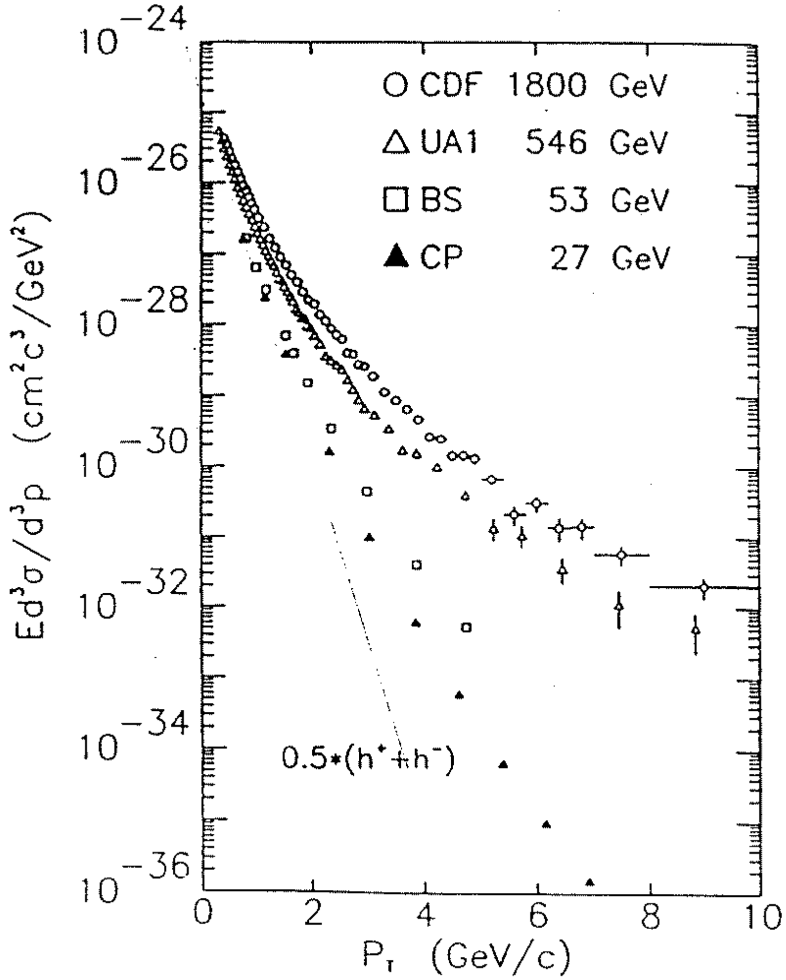
How to Discover the QGP by Single particle Semi-inclusive Measurements.
or
Using Leading Particles to Measure the Properties of Jets and Di-Jets

M.J.Tannenbaum
BNL/PHENIX
July 9, 1997

Of course, Experimental Physics is a Team Effort

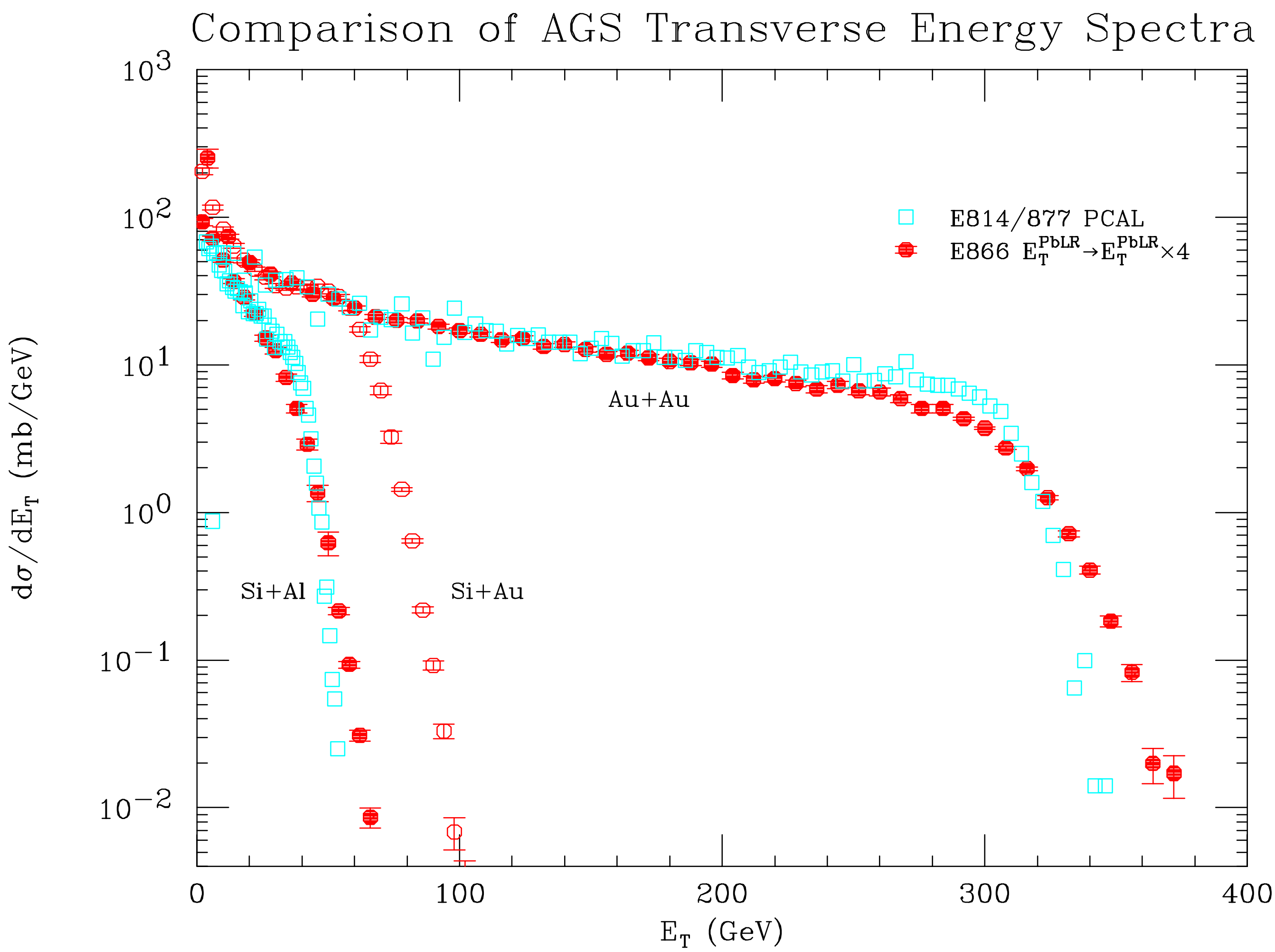
And we also need help from Theorists
to make sure that Quarks lose energy in hot matter

My Best Bet on Discovering QGP
Utilizes semi-Inclusive π^0 or $\pi^\pm$ production



Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T tablulated by CDF for a range of C.M. energies $\sqrt{s}$. There is an exponential tail (e^{-6p_T}) at low p_T, which depends very little on $\sqrt{s}$. This is the soft physics region, where the hadrons are fragments of 'beam jets'. At higher p_T there is a power-law tail which depends very strongly on $\sqrt{s}$. This is the hard-scattering region, where the hadrons are fragments of the high p_T QCD jets from constituent-scattering. **My hope is that the QGP causes the high p_T quarks to lose all their energy and stop, so that the high p_T tail will 'vanish' for central Au+Au collisions**
In RHI central collisions, leading particles are the only way to find jets because in one unit of Δr there is $\pi \times \frac{1}{2\pi}\frac{dE_T}{d\eta} \sim 375$ GeV !!!.

We can use Centrality Cuts
To see if the power-law tail returns at low E_T



Of course, using E_T for centrality may introduce a bias since E_T is dominated by low p_T π^0 and thus may distort the data. Another possibility is to use a gentle $E_T > 70$ GeV (see above) cut to define "not-peripheral" and then use the Zero Degree neutron calorimeter, with "few-neutrons" and "not-peripheral", to define centrality. Also, the PHENIX Silicon Vertex Detector (MVD) may be very useful as a centrality trigger, since we could use the parts of the MVD both inside or outside the EMcal acceptance and see whether these gave different results. **However, I think minimally we will have to run Si+Si to prove the any observed effect, and also p-p and p+Au.**

A Real Theoretical Calculation
X-N. Wang and Z. Huang PRC 55, 3047 (1997)
γ/π^0 is Enhanced!

dot-dashed line. However, one still has to face π^0's about 3 times higher than the direct photons at $p_T = 10$ GeV/c. At larger p_T, the situation improves, but one loses the production rate. Since the isolation cut method normally employed in pp collisions to reduce the background for direct photons does not work any more, the only way one can identify them with high accuracies has to be through the means of improved detectors.

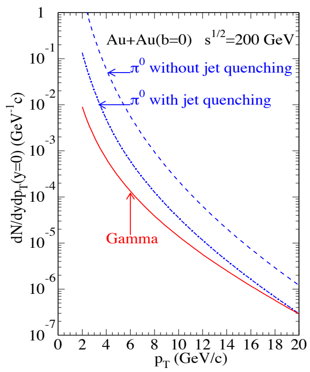


FIG. 13. The spectrum of direct photon production (solid) as compared to π^0 spectrum with (dot-dashed) and without (dashed) parton energy loss ($dE_q/dx = 1$ GeV/fm, $\lambda_q = 1$ fm) in central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV.

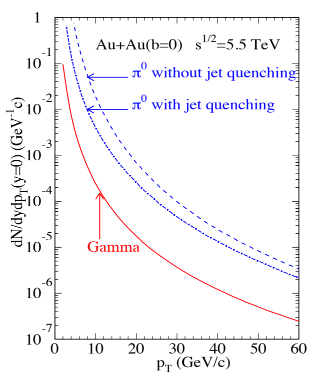


FIG. 14. The same as Fig. 13, except at $\sqrt{s} = 5.5$ TeV.

Similarly, we also list in Table III the number of γ+jet events per year per unit rapidity and unit (GeV) E_T at the LHC energy. We assume a luminosity of $\mathcal{L} = 2 \times 10^{27}$ cm^{-2}s^{-1} with 50 operation days per year for $Au + Au$ collisions. The production rates are reasonably high due to both the high luminosity and collider energy. However, the corresponding background of π^0's is also high (see Fig. 14) which may make the detection of direct photons more difficult.

At the LHC energy, $\sqrt{s} = 5.5$ TeV, the production rate for Z^0+jet becomes large even for reasonably large $P_T^{Z^0}$. Listed in Table IV are the number of Z^0+jet events per year per unit rapidity integrated over $P_T^{Z^0}$ with different low cut-off values. The production cross sections are provided by T. Han based on calculations as described in Ref. [30]. Note that the given Z^0 production rates are integrated ones, thus appearing to be larger than the differential rate of direct photon production at the same transverse momentum. One can detect Z^0 through the dilepton channel which has almost no background in the range of the dilepton invariant mass near M_{Z^0}. One can then apply the same procedure as we have discussed in this paper for direct photon events and measure the modification of the effective jet fragmentation function due to parton energy loss. However, the drawback of using the dilepton channel of Z^0 decay is that the effective number of events via this channel is about 6.7% of the total number of Z^0 events.

E_T^γ (GeV)	7	10	15	20
$dN^{\gamma-jet}/dydE_T$/year	20500	3550	400	70

TABLE II. Rate of direct photon production in central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV, with luminosity $\mathcal{L} = 2 \times 10^{26}$ cm^{-2}s^{-1} and 100 operation days per year.

E_T^γ (GeV)	40	50	60
$dN^{\gamma-jet}/dydE_T$/year	2880	1070	490

TABLE III. Rate of direct photon production in central $Au + Au$ collisions at $\sqrt{s} = 5.5$ TeV, with luminosity $\mathcal{L} = 2 \times 10^{27}$ cm^{-2}s^{-1} and 50 operation days per year.

$P_T^{Z^0}$ (GeV)	> 20	> 40	> 60
dN^{Z^0-jet}/dy/year	21100	7700	3470

TABLE IV. Rate of Z^0 production in central $Au + Au$ collisions at $\sqrt{s} = 5.5$ TeV, with luminosity $\mathcal{L} = 2 \times 10^{27}$ cm^{-2}s^{-1} and 50 operation days per year.

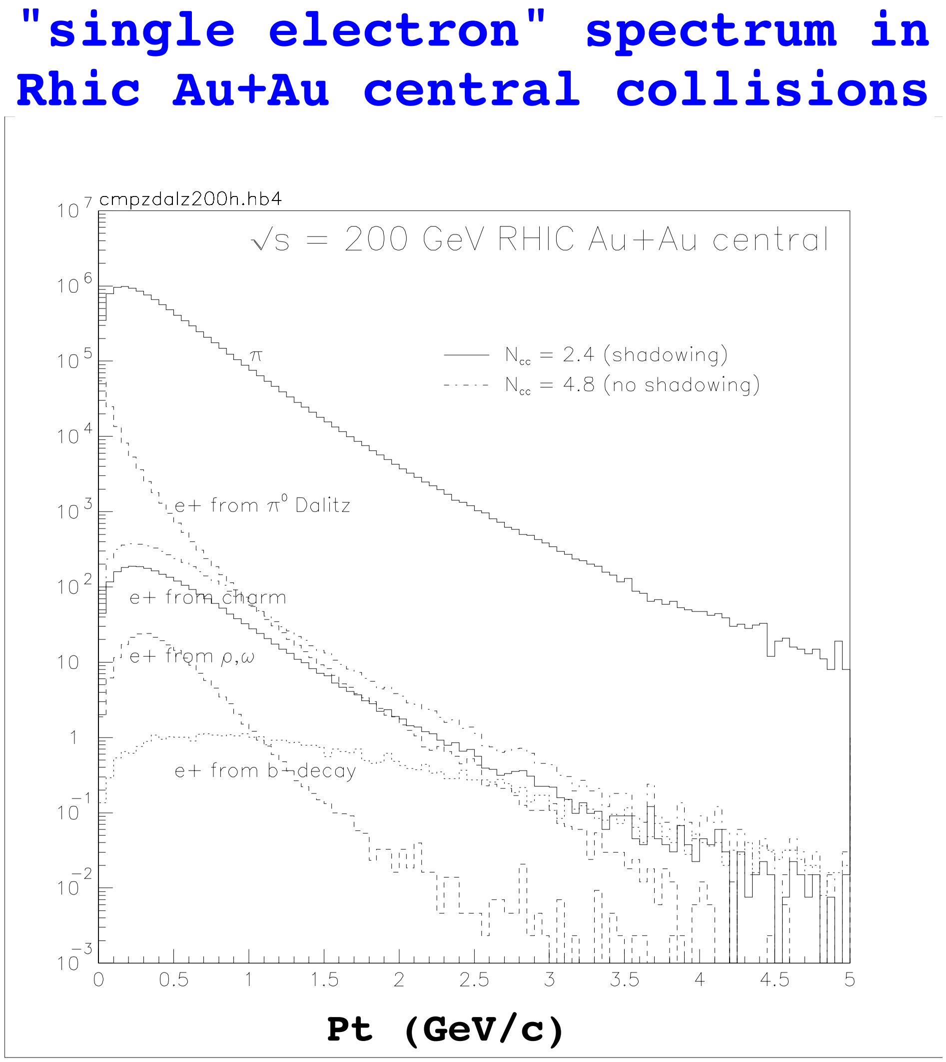
15

Note the predicted π^0 suppression by jet quenching is a factor of 10—But the direct Gammas are not reduced. Thus γ/π^0 is greater than 10% for $p_T > 3$ GeV/c, (so that even I can make the measurement). **Note that this predicted γ/π^0 is much larger than for p-p collisions since the π^0 background has been suppressed by an order magnitude—if the theorists are right!**

$e^{\pm}/\pi^0$ from Charm is also enhanced—kinetic energy of the c-quark is lost but the mass gives a boost

Even without this effect, $e^{\pm}/\pi^0$ from Charm is measurable for $p_T \geq 1.5$ GeV/c in Au+Au

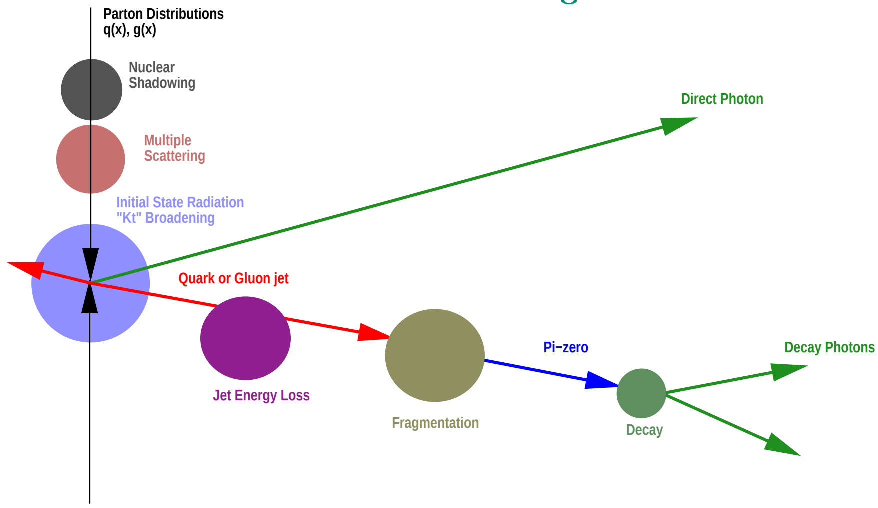
From Y. Akiba QM'95



Y. Akiba's calculation (UCRL-ID-121571) of sources of electrons in PHENIX for Au+Au central collisions at RHIC. Inclusive electrons from decays of J/Ψ and Υ have not been included. Depending on the exact model for $c-\bar{c}$ production, $e^{\pm}$ from charm dominates the $e^{\pm}$ from Dalitz decays of π^0 for $p_T \geq 1.5$ GeV/c. Any energy loss effect should ehance the $e^{\pm}$ from charm relative to the Dalitz background.

A Systematic Review of measurements of JETS in A+A collisions in PHENIX was recently made by Paul Stankus of ORNL

WWW→ **PHENIX Meetings 9706**



	Parton Distributions q(x), g(x)	Nuclear Shadowing	Multiple Scattering	Initial State Radiation "Kt" Broadening	Jet Energy Loss	Fragmentation	Decay
A+A							
Inclusive Photons	✔	✔	✔	✔	✔	✔	✔
Inclusive Pi–Zero	✔	✔	✔	✔	✔	✔	
Direct Photons	✔	✔	✔	✔			
Photon–Pi–Zero Back to Back			✔	✔	✔	✔	
Photon–Photon Back to Back			✔	✔			
p+p							
Direct Photons	✔			✔			
p+A							
Direct Photons	✔	✔	✔	✔			

Stankus shows in the top half of the figure a "typical" parton+parton → jet → leading particle process and identifies all the sub-processes which influence the final state spectra. Then listed below is a table: the rows show the measurements that we can expect to make in PHENIX, in the order that they should become available (considering statistics and analysis complexity); the columns show (my understanding of) which sub-processes influence which measurements. Paul Stankus' conclusion is that "the puzzle will come together over time: and it becomes quite clear that the photon $+\pi^0$ back-to-back measurement will be the one that addresses jet energy loss most directly." I'm more optimistic about the inclusive γ and inclusive π^0. Also note that measurements of direct photons in p-p and p+A would be **extremely useful** as a measurement of the Gluon Structure function, and γ-$\pi^{\pm}$ can measure "k_T."

Again, A Real Theoretical Calculation
X-N. Wang and Z. Huang PRC 55, 3047 (1997)

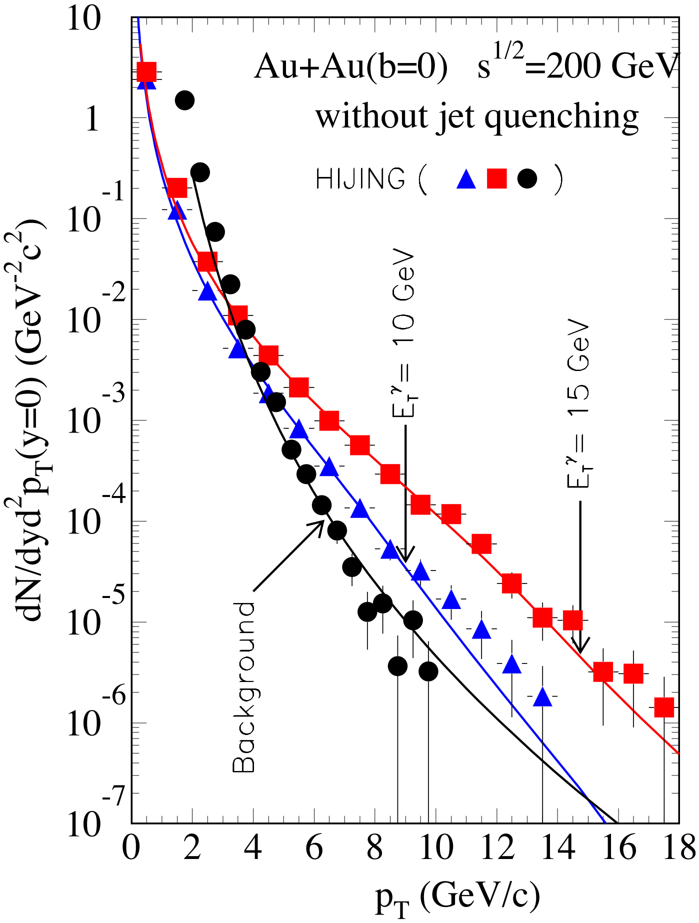
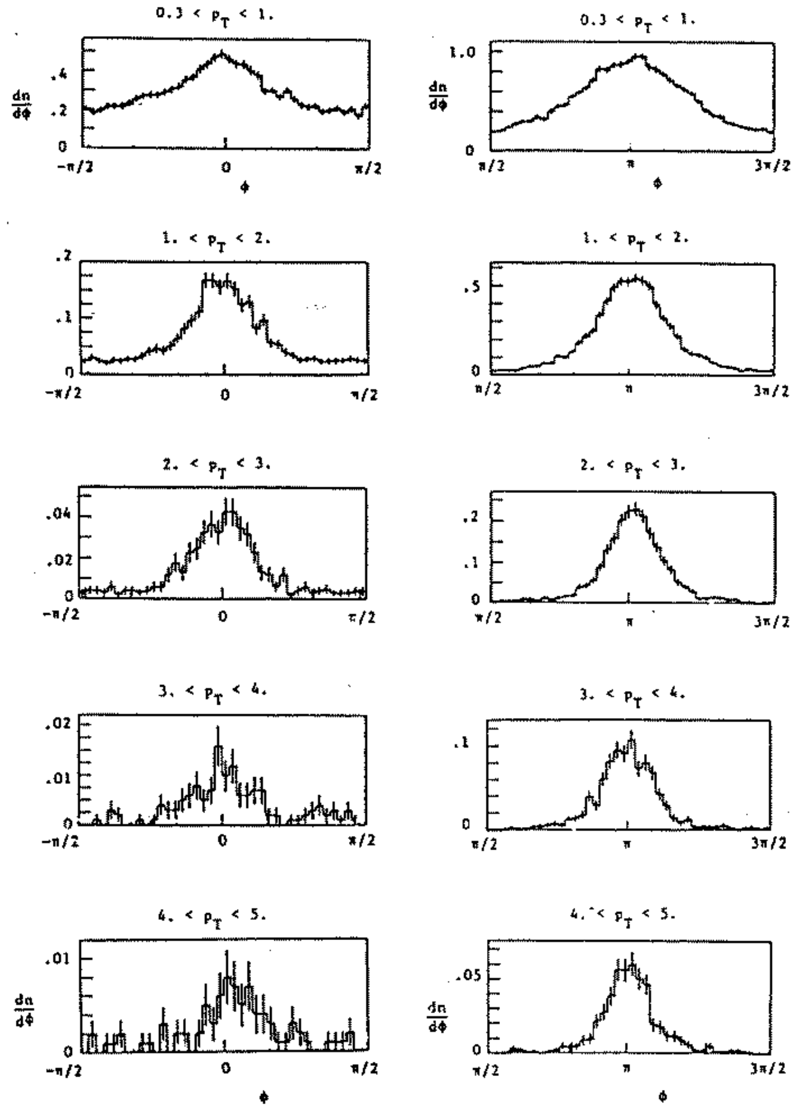


Fig. 3. The differential p_T spectrum of charged particles from the fragmentation of a photon-tagged jet with E_T^γ=10, 15 GeV and the underlying background in central Au+Au collisions at $\sqrt{s}$ = 200 GeV. The direct photon is restricted to $|y| \leq \Delta y/2 = 0.5$. Charged particles are limited to the same rapidity range and in the opposite direction of the photon, $|\phi - \phi_\gamma - \pi| \leq \Delta\phi/2 = 1.0$. Solid lines are HIJING simulation of 20K events.

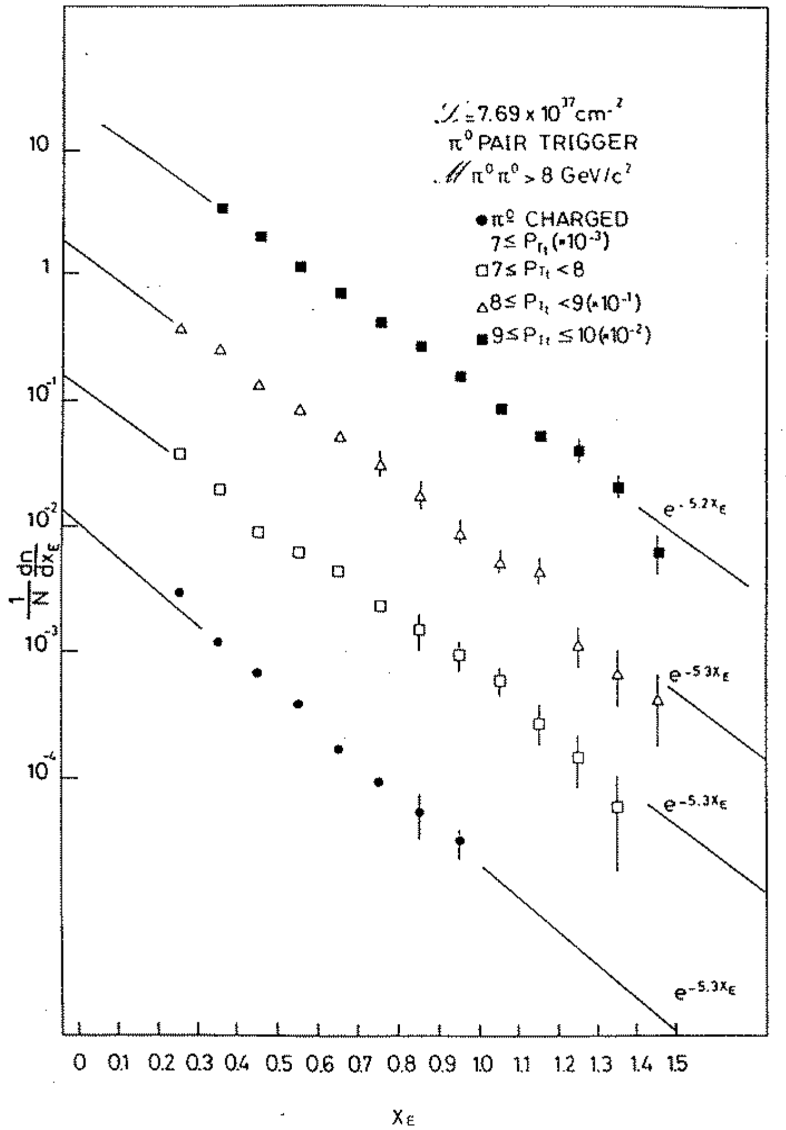
A calculation of charged particles in roughly PHENIX solid angle, opposite from a detected γ or π^0. The γ are direct constituents from the reaction, but the π^0 are the leading fragments of jets. In Au+Au collisions, the key problem is to cope with "background", which is just the p_T spectrum of inclusive charged particles randomly opposite any particle due to the large value of $dn^\pm/d\eta \sim 1000$—the same problem that makes direct detection of jets difficult. Interestingly, **the discovery of hard-scattering in hadron collisons at the CERN ISR and the first measurements of the properties of jets and di-jets were made with leading particles.**

How Everything You Want To Know about JETS can be done in PHENIX with leading particles in each arm c.f. CCOR



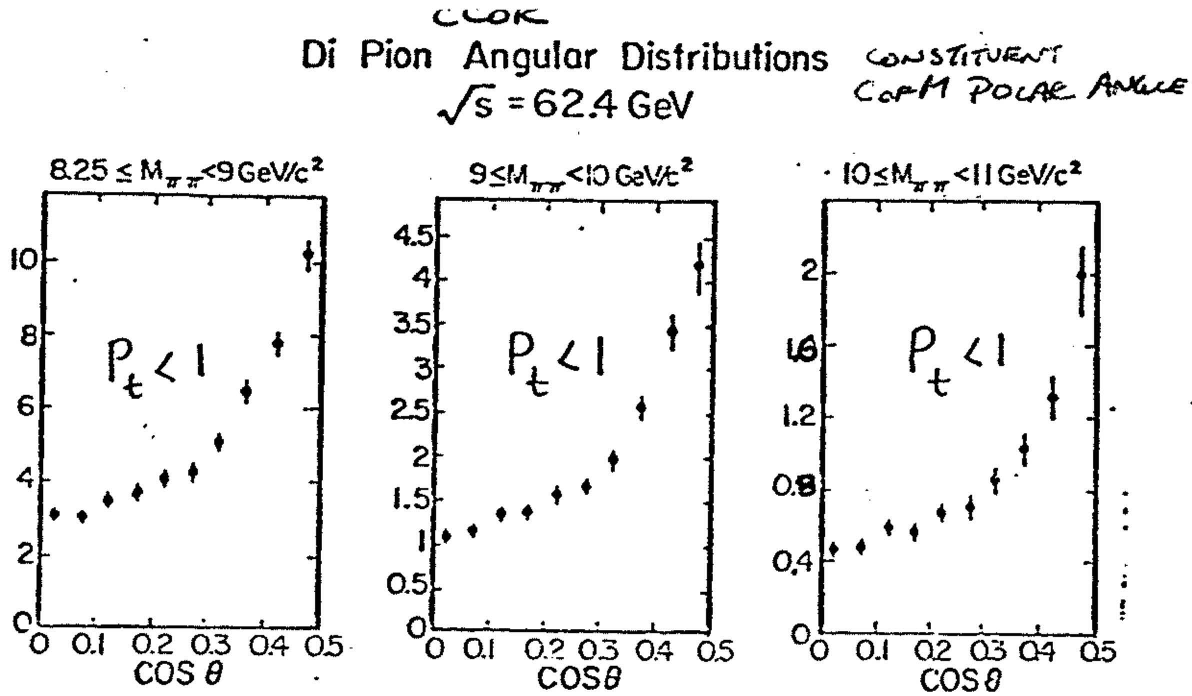
Two particle correlation in azimuth of charged particles relative to a triggering neutral with transverse momentum $p_{T_t} \geq 7.0$ GeV/c which defines the zero of azimuth, $\phi = 0$. Charged particles with $|\eta| < 0.7$ in the same 'arm' as the trigger are on the left and opposite 'arm' to the trigger on the right. As the p_T of the observed charged particle increases, the width of the away side peak (plots on the right) narrows. This effect clearly shows that the jets **are not collinear in azimuth** (they have a net transverse momentum k_T. If there were only fragmentation transverse momentum, then $p_T \times \Delta\phi$ would remain constant which would equal to $< j_T >$, the mean transverse momentum of fragmentation. [See PL 97B (1980) 163 for details]

Measurement of fragmentation function with the same data

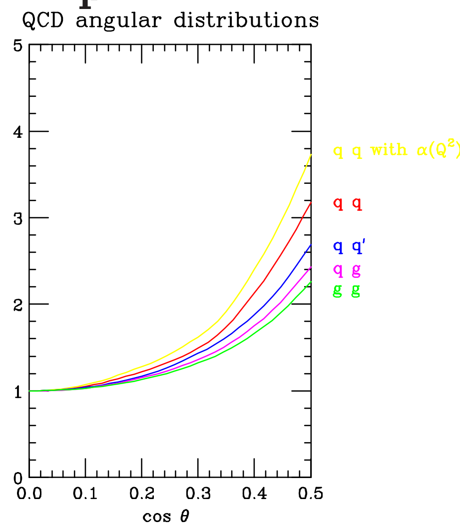


Distribution in x_E for a charged pion (or π^0) observed roughly back-to-back to a triggering π^0 of transverse momentum p_{Tt}, where both pions have $|\eta| < 0.5$ in the c.m. system. x_E is the ratio of the component of the p_T of the second pion, opposite in azimuth to the triggering pion, divided by p_{Tt}. **Exercise for students:** What do you have to know about the leading trigger particle to convert from $e^{-5.3x_E}$ to the jet fragmentation variable z $[e^{-6z}]$.

Same Data Set— First measurement of QCD subprocess angular distributions



QCD Subprocess predictions normalized at 90°



Angular distributions of pairs of nearly back-to-back π^0 as a function of the invariant mass $M_{\pi\pi}$ of the pair. The net P_t of the pion pair is restricted as indicated on the figure and the net rapidity of the di-pion system is restricted to $|Y_{\pi\pi}| < 0.35$. The distribution plotted is the polar angular distribution of the dipion axis in the frame with zero net longitudinal momentum. The important feature of the analysis in these variables, which are more typically used for lepton pairs, is that the di-pion angular distribution at fixed mass corresponds closely to the distribution of scattered partons at fixed $\hat{s}$, thus the data and QCD prediction at the parton level can be directly compared without recourse to a Monte Carlo. [see Nucl Phys **B209** (1982) 284].