Jet Quenching in Au+Au at $\sqrt{s}$=200 AGeV

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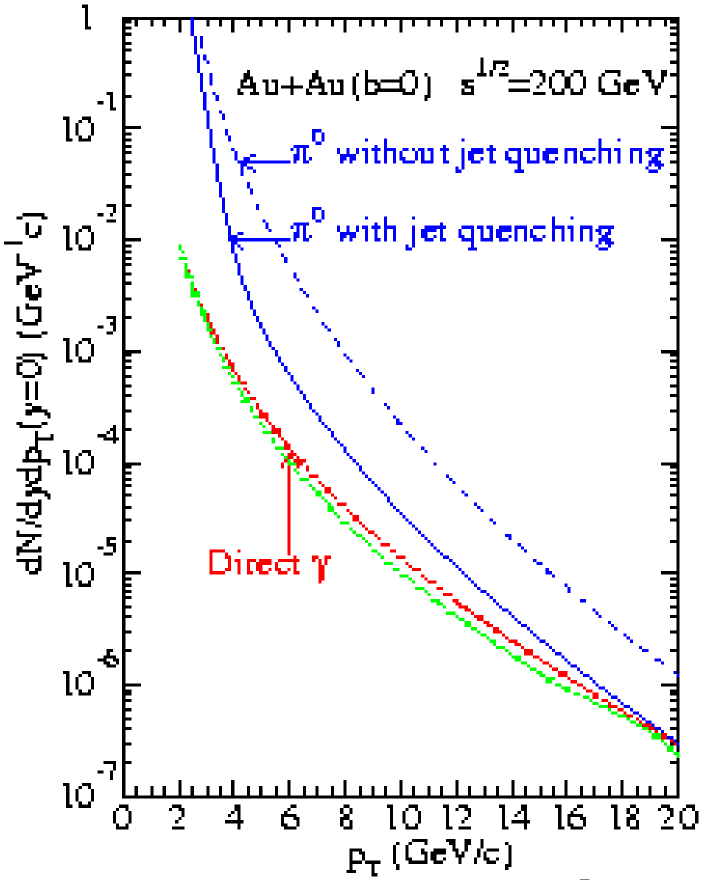
Outline

- Quark Gluon Plasma
    - Jet Quenching as probe
- What is jet ?
    - Soft or Hard
    - Jet Shape
    - π^-/π^+ ratio
    - Jet in H.I. Collision?
- Nuclear Effect
    - EMC Effect
    - Cronin Effect (Intrinsic kT effect)
    - Energy loss in QGP (Jet Quenching)
- Comparison of pQCD and A+A Collisions
    - Modeling of nuclear effect
    - pQCD Calculation
    - WA98
- Go to RHIC

Jet Quenching as probe of QGP

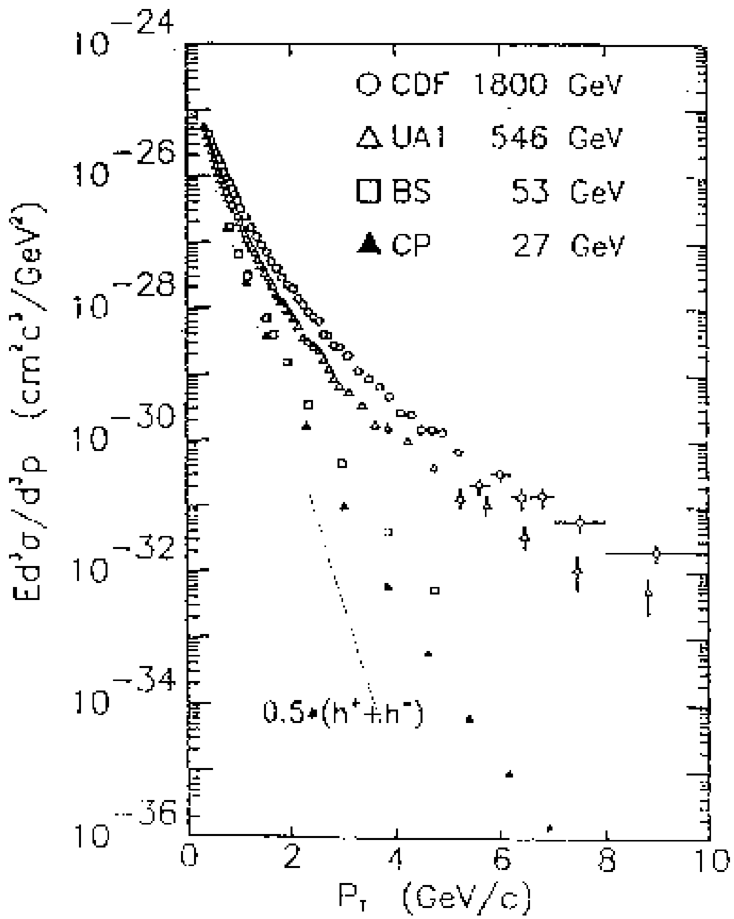
- Quark Gluon Plasma(QGP) search
  - One of the hard probe for QGP is “Jet Quenching”
  - Jet Quenching.
    - Quark energy loss in the QGP matter by gluon bremsstrahlung.
    - Energy loss can be observed by measuring fragmented pi0



Xin-Nian Wang
Phys.Rev.C58 2321(1998)
Au+Au √s=200GeV
(dE/dx=1GeV/c)

Soft or Hard

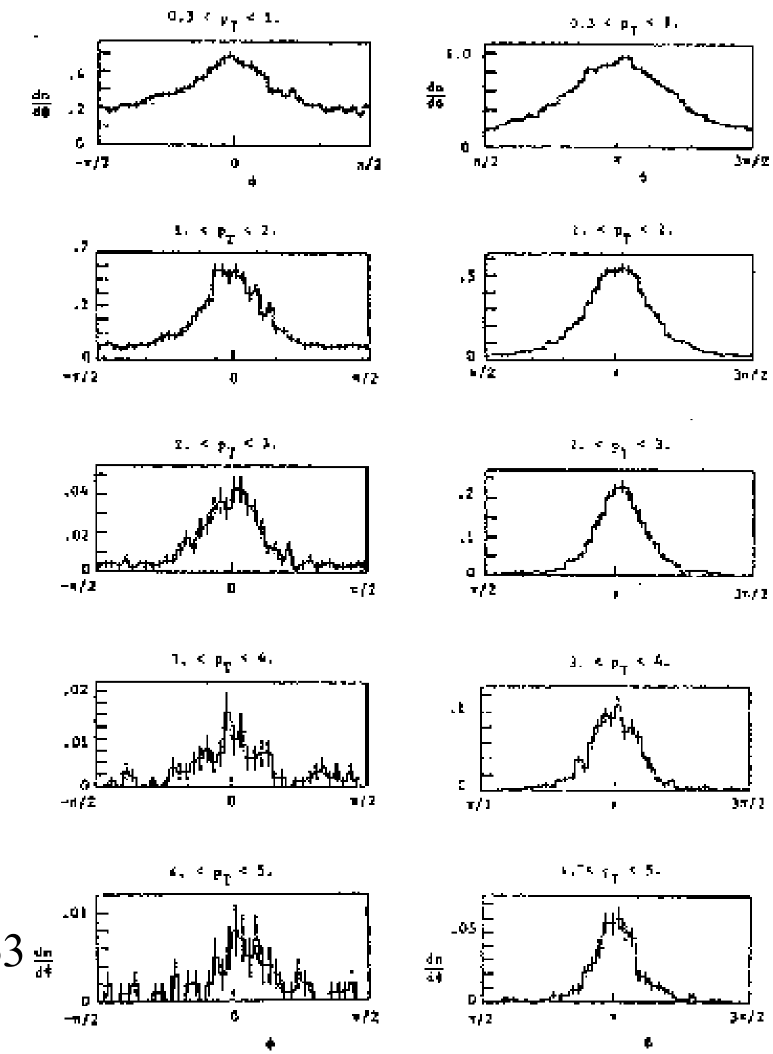
- Invariant cross section for pi+- or pi0
  – at p+p or p pbar
- Soft region
  – エネルギーによらず常にほぼ一定の傾きを示す。(pT<2)
- Hard region
  – エネルギー依存
  – 核子中の内部構造を反映している。
  – クォークの破砕化 (fragmentation)→ハドロン



Phys.Rev.Lett 61(1988)1819

Jet Shape

- Jet = hadronization
- Two particles correlation in CERN-ISR exp.
  - Triggerd by neutral with pT>7.0GeV/c
  - Large correlation in opposite side
    - → 2 Jets with 180deg
  - The width of opposite side(right) decrease as function of pT
    - Initial kT



Phys.Lett 97B(1980)163

π^-/π^+ ratio

- π^-/π^+ ratio
  - (Low pT) ~ 1
    - π isospin
  - (High pT) < 1
    - u,d quark isospin
    - (very naïve)
      - proton = 2u + d quark
      - π^-/π^+ = d/u quark = 1/2

nucl-th/9812021

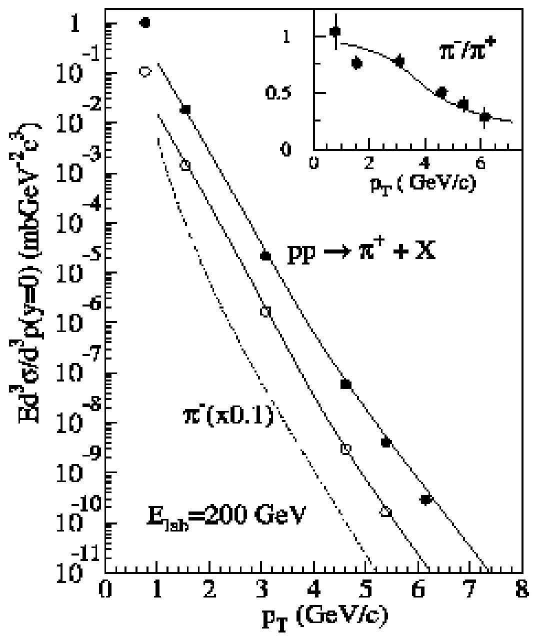


FIG. 1. Single-inclusive pion spectra in $p+p$ collisions at $E_{\rm lab} = 200$ GeV. The solid lines are pQCD parton model calculations with intrinsic k_T and the dot-dashed line is without. Experimental data are from Ref. [26]. The inserted figure shows the corresponding π^-/π^+ ratio.

Jet in Heavy Ion Collisions?

hep-ex/0003012

- π^-/π^+ ratio
  - Pb-Au Collisions at 158AGeV/c
  - CERN-NA45-CERES
    - Flat 1.03 upto 2.2GeV/c
    - (if hard process) π^-/π^+ = d/u quark =1.14
- No explicit evidence of jet at H.I. collisions

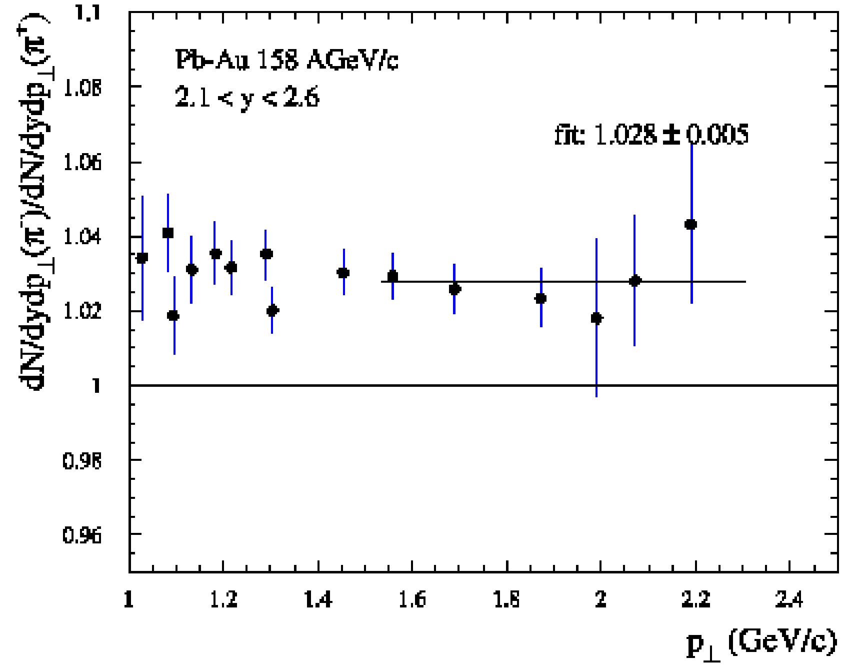
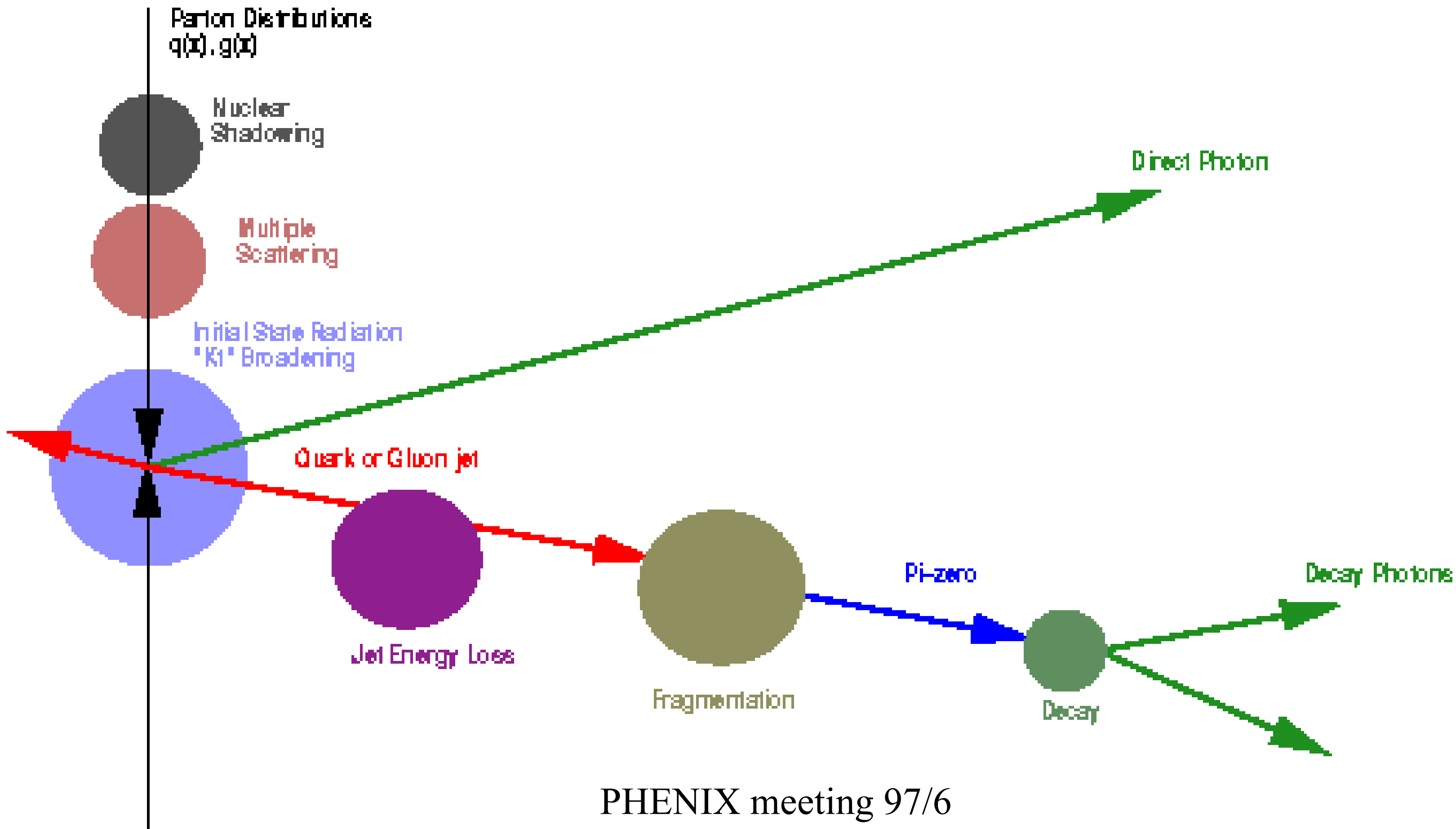


Figure 5. Transverse momentum dependence of the π^-/π^+ ratio.

Nuclear Effect in A+A collision



PHENIX meeting 97/6
by P.Stankus

Nuclear Effect
EMC effect (e + A)

- Parton Distribution Fuction(PDF)
  - Difference of PDF in nucleus and PDF in nucleon.
    - Fermi motion
    - Nuclear binding
    - Q2 shift
    - Virtual pion
    - Nuclear shadowing

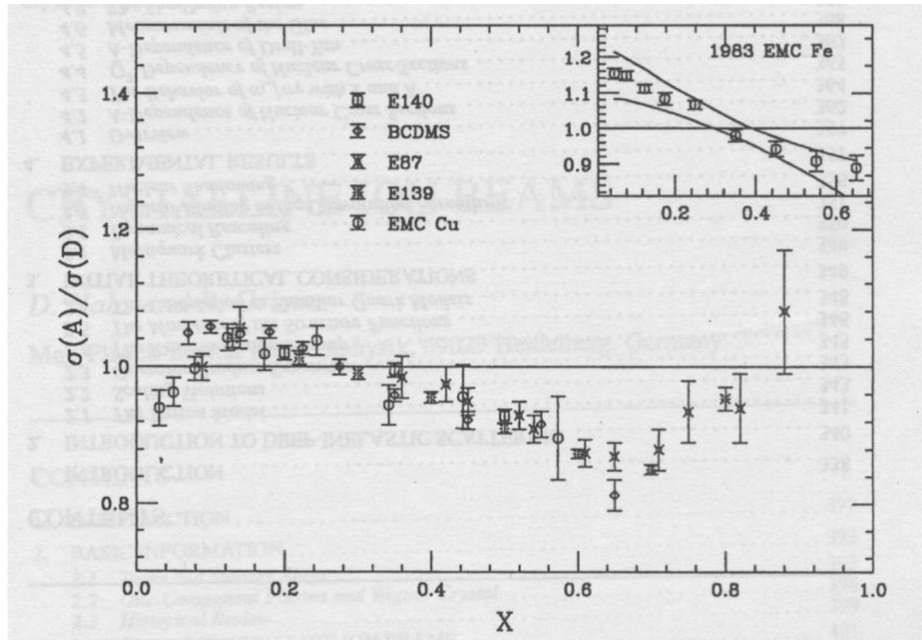


Figure 1 Ratios of the deep-inelastic cross sections on targets of iron or copper to those of deuterium (2–6). The insert contains the original EMC data, which have an additional 7% overall multiplicative uncertainty (1).

Annu.Rev.Nucl.Part.Sci.1995. 45:337-390

Nuclear Effect
Cronin Effect (p + A)

Phys.Rev.D23,(1981)604

- Lepton pair transverse momentum
  - Due to soft gluon radiation.
  - It means resummension is not incomplete.

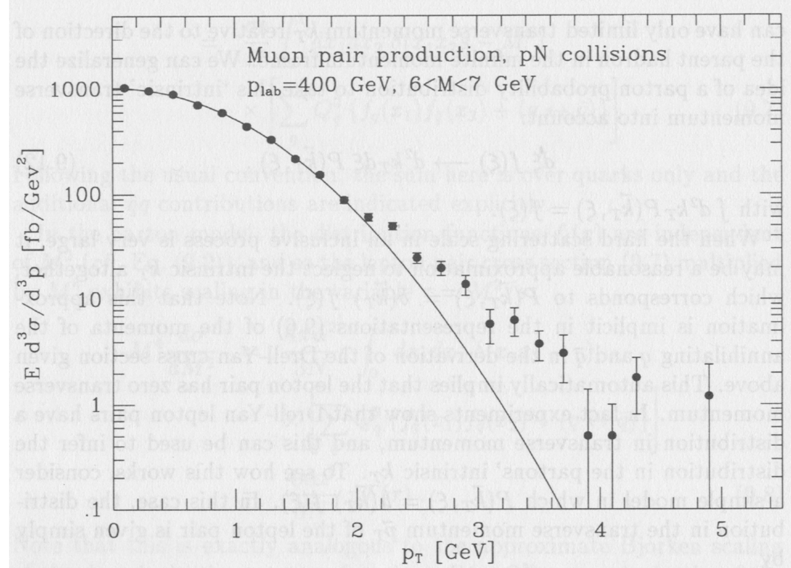


Fig. 9.2. The lepton pair transverse momentum from the CFS collaboration [4]. The curve corresponds to a Gaussian intrinsic k_T distribution for the annihilating partons.

Nuclear Effect
Cronin Effect (p + A)

Phys.Rev.D59,074007

- <kT> depends on √s strongly.
  - kTをGaussiannでランダムに振って入れてやる.

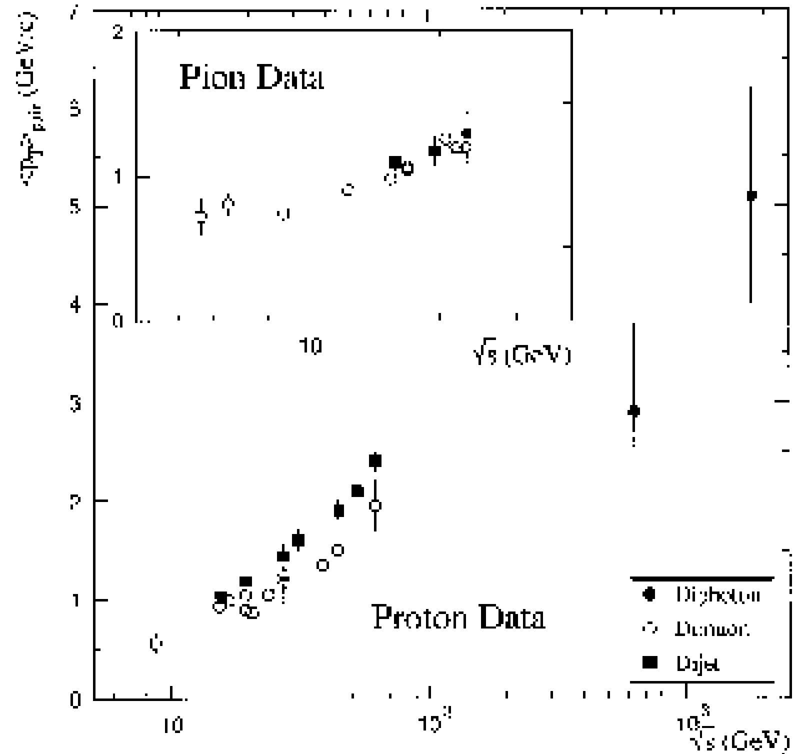


FIG. 1. $\langle p_T \rangle$ of pairs of muons, photons, and jets produced in hadronic collisions versus $\sqrt{s}$.

Jet Quenching
Energy loss in dense matter

- Gluon radiative energy loss
- R.Baier, Yu.L.Dokshitzer, A.H.Mueler, S.Peigne, D.Shiff達もいろいろやっているがmodel dependence が大きそうである
  - N.P.B484(1997)265 R.Baier et al.
    - T=250MeV dE/dx = 3GeV/fm (L=10fm)
    - cold matter dE/dx = 0.2GeV/fm (L=10fm)
  - N.P.B531(1998)403-425 R.Baier et al
    - 上の2倍
- 最近の理論計算では、dE がHot Matter中Parton の通過する積算距離 L の二乗に比例している。

Phys.Rev.D51,(1995)3464

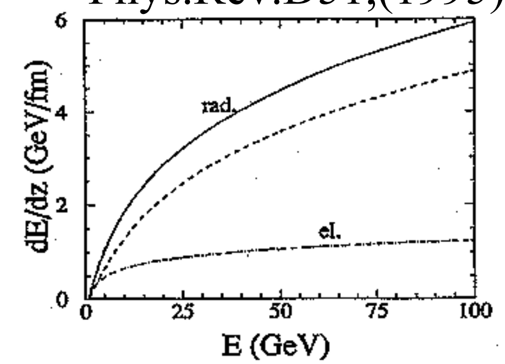


FIG. 4. The energy dependence of energy loss dE/dz of a quark with energy E inside a quark-gluon plasma at temperature $T = 300$ MeV. A weak coupling $\alpha_s = 0.3$ is used. The solid line is the full expression and the dashed line is the factorization limit of the radiative energy loss. The dot-dashed line is the elastic energy loss.

Modeling for nuclear effect & pQCD calculation

- Heavy Ion collisionにおいて原子核効果(nuclear effect)による影響を考慮しなければいけない
  - nuclear modification of the parton distribution : EMC effect

$$f_{a/A}(x,Q^2,b)=S_{a/A}(x,b)\left[\frac{Z}{A}f_{a/p}(x,Q^2)+\left(1-\frac{Z}{A}\right)f_{a/n}(x,Q^2)\right]$$

  - nuclear enhancement of pT hadron spectra : Cronin effect

$$\left\langle \kappa^2(b)\right\rangle_A=\left(1+0.2Q^2\alpha_{s(Q^2)}+\frac{0.23\sigma_{pp}t_A(b)ln^2 Q}{1+lnQ}\right)(GeV/c)^2$$

- これらのパラメーターをWA80,WA98で合わせたParameterizationをおこなっている。

$$\frac{d\sigma AB\rightarrow hX}{dyd^2p_T}=K\sum_{abcd}\int d^2\vec{\kappa}_a d^2\vec{\kappa}_b\, g(\vec{\kappa}_a)g(\vec{\kappa}_a)\times\int dx_a dx_b f_{a/A}(x_a,Q^2)f_{a/A}(x_a,Q^2)\times$$

$$\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\frac{D^0{}_{h/c}(z_c,Q^2)}{\pi z_c}$$

pQCD Calculation

p pbar

√s=0.2 to 1.8TeV

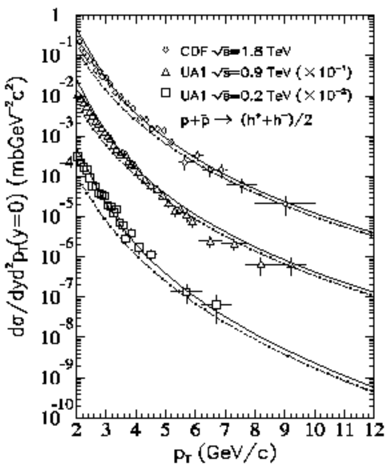


FIG. 5. Single-inclusive spectra of charged hadrons in $p + \bar{p}$ collisions at $\sqrt{s} = 200, 900, 1800$ GeV. The solid lines are pQCD parton model calculations with intrinsic k_T and the dot-dashed lines are without. Experimental data are from Refs. [28,29].

A A collisions

E_{lab}=158-200AGeV

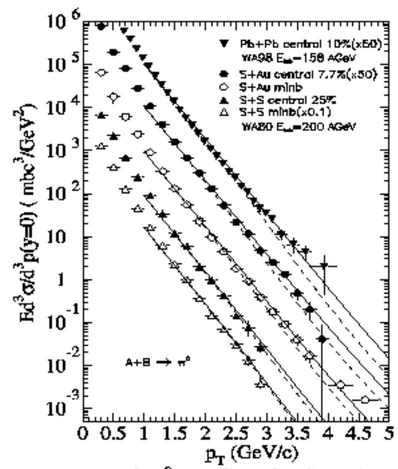


FIG. 11. Single-inclusive spectra of π^0 in $S + S$, $S + Au$ and $Pb + Pb$ collisions (both minimum-biased and central events) at the CERN SPS energies. The solid lines are pQCD parton model calculations with k_T broadening due to initial multiple parton scattering and the dashed lines are without. Experimental data are from Refs. [10,11].

nucl-ex/9812021

Jet Quenching at WA98

hep-ph/9804384

- WA98 Pb+Pb->pi0 data(N.P A638(1998) 147c-158c)
- 結論
  - 原子核効果(Cronin effect, EMC effect) を考慮するとJet Quenchingの効果なしで、pQCDの計算と良くあっておる。
  - dE/dx < 0.02GeV/fm

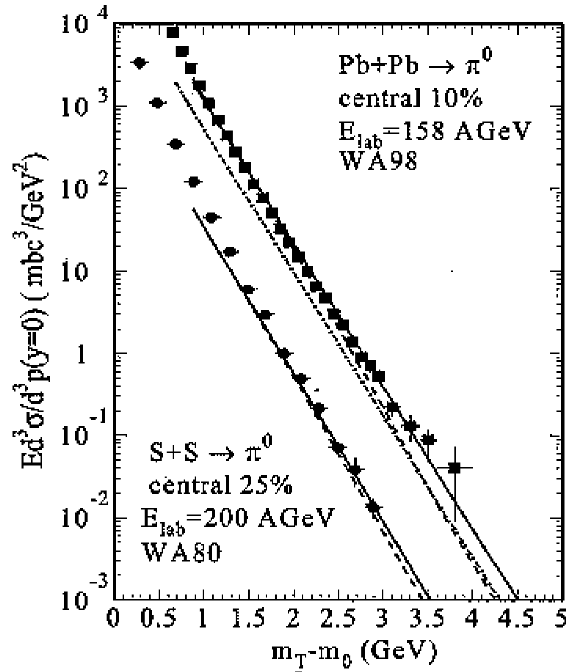


FIG. 2. Single-inclusive π^0 spectra in central $S+S$ at $E_{\rm lab}=200$ GeV and $Pb+Pb$ collisions at $E_{\rm lab}=158$ GeV. The solid lines are pQCD calculations with initial-k_T broadening and dashed lines are without. The $S+S$ data are from WA80 [27] and $Pb+Pb$ data are from WA98 [28]. The dot-dashed line is obtained from the solid line for $Pb+Pb$ by shifting p_T by 0.2 GeV/c.

Go to RHIC

- Fig.1a
  - pp,WA80,WA98との比較。
  - ppはGlauber model により、AAのpT分布に焼きなおしてある。
  - 結論は、HIJING の持っている kT(transverse momentum)の効果 はPbPbのデータのみを良く再現している。
  - RHICでは、pT分布がharderになっているため、原子核効果によるAdditional pTの寄与は小さい。有利である。
- Fig.1b
  - dE/dx = 0,or1GeV/fm にて大きく違う
  - 5GeV/c辺りで大きく違っているのは、pQCD semi-hard プロセスによるものではない、なぜなら、2GeV/c辺りのsemi-hard pQCD(mini-jet)領域では、quenchingの効果が見えていない。
  - HIJING model で見ているのは、multple soft collisions によるものである。

hep-ph/9807247

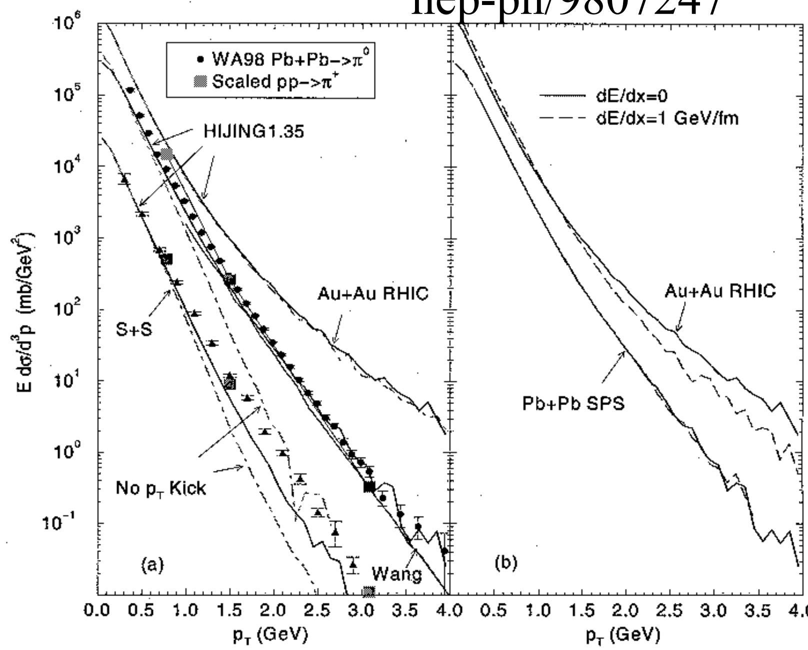


Figure 1: Invariant $A + A \to \pi^0$ cross section for central collision at SPS and RHIC energies are compared. a) The WA80 $S + S$ data [4] (triangles) and the preliminary WA98 $Pb + Pb$ data [1] (dots) are compared to HIJING1.35 [11] with soft $p_\perp$ kicks (full lines) and without p_T kicks (dot-dashed curves). The later scale with the wounded projectile number times σ_{AA} times the invariant distribution calculated for pp. The parton model curve from Ref. [2] is labeled by 'Wang'. The filled squares show $pp \to \pi^+$ data scaled by the (Glauber) number of binary collisions times σ_{AA} for both SS and $PbPb$. b) Jet quenching, predicted at RHIC energies[6], is not significant at SPS energies in the HIJING model.

Summary

- What is Jet?
- Nuclear Effects(EMC,Cronin)
- No signal of Jet Quenching yet.
  - $dE/dx < 0.02$GeV at WA98
- Go to RHIC
  - Yield will be suppressed by one order of magnitude.

kT effect in Direct Photon

Phys.Rev.D58,114020

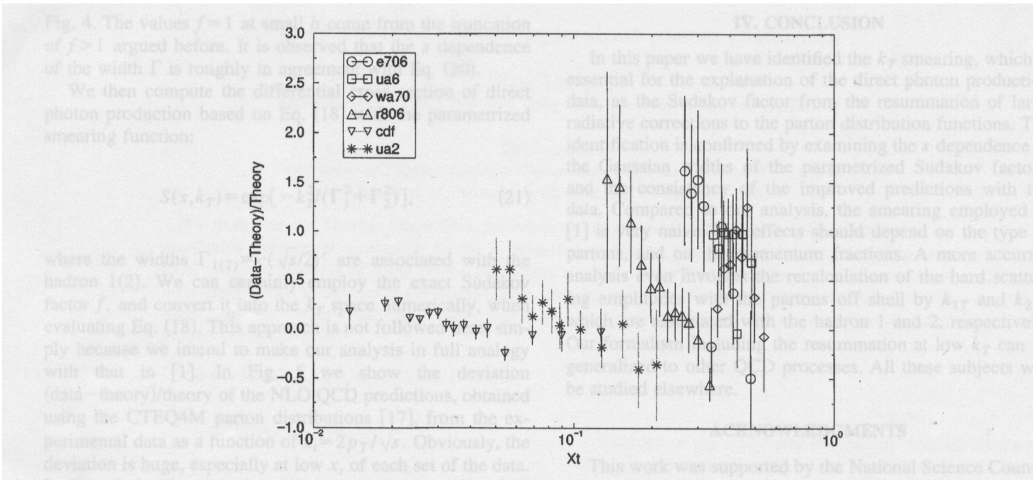


FIG. 5. Compilation of direct photon experiments compared to the NLO QCD predictions using the CTEQ4M parton distributions.

kT effect

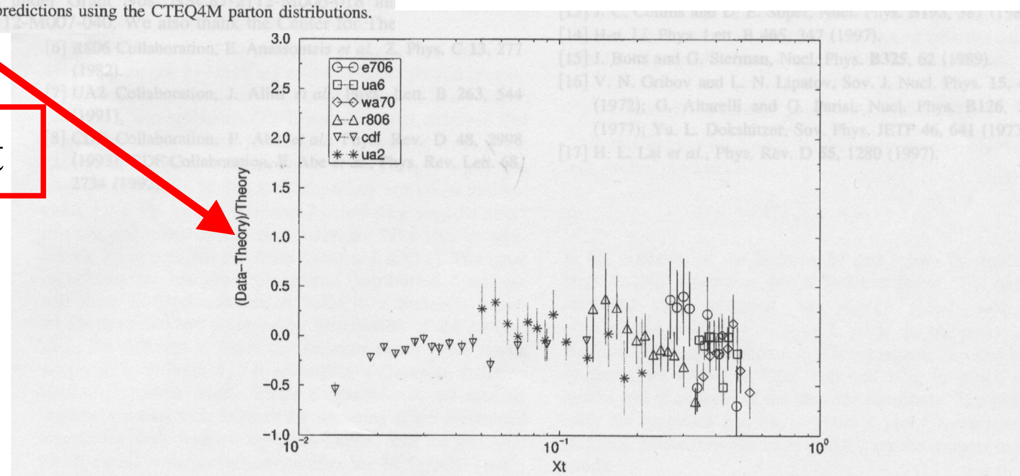


FIG. 6. Compilation of direct photon experiments compared to the k_T-resummed predictions using the CTEQ4M parton distributions.

Hydrodynamics model with WA80

nucl-ex/9805007

- WA80 S+S->pi0 200AGeV p+p, p+S, p+Au
- Hydrodynamic modelで説明できる。
- 特にQenching 及び　Kt の効果は見られない。
- 又、pQCDの計算でも説明できる。

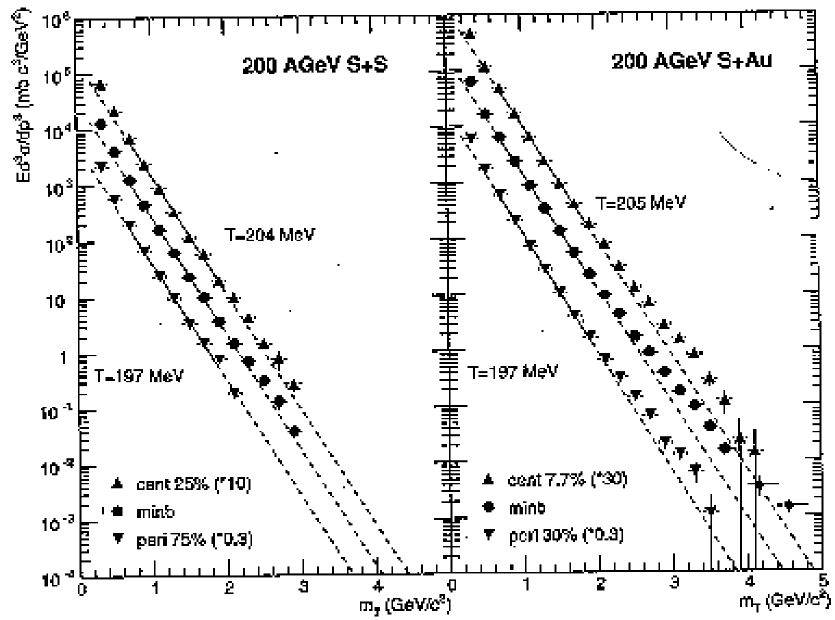
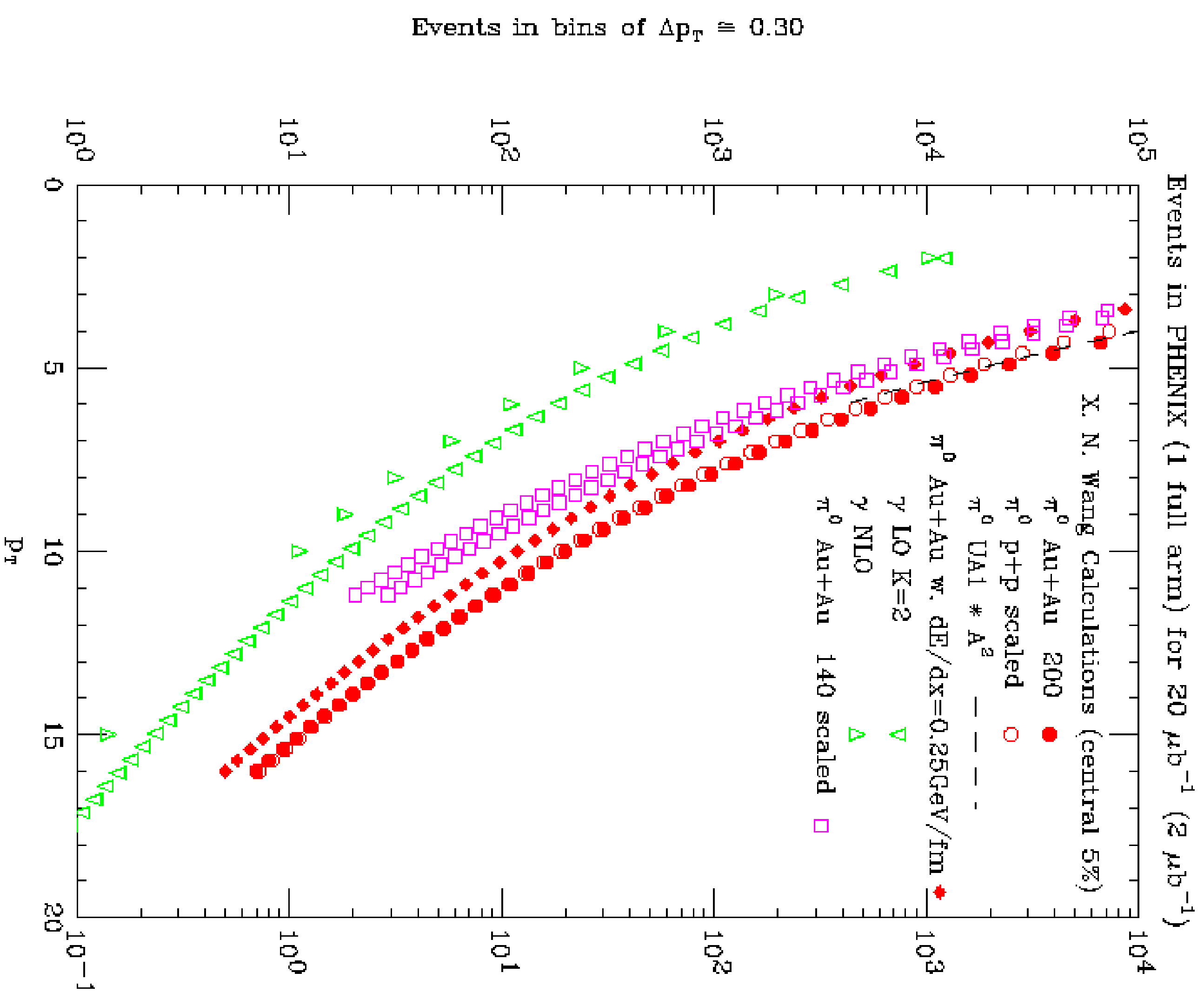


Fig. 6. Invariant cross sections of π^0 mesons from reactions of S+S (left) and S+Au (right) at 200 A·GeV measured in the rapidity range $2.1 \leq y \leq 2.9$. The events are selected for centrality with the percentage of the minimum bias cross section as indicated. The lines drawn with the data are exponentials fitted to the region 0.8 GeV/c^2 $\leq m_T \leq$ 2.0 GeV/c^2 with slope parameters as indicated.

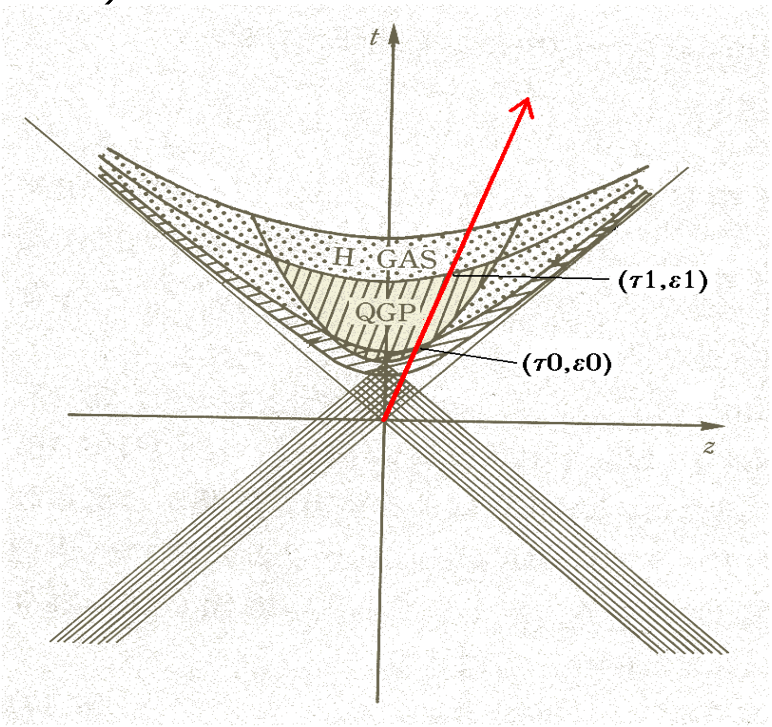
1-year in PHENIX (MJT's plot)



Xin-Nian Wang, Phys. Rev. C58, 2321 (1998)

Size of QGP
Uncertainty of dx

- ET Measurement give us an information
  - Bjorken formulae $$\varepsilon_0 = \frac{dE}{d\eta}\frac{1}{\pi\tau_0 R_A^2}$$
  - Energy conserv $$\varepsilon/\varepsilon_0 = \left(\tau_0/\tau\right)^{\alpha} \qquad 1 < \alpha < 4/3$$



- QGP formed
  - (t0, t1) to (e0,e1)
    - QGP need t0=1fm/c for thermal.
    - QGP critical energy density e1=1.0GeV/fm^3
- Wa98 1fm/c to 2.2-2.9fm/c
  - The (t0,t1) is too short in WA98. How about at RHIC?