Measurement of direct photons and dileptons in relativistic heavy-ion collisions

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Topical Collaboration on
Jet and Electromagnetic Tomography
of Extreme Phases of Matter in Heavy-ion Collisions

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Outline

• introduction
  • electromagnetic probes in heavy-ion collisions

• photon measurements
  • how to measure direct photons
  • results from pp and AA collisions

• dilepton measurements
  • how to measure dileptons
    • electron pairs
    • muon pairs
  • results from pp and AA collisions
INTRODUCTION

- Electromagnetic Probes in Heavy-Ion Collisions
QCD (Quantum Chromo Dynamics)

- strong interaction
  - binds quarks in hadrons
  - binds nucleons in nuclei

- described by QCD
  - interaction between particles carrying color charge
  - mediated by gluon exchange
  - gluons are colored themselves! (→ complicated vacuum)

- QCD: a very successful theory
  - jets / particle production with high momentum
  - heavy-flavor (charm & beauty) production
  - ...

- different “phases” of strongly interacting matter

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Strongly interacting matter

- naive picture of different phases of strongly interacting matter
  - increasing temperature → thermal motion and production of mesons
  - increasing density
→ hadrons „overlap“
→ quarks and gluons become the relevant degrees of freedom
main goal of relativistic heavy-ion physics
  - study the properties of nuclear matter, hadronic matter, and partonic matter

relations to other fields
  - nuclear physics
    - collective effects
    - in-medium effects
  - astrophysics
    - neutron stars
    - Supernovae
  - cosmology
    - early universe

only (!) experimental approach in the lab: nucleus-nucleus collisions
High energy heavy-ion accelerators

* fixed-target machines
  - ~1 AGeV beam energy $\Rightarrow \sqrt{s_{NN}} \sim 2$ GeV
    - Bevalac at LBNL, SIS at GSI
  - ~10 AGeV beam energy $\Rightarrow \sqrt{s_{NN}} \sim 5$ GeV
    - AGS at BNL (no dileptons, no „direct“ photons)
  - ~160 AGeV beam energy $\Rightarrow \sqrt{s_{NN}} \sim 17$ GeV
    - SPS at CERN
  - future: up to 30 AGeV beam energy $\Rightarrow \sqrt{s_{NN}} \sim 8$ GeV
    - SIS100(300) at FAIR

* colliders
  - ~100 AGeV beam energy $\Rightarrow \sqrt{s_{NN}} = 200$ GeV
    - RHIC at BNL
  - up to 2.25 ATeV beam energy $\Rightarrow \sqrt{s_{NN}} = 5.5$ TeV
    - LHC at CERN
BEVALAC at Berkeley

- BEVALAC = SuperHILAC + BEVATRON
SPS at CERN

- **SuperProtonSynchrotron (since 1976)**
  - **parameters**
    - circumference: 6.9 km
    - beams for fixed target experiments
      - protons up to 450 GeV/c
      - lead ions up to 158 GeV/c
  - **past**
    - SppS proton-antiproton collider
      → discovery of vector bosons $W^\pm$, $Z$
  - **present**
    - injector for LHC
  - **experiments**
    - Switzerland: west area (WA)
    - France: north area (NA)
SPS at CERN

- Super Proton Synchrotron
RHIC at Brookhaven

- Relativistic Heavy-Ion Collider
  - pp: $\sqrt{s} \leq 500$ GeV (polarized $p \rightarrow$ spin physics)
  - AA: $\sqrt{s_{NN}} \leq 200$ GeV (per nucleon-nucleon pair)

- Experiments with specific focus
  - BRAHMS (- 2006)
  - PHOBOS (- 2005)

- General purpose experiments
  - PHENIX
  - STAR
RHIC at Brookhaven

- Relativistic Heavy-Ion Collider
  - pp: $\sqrt{s} \leq 500$ GeV (polarized $p \rightarrow$ spin physics)
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- Experiments with specific focus
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LHC

- Large Hadron Collider 27 km ring
  - pp collisions: \( \sqrt{s} \leq 8 \text{ TeV} \)
    (design: 14 TeV)
  - Pb-Pb collisions: \( \sqrt{s_{NN}} \leq 2.76 \text{ GeV} \)
    (design: 5.5 TeV)
  - p-Pb collisions: \( \sqrt{s_{NN}} \leq 5.02 \text{ GeV} \)
    (design: 10.6 TeV)

- Global Language Monitor (2009)
  - word of the year:
    - but hadron came in at number 8
  - name of the year:
    - but LHC was number 4

source: Time Magazine
Experiments at the LHC

**ATLAS**
- General purpose
- Main focus pp
- Targeted AA program

**CMS**
- General purpose
- Main focus pp
- Targeted AA program

**ALICE**
- General purpose
- Main focus AA, pA

**LHCb**
- pp, B-physics
Pb-Pb collision in UrQMD

Pb+Pb $E_{cm}=5.5$ TeV

t=-19.00 fm/c

H. Weber / UrQMD Frankfurt/M
The experimental challenge

- Large Hadron Collider (LHC) at CERN
- Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
Schematic AA collision

- Hadronization
- Formation of QGP and thermalization
- Hard parton scattering
- Time
- Expansion
- Freeze-out
- Space
- γ, π, φ, Jet, pK, γ, π, e, Λ, c̅c, μ

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Probes for all time scales

- **bulk hadrons:** $\pi$, $K$, $p$
  - common, produced late (reflect freeze out but also initial state)
    - energy density
    - thermalization
    - collective motion

- **electromagnetic radiation:** $\gamma$, $e^+e^-$, $\mu^+\mu^-$
  - rare, no strong final state interaction
  $\Rightarrow$ probe for ALL time scales
  - black body radiation
    $\Rightarrow$ initial temperature (?)
  - in-medium properties of light vector mesons
    $\Rightarrow$ chiral symmetry restoration (?)

- **hard probes:** jets, heavy quarks, direct $\gamma$
  - rare, produced very early (prior to QGP formation)
    - interaction with produced hot and dense medium

production of $\sim$18000 charged particles per central collision
DIRECT PHOTONS

- how to measure direct photons
  - “real” photons
  - internal conversions
  - conversions in detector material
- yields and spectra from pp and AA collisions
- photon flow
HOW TO MEASURE DIRECT PHOTONS
Definition and challenges

- **direct photons are**
  - photons not originating from decays (experimentalists view I)
  - photons that are isolated (experimentalists view II)
  - photons that are created directly in hard scattering processes (theorists view?)

- **measurement is challenging**
  - large background from decay photons ($\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, and more)
  - finding isolated photons in large background in AA collisions
  - additional experimental difficulty: small opening angle of decay photons
    $\rightarrow \pi^0$ ($\eta$) decay photons merge into one detector signal
Direct photons in pp collisions

- late 1970’s: direct photons suggest existence of point-like charged objects within hadrons

- production processes
  - top row: quark-gluon Compton scattering (a), quark-antiquark annihilation (b)
  - bottom row: bremsstrahlung (a), jet fragmentation (b)

- test of QCD, processes well described

- direct photons can help to constrain gluon distribution functions
Direct photons in AA collisions - why?

- photons do not interact strongly and leave the medium (mostly) unaffected

- photons in different $p_T$ regions → sensitive to different issues
  - low $p_T$ (< 4 GeV/c): thermal photons, temperature of the QGP?
  - intermediate $p_T$ (between ~2 and 6 GeV/c): other sources from within the QGP (e.g. g from jet-plasma interaction)?
  - high $p_T$ (> 6 GeV/c): point like scaling of hard processes?

- ($\gamma$-hadron angular correlations
  - pp collisions: access to fragmentation functions
  - AA collisions: photon defines parton (jet) energy)

\[ q_{\text{hard}} + g_{\text{QGP}} \rightarrow \gamma + q \]

\[ \gamma-h \text{ azimuthal correlations} \]

\[ \text{transverse plane} \]
Photon sources in AA collisions

- Direct photons
- Decay photons
- Hard
- Direct fragmentation
Photon sources in AA collisions

- direct photons
- decay photons

Photon sources in AA collisions:

- these mechanisms are also present in pp collisions and are calculable within pQCD
Photon sources in AA collisions

- photons in AA
  - direct photons
  - decay photons

- hard
- direct
- fragmentation

**hard direct photons:**
**direct component**
(“prompt” photons)

- Compton
  \[ q + g \rightarrow \gamma + q \]
- annihilation
  \[ q + \bar{q} \rightarrow \gamma + g \]
Photon sources in AA collisions

- Direct photons
- Decay photons
- Hard direct photons: bremsstrahlung / fragmentation component
Photon sources in AA collisions

- direct photons
  - hard
  - pre-equilibrium photons
- thermal
- hard+thermal
  - jet-\(\gamma\)-conv.
  - medium induced \(\gamma\) bremsstrahlung

Photons in AA

Direct fragmentation

QGP

Hadron gas
Photon sources in AA collisions

- **direct photons**
- **pre-equilibrium photons**
- **thermal photons**
- **hard+thermal photons**

**direct**
- fragmentation
- QGP
- hadron gas

**pre-equilibrium photons**
- produced through rescattering of the primarily produced partons prior to thermalization
- difficult to treat theoretically

**hard+thermal photons**
- jet-$\gamma$-conv.
- medium induced $\gamma$ bremsstrahlung

** photons in AA**
- decay photons

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Photon sources in AA collisions

- Photons in AA
- Direct photons
- Decay photons
- Direct fragmentation
- Pre-equilibrium photons
- QGP
- Hadron gas
- Jet-$\gamma$-conv.
- Medium induced $\gamma$ bremsstrahlung

**Thermal photons**
- Reflect temperature of the system
- Caveat: produced over entire evolution of the system!
- Significant direct photon source only at low $p_T$
Photon sources in AA collisions

- direct photons
- decay photons
- pre-equilibrium photons
- thermal photons
- hard+thermal

**hard+thermal:**
jet-photon-conversion

Interaction of parton from hard scattering with soft parton:
\[ \sigma_{\text{jet-\gamma-conv}} \sim \delta^3 (p_{\text{jet}} - p_\gamma) \]

```
q_{\text{hard}} + g_{\text{QGP}} \rightarrow \gamma + q
q_{\text{hard}} + \bar{q}_{\text{QGP}} \rightarrow \gamma + g
```
Photon sources in AA collisions

- direct photons
- decay photons
- photons in AA

- direct
- fragmentation
- hard
- pre-equilibrium photons
- thermal
- hard+thermal
- jet-γ-conv.
- medium induced γ bremsstrahlung

medium induced photon bremsstrahlung
- due to multiple scattering of quarks in the medium
- different theoretical predictions, likely rather small contribution
Summary

sources of direct photons in AA collisions

- hard photons
- thermal photons
- photons form jet-plasma interaction
Schematic $\gamma$ spectrum: AA collisions

- thermal photons expected to be a significant contribution below $p_T \sim 3$ GeV/$c$
- hard photons dominant direct photon source for $p_T > \sim 6$ GeV/$c$
- jet-photon conversion might be significant contribution below $p_T \sim 6$ GeV/$c$
- experimental challenge: subtraction of decay photon background

Central Au+Au at RHIC

log scale

Photon Yield

$e^{-E_{\gamma}/T}$

Decay photons
$(\pi^0 \rightarrow \gamma\gamma, \eta \rightarrow \gamma\gamma, \ldots)$

$\approx 10$ GeV/$c$

hard: $\frac{1}{p_T^n}$

3 - 6 GeV/$c$

$p_T$ (GeV/$c$)
Direct photon predictions

- at RHIC

- at the LHC

- window for thermal photons from QGP in this calculation: $p_T = 1 - 3$ GeV/c

- window of opportunity extends to higher $p_T$
Photon rates in HG and QGP

- **total thermal photon spectrum:** QGP and hadron gas (HG) photon rates convoluted with space-time evolution of the system

- photon rates are similar for QGP and HG at the same temperature $T$

QGP rates: Arnold, Moore, Yaffe (2001)
How to measure real direct $\gamma$

- electromagnetic calorimeter measurement with isolation and shower shape cuts
  - works best in pp collisions and at high $p_T$

- statistical subtraction method
  - measure inclusive photon spectrum and subtract photons from hadron decays
    - inclusive photons can be measured directly with calorimeters or indirectly through conversions into $e^+e^-$ pairs
    - decay photon spectrum is calculated via simulations (using measured spectra of photon sources as input)

- tagging method
  - remove decay photons by tagging them, i.e. by identifying them as decay photon candidates (‘non isolation’)
Isolation cut: the idea

Compton

annihilation

Bremsstrahlung / fragmentation

transverse plane (momentum)

isolated direct photons: limit on transverse energy in a cone around the photon
Isolated photons with CMS

CMS Detector

- **Pixels**
- **Tracker**
- **ECAL**
- **HCAL**
- **Solenoid**
- **Steel Yoke**
- **Muons**

**Steel Return Yoke**
- ~13000 tonnes

**TWO-LEVEL TRIGGER SYSTEM**
- (Level-1 High-Level trigger)
- Each provide ~$10^3$ reduction

**SUPERCONDUCTING SOLENOID**
- Niobium-titanium coil carrying ~18000 A

**HADRON CALORIMETER (HCAL)**
- Brass + plastic scintillator
- ~7k channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~75k scintillating PbWO$_4$ crystals

**PRESHOWER**
- Silicon strips
- ~16m$^2$, ~137k channels

**FORWARD CALORIMETER**
- Steel + quartz fibres
- ~2k channels

**TOTAL WEIGHT**
- 14000 tonnes

**OVERALL DIAMETER**
- 15.0 m

**OVERALL LENGTH**
- 28.7 m

**MAGNETIC FIELD**
- 3.8 T
Opening angle of photons from $\pi^0$ decay

- increasing $\pi^0$ momentum
  - opening angle of decay photons decreases
  - clusters overlap in the calorimeter
Isolation requirements (CMS)

- $R$ measures the distance of a photon and other particles in pseudorapidity $\eta$ and azimuth $\phi$
  \[
  R^2 = (\eta - \eta^\gamma)^2 + (\phi - \phi^\gamma)^2
  \]
- three isolation requirements to reject photons from hadron decays
  - $\text{isoTRK} < 2 \text{ GeV/c}$ in $0.04 < R < 0.40$, excluding a rectangular strip of $\Delta \eta \times \Delta \Phi = 0.015 \times 0.400$ to remove the photon’s own energy if it converts into an $e^+e^-$
  - $\text{isoECAL} < 4.2 \text{ GeV}$ (transverse energy in ECAL in $0.06 < R < 0.40$, excluding again a central region for the photon)
  - $\text{isoHCAL} < 2.2 \text{ GeV}$ (transverse energy in HCAL)
- these conditions remove the bulk of the photons from neutral meson decays
Signal extraction

\[ \sigma_{\eta \eta}^2 = \sum_{i=1}^{25} w_i (\eta_i - \bar{\eta})^2 / \sum_{i=1}^{25} w_i \]

\[ w_i = \max\left(0, 4.7 + \ln\left(E_i / E\right)\right) \]

- calculate shower width, use towers in a 5x5 window around highest energy tower
- isolated photon yields extracted by fitting signal + background templates to measured shower width distribution
- signal template from MC (Pythia + Geant)
- background template determined in data-driven way
Statistical subtraction method

- measure ‘clean’ inclusive photon sample
  - understand detector effects, calibrations, geometry
  - subtract hadronic background
- measure $p_T$ spectrum of $\pi^0$ and $\eta$ mesons
- calculate number of decay photons per $\pi^0$
  - usually done with Monte-Carlo decayer
  - $m_T$ scaling for $(\eta), \omega, \ldots$
- finally:
  subtract decay background from inclusive photon spectrum
  \[ \gamma_{direct} = \gamma_{inclusive} - \gamma_{decay} \]

pocket formula:
\[
\frac{1}{p_T} \frac{dN}{dp_T} \propto \frac{1}{p_T^n}
\]
\[
\Rightarrow \frac{\gamma^{decay}_{\pi^0}}{\gamma_{\pi^0}} = \frac{2}{n-1} \approx 0.28 \text{ at RHIC}
\]
Example: PHENIX at RHIC

- **EMCal:**
  - PbSc (6 sectors) + PbGl (2 sectors)
- **PbSc:**
  - highly segmented lead scintillator sampling calorimeter
  - module size: 5.5 cm x 5.5 cm x 37 cm
- **PbGl:**
  - highly segmented lead glass Cherenkov calorimeter
  - module size: 4.0 cm x 4.0 cm x 40 cm
- **Ring Imaging Cherenkov Detector (RICH):**
  - electron identification (together with E/p matching in EMCal)
  - no signal for charged pions with $p < 4.6$ GeV/c

**pseudorapidity coverage:** $|\eta| < 0.35$
Statistical subtraction method

\[
\pi^0 \rightarrow \gamma + \gamma, \ \eta \rightarrow \gamma + \gamma, \ ...
\]

\[
\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{backgr}} = (1 - \frac{\gamma_{\text{backgr}}/\pi^0}{\gamma_{\text{inclusive}}/\pi^0}) \cdot \gamma_{\text{inclusive}}
\]

\[
= (1 - 1/R) \cdot \gamma_{\text{inclusive}}
\]

with \[ R = \frac{\gamma_{\text{inclusive}}}{\gamma_{\text{backgr}}} = 1 + \frac{\gamma_{\text{direct}}}{\gamma_{\text{backgr}}} \equiv \left( \frac{\gamma_{\text{inclusive}}/\pi^0}{\gamma_{\text{backgr}}/\pi^0} \right)_{\text{meas}} \frac{\gamma_{\text{backgr}}/\pi^0}{\gamma_{\text{inclusive}}/\pi^0}_{\text{calc}} \]

Calculated based on measured \( \pi^0 \) and \( \eta \) spectrum (includes \( \omega, \eta', \ldots \) decays)

Systematic uncertainties (e.g. energy scale non-linearity) partially cancel in this ratio
Decay photon cocktail

- “simple” Monte Carlo code
- pure kinematics (detector simulation not needed)
- \( \sim 96\% \) of the background photons originate from \( \pi^0 \) and \( \eta \) decays
- simulation based on measured \( \pi^0 \) spectra
- decay photons from other mesons are based on \( m_T \) scaling of the \( \pi^0 \) spectrum
Does $m_T$ scaling work?

- measure $\pi$ cross section and fit with power law, modified Hagedorn function, Tsallis parameterization
- $m_T$ scaling: replace $p_T$ with $\sqrt{(m^2-m_\pi^2+p_T^2)}$ in parameterization with $m$ being the mass of another hadron
- only free parameter: $h/\pi$ normalization, fixed at high $p_T$
- works extremely well!

PHENIX, PLB 670(2009)313
Inclusive photon yield

\[
\frac{1}{2\pi p_{T}N_{\text{in}}} \left. \frac{\text{d}^{2}N_{\gamma}}{\text{d}p_{T} \text{d}y} \right|_{\text{incl}} = \frac{1}{2\pi p_{T}N_{\text{in}}} \cdot \frac{(1 - X_{\text{n\bar{n}}}) \cdot (1 - X_{\text{ch}})}{\epsilon_{\gamma} \cdot a_{\gamma} \cdot c_{\text{conv}}} \cdot \frac{\Delta N_{\text{cluster}}}{\Delta p_{T} \Delta y},
\]

\text{fraction of neutral background (neutron, anti-neutrons)}

\text{fraction of charged clusters}

\text{efficiency}

\text{acceptance}

\text{photon conversion}
The ratio $\gamma/\pi^0$

$$ R = \frac{\gamma_{\text{inclusive}}}{\gamma_{\text{backgr}}} = 1 + \frac{\gamma_{\text{direct}}}{\gamma_{\text{backgr}}} \equiv \frac{(\gamma_{\text{inclusive}}/\pi^0)_{\text{meas}}}{(\gamma_{\text{backgr}}/\pi^0)_{\text{calc}}} $$

The ratio $\gamma/\pi^0$ calculated based on measured $\pi^0$ und $\eta$ spectra.
Result: double ratio

multiply inclusive photon spectrum by the double ratio to obtain direct-photon spectrum (and add systematic uncertainties of the inclusive photon spectrum which cancelled in the double ratio)
Systematic uncertainties

- $\pi^0$ measurement
  - peak extraction
  - yield correction (acceptance + efficiency)
  - energy scale

- inclusive photon measurement
  - hadronic background
  - yield correction (acceptance + efficiency)
  - energy scale

many systematic uncertainties of $\pi^0$ and photon measurements are highly correlated!

non-linearity in the EM calorimeter is also crucial. It is vital, for instance, that two 3 GeV photons have the identical response as one 6 GeV photon.
# Systematic uncertainties

- **example: PHENIX, Au-Au collisions in Run-2**

<table>
<thead>
<tr>
<th>$\pi^0$ error source</th>
<th>PbGl 3.25 GeV/c</th>
<th>PbGl 8.5 GeV/c</th>
<th>PbSc 3.25 GeV/c</th>
<th>PbSc 8.5 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield extraction</td>
<td>8.7%</td>
<td>7%</td>
<td>9.8%</td>
<td>7.2%</td>
</tr>
<tr>
<td>Yield correction</td>
<td>12%</td>
<td>12%</td>
<td>12%</td>
<td>13.3%</td>
</tr>
<tr>
<td>Energy scale</td>
<td>13.8%</td>
<td>14.1%</td>
<td>10.5%</td>
<td>11.4%</td>
</tr>
<tr>
<td>Total systematic</td>
<td><strong>20.3%</strong></td>
<td><strong>19.5%</strong></td>
<td>18.8%</td>
<td>19%</td>
</tr>
<tr>
<td>Statistical</td>
<td>10.6%</td>
<td>32.5%</td>
<td>3%</td>
<td>13.1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\gamma$ error source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-$\gamma$ correction</td>
</tr>
<tr>
<td>Yield correction</td>
</tr>
<tr>
<td>Energy scale</td>
</tr>
<tr>
<td>Total systematic</td>
</tr>
<tr>
<td>Statistical</td>
</tr>
</tbody>
</table>

- **treating photon and $\pi^0$ measurements as independent would yield a 28% systematic uncertainty for $\gamma/\pi^0$**

<table>
<thead>
<tr>
<th>$\gamma/\pi^0$ syst.</th>
<th>10.4%</th>
<th>10.4%</th>
<th>10.6%</th>
<th>10.6%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma/\pi^0$ stat.</td>
<td>10.7%</td>
<td>37.7%</td>
<td>3%</td>
<td>16.5%</td>
</tr>
</tbody>
</table>
Direct photons via internal conversion

- **motivation:**
  measure in low $p_T$ region where thermal photons are “abundant” and calorimetric measurements are difficult

- **internal conversion**
  - any source of real photons also emits virtual photons
  - example: $\pi^0$ Dalitz decay
  - rate and $m_{ee}$ distribution calculable in QED (Kroll-Wada formula)

- **hadron decays:** $m_{ee} < m_{hadron}$

- **no such limit for point-like processes,** such as direct photons

  improve signal-to-background ratio by measuring $e^+e^-$ pairs with $m_{ee} > \sim M_{pion}$
Kroll-Wada formula

number of virtual photons per real photon (in a given $\Delta \eta \Delta \varphi \Delta p_T$ interval):

$$\frac{1}{N_{\gamma}} \frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi m_{ee}} \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}} \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) S$$

hadron decay:

$$S = |F(m_{ee}^2)|^2 \left(1 - \frac{m_{ee}^2}{M_h^2}\right)^3$$

point-like process:

$$S \approx 1 \quad \text{(for } p_T^{ee} \gg m_{ee} \text{)}$$

about 0.001 virtual photons with $m_{ee} > m_{\pi\text{ion}}$ for every real photon

$\rightarrow$ possibility to avoid the $\pi^0$ decay background at the expense of a factor 1000 in statistics

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Extraction of direct photon signal

- two component fit

\[ f(m_{ee}) = (1 - r) \cdot f_{\text{cocktail}}(m_{ee}) + r \cdot f_{\text{direct}}(m_{ee}) \]

\[ \text{separately normalized to data at } m_{ee} < 30 \text{ MeV} \]

- deviation from hadronic cocktail \((\pi, \eta, \omega, \eta', \phi)\)

\[ \rightarrow \text{signal from virtual direct photons} \]

- direct photon fraction \(r\) from two-component fit

\[ r = \frac{\gamma^{*}_{\text{direct}}}{\gamma^{*}_{\text{inclusive}}} \mid m_{ee} < 30 \text{ MeV} \]

- fit yields good \(\chi^2/\text{NDF} (13.8 / 10)\)
External conversions: why?

- use $\gamma \rightarrow e^+e^-$ conversion (pair production) and get photon properties (energy, momentum) from pair

- use of tracking detectors for $e^\pm$ reconstruction
  $\rightarrow$ better resolution at low photon energy

- experiments use different methods for finding converted photons, depending on the detectors available

- ALICE: use displaced vertex reconstruction
  - find displaced vertex of $e^+e^-$ with tracking detectors
    $\rightarrow$ pair reconstructed as photon

- PHENIX: alternate track model
  - search for $e^+e^-$ pairs from conversion plane, then reconstruct photon properties for these pairs
ALICE: conversion reconstruction

- photons convert in material
- photon candidate = track pair
  - with opposite charges
  - not pointing back to primary vertex
  - small distance of closest approach

- $\pi^0$ candidate from $pp \rightarrow \pi^0 X$
  
  $$
  \pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^- + e^+e^- 
  $$

$pp$ at 900 GeV

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ALICE: conversion reconstruction

- necessary requirements
  - reasonably large photon conversion probability:
    in ALICE ~8.5% for $|\eta| < 0.9$ and $R < 1.8$ m
  - precise knowledge of material budget and implementation in
    GEANT based MC simulation for efficiency correction: current
    systematic uncertainty is ~4.5%

→ better resolution and higher purity of the photon sample at low $p_T$
  compared to calorimetric photon measurement
PHENIX: alternate track model

- reminder: no tracking close to event vertex (DC at $R \sim 2$ m, until recent addition of vertex trackers)
- photon conversions in the HBD shell ($R \approx 0.6$ m)
  - event vertex assumed as track origin in reconstruction
  - misreconstruction $\Rightarrow$ conversion pairs reconstructed with $m \neq 0$, instead mass is proportional to $R$
  - can correct for this with an alternate track model assumption
DIRECT PHOTON RESULTS

- pp COLLISIONS
p+p(\bar{p}) direct photon data and pQCD

● status as of ~ 2006

- decent agreement between data and NLO pQCD with one exception
  - cross sections from E706 (fixed target) substantially larger than predicted by NLO pQCD
  - questions:
    - can the introduction of additional transverse momentum (k_T) of initial partons solve the E706 vs. pQCD issue?
    - are the data sets mutually consistent?

Data from E706 fixed target experiment can be explained with NLO pQCD and additional broadening $\langle k_T \rangle \approx 1.3 \text{ GeV/c}$.
p+p(p) direct photon data and pQCD

- status as of ~ 2006

- only E706 data deviate from pQCD calculation

\[ x_T = \frac{2p_T}{\sqrt{s}} \]
Direct $\gamma$ in pp collisions at 200 GeV

- analysis includes a TOF cut to remove contamination from cosmics at very high $p_T$
- NLO pQCD calculation with three different factorization and renormalization scales are compared with data
- reasonably good agreement between theory and data over whole $p_T$ range

PHENIX, arXiv:1205.5533
Adding an isolation criterion

- applying isolation cut to photon candidates
  → most photons are isolated (~90% at high $p_T$)
- theoretical calculations agree with the data

PHENIX, arXiv:1205.5533
Isolated photons in pp collisions at 7 TeV

- photon reconstruction & selection efficiency determined using PYTHIA calculation: $\varepsilon = 0.916 \pm 0.034$
  (no significant dependence on photon energy)
- spectrum corrected for finite energy resolution
Isolated photons in pp collisions at 7 TeV

- agreement with NLO pQCD: very good!

(http://lapth.in2p3.fr/PHOX_FAMILY)

CMS $\sqrt{s} = 7$ TeV
L = 2.9 pb$^{-1}$
$|\eta^\gamma| < 1.45$
$E_T^{\gamma} < 5$ GeV

Data / JETPHOX 1.1
CT10 PDFs / BFG-II FFs
Stat. + syst. uncertainty
± 11% lumi. unc. not shown
Theory scale dependence
$E_T^\gamma/2 < \mu < 2 E_T^\gamma$
PDFs uncertainty
Direct photons in pp collisions vs. pQCD

- $x_T$ scaling of direct photon cross sections: data multiplied with empirical $(\sqrt{s})^n$ with exponent $n = 4.5$
- pure LO vector gluon exchange: $n=4$ as in Rutherford scattering
- scale breaking effects in QCD, empirically $n \rightarrow 4.5$
- all data are on one universal curve $\rightarrow$ QCD works!
Low $p_T$ direct photons in pp at the LHC?

- Signal predicted by NLO pQCD: much smaller than current (and future?!) systematic uncertainties of the measurement.
DIRECT PHOTON RESULTS

AA COLLISIONS
AA collision geometry: centrality

Centrality characterized (but NOT directly measured) via:

- \( b \): impact parameter
- \(<N_{\text{part}}\rangle\): number of nucleons, which took part in at least one inelastic nucleon-nucleon scattering
- \(<N_{\text{coll}}\rangle\): number of inelastic nucleon-nucleon collisions
- \(<N_{\text{part}}, N_{\text{coll}}\rangle\): from MC simulations based on Glauber model
Nuclear modification factor $R_{AA}$

- geometry of a nucleus-nucleus collision
  - participating nucleons: $N_{\text{part}}$
  - binary collisions: $N_{\text{coll}}$

- nuclear modification factor:
  $$R_{AA}(p_T) = \frac{1}{N_{\text{coll}}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- no medium effect
  - $R_{AA} = 1$ at high $p_T$

- medium effects (initial or final state)
  - $R_{AA} \neq 1$ at high $p_T$

- $R < 1$
  - "soft"

- $R = 1$
  - "hard"
Early SPS results: upper limits

**Early SPS results: upper limits**

![Graph showing upper limits for direct photon yields](image)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( p_T ) (GeV/c)</th>
<th>System</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>HELIOS 2(^1)</td>
<td>0.1 – 1.5</td>
<td>p-W, O-W, S-W</td>
<td>13%</td>
</tr>
<tr>
<td>WA80(^2)</td>
<td>0.4 – 2.8</td>
<td>O-Au</td>
<td>15%</td>
</tr>
<tr>
<td>CERES(^3)</td>
<td>0.4 – 2.0</td>
<td>S-Au</td>
<td>14%</td>
</tr>
<tr>
<td>WA80(^4)</td>
<td>0.5 – 2.5</td>
<td>S-Au</td>
<td>12.5%</td>
</tr>
</tbody>
</table>


early experiments at the CERN SPS only gave upper limits for direct photon yields
Photons as SPS: WA98 experiment

WA98 Experimental Setup
158 A GeV Pb+Pb Collisions at the CERN SPS (1996)

- Target (inside Plastic-Ball)
- Goliath Magnet
- Start Counter
- Plastic-Ball ($\pi^+, p, \ldots$ He in target region)
- Streamer Tubes
- Pad Chambers
- Time of Flight (#2) (PID of positive hadrons)
- Multistep Avalanche Chambers with CCD-readout (tracking of charged particles)
- Silicon-Pad and Silicon-Drift Detectors (pseudorapidity-dist. of charged particles)

- Had.-Calorimeter (transverse energy)
- Forward-Calorimeter
- Highly segmented Lead-Glass Calorimeter (identification of photons, $\pi^0$ and $\eta$-mesons)
- Charged Particle Veto-Detector
- Time of Flight (#1) (PID of negative hadrons)

fixed-target experiment: CMS at forward rapidity in the laboratory

Pb+Pb at $\sqrt{s_{NN}} = 17.3$ GeV

Columbus, Ohio, 6/2013
WA98 direct photon result

- no signal within experimental uncertainties in peripheral collisions
- 20% direct photon excess at high $p_T$ in central Pb-Pb collisions at the CERN SPS


158 A GeV $^{208}$Pb + $^{208}$Pb
Peripheral Collisions

Central Collisions

Transverse Momentum (GeV/c)
WA98 direct photon spectrum

- subtract background from inclusive photon spectrum
  → direct photon spectrum

- consistent with
  - hard scattering?
  - nuclear $k_T$ broadening?

- better pp and p-A data desirable

- unlikely that Pb-Pb spectrum is from hard scattering only

Cronin effect:
multiple soft scattering in p-A collision prior to hard scattering ("nuclear $k_T$")
Interpretation of the WA98 data

- interplay between $T$ and $k_T$
- contribution from QGP seems to be small
Direct $\gamma$ at the SPS: T or $k_T$?

- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons
- Data described with initial temperature $T_i = 205$ MeV + some nuclear $k_T$ broadening (Cronin-effect)
- Data also described without $k_T$ broadening but with high initial temperature ($T_i = 270$ MeV)
WA98: direct photons at low $p_T$

- two-photon correlations observed:
  attributed to Bose-Einstein correlations of direct $\gamma$
- correlation strength used to extract direct photon signal at low $p_T$
- possible explanation: photon bremsstrahlung from hot hadron gas

(Lui, Rapp, nucl-th/0604031)
Direct $\gamma$ at the SPS: conclusions

- data can be described under a variety of different assumptions:

<table>
<thead>
<tr>
<th>Authors</th>
<th>Model</th>
<th>Initial Temperature $T_i$</th>
<th>$\tau_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbide, Rapp, Gale (Phys.Rev.C69:014903,2004)</td>
<td>QGP + HG + pQCD with $k_T$</td>
<td>$T_i = 205$ MeV, $\tau_0 = 1$ fm/c</td>
<td></td>
</tr>
<tr>
<td></td>
<td>QGP + HG + pQCD without $k_T$</td>
<td>$T_i = 250 - 270$ MeV, $\tau_0 = 0.5$ fm/c</td>
<td></td>
</tr>
<tr>
<td>Renk (Phys.Rev.C67:064901,2003)</td>
<td>QGP + HG + pQCD</td>
<td>$250 &lt; T_i &lt; 370$ MeV, $0.5 &lt; \tau_0 &lt; 3$ fm/c</td>
<td></td>
</tr>
<tr>
<td>Svrivastava (nucl-th/0411041)</td>
<td>QGP + HG + pQCC (Bjorken hydro)</td>
<td>$T_i = 335$ MeV, $\tau_0 = 0.2$ fm/c</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pure HG + pQCD (Non-boost inv. hydro)</td>
<td>$T_i = 213 - 234$ MeV</td>
<td></td>
</tr>
</tbody>
</table>

- data consistent with QGP picture, but also with pure HG picture
- large variation in extracted initial temperature $T_i$
  (however, most models give $T_i > T_c$)
Direct photons with PHENIX at RHIC

- two spectrometer arms at mid-rapidity: $|\eta| < 0.35$
Direct $\gamma$ in Au-Au collisions at RHIC

Au-Au at $\sqrt{s_{NN}} = 200$ GeV
PHENIX, PRL 94(2005)232301

$T_{AB}$: nuclear overlap function

- high $p_T$ direct photons scale with $<T_{AB}>$
- no indication of nuclear effects

$T_{AB} = \langle N_{coll} \rangle / \sigma_{NN}^{inel}$

$0 - 10\%$: $
\langle N_{coll} \rangle = 955 \pm 94$

$60 - 92\%$: $
\langle N_{coll} \rangle = 14.5 \pm 4$
Centrality dependence of direct $\gamma$ and $\pi^0$

- Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV

- Direct photons follow $T_{AB}$ scaling (binary scaling) for $p_T > 6$ GeV/c

NLO pQCD used as $p+p$ reference
The high $p_T$ region: from pp to AA

- binary scaling is not perfect

arXiv:1208.1234

PRL 109(2012)152302
Centrality dependence at the highest $p_T$

- direct photon $R_{AA}$ consistent with unity up to the highest measured $p_T$ for all centralities

PRL 109(2012)152302
Additional evidence: \( v_2 \) of direct photons

- Direct photon \( v_2 \) should be \(~0\) AT HIGH \( p_T \)
  (modulo fragmentation or jet-medium photons)

- Confirmed in the experiment

PHENIX, PRL 109(2012)122302
Jet quenching at RHIC

- hadrons are suppressed, direct photons are not
- direct photon $R_{AA} \rightarrow$ binary scaling makes sense
Pb-Pb collisions at the LHC

● does the picture hold?

Isolated $\gamma$:
ATLAS, ATLAS-CONF-2012-051
CMS, PLB 710 (2012) 256

Z boson:
ATLAS, arXiv:1210.6486
ATLAS, PLB 697 (2011) 294]
CMS, PRL 106 (2011) 212301

W boson:
ATLAS, ATLAS-CONF-2011-78
CMS, PLB 715 (2012) 66

● direct photons, W, Z follow binary scaling!
THERMAL PHOTON RESULTS
Real vs. virtual photon measurement

\[ R_\gamma = \frac{N(\gamma^{\text{inc}})}{N(\gamma^{\text{B.G.}})} \]

- real photon
- virtual photon

\[ p_T \text{ [GeV/c]} \]

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Direct photon fraction: $pp \rightarrow Au-Au$

- direct photon fraction compared with NLO pQCD expectation

- no excess in $pp$ and $d$-$Au$ collisions but strong excess in $Au$-$Au$ collisions
**A measurement of the QGP temperature?**

- **pp:** spectrum described with
  \[ f_{p+p}(p_T) = A \cdot (1 + p_T^2 / b)^{-n} \]

- **Au-Au:** enhancement above pp described by an exponential (as expected for a thermal source)
  \[ f_{Au+Au}(p_T) = \frac{N_{coll}}{\sigma_{NN}^{inel}} \times f_{p+p}(p_T) + B \times e^{-\frac{p_T}{T}} \]

  • inverse slope parameter!
  \[ T = (221 \pm 23 \pm 18) \text{ MeV} \]

  a lower limit for the initial temperature?

---

**PHENIX**

\[ \gamma_{direct} = \gamma_{all} - \gamma_{decay} \]

**EMCal measurements**

**internal conversion method**


132301
One model comparison

- Model space-time evolution with ideal hydro
  - Hydro starts early ($\tau = 0.2$ fm/c)
  - Thermal equilibrium at $\tau_0 = 0.6$ fm/c; $T_{\text{initial}} = 340$ MeV
  - Photons from jet-plasma interaction needed to account for measured photon yield

similar conclusions for essentially all hydro models on the market

$T_{\text{initial}} > T_C \Rightarrow$ evidence for QGP formation?
Comparison with various models

![Graph showing comparison between initial temperature ($T_{\text{initial}}$) and time until equilibration ($\tau_0$) for different models. The graph includes data points for various models such as D. d’Enteria, S. Rasanen, D.K. Srivastava, S. Turbide, F. Liu, and J. Alam. The slope parameter of 221 MeV is indicated, along with $T_c$ from lattice QCD. The graph highlights initial temperatures above $T_c$ in all models.]

- $T_{\text{initial}}$ (MeV)
- Time until equilibration ($\tau_0$) in fm/c
- $T_c$ from lattice QCD
- Initial temperature above $T_c$ in all models

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Thermal photons at the LHC

- ALICE measurement via external conversion also done in Pb-Pb collisions
  - remember: no significant excess in pp collisions
  - same in peripheral Pb-Pb: no significant signal
  - central Pb-Pb → significant direct photon signal
    - low $p_T$: signal is also significantly above NLO pQCD
    → additional (thermal) photons
Direct photon spectrum at the LHC

inverse slope parameter from exponential fit:
\[ T = 304 \pm 51 \text{ MeV} \]

compare to RHIC:  \[ T = 221 \pm 23 \pm 18 \text{ MeV} \]

\[ \Rightarrow T(\text{LHC}) > T(\text{RHIC}) \]
Direct photon $v_2$ at RHIC

\[ v_2^{\text{dir}} = \frac{R_{\gamma} v_2^{\text{inc}} - v_2^{\text{decay}}}{R_{\gamma} - 1} \]
\[ R_{\gamma} = \frac{\gamma^{\text{inc}}}{\gamma^{\text{decay}}} \]

- $v_2^{\text{inc}}$ from calorimeter measurement
- Direct photon $v_2 > 0$ at low $p_T$
- As large as pion $v_2$
Cross check: external conversions

- use different method for $\gamma$ measurement: external conversions
- first: check $R_\gamma \rightarrow$ OK

- use different method for $\gamma$ measurement: external conversions
- second: check $v_2 \rightarrow$ OK
Direct photon $v_2$ at the LHC

- ALICE measurement of direct photon $v_2$ in 0-40% central Pb-Pb collisions $\Rightarrow v_2 > 0$ in thermal photon region
- consistent with observation at RHIC
Direct photon $v_2$: what does it mean?

Hydro after $\tau_0$

- expected $v_2$:
  - prompt photons: 0 (time zero)
  - thermal photons

- early
- late

small (flow not built up yet)

large (like hadrons)

Chatterjee, Srivastava
PRC79, 021901 (2009)
Theory comparison

Calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

slope of low $p_T$ direct photons spectrum points to early emission, $v_2$ suggests late emission from mixed/hadronic phase

- how to control the emission time??
Thermal radiation from AA collisions

- thermal radiation ($\gamma, l^+l^-$) sensitive to temperature and collective motion of source
  - Planck spectrum $\Rightarrow$ yield $\propto T^4$, mean $\propto T$
  - transverse and longitudinal expansion $\Rightarrow$ blue and/or red shift
  - integrated over space-time evolution

- photon and dilepton momentum spectrum
  - sensitive to temperature
  - sensitive to collective expansion

- dilepton mass spectrum is Lorentz invariant
  - sensitive to temperature

- dileptons
  - $dN/dM$: thermometer of the source
  - $d^4N/dMd^3p$: map of the space-time evolution
DILEPTON MEASUREMENTS - SHORT VERSION
Lepton-pair physics: topics

- known sources of lepton pairs

  - emitted over the full evolution of the collision
  - reach detectors undistorted from strong FSI
  - modifications expected due to the QCD phase transition(s)

- lepton pairs are
  - rich in physics
  - experimentally challenging

known sources of lepton pairs

- chiral symmetry restoration
- continuum enhancement
- modification of vector mesons

suppression (enhancement)

thermal radiation

Drell-Yan

\( \frac{dN_{ee}}{dydm} \)

mass [GeV/c^2]

Low- Intermediate- High-Mass Region

0 1 2 3 4 5
HI low-mass dileptons at a glance

- time scale of experiments

85 90 95 00 05 10

= period of data taking

ALICE/CMS

HADES

(KEK E235)

CERES

DLS

NA60

PHENIX / STAR

CBM
HI low-mass dileptons at a glance

- energy scale of experiments

today’s topic

- HADES
- CBM
- NA60
- PHENIX / STAR
- ALICE/CMS

DLS (KEK E235) CERES

$\sqrt{s_{NN}}$ [GeV]

[200] [158] [17] [10] [A GeV]

[ALICE/CMS] [PHENIX / STAR] [NA60] [CBM] [DLS] (KEK E235) CERES

Columbus, Ohio, 6/2013

Ralf Averbeck, GSI
### Dilepton experiments @ SPS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>System</th>
<th>Mass range</th>
<th>Publications</th>
</tr>
</thead>
<tbody>
<tr>
<td>HELIOS-1</td>
<td>μμ ee</td>
<td>p-Be (86)</td>
<td>low mass</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Z.Phys. C68 (1995) 64</td>
</tr>
<tr>
<td>HELIOS-3</td>
<td>μμ</td>
<td>p-W,S-W (92)</td>
<td>low &amp; Intermediate</td>
</tr>
<tr>
<td>CERES</td>
<td>ee</td>
<td>pBe, pAu, SAu (92/93)</td>
<td>low mass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pb-Au (95)</td>
<td>PRL (1995) 1272</td>
</tr>
<tr>
<td>CERES-2</td>
<td>ee</td>
<td>Pb-Au 40 GeV (99)</td>
<td>low mass</td>
</tr>
<tr>
<td>NA38/NA50</td>
<td>μμ</td>
<td>p-A, S-Cu, S-U, Pb-Pb</td>
<td>low (high (m_T)) intermediate</td>
</tr>
<tr>
<td>NA60</td>
<td>μμ</td>
<td>p-A, In-In (2002,2003)</td>
<td>&gt;2(m_\mu)</td>
</tr>
</tbody>
</table>
The CERES/NA45 experiment
Dielectron analysis strategy

- tracking

  - electron identification

    - $\pi^0$-Dalitz and $\gamma$-conversion rejection

    - pairing

      - subtraction of background (like-sign or mixed events)

        - efficiency correction

          - mass spectrum
Experimental setup: CERES-1

UV detector 2

W-shield
SiDC1/SiDC2

main coils

radiator 1

mirror 1

radiator 2

mirror 2

MWPC

multiplicity array

beam

target

UV detector 1

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Target region

- segmented target
  - 13 Au disks (thickness: 25 μm; diameter: 600 μm)

- Silicon drift chambers:
  - provide vertex: $\sigma_z = 216$ μm
  - provide event multiplicity ($\eta = 1.0 - 3.9$)
  - powerful tool to recognize conversions at the target
Electron identification: RICH

- main tool for electron ID
- use the number of hits per ring (and their analogue sum) to recognize single and double rings
**e^+e^- in p+Be & p+Au collisions**

- dielectron mass spectra and expectation from a ‘cocktail’ of known sources
  - Dalitz decays of neutral mesons ($\pi^0 \rightarrow \gamma e^+e^-$ and $\eta, \omega, \eta', \phi$)
  - dielectron decays of vector mesons ($\rho, \omega, \phi \rightarrow e^+e^-$)
  - semileptonic decays of particles carrying charm quarks

$\rightarrow$ dielectron production in ‘pp’ and ‘pA’ collisions at SPS well understood in terms of known hadronic sources!
What about heavy-ion collisions?

- discovery of low mass $e^+e^-$ enhancement in 1995
- significant excess in S-Au (factor ~5 for $m>200$ MeV)
As heavy as it gets: Pb+Au

- Dielectron excess at low and intermediate masses in HI collisions is well established
  - Onset at $\sim 2 \text{ m}_\pi$ → $\pi-\pi$ annihilation?
  - Maximum below $\rho$ meson near 400 MeV → Hint for modified $\rho$ meson in dense matter

- Resonances not resolved

CERES-1 $\rightarrow$ CERES-2

- Addition of a TPC to CERES
  - Improved momentum resolution
  - Improved mass resolution
  - $dE/dx \rightarrow$ hadron identification and improved electron ID
  - Inhomogeneous magnetic field $\rightarrow$ a nightmare to calibrate!
CERES: Pb+Au at 158 AGeV

- high resolution analysis
  - large excess yield in the low-mass region
  - also between $\omega$ and $\phi$
  - enhancement factor $(0.2 < m < 1.1 \text{ GeV/c}^2)$
    $\Rightarrow 3.1 \pm 0.3 \text{ (stat.)}$

- but the improvement in mass resolution isn’t ‘outrageous’
CERES: low-mass dilepton enhancement

- central AA collisions: strong enhancement of low-mass dilepton production compared to pA (CERES, HELIOS)
- inconsistent with vacuum properties of vector mesons
  → needed are
  - pion annihilation
  - in-medium modifications of vector meson properties
  - broadening and/or mass shift of the $\rho$ meson
And what about $p_T$ dependence?

- **Low mass $e^+e^-$ enhancement at low $p_T$**
  - Qualitatively in agreement with $\pi\pi$ annihilation
  - $p_T$ distribution has little discriminative power

\[ m_{ee} < 0.2 \text{ GeV/c}^2 \]
\[ 0.2 < m_{ee} < 0.7 \text{ GeV/c}^2 \]
\[ m_{ee} > 0.7 \text{ GeV/c}^2 \]
Centrality dependence of excess

- naïve expectation: quadratic multiplicity dependence
  - medium radiation $\propto$ particle density squared
- more realistic: smaller than quadratic increase
  - density profile in transverse plane
  - life time of reaction volume
CERES: theory versus data

- interpretations invoke
  - $\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-

- added to the cocktail:
  - calculation by R. Rapp using Rapp/Wambach medium modification of the $\rho$ spectral function
  - calculation by R. Rapp using Brown-Rho scaling
  - calculation by B. Kämpfer invoking thermal radiation

- model vs. data
  - in $0.8 < m < 0.98$ GeV:
    - Brown-Rho: $\chi^2/n = 2.4$
    - other two: $\chi^2/n = 0.3$
What did we get from CERES?

- first systematic study of $e^+e^-$ production in elementary and HI collisions at SPS energies
  - pp and pA collisions are consistent with the expectation from known hadronic sources
  - a strong low-mass low-$p_T$ enhancement is observed in HI collisions
  → consistent with in-medium modification of the $\rho$ meson
  → data can’t distinguish between two scenarios
    → dropping $\rho$ mass as direct consequence of CSR
    → collisional broadening of $\rho$ in dense medium

WHAT IS NEEDED FOR PROGRESS?
- STATISTICS
- MASS RESOLUTION
How to overcome these limitations

- more statistics
  - run forever → not an option
  - higher interaction rate
    - higher beam intensity
    - thicker target
  - needed to tolerate this
    - extremely selective hardware trigger
    - reduced sensitivity to secondary interactions, e.g. in target
  → can’t be done with dielectrons as a probe, but dimuons are just fine!

- better mass resolution
  - stronger magnetic field
  - detectors with better position resolution
  → silicon tracker embedded in strong magnetic field!
The NA60 experiment

- a huge hadron absorber and muon spectrometer (and trigger!)
- and a small, high resolution, radiation hard vertex spectrometer
• thick hadron absorber to reject hadronic background
• trigger system based on fast detectors to select muon candidates (1 in $10^4$ PbPb collisions at SPS energy)
• muon tracks reconstructed by a spectrometer (tracking detectors+magnetic field)
• extrapolate muon tracks back to the target taking into account multiple scattering and energy loss, but ...
  • poor reconstruction of interaction vertex ($\sigma_z \sim 10$ cm)
  • poor mass resolution (80 MeV at the $\phi$)
A step forward: the NA60 case

- 2.5 T dipole magnet
- Hadron absorber
- Targets
- Beam tracker
- Vertex tracker
- Muon trigger and tracking
- Magnetic field
- Origin of muons can be determined accurately
- Improved dimuon mass resolution

Matching of muon tracks
The NA60 pixel vertex spectrometer

- 12 tracking points with good acceptance
  - 8 small 4-chip planes
  - 8 large 8-chip planes in 4 tracking stations
- ~3% $X_0$ per plane
  - 750 $\mu$m Si readout chip
  - 300 $\mu$m Si sensor
  - ceramic hybrid
- 800,000 readout channels in 96 pixel assemblies
Vertexing in NA60

Beam Tracker sensors

windows

$\sigma_z \sim 200 \, \mu m$ along the beam direction

Good vertex identification with $\geq 4$ tracks

Resolution $\sim 10 - 20 \, \mu m$ in the transverse

Extremely clean target identification (Log scale!)
Contributions to mass resolution

- **two components**
  - multiple scattering in the hadron absorber
    - dominant at low momentum
  - tracking accuracy
    - dominant at high momentum

- **high mass dimuons (~3 GeV/c^2)**
  - absorber doesn’t matter

- **low mass dimuons (~1 GeV/c^2)**
  - absorber is crucial
  - momentum measurement before the absorber promises huge improvement in mass resolution

→ track matching is critical for high resolution low mass dimuon measurements!
Muon track matching

- track matching has to be done in
  - position space
  - momentum space
- to be most effective
  → the pixel telescope has to be a spectrometer!
Improvement in mass resolution

- Unlike sign dimuon mass distribution before quality cuts and without muon track matching

\[ \sigma_M(\phi) \sim 80 \text{ MeV} \]
\[ \sigma_M(J/\psi) \sim 100 \text{ MeV} \]

- Drastic improvement in mass resolution
- Still a large unphysical background

No centrality selection
opposite-sign pairs
combinatorial background
fake matches
signal pairs

S=360000
S/B=1/7
Nothing is perfect: fake matches

- fake match: $\mu$ matched to wrong track in pixel telescope
  - important in high multiplicity events

- how to deal with fake matches
  - keep track with best $\chi^2$ (but is it right?)
  - embedding of muon tracks into other event
  - identify fake matches and determine the fraction of these relative to correct matches as function of
    - centrality
    - transverse momentum

[Graph showing signal and fake matches with $\chi^2$ axis]
Event mixing: like-sign pairs

- compare measured and mixed like-sign pairs

accuracy in NA60: ~1% over the full mass range
NA60: dimuon invariant mass


- Peripheral collisions: well described by meson decay cocktail + charm (DD)

- More central collisions: clear excess of data above decay cocktail → spectra shape of excess?
Isolation of excess dimuons

- Subtraction of measured decay cocktail (w/o $\rho$), based on local criteria for the major sources: $\eta$, $\omega$, $\phi$

- $\omega$ and $\phi$: fix yields such as to get, after subtraction, a smooth underlying continuum

- $\eta$: fix yield at $p_T > 1$ GeV profiting from the sensitivity of the spectral shape of the Dalitz decay spectrum to any underlying admixture from other sources; lower limit from peripheral data

- Accuracy: 2-3%, but results are robust to mistakes even at the 10% level

- Contribution from charm decays (DD) determined via binary scaled PYTHIA calculation (consistent with NA60 data!)
Sensitivity to spectral function

- models for contributions from the hot medium (mostly $\pi\pi$ from hadronic phase)
  - vacuum spectral function
  - dropping mass scenario
  - broadening of spectral function
- yields normalized to data for $m < 0.9$ GeV
- broadening of spectral function clearly favored

$\pi\pi$ annihilation with medium modified $\rho$ works well at SPS energies!
Role of baryons

- whole spectrum described quite well, even in absolute terms
- this model: low-mass tail requires baryon interactions

baryons play an important role at SPS energies!
Acceptance correction

- individual contributions can be acceptance corrected
  - meson yield ($\eta$, $\rho$, $\omega$, $\phi$)
  - open heavy flavor
  - dimuon excess (assume $\gamma^*$)

- acceptance correction with separate treatment of the individual sources
  - in 4-dimensional space $M-p_T-y-\cos\theta_{CS}$
  - project to 2-dim. corrections, e.g. $M-p_T$
  - iterative, data-driven procedure

- acceptance vs. $M$, $p_T$, $y$, and $\cos\theta_{CS}$ under control within better than 10%
M-\(p_T\) matrix of excess

- after acceptance correction
Dimuon excess

• Planck-like dimuon mass spectrum for $M > 1$ GeV
  • 1.1 – 2.0 GeV: $T = 205 \pm 12$ MeV
  • 1.1 – 2.4 GeV: $T = 230 \pm 10$ MeV

• model comparison
  • main sources for $M < 1$ GeV
    - $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$
    - broadening spectral function
  • main sources for $M > 1$ GeV
    - $qq \rightarrow \mu^+\mu^-$
    - $\pi a_1 \rightarrow \mu^+\mu^-$
      (consistent up to 1.5 GeV)

Dimuons with $M > 1$ GeV mostly of partonic origin
**Dimuon excess: transverse mass spectrum**

$m_T$ spectra exponential for $m_T-M > 0.1$ GeV

$\Rightarrow$ fit with $1/m_T \, dN/dm_T \propto e^{-m_T/T_{eff}}$

- soft component for $m_T-M < 0.1$ GeV?
  - not seen for hadrons, only dileptons
Mass ordering of hadronic slopes

- separation of thermal and collective motion
- reminder
  - blast wave fit to all hadrons simultaneously
- simplest approach
  \[ T_{\text{eff}} \approx T_{\text{th}} + \frac{1}{2} M \left\langle v_T \right\rangle^2 p_T \ll M \]
- slope of \(<T_{\text{eff}}\) vs. M is related to radial expansion
- baseline is related to thermal motion
- works (at least qualitatively) at SPS
Unfolding the time evolution

- inverse slope vs. \( M \) for “thermal” dimuons
  - \( M < 1 \text{ GeV} \)
    → from hadronic phase
    \( T_{\text{eff}} \) grows linearly with \( M \)
    \( <T_{\text{th}}> \sim 140 \text{ MeV} < T_c \)
  - \( M > 1 \text{ GeV} \)
    → from partonic phase
    \( <T_{\text{th}}> \sim 200 \text{ MeV} > T_c \)

- schematic evolution
  - partonic phase
    early emission: high \( T \), low \( v_T \)
  - hadronic phase
    late emission: low \( T \), high \( v_T \)

\[ \chi^2 \text{ inverse slope vs. } M \]

- “thermal” dimuons
  - \( M < 1 \text{ GeV} \)
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    \( T_{\text{eff}} \) grows linearly with \( M \)
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\[ \chi^2 \text{ inverse slope vs. } M \]

- schematic evolution
  - partonic phase
    early emission: high \( T \), low \( v_T \)
  - hadronic phase
    late emission: low \( T \), high \( v_T \)

- dimuons with \( M > 1 \text{ GeV} \)
  mostly of partonic origin
Electromagnetic probes

- experimentally (and theoretically) challenging
- consistent picture is emerging
- lot of ‘real estate’ left for further exploration of properties of strongly interacting matter