Trigger Particle Correlation Results from PHENIX

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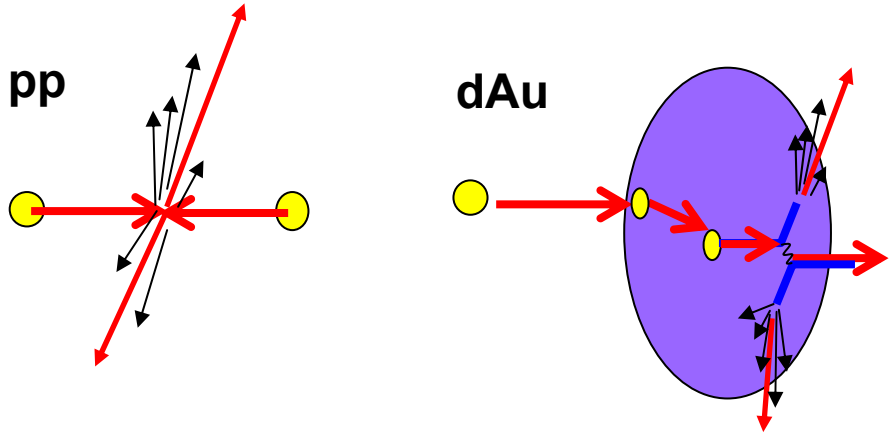
Hadronic Jets in Cold and Hot QCD matter (I)



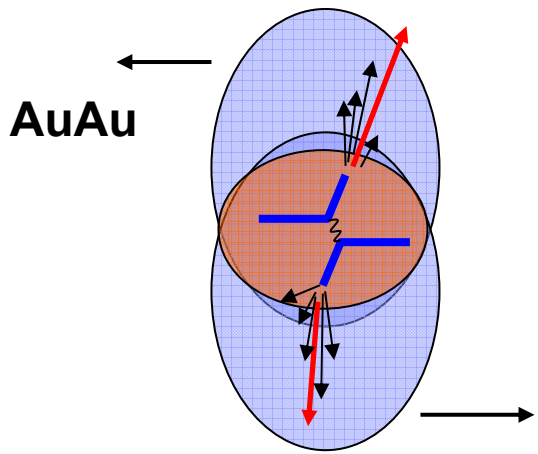
Medium effects on jets can be studied using dihadron angular correlations:

- Partonic transverse mometum **k_T** – away side ($\Delta\varphi \sim \pi$) shape in pp
- Parton FF **D(z)** – away side conditional yields pp and dAu

- **Cronin** (***multiple scattering***) modification of k_T in cold QCD medium – away side shape in dAu (vs. pp and centrality)

- **Monojet dominance** (***gluon saturation***) at low x in nuclear media – transition from dijets to monojets in dAu and AuAu at low x

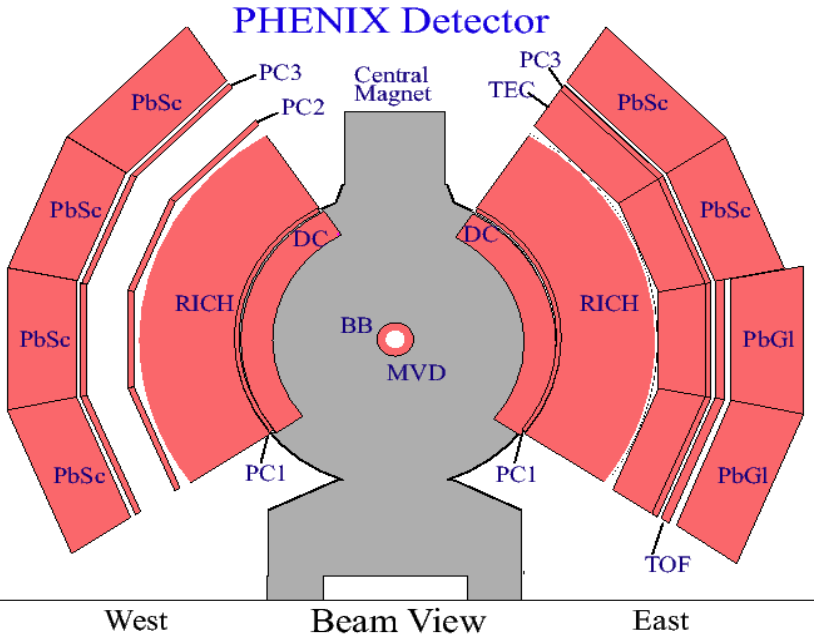
Hadronic Jets in Cold and Hot QCD matter (II)

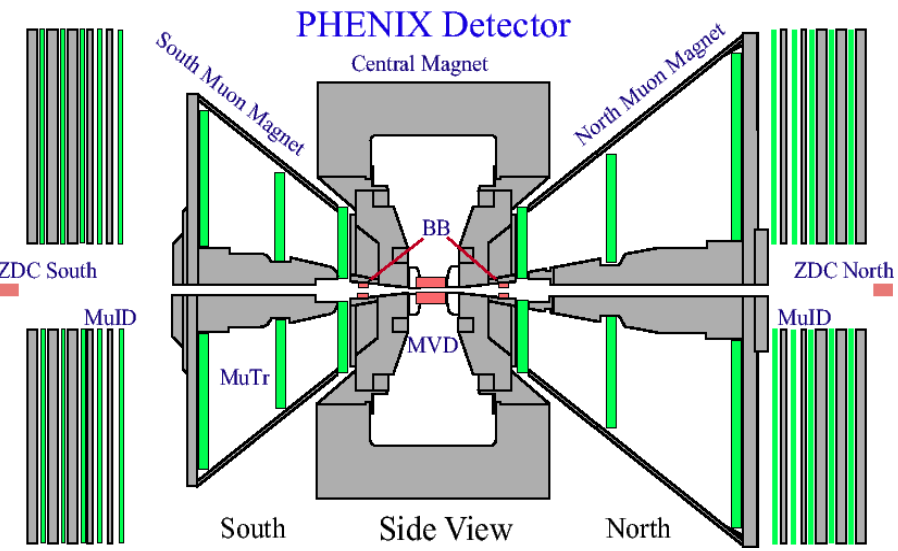


- **Jet broadening** (***gluon radiation***) in hot QCD medium – away side shape in AuAu (vs. dAu and centrality)
- **Jet suppression** (***gluon radiation***) in hot QCD medium – away side conditional yield in AuAu (vs. dAu and centrality)

- **Conic flow** (***sonic waves in liquid QGP***) – away side shape in AuAu

PHENIX Detector





- Beam-Beam Counters ($3<|\eta|<4$)
  - **centrality**: N_{part}, N_{coll}
  - **reaction plane orientation**: v_2 of particles at $\eta\sim0$ (central arms)
- Central Arms ($|\eta|<0.35$)
  - charged hadrons **$h^{\pm}$**: DC, PC1, PC3
  - neutral pions **π^0**: PbSc, PbGl
  - high p_T charged pions **$\pi^{\pm}$**: DC, PC1, PC3, RICH, PbSc, PbGl
  - identified charged hadrons **$\pi^{\pm}$,$K^{\pm}$, p/pbar**: DC, PC1, PC3, TOF
- Muon Arms ($1.4<|\eta|<2.2$)
  - charged hadrons **$h^{\pm}$**: MuTr, MuID

Dihadron Angular Correlations

We construct angular correlations by division with the mixed event distribution:

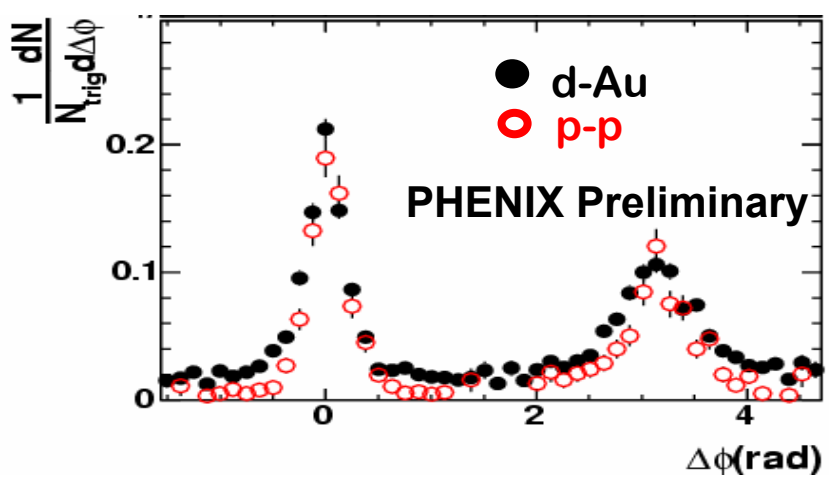
$$\frac{1}{N_{trigg}}\frac{dN_{real}}{d\Delta\varphi} = \boldsymbol{N}\frac{dN_{real}/d\Delta\varphi}{dN_{mix}/d\Delta\varphi} = B\left(1+2v_2\cos\left(2\Delta\varphi\right)\right) + Dijet\left(\Delta\varphi\right)$$

We normalize such that <u>*area is equal to the conditional yield*</u> (number of associated hadrons per trigger hadron):

$$\boldsymbol{N} \equiv \frac{1}{N_{trigg}}\frac{R_{\Delta\eta}}{\varepsilon}\frac{1}{2\pi}\int d\Delta\varphi \cdot N_{mix}\left(\Delta\varphi\right)$$

where $R_{\Delta\eta}$ is the rapidity acceptance correction and ε is the single hadron acceptance and efficiency correction for the associated hadron.

Dijets in pp and dAu are described by two Gaussians: near (Δφ~0) and away (Δφ~π). For high p_T triggers, there is no global correlation: v_n=0.



Calibrating Dijets – pp and dAu Collisions

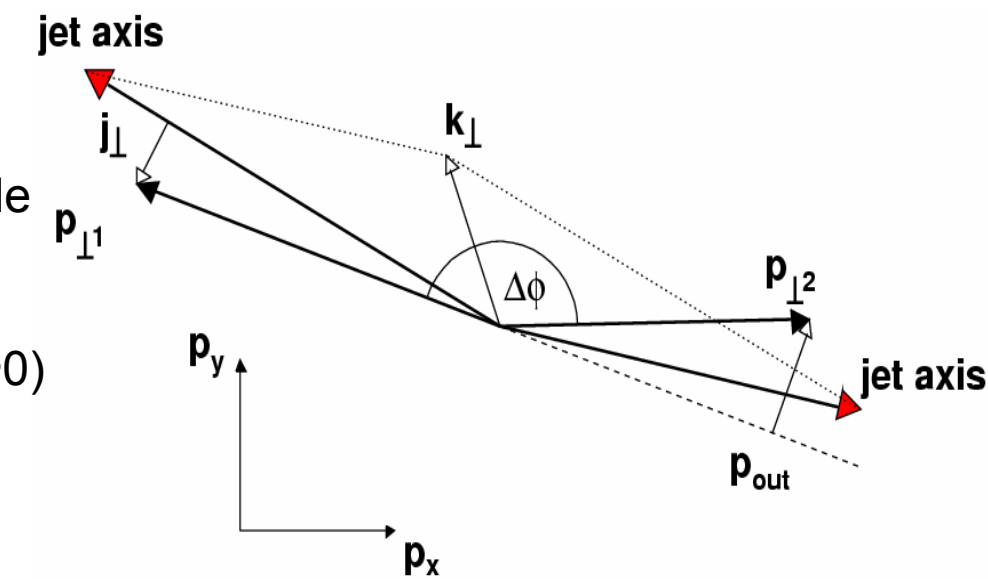
Dijet Parameters

Parton FF **D(z)** from away conditional yield with fixed trigger:

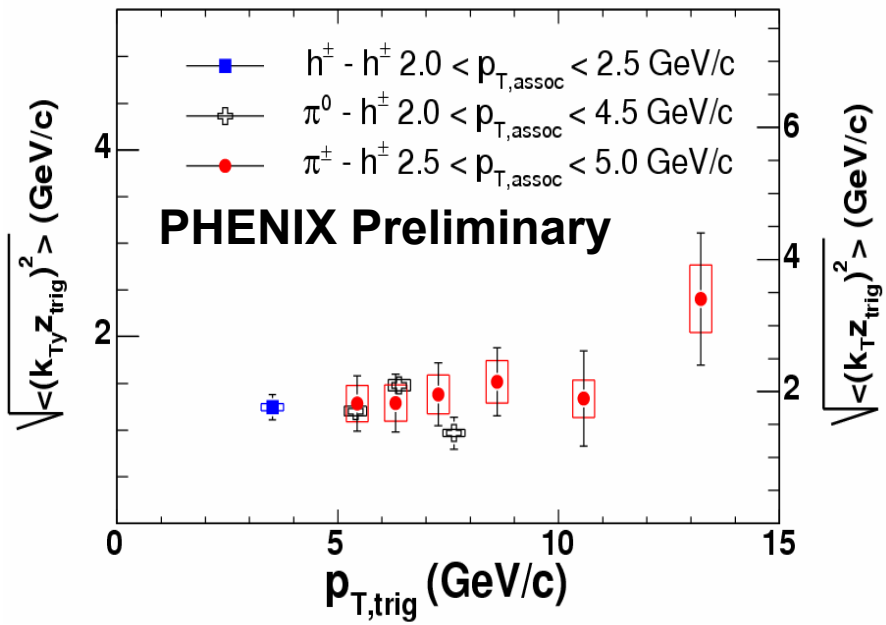
$$x_E \equiv \frac{\vec{p}_{Ttrig} \cdot \vec{p}_{Tasso}}{\left|\vec{p}_{Ttrig}\right|^2} \approx \frac{z_{asso}}{z_{trig}} \Rightarrow \frac{1}{N_{trig}} \frac{dN}{dx_E} = \frac{z_{trig}}{N_{trig}} \frac{dN}{dz_{asso}} \approx z_{trig} D(z_{asso})$$

Parton fragmentation transverse momentum $\mathbf{j_T}$ - constant value independent on fragment's p_T is characteristic of jet fragmentation (j_T-scaling): it is directly related to the near side ($\Delta\varphi$~0) Gaussian width: $\sigma_N \rightarrow \langle |j_{Ty}| \rangle$

Parton transverse momentum $\mathbf{k_T}$ – (intrinsic+NLO radiative corrections+multiple scattering) carries the information on the parton interaction with the QCD medium: it can be extracted from the near side ($\Delta\varphi$~0) and away side ($\Delta\varphi$~π) Gaussian widths and <z>: $\sigma_A \rightarrow \langle |j_{Ty}| \rangle \oplus \langle |k_{Ty}| \rangle \langle z \rangle$

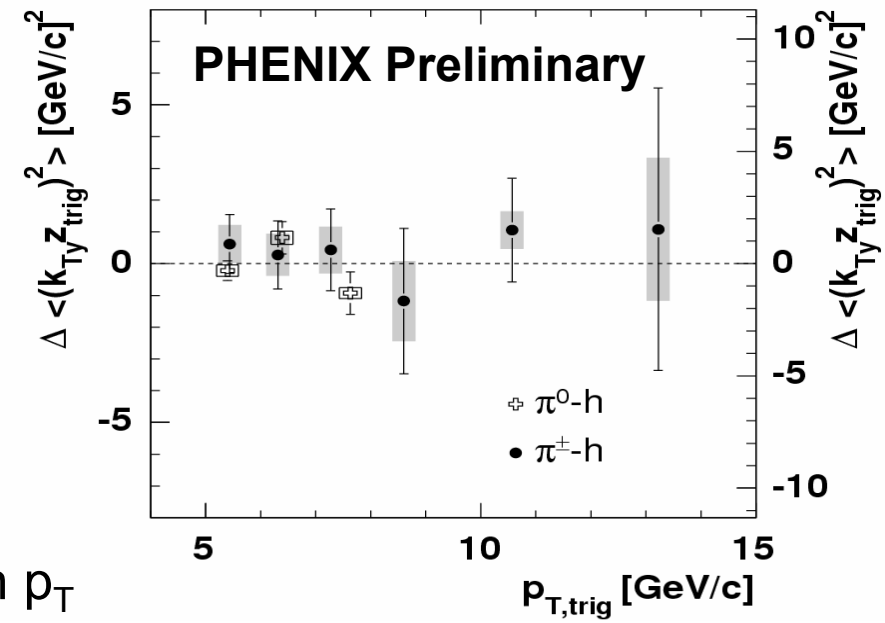


k_T in pp and dAu

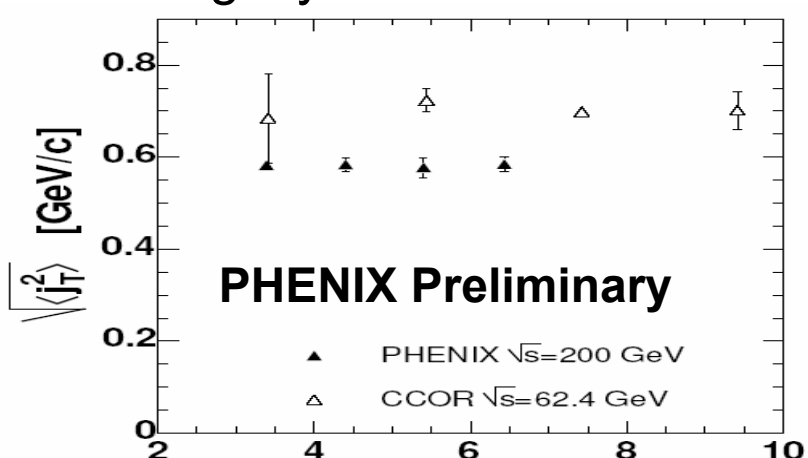


no k_T increase from pp to dAu:

$$\Delta\left\langle\left(k_T z_{trig}\right)^2\right\rangle = 0.01 \pm 0.31 \pm 0.14\ \mathrm{GeV/c}^2$$

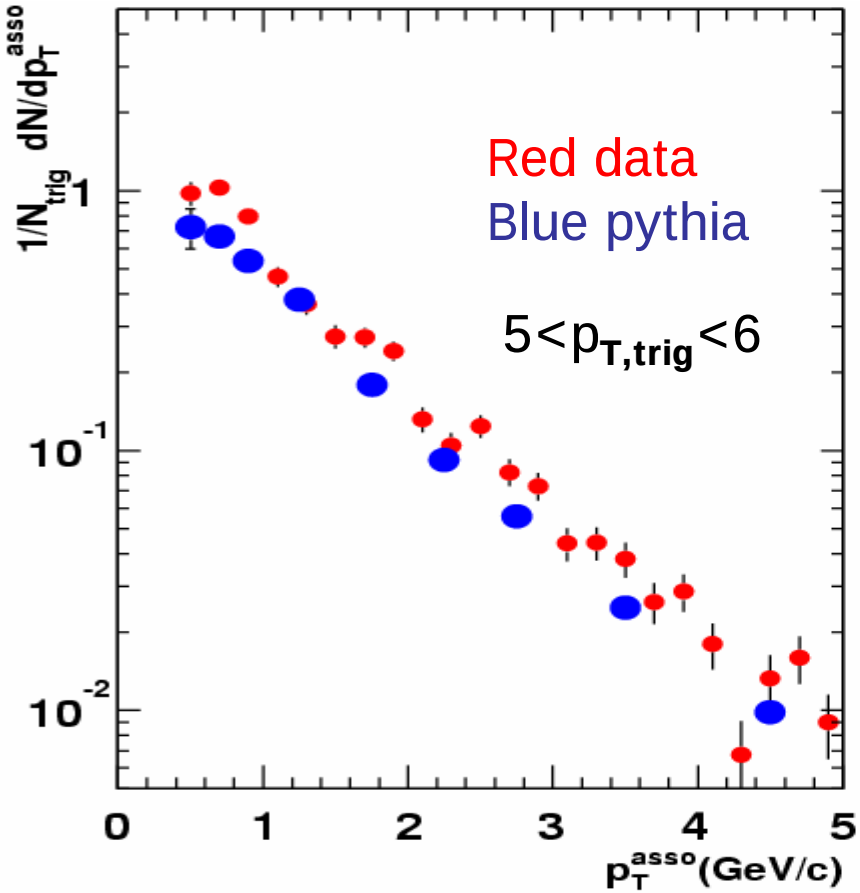


j_T scales with p_T
slightly lower than at ISR

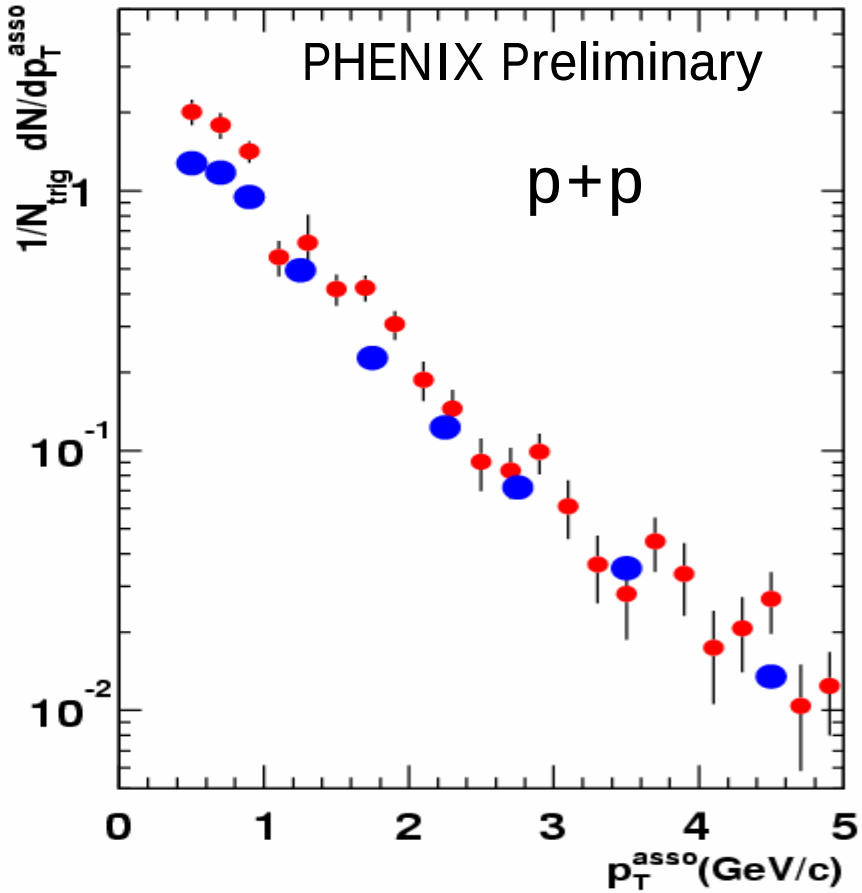


Parton FFs in QCD Vacuum

Near Side

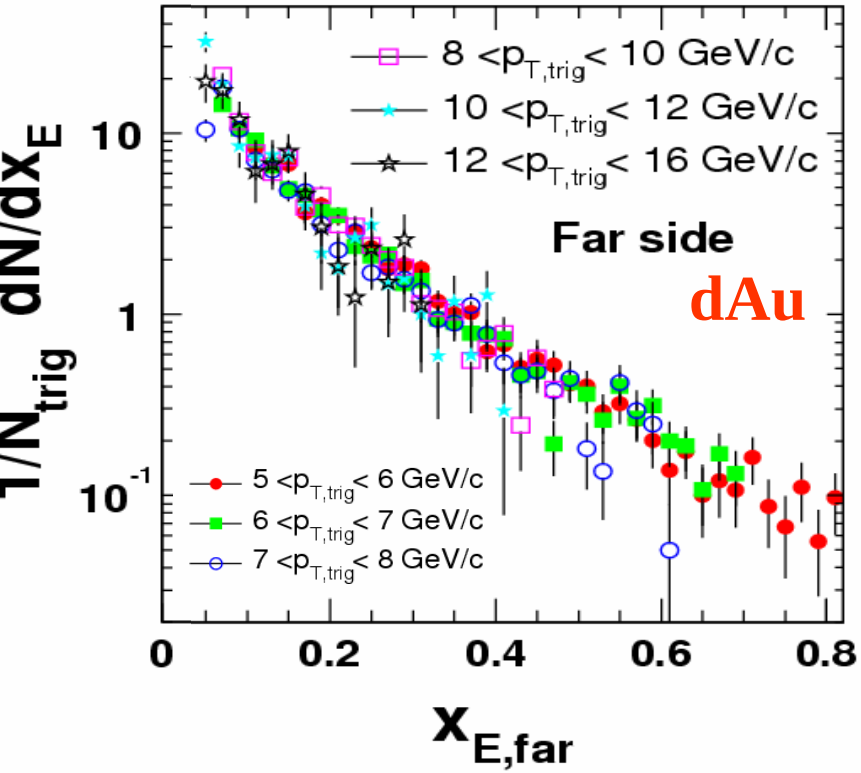


Away Side

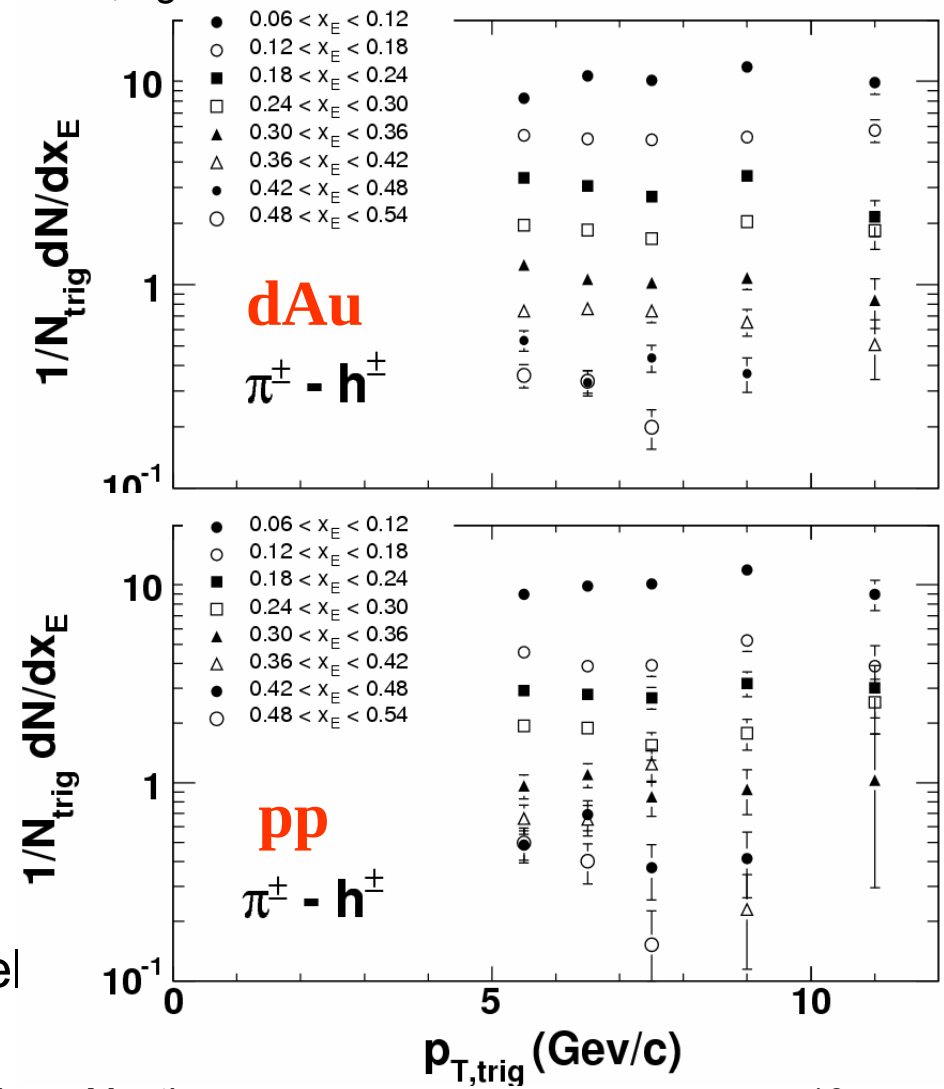


Parton FFs in cold QCD matter

x_E-scaling of FFs in dAu (and pp)



$p_{T,trig}$-scaling of FFs in pp and dAu



we do not see the factor of two larger conditional yields in dAu compared to pp predicted by the recombination model Hwa and Yang nucl-th/0407081

High-x and Low-x Triggers in dAu (and pp)

Trigger on hadrons from the low-x north muon arm (1.4<η<2.2) or from the high-x south muon arm (-2<η<-1.4) and associate with hadrons in the central arm (|η|<0.35):

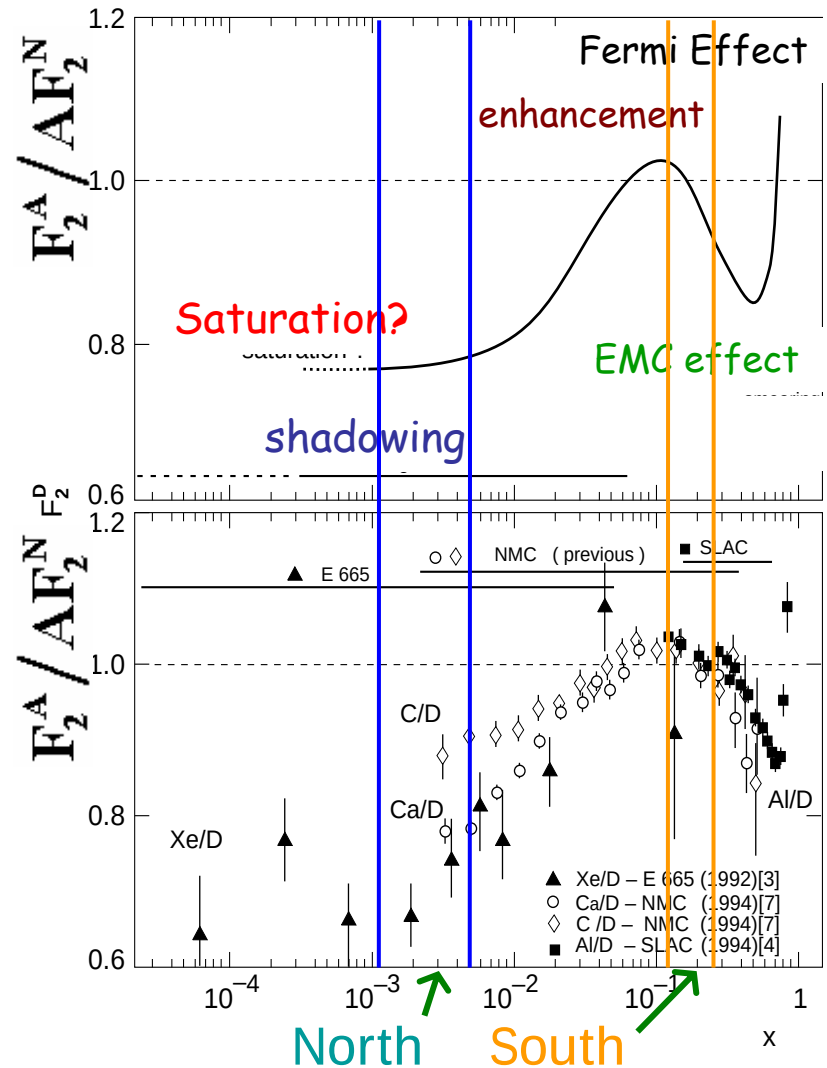
For Au nuclei (Going N to S)

$$x = \frac{M_T}{\sqrt{s}} e^{-y} \approx 10^{-3}$$

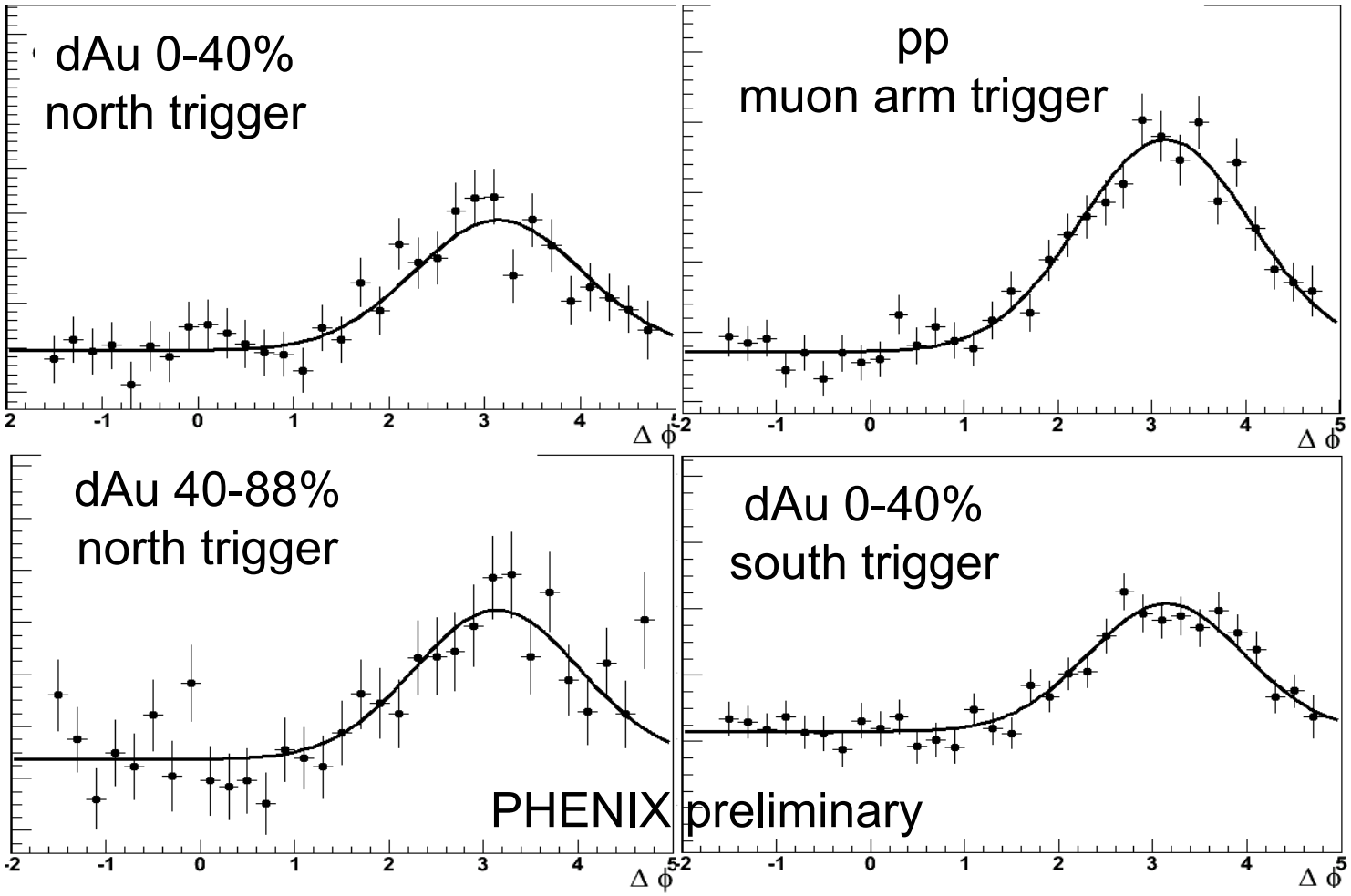
For deuterons (Going S to N)

$$x = \frac{M_T}{\sqrt{s}} e^{y} \approx 10^{-1}$$

Since |Δη|>1rad between central and muon arms, there is *no near side correlation*: it is driven by fragmentation which has a 1D opening angle of ~0.7rad.



Muon Arms – Central Arms Dihadron Correlations

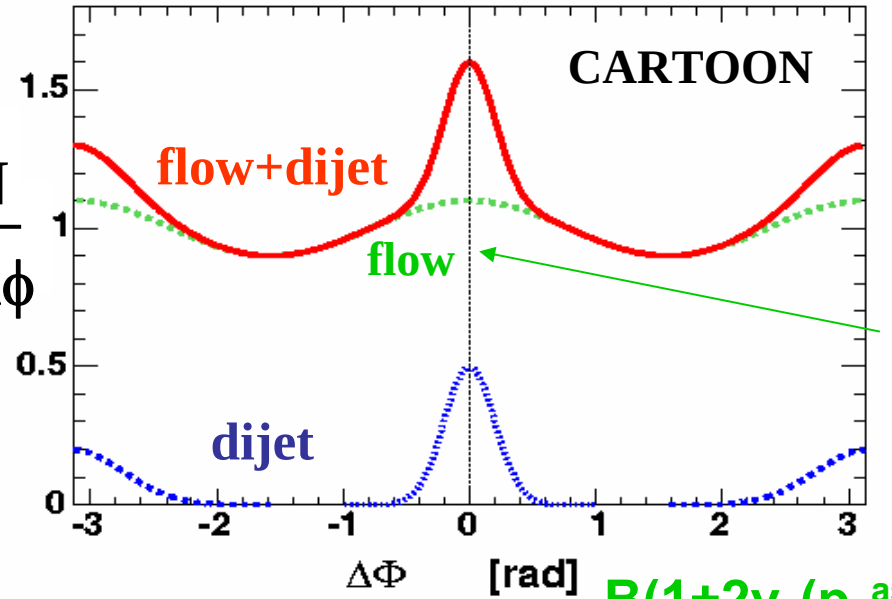


Unnormalized correlation functions between trigger hadrons in the muon arms and associated hadrons in the central arms: $p_{T,trig}$>2GeV/c, 0.5<$p_{T,asso}$<1GeV/c

Dijets in Hot QCD Matter – AuAu Collisions

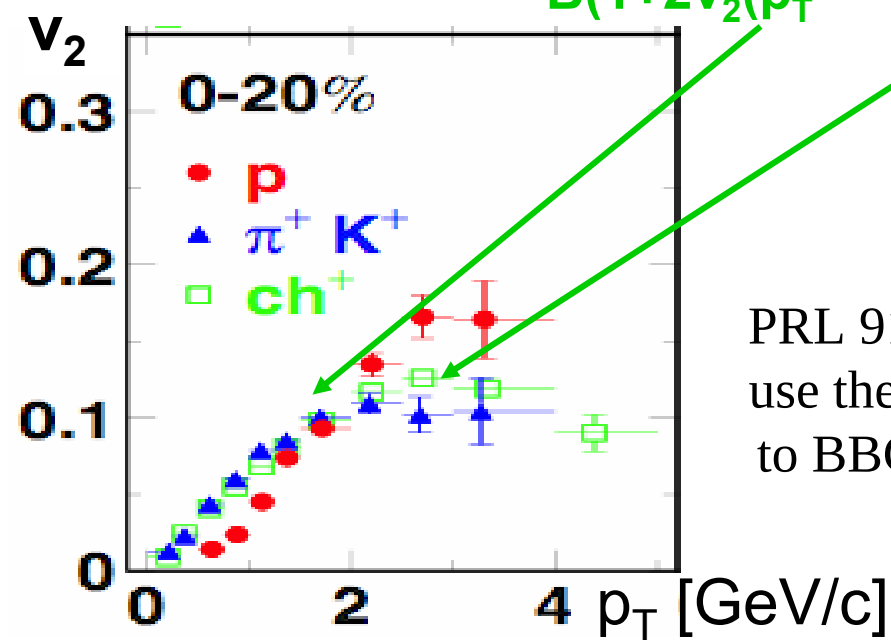
Subtraction of the Underlying Event

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi}$$



Collective flow causes another correlation:

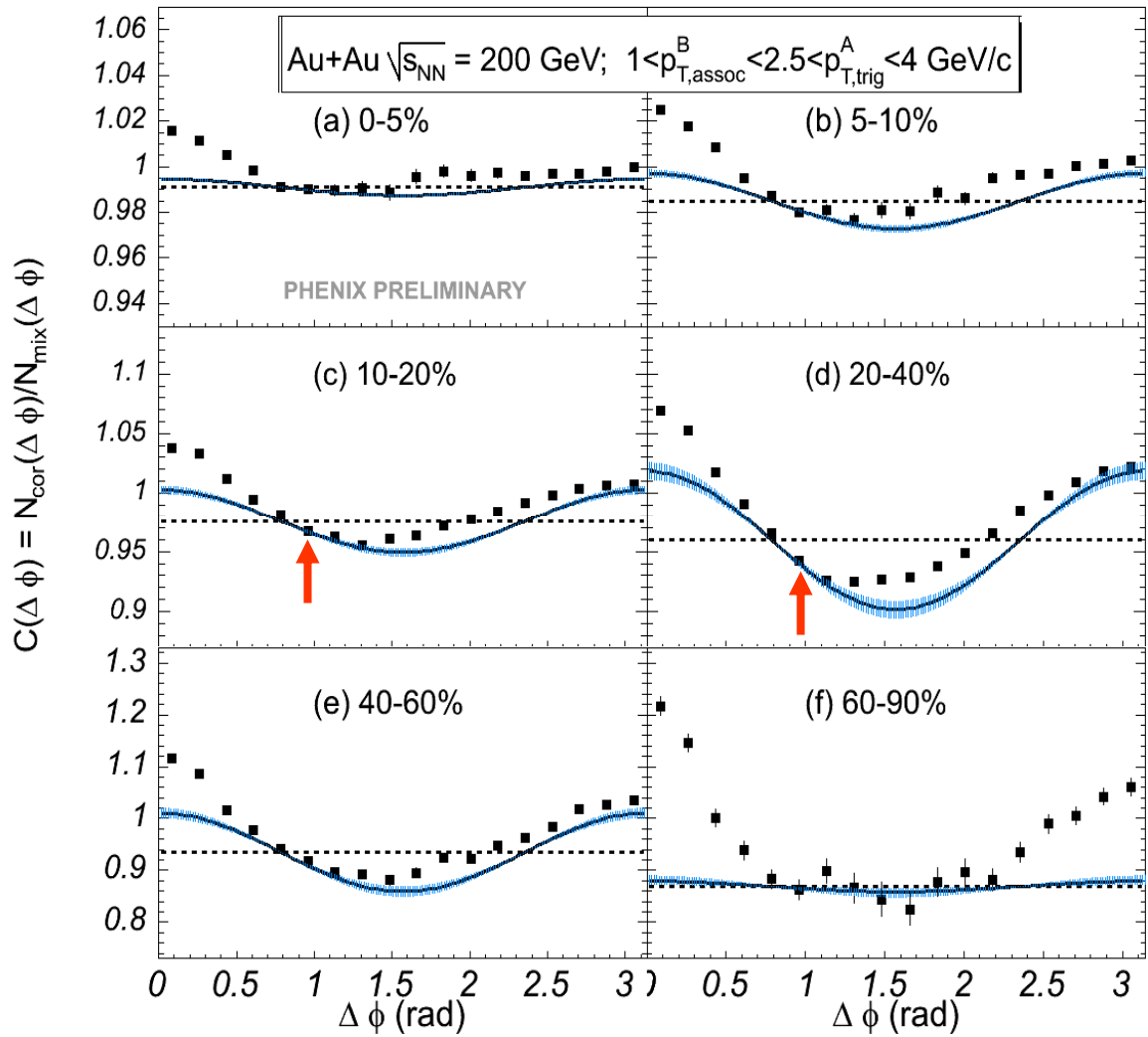
$B(1+2v_2(p_T^{asso})v_2(p_T^{trig})\cos(2\Delta\phi))$



PRL 91 (2003) 182301 use the v_2 with respect to BBC reaction plane

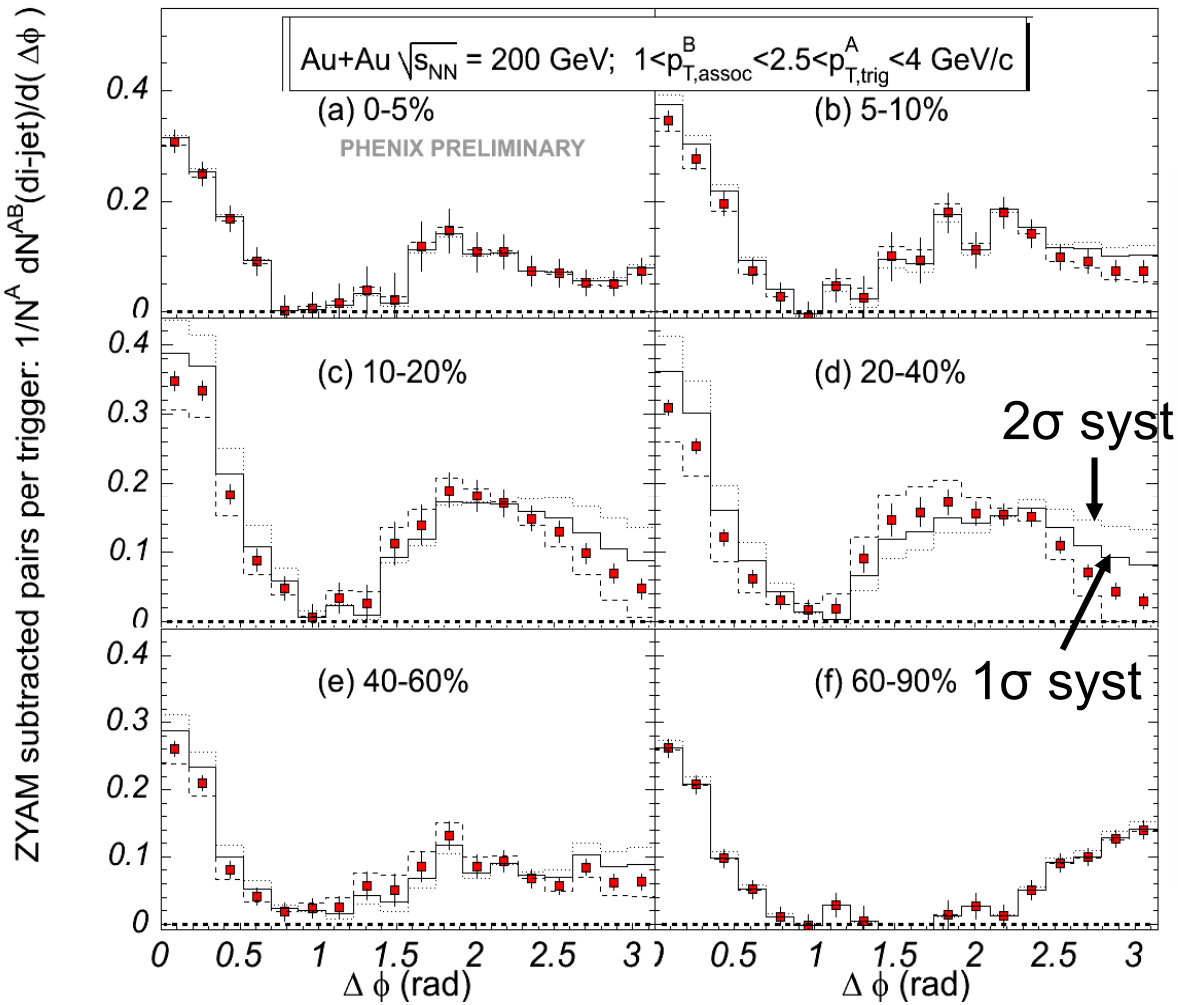
Dihadron Correlation Functions

Extraction of dijet correlations is done under the ZYAM ("Zero dijet Yield At Minimum") assumption: dijet yield is zero at some (variable) $\Delta\varphi_0$.
This fixes the value of B:
$B=C(\Delta\varphi_0)/(1+2v_2\cos(2\Delta\varphi_0))$

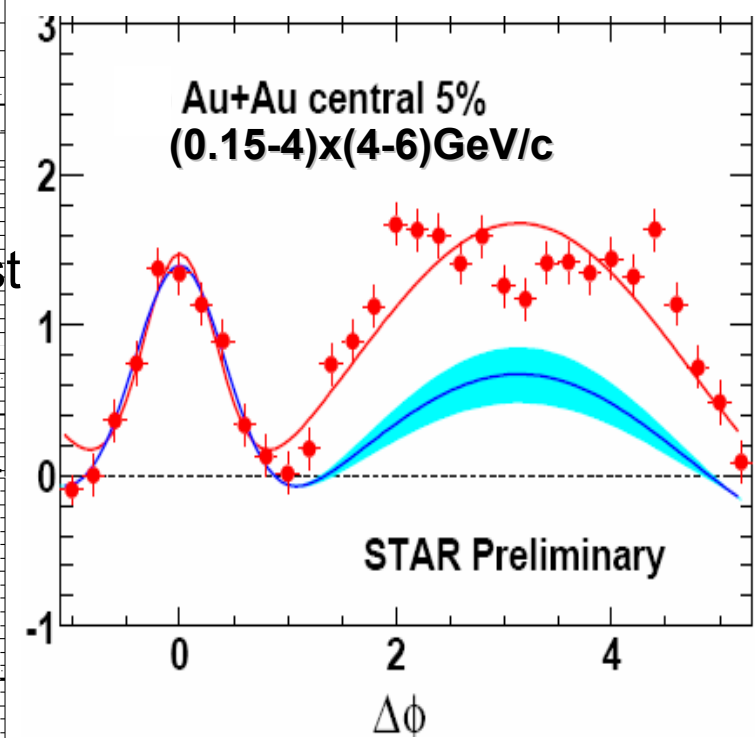


Dijet Correlation Functions

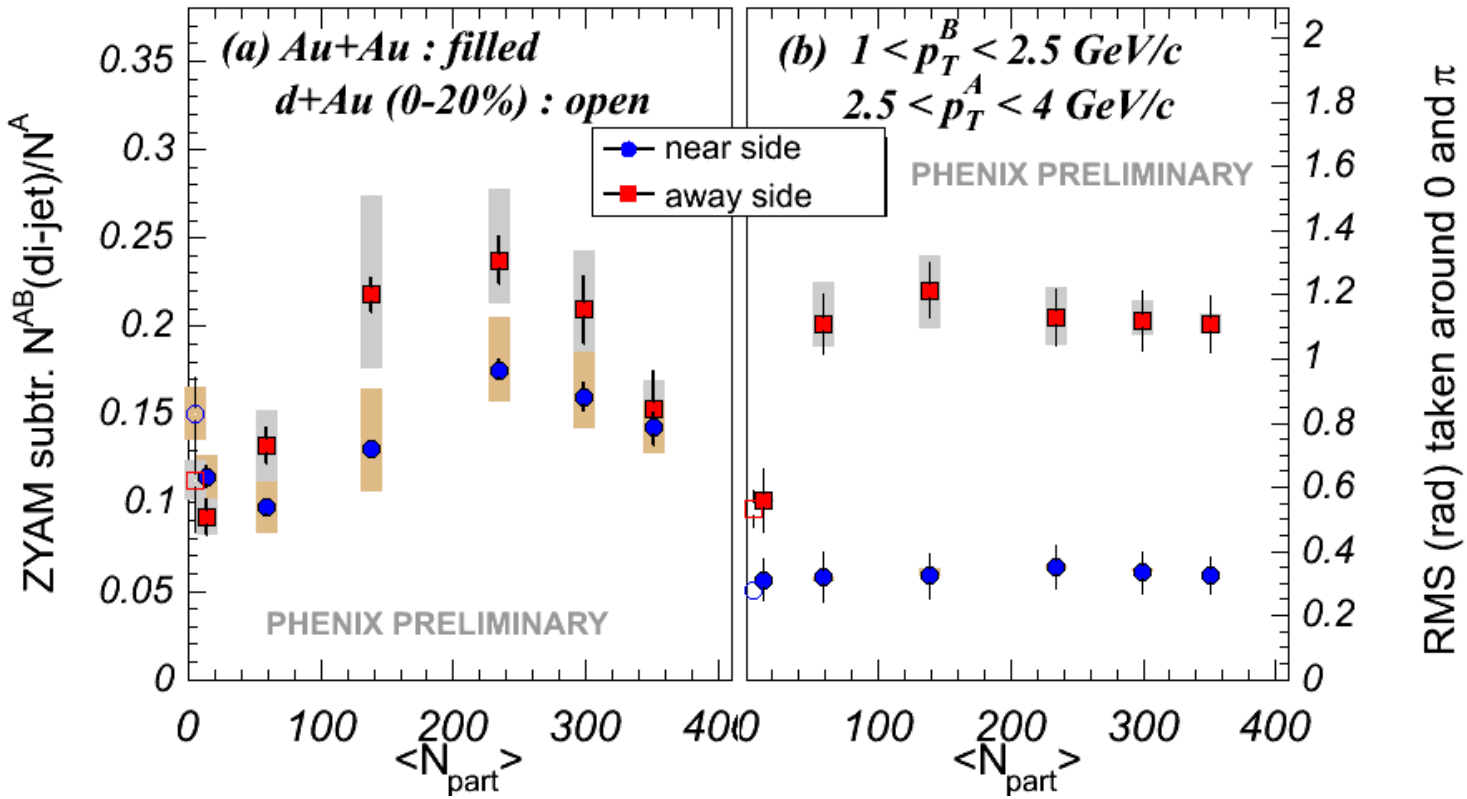
Strong modification of the away side dijet correlation: local minimum at Δφ~π and local maximum at |Δφ-π|~1rad… seen by STAR at lower momenta!



nucl-ex/0501016



Conditional Yields and RMS



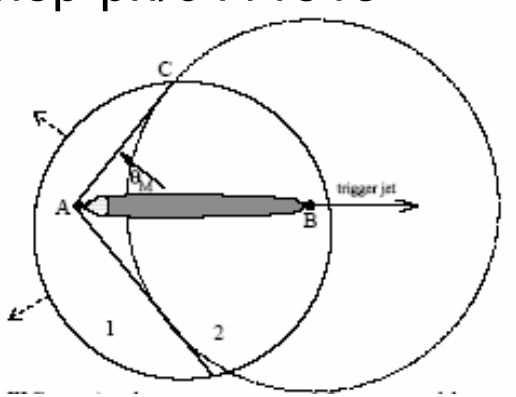
- Small enhancement with centrality of both near/away conditional yields
  - Recovery of the jet remnants from high p_T?
    (considering STAR away suppression at larger momenta)
- Large broadening away dijet RMS with centrality

Sonic shock waves, sound speed, and viscosity in liquid QGP

Casalderrey-Solana,Shuryak,Teaney

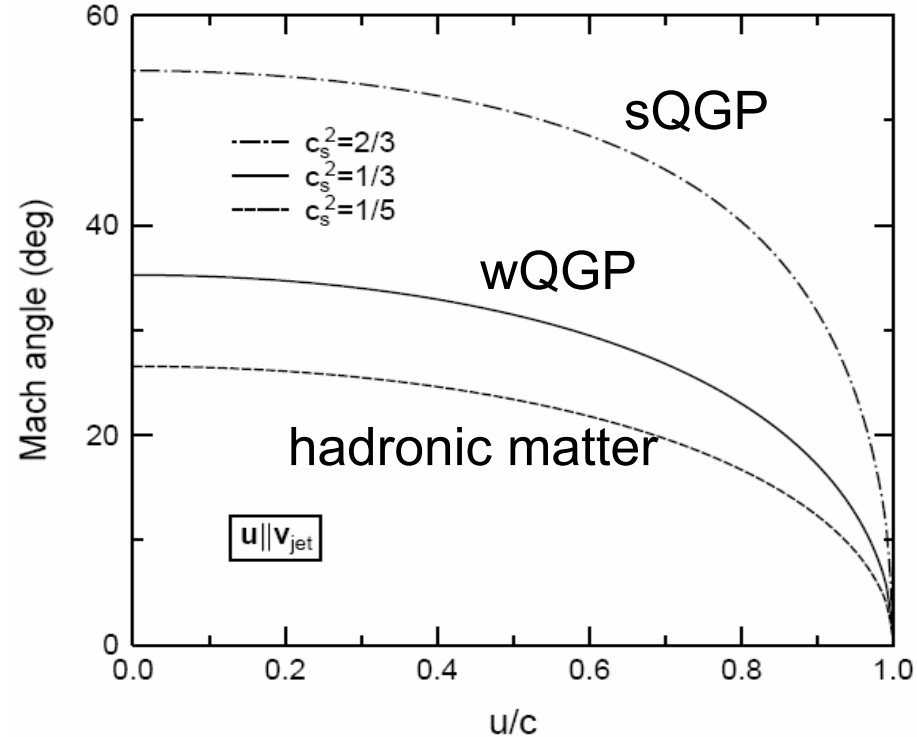
Sonic (Mach) shock waves

hep-ph/0411315



$\cos(\theta)=c_s$

H. Stocker nucl-th/0506013



$$\tan\theta = c_s \frac{\gamma_s}{\gamma_u}$$

u = matter flow velocity

v_{jet}~1(ultrarelativistic parton)

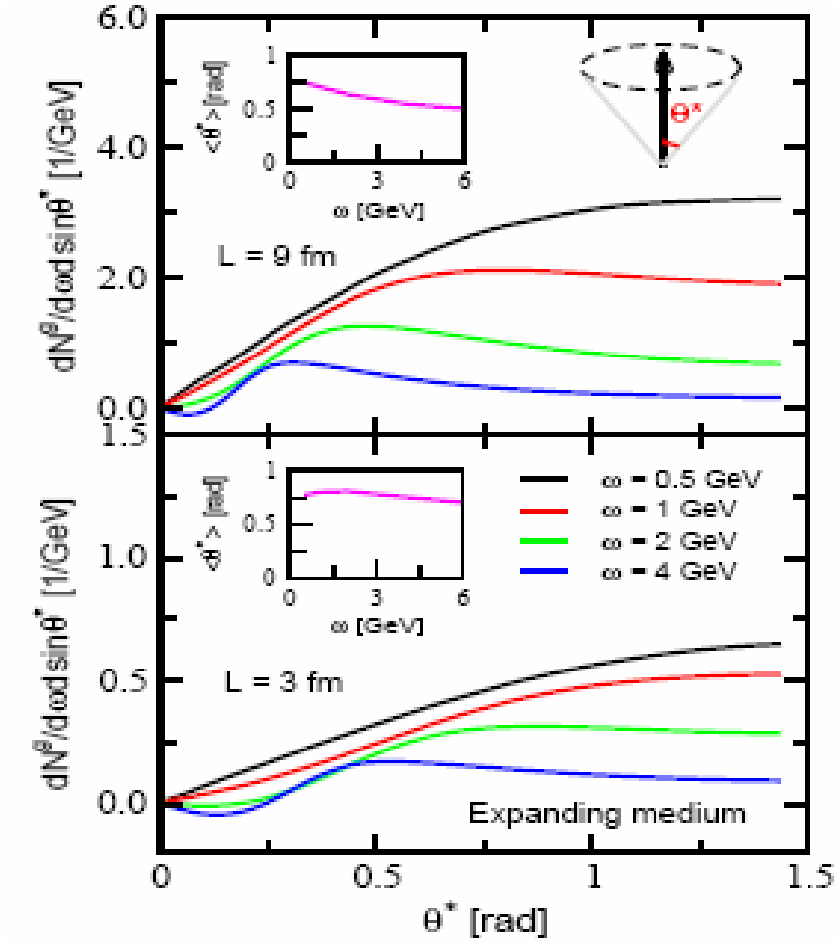
D. Molnar

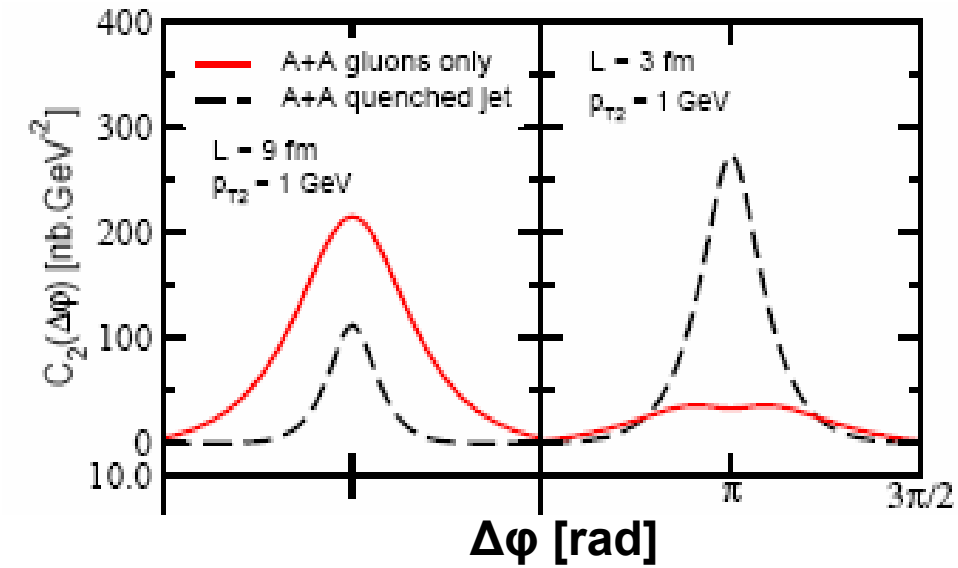
Sound attenuation in viscous QGP:

$$\omega(k) = c_s \cdot k - \frac{i}{2}\Gamma_s \cdot k^2; \quad \Gamma_s \sim \frac{\eta}{s}$$

$$\Psi(x,t) \propto e^{-\frac{1}{2}\Gamma_s k^2 t} \cdot e^{-i(c_s k t - kx)}$$

However…



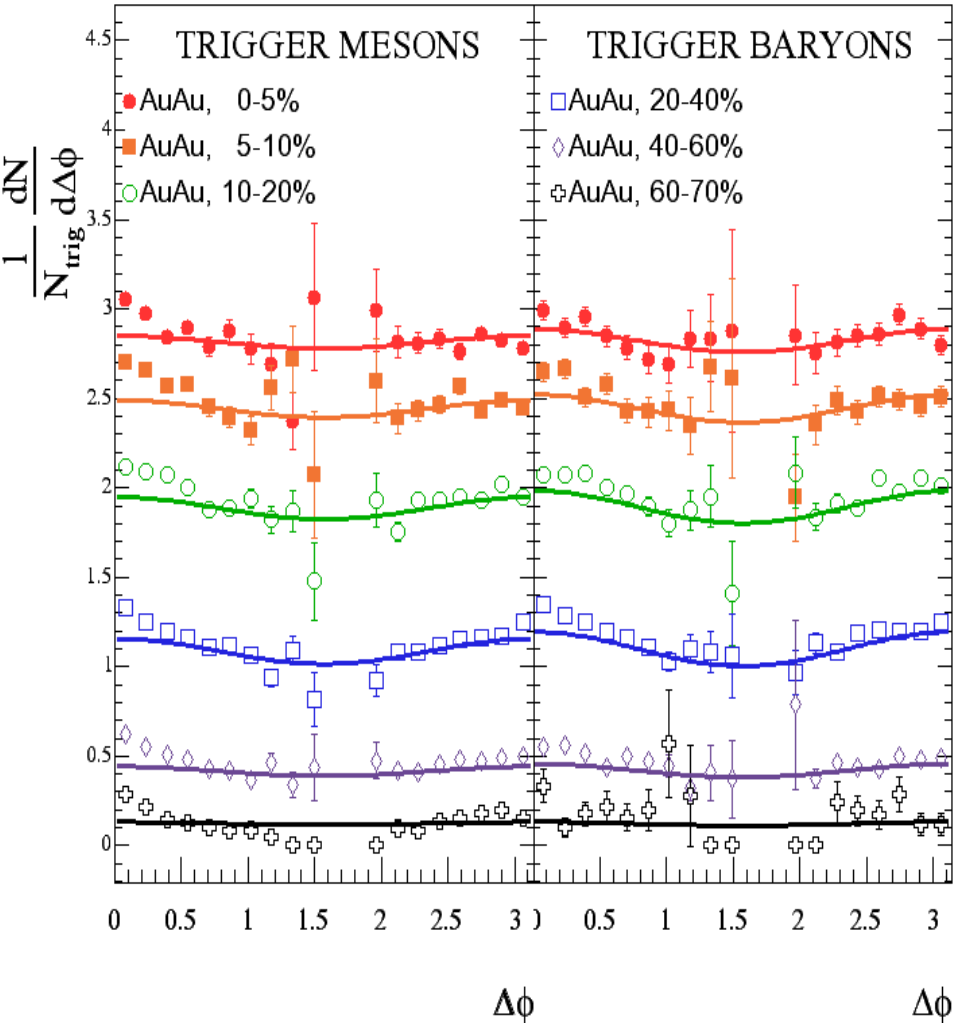


hep-ph/0501255

I. Vitev also gets a dip at θ^*~0 rad in the spectrum of radiated gluons, but when he translates to Δφ, it is gone! Effects of acoplanarity, projection to η~0, fragmentation of quenched parton should be included in the calculation.

Identified Trigger Correlations (I)

identified trigger hadron in (2.5-4)GeV/c
unidentified associated hadron in (1.7-2.5)GeV/c

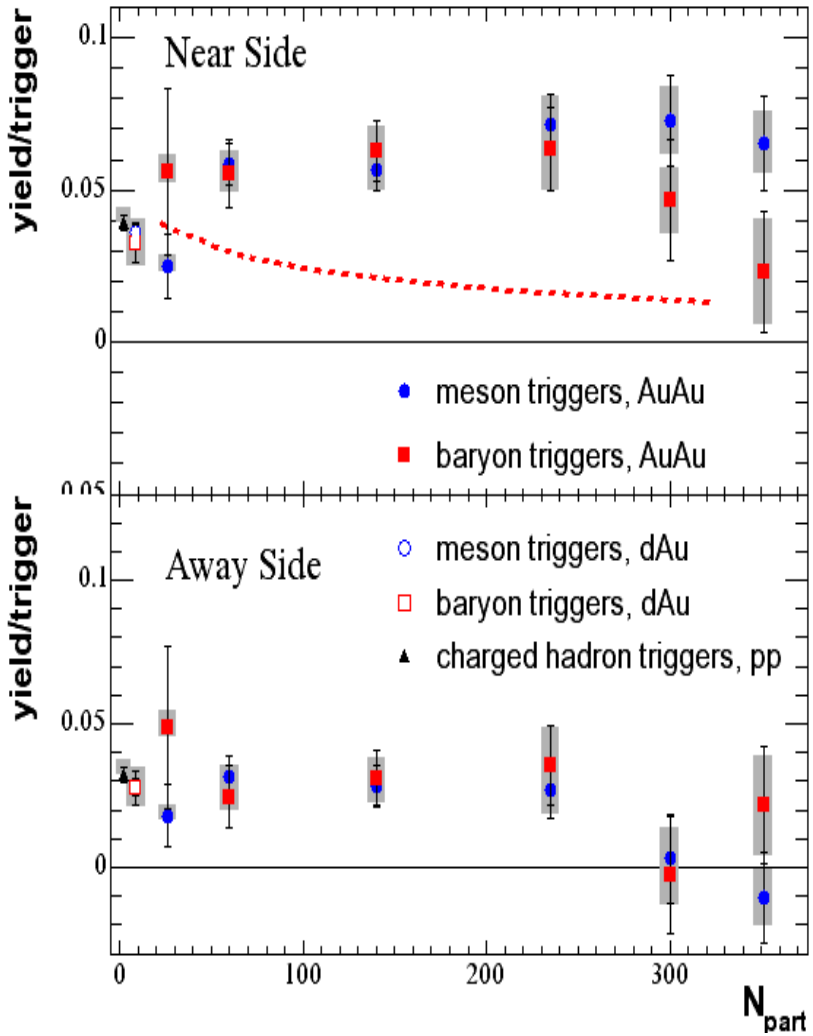


Method:

- Identify trigger hadrons with TOF detector and count associated $h^{\pm}$
- Use the v_2 with respect to BBC reaction plane (as above)
- Calculate the combinatorial background level B: $n_{ta}=n_t \cdot n_a(1+\xi)$ where ξ is the correction for residual multiplicity correlation
- Integrate over 55° and extract near/away conditional yields

Identified trigger correlations (II)

nucl-ex/0408007



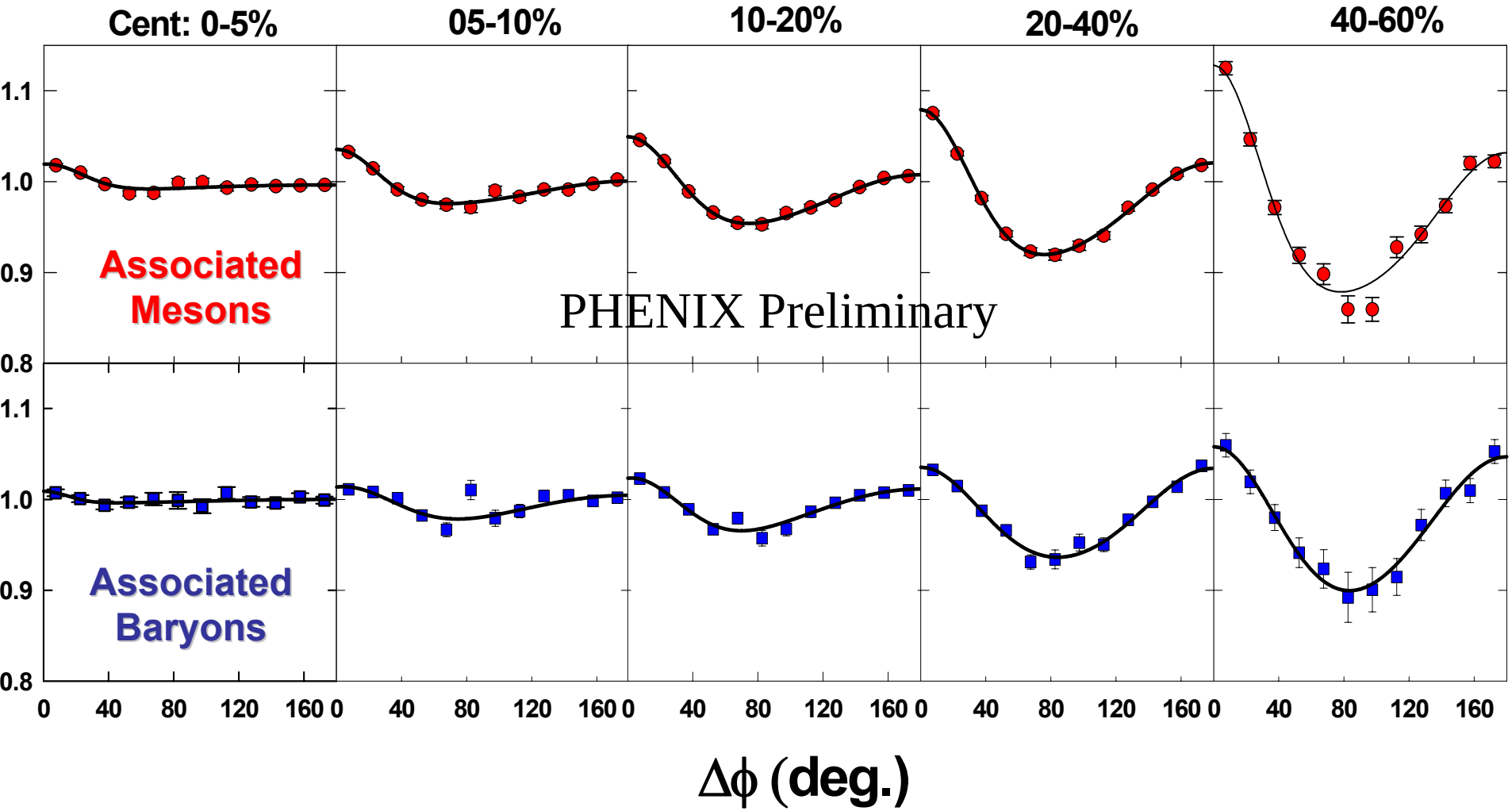
Jet partner likely for trigger baryons as well as mesons.

Same side: slight decrease with centrality for baryons.

Away side: partner rate as in pp/dAu confirms jet source of baryons.

Modification of fragmentation by hard-soft recombination

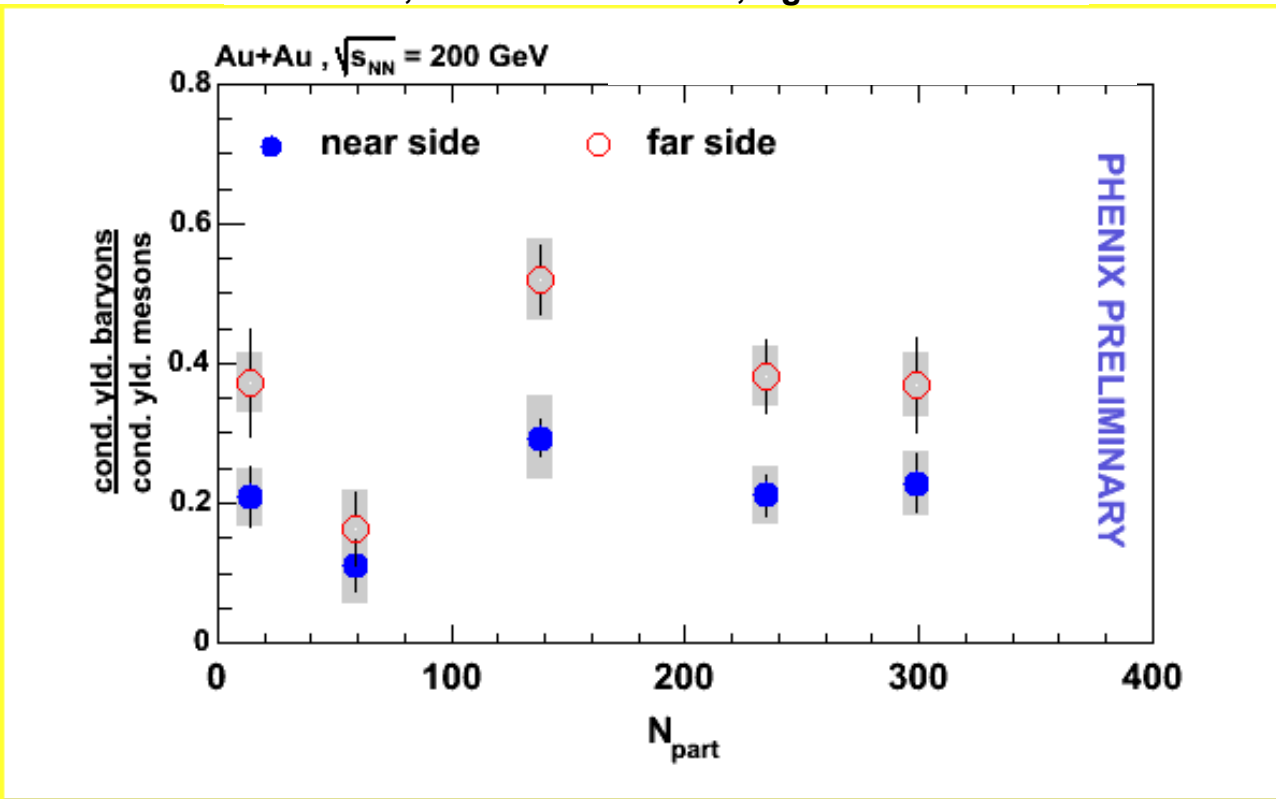
Identified Associated Correlations (I)



Dijet term is stronger with associated mesons than with associated baryons

Identified Associated Correlations (II)

$1 < p_{T,asso} < 2.5 < p_{T,trig} < 4$ GeV/c



Observed baryon to meson ratio is higher for away-side jets

Conclusions

- Dijets in pp and dAu collisions:
  - k_T measured in 3-15GeV/c p_{Ttrig} range in both pp and dAu. *No significant broadening in dAu with respect to pp*.
  - *FFs in both pp and dAu scale with x_E and p_{Ttrig}*. They also agree with Pythia.
  - correlation functions in dAu collisions triggered on low-x and high-x hadrons from the muon arms.
- Dijets in AuAu collisions:
  - strong modification of away side shape: *presence of local maximum at $|\Delta\varphi-\pi|\sim 1rad$*. Indication of sonic shock waves in the liquid QGP?
  - small enhancement of near/away conditional yields, indicative of the *recovery of jet remnants*.
  - *jet source for baryons at intermediate p_T*. Jet partner is as likely to be found if we trigger on baryon as on meson.
  - more associated mesons than baryons per trigger hadron; more baryons per trigger in the away side than in the near side.

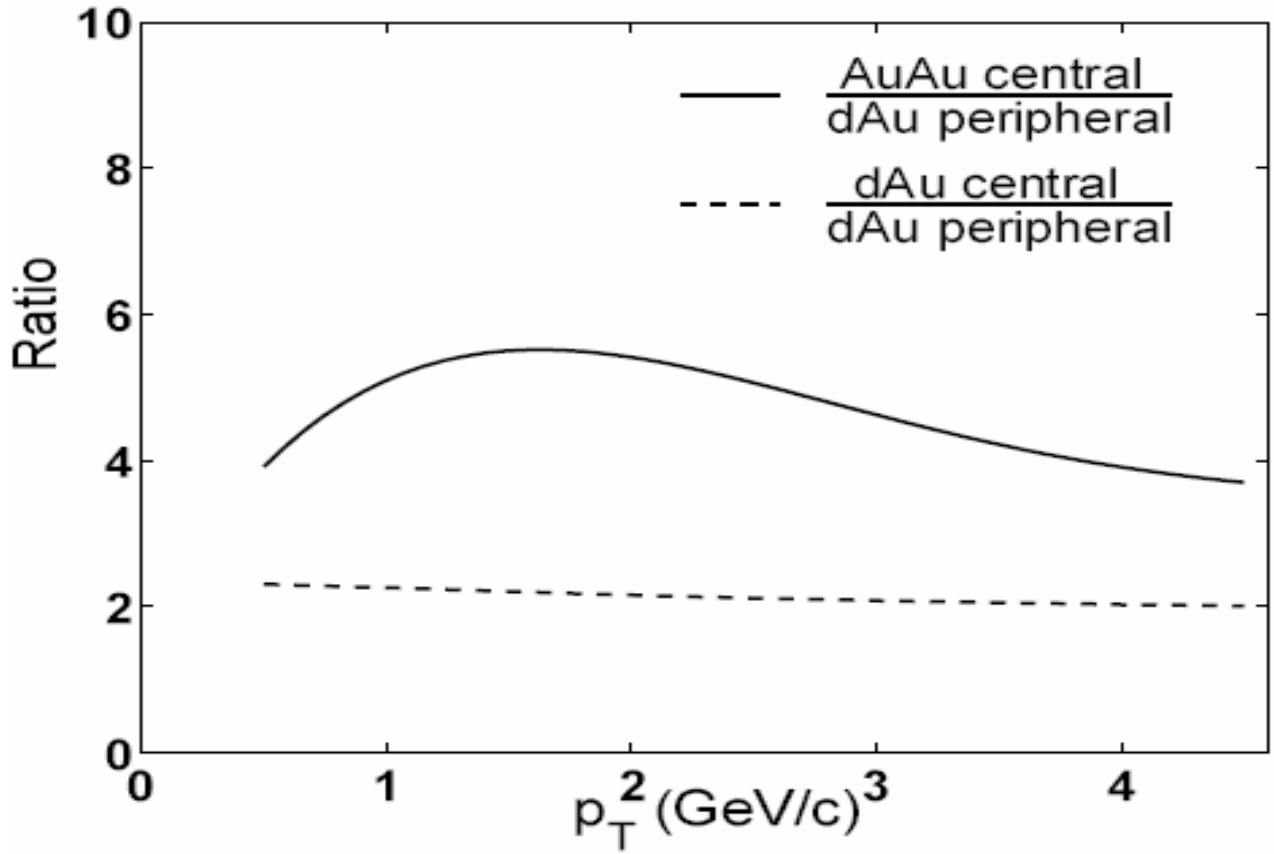
Looking Forward to QM'05…

- Finalized dihadron correlations between central and muon arms in pp and dAu
- Electron triggered correlations with charged hadron in central arm in pp, dAu and AuAu
- Detailed study of dihadron correlations in AuAu in the central arms: centrality, momentum, reaction plane dependence (Run4 AuAu data set: ~1.5 Billion events)
- Higher statistics identified dihadron correlations
- Direct photon tagged jets

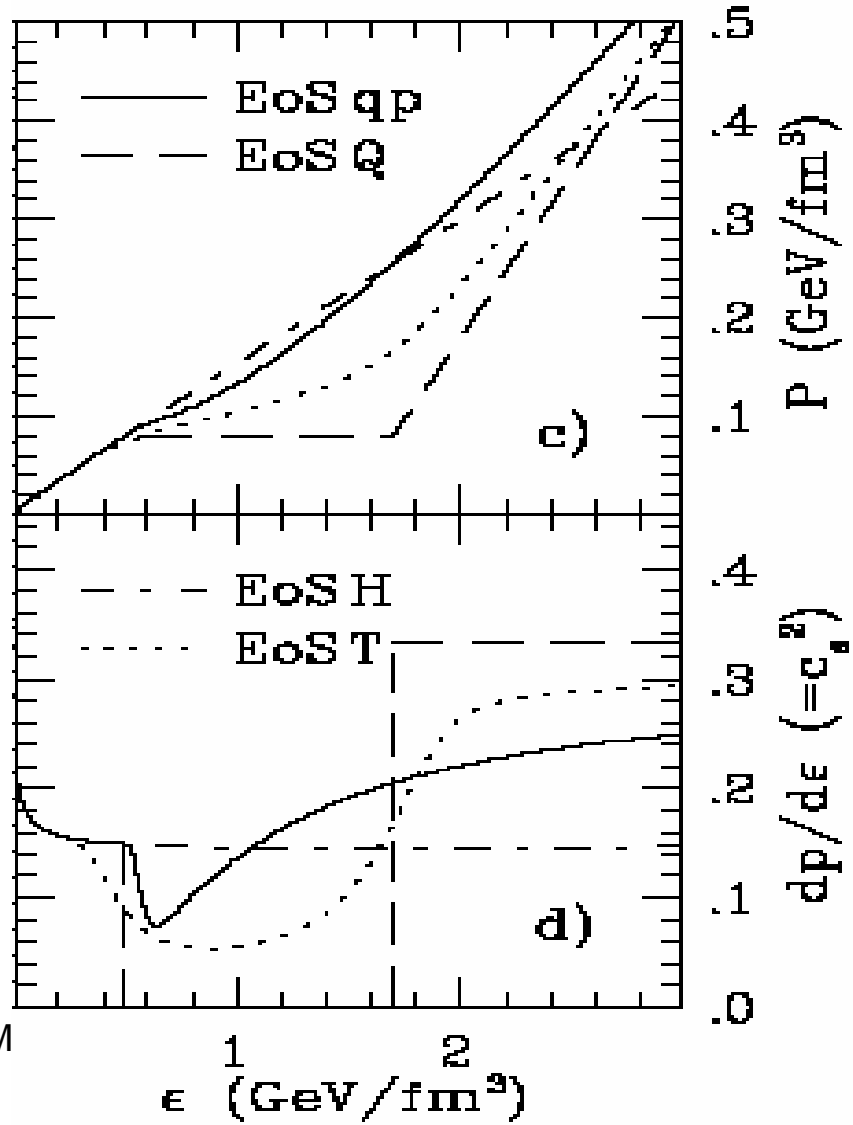
Backup Slides

Recombination

nucl-th/0407081



Ratios of conditional yields vs. p_T of associated meson


EoS qp
EoS Q
c)
EoS H
EoS T
d)
P (GeV/fm³)
dp/dε (=c_s²)
ε (GeV/fm³)
.5
.4
.3
.2
.1
.0
1
2

Absolute normalization

For an event sample with a finite spread in centrality the background pair rate will always exceed the combinatoric rate; but we can estimate by how much:

Centrality parameter N_{part}; event sample defines distribution $p(N_{\text{part}})$, width $\equiv \sigma(N_{\text{part}})$, mean $\equiv \langle N_{\text{part}} \rangle$

Assume: n^A and n^B proportional to N_{part}, but otherwise uncorrelated

Singles: $n^{\text{A}} = \sum_{N_{\text{part}}} p(N_{\text{part}}) F_A N_{\text{part}}; \quad n^B = \sum_{N_{\text{part}}} p(N_{\text{part}}) F_B N_{\text{part}}$

Joint: $n^{\text{AB}} = \sum_{N_{\text{part}}} p(N_{\text{part}}) F_A F_B (N_{\text{part}})^2$

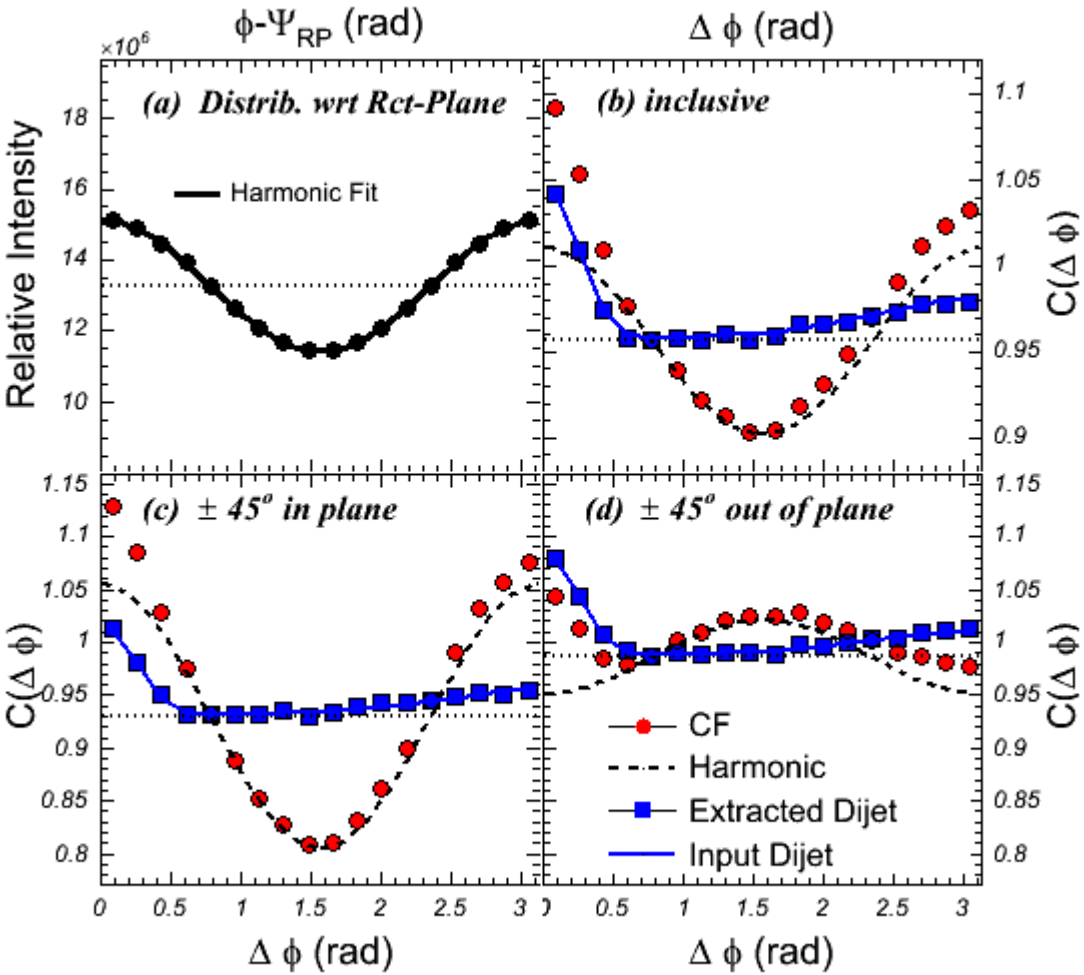
$$\frac{n^{AB}}{n^A n^B} = \frac{\sum p(N_{\text{part}}) F_A F_B (N_{\text{part}})^2}{\left(\sum p(N_{\text{part}}) F_A N_{\text{part}}\right)\left(\sum p(N_{\text{part}}) F_B N_{\text{part}}\right)}$$

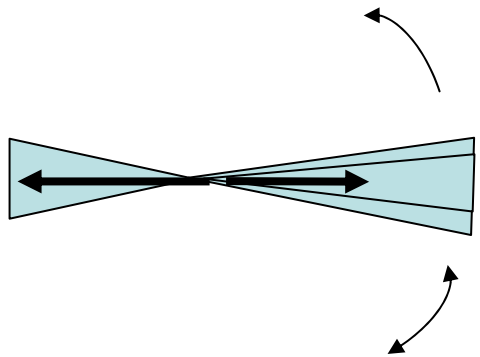
$$= \frac{\sum p(N_{\text{part}}) (N_{\text{part}})^2}{\left(\sum p(N_{\text{part}}) N_{\text{part}}\right)^2} = 1 + \left(\frac{\sigma(N_{\text{part}})}{\langle N_{\text{part}} \rangle}\right)^2 = 1 + \xi$$

In the example of N_{part} scaling the pair rate always exceed the combinatoric rate, by an amount which increases with the width of the N_{part} distribution relative to its mean.

If we assume that the rate of singles in background pairs are uncorrelated except for common centrality, then we can estimate the background rate "blind", without any distributions.

Simulation Test of Jet Recovery : Normal Shapes

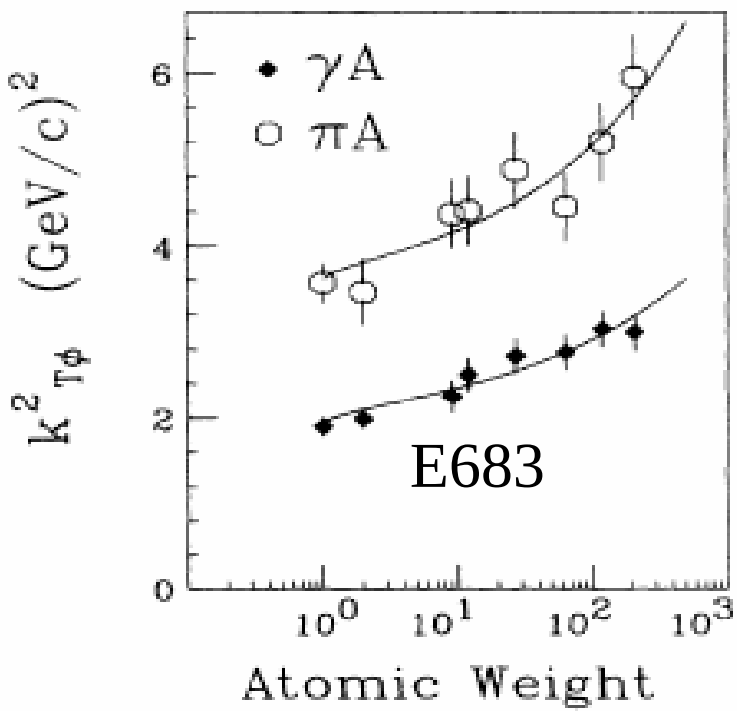
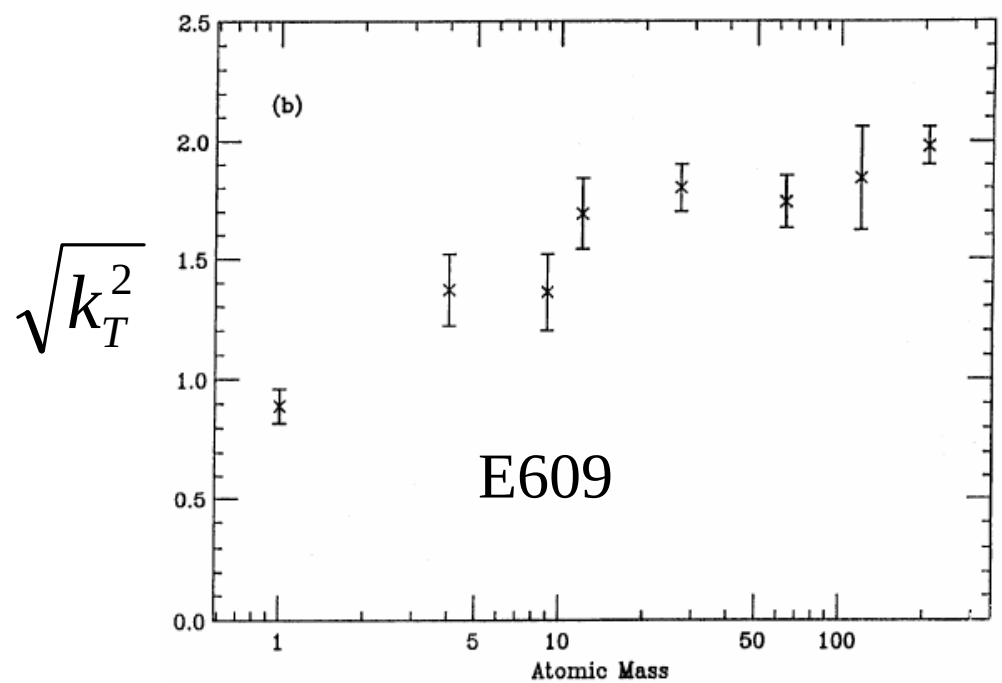




Normal Jet Shape

Di-jet faithfully recovered

Cronin from correlations at Fermilab

$\sqrt{s_{NN}}$ = 21 GeV

p → 400 GeV