Direct Photon Measurements in Heavy Ion Collisions

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ITP, April 11, 2002

Motivation (thermal and pQCD)

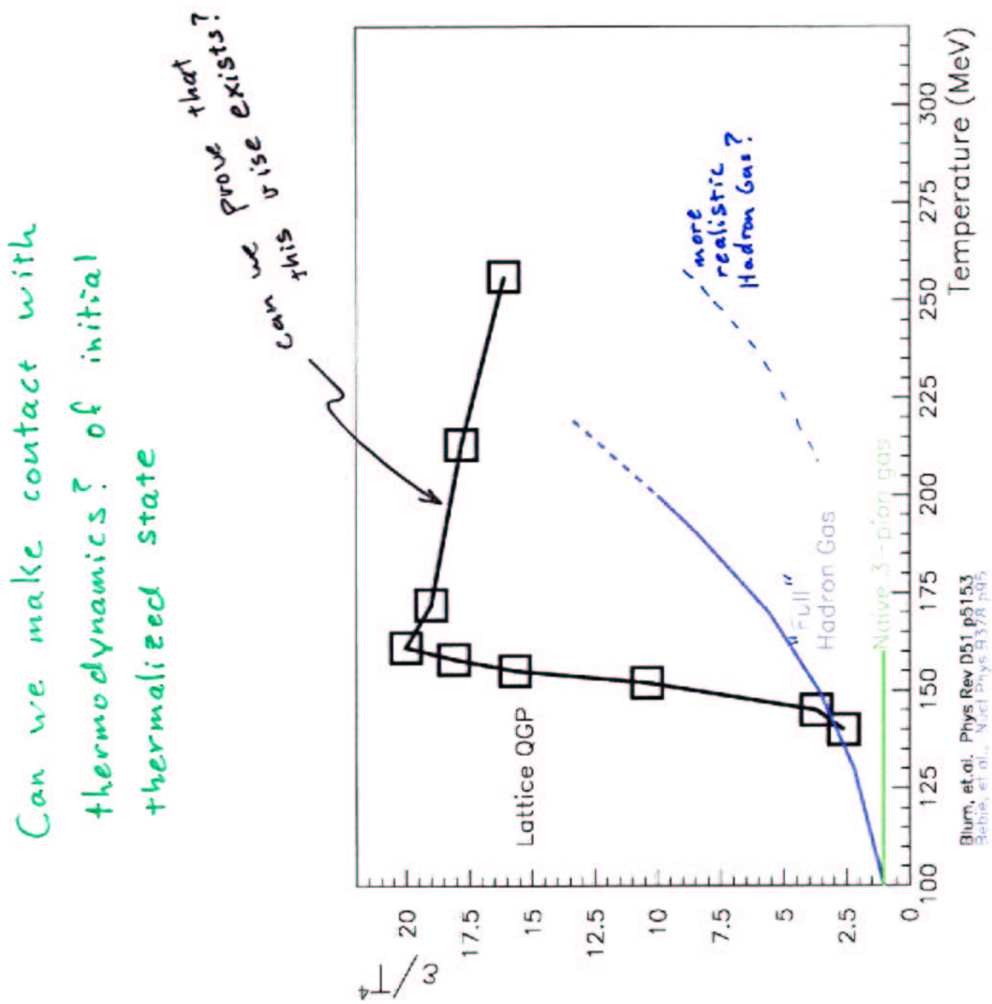
Technique

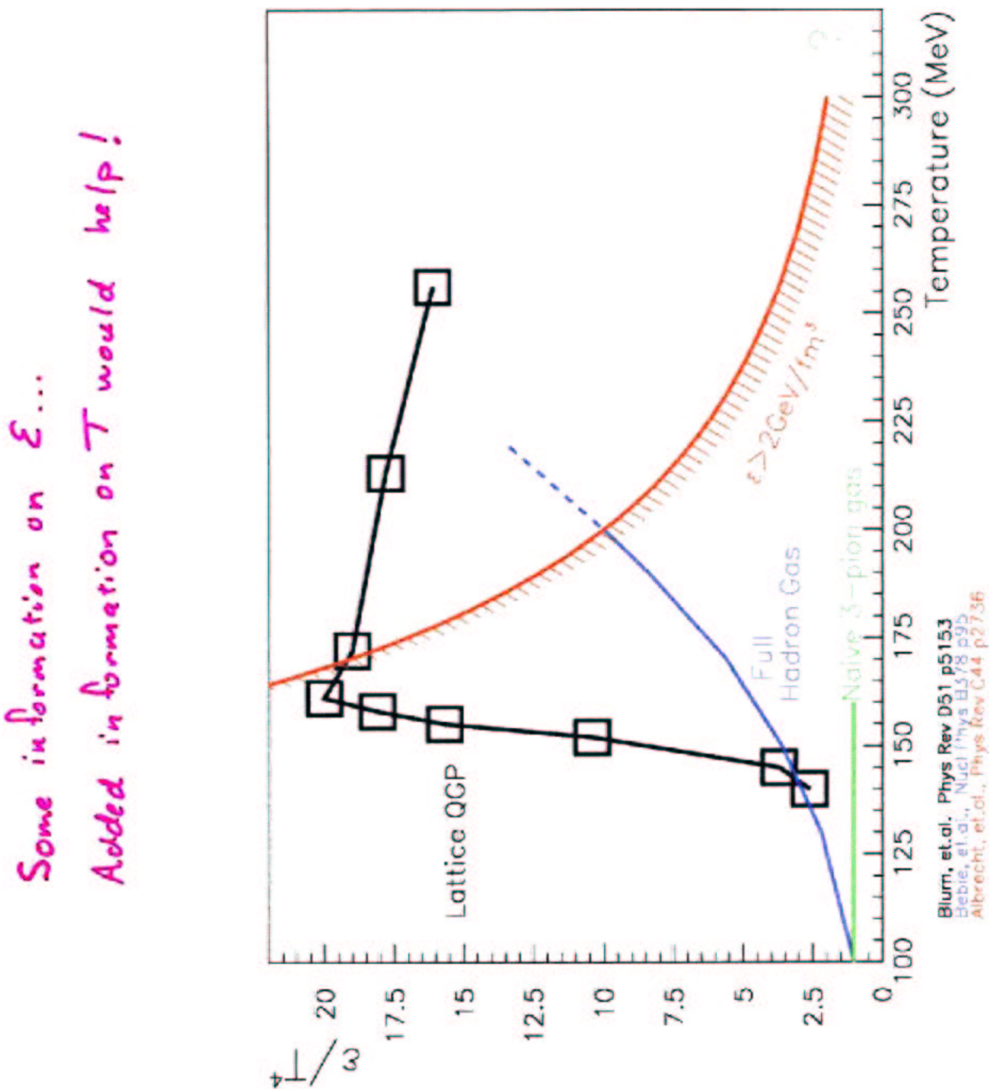
Example SPS S+Au and Pb+Pb results
What was learned at SPS?

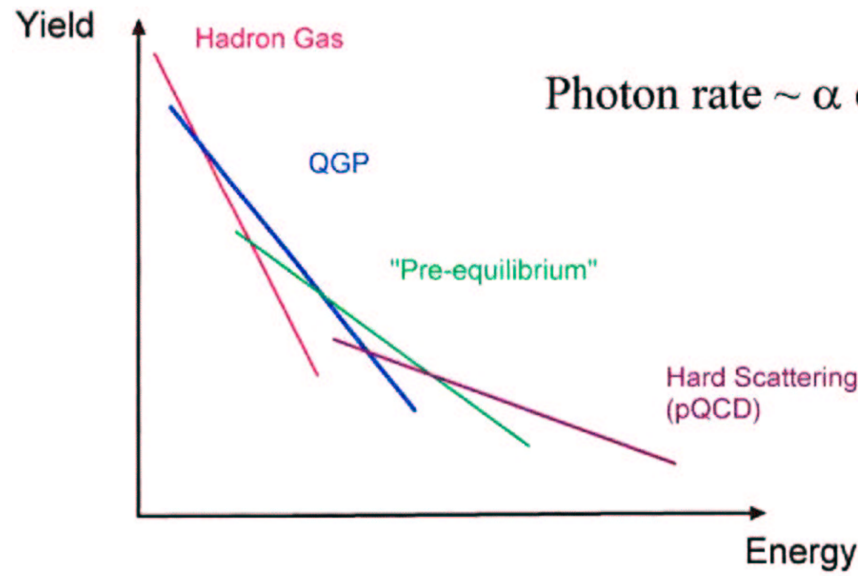
"The future, Mr. Gittes, the future!"
A few words about RHIC and LHC

My lessons and questions for theorists

Extra thanks to ITP staff!







Photon rate ~ $\alpha\, \alpha_s\, e^{-E/T}$

Different temperature sources show up at different secondary energies: need a differential measurement! High Pt reveals hotter, earlier stages.

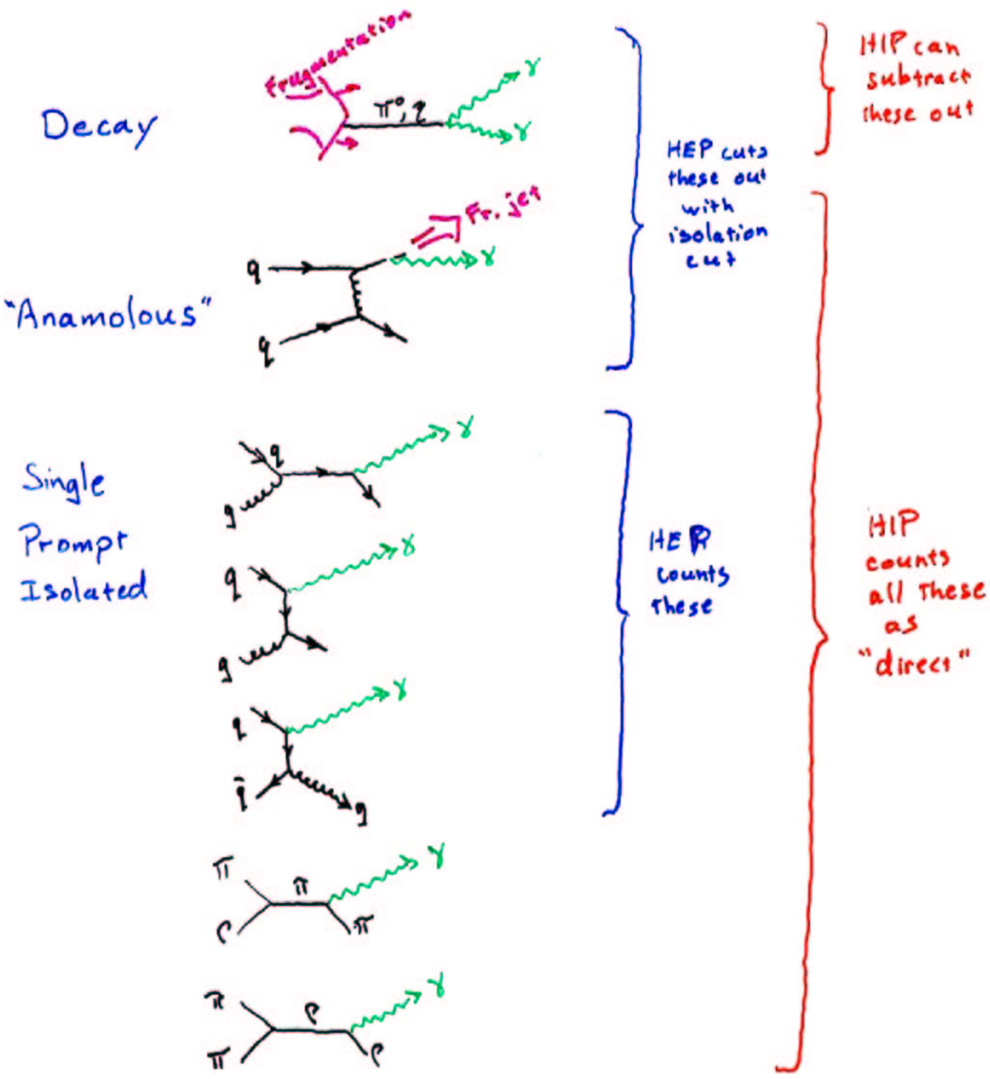
pQCD: Underlying N+N sources

"pre-equilibrium": Everything between pQCD and first thermalized state (open problem!)

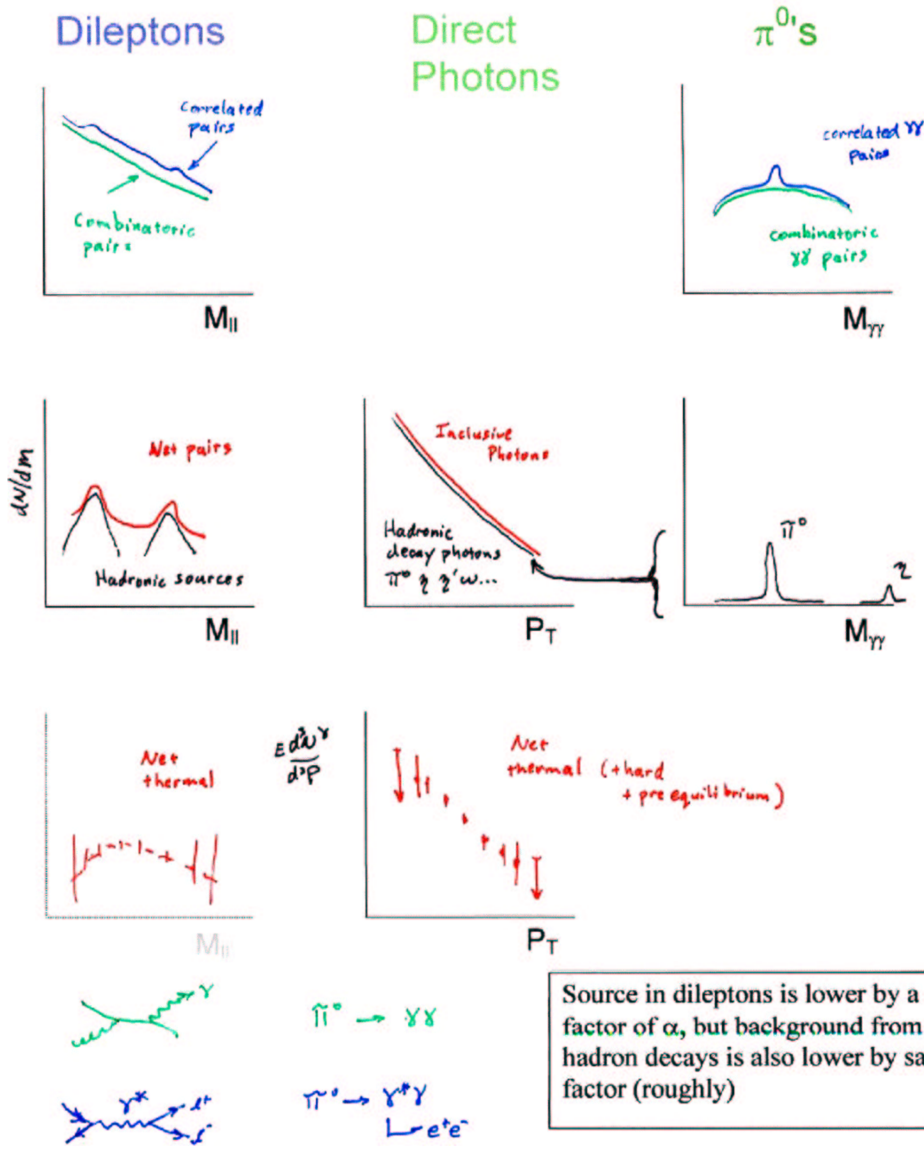
QGP: Thermalized quark matter (if it exists)

Hadron Gas: Mixed and hadron phases

What do you mean by "direct"?



Related but different problems experimentally



Source in dileptons is lower by a factor of α, but background from hadron decays is also lower by same factor (roughly)

Original direct photon logic, ca 1988

QGP has lots of quarks, since they're easy to create.
Lots of quarks means lots of electrical charges.
Lots of charges means lots of radiation.
QGP should shine brightly!
Direct photons will be a sign of QGP formation.

Upper limits only on O+C, O+Au

Albrecht, et.al, Z. Phys C51 (1991) 1-10

QGP and Hadron Gas shine equally brightly at the same temperature

Kapusta, Lichard, Siebert, Phys Rev D44 (1991) 2774

Upper limits only on S+Au

Albrecht, et.al., Phys Rev Lett 76 (1996) 3506

→ disappointment ...

VOLUME 76, NUMBER 19 PHYSICAL REVIEW LETTERS 6 MAY 1996

Limits on the Production of Direct Photons in 200*A* GeV ^{32}S + Au Collisions

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(WA80 Collaboration)

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(Received 16 November 1995)

A search for the production of direct photons in S + Au collisions at 200*A* GeV has been carried out in the CERN-WA80 experiment. For central collisions the measured photon excess at each p_T, averaged over the range $0.5 \leq p_T \leq 2.5$ GeV/c, corresponded to 5.0% of the total inclusive photon yield with a statistical error of $\sigma_{stat} = 0.8\%$ and a systematic error of $\sigma_{syst} = 5.8\%$. Upper limits on the invariant yield for direct photon production at the 90% C.L. are presented. Possible implications for the dynamics of high-energy heavy-ion collisions are discussed. [S0031-9007(96)00150-0]

PACS numbers: 25.75.Dw

Directly radiated thermal photons have long been considered an interesting penetrating probe with which to study the early phase of the hot and dense matter produced in ultrarelativistic nucleus-nucleus collisions. Single "direct" photons are expected at high transverse momentum, p_T, from well-known hard QCD processes, but also possibly in the p_T region below several GeV/c due to thermal radiation from the hot dense matter [1]. Since the mean free path of the produced photons is considerably larger than the size of the nuclear volume, photons produced throughout all stages of the collision will be observable in the final state. Thus, it is believed that the emitted photons should provide information about the initial conditions of the hot dense system and thereby provide evidence for the possible formation of a quark gluon plasma (QGP).

The search for direct photon production in ultrarelativistic nucleus-nucleus collisions has been a major emphasis of the WA80 experiment at CERN. The first results from WA80 found no excess photon yield beyond that attributable to resonance decays in central collisions of ^{16}O + Au at 200*A* GeV, setting an upper limit of $\gamma^{direct}/\pi^0 < 15\%$ [2]. The preliminary results of the 1990 WA80 ^{32}S + Au photon analysis showed no significant excess in peripheral collisions, while an excess at about the $\sim 2\sigma$ level was seen in central collisions [3]. Although preliminary, these results have generated a great deal of theoretical interest [4–8]. In this Letter we report the final results of the WA80 ^{32}S + Au direct photon analysis, we compare the final results to theoretical calculations, and discuss the implications towards the possible formation of a QGP.

The WA80 experimental setup for the 1990 run period with 200*A* GeV ^{32}S beams was upgraded from that used for the previous run periods with ^{16}O and ^{32}S beams [2,3,9]. The direct photon sensitivity for this data set, relative to the ^{16}O data [2], was improved by several factors [3] including an increased data sample, an increased detector coverage, a coverage closer to mid-rapidity, and improved analysis techniques. The WA80 photon spectrometer consisted of a finely segmented electromagnetic calorimeter composed of 3798 lead-glass modules with photomultiplier tube readout. The lead glass was arranged into three independently calibrated arrays, of roughly equal size. Two of the arrays consisted of TF1 lead-glass of 4 cm × 4 cm × 4 cm ($15X_0$) [10] deployed as towers to the left and right of the beam axis. The third array, located below the beam axis, was the SAPHIR lead-glass detector [11] used in the WA80 ^{16}O run period [2] which consisted of SF5 lead-glass modules of 3.5 cm × 3.5 cm × 46 cm ($18X_0$). The entire photon spectrometer provided coverage of from $\frac{1}{10}$ to $\frac{1}{2}$ of full ϕ over the rapidity range of $2.1 \leq y \leq 2.9$.

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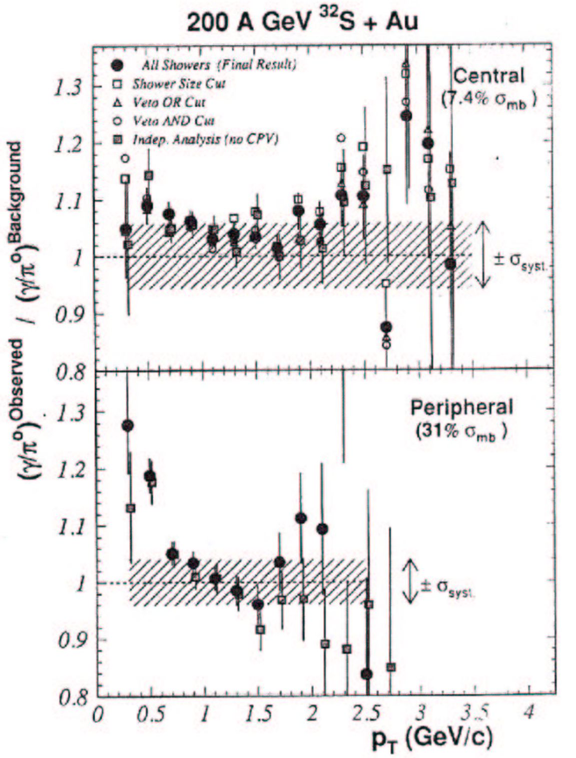

FIG. 1. The ratio $(\gamma/\pi^0)^{obs}/(\gamma/\pi^0)^{bkgd}$ as a function of transverse momentum for peripheral and central collisions of 200A GeV ^{32}S + Au. The errors on the data points (shown for the solid points only) indicate the statistical errors only. The shaded regions indicate the total estimated p_T-dependent systematic errors which bound the region corresponding to no photon excess.

Systematic errors are everything in this game.

the case of central collisions. This variation, in which the π^0 identification efficiency varies by more than a factor of 2, gives an indication of the level of systematic error which may be attributed to the π^0 yield extraction (see Table I). The total systematic error estimate is corroborated by the results of an independent complete γ and π^0 analysis shown by the light-shaded squares. This analysis was performed without the use of the CPV and featured

atic errors of the measurement summed quadratically, an upper limit can be calculated at each p_T for the excess photon yield per event. Upper limits, at the 90% confidence level, on the invariant yield of excess photons per central ^{32}S + Au collision are shown in Fig. 2. These limits are similar in magnitude to the excess photon yields reported in the preliminary analysis; accordingly, the theoretical predictions of the scenarios with QGP formation remain consistent with the final upper limits, while the predictions

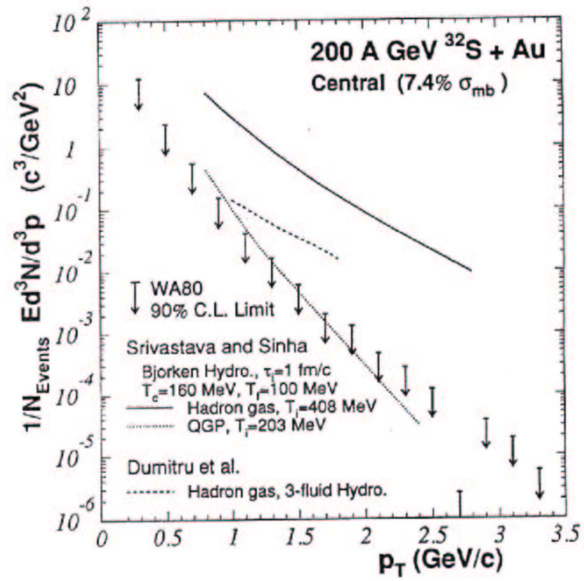

FIG. 2. Upper limits at the 90% confidence level on the invariant excess photon yield per event for the 7.4% σ_{mb} most central collisions of 200A GeV ^{32}S + Au. The solid curve is the calculated thermal photon production expected from a hot hadron gas taken from Ref. [5]. The dashed curve is the result of a similar hadron gas calculation taken from Ref. [7]. The dotted curve is the calculated thermal photon production expected in the case of a QGP formation also taken from Ref. [5].

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[2] R. Albrecht *et al.*, Z.
[3] R. Santo *et al.*, Nucl
[4] E. V. Shuryak and
(1994).
[5] D. K. Srivastava and
(1994).
[6] J. J. Neumann, D. S
1460 (1995).
[7] A. Dumitru, U. K
W. Greiner, and D.
(1995).
[8] N. Arbex, U. Ornik
R. M. Weiner, Phys.
[9] R. Albrecht *et al.*, P
[10] F. Berger *et al.*, Nuc
A **321**, 152 (1992).
[11] H. Baumeister *et al.*
Sect. A **292**, 81 (19
[12] R. Albrecht *et al.*,
Sect. A **276**, 131 (1
[13] T. C. Awes *et al.*, N
A **279**, 497 (1989).
[14] G. Hölker, Doctoral
[15] G. Clewing, Doctor

Original direct photon logic, ca 1988:

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Lots of quarks means lots of electrical charges.
Lots of charges means lots of radiation.
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Albrecht, et.al, Z. Phys C51 (1991) 1-10

QGP and Hadron Gas shine equally brightly at the same temperature

Kapusta, Lichard, Siebert, Phys Rev D44 (1991) 2774

Upper limits only on S+Au

Albrecht, et.al., Phys Rev Lett 76 (1996) 3506

New and improved direct photon logic, ca 1996:

What we fix is not initial temperature, but initial energy density.

For the same energy density, HG is hotter than QGP since HG has fewer degrees of freedom (d.o.f.).

For same initial energy density (ala Bjorken), QGP should radiate less than HG in initial state.

Less direct photon radiation is sign of QGP!

PHYSICAL REVIEW C VOLUME 55, NUMBER 1 1997

Hydrodynamical description of 200A GeV/c S+Au collisions: Hadron and electromagnetic spectra

PRC 55 1997

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We study relativistic S+Au collisions at 200A GeV/c using a hydrodynamical approach. We test various equations of state (EOS's), which are used to describe the strongly interacting matter at densities attainable in the CERN-SPS heavy ion experiments. For each EOS, suitable initial conditions can be determined to reproduce the experimental hadron spectra; this emphasizes the ambiguity between the initial conditions and the EOS in such an approach. Simultaneously, we calculate the resulting thermal photon and dielectron spectra, and compare with experiments. If one allows the excitation of resonance states with increasing temperature, the electromagnetic signals from scenarios with and without phase transition are very similar and are not resolvable within the current experimental resolution. Only EOS's with a few degrees of freedom up to very high temperatures can be ruled out presently. We deduce an upper bound of about 250 MeV for the initial temperature from the single photon spectra of WA80. With regard to the CERES dilepton data, none of the EOS's considered, in conjunction with the standard leading order dilepton rates, succeed in reproducing the observed excess of dileptons below the ρ peak. Our work, however, suggests that an improved measurement of the photon and dilepton spectra has the potential to strongly constrain the EOS. [S0556-2813(97)00701-2]

PACS number(s): 25.75.−q, 12.38.Mh, 12.40.Ee, 47.75.+f

I. INTRODUCTION

The use of hydrodynamics for simulations of nuclear collisions has a long tradition [1–3]. If applicable, hydrodynamics has some advantages over the more fundamental kinetic calculations, which are usually performed as Monte Carlo simulations. Besides its relative simplicity, the use of familiar concepts such as temperature, flow velocity, energy density, pressure, etc., leads to an intuitively transparent picture of the space-time evolution of the system. Another great advantage is the direct use of the equation of state (EOS) of strongly interacting matter. Testing different EOS's by comparing with experiments should give us more insight into the behavior of nuclear matter under extreme conditions of temperature and/or density. This is important, since one of the main reasons to study high energy heavy ion collisions is to confirm the possible phase transition from hadronic matter to the quark-gluon plasma (QGP) [4]. The necessary energy densities are estimated to be around 1–2 GeV/fm^3, presently experimentally available at the Brookhaven AGS and the CERN-SPS. Of these two facilities, conditions to observe signals of the phase transition are more favorable at the CERN-SPS, because of the higher incident momenta of the nuclei.

In this work, we analyze the data from the heavy ion experiments at the CERN-SPS with 200A GeV/c incident momentum [5–14], concentrating on the S + Au system. For this system, yields of both the hadronic and electromagnetic (dileptons and photons) probes are now available. A hydrodynamical treatment of the nuclear collisions in this energy range is not new [15–22], but the large set of new and updated experimental data allows us to achieve a deeper insight into the space-time evolution of these reactions.

In applying hydrodynamics to relativistic heavy ion collisions, we have relaxed many of the commonly used approximations. To be specific, (1) we solve the hydrodynamical equations locally, as they are formulated, in contrast to the global ansatz in Ref. [15]; (2) for central collisions, we determine the three-dimensional solutions, instead of using the one-dimensional (longitudinal) boost-invariant hydrodynamics (sometimes supplemented with approximate transverse expansion) as in [20–22]; (3) in addition to considering baryon number conservation in the hydrodynamical evolution, we include the baryonic contributions to the EOS, in contrast to [17–22]; and (4) for a scenario with no phase transition, we use an EOS which goes beyond the unrealistic ideal massless pion gas EOS, which is used in many of the other hydrodynamical simulations. A complete hydrodynamical simulation would require the inclusion of viscosity and finite impact parameter averaging, which is neglected here, as well as in the other appoaches cited above.

Also, previous work has mostly dealt with either hadronic spectra [15–19] or electromagnetic spectra [20–22], but not both. To arrive at definite conclusions about the reaction dy-

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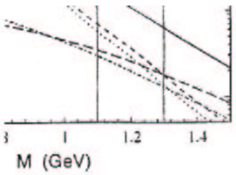

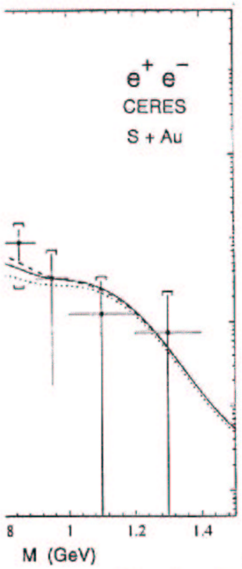

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thermalization is achieved in the latter approach. Specific medium modifications of the vector meson properties, in particular a decrease in their masses, have been found to yield a satisfactory description of the CERES data [76.67]. Whether a similar approach can be satisfactorily adopted in hydrodynamical simulations is a challenging future task.

IX. CONCLUSION

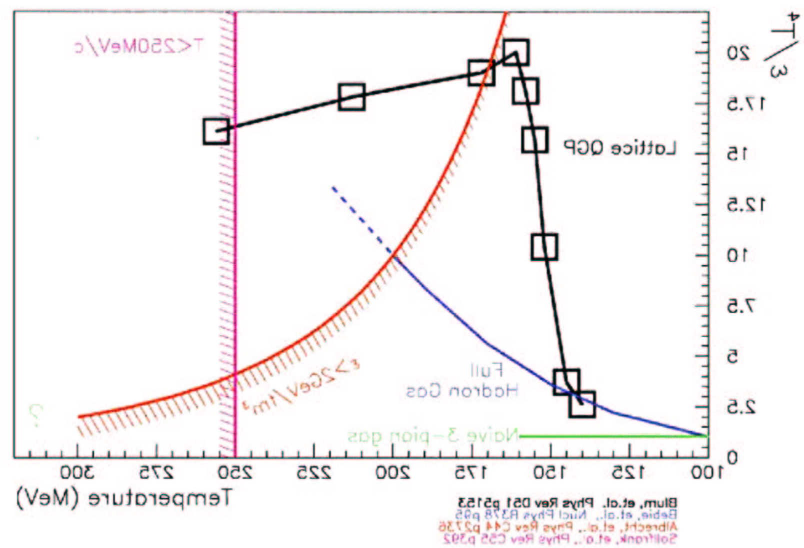
The aim of this work was to establish the extent to which one can constrain the EOS from the experimental data for S+Au collisions from a simultaneous description of the hadron and electromagnetic spectra using hydrodynamics. We have shown that, in general, the influence of the EOS on hadronic spectra can be counterbalanced by choosing different initial conditions. A simultaneous calculation of the electromagnetic signals can, in principle, distinguish between the different EOS's. However, the present experimental resolution allows us to rule out only extreme cases, such as the ideal pion gas EOS with only a few degrees of freedom. Also, the dilepton yield for the QGP equation of state with $T_c \simeq 140$ MeV, the EOS B, tends to fall below the data in the vector meson mass region, indicating an effective lower bound of 140 MeV for T_c, if the transition exists.

The constraint that can be drawn from the single photon data is that the initial temperature cannot be too high. The present data rules out temperatures above 250 MeV. This limit on the initial temperature can be achieved only if a large number of degrees of freedom is involved, be it in the form of quarks and gluons, or in the form of a large enough number of hadrons. However, if the data can be improved, the two cases can be distinguished, since the total emission from a hadron gas is larger than that from the QGP. In the total yield, the difference between a pure hadronic EOS and an EOS with a phase transition increases with decreasing T_c.

The behavior of the dilepton spectrum in the mass region between 200 and 600 MeV shows that the description of the hot and dense strongly interacting matter near T_c in terms of the free-space parameters is not adequate. With our present hydrodynamical approach, the dilepton spectrum can be explained only in the mass region of the vector mesons. The large experimental dilepton yield below the ρ mass may indicate medium modifications of the particle properties. These effects can be included in hydrodynamical calculations, but

$\varepsilon/T^4 > 14$ for S+Au initial state

First direct diagnosis of A+A initial state thermodynamics



Robust against all added effects which would add photons:

- ▷ hard component, or pre-equili brium
- ▷ un-even energy distribution
- ▷ increased hydro flow

namics included in the analysis. The analysis of Owens using the lowest-order QCD with a constant K-factor indicates that $<p_T^2>= 0.9$ (GeV/c)^2 gives a good agreement with photon production data in pp, π^+p and π^-p collisions at 19.4 GeV$< \sqrt{s} <$62 GeV [22]. Recent analysis [24] suggests even a greater value of $<p_T^2>$ of about 2 (GeV/c)^2. More future work is needed to clarify the situation on the the magnitude of the parton intrinsic transverse momentum.

Wong, Wong PRC58 (1998) 376

Include pQCD production?

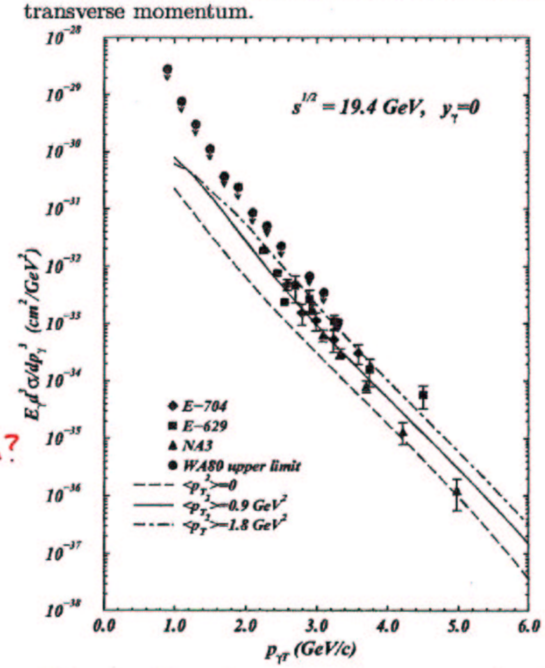


Fig. 3. The photon invariant cross section for nucleon-nucleon collisions at $\sqrt{s}$ = 19.4 GeV and $y_\gamma = 0$ calculated with different $<p_T^2>$ values of parton intrinsic momentum distribution and the Duke and Owens parton distribution function (set 1). The NLO corrections have been included.

To see the dependence of the photon transverse momentum distribution on the magnitude of $<p_T^2>$ of the parton intrinsic transverse momentum, we show in Fig.

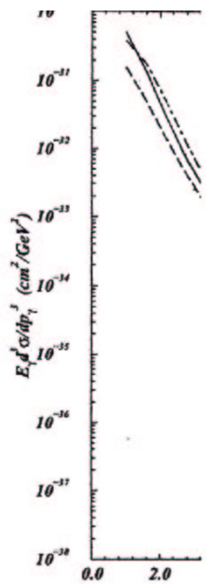


Fig. 4. The nucleon-nucleon $y_\gamma = 0$ calculate ton intrinsic mo and Owens part NLO correction

The enhancemen tion in the region c teresting puzzle. I be taken as a fixe tained by integrat independent of the sic transverse mon of the cross sectio olate this normali cross section. The cross section is no photon production gion $p_{\gamma T} >> \sqrt{<p}$

Lessons from S+Au direct photons (limits):

1) Upper limits are at a significant level.

2) Initial state is "cool", T_i< ~250 MeV.

3) Combined with ε estimate, initial state must have opened up a large number of degrees of freedom.

4) Hadron gas with lots of non-interacting resonances can have heat capacity similar to QGP. Can such a gas be ruled out on its own? can a "realistic" HG/non-QGP be modelled and ruled out by data?

5) Any reasonably complete calculation of the thermal radiation should be compared to *all* available data, both direct photons and dileptons, even if they're only limits.

Observation of Direct Photons in Central 158 *A* GeV ^{208}Pb+^{208}Pb Collisions

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(Draft 1.0, August 27, 2000)

At last!

(Was it worth the wait?)

A measurement of direct photon production in ^{208}Pb+^{208}Pb collisions at 158 *A* GeV has been carried out in the CERN WA98 experiment. The invariant yield of direct photons in central collisions is extracted as a function of transverse momentum in the interval $0.5 < p_T < 4$ GeV/c. A significant direct photon signal, compared to statistical and systematical errors, is seen at $p_T > 1.5$ GeV/c. The results constitute the first observation of direct photons in ultrarelativistic heavy-ion collisions which could be significant for diagnosis of quark gluon plasma formation.

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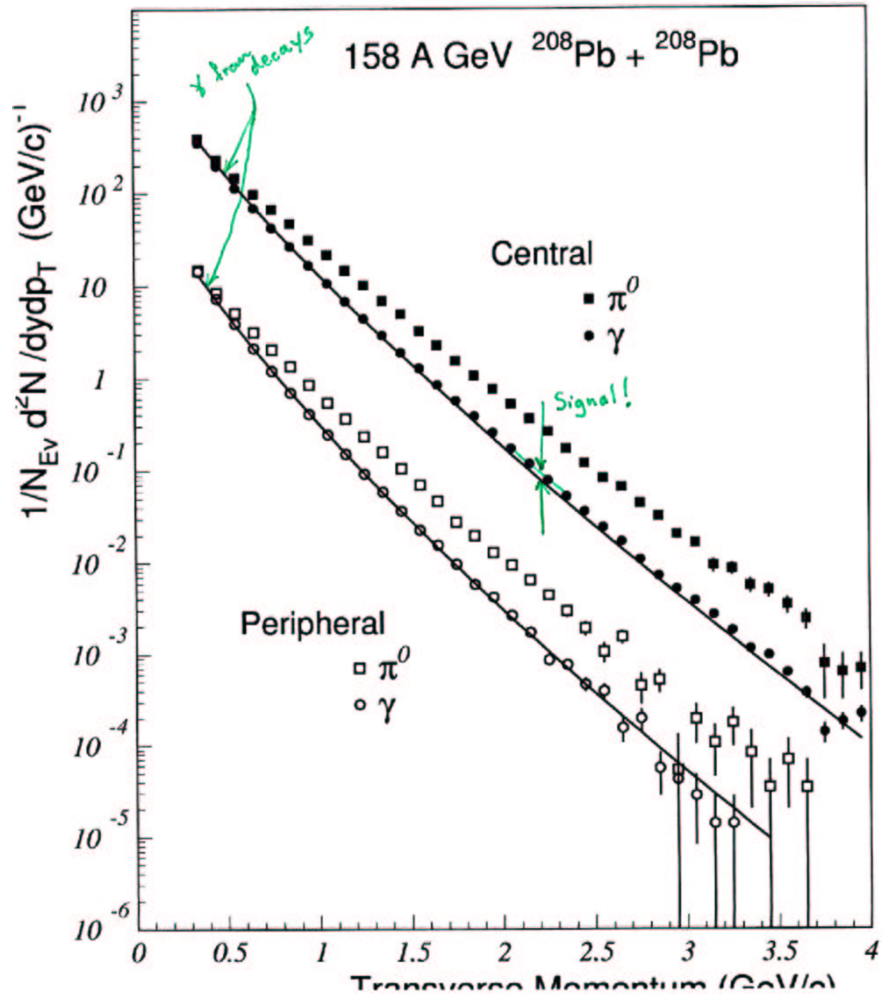

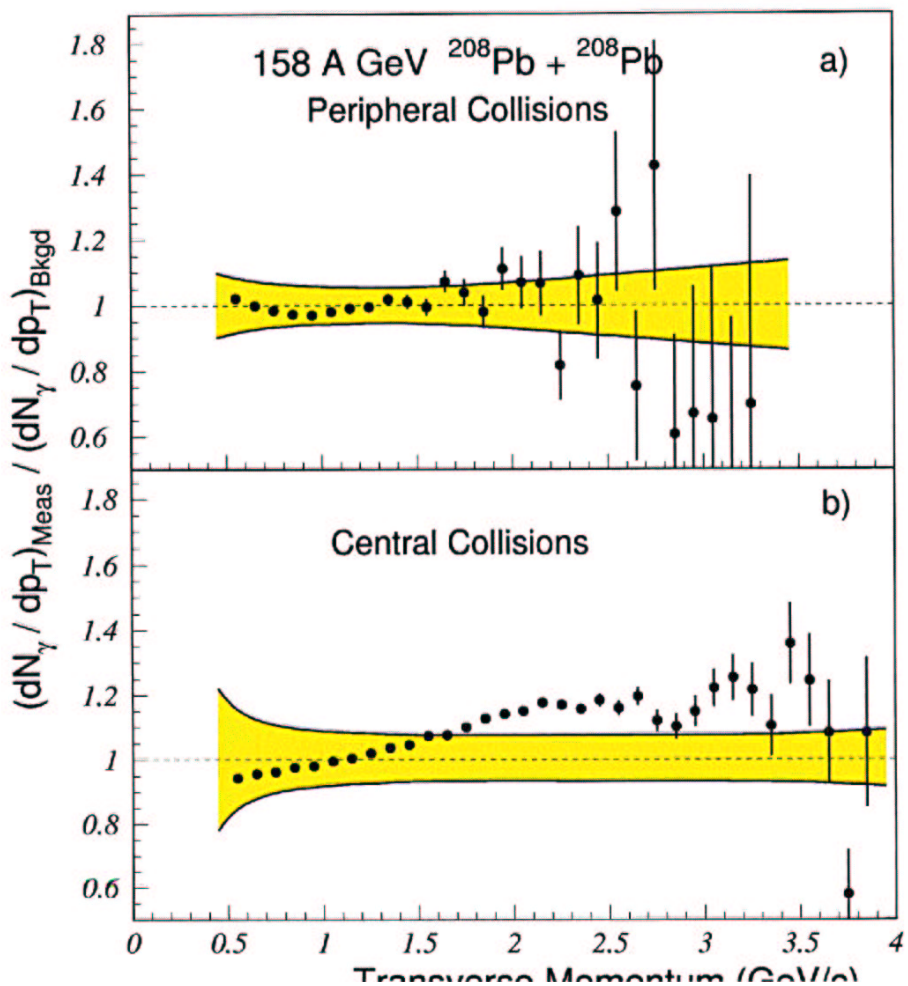
158 A GeV 208Pb + 208Pb
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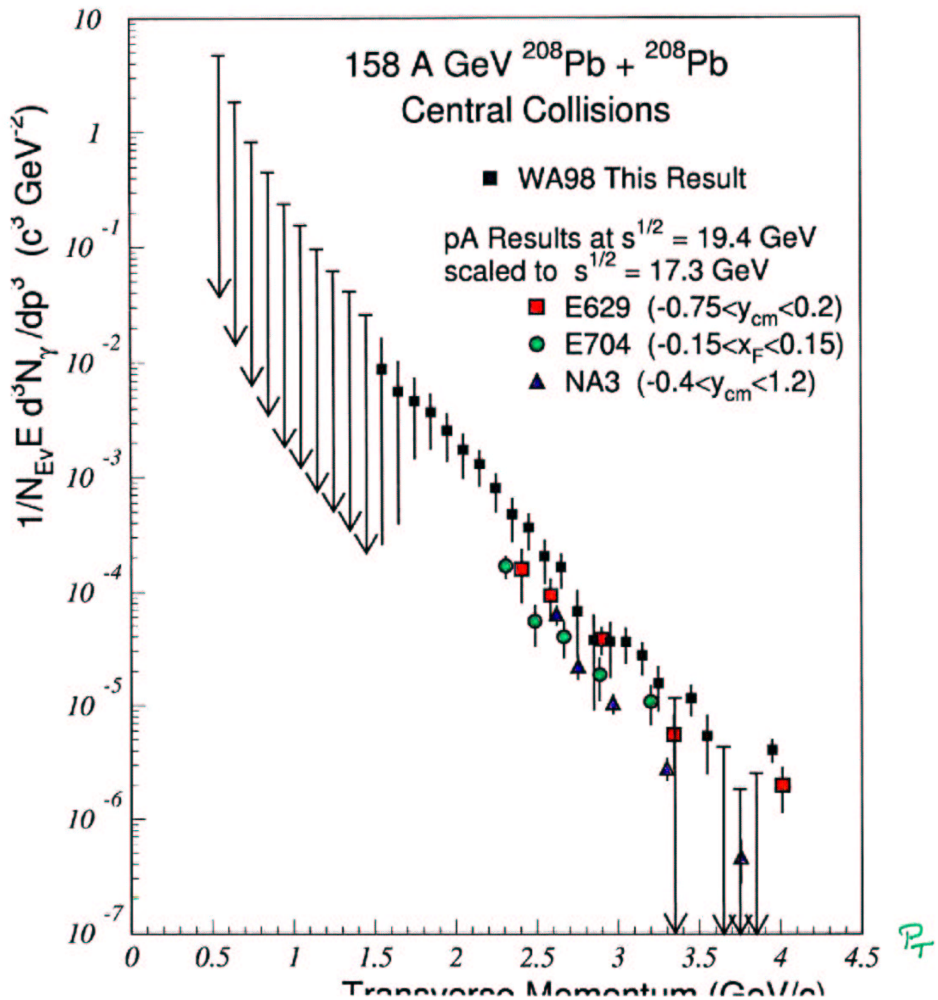
Peripheral Collisions
b)
Central Collisions
(dNγ / dpT)Meas / (dNγ / dpT)Bkgd
Transverse Momentum (GeV/c)


158 A GeV 208Pb + 208Pb
Central Collisions
WA98 This Result
pA Results at s1/2 = 19.4 GeV
scaled to s1/2 = 17.3 GeV
E629 (-0.75<ycm<0.2)
E704 (-0.15<xF<0.15)
NA3 (-0.4<ycm<1.2)
1/NEv E d3Nγ /dp3 (c3 GeV-2)
Transverse Momentum (GeV/c)
PT

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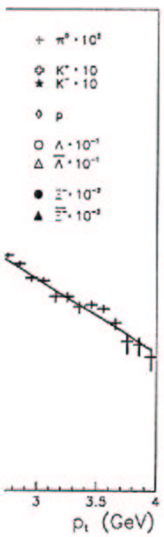

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while curves, calculated for $T_{in} = 200\,MeV$ ($\chi^2_\pi = 4.9/point$, $\chi^2_\gamma = 0.67/point$), and $T_{in} = 300\,MeV$ ($\chi^2_\pi = 3.5/point$, $\chi^2_\gamma = 2.3/point$) are still within experimental errors. The reason of this weak sensitivity to the initial temperature is following. As far as we introduce the initial radial velocity, all time stages contribute with more or less the same effective slopes. But, the difference between initial time for $T_{in} = 300$ MeV $- \tau_{in} = 0.12$ fm/c, and for $T_{in} = 230$ MeV $- \tau_{in} = 0.6$ fm/c is not large, and therefore contribution of this stage is not very important with respect to the subsequent evolution.

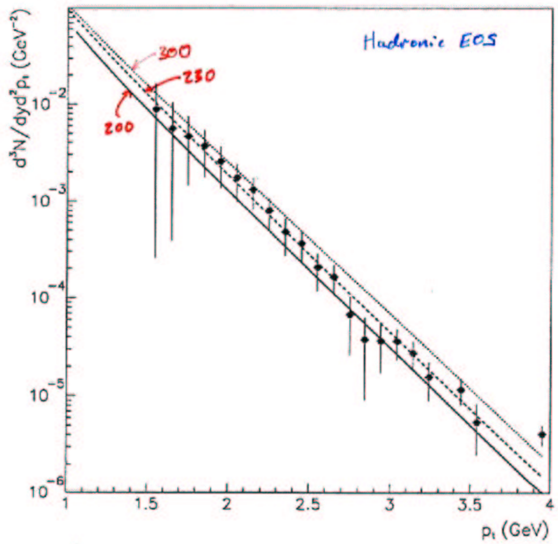

FIG. 3. Yield of direct photons in Pb+Pb collisions at SpS energy with pure hadronic gas EoS for different T_{in}: 200 (solid line), 230 (dashed line) and 300 MeV (dotted line). Dots – WA98 data.

We confirm the result found in [5] – 'reach' hadron gas EoS allows to describe the experimental p_t distribution of direct photons [3] within pure hadronic scenario. Our best fit value of $T_{in} = 230^{+60}_{-30}\,MeV$ is smaller, than the initial temperature estimated in [5] $T_{in} \approx 260\,MeV$. There are two reasons of this discrepancy: first is, the initial radial velocity which we included to describe final hadron spectra. In contrast to our approach, authors of

ibid.

time and, as a consequence, of the thermal photon yield.

Now let us consider EoS incorporating first order phase transition. In this case there is an additional parameter T_c which value is estimated from lattice QCD simulations to be $150-170\ MeV$ [1]. On the other hand $T_c \geq T_{ch}$. Therefore we use $T_c = T_{ch} = 168\ MeV$ to consider an extreme case with the most intensive QGP production.

As in the case of pure hadronic gas, first we try to describe experimental p_t distribution of π^0 with zero initial radial velocity, and find almost the same situation: for any reasonable set of model parameters the calculated p_t distribution of π^0 goes much steeper, and result in unreasonably large $\chi^2_\pi \sim 10^2/point$. So, we find again, that it is necessary to introduce initial radial velocity to describe momentum distributions of final hadrons. Repeating the same procedure as for pure hadronic gas EoS we obtain the following sets of model parameters:

T_{in}, MeV	τ_{in}, fm/c	V^{max}, c	Curve on fig. 4
180	2.0	0.40	solid
200	1.5	0.38	dashed
230	1.0	0.29	dotted
250	0.7	0.26	dash-dotted

We find the best agreement with experimental data at $T_{in} = 200^{+40}_{-20}$ MeV ($\chi^2_\pi = 3.3/point$, $\chi^2_\gamma = 0.8/point$), what means very short QGP phase and much more prolonged mixed phase.

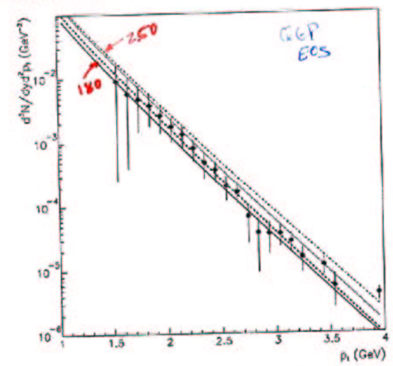

FIG. 4. Direct photon yields calculated for EoS with phase transition and linear initial velocity distribution at $T_{in} = 180$ MeV (solid line), $T_{in} = 200$ MeV (dashed line), $T_{in} = 230$ MeV (dotted line) and $T_{in} = 250$ MeV (dash-dotted line).

To conclude, we use 2+1 Bjorken hydrodynamics to analyze hadron yields, and midrapidity p_t distributions of hadrons and direct photons, measured in Pb+Pb collision at SpS energy. We find, that calculations with zero initial velocity, and EoS of hadronic gas accounting contribution of all known hadrons result in too soft p_t distributions of final hadrons, and a reasonable way to describe experimental slopes is to introduce nonzero radial velocity at the beginning of the one-fluid hydrodynamic stage. This initial radial velocity, which might be produced during the pre-equilibrium stage because of the strong radial energy density gradient originated from spherical shapes of colliding nuclei, is not small ($\approx 0.3\ c$ near the surface). Therefore the pre-equilibrium stage is expected to be long enough, and, in particular the 'prompt photons' have to be taken into account.

An introduction of the initial radial velocity to this model allows to describe simultaneously direct photon and hadron p_t distributions for the both EoS including phase transition and without it. We estimate an initial temperature of the just thermalized state $T_{in} = 200^{+40}_{-20}\ MeV$ in the case of EoS with phase transition to QGP, and $T_{in} = 230^{+60}_{-30}\ MeV$ in the pure hadronic scenario. Because the lower bounds of the estimated thermalization temperature are very close to the expected transition temperature we conclude that the SpS data considered in this letter can not distinguish between a production of QGP, and its absence: The initial temperature in central Pb+Pb collisions at SpS is too small, and experimental errors for the direct photon p_t distributions are too large.

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[1] C. Bernard *et al.*, Phys. Rev. D**54** (1996) 4585 .
[2] R.Albrecht et al., Phys. Rev. Lett. **76** (1996) 3506.
[3] M.M. Aggarwal et al., e-Print Archive: nucl-ex/0006008.
[4] E.V. Shuryak, L. Xiong, Phys.Lett. **B 333** (1994) 316. D.K. Srivastava, B.C. Sinha, Phys. Rev. Lett. **73** (1994) 2421. D.K. Srivastava, B.C. Sinha, Eur. Phys. J. C(1999).
[5] D.K. Srivastava, B.C. Sinha, e-Print: nucl-th/0006018
[6] Jan-e Alam et al., hep-ph/0008074.
[7] M. Gluck, E. Reya, A. Vogt, Z. Phys. **C67** (1995) 433.
[8] C.-Y. Wong and H. Wang, Phys. Rev. **C 58** (1998) 376.
[9] P. Aurenche et al., Phys.Rev. D58 (1998) 085003.
[10] L. Xiong et al., Phys. Rev. **D46** (1992) 3798.
[11] Particle Data Group, Phys. J. **C 3**, (1998).
[12] J. Cleymans et al., Phys. Rev. **C 55** (1997) 1431.
[13] P. Braun-Munzinger et al., nucl-th/9903010.
[14] M. Kaneta, NA44 Coll., Nucl.Phys. **A 638** (1998) 419c.
[15] P.G. Jones, NA44 Coll., Nucl.Phys. **A 610** (1996) 188c, G. Roland, NA49 Coll., Nucl.Phys. **A 638** (1998) 91c,

Peressounko, Pokrovsky (Kurchatov)
hep-ph/0009025

Chaudhuri (VECC)
nucl-th/0002058

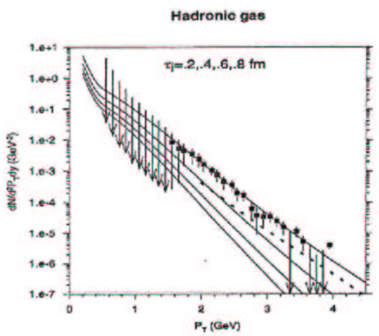

FIG. 3. The single photon yield in the no phase transition scenario for four different τ_i's, .2,.4,.6,.8 fm (from top to bottom). Corresponding tempertures are listed in table 1. Experimental points are also shown. The dotted line is the direct QCD photons calculated in ref. [9]

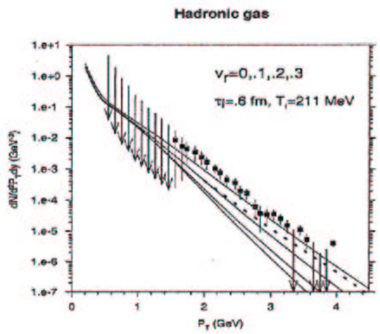

FIG. 4. The single photon yield in the no phase transition scenario for four different initial radial velocity v_r^{ini}=0,.1,.2,.3 (in units of c). The initial time and temperatures are τ_i=.6 fm and T_i=211 MeV respectively. The dotted line is the direct QCD photons calculated in ref. [9].

[19] P. Aurenche, private communication.
[20] F. D. Steffen and M. A. Thoma, hep-ph/0103044.
[21] C. T. Traxler and M. H. Thoma, Phys. Rev. C53(1996)1348.
[22] P. Roy, J. Alam, S. Sarkar, B. Sinha and S. Raha, Nucl. Phys. A624 (1997)687.

TABLE I. The initial temperature of the QGP and the hot hadronic gas for different initial times τ_i. Also shown are the corresponding hadron density

$\tau_i(fm)$	$T_i^{QGP}(MeV)$	$T_i^{Had}(MeV)$	$\rho_i^{Had}(fm^{-3})$
0.2	341	304	10.41
0.4	271	242	2.89
0.6	237	211	1.32
0.8	215	192	0.78
1.0	200	178	0.52

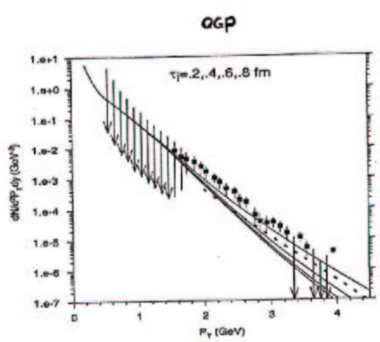

FIG. 2. The single photon yield in the phase transition scenario for four different initial times, τ_i's, .2,.4,.6,.8 fm (from top to bottom). Corresponding temperatures are listed in table 1. Experimental points are also shown. The dotted line is the direct QCD photons calculated in ref. [9]

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ploited by using the WA98 measurements of the direct photon yield [3] to specify upper limits on the initial temperature, $T_0^{\max}$, reached in the SPS 158 GeV Pb+Pb collisions. This is presented in Fig. 4. For *typical* parameters $\tau_0 = 1$ fm, $T_c = 170$ MeV, $T_f = 150$ MeV, nucleon number $A = 208$ (corresponding to Pb+Pb collisions), projectile rapidity $y_{\rm nucl} = 2.8$ (corresponding to a center-of-mass energy of $\sqrt{s} = 17$ GeV), and with an ideal massless pion gas of $g_h = 3$ effective degrees of freedom, even with an initial temperature of $T_0 = T_c = 170$ MeV (dotted line)

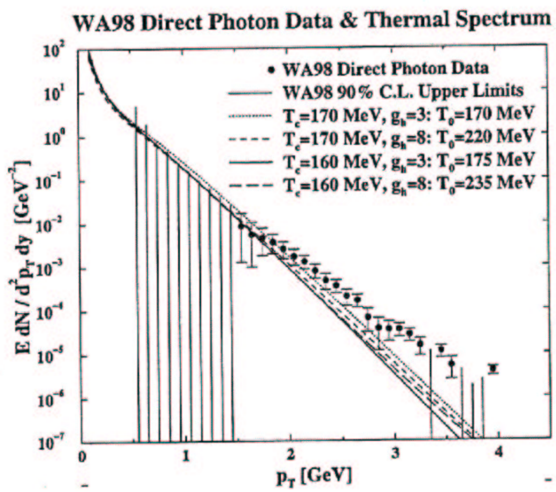

Fig. 4. WA98 direct photon data and upper limits on the initial temperature. The theoretical spectra supporting the phase transition from QGP to HHG (solid, short-dashed, and long-dashed lines) are compared with the experimental upper limits (vertical lines) and data (points with error bars). The discrepancy in the high-p_T-region demonstrates that a significant prompt photon contribution is necessary for a theoretical explanation of the experimental results within the phase transition scenario.

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Apanesevich, et.al. (E706)

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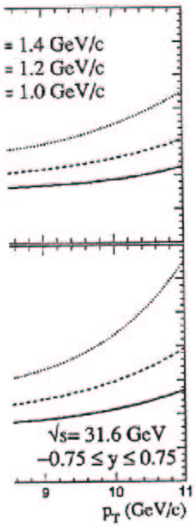

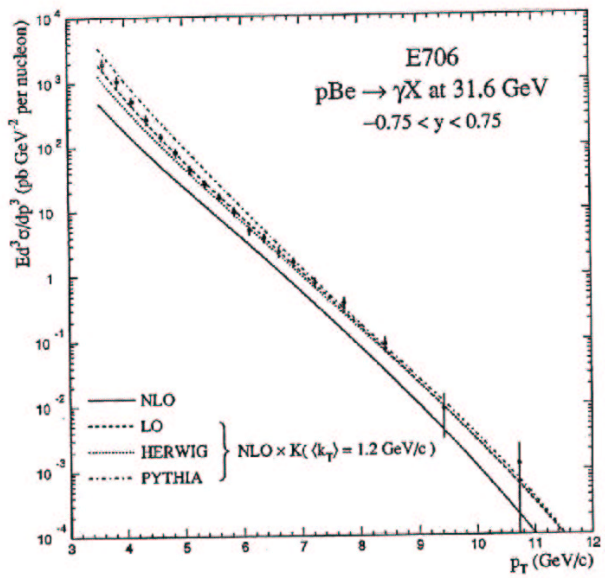

FIG. 11. Comparison between the E706 direct-photon data at $\sqrt{s}=31.6$ GeV and the NLO PQCD calculation (solid), and the NLO theory enhanced by K-factors associated with the LO calculation (dashed), HERWIG (dotted), and PYTHIA (dashed-dotted).

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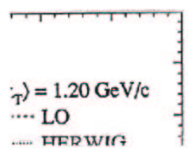
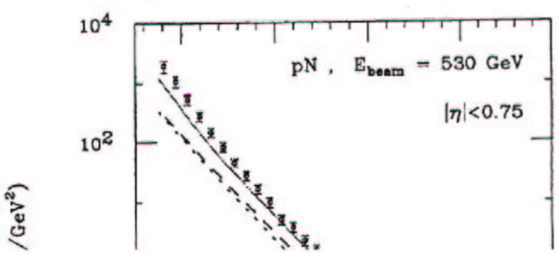
surements from E706 [41]. As shown in Fig. 12, this theoretical result is substantially higher than the prediction from NLO PQCD, higher than the theory using just threshold resummation, and closer to the phenomenological k_T-smearing model used in Fig. 11.





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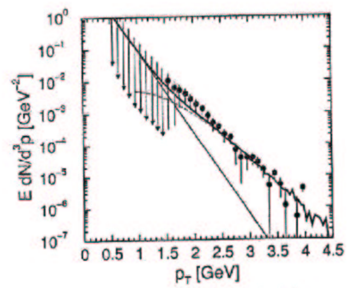


FIG. 2. Comparison of the thermal photon yield (thin curve, no transverse expansion) and the hard background (dashed curve) with the direct photon data [11] for the reaction Pb(158A GeV) + Pb. The solid line depicts the sum of the thermal and hard yields.

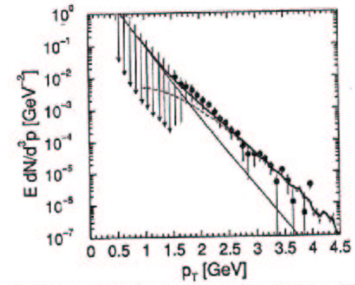


FIG. 3. As in Fig. 2, however, with transverse flow ($v_0=0.3$).

pling [20].[2] For such a flow parameter one finds good agreement with the data [11] when adding the thermal yield and the hard contribution (see Fig. 3).[3]

To make more firm conclusions on the role of thermal photons in Pb + Pb collisions at CERN-SPS energies, one needs a more reliable procedure to fix the hard background. Similarly to dileptons, an accurate adjustment of the hard rate at the high-$p_\perp$ tail requires an improvement of the data statistics. Notice that our present up scaling from PYTHIA simulations of pp collisions to heavy-ion data can be considered as an upper bound for the hard radiation. Nevertheless, a remarkable space is left for the secondary radiation.

An additional insight can be gained by an analysis of noncentral collisions which should allow a link to pA collisions, where also data are at hand [21]. This will be subject of a separate future study.

In summary we analyze the direct photon production in the reaction Pb(158A GeV) + Pb by using a model with a minimum parameter set, i.e., the effective temperature and the space-time volume of the thermal source, both ones adjusted to dilepton data in similar central reactions. The model employs the hadron-quark "duality" for the rate of electromagnetic radiation off matter. We have shown that our model, supplemented by the hard photon yield as described by PYTHIA, is in good agreement with the WA98 data. This result supports the assumption of an extended and long-living source of the electromagnetic radiation, which can be seen in both the real and virtual photon channels. The comparatively large value of the space-time factor V_4 in our model can be related to previous expectations on a long-living fireball [22] or a phase space overpopulation of hadrons [2,10].

It should be emphasized that our effective temperature parameter $T_{eff}=170$ MeV is in perfect agreement with the temperature parameter needed to describe hadron species ratios [23]. Since T_{eff} is to be considered as average of the temperature, one concludes that the electromagnetic probes indeed point to temperatures above the expected deconfinement temperature. This corroborates the expectation of exciting deconfined matter in central heavy-ion collisions already at CERN-SPS energies.

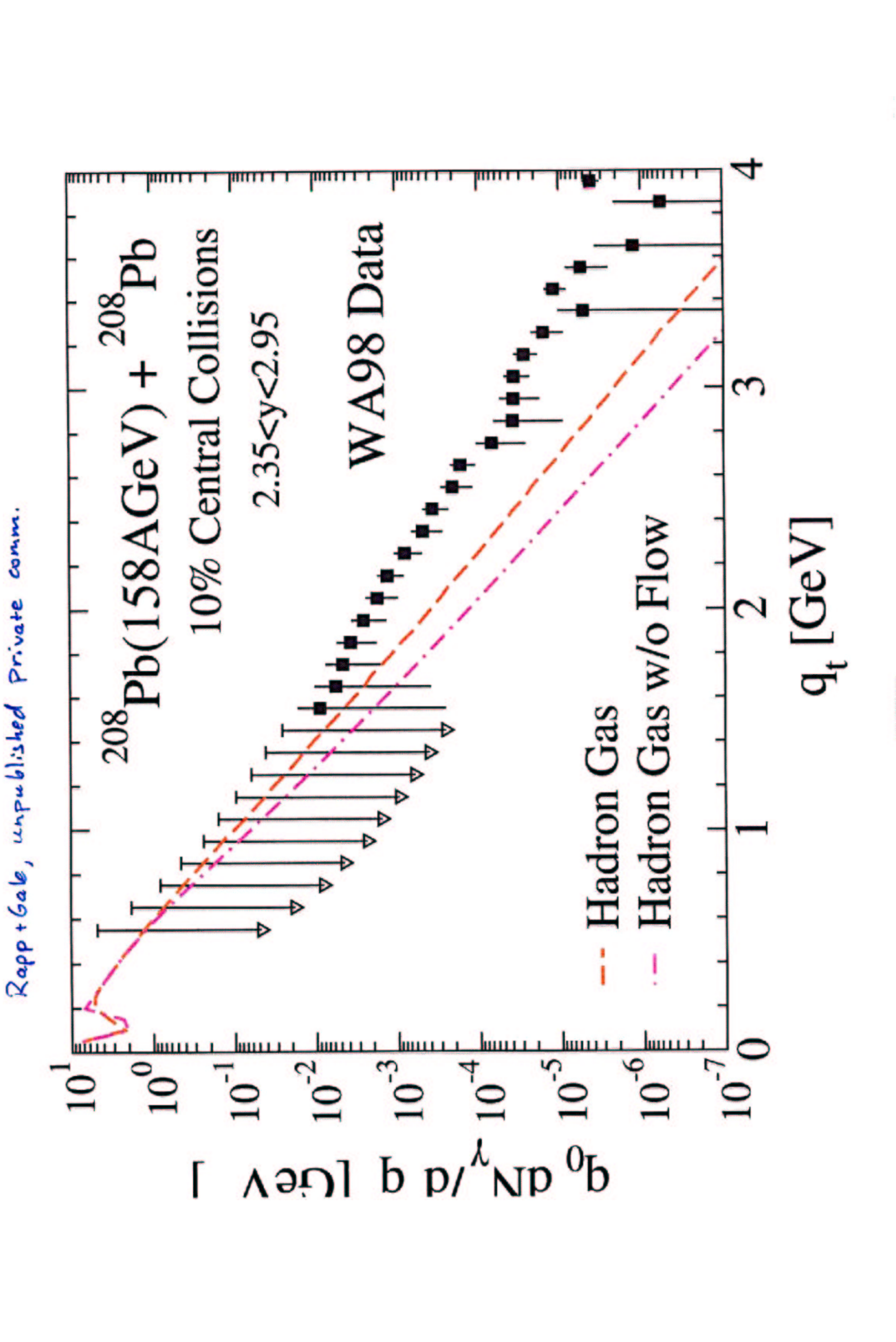
The photon spectra are shown to be useful in extracting information on transverse flow. For firm conclusions, however, the hard photon production processes must be reliably accessible. Our approach can be contrasted with attempts to interpret the data either without any hard contribution [14,24] or by the hard yield alone by tuning parameters. Transport approaches [25] should smoothly interpolate between these extreme cases.

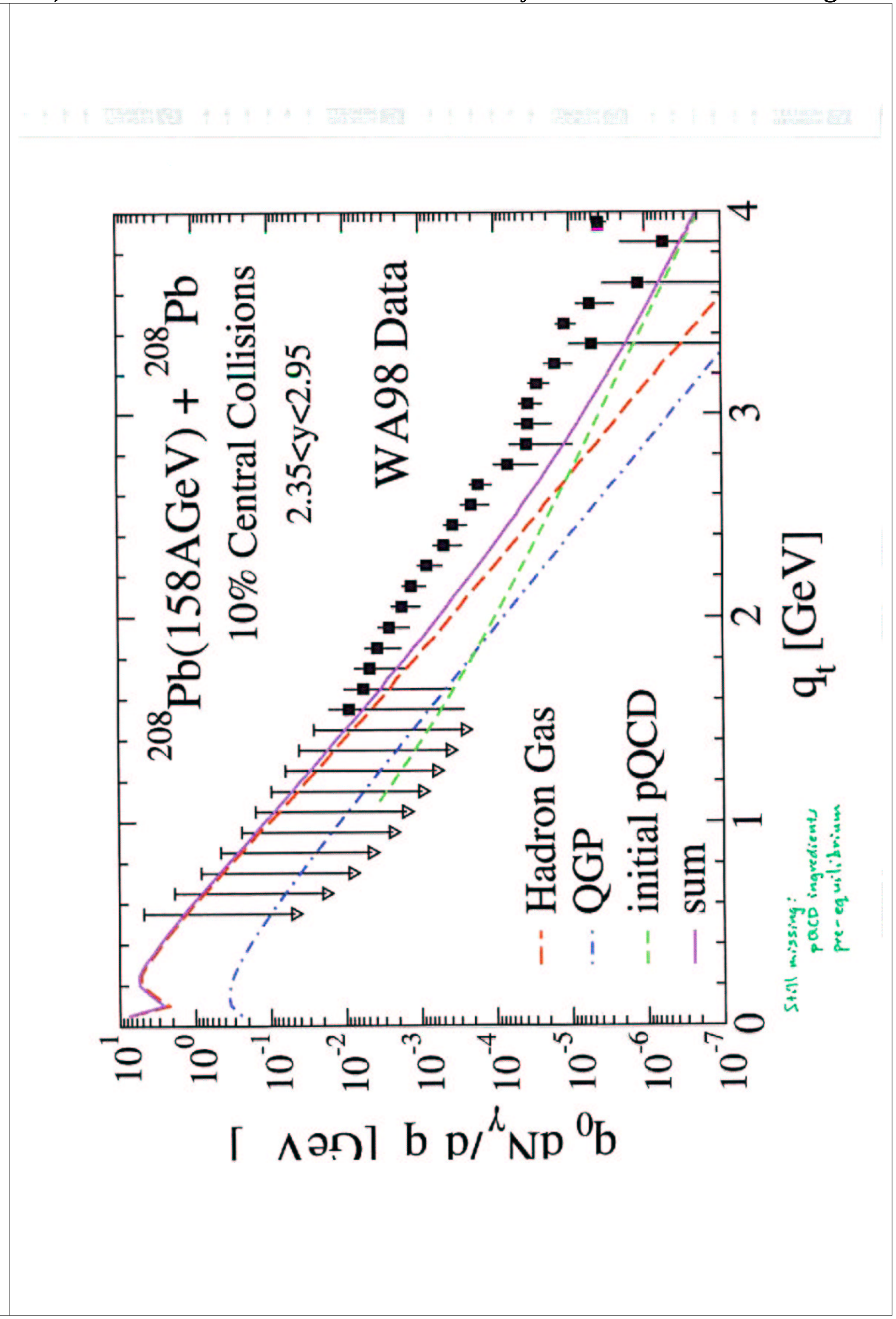
We expect that the future analysis of the starting experiments at the relativistic heavy-ion collider RHIC at Brookhaven National Laboratory should deliver a higher value of T_{eff} since the estimated maximum temperatures will be significantly larger.

Useful discussions with H.W. Barz, P. Levai, and G. Zinovjev are gratefully acknowledged, in particular Th. Peitzmann for valuable explanations of the WA98 data. O.P.P. thanks the warm hospitality of the nuclear theory group in the Research Center Rossendorf. The work was supported by Grants No. BMBF 06DR829/1, BMBF 06DR921, STCU 015, and WTZ UKR-008-98.

[2]The quantity v_0, as T_{eff}, is to be understood as temporal average and, therefore, it should be smaller than the final hadron flow velocity at kinetic freeze-out. Indeed, values of $v_0 \geq 0.5$ would be incompatible with the photon data.

[3]An optimum description of the data is achieved by $v_0=0.4$. However, with respect to the uncertainty related to the hard background, we do not attempt such a fine tuning.


Rapp+Gale, unpublished private comm.
208Pb(158AGeV) + 208Pb
10% Central Collisions
2.35<y<2.95
WA98 Data
Hadron Gas
Hadron Gas w/o Flow
q_t [GeV]
q_0 dN_γ/d q [GeV]


208Pb(158AGeV) + 208Pb
10% Central Collisions
2.35<y<2.95
WA98 Data
Hadron Gas
QGP
initial pQCD
sum
q_t [GeV]
q_0 dN_γ/d q [GeV]
Still missing:
pQCD ingredients
pre-equilibrium

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Nonthermal direct photons in Pb+Pb at 160*A* GeV from microscopic transport theory

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Direct photon production in central Pb+Pb collisions at CERN-SPS energy is calculated within the ultrarelativistic quantum molecular dynamics model (UrQMD), and within distinctly different versions of relativistic hydrodynamics. We find that in UrQMD the local momentum distributions of the secondaries are strongly elongated along the beam axis initially. Therefore, the pre-equilibrium contribution dominates the photon spectrum at transverse momenta above ≈1.5 GeV. The hydrodynamics prediction of a strong correlation between the temperature and radial expansion velocities on the one hand, and the slope of the transverse momentum distribution of direct photons on the other hand thus is not recovered in UrQMD. The rapidity distribution of direct photons in UrQMD reveals that the initial conditions for the longitudinal expansion of the photon source (the meson "fluid") resemble boost invariance rather than Landau-like flow.
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PACS number(s): 25.75.Dw, 12.38.Mh, 24.10.Lx, 24.85.+p

The radiation of real and virtual photons has frequently been proposed as a diagnostic tool for the hot and dense matter created in (ultra)relativistic heavy-ion collisions [1,2]. The mean free path of photons with high transverse momentum exceeds the expected source sizes by one order of magnitude [2,3]. Hard photons thus can give insight into the early stage of these reactions.

Transverse momentum-dependent upper limits for direct photon production in central S+Au collisions at 200*A* GeV have been published by the WA80 Collaboration [4] (see also the data of the CERES Collaboration [5]). These data initiated theoretical studies [6–9] which showed that direct photon production is strongly overestimated if the photon source is thermalized (having an initial energy density of 2 −5 GeV/fm^3) and if one assumes that it is composed of light mesons only (say π, η, ρ, ω). Due to the low specific entropy of these particles a reasonable final-state multiplicity of secondaries and a maximum temperature that is consistent with the WA80 data ($T_{max} \leq 300$ MeV) cannot be achieved simultaneously (at least if the expansion is approximately isentropic).

Most of the calculations quoted (except those of Ref. [7]), however, assumed that the photon source is in local thermal equilibrium and that ideal hydrodynamics can be applied to determine the space-time evolution of the temperature. Here, we perform a calculation within the microscopic transport model UrQMD, which includes the pre-equilibrium contributions to direct photon production. This is of particular relevance in view of the fact that local thermalization (i.e., locally isotropic momentum distributions) in (ultra)relativistic heavy-ion collisions is probably not achieved within the first few fm/*c* [10,11] where the high-k_T photons are produced. Since neither thermal nor chemical equilibrium is assumed, the effects of finite viscosity (i.e., finite mean free paths) [12] and inhomogeneous or fluctuating energy density distributions [13] are included. Comparisons of the transverse momentum and rapidity distributions of direct photons with those calculated within two fluid-dynamical models are made.

The calculations presented here are based on the UrQMD model [14], which spans the entire presently available range of energies from GSI-SIS to CERN-SPS. Its collision term contains 50 different baryon species (including nucleon, delta, and hyperon resonances with masses up to 2.2 GeV) and 25 different meson species (including strange meson resonances), which are supplemented by their corresponding antiparticles and all isospin-projected states.

The model is based on the covariant propagation of all hadrons on classical trajectories, excitation of resonances and strings and their subsequent decay, respectively, fragmentation. UrQMD accounts for secondary interactions: the annihilation of produced mesons on baryons can lead to the formation of *s*-channel resonances or strings. Free cross sections for hadron-hadron scattering in the hot and dense nuclear matter are employed. Comparisons of UrQMD calculations to experimental hadron yields from SIS to SPS are documented elsewhere [14].

We briefly discuss the two most important reactions for the creation of direct photons. Below 2 GeV center of mass energy intermediate resonance states are excited. The total cross section for these reactions are given by

$$\sigma_{tot}^{M_1 M_2}(\sqrt{s}) = \sum_{R=\rho, f_2, \ldots} \langle j_{M_1}, m_{M_1}, j_{M_2}, m_{M_2} \| J_R, M_R \rangle \times \frac{2I_R+1}{(2I_{M_1}+1)(2I_{M_2}+1)} \times \frac{\pi}{p_{c.m.}^2} \frac{\Gamma_{R\to M_1 M_2}\Gamma_{tot}}{(M_R-\sqrt{s})^2+\Gamma_{tot}^2/4}, \quad (1)$$

which depends on the total decay width Γ_{tot}, the partial decay width $\Gamma_{R\to M_1 M_2}$, and on the c.m. energy $\sqrt{s}$. The corresponding isospins, isospin-projections, and spins are denoted by *j*, *m*, *I*, respectively. At higher energies these processes become less important. One then enters the region of *t*-channel scattering of the hadrons.

Lessons from Pb+Pb photons:

1) Hard or pre-equilibrium component seems to be present at higher level, compared to thermal, than in S+Au.
Hard/Thermal ~ N_{Coll}/N_{Part} increases from S to Pb.

2) Radial flow can greatly increase contribution from HG phase at high photon PT. Boosted source looks like higher temperature, T_{HG}=170 MeV can look like >200 MeV.

3) Since HG wins on volume, a "cool" QGP initial state can be completely hidden by expanding HG.

4) So-called "rich hadron gases" allow high #d.o.f. in initial state, making HG ambiguous with QGP. Can't someone stop these non-interacting calculations?

5) Hard component non-trivial to calculate. Even elementary k_T broadening tough, but need to include double Cronin effect as well.

6) Pre-equilibrium contribution may become visible. Calculation still an open question.

Lessons from Pb+Pb photons, con't:

7) Data can probably still access initial state to address initial temperatures, but full calculation would include:

a) Radial flow in HG phase
b) Hard component with k_T broadening and nuclear effects
c) Realistic HG EOS
d) Some form of pre-equilibrium component allowed

Full calculation still waiting! Be the first on your block.

Observations:

People prefer data with upper and lower limits over upper limits alone. A flurry of activity! after Pb+Pb results. (Not unfair: more attractive to *fix* T_i than to limit it).

There's still too much emphasis on "my model fits" and not enough on what can be ruled out/what limits can be set.

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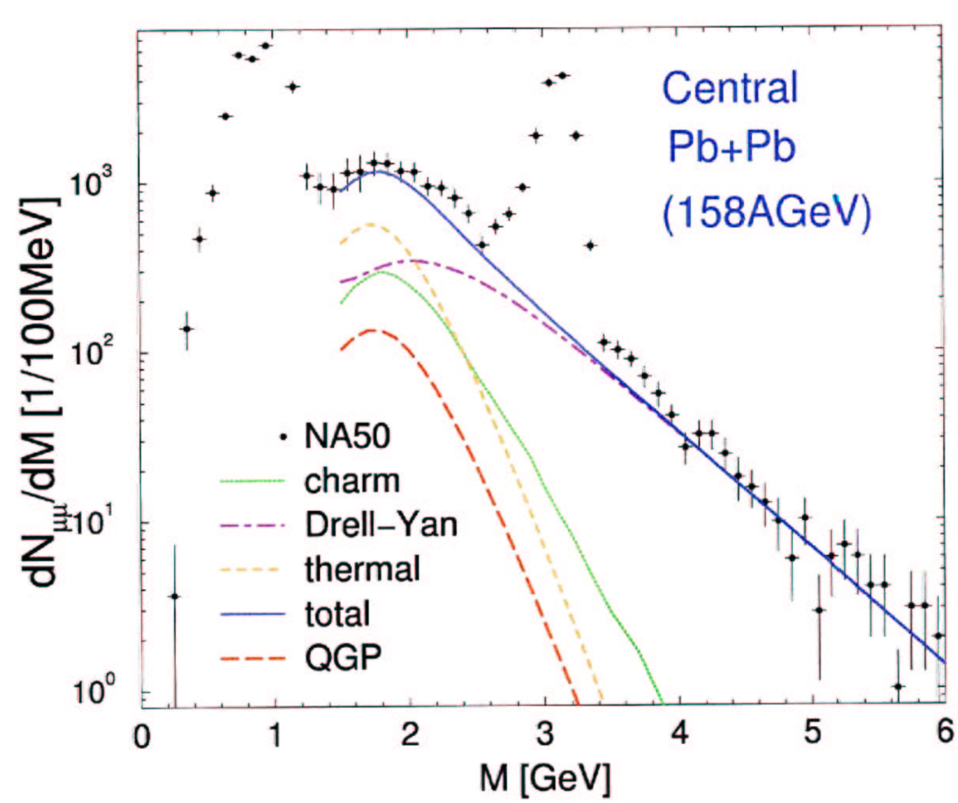

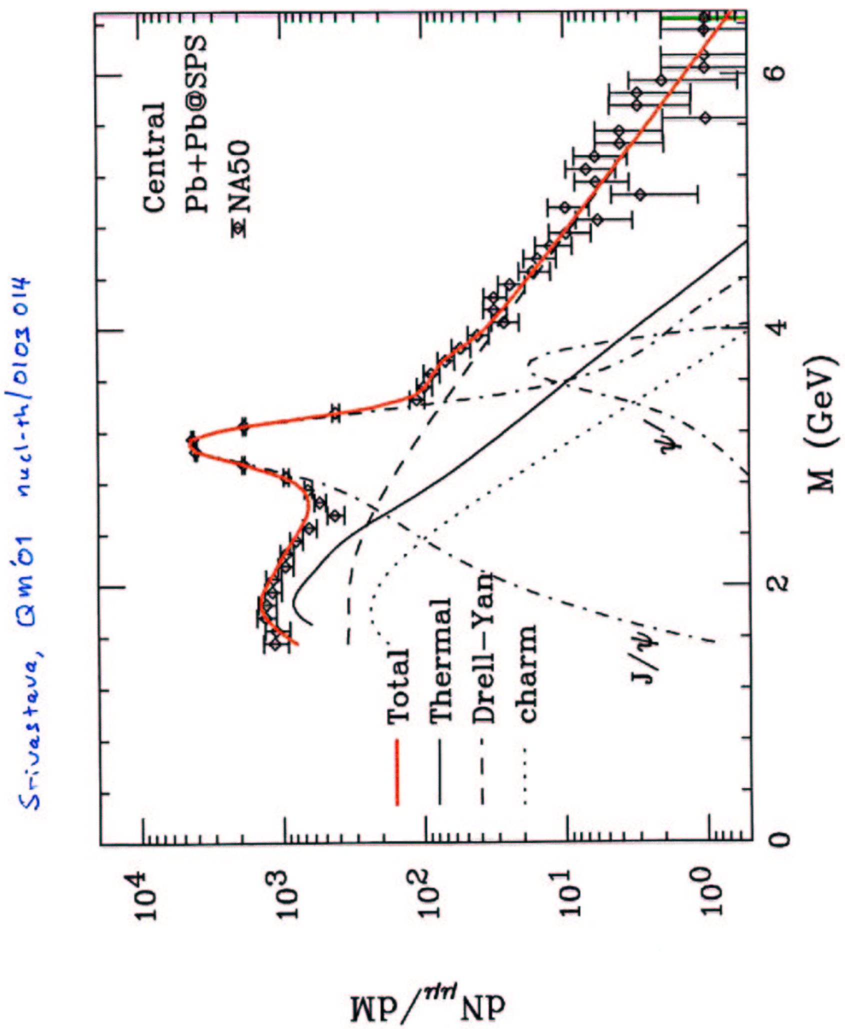

What about RHIC?

Compared to SPS, pQCD and pre-equilibrium sources at higher scale, and QGP may be at higher temperature, while HG phase similar; so pQCD, pre-equilibrium and (maybe) QGP should be *more visible*.

Experimental: Briefly, will probably measure γ^{direct} in 2-5 GeV/c < Pt < 15 GeV/c; also will see individual γ^{direct} for correlations (ie γ + jet)

Theoretical: **We *are completely un-prepared* to interpret direct photons at RHIC!** Some thermal source calculations have been done, but pQCD calculations are not reliable and pre-equilibrium (including CGC evolution) sources are completely unknown!

You might be tempted to give up! but the potential payoff is *huge*: a direct look at the approach to thermalization, *ie* how gluons come to be.

And at LHC?

Everything said about RHIC is even more true at LHC. I suspect: all hard scattering products in the Pt ~ 10-30 GeV/c range will be dominated by the pre-equilibrium phase! but only direct photons (and high-mass dileptons) will be sure to survive.

IMHO: By the time HI collisions at the LHC begin, the QGP will be "old hat," textbook physics (ie *boring!*).

I predict: The interesting physics of HI collisions at LHC energies will be the physics of non-perturbative, non-equilibrium QCD at high energy density, which will be present in the initial and early stages of such a collision. How does energy cascade down from the initial parton-parton scale (~10's of GeV) to the thermalized state (~1 GeV)? is a fundamental question! Once these collisions start, direct photons will be a very important tool to observe this process.

Finally

The SPS results are **interesting, but puzzling.** There is meaningful contact with thermodynamics of initial state (finally!) in S-beam results, but less clear in Pb-beam results; some evidence that pQCD products are visible. Need "full" calculation with all ingredients.

General: need *less* "my model fits all data" and *more* "here's what I can rule out."

Hot QGP radiation at RHIC may be visible, but will be **very hard** to interpret without reliable pQCD machinery and *some kind* of picture of pre-equilibrium. Describing the pre-equilibrium state is the great frontier for RHIC collisions! Can parton cascades ever deliver the "real" answer?

At LHC energies, the pre-equilibrium phase **will dominate all** medium-Pt production. You now have a ten-year headstart; will it be enough?

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TABLE II. For each bin of single photon P_T, we give the mean P_T, the diphoton differential cross section, and its statistical and systematic uncertainties. Each photon was counted once, so that multiplying by the luminosity, bin width, and acceptance gives the number of photons in these diphoton events.

P_T bin (GeV)	Mean P_T (GeV)	$d\sigma/dP_T$ (pb/GeV)	Statistical (%)	Systematic (%)
10–12	11.1	17.5	57	+31 −21
12–15	13.5	11.6	46	+45 −35
15–19	17.4	4.2	65	+41 −29
10–19	13.3	9.6	31	+37 −27

at 10 GeV falling to 93% at 20 GeV per photon), and the isolation cut efficiency in the presence of an underlying event (> 90% per photon). The diphoton cross section, which is the differential cross section for finding a photon in a bin of P_T in a diphoton event in which both photons have $P_T > 10$ GeV, is simply given by $d\sigma/dP_T = N_{\gamma\gamma}/\mathcal{L}\Delta P_T$, where $\mathcal{L}$ is the luminosity and ΔP_T is the bin width. The diphoton cross section is given in Table II and Fig. 2. In Fig. 2, and in subsequent figures, the inner error bars are statistical and the outer error bars are the statistical and systematic uncertainties added in quadrature. Sources of systematic uncertainty (u) include the trigger efficiency ($1\% < u < 10\%$), the isolation cut efficiency in the presence of an underlying event ($9\% < u < 19\%$), and the background subtraction ($12\% < u < 42\%$).

In Fig. 2 we compare the diphoton differential cross section to the predictions of a QCD calculation [6] to order $\alpha^2\alpha_s$, which includes lowest order Born, box, and bremsstrahlung processes and most next-to-lowest-order (NLO) processes. The CDF diphoton cross section is roughly 3 times what the NLO QCD calculation predicts, similar to single photons [4] at low P_T. More precisely, the ratio of the total measured cross section to the NLO QCD prediction is $3.2 \pm 1.0(\text{stat})^{+1.2}_{-0.9}(\text{syst})$. Also shown is an analytic calculation of the Born+box processes alone [6], and for comparison the calculation is repeated using the Monte Carlo program PYTHIA [5] with and without bremsstrahlung. All calculations include the isolation cut and use HMRSB parton distributions [7]; when MRSD_0 parton distributions [8] are used the NLO cross section increases by roughly 20%. All calculations, except the NLO one, are mixtures of lowest order theory and NLO parton distributions (HMRSB). The renormalization scale was $\mu^2 = (P_{T1}^2 + P_{T2}^2)/2$ for the analytic calculation, and $\mu^2 = \hat{s}/4$ for PYTHIA because the first scale was not available in PYTHIA. The NLO cross section decreases by less than 6% when μ^2 is increased or decreased by a factor of 10. The differences between the Born+box analytic calculation and PYTHIA are primarily due to K_T effects, discussed in the next paragraph. Calculations that only include the Born and box diagrams, which are commonly used to estimate the prompt diphoton background to Higgs decay at future hadron colliders, are too low by roughly a factor of 5. More precisely, the ratio of the total measured cross section to the Born+box prediction is $4.7 \pm 1.5(\text{stat})^{+1.7}_{-1.3}(\text{syst})$ for the analytic calculations, and similarly the ratio is $4.4 \pm 1.4(\text{stat})^{+1.6}_{-1.2}(\text{syst})$ for PYTHIA without bremsstrahlung, but the ratio is only $2.2 \pm 0.7(\text{stat})^{+0.8}_{-0.6}(\text{syst})$ for PYTHIA including bremsstrahlung.

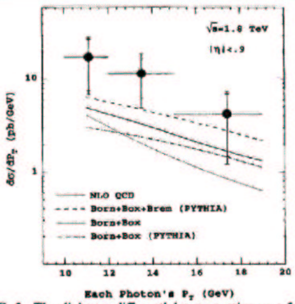

FIG. 2. The diphoton differential cross section as a function of the P_T of each photon is compared to analytic QCD predictions [6] at next-to-lowest order (solid) and lowest order (dotted). Monte Carlo calculations using PYTHIA are shown at lowest order with bremsstrahlung (dashed) and without (dot-dashed).

We now use diphotons to study the P_T of the initial state partons. Correlations between the two photons in azimuthal angle and P_T can be related directly to the kinematics of the initial state. In Fig. 3 we present measurements of the correlation between the two photons compared with the predictions of PYTHIA using the Born and box diagrams only; including final state photon bremsstrahlung processes in the PYTHIA calculations does not significantly change these predictions. The three variables shown are the vector sum of the transverse momenta $K_T = |\mathbf{P}_{T1} + \mathbf{P}_{T2}|$, the P_T balance $B = P_{T2}/P_{T1}$, and the azimuthal angular separation $\Delta\phi = \phi_2 - \phi_1$. All of the measurements agree with the PYTHIA calculation which effectively sums up multiple gluon bremsstrahlung in the initial state. However, analytic QCD calculations [6] to order $\alpha^2\alpha_s$ do not include multiple gluon bremsstrahlung. Unfortunately, this may reduce the precision of analytic calculations, because the correlation variables show that the transverse momentum of initial state partons can significantly affect the final state even for $P_T > 10$ GeV. The mean value of K_T is quite large, $\langle K_T \rangle = 5.1 \pm 1.1$ GeV is the mean of the data in Fig. 3(a), and Fig. 4 shows that $\langle K_T \rangle$ is larger at CDF than in previous measurements at lower $\sqrt{s}$. The increase in $\langle K_T \rangle$ with $\sqrt{s}$

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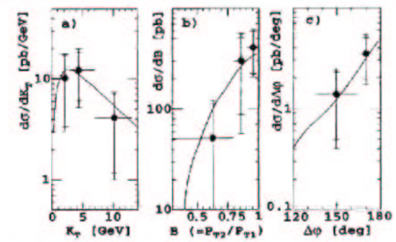

FIG. 3. The correlation of the two photons is shown by the cross section vs (a) the vector sum of the transverse momenta $K_T = |\mathbf{P}_{T1} + \mathbf{P}_{T2}|$, (b) the P_T balance $B = P_{T2}/P_{T1}$, and (c) the azimuthal angular separation $\Delta\phi = \phi_2 - \phi_1$. Our measurement is compared with a Monte Carlo prediction normalized to the data.

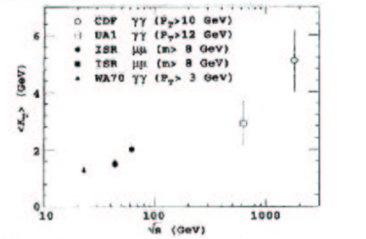

FIG. 4. The mean value of K_T vs collision energy measured in diphoton events at CDF, UA1 [9], and WA70 [1] and in high mass dimuon events at the CERN ISR [10].

may be caused by the roughly increasing P_T of the measurements, also shown in Fig. 4. We have measured $\langle K_T \rangle$ for diphotons with $10 < P_T < 19$ GeV and $0 < K_T < 13$ GeV; measurements with data samples that have enough events to find diphotons at higher P_T and K_T should also find a larger $\langle K_T \rangle$. Significant K_T, which is often not adequately included in QCD calculations, can affect P_T distributions in hadronic collisions.

In summary, we have measured the diphoton cross section to be $86 \pm 27(\text{stat})^{+32}_{-23}(\text{syst})$ pb for photons with P_T in the range 10–19 GeV in events containing two isolated photons with pseudorapidity $|\eta| < 0.9$. We have measured the mean transverse momentum of the diphoton system to be $\langle K_T \rangle = 5.1 \pm 1.1$ GeV. The diphoton differential cross section is roughly 3 times what QCD calculations predict, and may be a larger background to Higgs boson detection than was previously anticipated.

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[a] Visitor.

[1] E Bonvin *et al.*, Phys. Lett. B **236**, 523 (1990).
[2] F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).
[3] F. Abe *et al.*, Phys. Rev. D **43**, 2070 (1991).
[4] F. Abe *et al.*, Phys. Rev. Lett. **68**, 2734 (1992); Fermilab-PUB-92/01-E, 1992 (unpublished).
[5] PYTHIA 5.4 described in H. Bengtsson and T. Sjostrand, Comput. Phys. Commun. **46**, 43 (1987), was used to generate events which we passed through a detector simulation when necessary.
[6] B. Bailey, J. F. Owens, and J. Ohnemus, Phys. Rev. D **46**, 2018 (1992).
[7] Set B with $\Lambda_{\overline{MS}} = 190$ MeV in P. N. Harriman *et al.*, Phys. Rev. D **42**, 798 (1990).
[8] Set D_0 in A. D. Martin, W. J. Stirling, and R. G. Roberts, Phys. Rev. D **47**, 867 (1993).
[9] The K_T was calculated from the data in UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. B **209**, 385 (1988).
[10] D. Antreasyan *et al.*, Phys. Rev. Lett. **47**, 12 (1981).