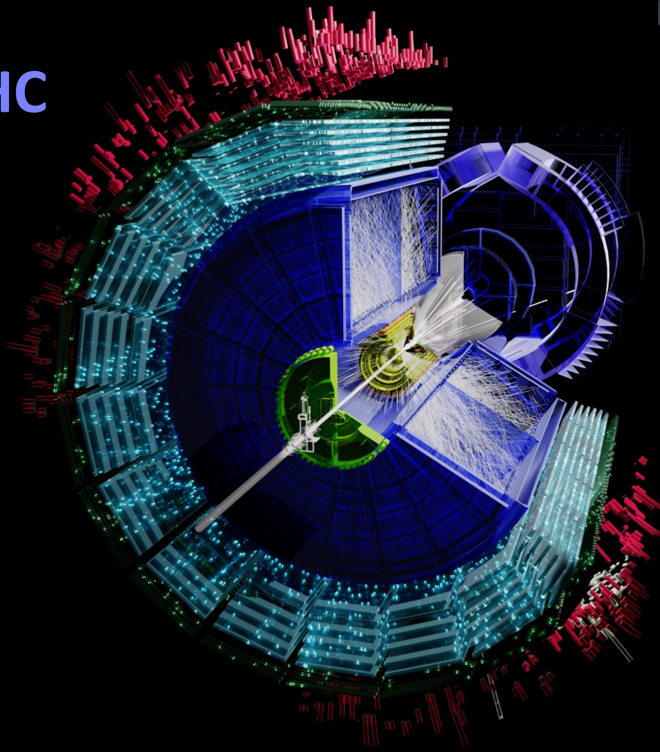
Dielectrons at the LHC
chances and challenges



Harald Appelshäuser

Goethe Universität Frankfurt

for the ALICE Collaboration

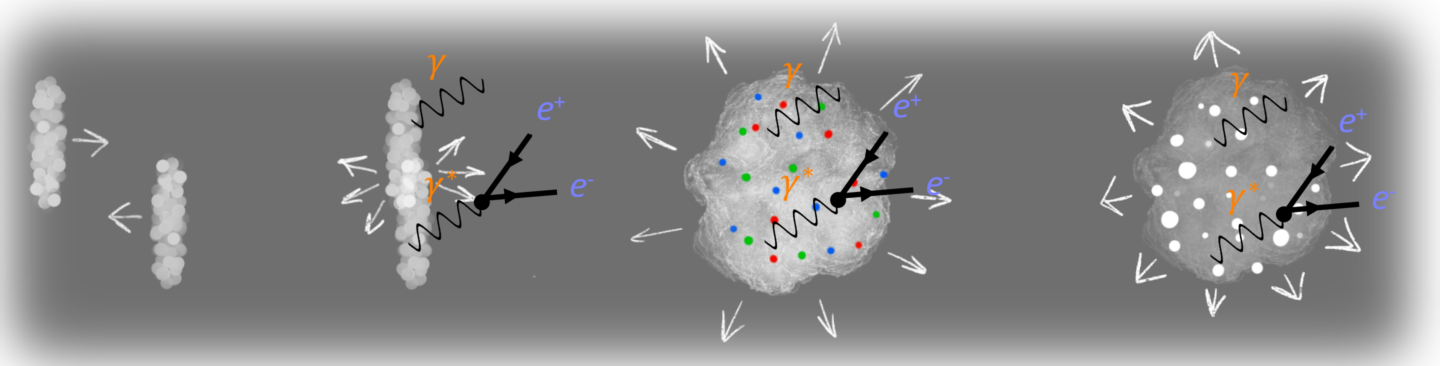
WPCF 2023 - XVI Workshop on Particle Correlations and Femtoscopy
& IV Resonance Workshop 2023
November 6-10, 2023, Catania, Italy

Outline

- EM probes are unique
- dielectrons are particularly unique
- the boon and bane of dielectrons at the LHC
- dielectron results in pp, p-Pb, Pb-Pb from ALICE
- let there be light: ALICE 2 and ALICE 3

Photons and dileptons

- are produced **at all stages** of the collison
- leave the system **without strong FSI**
  - ➢ messengers of **QGP bulk properties and in-medium properties of hadrons**



hard scattering, pre-equilibrium	**thermal QGP** $(T > T_c)$	**thermal hadronic** $(T < T_c)$ **hadronic decays** $\pi, \eta, \eta', \omega, \varrho, \phi, J/\psi\ c\bar{c}, b\bar{b}$

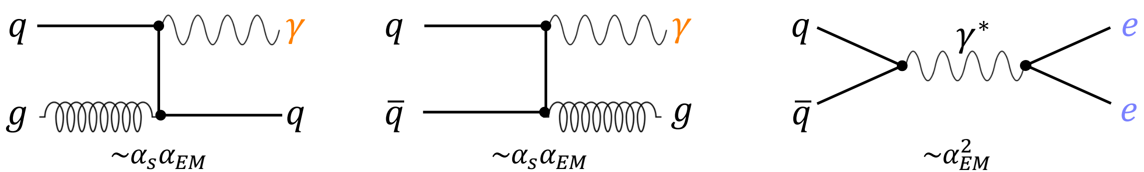
Photons *or* dileptons

Technical:

- Photon measurements are **limited by systematics:** large background from π^0 **and** η **decays**
- Dielectrons **suffer from statistics** (additional factor α_{EM}), systematics dominated by physical background from **hadron decays**

Physics:

- Photons integrate over space-time evolution, different collision stages **cannot be distinguished (cf. *direct photon puzzle*)**
- Dielectrons do as well but **carry *mass* which can serve as a clock**
- every process that produces a real photon can also produce a virtual photon
- the opposite is not true



Dileptons

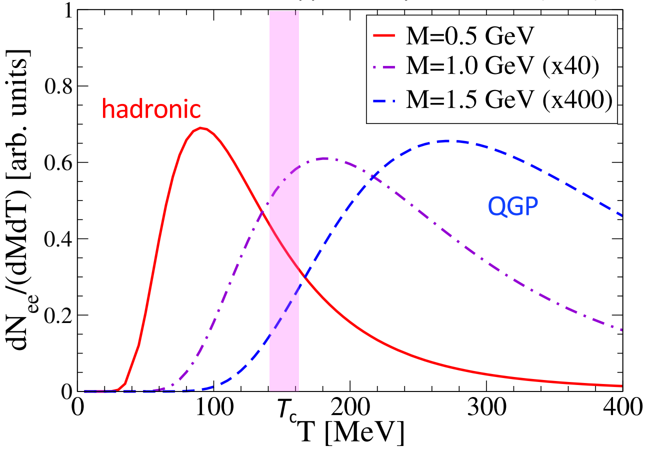
- dilepton yield: space-time integral over **thermal emission rate:**

$$\frac{dN_{ee}}{d^4x d^4q} = -\frac{\alpha^2}{\pi^3 m_{ee}^2} f^{BE}(q_0,T)\,\mathrm{Im}_{EM}(m_{ee},q,\mu_B,T)$$

- mass dependence allows **separation of collision stages**

- QGP radiation **dominates at $m_{ee} \gtrsim 1$ GeV**

R. Rapp Acta Phys.Polon. B42 (2011)



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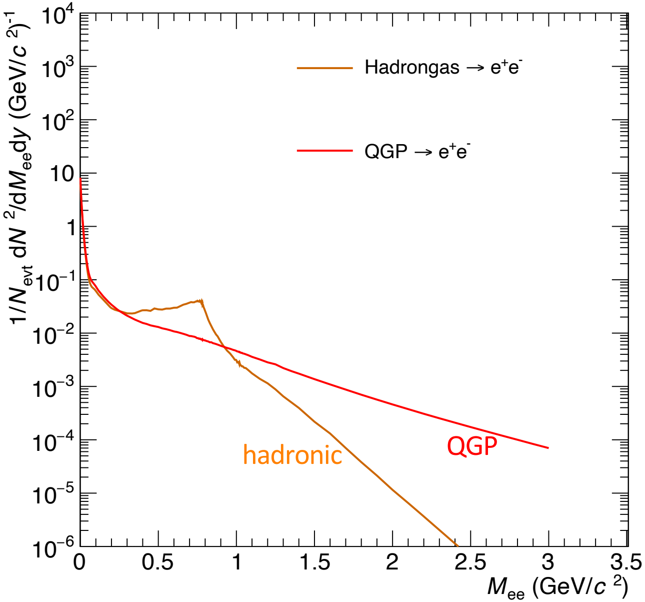
- mass dependence allows **separation of collision stages**

- QGP radiation **dominates at $m_{ee} \gtrsim 1$ GeV**

- structureless spectral function allows **most direct temperature determination from exponential in m_{ee},** no blue shift

R. Rapp and J. Wambach, *Eur. Phys. J. A* 6 (1999)



Dielectrons at the LHC

- Pb-Pb at the LHC produces the **largest, hottest and longest-lived QGP**

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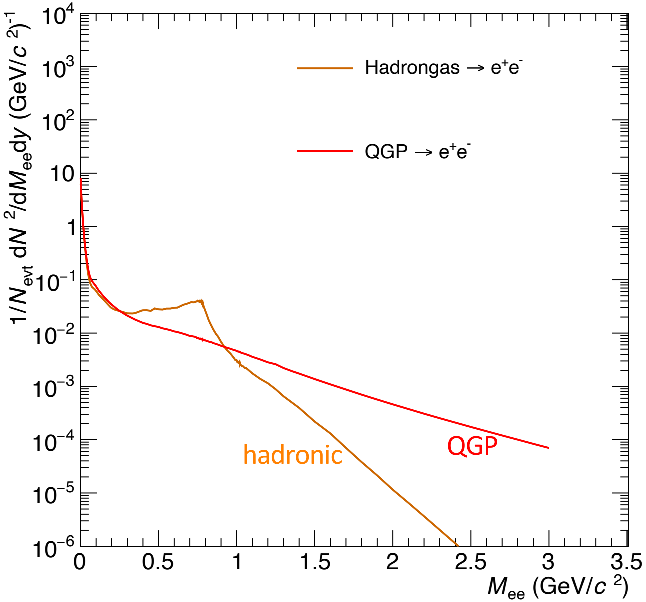
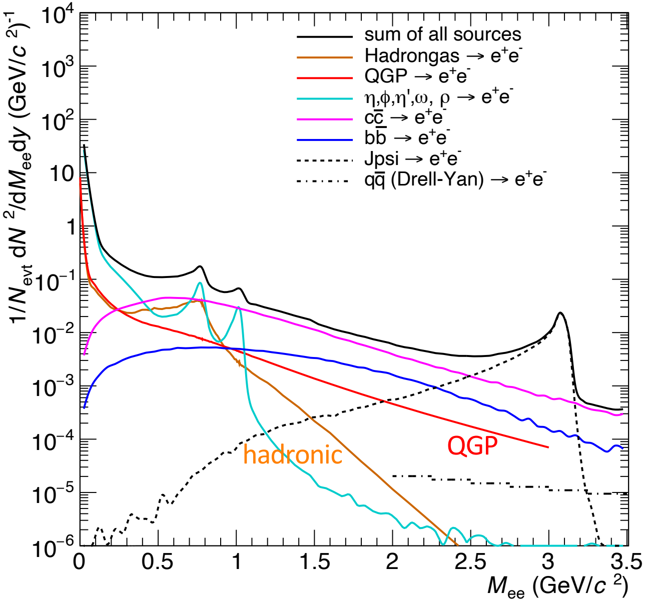


Dielectrons at the LHC

- Pb-Pb at the LHC produces the **largest, hottest and longest-lived QGP**
- Large combinatorial and **physical backgrounds**
- In the **Intermediate Mass Region (IMR)** (1—2.5 GeV/c²):
  - $S/B \leq 10\%$
  - heavy-flavor contribution must be known **within $\leq 1\%$**

R. Rapp and J. Wambach, *Eur. Phys. J. A* 6 (1999)



Heavy-flavour cross sections in pp

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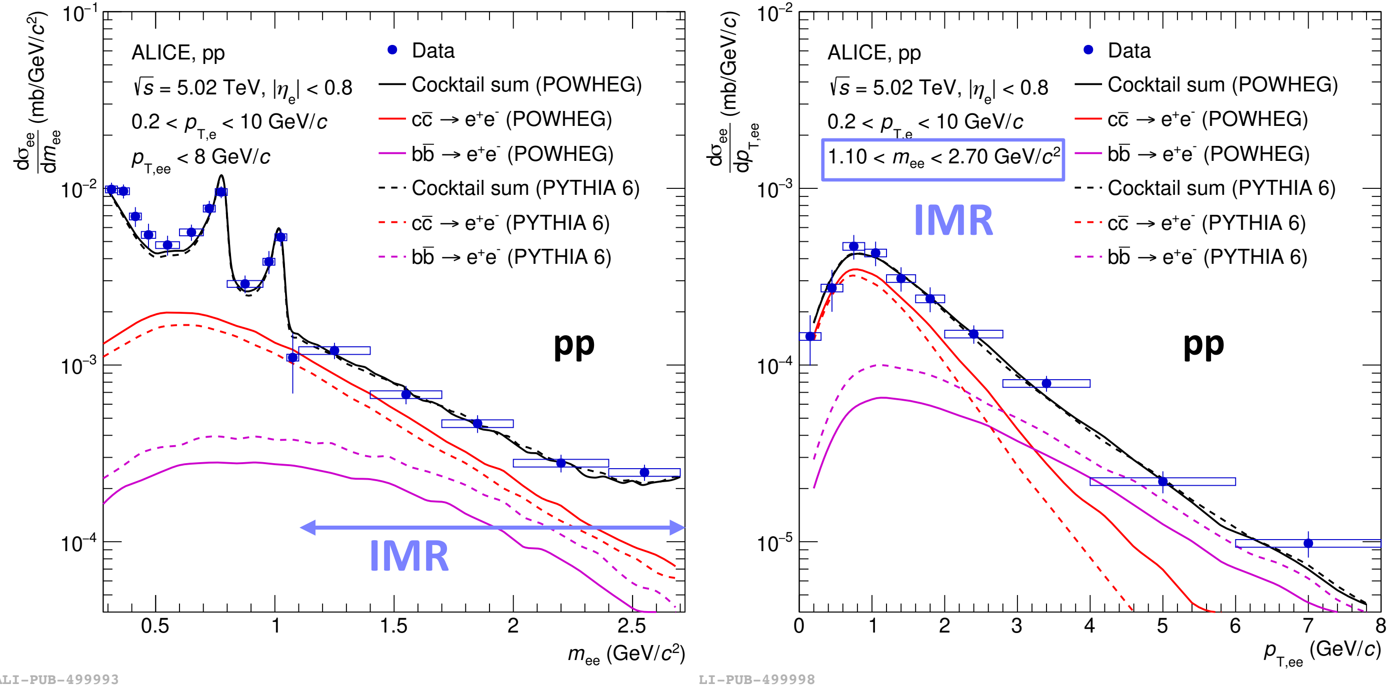
ALICE, Phys. Rev. C102 055204 (2020)



- Charm and beauty contribution can be determined from a **template fit to the IMR**

Heavy-flavour cross sections in pp

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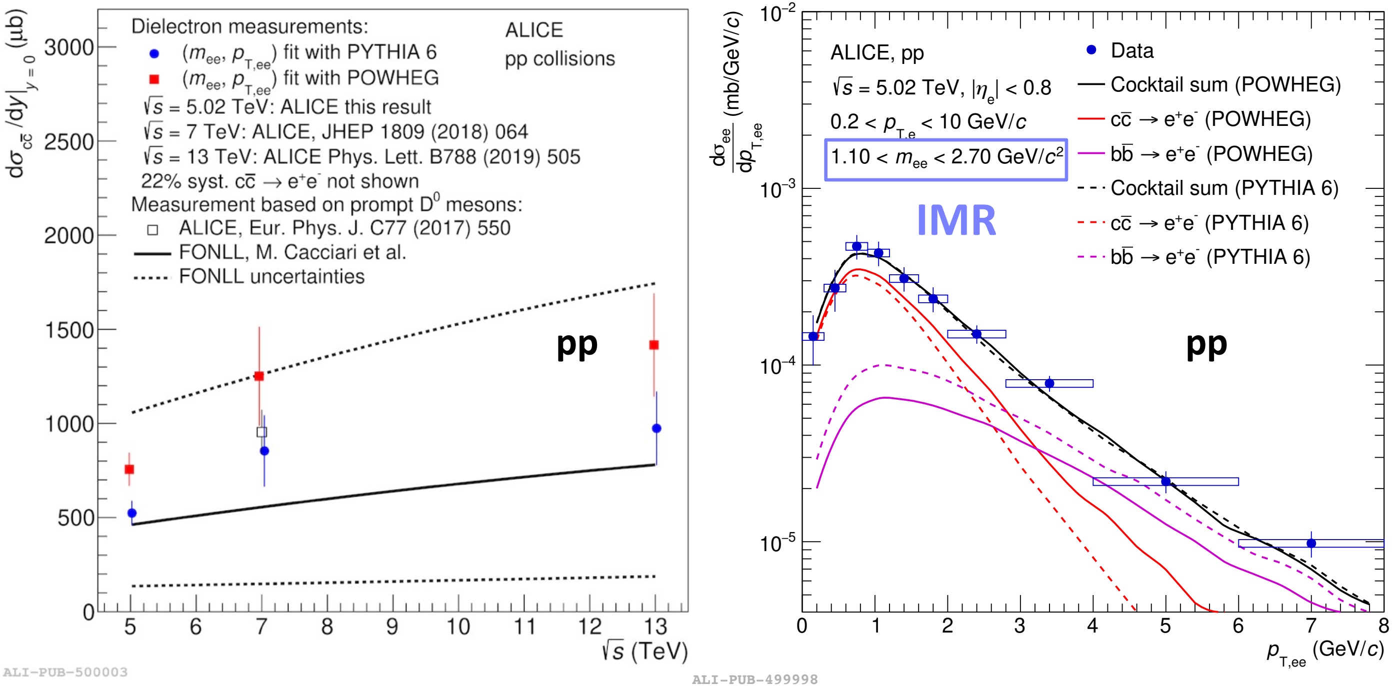

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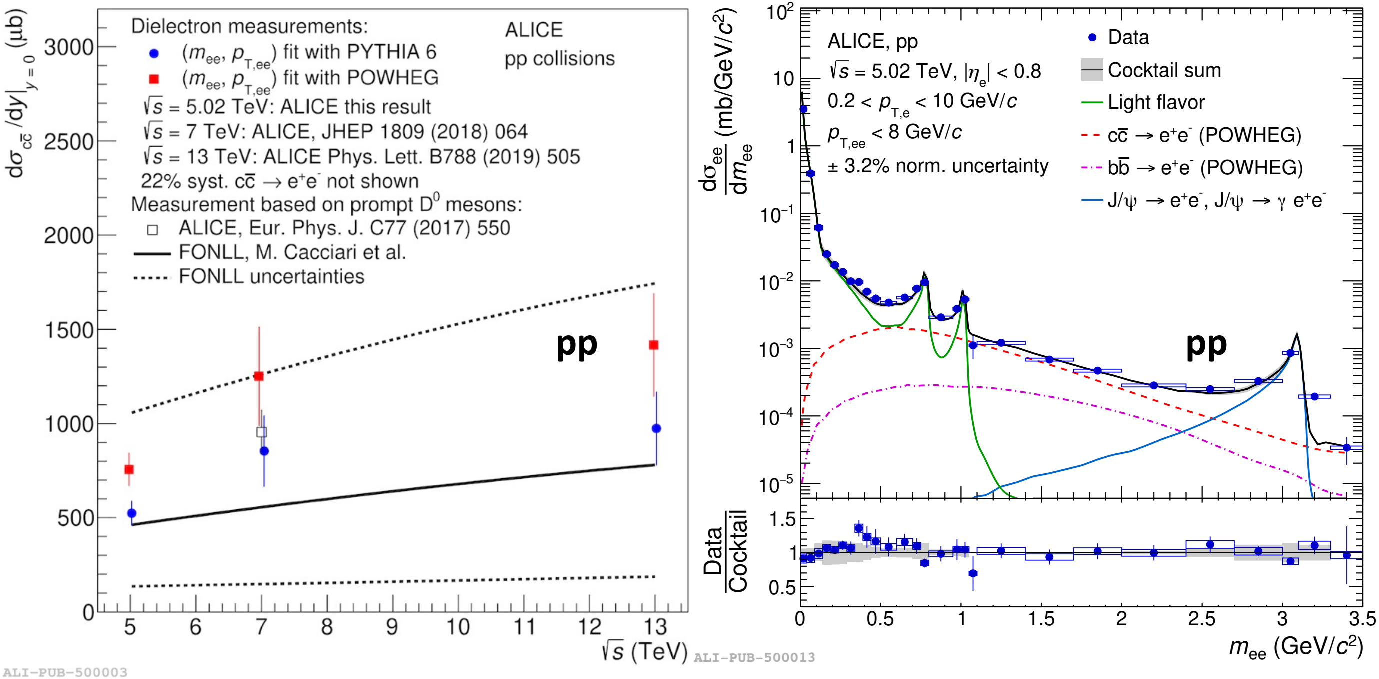
- Extraction of cross sections possible but **additional uncertainties introduced**

Dielectron production in pp

ALICE, Phys. Rev. C102 055204 (2020)

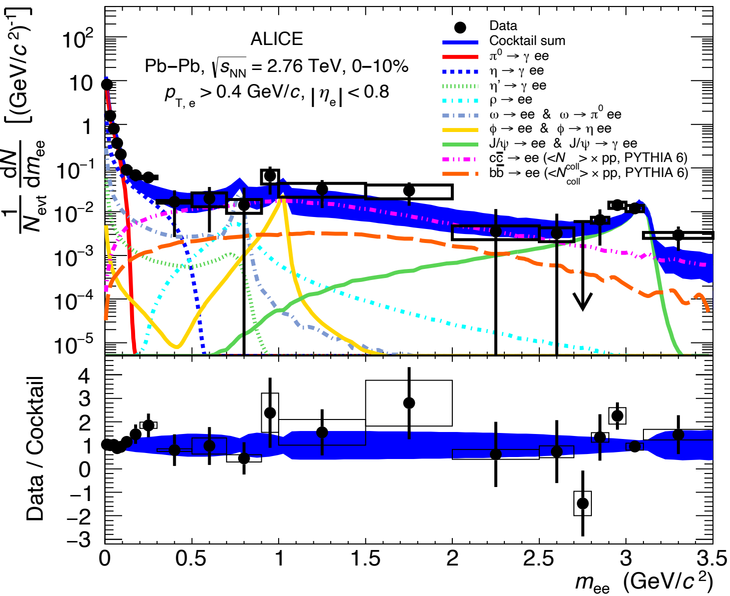


- Charm and beauty contribution can be determined from a **template fit to the IMR**
- Extraction of cross sections possible but **additional uncertainties introduced**
- HF fit provides **good description of pp dielectron results**

Dielectrons in Pb-Pb

Dielectrons in Pb-Pb

ALICE, PRC99, 024002 (2019)

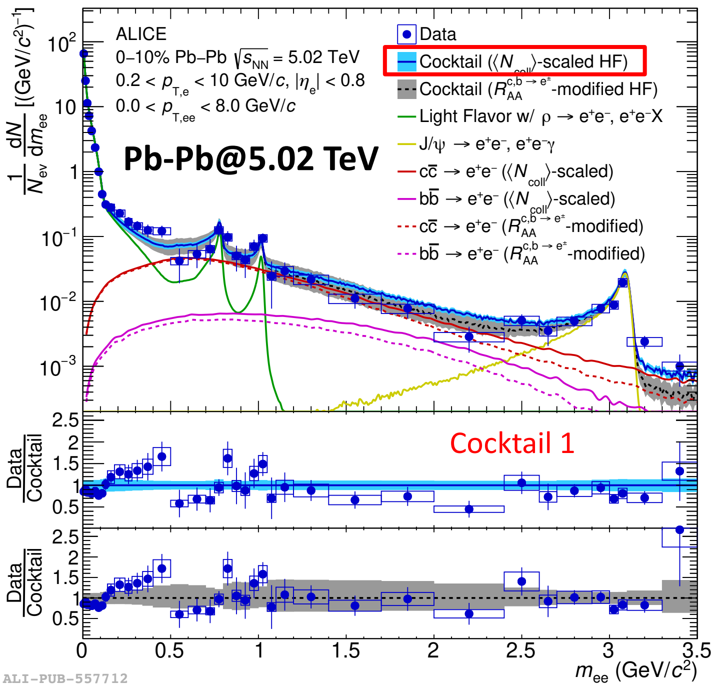


Pb-Pb results from Run 1:

- Large statistical and systematic uncertainties
- No conclusion about thermal radiation can be drawn

Dielectrons in Pb-Pb

ALICE, arXiv:2308.16704



Pb-Pb results from Run 2:

- **Cocktail 1:** N_{coll} - scaled HF measurement in pp
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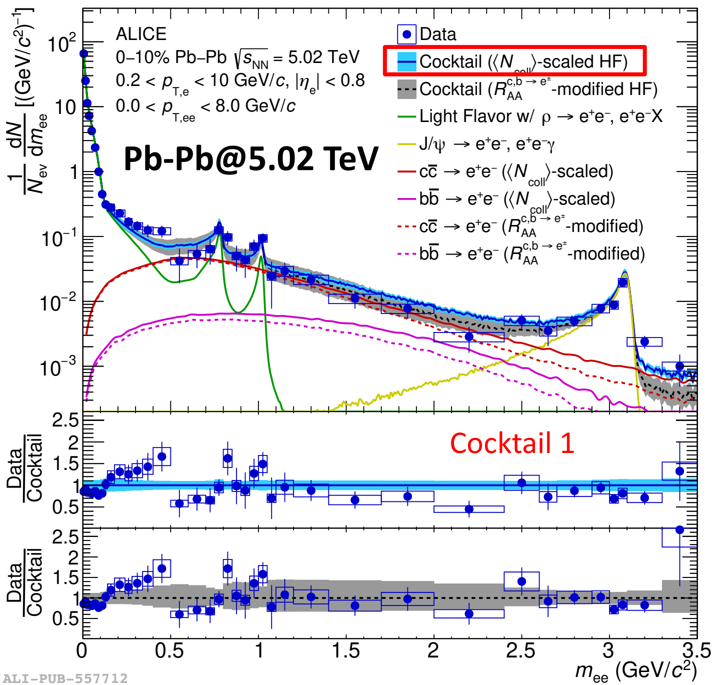

Pb-Pb results from Run 2:

- **Cocktail 1:** N_{coll} - scaled HF measurement in pp
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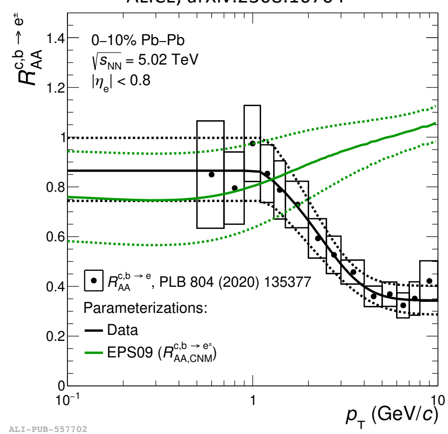
- But: **HF is modified** in the final state in Pb-Pb

ALICE, arXiv:2308.16704



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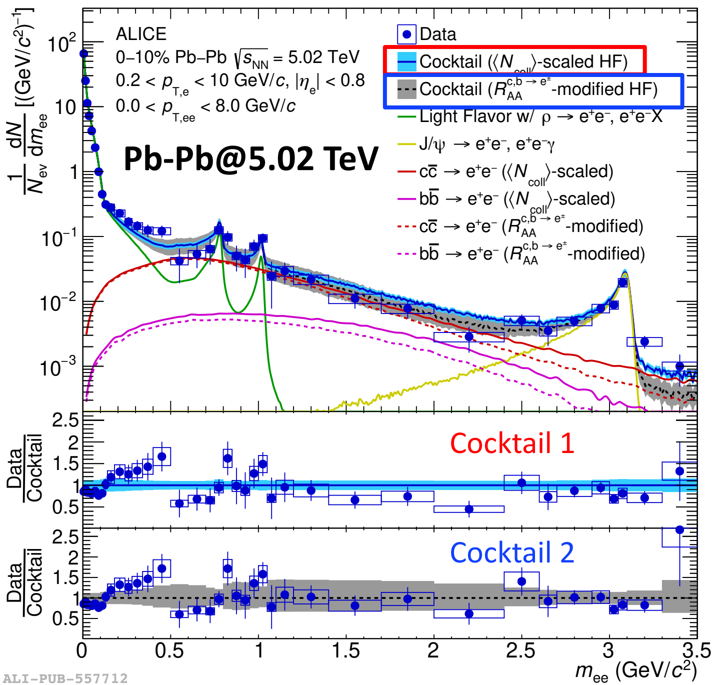

Pb-Pb results from Run 2:

- **Cocktail 1:** N_{coll} - scaled HF measurement in pp
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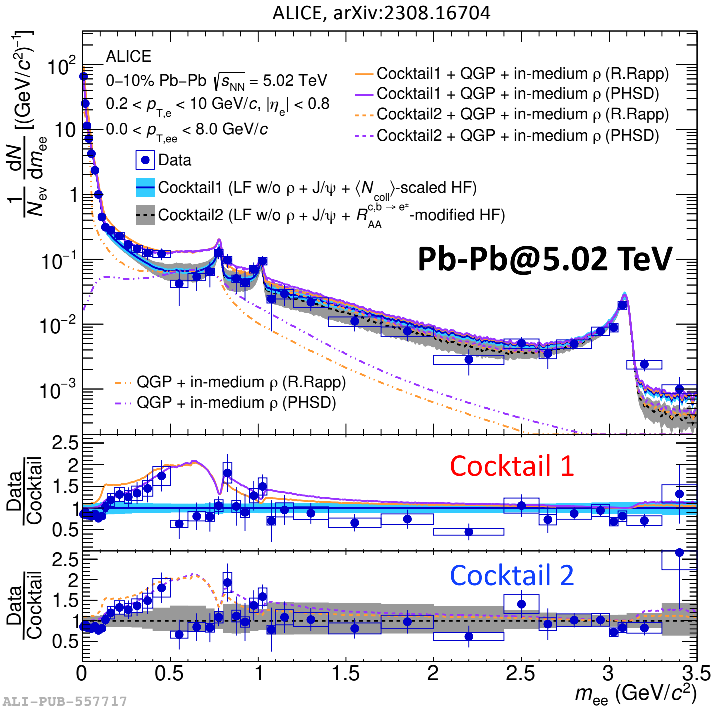
- **Cocktail 2:** based on EPS09 and HFE R_{AA}
  - Description improved, but **additional uncertainties introduced**

Dielectrons in Pb-Pb - models



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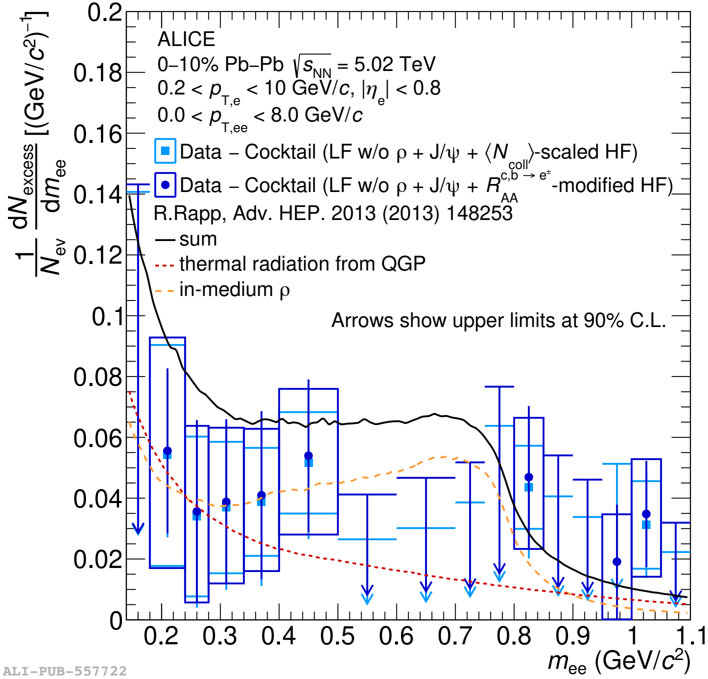
  - Comparison to models reveals **slight tension** in the ρ/ω region

Dielectron excess in Pb-Pb

ALICE, arXiv:2308.16704



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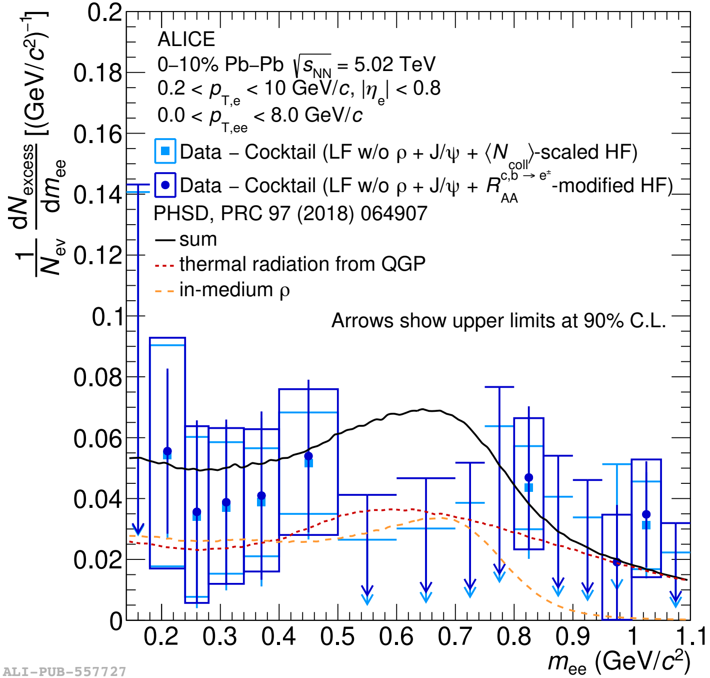

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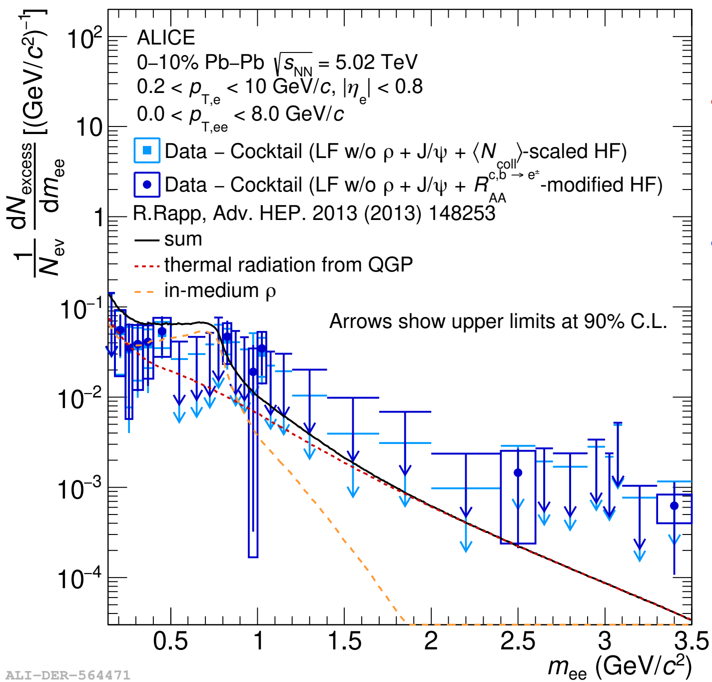

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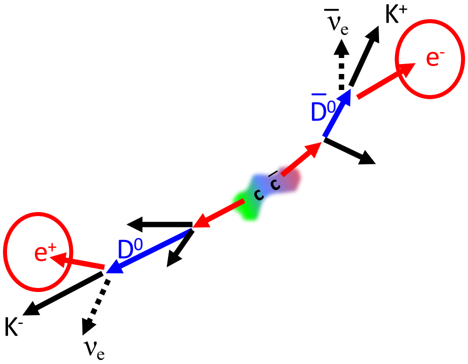
  - ➢ Possible QGP contribution in the IMR **not resolvable** within systematic (and statistical) uertainties
  - ➢ Comparison to models reveals **slight tension** in the ρ/ω region
  - ➢ Measurement of dielectron excess requires a **cocktail-independent approach!**

Topological separation of dielectron sources



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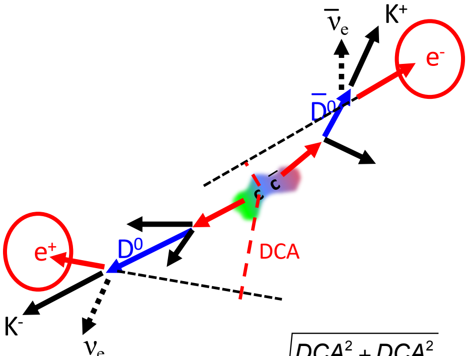

$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

- DCA_{ee} allows **separation of prompt from delayed dielectron sources**

Topological separation of dielectron sources

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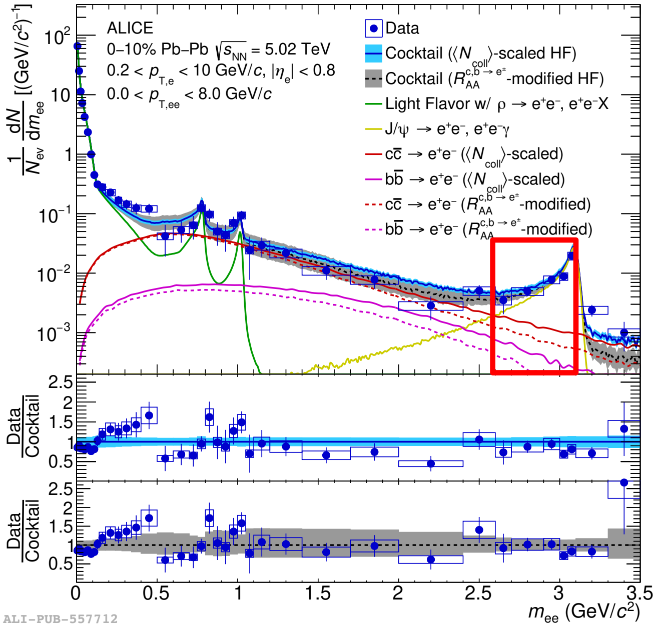

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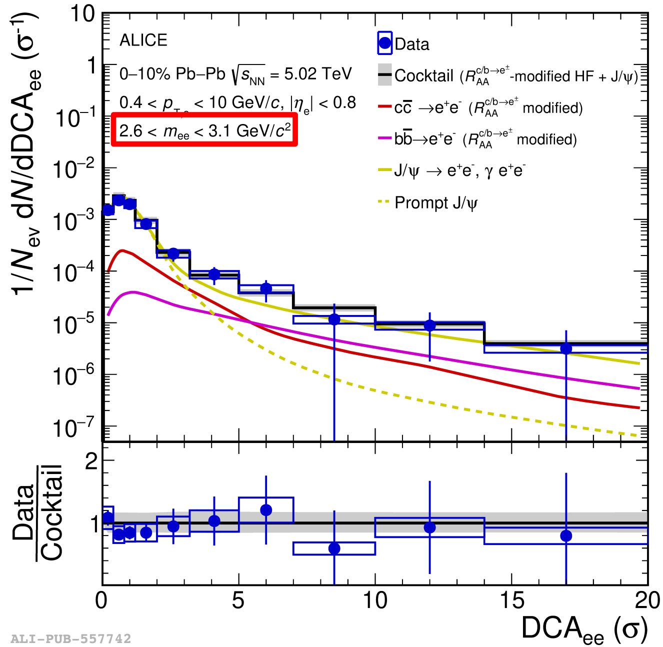
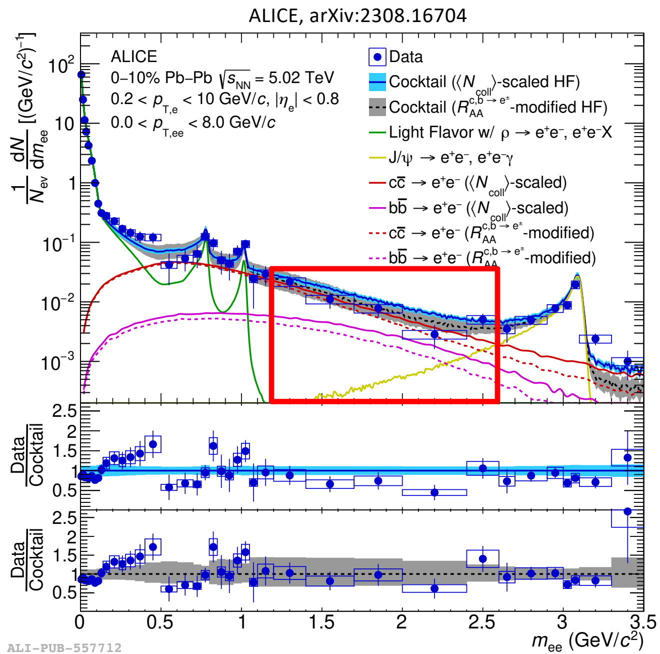
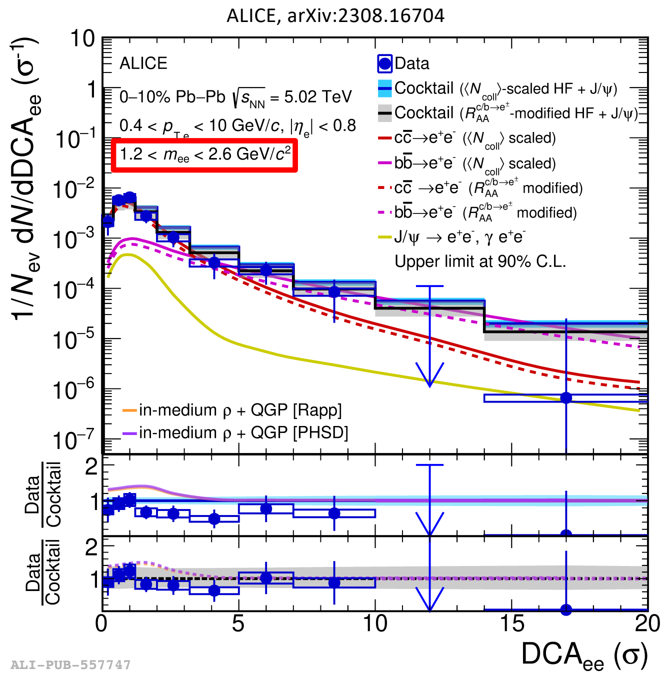


- Cross check: DCA_{ee} distributions **in the J/ψ region** are well described by cocktail

Topological separation of dielectron sources

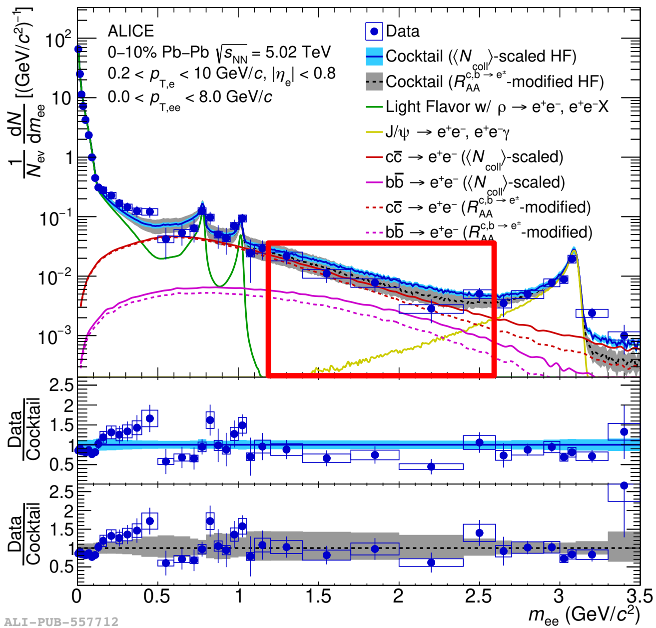




- In the IMR, **cocktail uncertainties** are too large to draw conclusions on thermal radiation

Topological separation of dielectron sources

ALICE, arXiv:2308.16704



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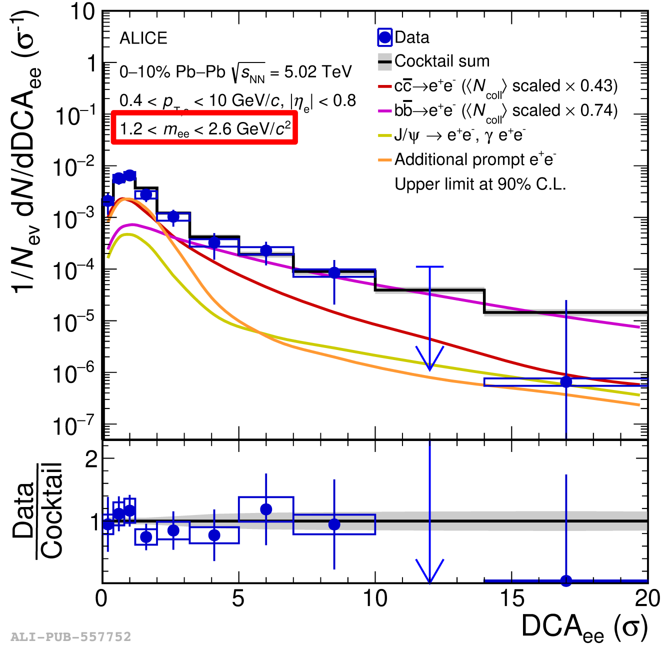

- Simultaneous fit of charm and prompt contribution gives **hint for thermal dielectrons:**

$c\bar{c}$: $0.43 \pm 0.40(\text{stat.}) \pm 0.22(\text{syst.})$ × N_{coll} scaling

prompt: $2.64 \pm 3.18(\text{stat.}) \pm 0.29(\text{syst.})$ × Rapp

The future is bright

Future dielectron measurements require:

- **much more statistics**
- **significant improvement of vertex resolution**

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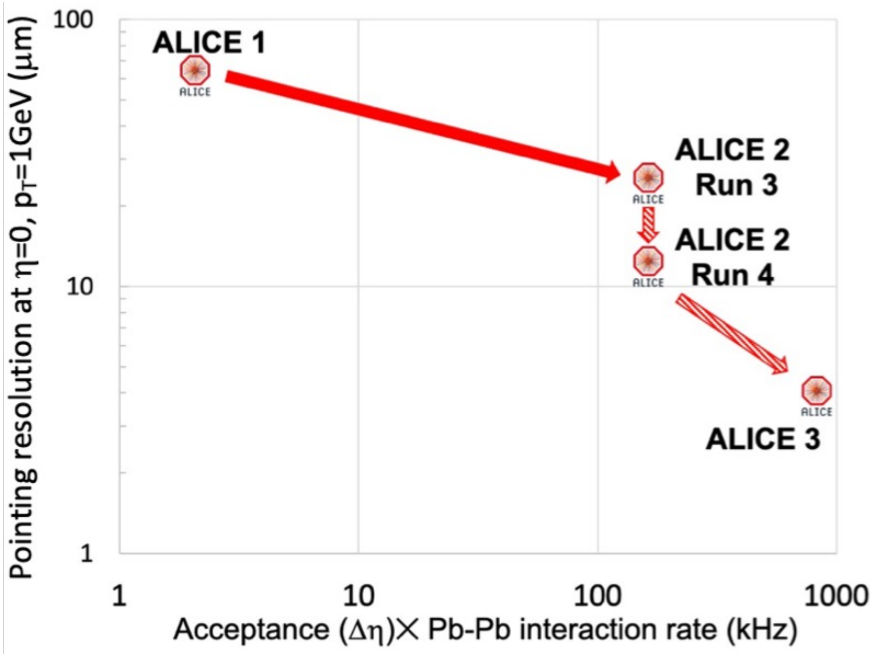
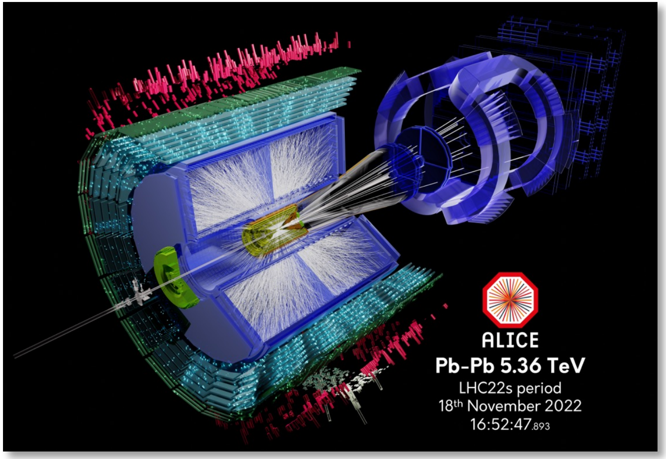
➢ **ALICE 2** in Run 3 and 4
➢ **ALICE 3** in Run 5 and 6



ALICE 2 in Run 3



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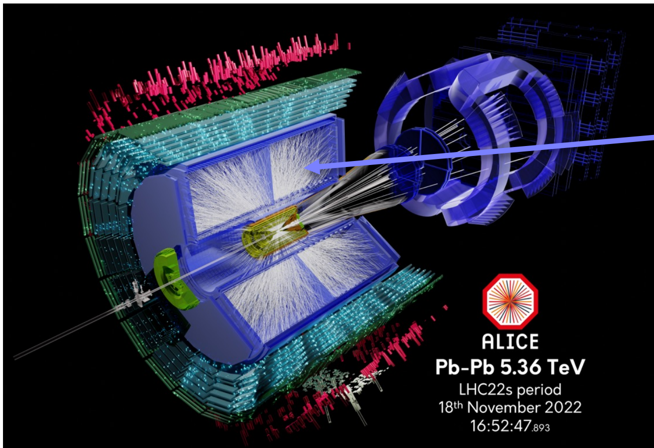
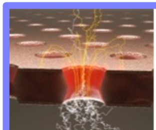
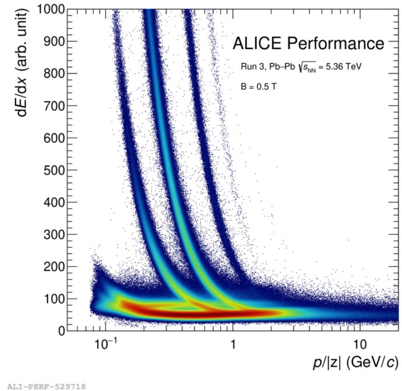




New TPC readout system

- GEM-based readout chambers
- new electronics, continuous readout



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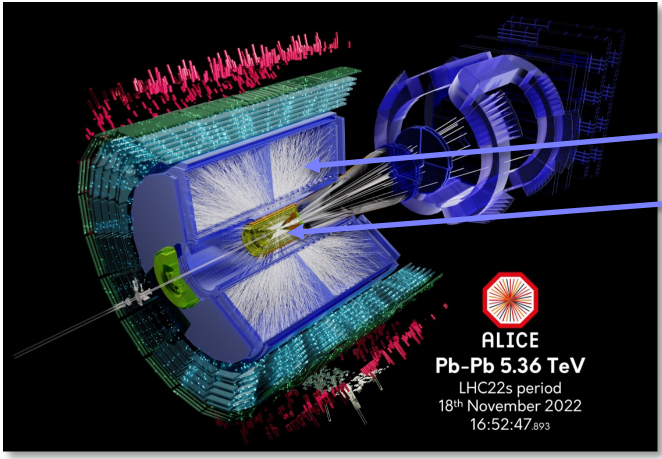

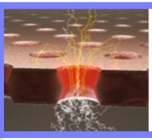

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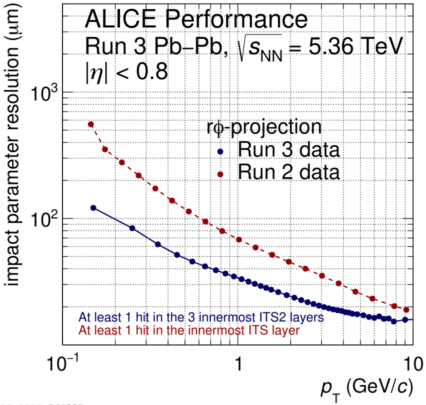
New Inner Tracking System (ITS2)

- CMOS MAPS technology
- better resolution, less material, faster readout



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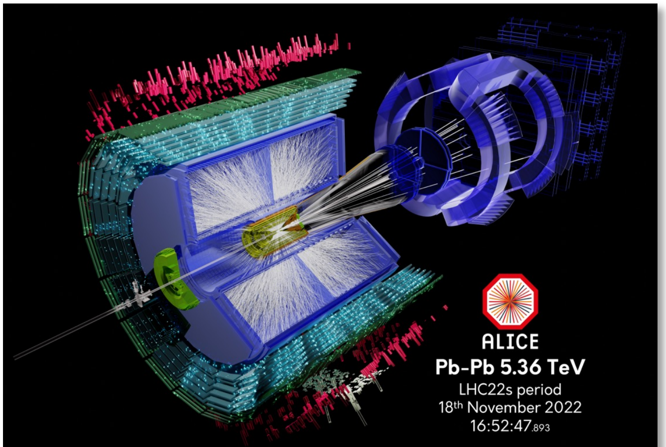

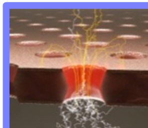

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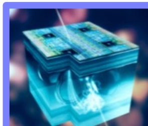

New Inner Tracking System (ITS2)

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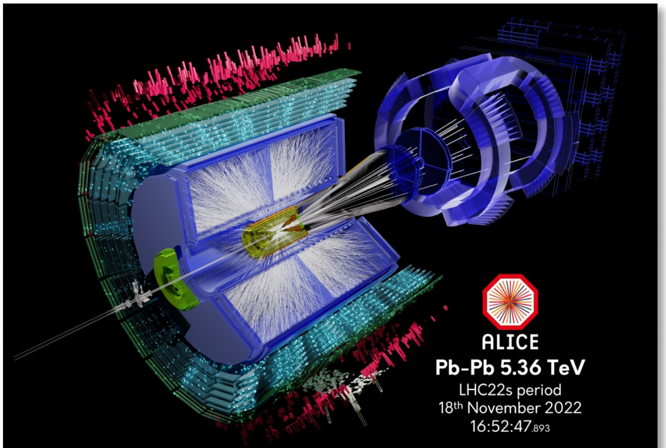
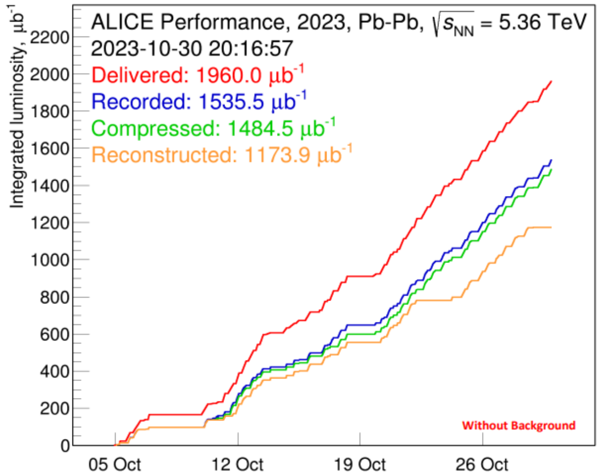
Integrated online-offline system O^2

- online reconstruction Pb-Pb at 50 kHz
- highly selective data reduction

ALICE 2 in Run 3

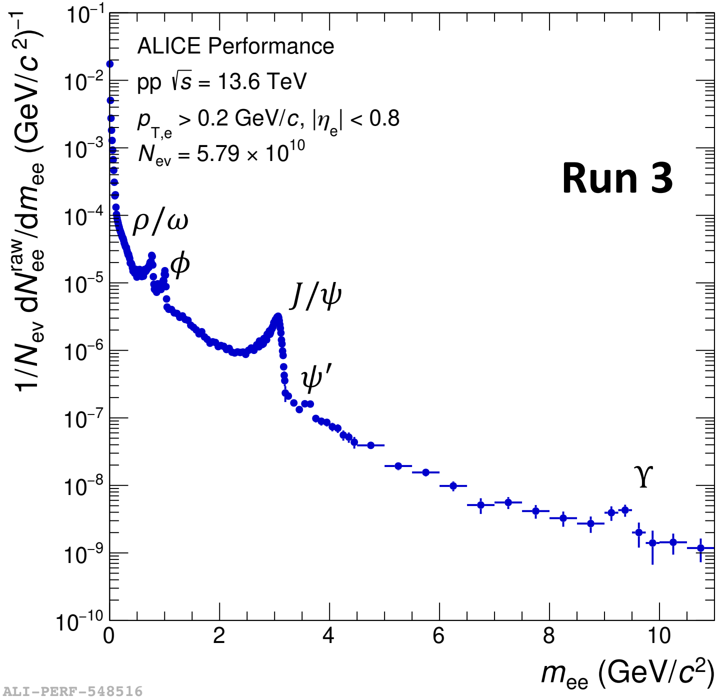




ALICE 2 in Run 3:

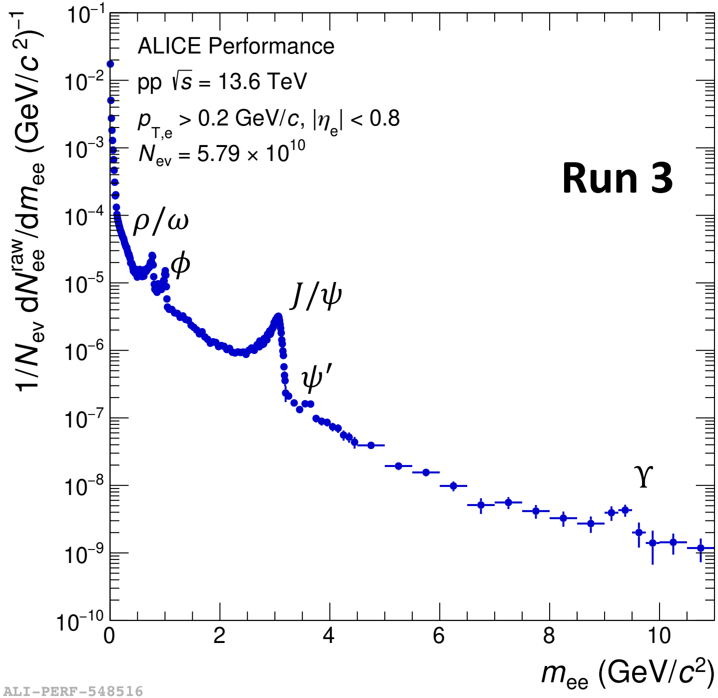
- **47 kHz** achieved in Pb-Pb and continuous readout
- **factor 20** more Pb-Pb events collected in 2023 than in Run 1+2
- **factor ~1000** more pp data than in Run 1+2

Dielectron mass spectrum in Run 3

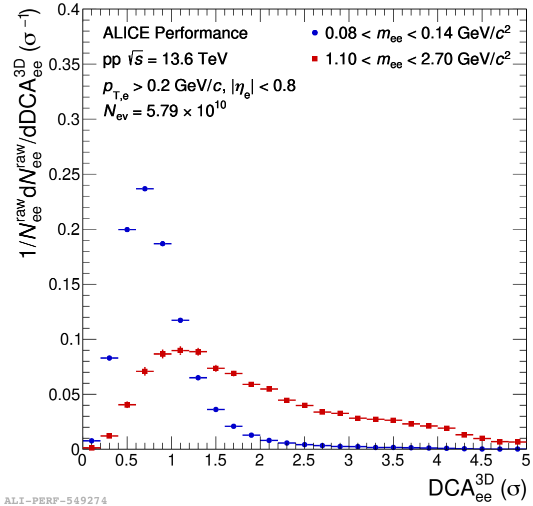


- **High-statistics** dielectron measurement

Dielectron mass spectrum in Run 3



- **High-statistics** dielectron measurement
- **Improved impact parameter resolution** from ITS2



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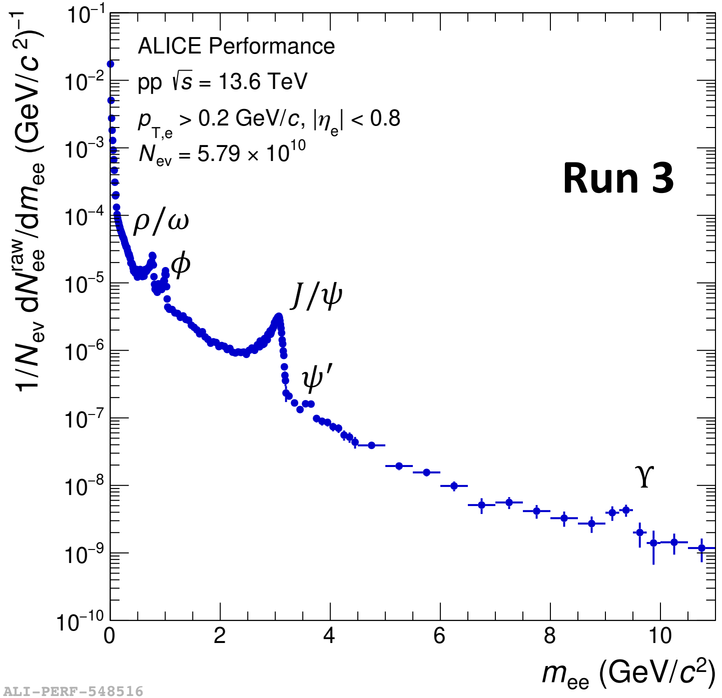

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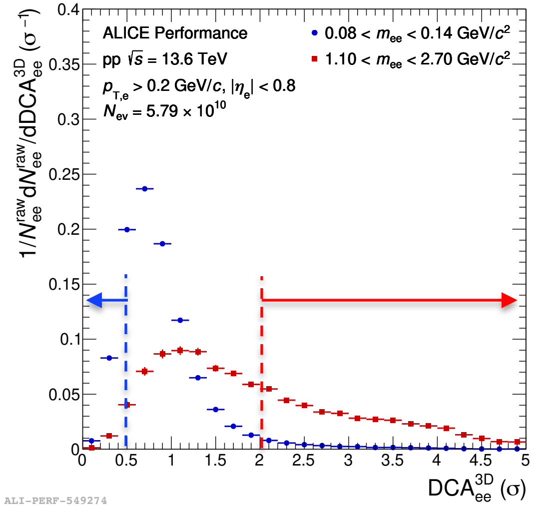

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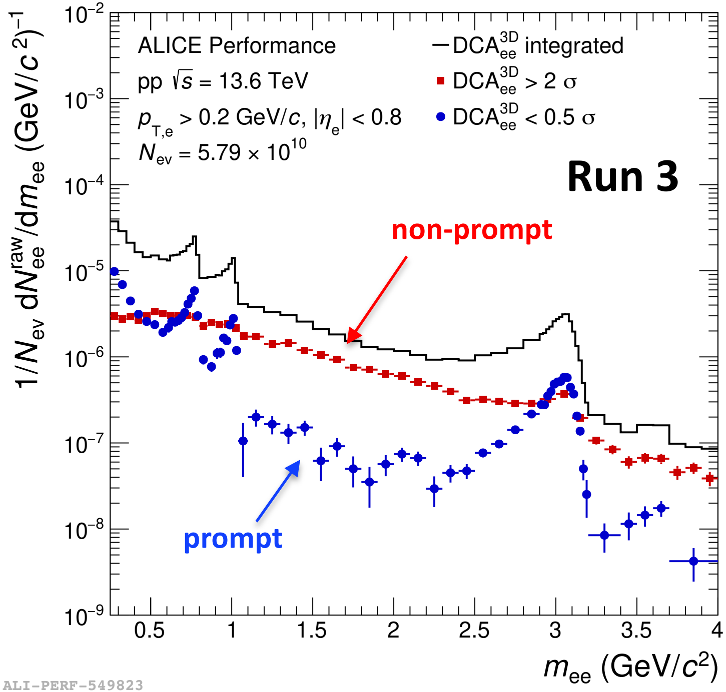

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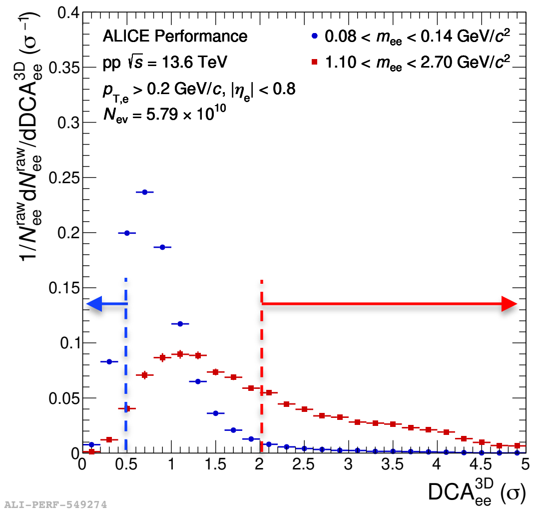
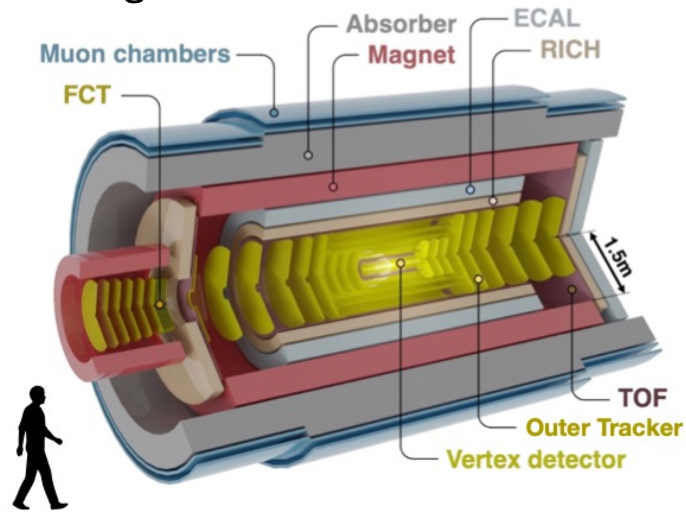


- ALICE 2 in Run 3+4 will allow **systematic studies of prompt thermal dielectron radiation**

Dielectrons with ALICE 3

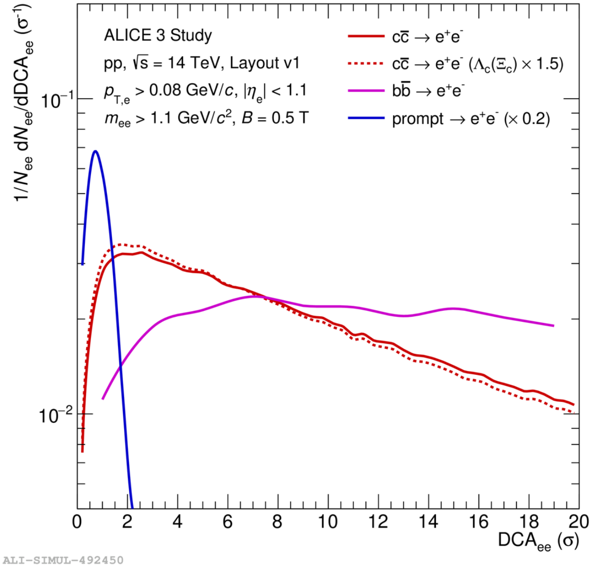
arXiv:2211.02491

Starting 2034

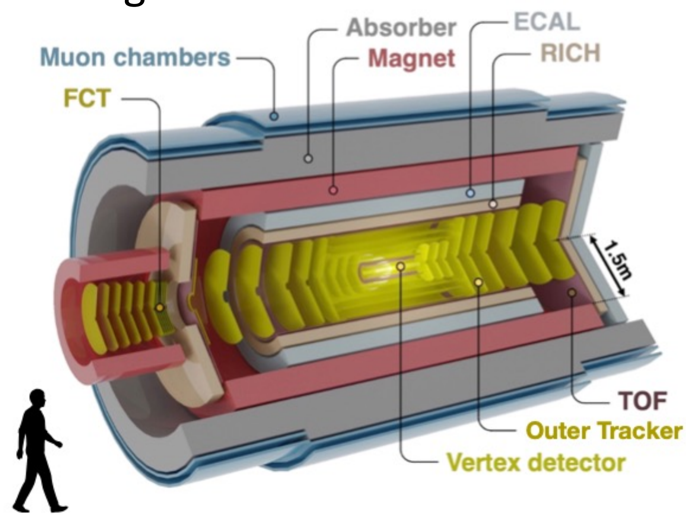


- Multiply heavy-flavored hadrons: Ξ_{cc}, Ω_{cc}, Ω_{ccc}
- X,Y,Z charmonium-like states (e.g. X(3872))
- Light exotic nuclei with charm baryons and multiple hyperons up to A=6
- Thermal EM radiation, chiral symmetry restoration
- Soft theorems

Dielectrons with ALICE 3

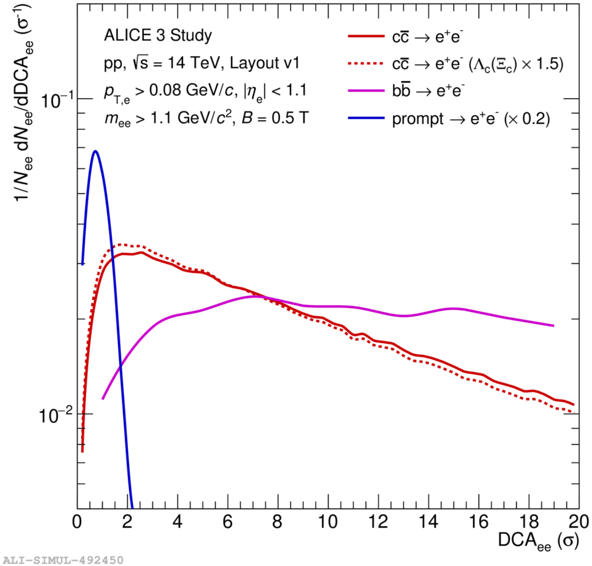


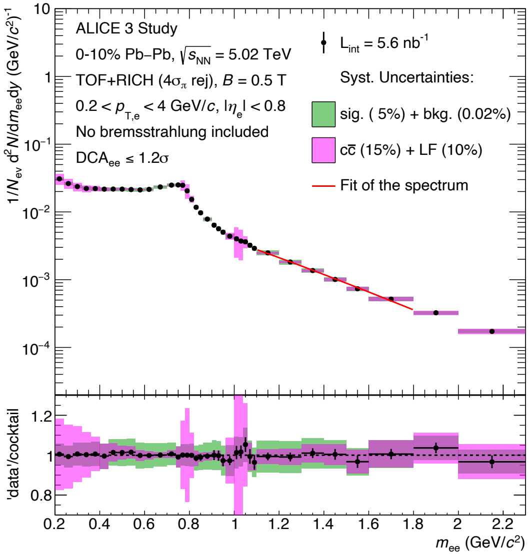
Starting 2034



- Multiply heavy-flavored hadrons: Ξ_{cc}, Ω_{cc}, Ω_{ccc}
- X,Y,Z charmonium-like states (e.g. X(3872))
- Light exotic nuclei with charm baryons and multiple hyperons up to A=6
- **Thermal EM radiation, chiral symmetry restoration**
- Soft theorems

Dielectrons with ALICE 3





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Summary

- EM probes provide **unique access** to the hot and dense phase of the system
- Dielectrons are challenging but **have a large potential** with new generation of experiments
- ALICE 2 and ALICE 3 will be **ideally suited** for detailed precision studies:
  - Pre-equilibrium dynamics
  - QGP temperature
  - Early (initial) flow
  - Chiral mixing
  - Electric conductivity

Backup

Dileptons

- dilepton yield: space-time integral over **thermal emission rate:**

$$\frac{dN_{ee}}{d^4x d^4q} = -\frac{\alpha^2}{\pi^3 m_{ee}^2} f^{BE}(q_0, T)\, \mathrm{Im}_{EM}(m_{ee}, q, \mu_B, T)$$

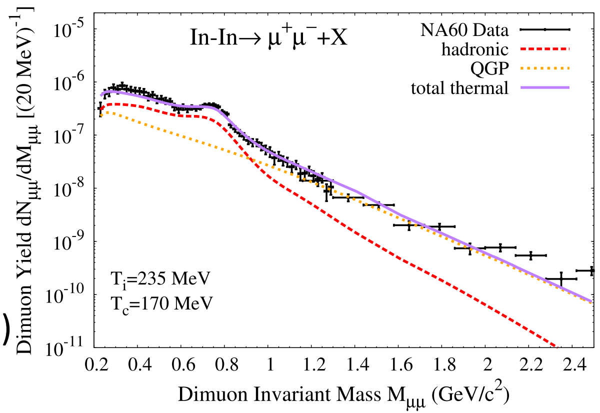
- mass dependence allows **separation of collision stages**

- QGP radiation **dominates at $m_{ee} \gtrsim 1$ GeV**

- **NA60:** Exponential fit yields
  $T = 205 \pm 12$ **MeV**, i.e. $> T_c$ (no blue shift!)
  - Thermal radiation **dominated by QGP**
  - Consistent with **initial temperature T_i=235 MeV**

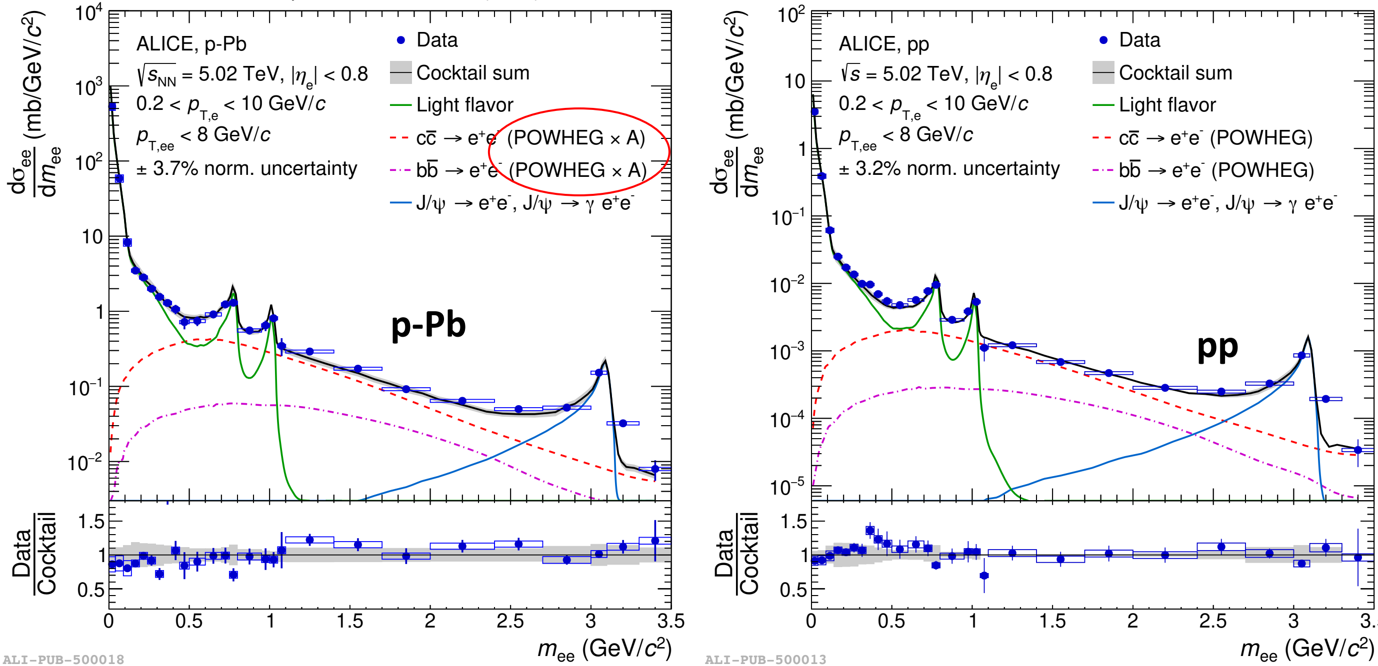
- also **HADES, STAR**

Rapp, v.Hees PLB 753 (2016) 586



Dielectrons in p-Pb

ALICE, Phys. Rev. C102 055204 (2020)



- In p-Pb **new phenomena may occur:** CNM, thermal radiation

Dielectrons in p-Pb

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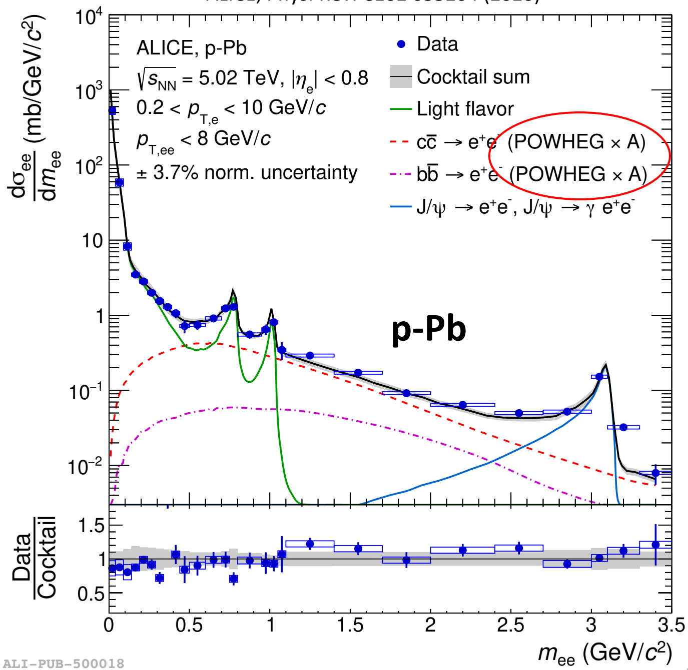

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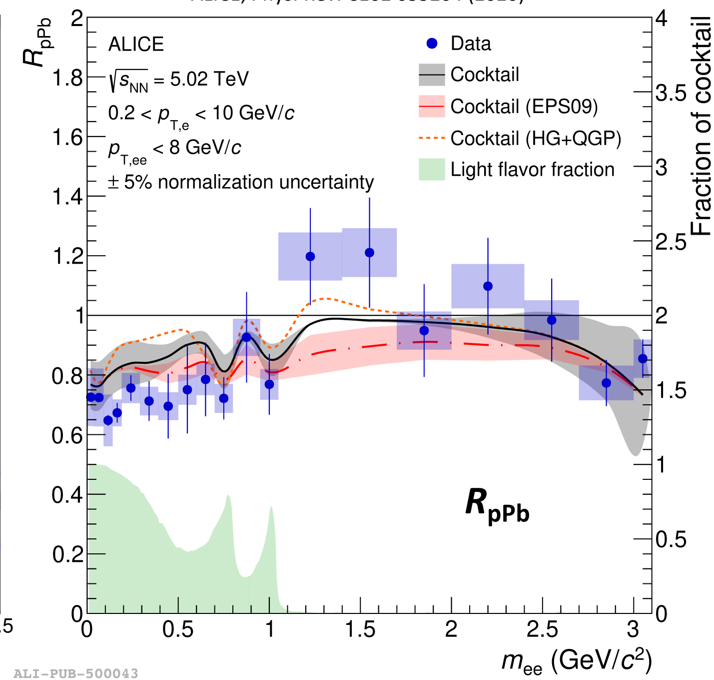
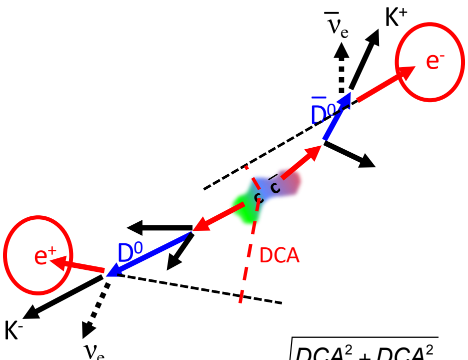


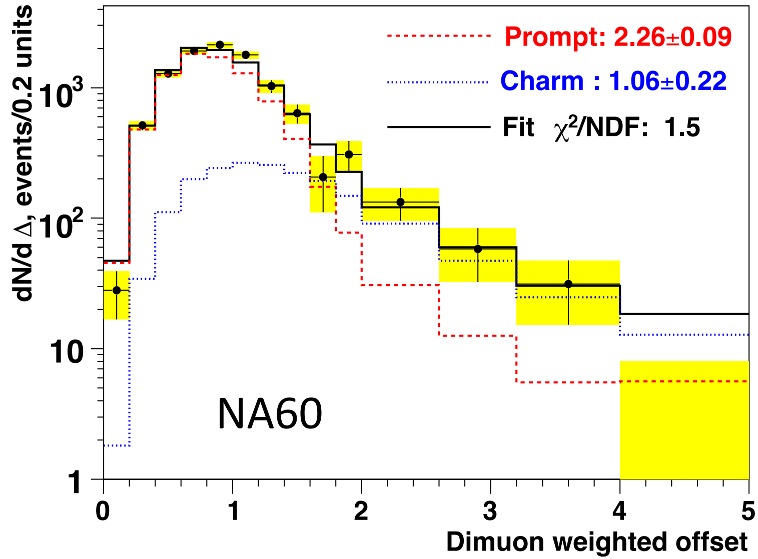
- In p-Pb new phenomena may occur: CNM, thermal radiation
- Dielectron R_{pPb} compatible with N_{coll} - scaled HF contribution, but also with CNM effects (EPS09) and small thermal contribution

Topological separation of dielectron sources



$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

NA60 EPJ C59 (2009) 607



- DCA_{ee} allows **separation of prompt from delayed dielectron sources**
- Pioneered by **NA60** at the SPS
    - ➢ first experimental **evidence for thermal dielectrons** in the IMR