Low-mass dilepton measurements with ALICE at the LHC


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Outline

Introduction & physics motivation

Dimuon measurements:

- $\phi$ meson production in pp and Pb-Pb collisions
  - Improved precision of the measurement in pp collisions at $\sqrt{s} = 5.02$ TeV (preliminary)

Dielectron measurements:

- Published results in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- Preliminary results in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Dielectron invariant-mass spectra & heavy-flavor cross sections in pp collisions
Dileptons are produced continuously during the space-time evolution of nucleus-nucleus collisions

Negligible final state interaction:
- Unperturbed signals on production process

**Low-mass vector-meson production:**
- Input for phenomenological models that describe particle production in a non-perturbative QCD regime
- Strangeness production via the ϕ meson measurement

**Dilepton continuum:**
- In-medium effects of low-mass vector mesons (broadening)
- Thermal radiation from virtual component of direct photons
- Measurement of charm and bottom production & modification

Measurements in pp collisions → fundamental baseline for AA collisions
The ALICE setup

**ITS (Inner Tracking System)**
- Tracking, vertexing & PID (via $dE/dx$ in silicon layers)

**TPC (Time Projection Chamber)**
- Tracking & PID (via $dE/dx$ in the gas)

**TOF (Time Of Flight)**
- PID (via TOF measurement)

**V0**
- Centrality estimator

**Muon spectrometer**
- Trigger & tracking of muons
Dimuon measurements
Signal extraction of $\phi$ meson

Single muons are selected with $-4 < \eta_\mu < -2.5$

Minimum $p_T$ for dimuon pairs:
- 2 GeV/c in Pb-Pb collisions
- $\approx 0$ GeV/c in pp collisions for most forward rapidity

**Combinatorial background:**

Unlike-sign invariant-mass distribution from mixed events normalized to $2R\sqrt{N_{++} \cdot N_{--}}$

$$R = \frac{N_{+-}^{\text{mixed}}}{\left[2\sqrt{N_{++}^{\text{mixed}} \cdot N_{--}^{\text{mixed}}}\right]}$$

correction for geometrical asymmetry of the detector

Contribution from light-meson decays estimated from a fit with mass shapes given by simulations

**Continuum background** from open charm and bottom “regularized” to describe the residual contribution from correlated background.
EPOS 3 and HIJING 2 underestimate the $\phi$ meson yield by a factor ~2 at low $p_T$

$$dN_\phi/dy$$ per participant: increasing trend vs. $<N_{\text{part}}>$ followed by saturation

- Constant ratio (~2) between production at mid-rapidity and forward

$$R_{AA}$$ at forward and mid-rapidity are consistent: similar interaction with the bulk
$\phi$ meson in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

$\rho_T$ spectrum described by power-law function in all centralities

Tails become harder going from central to more peripheral collisions

- Consistent with previous results from ALICE and PHENIX

$\rho_T$-dependent $R_{AA}$: stronger suppression in central collisions
Energy dependence of $\phi$ meson production

New measurement of the $\phi$ meson spectrum in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- Improved statistical precision and wider $p_T$ range
- Smaller systematic uncertainties

$p_T$ spectrum of $\phi$ meson becomes harder for increasing center-of-mass energy
The full rapidity dependence of the $\phi$ meson $p_T$-integrated production cross section is not reproduced by the models

- PYTHIA 8 consistent with the data only at forward rapidity

The $\sqrt{s}$ dependence of the $\phi$ meson cross section, integrated over common phase space of the measurements, is described by PHOJET
Dielectron measurements
Electron candidates are selected in the pseudorapidity range $|\eta_e| < 0.8$

Particle identification based on $dE/dx$ measured by ITS and TPC and time-of-flight measured by TOF

Combinatorial background described by like-sign invariant-mass spectrum:

$$2R \sqrt{N_{++} \cdot N_{--}}$$

correlated & uncorrelated background
Dielectrons in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

Cocktail of known hadronic sources:
- \( \pi^0 \) from ALICE measurement
- \( \eta \) from K/\( \pi \) ratio in Pb-Pb and \( \eta/\pi \) ratio in pp collisions
- Other mesons from \( m_T \) scaling

Dielectrons from charm and bottom decays obtained as \(<N_{\text{coll}}> \times (dN/dm_{ee})_{pp}\)

Data are consistent with the cocktail within the uncertainties

Data / cocktail (w/o vacuum \( \rho^0 \)) in \( 150 < m_{ee} < 700 \) MeV/c\(^2\):
1.40 \( \pm 0.28 \) (stat.) \( \pm 0.08 \) (syst.) \( \pm 0.27 \) (cocktail)

Limited sensitivity to low-mass excess due to low statistics
Thermal dielectrons

Theoretical model calculations:

R. Rapp:

Thermal dielectrons from expanding fireball model and in-medium broadening of $\rho^0$ from hadronic many-body theory

PHSD:

Thermal dielectrons from QGP assuming that quarks are massive off-shell quasi particles. Collision broadening of $\rho^0$ spectral function

The two models are consistent with the data within the uncertainties
Virtual direct photons

Contribution from virtual direct photons measured from minimized $\chi^2$ fit of data in the mass range $100 < m_{ee} < 300$ MeV/$c^2$:

$$f(m_{ee}) = r \cdot f_{dir}(m_{ee}) + (1 - r) \cdot f_{LF}(m_{ee}) + f_{HF}(m_{ee})$$

Virtual photon mass shape (Kroll-Wada eq.)

Light-flavor cocktail

Heavy-flavor contribution

Fraction of virtual direct photons extrapolated for $m_{ee} \to 0$ GeV/$c^2$

Virtual direct photon measurement is at lower edge of real photon measurement remaining consistent with it within the uncertainties

arXiv:1807.00923 [nucl-ex], Submitted to PRC
Dielectrons in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Hadronic cocktail parametrization:

- Charged pions as proxy for $\pi^0$
- $\eta$ from $K/\pi$ ratio in Pb-Pb
- Other mesons from $m_T$ scaling
- $J/\psi$ from ALICE measurement in Pb-Pb collisions at 5.02 TeV

Dielectrons from charm and bottom decays obtained as $<N_{\text{coll}}> \times (dN/dm_{ee})_{pp}$

First evidence of charm modification as compared to $N_{\text{coll}}$ scaling from PYTHIA from the comparison to hadronic cocktail in $1.1 < m_{ee} < 2.5$ GeV/$c^2$:

- data / cocktail = $0.53 \pm 0.19$ (stat) $\pm 0.12$ (syst) $\pm 0.13$ (cocktail)
**Cold nuclear matter effects**

\[ R_{AA} \] of charm quarks including only shadowing effects (EPPS16NLO)

R. Rapp et al., NPA 979 (2018) 21

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**Simulation of charm suppression:**

Electrons from charm decays in PYTHIA are weighted using the \( p_T \)-dependent \( R_{AA} \):

- Data are consistent with the cocktail with modified charm in the mass range \( 1.1 < m_{ee} < 2.5 \) GeV/c²:
  - Data/cocktail = \( 0.82 \pm 0.26 \) (stat.) \( \pm 0.18 \) (syst.) \( \pm 0.29 \) (cocktail)
Dielectrons in pp collisions at \( \sqrt{s} = 7\) TeV

Low-mass dileptons

Dielectron spectrum consistent with the cocktail within uncertainties

DCA\(_{ee}\) is a powerful tool to separate prompt and non-prompt dielectron sources

- improved resolution in Run 3 with upgraded ITS

\[
DCA_{ee} (\sigma) = \sqrt{\frac{DCA_{e+}^2}{\sigma^2} + \frac{DCA_{e-}^2}{\sigma^2}}
\]

DCA\(_{e}(\sigma)\): Distance-of-closest approach to the vertex in unit of DCA resolution (\(\sigma\))
Charm & bottom cross sections extracted from a double-differential \((m_{ee}, p_T)\) fit of data in the intermediate mass region \((1.1 < m_{ee} < 2.7 \text{ GeV}/c^2)\)

Measured cross sections are consistent with independent measurements

Model dependence (PYTHIA vs. POWHEG):

- Dielectrons are sensitive to charm production mechanism and angular correlations
Dielectrons in pp collisions at $\sqrt{s} = 13$ TeV

arXiv:1805.04407 [hep-ex], submitted to PLB

Good understanding of hadronic component in pp collisions

**First measurement of $\sigma_{c\bar{c}}$ and $\sigma_{b\bar{b}}$ in pp collisions at $\sqrt{s} = 13$ TeV from 2D fit in intermediate-mass region ($1.03 < m_{ee} < 2.86$ GeV/$c^2$):**

- Using PYTHIA
  - $d\sigma_{c\bar{c}} / dy|_{y=0} = 974 \pm 138$ (stat.) $\pm 140$ (syst.) $\mu$b
  - $d\sigma_{b\bar{b}} / dy|_{y=0} = 79 \pm 14$ (stat.) $\pm 11$ (syst.) $\mu$b
- Similar model dependence as for pp collisions at 7 TeV

- Using POWHEG
  - $d\sigma_{c\bar{c}} / dy|_{y=0} = 1417 \pm 184$ (stat.) $\pm 204$ (syst.) $\mu$b
  - $d\sigma_{b\bar{b}} / dy|_{y=0} = 48 \pm 14$ (stat.) $\pm 7$ (syst.) $\mu$b

Consistent with extrapolations from lower energies
Dielectrons in high-multiplicity pp collisions

Observable: \[
\frac{N_{ee}(HM)}{\langle N_{ee}(INEL) \rangle} \times \frac{\langle dN_{ch}/d\eta(INEL) \rangle}{dN_{ch}/d\eta(HM)}
\]
account for trivial scaling with charged-particle multiplicity

Ratio is in good agreement with hadronic cocktail in all $p_T$ ranges
Dielectrons in high-multiplicity pp collisions

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Ratio is in good agreement with hadronic cocktail in all \( p_T \) ranges

High \( p_T \) (3 < \( p_T < 6 \text{ GeV/c} \)) dominated by bottom:

- multiplicity dependence similar to that of open charm (first clear evidence)
Dielectrons in high-multiplicity pp collisions

Virtual direct-photon measurement:

No significant direct-photon contribution is observed: upper limits at 90% C.L. are set

Consistent with pQCD calculations

<table>
<thead>
<tr>
<th>Data sample</th>
<th>1 &lt; ( p_{T,ee} &lt; 2 ) GeV/c</th>
<th>2 &lt; ( p_{T,ee} &lt; 3 ) GeV/c</th>
<th>3 &lt; ( p_{T,ee} &lt; 6 ) GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bias</td>
<td>0.057</td>
<td>0.072</td>
<td>0.023</td>
</tr>
<tr>
<td>High multiplicity</td>
<td>0.060</td>
<td>0.083</td>
<td>0.055</td>
</tr>
<tr>
<td>pQCD</td>
<td>0.003</td>
<td>0.007</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Observable:

\[
\frac{N_{ee}(HM)}{\langle N_{ee}(INEL) \rangle} \times \frac{\langle dN_{ch}/d\eta(INEL) \rangle}{dN_{ch}/d\eta(HM)}
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account for trivial scaling with charged-particle multiplicity

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Low-mass dileptons

arXiv:1805.04407 [hep-ex], submitted to PLB
Low-\(B\) field results

Pilot runs of pp collisions at \(\sqrt{s} = 13\) TeV with reduced magnetic field

- Performance test for Run 3 after the upgrade

Larger efficiency due to higher TOF acceptance at the same \(p_T\)

Measurement extended to lower \(p_T\): 200 MeV/c \(\rightarrow\) 75 MeV/c
Summary

**ϕ meson production:**
- No consistent description by the models in pp collisions
- Yield underestimated by HIJING and EPOS in Pb-Pb collisions

**Dielectron measurements:**
- Limited sensitivity to low-mass excess in Pb-Pb collisions
  - Precision measurement is expected after the upgrade
- First indication of deviation of charm yields from binary scaling at $\sqrt{s_{NN}} = 5.02$ TeV
- Sensitivity to charm and bottom production in pp collisions
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Thank you for your attention
Backup slides
ω and φ mesons in pp collisions at $\sqrt{s_{NN}} = 13$ TeV

Large data sample of pp collisions at $\sqrt{s_{NN}} = 13$ TeV:

- double-differential ($p_T, y$) production cross-sections of ω and φ mesons

PYTHIA 8 fairly describes the φ meson spectrum over the measured $p_T$ range

PHOJET overestimates the production cross-section of both the ω and φ mesons

A. Calivà for the ALICE Collaboration

Low-mass dileptons
Charm in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV

Random angular correlations of dielectrons from charm decays:
- Charm contribution suppressed by a factor \( \sim 2 \)
Thermal $e^+e^-$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

A. Calivà for the ALICE Collaboration

Low-mass dileptons

PHSD

R. Rapp

ALICE Preliminary

Data

Cocktail (PHSD, arXiv:1803.02698v2)

light flavour (PHSD)

$\rho \rightarrow e^+e^-$ (PHSD)

$cc \rightarrow e^+e^-$ (not LS-subtracted, PHSD)

$bb \rightarrow e^+e^-$ (not LS-subtracted, PHSD)

$q+q \rightarrow e^+e^-$ (PHSD)

$q+g \rightarrow e^+e^-$ (PHSD)

$J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \gamma e^+e^-$ (ALICE prel.)

ALICE Preliminary

Data

Cocktail

$\pi^0 \rightarrow e^+e^-$

$\eta \rightarrow \gamma e^+e^-$

$\eta' \rightarrow \gamma e^+e^-$, $\eta' \rightarrow \omega e^+e^-$

$\omega \rightarrow e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-

$\phi \rightarrow e^+e^-$, $\phi \rightarrow \eta e^+e^-$, $\phi \rightarrow \pi^0 e^+e^-

$cc \rightarrow e^+e^-$ (PYTHIA $6 \times N_{coll}$)

$bb \rightarrow e^+e^-$ (PYTHIA $6 \times N_{coll}$)

HG + in-med. p (Rapp)

QGP radiation (Rapp)

Adv. HEP 2013 (2013) 148253

and PRC 63 (2001) 054907
Modified charm from EPS09 calculation
Anomalous dielectron pairs

Excess of dielectrons observed by the AFS experiment at the ISR for $0.05 < m_{ee} < 0.6 \text{ GeV/c}^2$ and very low pair-$p_T$


Probe similar kinematic region at the LHC

More data and precise $\eta$ measurement at low $p_T$ are needed
 Perspectives after the ALICE upgrade


New ITS: suppression of main background sources (Dalitz, conversion & charm)
Continuous TPC readout will increase event rate by a factor ∼100
  - Detailed measurement of in-medium modification & thermal radiation

- New ITS, 2.5x10^9 events with DCA cuts
- Continuous TPC readout will increase event rate by a factor ∼100
  - Detailed measurement of in-medium modification & thermal radiation