Direct-Photon Physics with ALICE

New perspectives on Photons and Dileptons in Ultrarelativistic Heavy-Ion Collisions at RHIC and LHC, ECT*, Trento, 30 Nov - 11 Dec, 2015

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The Role of Direct Photons in Heavy-Ion Physics

- Escape medium unscathed
- Produced over the entire duration of the collision
  - Test of space-time evolution, in particular of the hydro paradigm
- Experimental access to initial QGP temperature (?)

QGP photon rate $r_\gamma$ (lowest order):

$$E_\gamma \frac{dr_\gamma}{d^3p} \propto \alpha \alpha_s T^2 e^{-E_\gamma/T} \log \frac{E_\gamma T}{k_c^2}$$

Total emission rate:

$$r_\gamma \propto T^4$$
A Complication for the Temperature Measurement: Blueshift due to Radial Flow

- Large blueshift at late times when $T \approx 150 - 200$ MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

\[ E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}} \]

\[ T_{\text{eff}} = \sqrt{\frac{1 + \beta_{\text{flow}}}{1 - \beta_{\text{flow}}} \times T} \]

2 for $\beta_{\text{flow}}=0.6$
ALICE

Photons/$\pi^0$'s:
- Conversions (TPC [+ ITS])
- PHOS
- EMCal

used in arXiv:1509.07324 (focus of this talk)
Direct Photons in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV: PHOS

- 4.6 m from interaction point
- $260^\circ < \phi < 320^\circ$
- $|\eta| < 0.13$
- 3 modules
- Each module
  - 64 $\times$ 56 lead tungstate crystals
  - Crystal size: 2.2 $\times$ 2.2 $\times$ 18 cm$^3$
  - Avalanche photodiode readout
- Energy resolution
  $$\frac{\sigma_E}{E} = \frac{1.3\%}{E/\text{GeV}} \oplus \frac{3.3\%}{\sqrt{E/\text{GeV}}} \oplus 1.12\%$$
  $$\frac{\sigma_E}{E} = 3.7\% \text{ for } E = 1 \text{ GeV}$$
Direct Photons in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV: Photon Conversion Method (PCM)

- Photon candidates from pairs of secondary, oppositely charged tracks with reconstructed conversion point in $5 < r < 180$ cm (TPC [+ ITS])
- Large acceptance: $|\eta| < 0.9$, $0 \leq \phi \leq 360^\circ$
- Electron ID with TPC $dE/dx$ (+ TOF, if available)
- Purity of the photon candidate sample for $p_T < 3$ GeV/c
  - $\geq 98\%$ in peripheral Pb-Pb
  - $\geq 90\%$ in central collisions
- Very good photon energy resolution
  - $\sigma_E/E \approx 1.6\%$ for $1 \approx E \leq 2$ GeV
Reconstructed photon conversion points

ALICE, arXiv:1402.4476
Material Budget

- Precise knowledge of material key for conversion method
- 4.5% uncertainty ($|\eta| < 0.9$, $r < 180$ cm)
  - $X/X_0 = 0.114 \pm 0.005$
- Corresponds to conversion probability of 8.5%
The Statistical Subtraction Method

- Idea: Cancellation of uncertainties common to photon and $\pi^0$ measurement

$$\gamma_{\text{direct}} = \gamma_{\text{incl}} - \gamma_{\text{decay}} = (1 - \frac{1}{R_{\gamma}}) \cdot \gamma_{\text{incl}}$$

$$R_{\gamma} = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}} \equiv \frac{\gamma_{\text{incl}}}{\pi^0_{\text{param}}} \div \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}}$$

- Which uncertainties cancel (partially)?
  - Calorimeter: global energy scale, energy non-linearity
  - Photon conversions: conversion probability, photon selection
No Significant Direct Photon Signal in pp@7 TeV
(Photon Conversion Method)

\[ \left( \frac{\gamma_{NC}}{\pi^0} \right) / \left( \frac{\gamma_{\text{decay}}}{\pi^0} \right) \]

**pp, \( \sqrt{s} = 7 \) TeV**

- Direct photon double ratio
- NLO prediction: \( 1 + \left( \frac{\gamma_{\text{direct,NLO}}}{\gamma_{\text{decay}}} \right) \)
  for \( \mu = 0.5, 1.0, 2.0 \) \( p_T \)

pQCD consistent with data

ALICE PRELIMINARY

ALI-PREL-27932
Decay Photon Calculation (Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV)

- **Input:** $\pi^0$ spectrum
- **$\eta$, $\omega$: modeling**
  - $m_T$ scaling
  - Alternatively (for $\eta$): $p_T$ shape from $K_{s0}$
- **All other hadrons negligible**

$\pi^0$: 82-88%
$\eta$: 10-15%
$\omega$: 2-3%
$\eta/\pi^0$ Ratio in Pb-Pb (1): $m_T$ Scaling vs. $K_s^0$ Shape

- At $p_T = 2.5$ GeV/c: $\eta/\pi^0|_{m_T \text{ scaling}} = 0.4$, $\eta/\pi^0|_{K_s^0 \text{ shape}} = 0.5$

- $\eta/\pi^0$ in the decay photon calculation:
  Average of the two approaches
$\eta/\pi^0$ Ratio in Pb-Pb (2): ALICE Data

- $\eta/\pi^0$ ratio from 2011 Pb-Pb data set
- Current measurement not precise enough for use in decay photon calculation
Comparison btw. PHOS and PCM
Inclusive Photon Spectra

- Systematic uncertainties classified as
  - Point-by-point uncorrelated (type A)
  - Correlated and $p_T$ dependent (type B)
  - Normalization uncertainty (type C)
- Level of agreement btw. PCM and PHOS quantified with MC pseudo experiments
- PCM and PHOS inclusive photon spectra agree on the level of $1.2\sigma$
Combined Inclusive Photon Spectra

- **Analysis strategy**
  - Combined PHOS+PCM direct photon spectrum from combined inclusive photon spectrum and combined double ratio $R_\gamma$
  - Uses information from both measurements even if measured $R_\gamma$ from one system fluctuates below unity

- **$p_T$ reach**
  - $0.9 < p_T < 14$ GeV/c
Double Ratio (PCM, PHOS)

- \( R_{\gamma,X} \) with \( \pi^0 \) spectrum from \( X \) (\( X = \text{PCM, PHOS} \))
  - Cancellation of systematic uncertainties
- Level of agreement: 1.4\( \sigma \)

\( \pi^0 \)'s from PCM and PHOS published in arXiv:1405.3794
### Systematic Uncertainties: PHOS

<table>
<thead>
<tr>
<th>Centrality</th>
<th>0–20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV/c)</td>
<td>2</td>
</tr>
</tbody>
</table>

#### $\gamma_{incl}$ yield

<table>
<thead>
<tr>
<th>Source</th>
<th>0–20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (B)</td>
<td>3.0</td>
</tr>
<tr>
<td>Contamination (B)</td>
<td>2.0</td>
</tr>
<tr>
<td>Conversion (C)</td>
<td>1.7</td>
</tr>
<tr>
<td>Acceptance (C)</td>
<td>1.0</td>
</tr>
<tr>
<td>*Global E scale (B)</td>
<td>9.6</td>
</tr>
<tr>
<td>*Non-linearity (B)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

#### $\pi^0$ yield

<table>
<thead>
<tr>
<th>Source</th>
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</tr>
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<tbody>
<tr>
<td>Yield extraction (A)</td>
<td>2.7</td>
</tr>
<tr>
<td>Efficiency (B)</td>
<td>1.8</td>
</tr>
<tr>
<td>Acceptance (C)</td>
<td>1.0</td>
</tr>
<tr>
<td>Pileup (C)</td>
<td>1.0</td>
</tr>
<tr>
<td>Feed-down (B)</td>
<td>2.0</td>
</tr>
</tbody>
</table>

#### $\gamma_{decay}/\pi^0$

<table>
<thead>
<tr>
<th>Source</th>
<th>0–20%</th>
</tr>
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<tbody>
<tr>
<td>$\pi^0$ spectrum (B)</td>
<td>1.3</td>
</tr>
<tr>
<td>$\eta$ contribution (B)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

| Total $R_\gamma$               | 6.8   | 7.9  |
| Total $\gamma_{incl}$          | 12.4  | 12.7 |
Systematic Uncertainties: PCM

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<td>$p_T$ (GeV/c)</td>
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<th>$\gamma_{incl}$ yield</th>
<th></th>
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<tr>
<td>Track quality (A)</td>
<td>0.6 0.6</td>
</tr>
<tr>
<td>Electron PID (A,B)</td>
<td>1.5 6.9</td>
</tr>
<tr>
<td>Photon selection (A,B)</td>
<td>4.0 1.8</td>
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<tr>
<td>Material (C)</td>
<td>4.5 4.5</td>
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<td>$\pi^0$ spectrum (B)</td>
<td>0.5 1.2</td>
</tr>
<tr>
<td>$\eta$ yield (C)</td>
<td>1.4 1.4</td>
</tr>
<tr>
<td>$\eta$ shape (B)</td>
<td>1.6 0.5</td>
</tr>
</tbody>
</table>

- Material budget uncertainty dominant
  - 4.5% for $\gamma_{incl}/\pi^0$
    - (9% for $\pi^0$ spectrum)
- Followed by photon selection uncertainties
  - 3.2% (from cut variations)
Combined Double Ratio

- Significance of the excess for $0.9 < p_T < 2.1$ GeV/c
  - $2.6\sigma$ for 0-20%
- Calculated from pseudo experiments taking into account correlated uncertainties
Testing the Null Hypothesis $R_Y \equiv R_0 = 1$

- Model of the measurement based on type A, B, C uncertainties
- Deviations from central values described by Gaussian-distributed nuisance parameters $\varepsilon_B$, $\varepsilon_C$
- Distribution of test statistic $t$ for $H_0(R_0=1)$ from pseudo experiments
- $p$-value: fraction of pseudo experiments above $t_{\text{data}}$
- Translated into units of Gaussian standard deviations with a two-sided test

$$R_{\text{mod},i} = R_0(1 + \varepsilon_B \sigma_{B,i,\text{rel}})(1 + \varepsilon_C \sigma_{C,\text{rel}})$$

$$t = \sum_{i=1}^{n_{\text{data points}}} \left( \frac{R_{pd,i} - R_0}{\sigma_{0,i}} \right)^2, \quad \sigma_{0,i} = R_{\text{mod}}\sigma_{i,\text{stat}+A,\text{rel}}$$
Double Ratio: Comparison with pQCD

- pQCD curves:

\[ R_{\gamma}^{\text{pQCD}} = 1 + N_{\text{coll}} \frac{\gamma_{\text{pQCD}}}{\gamma_{\text{decay}}} \]

calculated based measured \( \pi^0 \) spectrum

- pQCD agrees with data for \( p_T \gtrsim 5 \text{ GeV}/c \)

- Evidence for an additional photon source at lower \( p_T \)
Combined Direct Photon Spectra

- Approximately exponential spectrum for $p_T \lesssim 3$ GeV/$c$
Combined Direct Photon Spectra

- Approximately exponential spectrum for $p_T \lesssim 3$ GeV/$c$
- pQCD uncertainties growing towards lower $p_T$
  - 20-30% for $p_T \gtrsim 5$ GeV/$c$
  - 50-60% at $p_T \approx 1$ GeV/$c$
Direct Photon $R_{AA}$

- Calculated using pQCD pp reference (McGill calculation)
- Confirmation of $N_{\text{coll}}$ scaling of pQCD photons for $p_T \approx 5 \text{ GeV/c}$
Comparison with Au-Au at 200 GeV (PHENIX)

- Inverse slope parameter $T_{\text{eff}}$ for 0-20% Pb-Pb at 2.76 TeV
  - without pQCD subtraction: $T_{\text{eff}} = 304 \pm 11_{\text{stat}}^{+40}_{-40} \text{ MeV}$
  - with pQCD subtraction: $T_{\text{eff}} = 297 \pm 12_{\text{stat}}^{+41}_{-41} \text{ MeV}$

- 0-20% Au-Au at 0.2 TeV
  - $T_{\text{eff}} = 239 \pm 25_{\text{stat}}^{+7}_{-7} \text{ MeV}$
    (pp parameterization subtracted)

- Indication for larger inverse slope parameter in Pb-Pb at 2.76 TeV
Do we Understand the $\sqrt{s_{NN}}$ Dependence of the Direct Photon Signal?

- Low $p_T$ photon excess (0-20%)
  - 0.2 TeV Au-Au: $R_\gamma \approx 1.20$
  - 2.76 TeV Pb-Pb: $R_\gamma \approx 1.12$

- Observed increase of “thermal” yield (LHC/RHIC, from previous slide)
  - factor $\sim 2.5$ at $p_T = 1\, \text{GeV}/c$
  - factor $\sim 5$ at $p_T = 2\, \text{GeV}/c$

- Hydro expectation
  - Similar or smaller $R_\gamma$ at the LHC than at RHIC expected
  - Observed increase of “thermal” yield somewhat smaller than in hydro, but approximately consistent

Hydro expectation for $\sqrt{s_{NN}}$ dependence, figure courtesy of Jean-François Paquet, based on arXiv:1509.06738
Comparison with State-of-the-Art Models

- **Models (all with QGP formation)**
  - v. Hees et al.:
    Ideal hydro with initial flow,
    \( \tau = 0.2 \text{ fm}/c, \, T_{0-20\%} = 682 \text{ MeV} \)
  - Chatterjee et al.:
    2+1 hydro, fluctuating initial conditions,
    \( \tau = 0.14 \text{ fm}/c, \, T_{0-20\%} \approx 740 \text{ MeV} \)
  - Paquet et al.:
    2+1 viscous hydro with IP-Glasma initial conditions,
    \( \tau = 0.4 \text{ fm}/c, \, \langle T_{0-20\%} \rangle = 385 \text{ MeV} \)
  - Linnyk et al.:
    Off-shell transport, microscopic description of evolution

  - Currently not possible to rule out one or more of these models
Direct Photon Azimuthal Asymmetries

- Thermal photon $v_2$ (QGP, HG)
  - $v_2(HG) \approx v_2(\pi)$
  - Collective flow velocity takes time to build up in hydro models:
    $v_2(QGP) \ll v_2(HG)$

- Expect $v_2(\gamma_{\text{dir}}) \ll v_2(\pi)$ if QGP photons dominate at low $p_T$

- $v_2(\gamma_{\text{dir}})$ tests hydro models and photon production rates (QGP, HG)

- Non-hydro mechanisms producing $v_2(\gamma_{\text{dir}})$ conceivable
  - E.g. photon production related to large initial B field in non-central A-A
  - Can be tested with $v_3$
How to Measure the Direct-Photon $v_2$?

- Reaction plane (RP) from charged particles in forward direction

- Inclusive photons (mid-rapidity):
  \[ v_2^\gamma,\text{incl} = \frac{\langle \cos(2(\varphi - \psi_2^{\text{RP}})) \rangle}{C}, \]
  \( C = \text{resolution correction} \)

- Decay photon $v_2$ from cocktail calculation based on measured pion $v_2$ (+ higher mass hadrons, based on $KE_T$ scaling where $KE_T = m_T - m$)

- Inclusive photon $v_2$ is weighted average of decay photon and direct photon $v_2$. Thus one can calculate the direct-photon $v_2$ as

\[
v_2^\gamma,\text{direct} = \frac{R_\gamma v_2^\gamma,\text{incl} - v_2^\gamma,\text{decay}}{R_\gamma - 1} \quad \text{with} \quad R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}} = 1 + \frac{\gamma_{\text{direct}}}{\gamma_{\text{decay}}} \]

\[2.8 < \eta < 5.1 \quad \text{and} \quad -3.7 < \eta < -1.7\]
Measured Inclusive Photon and Calculated Decay Photon $v_2$

- $v_2^{(incl)} < v_2^{(decay)}$ for $p_T > 3$ GeV/c
  - Expected from $v_2 = 0$ of prompt photons

- $v_2^{(incl)} \approx v_2^{(decay)}$ for $p_T < 3$ GeV/c
  - $v_2^{(incl)}$ maybe slightly smaller
  - If there is a large direct photon component its $v_2$ must be very similar to the decay photon $v_2$
  - $v_2^{(incl)}$ described by models with small $R_\gamma$ ($\lesssim 1.05$) predicted by the same models

ALICE preliminary
0-40% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
V0 event plane

- $v_2^{(incl)}$
- $v_2^{(decay)}$
- $v_2$

\[ \text{decay + NLO} \]
\[ \text{Phys.Rev. D50 (1994) 1901-1916} \]
\[ \text{decay + NLO + thermal (Shen et al.)} \]
\[ \text{arXiv:1308.2111} \]
\[ \text{decay + NLO + thermal (Holopainen et al.)} \]
\[ \text{Phys.Rev. C84 (2011) 064903} \]
Direct Photon Elliptic Flow Appears to be Larger than Expected in Hydro Models

- $v_2(\gamma_{dir})$ only slightly lower than $v_2(\text{incl})$
- Many direct photons from late stage with $T \approx T_c \approx 150 - 160$ MeV?
- Then large inverse slope parameter due to Doppler blueshift with typical hadronic flow velocity $\beta_{\text{flow}} \approx 0.6 \, c$?
- However, current systematic uncertainties are sizable so that there is no big puzzle looking at the ALICE data alone
Inclusive Photon $\nu_3$

- $\nu_3^{(incl)} \approx \nu_3^{(decay)}$ for $p_T < 3$ GeV/c:
  - If there is a large direct photon component its $\nu_3$ must be very similar to the decay photon $\nu_3$
  - $\nu_3^{(incl)}$ described by models with small $R_\gamma (\lesssim 1.05)$ predicted by the same models

- Uncertainty $\sigma(R_\gamma)$ is key for concluding whether $\nu_2(\gamma_{\text{dir}})$ and $\nu_3(\gamma_{\text{dir}})$ agree or disagree with models

- Error propagation non-trivial (no $\nu_3(\gamma_{\text{dir}})$ from ALICE so far)

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ALICE preliminary
0-40% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
V0 event plane

- $\nu_3^{(incl)}$ vs $\nu_3^{(decay)}$
- Models:
  - Decay + NLO
  - Decay + NLO + thermal (Shen et al.)
  - Decay + NLO + thermal (Chatterjee et al.)

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ALI-PREL-75777
The Direct Photon Puzzle

- Au-Au at RHIC
  - Models fail to describe direct photon data
- Puzzle has two parts
  - yields
  - $v_2$
- Pb-Pb at the LHC
  - Similar trends
  - However, no puzzle with current uncertainties

Plots: Paquet et al., arXiv:1509.06738
Towards Higher Precision (1): Virtual Photon Method

- Two-component fit to $m_{ee}$ distribution
  - Hadronic cocktail
  - Virtual direct photon $m_{ee}$ shape (Kroll-Wada formula)
- Extrapolated to $m = 0$ (real photons)
- More model assumptions than in direct measurement
- Reasonably small uncertainties in pp
Towards Higher Precision (1):
Virtual Photon Method

- Virtual photon method in pp@7 TeV
  - Agreement with pQCD
- Virtual Photon Method in Pb-Pb?
  - Method is statistics hungry
  - Hadronic cocktail needs to be understood very well
- In Pb-Pb likely only doable with LHC Run 3 data (2019-21)

\[ \gamma_{\text{incl}}^{\text{PCM}} \times r = \gamma_{\text{direct}}^{\text{PCM}} \]

95 % C.L.
Towards Higher Precision (2): Standard Statistical Subtraction Method

- More statistics helps
  - $\pi^0$ statistical uncertainty traded for systematic uncertainty by using a parameterization of the $\pi^0$ spectrum in the double ratio
  - Statistics for 0-20% Pb-Pb
    - Current analysis (2010 data): $4 \times 10^6$ events
    - 2011: $17 \times 10^6$ events
    - 2015: $30 \times 10^6$ events (expected)

- Photon conversion method:
  Reduce material budget uncertainty
  - No direct-photon signal in pp for $p_T < 2$ GeV/c
  - Estimate material budget (and other) uncertainties from double ratio?

![Graph showing direct photon double ratio](image)
Towards Higher Precision (3)
Tagging Method, External Converter

- Use $\pi^0$ tagging with EMCal, PHOS (like PHENIX)
  - Conversion probability drops out
  - At the cost of adding, e.g., the energy scale uncertainty of the calorimeter (via the matching of the lower energy threshold for the $\pi^0$ tagging in data and MC)
  - Will be tried, not clear if errors will be smaller
- For LHC Run 3 (2019-21) the use of an external converter of known $X_0$ is an option

\[ R_\gamma = \frac{\gamma^{\text{incl}}}{\gamma^{\text{decay}}} = \frac{\langle \varepsilon f \rangle}{\left( \frac{N_\gamma^{\text{incl}}}{N_{\gamma,\pi^0-\text{tag}}} \right)_{\text{data}}} \left( \frac{\gamma^{\text{dec}}}{\gamma^{\pi^0}} \right)_{\text{calc}} \]

\[ N^{\gamma-\text{incl}} = p_{\text{conv}} \varepsilon_{ee} a_{ee} \gamma^{\text{incl}} \]

\[ N^{\gamma,\pi^0-\text{tag}} = \langle \varepsilon f \rangle p_{\text{conv}} \varepsilon_{ee} a_{ee} \gamma^{\pi^0} \]
Conclusions

- **pp@7TeV**
  - Photon conversion and virtual photon method
  - No significant direct photon excess for $p_T < 2.5$ GeV/$c$
  - Consistent with pQCD

- **Pb-Pb@2.76 TeV (2010 data set)**
  - Electromagnetic calorimeter (PHOS) and photon conversion (PCM)
  - Consistent results
  - Direct photon excess in 0-20%:
    $R_\gamma \approx 1.12$ for $0.9 < p_T < 2.1$ GeV/$c$, 2.6$\sigma$ significance
  - Excess w.r.t. pQCD consistent with thermal photon source

- **Direct photon puzzle**
  - Mostly at RHIC
  - Similar trend at the LHC, but no big puzzle with current uncertainties
Extra slides
Omega meson / $\pi^0$ in pp at 7 TeV

![Graph showing the ratio $\omega/\pi^0$ vs. $p_T$ (GeV/c) with ALICE preliminary data and cocktail calculations.](image)

ALICE preliminary, pp $\sqrt{s} = 7$ TeV

Cocktail Calculations

-$\omega$ from $m_T$ scaled $\pi^0$
Model Predictions for $R_Y$

![Graph showing model predictions for $R_Y$]

- **ALICE preliminary**
- 0-40% Pb-Pb, $\sqrt{s_{\text{NN}}} = 2.76$ TeV

**Legend:**
- • Direct photon double ratio
- Blue line: NLO prediction: $1 + \left( N_{\text{coll}}^{\gamma_{\text{direct,pp,NLO}}} / N_{\text{decay}}^{\gamma} \right)$
- Red line: thermal (Shen et al., arXiv:1308.2111)
Virtual Photon Method (ALICE, pp, 7 TeV)

\[ \frac{d^2\sigma}{dm_{ee}dp_T} \] (mb/ GeV/c^2)

ALICE preliminary
pp, \( \sqrt{s} = 7 \) TeV
\( p_T^e > 0.2 \) GeV/c
\(|\eta^e| < 0.8\)

\[ 2.4 < p_T^{ee} < 3.2 \] GeV/c

\[ \text{cocktail sum} \]

- data
- \( f_{\gamma,\text{dir}} \)
- \( (1-r) f_{\text{cocktail}} + r f_{\gamma,\text{dir}} \)

\( \pi^0 \)
\( \eta' \)
\( \omega \)
\( \phi \)
\( c \)

ALICE preliminary = 7 TeV
pp, \( \sqrt{s} = 7 \) TeV
\( p_T^e > 0.2 \) GeV/c
\(|\eta^e| < 0.8\)

\[ 2.4 < p_T^{ee} < 3.2 \] GeV/c