Jet quenching at RHIC

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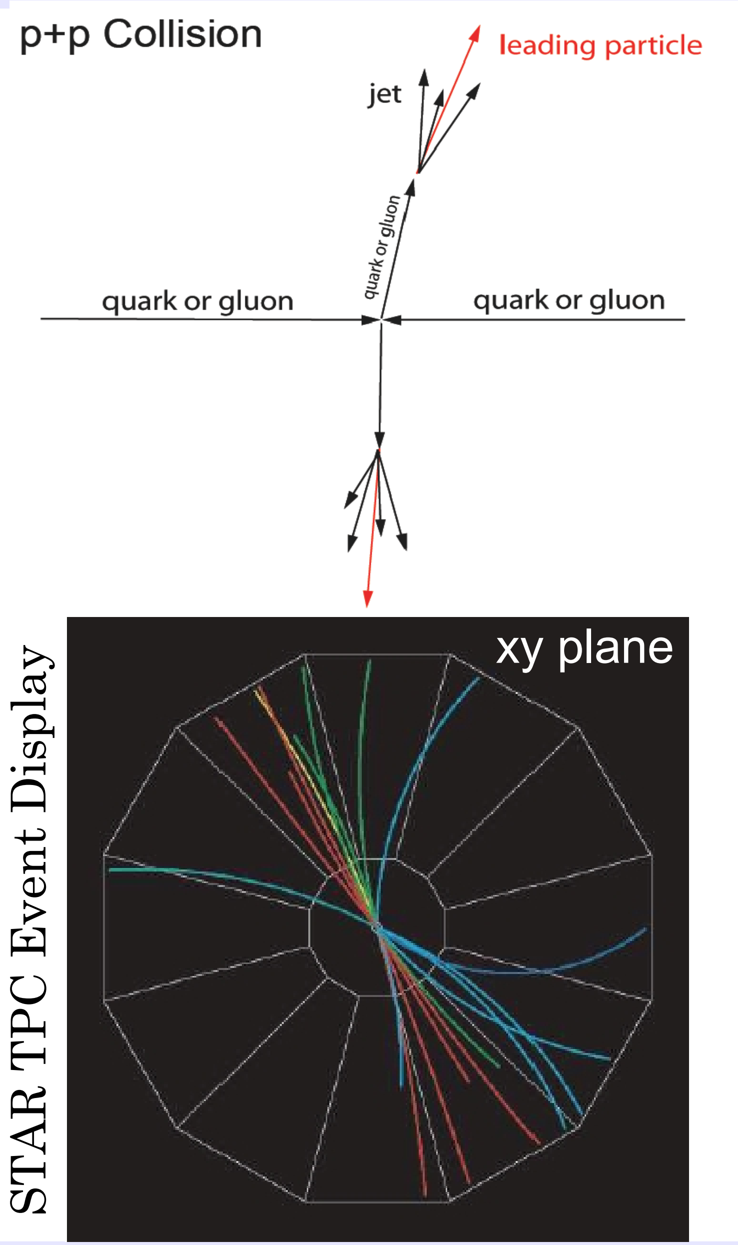
for STAR Collaboration

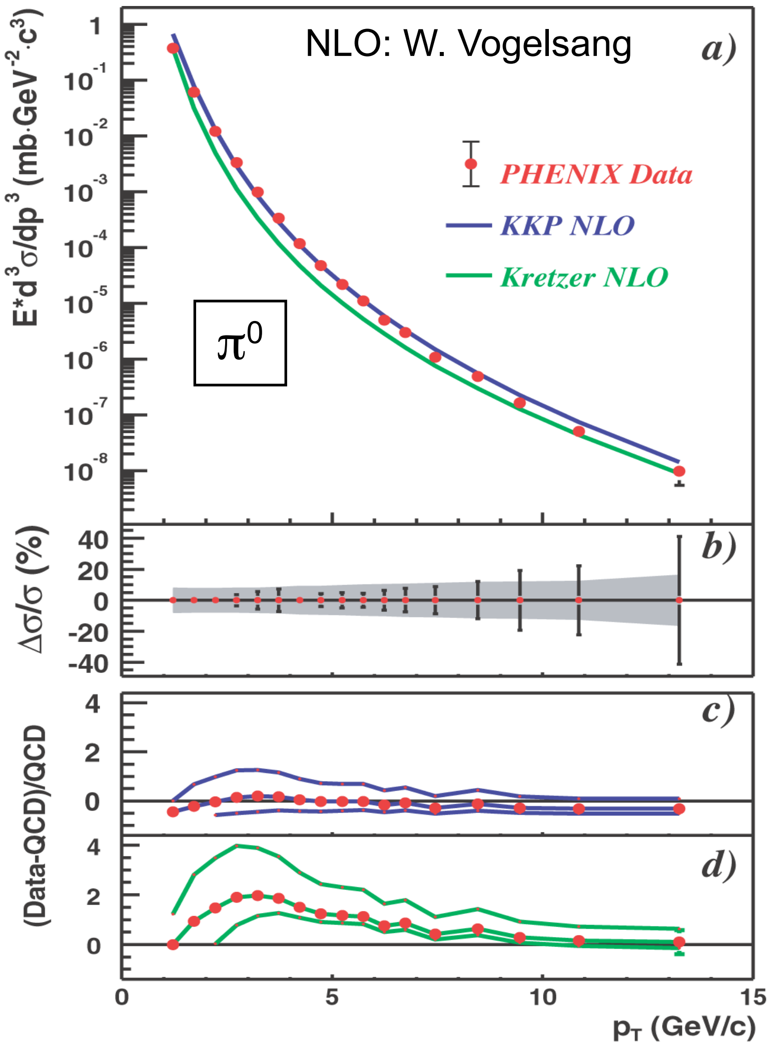
Outline

- What is jet quenching?
- Experimental observations of jet energy loss in Heavy-Ion collisions
- Full jet reconstruction in HI collisions

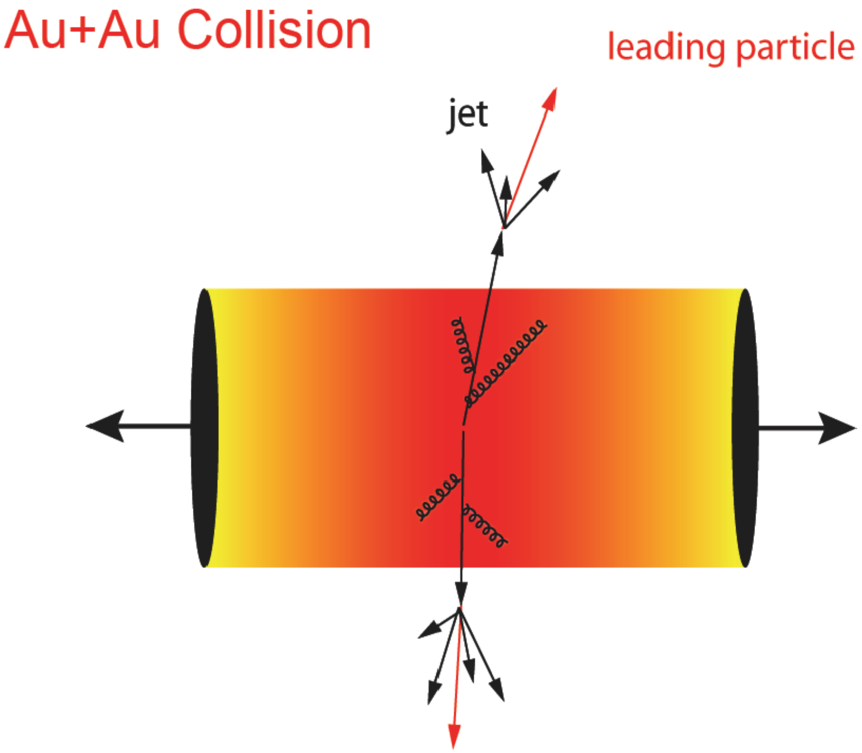
Reference: pQCD at sqrt(s) = 200 GeV p+p collisions at RHIC



$$d\sigma \propto (PDF) \otimes (Hard) \otimes (Fragm)$$

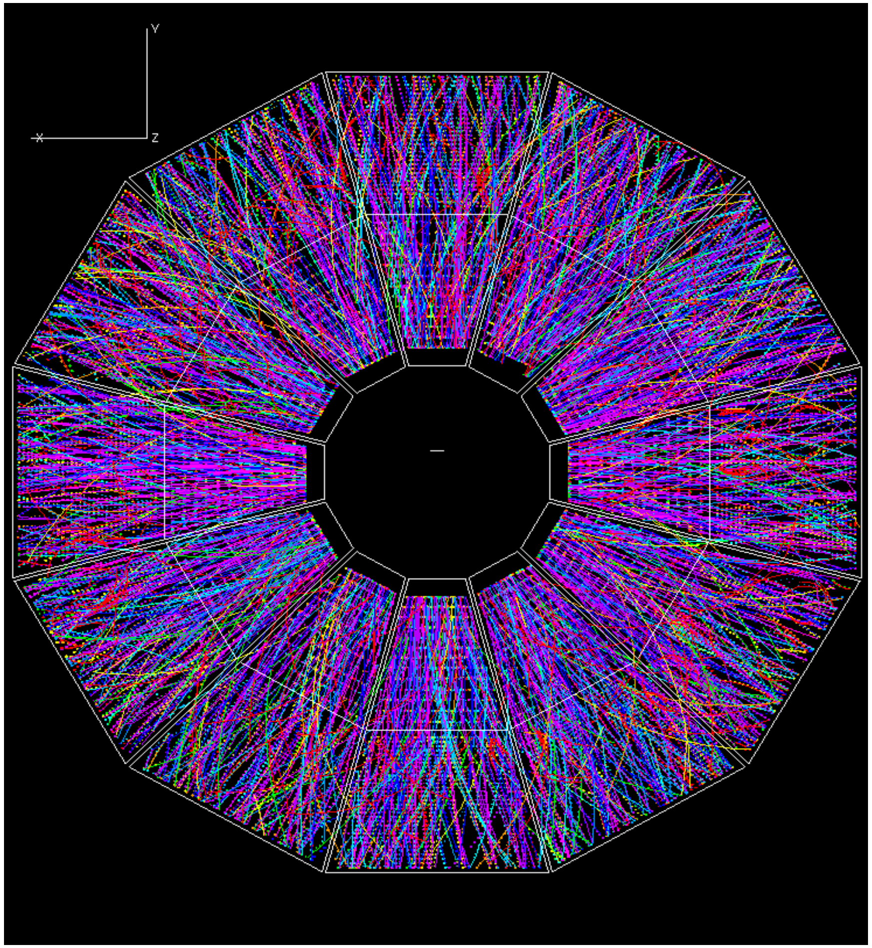


Heavy Ion collisions: Jets interacting with the medium



We use the jets to probe the medium!

STAR TPC Event Display

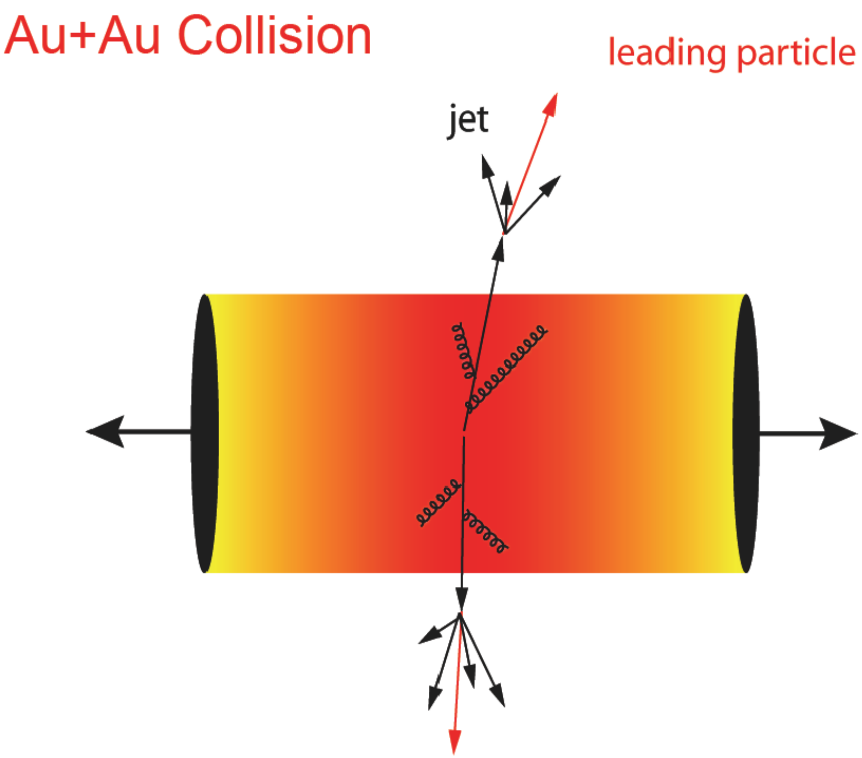


Au+Au at 200 GeV

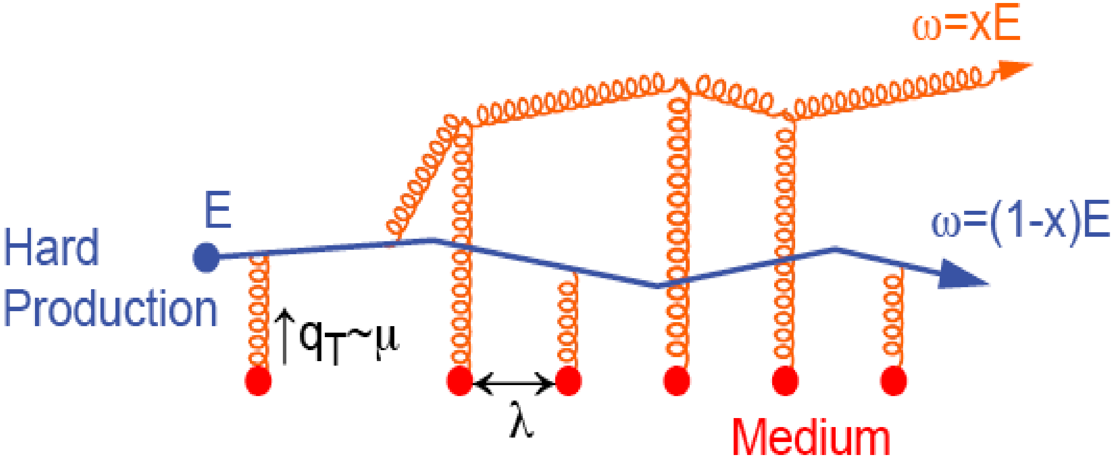
Describing jet quenching

Medium can be characterized by the transport coefficient qhat:

$$\hat{q} \sim \mu^2 / \lambda$$



Parton loosing energy via gluon radiation
- QCD Bremstrahlung



$$E_{loss} \sim L^2$$

$$E_{loss} \sim \rho \sim \frac{dN_g}{dy}$$

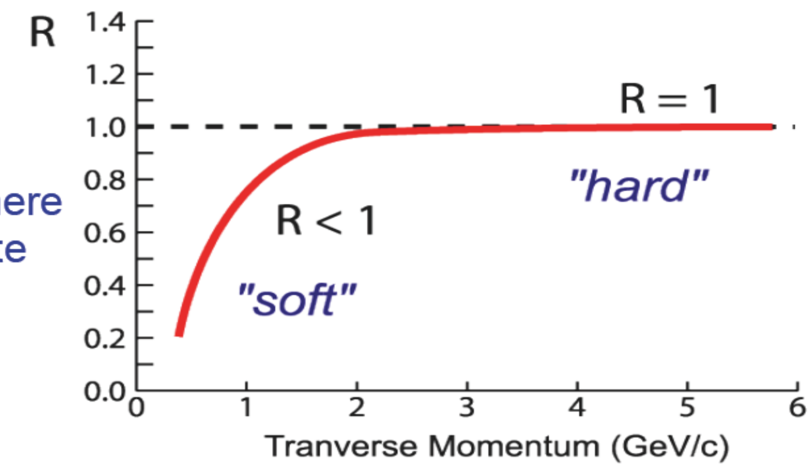
Nuclear modification factor

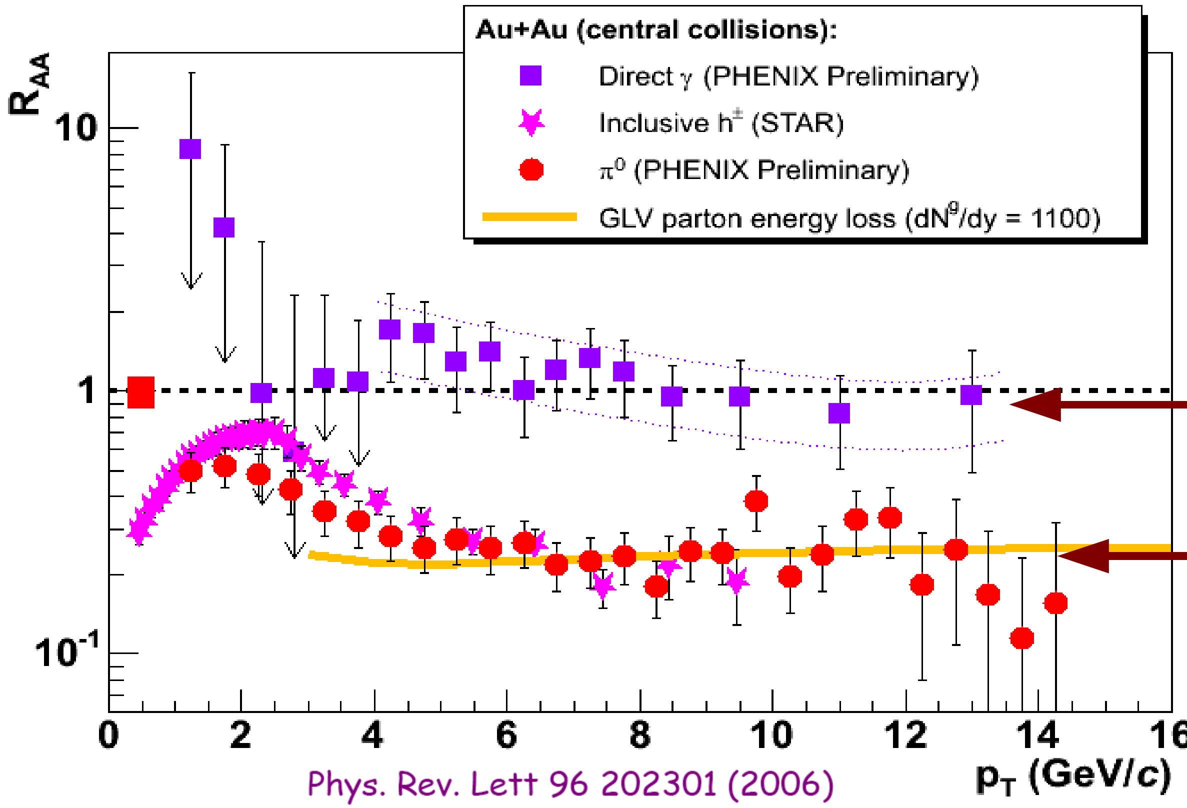
$$R_{AB} = \frac{d^2N/dp_t d\eta}{T_{AB} d^2\sigma^{pp}/dp_t d_\eta}$$

$$T_{AB} = < N_{bin} > / \sigma^{pp}_{inel}$$

No “Effect”:
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate

Suppression: R < 1

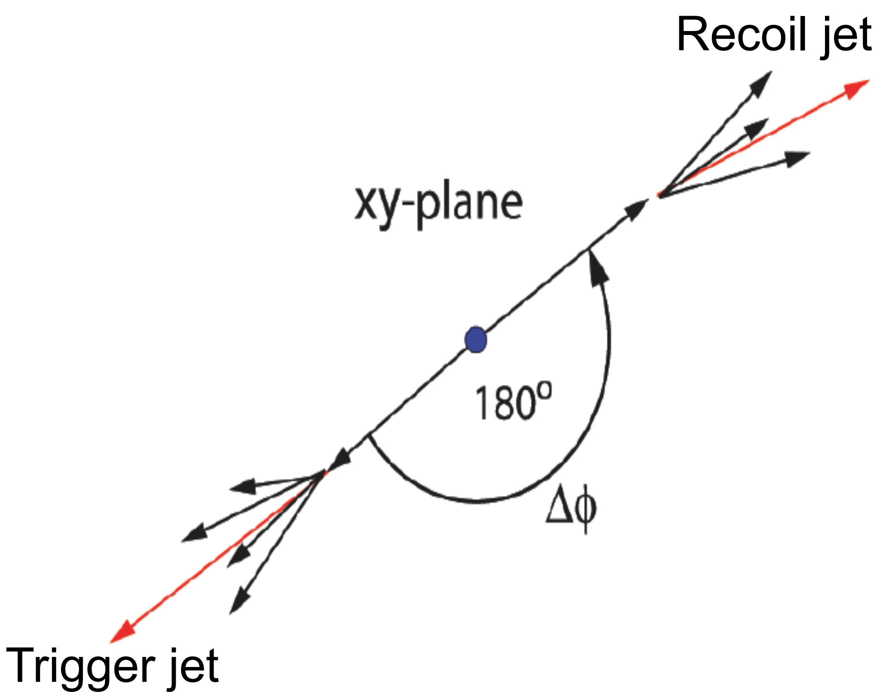


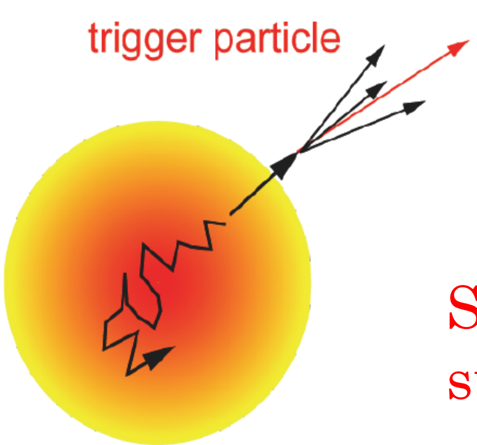


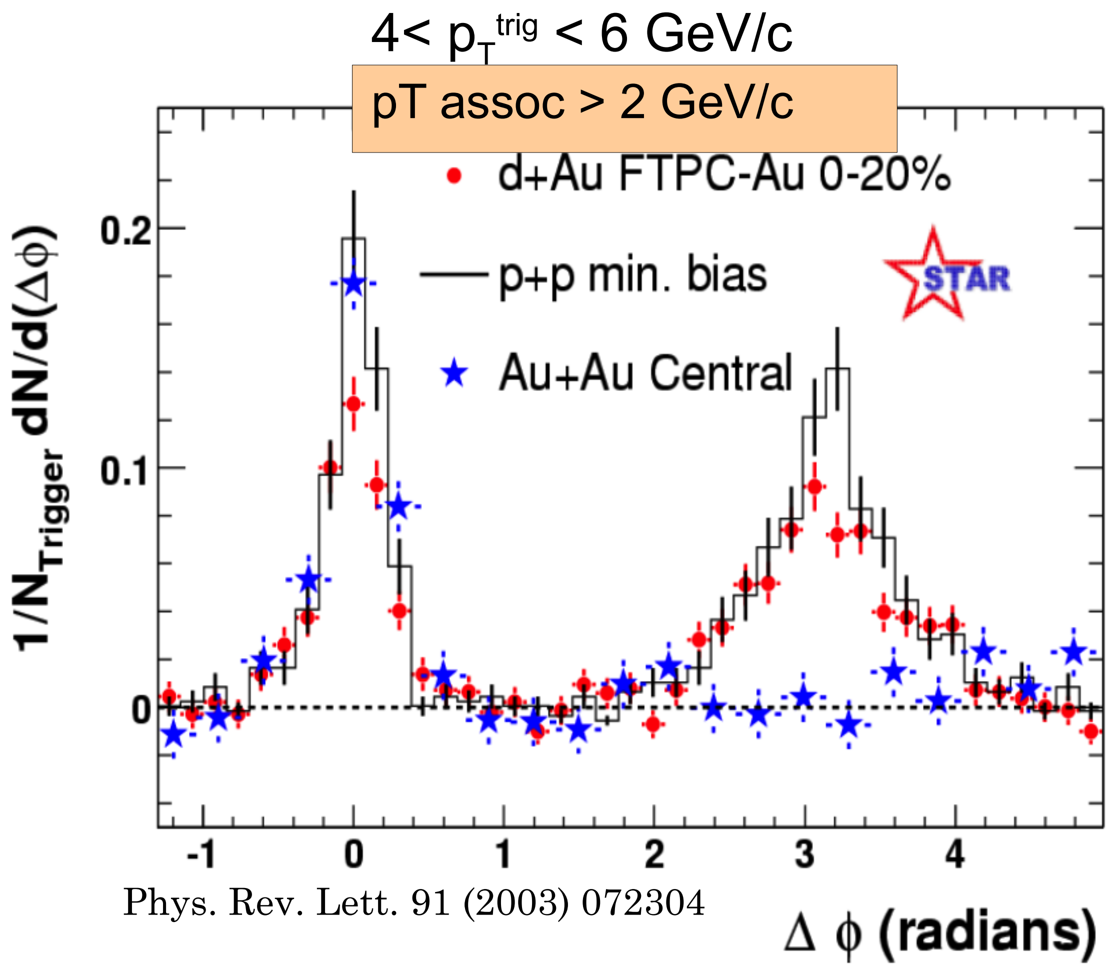
Photon – color neutral probe => No suppresion

Hadrons from color charged jets => Suppresion

Jet suppression via di-hadron correlations



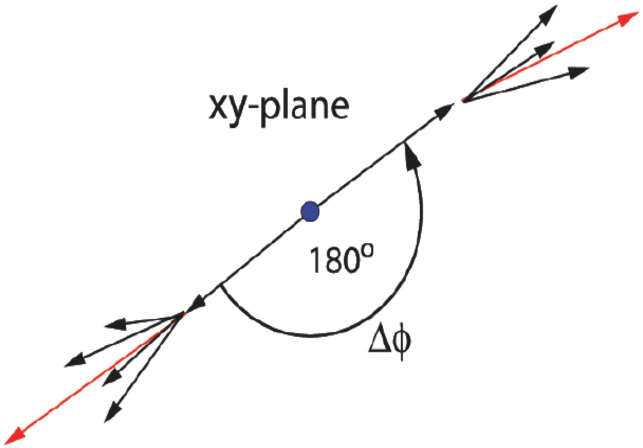


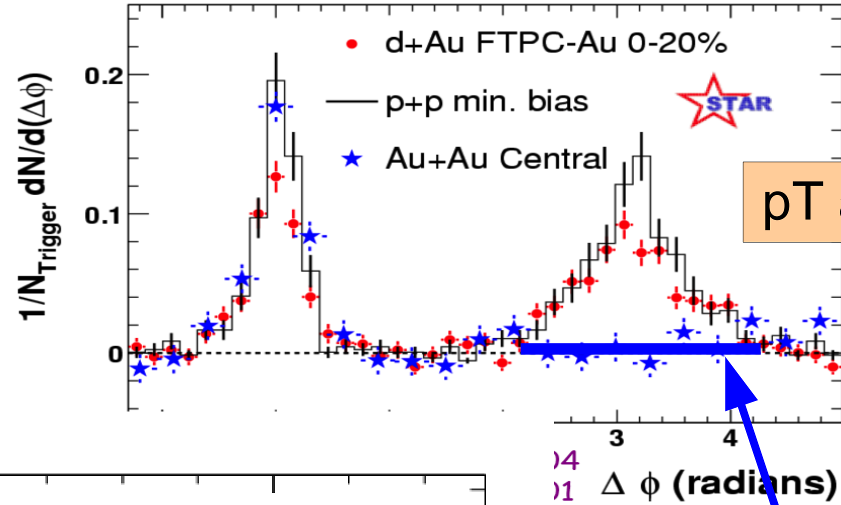


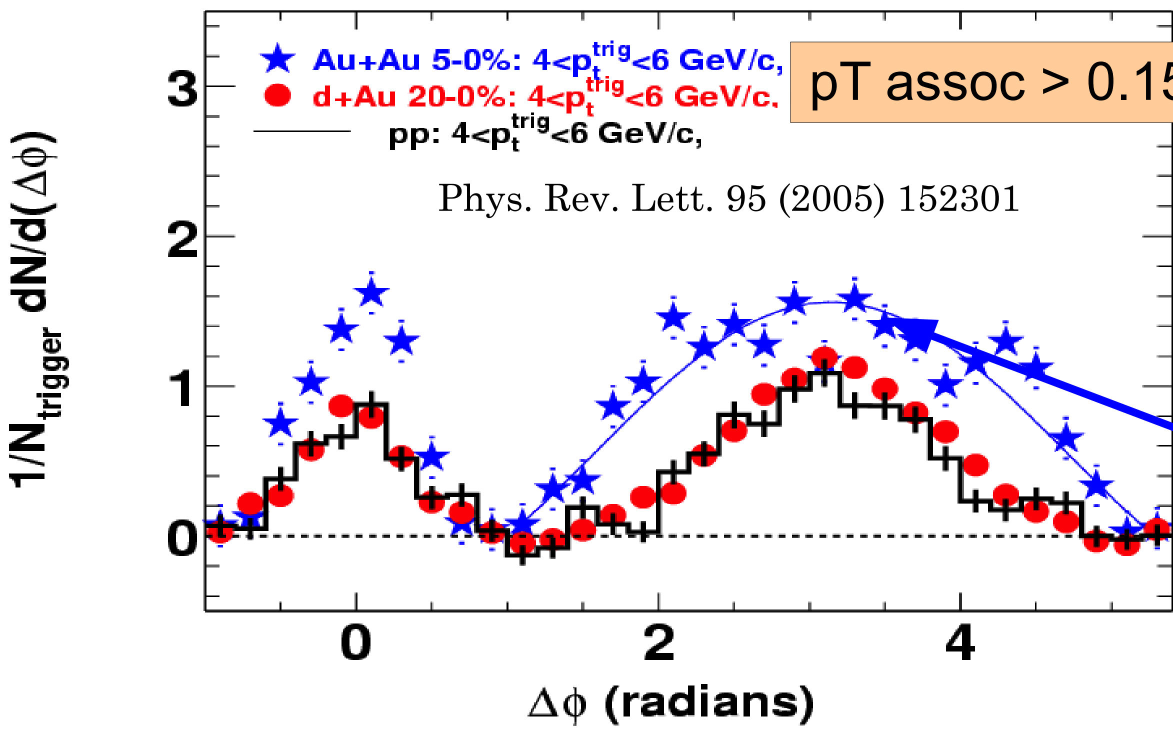
Phys. Rev. Lett. 91 (2003) 072304

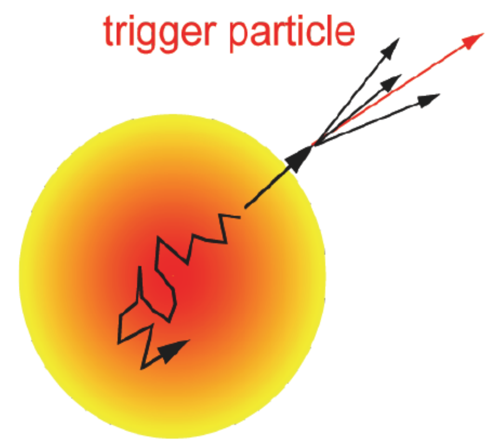
Strong modification of the recoil-jet indicates substantial partonic interaction within the medium

Di-hadron correlations



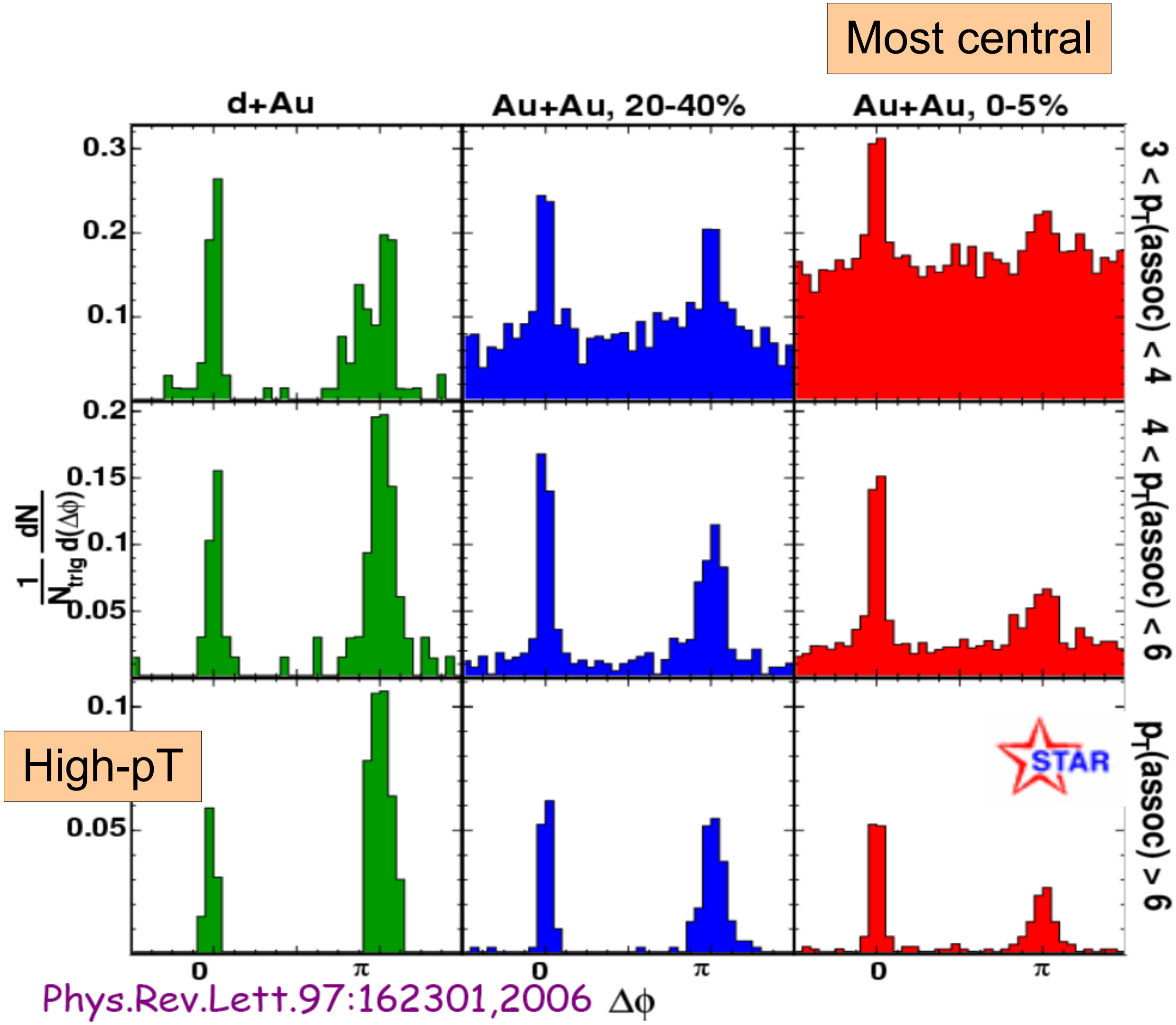






Lowering pT assoc. recovers broad recoil correlation (momentum conservation ~ cos(Δφ))
Increase of soft particle yield as compared to p+p or d+Au!

Di-hadron correlations at high-pT

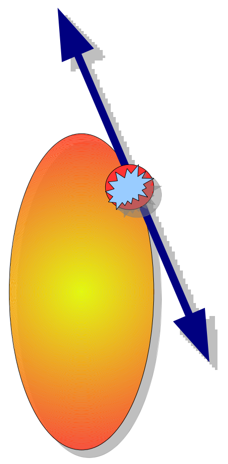


Reaperance of the away side peak at high-assoc.-pT:

- similar suppression as in the inclusive spectra
- unmodified shape

Differential measurement of jets w/o interaction

-> limitation of the LO probes



Medium described by theory

PHENIX '08; J. Nagle WWND08

Model parameters (within a given set of assumptions) are constrained within ~20%

Matter density large:
~30-50 times cold nuclear matter

Additional assumptions → different models are broadly consistent (except PQM – much larger than others)

Different modeling approaches of radiative energy loss operating with different parameters but "connected" with each-other

- $< \hat{q} > \approx 13.2\ GeV^2/fm \quad \pm 20\% \quad (PQM/ASW)$
- $\frac{dN_g}{dy} \approx 1400 \quad \pm\ 20\% \quad (GLV\ and\ WHDG)$
- $\epsilon_0 \approx 1.9\ GeV/fm\ \pm\ 20\% \quad (ZOWW)$
- $\alpha_s \approx 0.28\ \pm\ 8\% \quad (AMY)$

Strong conclusions:

- initially generated medium is highly opaque to energetic partons
- very dense, high temperature matter has been created

Key points learned so far – onset of jet quenching

- Hard partons interact with the medium
  - High-p_t hadrons are strongly suppressed in heavy-ion collisions
  - Leading hadron azimuthal correlations show strong modifications of the recoiling jet fragments at low and intemediate-p_t
- At high-pT: finite measurement of the recoil-jet at the expense of strong bias towards hard fragmentation and little interaction
- **Initial gluon density constrained –> created matter is very dense and hot**

However, we would like to learn more about the interaction…
Need for an unbiased and calibrated jet probe.

Full jet reconstruction in heavy-ion collisions

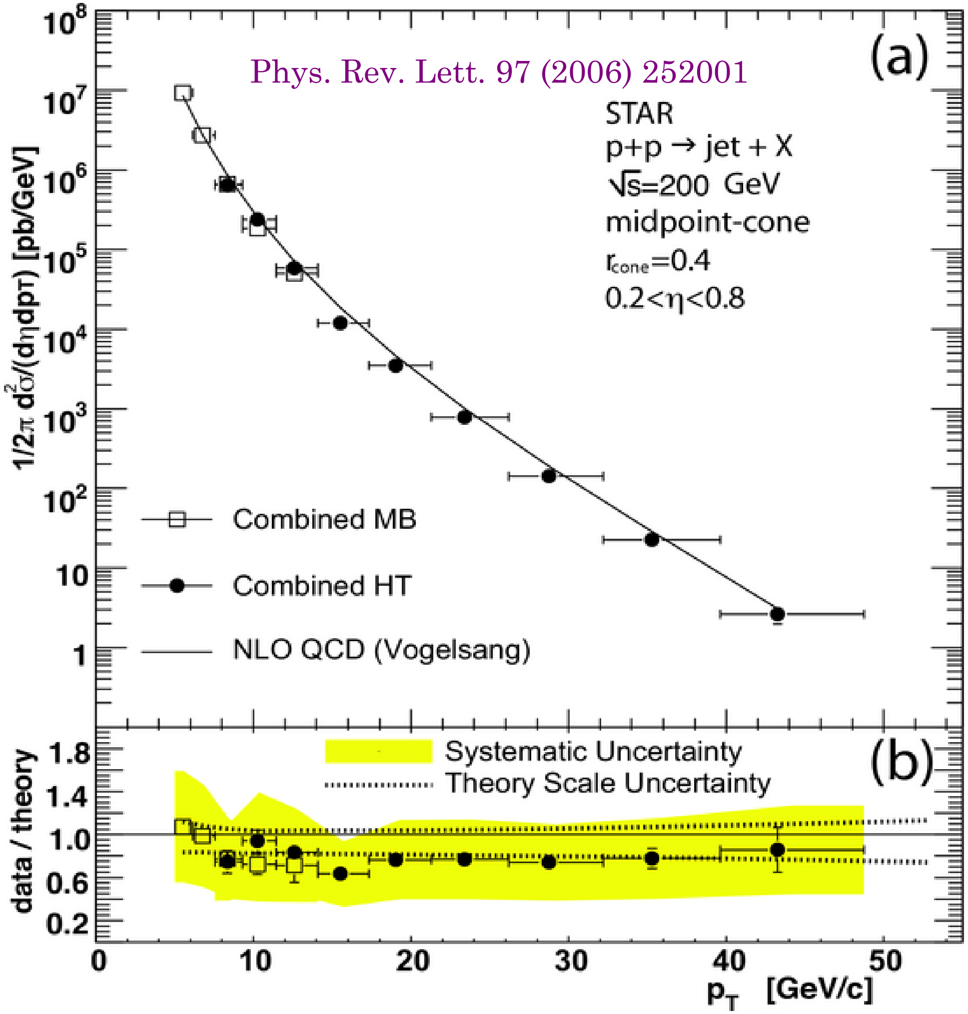
Measure the initial parton energy

Access to unbiased fragmentation and its properties in the presence of medium

Possibly the best tool to asses and discriminate between quenching (energy loss) mechanisms

Exploration of full spectrum of jet modifications in medium

Reference jet measurement



Experimental uncertainty ~50%

p+p jet spectrum agree with NLO pQCD

Unbiased jet reconstruction in AuAu must result in N_{binary} scaling relative to p+p – an essential test!

$$\frac{dN^{jet}_{Au+Au}}{dE_T} = T_{AA}\frac{\sigma^{jet}_{p+p}}{dE_T}$$

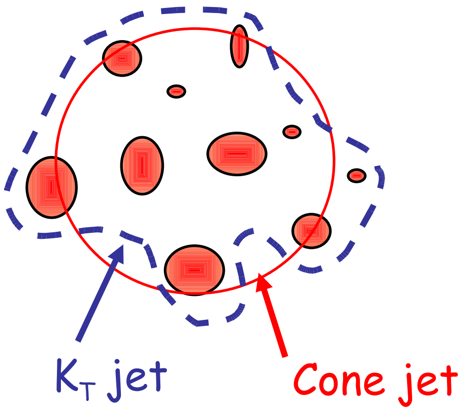
STAR 2007 Au+Au 200 GeV: high statistics – high reach in pT (jets up to 50 GeV!)

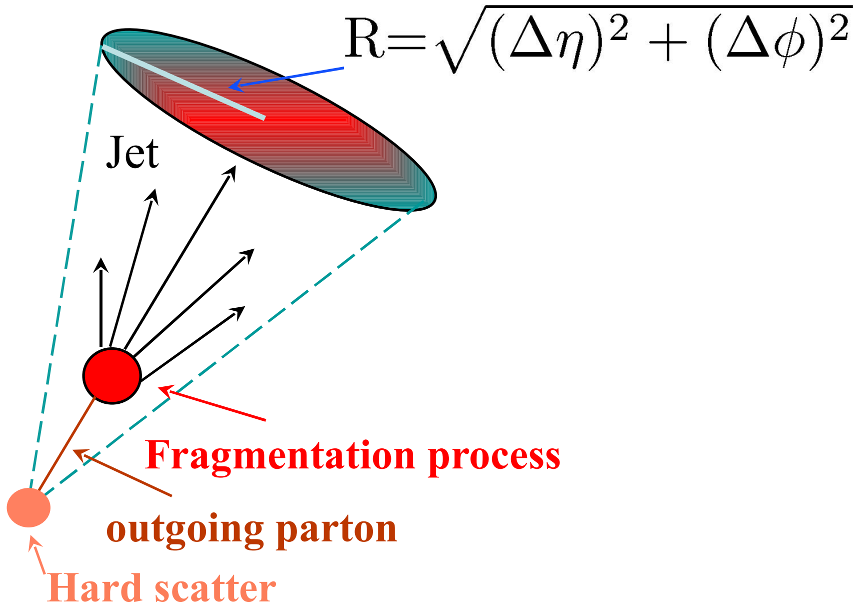
Jet finding algorithms employed in STAR

- Cone algorithms
  - Leading Order High Seed Cone (LOHSC)
  - Mid Point Cone (Used in p+p only) Merging & Splitting

Phys. Rev. Lett. 97 (2006) 252001

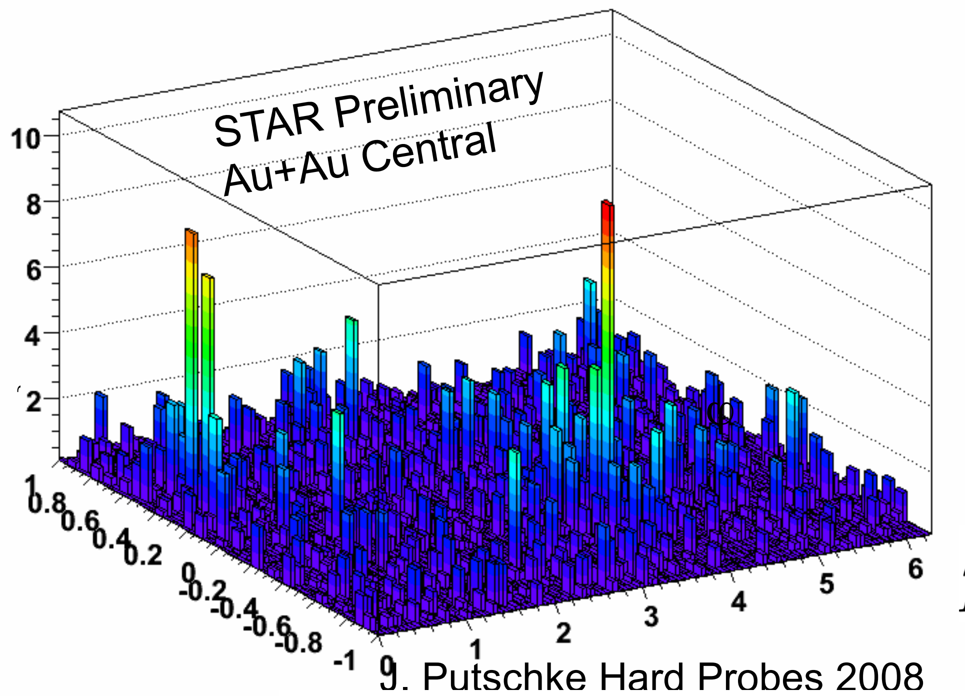
- Recombination algorithms
  - KT
  - Cambridge/ Aachen





M. Cacciari, G. Salam, G. Soyez 0802.1188 [hep-ph]

Jets and the heavy-ion underlying event



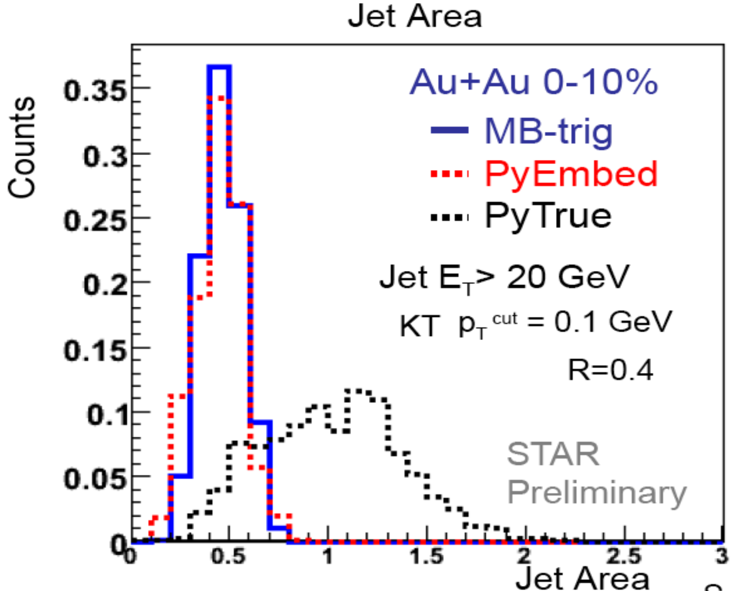
Main difficulty: constrain and control of the background fluctuations

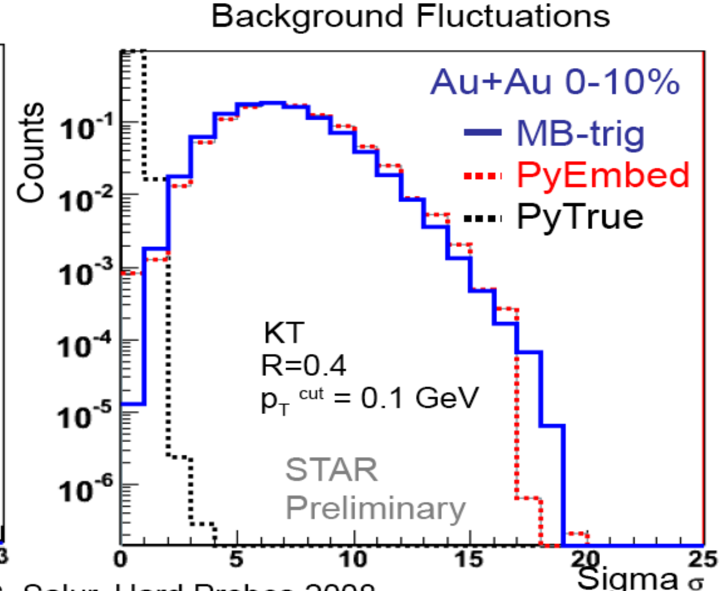
-> Inhibiting background: introduction of p_t cut on the input particles – source of a bias (Cone Alrorithm!)

M. Cacciari, G. Salam, G. Soyez 0802.1188 [hep-ph]

$$p_T^{measured} \approx p_T^{parton} + \rho \cdot A \pm \sigma\sqrt{A}$$

ρ = Diffuse noise, σ = noise fluctuations

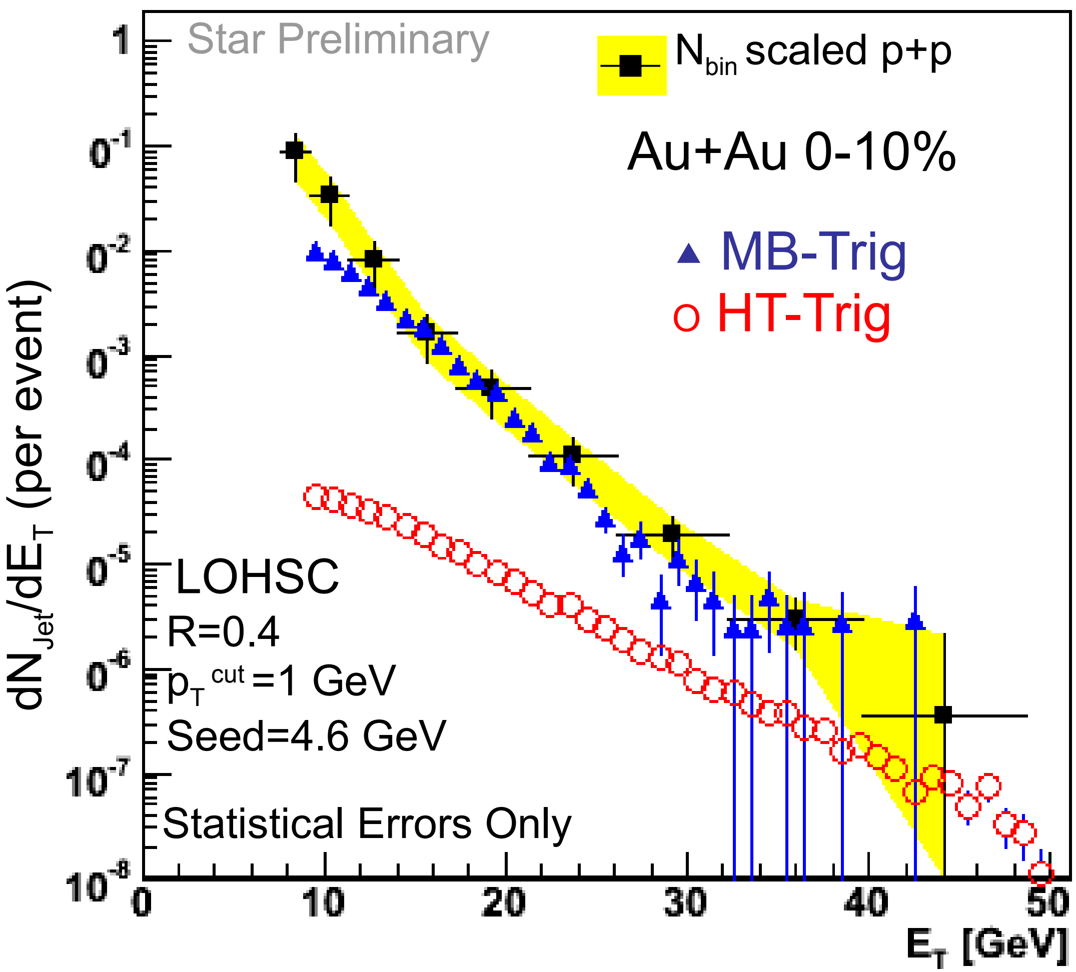




S. Salur, Hard Probes 2008

Cross section compared to binary-scaled p+p

S. Salur, Hard Probes 2008



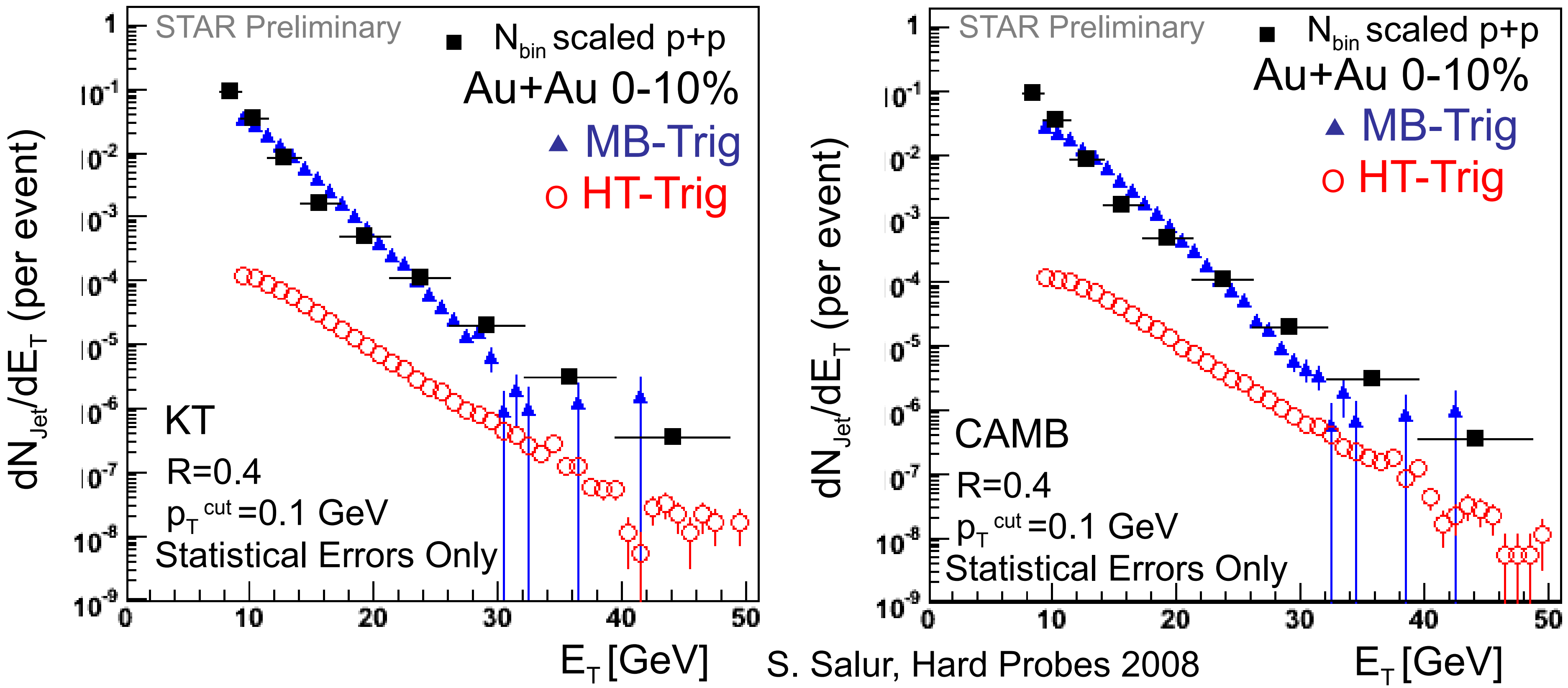
Inclusive spectrum correction based on PYTHIA

MB-Trig: Good agreement (within errors) with binary-scaled p+p → unbiased jet reconstruction?

HT-Trig: hardware cluster trigger (requirement of ~7.5 GeV) in EMcalorimeter -> large trigger bias persists beyond 30 GeV

MB-Trig is essential for unbiased measurement - good news: factor ~20 more on tape than shown here!

Scaling for sequential recomb. w/ low p_T cut



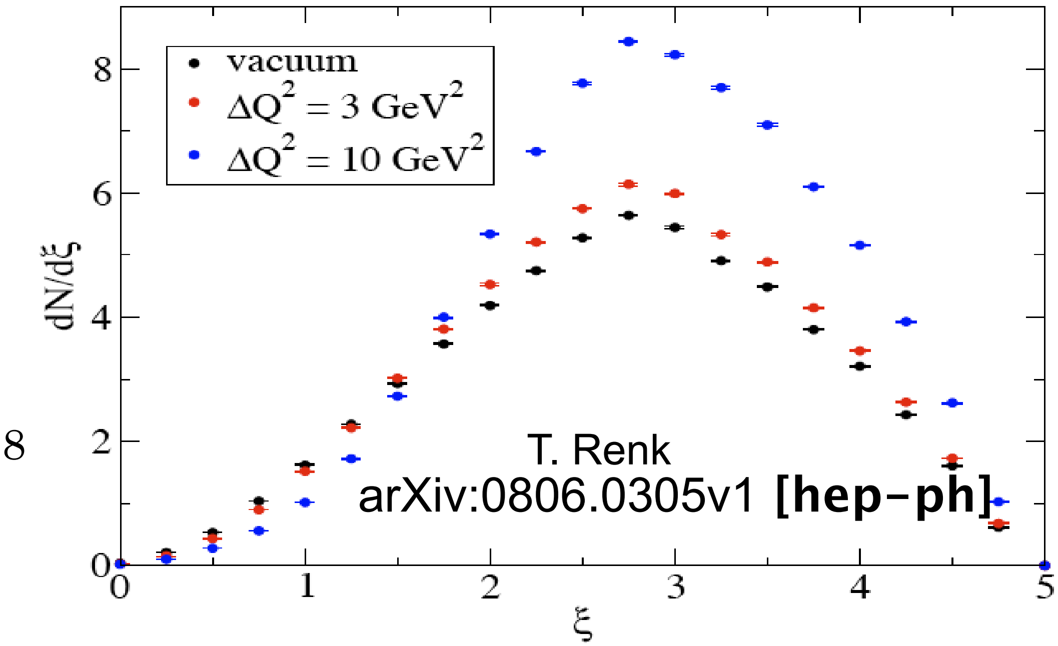
S. Salur, Hard Probes 2008

Also good agreement with binary-scaled p+p!
Interesting because:

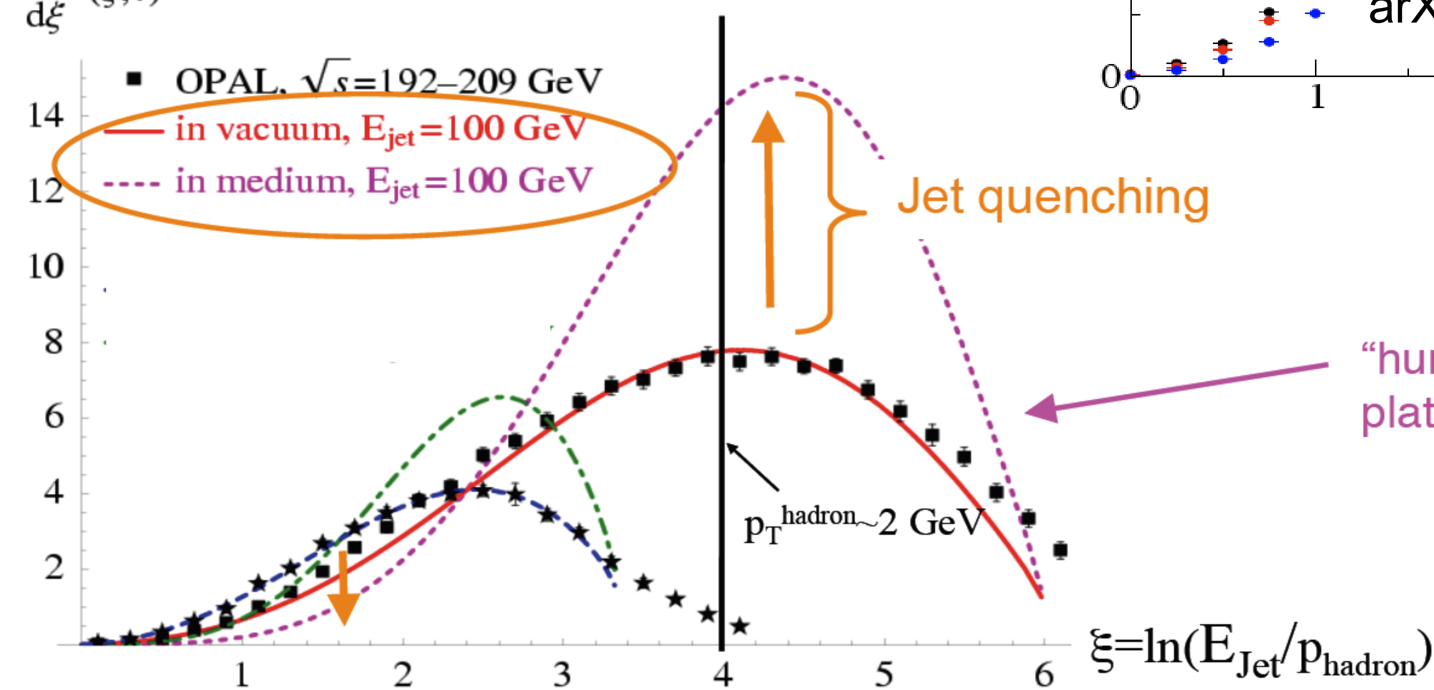
- seedless algorithms: no seed bias
- pT>100 MeV (!): minimal p_T cut bias
- spectrum correction factors (much) closer to unity

Fragmentation function: The Shape and Quenching

$$\xi = ln(E^{Jet}/p_{hadron})$$



$\frac{dN^h}{d\xi}(\xi,\tau)$ Borghini and Wiedemann, hep-ph/0506218

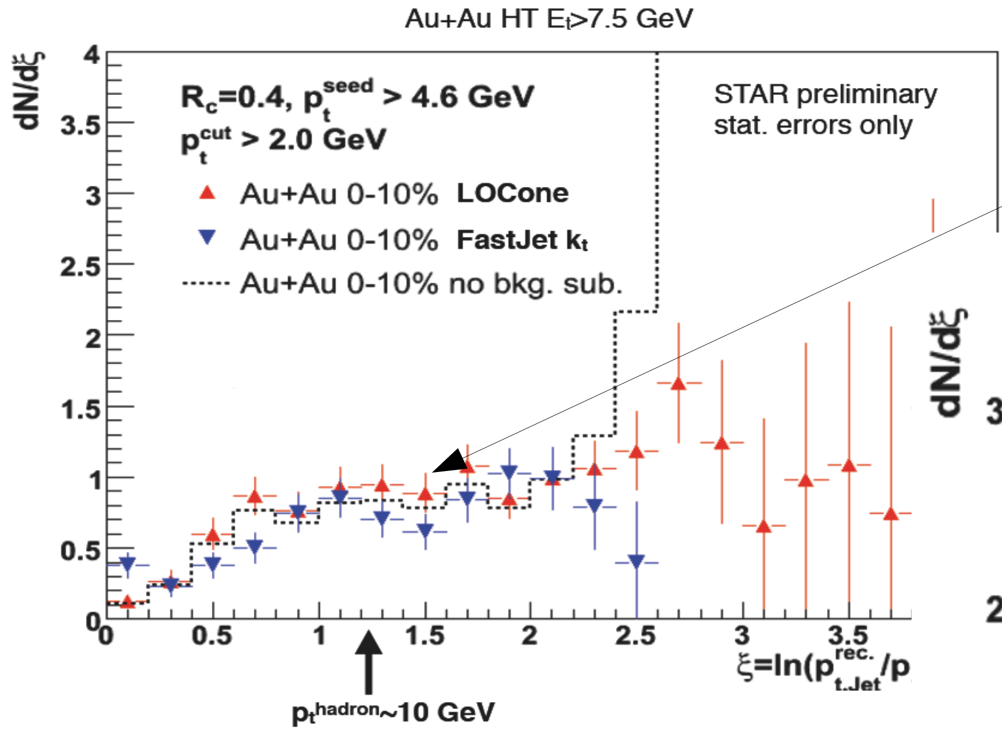


Summary

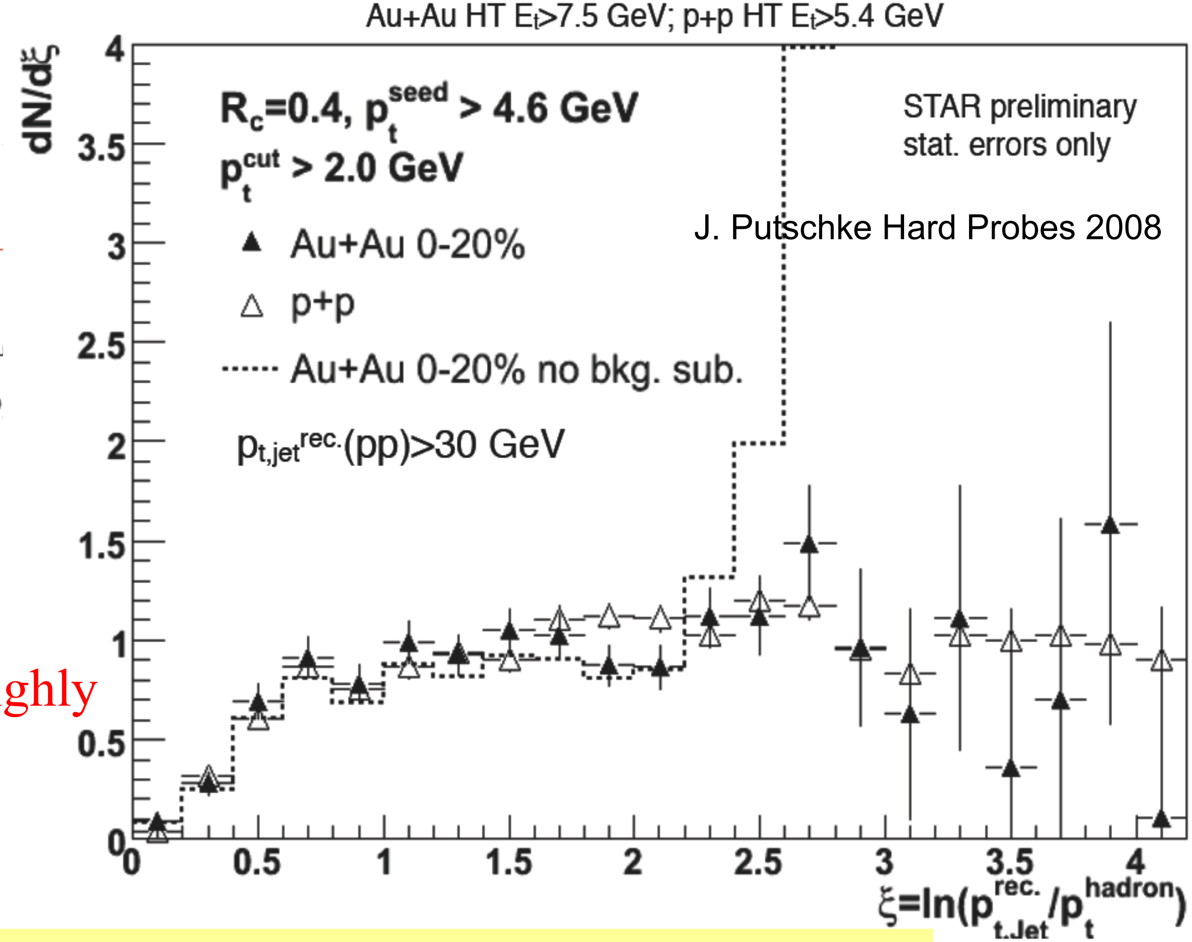
- Leading hadron studies in Heavy-Ion collisions at RHIC show a strong evidence of jet quenching – constrain theoretical undestanding of the medium density and temperature
- Studies of parton energy loss in hot QCD medium (Quark Gluon Plasma) require unbiased probes
- Full jet reconstruction in HI collisions works extremely well - gamma-jet, di-jet studies are under way, access to the fragmentation function
- Theoretical developments, MC models including quenching will provide understanding of the energy loss mechanisms – in case of strongly coupled QGP we may explore unique access and sensitivity to non-perturbative QCD dynamics

Additional material

FF for Jet energies > 30 GeV



Agreement for different algorithms



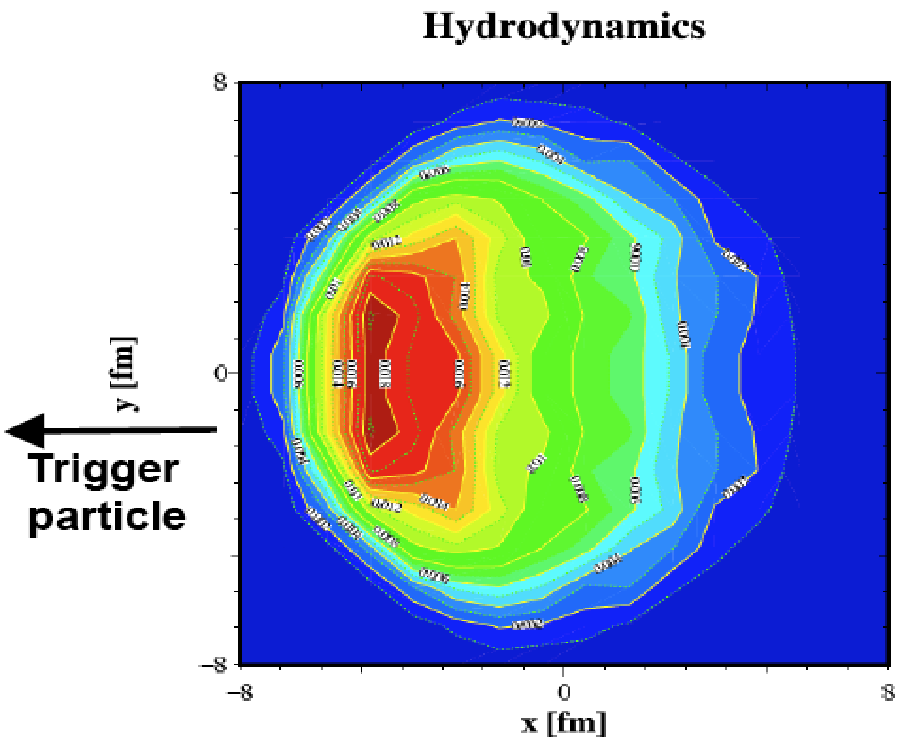
Provisional conclusion: apparently no medium-induced FF modification!

but consistent with HT-trig being highly biased (require 7.5 GeV π^0 in jet)

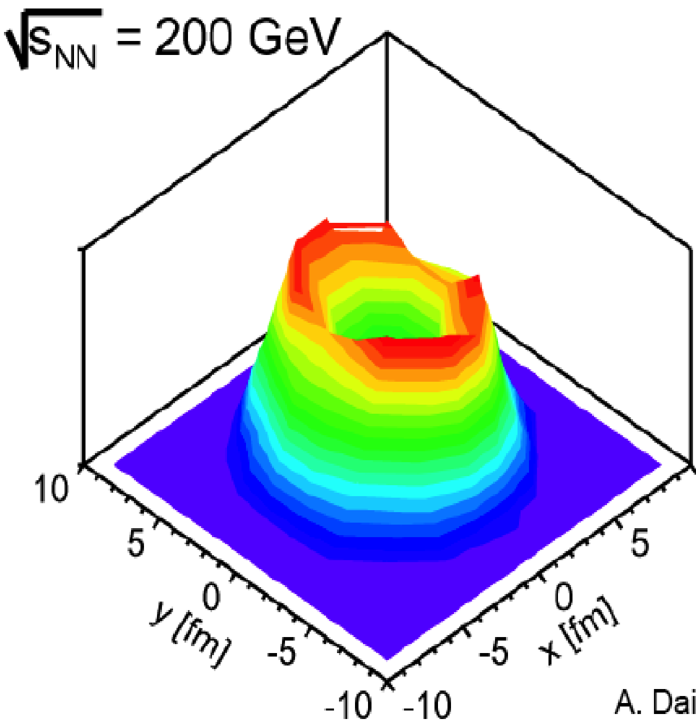
Factor 20 more MB-trig data on tape – crucial to analyse it!

Trigger Bias

Setup of the trigger (online and offline) biases studied sample towards harder fragmentation



Renk and Eskola, hep-ph/0610059



Distributions of parton production points in the transverse plane

A. Dainese et al., Eur. Phys. J. C38(2005) 461

Need more unbiased methods to constrain and reconstruct the jet energy and di-jet studies

-> Full jet reconstruction, gamma-jet correlations

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PQM/ASW $\langle \hat{q} \rangle = 13.2^{+2.1}_{-3.2}$ GeV^2/fm

GLV $\frac{dN_g}{dy} = 1400^{+270}_{-150}$

WHDG $\frac{dN_g}{dy} = 1400^{+200}_{-375}$

ZOWW $\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm

AMY $\alpha_S = 0.280^{+0.016}_{-0.012}$

Strong conclusions:

- initially generated medium is highly opaque to energetic partons
- very dense, high temperature matter has been created