A Large Ion Collider Experiment

ALICE

Thermal radiation and direct-photon production in Pb–Pb and pp collisions with dielectrons in ALICE

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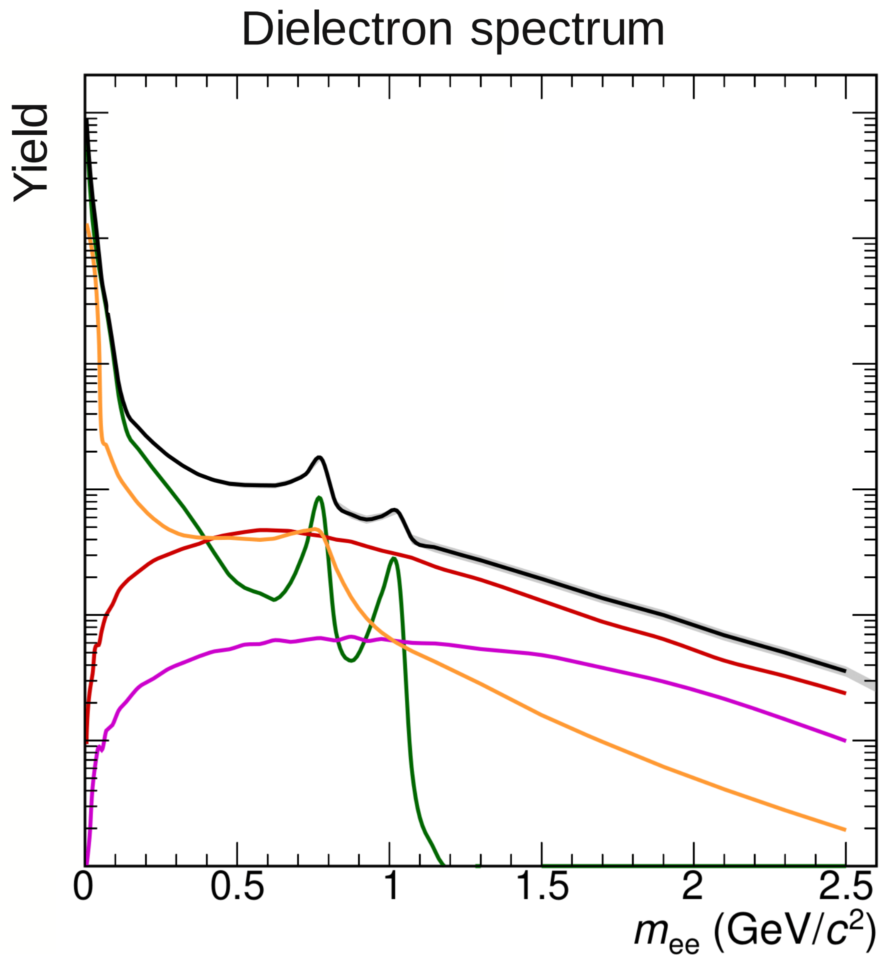
QM QUARK MATTER KRAKÓW 2022

Motivation

Dielectron production

Several sources of correlated electron pairs in Pb–Pb:

→ Separation via invariant mass



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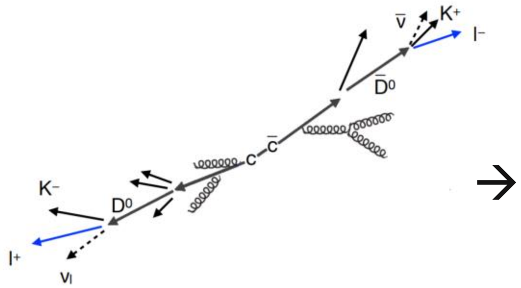
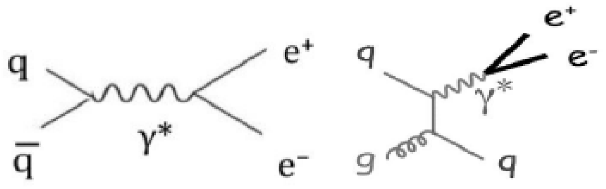
At higher masses ($1.1 < m_{ee} < 2.7\ \mathrm{GeV}/c^2$):
- Correlated semi-leptonic decays of heavy flavour (HF)

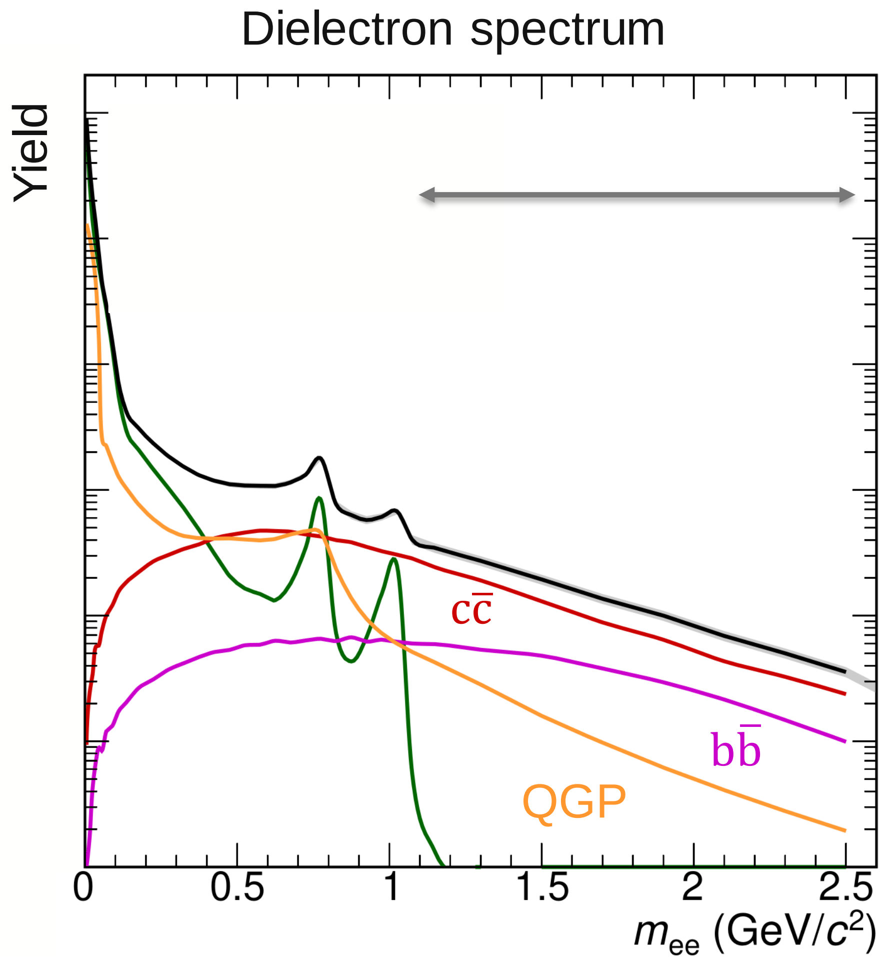


→ Suppression of HF production

- Quark-gluon plasma (QGP)



→ Temperature of the QGP



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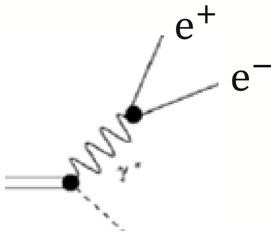
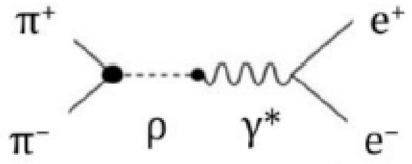
- Pseudoscalar and vector mesons ($\pi^0, \eta, \rho, \omega, \phi$)

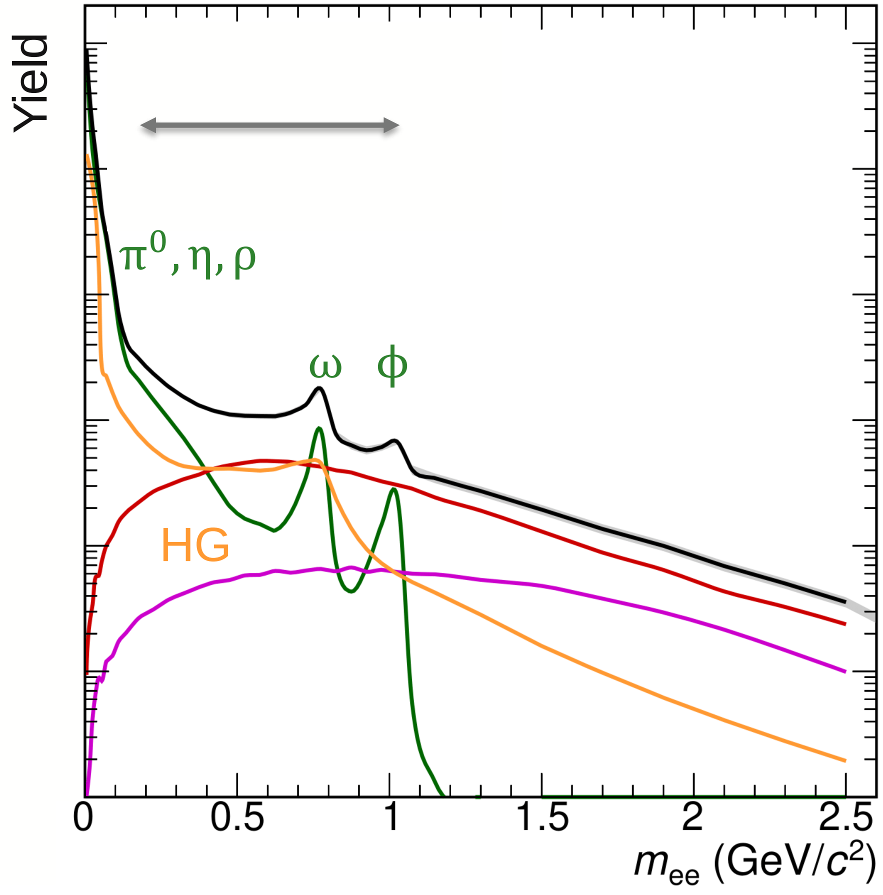


- Hadron-gas (HG) phase



→ Temperature of the HG
Modification of the ρ spectral function

Dielectron spectrum



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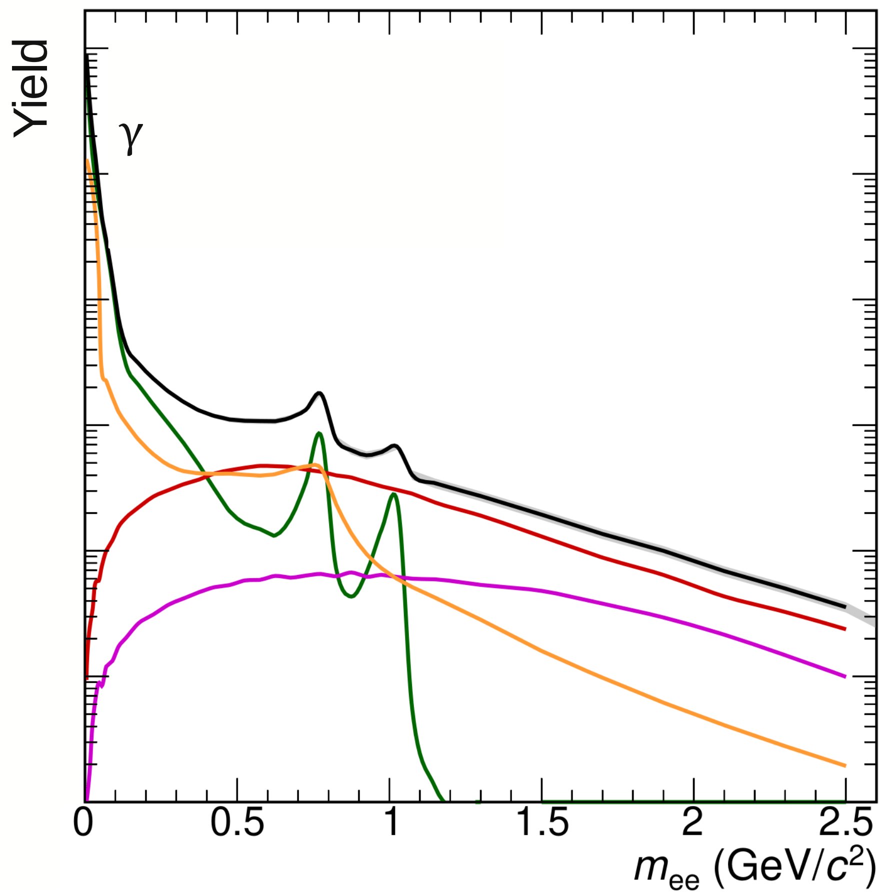
At vanishing mass ($m_{\mathrm{ee}} \rightarrow 0$):

- Equivalent to real-photon measurement

Dielectron spectrum



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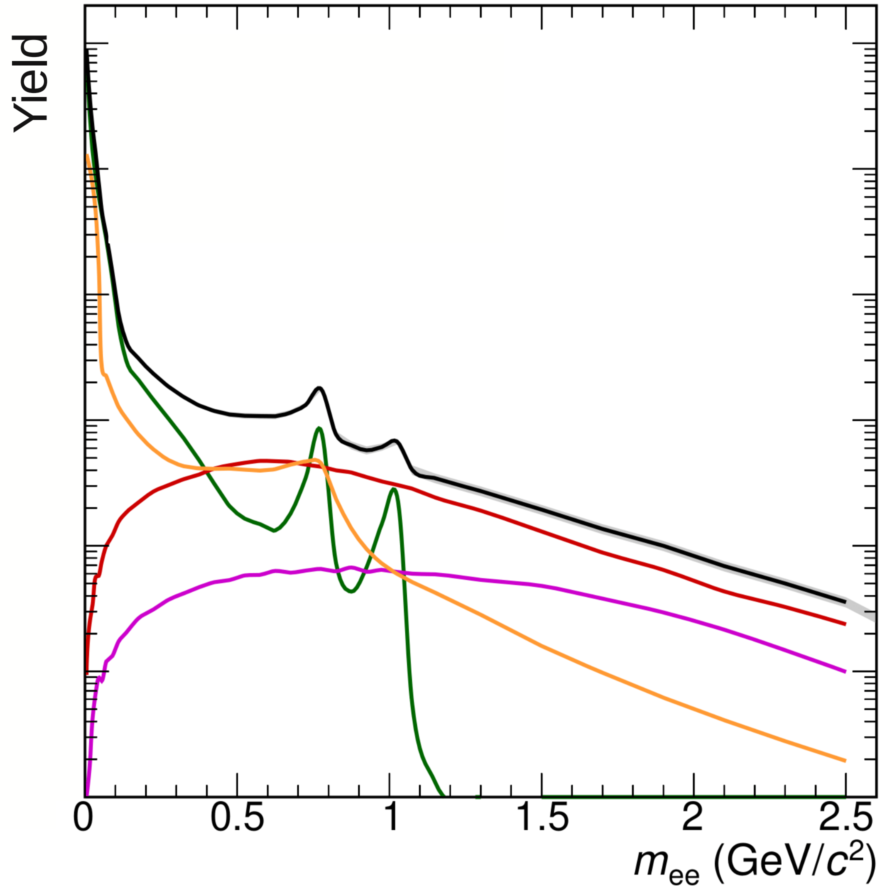


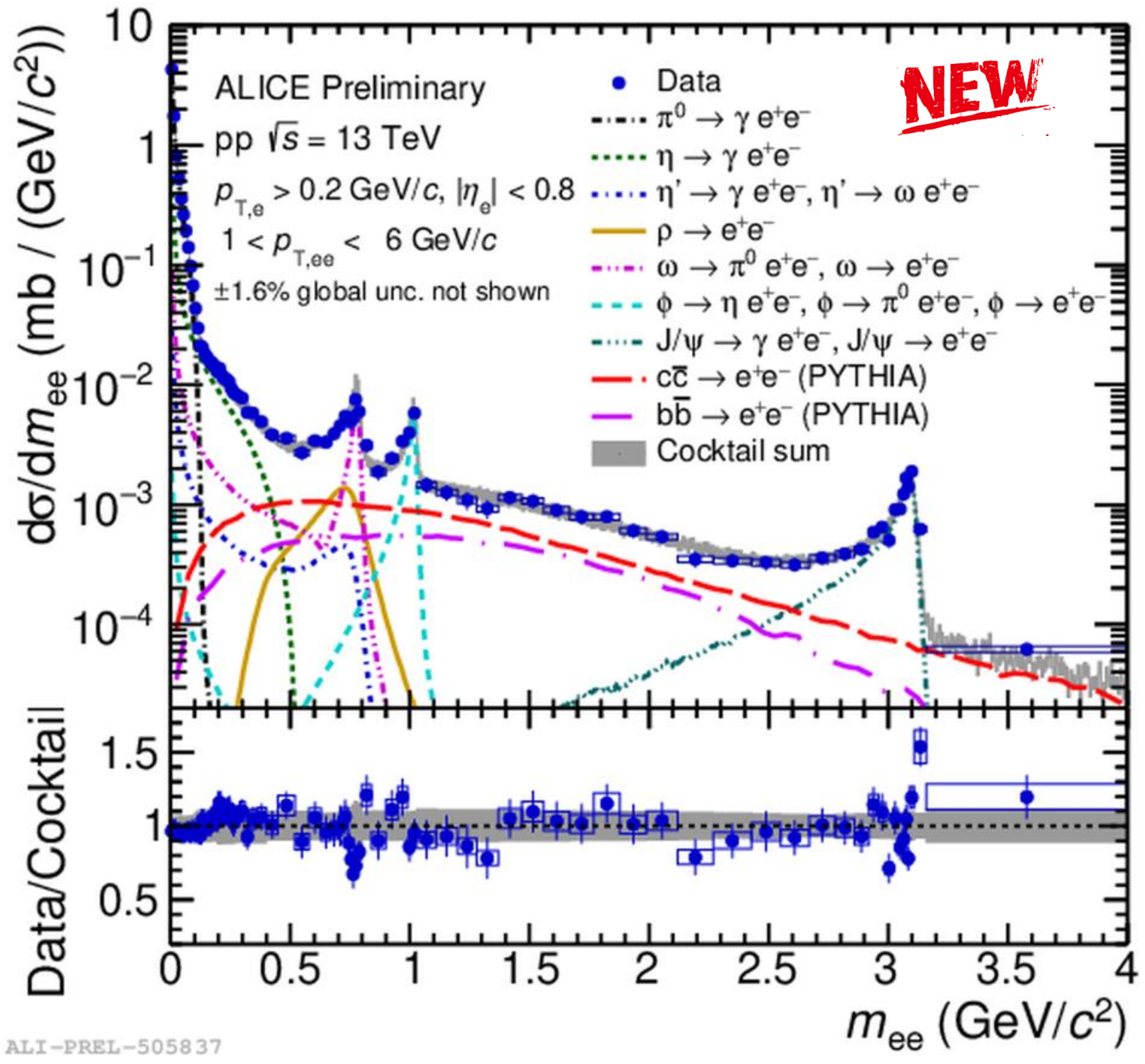
<u>Measurements in pp:</u>

- Vacuum baseline for Pb−Pb studies (HF, direct photons)
- Search for new phenomena in high-multiplicity (HM) events or at low momenta

  Phys. Rev. Lett. 127, 042302 (2021)

Dielectron production in pp at $\sqrt{s}$ =13 TeV

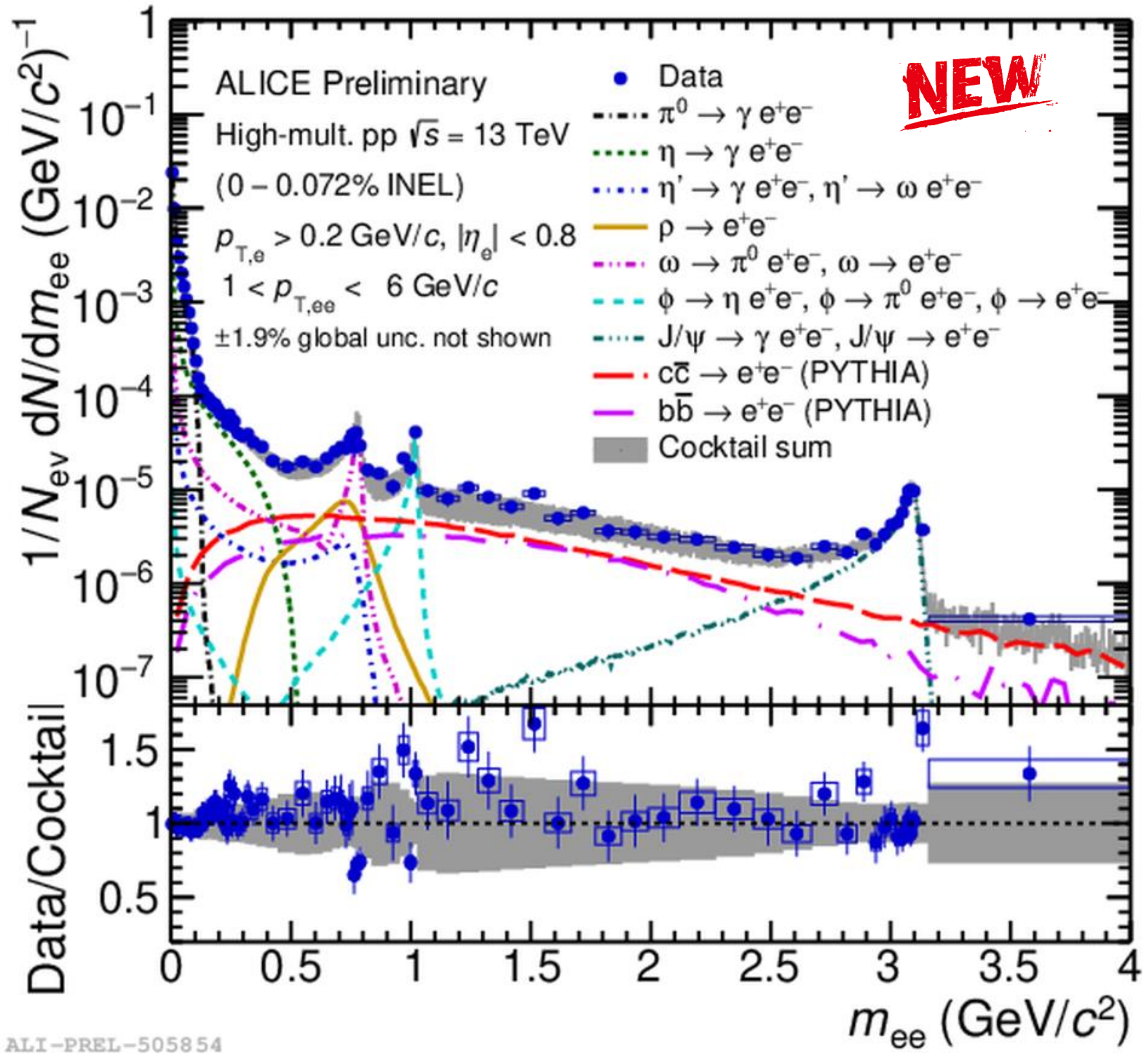
Minimum bias (MB)



- Analysis of the full Run 2 data set
  → Poster by H. Murakami: Session 2 T13
- Increase of statistics compared to previous publication:
  Phys. Lett. B 788 (2019) 505
  MB: a factor of 3.8 & HM: a factor of 4.4
- Updated hadronic cocktail estimation with independent measurements at $\sqrt{s}$ = 13 TeV
  → π^0 and η mesons in the same multiplicity intervals
  → Poster by J. Konig: Session 1 T14_2
- MB ($p_{T,ee} > 1\ \mathrm{GeV}/c$) well described by hadronic sources

Dielectron production in pp at $\sqrt{s}$ =13 TeV

High multiplicity (HM)



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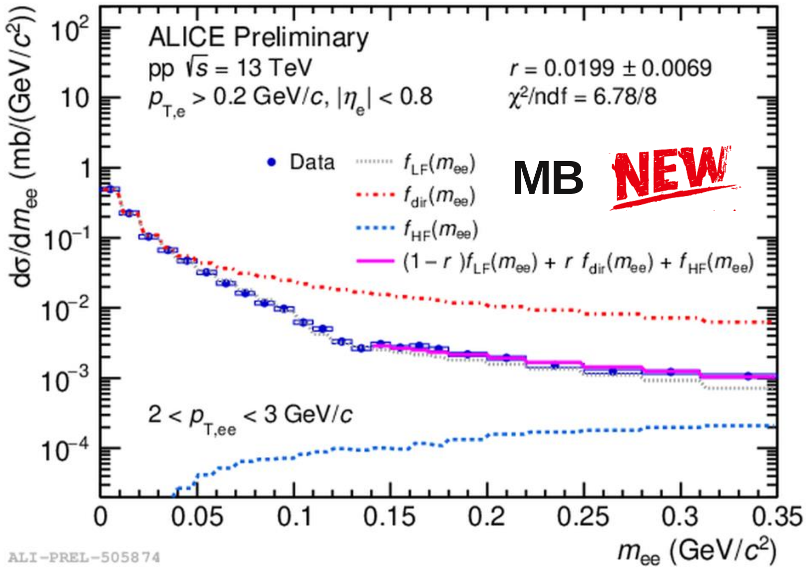
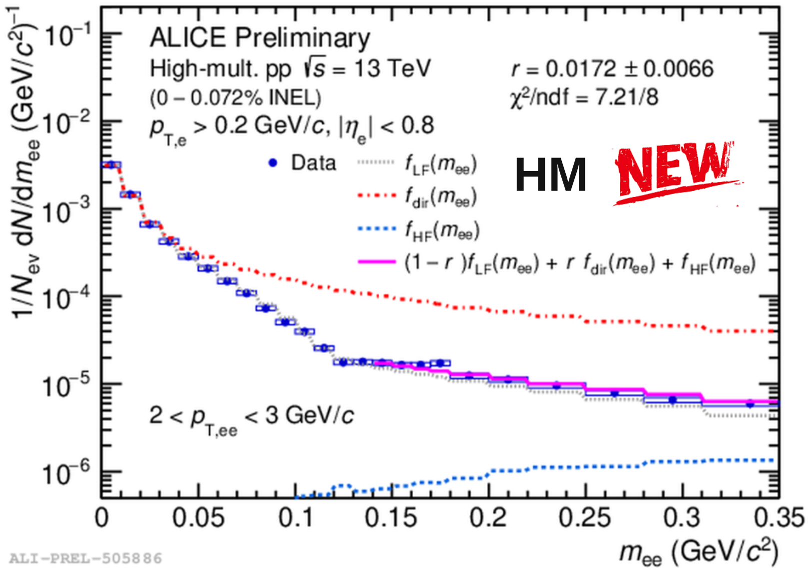
- Updated hadronic cocktail estimation with independent measurements at $\sqrt{s} = 13$ TeV

  → π^0 and η mesons in the same multiplicity intervals
  → Poster by J. Konig: Session 1 T14_2
  → Larger cocktail uncertainties due to multiplicity dependence of HF production

- Within uncertainties no sign of thermal radiation in HM pp events

Direct-photon fraction in pp at $\sqrt{s} = 13$ TeV





Direct photons in pp

→ Important baseline for Pb−Pb

→ Search for possible thermal contributions in HM pp events

Kroll-Wada formula f_{dir} used for extraction:

$$f_{fit} = r \times f_{dir} + (1-r) \times f_{LF} + f_{HF}$$

Direct-photon fraction r :

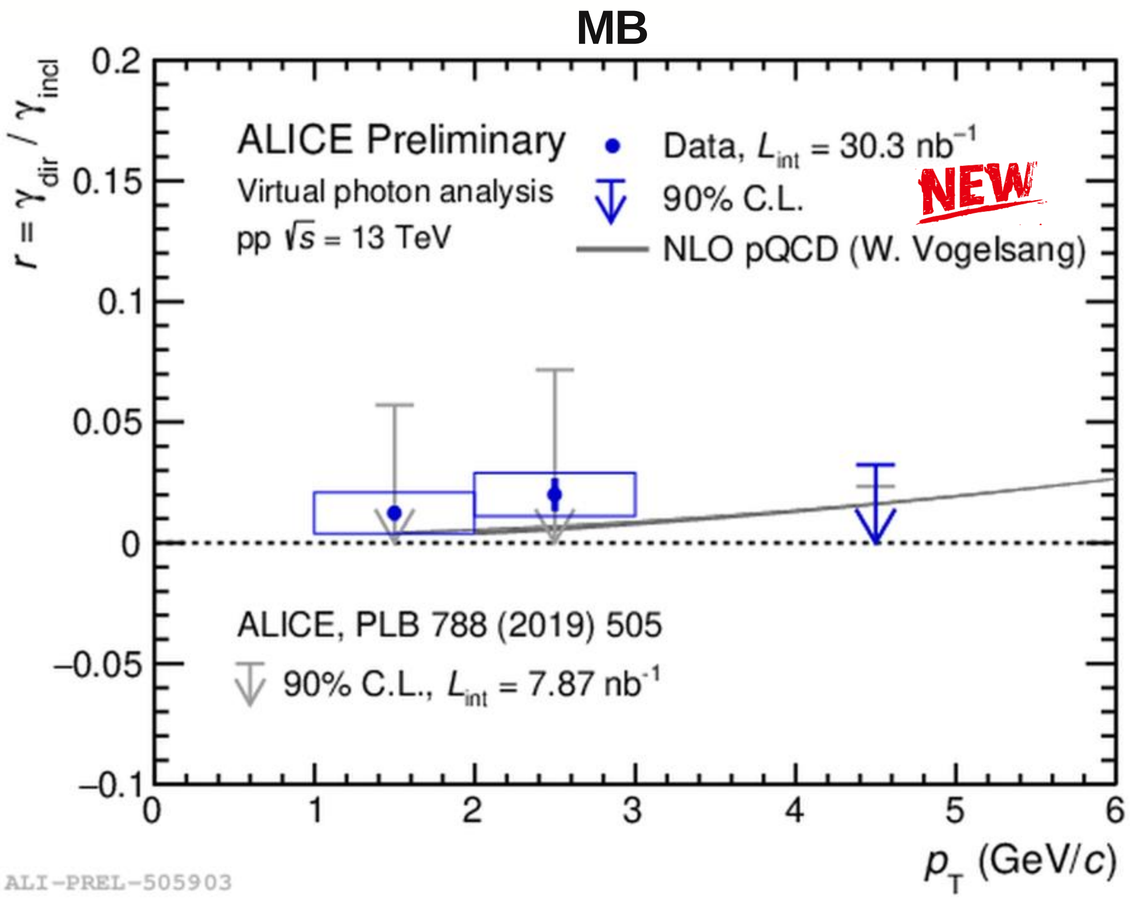
$$r = \gamma^*_{dir}/\gamma^*_{incl} \overset{m_{ee} \to 0}{=} \gamma_{dir}/\gamma_{incl}$$

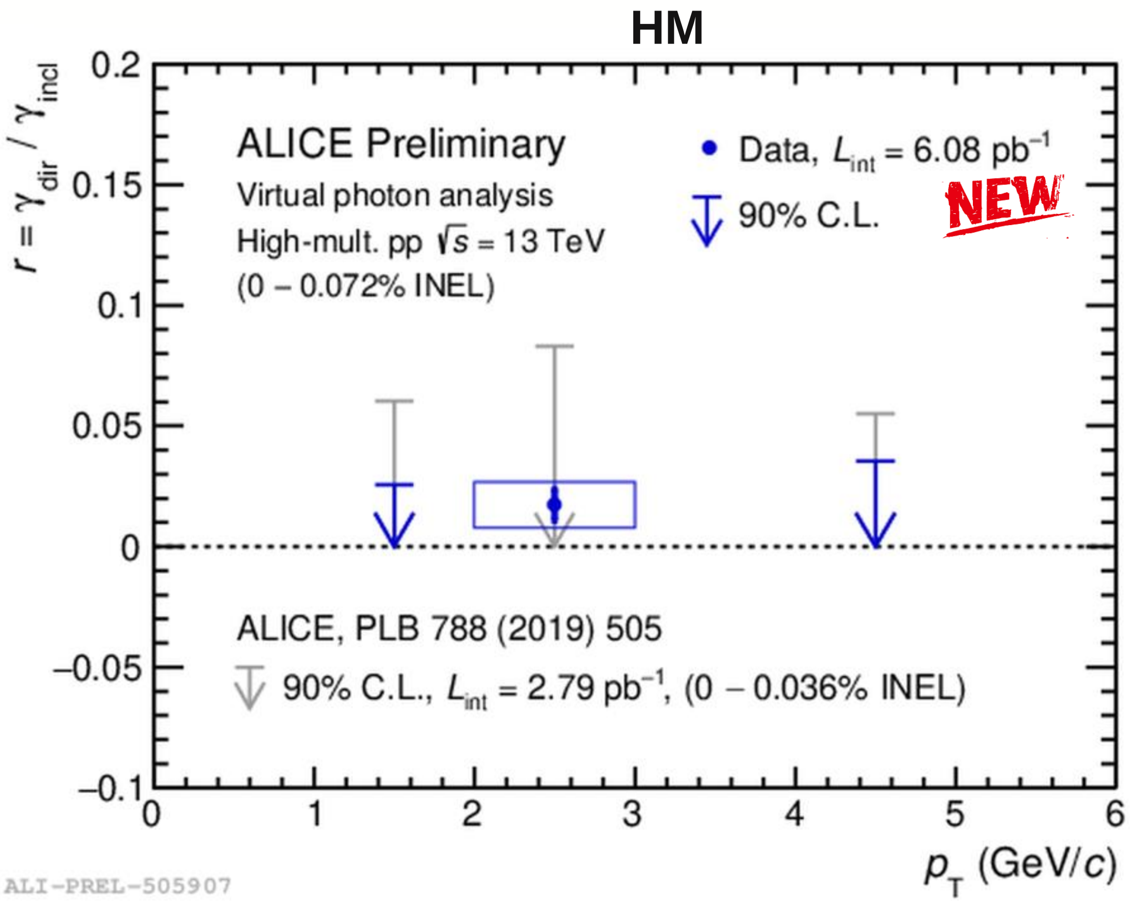
Link to real-photon yield

- Direct-photon fraction r as the only free parameter
- Spectrum fitted above pion mass
  → Large reduction of systematic uncertainties compared to real-photon measurement

Direct-photon fraction in pp at $\sqrt{s} = 13$ TeV

Comparison to published results and theory





Significant reduction of statistical and systematic uncertainties in new analysis

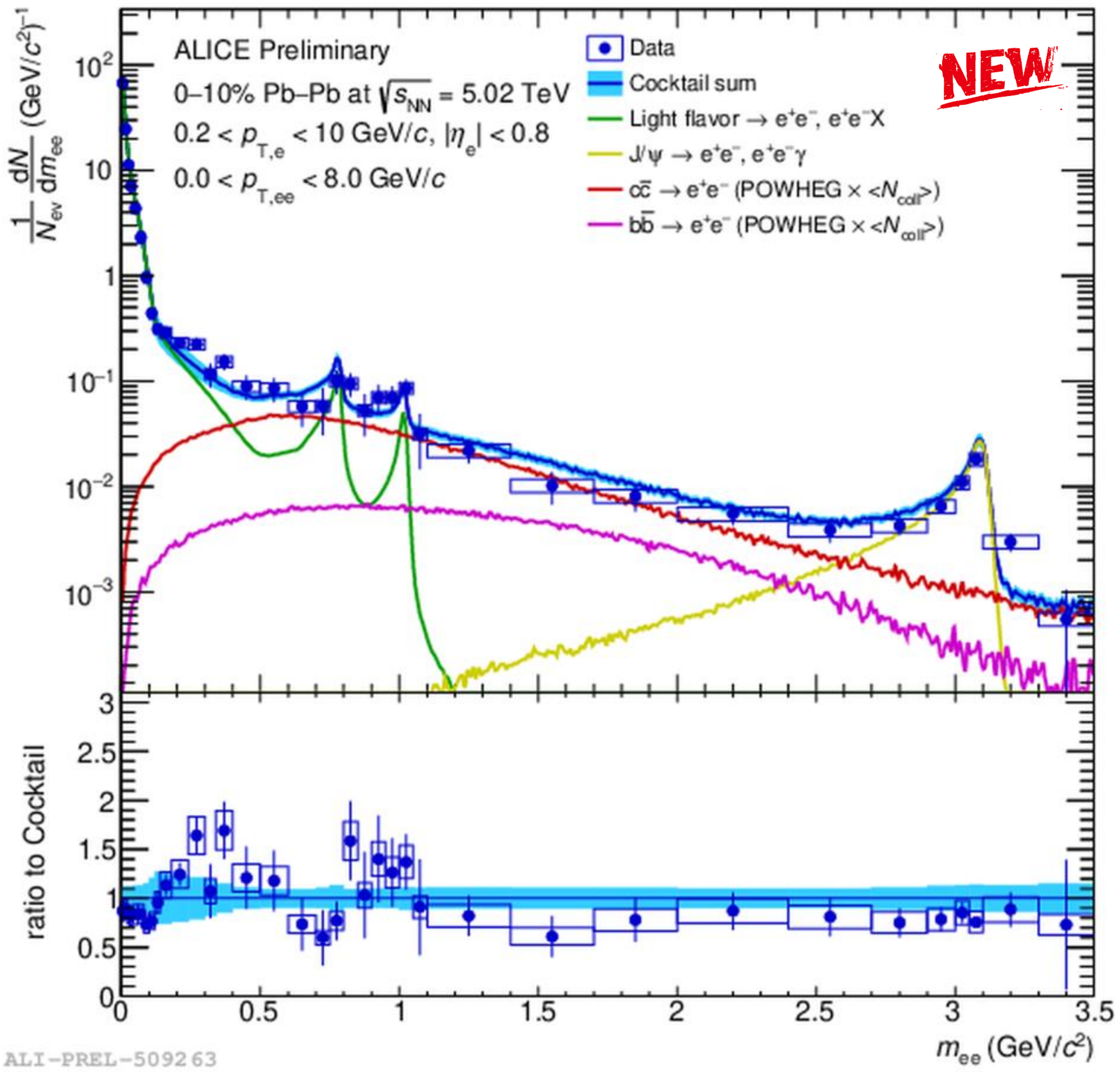
→ Direct-photon fraction in MB in good agreement with pQCD calculations

→ Measurement in HM compatible with MB results

Poster by H. Murakami: Session 2 T13

Dielectron production in central Pb−Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Invariant-mass spectrum



Comparison to hadronic cocktail, including:

- N_{coll}-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  Phys. Rev. C 102 (2020) 055204
  → Vacuum baseline

Data at the edge of the uncertainty of hadronic cocktail

However: HF contribution is expected to be modified
→ CNM and hot medium effects

Dielectron production in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

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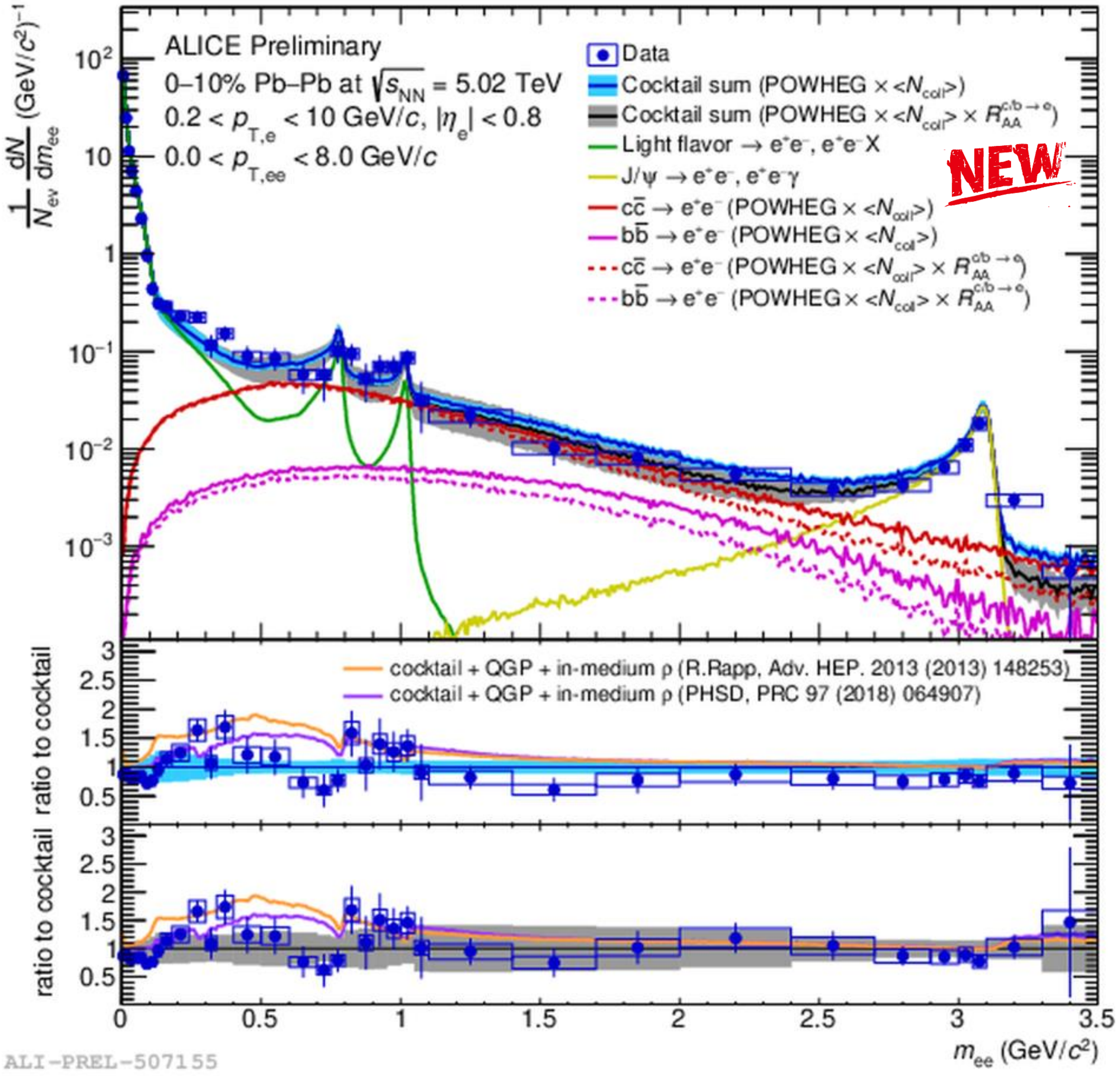


Comparison to hadronic cocktail, including:

- N_{coll}-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  Phys. Rev. C 102 (2020) 055204
  → Vacuum baseline
- Include measured R_{AA} of $c/b \rightarrow e^{\pm}$
  Phys.Lett.B 804 (2020) 135377
  → Modified-HF cocktail

Intermediate-mass region (IMR) from $1.1 < m_{ee} < 2.7\ \text{GeV}/c^2$
→ Consistent with HF suppression & therm. radiation from QGP

Indication for an excess at lower mass
→ Compatible with thermal radiation from HG

Direct-photons fraction in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

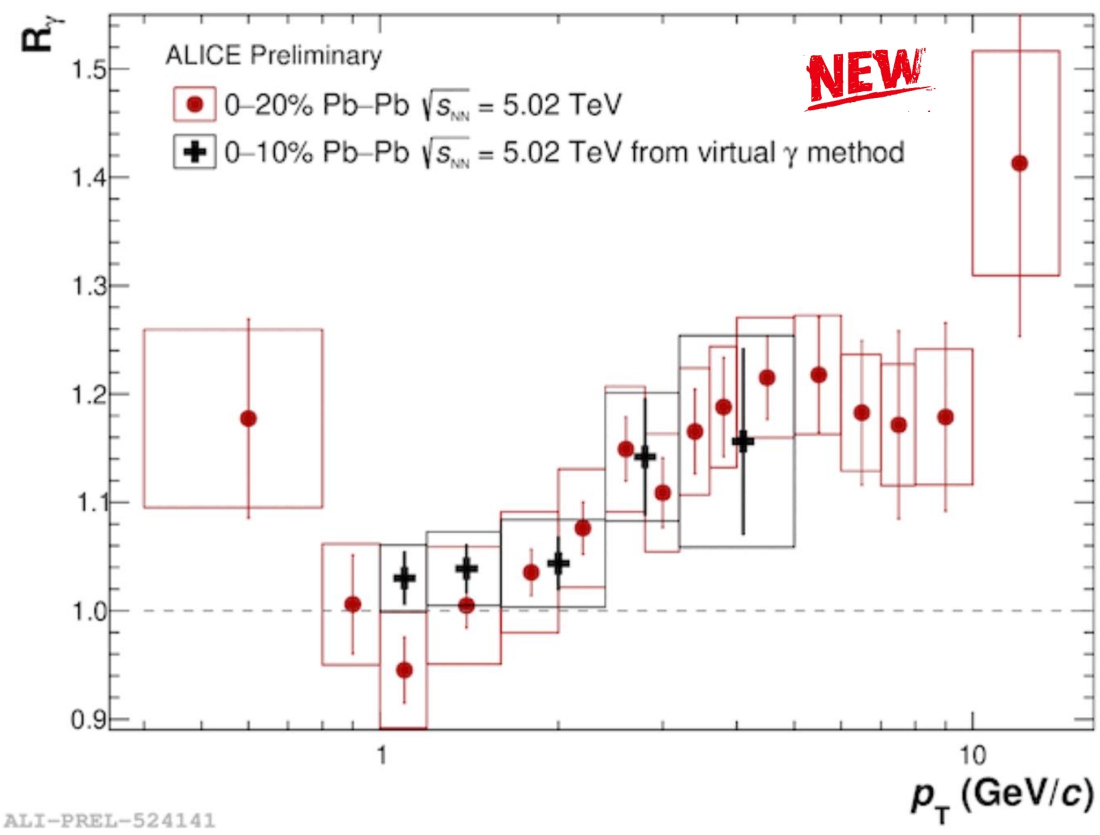


Figure corrected after the conference

Direct-photon fraction r extracted with same method as in pp

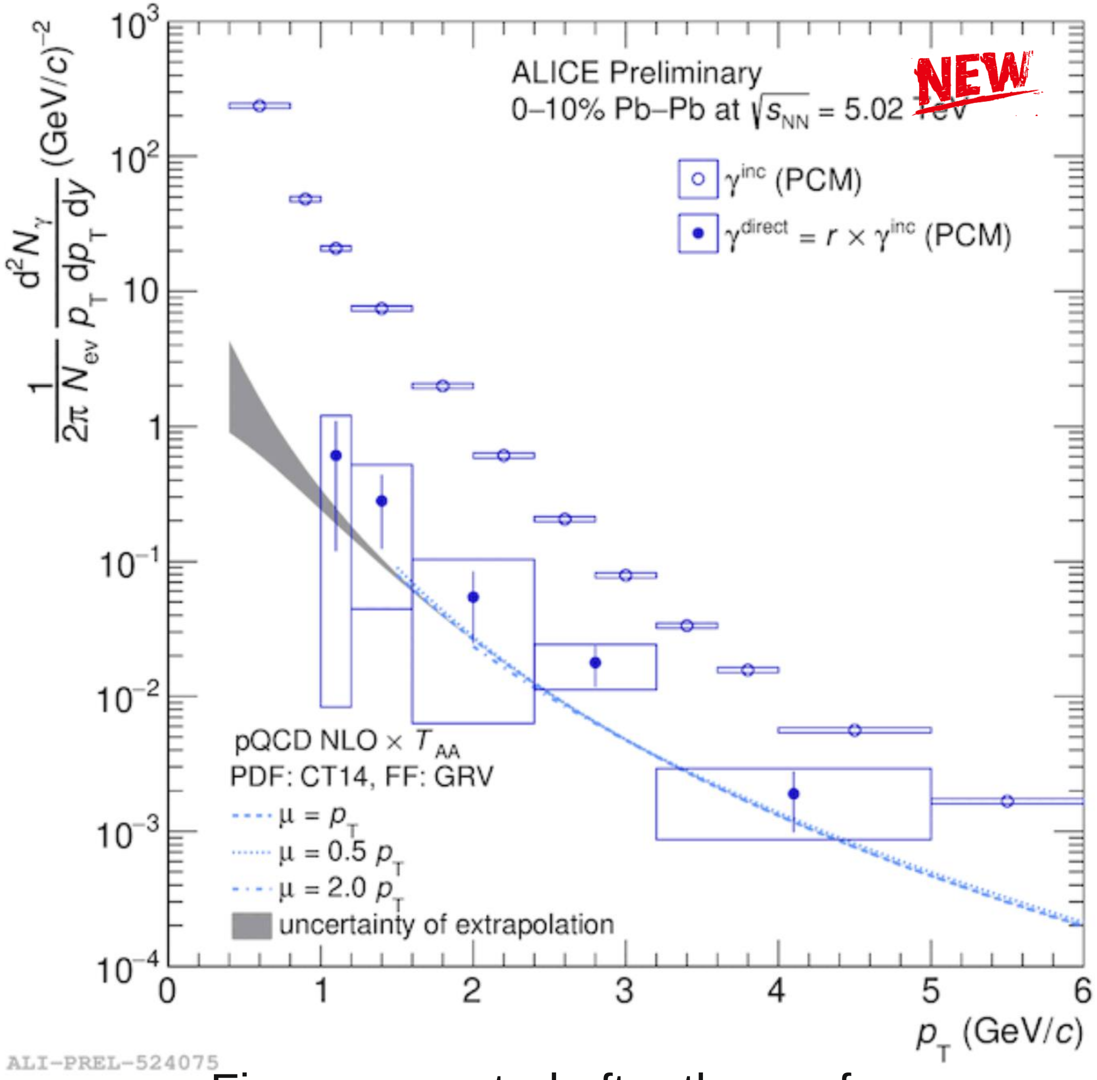
$$\rightarrow R_\gamma = \frac{1}{1-r} = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}}$$

First measurements in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV:

- Good agreement with real-photon method
  Talk by M. Danisch: Parallel Session T13
- Smaller syst. uncertainties at low p_T compared to real photons
- Virtual-photon measurement limited by statistics

Direct-photons Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Direct-photon yield – Effective-temperature extraction



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Direct-photon yield

- Constructed with inclusive-photon spectrum from PCM
  → $\gamma^{\mathrm{dir}} = \gamma^{\mathrm{inc}}(\mathrm{PCM}) \times r$
- Data consistent with pQCD with a hint for an excess above pQCD expectation at low p_{T}

Direct-photons Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Direct-photon yield – Theory comparison

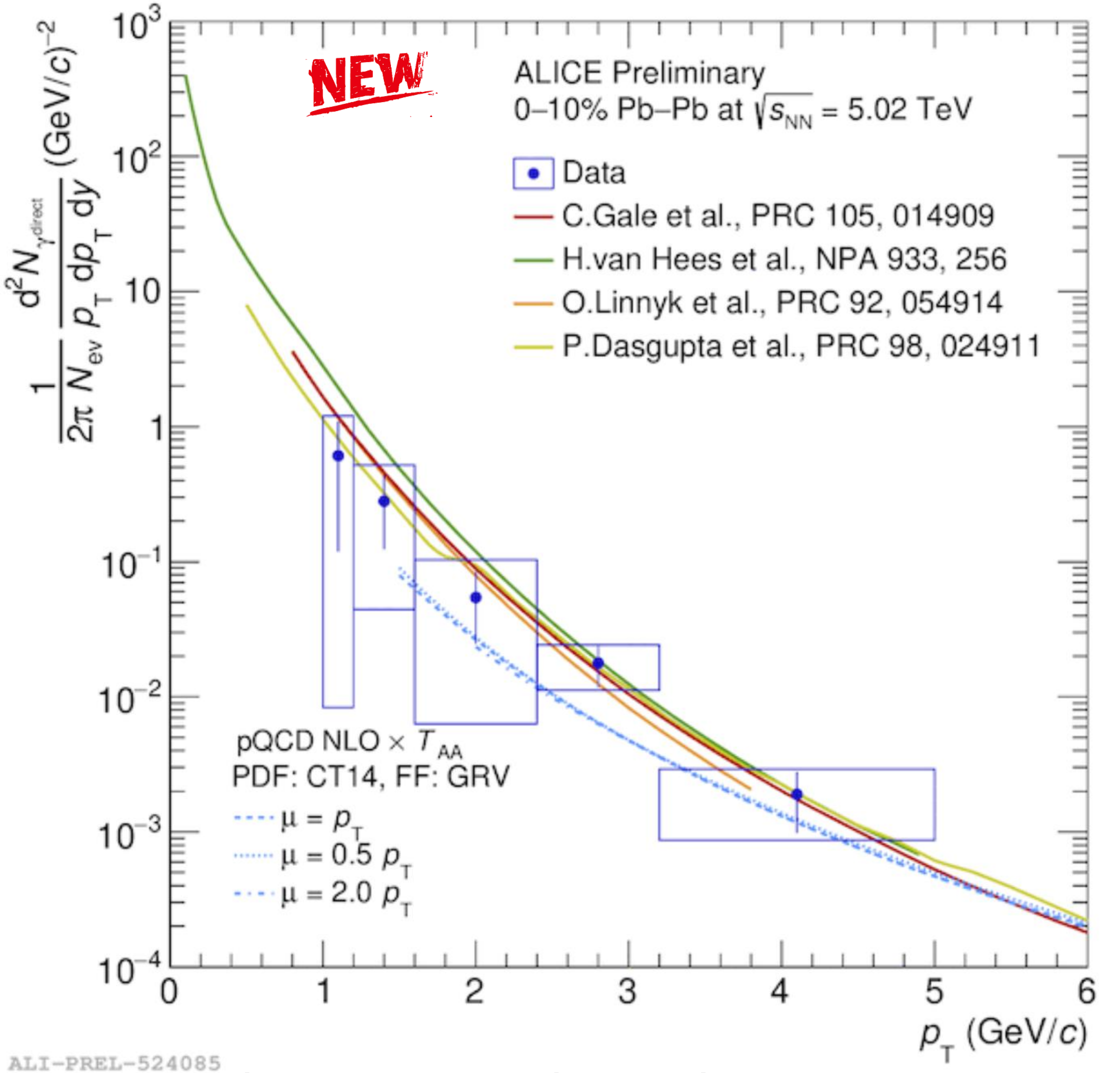


Figure corrected after the conference

Data compared to models including thermal & pQCD photons:

Thermodynamic models:

- C. Gale: Radiation from all stages of the collision including the pre-equilibrium phase
- H. van Hees: Therm. radiation from QGP & hadr. many body calc. and meson-exchange reactions
- P. Dasgupta: Thermal photons with fluctuations in the initial-state

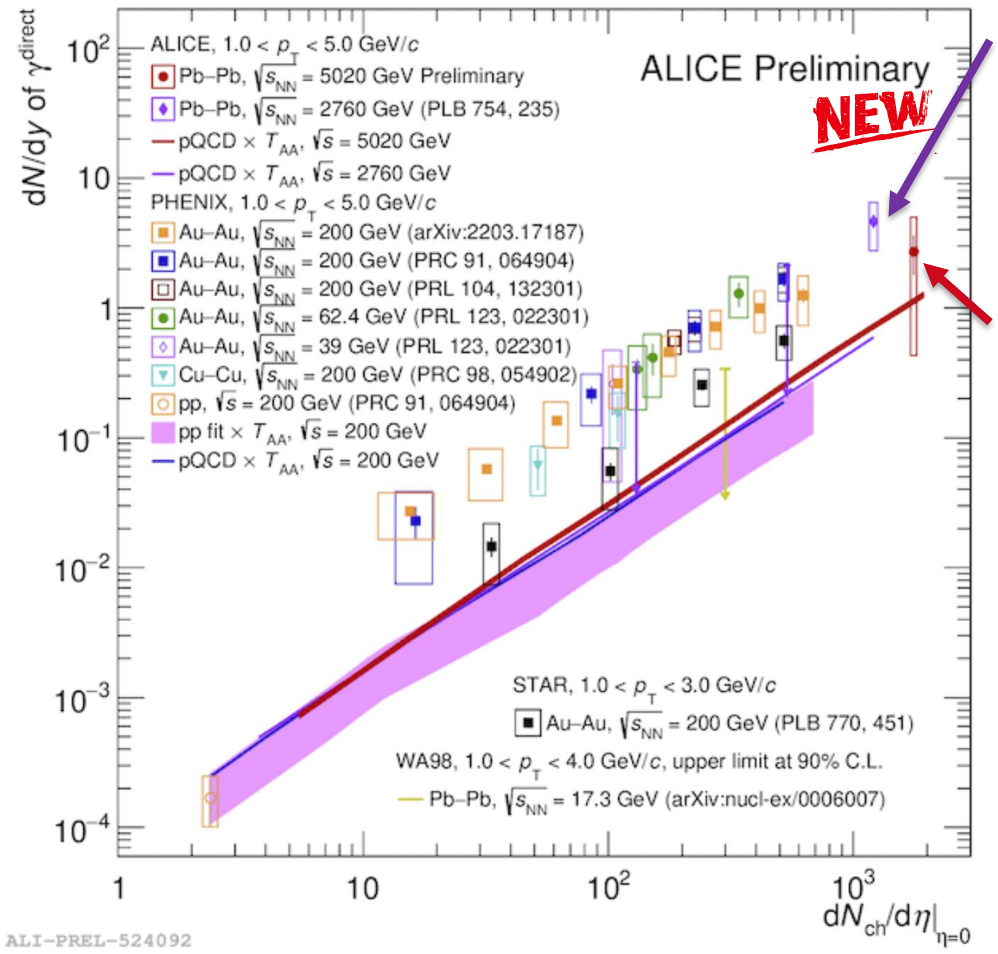
Microscopic transport model:

- O. Linnyk: Direct photons via PHSD

→ Models including thermal radiation tend to overestimate the data at lower p_{T}

Direct-photons Pb−Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Experimental comparison overview



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Real-photon measurement in 0-20% Pb−Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

→ $T_{\mathrm{eff}} = 297 \pm 12(\mathrm{stat.}) \pm 41(\mathrm{syst.})$ MeV

Phys. Lett. B 754 (2016) 235-248

New ALICE results:

Virtual-photon measurement in central Pb−Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

→ Need to decrease uncertainties first in order to extract a temperature

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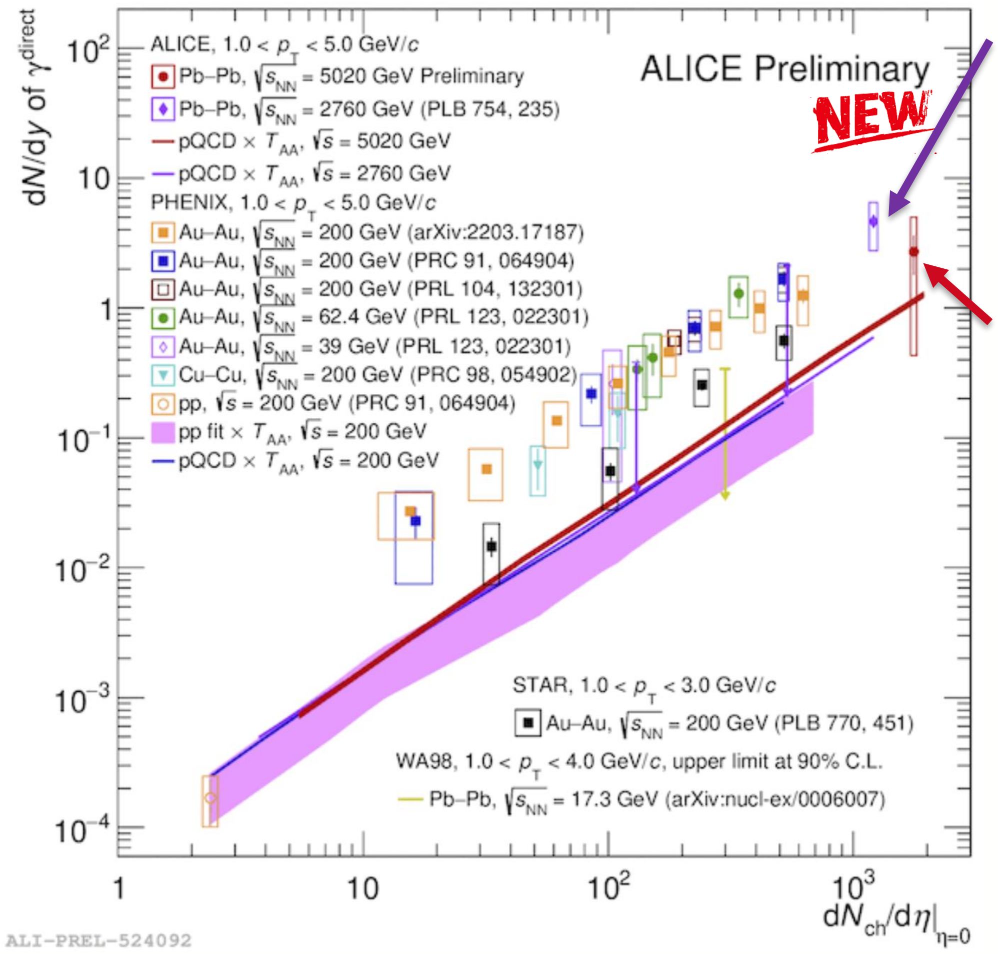

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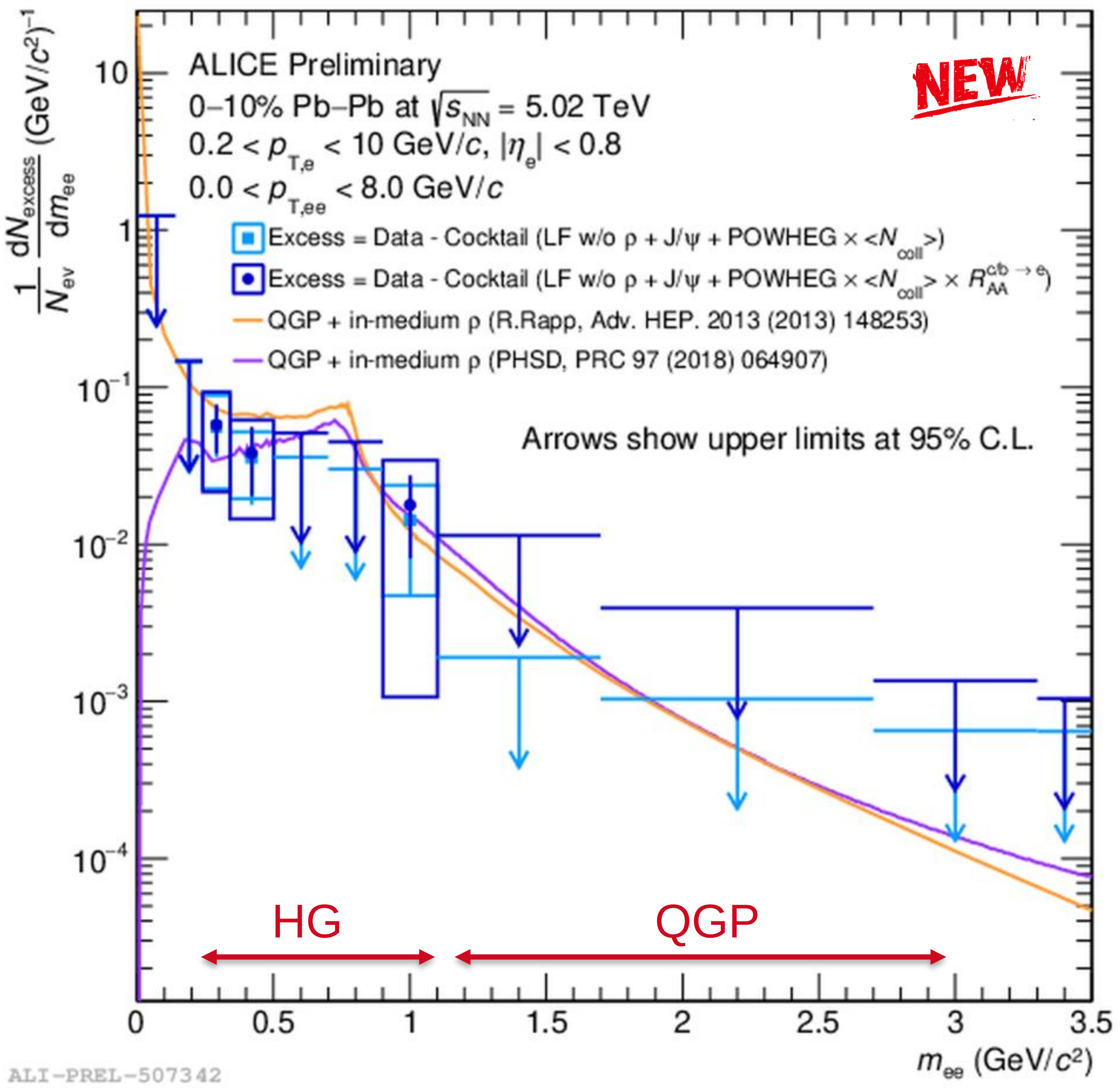
Consistent with a universal scaling behaviour of direct-photon yield with charged-particle multiplicity postulated by PHENIX

Dielectron production in central Pb–Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV

Excess-yield determination



Excess yield = Data – cocktail (w/o ρ contribution)

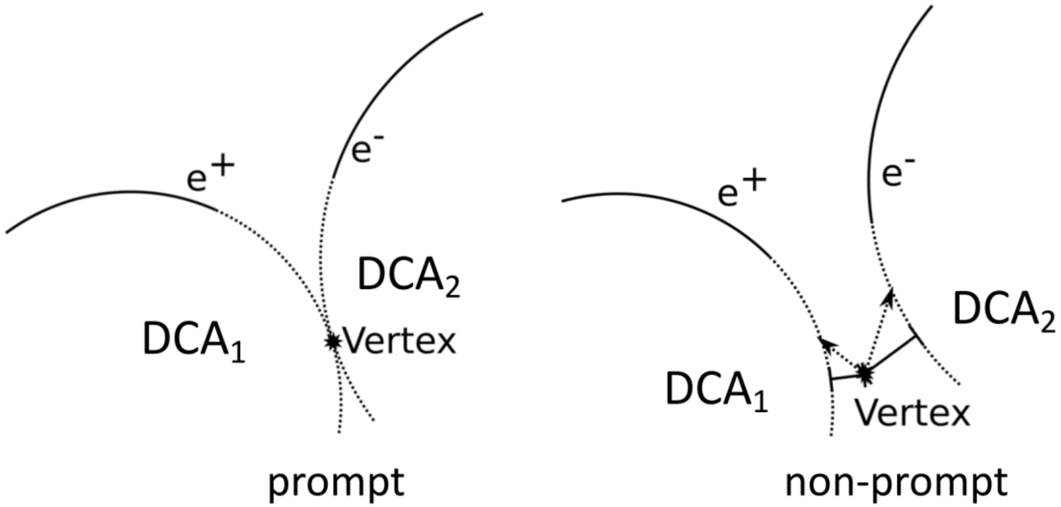
Invariant mass allows to separate different thermal contributions

$m_{\rm ee} < 1\ {\rm GeV}/c^2$: Contributions from Hadron Gas
$m_{\rm ee} > 1\ {\rm GeV}/c^2$: QGP radiation

→ Current understanding of the cocktail limits the interpretation of the data

→ Develop cocktail independent approach

$\mathrm{DCA_{ee}}$ analysis in central Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



Distance-of-closest approach (DCA):

$$\mathrm{DCA_{ee}} = \sqrt{\frac{\mathrm{DCA}_1^2 + \mathrm{DCA}_2^2}{2}}$$

Separation of prompt and non-prompt sources based on their decay topology:

→ $\mathrm{DCA_{ee}(thermal)} < \mathrm{DCA_{ee}(HF)}$

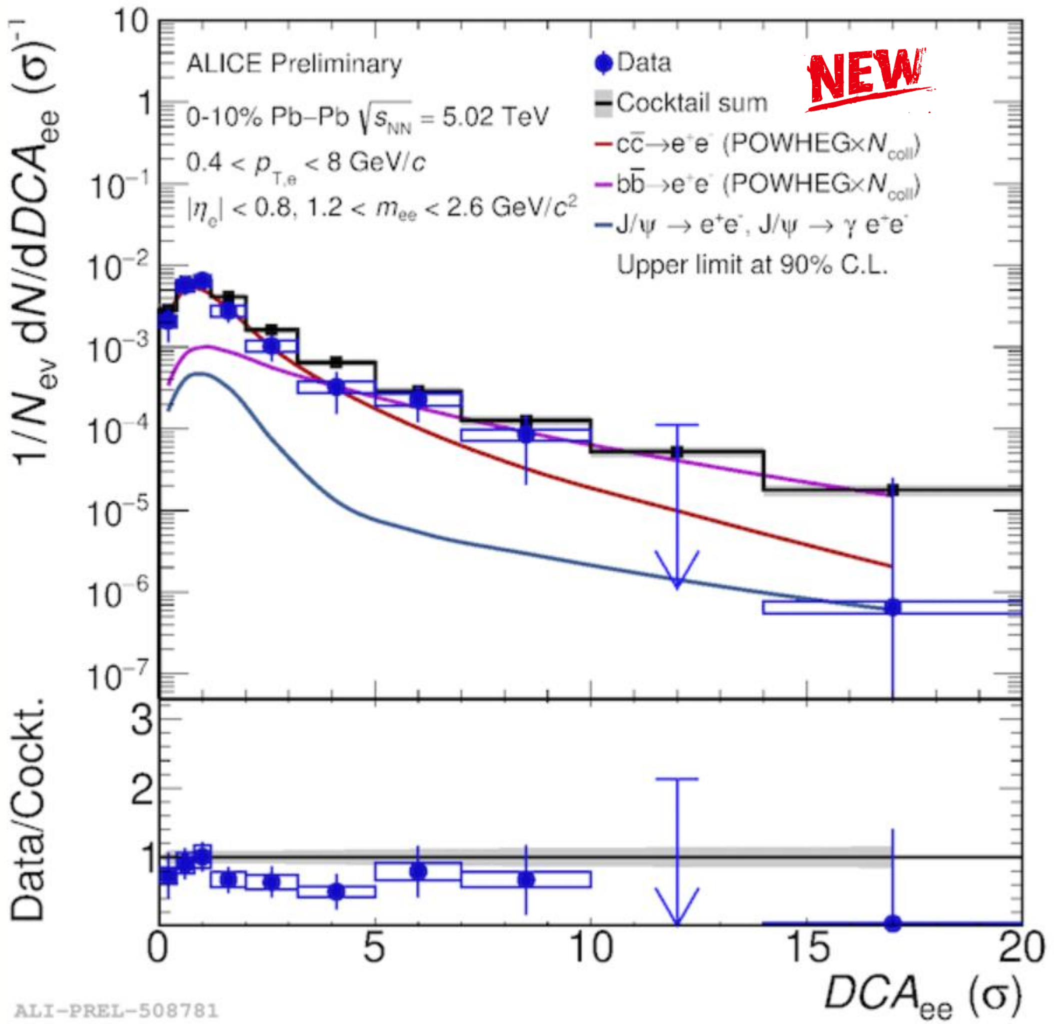
Gives access to measurements of:

→ Thermal radiation at low $\mathrm{DCA_{ee}}$

→ Suppression of HF production at high $\mathrm{DCA_{ee}}$

$\mathrm{DCA_{ee}}$ analysis in central Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Intermediate-mass region



Prompt signal → Non-prompt signal

First $\mathrm{DCA_{ee}}$ analysis in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Comparison to N_{coll}-scaled cocktail:

- Beauty dominates the spectrum at high $\mathrm{DCA_{ee}}$
- Charm more prominent at low $\mathrm{DCA_{ee}}$

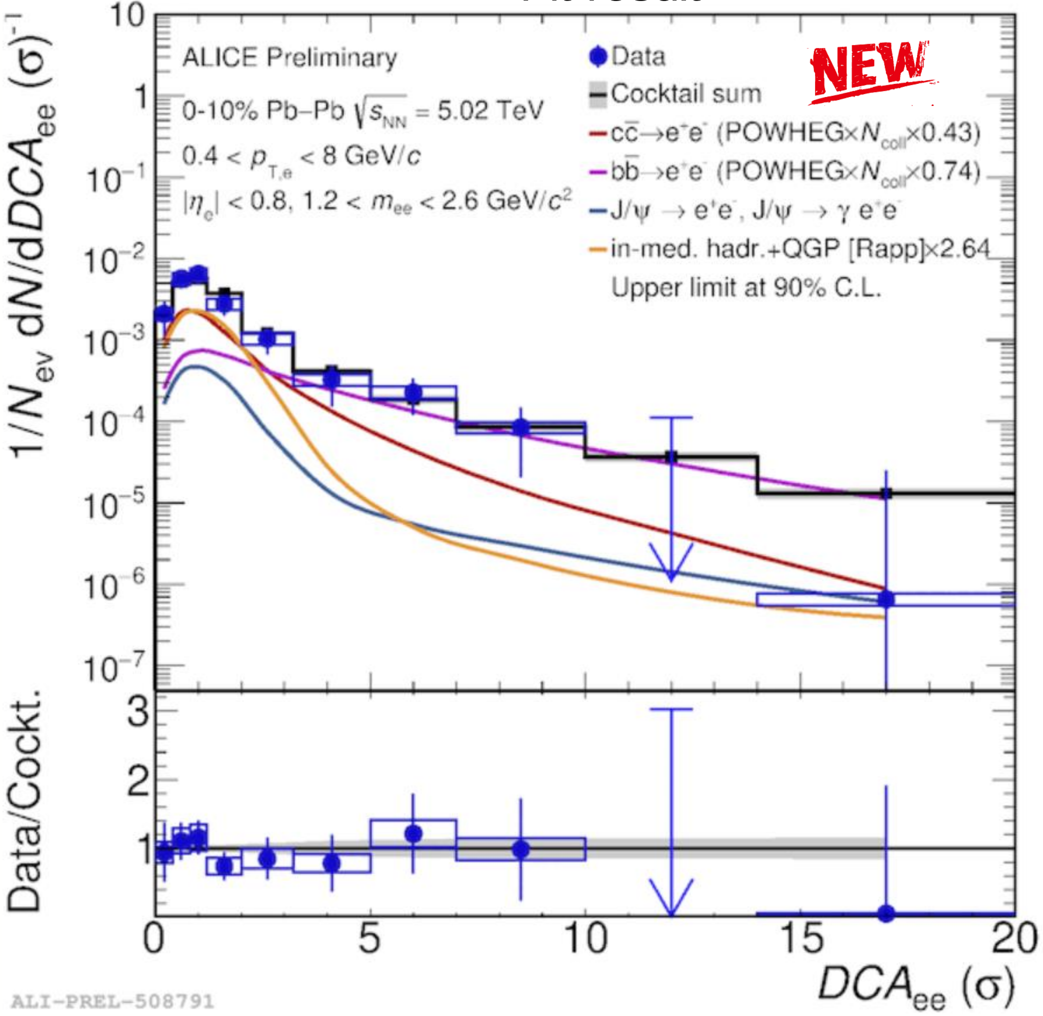
→ Data below HF expectation

→ Clear indication of HF suppression

$\mathrm{DCA_{ee}}$ analysis in central Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

DCA template fit

Fit result



Extraction of prompt thermal signal via template fits:

- Beauty contribution fixed via separate fit at high $\mathrm{DCA_{ee}}$
  $\mathrm{b\bar{b}}$: 0.74±0.24(stat.)±0.12(syst.) (w.r.t. N_{coll} scaling)

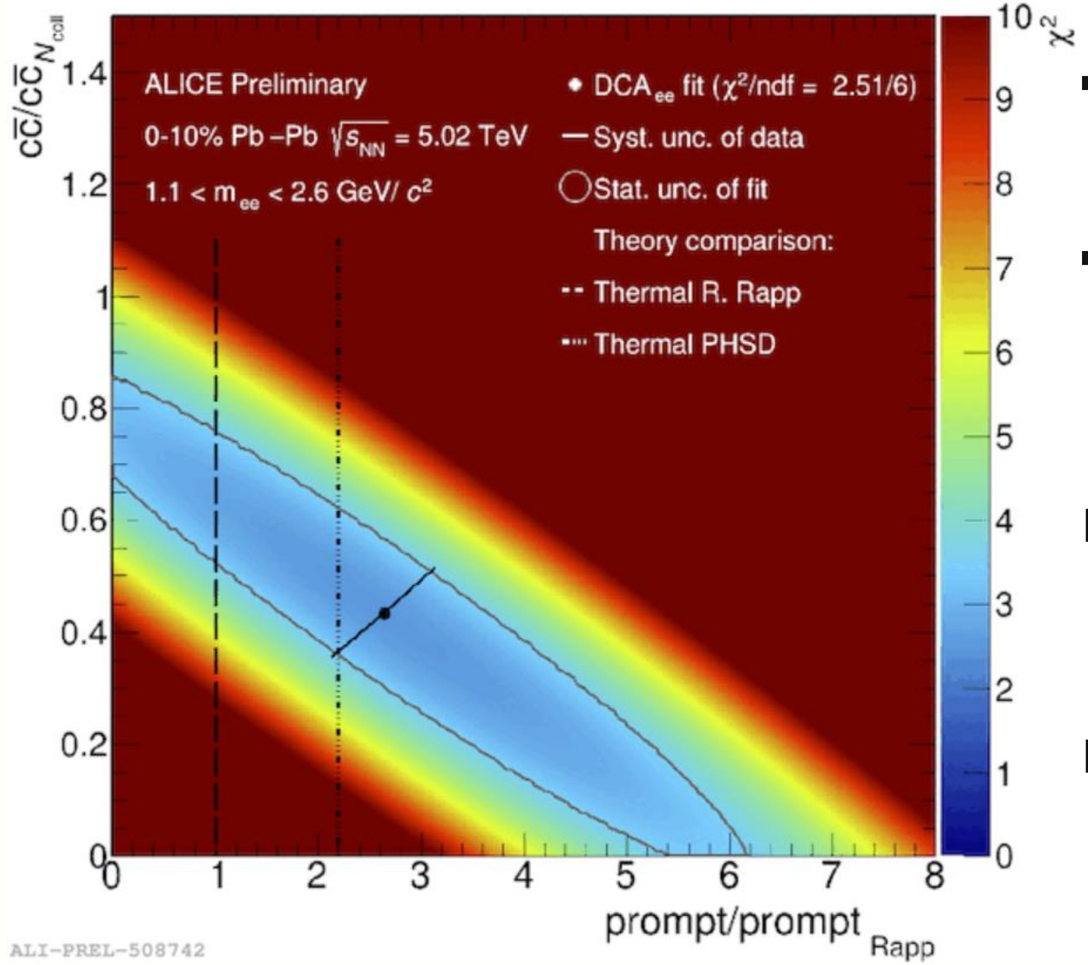
- Simultaneous fit of charm and prompt contribution
  $\mathrm{c\bar{c}}$: 0.43±0.40(stat.)±0.22(syst.) (w.r.t. N_{coll} scaling)
  prompt: 2.64±3.18(stat.)±0.29(syst.) (w.r.t. R. Rapp)

$\mathrm{DCA_{ee}}$ analysis in central Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

DCA spectra – template fits

Fit result

NEW



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Results in agreement with:

- Charm suppression
- Thermal contribution in the order of Rapp/PHSD

Method independent of hadronic cocktail:

→ Smaller syst. uncertainties
→ More statistics enables the extraction of a thermal dielectron yield in the IMR

Outlook

Dielectron production in Run 3 and 4

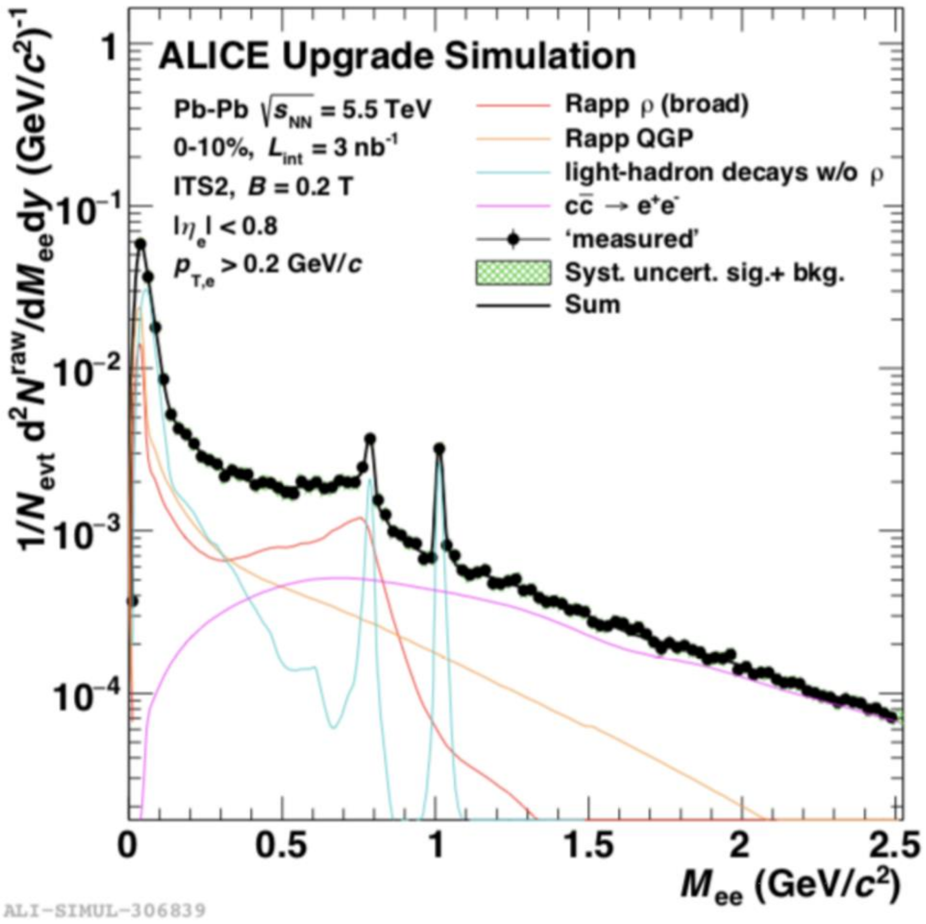
[CERN-LHCC-2013-020,CERN-LHCC-2013-024, CERN-LHCC-2015-001, ALICE-PUBLIC-2020-005]

New Pb–Pb data taking at the end of this year

New ITS and upgrade of the TPC to a GEM based readout system:

- Increase the readout rate in Pb–Pb by a factor 100
  → 13 nb^{-1} MB Pb–Pb planned
- Improve the vertex pointing resolution by a factor 3-6
  → Improves topological separation ($\mathrm{DCA}_{\mathrm{ee}}$)

→ Talks by A. Alkin: Parallel Session T15



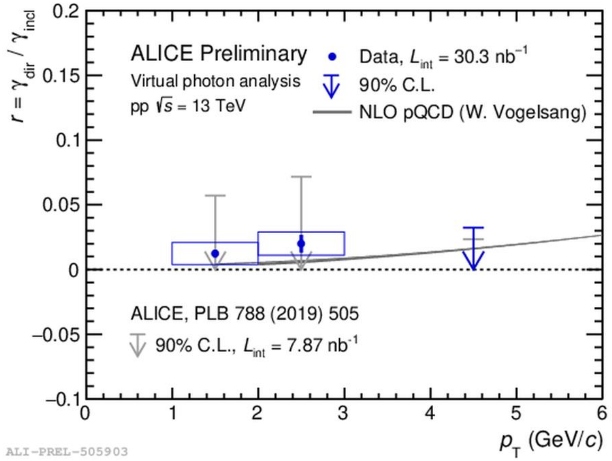
Citron, Z. et al, 1812.06772

Summary

Analysis of full Run 2 dataset of pp at $\sqrt{s}$ =13 TeV

→ Significant increase in statistics & reduction of syst. uncertainties

→ Extraction of direct-photon fraction in MB & HM events

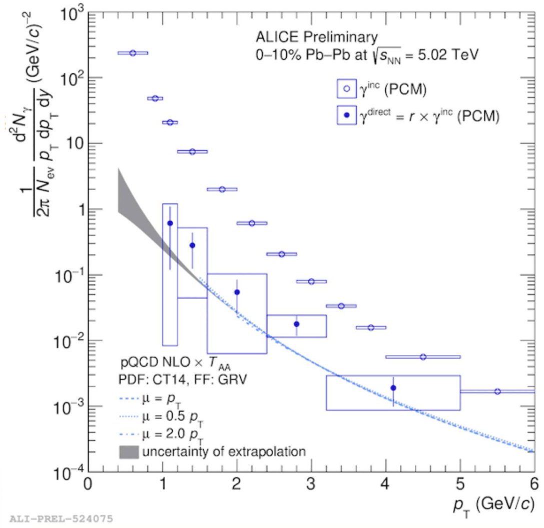


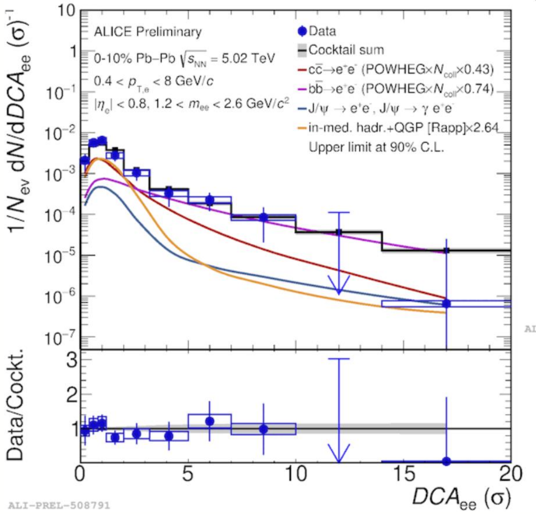
Measurement of dielectron production in central Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

→ First measurement of direct-photon yield

→ Limits for thermal radiation

→ First $\mathrm{DCA_{ee}}$ analysis in Pb−Pb to separate thermal radiation & heavy-flavor background





Backup

ALICE apparatus

Low-mass dielectrons

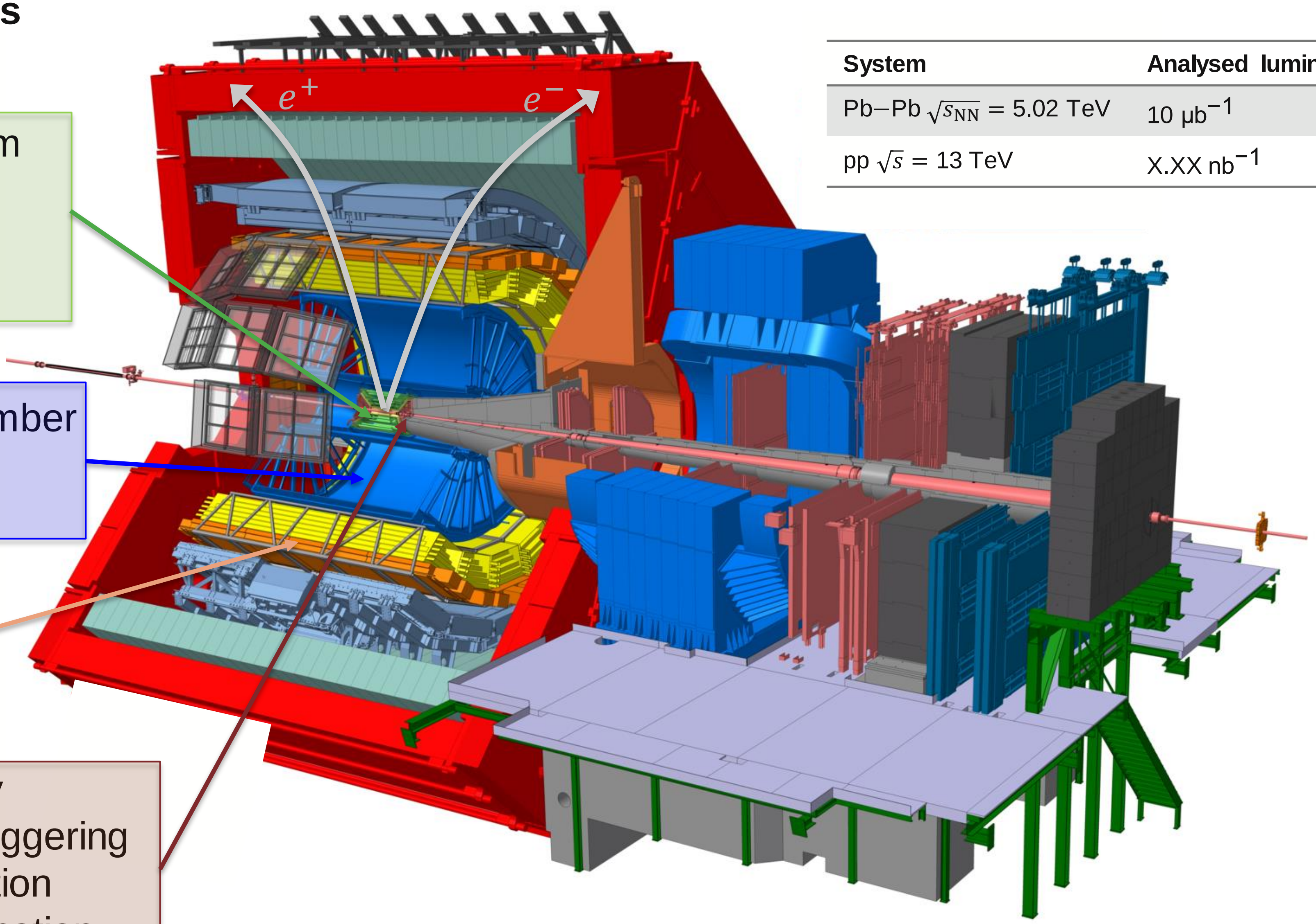
System	Analysed luminosity
Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV	10 μb^{-1}
pp $\sqrt{s}$ = 13 TeV	X.XX nb^{-1}

Inner Tracking System
- Vertexing
- Tracking
- PID

Time Projection Chamber
- Tracking
- PID

Time of Flight
- PID

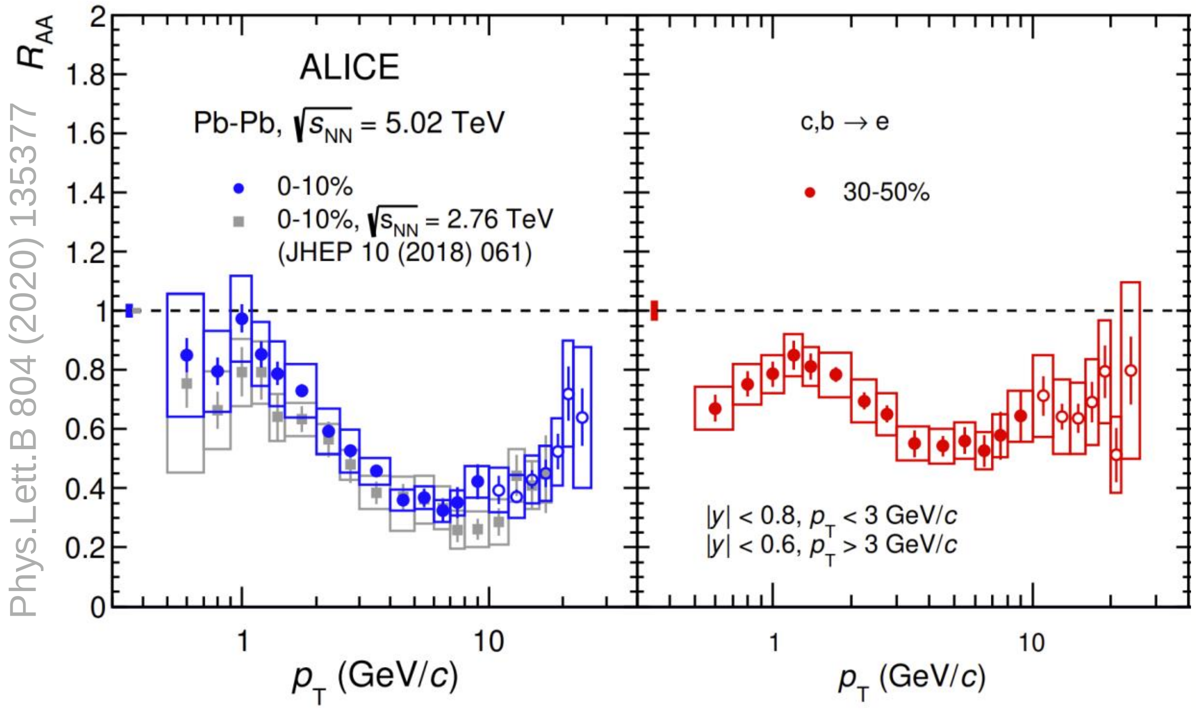
V0 at forward rapidity
- MB & HM event triggering
- Multiplicity estimation
- Centrality determination



Dielectron production in semi-central Pb−Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Cocktail weighting method

ALICE HFe measurement



Dielectron spectrum dominated by 1-2 GeV/c region

Parametrisation of measured of HF electron R_{AA}
→ Contains CNM effects & energy loss in the medium

Disentangle CNM effects using EPS09

CNM effects & energy-loss affect pair production differently

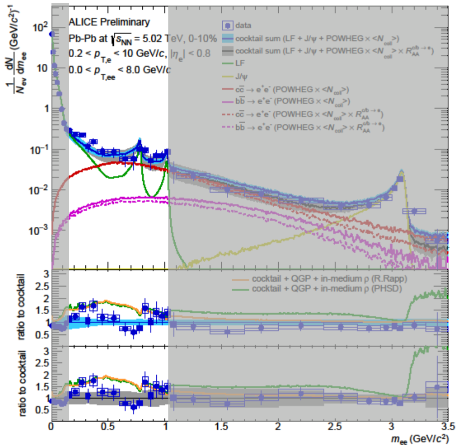
CNM	Energy loss
Affects whole pair	Affects each electron independently
$w_1 = \frac{R_{\mathrm{AA}}(p_{\mathrm{T,e^+}}) + R_{\mathrm{AA}}(p_{\mathrm{T,e^-}})}{2}$	$w_2 = R_{\mathrm{AA}}(p_{\mathrm{T,e^+}}) \times R_{\mathrm{AA}}(p_{\mathrm{T,e^-}})$

→ Total weight $w = w_1 \times w_2$ applied as a function of m_{ee} & $p_{\mathrm{T},ee}$

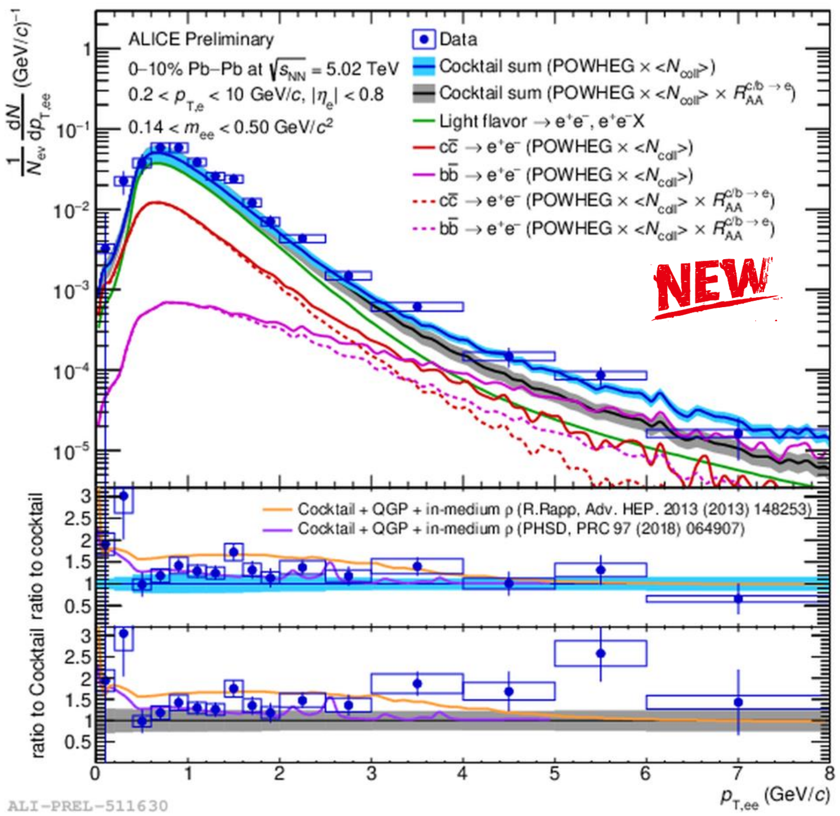
<u>However</u>: Correction with large uncertainties from HFe R_{AA} & EPS09
Assumes same suppression for charm & beauty

Dielectron production in central Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

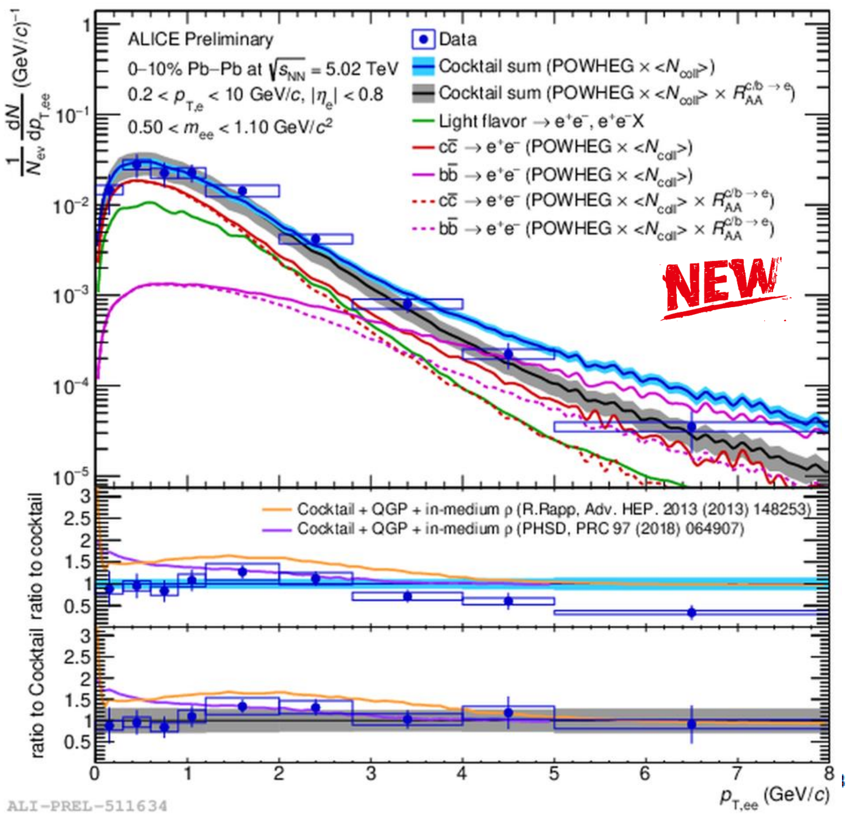
Cocktail comparison – Pair-momentum spectra at low masses



$0.14 < m_{\mathrm{ee}} < 0.5\ \mathrm{GeV}/c^2$



$0.5 < m_{\mathrm{ee}} < 1.1\ \mathrm{GeV}/c^2$



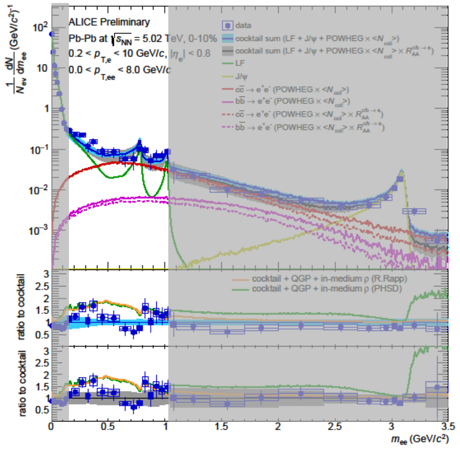
Excess yield: $p_{\mathrm{T,ee}} < 4\ \mathrm{GeV}/c$ dominated by thermal radiation

$p_{\mathrm{T,ee}} > 4\ \mathrm{GeV}/c$ more prompt photons expected

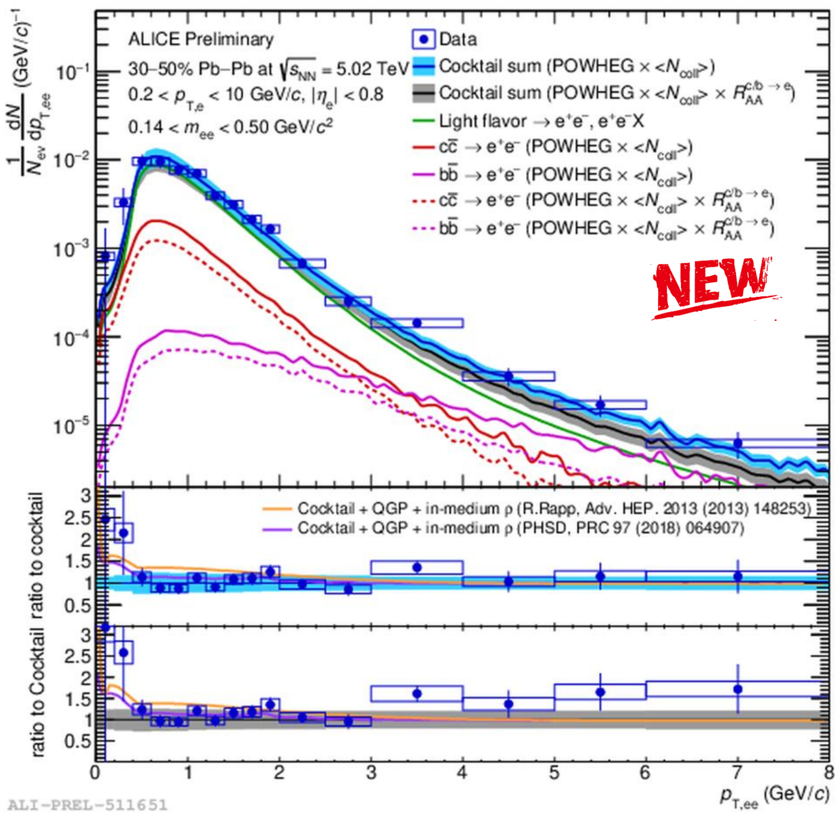
Inclusion of HF modification crucial to describe $p_{\mathrm{T,ee}}$ shape

Dielectron production in semi-central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

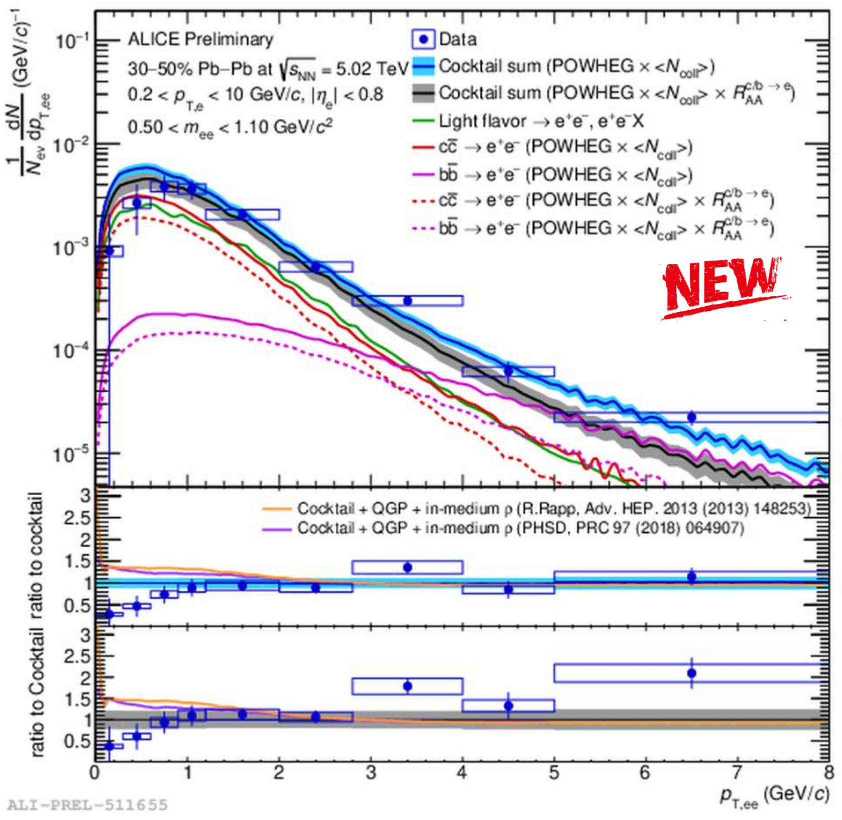
Cocktail comparison – Pair-momentum spectra at low masses



$0.14 < m_{ee} < 0.5\ \mathrm{GeV}/c^2$



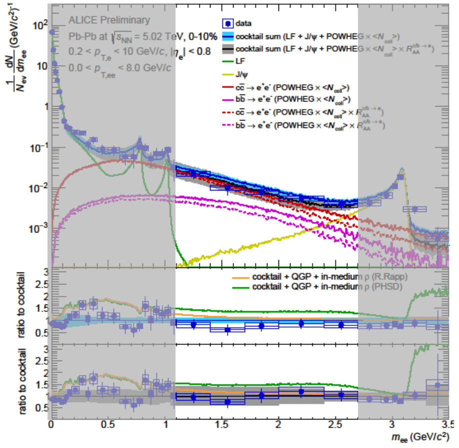
$0.5 < m_{ee} < 1.1\ \mathrm{GeV}/c^2$

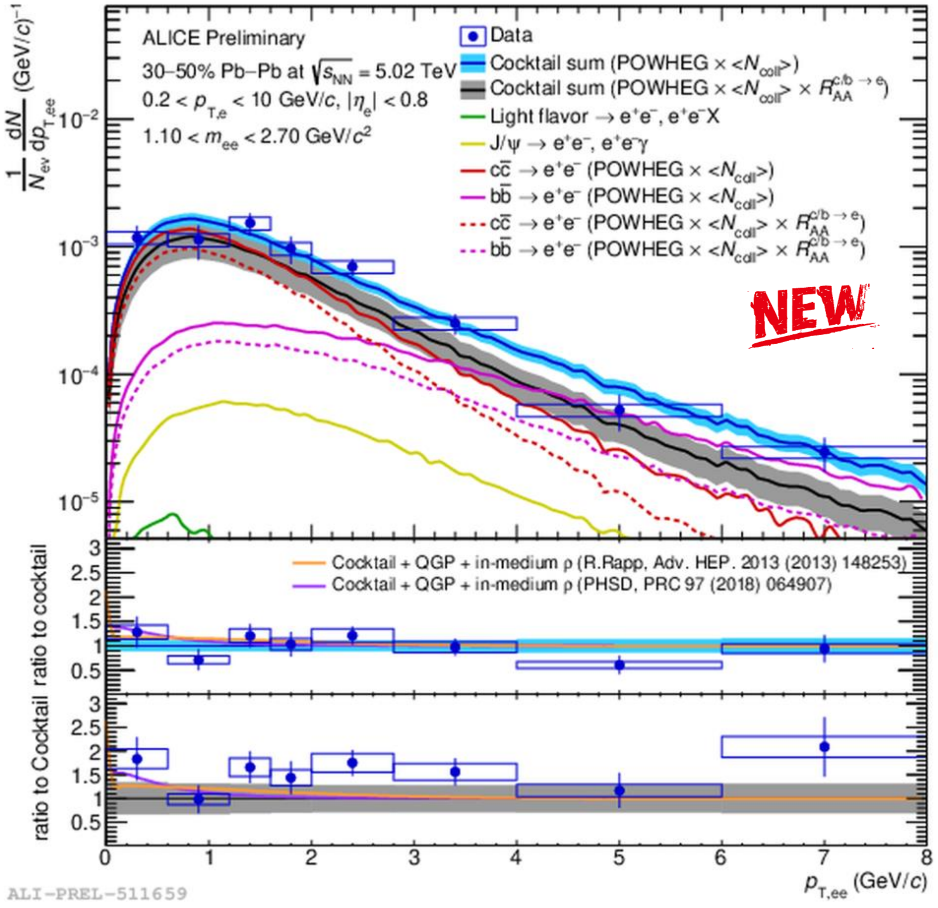


Excess yield: $p_{T,ee} < 4\ \mathrm{GeV}/c$ dominated by thermal radiation
$p_{T,ee} > 4\ \mathrm{GeV}/c$ more prompt photons expected

Dielectron production in central PbPb at 5.02 TeV

Cocktail comparison – Pair-momentum spectra at intermediate masses





Comparison to binary scaled HF

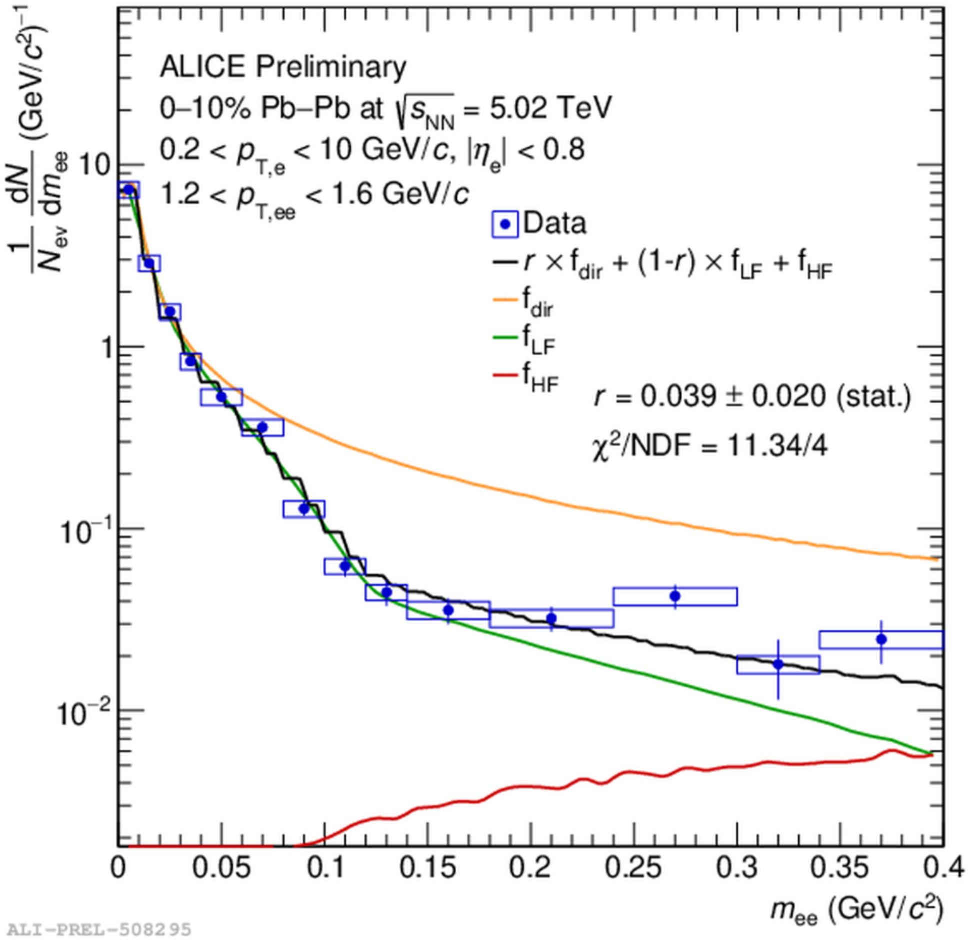
→Data overall in good agreement

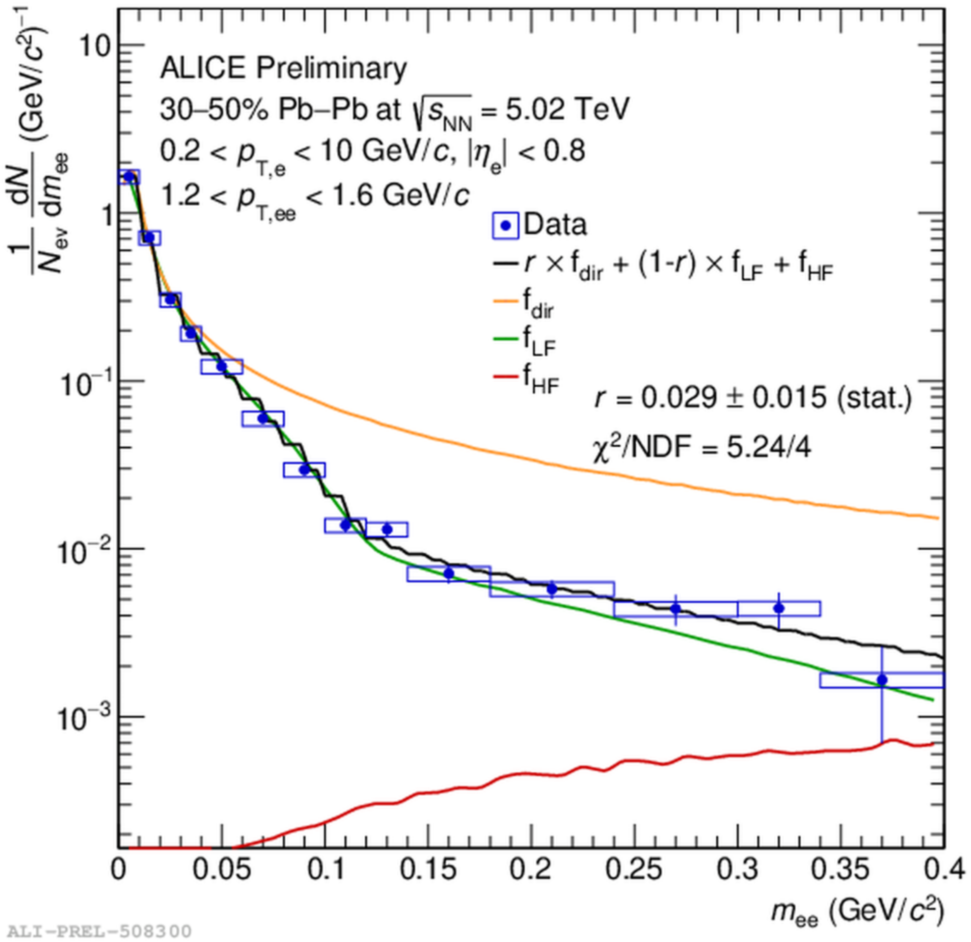
Inclusion of HF modification in the cocktail

→ Data above cocktail expectation

Direct-photons Pb−Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Direct-photon fraction extraction



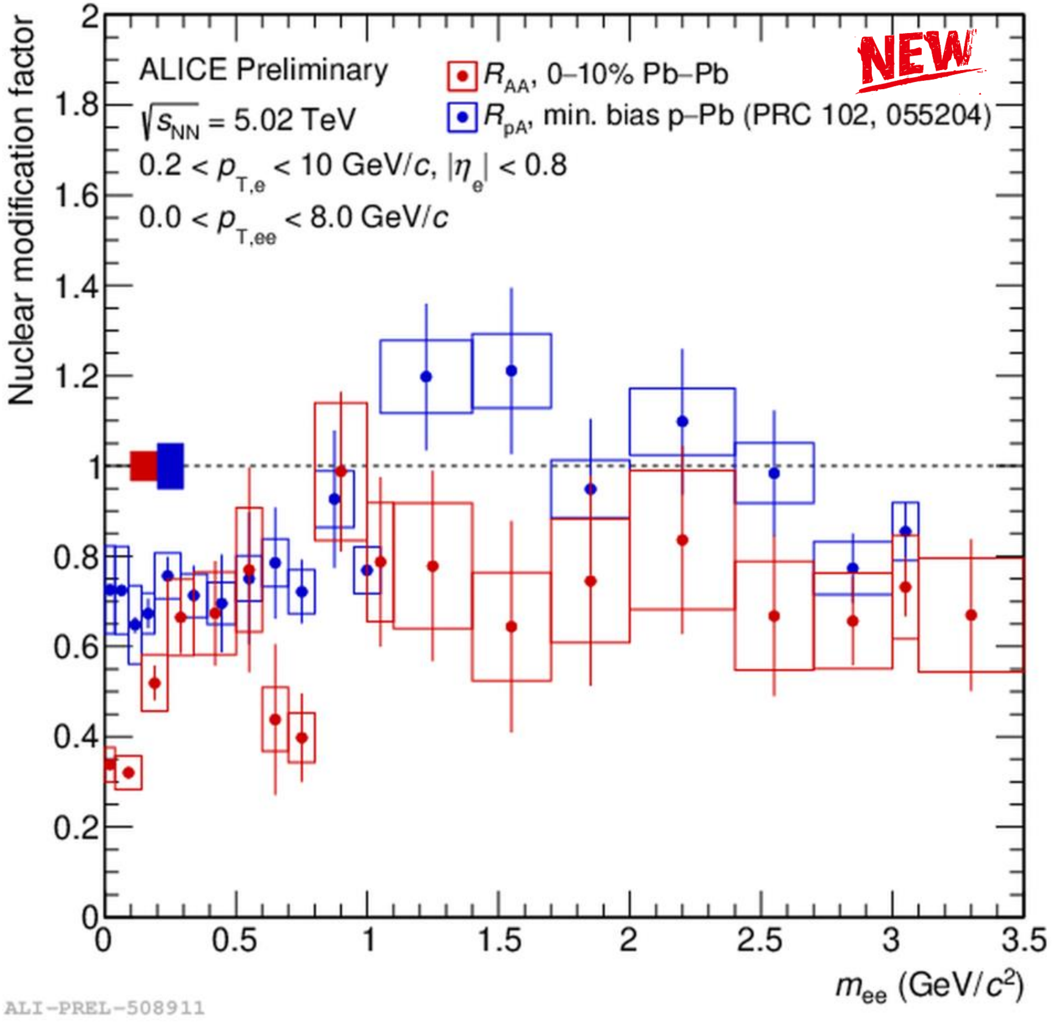


Direct-photon fraction r extracted with same method as in pp: (Kroll-Wada function f_{dir})

$$f_{fit} = r \times f_{\mathrm{dir}} + (1-r) \times f_{\mathrm{LF}} + f_{\mathrm{HF}}$$

Dielectron production in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

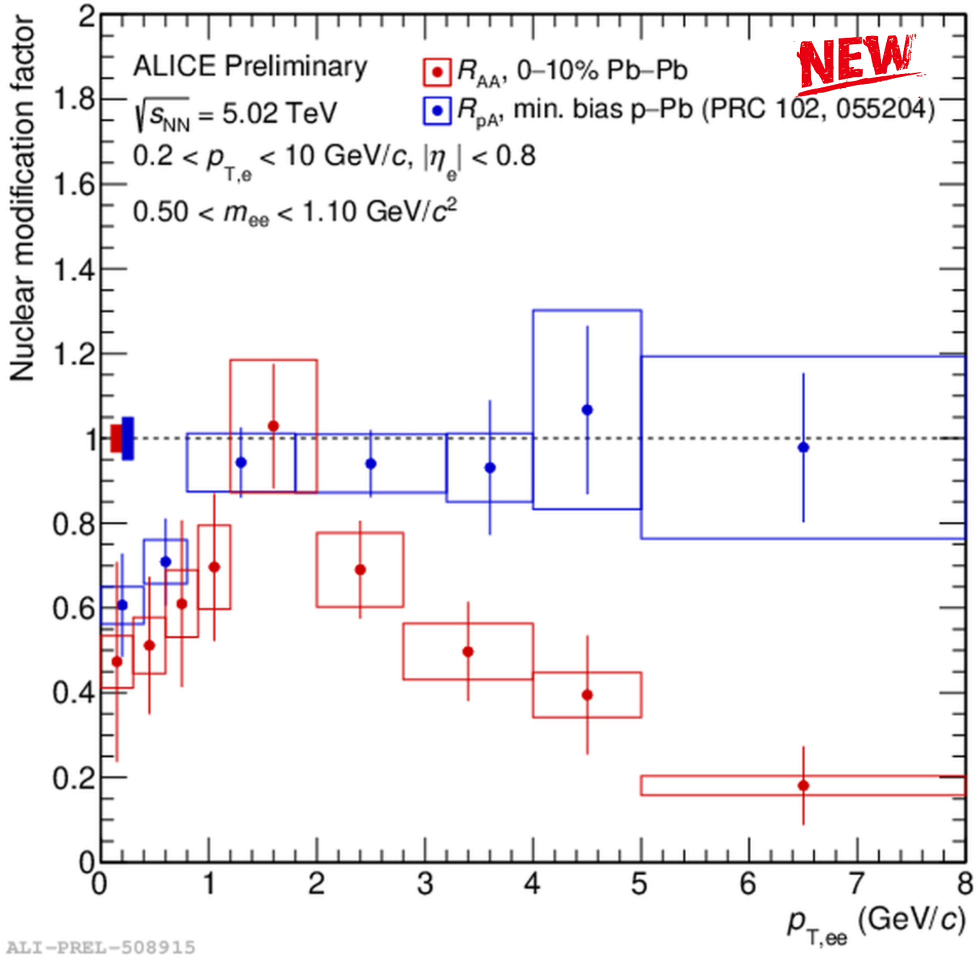
Nuclear modification factor

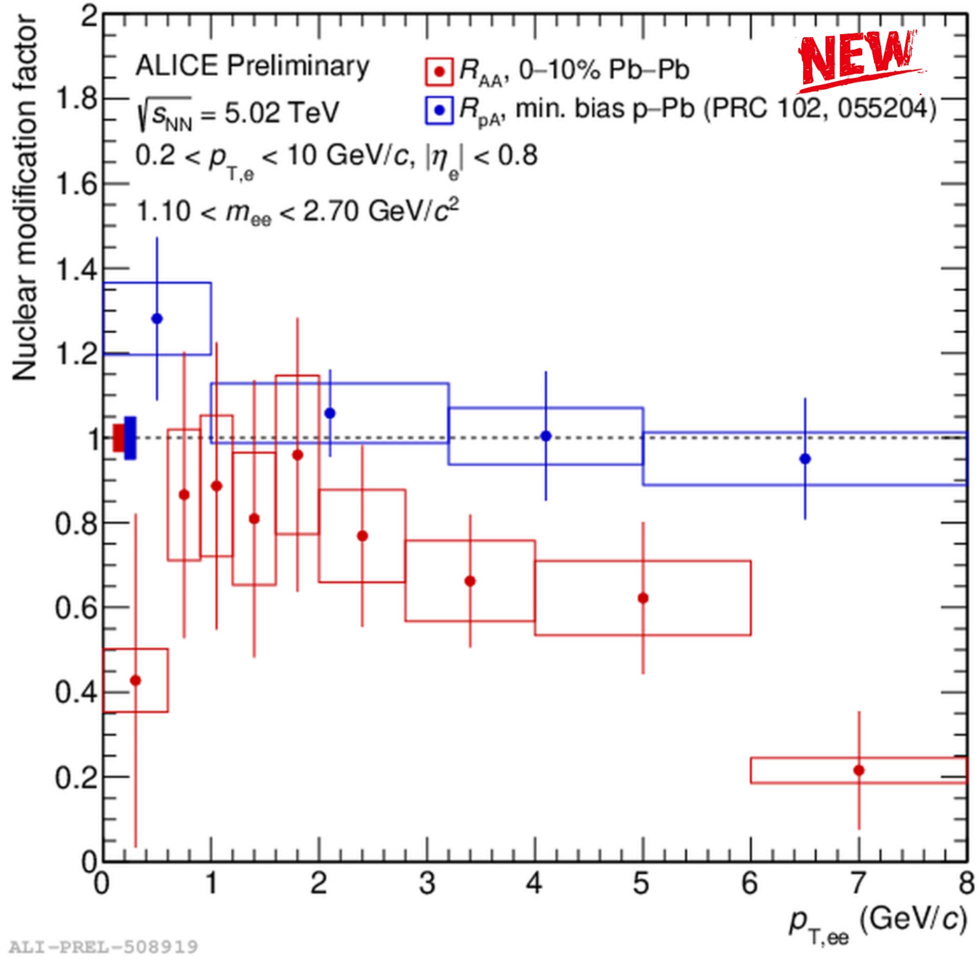


Indication of HF suppression in the IMR in Pb–Pb collisions

Dielectron production in central Pb−Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Nuclear modification factor

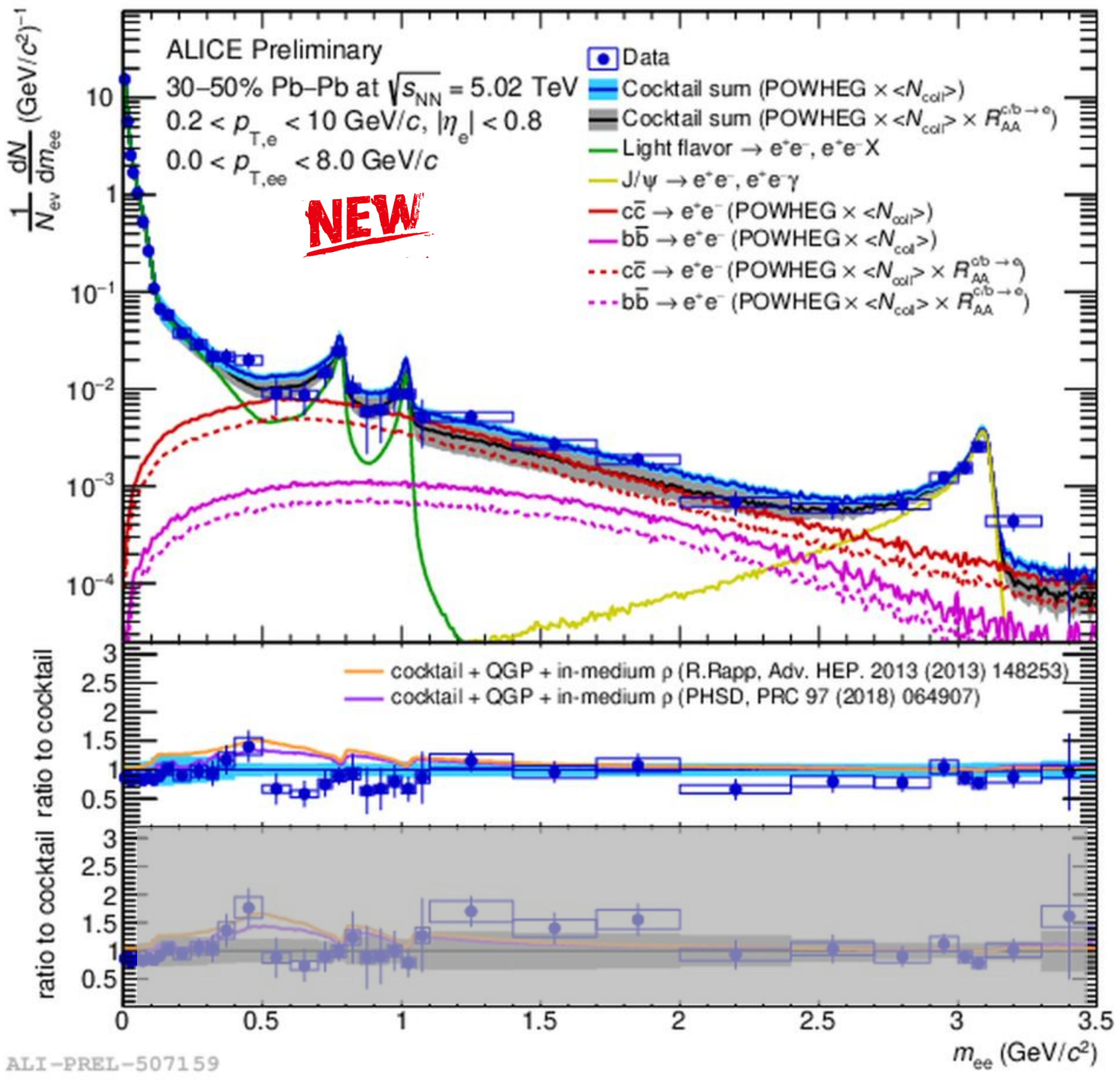




Signs of suppression as a function of $p_{T,ee}$ in Pb−Pb collisions

Dielectron production in semi-central Pb–Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV

Cocktail comparison – Invariant-mass spectrum



First measurement of the dielectron production in semi-central collisions

Compared to different hadronic cocktails:

Binary $N_{\rm coll}$ scaled HF measurement
→ vacuum baseline

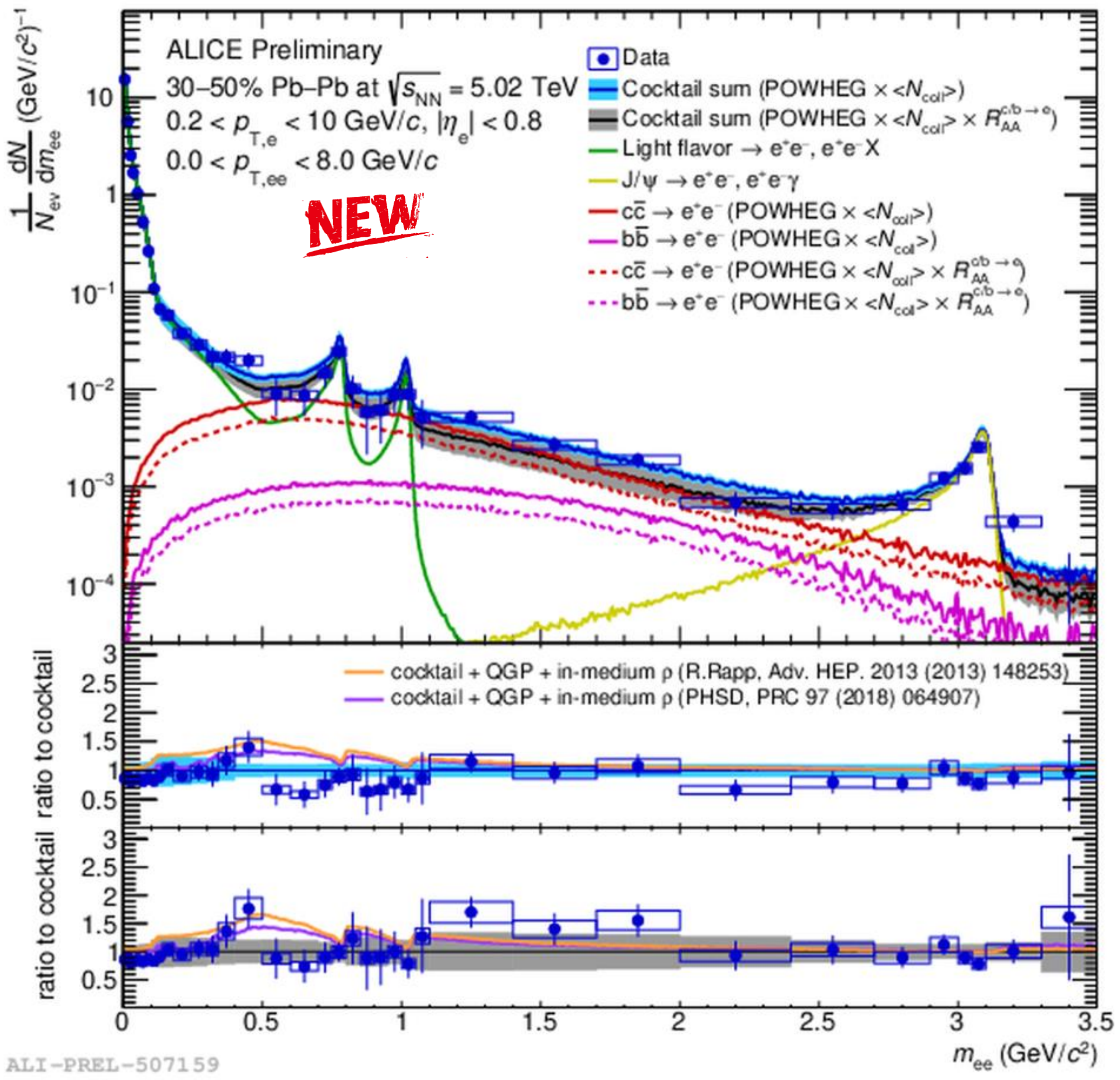
Input: HF measurement from pp at $\sqrt{s} = 5.02$ TeV
→ Phys. Rev. C 102 (2020) 055204

Data on the edge of the uncertainty of hadronic expectations
→ Tension in the region $0.5 < m_{\rm ee} < 1.1$ GeV$/c^2$

However: HF contribution is expected to be modified
→ CNM and hot medium effects

Dielectron production in semi-central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Cocktail comparison – Invariant-mass spectrum



First measurement of the dielectron production in semi-central collisions

Compared to different hadronic cocktails:

- Binary N_{coll} scaled HF measurement → vacuum baseline
- Weighted HF based R_{AA} of $c/b \rightarrow e^{\pm}$ → to model a HF suppression

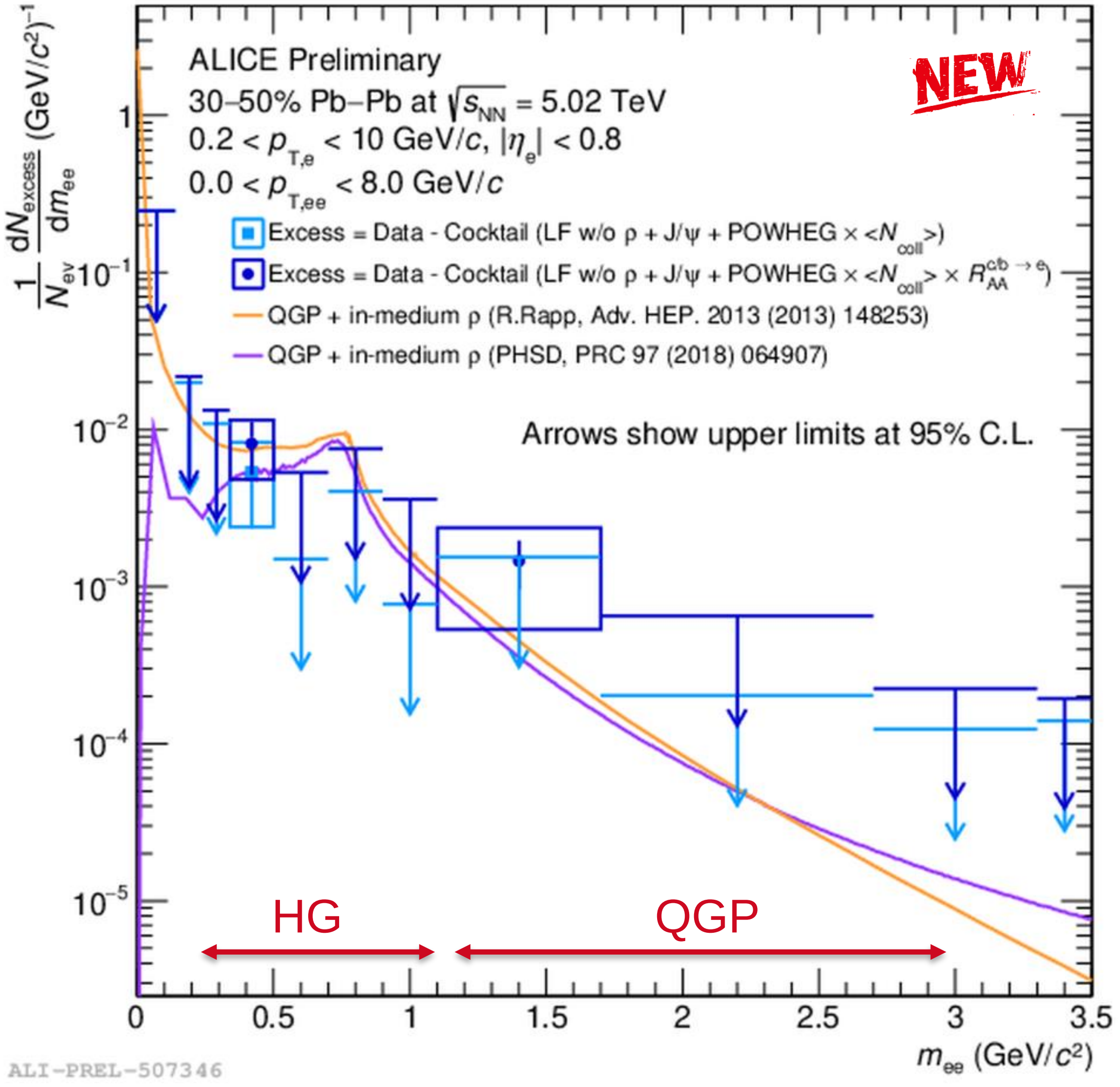
Inclusion of HF modification improves the overall description

Compared to theory calculations including thermal radiation

However: Therm. signal in the order of syst. uncertainties of the modified cocktail

Dielectron production in semi-central Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Excess-yield determination



Excess yield = Data – cocktail (w/o ρ contribution)

Invariant mass allows to separate different thermal contributions

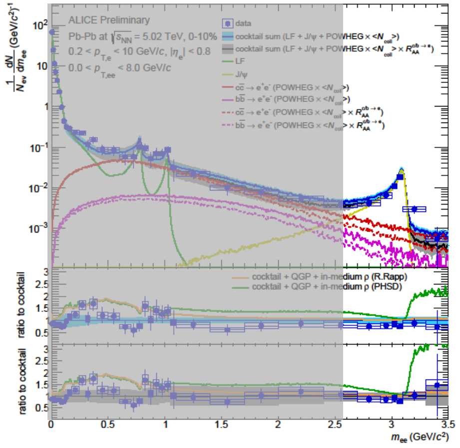
$m_{\mathrm{ee}} < 1\ \mathrm{GeV}/c^2$: Contributions from Hadron Gas
$m_{\mathrm{ee}} > 1\ \mathrm{GeV}/c^2$: QGP radiation

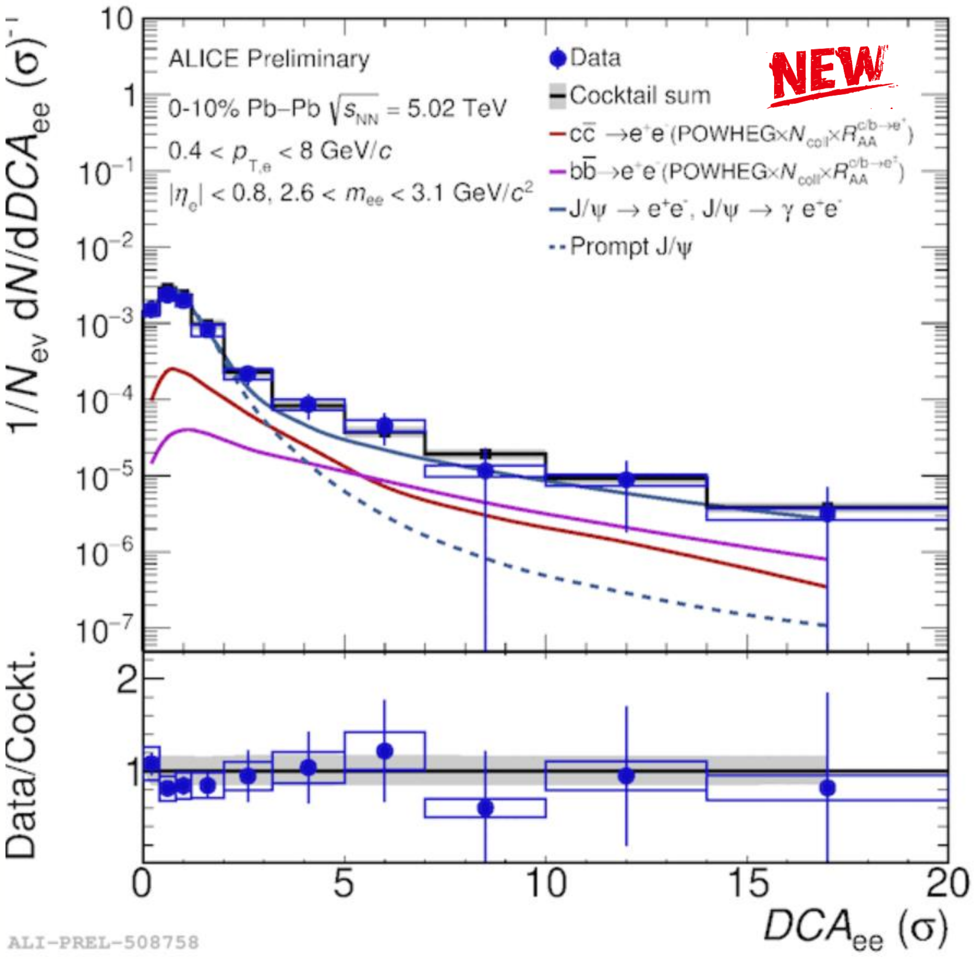
→ Current understanding of the cocktail limits the understanding of the data

→ Develop cocktail independent approach

$\mathrm{DCA_{ee}}$ analysis in central Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Cocktail-scaled DCA spectra – J/ψ region





Prompt signal → Non-prompt signal

Well suited as a control region:

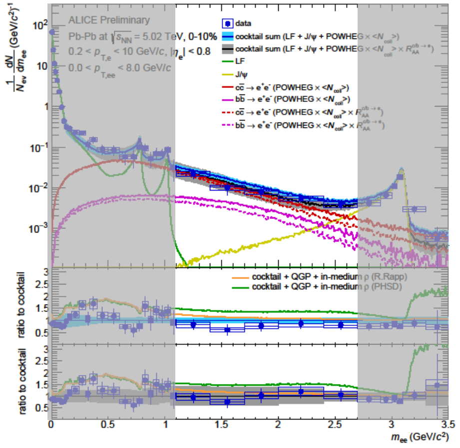
Mixture of prompt & non-prompt sources

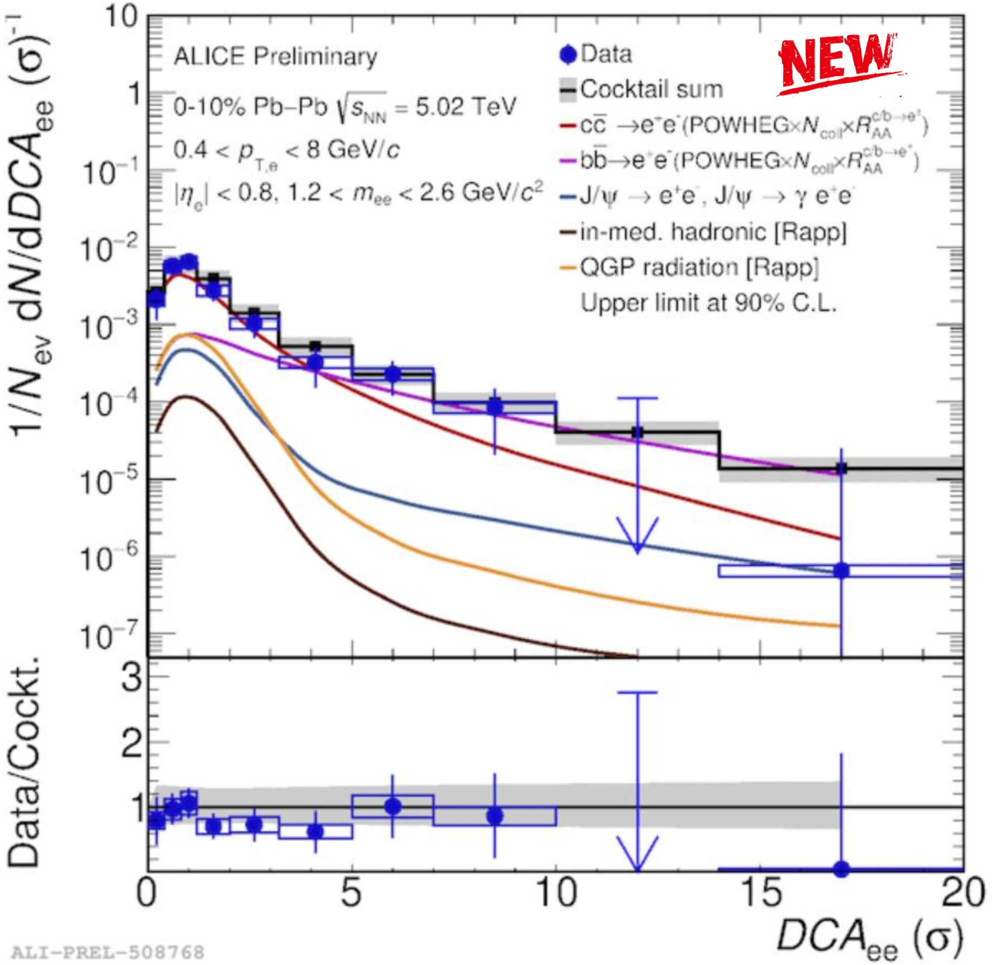
J/ψ production well constrained

Data well described by $\mathrm{DCA_{ee}}$ templates scaled with the hadronic cocktail

Dielectron production in central PbPb at 5.02 TeV

Scaled DCA spectra – Intermediate-mass region





Prompt signal → Non-prompt signal

Inclusion of weighting with HFe R_{AA}:

Better description of high DCA_{ee} values

Spectrum consistent with theory calculations for thermal radiation by R. Rapp