Dileptons as a Probe of QGP

See: Ch. Wong Introduction to High Energy Heavy Ion Collisions Ch.14
R. Vogt Ch. 7

The contributions to final spectra could be
1. from QGP phase $qq \rightarrow l^+l^-$
2. from mixed phase: $qq$ and hadrons $\rightarrow l^+l^-$
3. from hadron gas phase

At high $T$ for masses above $\phi$ (1.004 GeV) and below $J/\psi$ (3 GeV) there is a gap for thermal dilepton $l^+l^-$ spectra from QGP.

How to calculate it and to measure it?

Do we see any excess of dileptons in $dN/dM$ mass spectra in the experiment?
Why do we measure them

Convey dual information convoluted over the history of the collisions:

- probe surrounding matter properties: T, density, flow...
- probes themselves are affected by hot and dense matter

Modification of Vector Meson spectral functions close to Chiral Symmetry Restoration point:
VM broadening vs mass shift.

Thermal emission: both from QGP and Hadronic phase
Rich variety of dilepton contributions in hadronic phase:
- Low Mass Range (LMR, \( m_{\mu\mu} \leq m_{\phi} \)) : resonant (VM, mostly \( \rho \));
- Intermediate Mass Range (IMR, \( m_{\phi} < m_{\mu\mu} < m_{J/\psi} \)) : continuum-like; rates determined by T (parton–hadron duality?)
  \( \Rightarrow \) need to disentangle experimentally QQP and HG contributions.

Strangeness (\( \phi \)) enhancement from \( SS \) abundantly produced in QGP

Quarkonia suppression by colour screening in QGP (covered by R.Arnaldi talk)

Caveats: experimental: small yields, strong backgrounds ...
interpretational: underlying ‘conventional’ sources need to be understood ...
Lepton-Pair Continuum Physics

Modifications due to QCD phase transition

Chiral symmetry restoration
continuum enhancement
modification of vector mesons

Sources “long” after collision:
- $\pi^0, \eta, \omega$ Dalitz decays
- $(\rho), \omega, \phi, J/\psi, \psi'$ decays

Early in collision (hard probes):
- Heavy flavor production
- Drell Yan, direct radiation

Baseline from p-p

Thermal (blackbody) radiation
in dileptons and photons
temperature evolution

Medium modifications of meson
- $\pi\pi \rightarrow \rho \rightarrow l^+l^-$
- chiral symmetry restoration

Medium effects on hard probes
- Heavy flavor energy loss

Large discovery potential also RHIC
14. Signatures for the Quark-Gluon Plasma (I)

In the previous chapter, we discussed the evolution of the matter produced after the collision of two heavy nuclei at high energies. The produced matter may make an excursion from the hadron phase into the quark-gluon plasma phase. Subsequent cooling allows the matter to return to the hadron phase and to appear as hadrons. During the time that the matter is in the quark-gluon plasma phase, particles which arise from the interactions between the constituents of the plasma will provide information concerning the state of the plasma. The detection of the products of their interactions will be useful as a plasma diagnostic tool.

It is generally recognized that there is no single unique signal which allows an unequivocal identification of the quark-gluon plasma phase. What can be achieved may be an accumulative set of data which taken together may indicate the presence of the deconfined phase. Chapter 14 to Chapter 19 will discuss different signatures used to search for the quark-gluon plasma.

§14.1 Dilepton Production in the Quark-Gluon Plasma

In the quark-gluon plasma, a quark can interact with an antiquark to form a virtual photon \( \gamma^* \) and the virtual photon subsequently decays into a lepton \( l^- \) and an antilepton \( l^+ \). The diagram which describes the reaction \( q + \bar{q} \rightarrow l^+ + l^- \) is shown in Fig. 14.1.

![Fig. 14.1 The diagram for the reaction \( q + \bar{q} \rightarrow l^+ + l^- \).](image)

The system of the produced lepton-antilepton pair is called a dilepton. It is also called an \( l^+l^- \) pair, or simply a lepton pair. The dilepton is characterized by a dilepton invariant mass squared \( M^2 = (l^+ + l^-)^2 \), a dilepton four-momentum \( P = (l^+ + l^-) \) and a dilepton transverse momentum \( P_T = l^+_T + l^-_T \).

After the lepton \( l^- \) and its antiparticle partner \( l^+ \) are produced, they must pass through the collision region to reach the detectors, in order to be observed. Since the leptons interact with the particles in the collision region only through the electromagnetic interaction, their interaction is not strong. The lepton (charge particle) cross section is of the order \( (\alpha/\sqrt{s})^2 \) where \( \alpha = 1/137 \) is the fine structure constant and \( \sqrt{s} \) is the lepton (charge particle) center-of-mass energy. Consequently, the mean-free path of the leptons is expected to be quite large and the leptons are not likely to suffer further collisions after they are produced. On the other hand, the production rate and the momentum distribution of the produced \( l^+l^- \) pairs depend on the momentum distributions of quarks and antiquarks in the plasma, which are governed by the thermodynamic condition of the plasma. Therefore, \( l^+l^- \) pairs carry information on the thermodynamical state of the medium at the moment of their production [1-11].

We consider for simplicity a plasma where the net baryon density is zero so that the quark distribution \( f(E) \) can be taken to be the same as the antiquark distribution. The case with unequal quark and antiquark distributions can be easily generalized (see Section 18.2 for an example how this can be carried out). The number of quarks with momentum \( p_1 \) in the spatial volume element \( d^3x \), and in the momentum element \( dp_1 \) is

\[
\frac{dN_q}{d^3x dp_1} = g_q \frac{d^3x dp_1}{(2\pi)^3} f(E_1),
\]

where \( g_q \) is the degeneracy of the quarks (or antiquarks) as given by Eq. (9.5),

\[ g_q = (\text{no. of colors } N_c) \times (\text{no. of flavors } N_f) \times (\text{no. of spins } N_s), \]

and \( E_1 \) is the energy of the quark with a rest mass \( m_q \),

\[ E_1 = \sqrt{p_1^2 + m_q^2}. \]

The integration of the phase space density with respect to the momentum coordinates gives the quark spatial density \( n_q \),

\[
\frac{dN_q}{d^3x} = n_q = g_q \int \frac{dp_1}{(2\pi)^3} f(E_1). \]
We shall show in Exercise 14.2 that the number of $l^+l^-$ pairs produced per unit spatial volume per unit time is

$$\frac{dN_{l^+l^-}}{dt \, d^3x} = N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{\epsilon} \right)^2 \int \frac{d^3p_1 \, d^3p_2}{(2\pi)^6} f(E_1) f(E_2) \sigma(M) \nu_{12}, \quad (14.1)$$

and the number of $l^+l^-$ pairs produced per unit dilepton invariant mass squared $M^2$, per unit four-volume, is given by [11]

$$\frac{dN_{l^+l^-}}{dM^2 \, d^3x} = N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{\epsilon} \right)^2 \frac{\sigma(M)}{2(2\pi)^3} \frac{1}{M^2} \left( 1 - \frac{4m_q^2}{M^2} \right)^{-\frac{1}{2}} \frac{1}{2} \int_0^\infty \frac{F(M^2)}{M^2} \frac{2\pi}{w(e)} \sqrt{\frac{2\pi}{w(e)}} \left( f(e) \eta \right) \frac{M^2}{4\epsilon} \right), \quad (14.2)$$

where $e_f$ is the electric charge of a quark with flavor $f$, $\sigma(M)$ is the $q \bar{q} \to l^+l^-$ cross section,

$$\sigma(M) = \frac{4\pi \alpha^2}{3} M^2 \left( 1 - \frac{4m_q^2}{M^2} \right)^{-\frac{1}{2}} \left[ 1 - \frac{4m_q^2}{M^2} \left( 1 + \frac{m_q^2}{M^2} \right)^2 + \frac{m_q^2 M^2}{4M^4} \right], \quad (14.3)$$

(see Exercise 14.1), and $m_q$ is the rest mass of the lepton. In Eq. (14.2), the function $F(E)$ is the indefinite integral of $-f(E)$,

$$F(E) = -\int_0^E f(E') \, dE', \quad (14.4)$$

and $\epsilon = \epsilon(M)$ is the location of the extremum of the function $g(E)$,

$$g(E) = \ln f(E) + \ln \left( \frac{M^2}{4\epsilon} \right). \quad (14.5a)$$

In other words, the location $\epsilon$ is the root of the extremum condition

$$\left\{ \frac{d}{d\epsilon} \left[ \ln f(E) + \ln \left( \frac{M^2}{4\epsilon} \right) \right] \right\}_E = 0. \quad (14.5b)$$

The quantity $-w(\epsilon)$ is the second derivative of $g(E)$ with respect to $E$ at the extremum, or,

$$w(\epsilon) = \left\{ \frac{d^2}{dE^2} \left[ \ln f(E) + \ln \left( \frac{M^2}{4\epsilon} \right) \right] \right\}_E. \quad (14.5c)$$

The distribution of $l^+l^-$ pairs, with respect to dilepton invariant mass squared $M^2$ and transverse mass squared $M_T^2 = M^2 + P_T^2$, per unit four-volume, is

$$\frac{dN_{l^+l^-}}{dM^2 \, dM_T^2 \, dt \, d^3x} = N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{\epsilon} \right)^2 \frac{\sigma(M)}{2(2\pi)^3} M^2 \left( 1 - \frac{4m_q^2}{M^2} \right)^{-\frac{1}{2}} \left[ -\frac{d}{dM_T^2} \left( \left( \ln \left( \frac{M_T^2}{\epsilon} \right) \right) \eta \right) \right) \frac{M^2}{4\epsilon} \right), \quad (14.6)$$

The above results are valid for a general distribution $f(E)$ that is a function of $E$ only. It shows that the dilepton distribution depends on the quark distribution $f(E)$ and its integral $F(E)$. However, we can extract the dilepton distribution coming from the quark-gluon plasma by experimental measurements, then we can determine the characteristics of the quark distribution in the quark-gluon plasma.

We can specialize to a quark-gluon plasma in which the quark and the antiquark distribution $f(E)$ is given by $e^{-E/T}$ characterized by a temperature $T$. We shall show in Exercise 14.3 that the $M^2$ distribution of the $l^+l^-$ pairs produced in the plasma per unit four-volume, is [2]

$$\frac{dN_{l^+l^-}}{dM^2 \, d^3x} \sim N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{\epsilon} \right)^2 \frac{\sigma(M)}{2(2\pi)^3} M^2 \left( 1 - \frac{4m_q^2}{M^2} \right)^{-\frac{1}{2}} \left( \frac{T M K_1 \left( \frac{M}{T} \right)}{T M K_1 \left( \frac{M}{T} \right)} \right), \quad (14.7)$$

where $K_\nu$ is the modified Bessel function of order $\nu$ [12]. The distribution in dilepton invariant mass squared $M^2$ and transverse mass squared $M_T^2$, per unit space-time volume, is [2]

$$\frac{dN_{l^+l^-}}{dM^2 \, dM_T^2 \, dt \, d^3x} \sim N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{\epsilon} \right)^2 \frac{\sigma(M)}{4(2\pi)^3} M^2 \left( 1 - \frac{4m_q^2}{M^2} \right)^{-\frac{1}{2}} \left( \frac{T M K_1 \left( \frac{M}{T} \right)}{T M K_1 \left( \frac{M}{T} \right)} \right) K_0 \left( \frac{M_T}{T} \right). \quad (14.8)$$

The above results are for a static plasma in which the temperature of the plasma is held fixed. We learned in the last chapter that the temperature of a plasma will decrease as a function of the proper time. In Bjorken's hydrodynamical model for the evolution of the plasma, the temperature $T$ as a function of the proper time $\tau$ is given by

$$T(\tau) = \frac{1}{\tau} \int_0^{\tau} \frac{d\tau'}{\sqrt{1 - \left( \frac{\tau'}{\tau} \right)^2}},$$

where $\sqrt{1 - \left( \frac{\tau'}{\tau} \right)^2}$ is the velocity of sound. This is the speed at which energy and momentum are transmitted through the plasma.
(13.18),
\[
T(\tau) = T_0 \left( \frac{\tau_0}{\tau} \right)^{1/3}, \quad \tau = \sqrt{t^2 - z^2}
\]
where \( T_0 \) is the initial temperature of the plasma formed in heavy-ion collisions at the initial proper time \( \tau_0 \). When the temperature drops below the transition temperature \( T_c \) at the proper time \( \tau_c \), the system will be in the mixed phase and no longer in the quark-gluon plasma phase. The \( \ell^+\ell^- \) pairs produced during the quark-gluon plasma phase can be obtained by integrating the production rate from the proper time \( \tau_0 \) to \( \tau_c \).

We shall show in Exercise 14.4 that after we integrate over the contributions from the proper time \( \tau_0 \) to \( \tau_c \), in which the system is in the quark-gluon plasma phase, the distribution of \( \ell^+\ell^- \) pairs in dilepton invariant mass squared \( M^2 \) and dilepton rapidity \( y \) is [2]
\[
\frac{dN_{\ell^+\ell^-}}{dM^2 dy} \sim \pi R_A^2 N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{\pi} \right)^2 \frac{\sigma(M)}{2(2\pi)^4} \left( 1 - \frac{4m_q^2}{M^2} \right) \frac{1}{2} \left( \frac{3\tau_0^2\tau_0^3}{M^2} \right) \\
\times \left[ H \left( \frac{M}{T_0} \right) - H \left( \frac{M}{T_c} \right) \right],
\]
(14.9)
where \( R_A \) is the radius of the colliding nuclei (which are taken to be equal), and
\[
H(z) = z^2(8 + z^2)K_0(z) + 4z(4 + z^2)K_1(z).
\]
In a similar way, we can integrate the contributions from the proper time \( \tau_0 \) to \( \tau_c \), to obtain the distribution of the \( \ell^+\ell^- \) pairs in \( M^2, M_T^2 \), and rapidity, given by [2]
\[
\frac{dN_{\ell^+\ell^-}}{dM^2 dM_T^2 dy} \sim \pi R_A^2 N_c N_s^2 \sum_{f=1}^{N_f} \left( \frac{e_f}{\pi} \right)^2 \frac{\sigma(M)}{4(2\pi)^4} M^2 \left( 1 - \frac{4m_q^2}{M^2} \right) \frac{1}{2} \left( \frac{3\tau_0^2\tau_0^3}{M_T^2} \right) \\
\times \left[ G \left( \frac{M_T}{T_0} \right) - G \left( \frac{M_T}{T_c} \right) \right],
\]
(14.10)
where
\[
G(z) = z^3(8 + z^2)K_3(z).
\]
Eqs. (14.9) and (14.10) give the distribution of the \( \ell^+\ell^- \) pairs as a function of the initial temperature \( T_0 \) and the transition temperature \( T_c \) of the plasma, after we take into account the hydrodynamical evolution of the system. Thus, the measurement of the \( \ell^+\ell^- \) pairs, if they can be identified as arising from this phase of matter, will reveal the thermodynamical state of the plasma.

It is instructive to obtain some intuitive insight into the dilepton distribution if the dileptons originate from \( q\bar{q} \) annihilations in the quark-gluon plasma. For definiteness, we can integrate the quark-gluon plasma with flavors \( u \) and \( d \) whose quark and antiquark momentum distribution is described by a Boltzmann distribution \( \exp \{-c/T\} \) with temperature \( T \). For \( M \gg T_0 \gg T_c \), one can use an exponential function to approximate the modified Bessel function, as given according to Eq. (9.7.2) of Ref. [12] by
\[
K_1(z) \sim \sqrt{\frac{\pi}{2z}} e^{-z}.
\]
For simplicity, we can neglect the quark mass and the lepton mass. It is easy to show that upon substituting Eq. (14.3) into Eq. (14.9), the dilepton distribution in invariant mass and rapidity is approximately given by
\[
\frac{dN_{\ell^+\ell^-}}{dM dy} \sim \frac{5}{3\pi^2} \sqrt{\frac{\pi}{2}} \alpha_s^2 \tau_0^2 R_A^2 T_0^3 \left( \frac{M}{T_0} \right)^{3/2} e^{-M/T_0} f \left( \frac{M}{T_0} \right) \\
\times \left\{ 1 - \left( \frac{T_0}{T_c} \right)^{3/2} \frac{f(M/T_c)}{f(M/T_0)} e^{-\left( T_0^2 - T_c^2 \right) / T_0^2} \right\},
\]
(14.11)
where
\[
f(z) = 1 + \frac{4}{z} + \frac{8}{z^2} + \frac{16}{z^3}.
\]
The dominant invariant mass dependence comes from the factor \( e^{-M/T_0} \). If we parametrize the dilepton invariant mass distribution in terms of a dilepton temperature in the form \( M^{1/2} \exp \{-M/T_{\text{dilepton}}\} \), then the dilepton “temperature” \( T_{\text{dilepton}} \) is approximately the same as the quark initial temperature \( T_0 \). Therefore, the dilepton invariant mass distribution varies approximately as the initial quark distribution. If one can extract the dilepton spectrum coming from the quark-gluon plasma, then one may determine the plasma initial temperature \( T_0 \).
§14.2 Dilepton Production from Other Processes

In a high-energy nucleus-nucleus collision, the possible formation of the quark-gluon plasma is not the only source of $l^+l^-$ pairs. There are other processes which also contribute to dilepton production. To separate out the portion due to the quark-gluon plasma, it is necessary to analyze the contributions from the other sources.

§14.2.1 Drell-Yan Process

An important contribution to dilepton production comes from the Drell-Yan process [17-20], which is specially important for large values of the invariant mass of the $l^+l^-$ pair. In the Drell-Yan process in a nucleus-nucleus collision, we envisage that a valence quark of a nucleon of one of the nuclei can interact with a sea antiquark of a nucleon of the other nucleus. They annihilate to form a virtual photon which subsequently decays into an $l^+l^-$ pair. In this process, the effects of the correlations of the nucleons within a nucleus are not important and
14. Signatures I: Dilepton Production

where \( q_f^{(B,A)}(x) \) and \( \bar{q}_f^{(B,A)}(x) \) are the probability of finding respectively a quark and an antiquark of flavor \( f \), with a light-cone variable \( x \) in the beam nucleon \( B \) or in the target nucleon \( A \). The quantities \( x_{1,2} \) are related to \( x_\rho \) and \( M^2 \) by

\[
    x_{1,2} = \frac{1}{2} \left( \sqrt{x^2 + \frac{4M^2}{s}} \pm x_\rho \right),
\]

(14.15a)

and

\[
    x_1x_2 = x_\rho,
\]

(14.15b)

and

\[
    x_1x_2s = M^2.
\]

(14.15c)

From Eqs. (14.13) and (14.15b), we can understand the kinematic configurations in the production of the \( l^+l^- \) pair. Working in the center-of-mass system of the colliding nucleons and using \( \sqrt{s}/2 \) as the unit of momentum, we define \( x_\rho \) as the longitudinal momentum of the \( l^+l^- \) pair with Eq. (14.13). The longitudinal momentum \( x_\rho \) of the dilepton comes from the parton with the longitudinal momentum \( x_1 \) and another parton with the longitudinal momentum \( -x_2 \), in units of \( \sqrt{s}/2 \). Hence, the sum of the parton longitudinal momentum \( x_1 + x_2 \) gives the dilepton longitudinal momentum \( x_\rho \), as in Eq. (14.15b).

The square of the momentum of a parton gives the invariant mass of the parton. At very high energies, the invariant mass of the parton can be neglected and the energy of the parton is approximately the same as the magnitude of its longitudinal momentum. Consequently, \( x_1\sqrt{s} \) is the forward light-cone momentum of one parton and \( x_2\sqrt{s} \) is the backward light-cone momentum of the other parton. Hence, the product of \( x_1\sqrt{s} \) and \( x_2\sqrt{s} \) gives the invariant mass squared of the parton pair, which is the same as the invariant mass squared of the \( l^+l^- \) pair. Therefore, the invariant mass squared of the \( l^+l^- \) pair is \( x_1x_2s \), as in Eq. (14.15c).

Eq. (14.15a) reveals that given an \( l^+l^- \) pair which is characterized by the Feynman scaling variable \( x_\rho \) and an invariant mass squared \( M^2 \), one can determine the light-cone momentum fractions \( x_1 \) and \( x_2 \) from which the \( l^+l^- \) pair originated. Thus, another way to present the result of Eq. (14.14) is to rewrite it as a differential cross section in \( x_1 \) and \( x_2 \)

\[
    \frac{d\sigma}{dx_1dx_2} = \frac{1}{N_c} \sigma(M) \sum_f \left( \frac{e_f}{e} \right)^2 \frac{q_f^B(x_1)\bar{q}_f^B(x_2) + \bar{q}_f^B(x_1)q_f^B(x_2)}{\sqrt{x^2 + 4M^2/s}} \left( q_f^A(x_1)q_f^A(x_2) + q_f^A(x_1)\bar{q}_f^A(x_2) \right). \tag{14.16}
\]

In terms of the variables \( M \) and \( y \), the differential cross section is
where $x = M/\sqrt{s}$. The differential cross section in $M$ and $y$ at $y = 0$ assumes the form given by

$$\frac{d\sigma}{dMdy} = \frac{8\pi\alpha^2}{3sN_cM} \sum_f \frac{\alpha_f^2}{\alpha^2} \left[ q_f^B(xe^y)q_f^A(xe^{-y}) + q_f^A(xe^y)q_f^B(xe^{-y}) \right],$$

(14.17)

When one plots the left-hand side quantity of Eq. (14.18) as a function of $M/\sqrt{s}$, the data points from different measurements at different energies should fall on the same curve (see Fig. 1.7 of Ref. 19). This is confirmed by experimental dilepton production data which can be well represented by the relation

$$M^2 \frac{d^2\sigma}{dMdy} \bigg|_{y=0} = 3 \times 10^{-32} e^{-15M/\sqrt{s}} \text{ (cm}^2\text{GeV}^2).$$

(14.19)

This ‘scaling behavior’ and the results of Eqs. (14.14) and (14.16) allow one to extract the quark and antiquark distribution functions in a nucleon.

Eqs. (14.14)-(14.18) for the Drell-Yan process are obtained by using the leading order diagram (Fig. 14.1 and Fig. 14.4) in which there are no initial-state or final-state interactions. The main result is that the cross section consists of three factors: a distribution function which pertains to the constituent in the projectile nucleon, another distribution function for another constituent in the target nucleon, and the basic elementary constituent-constituent cross section $\sigma(M)$. This property of the Drell-Yan cross section is called the factorization property. It turns out that the factorization property has validity beyond the leading order because of a cancellation of amplitudes [21].

Because of this factorization property, the parton distribution functions obtained in the Drell-Yan process should be the same as the parton distribution functions (also known as the parton structure functions) obtained from lepton-nucleon deep-inelastic collisions, in which there is a large momentum transfer $Q$ from the lepton to a constituent of the nucleon.

Upon using the quark and antiquark structure functions deduced from deep-inelastic lepton-nucleon measurements to analyze the dilepton data, one finds that the experimental dilepton data will be consistent with the theoretical distributions if the lowest order theoretical results using the lowest order diagram of Fig. 14.1 are multiplied by an overall factor, the $K$ factor [18,20]. Experimentally, this $K$ factor is found to range from 1.6 to 2.8 [24].

If one considers only the lowest order diagram of Fig. 14.4, the Drell-Yan dilepton cross section will be proportional to $\alpha^2$, which is second order in the electromagnetic coupling constant $\alpha$ but zeroth order in the strong coupling constant $\alpha_s$. Higher-order QCD corrections to the Drell-Yan cross section, up to $O(\alpha_s^2)$ [22] and $O(\alpha_s^3)$ [23], have been worked out. These investigations show that the $K$ factor can be accounted for by including high-order QCD corrections [22,23]. The most important contribution to the dilepton cross section due to the $\alpha_s$-order (the next-to-leading-order) diagrams is the vertex correction at the $q\bar{q}g$ vertex, which leads to a factor equal to $(1 + 2\pi\alpha_s/3)$ [18,20]. For a coupling constant of $\alpha_s = 0.3$, the vertex correction gives a factor of about 1.7. Additional contributions from the $\alpha_s$-order Compton diagrams bring the $K$ factor within the observed range of 1.6 to 2.8 [22,23].

The large magnitude of the $\alpha_s$-order corrections raises questions concerning the convergence of the perturbation series. From the higher-order $\alpha_s$-order corrections, Hamberg et al. [23] find that for the case of very high energies and very large dilepton masses, the total contribution from the $\alpha_s^2$-order corrections is small compared to that from the $\alpha_s$-order corrections.

Using the parton model and perturbative QCD, with a $K$ factor either taken to be a constant [26] or determined by the $\alpha_s$-order QCD corrections [27-28], a large set of experimental data, including dilepton and deep-inelastic data, have been analyzed globally. Consistent sets of parameters for the parton distributions have been obtained by many workers [25-31]. Most groups use a functional representation of the parton distributions of the form

$$xq^a(x,Q) = A_0 \bar{x} A^T(1-x) A^a P^a(x),$$

(14.20)

where the superscript $a$ is a flavor label (including the gluon and the antiquark label), and $P^a(x)$ is a smooth function. The choice of the function $P^a(x)$ varies considerably. For example, Ref. [26] uses a polynomial in $x$ while Ref. [27] uses a logarithmic function of $(1 + x/2)$. The constants $A_0$ are functions of $Q^2$.

The parton distribution function depends on the momentum scale in which the parton distribution is probed. In Eq. (14.20), such a dependence is expressed by having $xq^a$ as a function of $Q^2$. In a deep-inelastic lepton-nucleon scattering, the quantity $Q$ is the momentum transfer from the lepton to the constituent and is equal to the four-momentum of the probing intermediate space-like virtual photon. (A virtual photon is space-like or time-like if the square of the photon four-momentum $Q^2$ is negative or positive.) In the Drell-Yan process, the quantity $Q$ is the four-momentum of the intermediate time-like
virtual photon and \( Q^2 \) is the square of the invariant mass of the photon, which is the same as the square of the invariant mass of the \( l^+l^- \) pair.

It is instructive to gain an intuitive insight into the main features of the dilepton distribution arising from the Drell-Yan process. From Eq. (14.18), we infer that the Drell-Yan dilepton differential cross section at \( y = 0 \) is given by the product of the quark distribution \( xq(x) \) and the antiquark distribution \( x\bar{q}(x) \). Using the quark and the antiquark distributions of the form of Eq. (14.20), the dilepton differential cross section at \( y = 0 \) is given from Eq. (14.18) by

\[
\frac{d\sigma}{dMd\gamma} \bigg|_{y=0} \propto \frac{1}{M^3 x} A_1^q + A_1^{\bar{q}} (1 - x) A_2^q + A_2^{\bar{q}} p(x) P\bar{q}(x).
\]

Because the functions \( p(x) \) and \( P\bar{q}(x) \) are smooth functions of \( x \), the dilepton differential cross section is approximately

\[
\frac{d\sigma}{dMd\gamma} \bigg|_{y=0} \sim \text{constant} \left( \frac{M}{\sqrt{s}} \right)^{A_1^q + A_1^{\bar{q}}} \left( 1 - \frac{M}{\sqrt{s}} \right)^{A_2^q + A_2^{\bar{q}}}
\]

\[
\sim \text{constant} \left( \frac{M}{\sqrt{s}} \right)^{A_1^q + A_1^{\bar{q}}} e^{-M (A_1^q + A_1^{\bar{q}})/\sqrt{s}}. \tag{14.21}
\]

The above differential cross section, with the exponential dependence \( \exp \{-M (A_1^q + A_1^{\bar{q}})/\sqrt{s}\} \), is in approximate agreement with the experimental data represented by Eq. (14.19), with \( A_1^q + A_1^{\bar{q}} \sim 15 \).

We can introduce a parameter \( T_{DY} \) to express the Drell-Yan dilepton differential cross section (14.21) in the form

\[
\frac{d\sigma}{dMd\gamma} \bigg|_{y=0} \sim \frac{1}{M^3} \left( \frac{M}{\sqrt{s}} \right)^{A_1^q + A_1^{\bar{q}}} e^{-M/T_{DY}}. \tag{14.22}
\]

The Drell-Yan dilepton differential cross section at \( y = 0 \) behaves as if there is an effective ‘temperature’ \( T_{DY} \) arising from the intrinsic motion of the quarks and antiquarks in the nucleon given by

\[
T_{DY} \sim \frac{\sqrt{s}}{A_1^q + A_1^{\bar{q}}}. \tag{14.23}
\]

As the parameters \( A_1^q \) and \( A_1^{\bar{q}} \) depend on \( Q^2 \), the effective Drell-Yan ‘temperature’ \( T_{DY} \) also depends on \( Q^2 \).

To provide a better insight to the dilepton spectrum, we consider Set I of the structure functions of Duke and Owens [26]. For the valence quark distribution (averaged over up quarks and down quarks), the parameters are

\[
A_1^q = 0.419 + 0.004k - 0.007k^2, \tag{14.24a}
\]

and

\[
A_1^{\bar{q}} = 3.46 + 0.724k - 0.066k^2, \tag{14.24b}
\]

and for the antiquark distribution, the parameters are

\[
A_2^q = -0.327k - 0.029k^2, \tag{14.24c}
\]

and

\[
A_2^{\bar{q}} = 8.05 + 1.59k - 0.153k^2, \tag{14.24d}
\]

where \( k = \ln[(\ln Q^2/\Lambda^2)/(\ln Q_0^2/\Lambda^2)] \),

\[
T_{DY} \sim \frac{\sqrt{s}}{11.51 + 2.31k - 0.219k^2}, \tag{14.25}
\]

with \( Q_0^2 = 4 \text{ GeV}^2 \) and \( \Lambda = 0.2 \text{ GeV} \).

Upon using the parameters Set I of Duke and Owens [26], the dilepton differential cross section at \( y = 0 \) is characterized approximately by a temperature

\[
T_{DY} \sim \sqrt{s}/11.51 \text{ for a dilepton with an invariant mass } M = 2 \text{ GeV}.
\]
§14.2.2 Drell-Yan Process in Nucleus-Nucleus Collisions

In the collision of a beam nucleus \( B \) and a target nucleus \( A \), how does the probability for a Drell-Yan process depend on the mass numbers of the colliding nuclei? Following arguments similar to those leading to Eq. (12.3), the total probability for the occurrence of a Drell-Yan process in a nucleus-nucleus collision when the nuclei \( B \) and \( A \) are situated at an impact parameter \( b \) relative to each other, is the sum of the products of three factors: the probability element \( \rho_A(b, z_A)db_Adz_A \) for finding a nucleon in the volume element \( db_Adz_A \) in nucleus \( A \) at the position \( (b, z_A) \), (ii) the probability element \( \rho_B(b, z_B)db_Bdz_B \) for finding a nucleon in the volume element \( db_Bdz_B \) in nucleus \( B \) at the position \( (b, z_B) \), and (iii) the probability \( t(b - b_A - b_B)\sigma_{DY}^{NN} \) for a nucleon-nucleon Drell-Yan process. We call this probability \( T(b)\sigma_{DY}^{NN} \):

\[
T(b)\sigma_{DY}^{NN} = \int \rho_A(b, z_A)db_Adz_A \rho_B(b, z_B)db_Bdz_B t(b - b_A - b_B)\sigma_{DY}^{NN},
\]

where \( \rho \) is the density function (12.2), \( t(b) \) is the nucleon-nucleon thickness function, and \( \sigma_{DY}^{NN} \) is the nucleon-nucleon Drell-Yan cross section. Eq. (14.26) leads to the thickness function for nucleus-nucleus collision as given by

\[
T(b) = \int db_A db_B T_A(b_A)T_B(b_B) t(b - b_A - b_B),
\]

which is just Eq. (12.8). The total probability for the occurrence of a Drell-Yan process in the collision of \( A \) and \( B \) at an impact parameter \( b \) is the sum

\[
P_{DY}^{AB}(b) = \sum_{n=1}^{AB} \binom{AB}{n} [T(b)\sigma_{DY}^{NN}]^n [1 - T(b)\sigma_{DY}^{NN}]^{AB-n}.
\]

The nucleon-nucleon Drell-Yan cross section being proportional to \( \alpha^2 \), the summation is dominated by the first term with \( n = 1 \). Terms with \( [T(b)\sigma_{DY}^{NN}]^n \) and \( n > 1 \) represent multiple Drell-Yan collisions and the term \( [1 - T(b)\sigma_{DY}^{NN}]^{AB-n} \) the shadowing corrections. As an approximation, these corrections can be neglected as the cross section \( \sigma_{DY}^{NN} \) is small and the probability for a Drell-Yan process in a nucleus-nucleus collision is

\[
P_{DY}^{AB}(b) = AB[T(b)\sigma_{DY}^{NN}].
\]

Consequently, the differential probability for finding an \( l^+l^- \) pair with an invariant mass \( M \) and a rapidity \( y \) in a nucleus-nucleus collision is given by

\[
\frac{dP_{DY}^{AB}}{dMdy}(b) = AB T(b) \frac{d\sigma_{DY}^{NN}}{dMdy}.
\]

Each Drell-Yan event produces one pair of dilepton. Consequently, the differential number of \( l^+l^- \) pairs produced with a rapidity \( y \) and an invariant mass \( M \) is given by

\[
\frac{dN_{l^+l^-}}{dMdy}(b) = AB T(b) \frac{d\sigma_{DY}^{NN}}{dMdy}.
\]

Therefore, when we integrate over the transverse area, we have

\[
\frac{d\sigma_{DY}^{AB}}{dMdy} = \int db \frac{dN_{l^+l^-}}{dMdy}(b) = AB \frac{d\sigma_{DY}^{NN}}{dMdy}.
\]

How does one parametrize the nucleus-nucleus thickness function \( T(b) \)? We found earlier that for nucleus-nucleus collisions, the thickness function can be approximated by Eq. (12.26),

\[
T(b) = \exp(-b^2/2\beta^2)/2\pi\beta^2,
\]

where

\[
\beta^2 = \beta_A^2 + \beta_B^2 + \beta_p^2,
\]

\[
\beta_A = r_0 A^{1/3}/\sqrt{3},
\]

\[
\beta_B = r_0 B^{1/3}/\sqrt{3},
\]

\[
\beta_p = r_0 p_{trans}/\sqrt{3},
\]

\[
\beta = \beta_A + \beta_B + \beta_p.
\]
$r'_0 \sim 1.05 \text{ fm}$, and $\beta_p = 0.68 \text{ fm}$ [32]. The quantity $\beta_p$ is small in comparison with the radii of heavy nuclei and can be neglected in qualitative estimates.

Accordingly, the differential number of $l^+l^-$ pairs depends on the impact parameter $b$ between the two nuclei as given by

$$\frac{dN_{l^+l^-}(b)}{dM dy} = \frac{3}{2\pi r_0^2} \frac{A B}{A^{2/3} + B^{2/3}} \frac{-\hat{s}^2}{2s^3} \frac{d\sigma^{NN}_{dy}}{dM dy} \tag{14.31}$$

When we consider the collision of two equal nuclei with mass number $A$, we have

$$\frac{dN_{l^+l^-}(b)}{dM dy} = \frac{3}{4\pi (r_0')^2} A^{4/3} \frac{\hat{s}^2}{2s^3} \frac{d\sigma^{NN}_{dy}}{dM dy}.$$ 

In particular, for a head-on collision, the number of $l^+l^-$ pairs from the Drell-Yan process is given by

$$\frac{dN_{l^+l^-}}{dM dy} \bigg|_{b=0} = \frac{3}{4\pi (r_0')^2} A^{4/3} \frac{d\sigma^{NN}_{dy}}{dM dy}. \tag{14.32}$$

Thus, the number of $l^+l^-$ pairs from the Drell-Yan process for the head-on collision of two equal nuclei scales as $A^{4/3}$.

§14.2.3 Dilepton Production from Hadrons and Resonances

Dilepton pairs can be produced from the interaction of charged hadrons and their antiparticles by processes such as $\pi^+\pi^- \rightarrow l^+l^-$. Dilepton pairs can also come from the decay of hadron resonances such as the $\rho$, $\omega$, $\phi$, and $J/\psi$. Therefore, hadron collisions and hadron resonance decays are additional sources of $l^+l^-$ pairs.

Hadrons and resonances are produced in the initial nucleus-nucleus collision. If the quark-gluon plasma is produced, hadronic matter will also be present when the quark-gluon plasma cools down below the transition temperature. Dileptons from hadron sources must be identified separately in order to look for dilepton production from the quark-gluon plasma.

One can estimate the contribution of the $l^+l^-$ pairs which come from the hadronic matter. As the dominant constituents of the hadronic matter are pions, we shall for simplicity consider the hadronic matter to consist only of pions. The collision of a $\pi^+$ with a $\pi^-$ leads to an $l^+l^-$ pair through the diagram depicted in Fig. 14.5. The wavy line in Fig. 14.5 represents a virtual photon $\gamma^*$ in scalar electrodynamics. In the vector dominance model, it represents a $\rho$ meson intermediate state.

For the production of $l^+l^-$ pairs in hadronic matter, the evaluation of the production rate follows the same considerations as those from quark-gluon matter discussed previously in Section 14.1. The only differences are the different degeneracies of the quarks and pions, and the different basic annihilation cross sections due to the difference in the coupling and the formation of a $\rho$ resonance intermediate state. The hadron matter starts to interact at the initial temperature $T_i$ and stops interacting at the freeze-out temperature $T_f$. As a consequence, all of the results of Eqs. (14.1)-(14.10) for $l^+l^-$ pair production in the quark-gluon plasma can be used for $l^+l^-$ pair production in the hadronic matter, with the following replacements:

$$N_i \rightarrow 1$$
$$N_f \rightarrow 1$$
$$N_x \rightarrow 1$$
$$m_q \rightarrow m_{\pi}$$
$$e_f \rightarrow e$$
$$T_0 \rightarrow T_i$$
$$T_e \rightarrow T_f$$

and

$$\sigma(M) \rightarrow \tilde{\sigma}(M),$$

where $m_{\pi}$ is the mass of the pion and $\tilde{\sigma}(M)$ is the cross section for
the process \( \pi^+ \pi^- \rightarrow l^+ l^- \) given by (see Exercise 14.6),

\[
\hat{\sigma}(M) = \frac{4\pi}{3} \frac{\alpha^2}{M^2} \left(1 - \frac{4m_\pi^2}{M^2}\right)^{1/2} \left(1 - \frac{4m_l^2}{M^2}\right)^{1/2} \left(1 + \frac{2m_l^2}{M^2}\right)|F_\pi(m_\rho)|^2.
\]

(14.33)

The square of the absolute value of the form factor \( F_\pi(m_\rho) \) is

\[
|F_\pi(m_\rho)|^2 = \frac{m_\rho^4}{(M^2 - m_\rho^2)^2 + \Gamma^2 m_\rho^2},
\]

(14.34)

where \( m_\rho \) and \( \Gamma \) are the mass and the width of the \( \rho \) meson. With these changes, Eqs. (14.7)-(14.10) can be used to estimate the rate of \( l^+ l^- \) pair production from the hadron phase.

The decays of the hadron resonances will show up as sharp peaks in the invariant mass spectrum of \( l^+ l^- \) pairs, with a width reflecting the mean lifetime of the resonance and a magnitude depending on the abundance of the resonance. Hadron resonances such as the \( \rho \), \( \omega \), and \( \phi \) may arise from the initial nucleus-nucleus collision before thermalization. They may also come from collisions of pions in dense pion gas during the thermalization of the hadron gas. The decay of the \( J/\psi \) resonance will give a peak at a dilepton invariant mass of about 3.1 GeV. The large mass of the \( J/\psi \) resonance makes it unlikely that it can be produced in soft processes or in the thermalization of the hadronic matter. Thus, the \( J/\psi \) production comes mainly from hard-scattering processes. We shall consider \( J/\psi \) production and its suppression in more detail in the next chapter.
§14.2.4 Dileptons from the Decay of Charm Particles

In nucleon-nucleon hard-scattering processes, charm mesons such as $D^+$ and $D^-$ are produced by the interaction of a constituent of one nucleon with a constituent of the other colliding nucleon. In particular, in the lowest order QCD theory, the quark of one nucleon interacts with the antiquark of the other nucleon to form a virtual gluon which decays into a $c\bar{c}$ pair,

$$q + q \rightarrow g^* \rightarrow c + \bar{c}, \quad (14.35)$$

as illustrated in Fig. 14.7a. A $c\bar{c}$ pair can also be produced by the interaction of a gluon of one nucleon with a gluon of the other colliding nucleon,

$$g + g \rightarrow c + \bar{c}, \quad (14.36)$$

as illustrated in Fig. 14.7b, 14.7c, and 14.7d.

A charm meson $D^+$ is a composite particle which consists of a charm quark and a $\bar{u}$, $d$, or $s$ antiquark. The corresponding antiparticle $D^-$ meson is the composite particle which consists of a charm antiquark and a $u$, $d$ or $s$ quark. Following the production of the $c\bar{c}$ pair in a nucleon-nucleon hard-scattering collision by the processes (14.35) and (14.36), the fragmentation of the $c$ quark into a $D^+$ meson and the fragmentation of the $\bar{c}$ antiquark into a $D^-$ meson result in the production of a $D^+D^-$ pair. The subsequent decay of the $D^+$
into $l^+X$ (for example, through the decay of $D^+ \to l^+K^0\nu$) and the decay of $D^-$ into $l^-X$ (for example, through the decay of $D^- \to l^-K^0\nu$) give rise to an $l^+l^-$ pair.

Dilepton production by nucleon-nucleon collisions through the intermediate $D^+D^-$ production provide an additional contribution to the dilepton spectrum. This contribution must be subtracted in order to extract the dileptons arising from the transient quark-gluon plasma.

There has been much work to investigate the mechanism for the production of $D^+D^-$ pairs [33-40]. Lowest order QCD results to study heavy quark production using the diagrams in Fig. 14.7 have been presented in Refs. [33]-[35]. It is generally recognized that charm production cannot be described by lowest order perturbative QCD diagrams in Fig. 14.7 because of the small value of the charm quark mass [36]-[41]. An additional phenomenological factor, similar to the $K$ factor in the Drell-Yan process (see Section §14.2.1), is needed to bring the calculated cross section to agree with experimental data [35].

Much work remains to be done to understand the spectrum of dileptons by charm production in nucleus-nucleus collisions. Higher order QCD effects can be included order by order in terms of the summation of amplitudes using Feynman diagrams, as is done in Ref. [36]-[39]. It can also be carried out using the phenomenological parton shower program PYTHIA where a parton splits into other partons with a probability distribution and the resultant strings are fragmented according to the Lund model of string fragmentation [40,41].

When we consider the production of $\mu^+\mu^-$ pairs through the intermediate stage of $D^+D^-$ production, we note that because of the large masses of the charm quark and $D^\pm$ mesons, the partons which participate in charm production need to have large momenta, which occur with a small probability. Furthermore, the $l^+\mu^-$ particle is the product of a multi-particle decay of the $D^\pm$ meson. The invariant mass of the $l^+\mu^-$ pair is only a fraction of the invariant mass of the originating $D^+D^-$ or the $c\bar{c}$ pair. In addition, the branching ratio for the the $D^\pm$ meson to decay into an $l^\pm$ is of the order of 10 percent. As a consequence of these factors, the estimates from Ref. [41] using the PYTHIA program show that the number of $\mu^+\mu^-$ pairs with $M > 1.5$ GeV arising from charm production is less than the number of dileptons from the Drell-Yan process, in nucleon-nucleon collision at 200 GeV on fixed targets. The dileptons produced via charm production have an approximately exponential invariant mass distribution with a slope parameter corresponding to an effective 'temperature' much smaller than the corresponding Drell-Yan process.

§14.3 Spectrum of Dileptons

It is of interest to inquire whether the dilepton yield arising from the produced matter in the quark-gluon plasma phase can be strong enough to make it observable. In order to be observable, the dilepton yield from the transient quark-gluon plasma must be greater than or comparable to the dilepton yields from non-quark-gluon-plasma sources.

In the region below an invariant mass of 1 GeV, the decays from $\rho$, $\omega$, and $\phi$ dominate over the production of low-mass $l^+l^-$ pairs arising from the possible formation of the quark-gluon plasma [42]. Furthermore, hadron collisions and charm meson production are dilepton sources with low temperatures and they contribute dileptons in the low invariant mass region. In the region below about 1 GeV, it may be difficult to separate out the quark-gluon plasma contribution to the dilepton spectrum.

If we examine dileptons with an invariant mass greater than 1.5 GeV and away from the resonance peaks, dileptons from hadron-hadron interactions and charm meson production may not be important. The dominant non-quark-gluon plasma contribution comes from the Drell-Yan process. It is of interest to compare dilepton production from the Drell-Yan process and from the quark-gluon plasma.

Equation (14.11) in Section 14.1 shows that dileptons produced by the transient quark-gluon plasma has an apparent temperature about the same as the initial temperature $T_0$ of the quarks in the plasma. Since the magnitude of the transition temperature is about 200 MeV (see Chapter 9), the magnitude of the initial temperature $T_0$ is of the order of a few hundred MeV. On the other hand, dileptons from
the Drell-Yan process has a distribution with an effective temperature $T_{DY}$ approximately $\sqrt{s}/(12$ to $15)$, as given by Eq. (14.25) or (14.19). For the RHIC collider with an energy of 100 GeV per nucleon, $\sqrt{s} = 200$ GeV. The dileptons from the Drell-Yan process have an effective temperature $T_{DY}$ of about 13 to 17 GeV, which is much greater than the effective temperature of the dileptons from the quark-gluon plasma. The large value of the effective temperature implies that the dilepton yield from the Drell-Yan process will be greater than the dilepton yield from the quark-gluon plasma at large dilepton invariant masses. At what value of the dilepton invariant mass will the dilepton yields from these two different sources be comparable and the role of the dominance of one signal over the other begins to reverse?

![Diagram](image)

**Fig. 14.8** The distribution $dN_{ll}/dM dy$ of $\ell^+\ell^-$ pairs at $y = 0$, as a function of the dilepton invariant mass $M$.

Clearly, the location where the dilepton yield from the quark-gluon plasma exceeds the dilepton yield from the Drell-Yan process depends on the quark-gluon plasma initial temperature, which is related to the initial dynamics of the collision process. The initial temperature can be obtained from the energy density, for which various estimates have been made [43]-[47]. Since the initial dynamics of the collision process remains a subject of current research, we shall examine the dilepton yield as a function of the initial temperature. We shall discuss $\mu^+\mu^-$

results; the $e^+e^-$ distributions behave in a similar way. Using Eq. (14.9) and assuming a transition temperature $T_0 = 200$ MeV and an initial time $\tau_0 = 1$ fm/c, we show in Fig. 14.8 dilepton yields for a quark-gluon plasma with initial temperatures $T_0 = 250, 300$ and $350$ MeV, in a head-on collision of Pb on Pb. In Fig. 14.8, we show the dilepton distribution for the Drell-Yan process estimated by using Eq. (14.32) and (14.19), at $\sqrt{s} = 200$ GeV. Schematic dilepton yields from resonances are also shown in Fig. 14.8, to indicate the locations where they may be important. Fig. 14.8 indicates that if the quark-gluon plasma initial temperature is greater than $350$ MeV, the dilepton yield from the quark-gluon plasma will be much greater than the dilepton yield from the Drell-Yan process in the region $1$ GeV $< M < 2.8$ GeV and the observation of dileptons from the quark-gluon plasma may be possible. If the quark-gluon plasma temperature is about $300$ MeV, the dilepton yield from the quark-gluon plasma will be greater than the dilepton yield from Drell-Yan processes only around $1$ to $1.6$ GeV. Observation of the dileptons from the quark-gluon plasma is possible but not as clean as at higher temperatures. On the other hand, at a still lower temperature, $T_0 = 250$ MeV, the dilepton yield from the Drell-Yan process is greater than the dilepton yield from the quark-gluon plasma and the signal from the quark-gluon plasma may be masked. The observation of dileptons from the quark-gluon plasma will depend on the initial temperature of the plasma. Because the energy density is approximately proportional to the fourth power of the temperature, an initial temperature of $300$ MeV corresponds to an energy density of the quark-gluon plasma about 5 times the transition energy density. Future experiments will reveal whether high-energy heavy-ion collisions will go through the transient state of the quark-gluon plasma with such an energy density or not.

§References for Chapter 14

1. Excellent reviews of dilepton production in high-energy heavy-ion collisions can be found in P. V. Ruuskanen, Nucl. Phys. A522, 255c (1991), P. V. Ruuskanen, Nucl. Phys. A544, 169c (1992), and Ref. 2.
Dileptons and direct photons at SPS

R. Shahoyan, CERN

Motivation and milestones
Excess in dilepton production
ϕ-puzzle
Photons
Why do we measure them

Convey dual information convoluted over the history of the collisions:

- probe surrounding matter properties: T, density, flow...
- probes themselves are affected by hot and dense matter

Modification of Vector Meson spectral functions close to Chiral Symmetry Restoration point:
VM broadening vs mass shift.

Thermal emission: both from QGP and Hadronic phase
Rich variety of dilepton contributions in hadronic phase:
- Low Mass Range (LMR, $m_{\mu\mu} \leq m_\phi$): resonant (VM, mostly $\rho$);
- Intermediate Mass Range (IMR, $m_\phi < m_{\mu\mu} < m_{J/\psi}$): continuum-like;
  rates determined by T (parton–hadron duality?)
  ⇒ need to disentangle experimentally QQP and HG contributions.

Strangeness ($\phi$) enhancement from abundantly produced in QGP

Quarkonia suppression by colour screening in QGP (covered by R.Arnaldi talk)

Caveats:
- experimental: small yields, strong backgrounds ...
- interpretational: underlying ‘conventional’ sources need to be understood ...
Milestones I

Helios-3  
**p-W, S-W @ 200 A GeV**: LMR/IMR enhancement

Thermal emission?

Strong $\pi a_1 \rightarrow \mu\mu$ contribution at IMR


---

NA38  
**p-W, S-U @ 200 A GeV**

NA50  
**p-Al,Cu,Ag,W @ 450 GeV**

**Pb-Pb @ 158 A GeV**

- IMR in p-A described by Drell-Yan and Open Charm
- Yields in Pb-Pb exceed the extrapolation from the p-A
- IMR excess resembles $(m, p_T)$: nuclear modifications?

Also described by thermal emission from GQP and HG


---

Nucl.Phys.A590 1995) 93c


**200 A GeV/c**

**Helios-3**

![Graph](image.png)


![Graph](image.png)


---

NA50  
**Pb-Pb 158 GeV/c**

**S-U 200 GeV/c**

**p-p 450 GeV/c**

Data/Expected sources

![Graph](image.png)

central collisions

**D0**

**DY**

---

$<N_{part}> = 381$
Milestones I

Helios-3  
\( p-W, S-W @ 200 \text{ A GeV} \) : LMR/IMR enhancement

Thermal emission?

Strong \( \pi a_1 \rightarrow \mu \mu \) contribution at IMR


\[ \text{NA38} \quad p-W, S-U @ 200 \text{ A GeV} \quad \text{NA50} \quad p-A \]

\( \text{Al, Cu, Ag, W @ 450 GeV} \quad \text{Pb-Pb @ 158 A GeV} \)

- IMR in p-A described by Drell-Yan and Open Charm
- Yields in Pb-Pb exceed the extrapolation from the p-A
- IMR excess resembles \((m, p_T)\) : nuclear modifications?

Also described by thermal emission from GQP and HG


\[ \text{Nucl. Phys. A590 1995) 93c} \]


Helios-3

\[ \text{200 A GeV/c} \]


\[ \text{NA50 Pb-Pb 158 GeV/c} \]

\[ \text{S-U 200 GeV/c} \]

\[ \text{p-p 450 GeV/c} \]

\[ \text{central collisions} \]

\[ \text{D\O} \]

\[ \text{DY} \]

\[ \text{NUCLEUS-NUCLEUS} \]
Milestones I

Helios-3  \( p-W, S-W \) @ 200 A GeV : LMR/IMR enhancement
Thermal emission?
Strong \( \pi a_1 \rightarrow \mu \mu \) contribution at IMR

NA38  \( p-W, S-U \) @ 200 A GeV  NA50  \( p-A, Cu, Ag, W \) @ 450 GeV  Pb-Pb @ 158 A GeV

• IMR in p-A described by Drell-Yan and Open Charm
• Yields in Pb-Pb exceed the extrapolation from the p-A
• IMR excess resembles \((m, p_T)\) : nuclear modifications?

Also described by thermal emission from GQP and HG

Nucl.Phys.A590 1995) 93c

\[ \begin{align*}
\text{Helios-3} \\
\text{200 A GeV/c} \\
\end{align*} \]
Milestones II / CERES measurements

- Two RICH detectors separated by solenoidal field
- 2 SiDC in vertex region
- trigger on multiplicity

p-Be,Au 450 GeV: good description by hadronic 'cocktail' decays

Central S-Au 200 A GeV excess: $5.0 \pm 0.7 \text{(stat)} \pm 2.0 \text{(syst)}$

---


- p-Be 450 GeV/u: $2.1 < \eta < 2.65$
- $p_T > 50 \text{ MeV/c}$
- $\langle dN_{ch}/d\eta \rangle = 3.8$

- p-Au 450 GeV/u: $2.1 < \eta < 2.65$
- $p_T > 50 \text{ MeV/c}$
- $\langle dN_{ch}/d\eta \rangle = 7.0$


- S-Au 200 GeV/u: $2.1 < \eta < 2.65$
- $p_T > 200 \text{ MeV/c}$
- $\langle dN_{ch}/d\eta \rangle = 125$

> 400 citations
LMR excess by CERES / S-Au 200 A GeV

\[ (\frac{d^2N_{ee}}{d\Omega dE}) / (100 \text{ MeV}/c^2) \]

Vacuum \( \rho \)

hadron decays after freezeout

Not described by \( \pi\pi \) annihilation in vacuum

\( \rho \) mass drop (Brown/Rho scaling): Li, Ko, Brown, Phys.Rev.Lett.75 (1995) 4007

\( \rho \) broadening: Chanfray, Rapp, Wambach, Phys.Rev.Lett. 76 (1996) 368
LMR excess by CERES / Pb-Au 158 A GeV

Excess seen in S-Au confirmed in Pb-Au 158 A GeV
2.73 ±0.25(stat) ±0.65(syst) ±0.82(decays)

1999 TPC upgrade: σ_M/M 6% ⇒ 4% at ρ/ω region

Effect of higher baryonic density?

The only dilepton data at 40 A GeV
higher excess: 5.9±1.5(stat)±1.2(syst)±1.8(decays)
Measuring dimuons in NA60

Radiation-hard silicon pixel **vertex tracker**

Muons from the **NA50** spectrometer matched to tracks in the vertex region:
- Improved mass resolution
- \( \mu \) offset wrt the vertex (\( \sigma \approx 40 \mu m, \sim 20 \text{ GeV} \))
  \( \Rightarrow \) prompt vs open charm (c\( \tau \)=123,312 \( \mu \text{m} \)) separation
- Dipole improves low-mass and low-\( p_T \) acceptance
- Matching rejects \( \pi, K \rightarrow \phi \) decay kinks \( \Rightarrow \) improved S/B
- Selective trigger, high luminosity

NA60 LMR data: peripheral (N_{ch}<30) In-In collisions

Well described by meson decay ‘cocktail’: \eta, \eta', \rho, \omega, \phi and \bar{D}D contributions

(Genesis generator developed within CERES and adapted for dimuons by NA60).

Similar cocktail describes NA60 p-Be, In, Pb 400 GeV data
EM transition form-factors for peripheral NA60 InIn data (hep-ph/0902.2547, submitted to PLB)

Acceptance-corrected data (after subtraction of $\eta, \omega$ and $\phi$ peaks) fitted by three contributions:

$$\frac{d\Gamma(\eta \to \mu^+ \mu^- \gamma)}{dm_{\mu\mu}^2} = \frac{2\alpha}{3\pi} \frac{\Gamma(\eta \to \gamma\gamma)}{m_{\mu\mu}^2} \left(1 - \frac{m_{\mu\mu}^2}{m_{\eta}^2}\right)^3 \left(1 + \frac{2m_{\mu}^2}{m_{\mu\mu}^2}\right)^{1/2} \left(1 - \frac{4m_{\mu}^2}{m_{\mu\mu}^2}\right)^{1/2} \times |F_{\eta}(m_{\mu\mu}^2)|^2$$

$$\frac{d\Gamma(\omega \to \mu^+ \mu^- \pi^0)}{dm_{\mu\mu}^2} = \frac{\alpha}{3\pi} \frac{\Gamma(\omega \to \pi^0\gamma)}{m_{\mu\mu}^2} \left(1 + \frac{2m_{\mu}^2}{m_{\mu\mu}^2}\right) \left(1 - \frac{4m_{\mu}^2}{m_{\mu\mu}^2}\right)^{1/2} \left(1 + \frac{m_{\mu\mu}^2}{m_{\omega}^2 - m_{\pi}^2}\right)^{1/2} \left(1 + \frac{m_{\mu\mu}^2}{m_{\omega}^2 - m_{\pi}^2}\right)^{3/2} \times |F_{\omega}(m_{\mu\mu}^2)|^2$$

$$\frac{dR(\rho \to \mu^+ \mu^-)}{dM} = \frac{\alpha^2 m_{\rho}^4}{3(2\pi)^4} \frac{\left(1 - \frac{4m_{\rho}^2}{M^2}\right)^{3/2} \left(1 + \frac{4m_{\rho}^2}{M^2}\right)^{1/2} \left(1 + \frac{m_{\rho}^2}{M^2}\right)^{1/2} \left(2\pi M\right)^{1/2}}{M^2 - m_{\rho}^2 + M^2 \Gamma^2} e^{-\frac{M^2}{2\pi M}}$$

- Confirmed anomaly of $F_{\omega}$ wrt the VDM prediction.
- Improved errors wrt the Lepton-G results.
- Removes FF ambiguity in the ‘cocktail’

In-In, peripheral data

- $\eta \to \mu^+ \mu^- \gamma$
- $\omega \to \mu^+ \mu^- \pi^0$
- $\rho \to \mu^+ \mu^-$

KW($\eta$)

KW($\omega$)
More central In-In data

- Excess isolated subtracting the measured decay cocktail (without $\rho$), independently for each centrality bin
- Based solely on local criteria for the major sources: $\eta$, $\omega$ and $\phi \Rightarrow 2-3\%$ accuracy.
  - No need of reference data ($pA$, peripheral data, models)
  - Less uncertainties (e.g. strangeness enhancement: $\eta, \phi$)
Excess above the cocktail $\rho$ (bound by $\rho/\omega=1.0$), centered at nominal $\rho$ pole

Monotonically rises and broadens with centrality

By coincidence, NA60 acceptance roughly removes the phase-space factor

$\Rightarrow$ $\rho$ spectral function convoluted over the fireball evolution is directly measured
Centrality dependence of LMR excess

**NA60, In-In 158A GeV**

In-In SemiCentral all $\rho_r$

- **L**
- **C**
- **U**

**peak:** $R = C - 1/2(L + U)$

**continuum:** $3/2(L + U)$

**cocktail $\rho$ is fixed by** $\rho/\omega = 1.0$

**Yield ratios**
- $0.2 < m < 0.6 \text{ GeV}/c^2$
- $m > 0.6 \text{ GeV}/c^2$


**CERES, Pb-Au 158A GeV**

**Excess rises faster than linear** with multiplicity: compatible with emission from annihilation processes

**95/96 data combined**

**Total excess wrt “cocktail” $\rho$: roughly indicative of the number of rho generations: $\rho$ – clock?**

**Question to theory:**
- can the fireball life-time be inferred?
- How does the modified $\rho$ life-time evolve?
LMR Excess: $\rho$ dropping mass vs broadening

Calculations by R. Rapp for both scenarios

Only broadening of $\rho$ observed; interactions with baryons is very important

Mass shift (Brown/Rho scaling) is ruled out.

(CERES data also described by flat spectral function: Kämpfer et al., Nucl. Phys. A 688 (2001) 939)
NA60 IMR data (1.16 < M < 2.56 GeV/c²)

Mass spectrum is similar to NA50:
Good description by Drell-Yan + ~2×Open Charm (extrapolated from pA data)

Such explanation is rejected by the spectra of dimuon offsets wrt the interaction vertex!

\[ \Delta_\mu = \sqrt{\Delta x^2 V_{xx}^{-1} + \Delta y^2 V_{yy}^{-1} + 2\Delta x \Delta y V_{xy}^{-1}} / 2 \]
\[ \Delta_{\mu\mu} = \sqrt{\Delta_{\mu1}^2 + \Delta_{\mu2}^2} / 2 \]

Data
Prompt: 1.10 (fixed)
Charm: 1.84±0.09
Fit \( \chi^2/NDF: 1.0 \)

Data
Prompt: 2.29±0.08
Charm: 1.16±0.16
Fit \( \chi^2/NDF: 0.6 \)

Offset fit shows that the enhancement is not due to Open Charm ⇒ the excess is prompt
NA60 IMR excess \((1.16 < M < 2.56 \text{ GeV/} c^2)\)

Mass shape and yield close to Open Charm contribution measured agrees within \(\sim 20\%\) with \(\bar{p}p\) NA50 pA data (same kinematical domain \(|\cos \theta_{\text{CS}}|<0.5\) \(\Rightarrow \) no strong \(\bar{D}\bar{D}\) modifications.

Scales with centrality faster than Drell-Yan (\(\sim N_{\text{bin.coll}}\)), but less faster than \(N_{\text{participants}}^2\)


NA60 excess: comparison to theory

- All known sources subtracted ('cocktail', Drell-Yan, Open Charm)
- Corrected for acceptance
- Integrated over $p_T$
- Absolute normalization: data and models.

mostly $\pi\pi$ annihilation in LMR (collisional broadening of $\rho$, strong effect from baryons),
$4\pi$ in IMR (full chiral mixing $\Rightarrow$ enhanced $\pi a_1 \rightarrow \mu \mu$), QGP contribution 20 – 60% (fireball scenario A ... C)

mostly $\pi\pi$ annihilation in LMR ($\rho$ spectral function by Eletsky et al, Phys.Rev.C 69 (2001) 035202),
QGP dominates (~80%) in IMR

hydrodynamic calculation with virial expansion of hadronic rates,
QGP contribution dominates in IMR: 60 – 90%
NA60 excess vs $p_T$: comparison to theory

Absolute normalization both for theory and data

Differences at low masses reflect differences in the tail of $\rho$ spectral function

Differences at high masses, $p_T$ reflect differences in flow strength
m_T spectra of NA60: excess

Fit of excess by \[ \frac{dN}{dm_T^2} \sim \exp\left(-\frac{m_T}{T_{\text{eff}}}\right) \]

('cocktail' \( \rho \) is not subtracted)

- \( T_{\text{eff}} \) rises up to the \( \phi \) mass, then drops
- Spectra steepen at low \( m_T \) (not for hadrons)

Confirmed by independent IMR excess analysis
m\textsubscript{T} spectra from NA60
Hierarchy of hadrons freeze-out


Large difference between $\rho$ and $\omega$

Blast wave analysis of NA60 data:
crossing of hadrons with $\pi$ defines $T_f$ and $\beta_{T\text{ max}}$ reached at respective hadron freeze-out
Suggests different freeze-out time for different hadrons: $\phi$ first, $\rho$ last (maximal coupling to pions)
**IMR**

**RR, DZ**: thermal emission dominates in the QGP phase, when flow has not yet built up

⇒ $T_{\text{eff}}$ are not affected by blue shift

⇒ no strong mass dependence

**RH**: emission from HG dominates

---

**LMR**

- Thermal emission dominates in HG phase
  (RH, RR, DZ models agree)

- Integration over the flow development
  ⇒ rise of $T_{\text{eff}}$ with mass

(RH: relatively week flow compensated by primordial contributions, but insufficient for pure in-medium LMR emission)

- Hadrons affected by different freeze-out times

---

**Expansion dynamics for 158A GeV In-In (schem.)**

\[ T_{\text{eff}} \approx <T_{\text{th}}> + M<v_{T}^2> \]

**T_{\text{th}}**

**T_{c}**

**T_{f}**

**only q\bar{q}**

**only hadrons (n\pi, ...)**

---

NA60 also measured the polarization (in the Collins-Soper frame) for $m \leq m_\phi$

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi$$

Lack of any polarization in excess (and in hadrons) supports emission from thermalized source.

Details in the presentation of G.Usai /session 4C/
Evidence of \( \omega \) in-medium effects?

Low-\( p_T \) \( \omega \)'s have more chances to decay inside the fireball?

Appearance of that yield elsewhere in the spectrum, due to \( \omega \) mass shift and/or broadening, unmeasurable due to masking by the much stronger \( \pi\pi \rightarrow \mu\mu \) contribution.

Disappearance of yield out of narrow \( \omega \) peak in nominal pole position

\( \Rightarrow \) Can only measure disappearance
NA60 results on omega yield suppression

Determine suppression vs $p_T$ with respect to $dN/dm_T^2 \sim \exp(-\omega_{\text{exp}}/(T_{\text{eff}}))$ extrapolated from $p_T>1\text{GeV/c}$

Account for difference in flow effects using the results of the Blast Wave analysis

Reference line: $\omega/N_{\text{part}} = 0.131 \text{ f.ph.s.}$

Strong centrality-dependent suppression at $p_T<0.8 \text{ GeV/c}$, beyond flow effects
Disagreement between results for $\phi$ in Pb-Pb 158A GeV

$\text{NA49} \quad \phi \rightarrow K^{+}K^{-} \quad (p_T < 1.6 \text{ GeV/c})$
$\text{NA50} \quad \phi \rightarrow \mu^{+}\mu^{-} \quad (p_T > 1.1 \text{ GeV/c})$


- NA50 sees >2 times higher yield than NA49
- Large difference in $T_{\text{eff}}$: $T_{\mu\mu} = 218 \pm 6 \quad T_{KK} = 305 \pm 15$
  
  In-medium effects on $\phi$ and K + K absorption and rescattering

$\Rightarrow$ reduced yield and harder $p_T$ spectrum in hadronic channel?

Recent developments:
CERES measured $\phi \rightarrow K^{+}K^{-}$ and $\phi \rightarrow e^{+}e^{-}$ channels in central Pb-Au 158A GeV  [Phys. Rev. Lett. 96 (2006) 152301]

$\Rightarrow$ Both channels agree with each other (large errors on $e^{+}e^{-}$ channel) and with NA49


$\Rightarrow$ Old results are confirmed within 8%

New results from NA60 in In-In 158 A GeV data:
comparison of $\phi \rightarrow \mu^{+}\mu^{-}$ and $\phi \rightarrow K^{+}K^{-}$
- **NA60** finds good agreement between the $\mu^+\mu^-$ and $K^+K^-$ channels $\Rightarrow$ no $\phi$–puzzle in In-In

- $T_{\text{eff}}$ in central In-In collisions is lower compared to central Pb-Pb of NA49 and CERES

- $<\phi>/N_{\text{part}}$ in central In-In collisions is lower than the NA50 results (f.ph.s), but slightly higher than measured by NA49 and CERES

**Details in the presentation of A.de Falco /session 5D/**
Direct photon (old) measurements at SPS

Extremely difficult to measure: large background from $\pi^0$ and $\eta'$ \(\Rightarrow\) very few results

(especially at low $p_T$ where QCD contribution is small)

15-20% upper limits (90%CL) wrt the hadronic sources for central S-Au 200 A GeV/c from


excess of up to 20±7% for $p_T$>1.5 GeV/c

Calculation by Turbide, Rapp and Gale within the same approach as for $l^+l^-$ Phys.Rev.C69 (2004) 014903

Even more difficult to interpret than in the case of dileptons:

- same ambiguity:
  close to the $T_c$ hadronic and partonic descriptions provide similar rates...
- no extra handle like mass, only $p_T$

Even more difficult to interpret than in the case of dileptons:

- same ambiguity:
  close to the $T_c$ hadronic and partonic descriptions provide similar rates...
- no extra handle like mass, only $p_T$
Direct photons from internal conversion?

**PHENIX**: interpret enhancement at $p_T >> m_{ee}$ as **internally converted direct photons** ('almost' real: $0.1 < m_{ee} < 0.3$ GeV/$c^2$, $p_T > 1$ GeV/$c$)

$\Rightarrow T_{\text{eff}} = 221 \pm 23 \pm 18$ MeV interpret as $T_{QGP}$ (weighted over the QGP evolution) $\Rightarrow T_i = 300 - 600$ MeV

**NA60** observes an excess at same masses

Smoothly continues to $m_{\mu\mu} > 0.3$ GeV/$c^2$ (in PHENIX also)

Exponential down to low $p_T$'s ('high' virtuality)

$T_{\text{eff}} = 183$ MeV fits well to the smooth rise with $M$ (flow) $\Rightarrow T_{th} \sim 160$ MeV

No evidence of direct 'real' photons?

---

![Graph showing $T_{eff}$ vs $p_T$ and $M$ vs $p_T$ with data points and fits for different processes](image.png)

**$T_i = 210 - 350$ MeV**

**$T_{eff} = 183 \pm 10$ MeV**

**Direct photons from internal conversion?**
Prospects from LHC?

Much higher $T_{\text{initial}}$ and life-time of the fireball $\Rightarrow$ stronger thermal emission of $\gamma, l^+l^-$

(Surprisingly, PHENIX sees excess only at $M < 750$ MeV/c$^2$, see next presentation by A.Drees)

Even higher background to cope with: $S_{\parallel}/B < 10^{-2}$ vs $10^{-1}$ on SPS

**ALICE, ATLAS, CMS**: excellent capabilities to measure photons (ALICE and CMS from $p_T \sim 1$ GeV/c)

[See presentation of D. Peressounko on photons in Alice /session 5D/]

Possibilities of $l^+l^-$ measurements below $J/\psi$ are limited by acceptance, tracking, PID

Currently, only **ALICE** has some preliminary estimates for low mass dileptons:

$\mu^+\mu^-$: no acceptance below $m_T \sim 1$ GeV/c due to the 0.5 GeV/c cut on single $\mu p_T$

e$^+e^-$: good PID using TPC+TRD for $p_T > 1$GeV/c

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### Meson

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<th>Meson</th>
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<th>$B[\times10^3]$</th>
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Expectations from Alice Muon Arm

1 month of Pb-Pb
Excess in dilepton emission at SPS: good agreement with models of thermal emission

- ‘Planck’-like mass spectra (slightly modified by non-flat spectral function in LMR)
- $T_{\text{eff}}$ rising with mass in LMR and, after sharp drop, flat in IMR
- Lack of polarization: emission from isotropic source
- Faster than linear scaling with $N_{\text{charged}}$
- LMR: major contribution from $\pi\pi$ annihilation
- IMR: naturally explained by mostly partonic radiation

First evidence of low-$p_T$ $\omega$ in-medium modifications in central In-In collisions

$\phi$-puzzle

- Pb-Pb: impossible to reconcile results of $\mu\mu$ from NA50 with KK from NA49 $ee$ and KK channels measured by CERES agree with each other and NA49
- In-In: $\mu\mu$ and KK channels measured by NA60 agree (both yield and $T_{\text{eff}}$)
  
  $<\phi>/N_{\text{part}}$ exceeds Pb-Pb value, $T_{\text{eff}}$ is in-between of conflicting Pb-Pb values

Direct photons: no conclusive results. Excess seen by WA98 in Pb-Pb is compatible with thermal emission but the errors are very large
Dileptons and Photons at RHIC Energies

- Introduction
- Experimental Results
  - We know our reference ... p+p data
  - Low mass dilepton enhancement in Au+Au
  - Direct virtual photons in Au+Au
- Comparison to Models
- Outlook
- Summary

C4-1 Y. Akiba: “Dilepton Radiation in PHENIX”
C4-3 Y. Yamaguchi: “Photons from PHENIX”
Lepton-Pair Continuum Physics

Modifications due to QCD phase transition
- Chiral symmetry restoration
- Continuum enhancement
- Modification of vector mesons

Sources "long" after collision:
- $\pi^0, \eta, \omega$ Dalitz decays
- $(\rho), \omega, \phi, J/\psi, \psi'$ decays

Early in collision (hard probes):
- Heavy flavor production
- Drell Yan, direct radiation

Baseline from p-p

Thermal (blackbody) radiation
- in dileptons and photons
- Temperature evolution

Medium modifications of meson
- $\pi\pi \rightarrow \rho \rightarrow l^+l^-$
- Chiral symmetry restoration

Medium effects on hard probes
- Heavy flavor energy loss

Large discovery potential also RHIC
Key Challenge for PHENIX: Pair Background

- No background rejection $\rightarrow$ Signal/Background $\geq 1/100$ in Au-Au
- Combinatorial background: $e^+$ and $e^-$ from different uncorrelated source
  \[ \pi^0 \rightarrow e^+e^-\gamma \quad \gamma \rightarrow e^+e^- \]
  - Need event mixing because of acceptance differences for $e^+$ and $e^-$
  - Use like sign pairs to check event mixing

- Unphysical correlated background
  - Track overlaps in detectors
  - Not reproducible by mixed events: removed from event sample (pair cut)

- Correlated background: $e^+$ and $e^-$ from same source but not "signal"
  - "Cross" pairs

Subtractions dominate systematic uncertainties
But are well under control experimentally!
Estimate of Expected Sources

- Hadron decays:
  - Fit $\pi^0$ and $\pi^\pm$ data $p+p$ or $Au+Au$
  
  \[ E \frac{d^3\sigma}{d^3p} = \frac{A}{\left(\exp(-ap_T - bp_T^2) + p_T/p_0\right)^n} \]
  - For other mesons $\eta$, $\omega$, $\rho$, $\phi$, $J/\psi$ etc. replace $p_T \rightarrow m_T$ and fit normalization to existing data where available

Hadron data follows “$m_T$ scaling”

- Heavy flavor production:
  - $\sigma_c = N_{coll} \times 567\pm57\pm193\mu b$ from single electron measurement

Predict cocktail of known pair sources

Axel Drees
Data and Cocktail of known sources represent pairs with $e^+$ and $e^-$ PHENIX acceptance

Data are efficiency corrected

Excellent agreement of data and hadron decay contributions with 30% systematic uncertainties
Charm and Bottom Contribution


\[ \sigma_c = 544 \pm 39 \text{ (stat)} \pm 142 \text{ (sys)} \pm 200 \text{ (model)} \mu b \]

Simultaneous fit of charm and bottom:

\[ \sigma_c = 518 \pm 47 \text{ (stat)} \pm 135 \text{ (sys)} \pm 190 \text{ (model)} \mu b \]

\[ \sigma_b = 3.9 \pm 2.4 \text{ (stat)} +3/-2 \text{ (sys)} \mu b \]
Measuring direct photons via virtual photons:

- any process that radiates $\gamma$ will also radiate $\gamma^*$
- for $m << p_T$ $\gamma^*$ is “almost real”
- extrapolate $\gamma^* \rightarrow e^+e^-$ yield to $m = 0 \rightarrow$ direct $\gamma$ yield
- $m > m_\pi$ removes 90% of hadron decay background
- $S/B$ improves by factor 10: 10% direct $\gamma \rightarrow$ 100% direct $\gamma^*$

Small excess at for $m << p_T$ consistent with pQCD direct photons
Au+Au Dilepton Continuum

Excess $150 < m_{ee} < 750$ MeV:
$3.4 \pm 0.2\text{(stat.)} \pm 1.3\text{(syst.)} \pm 0.7\text{(model)}$

hadron decay cocktail tuned to AuAu

Charm from PYTHIA filtered by acceptance
\[ \sigma_c = N_{\text{coll}} \times 567 \pm 57 \pm 193 \mu\text{b} \]

Charm “thermalized” filtered by acceptance
\[ \sigma_c = N_{\text{coll}} \times 567 \pm 57 \pm 193 \mu\text{b} \]

Intermediate-mass continuum: consistent with PYTHIA if charm is modified room for thermal radiation
Centrality Dependence of Low Mass Continuum

Excess region: 150 < m < 750 MeV

- Yield / \( (N_{\text{part}}/2) \) in two mass windows

- \( \pi^0 \) region: production scales approximately with \( N_{\text{part}} \)

- Excess region: expect contribution from hot matter
  - in-medium production from \( \pi\pi \) or qq annihilation
  - yield should scale faster than \( N_{\text{part}} \) (and it does)

\( \pi^0 \) region: \( m < 100 \) MeV

Excess mostly in central AuAu yield increase faster than \( N_{\text{part}} \)
Axel Drees

Dependence of Low Mass Enhancement

\[ p_T \text{ Dependence of Low Mass Enhancement} \]

\[ 0 < p_T < 8.0 \text{ GeV/c} \]

\[ 0 < p_T < 0.7 \text{ GeV/c} \]

\[ 0.7 < p_T < 1.5 \text{ GeV/c} \]

\[ 1.5 < p_T < 8.0 \text{ GeV/c} \]

\[ p+p \]

\[ \text{Au+Au} \]

\[ \text{Low mass excess in Au-Au concentrated at low } p_T! \]
Mass Dependent Dilepton $p_T$ Spectra

$p+p$ consistent with cocktail up to 3 GeV/c
Above $m_\pi$ Au+Au data enhanced for all $p_T$
most prominent for $p_T < 1$ GeV/c

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Local Slopes of Inclusive $m_T$ Spectra

Data have soft $m_T$ component not expected from hadron decays

Note: Local slope of all sources!

Soft component below $m_T \sim 500$ MeV:
- $T_{\text{eff}} < 120$ MeV independent of mass
- More than 50% of yield

- Data have soft $m_T$ component not expected from hadron decays
- Note: Local slope of all sources!
Dilepton Excess at High $p_T$ – Small Mass

(b) Au+Au (Min Bias)

1 < $p_T$ < 2 GeV
2 < $p_T$ < 3 GeV
3 < $p_T$ < 4 GeV
4 < $p_T$ < 5 GeV

hadron decay cocktail

Significant direct photon excess beyond pQCD in Au+Au
**Interpretation as Direct Photon**

Relation between real and virtual photons:

\[
L(M) = \sqrt{1 - \frac{4m_e^2}{M^2} (1 + \frac{2m_e^2}{M^2})}
\]

\[
\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \approx \frac{\alpha}{3 \pi M^2} L(M) \frac{d\sigma_\gamma}{dp_T^2 dy}
\]

Extrapolate real \(\gamma\) yield from dileptons:

\[
M \times \frac{dN_{ee}}{dM} \to \frac{dN_\gamma}{dM} \quad \text{for} \quad M \to 0
\]

Example for one \(p_T\) range:

Virtual Photon excess

At small mass and high \(p_T\)

Can be interpreted as real photon excess

![Graph showing excess *M (A.U.) vs. \(m_{ee}\) (GeV/c²)]

no change in shape can be extrapolated to \(m=0\)
First Measurement of Thermal Radiation at RHIC

• Direct photons from real photons:
  – Measure inclusive photons
  – Subtract $\pi^0$ and $\eta$ decay photons at $S/B < 1:10$ for $p_T < 3$ GeV

• Direct photons from virtual photons:
  – Measure $e^+e^-$ pairs at $m < m_p$

First thermal photon measurement: $T_{ini} > 220$ MeV $> T_C$
Comparison to Theoretical Models

A short reminder:

- Models for contributions from hot medium (mostly $\pi\pi$ from hadronic phase)
  - Vacuum spectral functions
  - Dropping mass scenarios

- $\pi\pi$ annihilation with medium modified $\rho$ works very well at SPS energies!
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In Medium Mesons at RHIC???

• Models calculations with broadening of spectral function:
  – Rapp & vanHees
    • Central collisions
      • + PHENIX cocktail
  – Dusling & Zahed
  – Bratkovskaya & Cassing

\( \pi\pi \) annihilation with medium modified \( \rho \) insufficient to describe RHIC data!

Axel Drees
• $\pi\pi$-annihilation with meson broadening
  – underestimates range 300 to 500 MeV

How about direct radiation?
Thermal Photon Contribution

\[ M \times \frac{dN_{ee}}{p_t dp_t dM dy} \propto \frac{dN_{\gamma^*}}{p_t dp_t dy} \]

Vaccuum EM correlator
Hadronic Many Body theory
Dropping Mass Scenario
QGP (qq annihilation only
\( q+g \rightarrow q+\gamma^* \) not included)

\[ \frac{dN_{\gamma}}{p_t dp_t dy} \]

Expect virtual photon yield
from QGP as large as from Hadron Gas

Real photon yield
Turbide, Rapp, Gale PRC69,014903(2004)

Central Au+Au (s^{1/2} = 200 A GeV)
\( <N_{ch}> = 800 \)
|y| < 0.35

\( q+g \rightarrow q+\gamma \) included

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Calculation of Thermal Photons

- Reasonable agreement with data
  - factors of two to be worked on..

- Initial temperatures and times from theoretical model fits to data:
  - \( T_{ini} = 300 \text{ to } 600 \text{ MeV} \)
  - \( \tau_0 = 0.15 \text{ to } 0.5 \text{ fm/c} \)
  - 0.15 fm/c, 590 MeV (d'Enterria et al.)
  - 0.2 fm/c, 450-660 MeV (Srivastava et al.)
  - 0.17 fm/c, 580 MeV (Rasanen et al.)
  - 0.33 fm/c, 370 MeV (Turbide et al.)
A VERY Naïve Speculation:

- Extrapolate direct photons to all mass, and

\[ \frac{d^2\sigma_{ee}}{dM^2 dt} = \frac{\alpha}{3\pi} \frac{L(M) d\sigma_{\gamma}}{dt} \times \left(1 + \frac{2u}{t^2 + s^2 M^2}\right) \]

Maybe not that simple! Needs a theorist to calculate properly!
Outlook into the Future (on Tape)

- Cu+Cu data finalized soon
  - Cover low $N_{\text{part}}$ range

- High statistics pp data (4x)
  - Continuum between $J/\Psi$ and $\Upsilon$
  - Even better reference including d+Au

- High statistics d+Au
  - Cold nuclear matter effects

Axel Drees

Poster by S. Campbell

Poster by J. Kamin
Open experimental issues

- Large combinatorial background prohibits precision measurements in low mass region!
- Disentangle charm and thermal contribution in intermediate mass region!

Need tools to reject photon conversions and Dalitz decays and to identify open charm

PHENIX $\rightarrow$ hadron blind detector (HBD) vertex tracking (VTX)

- HBD is fully operational
  - Proof of principle in 2007
  - Taking data right now with p+p
  - Expect large Au+Au data set in 2010

I’m looking forward to competition from STAR once TOF is completed.

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Summary

• Dilepton Data from PHENIX
  – background subtraction well controlled experimentally
  – well established p+p reference
  – discovered a low mass enhancement in central Au+Au
    • mostly in central collisions
    • mostly at low $m_T$ component with $T \sim 120$ MeV independent of mass
  – present a first measurement of thermal photons
    • indicate initial temperature $> 220$ MeV

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Backup Slides
Search for Thermal Photons via Real Photons

• PHENIX has developed different methods:
  – Subtraction or tagging of photons detected by calorimeter

The internal conversion method should also work at LHC!
Combinatorial Background: Like Sign Pairs

- Shape from mixed events
  - Excellent agreements for like sign pairs
  - Also with centrality and $p_T$

- Normalization of mixed pairs
  - Small correlated background at low masses from double conversion or Dalitz+conversion
  - Normalize $B_{++}$ and $B_{--}$ to $N_{++}$ and $N_{--}$ for $m > 0.7$ GeV
  - Normalize mixed $+ -$ pairs to
    \[
    \langle N_{+-} \rangle = 2 \sqrt{\langle N_{++} \rangle \langle N_{--} \rangle}
    \]
  - Subtract correlated BG

- Systematic uncertainties
  - Statistics of $N_{++}$ and $N_{--}$: 0.12 %
  - Different pair cuts in like and unlike sign: 0.2 %

Normalization of mixed events: systematic uncertainty = 0.25%
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Au-Au Raw Unlike-Sign Mass Spectrum

Unlike sign pairs data

Mixed unlike sign pairs normalized to:

$$\langle N_{-+} \rangle = 2\sqrt{\langle N_{++} \rangle \langle N_{--} \rangle}$$

Run with added Photon converter

2.5 x background

Excellent agreement within errors!

Systematic errors from background subtraction:

$$\frac{\sigma_{\text{signal}}}{\text{signal}} = \sigma_{\text{BG}}/\text{BG} \times \frac{\text{BG}}{\text{signal}} \rightarrow \text{up to 50% near 500 MeV}$$

$$0.25\% \quad \text{as large as 200!!}$$
p-p Raw Data: Correlated Background

**Cross pairs**
- Simulate cross pairs with decay generator
- Normalize to like sign data for small mass

**Jet pairs**
- Simulate with PYTHIA
- Normalize to like sign data

**Unlike sign pairs**
- Same simulations
- Normalization from like sign pairs

**Alternative method**
- Correct like sign correlated background with mixed pairs

\[ FG_+ (m_T, p_T) = 2 \sqrt{FG_- FG_{++}} \times \frac{BG_+}{2 \sqrt{BG_- BG_{++}}} \]

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Compare like sign data and mixed background

**TABLE III: Fit parameters.**

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$p_0$</th>
<th>$\chi^2$/NDF</th>
<th>$\chi^2$ test</th>
<th>max dist</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>0.000630 ± 0.000876</td>
<td>1.25</td>
<td>0.585</td>
<td>0.00133</td>
</tr>
<tr>
<td>10-20%</td>
<td>-0.000941 ± 0.00137</td>
<td>1.42</td>
<td>0.540</td>
<td>0.00175</td>
</tr>
<tr>
<td>20-40%</td>
<td>-0.00242 ± 0.00181</td>
<td>1.12</td>
<td>0.555</td>
<td>0.00370</td>
</tr>
<tr>
<td>40-60%</td>
<td>-0.00850 ± 0.00495</td>
<td>1.42</td>
<td>0.692</td>
<td>0.00986</td>
</tr>
<tr>
<td>60-92%</td>
<td>-0.0178 ± 0.0158</td>
<td>1.56</td>
<td>1.0187</td>
<td>0.0415</td>
</tr>
<tr>
<td>00-92%</td>
<td>-0.000259 ± 0.000633</td>
<td>1.45</td>
<td>0.509</td>
<td>0.00112</td>
</tr>
</tbody>
</table>

Evaluation in 0.2 to 1 GeV range

For all centrality bins mixed event background and like sign data agree within quoted systematic errors!!

Similar results for background evaluation as function $p_T$
Background Description of Function of $p_T$

Good agreement

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