A Large Ion Collider Experiment

Direct-photon measurement in small systems and thermal radiation from QGP with ALICE

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for the ALICE collaboration

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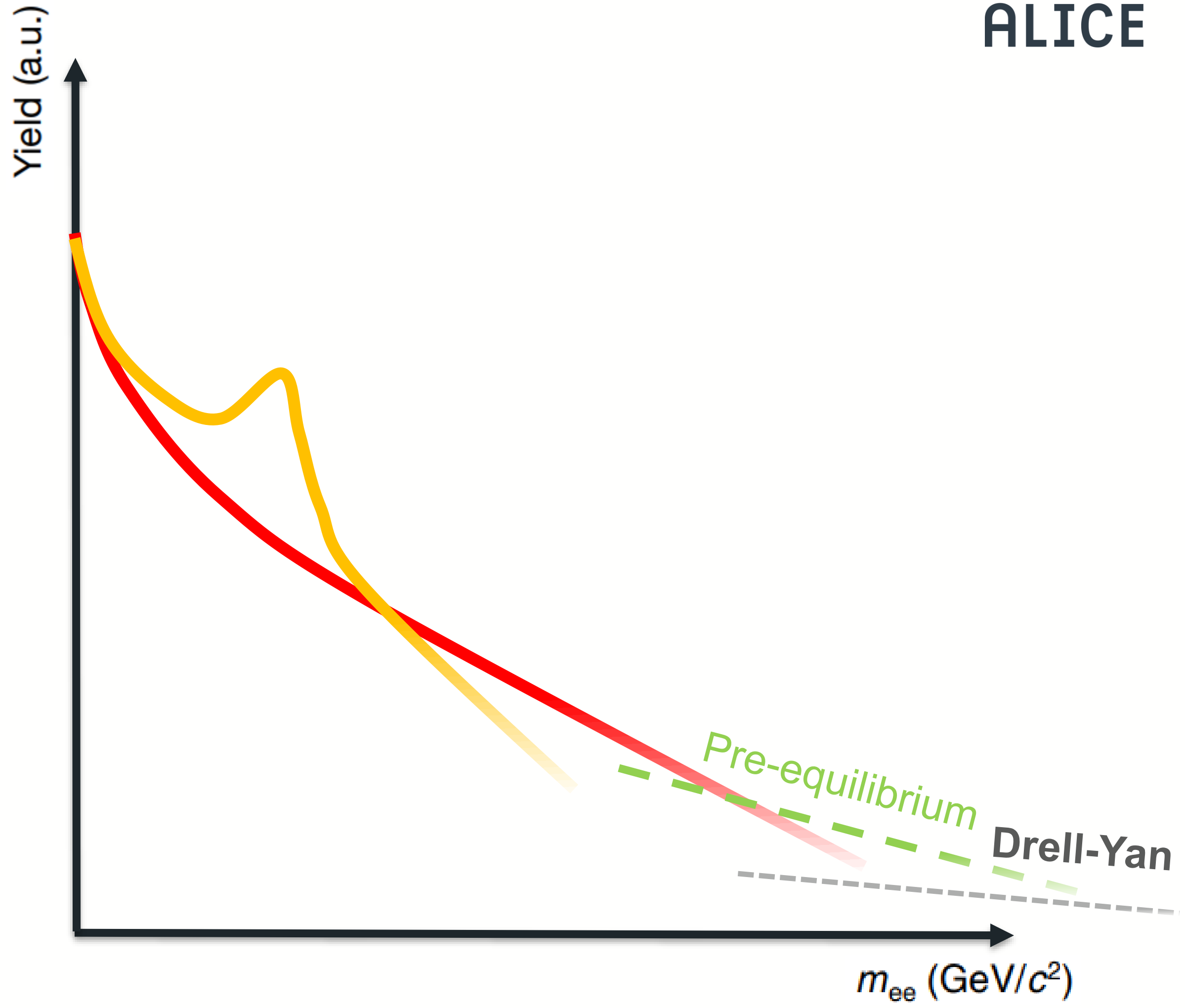
HP2024 NAGASAKI

Motivation

Dielectron production in Pb–Pb collisions

<u>Composition of the dielectron spectrum:</u>

Initial stage of the collision
- **Drell-Yan** & hard scatterings
- Pre-equilibrium contributions



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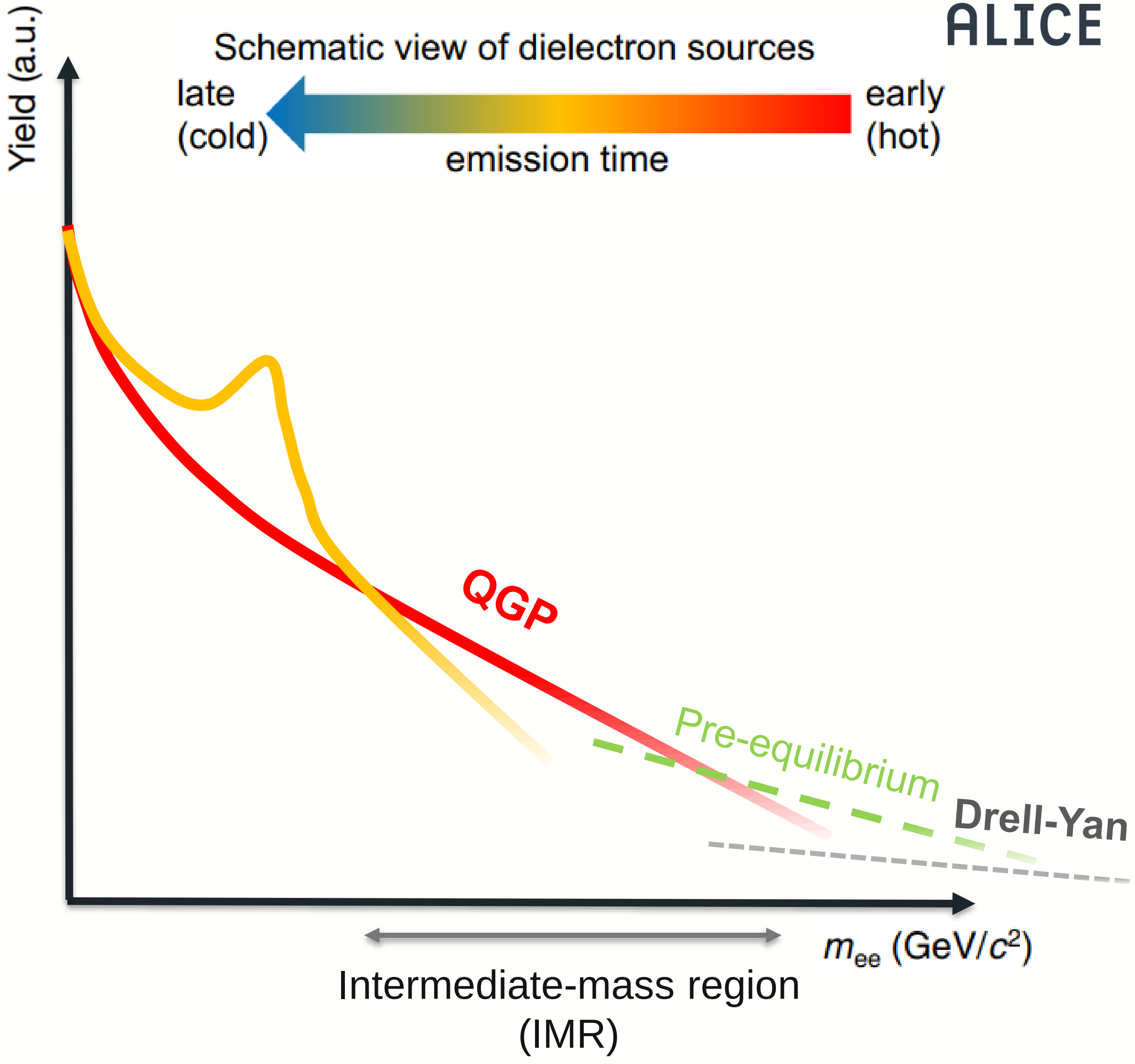

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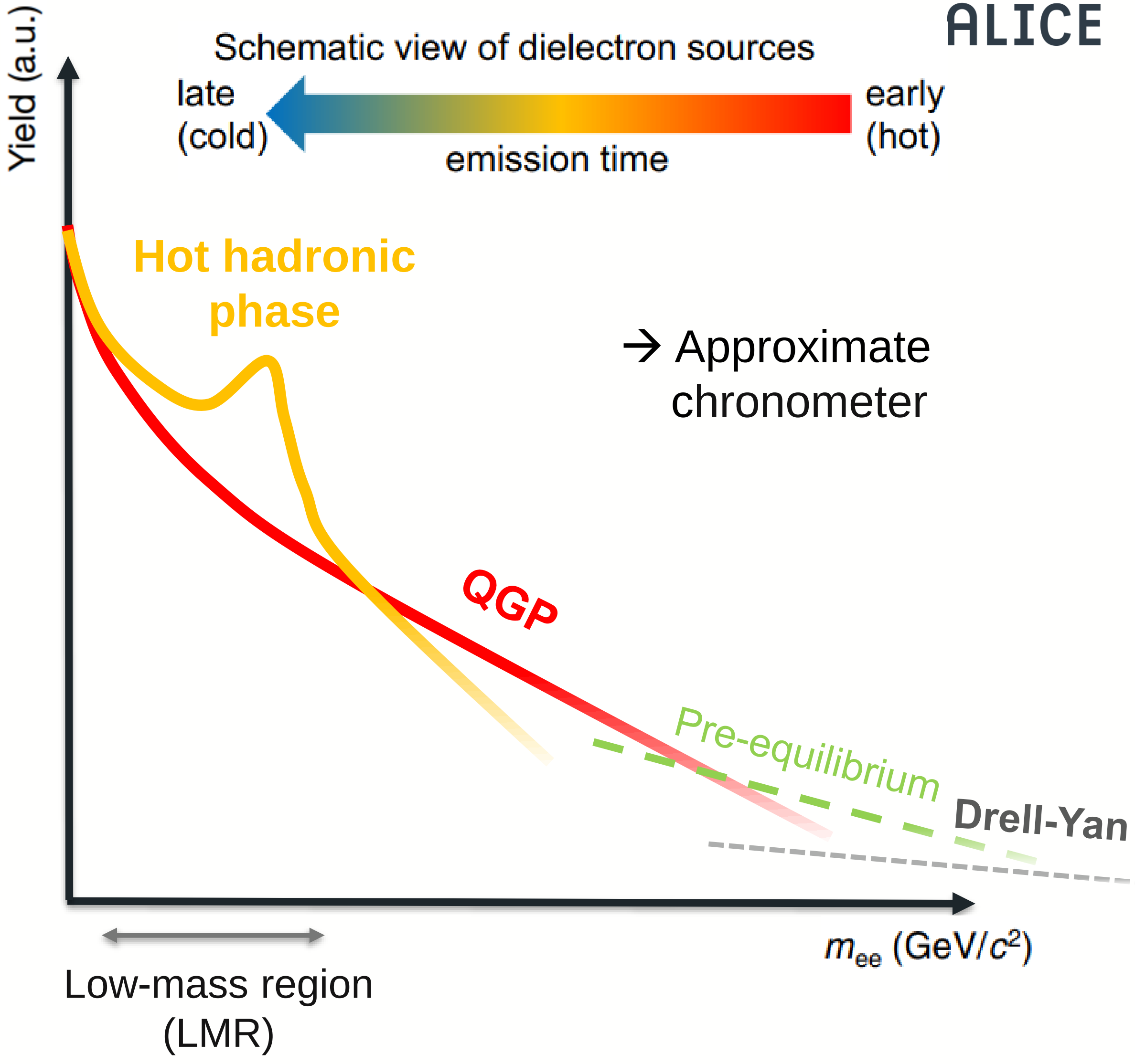
→ Separation via invariant mass (m_{ee})
→ Direct temperature extraction from exp. fit to the IMR



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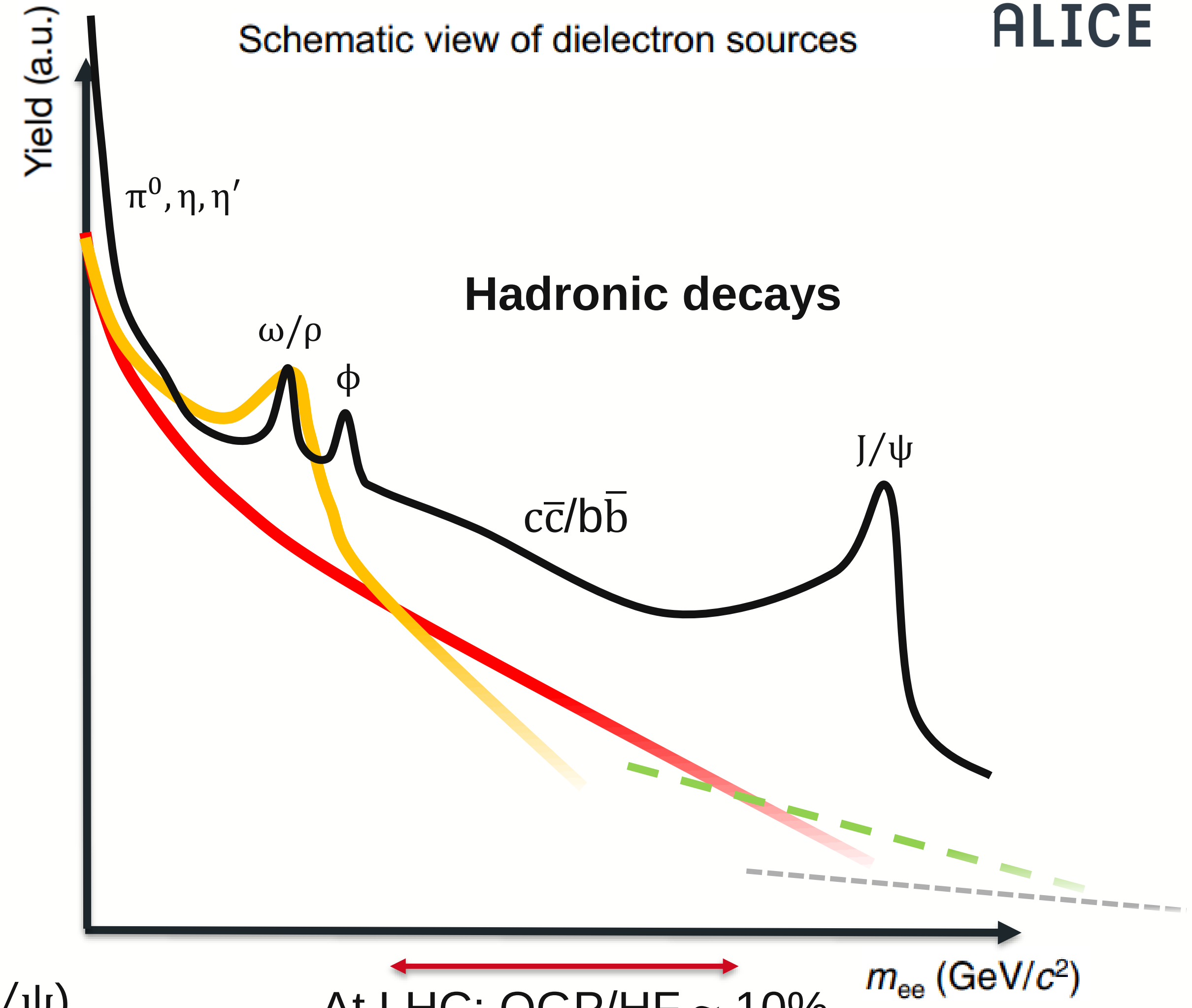
However: Large combinatorial & physical backgrounds

Hadronic decays
- Pseudoscalar and vector mesons ($\pi^0, \eta, \eta', \rho, \omega, \phi, J/\psi$)
- Correlated semi-leptonic decays of heavy-flavor (HF)



At LHC: QGP/HF ~ 10%
→ Required HF uncertainty < 1%

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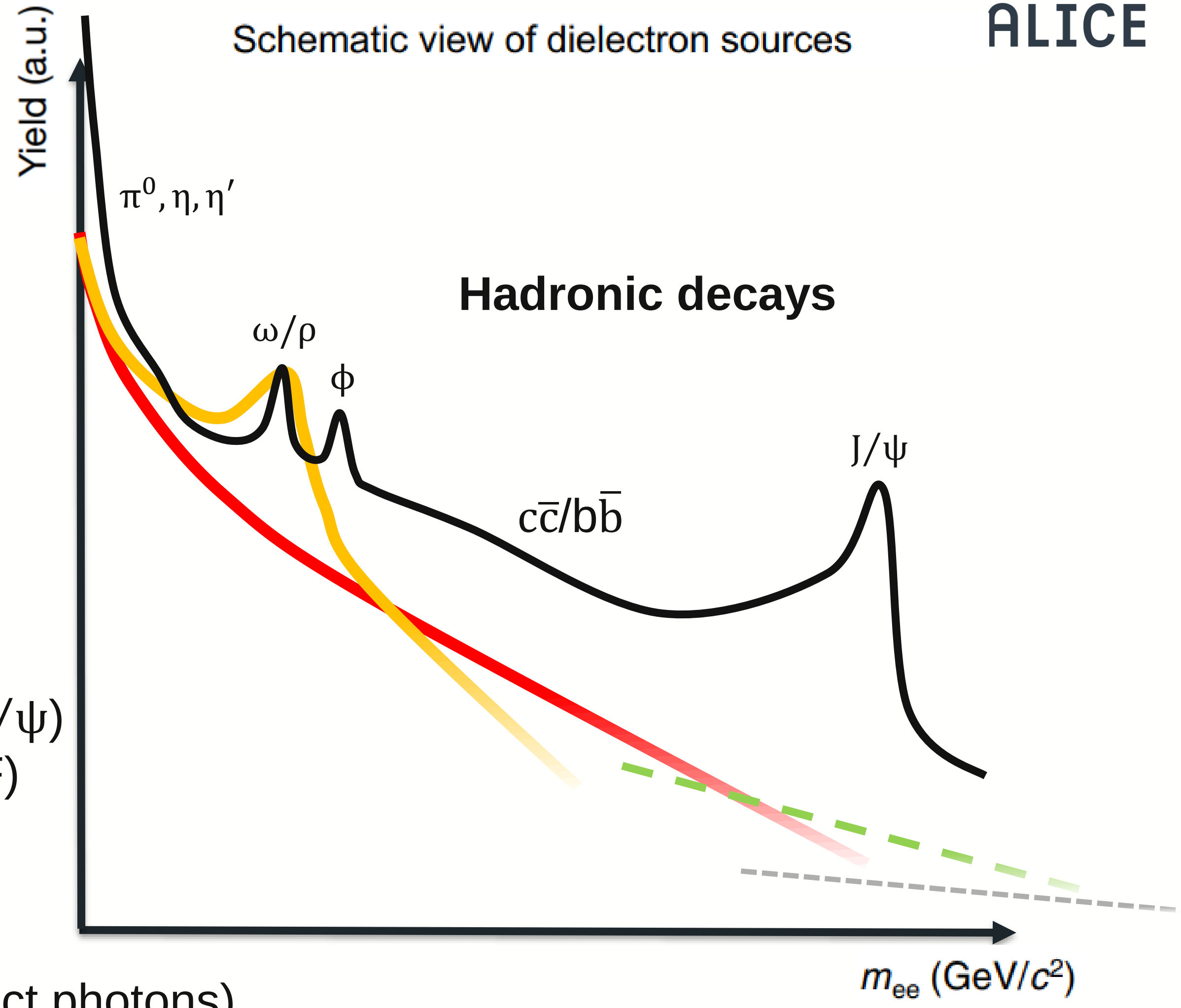


Measurements in pp:
- Vacuum baseline for Pb–Pb studies (HF, Drell-Yan, direct photons)
- Search for new phenomena in high-multiplicity (HM) events or at low momenta

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

ALICE apparatus

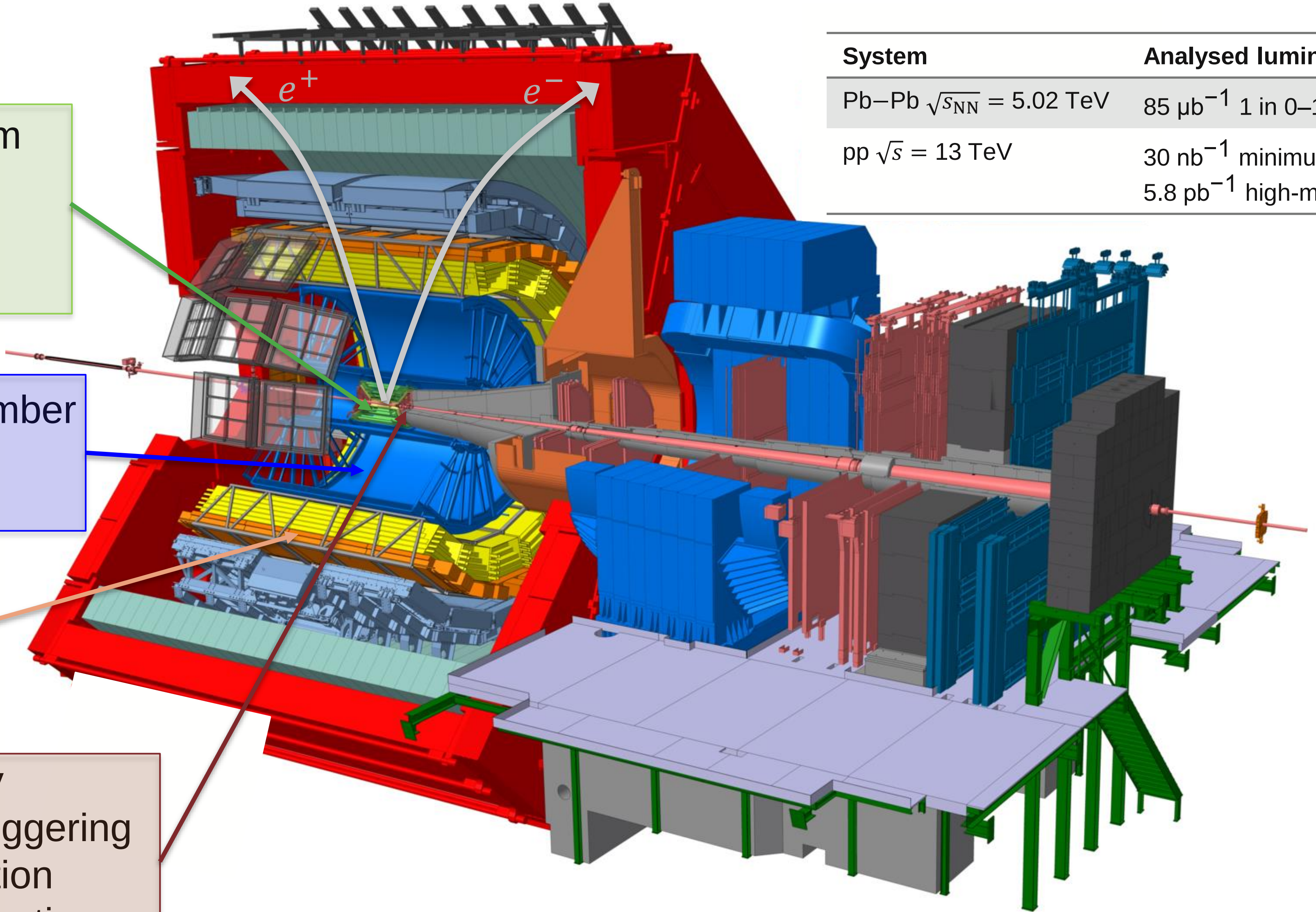
Run 2 (2015-18)

Inner Tracking System
- Vertexing
- Tracking
- PID

Time Projection Chamber
- Tracking
- PID

Time of Flight
- PID

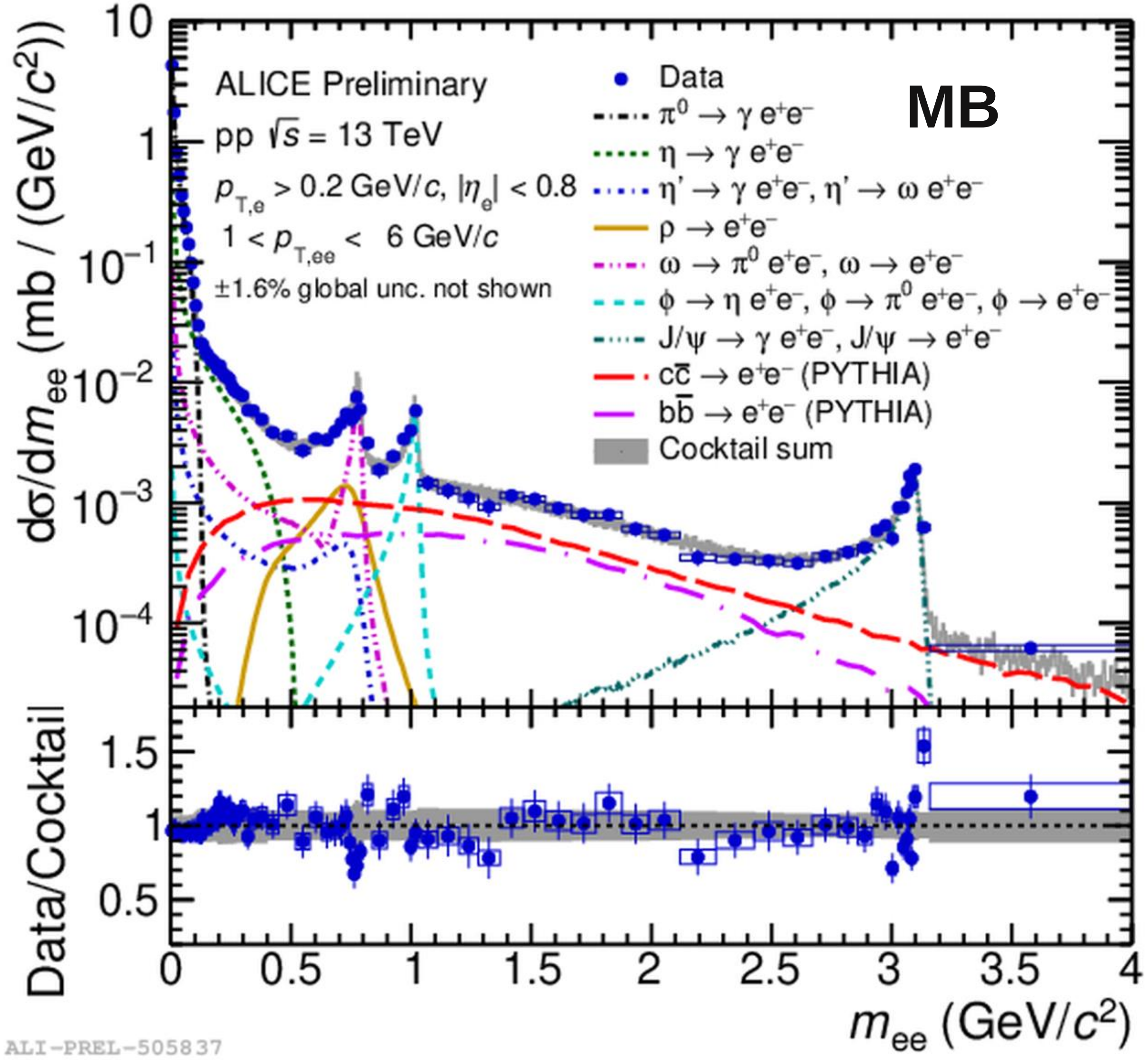
V0 at forward rapidity
- MB & HM event triggering
- Multiplicity estimation
- Centrality determination



System	Analysed luminosity
Pb–Pb $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV	85 μb^{-1} 1 in 0–10%
pp $\sqrt{s} = 13$ TeV	30 nb^{-1} minimum bias (MB) 5.8 pb^{-1} high-multiplicity (HM)

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

Minimum bias (MB)



- Analysis of the full Run 2 data set
- Increase of statistics compared to previous publication:
  ALICE, 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

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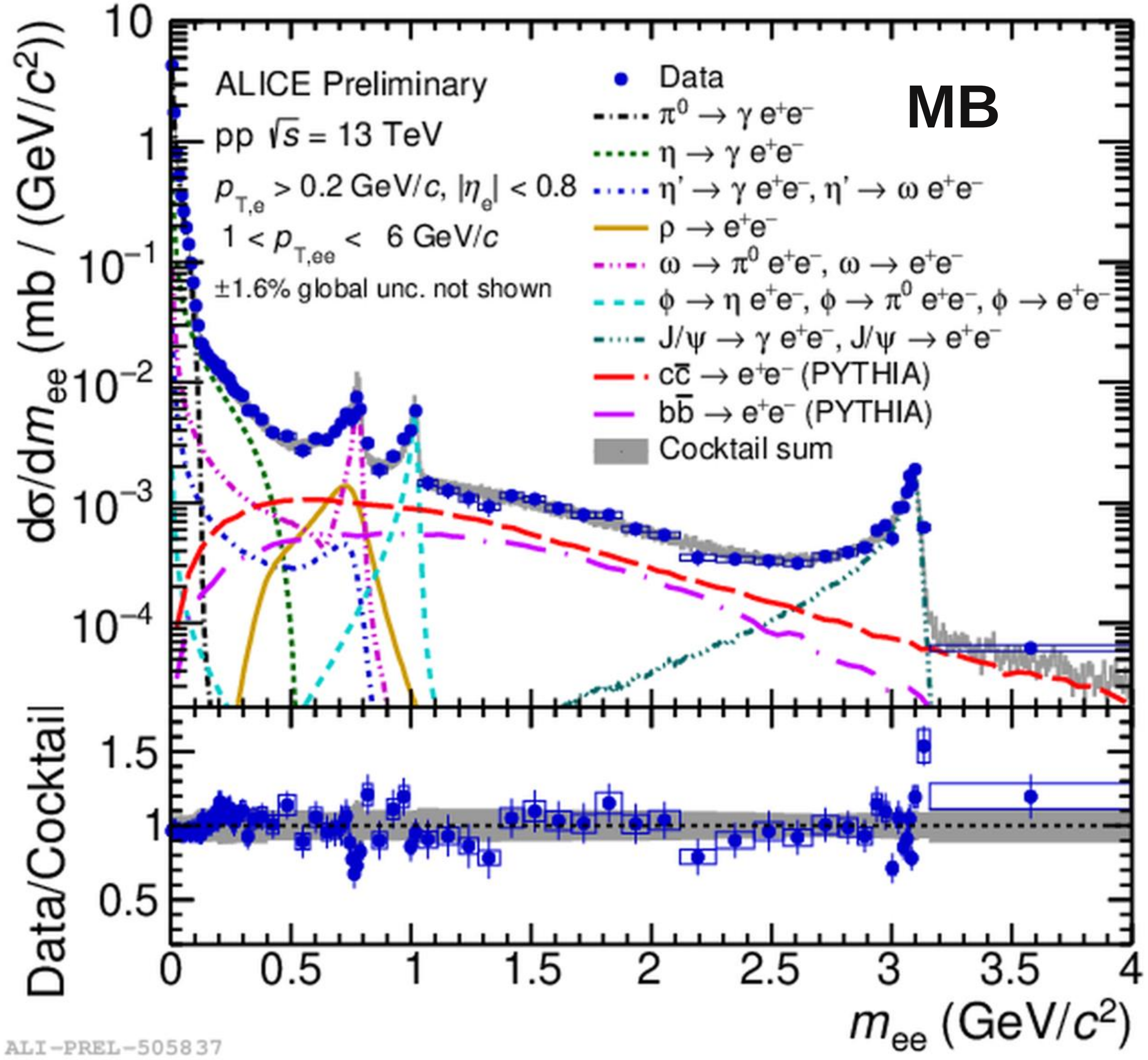

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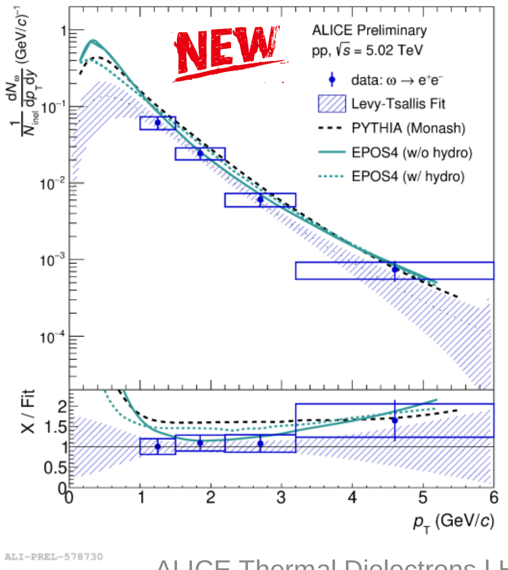

→ **Poster by M. Wälde:**
ω production in pp at $\sqrt{s} = 5.02$ TeV
https://indi.to/zH5RG

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

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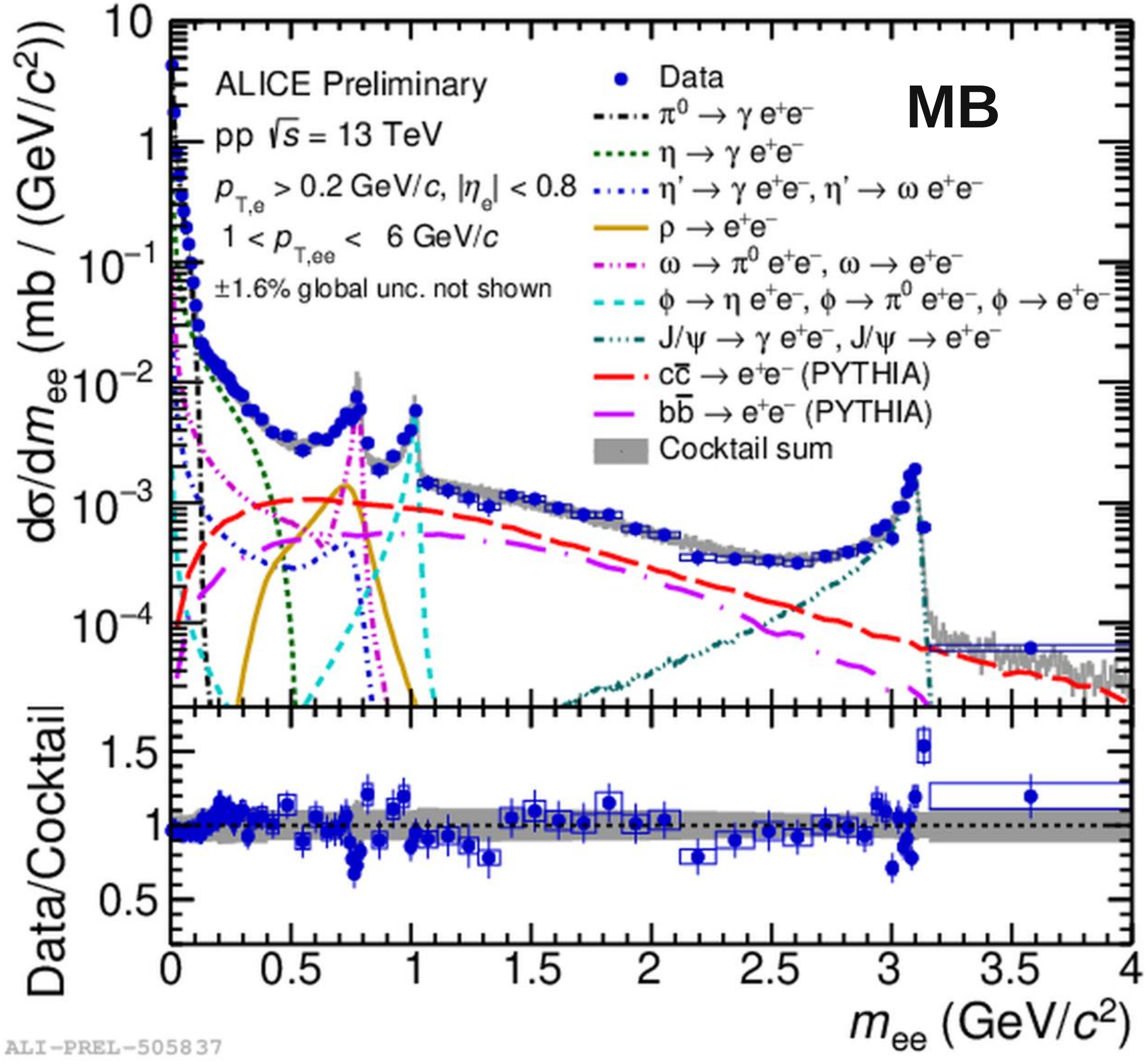

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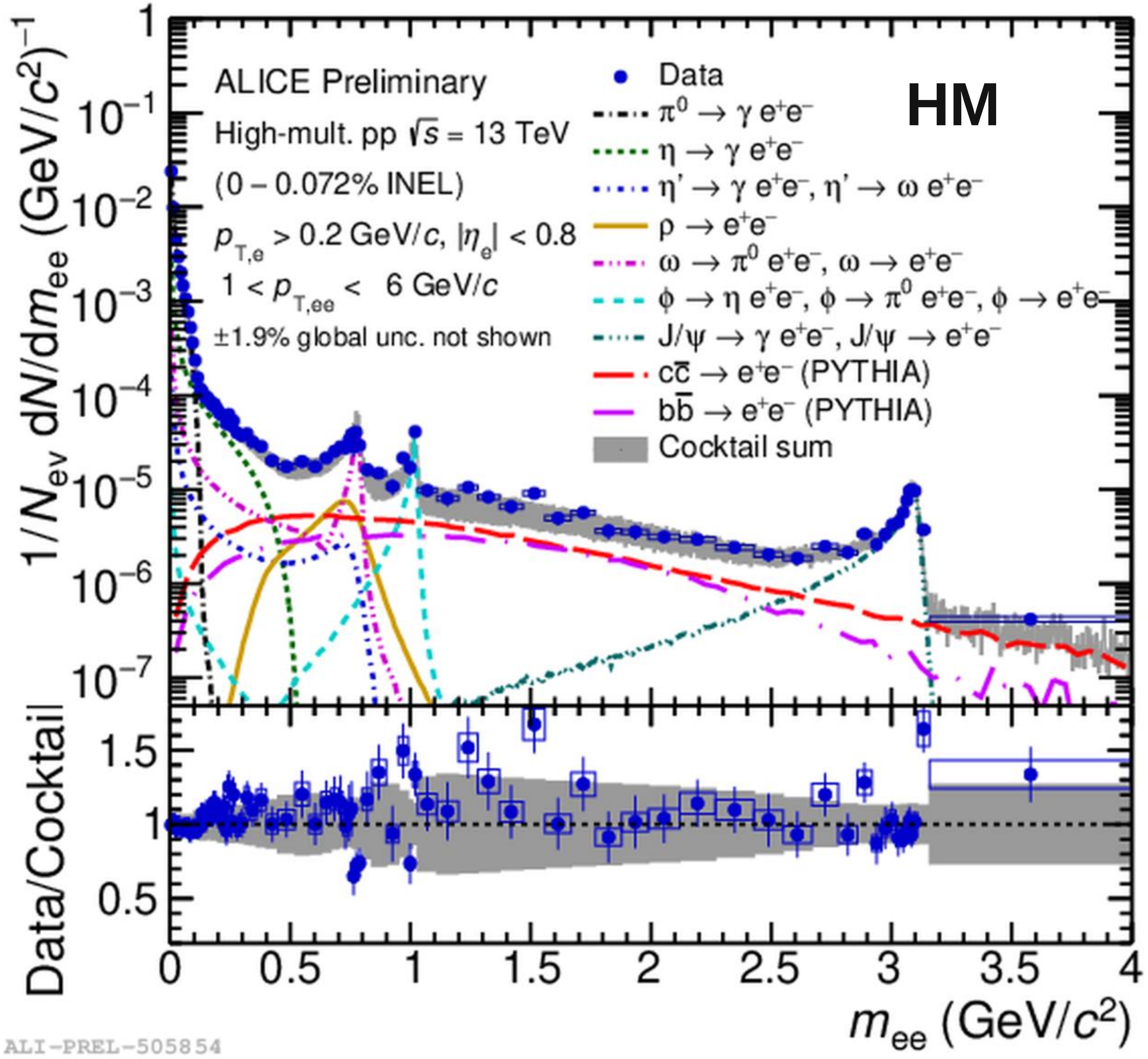
→ MB ($p_{\mathrm{T,ee}} > 1\ \mathrm{GeV}/c$) well described by hadronic sources

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

High multiplicity (HM)



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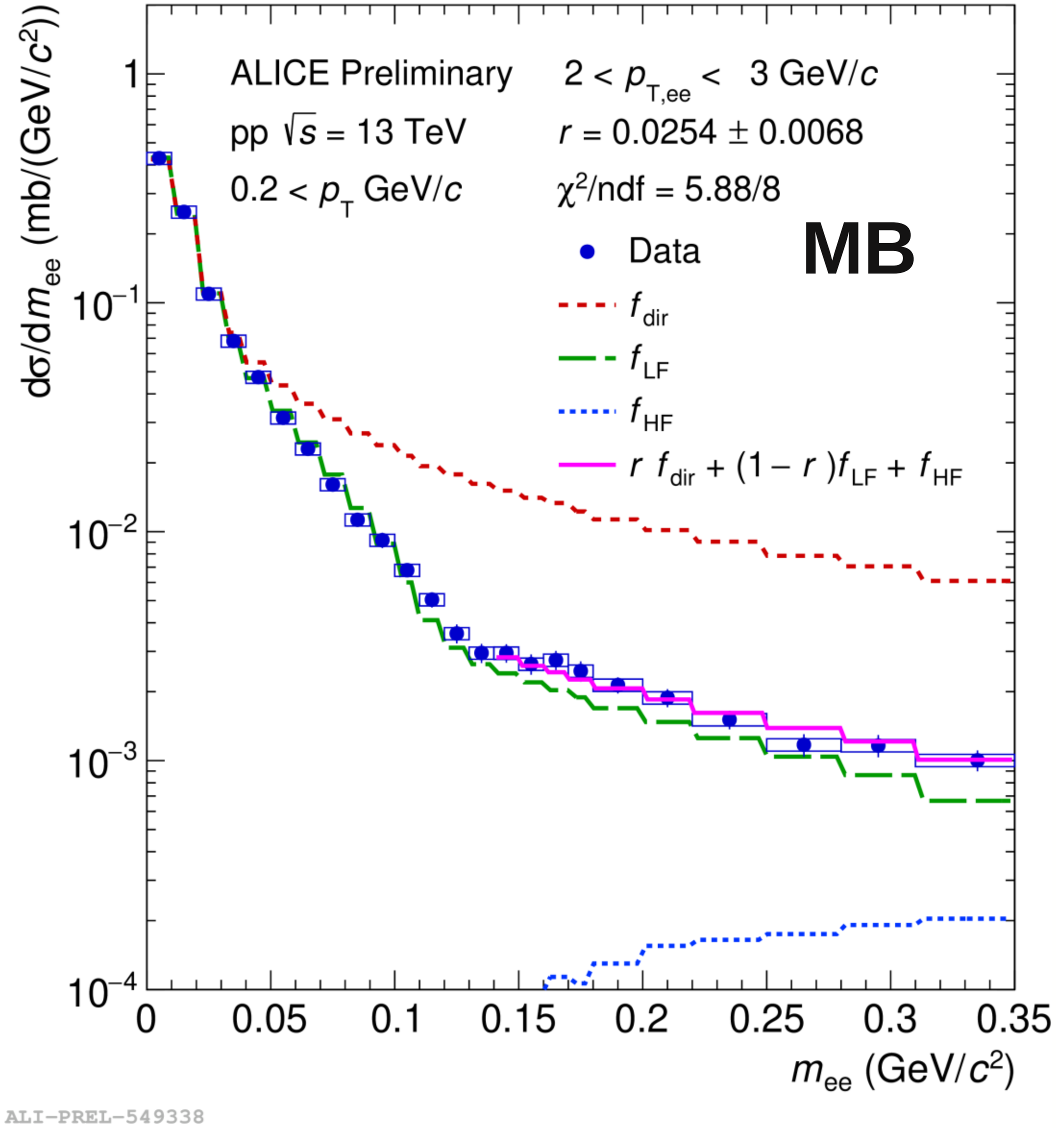
- Updated hadronic cocktail estimation with independent measurements at $\sqrt{s}$ = 13 TeV
  → π^0 and η mesons in the same multiplicity intervals

  → 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

→ Photons not originating from hadronic decays

→ Search for possible thermal contributions in HM pp events

Direct-photon fraction r:

$$r = \gamma^*_{dir}/\gamma^*_{incl} \overset{m_{ee} \to 0}{=} \gamma_{dir}/\gamma_{incl}$$ Link to real-photon yield

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

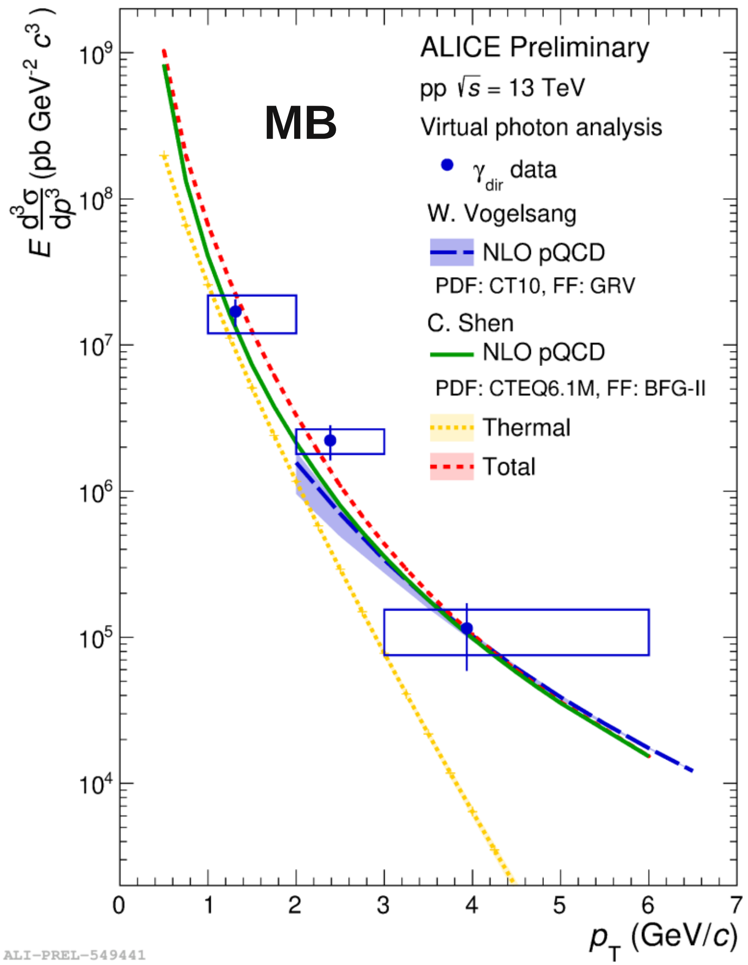
$$f_{fit} = r \times f_{dir} + (1-r) \times f_{LF} + f_{HF}$$

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

- Access the real direct-photon yield: $\gamma^{dir} = r \cdot \gamma^{incl}$

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

Search for thermal radiation in small systems



First measurement of direct photons in small systems at low p_{T} at the LHC
→ Direct-photon fraction *r* = 0.01-0.03

MB: Data can be reproduced by both prompt only or prompt + thermal radiation

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

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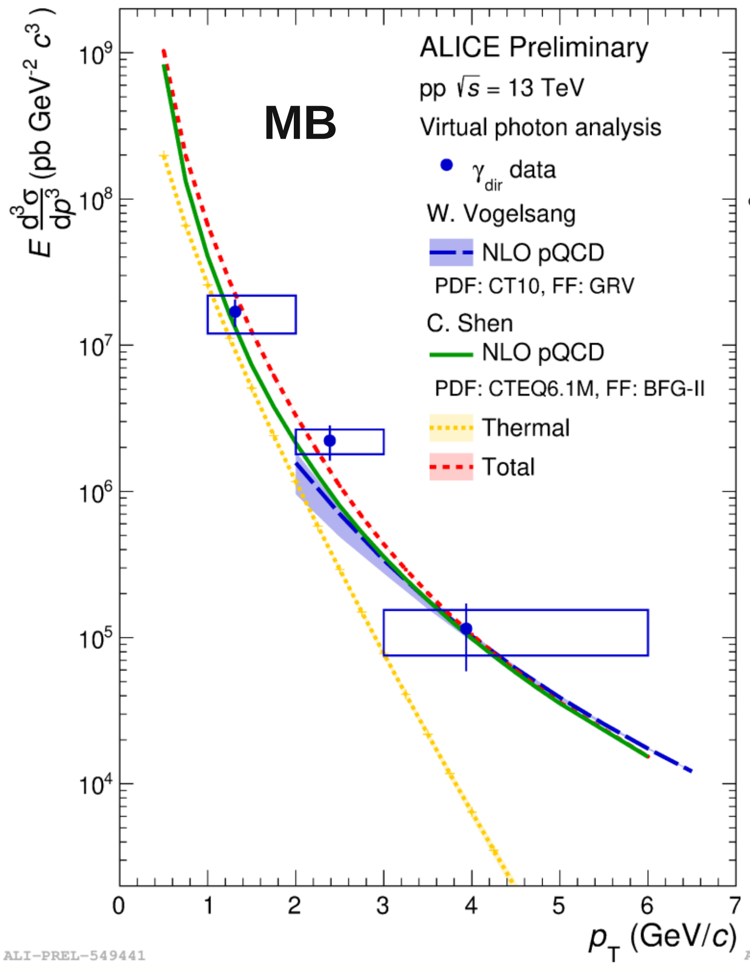
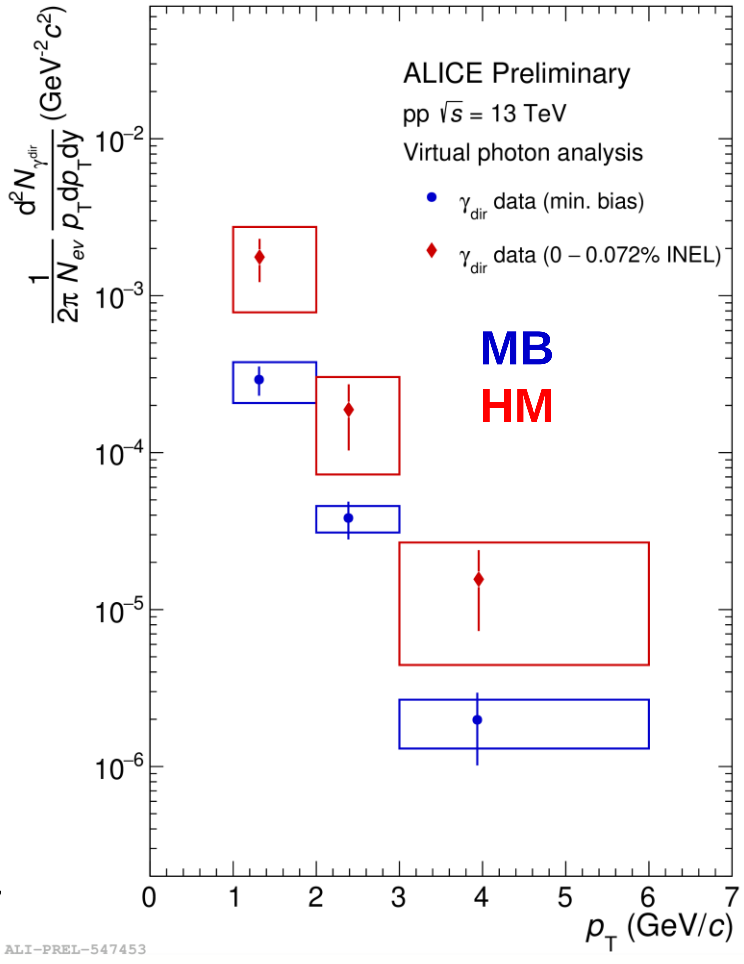




First measurement of direct photons in small systems at low p_{T} at the LHC

→ Direct-photon fraction *r* = 0.01-0.03

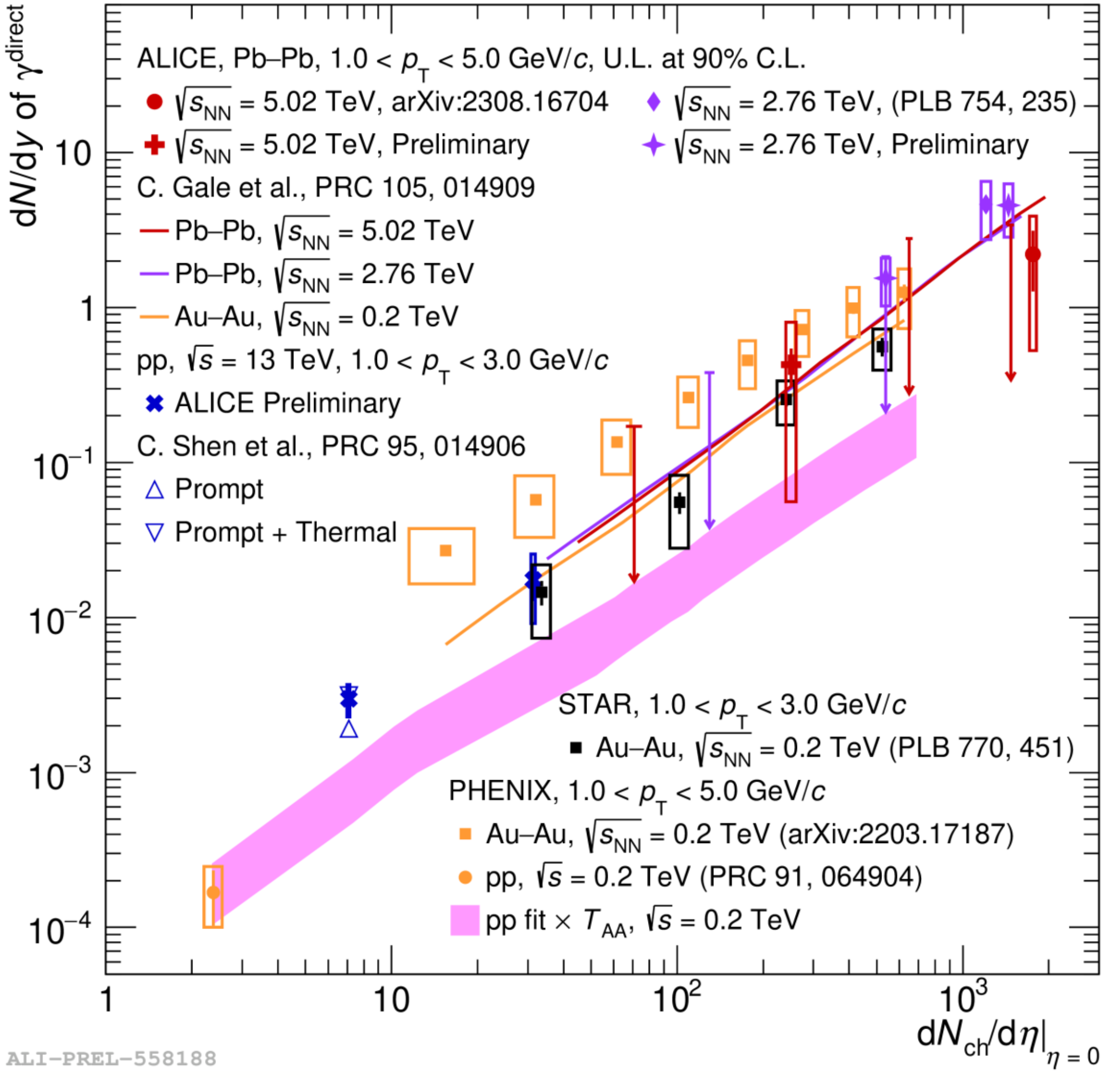
MB: Data can be reproduced by both prompt only or prompt + thermal radiation

HM: Significant increase of direct-photon yield compared to MB collisions

Challenging to calculate photon production in HM pp collisions

Direct-photon signal

p_{T}-integrated direct photon yields



Power-law dependence of direct-photon yield on charged-particle multiplicity proposed by PHENIX
→ Suggests scaling independent of energy or centrality

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

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

Virtual-photons in 0-10% Pb−Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

ALICE, arXiv:2308.16704

→ Both measurements consistent with model predictions

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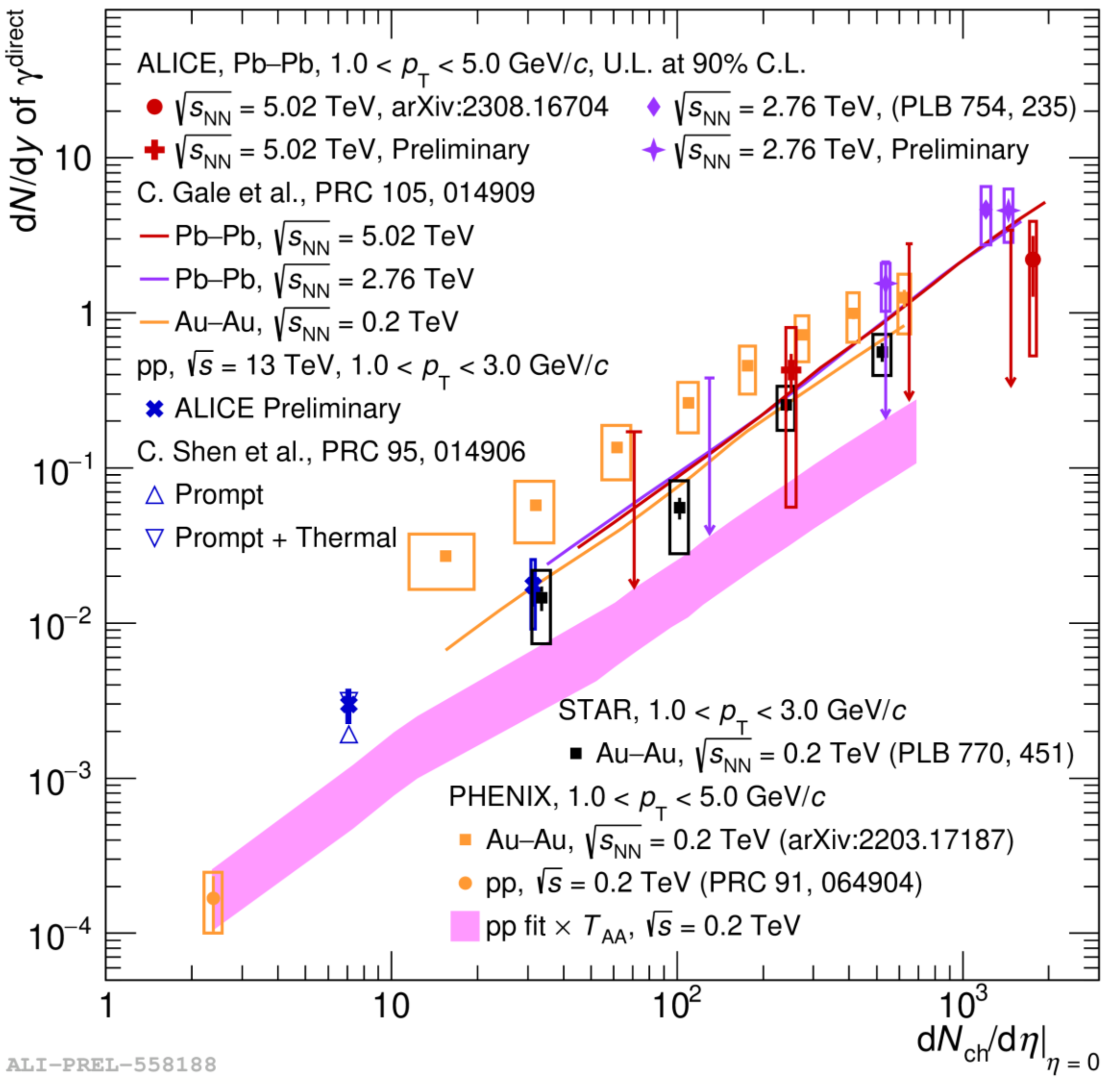

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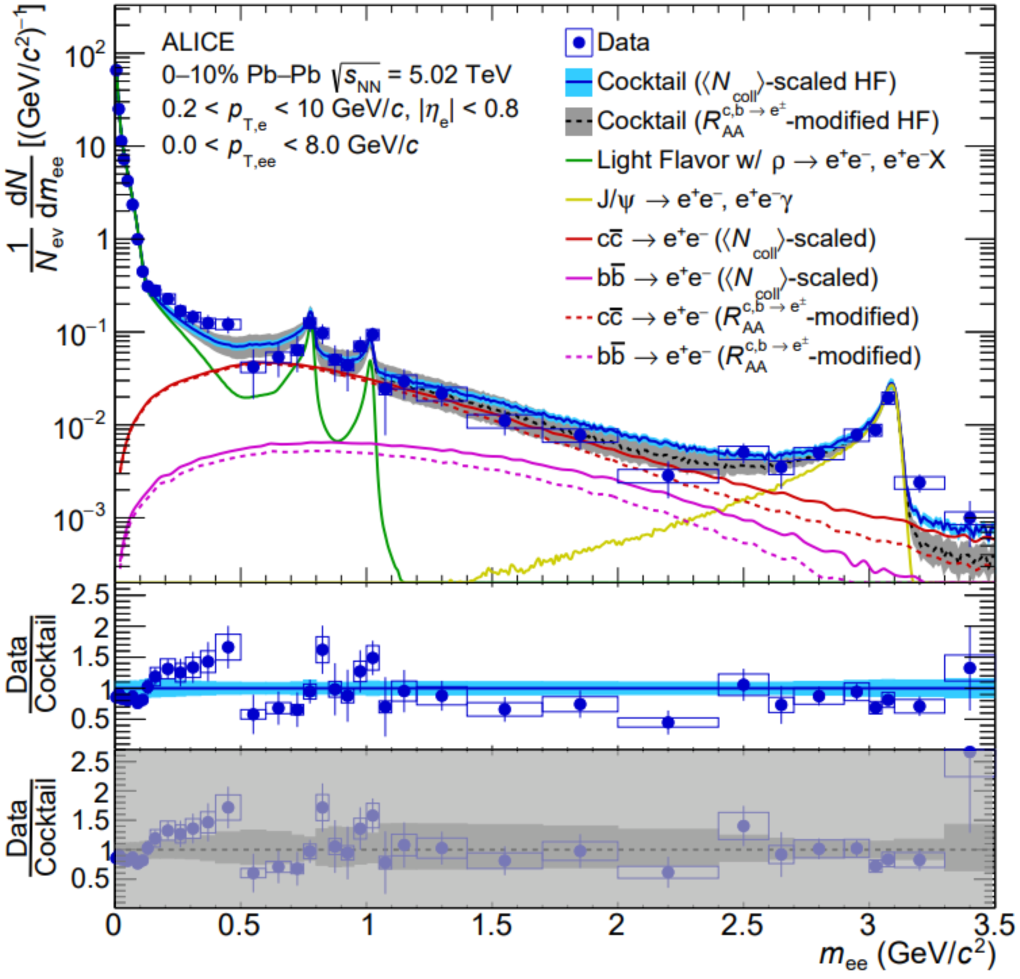
Virtual-photons in pp at $\sqrt{s} = 13$ TeV
→ Crucial inputs to constrain theoretical developments

Results at LHC energies not sensitive enough yet to confirm:
- Universal scaling behavior
- Onset of thermal radiation

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

Invariant-mass spectrum

ALICE, arXiv:2308.16704



Intermediate-mass region

Comparison to hadronic cocktail, including:

- N_{coll}-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  → Vacuum baseline

→ Good description of π^0-Dalitz and J/ψ decays

→ Indication of HF suppression compared to pp

→ Expected due to cold-nuclear matter (CNM) and hot-nuclear matter (HNM) effects

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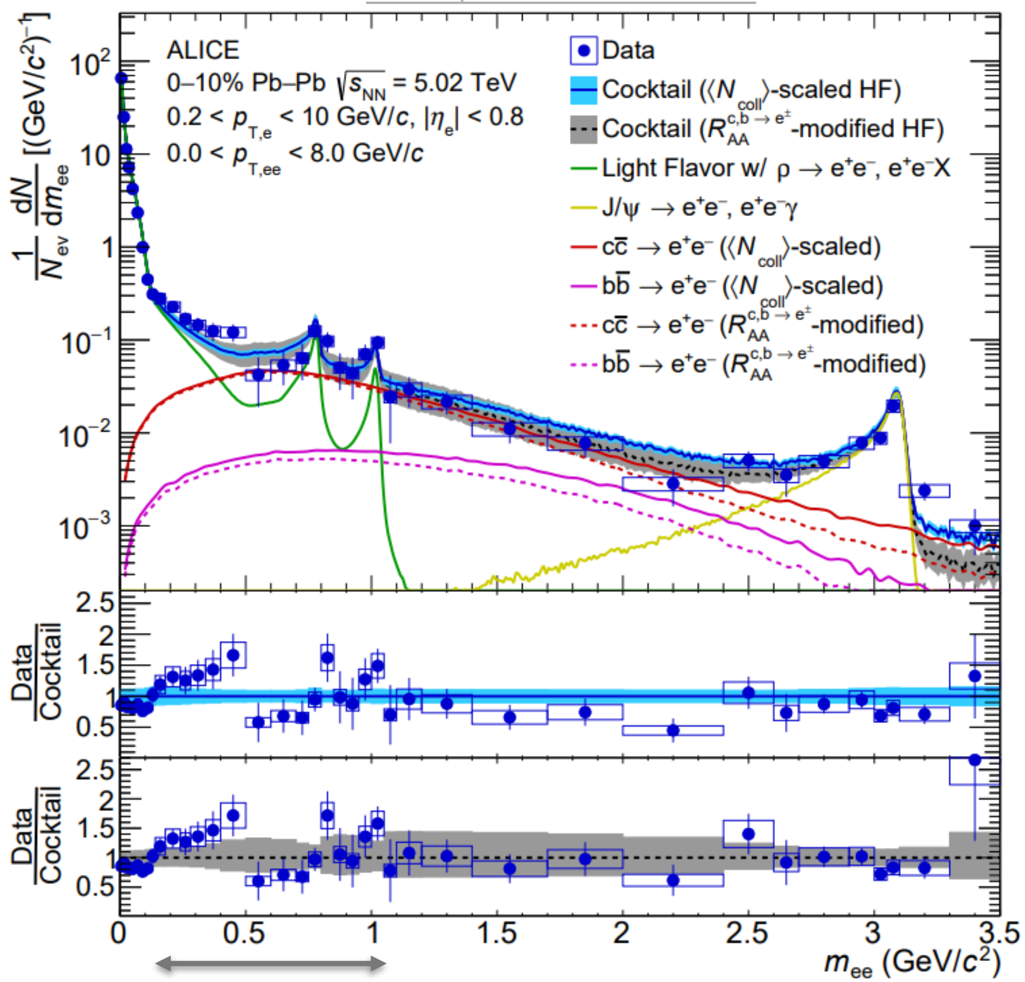

Low-mass region (LMR)

Comparison to hadronic cocktail, including:

- N_{coll}-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  → Vacuum baseline
- Include measured R_{AA} of $c/b \rightarrow e^{\pm}$
  → Modified-HF cocktail

→ Overall improved description of the data including the HF suppression

→ A hint for an excess at low m_{ee} (1.3σ)

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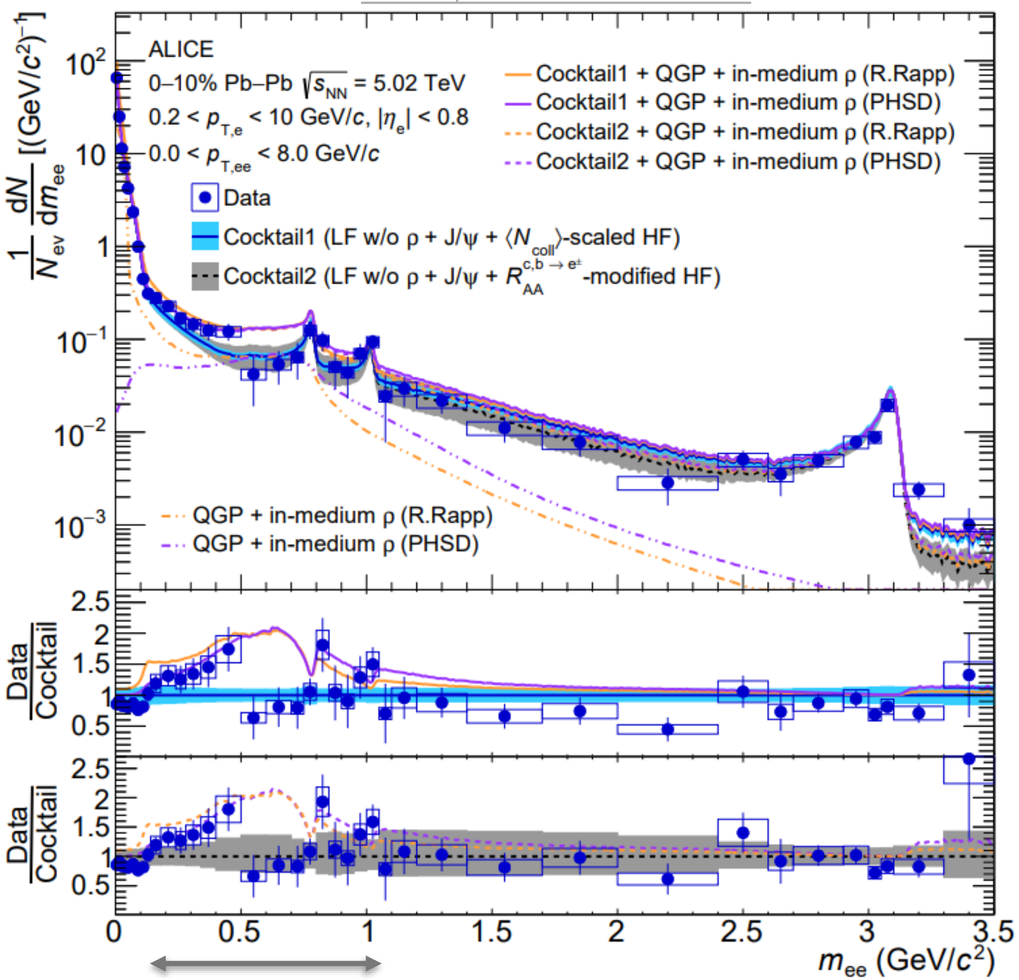

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Comparison to theoretical models: R. Rapp & PHSD

Rapp, Adv. HEP. 2013 (2013) 148253
PHSD, PRC 97 (2018) 064907

→ Excess in LMR: Expected from ρ mesons produced thermally in the medium

→ Short lifetime and strong coupling to $\pi^+\pi^-$ channel

→ Regeneration in the hot hadronic phase & broadening of its spectral function

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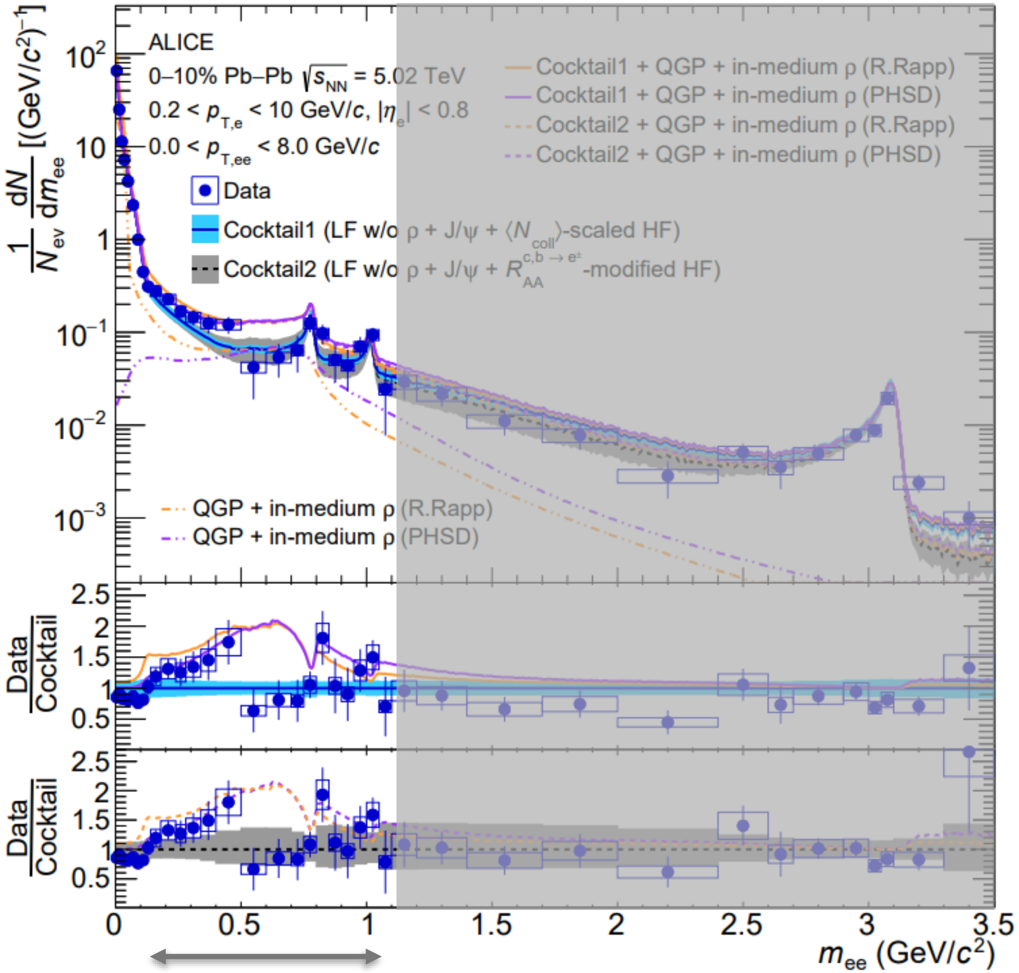

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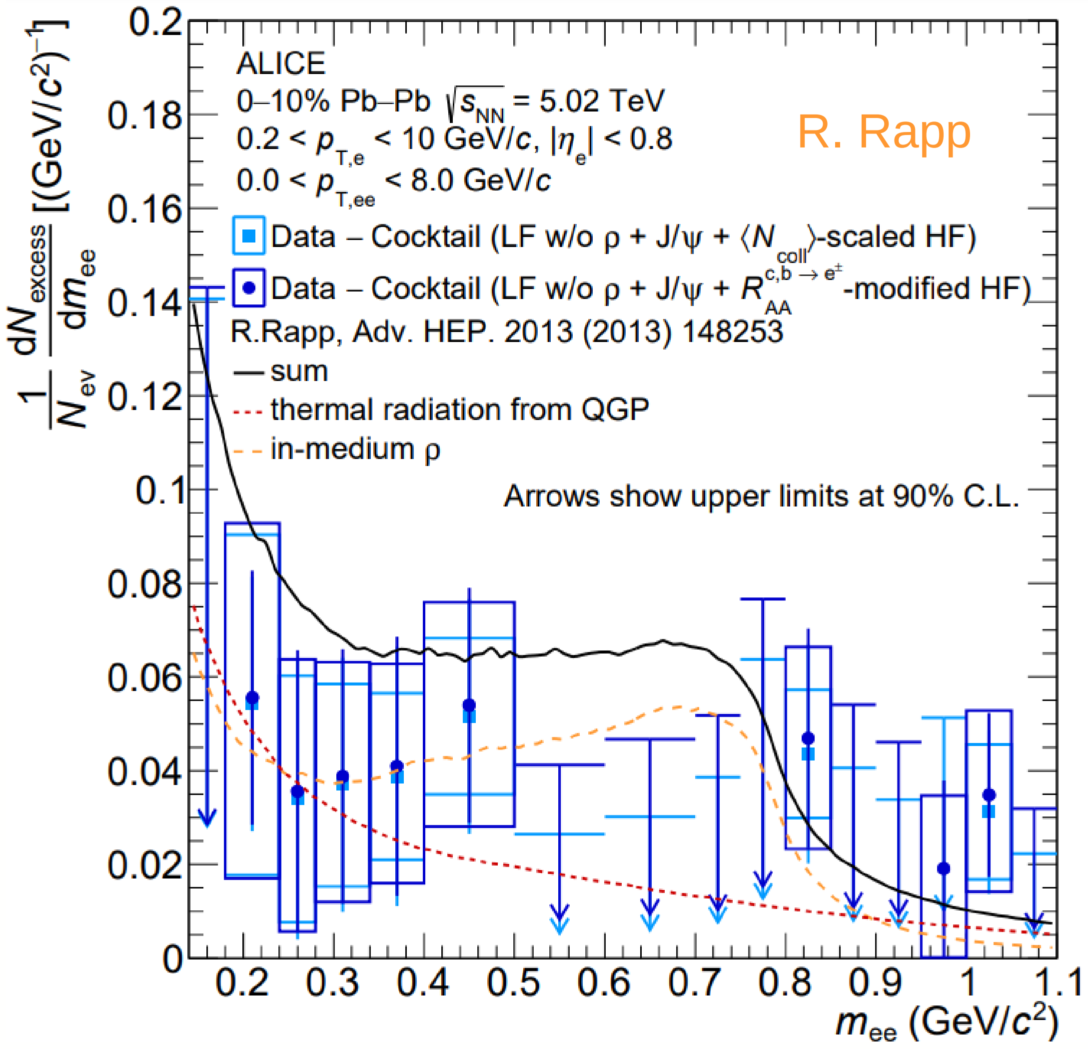

Subtraction of known hadronic sources without ρ

Compared with sum of 2 contributions:
- In-medium ρ produced thermally in hot hadronic matter
- Thermal radiation from QGP

Implemented in 2 different ways:
- R. Rapp's expanding fireball model

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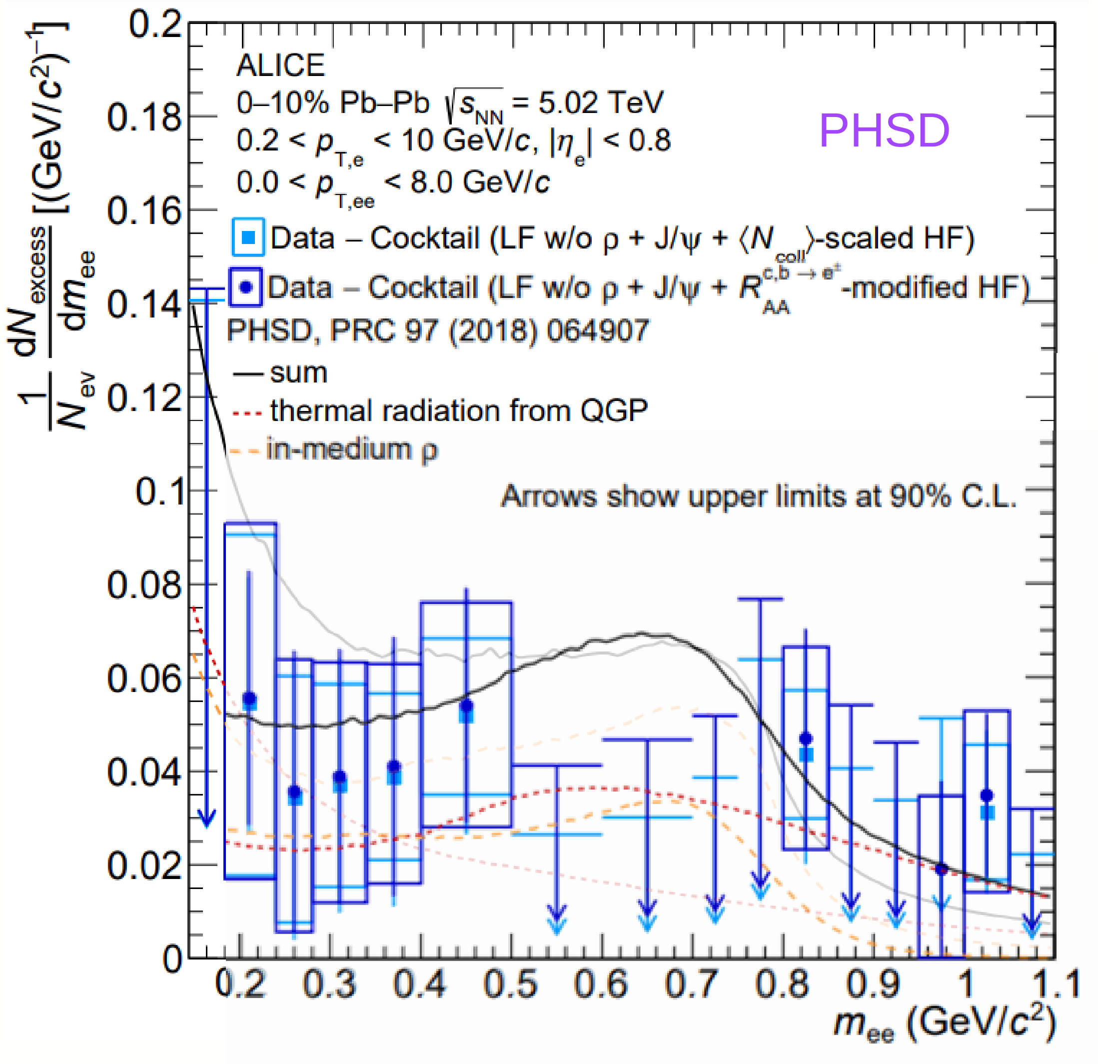

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Implemented in 2 different ways:
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- Parton-Hadron-String Dynamics (PHSD): transport model

Both models compatible with data:
→ Less yield predicted by PHSD
→ Some tension in $0.5 < m_{ee} < 0.7$ GeV/c^2 by 2.7σ (4.0σ)
  → More data needed to confirm

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

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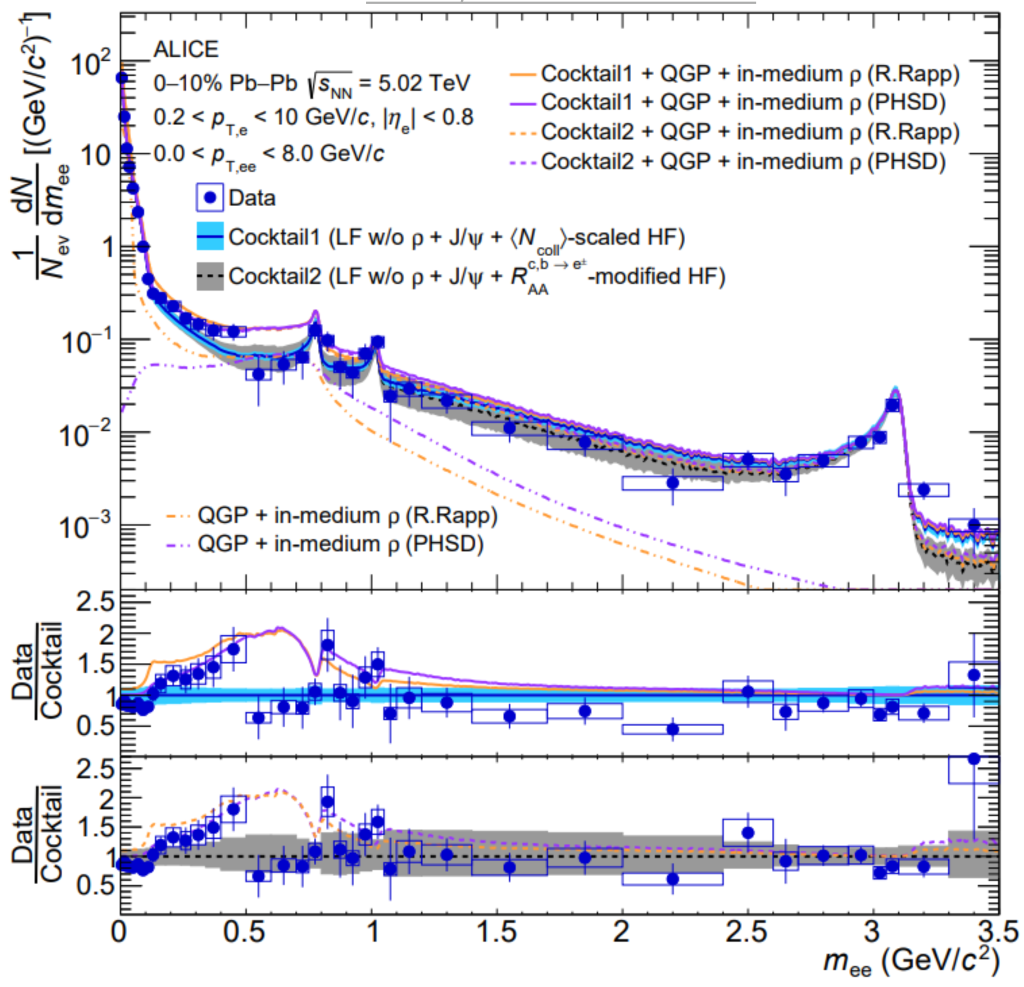

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Focus on IMR:

→ Dominated by HF contributions

→ Most sensitive for radiation of the QGP

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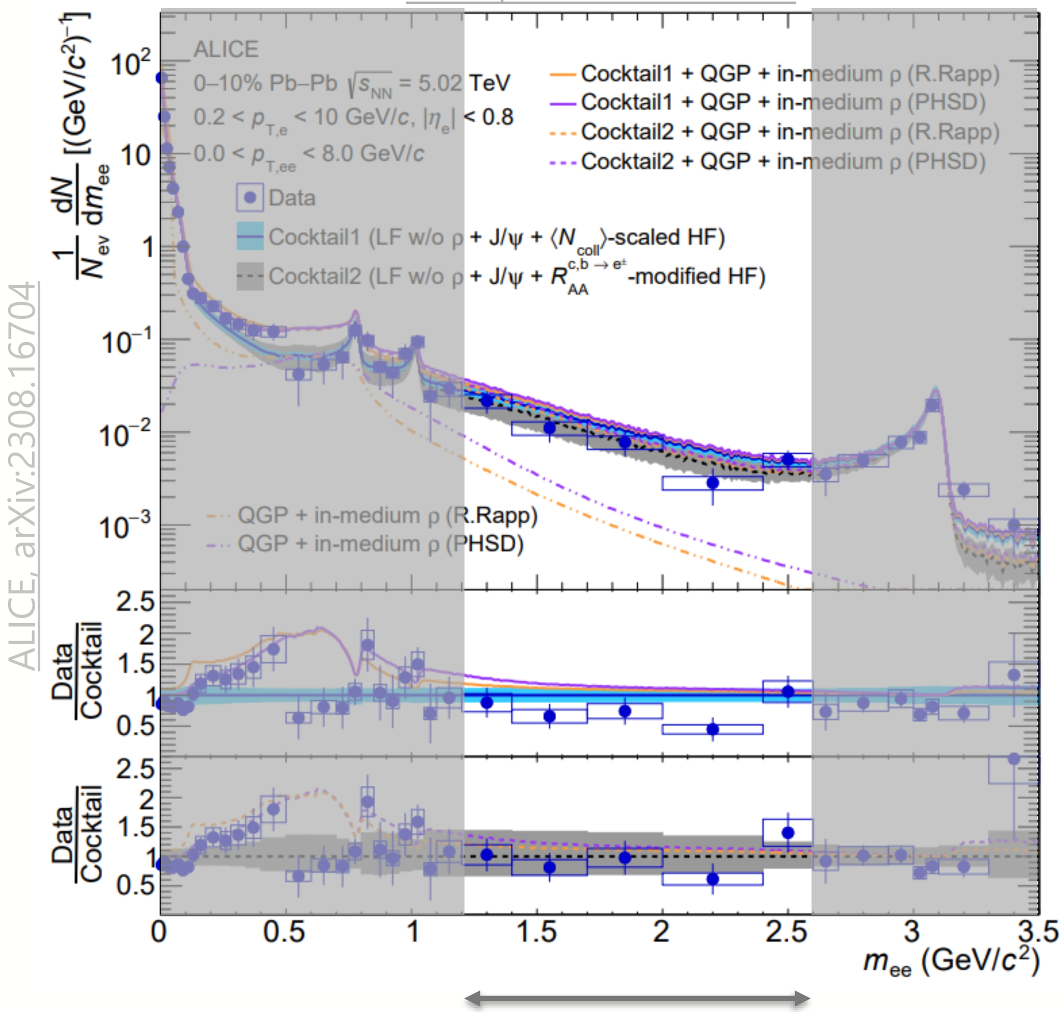

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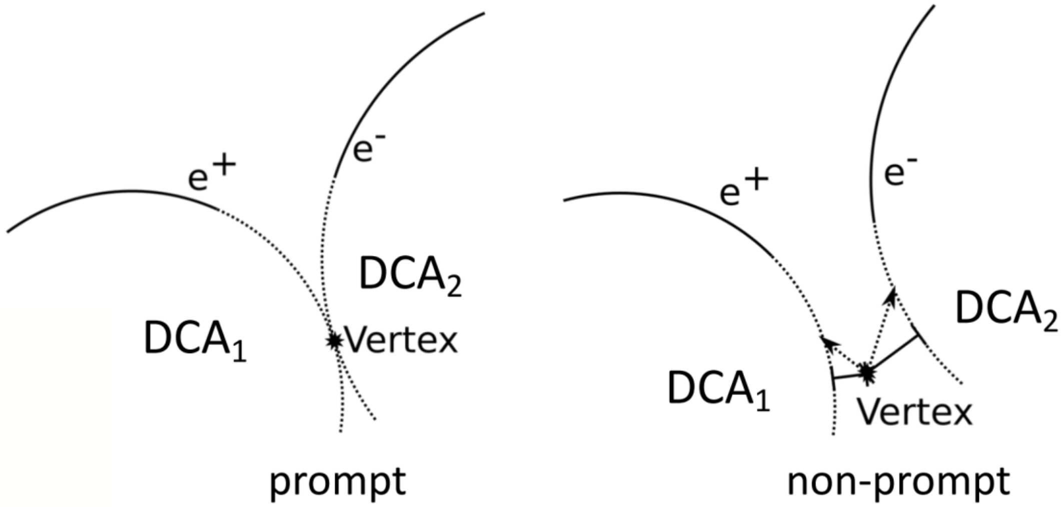
Topological separation
Approach

Distance-of-closest approach (DCA):



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

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

→ Decay length of charm and beauty hadrons much larger than that of prompt sources

→ Electrons do not point back the vertex

DCA for pairs taking into account the DCA resolution:

$$\mathrm{DCA_{ee}} = \sqrt{\frac{(\mathrm{DCA}_1/\sigma_1)^2 + (\mathrm{DCA}_2/\sigma_2)^2}{2}}$$

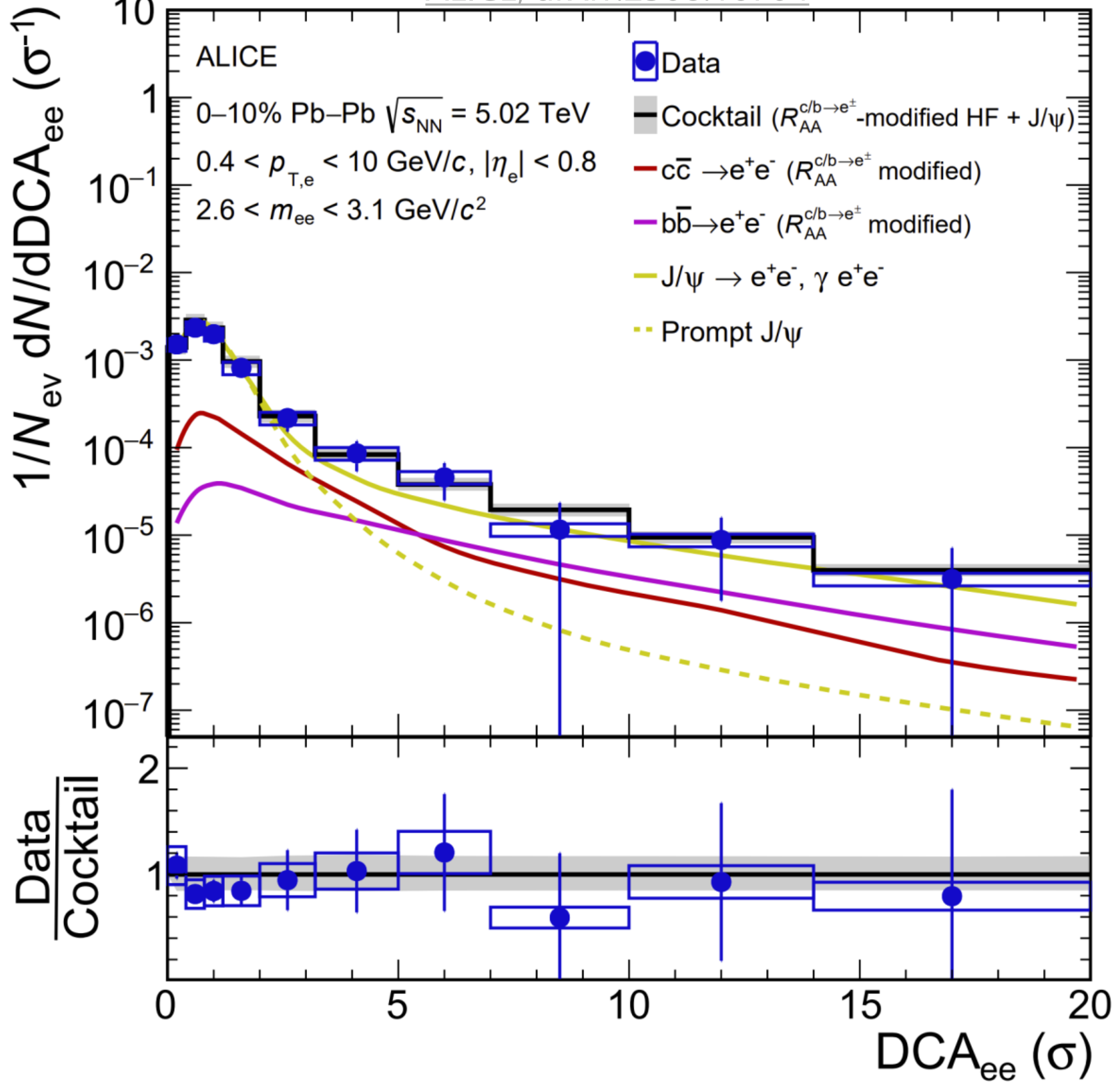
→ Method only relies on the well-known decay kinematic

→ Independent of cocktail and theory input

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

Topological separation - $\mathrm{DCA_{ee}}$ in J/ψ region

ALICE, arXiv:2308.16704



Test separation of prompt and non-prompt sources in J/ψ mass region:

- J/ψ contribution dominates and is well constraint by independent ALICE measurements

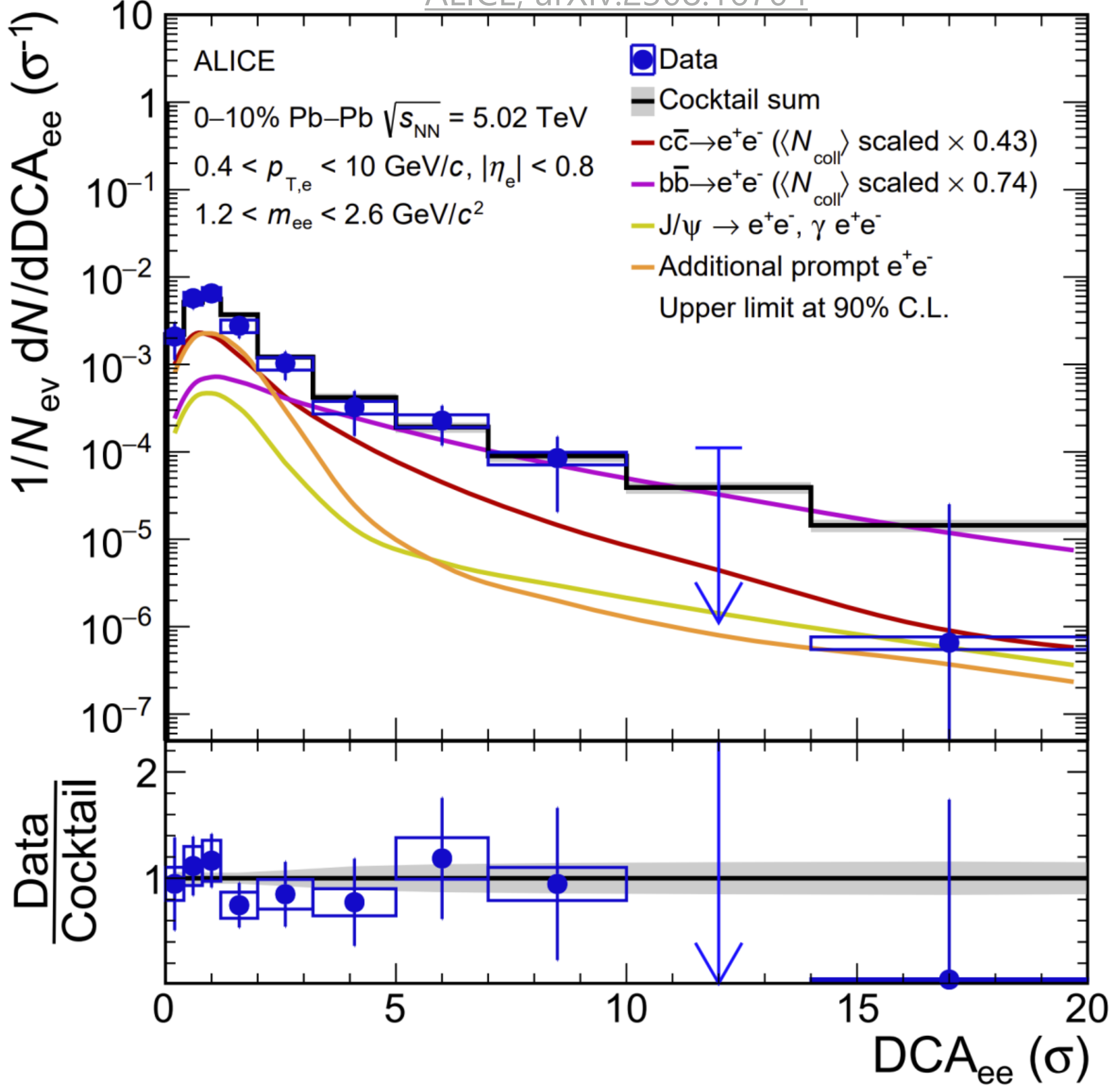
- Only 2 other components: charm & beauty scaled by the modified-HF cocktail
  → Relative contributions of different hadrons: Combined based on measured fragmentation functions and branching ratios

Data well described by the sum of all templates
→ Validating the DCA resolution in the MC simulation

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

Topological separation - $\mathrm{DCA_{ee}}$ in IMR fitted

ALICE, arXiv:2308.16704



Extraction of prompt thermal signal via template fits:

- Beauty contribution fixed via separate fit at high $p_{\mathrm{T,ee}}$
  $\mathrm{b\bar{b}}$: 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)

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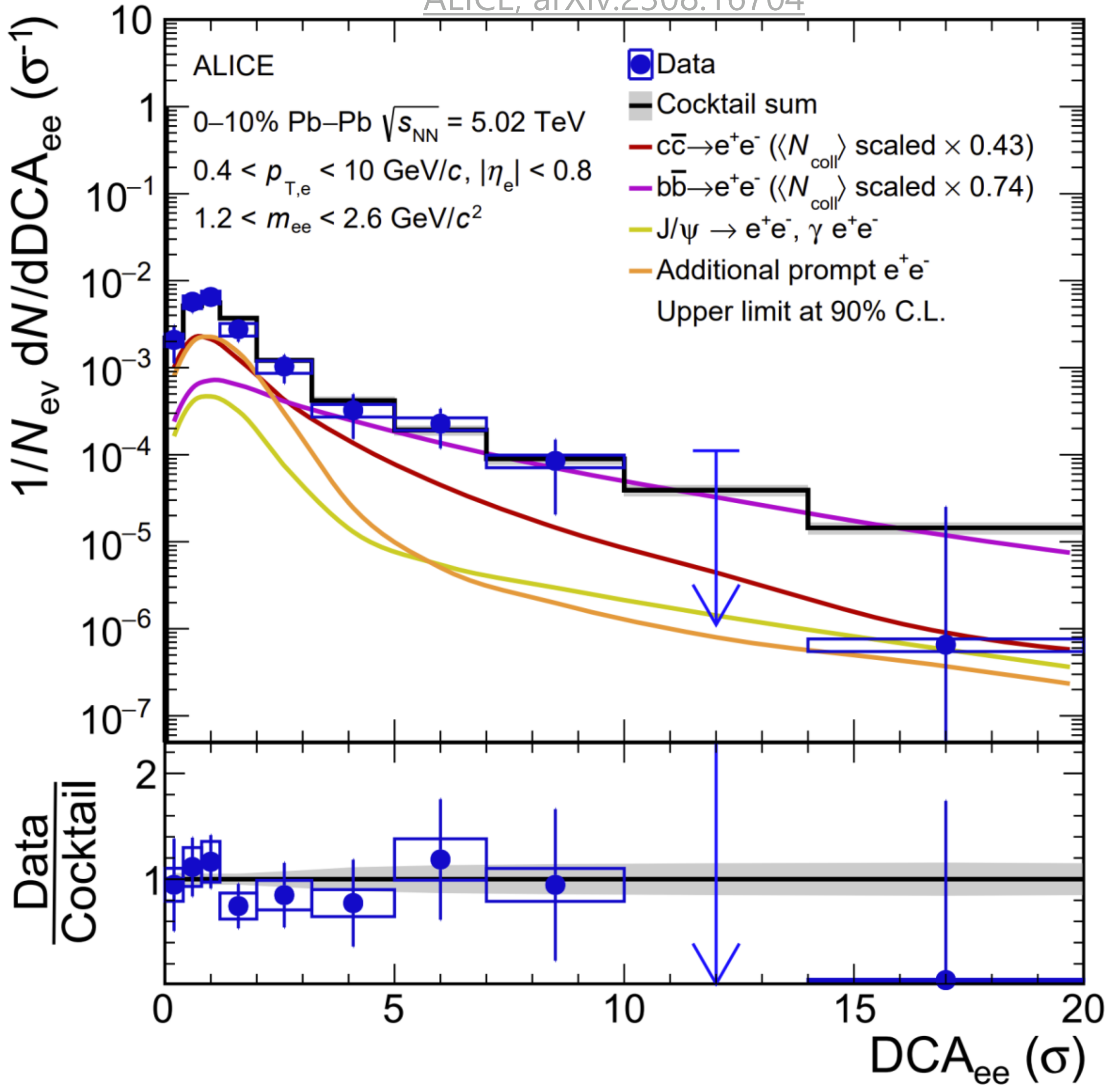

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Results in agreement with:

- Charm suppression
- Thermal contribution in the order of expectations by 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

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

- Increased readout rate of 1000 in pp and 100 Pb–Pb
- Improved vertex pointing resolution by a factor larger than 3

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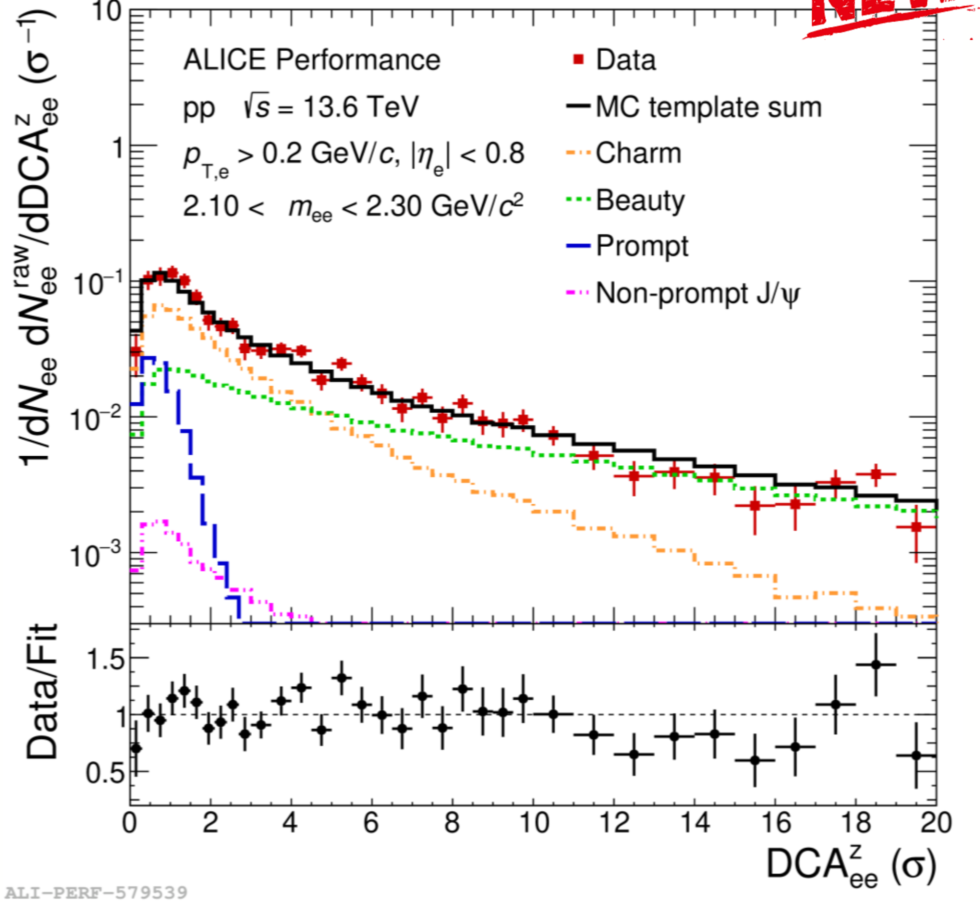
pp collisions: 200 pb^{-1} at $\sqrt{s} = 13.6$ TeV expected

Large MB data set of pp collisions recorded in 2022/23:
- First look at performance (0.97 pb^{-1})
→ Much more compared to full Run 2 (0.03 pb^{-1})
- Better separation between prompt & non-prompt sources

Poster by F. Eisenhut
https://indi.to/RWGTY

NEW



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  → Fully unfold spectrum as a function of DCA

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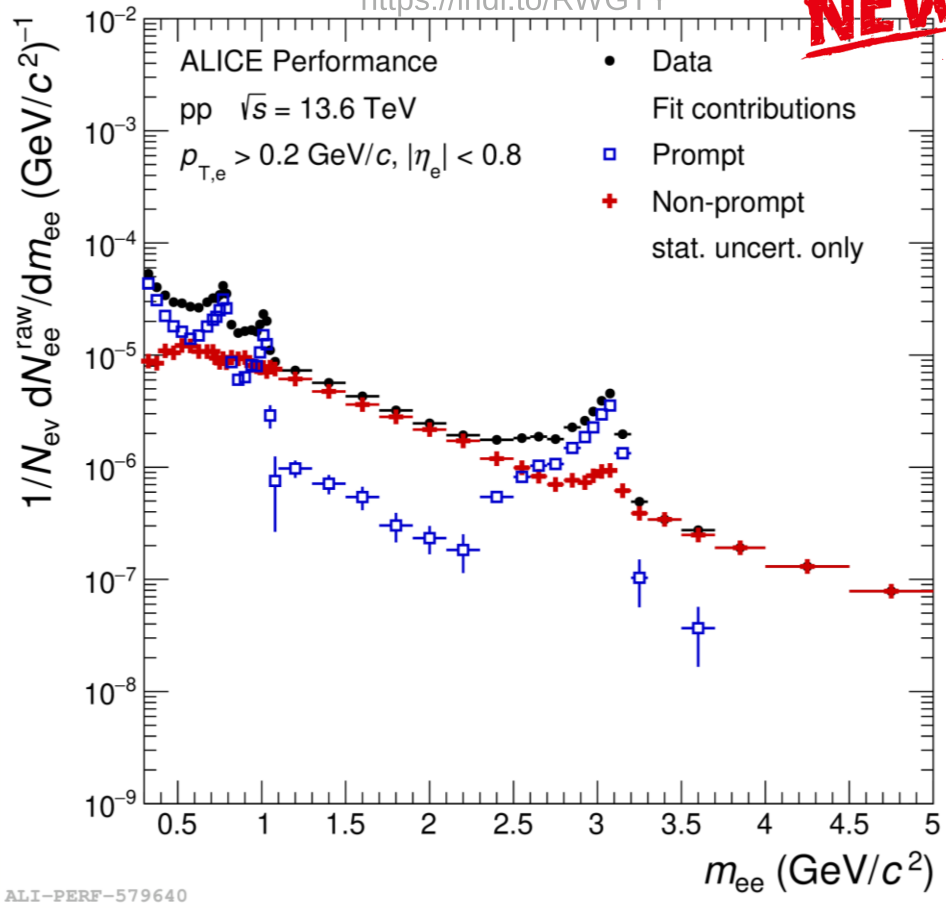

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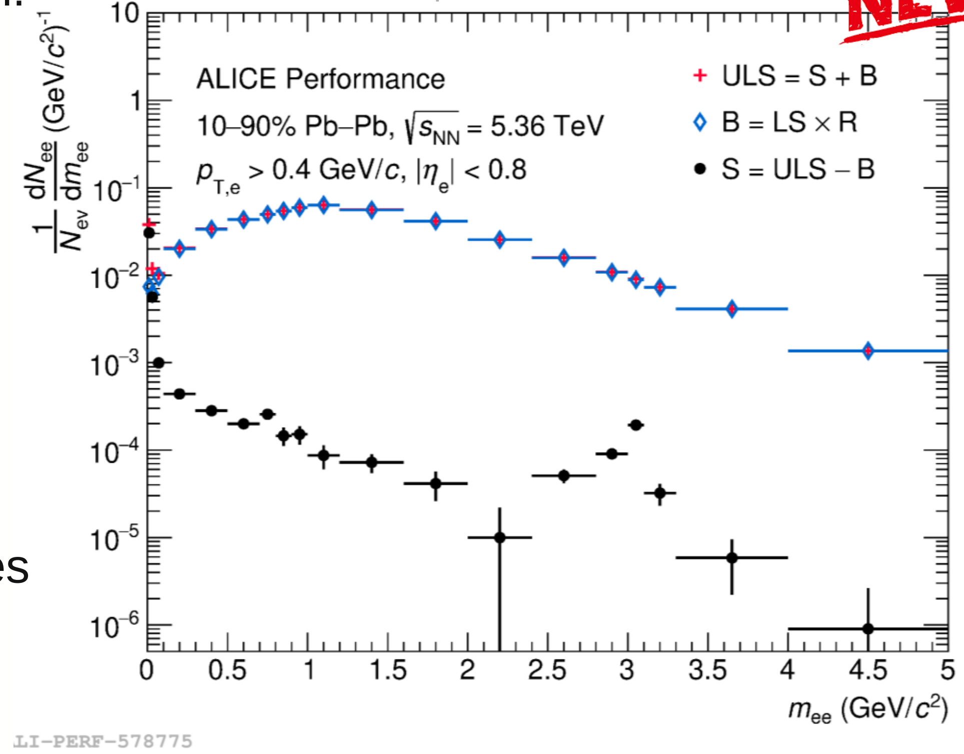
- First look at performance (0.97 pb^{-1})
→ Much more compared to full Run 2 (0.03 pb^{-1})
- Better separation between prompt & non-prompt sources
→ Fully unfold spectrum as a function of DCA

Pb–Pb collisions: 13 nb^{-1} at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV planned

1.5 nb^{-1} taken during the heavy-ion campaign of 2023
→ First look at the performance of the dielectron signal extraction

Poster by E. Ege
https://indi.to/Nk8Wx

NEW



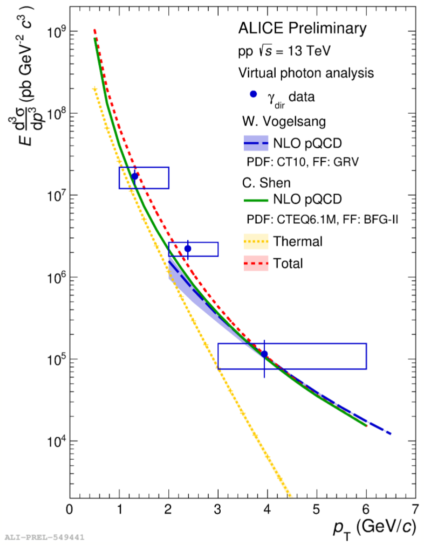
Summary

Dielectrons analysis from Run 2 are being finalized

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

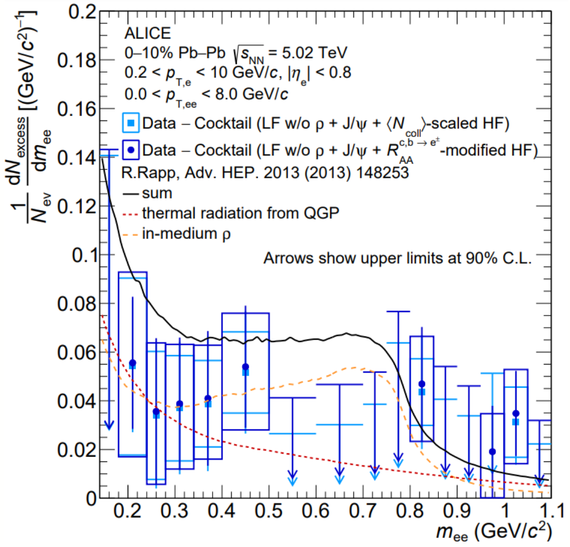


Measurement of dielectron production in central Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

→ First measurement of direct-photon yield

→ Limits for thermal radiation

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

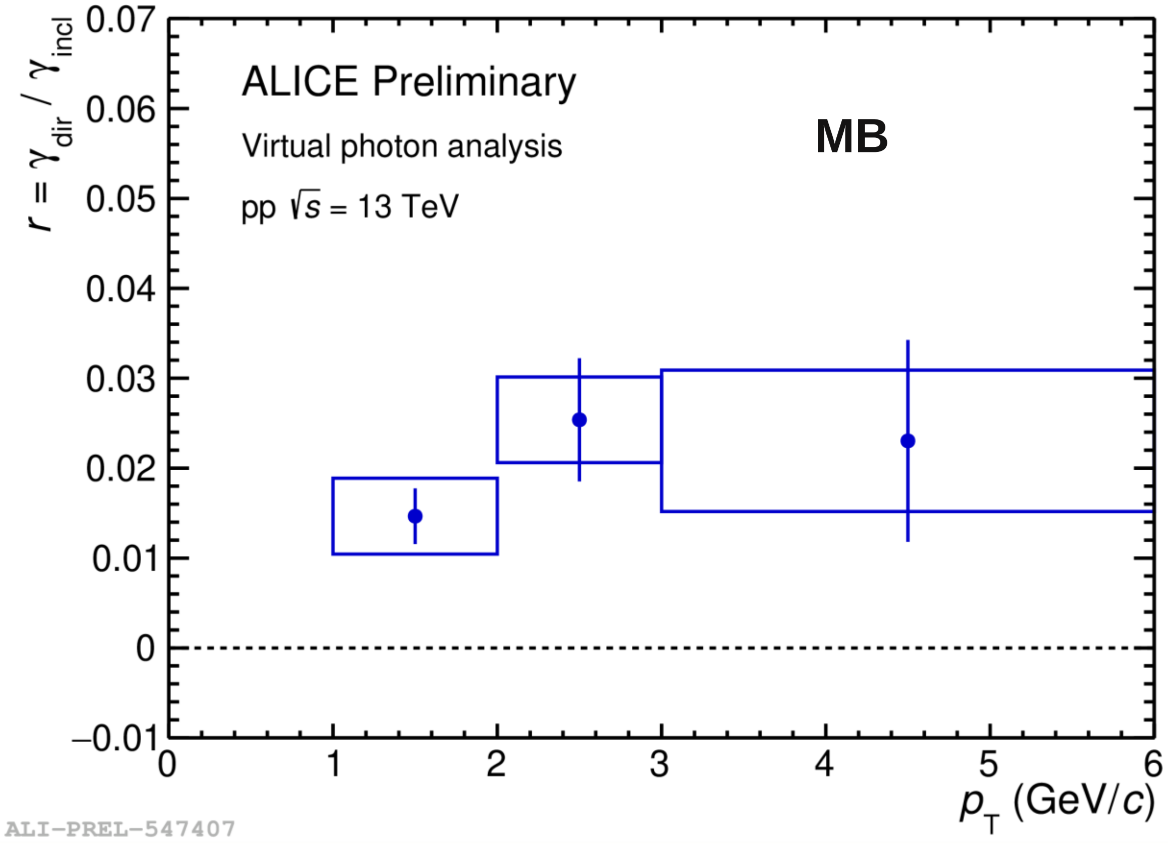


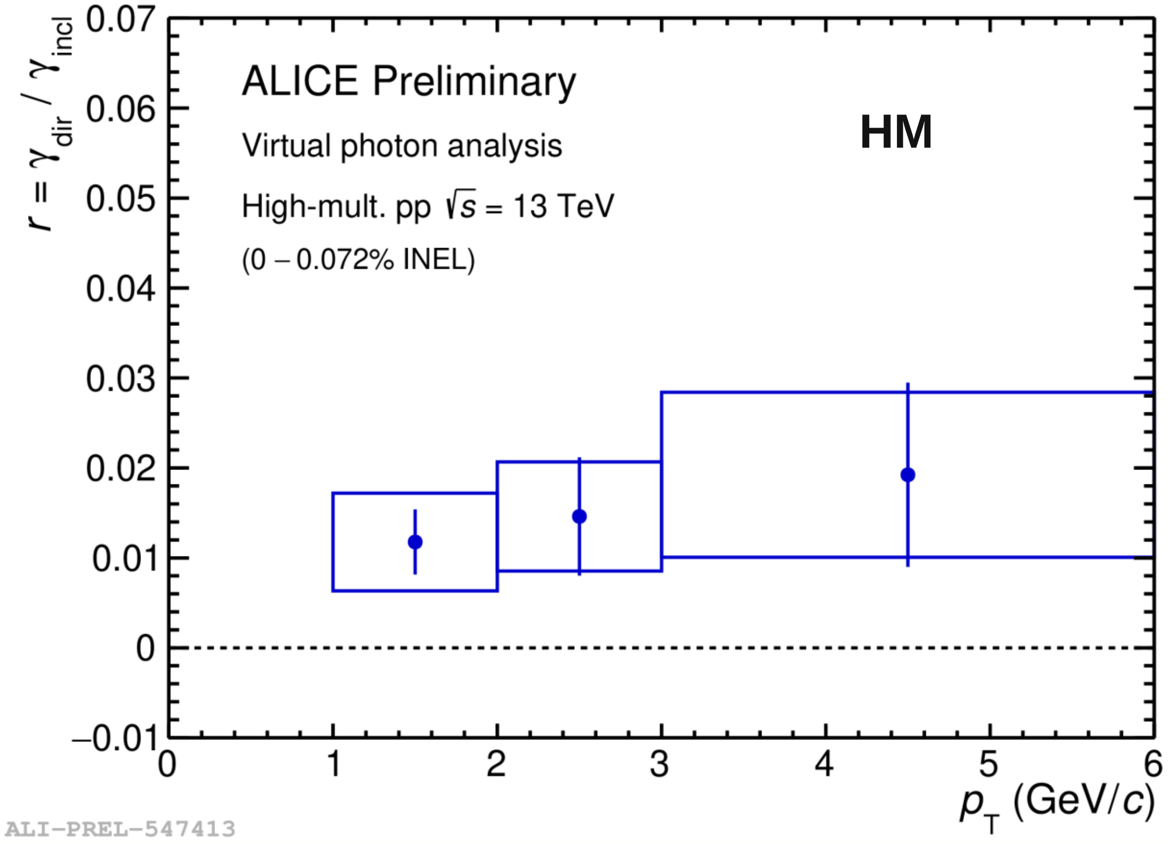
Data taken in Run 3/4 will significantly increase the precision of these results

Backup

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

Comparison to published results





Significant reduction of statistical and systematic uncertainties in new analysis

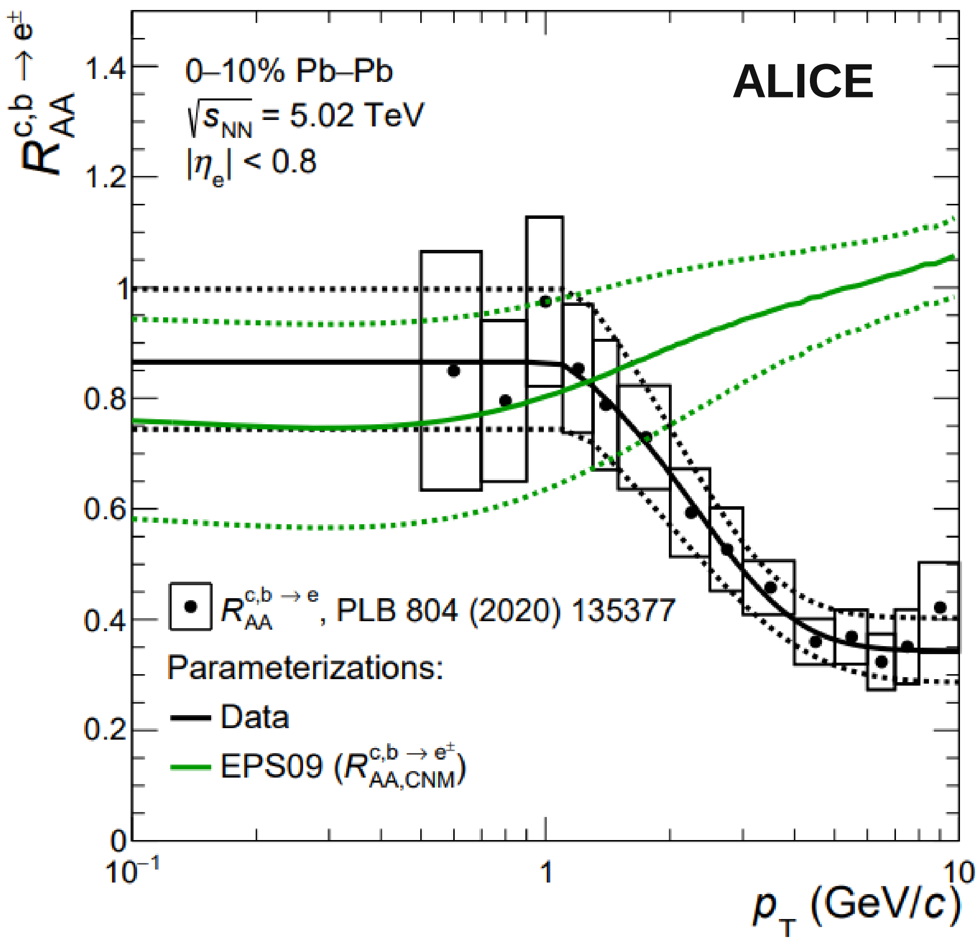
→ Notable contribution of direct-photons in MB & HM collisions

→ Measurement in HM compatible with MB results

Hadronic-cocktail improvements

Modeling of HF suppression

Ratio of HF electrons in Pb−Pb/pp



Dielectron spectrum dominated
by 1-2 GeV/c region

Modify cocktail: Measured $R_{AA}^{c,b\to e^{\pm}}$ as p_T-dependent weights

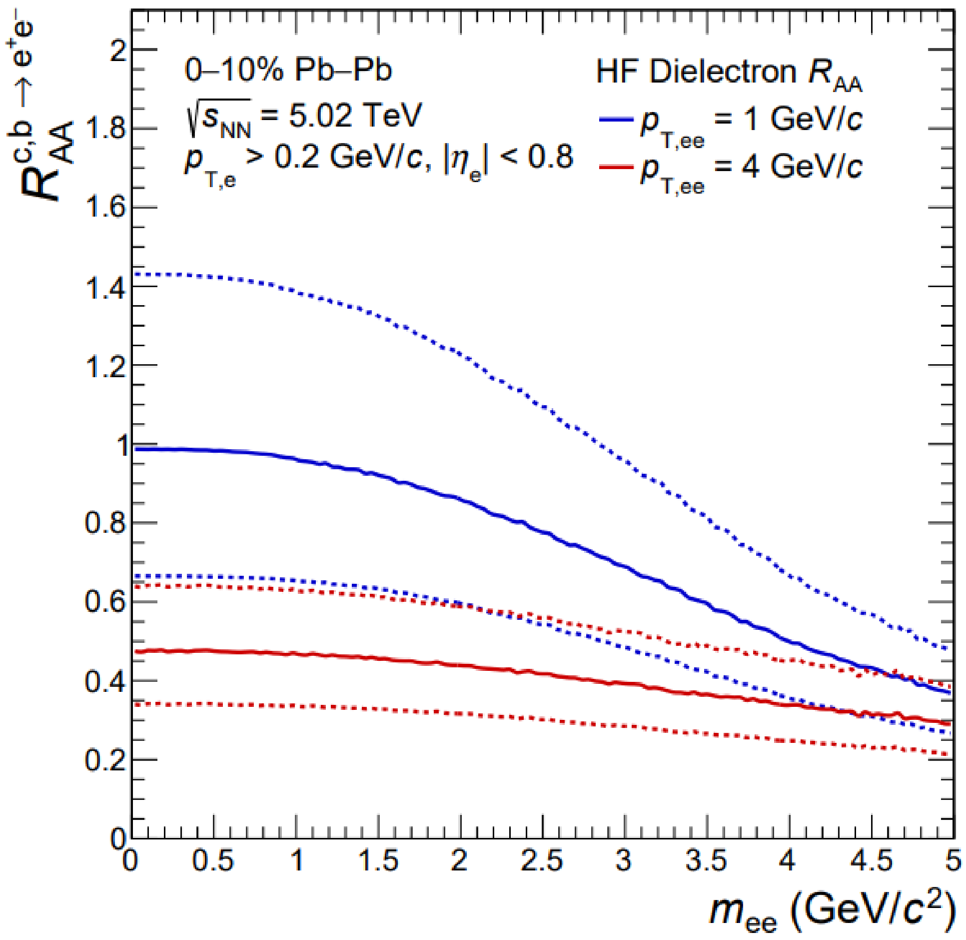
Contains both CNM & HNM effects
→ However: Affects dielectrons differently
CNM: whole pair
HNM: each electron independently

Disentangle CNM effects using EPS09

Hadronic-cocktail improvements

Modeling of HF suppression

Effective cocktail modification



Modify cocktail: Measured $R_{AA}^{c,b\to e^{\pm}}$ as p_T-dependent weights

Contains both CNM & HNM effects
→ However: Affects dielectrons differently
CNM: whole pair
HNM: each electron independently

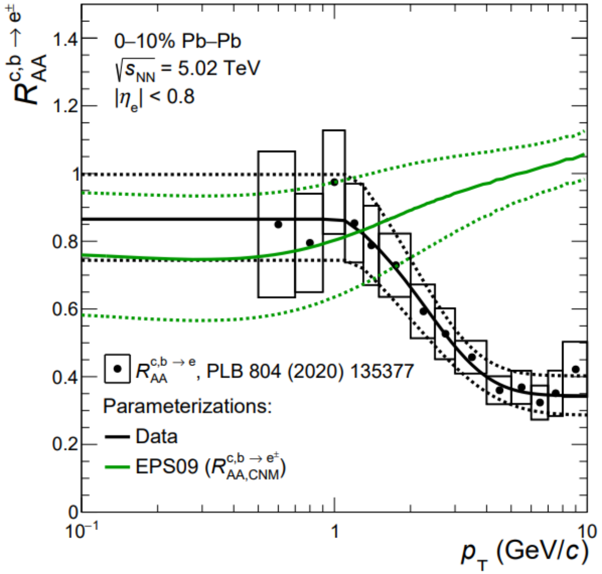
Disentangle CNM effects using EPS09

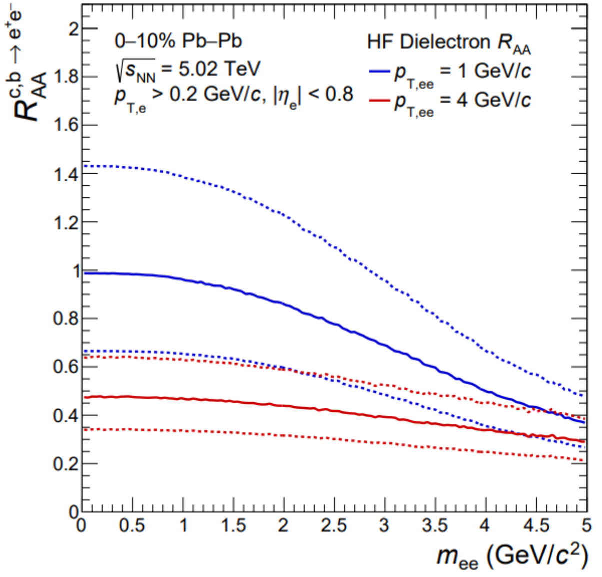
Final modification factor $R_{AA}^{c,b\to ee}$ combining CNM & HNM weights
→ More suppression of pairs at higher m_{ee} & $p_{T,ee}$

However: Large uncertainties from HFe R_{AA} & EPS09 inputs
Same suppression for charm & beauty hadrons

Hadronic-cocktail improvements

Modeling of HF suppression





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

Disentangle CNM effects using EPS09: $R_{\mathrm{AA}}^{\mathrm{c,b}\rightarrow\mathrm{e}^{\pm}} = R_{\mathrm{AA,CNM}}^{\mathrm{c,b}\rightarrow\mathrm{e}^{\pm}} \times R_{\mathrm{AA,HNM}}^{\mathrm{c,b}\rightarrow\mathrm{e}^{\pm}}$

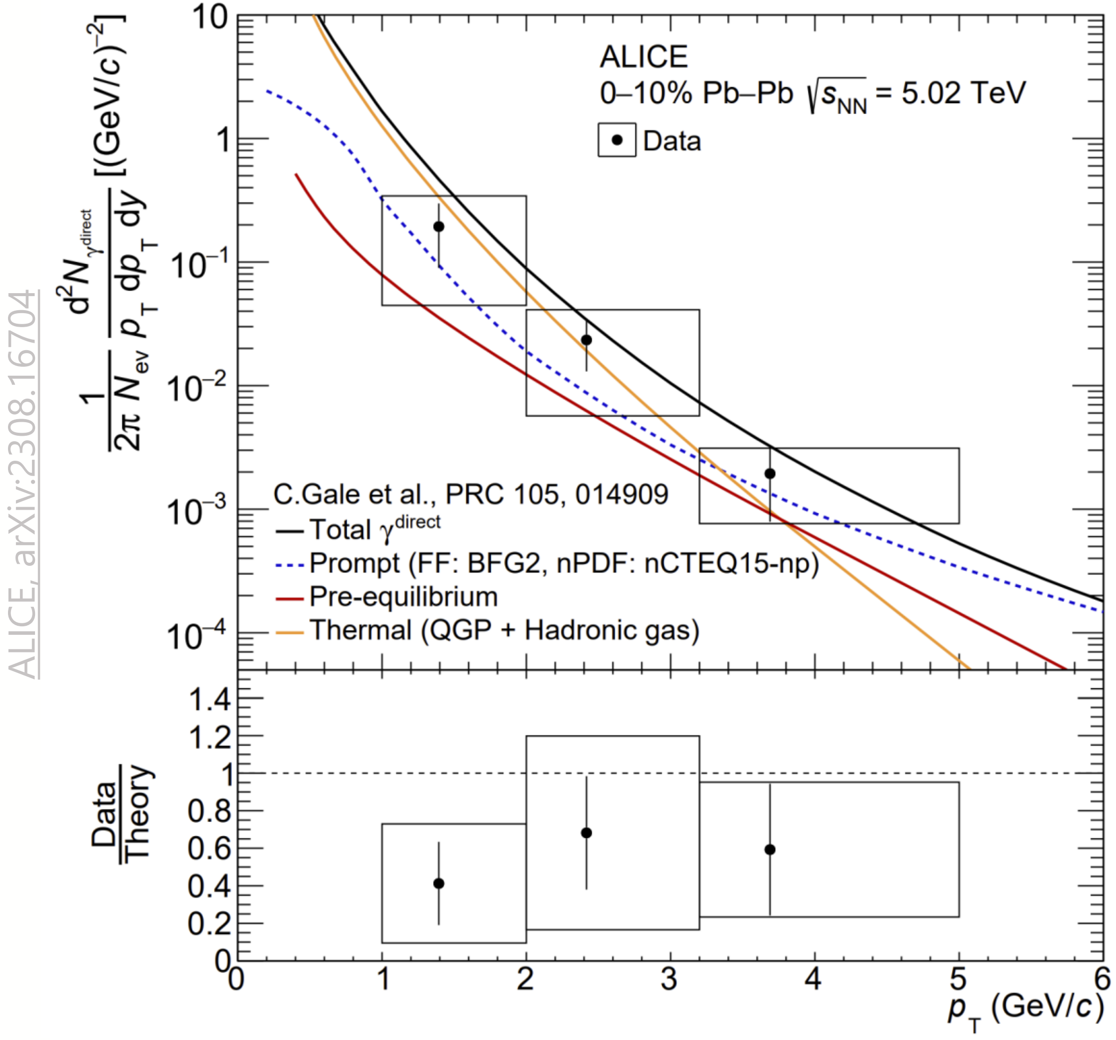
CNM effects & energy-loss affect pair production differently

CNM: $R_{\mathrm{AA,CNM}}^{\mathrm{c,b}\rightarrow ee}$	Energy loss/HNM: $R_{\mathrm{AA,HNM}}^{\mathrm{c,b}\rightarrow ee}$
Affects whole pair	Affects each electron independently
$\frac{R_{\mathrm{AA,CNM}}^{\mathrm{c,b}\rightarrow\mathrm{e}^{\pm}}(p_T^{e^+}) + R_{\mathrm{AA,CNM}}^{\mathrm{c,b}\rightarrow\mathrm{e}^{\pm}}(p_T^{e^-})}{2}$	$R_{\mathrm{AA,HNM}}^{\mathrm{c,b}\rightarrow\mathrm{e}^{\pm}}(p_T^{e^+}) \times R_{\mathrm{AA,HNM}}^{\mathrm{c,b}\rightarrow\mathrm{e}^{\pm}}(p_T^{e^-})$

→ Total weight $R_{\mathrm{AA}}^{\mathrm{c,b}\rightarrow ee}(m_{ee}, p_{\mathrm{T,ee}}) = R_{\mathrm{AA,CNM}}^{\mathrm{c,b}\rightarrow ee} \times R_{\mathrm{AA,HNM}}^{\mathrm{c,b}\rightarrow ee}$

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

p_{T}-differential spectrum



First direct-photon p_{T}-differential spectrum at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Hybrid model: Contributions from all stages of the collision

- Prompt photons from NLO pQCD calculations
- Pre-equilibrium contributions
- Thermal (QGP & hadronic gas)

$N_{\gamma^{\mathrm{dir}}}$ consistent with only prompt photons

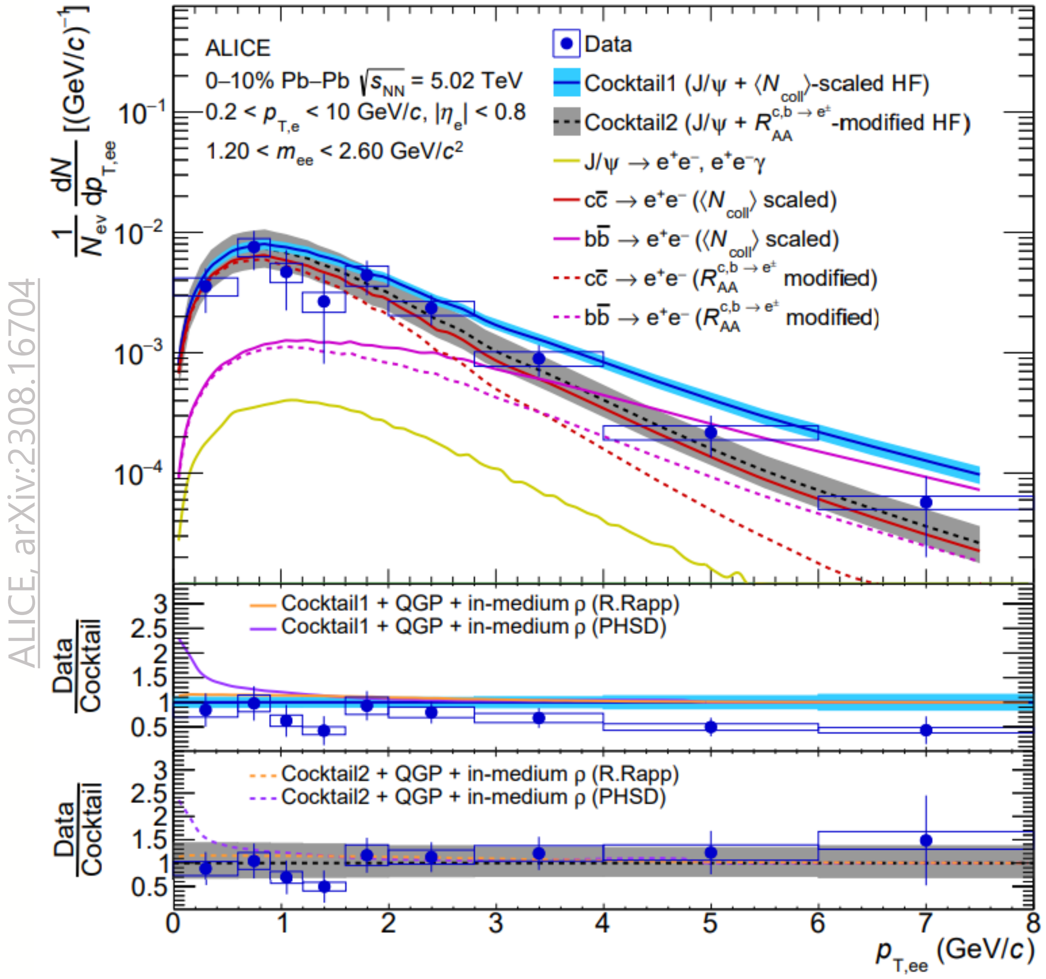
However: All central values above pQCD baseline

Measurement also described by full model prediction

But: Data overestimated by ~1σ

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

Pair-momentum spectrum



Comparison to hadronic cocktail, including:

- N_{coll}-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  → Vacuum baseline
- Include measured R_{AA} of $c/b \rightarrow e^{\pm}$
  → Modified-HF cocktail

Studying the HF as a function of pair momentum:

- Increasing suppression at high $p_{\mathrm{T,ee}}$ compared to pp
- Modified-HF cocktail improves the data description

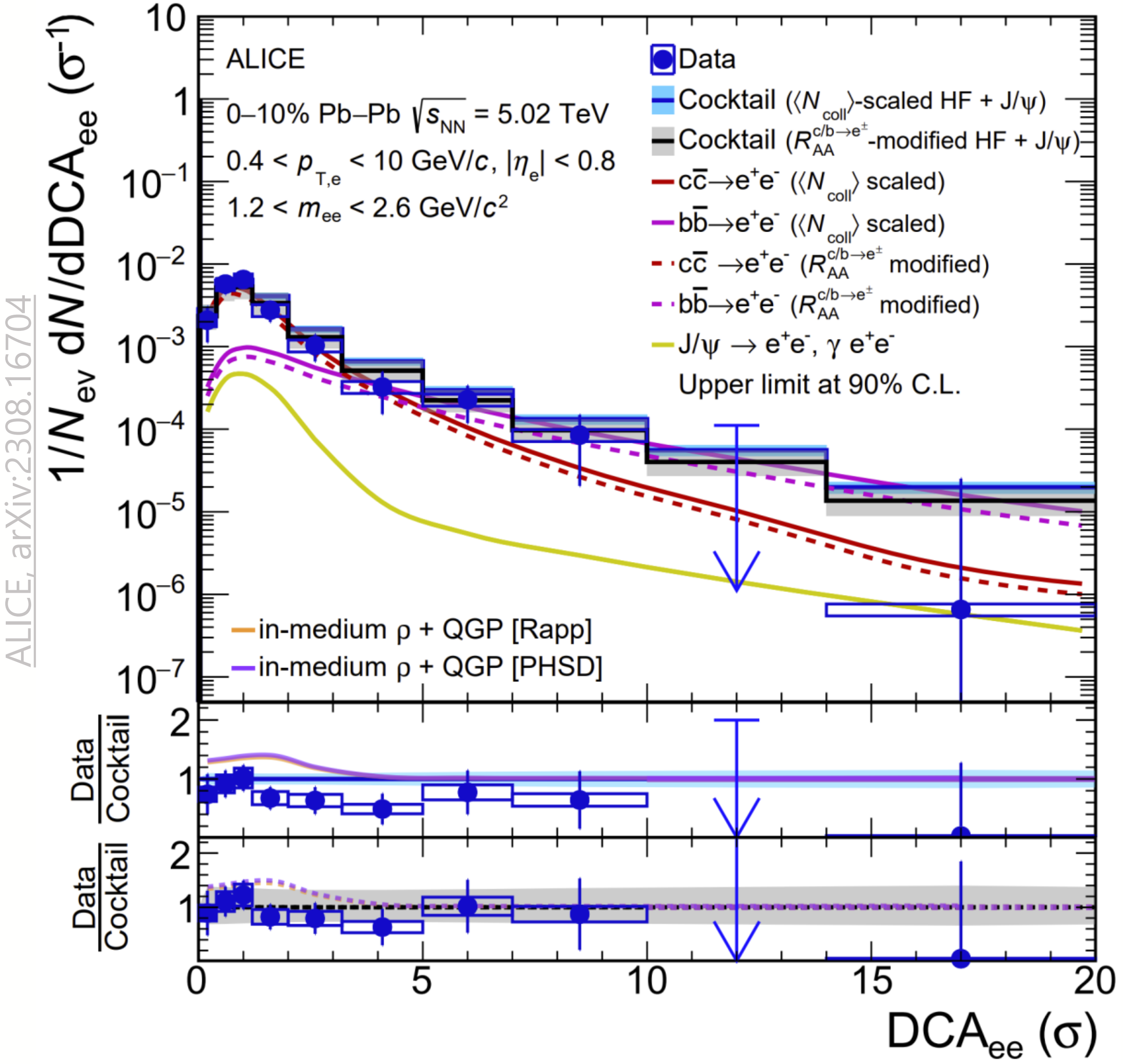
Caveats: Cocktail modification introduces additional uncertainties

- Large uncertainties limit the interpretation of the data
- Applies same modification to charm and beauty

→ Cocktail independent method needed to access QGP

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

Topological separation – $\mathrm{DCA_{ee}}$ in IMR scaled



Comparison to cocktail-scaled templates in the IMR:

- N_{coll}-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  → Vacuum baseline
- Include measured R_{AA} of $c/b \rightarrow e^{\pm}$
  → Modified-HF cocktail

Again, the data favors a reduced contribution of HF
→ Hint for a larger suppression of charm

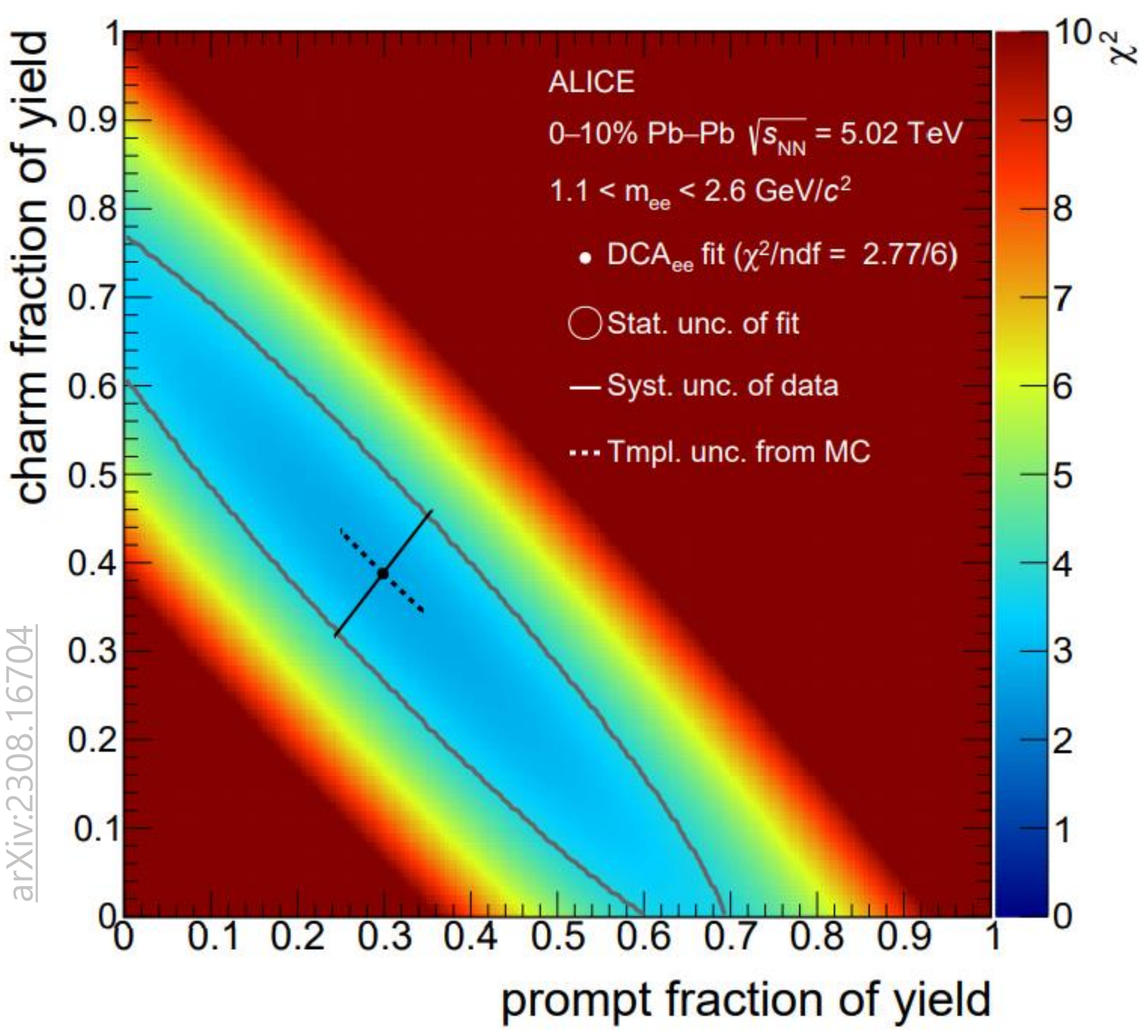
Comparison to expectation from theory by normalizing the prompt template to their respective integral

→ Expected thermal signal in the order of 10-40%

→ Consistent within current uncertainties

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

Topological separation – $\mathrm{DCA_{ee}}$ in IMR fitted



Extraction of prompt thermal signal via template fits:

- Beauty contribution fixed via separate fit at high $p_{T,ee}$
  $\mathrm{b\bar{b}}$: 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)

Outlook

Dielectron production in Run 3 and 4

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

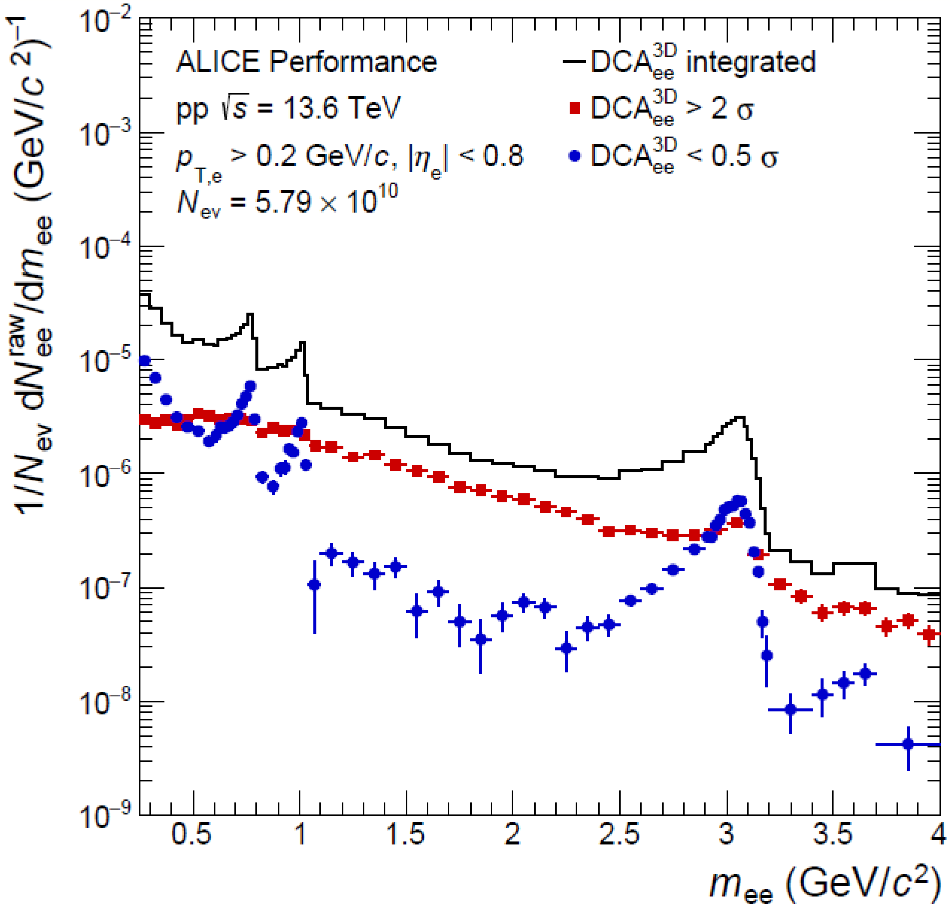
- Increased readout rate of 1000 in pp and 100 Pb–Pb
- Improved vertex pointing resolution by a factor larger than 3

Large data set of pp collisions recorded in 2022/23:

- First look at performance (0.97 pb^{-1})
  → Much more compared to full Run 2 (0.03 pb^{-1})

- Better separation between prompt & non-prompt sources

Expected: 200 pb^{-1} in pp at $\sqrt{s} = 13.6$ TeV
13 nb^{-1} in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV

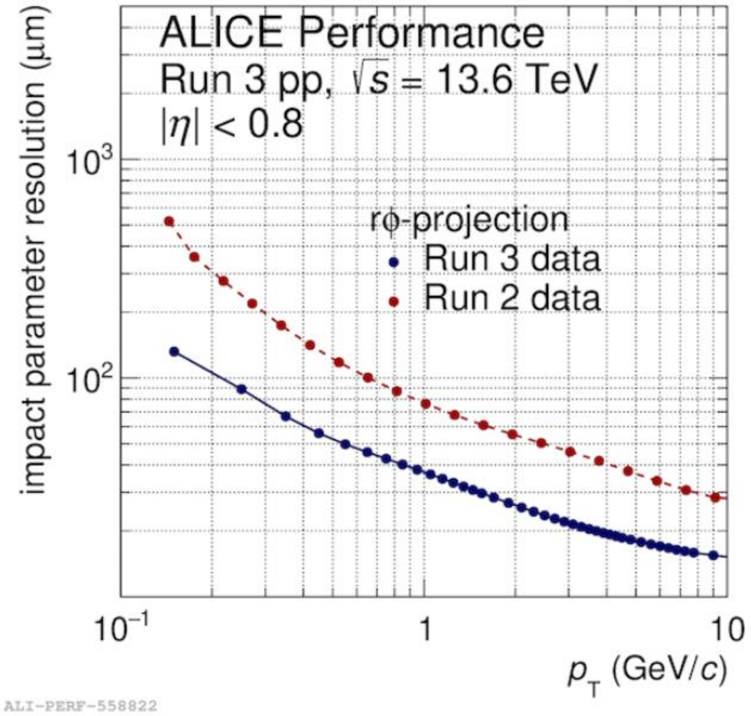


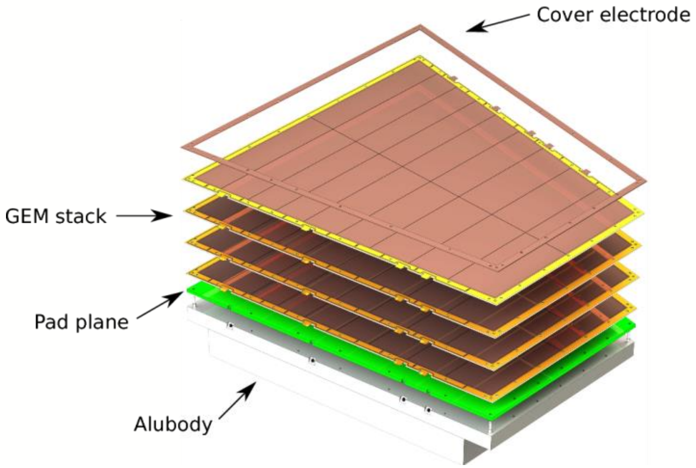
Outlook

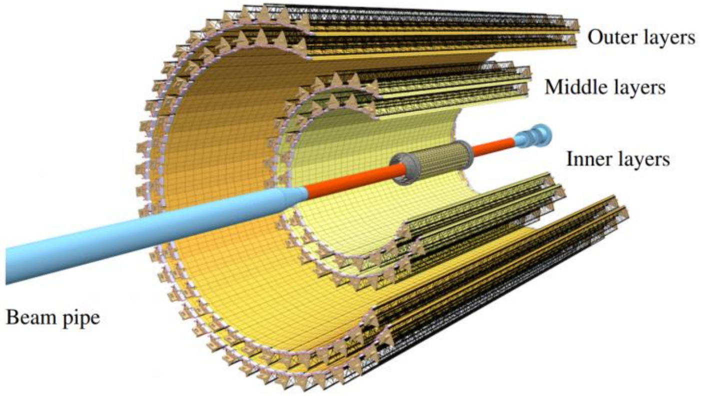
Dielectron production in Run 3 and 4

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

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







arXiv:2111.08301v3