Direct Photons in p+p and A+A Collisions:
A Short Introduction

Lecture week of the Helmholtz Research School for Quark Matter Studies in Heavy Ion Collisions
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- Direct Photons in A+A: Overview
- Measurement of Direct Photons in A+A Collisions
- Results on Direct Photon Production in A+A Collisions (Measured With Real Photons)
- The Internal Conversion Method
- Direct Photon Flow
Why Direct Photons?

- Direct Photons
  - Definition (heavy-ion flavor): Photons not coming from hadron decays
  - Definition (particle physics flavor): Isolated Photons
  - Difficult measurement: Large Background from $\pi^0 \rightarrow \gamma+\gamma$, $\eta \rightarrow \gamma+\gamma$
  - Exp. problem at high $p_T$ (calorimeters, $E(\pi^0) > \sim 20$ GeV): merging of $\pi^0$ ($\eta$) decay photons

- p+p:
  - Late 1970’s: Direct Photons suggested presence of point-like charged objects within hadrons
  - Test of QCD
  - Focus now on constraining gluon distribution functions
    - Quark-Gluon Compton scattering contributes at leading order (LO)
    - This is in contrast to Deep Inelastic Scattering and Drell-Yan where gluon is involved only at NLO
  - However, direct photon data often not used in global fits due to discrepancies between data and theory
Why Direct Photons in Nucleus-Nucleus Collisions? Because They Escape the Medium Unscathed!

- Direct photon yields at low $p_T (<5 \text{ GeV}/c)$
  - Measure thermal photons → initial temperature of the fireball
  - Find further photon sources related to presence of the QGP (e.g. photons from jet-plasma interaction)

- Direct photon yields at high $p_T$
  - Confirm point-like scaling for hard processes

- Direct $\gamma$-hadron azimuthal correlations
  - p+p: measure fragmentation function
  - A+A: $E_\gamma = E_{\text{jet}}$ → study parton energy loss for partons with known initial energy
Direct Photon Measurement: Methods

- **Isolated photons + shower shape cuts**

- **Statistical subtraction Method**
  - Measure inclusive photon spectrum and subtract photons from hadron decays
  - Inclusive photon spectrum via
    - Electromagnetic calorimeters
    - External conversion

- **Hanbury Brown-Twiss (HBT) Method**
  - Bose-Einstein correlation expected for direct photons
  - Direct photon yield from correlation strength
Direct Photons in p+p
p+p(p bar) Direct Photon Data and pQCD – Status as of ~ 2006 (I)

- Decent agreement at large $\sqrt{s}$
- Substantial deviations between data and NLO pQCD at small $\sqrt{s}$

Questions:

- Is there a systematic pattern of deviation?
- If so, can the introduction of additional transverse momentum ($k_T$) of initial partons improve the agreement?
- Are the data sets mutually consistent?
Is $k_T$ Broadening Needed to Describe Direct Photon Data?

- Data from E706 fixed target experiment can be explained with $\langle k_T \rangle \approx 1.3 \text{ GeV/c}$

E706, Phys.Rev.D70:092009,2004

Is there evidence for $k_T$ broadening in $p+p$ at larger $\sqrt{s}$?
Only E706 data show strong deviation from NLO QCD. Probably need new data at low $\sqrt{s}$ to settle the issue.
Isolation Cuts

Compton

Annihilation

Bremsstrahlung / Fragmentation

\[ \gamma \rightarrow p_x \]

\[ \gamma \rightarrow p_y \]
Isolation Cuts

Compton

Annihilation

Bremsstrahlung / Fragmentation

Isolated direct photons: Limit on transverse energy in a cone around the photon

Transverse plane (Momentum)

\[ p_x \]

\[ p_y \]
An Example of an Isolated Photon Measurement (CMS)
Isolated Photon Measurement (CMS): Isolation Cuts

- Photon candidates must satisfy three isolation requirements that reject photons produced in hadron decays
  - IsoTRK < 2 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-
  - IsoECAL < 4.2 GeV (transverse energy in ECAL in 0.06 < \( R < 0.40 \), excluding again a central region for the photon)
  - IsoHCAL < 2.2 GeV (transverse energy in HCAL)

- These conditions remove the bulk of the photons from neutral meson decays

\[
R^2 = (\eta - \eta^\gamma)^2 + (\phi - \phi^\gamma)^2
\]

[Minimum Opening Angle of $\pi^0$ Decay Photons]

\[ \theta_{\text{min}} = 2 \arctan \left( \frac{m}{p} \right) \]
Isolated Photon Measurement (CMS): Signal Extraction

\[ \sigma^2_{\eta\eta} = \frac{\sum_{i=1}^{25} w_i (\eta_i - \bar{\eta})^2}{\sum_{i=1}^{25} w_i} \]

\[ \omega_i = \max(0, 4.7 + \ln(E_i/E)) \]

- Isolated photon yields extracted by fitting signal + background templates to measured shower width distribution
- Signal template from MC (Pythia + Geant)
- Background template determined in a data-driven way
Isolated Photon Spectrum in p+p at 7 TeV (CMS)

- The photon reconstruction and selection efficiencies are determined from PYTHIA:
  \( \varepsilon = 0.916 \pm 0.034 \) (rather independent of photon energy)

- Spectrum corrected for finite energy resolution

Isolated Photons in p+p at 7 TeV: Agreement with NLO pQCD

Direct Photon Search in p+p at the LHC at Low $p_T$: A Tough Job

Possible signal much smaller than systematic errors
Direct Photons in A+A: Overview
Known and Presumed Photon Sources in A+A

- Direct Photons
  - hard
  - direct
  - fragmentation
- Decay Photons
- Photons in A+A
Known and Presumed Photon Sources in A+A

These mechanisms are also present in p+p collisions and are calculable within pQCD.
Known and Presumed Photon Sources in A+A

Hard direct photons:
- **Direct component**
- Compton
- Annihilation
Hard direct photons: direct component

Compton
\[ q + g \rightarrow \gamma + q \]

Annihilation
\[ q + \bar{q} \rightarrow \gamma + g \]
Known and Presumed Photon Sources in A+A

Hard direct photons:
- bremsstrahlung /
- fragmentation component

Decay Photons

Direct Photons

Known and Presumed Photon Sources in A+A
Known and Presumed Photon Sources in A+A

- **Direct Photons**
  -硬的（hard）
  -预平衡（Preequilibrium）光子
- **Decay Photons**
  -硬的+热的（hard+thermal）
  -QGP（Quark-Gluon Plasma）
  -hadron gas（强子气）
  -jet-γ-conv.（jet-γ- conversion）
  -medium induced γ bremsstr.（介质诱导的γbremsstrahlung）
Known and Presumed Photon Sources in A+A

**Preequilibrium photons**
- Produced through rescattering of the primarily produced partons prior to thermalization
- Difficult to treat theoretically

Diagram showing the sources of photons in A+A collisions:
- Direct Photons
  - Hard
  - Direct
  - Fragmentation
  - Preequilibrium photons
- Thermal Photons
  - QGP
  - Hadron gas
- Hard+thermal Photons
  - Jet-\(\gamma\)-conv.
  - Medium induced \(\gamma\) bremsstr.

- Photons in A+A
- Decay Photons
Known and Presumed Photon Sources in A+A

- Direct Photons
  - hard
  - Preequilibrium photons
  - direct fragmentation

- thermal
  - QGP
  - Hadron gas

- Decay Photons
  - hard+thermal
  - jet-\(\gamma\)-conv.
  - Medium induced \(\gamma\) bremsstr.

**Thermal photons**
- Reflect temperature of the system, produced over entire evolution
- Significant direct photon source only at low \(p_T\)
Photons in A+A

Direct Photons

Decay Photons

Hard

Preequilibrium photons

direct fragmentation

QGP Hadron gas

Hard+thermal

jet-γ-conv.

Medium induced γ bremsstr.

Hard+thermal: Jet-Photon-Conversion

Interaction of parton from hard scattering with soft parton

\[ \sigma_{\text{jet-γ-conv}} \sim \delta^3 (p_{\text{jet}} - p_{\gamma}) \]

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

\[ q_{\text{hard}} + \bar{q}_{\text{QGP}} \rightarrow \gamma + g \]
Known and Presumed Photon Sources in A+A

Medium induced photon bremsstrahlung
- Due to multiple scattering of quarks in the medium
- Different theoretical predictions, likely rather small contribution
Summary: Direct Photons in A+A Collisions - Hard, Thermal, Hard+Thermal

- **Hard photons**
  - Photons form jet-plasma interaction

- **Thermal photons**

- **Photons form jet-plasma interaction**
Schematic Photon Spectrum in A+A

- Thermal photons expected to be 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
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Direct Photons in A+A: Realistic Calculation

Window for thermal photons from QGP in this calculation:

\[ p_T = 1 - 3 \text{ GeV}/c \]

Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004
Photon Rates in HG and QGP

- Final thermal photon spectrum: QGP and HG photon rates convoluted with space-time evolution of the reaction
- Very similar thermal photon rates for QGP and hadron gas at same temperature \( T \)

QGP rates: Arnold, Moore, Yaffe (2001)
Measurement of Direct Photons in A+A Collisions
Measurement of Direct Photons with the Subtraction Method

- Get clean inclusive photon sample
- Measure $p_T$ spectrum of $\pi^0$ and $\eta$ mesons with high accuracy
- Calculate number of decay photons per $\pi^0$
  - Done with Monte-Carlo
  - $m_T$ scaling for ($\eta$, $\eta'$, $\omega$, ...)
- Finally:
  Subtract decay background from inclusive photon spectrum

Pocket formula:

$$\frac{1}{p_T} \frac{dN_{\pi^0}}{dp_T} \propto \frac{1}{p_T^n}$$

$$\frac{\gamma_{\pi^0}^{\text{decay}}}{\pi^0} = \frac{2}{n-1} \approx 0.28 \text{ at RHIC}$$

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}}$$
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$$\Rightarrow \frac{\gamma^\text{decay}_{\pi^0}}{\pi^0} = \frac{2}{n-1} \approx 0.28 \text{ at RHIC}$$

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}}$$
Direct Photons: Statistical Subtraction Method

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

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

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

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

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

Systematic errors (e.g. energy scale non-linearity) partially cancel in this ratio
Pocket Formula for Decay Photons

Decay photon $p_T$ distribution for $\pi^0$'s with a given trans. momentum

$$g(p_T, p_T, \pi^0) \approx \begin{cases} 
\frac{2}{p_T, \pi^0}, & p_T < p_T, \pi^0 \\
0, & \text{else}
\end{cases}$$

For

$$\frac{1}{p_T} \frac{dN_{\pi^0}}{dp_T} \propto p_T^{-n} :$$

$$\frac{\gamma_{\text{decay}} - \pi^0}{\pi^0} \bigg|_{p_T} = \frac{\int_{p_T}^{\infty} g(p_T, p_T, \pi^0) \frac{dN_{\pi^0}}{dp_T, \pi^0} dp_T, \pi^0}{\int_{p_T}^{\infty} p_T^{-n+1} dp_T, \pi^0} = \frac{2 \cdot \int_{p_T}^{\infty} p_T^{-n} dp_T, \pi^0}{p_T^{-n+1}} = \frac{2}{n - 1}$$
Decay Photon Calculation

- Simple Monte Carlo code
- Pure kinematics (no detector simulation needed)
- ~96% of the background photons from $\pi^0$ and $\eta$ decays
Background Photons from $K_s^0 \rightarrow \pi^0 + \pi^0$

Probability to miss a $\pi^0$ from $K_s^0 \rightarrow \pi^0 + \pi^0$ in the $\pi^0$ reconstruction due to displaced decay vertex

\[ K_s^0 : c\tau_0 = 2.67 \text{ cm} \]
\[ L_{\text{lab}} = v \cdot \gamma \cdot \tau_0 = \beta \cdot \gamma \cdot \tau_0 \cdot c \]
\[ \beta \cdot \gamma = \frac{p}{mc} \]

<table>
<thead>
<tr>
<th>$p$</th>
<th>1 GeV</th>
<th>5 GeV</th>
<th>10 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle L_{\text{lab}} \rangle$</td>
<td>5.37 cm</td>
<td>26.9 cm</td>
<td>53.7 cm</td>
</tr>
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</table>
Formula for Fully Corrected Inclusive Photon Spectrum

\[
\frac{1}{2\pi p_T N_{\text{in}}} \left. \frac{d^2 N_{\gamma}}{dp_T dy} \right|_{\text{incl}} = \frac{1}{2\pi p_T N_{\text{in}}} \cdot \frac{(1 - X_{n\bar{n}}) \cdot (1 - X_{\text{ch}})}{\varepsilon_\gamma \cdot a_\gamma \cdot c_{\text{conv}}} \cdot \frac{\Delta N_{\text{cluster}}}{\Delta p_T \Delta y},
\]
Formula for Fully Corrected Inclusive Photon Spectrum

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

Fraction of charged clusters
Formula for Fully Corrected Inclusive Photon Spectrum

\[
\frac{1}{2\pi p_T N_{in}} \frac{d^2 N_\gamma}{dp_T dy}_{incl} = \frac{1}{2\pi p_T N_{in}} \cdot \left( 1 - X_{n\bar{n}} \right) \cdot \left( 1 - X_{ch} \right) \cdot \frac{\Delta N_{\text{cluster}}}{\Delta p_T \Delta y},
\]

- Fraction of neutral background (neutron, anti-neutrons)
- Fraction of charged clusters
Formula for Fully Corrected Inclusive Photon Spectrum

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

- **Fraction of neutral background (neutron, anti-neutrons)**
- **Fraction of charged clusters**
- **Efficiency**
Formula for Fully Corrected Inclusive Photon Spectrum

\[
\frac{1}{2\pi p_T N_{in}} \frac{d^2N_\gamma}{dp_T dy}_{incl} = \frac{1}{2\pi p_T N_{in}} \cdot \frac{(1 - X_{n\bar{n}})}{\varepsilon_\gamma \cdot a_\gamma \cdot c_{conv}} \cdot \frac{\Delta N_{cluster}}{\Delta p_T \Delta y} \cdot (1 - X_{ch})
\]
Formula for Fully Corrected Inclusive Photon Spectrum

\[
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\]

- Fraction of neutral background (neutron, anti-neutrons)
- Fraction of charged clusters
- Efficiency
- Acceptance
- Photon conversion
Charged Background: $X_{\text{ch}}$

- $X_{\text{ch}} > 0$ at high $p_T$ largely due to photon conversion
- Artificial decay photon-charged hit (PC3) correlations at high $p_T$:

**Diagram**

- $X_{\text{ch}}$ vs $p_T$ (GeV/c)
- PID0, PID1, PID2, PID3 markers
- Final correction

**Legend**

- EmCal
- PC3
- Conversion
- $\gamma$ $\gamma$
- $\pi^0$
Charged Background: $X_{\text{ch}}$

- $X_{\text{ch}} > 0$ at high $p_T$ largely due to photon conversion
- Artificial decay photon-charged hit (PC3) correlations at high $p_T$:

![Graph showing $X_{\text{ch}}$ vs. $p_T$](image)

- Final correction

Additional diagram showing the conversion process: $\gamma \rightarrow \pi^0$.
Charged Background: $X_{ch}$

- $X_{ch} > 0$ at high $p_T$ largely due to photon conversion
- Artificial decay photon-charged hit (PC3) correlations at high $p_T$:

![Graph showing $X_{ch}$ vs. $p_T$ with data points and fitted curves.]

**Final correction**
Neutral Background: $X_{nn}$

- Background from neutrons and antineutrons needs to be simulated (GEANT)
- Input neutron and anti-neutron spectra “determined” from measured proton and anti-proton spectra

\[
\left. \frac{d^2N}{dp_T dy} \right|_{\bar{n}} = \left. \frac{d^2N}{dp_T dy} \right|_{\bar{p}},
\]

\[
\left. \frac{d^2N}{dp_T dy} \right|_{n} = \left. \frac{d^2N}{dp_T dy} \right|_{\bar{p}} + \left( \left. \frac{d^2N}{dp_T dy} \right|_{p} - \left. \frac{d^2N}{dp_T dy} \right|_{\bar{p}} \right) \frac{A - Z}{Z}
\]
Multiply Inclusive Photon Spectrum by the double ratio to obtain direct-photon spectrum (and add sys. errors of the inclusive photon spectrum which cancelled in the double ratio)
Systematic Uncertainties of the Subtraction Method

- $\pi^0$ measurement
  - Peak extraction
  - Yield correction (acceptance + efficiency)
  - Energy scale

- Inclusive photon measurement
  - Non-photon background
  - Yield correction (acceptance + efficiency)
  - Energy scale

[talk by Andreas Arend]
Systematic Uncertainties of the Subtraction Method

- $\pi^0$ measurement
  - Peak extraction
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- Inclusive photon measurement
  - Non-photon background
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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 of the Subtraction Method

- $\pi^0$ measurement
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- Inclusive photon measurement
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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, Run-2 Au+Au)

<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>
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</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>
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<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>20.3%</td>
<td>19.5%</td>
<td>18.8%</td>
<td>19%</td>
</tr>
<tr>
<td>Statistical</td>
<td>10.6%</td>
<td>32.5%</td>
<td>3%</td>
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<td>Non-$\gamma$ correction</td>
<td>2.4%</td>
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<td>0.7%</td>
<td>7.9%</td>
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<tr>
<td>$\gamma/\pi^0$ syst.</td>
<td>10.4%</td>
<td>10.4%</td>
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<td>1.2%</td>
<td>14.1%</td>
<td>0.7%</td>
<td>7.9%</td>
</tr>
</tbody>
</table>

$\gamma/\pi^0$ systematic: 10.4% 10.4% 10.6% 10.6%

$\gamma/\pi^0$ statistical: 10.7% 37.7% 3% 16.5%

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

---

K. Reygers, Direct Photons in p+p and A+A Collisions: A Short Introduction
Measuring Photons via Conversions

ALICE: photon conversion probability \( \sim 8\% \) up to the middle of the TPC

Advantage of the conversion method:
Better resolution and higher purity of the photon sample at low \( p_T \)
Direct Photon Measurement via $\gamma\gamma$-HBT

- Two-photon correlations observed and attributed to Bose-Einstein correlations
- Direct photon yield extracted from correlation strength:

$$C_2(Q_{\text{inv}}) = A[1 + \lambda_{\text{inv}} \exp(-R_{\text{inv}}^2 Q_{\text{inv}}^2)]$$

$$\frac{N_{\gamma}^{\text{direct}}}{N_{\gamma}^{\text{total}}} = \sqrt{2\lambda} = \sqrt{8\lambda_{\text{inv}} K_T R_O / \sqrt{\pi} \text{Erf}(2K_T R_O)}$$

WA98, Phys. Rev. Lett. 93 (022301), 2004
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WA98, Phys. Rev. Lett. 93 (022301), 2004

Central Pb+Pb at \( \sqrt{s} = 17.2 \text{ GeV} \)
Results on Direct Photon Production in A+A Collisions (Measured With Real Photons)
Early CERN SPS Results: Upper Limits

<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 fixed target experiments at the CERN SPS only gave upper limits.
WA98 Experiment

**WA98 Experimental Setup**

*158 A GeV Pb+Pb Collisions at the CERN SPS (1996)*

**Pb+Pb at √s_{NN} = 17.3 GeV**
WA98 Result on Direct Photons

- No signal within errors in peripheral collisions
- 20% direct photon excess at high $p_T$ in central Pb+Pb collisions at CERN SPS

WA98 Direct Photon Spectrum: Hard Scattering + Nuclear $k_T$ Broadening?

- Better $p+p$ and $p+A$ measurement desirable
- Very unlikely that $Pb+Pb$ spectrum is just hard scattering

Cronin-effect: Multiple soft scattering in $p+A$ prior to hard scattering ("nuclear $k_T$")
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Interpretation of the WA98 Data

Interplay between $T$ and $k_T$, contribution from QGP small
Direct Photons at CERN SPS: $T$ or $k_T$?
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- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons
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- Data described with initial temperature $T_i = 205$ MeV + some nuclear $k_T$ broadening (Cronin-effect)
Direct Photons at CERN 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: New low-$p_T$ Points

- Two-photon correlations observed and attributed to Bose-Einstein correlations of direct photons
- 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)

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WA98, Phys. Rev. Lett. 93 (022301), 2004
**Direct Photons at CERN SPS: Conclusions**

Data can be described under a variety of different assumptions, e.g.:

<table>
<thead>
<tr>
<th>Study</th>
<th>Model</th>
<th>Initial Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turvide, 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>
</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>
</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>
</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>
</tr>
<tr>
<td></td>
<td>Pure HG + pQCD (Non-boost inv. hydro)</td>
<td>$T_i = 213 - 234$ MeV</td>
</tr>
</tbody>
</table>

- Data consistent with QGP picture, but also with pure HG picture
- Large variations in extracted initial temperature $T_i$
  (however, most models give $T_i > T_c$)
PHENIX: Photon and Electron Detectors

- **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: $|\eta| < 0.35$
How Do We Measure Direct Photons in PHENIX?

- **Intermediate and high $p_T$:**
  - Real photons with EMCal
    - Statistical Subtraction (typically no isolation cut)

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

- **Low $p_T$:**
  - Virtual photons ($\gamma^* \rightarrow e^+e^-$) with RICH (internal conversion)

- **Assumption:**

\[
\frac{\gamma_{\text{direct}}}{\gamma_{\text{inclusive}}} = \frac{\gamma^*}{\gamma^*} \bigg|_{m_{ee} < 30 \text{MeV}}
\]
Direct-Photon Spectra in Au+Au

Au+Au at $\sqrt{s_{NN}} = 200$ GeV (RHIC run 2)

$T_{AB}$: increase in parton-luminosity per event ($p+p \rightarrow Au+Au$)

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

$60 - 92\%$: 
$\langle N_{coll} \rangle = 14.5 \pm 4$

$T_{AB} = N_{coll}/\sigma_{NN}^{\text{inel}}$
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- High-$p_T$ direct photons scale with $\langle T_{AB} \rangle$
- No indication of nuclear effects
Centrality Dependence of the Direct Photon and $\pi^0 R_{AA}$ in Au+Au Collisions at 200 GeV

Direct photons follow $T_{AB}$ scaling

- $R_{AA}(p_T > 6.0 \text{ GeV/c})$ vs $N_{\text{participant}}$
- Points for photons and $\pi^0$
- NLO pQCD used as p+p reference
Direct-Photon Production in p+p at $\sqrt{s} = 200$ GeV

- Direct-photon data in p+p at $\sqrt{s} = 200$ GeV consistent with NLO pQCD
- No need for additional $k_T$ broadening
Hadron Suppression: A Final State Effect!

PHENIX Au+Au (central collisions):

\[ R_{AA} = \frac{dN/dp_T(A + A)}{\langle T_{AA} \rangle \times d\sigma/dp_T(p + p)} \]
Hadron Suppression: A Final State Effect!

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**PHENIX Au+Au (central collisions):**

- \( \pi^0 \) Preliminary
- \( \eta \)

59 K. Reygers, Direct Photons in p+p and A+A Collisions: A Short Introduction
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Factor 5 suppression
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- $\eta$
- GLV parton energy loss ($dN/dy = 1200$)

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Factor 5 suppression
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Hadron Suppression: A Final State Effect!

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- Direct $\gamma$
- $\pi^0$ Preliminary
- $\eta$
- GLV parton energy loss ($dN/dy = 1200$)

$$R_{AA} = \frac{dN/dp_T(A + A)}{\langle T_{AA} \rangle \times d\sigma/dp_T(p + p)}$$

- No energy loss for $\gamma$'s
- Factor 5 suppression
- Energy loss for $q$ and $g$
Hadron Suppression: A Final State Effect!

Hadrons are suppressed whereas direct photons are not: Evidence for parton energy loss (as expected in the QGP)
Bremsstrahlung/fragmentation contribution large

Suppression of bremsstrahlung/fragmentation contribution expected in A+A
pQCD: Bremsstrahlung/Fragmentation Component

- Bremsstrahlung/fragmentation contribution large
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pQCD: Bremsstrahlung/Fragmentation Component

- Bremsstrahlung/fragmentation contribution large
- Suppression of bremsstrahlung/fragmentation contribution expected in A+A
Effect of Parton Energy Loss

- 20-30% reduction of direct photon $R_{AA}$ expected due to parton energy loss
- Consistent with PHENIX data

F. Arleo, hep-ph/0601075
The Puzzle of the Preliminary Direct Photon $R_{AA}$

at high $p_T$ (PHENIX, Run 4 Au+Au data)
Interpretation of the Direct-Photon Spectrum at RHIC $(p_T > 4 \text{ GeV/c})$ (I)

Indication for relevance of photons from jet-plasma interactions for $p_T < 6 \text{ GeV/c}$ ?
Interpretation of the Direct-Photon Spectrum at RHIC ($p_T > 4$ GeV/$c$) (II)
Interpretation of the Direct-Photon Spectrum at RHIC ($p_T > 4$ GeV/c) (III)
Pb+Pb at the LHC: Test of $T_{AA}$ Scaling With Prompt Photons (and Z Bosons)

$R_{AA} = \frac{dN/dp_T(A + A)}{\langle T_{AA} \rangle \times d\sigma/dp_T(p + p)}$

Prompt Photons (and Z\(^0\)s) are not suppressed: Strong Evidence for Parton Energy Loss Picture
γ-Triggered Away-Side Correlations: Basic Idea

- p+p:
  (Effective) jet fragmentation functions can be extracted from γ-hadron azimuthal correlations (modulo initial $k_T$ effect)

- A+A:
  Modification of fragmentation function provides information on parton energy loss

Variables:

\[
D(z_T) = \frac{1}{N_{\text{trig}}} \frac{dN(z_T)}{dz_T}
\]

\[
z_T = \frac{p_T^h}{p_T^\gamma}
\]

\( \gamma \)-Triggered Away-side Correlations: Jet Fragmentation Function in p+p and Au+Au

- Fit effective FF’s with
  \[
  \frac{dN}{dz_T} = Ne^{-bz_T}
  \]
- p+p: \( b = 6.89 \pm 0.64 \)
- Au+Au: \( b = 9.49 \pm 1.37 \)
- Difference reflects influence of the medium
$I_{AA} = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$

- Different $z_T$ regions probe different regions of the fireball (arXiv:0902.4000v1)

- Agreement with NLO pQCD + parton energy loss: Indication that energy loss in different regions of the fireball is understood

NLO calculation:
Zhang et al. (ZOWW), arXiv:0902.4000v1
The Internal Conversion Method
Direct Photons via Internal Conversion

- Motivation:
  Measure where thermal photons are expected and calorimetric measurements are difficult

- Internal conversion
  - Any source of real photons also emits virtual photons
  - Well known example: \[ \pi^0 \text{ Dalitz decay} \]

  - Rate and \( m_{ee} \) distribution calculable in QED (Kroll-Wada formula)

- Hadron decays: \( m_{ee} < M_{\text{hadron}} \)

- Essentially no such limit for point-like processes

Improve signal-to-background ratio by measuring \( e^+e^- \) pairs with \( m_{ee} > \sim M_{\text{pion}} \)
Kroll-Wada Formula

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

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

**Hadron decay:**

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

**Point-like process:**

$$S \approx 1$$

(for $p_T^{ee} \gg m_{ee}$)

Direct photon

About 0.001 virtual photons with $m_{ee} > M_{\text{pion}}$ for every real photon

→ Avoid the $\pi^0$ background at the expense of a factor 1000 in statistics
Extraction of the Direct Photon Signal: Two-Component Fit

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

- Interpreted deviation from hadronic cocktail (π, η, ω, η', φ) as signal from virtual direct photons.
- Extracted fraction \( r \) with two-component fit:
  \[ r = \frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}} \]
  \( \chi^2/\text{NDF} = 13.8/10 \)
- Fit yields good \( \chi^2/\text{NDF} \) (13.8 / 10)

Separately normalized to data at \( m_{ee} < 30 \text{ MeV} \)

Fit range: 80 < \( m_{ee} < 300 \text{ MeV} \)
Direct Photon Fraction in p+p and Au+Au at $\sqrt{s_{NN}} = 200$ GeV

- Lowest $p_T$ ever measured in p+p
- Comparison to NLO pQCD (colored lines)
- p+p: Agreement
- Au+Au: Strong enhancement at low $p_T$

Comparison Between the Internal Conversion Method and the Calorimeter Measurement

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

- real photon
- virtual photon

PHOENIX

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

K. Reygers, Direct Photons in p+p and A+A Collisions: A Short Introduction
Low $p_T$ Direct Photon Excess at RHIC: A Handle to Measure the Temperature of the QGP

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

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

- **Slope parameter (0-20%)**:
  \[ T = (221 \pm 23 \pm 18) \text{ MeV} \]

Expected to be a lower limit for the initial temperature!
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  \]

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Expected to be a lower limit for the initial temperature!
Critical d+Au Check: No exponential excess in d+Au

Direct photon spectra at $\sqrt{s_{NN}} = 200\text{GeV}$

- $T_{AA}/T_{dAu} \times d+Au$ (RUN8)
- $T_{AA}/T_{dAu} \times d+Au$ (RUN3)
- Au+Au (MB, PRL104 132301)
- $T_{AA} \times p+p$ fit result

PHENIX preliminary
Model Comparison

- Model space-time evolution with ideal hydro
- This calculation (arXiv:0904.2184v1)
  - Hydro starts early ($\tau_0 = 0.2 \text{ fm/c}$) to take pre-equilibrium photons into account
  - Thermal equilibrium expected at $\tau_0 = 0.6 \text{ fm/c}$ ($T_{\text{initial}} = 340 \text{ MeV}$)
  - Photons from jet-plasma interaction needed
- Similar conclusions for essentially all hydro models on the market
- $T_{\text{initial}} > T_c \approx 170 - 190 \text{ MeV}$ → evidence for the formation of a quark-gluon plasma
PHENIX Low $p_T$ Direct Photon Data: Comparison with Different Hydro Models

Initial temperature above $T_c$ in all models
Direct Photon Flow
Direct photon $v_2$ further constrains $T_i$

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

---

Chatterjee, Srivastava  
PRC79, 021901 (2009)
Significant Elliptic Flow of Direct Photons Found in Au+Au at 200 GeV for $p_T < 3$ GeV/c

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

$$R_\gamma = \frac{\gamma^{\text{inc}}}{\gamma^{\text{decay}}}$$

$\nu_2^{\text{inc}}$ from calorimeter measurement

Reygers, Direct Photons in p+p and A+A Collisions: A Short Introduction

PHENIX, arXiv:1105.4126
Direct Photon $v_2$ at $p_T = 2$ GeV/c as larger as for Pions
The slope of low $p_T$ direct photons spectrum points to early emission, $v_2$ suggests late emission from mixed/hadronic phase.

Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

Hendrik van Hees, Charles Gale, Ralf Rapp,

Theory Comparison: A Big Puzzle (!?)
Expected Thermal Photon Signal (from ALICE Physics Performance Report II)

Stay tuned for low $p_T$ direct-photon data from the LHC!
Extra Slides
Direct Photons in A+A collisions – Why?

Photons escape the medium unscathed

$\Rightarrow$

High $p_T$ photons
- test hard scattering predictions
- measure rate of hard processes

Low $p_T$ photons
- reflect the initial temperature of the thermalized fireball ($T_i > T_c \Rightarrow \text{QGP}$)
- could indicate jet-plasma interactions

Control Measurement

Thermometer
RHIC: Relativistic Heavy Ion Collider

PHENIX:
- Real photons with electromagnetic calorimeters
- Virtual photons ($\gamma^* \rightarrow e^+e^-$) with Ring Imaging Cherenkov
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Au+Au at RHIC

0 - 20 % Central

- SUM
- jet-QGP
- HG
- prompt
- Thermal QGP
- PHENIX (1)
- PHENIX (2)
Limitations of the Different Methods
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Subtraction method at low $p_T$ largely limited by uncertainty of $\pi^0$ measurement:

- Energy Scale
- Reconstruction Efficiency
- Peak Extraktion
Limitations of the Different Methods

Low $p_T$ limitation of HBT method:
Huge charged particle background ($p_T$ for MIP’s ~ 100 MeV)

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Limitations of the Different Methods

Low $p_T$ limitation of HBT method:
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High $p_T$ limitation of HBT method:
Hit distance cut of $D > 20$ cm (cluster splitting!) limits usable $Q_{inv}$ range

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- Energy Scale
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- Peak Extraktion