Direct Photons in Heavy-Ion Collisions: Historical Introduction

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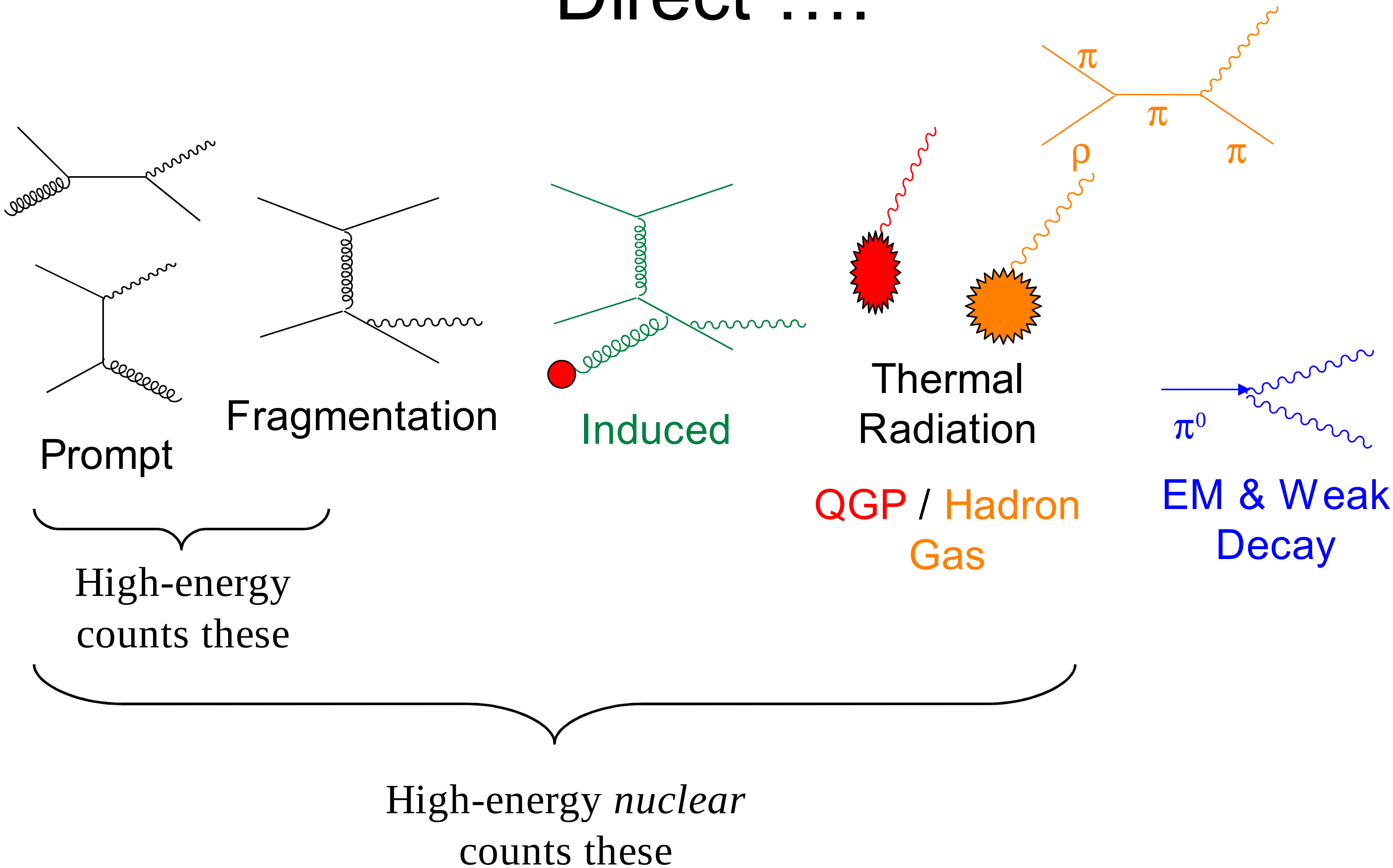
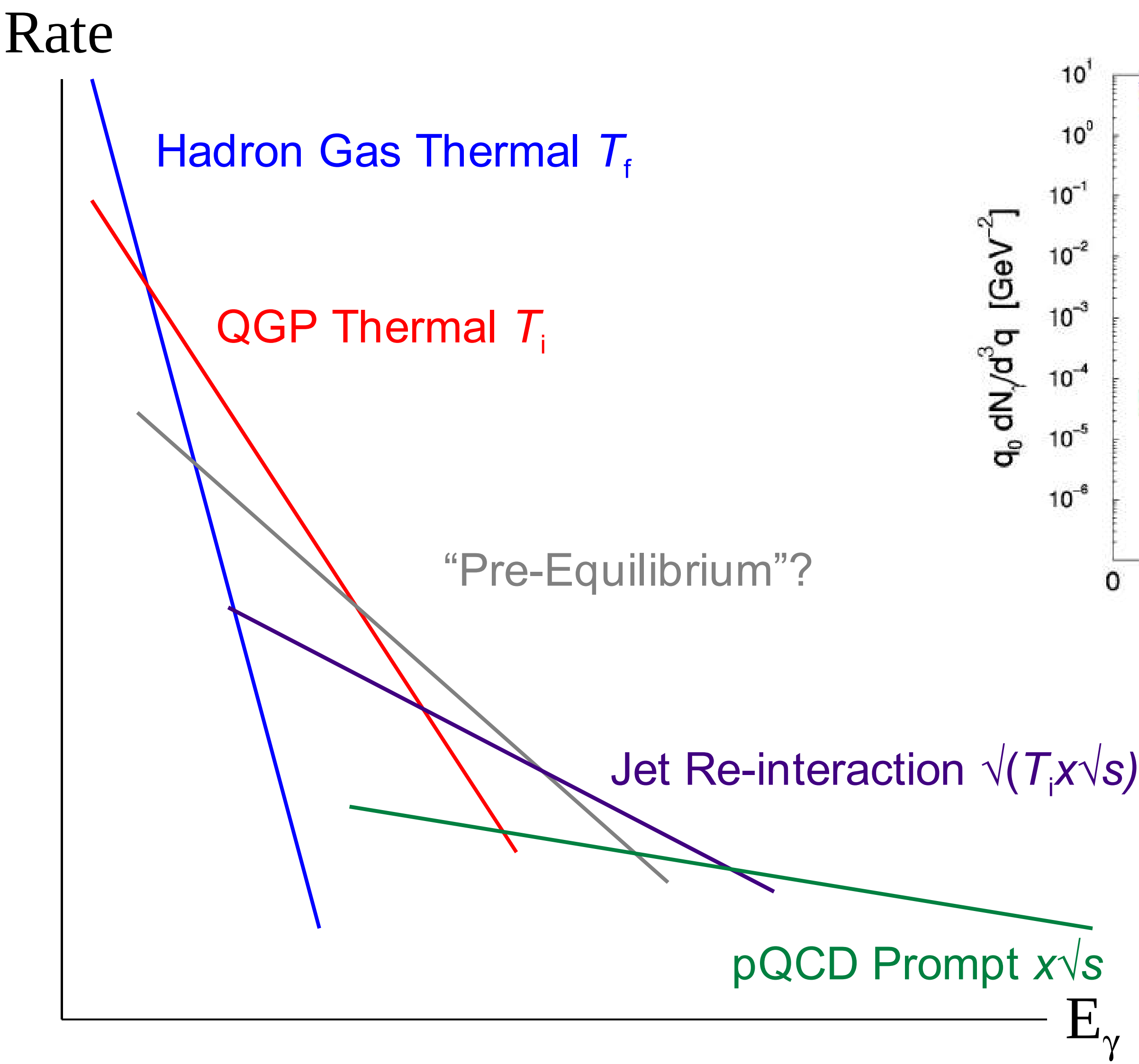
RHIC-AGS Users' Meeting

June 21, 2005

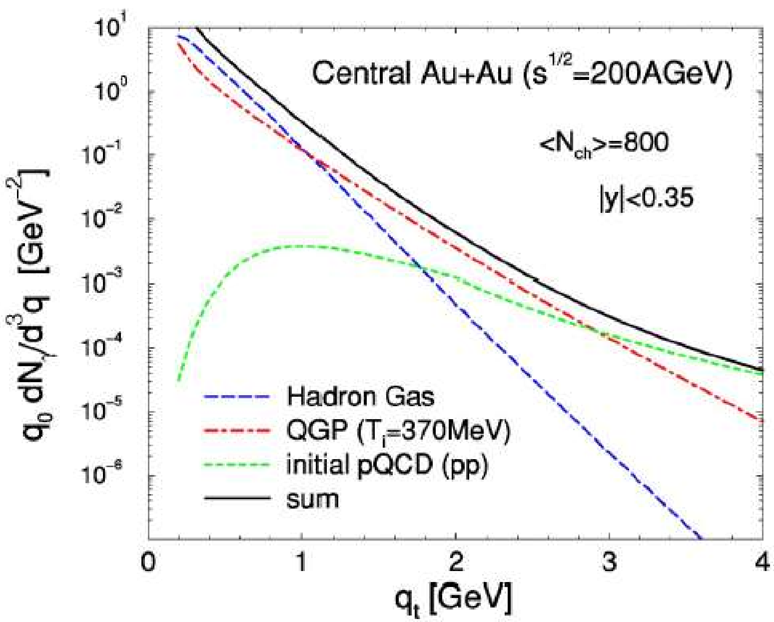
That depends on what you mean by "Direct"….



Photons: More Sources, More Theory



PHYSICAL REVIEW C 69, 014903 (2004)



Turbide, Rapp, Gale

Final-state photons are the sum of emissions from the entire history of a nuclear collision.

Thermal Photon Logic, ca 1985

QGP has chiral symmetry restored, quark masses ~0

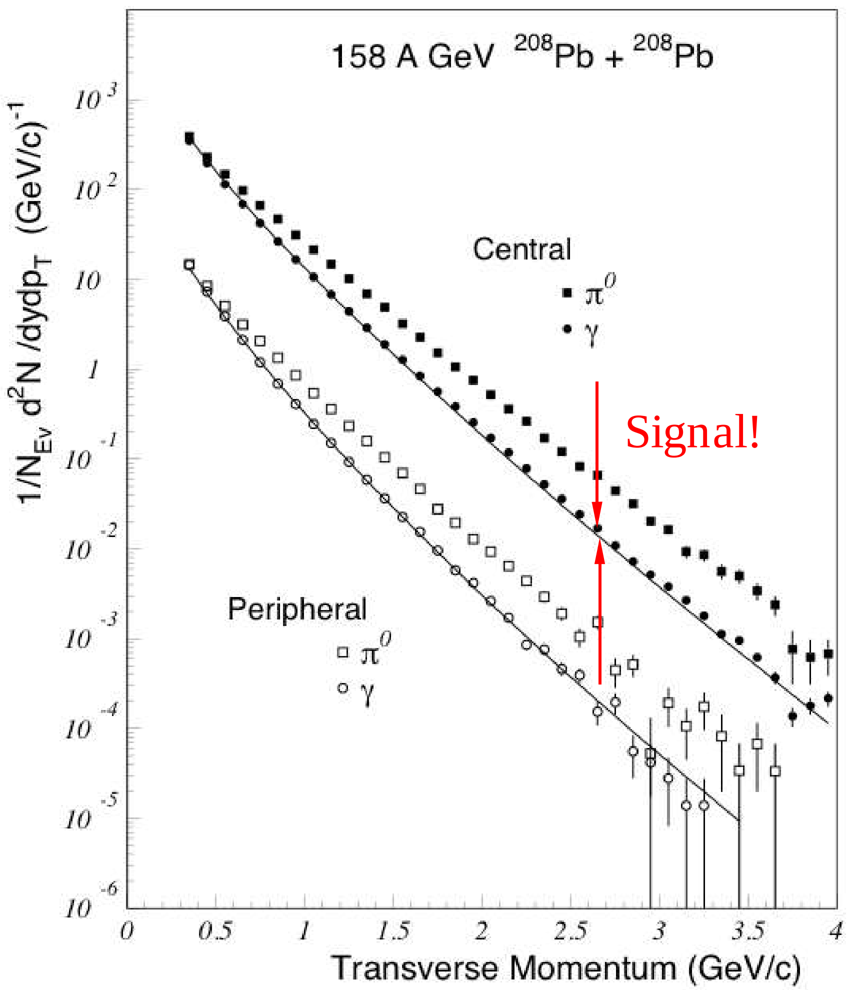
-> QGP has lots o' quarks flying around

-> QGP radiates more than HG at same temperature (false!)

-> Lots o' thermal radiation is evidence for QGP

Ah, for the good old days….

Why this is difficult



Theoretical (or IRS) version

$$\gamma^{Direct} = \gamma^{Inclusive} - \gamma^{Decay}$$

Traditional experimental version

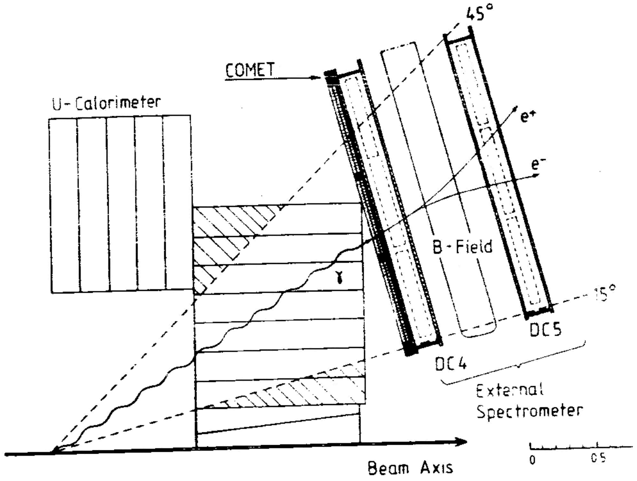
$$\gamma^{Direct} = \pi^0 \left(\frac{\gamma^{Inclusive}}{\pi^0} - \frac{\gamma^{Decay}}{\pi^0} \right)$$

Improved experimental version

$$\gamma^{Direct} = \gamma^{Decays} \left(\frac{\gamma^{Inclusive}/\pi^0}{\gamma^{Decays}/\pi^0} - 1 \right)$$

Integral Limits from Conversion

HELIOS



p,O,S + Pt, W

Limit γ/π^- in $0.1<p_T<1.5$ GeV/c

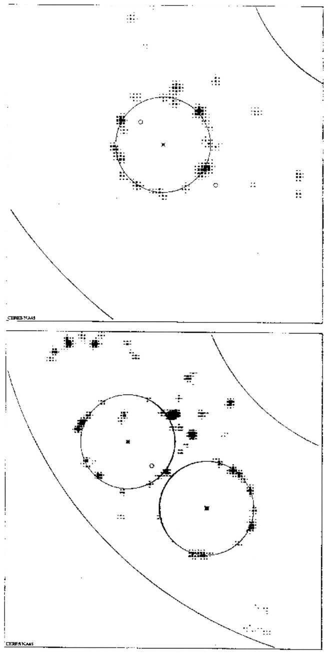
Z. Phys C **46**, 369 (1990)

CERES

S + Au

Limit $\gamma/(dN^{Ch}/d\eta)$ in $0.4<p_T<2.0$ GeV/c

Z. Phys C **71**, 571 (1996)



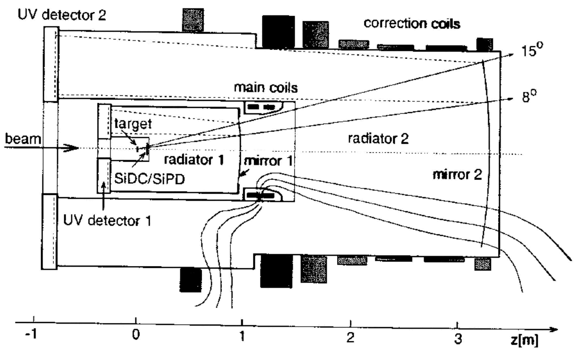


Fig. 1. Schematic view of the CERES spectrometer

Spectrum Limits from Calorimeter

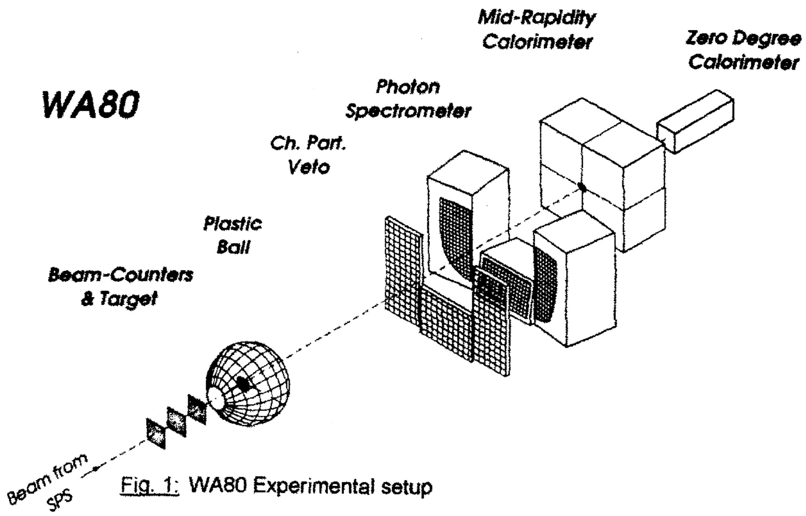
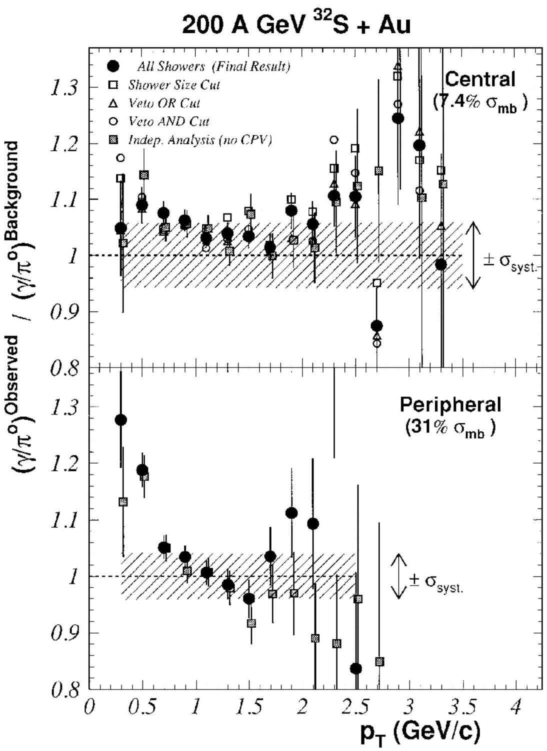
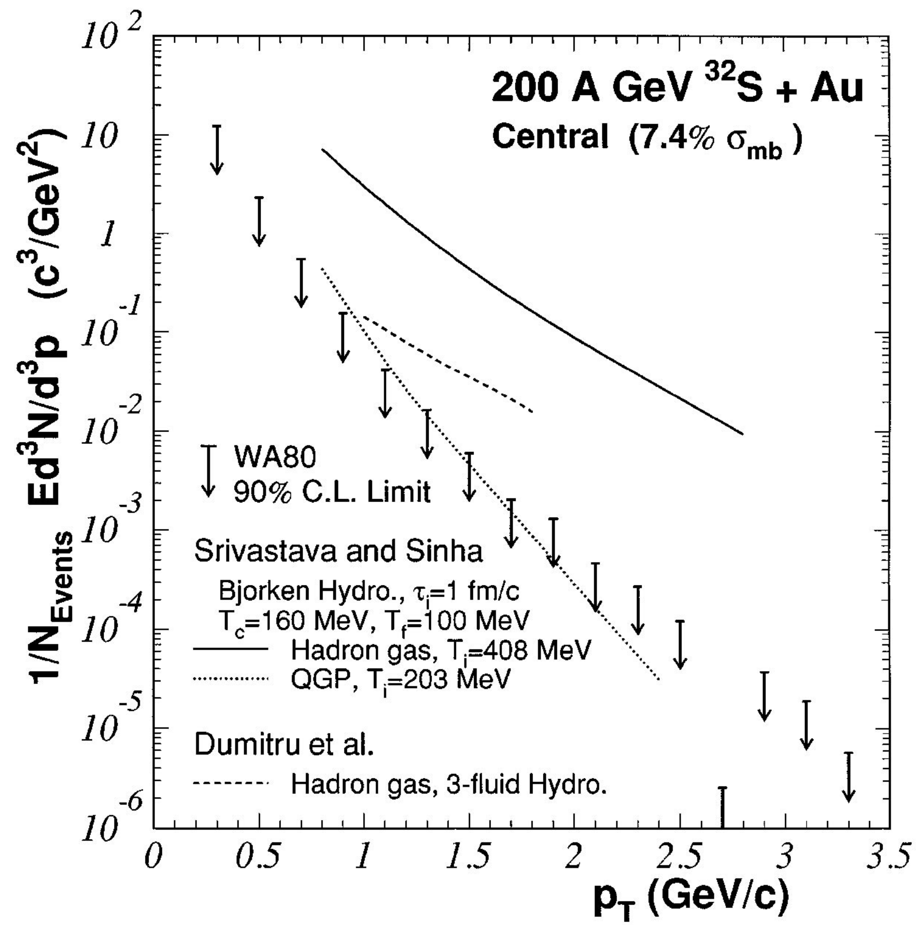


Fig. 1: WA80 Experimental setup



ME 76, NUMBER 19 PHYSICAL REVIEW LETTERS 6 MAY 1996

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



Thermal Photon Logic, ca 1997

QGP has chiral symmetry restored, quark masses ~0 1985

-> QGP has lots o' quarks flying around

-> QGP radiates more than HG at same temperature (false!)

-> Lots o' thermal radiation is evidence for QGP

1. Experiment: Not much radiation, only limits.
2. Theory: QGP and HG radiate similarly at same T

Final-state data does not constrain T, but rather energy density ε

-> At same ε, QGP has more d.o.f. than HG, higher ε/T^4

-> At same ε, QGP has lower T

-> At same ε, QGP radiates *less* than HG

-> *Lack* of radiation is evidence for QGP!

Thermal Photon Rates Calculated

$$\underbrace{E_\gamma \frac{dR}{d^3p_\gamma}}_{\text{Rate per volume per time}} = \underbrace{\frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}}_{\text{Couplings and color factors}} \underbrace{T^2 e^{-E_\gamma/T}}_{\text{Planck}} \underbrace{\ln\left(\frac{2.912}{g^2}\frac{E_\gamma}{T}\right)}_{\text{Infrared Cutoff f... Hard Thermal L... effective mass } g^2T}$$

Rate per volume per time

Couplings and color factors

Planck

Infrared Cutoff f
Hard Thermal L
effective mass g^2T

Photon radiation from an equilibrated quark & gluon plasma.

(Kapusta, Lichard, Seibert PRD ‘ 91) Includes lowest-order Compton and annih. graphs, and lowest order HTL cutoff (Braaten & Pisarski NP ‘ 88, PRL ‘ 89).

A lowest-order pocket formula. (For fuller, higher-order version consult Gale & Haglin hep-ph/0306098)

Reasonably rigorous -- but need to *integrate* over space-time!

Rate from thermal hadron gas also calculated. Version 1991, QGP and HG rates same at same T; after much work, version 2003 is basically the same conclusion.

Temperature Limits: Contact With Thermodynamics At Last

PHYSICAL REVIEW C VOLUME 55, NUMBER 1 JANUARY 1997

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

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Pasi Huovinen, Markku Kataja, and P. V. Ruuskanen
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Madappa Prakash
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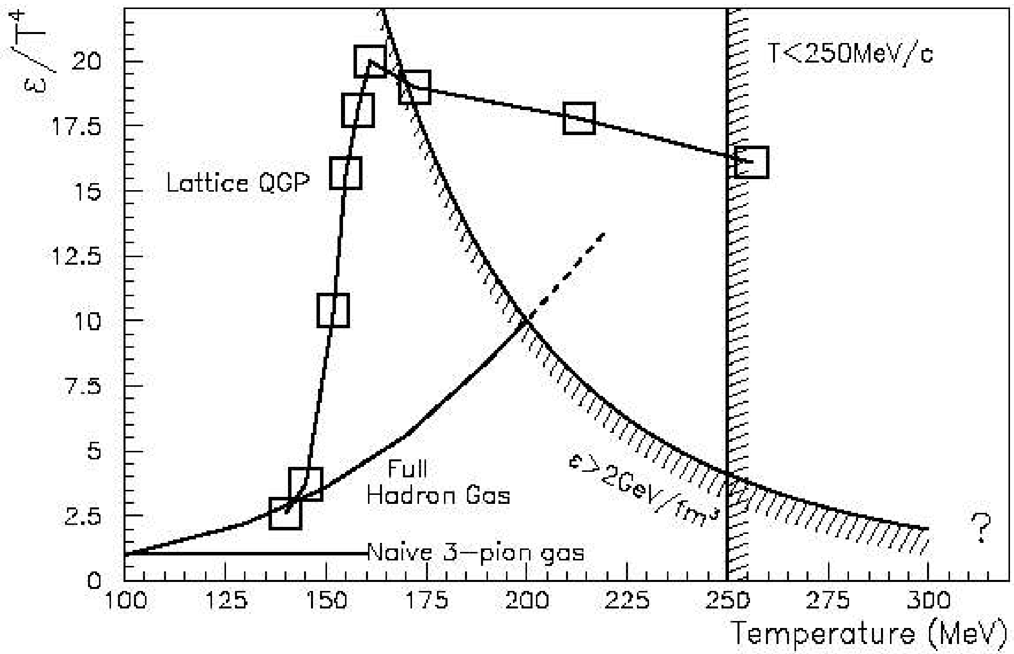
National Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195

(Received 15 July 1996)

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,



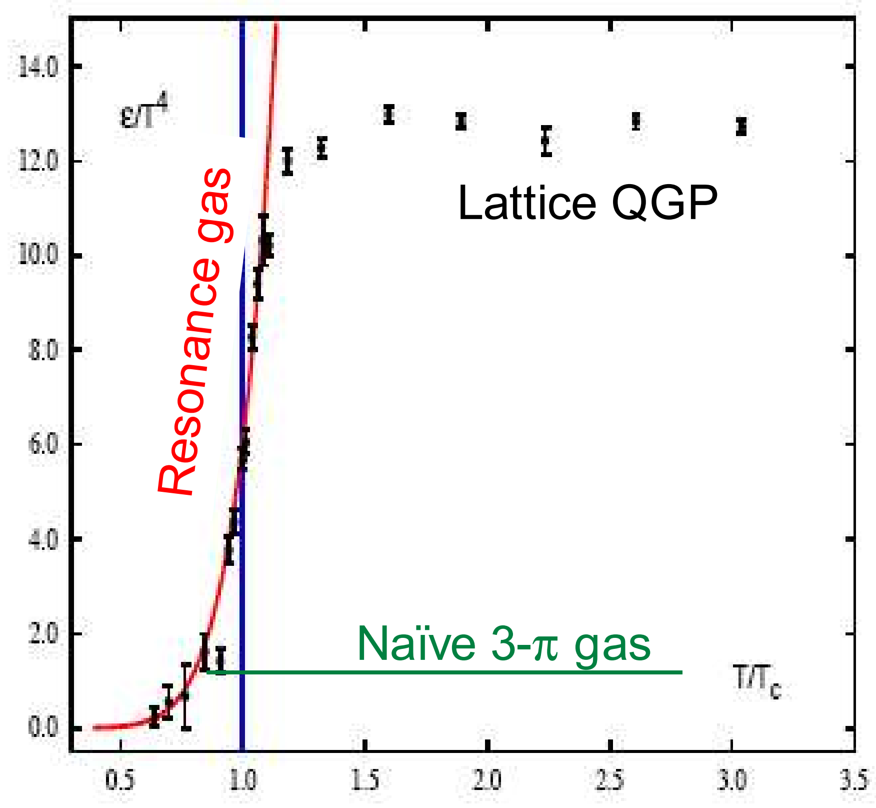
Combination of *high* energy density and *low* temperature is evidence for high number of degrees of freedom -> QGP.

Thermal Photon Logic, ca 2003

The 3-π gas is defunct!

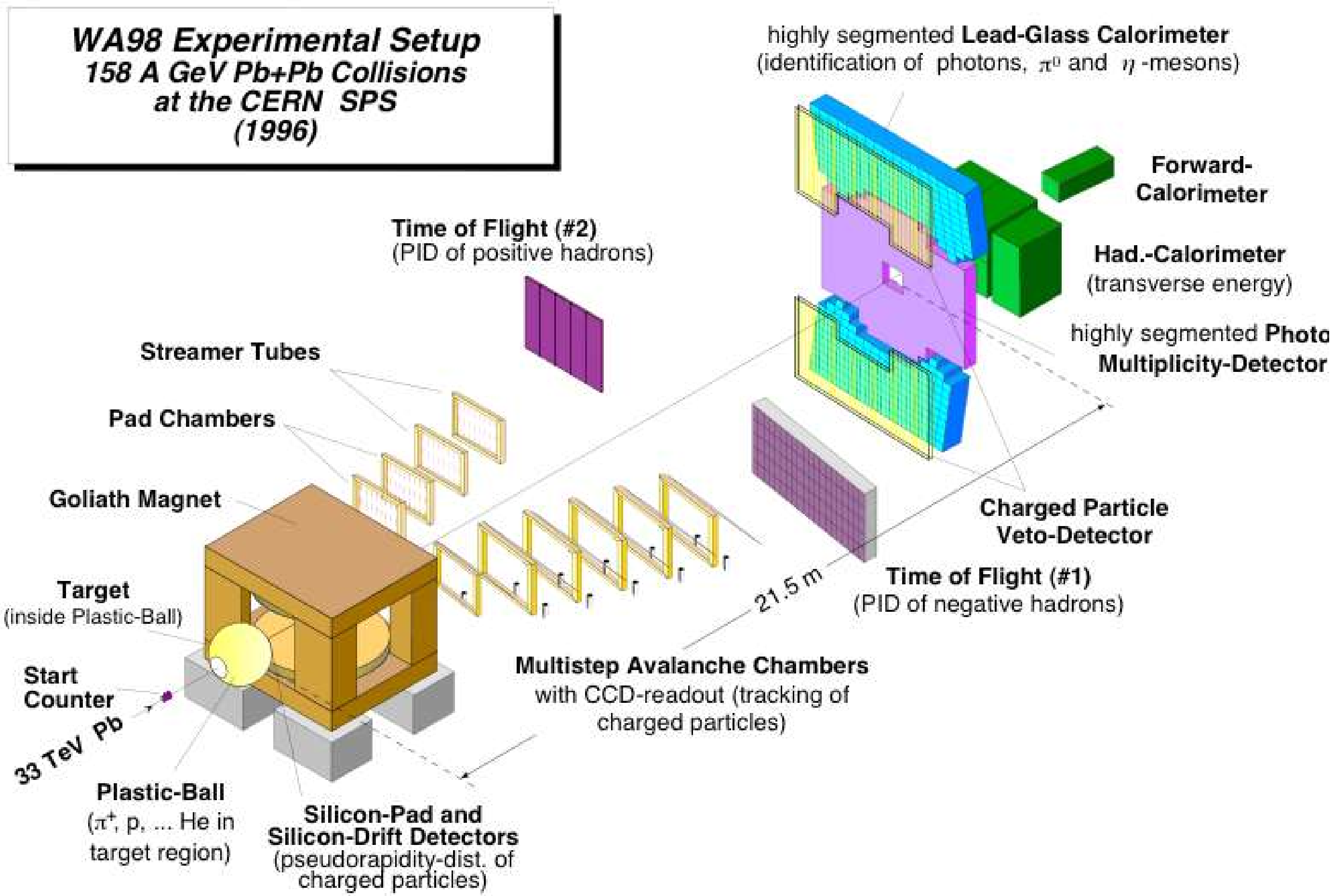
Once the resonance gas is taken seriously, it has a (much) *larger* number of degrees of freedom than the QGP at any $T>T_C$!

To distinguish between lattice-predicted QGP and "full" resonance gas, need to put lower limit on temperature, or upper limit on ε/T^4, in high-temp phase.

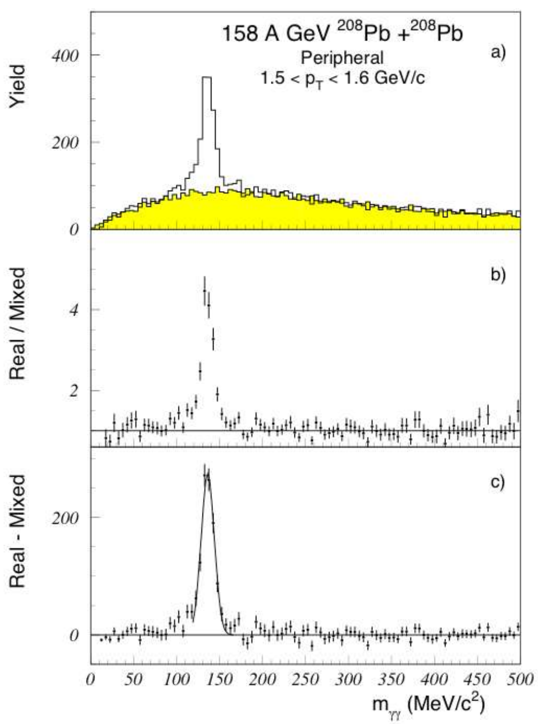


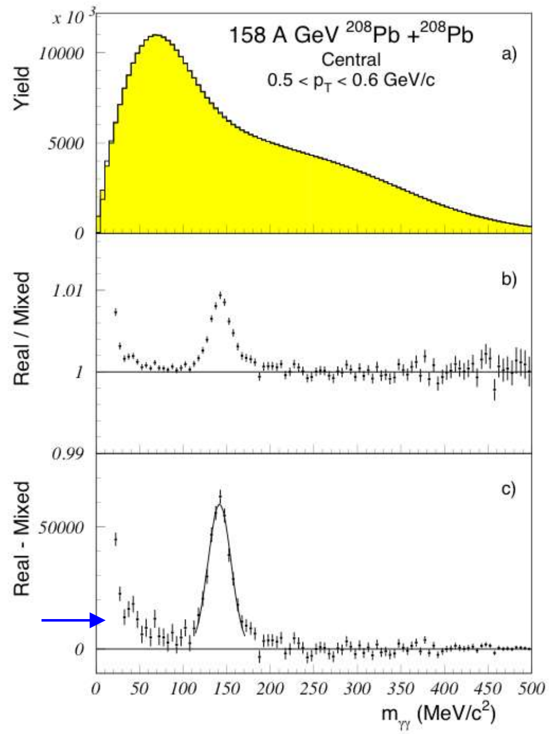
Karsch, Redlich, Tawfik,
Eur.Phys.J.**C29**:549-556,2003

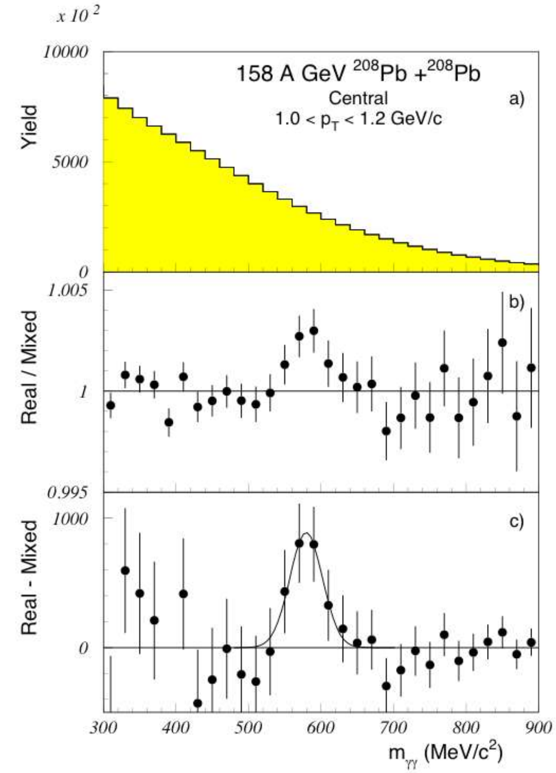
Pb+Pb: "Truly Heavy" Ion Collisions



Why this is doubly difficult





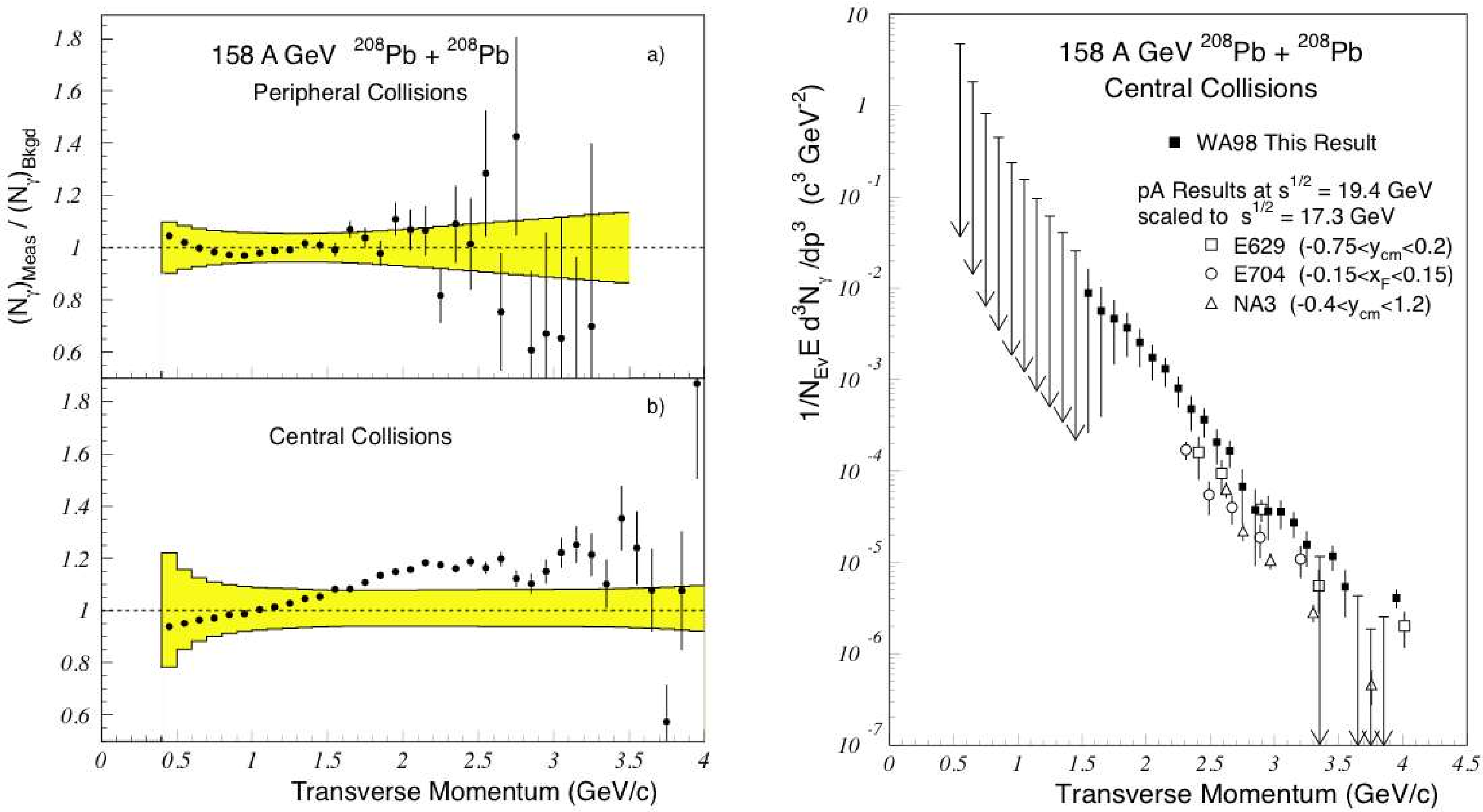


Subtraction of decay photons **depends critically on accurate π^0 reconstruction**. In low-multiplicity A+A collisions, similar to p+p collisions, the π^0 peak stands out immediately (left). In high-multiplicity collisions, and especially at low p_T, the extraction is extremely challenging, S/B<1% (center). Also, we must measure η's in-situ (right); they contribute about 15% to decay photons but we cannot presume η /π.

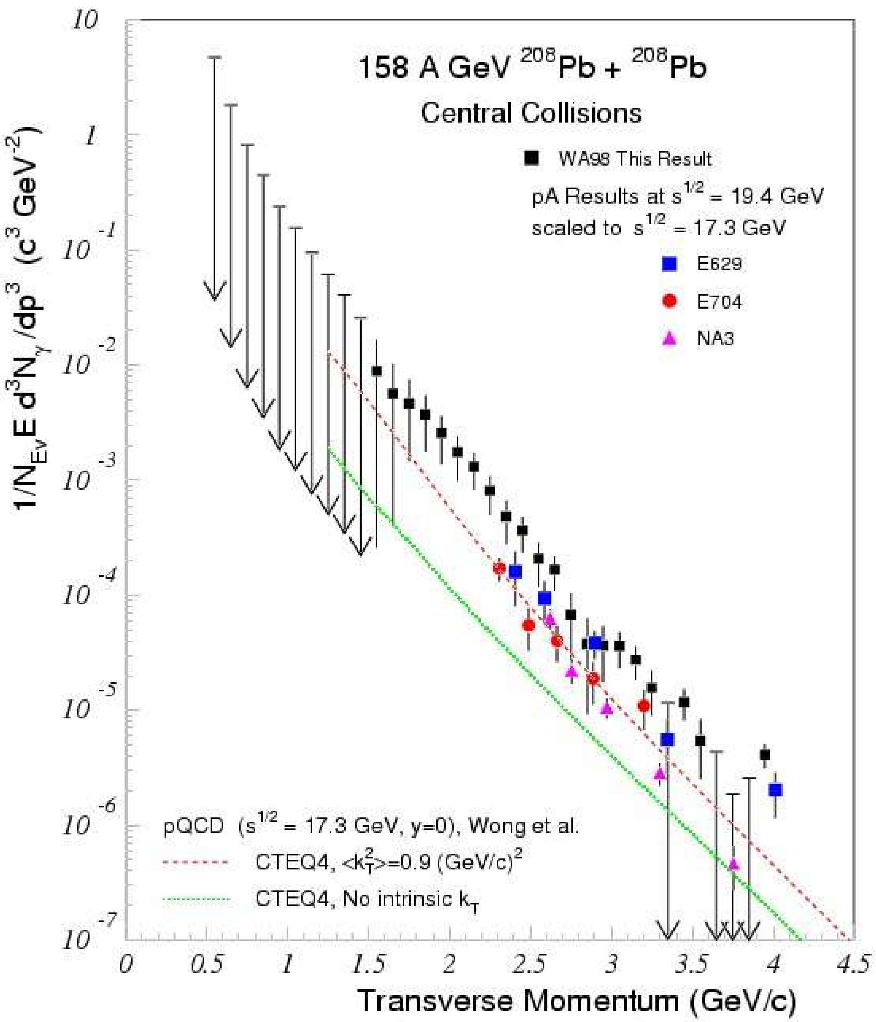
A Spectrum at Last!

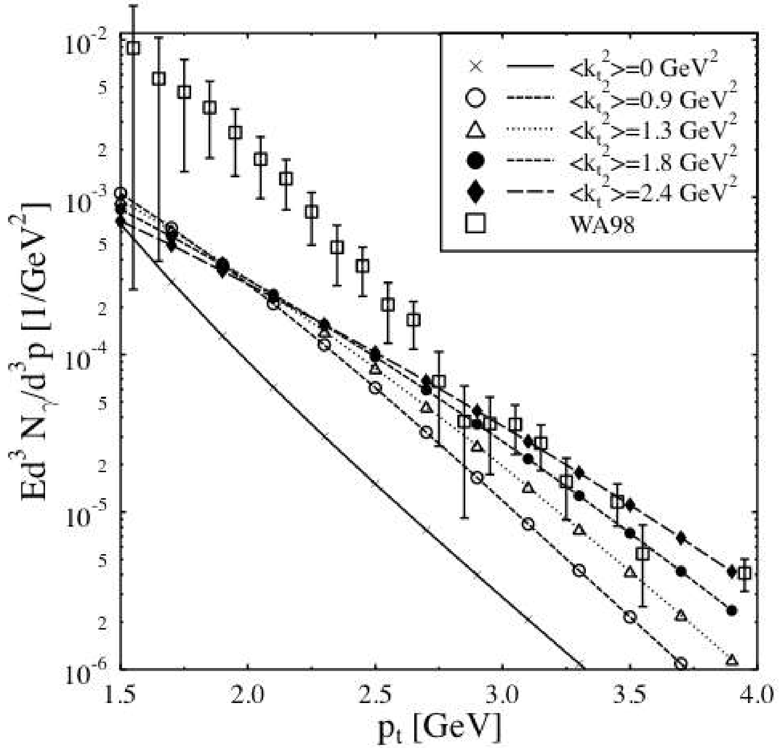
VOLUME 85, NUMBER 17 PHYSICAL REVIEW LETTERS 23 OCTOBER 2000

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



WA98 Interpretation I: pQCD?





Dumitru, et.al., PRC 64 054909 (01)

Some amount of k_T required, but still can’ t fill the whole spectrum

WA98 Interpretation II: k_T or T?

PHYSICAL REVIEW C **69**, 014903 (2004)

Hadronic production of thermal photons

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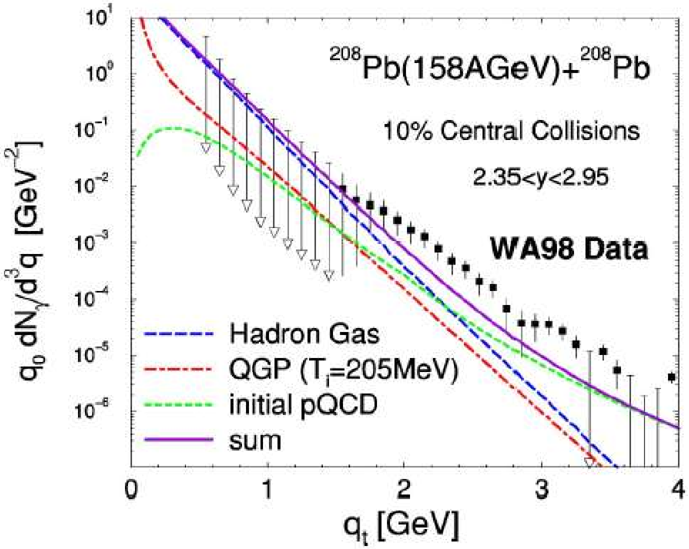
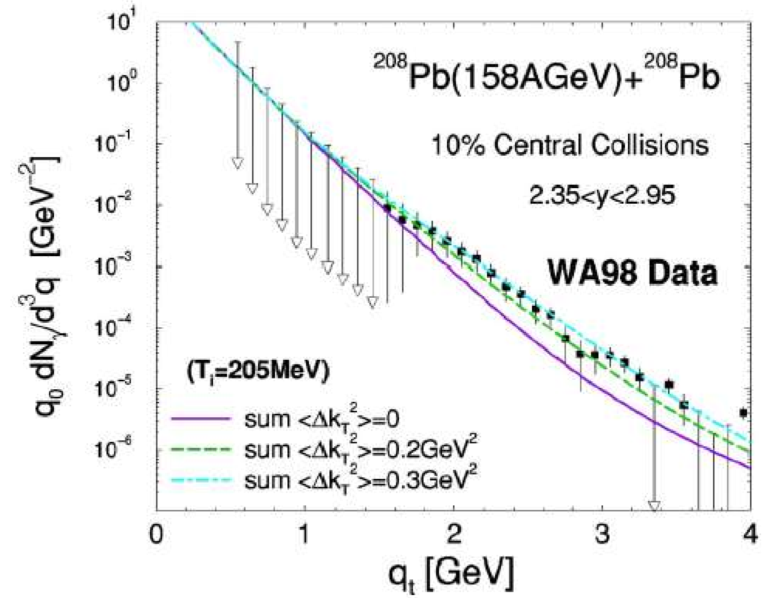
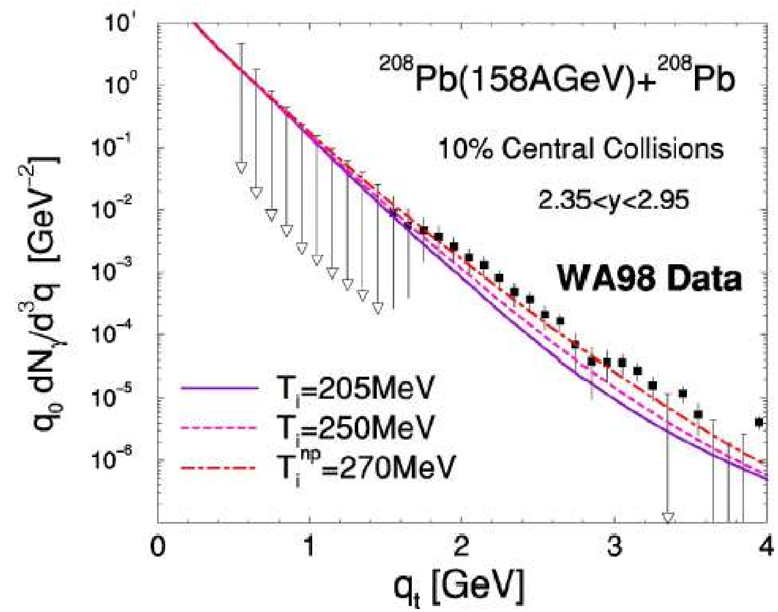
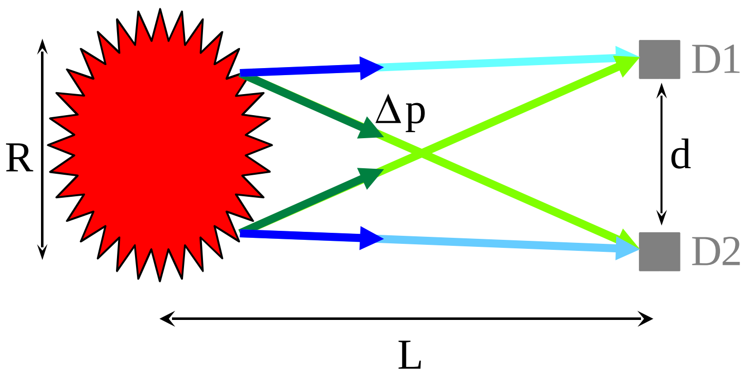


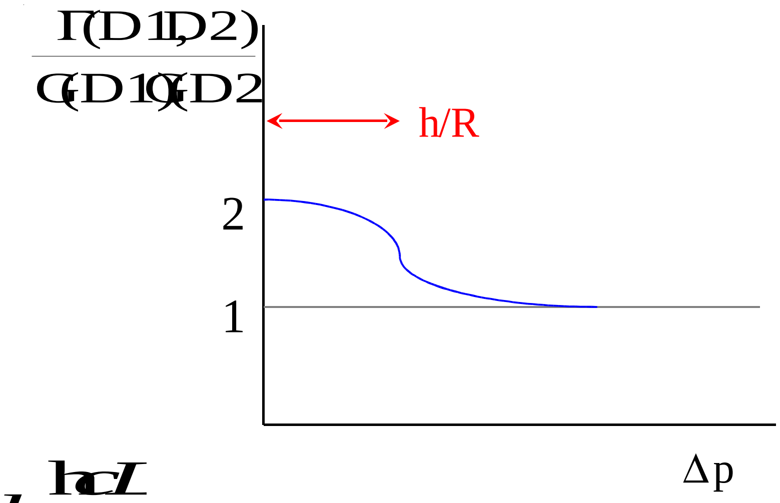




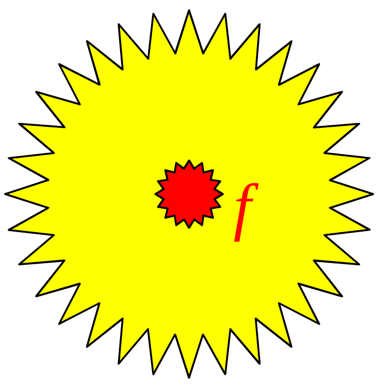
A nominal, complete scenario (above) under-predicts the observed photon rate. The gap can be closed either by increasing intrinsic k_T effects (above, right), or by assuming a higher initial temperature (below, right). Thus, resolution of the thermal component depends on accurate separation of the prompt component.

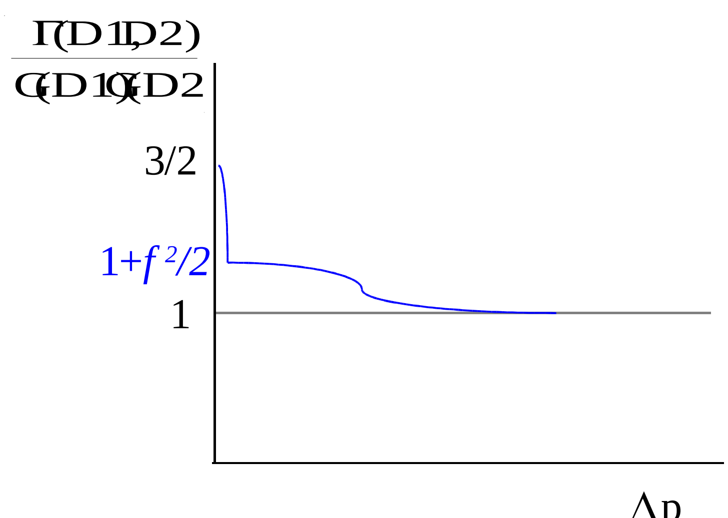
A New Technique: γγHBT





Enhancement for $\frac{Rpd}{L} \lesssim \hbar c$ or $d \lesssim \frac{\hbar c L}{E R}$





The Hanbury-Brown-Twiss method of photon interferometry works from stars to nuclei!

Direct Photons at *Very* Low p_T

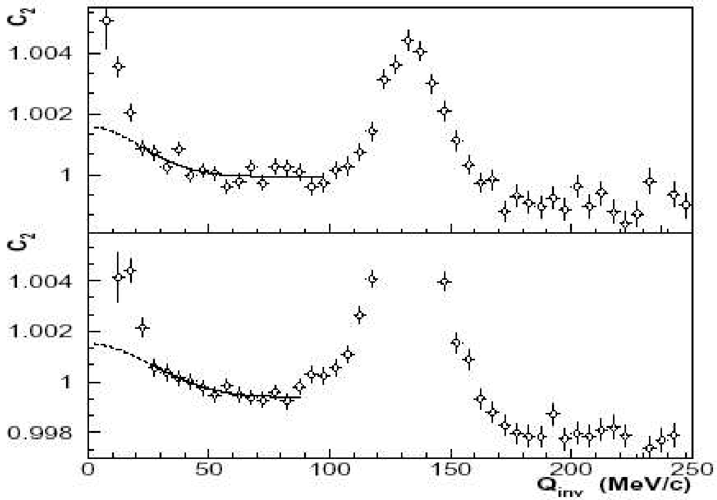


FIG. 1: The two-photon correlation function for narrow showers with $L_{min} > 20$ cm (diamonds) and average photon momenta $100 < K_T < 200$ MeV/c (top) and $200 < K_T < 300$ MeV/c (bottom) fitted with Eq. 1. The solid line shows the fit result in the fit region used (excluding the π^0 peak at $Q_{inv} \approx m_{\pi^0}$) and the dotted line shows the extrapolation into the low Q_{inv} region where backgrounds are large.

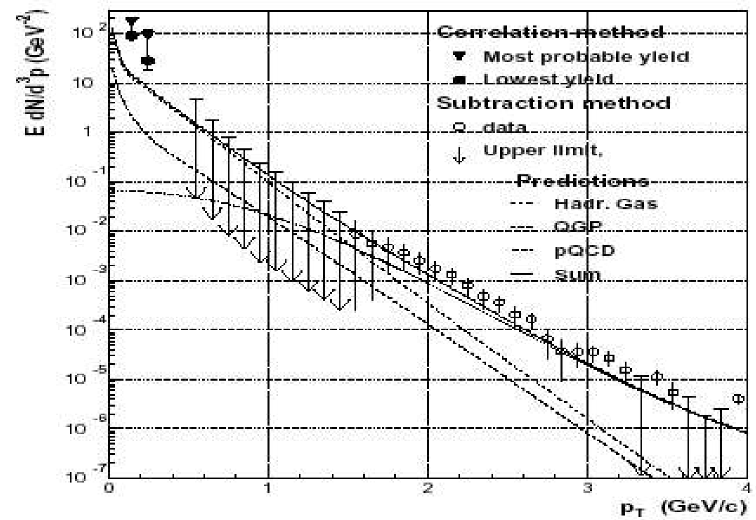
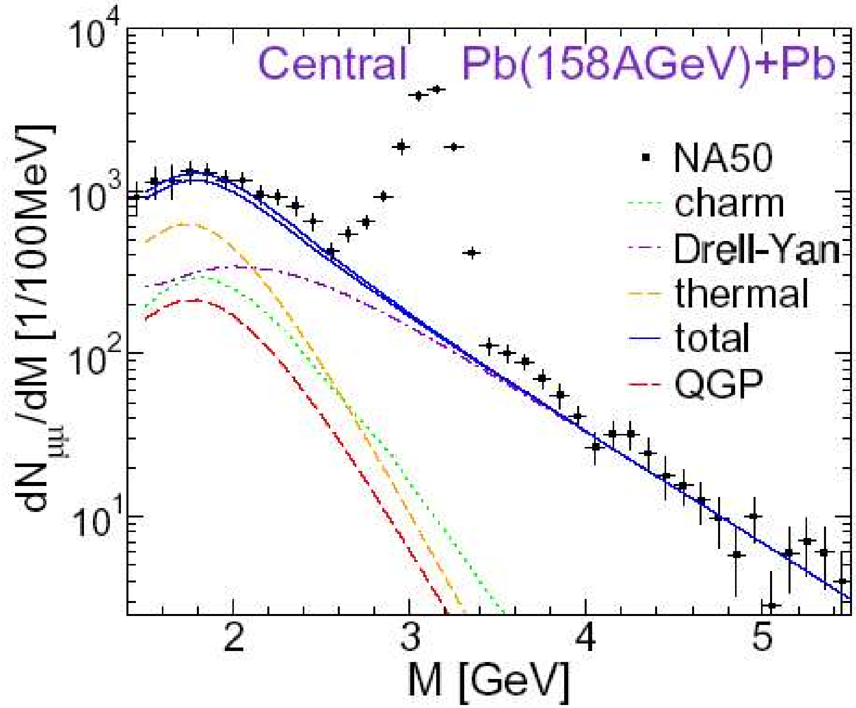


FIG. 4: Yield of direct photons extracted from the strength of the two-photon correlation (closed circles and triangles) and by the statistical subtraction method (open circles, or arrows indicating upper limits) [8]. Total statistical plus systematical errors are shown. The calculations are described in the text.

Phys.Rev.Lett.**93**:022301,2004
also hep-ph/0403274

Credit: Dmitri Peressounko for WA98

Continuum Dileptons at High Masses



NA50 Eur Phys J C14 (2000) 443

R. Rapp hep-th/0201101

Dileptons in the intermediate mass range $M_\phi < m_{\mu\mu} < M_{J/\Psi}$ are also good candidates for thermal radiation, though there is uncertainty on the contribution from associated open charm decays.

In principle, a high-statistics measurement of intermediate-mass dileptons vs p_T could be a *better* measure of thermal radiation than direct photons! But this avenue has not been thoroughly explored.

Beyond Thermal Photons

The traditional interest in thermal direct photons continues in RHIC and LHC nuclear collisions. But photon production, as well as W and Z production, touches on a wide range of physics topics beyond thermodynamics:

- Jet+medium -induced direct photons
- Direct photon-tagged (and Z^0-tagged) jet fragmentation
- Z^0 production and in-medium modification
- W production and parton measurements
- Beam-stopping bremstrahlung
- Investigate the approach to thermal equilibrium

Fixed-Target Results: Conclusions

1. The early days had more enthusiasm than rigor.
2. In S+Au upper limits on thermal photons were used to set limits on initial temperatures; weak evidence for high #d.o.f.
3. Direct photon spectrum (ie upper *and* lower limits) observed in heavier Pb+Pb collisions.
4. Thermal radiation from boosted Hadron Gas may dominate thermal radiation from cooler QGP.
5. Ambiguity between pQCD sources with intrinsic plus nuclear k_T effects, and hotter thermal sources. More definitive pQCD calculations would be a great help.
6. Limiting initial temperatures in Pb+Pb possible, not yet done.