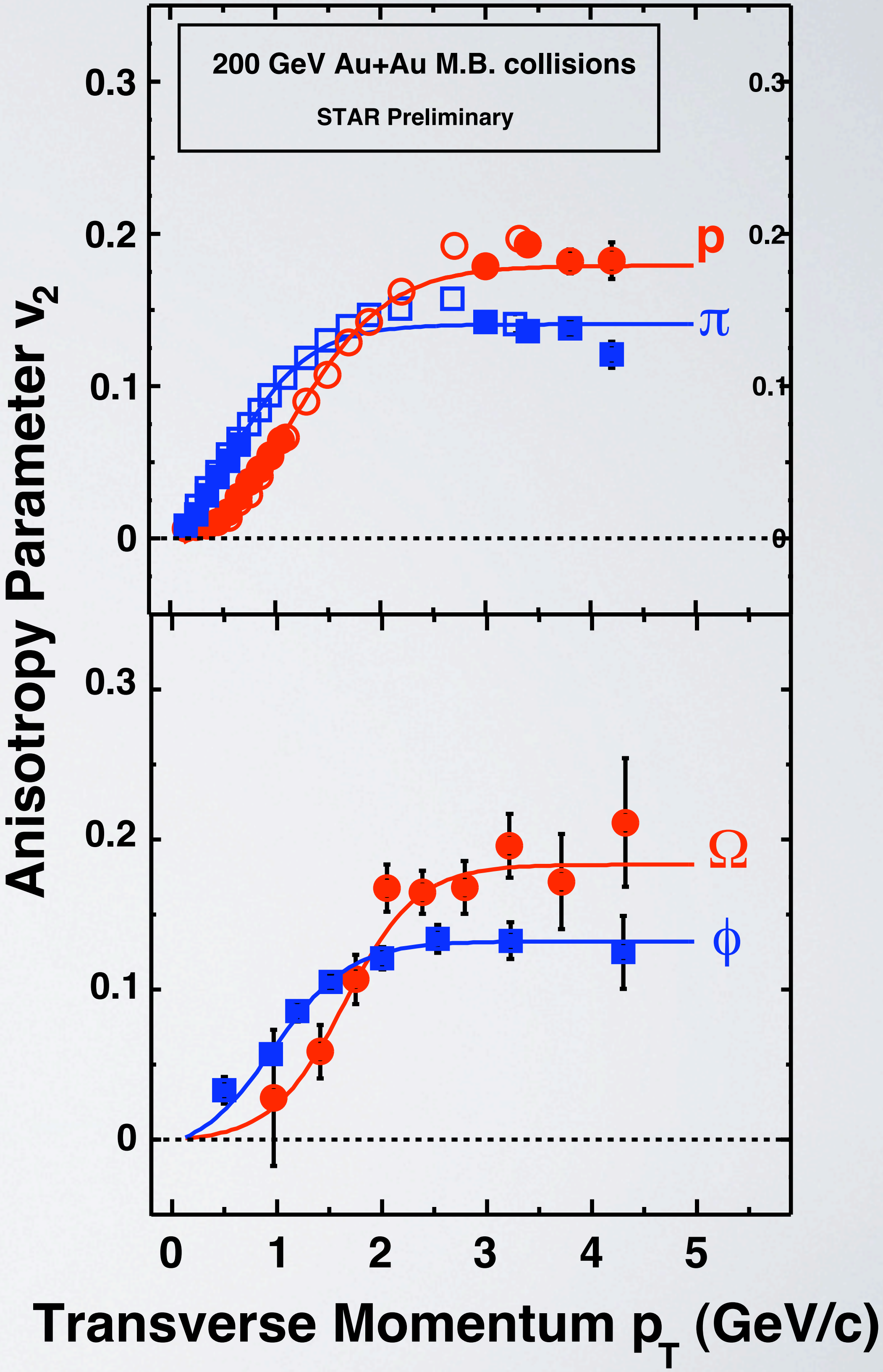
P. Huovinen et al., PLB 503 (2001) 58

- spatial anisotropy of reaction zone results in momentum anisotropy of emitted particles
- requires pressure: equilibration!
  - measured as $v_2 \equiv \langle \cos 2(\phi - \Phi_R) \rangle$
- strong elliptic flow observed at RHIC
  - consistent with ideal hydrodynamics
- mass splitting requires phase transition!

BARYON/MESON V_2

- elliptic flow in larger p_T range
  - baryon-meson splitting
  - for high p_T: $v_2^{(\mathrm{baryon})} \approx \frac{3}{2} v_2^{(\mathrm{meson})}$
- suggests quark number scaling

$$v_2^{(hadron)} \approx n_q \cdot f\left(\frac{m_T - m}{n_q}\right)$$



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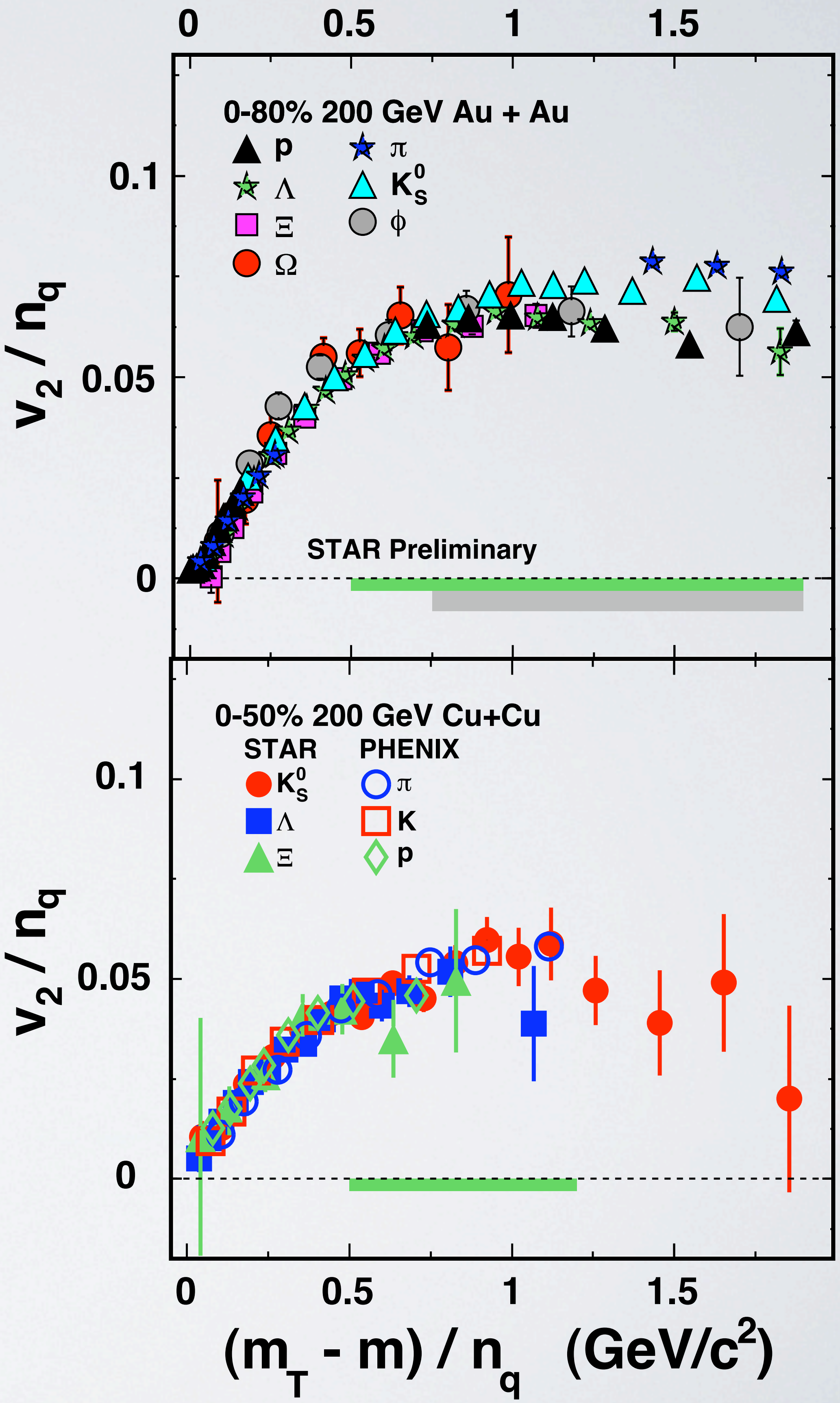
$$v_2^{(hadron)} \approx n_q \cdot f\left(\frac{m_T - m}{n_q}\right)$$

- elliptic flow carries memory from quark phase
- natural in recombination/ coalescence models
  - hadrons formed in a coalescence process from existing quarks



D. Molnar and S. Voloshin, PR**L91**, 092301 (2003)
R. J. Fries et. al., PR**C68**, 044902 (2003)
V. Greco et. al, PR**C68**, 034904 (2003)
J. Jia and C. Zhang, PR**C75**, 031901(R) (2007)...

V_2 AND ECCENTRICITY

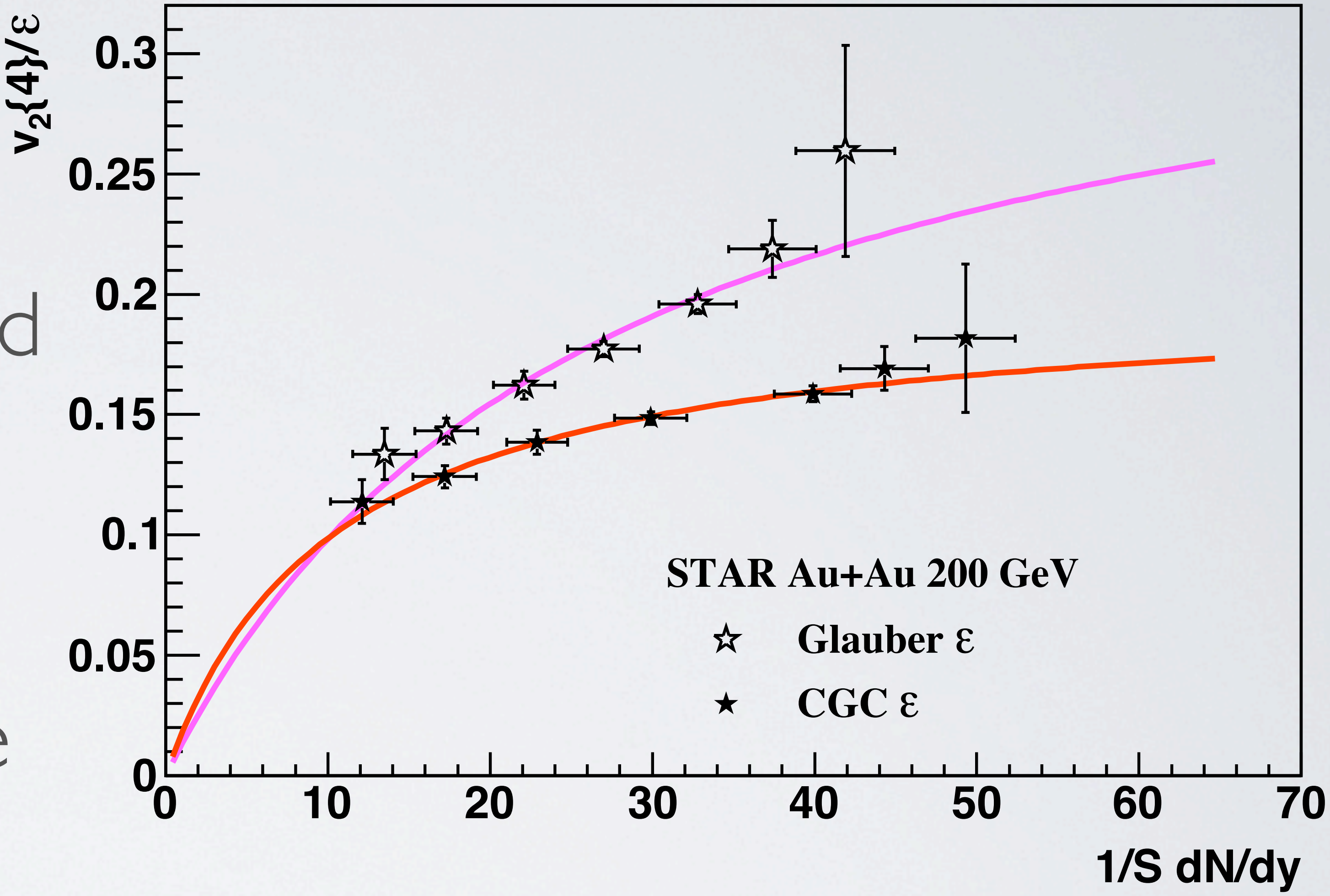
- elliptic flow depends on initial eccentricity ε
- for perfect fluid (i.e. no viscosity) v_2/ε should depend only on equation of state

$$h \equiv v_2^{(\mathrm{perfect})}/\epsilon$$

- dissipative corrections more important for small particle densities
  - parameterize as

$$v_2/\epsilon = \frac{h}{1 + B/(1/S\, dN/dy)}$$

R. Snellings et al., talk at QM2009



CGC leads to larger eccentricity than "traditional" Glauber calculation for central collisions

VISCOSITY ESTIMATES

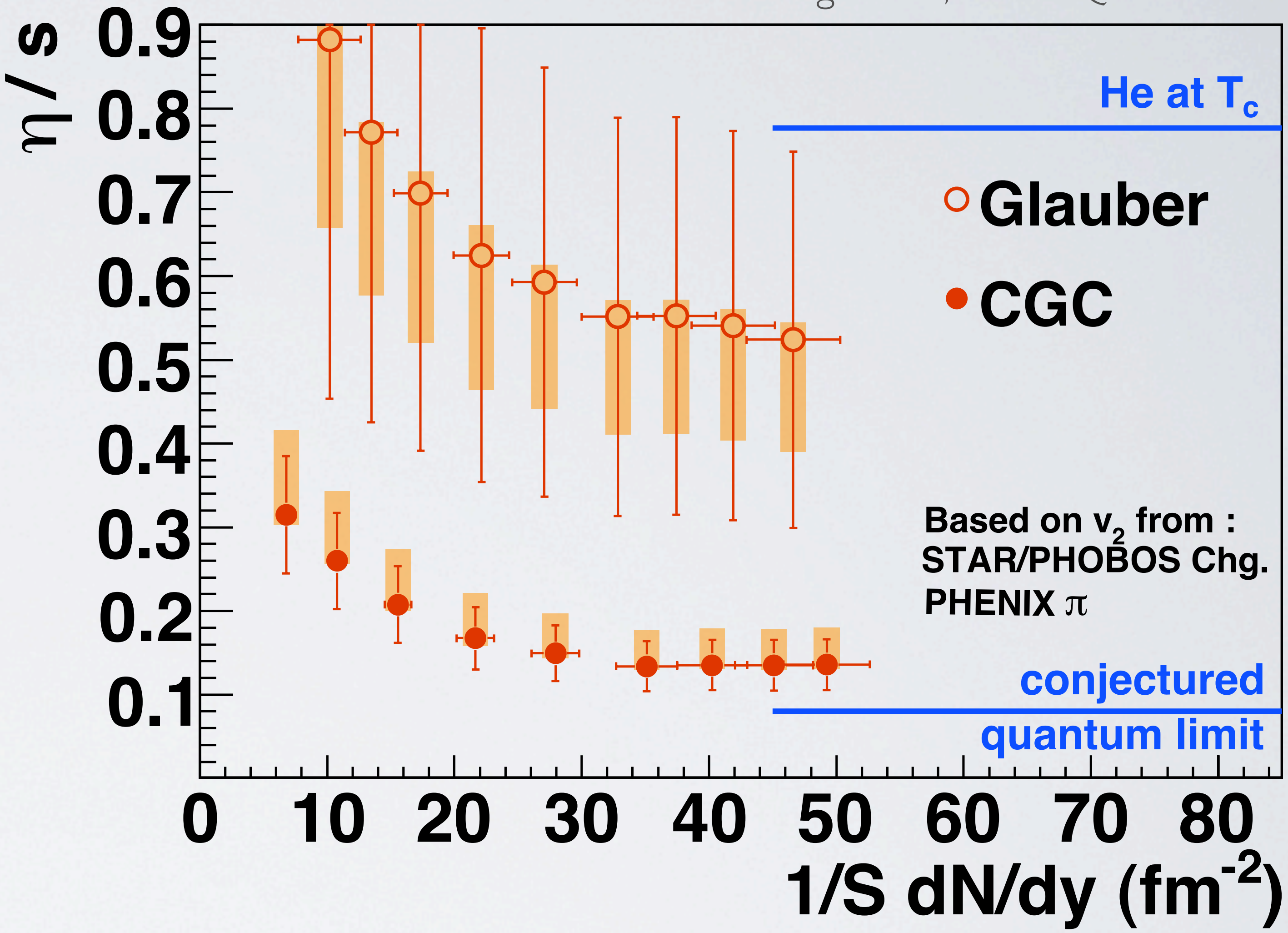
- extracted parameters can be related to viscosity

$$B \approx \frac{1.4}{\sigma c_s}, \qquad \frac{\eta}{s} \approx 0.3 \frac{T}{c\sigma n}$$

  - many caveats - needs e.g. assumptions on temperature and speed of sound

- yields low viscosity
  - Glauber: harder EOS, higher viscosity
  - CGC: softer EOS, lower viscosity

R. Snellings et al., talk at QM2009



viscosity calculable from AdS/CFT correspondence: quantum limit

RHIC data close to minimum viscosity?

THERMALIZATION

- strong elliptic flow requires early local equilibrium
  - most easily explained with quark-gluon plasma
  - extremely small viscosity!
- look at other observables with this in mind
  - consequences in a thermal picture?

- examples:
  - intermediate momentum hadron spectra
    - recombination
  - relative hadron abundances
    - statistical hadronization

INTERMEDIATE MOMENTUM

- baryon/meson ratio at intermediate p_T

$$2 \leq p_T \leq 5\,\mathrm{GeV}/c$$

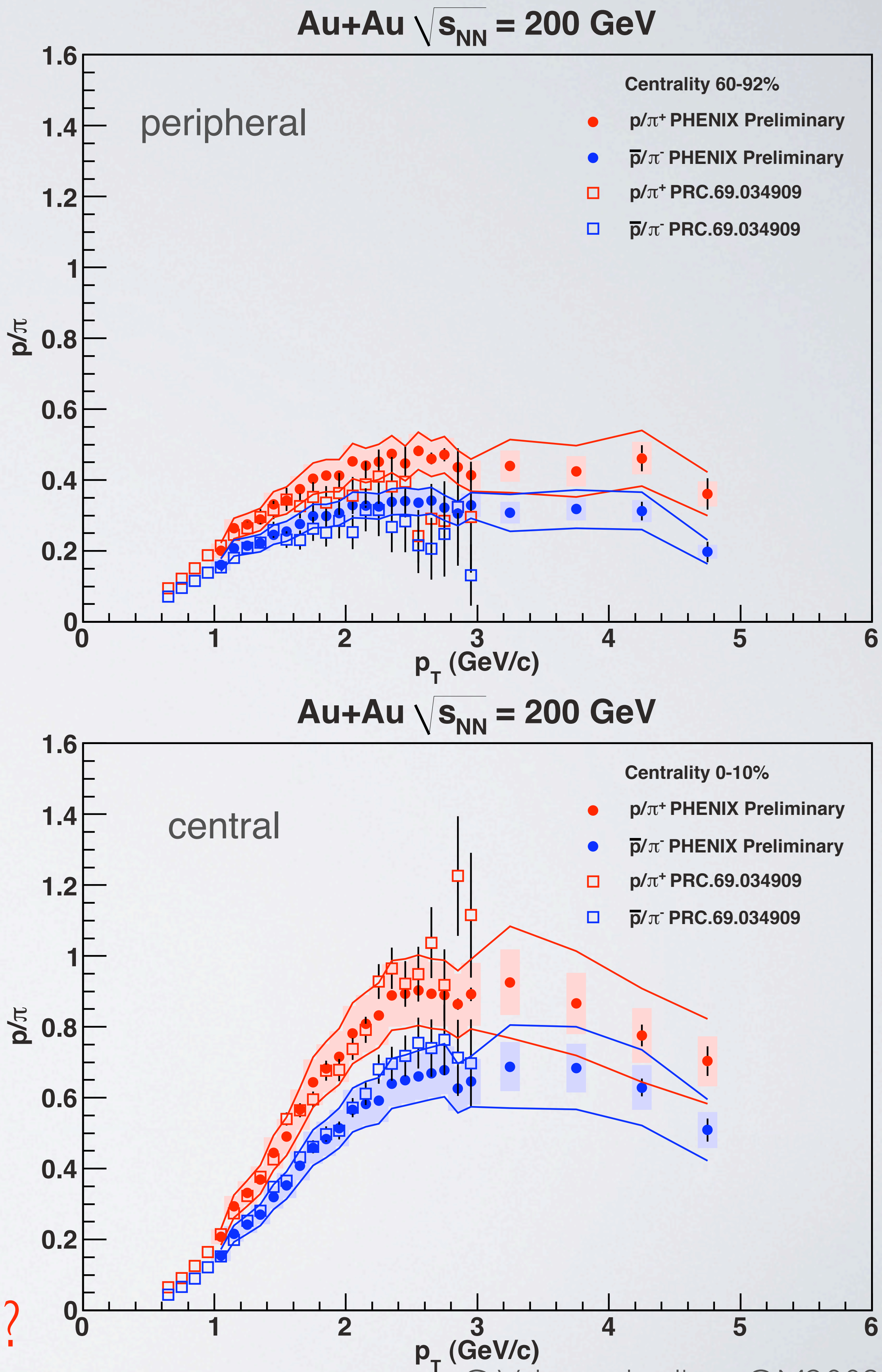
  - in central Au+Au collisions much larger than in p+p: not consistent with standard jet fragmentation
  - can be explained in recombination models: baryons get stronger boost

$$\left\langle p_T^{(baryon)} \right\rangle \approx 3 \cdot \left\langle p_T^{(quark)} \right\rangle$$

$$\left\langle p_T^{(meson)} \right\rangle \approx 2 \cdot \left\langle p_T^{(quark)} \right\rangle$$

    - enhance baryons relative to mesons

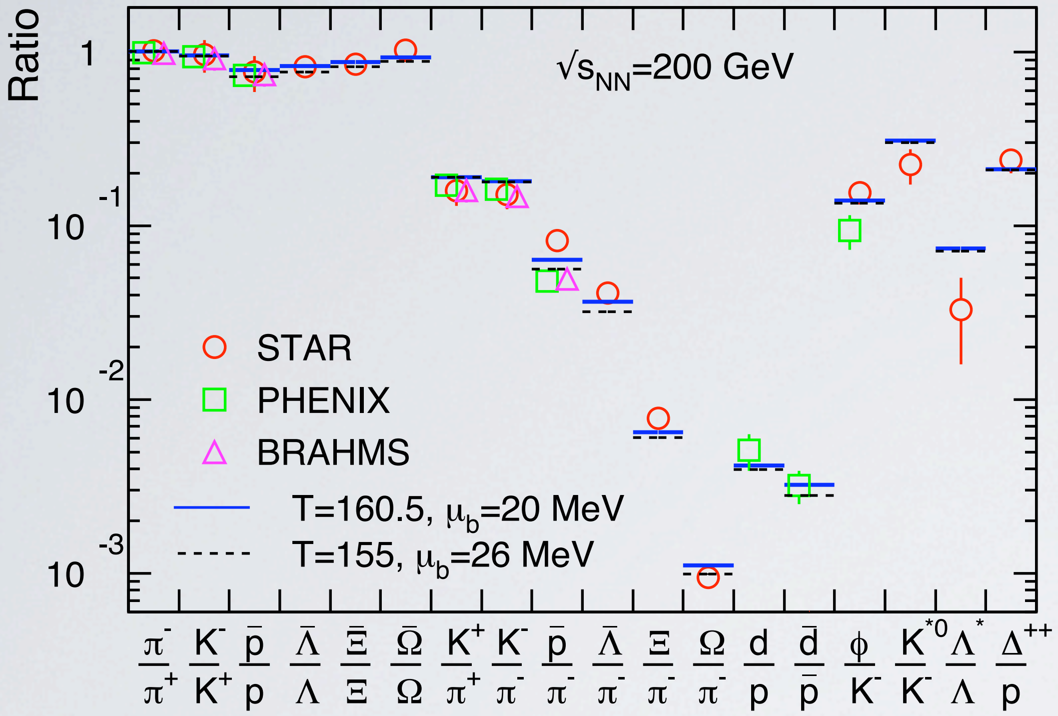
recombination of quarks from thermal system?



C.Vale et al, talk at QM2009

HADRO-CHEMISTRY

Andronic et al., nucl-th/0511071

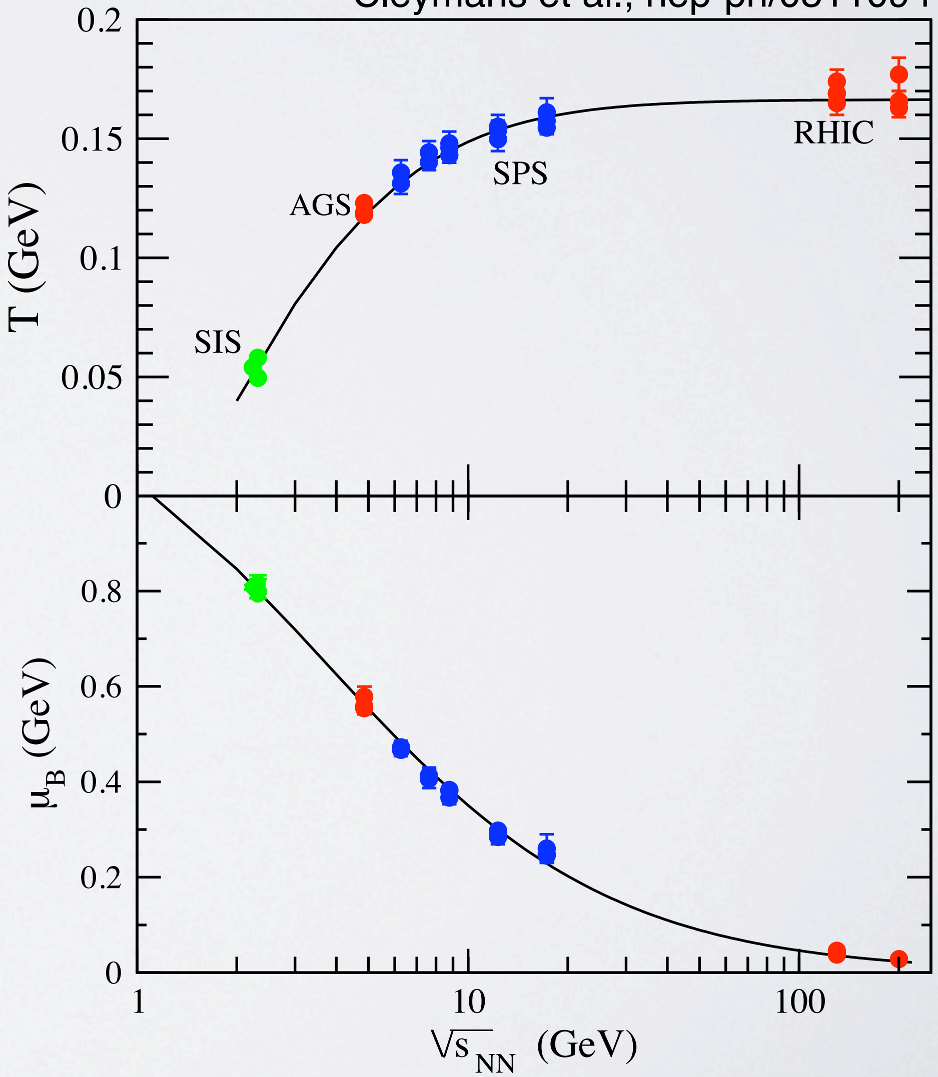


- relative abundances of hadron species can be described by statistical distributions
  - also applicable in very small systems
  - doesn't require equilibration: statistical hadronization

- thermodynamic interpretation of model parameters in high energy A+A collisions:

$$\boxed{T_{chem} \approx T_c}$$

Cleymans et al., hep-ph/0511094



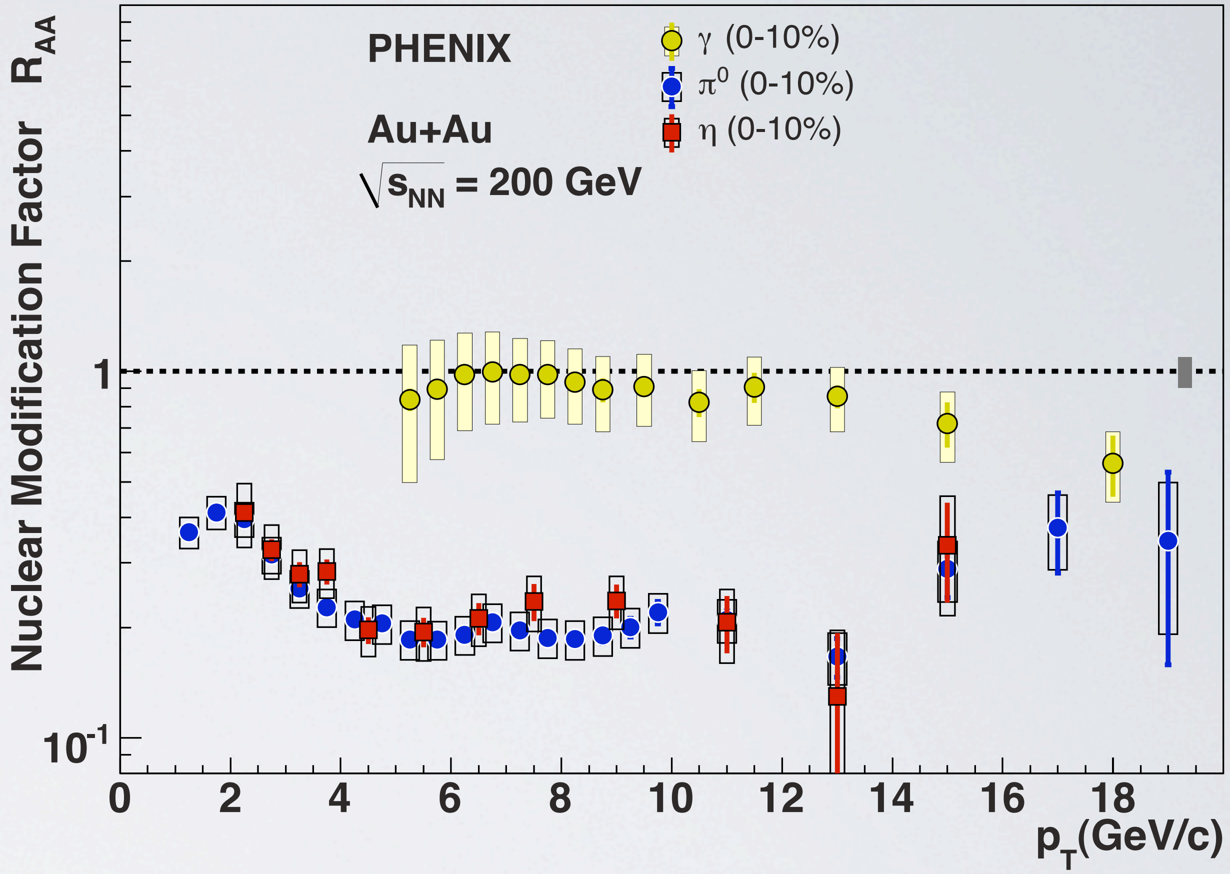
PARTON ENERGY LOSS

- high p_T hadrons strongly suppressed in central Au+Au
- nuclear modification factor

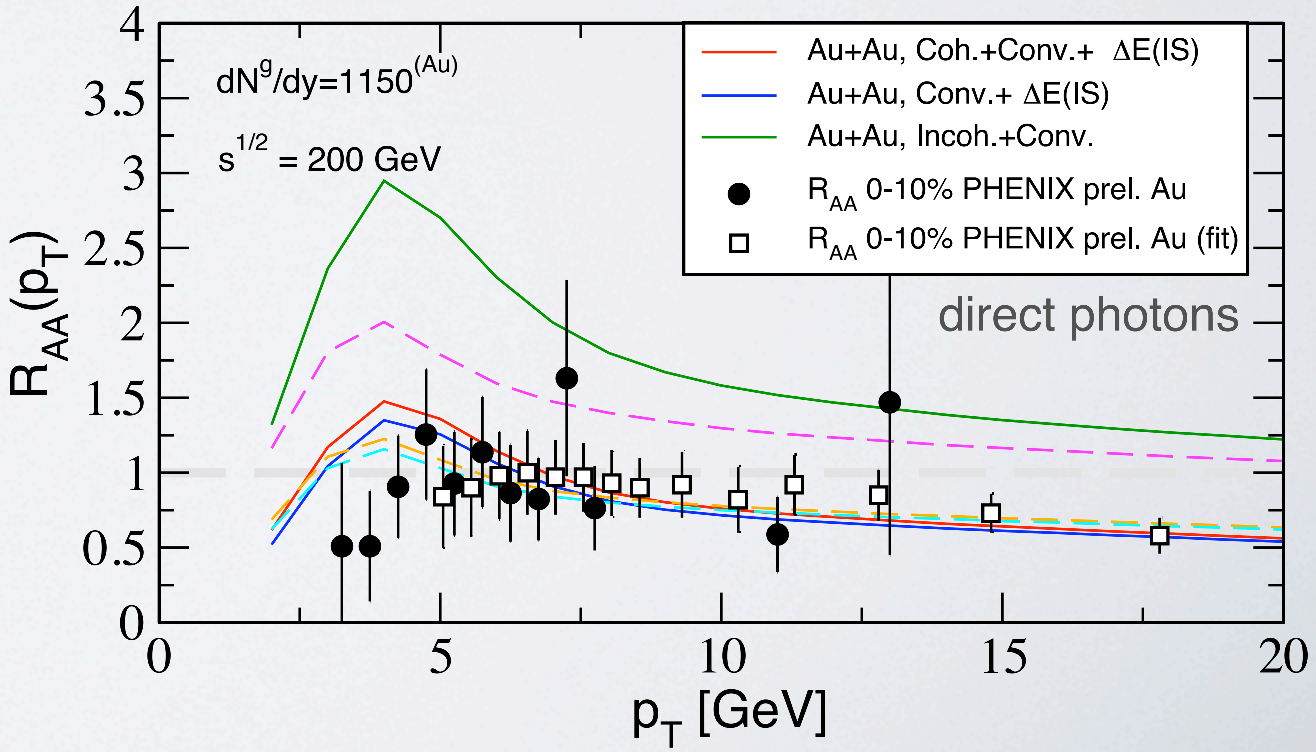
$$R_{AA} \equiv \frac{dN/dp_T^2(AA)}{\langle N_{coll}(AA)\rangle \cdot dN/dp_T^2(pp)}$$

- final state effect due to strong interaction
  - photons not suppressed
- parton energy loss in dense medium

C.Vale et al, talk at QM2009



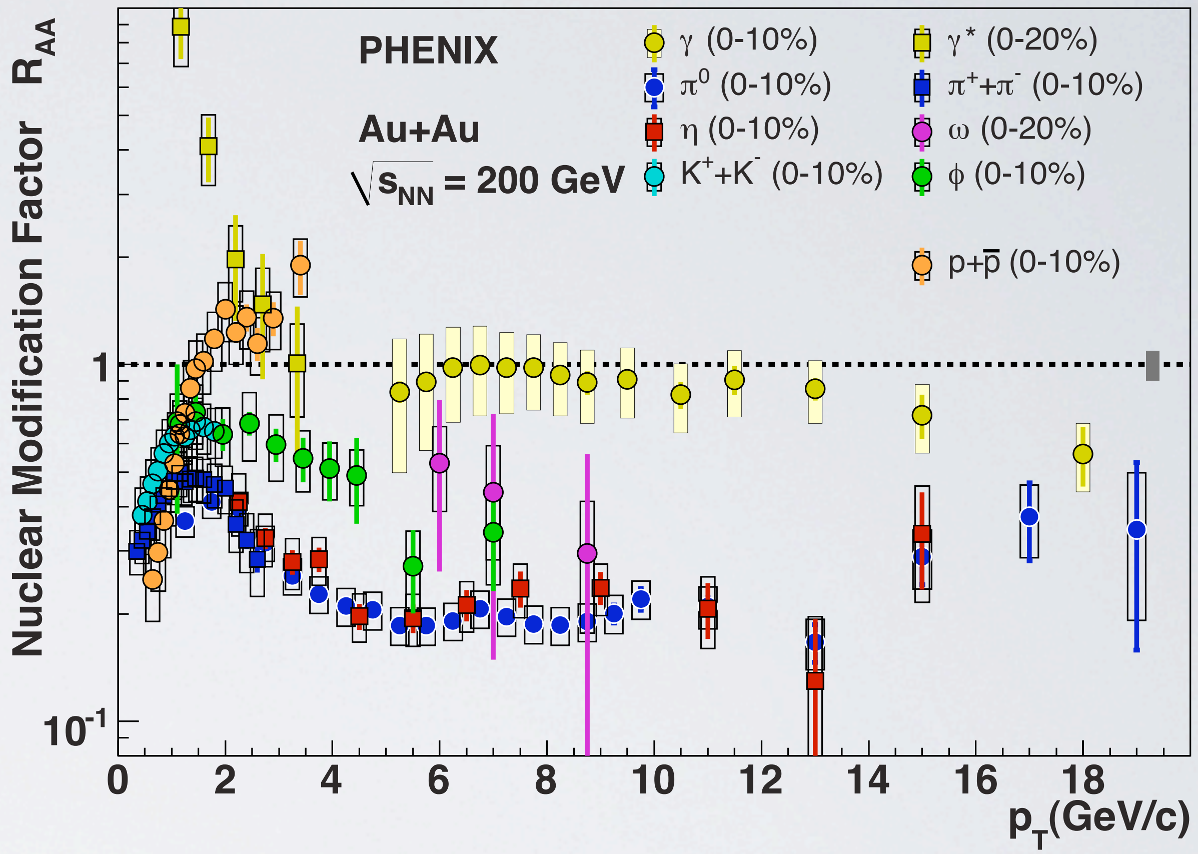
Zhang and Vitev, arXiv:0810.3194

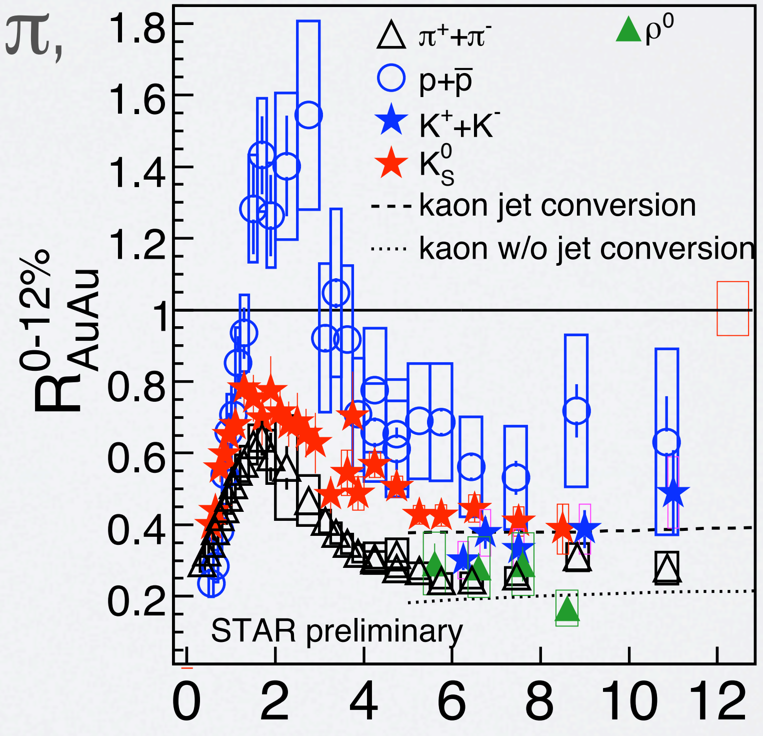


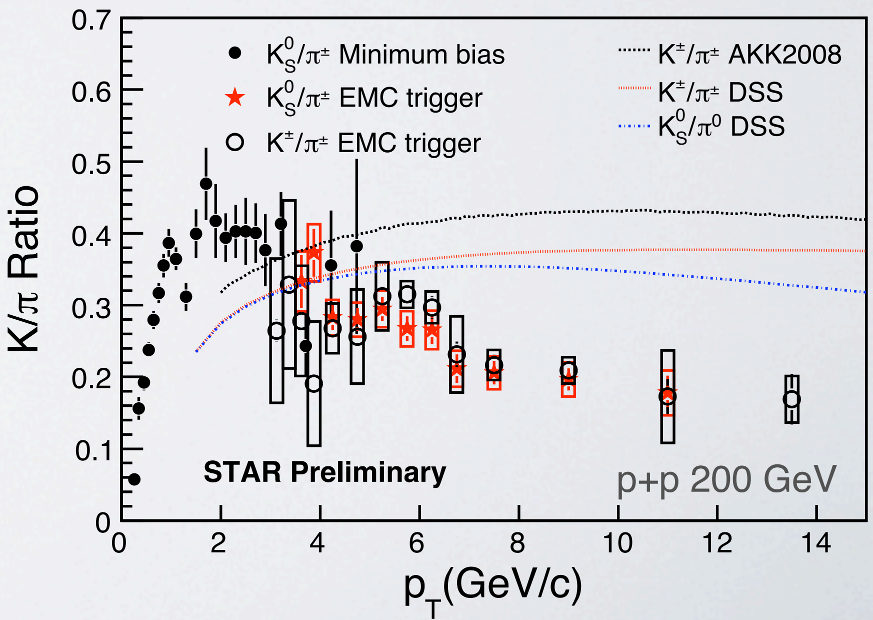
SPECIES DEPENDENCE

- nuclear modification factor for many identified particles out to very high p_T
  - not universal!
- different species probe different partons
  - p, K larger contribution from gluon fragmentation than π, expect: $R_{AA}^{(p,K)} < R_{AA}^{(\pi)}$
  - observed in data: $$R_{AA}^{(p,K)} > R_{AA}^{(\pi)}$$
  - already fragmentation functions in pp disagree!

C.Vale et al, talk at QM2009







Y. Xu et al, talk at QM2009

ENERGY LOSS OBSERVABLES

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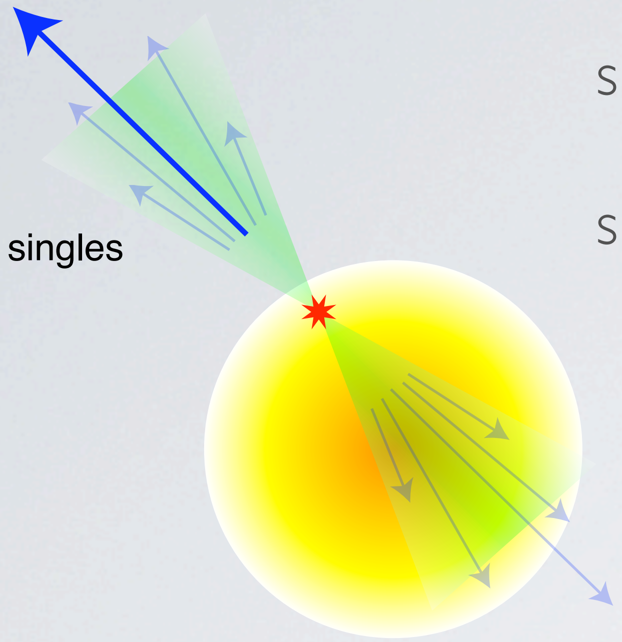
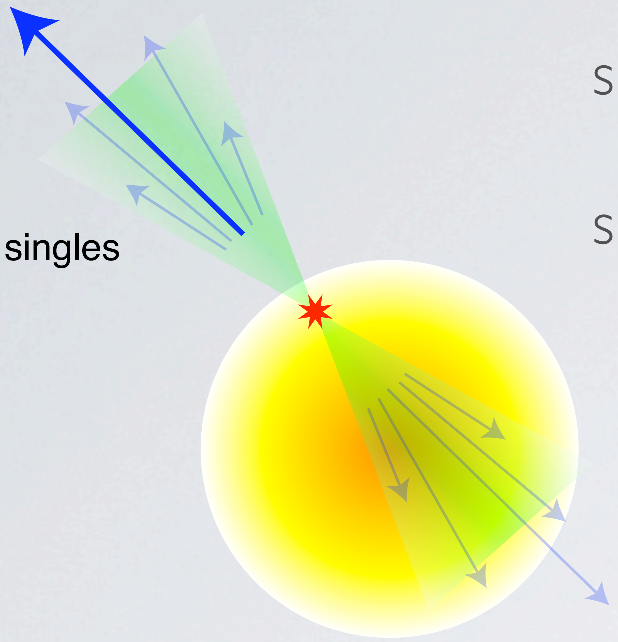


single hadrons

surface bias?

ENERGY LOSS OBSERVABLES



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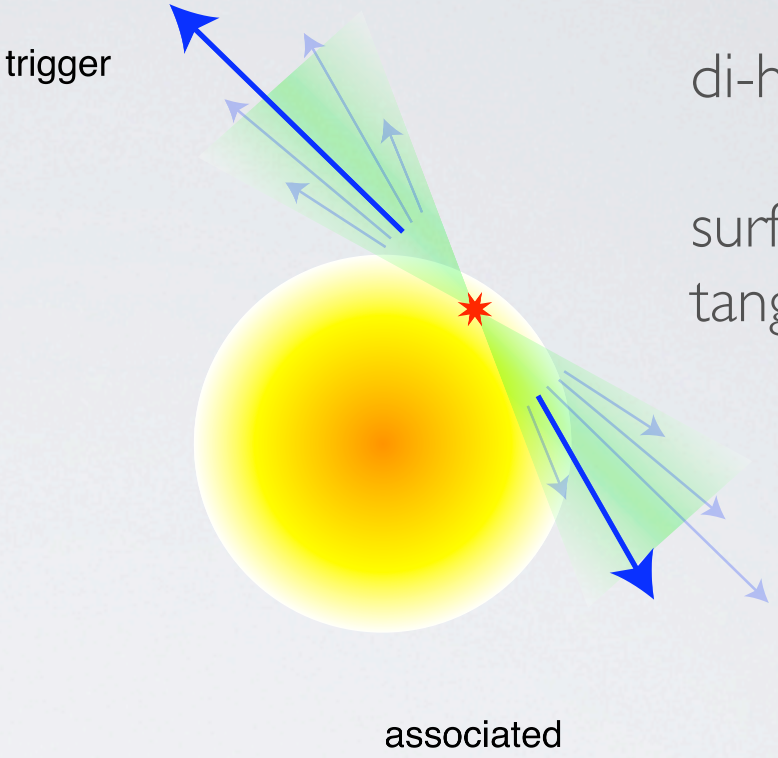

di-hadrons

surface bias,
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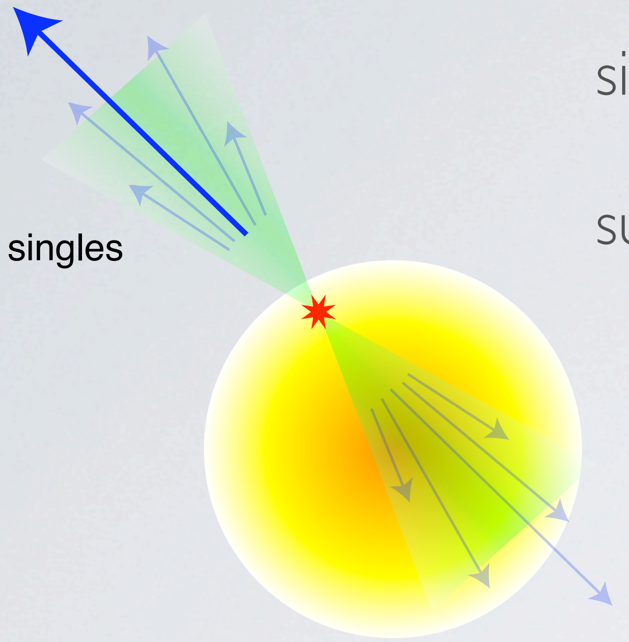

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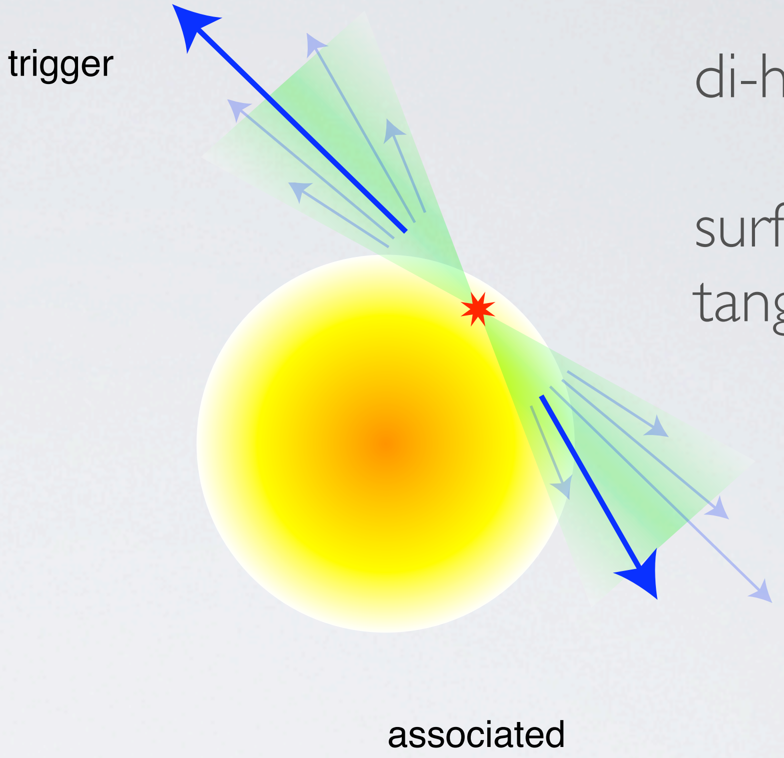

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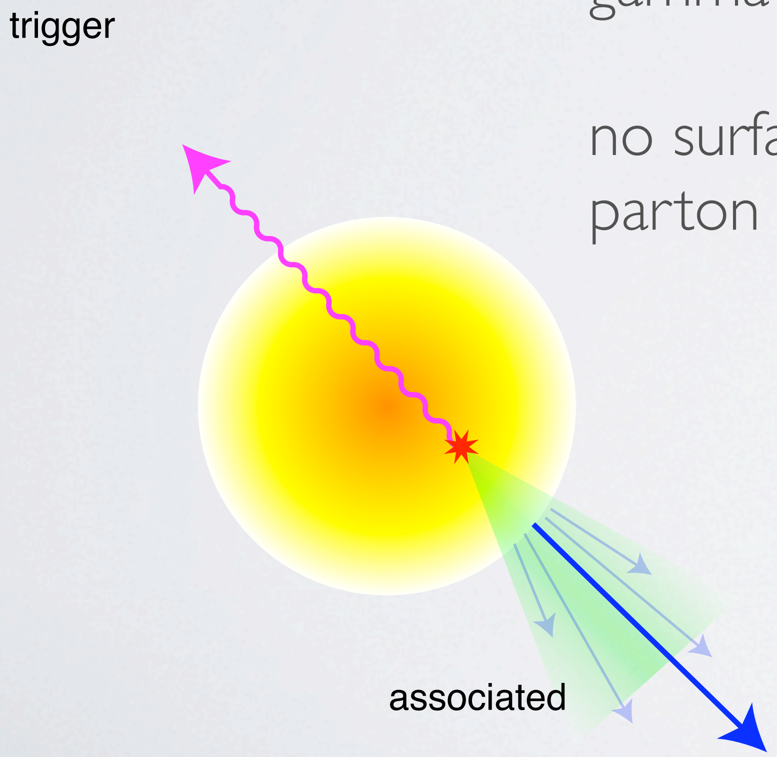
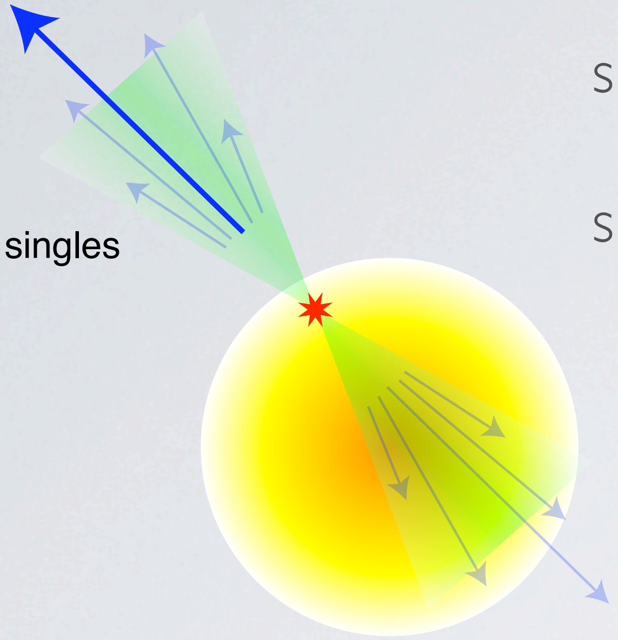


gamma-hadron

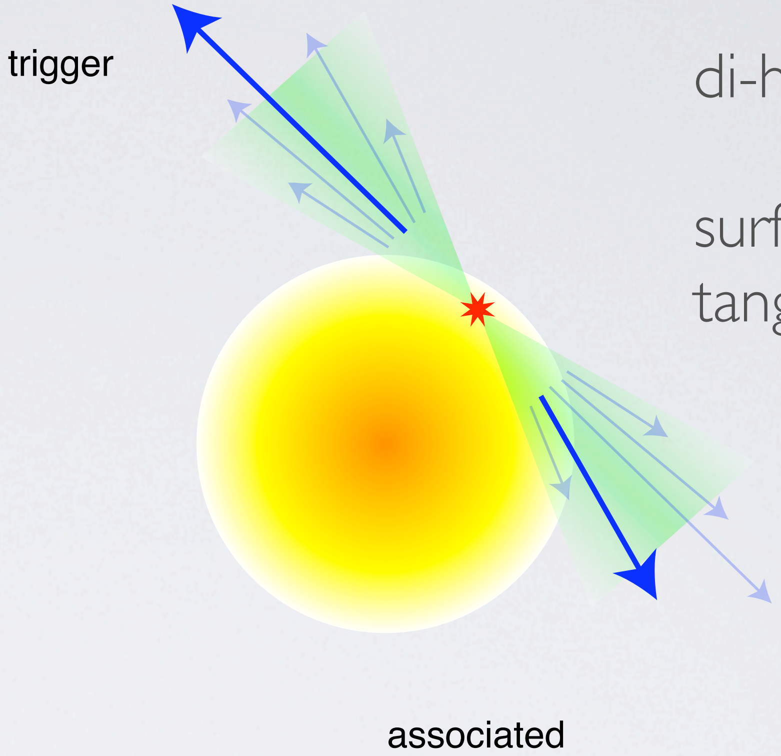
no surface bias,
parton p_T known?

ENERGY LOSS OBSERVABLES



single hadrons

surface bias?



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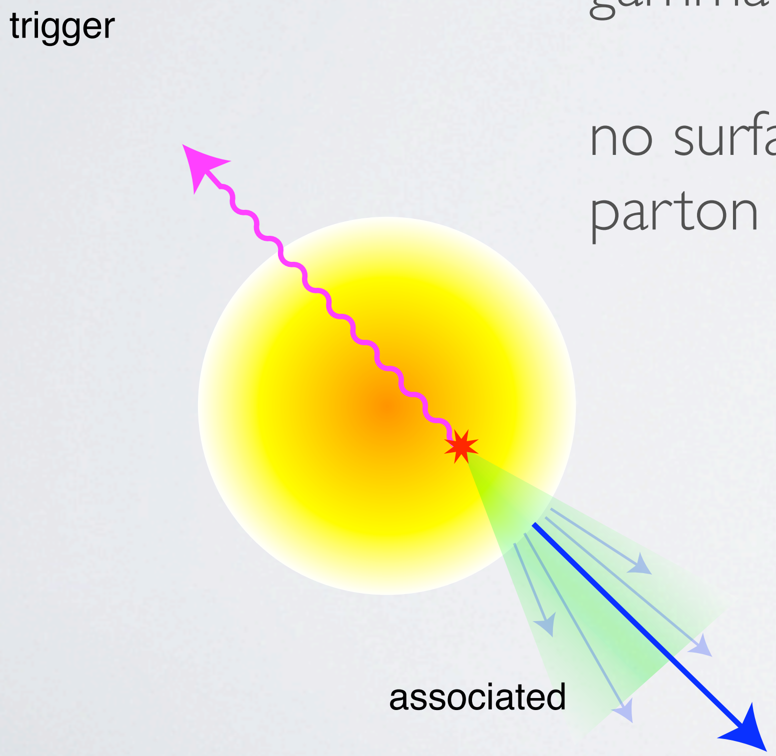

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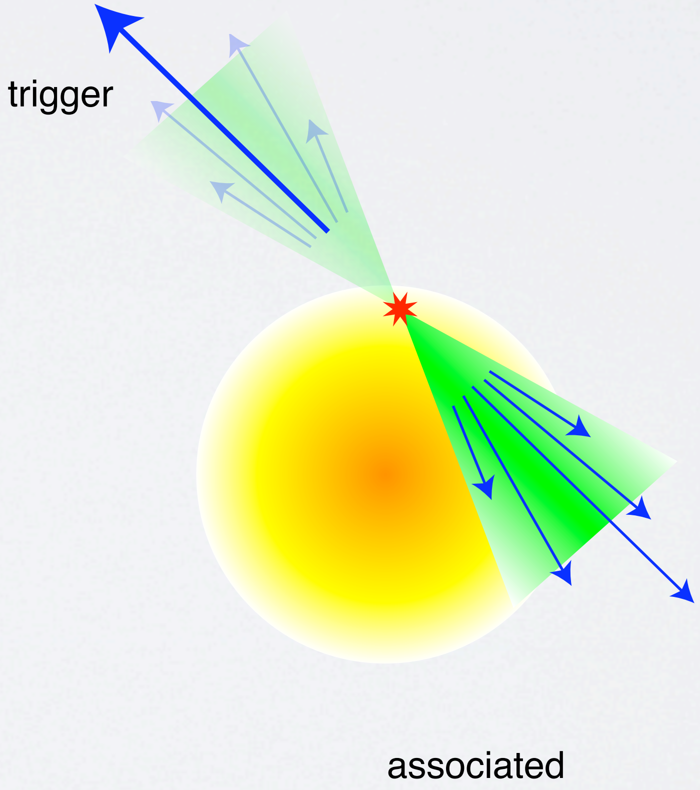
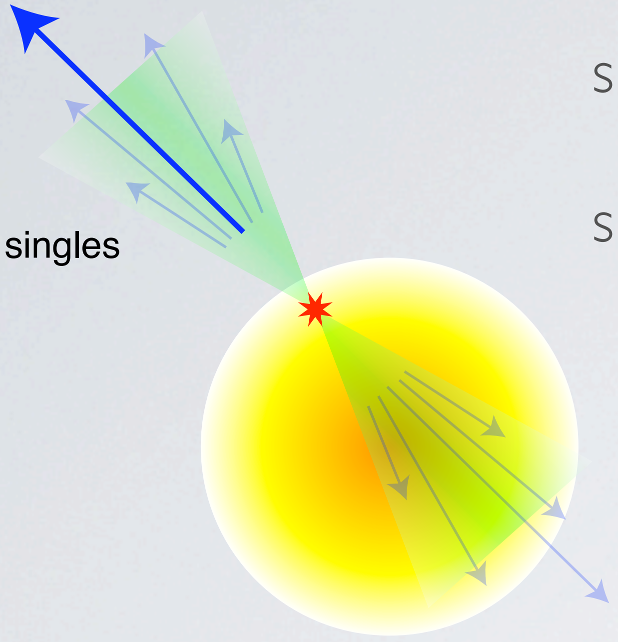


hadron-jet

variable surface bias,
smaller uncertainty
from fragmentation?

ENERGY LOSS OBSERVABLES



single hadrons

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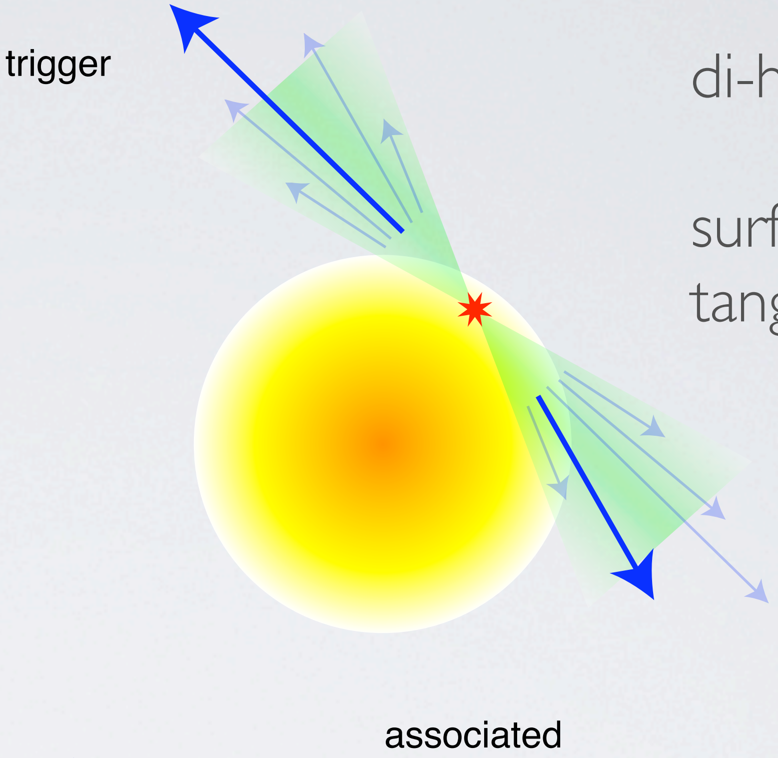

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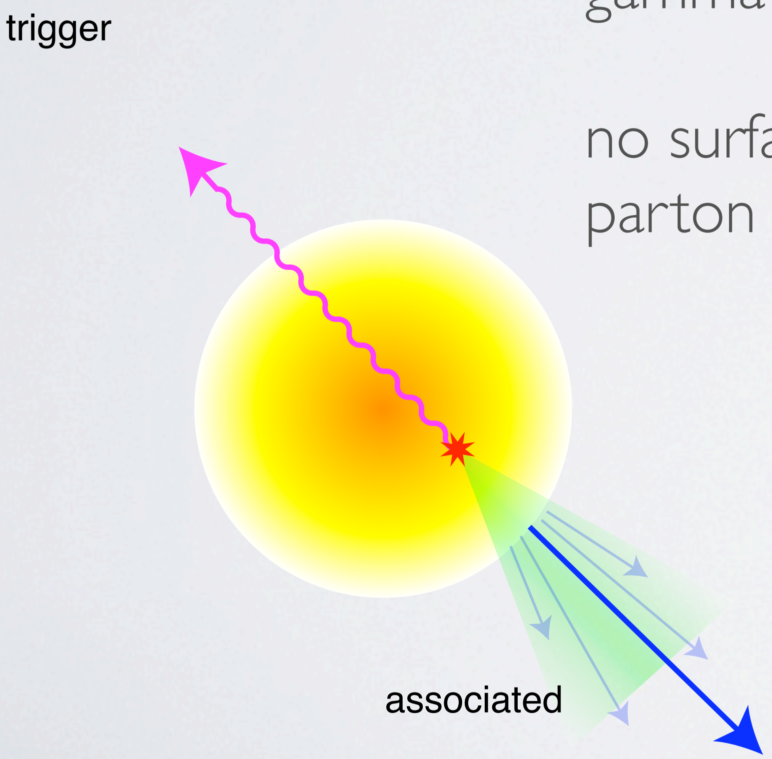

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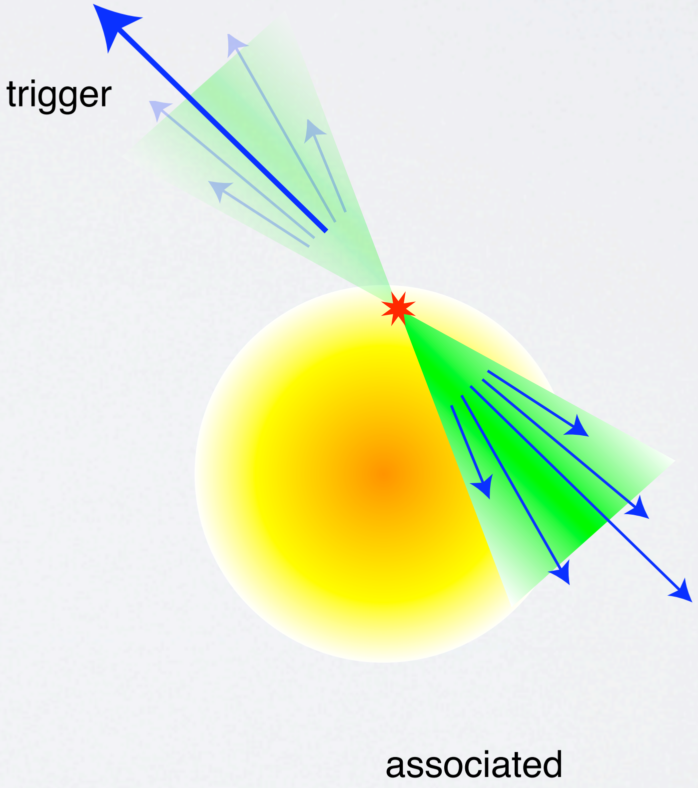
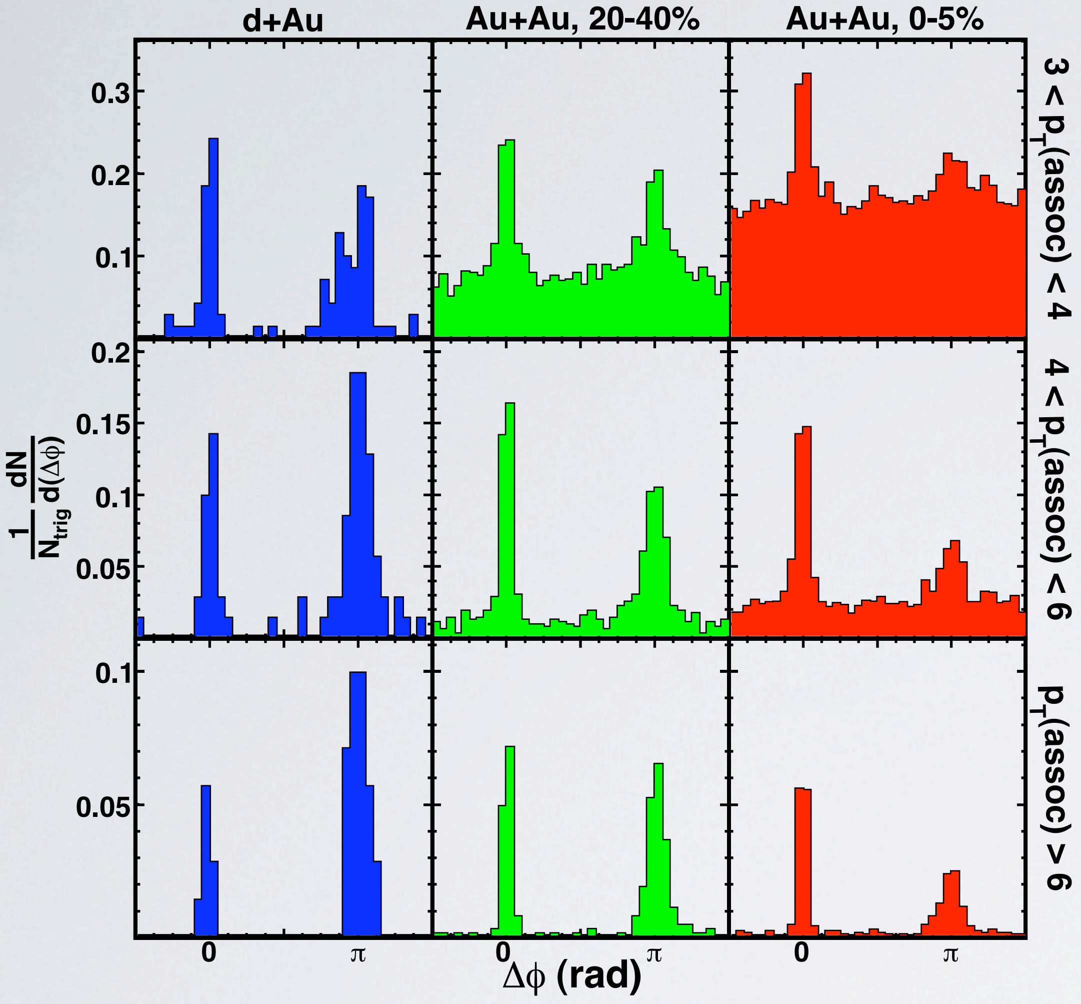


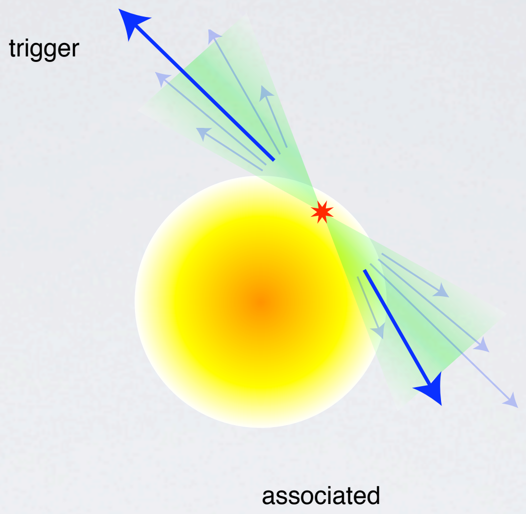
hadron-jet

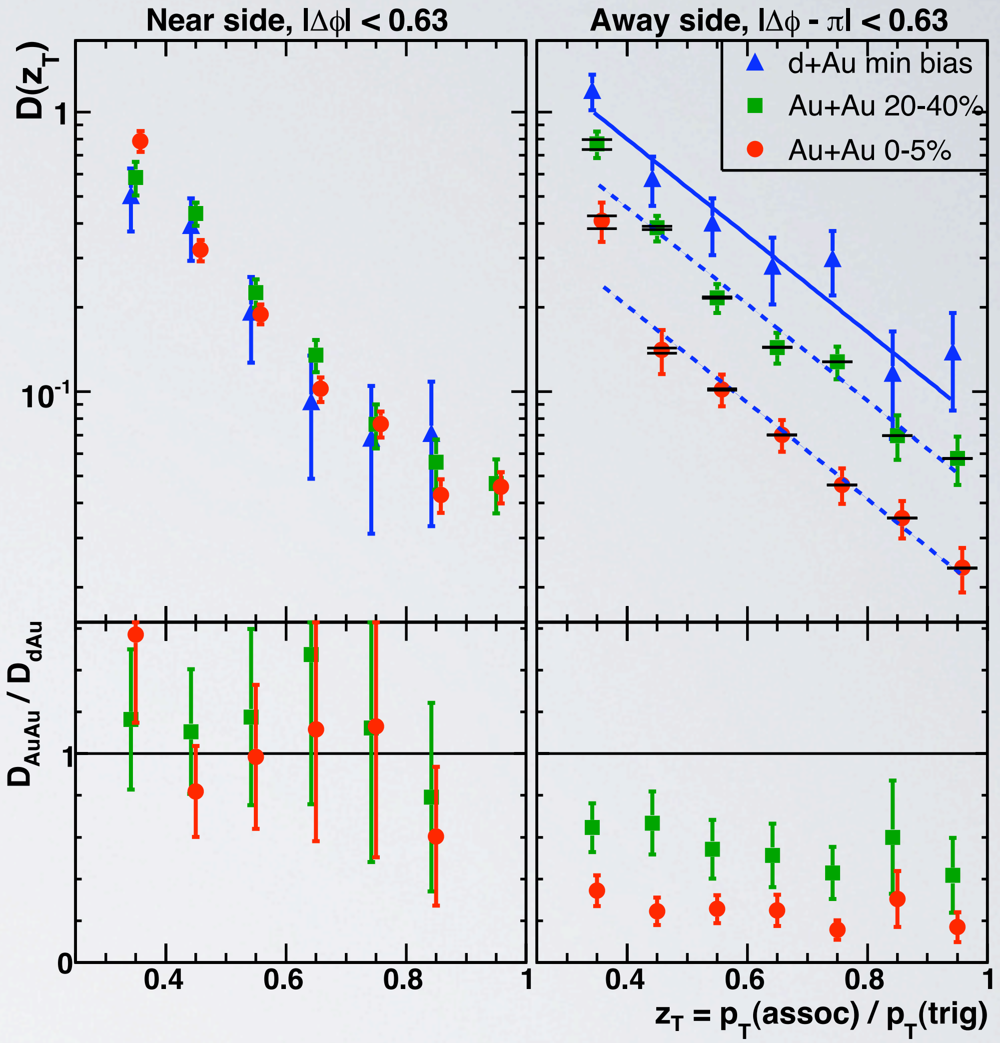
variable surface bias,
smaller uncertainty
from fragmentation?

different observables put different constraints on energy loss models!

DI-HADRON DISTRIBUTIONS







STAR Collaboration, PRL 97 (2006) 162301

- high p_T hadron trigger shows jet-like correlation for all systems
- near-side yield not modified
  - vacuum fragmentation, surface bias?
- away-side yield strongly suppressed in central Au+Au
  - hadron momentum distributions have similar shape

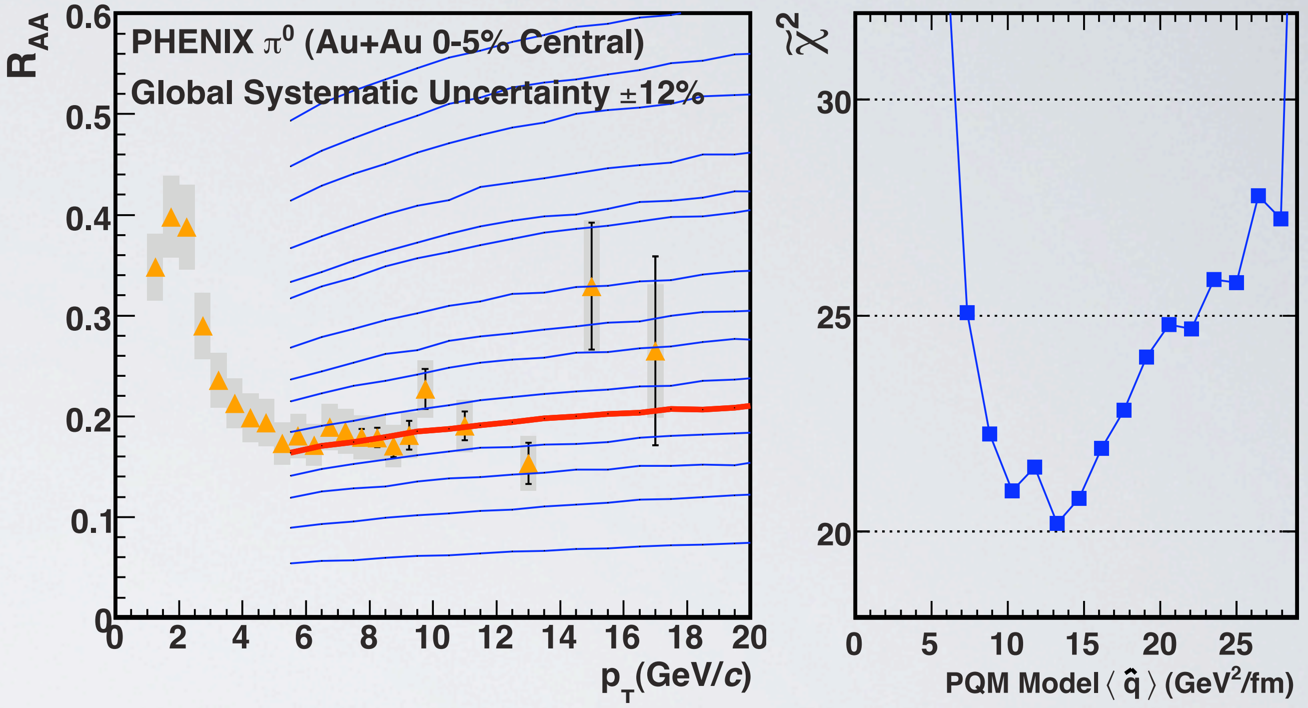
MODEL COMPARISON

- study R_{AA} and I_{AA} quantitatively

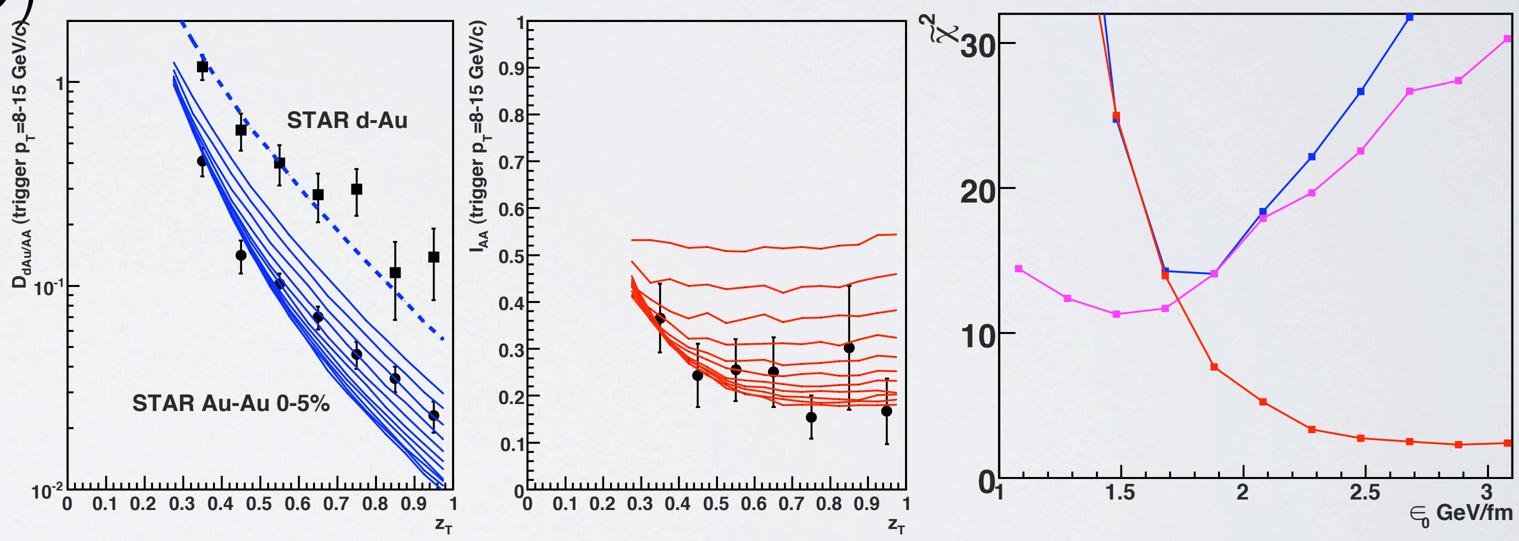
$$R_{AA} \equiv \frac{dN/dp_T^2(AA)}{\langle N_{coll}(AA)\rangle \cdot dN/dp_T^2(pp)}$$

$$I_{AA} \equiv \frac{1/N_{trig} \cdot dN_{assoc}/dp_T^2\,(AA)}{1/N_{trig} \cdot dN_{assoc}/dp_T^2\,(pp)}$$

Zhang et al., PRL 98 (2007) 212301



Zhang et al., PRL 98 (2007) 212301



- different models use different assumptions and parameters
  - need reproducibility between models

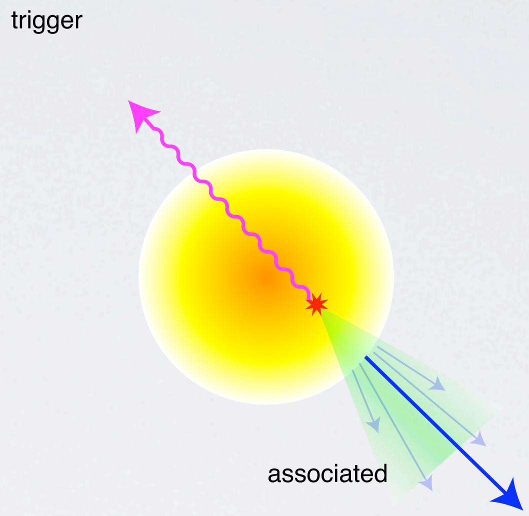
$$dN_{gluons}/dy \approx 1400$$

$$\epsilon_0 \approx 2\,\mathrm{GeV/fm}$$

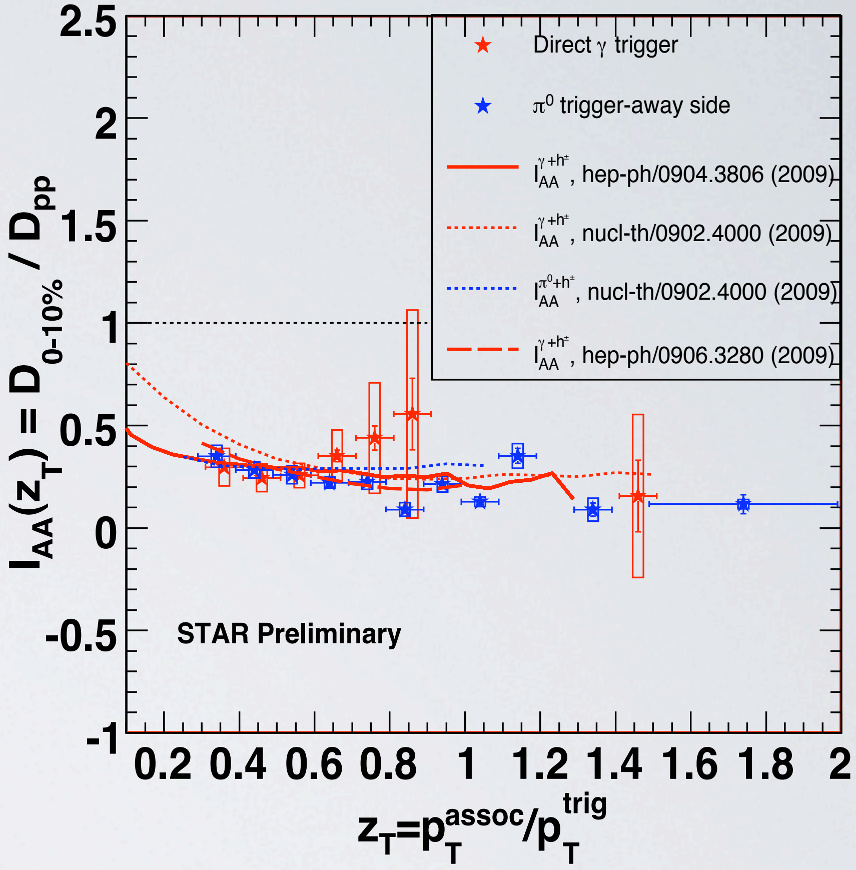
$$\hat{q} \approx 13\,\mathrm{GeV^2/fm}$$

GAMMA-HADRON CORRELATIONS

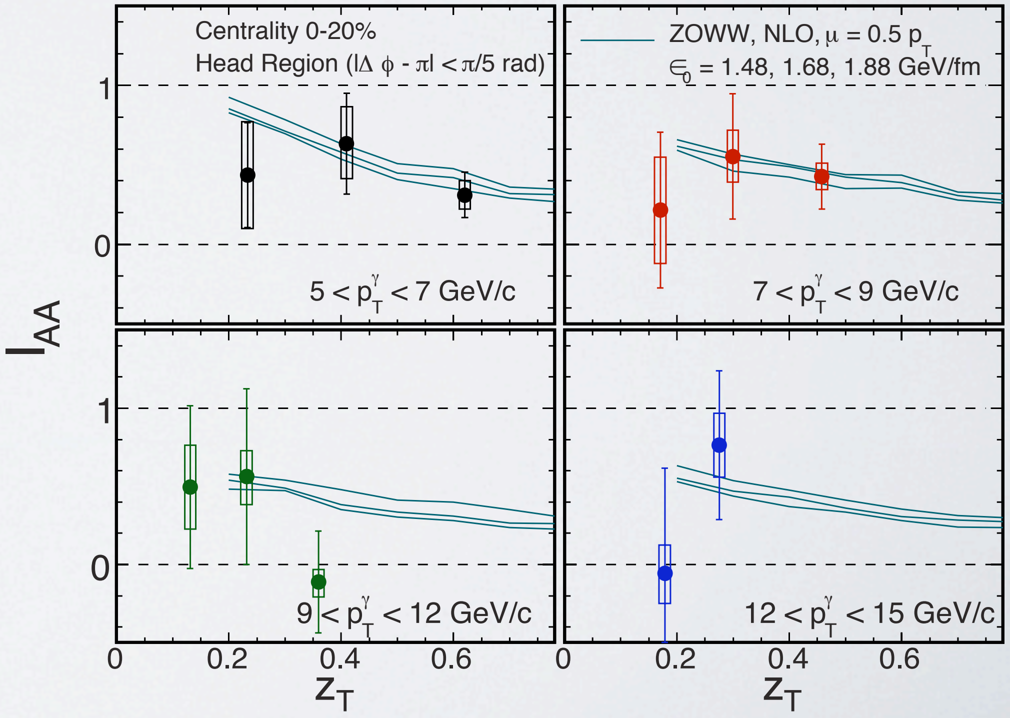
- prompt photon trigger defines parton energy
  - no energy loss
  - sensitive to full volume
- associated hadron yield strongly suppressed
  - similar to hadron trigger
  - consistent with model predictions
- higher statistics needed!



A. Hamed et al, talk at QM2009



PHENIX arXiv: 0903.3399



JET RECONSTRUCTION

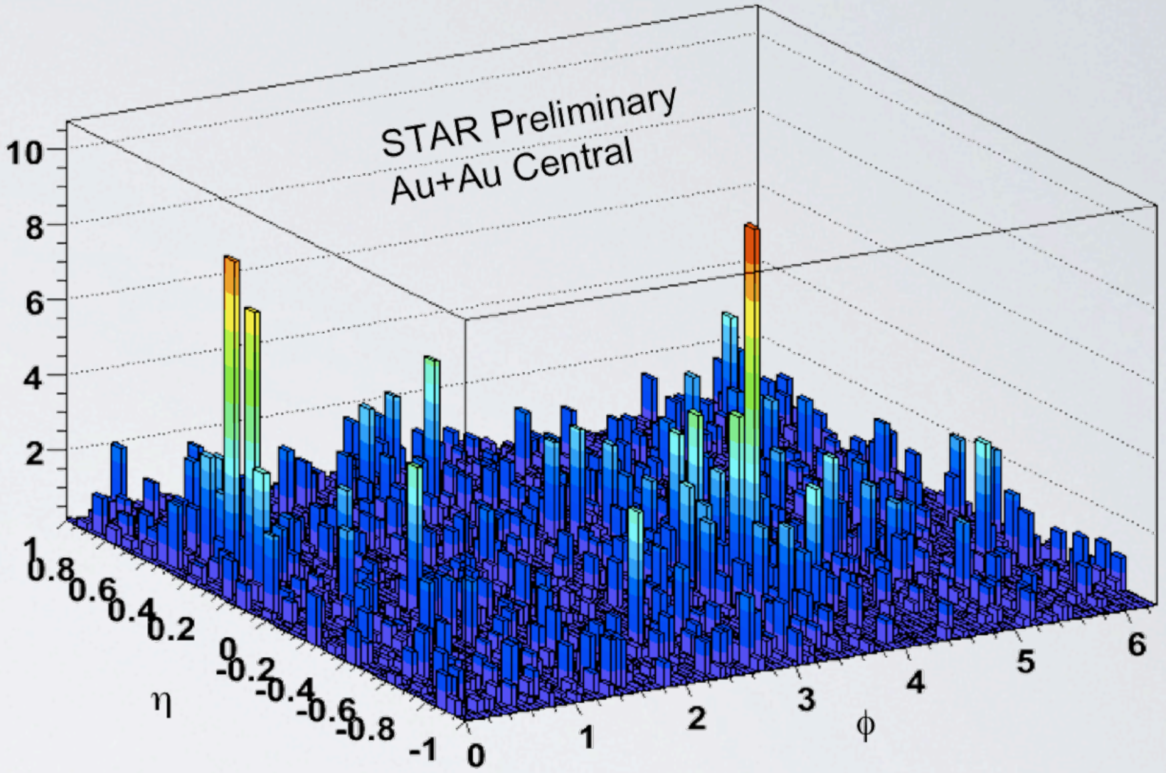
- first steps to full jet reconstruction in Au+Au
  - high E_T jets still visible above large background
  - use kT and anti-kT algorithms
  - background subtraction crucial

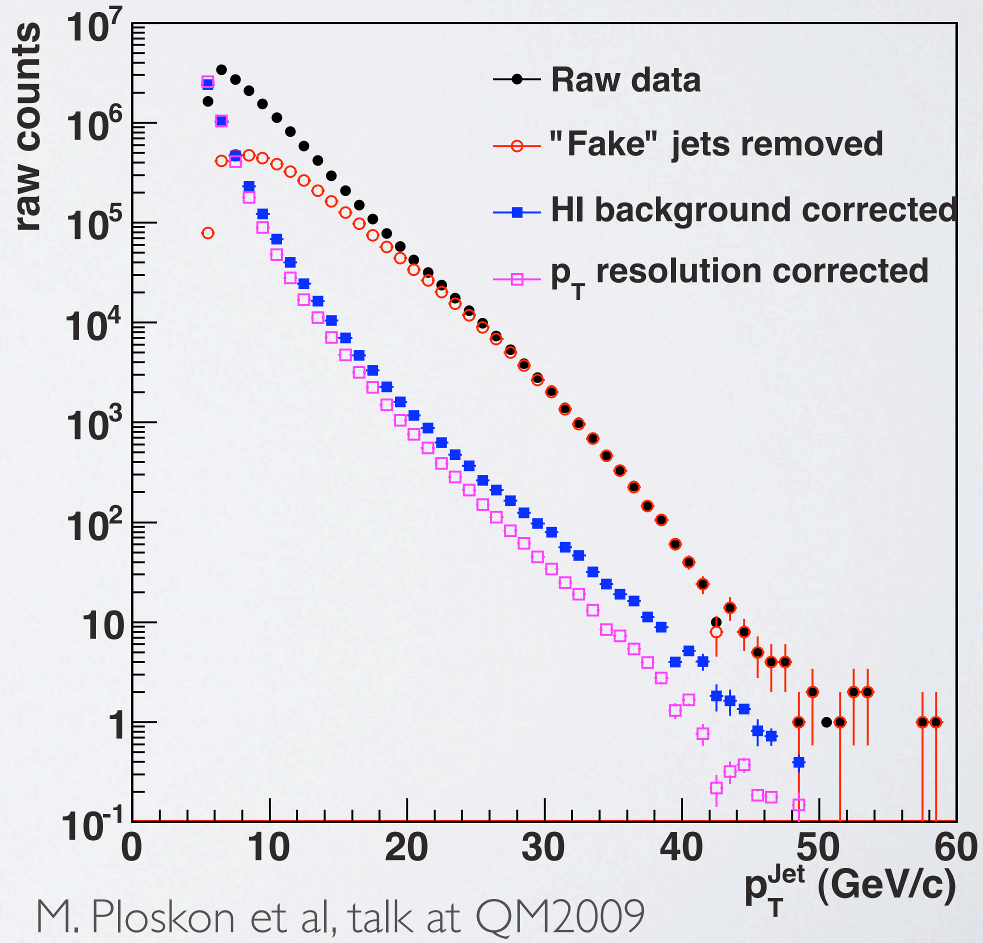
$$p_T^{(true)} = p_T^{(meas)} - \rho_{bkg} A$$

  - energy smearing:

$$\sigma^{(bkg)} \approx 6.8\,\mathrm{GeV}$$

  - for pp reasonable agreement with published result (mid-point cone algorithm)

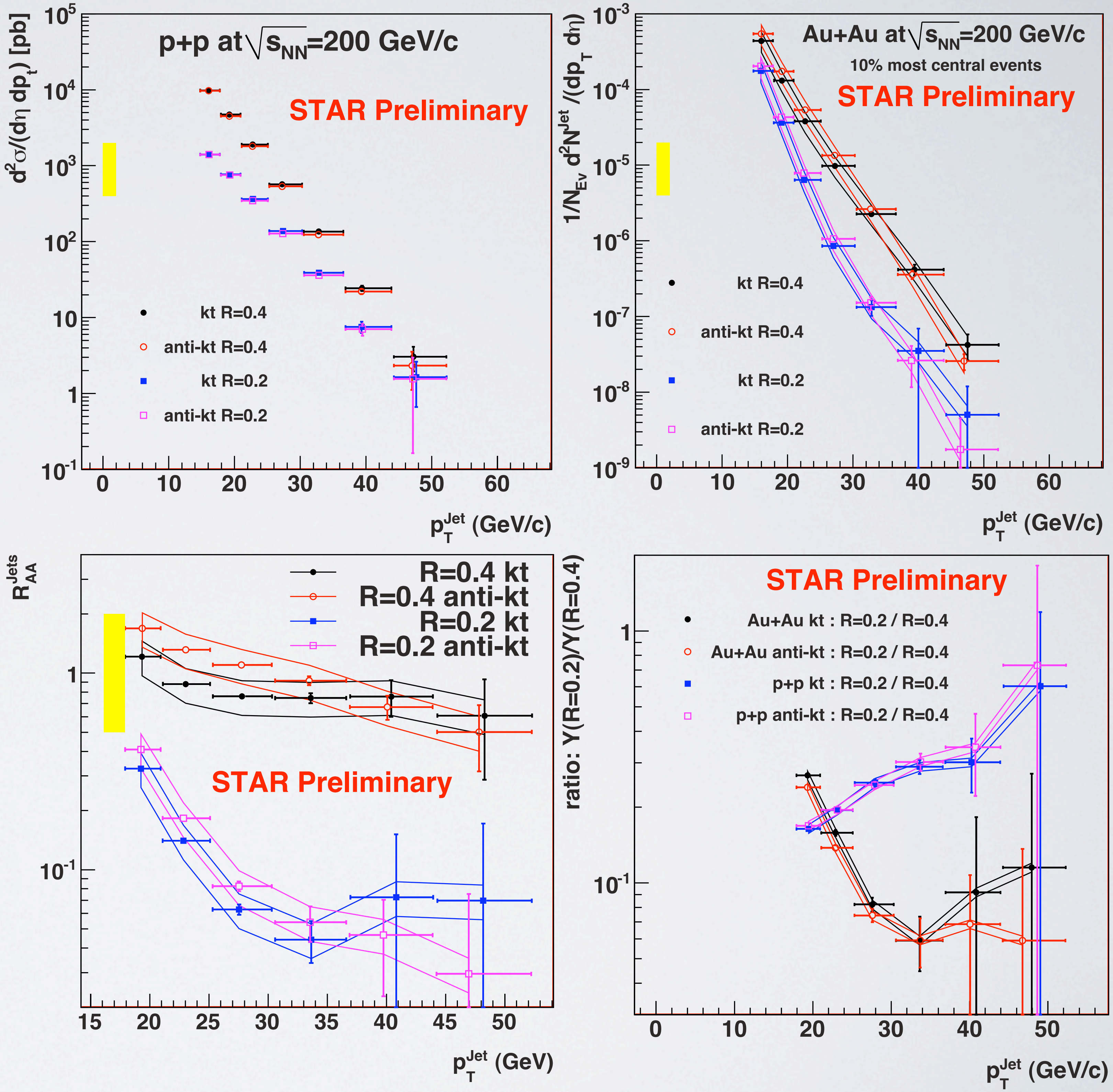




M. Ploskon et al, talk at QM2009

INCLUSIVE JETS

- measurements for different cone sizes
- for large cone size $R_{AA} \approx 1$ for jets
    - $R_{AA}=1$ expected for full reconstruction - not yet!
- with increasing p_T:
    - p+p: narrowing
    - Au+Au central: widening
        - effect of jet-medium interaction (parton energy loss)



M. Ploskon et al, talk at QM2009

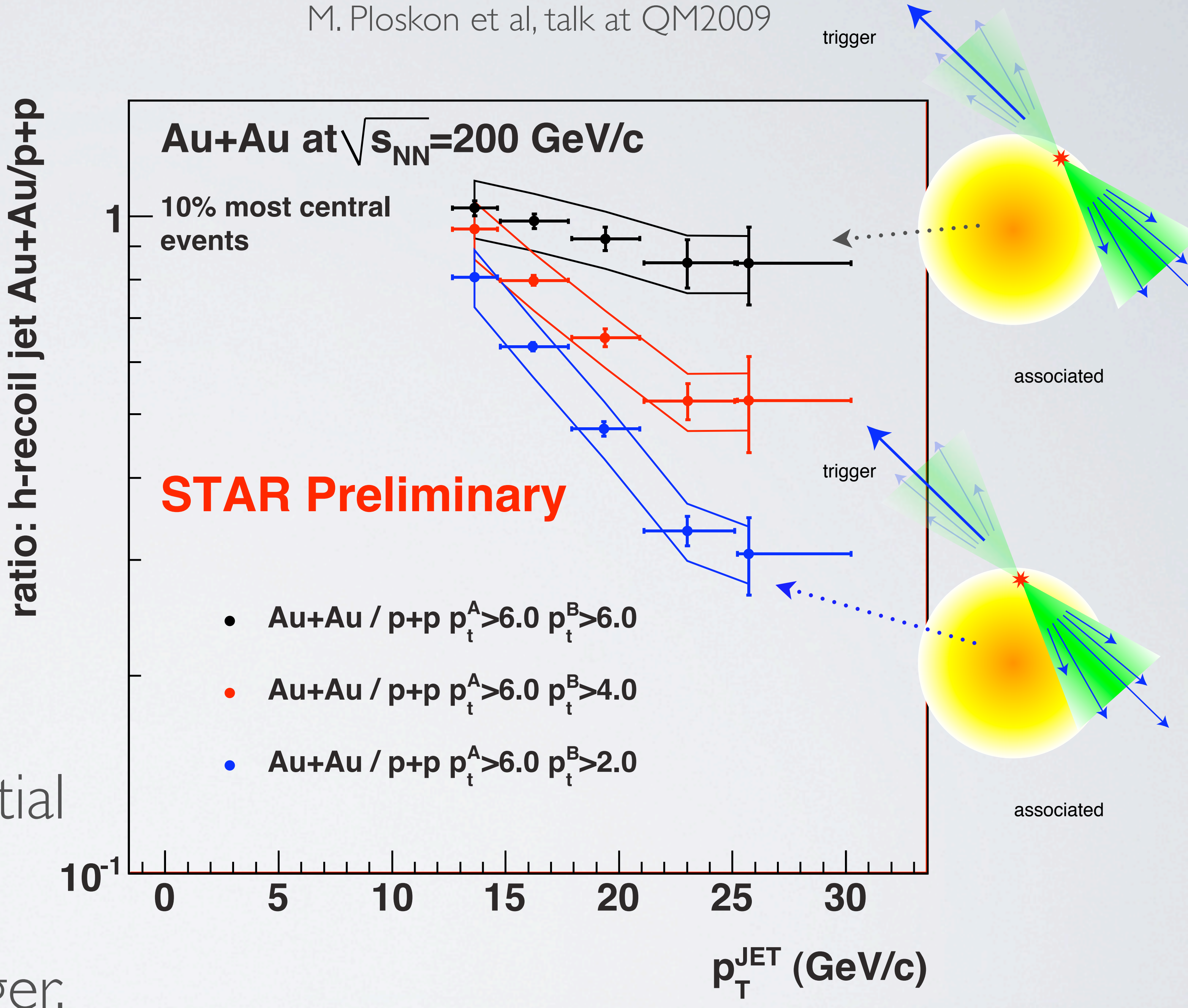
RECOIL JET STUDIES

- hadron-jet correlation strength:

$$I_{AA}^{(h-j)} = \frac{N_{h-j}/N_{trig}\,(AA)}{N_{h-j}/N_{trig}\,(pp)}$$

  - choose high p_T hadron trigger
  - require associated hadron in jet, vary p_T : dial production point of jets
  - high p_T : surface bias, tangential emission
  - low p_T : surface bias for trigger, significant in-medium path length for jet

M. Ploskon et al, talk at QM2009

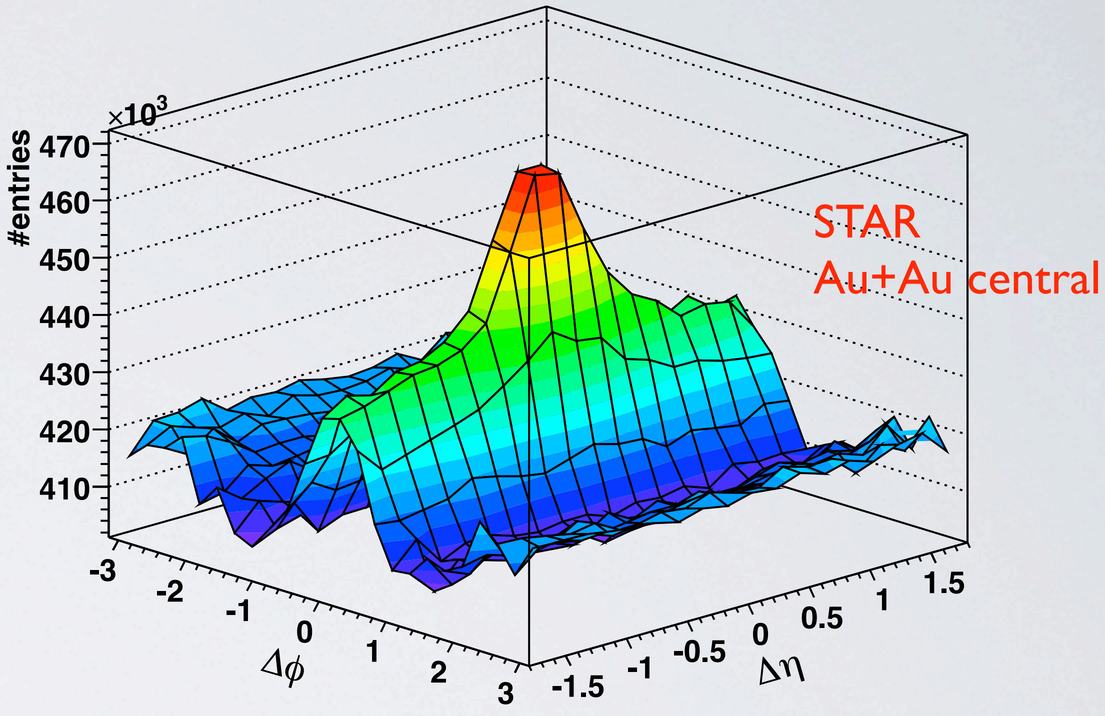


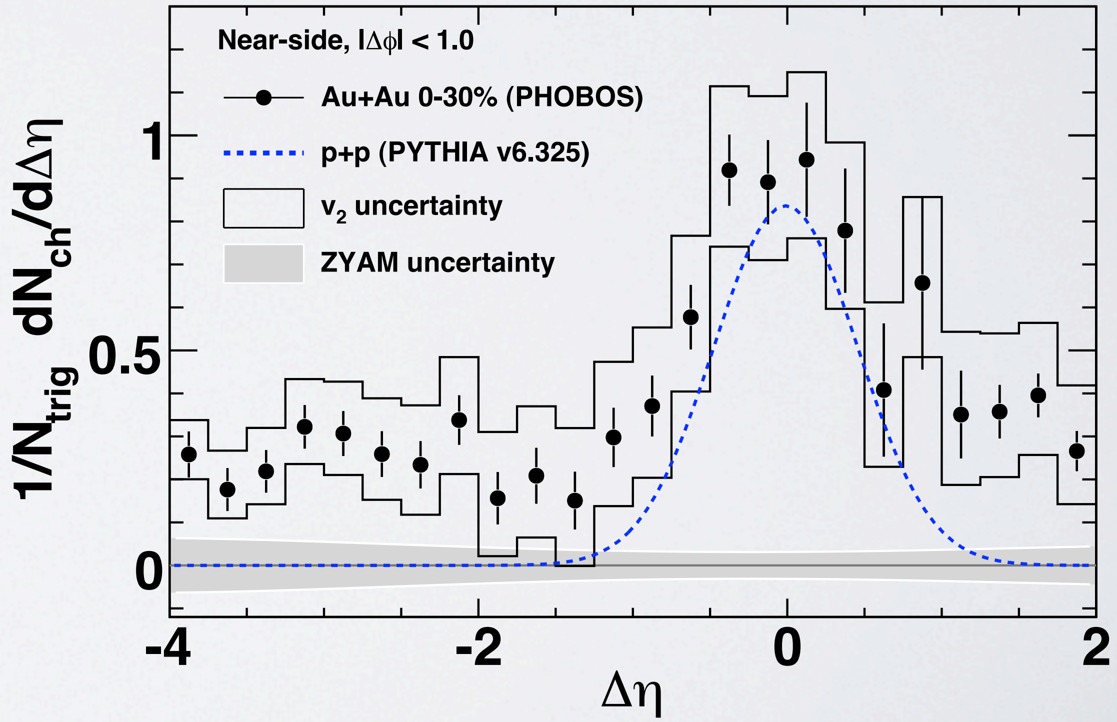
promising new jet quenching observable!

JET-MEDIUM: NEAR SIDE

- associated hadrons with high p_T trigger hadron
  - correlation of long range in pseudorapidity: the ridge
  - increasing with centrality
  - momentum spectra softer than jet
- origin unclear
  - large η range: early times
  - string, flux tube with radial motion?
  - parton energy transferred to medium?
- more studies needed!

J. Putschke et al, JPG 34 (2007) S679



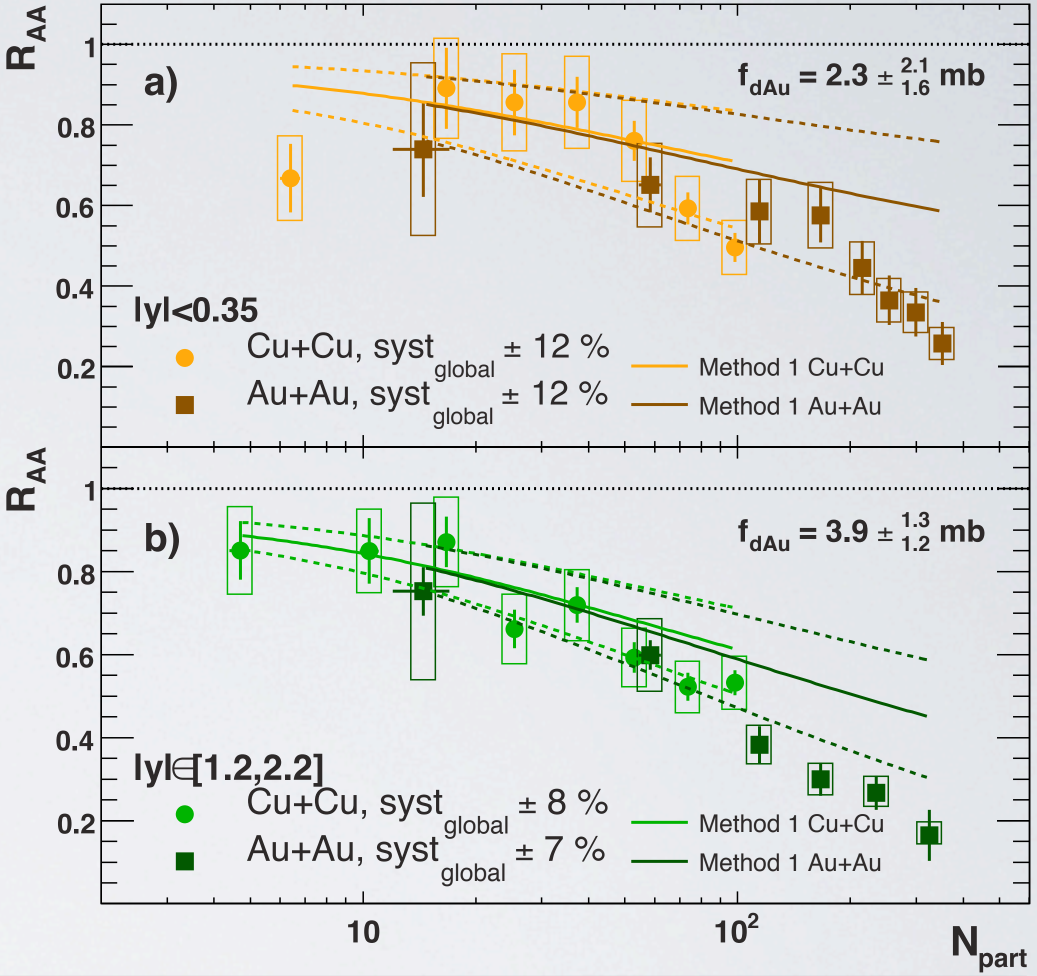


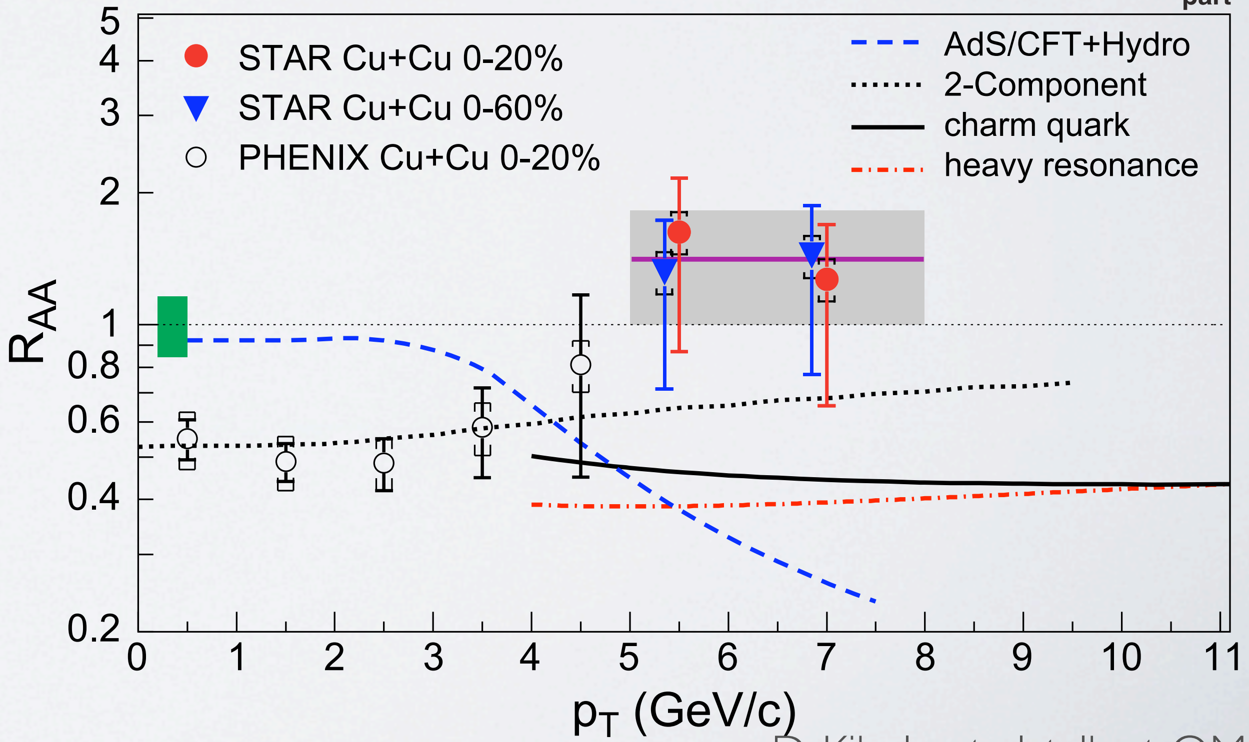
PHOBOS, arXiv: 0903.2811

J/PSI PRODUCTION

- J/ψ suppressed in central collisions
  - similar magnitude as at SPS energies
    - higher energy density at RHIC!
  - interplay of suppression and enhancement?
  - suppression stronger at forward rapidity
- p_T dependence
  - only hadron from hard process not suppressed at high p_T?

M. Leitch et al, talk at QM2009



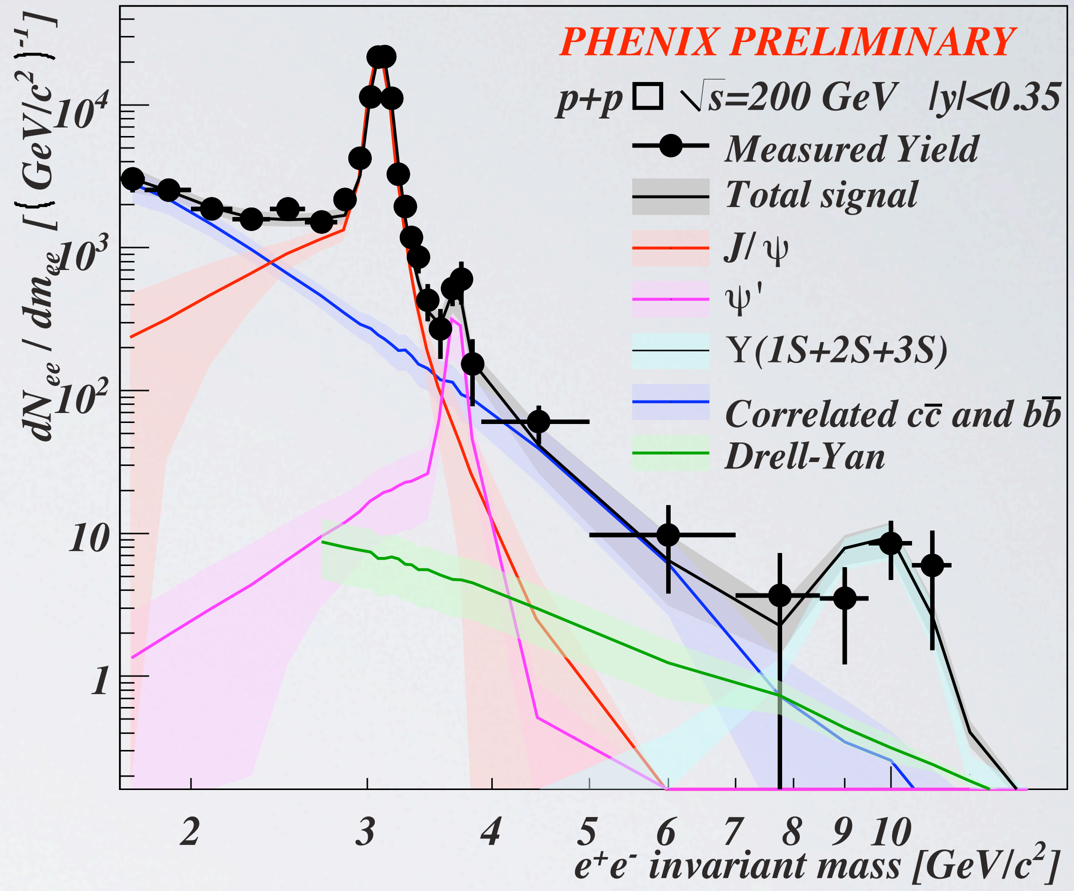


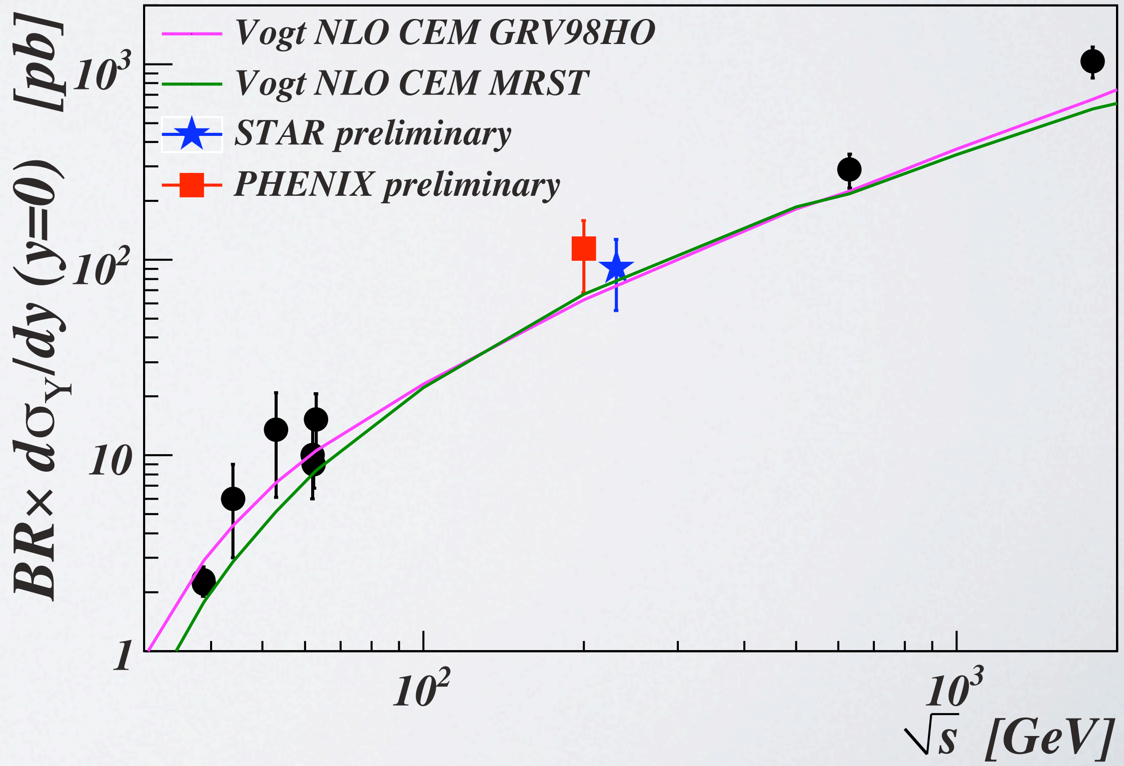
D. Kikola et al, talk at QM2009

UPSILON PRODUCTION

M. Leitch et al, talk at QM2009

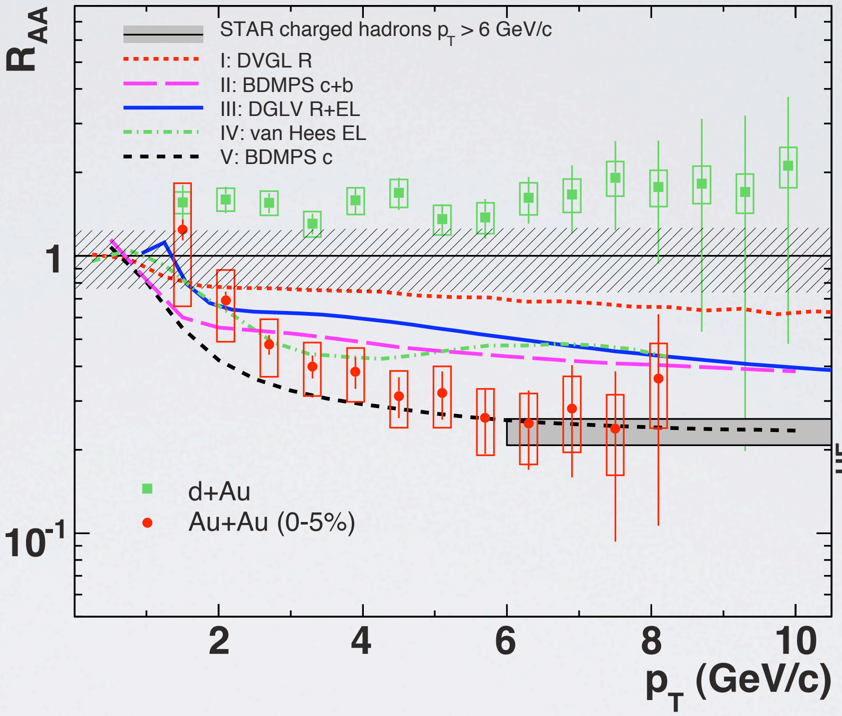
- important to check picture of quarkonium suppression
  - higher dissociation temperature in QGP
  - impossible (?) to produce thermally
- first data by STAR and PHENIX
- higher statistics needed!



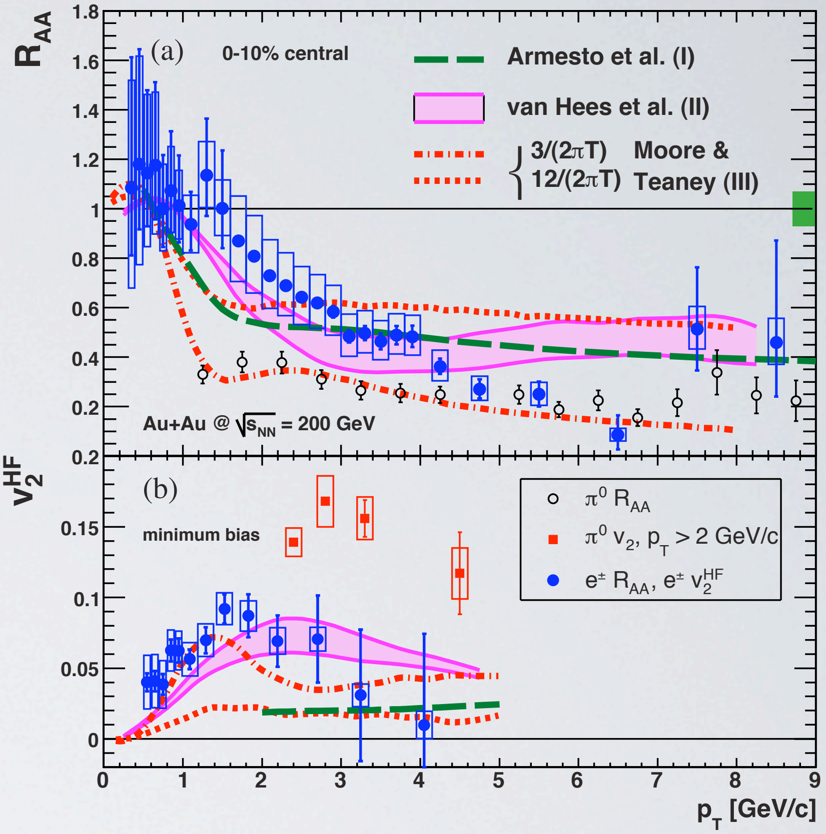


OPEN HEAVY FLAVOR

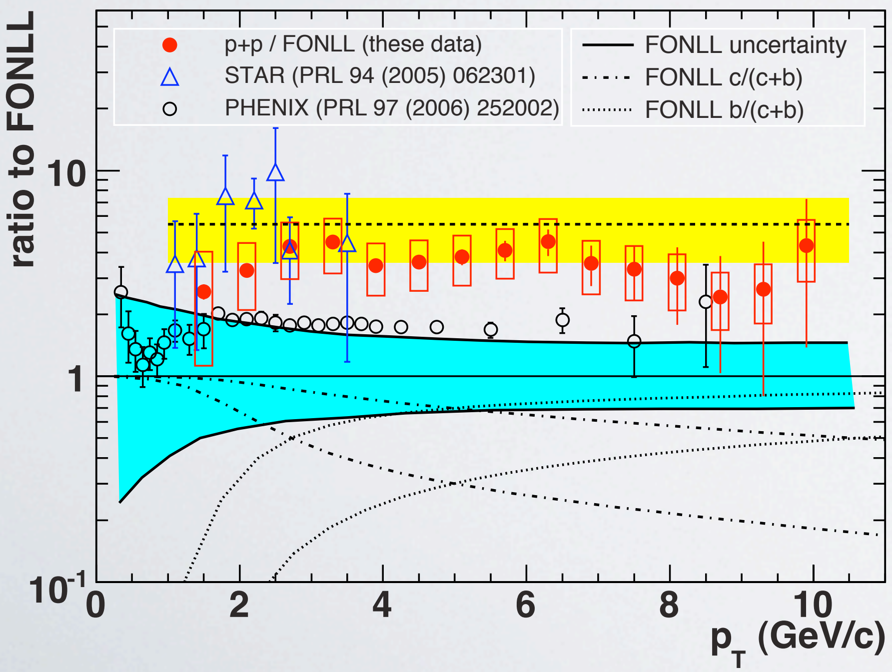
- open charm measured via decay electrons
- strong suppression in central Au+Au
- discrepancy factor ≈ 2 for charm yield in PHENIX and STAR



STAR, PRL 98 (2007) 192301

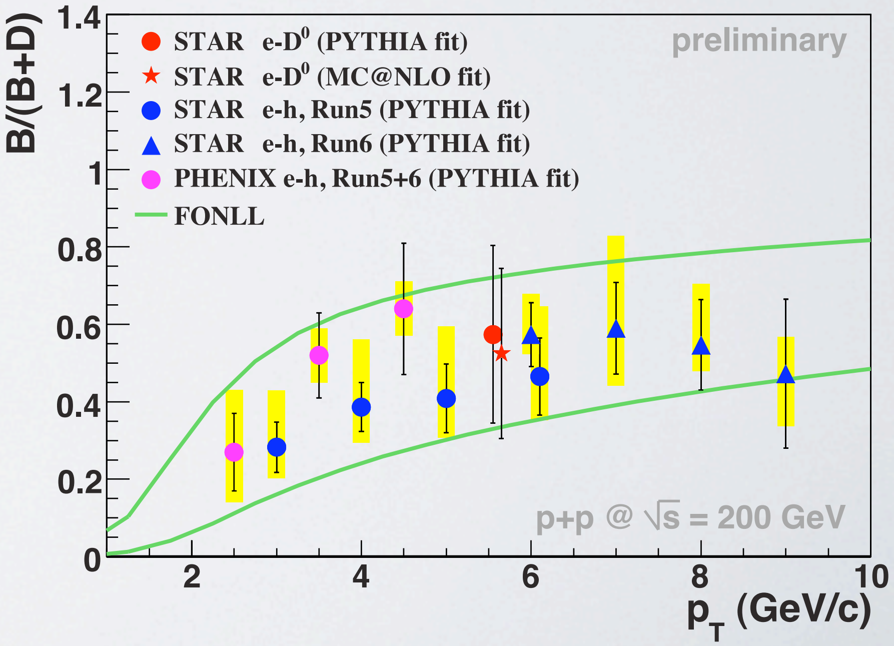


PHENIX, PRL 98 (2007) 172301



STAR, PRL 98 (2007) 192301

- not understood
  - heavy quarks should suffer less energy loss
  - significant bottom contribution!

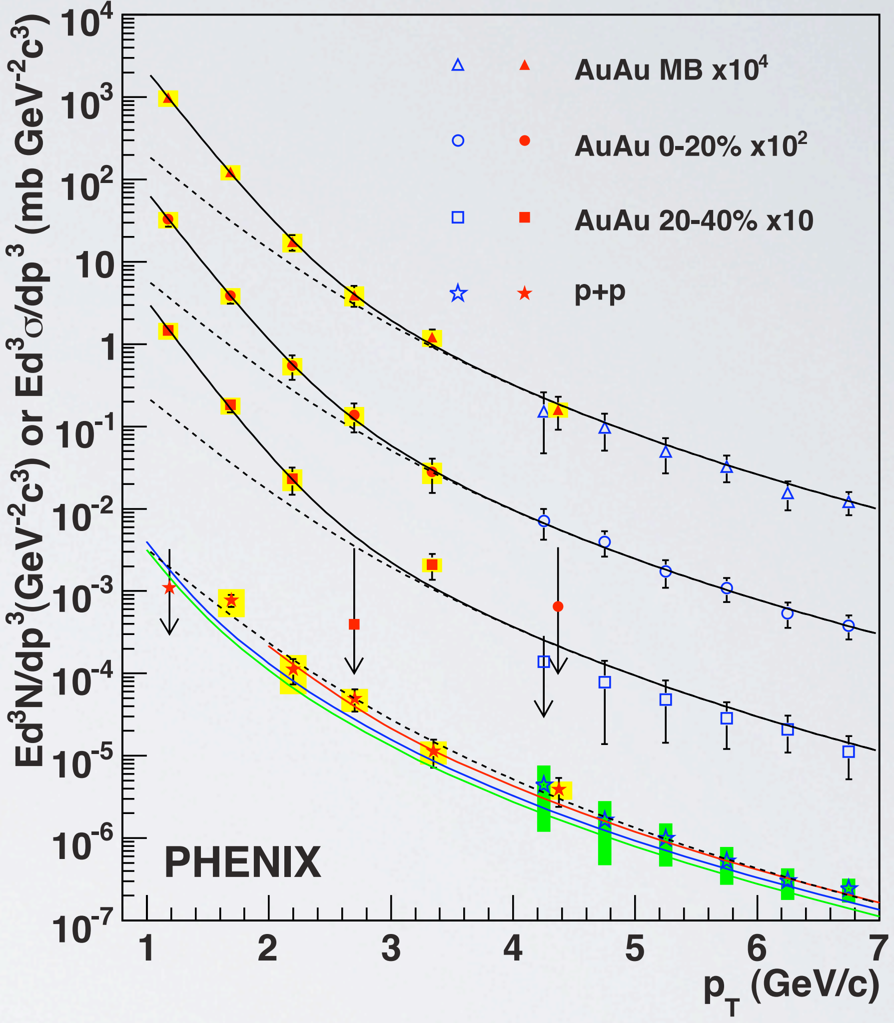


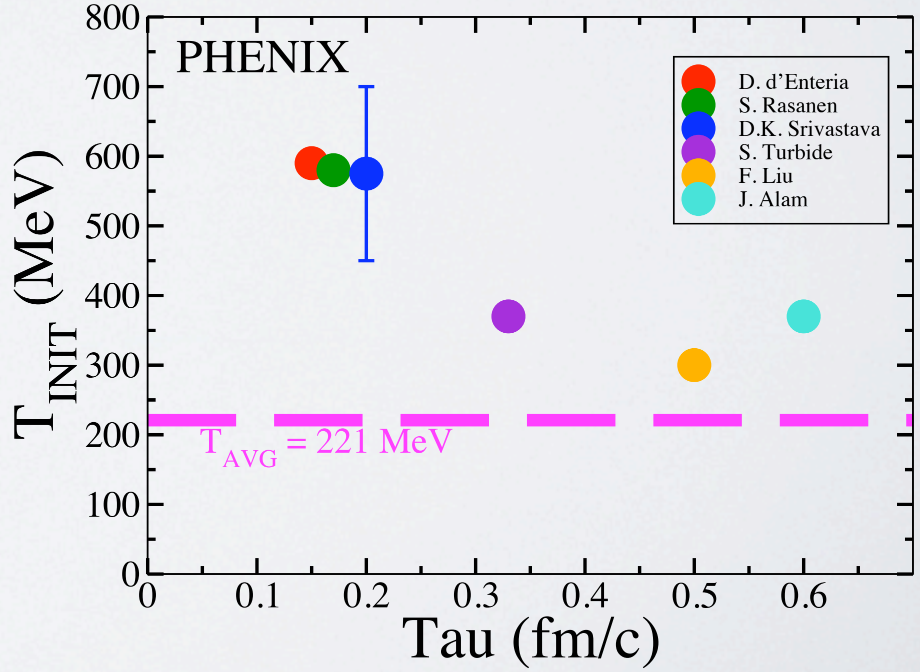
A. Mischke et al, JPG 35 (2008) 104117

THERMAL PHOTONS?

- direct photon estimate from low mass di-electrons
  - extrapolate $m_{e^+e^-} \to 0$
  - mass spectrum of Dalitz decays known
  - "direct photons" obtained from subtraction
- analysis possible at low p_T
  - expected range of thermal photons
  - can be used to estimate initial temperature

PHENIX, arXiv:0804.4168





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    - species dependence?
  - new observables:
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- **heavy flavor:**
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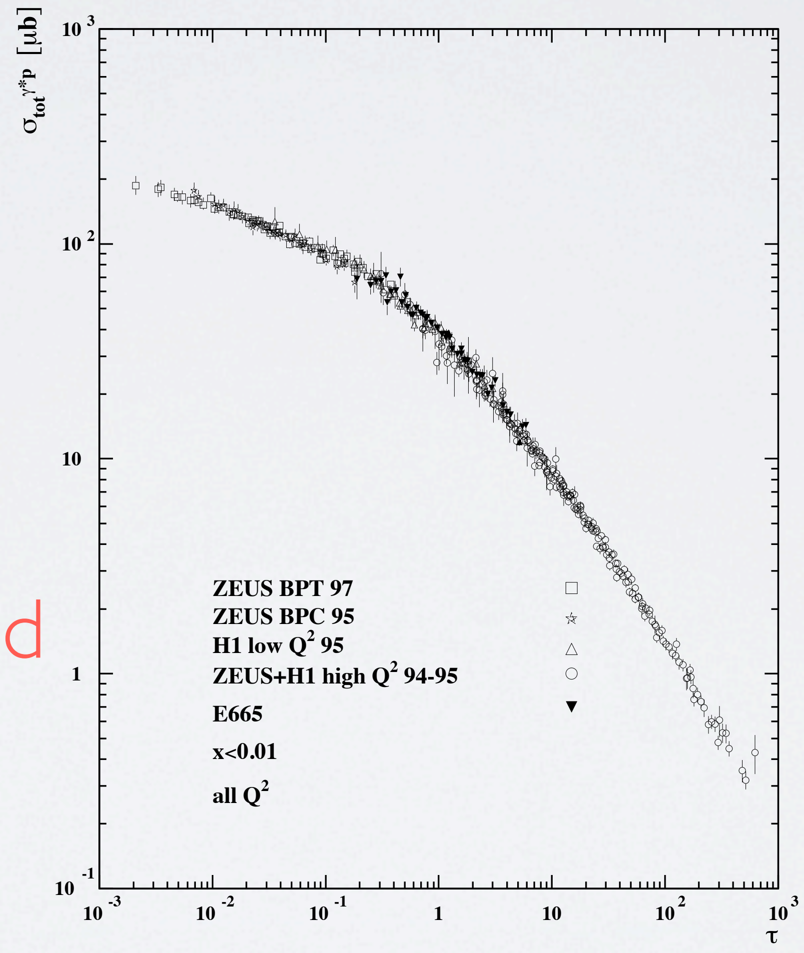
- **thermal photons:**
  - initial temperature?

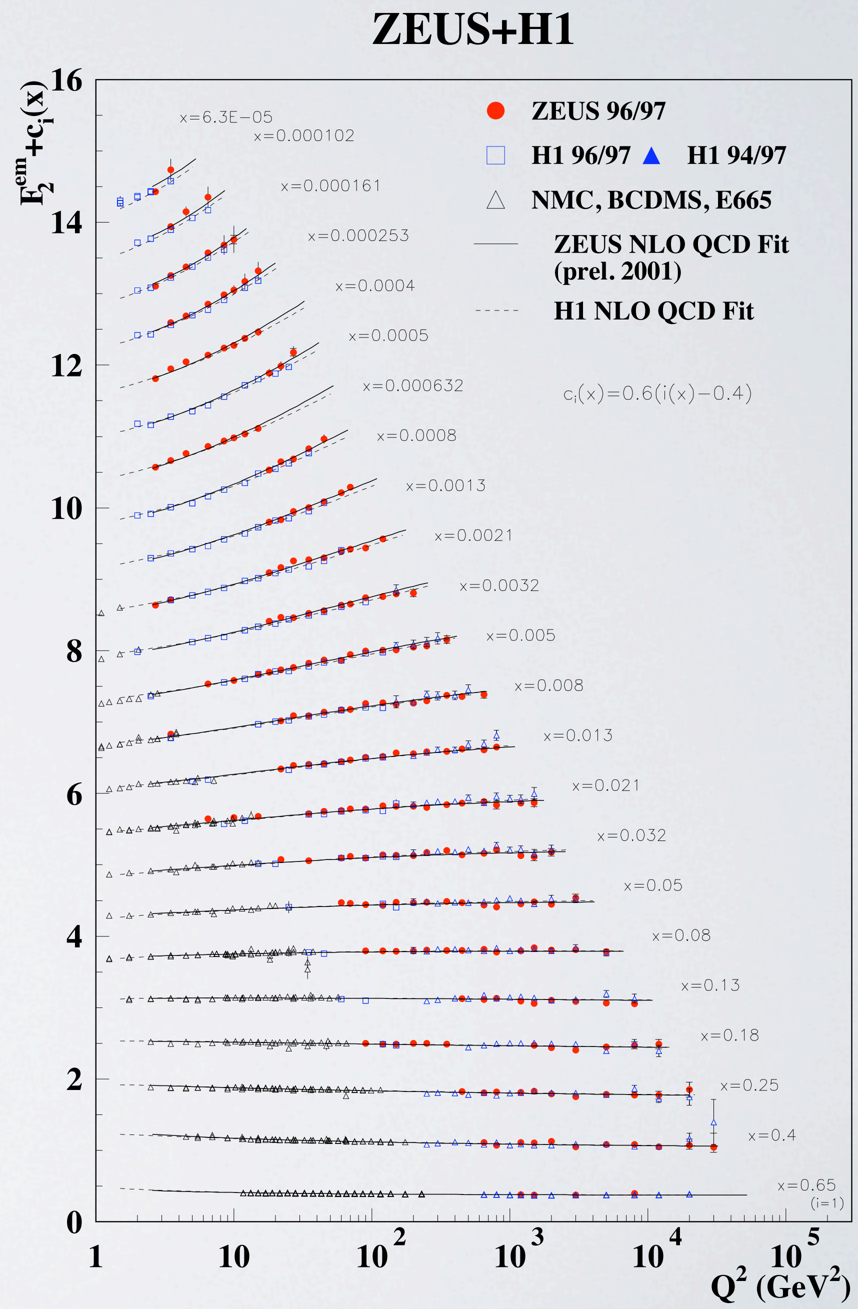
GEOMETRIC SCALING IN DIS

- saturation models predict geometric scaling

$$\sigma(x,Q^2)=\sigma(\tau),\quad \tau=\frac{Q^2}{Q_S(x)^2}$$

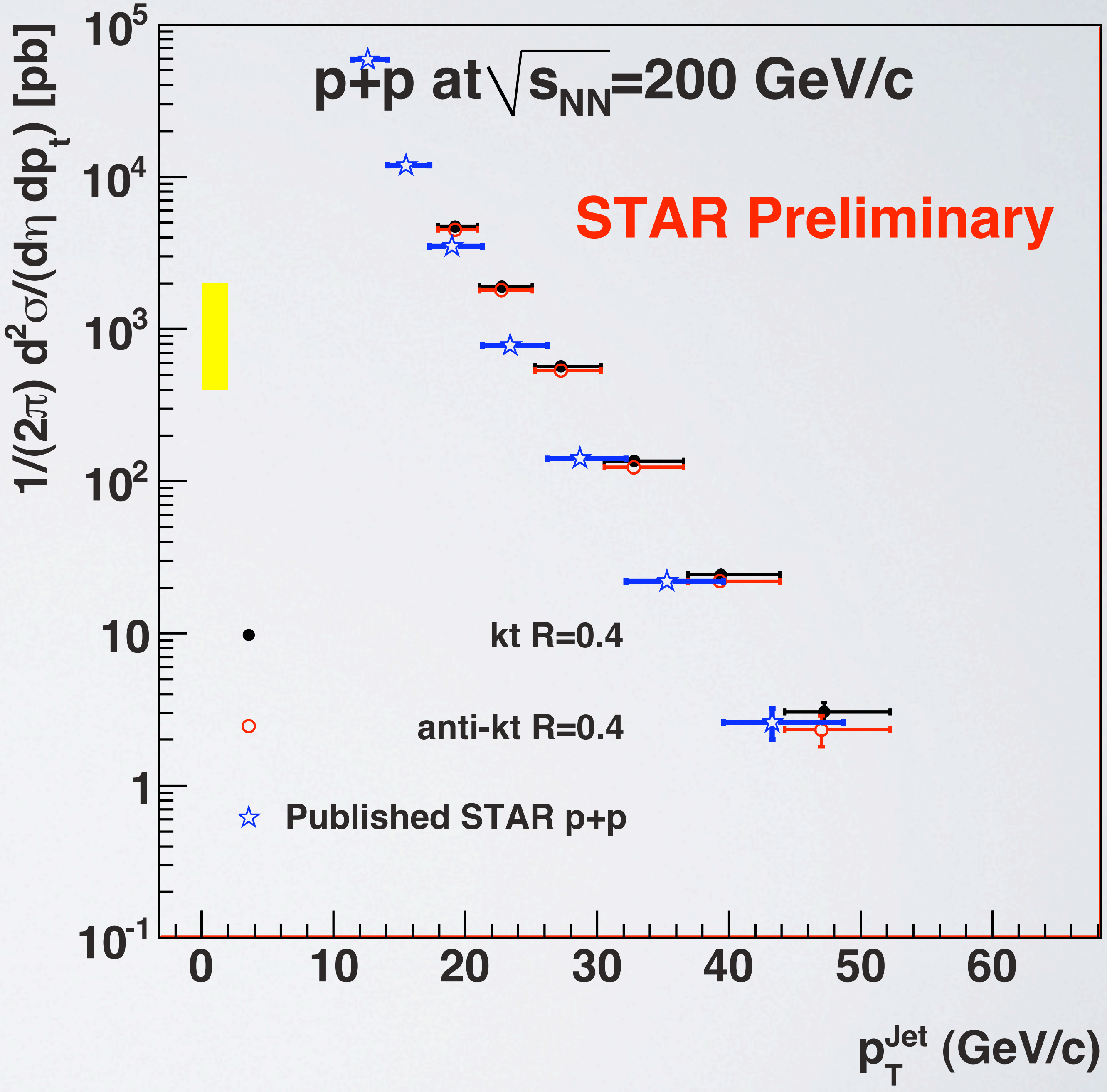
  - observed in DIS for x<0.01
  - same data well described by NLO pQCD





JET CROSS SECTION

- reasonable agreement of new analysis with published STAR results in p+p
- efficiency still under study



JET-MEDIUM: AWAY SIDE

- for intermediate p_T away side correlation different in heavy ions collisions
  - recoil jet structure invisible (dip at $\Delta\phi=\pi$)
  - maximum off-center
  - origin debated: conical shock waves?
- for non-central collisions structure depends on direction relative to reaction plane