Low Mass Dielectrons in pp, p-Pb and Pb-Pb Collisions with ALICE

Aaron Capon, on behalf of ALICE
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Dielectrons as Probes of the QGP

- Many sources of dielectrons created during the course of the collision
  → dielectron spectrum contains the whole “history” of the collision

- Photons and leptons experience no strong interactions and can therefore probe the inner regions of collisions unperturbed
  → medium is transparent to dielectrons
Dielectron Mass Spectrum

Low Mass Region

- \( m_{ee} < 1.1 \text{ GeV}/c^2 \)
- Populated with light neutral mesons
  - \( \pi^0, \eta, \eta', \rho, \omega \) and \( \phi \)
- Decaying via Dalitz, or two body decays

- Potentially sensitive to chiral symmetry restoration which is predicted at the high temperatures reached in heavy ion collisions
  - broadening of \( \rho \) observed at SPS and RHIC
    - measure at LHC: \( \mu_B = 0 \)
- Thermal radiation via measurement of quasi-real photons

Earlier production time
Dielectron Mass Spectrum

**Intermediate Mass Region (IMR)**

- $1.1 < m_{ee} < 2.5 \text{ GeV}/c^2$

- Dominated by decays of correlated “open heavy flavour”

- $c\bar{c}$ and $b\bar{b}$ pairs created during the collision can form a bound state with a lighter quark and then decay semi-leptonically ($c\bar{c} \rightarrow DD \rightarrow XY e^+e^-$)

- Measure/investigate:
  - $\sigma_{cc,b\bar{b}}$
  - Nuclear parton distribution functions (PDF’s) in p-Pb and Pb-Pb
  - Sensitive to production mechanisms in pp
  - Thermal radiation from the partonic phase
  - Photo-production: $\gamma\gamma \rightarrow e^+e^-$

Earlier production time
ALICE’s Results Overview

**pp**
- **Run 1**
  - $\sqrt{s} = 7$ TeV
    - JHEP 1809 (2018) 064
- **Run 2**
  - $\sqrt{s} = 13$ TeV
    - PLB 788 (2019) 505
  - $\sqrt{s} = 13$ TeV ($B = 0.2$T)
    - preliminary result
  - $\sqrt{s} = 5.02$ TeV
    - analysis ongoing

**Pb-Pb**
- **Run 1**
  - $\sqrt{s_{NN}} = 2.76$ TeV (0-10% centrality)
- **Run 2**
  - $\sqrt{s_{NN}} = 5.02$ TeV
    - preliminary (2015 data)
    - $\sim 10 \times$ more statistics from 2018 (0-10% centrality)

**p-Pb**
- **Run 1**
  - $\sqrt{s_{NN}} = 5.02$ TeV
    - preliminary
- **Run 2**
  - $\sqrt{s_{NN}} = 5.02$ TeV
    - $\sim 5 \times$ more statistics
    - ongoing work
      - DCA studies
      - multiplicity dependence
Dielectron Invariant Mass in pp

$\sqrt{s} = 7$ TeV

- Dielectron mass spectra in pp act as baseline for measurements in p-Pb and Pb-Pb

- Compare spectrum to cocktail of known hadronic sources

- Cocktail at $\sqrt{s} = 7$ TeV comprised of:
  - $\pi^\pm$ (for $\pi^0$), $\eta$, $\phi$, $J/\psi$: measurements used for input
  - $\eta'$: $m_1$ scaling
  - $\omega$ & $\rho$: $\omega/\pi^\pm$ and $\rho/\pi^\pm$ ratios from PYTHIA 8 Monash 2013 tune and measurements in pp at $\sqrt{s} = 7$ TeV
  - $c\bar{c}$ and $b\bar{b}$: PYTHIA 6 Perguia 2011 tune scaled to measured $\sigma_{c\bar{c},b\bar{b}}$

- Data well described by cocktail within uncertainties
  → baseline measurement well understood
Dielectron Invariant Mass in pp
\( \sqrt{s} = 13 \text{ TeV} \)

- Dielectron mass spectra in pp act as baseline for measurements in p-Pb and Pb-Pb

- Compare spectrum to cocktail of known hadronic sources

  - Cocktail at \( \sqrt{s} = 13 \text{ TeV} \) comprised of:
    - \( \pi^\pm \) (for \( \pi^0 \)): via scaling by the \( \pi^\pm / \text{hadrons}^{\pm} \) ratio from measurement at \( \sqrt{s} = 7 \text{ TeV} \)
    - \( \eta \): measured \( \eta / \pi^0 \) ratio at 7 TeV
    - \( \eta' \) & \( \phi \): \( m_T \) scaling
    - \( \omega \) & \( \rho \): \( \omega / \pi^\pm \) and \( \rho / \pi^{\pm} \) ratios from PYTHIA 8 Monash 2013 tune
    - \( c\bar{c} \) and \( b\bar{b} \): PYTHIA 6 Perguia 2011 tune scaled to \( d\sigma_{c\bar{c},b\bar{b}} / dy|_{y=0} \) scaled with FONLL from \( \sqrt{s} = 7 \text{ TeV} \) measurement

- Data well described by cocktail within uncertainties → baseline measurement well understood
DCA Studies in pp

- Observable → DCA = Distance of Closest Approach - normalised to track resolution

- Useful variable to separate prompt from non-prompt dielectron sources

\[ DCA_{ee}^{\text{prompt}} < DCA_{ee}^{\text{charm}} < DCA_{ee}^{\text{beauty}} \]
DCA Studies in pp

- Observable \( \rightarrow \) DCA = Distance of Closest Approach
  - normalised to track resolution
- Useful variable to separate prompt from non-prompt dielectron sources
  \[ DCA_{ee}^{\text{(prompt)}} < DCA_{ee}^{\text{(charm)}} < DCA_{ee}^{\text{(beauty)}} \]
- No evidence of prompt sources in pp
  - as expected in IMR

\[ DCA_{ee} = \sqrt{0.5 \left( \left( \frac{DCA_1}{\sigma_1} \right)^2 + \left( \frac{DCA_2}{\sigma_2} \right)^2 \right)} \]

JHEP 1809 (2018) 064

Aaron Capon | ALICE | Strange Quark Matter, 2019
HF Cross Sections in pp

- Both $DCA_{ee}$ and $m_{ee}/p_{T,ee}$ fit methods in agreement
- Dominant systematic uncertainty coming from $c\bar{c} \rightarrow ee$ branching ratio ($\pm 22\%$)
- PYTHIA fits in agreement with independent measurements using single HF hadrons
- Discrepancy between PYTHIA and POWHEG $c\bar{c}$ and $b\bar{b}$ results
  → Sensitive to production mechanisms from Monte Carlo generators

Reference:
- $\sigma_{bb}$ Eur. Phys. J. C 71 2011
- $\sigma_{cc}$ Eur. Phys. J. C 77 2017

JHEP 1809 (2018) 064

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Dielectron Invariant Mass in PbPb

- Run 2 data from 2015
  - Higher collision energy than Run 1
  - Acceptance increase due to lowered $p_T$ cut
    $0.4 \text{ GeV/c} \rightarrow 0.2 \text{ GeV/c}$

- Data consistent with an enhancement in the low mass region ($0.14 < m_{ee} < 0.7 \text{ GeV/c}^2$)
  - Statistics too low to address spectral shape changes
  - Awaiting analysis of 2018 data
    -> $\sim 10\times$ more events (0-10% centrality)
Photo-Production in Hadronic AA

\[ \gamma \gamma \rightarrow e^+ e^- \]

• Photo-production scales with \( Z^4 \)

• Coherent scattering \( \rightarrow \) peak at low-\( p_{T,ee} \)

• Relative contributions from photo-production expected to be smaller in central collisions compared to peripheral collisions

• Recently photo-production in peripheral collisions measured by STAR

STAR, Phys. Rev. Lett. 121, 132301
Photo-Production in Hadronic AA

- Run 2 data from 2015

- $1.1 < m_{ee} < 2.7 \text{ GeV}/c^2 \rightarrow$ HF dominated region

- MVA employed to suppress combinatorial background from electrons originating from photon conversions

- No significant discrepancy in 0 – 40\% centrality
Photo-Production in Hadronic AA

- Run 2 data from 2015

- $1.1 < m_{ee} < 2.7 \text{ GeV}/c^2 \rightarrow$ HF dominated region

- MVA employed to suppress combinatorial background from electrons originating from photon conversions

- 3.6$\sigma$ excess observed in 70-90% centrality

- Relative excess smaller than observed by STAR
Dielectron Production in Small Systems

- Study heavy-ion like phenomena in high multiplicity pp and p-Pb collisions with dielectrons
  - Production of $\rho$, thermal radiation, etc...?
- Study with dielectrons

Observable: \[ \frac{N_{ee}(HM)/dN_{ch}/d\eta(HM)}{N_{ee}(INEL)/<dN_{ch}/d\eta(INEL)>>} \]

- High multiplicity (HM) trigger selected 0.036% of events in pp
- Cocktail takes into account the following modifications:
  - Hardening of hadronic $p_T$ spectrum
    → assume same for LF hadrons at same $m_T$
  - D and J/$\psi$ scale faster than multiplicity
    → assume same enhancement for open beauty as for open charm
- No excess observed in $\rho$ dominated region
- Beauty assumption confirmed in high $p_T$ IMR

ALICE pp $\sqrt{s} = 13$ TeV
\[ p_{T,\ell} > 0.2 \text{ GeV}/c, |\eta| < 0.8 \]
\[ dN_{ee}/d\eta(HM) / \langle dN_{ee}/d\eta(INEL) \rangle = 6.27 \pm 0.22 \]
\[ p_{T,ee} < 6 \text{ GeV}/c \]

PLB 788 (2019) 505

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Summary and Outlook

**pp:** $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV

- Baseline $m_{ee}/p_{T,ee}$ and DCA$_{ee}$ measurements well understood
- Complementary measurements of $\sigma_{c\bar{c},b\bar{b}}$

**p-Pb:** $\sqrt{s_{NN}} = 5.02$ TeV

- Both DCA$_{ee}$ and $m_{ee}/p_{T,ee}$ multiplicity dependant analyses under way using run 2 data
  - Utilising MVA for ePID

**Pb-Pb:** $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV

- $m_{ee}/p_{T,ee}$ measurements statistics limited
  - $\sim 10 \times$ more data obtained in 2018 (0-10% centrality)
  - Promising outlook for Run 3

→ Talk at SQM: “Physics with the detector upgrades at LHC”
  By M. Weber, Friday, 17:00

- Photo-production observed, 3.6$\sigma$, in 70-90% centrality
Backup slides
Dielectron Invariant Mass in PbPb

- Run 2 data from 2015
  - Higher collision energy than Run 1
  - Acceptance increase due to lowered $p_T$ cut
    0.4 GeV/$c$ → 0.2 GeV/$c$

- Potential suppression in the intermediate mass region ($1.1 < m_{ee} < 2.5$ GeV/$c^2$)
  - $1.67\sigma$ effect
  - If including cold nuclear matter effects (EPPS16)
    - $0.41\sigma$ effect
Dielectron Invariant Mass in PbPb

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Run 3

- Major TPC and ITS upgrades
- Dielectron Future
  - Modified rho meson spectral function with uncertainty of ~15%
  - Extract temperature at $m_{ee} > 1$ GeV/$c^2$ with uncertainty of ~20%

Dedicated low B-field run (0.2T)

ALICE Upgrade Simulation

Excess in spectrum after one Pb-Pb run
DCA in p-Pb

- DCA studies also under way for Run 2 pPb data
- Investigate effects of cold nuclear matter on heavy flavour production
Heavy Flavour Production

- Concept: investigate different charm production processes using PYTHIA6 simulations

- Default production fractions:
  - Gluon splitting (GSP): 55%
  - Flavour excitation (FEX): 20%
  - Flavour creation (FCR): 10%

\[ m_{ee}^2 \approx 2p_{T,1} p_{T,2} (1 - \cos \Delta \varphi_{ee}) \]
QCD & Heavy Ion Collisions

- QCD at high temperatures → “deconfinement”
- Quarks and gluons become relevant dof’s → “Quark Gluon Plasma”
- Creation of hot, dense matter in lab → High-energy Heavy Ion collisions at the LHC and RHIC

Reference systems:
- Vacuum production → pp collisions
- Cold nuclear matter → pA collisions

Critical Point
Quark-Gluon Plasma
Hadron gas
Baryon Chemical Potential ($\mu_B$)

Early Universe
Crossover transition
Neuclei
Neutron stars

Time

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Small Systems

- Small systems used as reference measurements
  → pp and p-Pb collisions

- However, high multiplicity events in pp and p-Pb exhibit collective behaviour
  → Creation of Hot Dense Matter?

What signals can we look for?
- Final spectrum can be compared to “cocktail” of known hadronic sources*
  → in-medium meson modifications?
  → thermal photons?

*Known sources, as measured in p–Pb, or from pp and up scaled by number of participants

R.Rapp, IS2014
Chiral Symmetry

- In vacuum: $\langle q\bar{q}\rangle$ condensate $\neq 0$ → mass splitting of chiral partners

- High enough temperatures/densities → restoration of chiral symmetry
Chiral Symmetry Restoration

- Mechanism for restoration?

- Two main ideas:
  - dropping masses
    - Weinberg sum rules: $\rho_V - \rho_A \sim \langle qq \rangle$
  - Melting resonances
    - QCD sum rules: $\rho_V \sim \langle qq \rangle$

Dropping Masses?

Melting Resonances?

<table>
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<tr>
<th>Spectral Function</th>
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Mass

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MVA ePID
Particle Identification

Inner Tracking System
- PID (dE/dx), vertex, and tracking

Time Projection Chamber
- PID (dE/dx), and tracking

Time of Flight
- PID (β)
Classifier Training

- Input features shown to classifier

\[ e^\pm, \pi^\pm, K^\pm, p^\pm \text{ and } \mu^\pm \]
ePID Results

- Cut on classifier output via maximisation of \( \text{significance}(\text{PID}) = \frac{\text{signal}}{\sqrt{\text{signal} + \text{background}}} \)

Purity: 97%, Efficiency: 95%
Dielectron Analysis
Obtaining the Spectrum

- Track quality cuts applied to ensure only “good” quality tracks are used
  - $\chi^2$/n.d.f in each detector etc
- Electron particle identification performed
- Real photons decaying into electrons need to be removed
  - $\rightarrow$ conversion rejection cuts
- Obtain spectrum via like-sign subtraction

$$LS_{all} = R \cdot \sqrt{N_{++} \cdot N_{--}}$$

$$US_{signal} = US_{all} - LS_{all}$$

Additional factor needed during like-sign subtraction to account for different acceptances between ++/-- and +- tracks. Currently not implemented.
Background Subtraction

- For the final spectrum each positive and negative track, within each event, are paired together. These are labelled as the same event unlike-sign spectrum, $N_{same}^{+-}$, and contains not only the real dielectron pairs, but also many pairs which are merely combinatorial.

- The combinatorial background is calculated via the geometric mean (arithmetic if empty bins) of the like-sign pair spectra within the same event, $B$.

$$B = 2 \cdot \sqrt{N_{same}^{++} \cdot N_{same}^{--}}$$

- The difference in acceptance between unlike and like-sign pairs is calculated with the acceptance factor, $R$, which uses event mixing to remove an correlations between pairs:

$$R = \frac{N_{mixed}^{+-}}{2 \cdot \sqrt{N_{mixed}^{++} \cdot N_{mixed}^{--}}}$$

- The final raw spectrum is then determined with:

$$signal = N_{same}^{+-} - R \cdot B$$
Low-mass Thermal Radiation
Thermal Radiation

- Key QGP signature: thermally radiated photons

- Thermal radiation can be directly related to the temperature via

\[ \frac{dN}{dp_T} \propto \exp\left(-\alpha \frac{p_T}{T}\right) \]

- However, photon measurements contain doppler and flow effects due to expanding medium.

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Direct Photon Measurement

- Key QGP signature
  \[ \rightarrow \text{thermally radiated photons} \]

- Need to extract direct photons from inclusive photons
  \[ \text{direct: all photons not from hadron decays} \quad \text{inclusive: all photons} \]

- Relationship between yield of virtual photons and dielectron yield given by Kroll-Wada:

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

\[ \text{Process dependent factor} \]

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\[ \text{Direct photons}^* \quad \text{If } p_T^2 > M_{ee}^2 \rightarrow S = 1 \]
Direct Photon Measurement

- Key QGP signature → thermally radiated photons

- Need to extract direct photons from inclusive photons
  - direct: all photons not from hadron decays
  - inclusive: all photons

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\[
\frac{1}{N_y} \frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}} \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) \frac{1}{m_{ee}} F(m_{ee})^2 \left(1 - \frac{m_{ee}^2}{M^2}\right)^3
\]

\[S = 0 \text{ when } m_{ee} > M_{\text{hadron}} \]

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

\[\text{Hadrons} \quad \text{S} = 0 \text{ when } m_{ee} > M_{\text{hadron}} \]

\[\text{Direct photons*} \quad \text{If } p_T^{ee} > M_{ee}^2 \rightarrow S = 1 \]
Extracting Direct Photons

Fit the following function to the data:

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

Cocktail contributions

Photon input from Kroll-Wada

- $r$ is the ratio of direct to inclusive photons

- Under the assumption that the ratio of direct to inclusive is the same as real to virtual
  $$\rightarrow \text{direct} = r \times \text{inclusive}$$

- Where the inclusive photon cross section is known via photon conversions\(^1\)

\[\begin{align*}
\text{ALICE preliminary} &  \\
pp, \sqrt{s} = 7 \text{ TeV} &  \\
\rho_T^2 > 0.2 \text{ GeV}/c &  \\
|\eta| < 0.8 &  \\
2.4 < \rho_T^2 < 3.2 \text{ GeV}/c &  \\
\end{align*}\]

\[\begin{align*}
data &  \\
f_T^{\gamma, \text{dir}} &  \\
(1-r)f_{\text{cocktail}} + rf_T^{\gamma, \text{dir}} &  \\
\text{cocktail sum} &  \\
\end{align*}\]

\[\begin{align*}
\frac{d\sigma}{dp_T} &  \\
\text{measured} &  \\
\text{predictions} &  \\
\text{sum} &  \\
\end{align*}\]