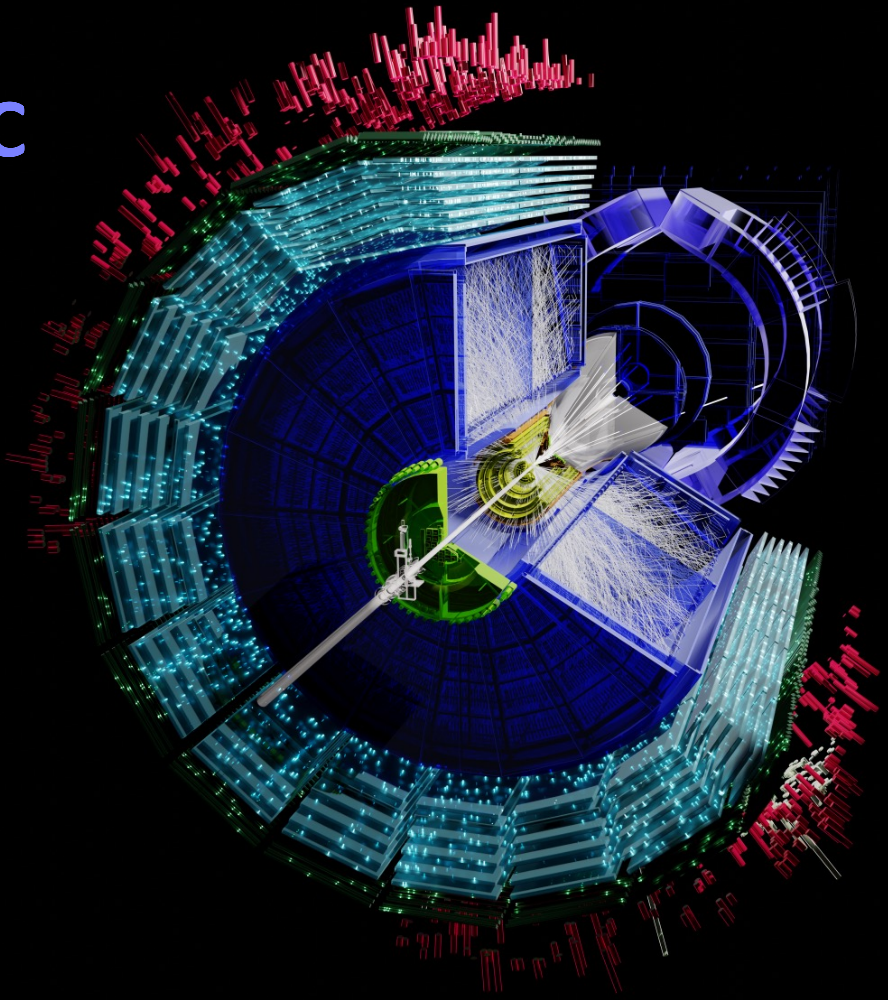
Dielectrons at the LHC chances and challenges

Harald Appelshäuser
Goethe Universität Frankfurt



38th Winter Workshop on Nuclear Physics
February 5-11, 2023, Puerto Vallarta, Mexico

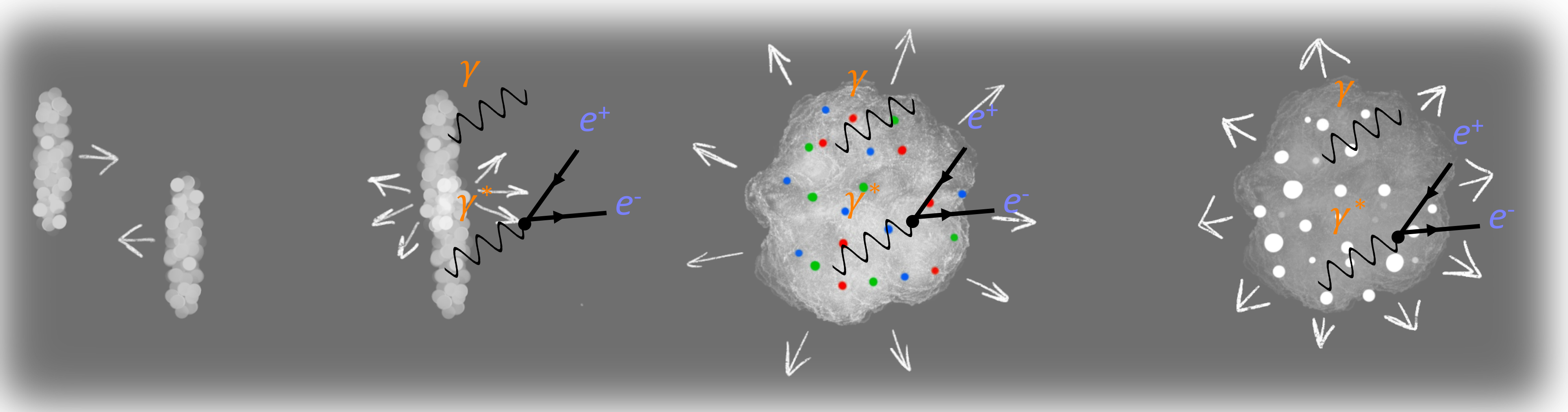
Outline

- EM probes are unique
- Photons versus dielectrons
- Experimental status at the LHC: pp, p-Pb, Pb-Pb from ALICE
- Outlook: ALICE 2 and ALICE 3

Photons and dileptons

- leave the system **without strong FSI**
- are produced **at all stages** of the collison

  → 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:

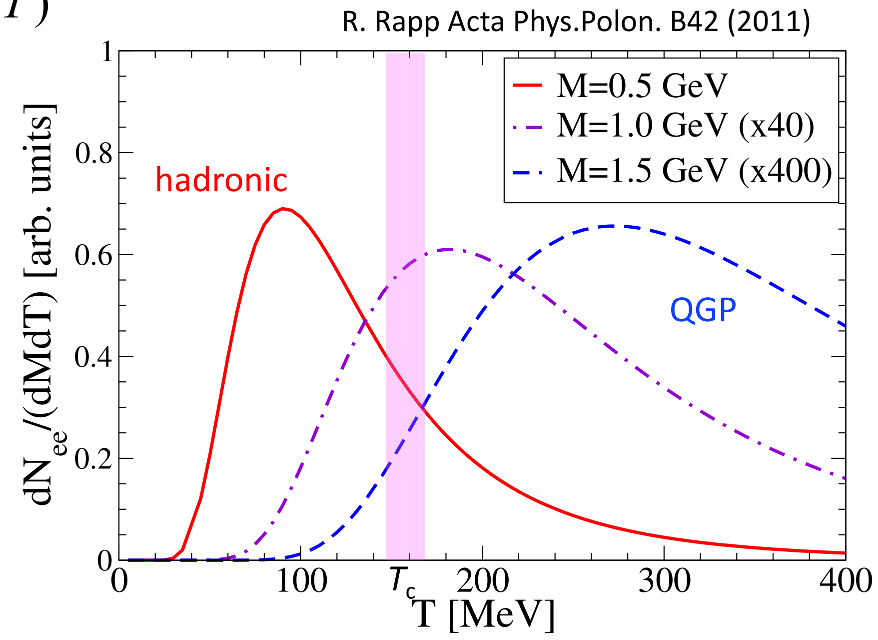
- Photons integrate over space-time evolution, different collision stages **cannot be distinguished (aka *direct photon puzzle*)**
- Dielectrons do as well but **carry mass which can serve as a clock**

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**



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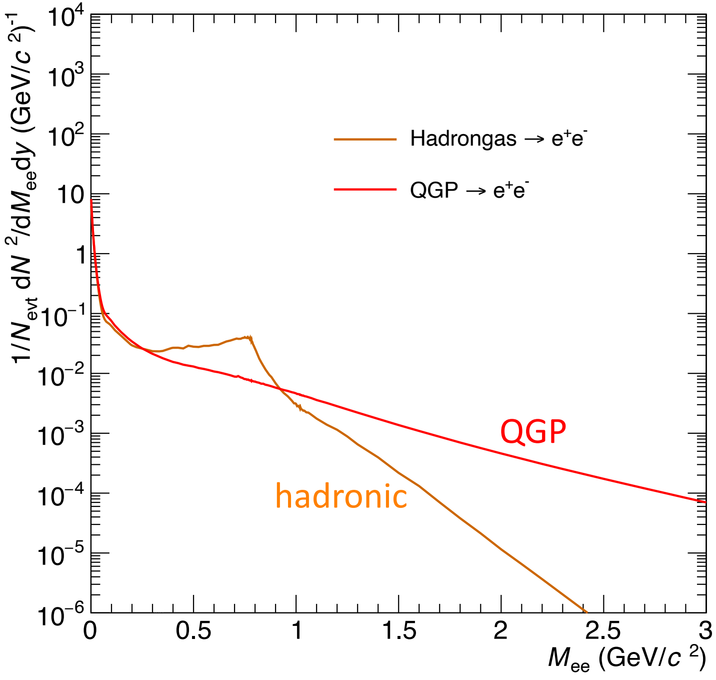
- mass dependence allows **separation of collision stages**

- 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)



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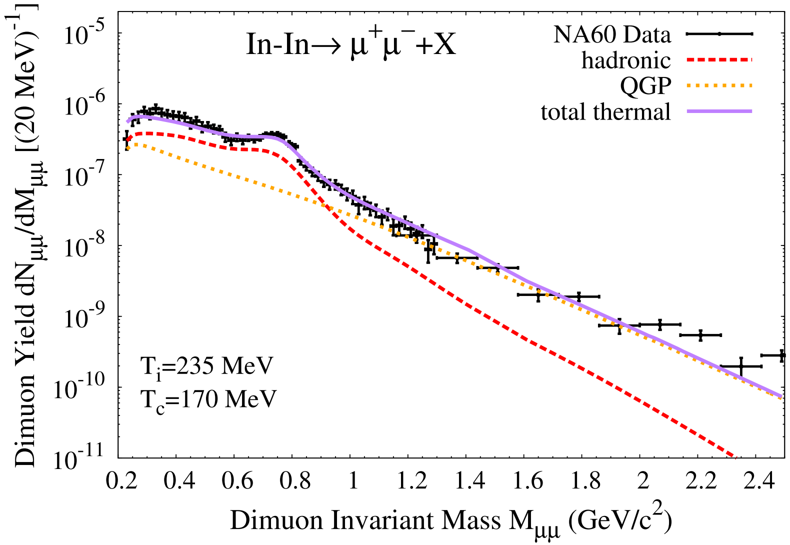
- mass dependence allows **separation of collision stages**
- QGP radiation **dominates at $m_{ee} \gtrsim 1$ GeV**
- **NA60:** Exponential fit yields **T=205±12 MeV**, i.e. >T_c (no blue shift!)
  - Thermal radiation **dominated by QGP**
  - Consistent with **initial temperature T_i=235 MeV**

Rapp, v.Hees PLB 753 (2016) 586



Dielectrons at the LHC

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

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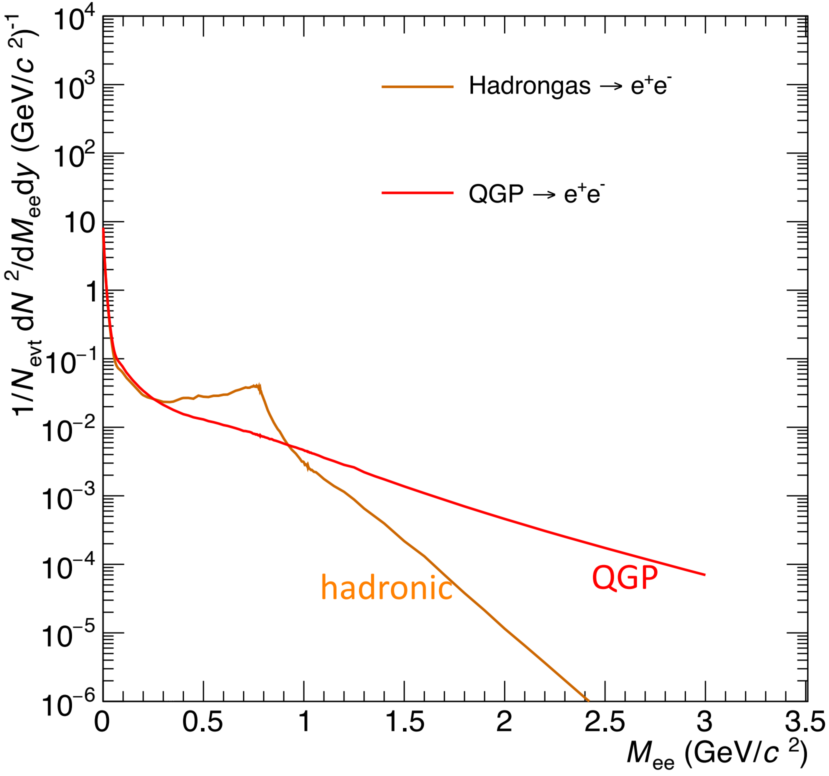
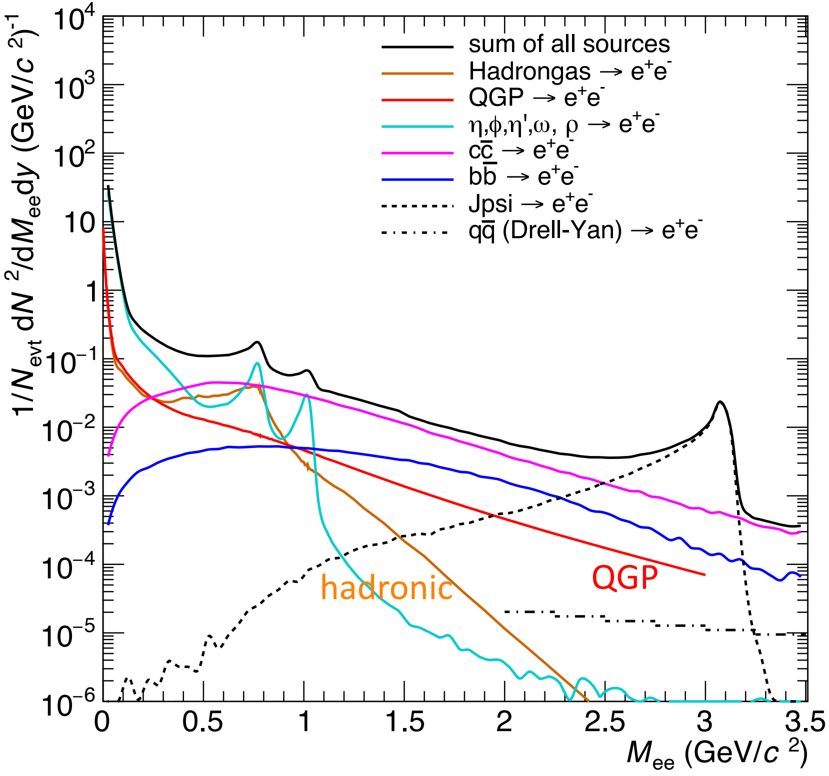


Dielectrons at the LHC

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



Heavy-flavour cross sections in pp

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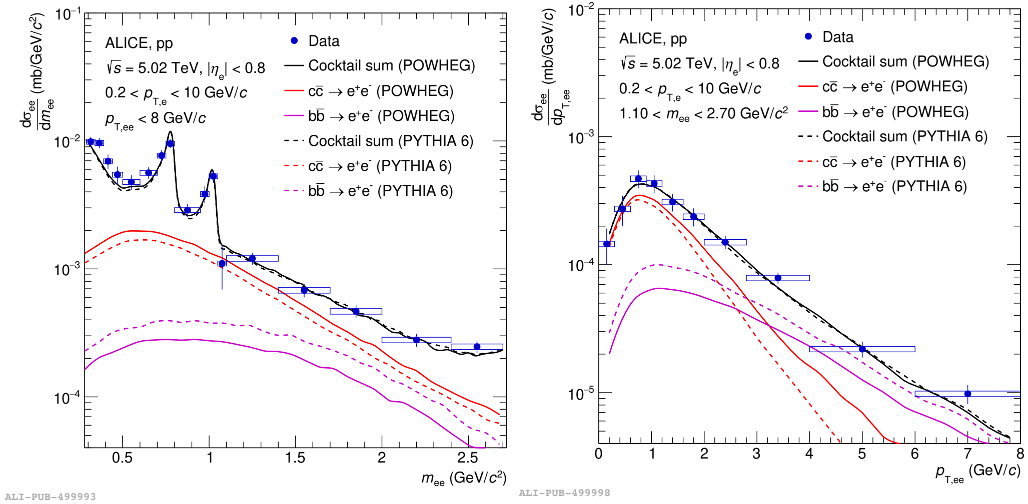
ALICE, Phys. Rev. C102 055204 (2020)



- Charm and beauty contribution can be determined from a **template fit to the IMR**
- Extraction of cross sections possible but **additional uncertainties introduced**

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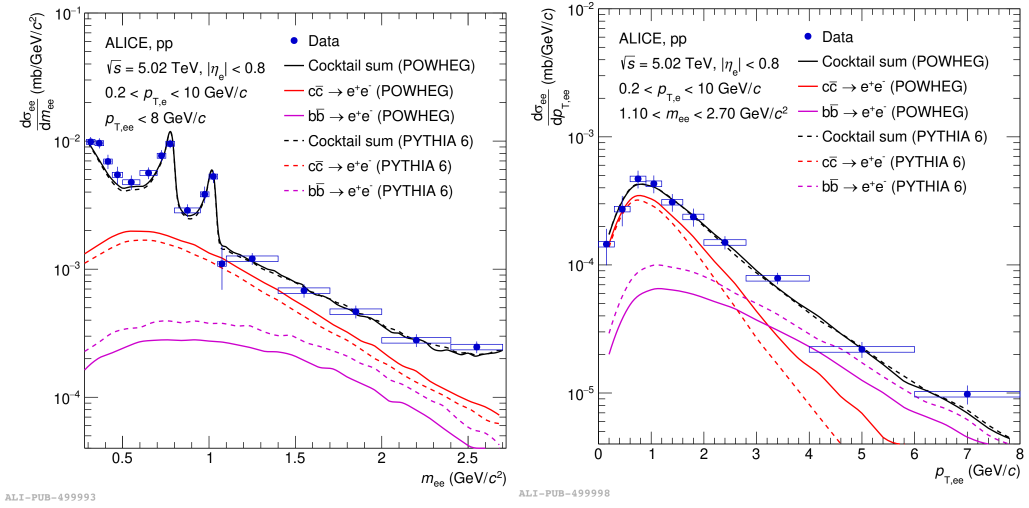

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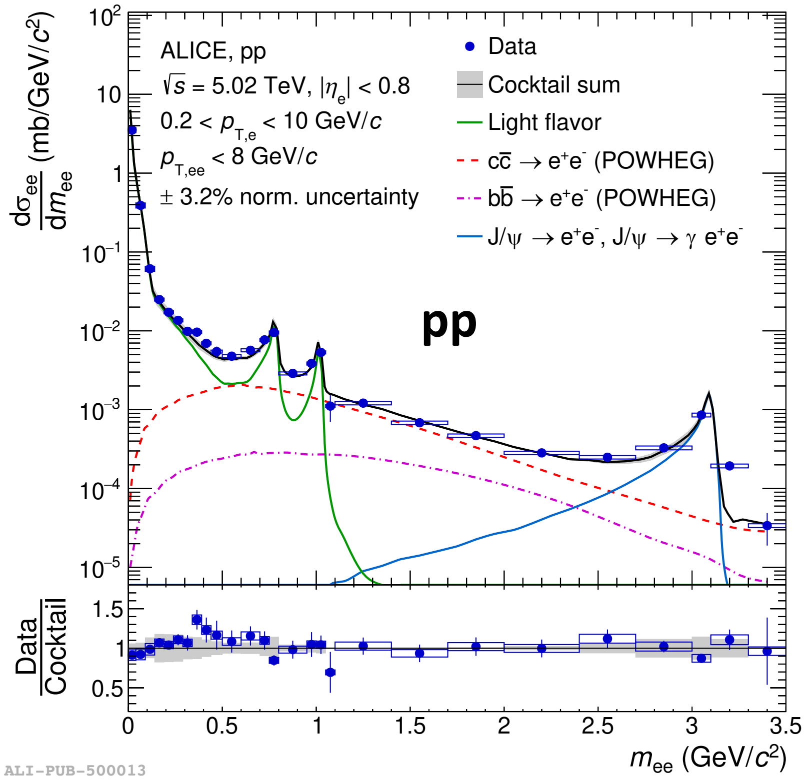

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Heavy-flavour cross sections in pp and p-Pb

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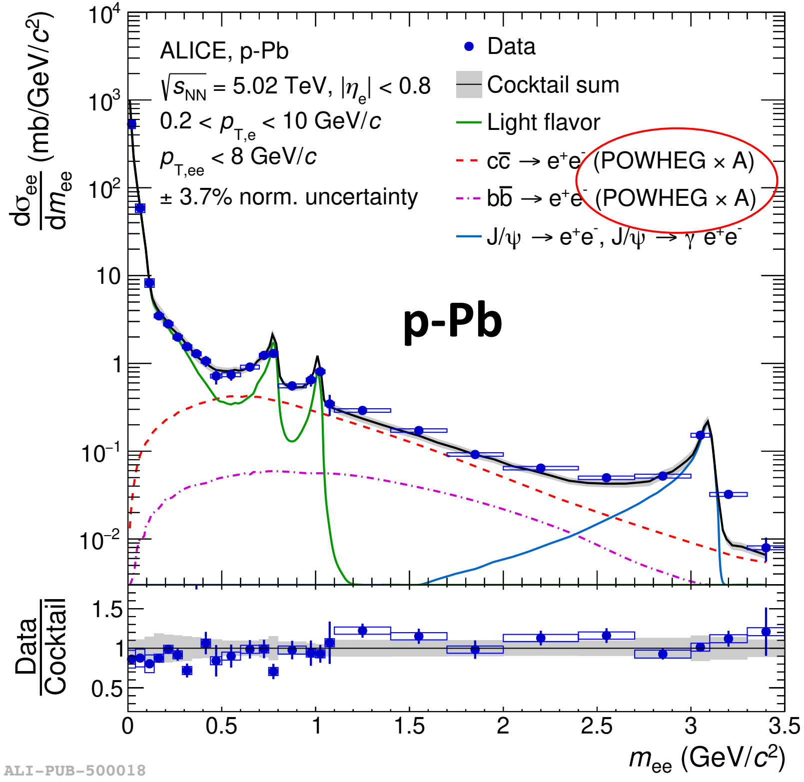

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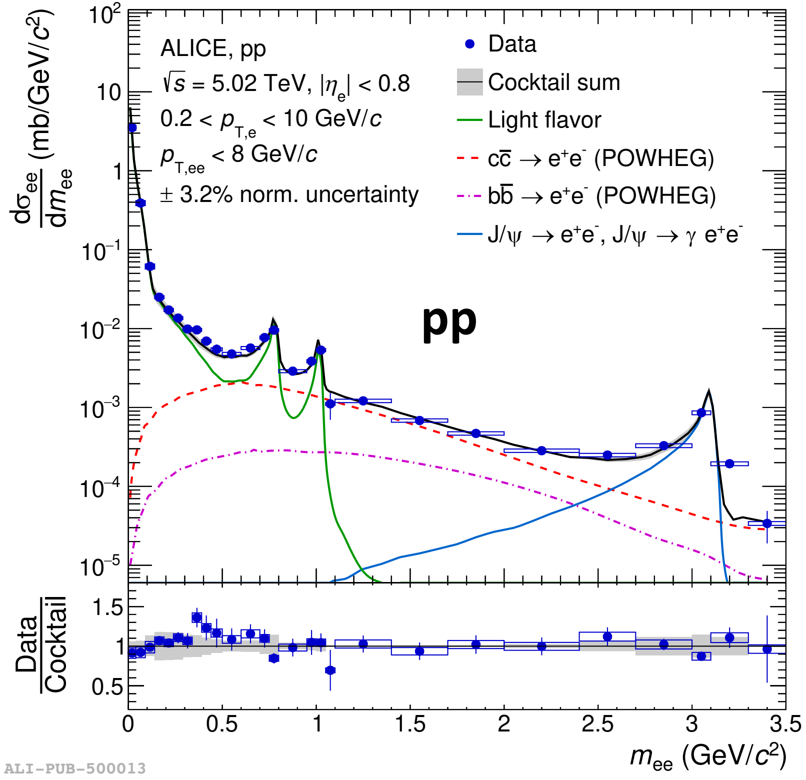

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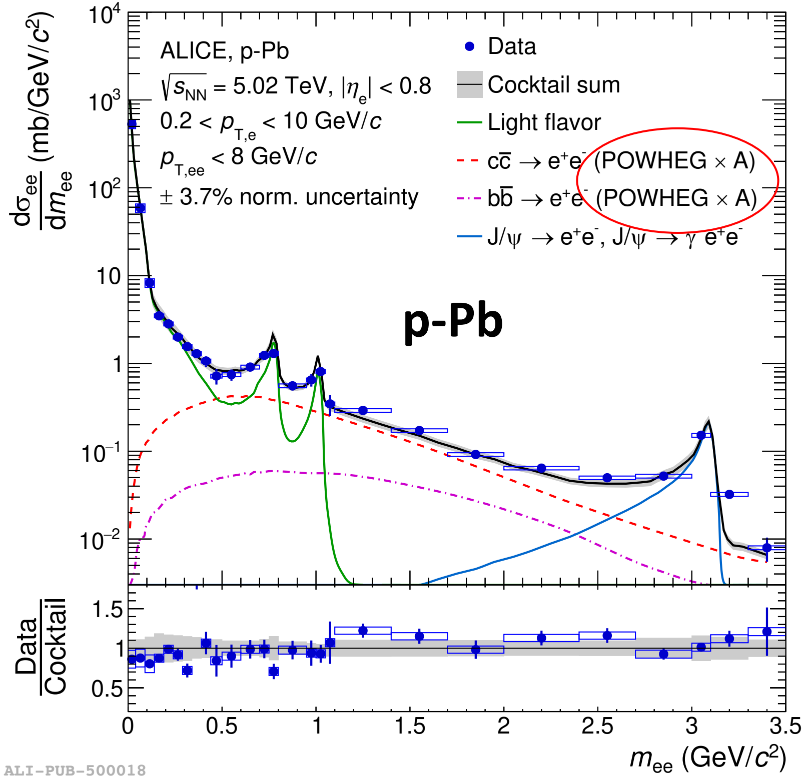

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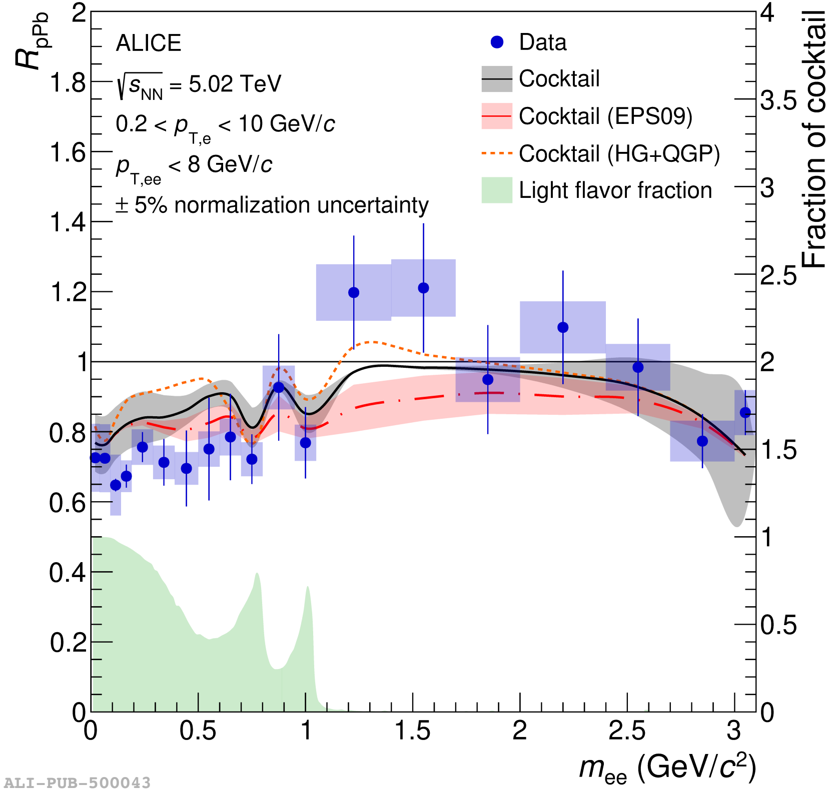
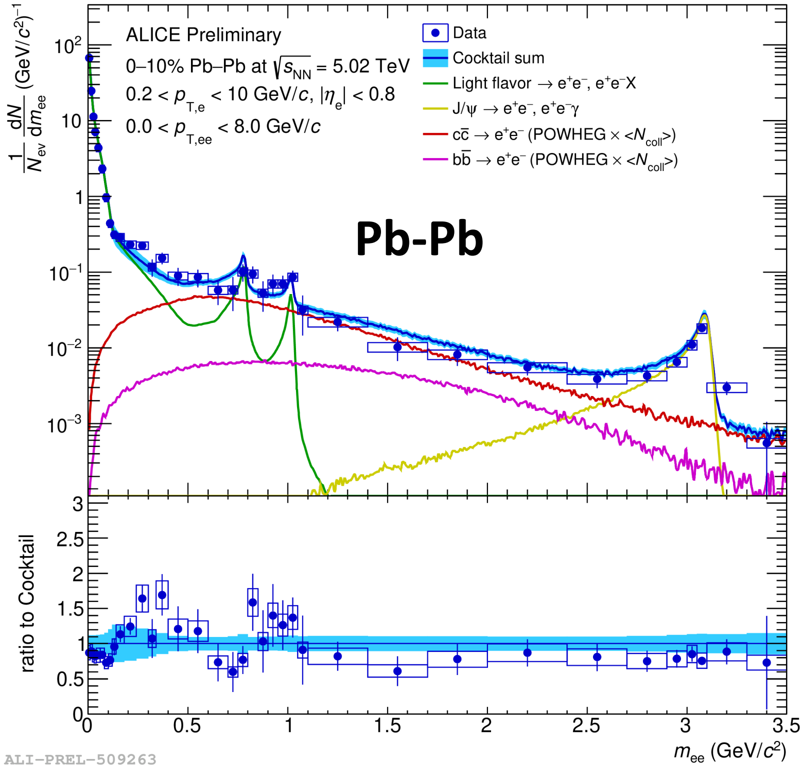


Dielectrons in Pb-Pb

Jerome Jung, QM22



Pb-Pb results from Run 2:

- Cocktail: N_{coll} – scaled HF measurement in pp
- At the edge of systematic uncertainty in the IMR

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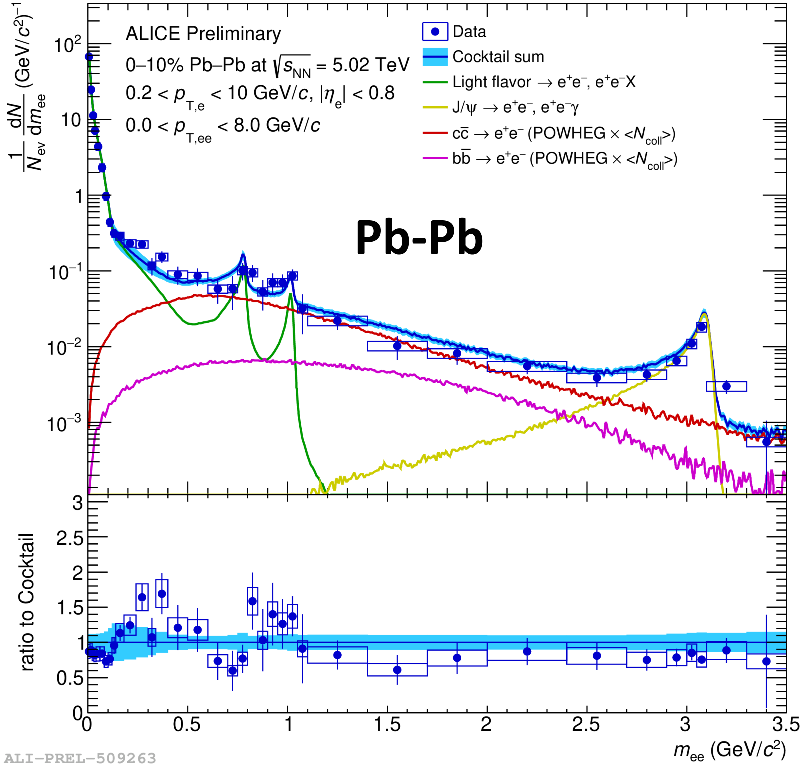

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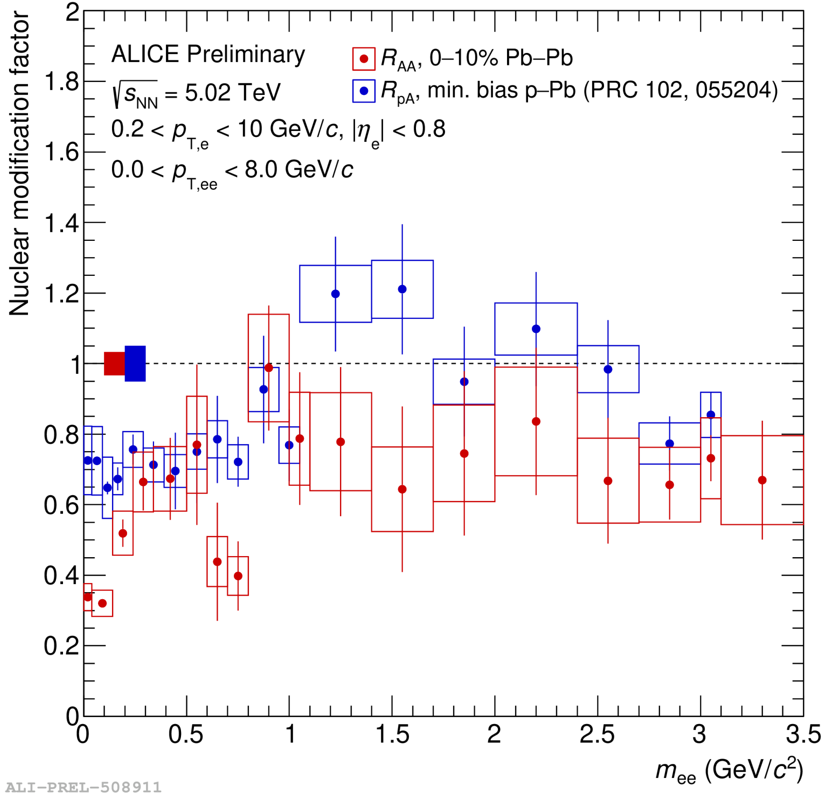

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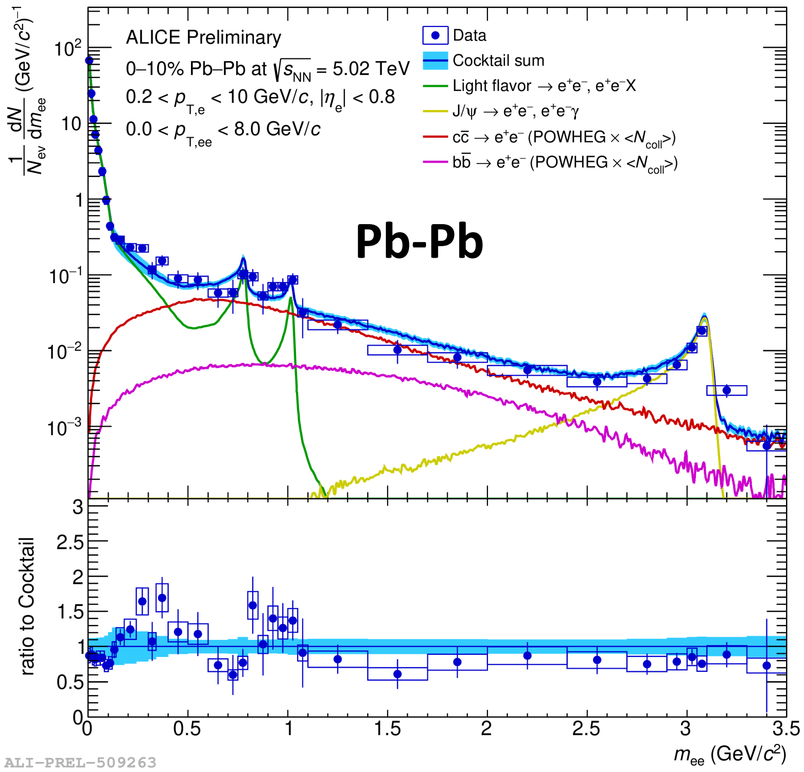

Pb-Pb results from Run 2:

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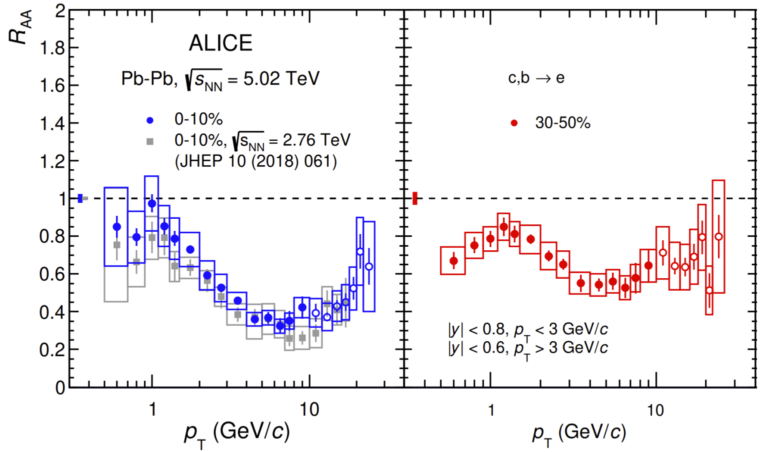
- HF is **known to be modified** in Pb-Pb

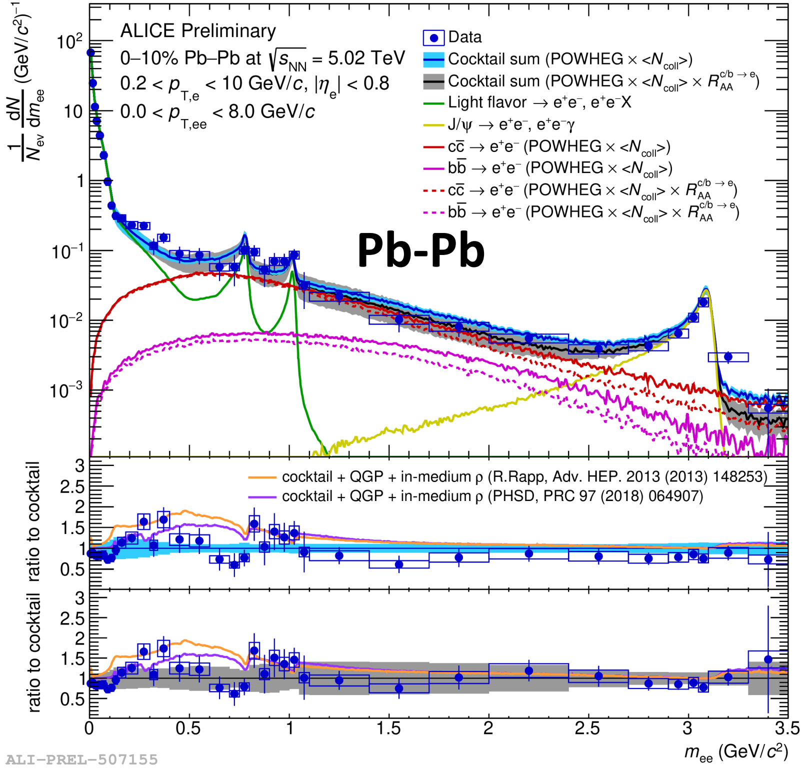
→ Construct **modified HF cocktail** based on HFE R_{AA}

ALICE, PLB804 (2020) 135377



Dielectrons in Pb-Pb – modified HF cocktail

Jerome Jung, QM22



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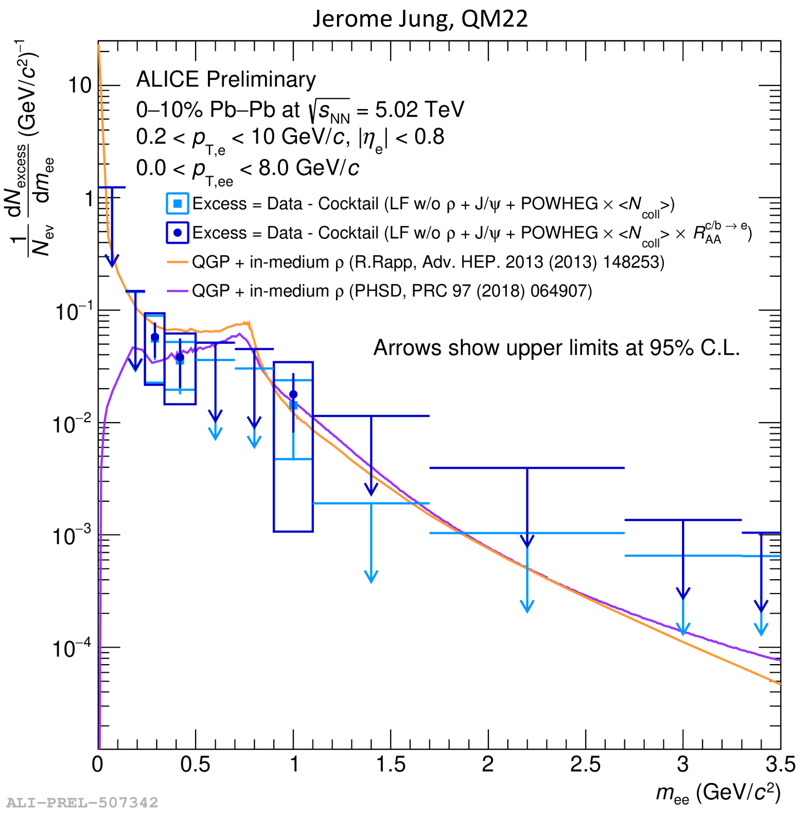
- Description improved, but **additional uncertainties introduced**
- Possible QGP contribution **not resolvable** within systematic (and statistical) unertainties

Dielectron excess in Pb-Pb



Pb-Pb results from Run 2:

- Cocktail: N_{coll} – scaled HF measurement in pp
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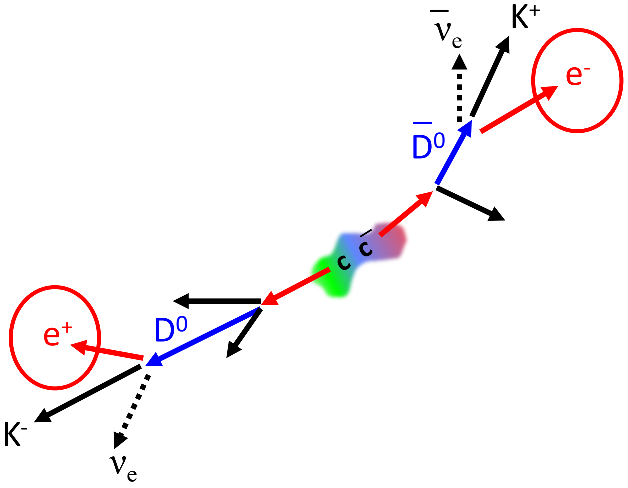
- HF is **known to be modified** in Pb-Pb

→ Construct **modified HF cocktail** based on HFE R_{AA}

- Description improved, but **additional uncertainties introduced**
- Possible QGP contribution **not resolvable** within systematic (and statistical) unertainties
- Measurement of dielectron excess requires a **cocktail-independent approach!**

Topological separation of dielectron sources



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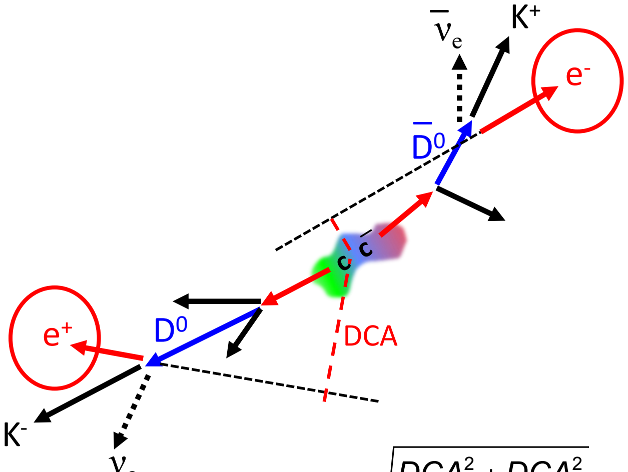

$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$

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

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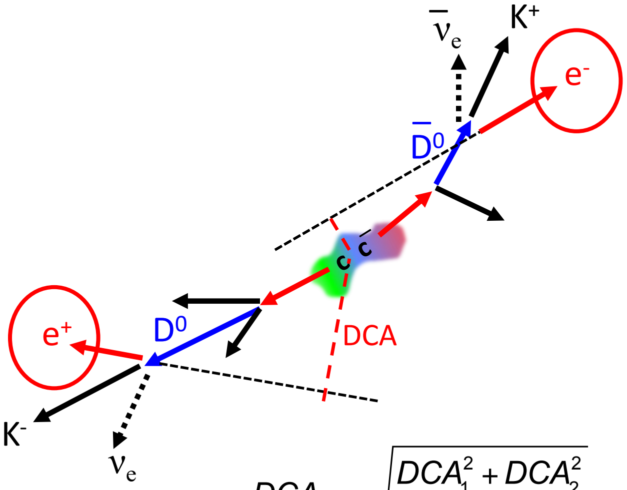

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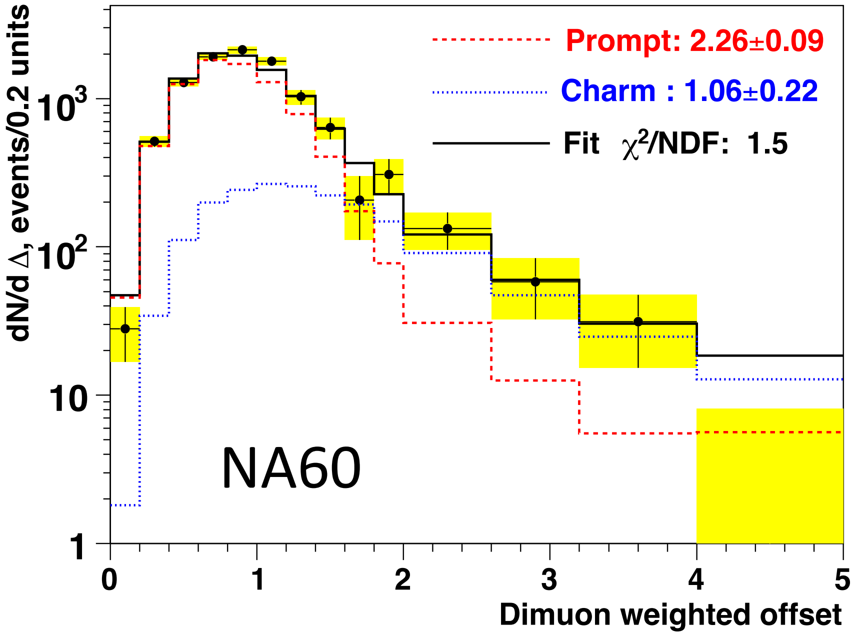
NA60 EPJ C59 (2009) 607



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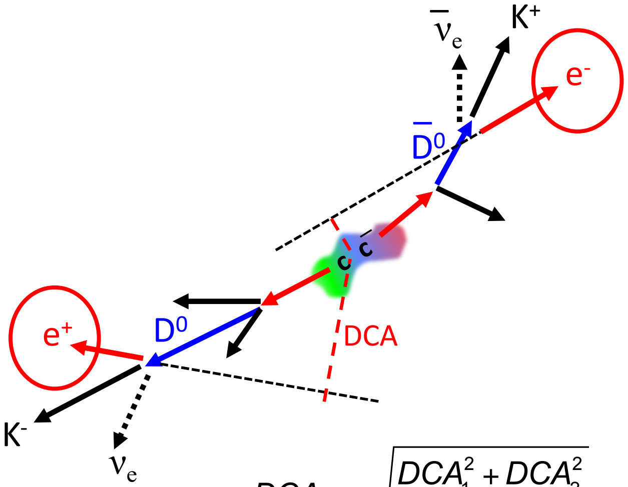

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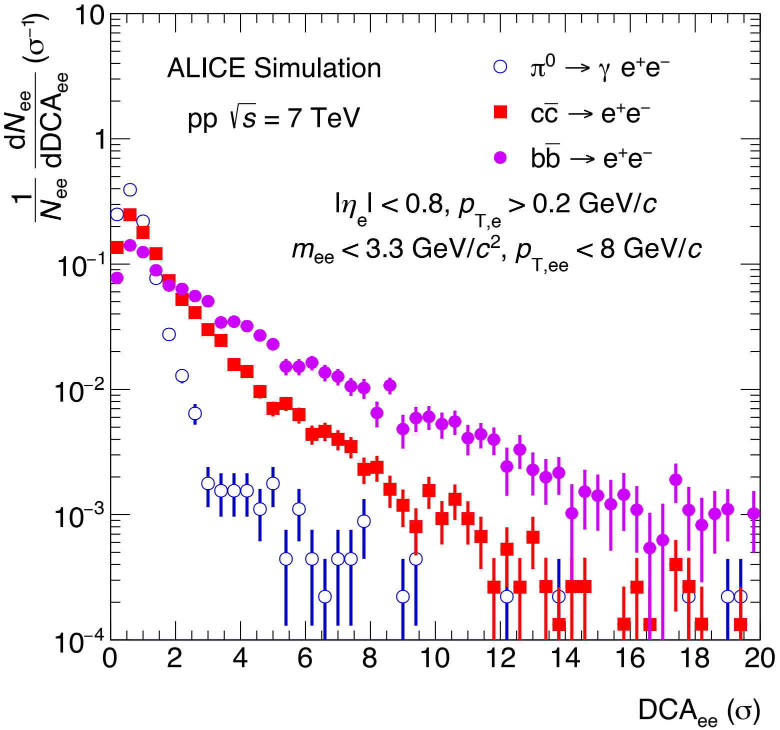
ALICE, JHEP 1809 (2018) 064



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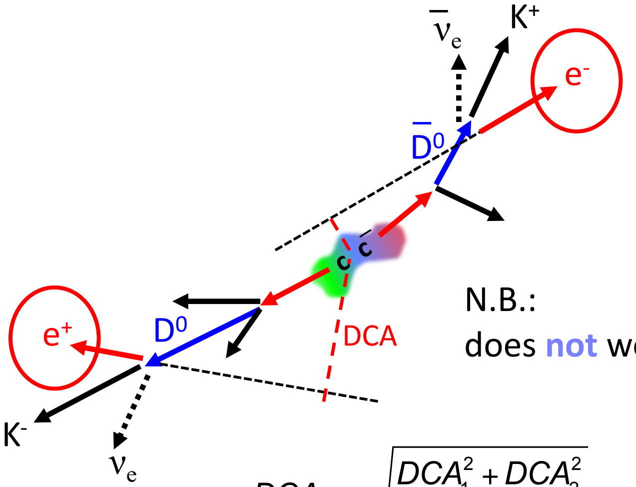
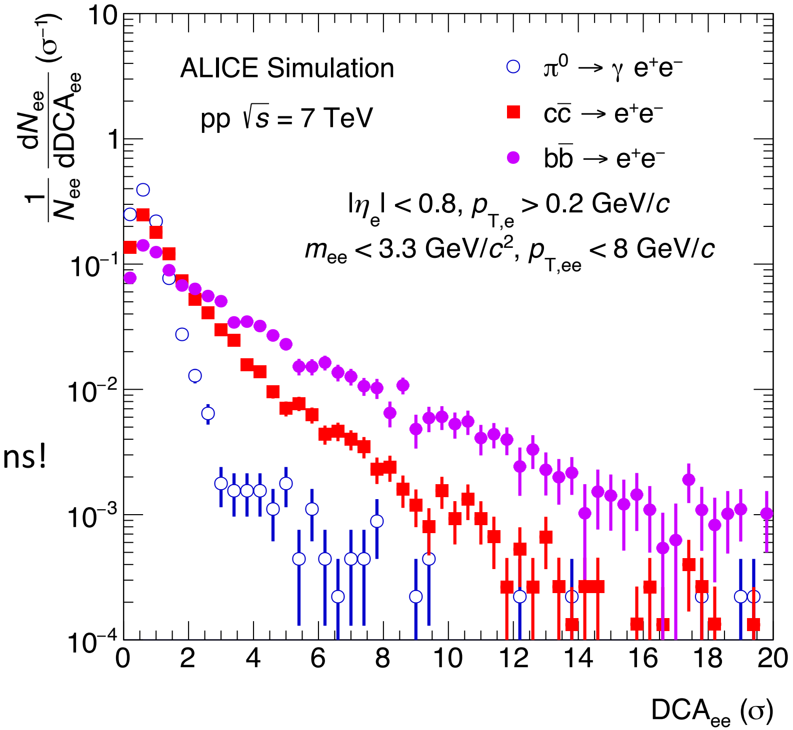


N.B.:
does **not** work for photons!

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

ALICE, JHEP 1809 (2018) 064



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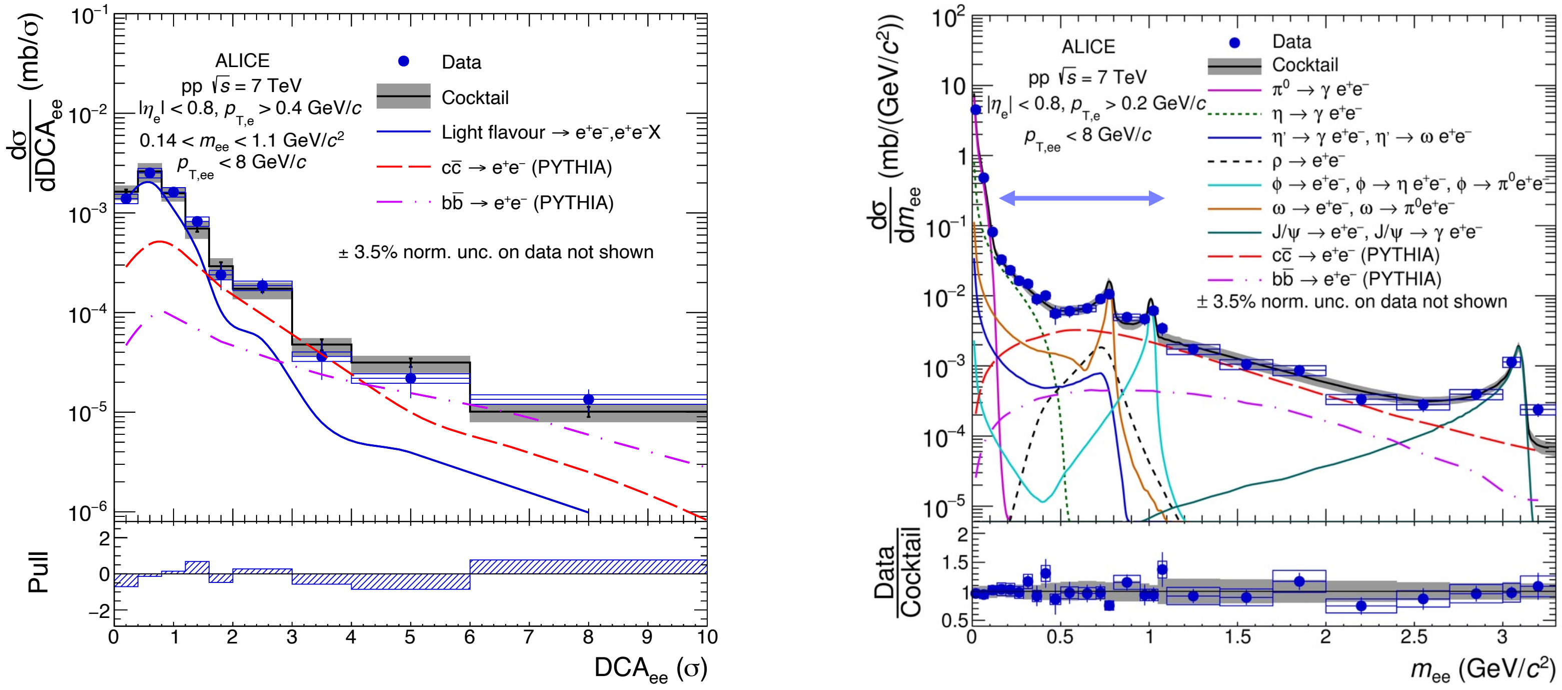
Topological separation of dielectron sources – pp

ALICE, JHEP 1809 (2018) 064

η, ρ, ω, ϕ mass region



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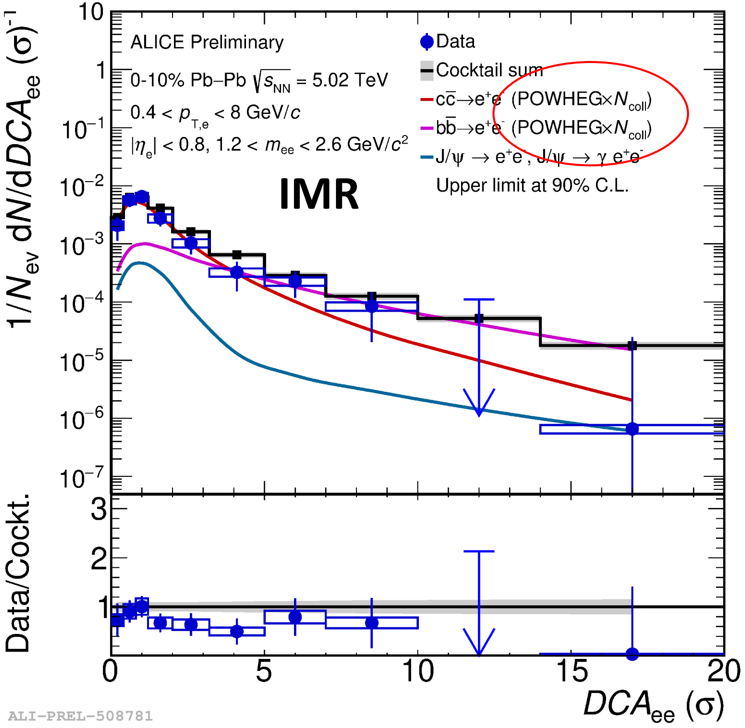
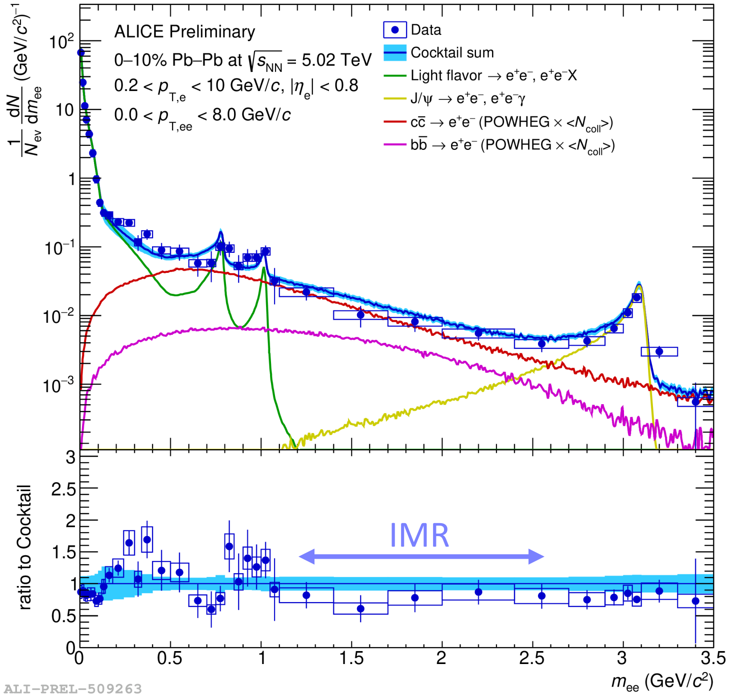
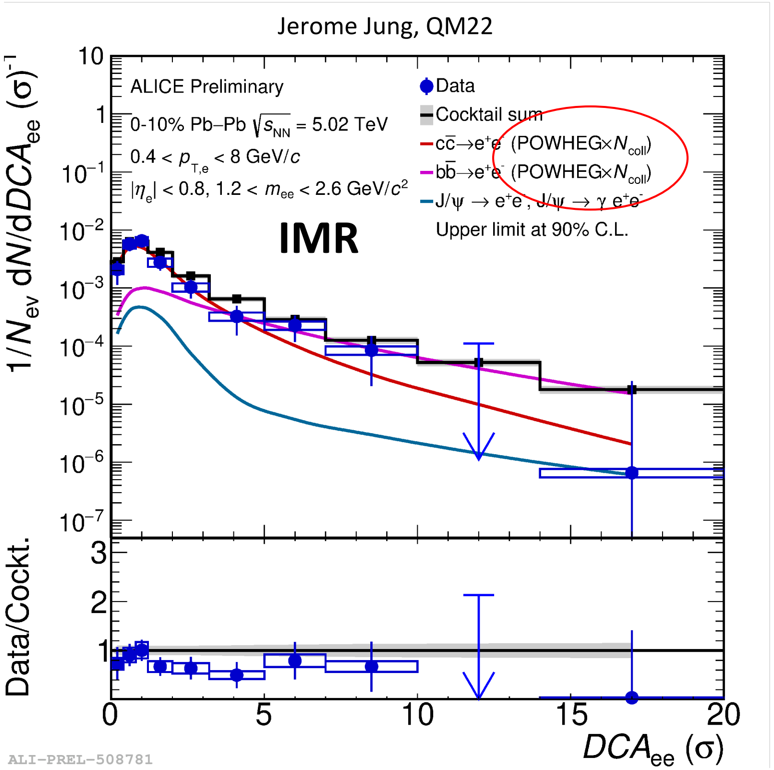
Topological separation of dielectron sources – Pb-Pb

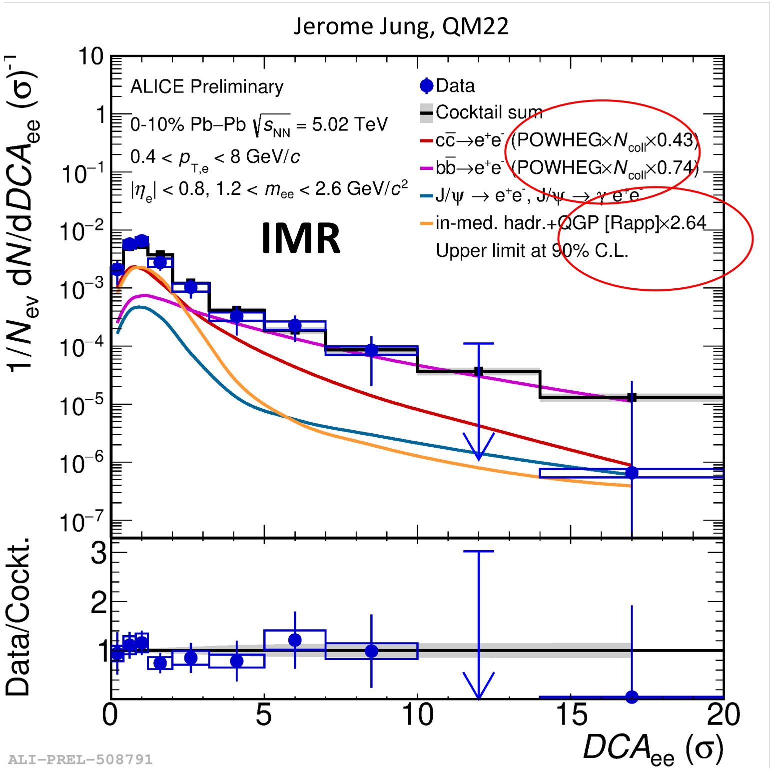
Jerome Jung, QM22





Topological separation of dielectron sources – Pb-Pb





- Reduction of HF and **inclusion of a prompt source** improves description of the data

Topological separation of dielectron sources - Pb-Pb

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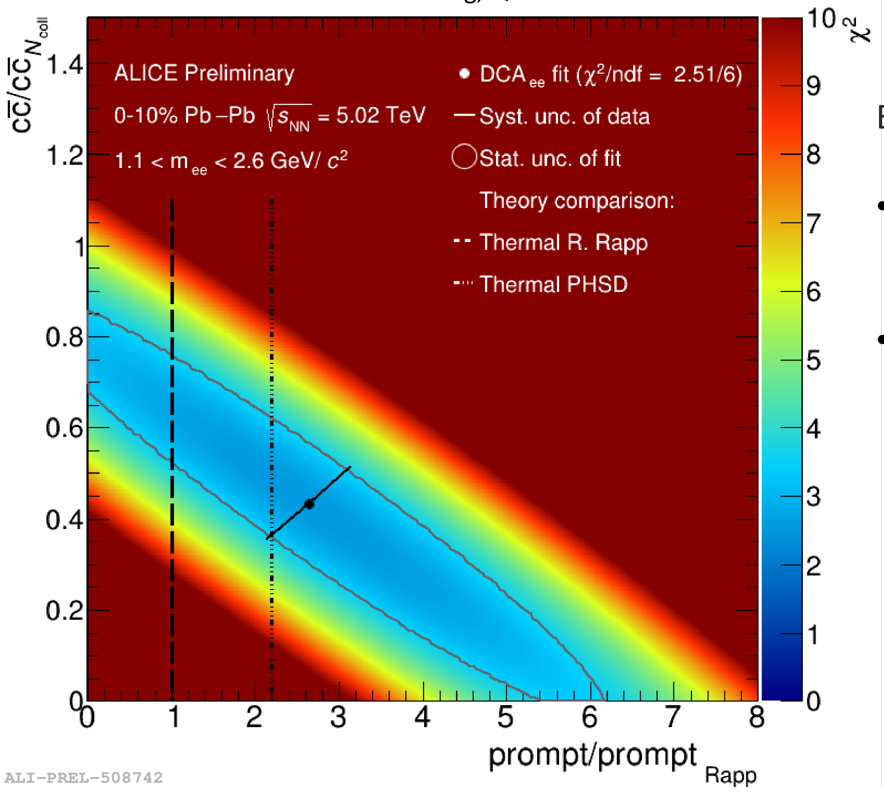


Extraction of prompt thermal signal via template fits:

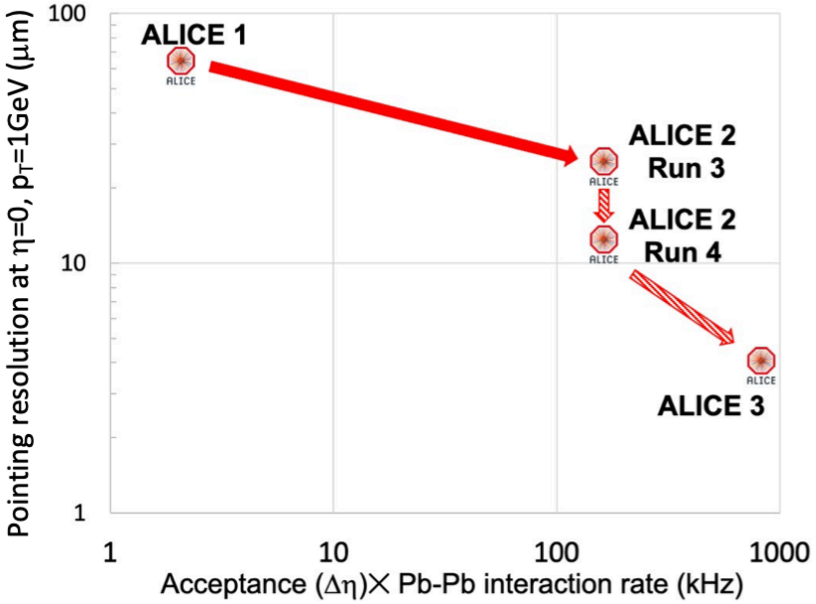
- Beauty contribution fixed via separate fit at high $\mathrm{DCA_{ee}}$
  $b\bar{b}$: $\mathbf{0.74 \pm 0.24(stat.) \pm 0.12(syst.)}$ $\times N_{coll}$ scaling

- Simultaneous fit of charm and prompt contribution
  $c\bar{c}$: $\mathbf{0.43 \pm 0.40(stat.) \pm 0.22(syst.)}$ $\times N_{coll}$ scaling
  prompt: $\mathbf{2.64 \pm 3.18(stat.) \pm 0.29(syst.)}$ × Rapp

Results in agreement with:

- **HF suppression**
- **Thermal contribution** in the order of Rapp

The future

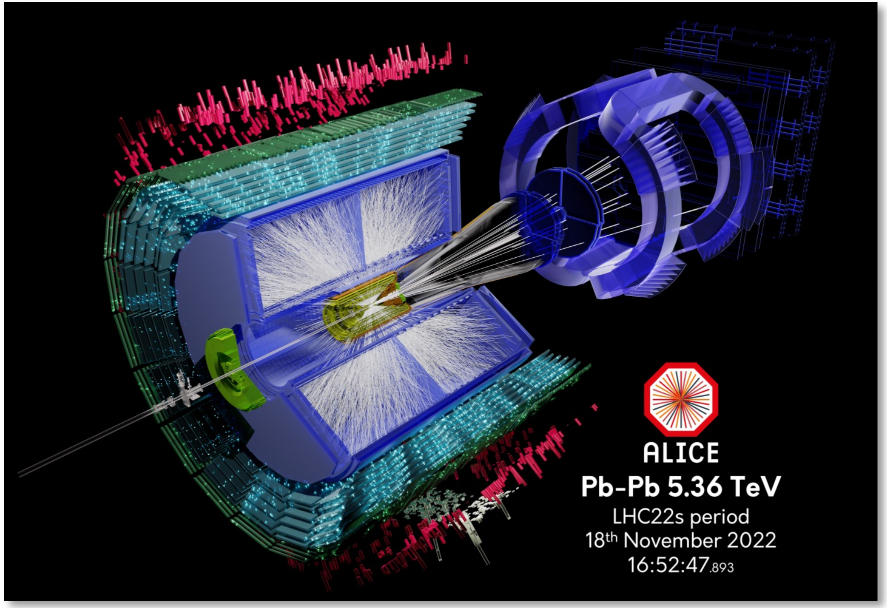


Future dielectron measurements require:

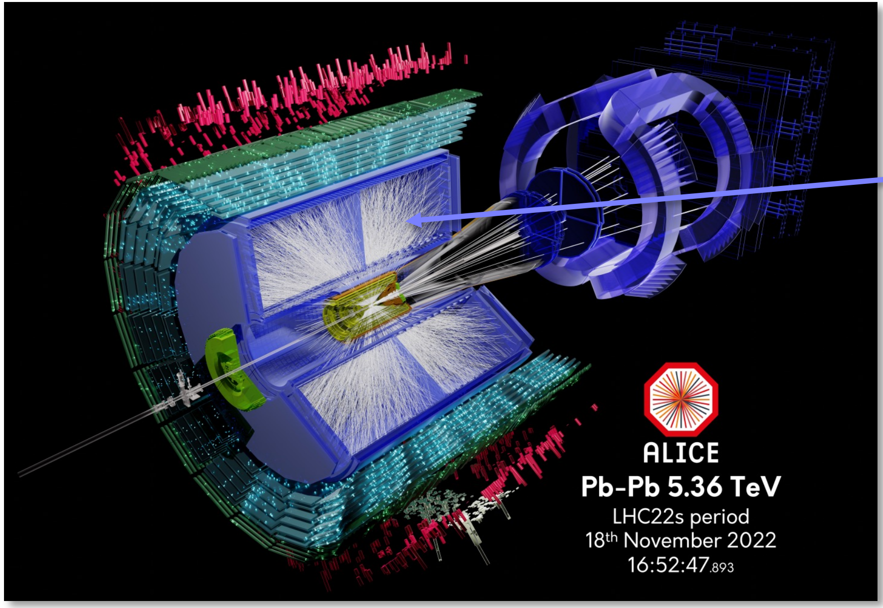
- much more statistics
- significant improvement of vertex resolution

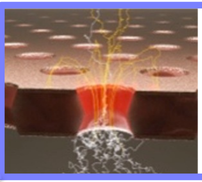
ALICE 2 in Run 3 and 4
ALICE 3 in Run 5 and 6

ALICE 2 in Run 3



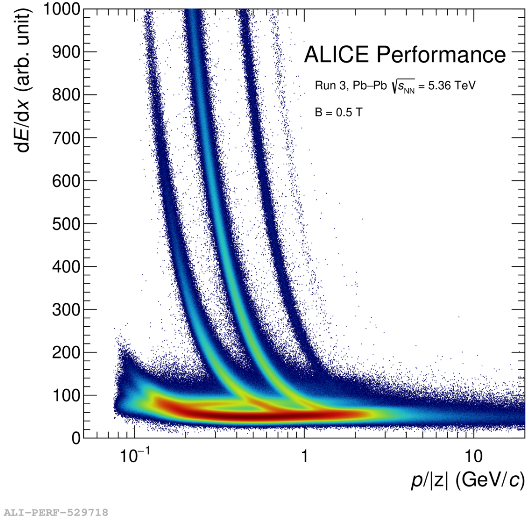
ALICE 2 in Run 3





New TPC readout system

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



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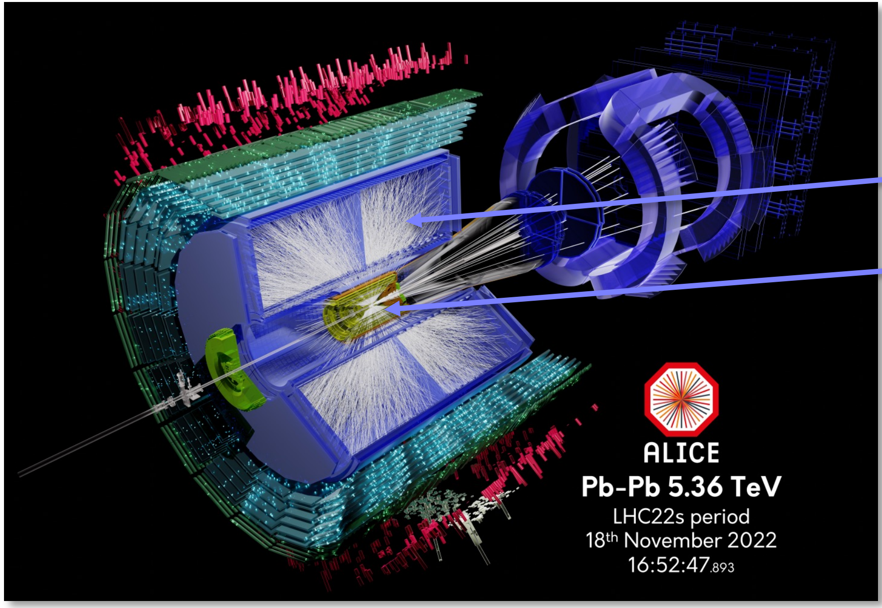

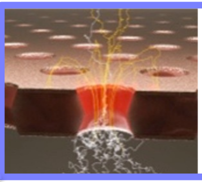

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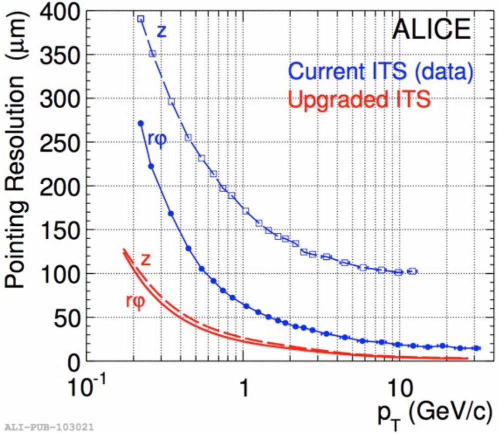
- CMOS MAPS technology
- better resolution, less material, faster readout



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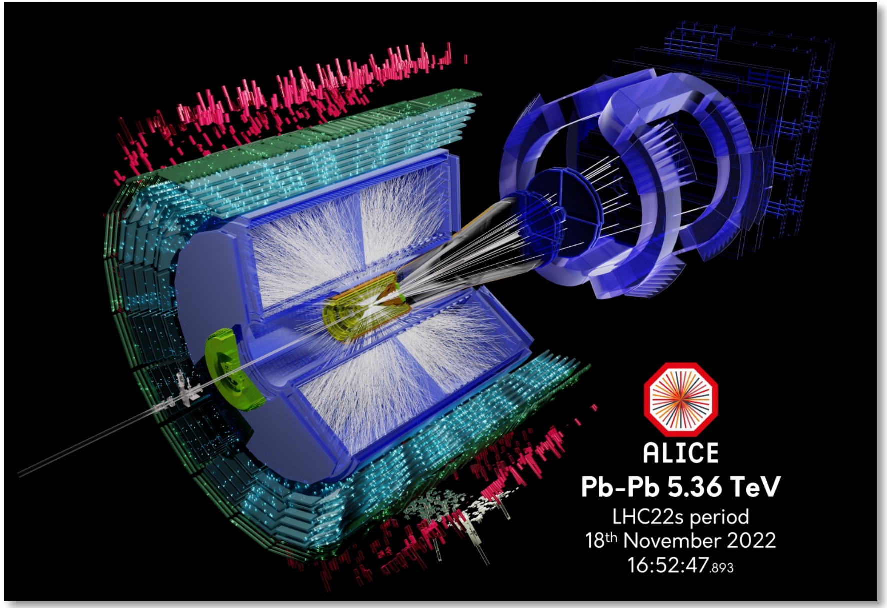

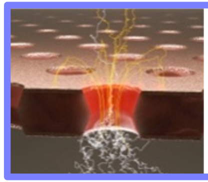

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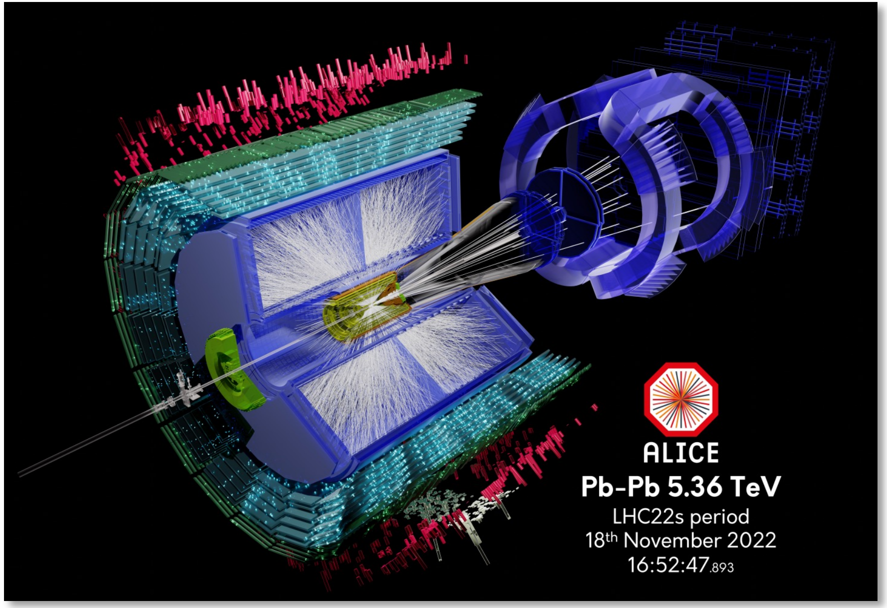
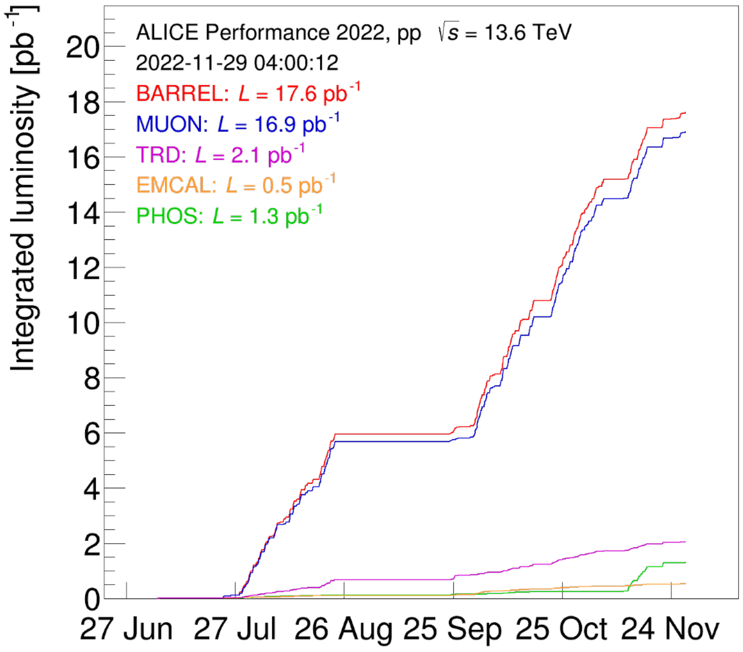
Integrated online-offline system O^2

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

ALICE 2 in Run 3

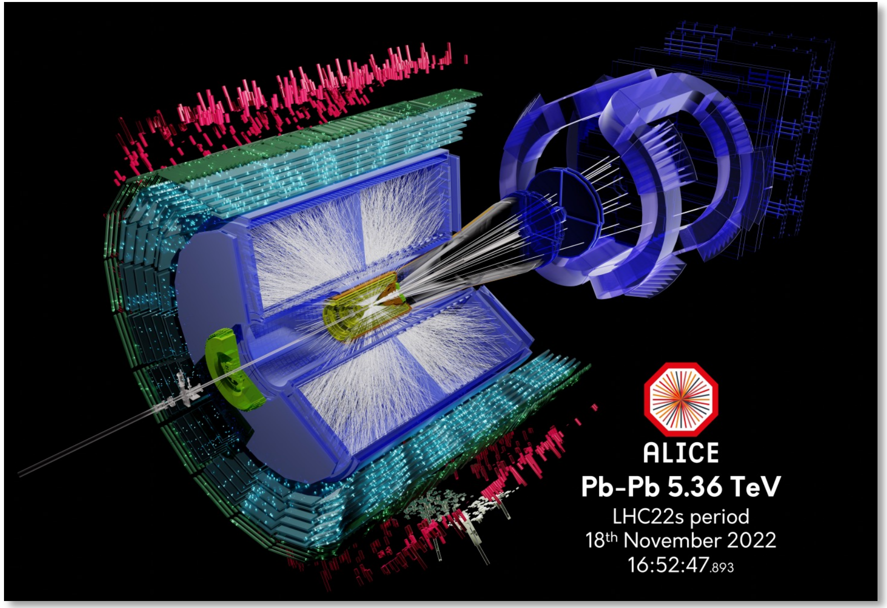


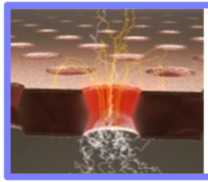


$700 \cdot 10^9$ pp events at 13.6 TeV recorded in 2022

→ **factor ~400** more pp data than in Run 1 and 2

ALICE 2 in Run 3





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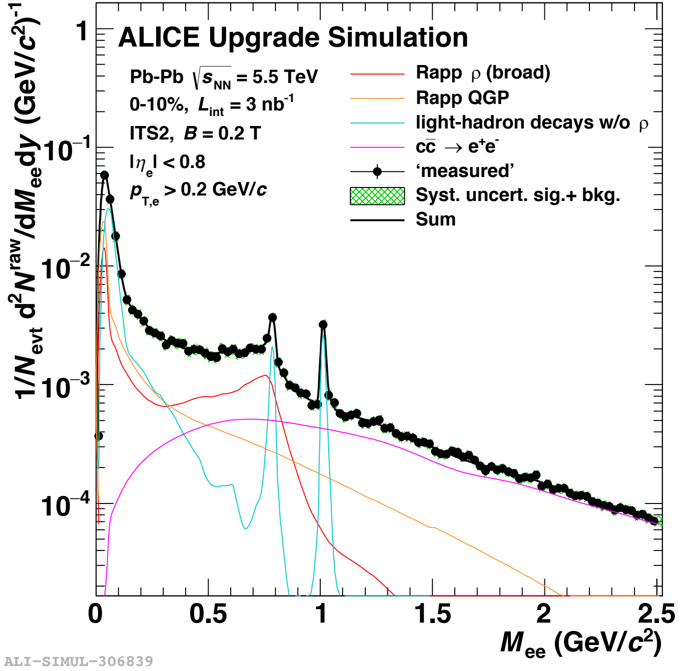
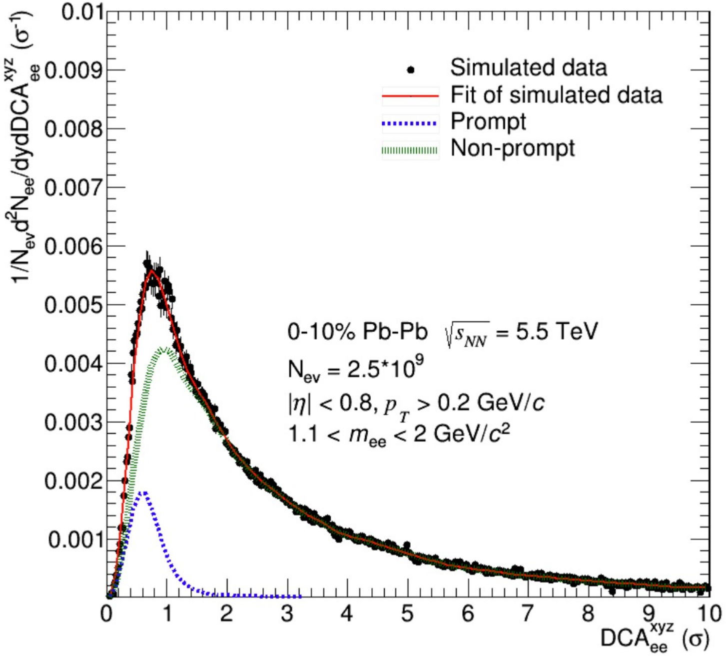
→ ALICE 2 will be a **game changer** in the field

Dielectron mass spectrum in Run 3

Z. Citron et al., CERN Yellow Rep. Monogr. (2019) 1159





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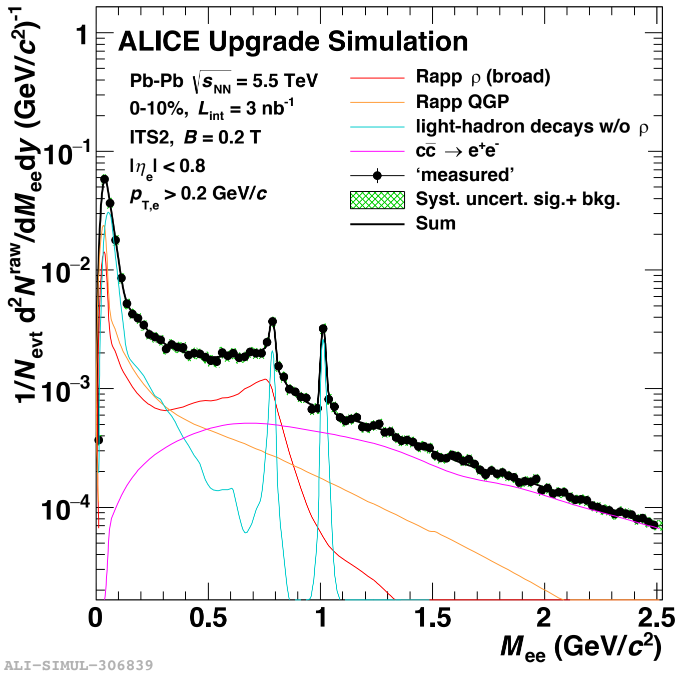
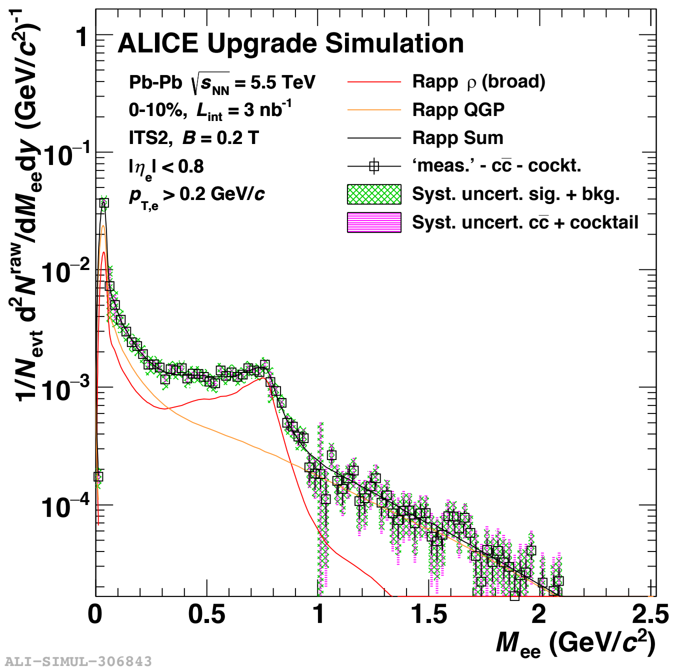
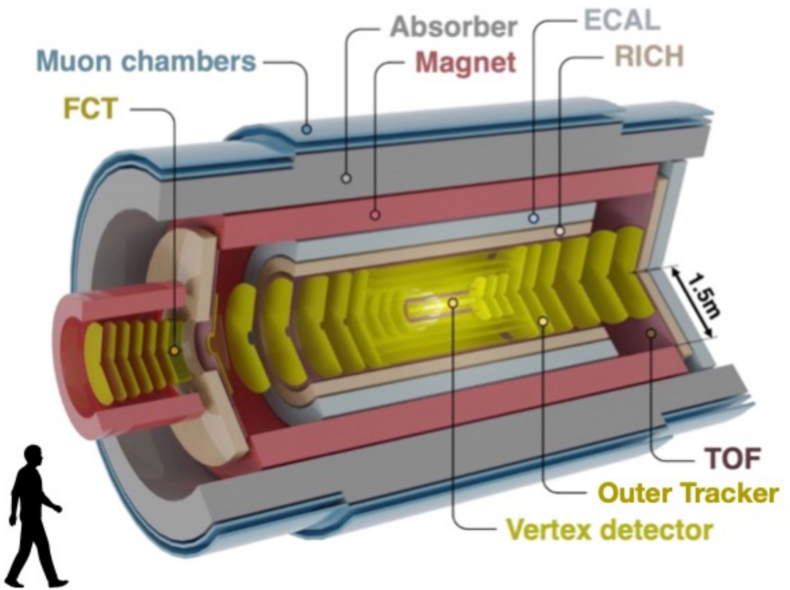
Z. Citron et al., CERN Yellow Rep. Monogr. (2019) 1159





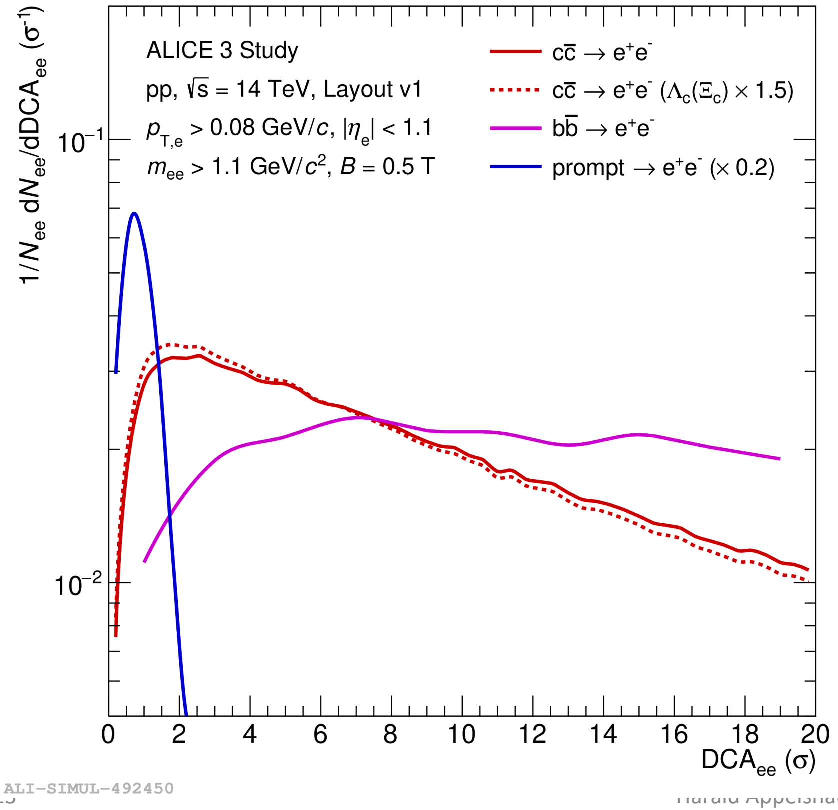
Dielectrons with ALICE 3

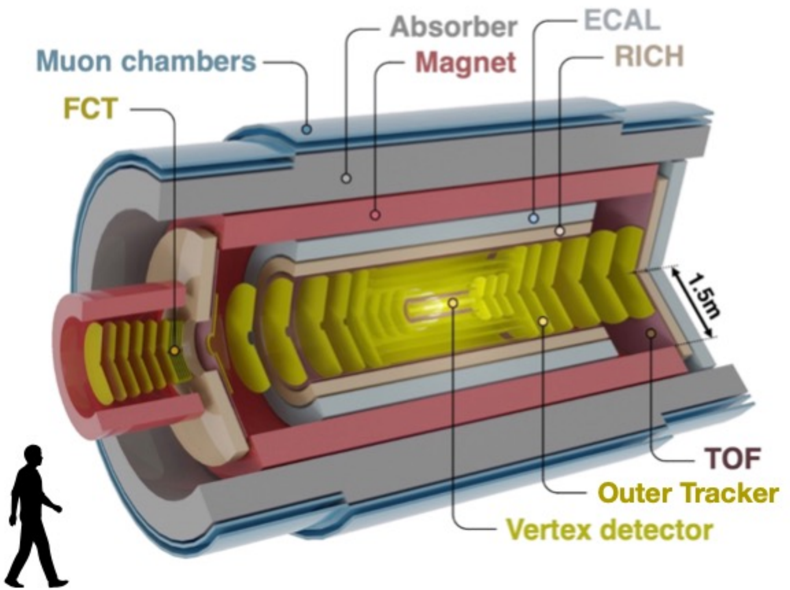
arXiv:2211.02491



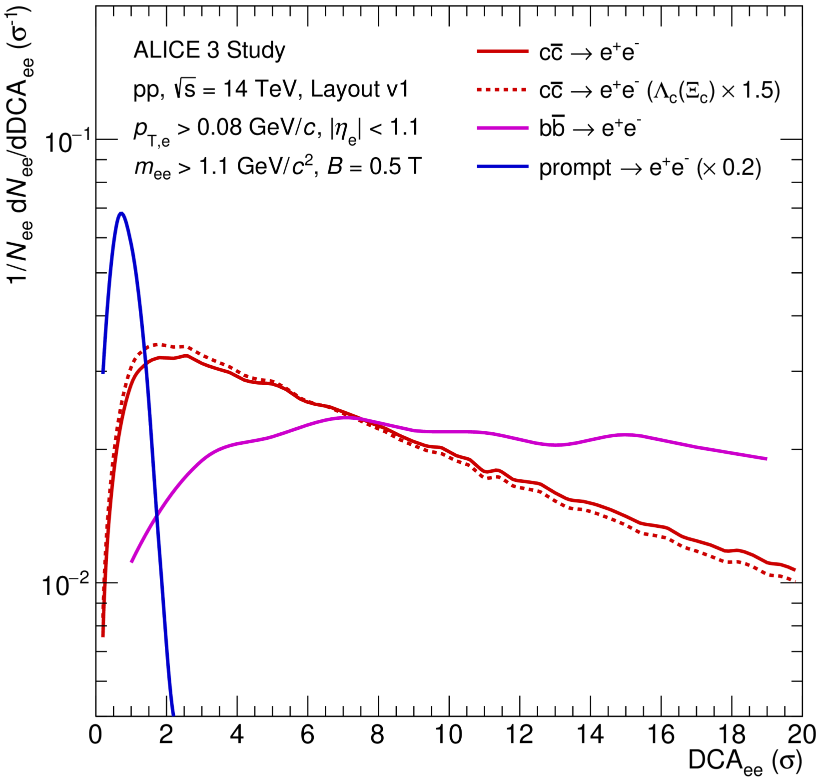
- Multiply heavy-flavored hadrons: Ξ_{cc}, Ω_{cc}, Ω_{ccc}
- X,Y,Z charmonium-like states (e.g. X(3872))
- Light exotic nuclei with charm baryons and multiple hyperons up to A=6
- Thermal EM radiation, chiral symmetry restoration
- Soft theorems

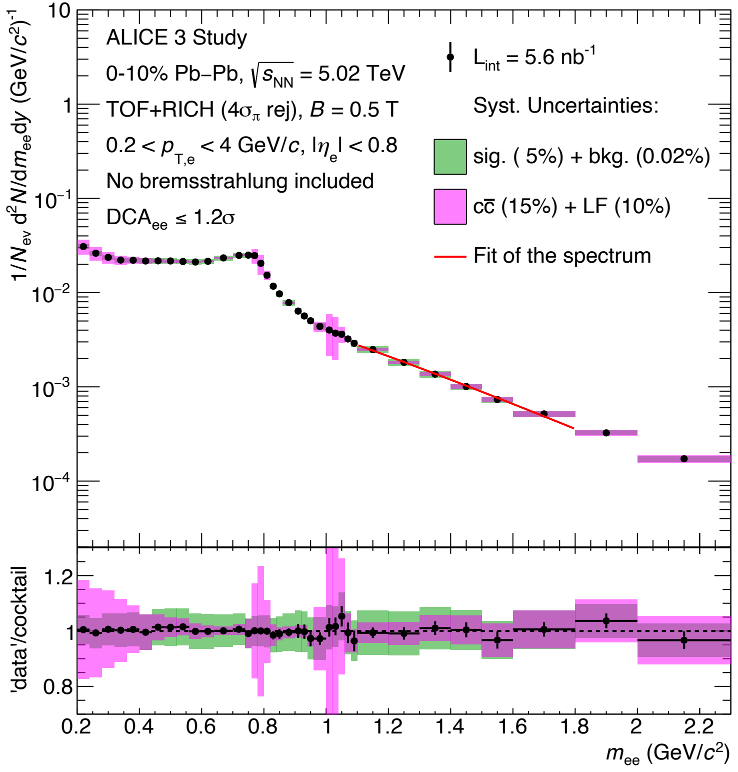
Dielectrons with ALICE 3





Dielectrons with ALICE 3





ALI-SIMUL-492450

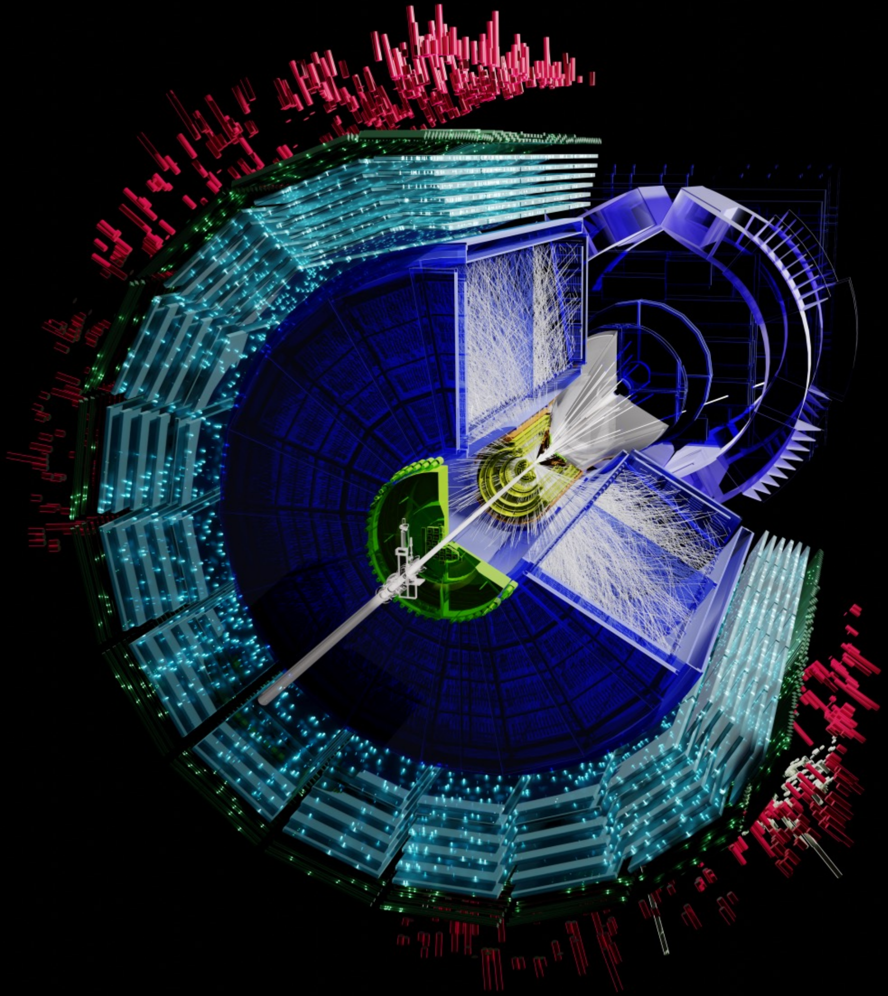
Summary

- EM probes provide **unique access** to the hot and dense phase of the system

- Dielectrons are challenging but **have a large potential** with future 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



Tom Cormier 1947-2022

ALICE

Pb-Pb 5.36 TeV

LHC22s period

18th November 2022

16:52:47.893

Backup

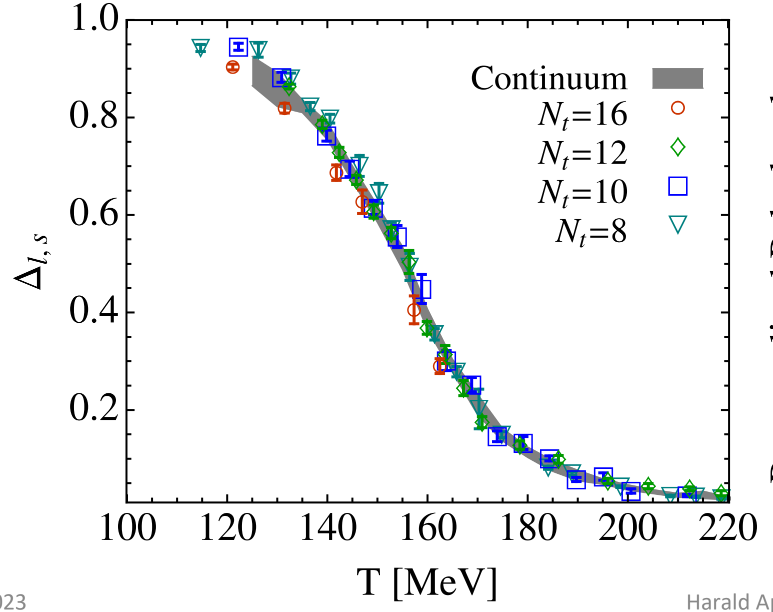
Low mass: chiral symmetry restoration

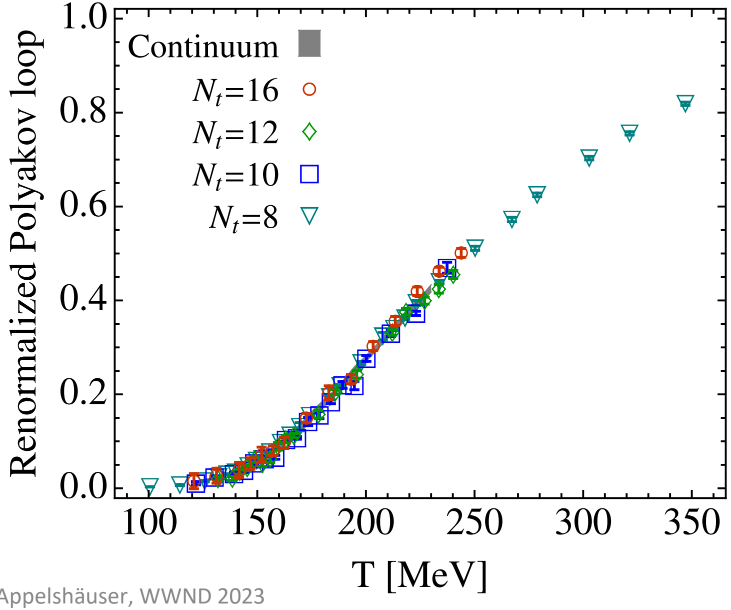
LQCD: chiral transition region (T = 130-170 MeV) in confined phase

→ observable via in-medium properties of hadrons, i.e. the ρ-meson:

$J^P = 1^-$, $c\tau$ = 1.3 fm

→ thermal radiation in the low mass region (m_{ee} < 1 GeV/c^2)

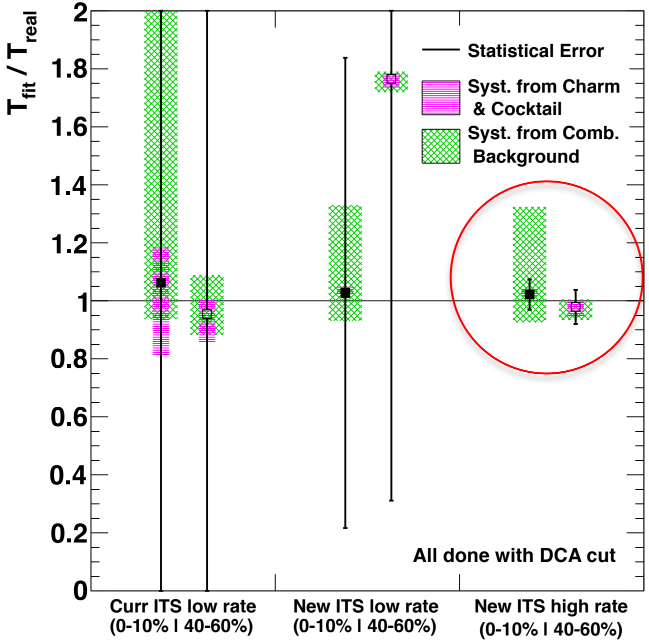


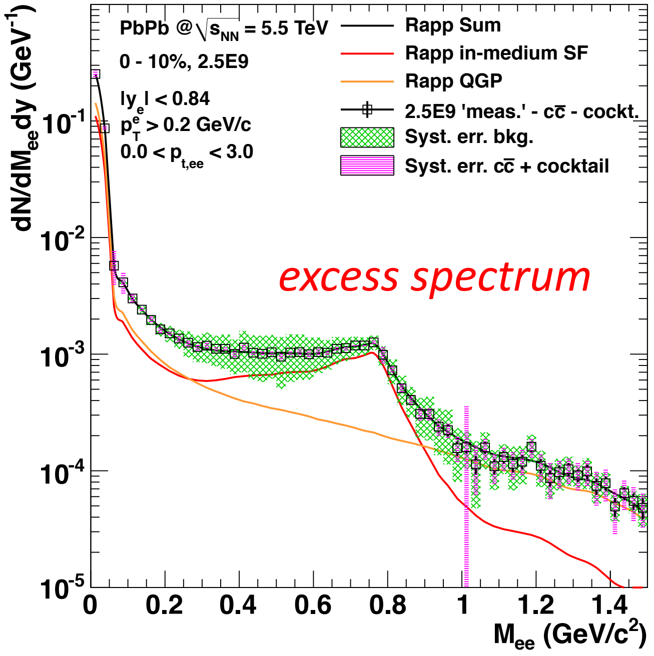


J. Borsanyi et al., JHEP 1009 (2010)

Excess mass spectrum and QGP temperature

ALICE LoI J. Phys. G41 (2014)

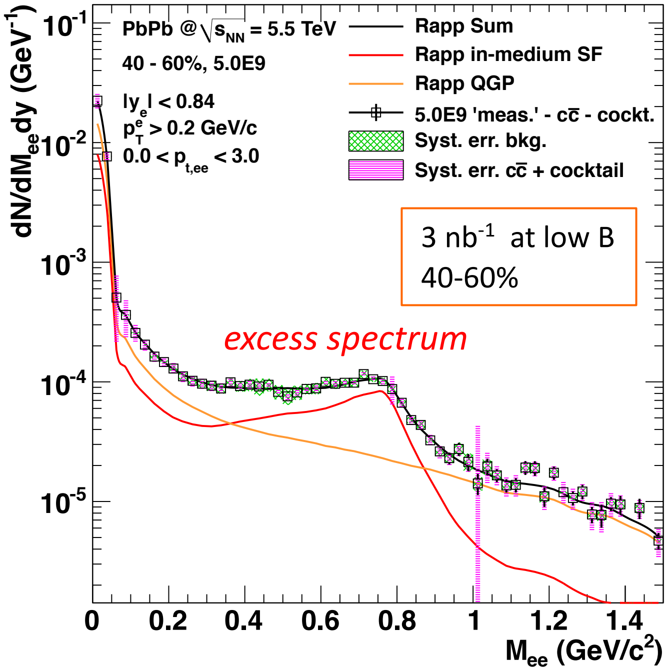


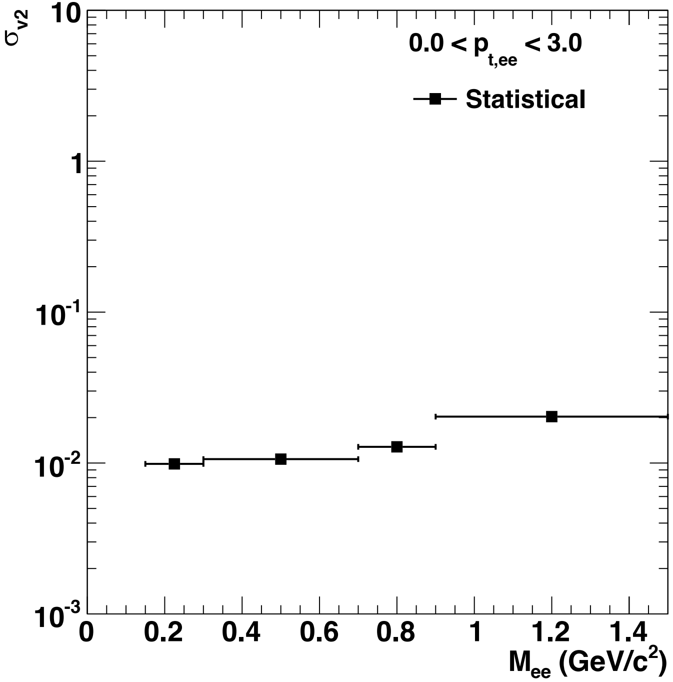


Fit to the IMR makes precise determination of T_{eff} possible

Flow of QGP radiation

ALICE LoI J. Phys. G41 (2014)



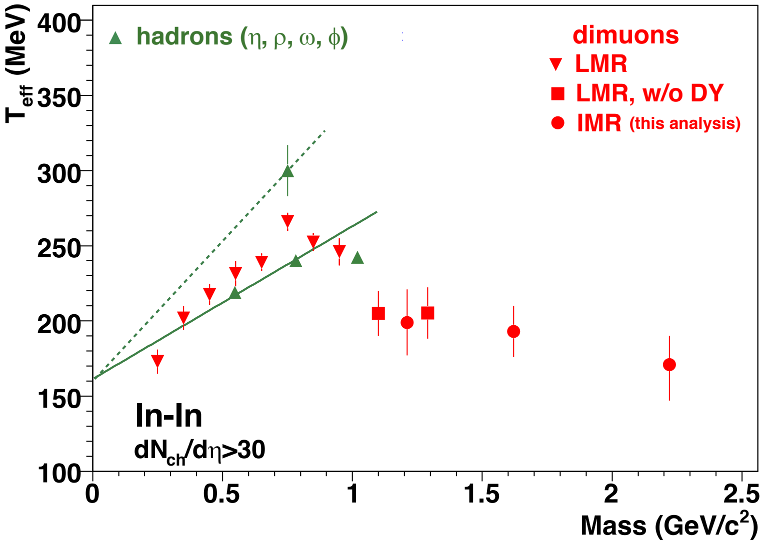


Statistical precision of v_2 measurement: 0.01-0.02

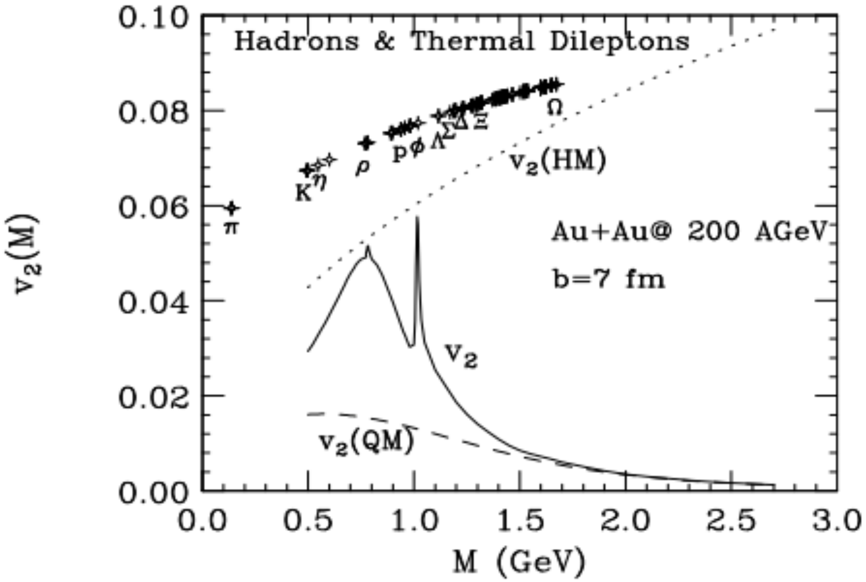
Space-time evolution

- Transverse momentum spectra contain information on collective radial and elliptic flow (T_{eff} and v_2)
- Mass dependence gives access to EoS of QGP

NA60, EPJ C61 (2009) 711



Chatterjee, Srivastava, Heinz, Gale PRC 2008



EM spectral function

- Dilepton yield: space-time integral over thermal emission rate:

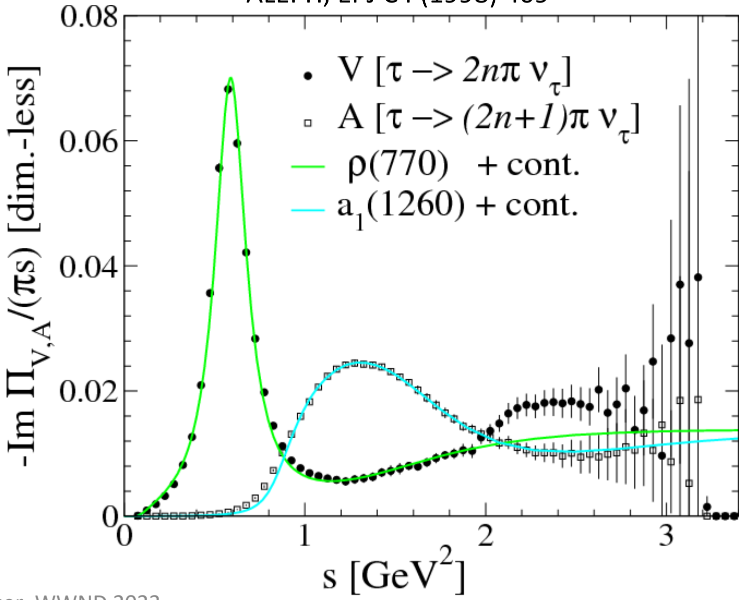
$$\frac{dN_{ee}}{d^4x d^4q} = -\frac{\alpha^2}{\pi^3 m_{ee}^2} f^{BE}(q_0,T)\,\mathrm{Im}_{EM}(m_{ee},q,\mu_B,T)$$

- V and A spectral function in vacuum:
  chiral symmetry breaking

- Spectral functions change in medium:
  key to chiral symmetry restoration

- The messenger: ρ-meson modification
  $c\tau_\rho$ = 1.3 fm

ALEPH, EPJ C4 (1998) 409

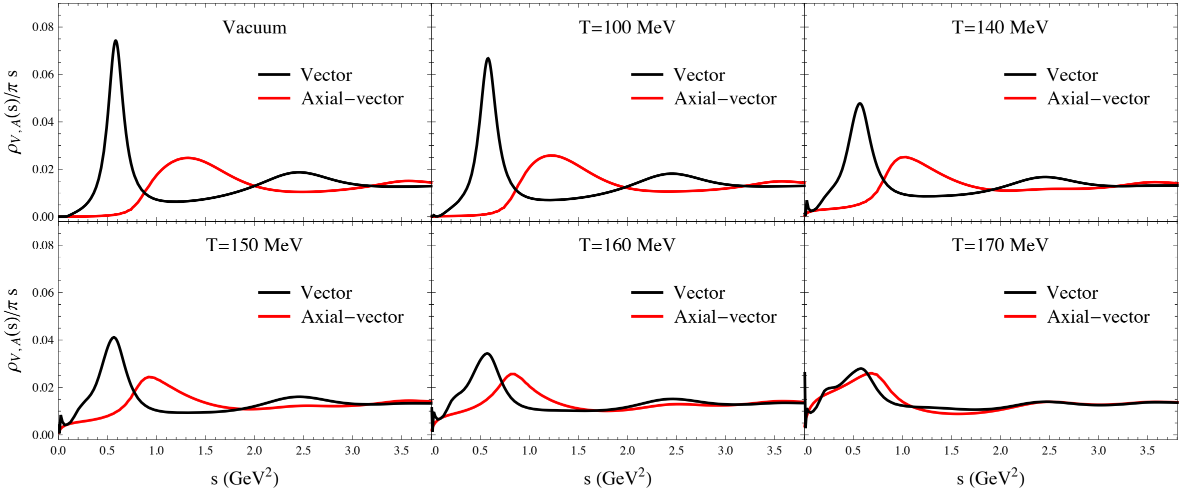


Chiral symmetry restoration

CSR ←→ vector-axialvector degeneracy (ρ-a_1)

Axial-vector experimentally inaccessible (a_1→πγ)

P. Hohler, R. Rapp, Phys. Lett. B731 (2014) 103



Vector spectral function in medium exhibits ρ – melting

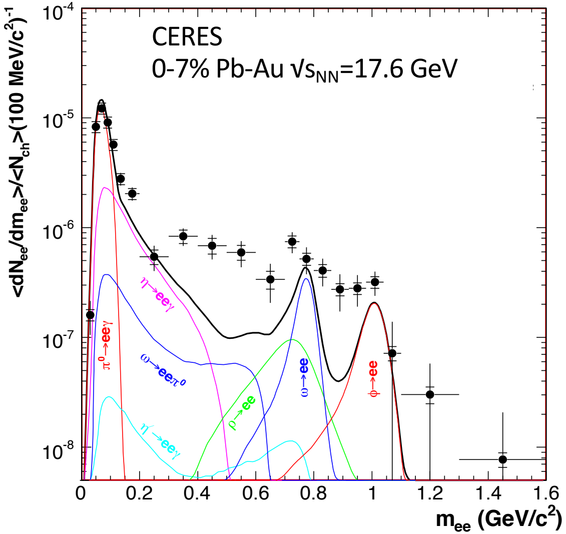
Towards CSR: connection to axial vector requires constraints from theory (LQCD, sum rules)

→ Possible at μ_B=0

SPS – ρ-melting

- Dielectron yield in A-A shows significant low-mass excess over hadronic decays

CERES, PLB 666 (2008) 425



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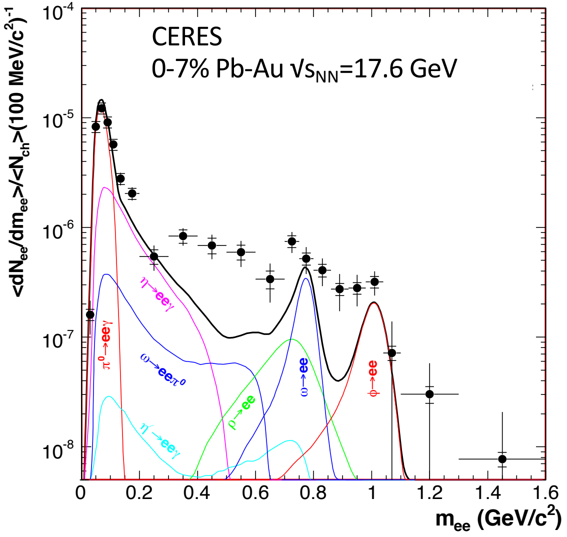
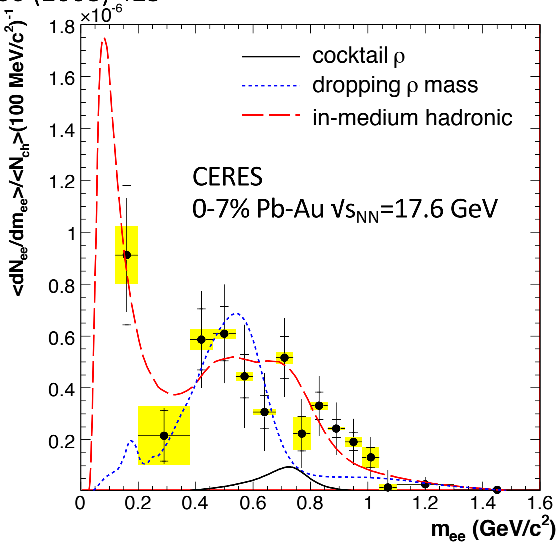
CERES, PLB 666 (2008) 425





- Excess is compatible with strong in-medium modifications of the ρ-meson, well described by hadronic many-body theory

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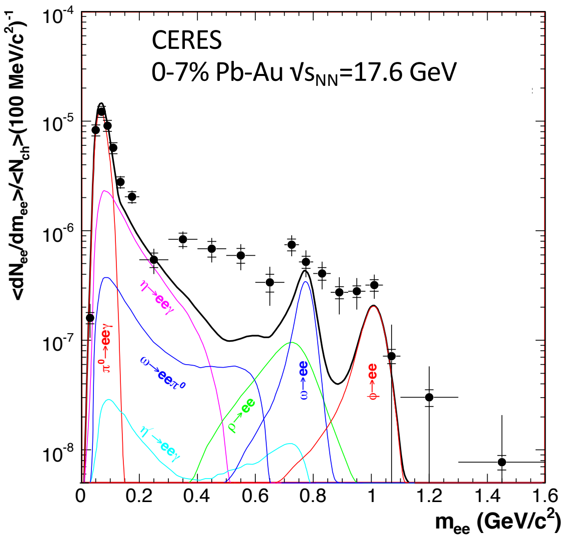
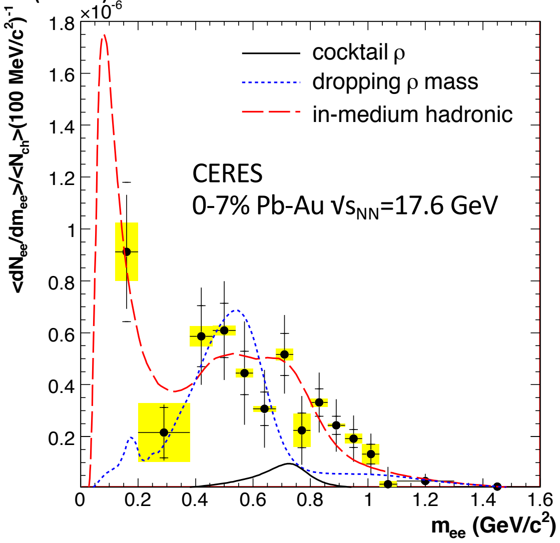
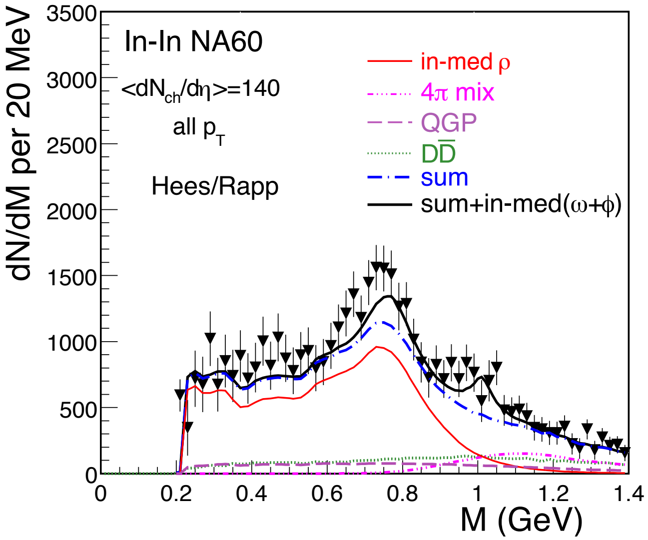
CERES, PLB 666 (2008) 425





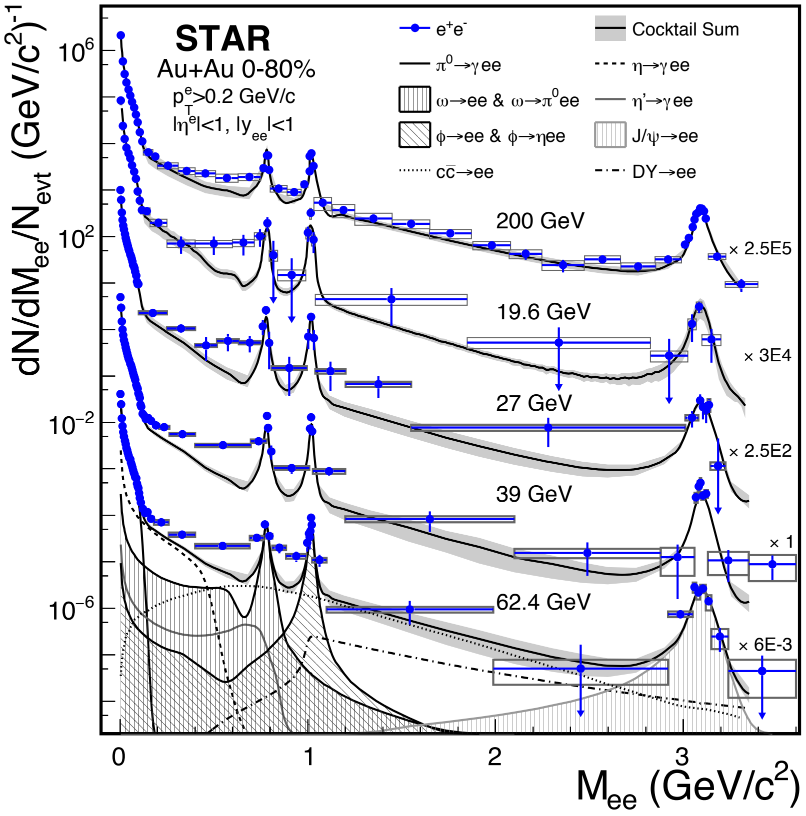
NA60, EPJ C61 (2009) 711



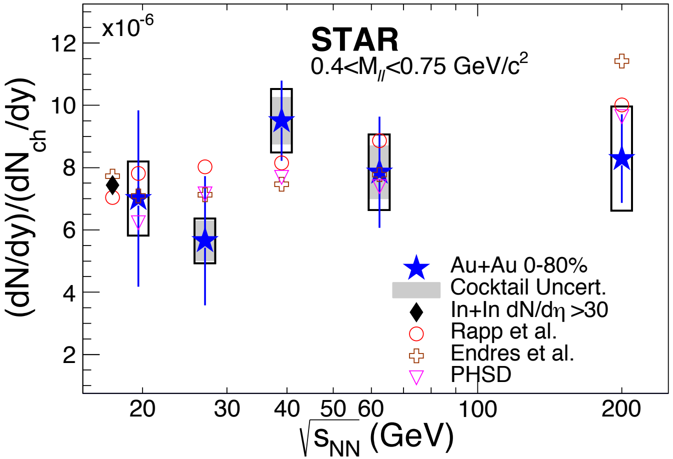
- Excess is compatible with strong in-medium modifications of the ρ-meson, well described by hadronic many-body theory
- Confirmed by high-precision dimuon data – ρ-melting established

RHIC Beam Energy Scan (BES)

STAR arXiv:1810.10159

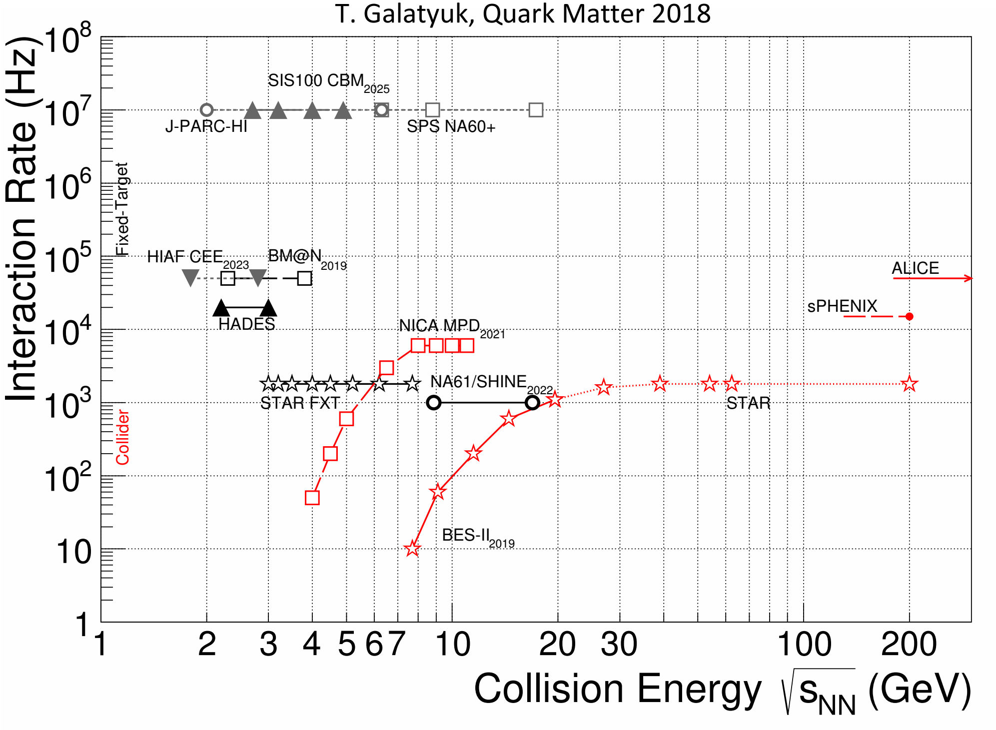


STAR arXiv:1810.10159



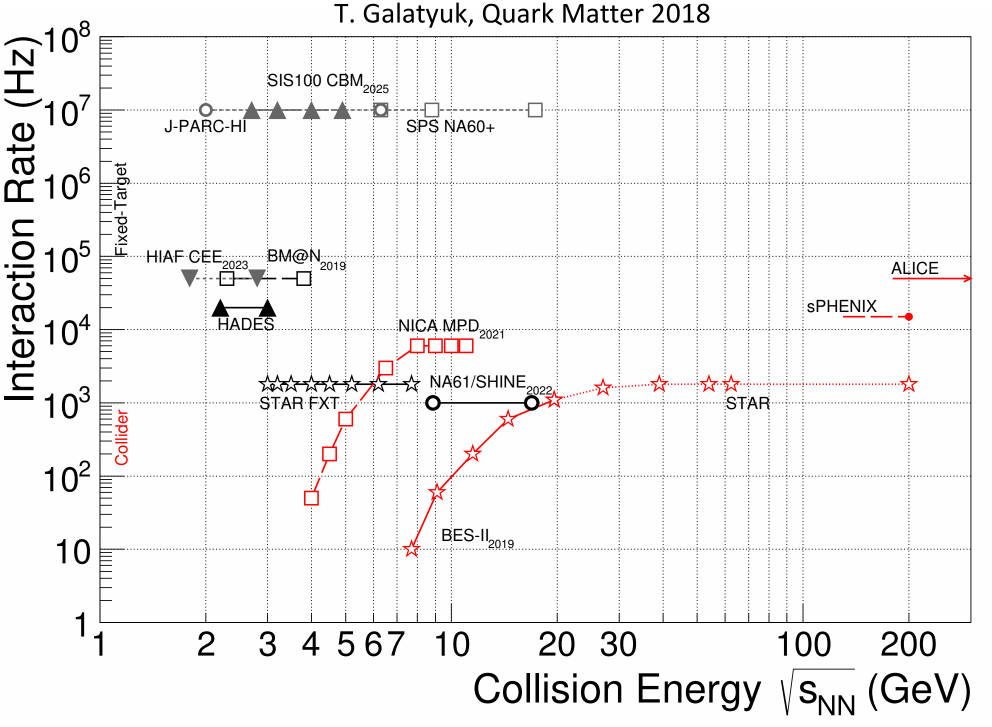
- STAR measures Au-Au in fixed-target and collider mode in $3.5 < \sqrt{s_{NN}} < 200$ GeV
- Results from BES1 available
- BES2 ongoing

Mapping the QCD phase diagram with dileptons



Detailed mapping of the QCD phase diagram with dileptons expected in this decade

Mapping the QCD phase diagram with dileptons

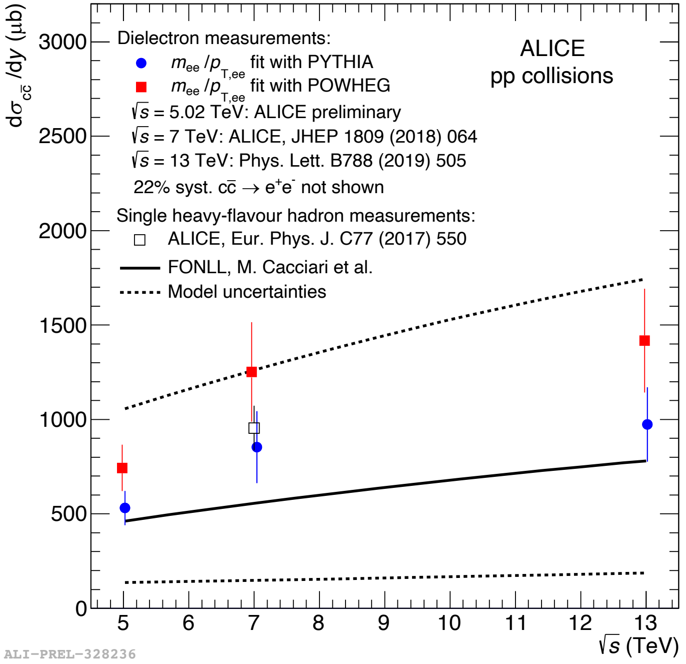


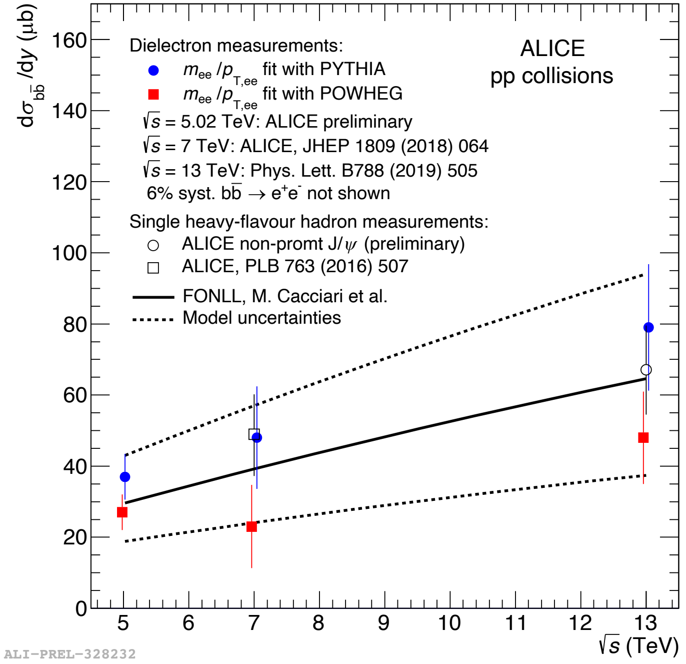
Detailed mapping of the QCD phase diagram with dileptons expected in this decade

What happens at the energy frontier?

Heavy-flavour cross sections in pp

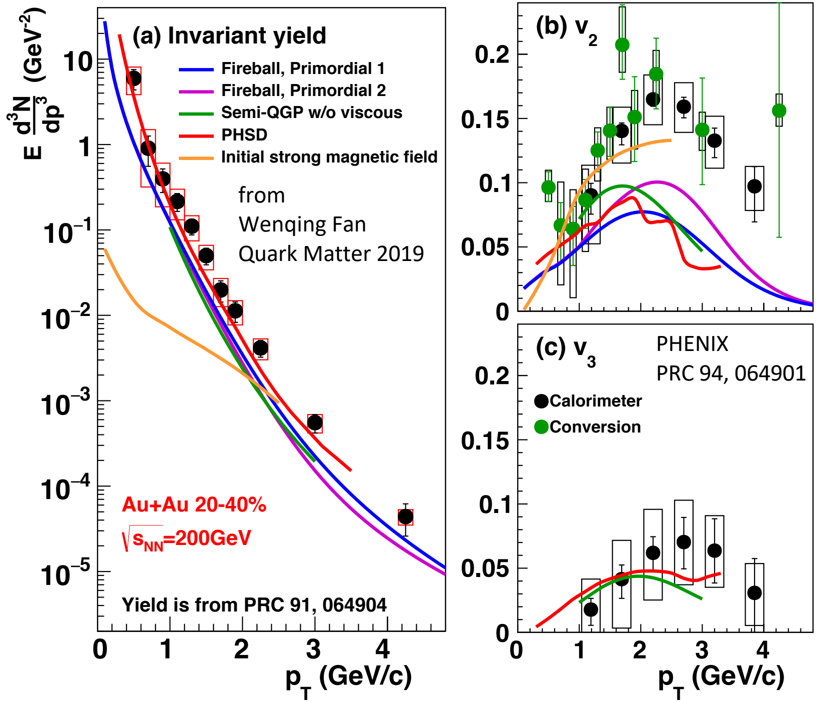
S. Scheid (ALICE) QM2019

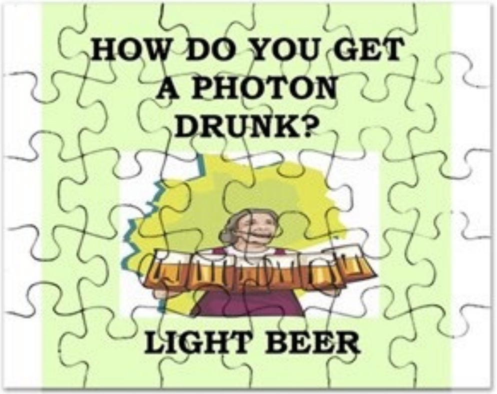




- PYTHIA and POWHEG give systematically different results
  → access to different production mechanisms
- Compatible with FONLL calculations

Photons puzzle





Direct photons (at RHIC) show:

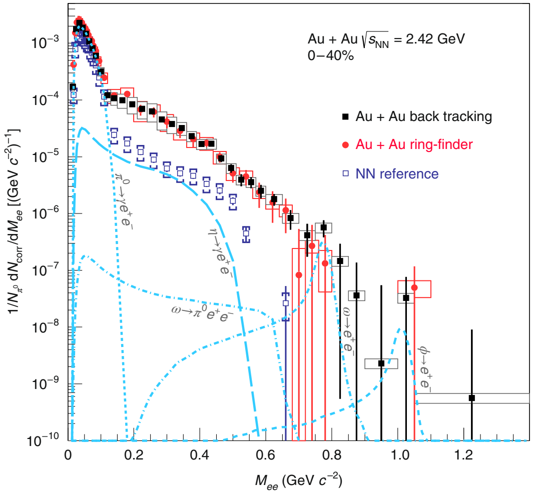
- large yields (indicative of early emission)
- large collectivity (i.e. v_2, indicative of late emission)
- Hard to reconcile in models
- „Direct-photon puzzle“

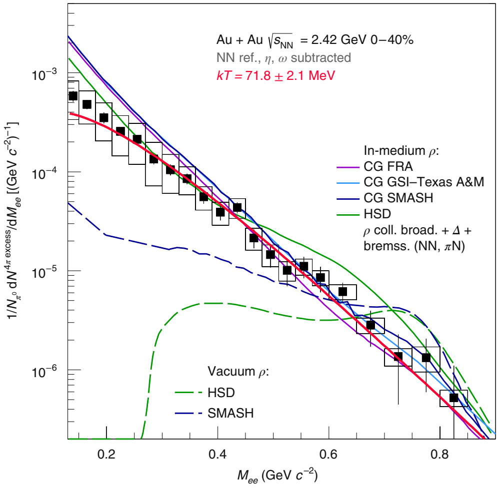
- Early and late emission times of photons are not separable
- Worst case: Early QGP radiation could be outshined by late hadronic processes

Hadronic radiation - HADES

- Large enhancement in Au-Au at $\sqrt{s_{NN}}$ = 2.42 GeV
- Excess compatible with hadronic thermal radiation and a strong medium modification of the ρ
- Exponential fit yields T = 71.8 ± 2 MeV

HADES Nature Phys. 15 (2019) 1040

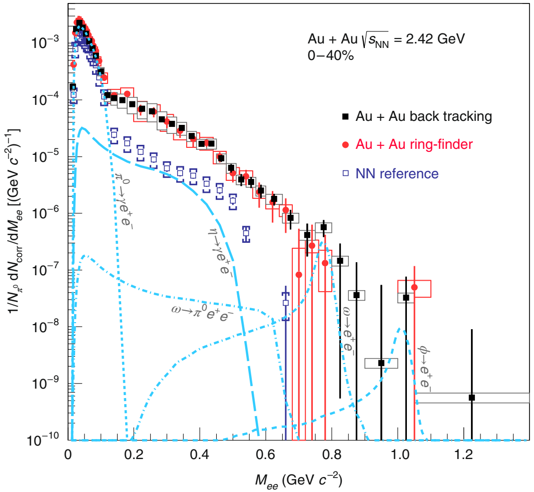


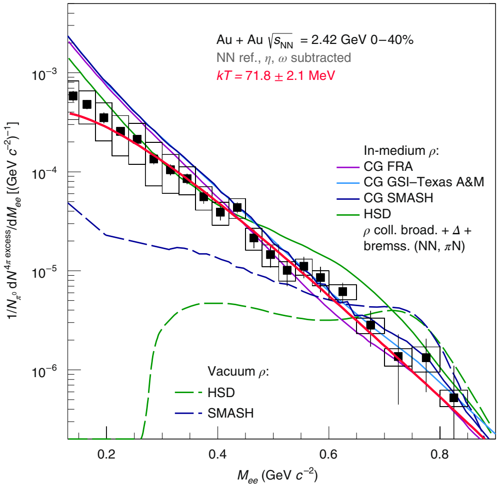


Excitation function

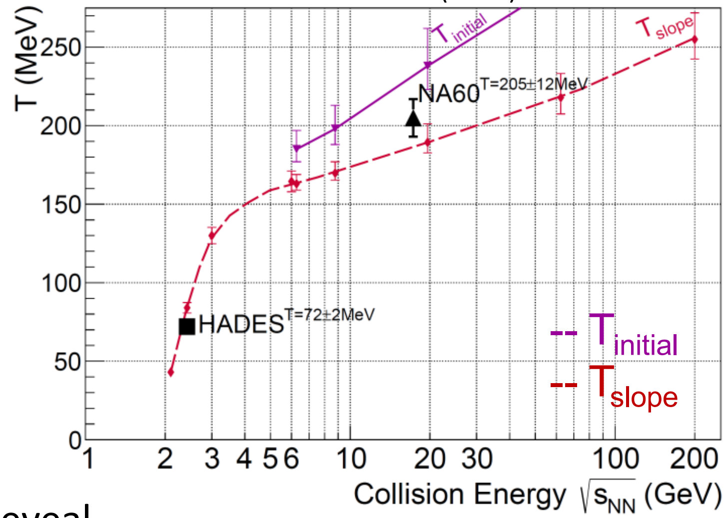
- Large enhancement in Au-Au at $\sqrt{s_{NN}}$ = 2.42 GeV
- Excess compatible with hadronic thermal radiation and a strong medium modification of the ρ
- Exponential fit yields T = 71.8 ± 2 MeV

HADES Nature Phys. 15 (2019) 1040



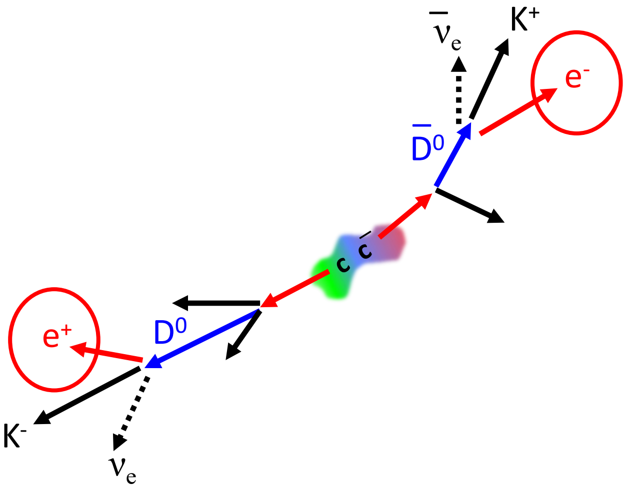


Rapp, v.Hees PLB 753 (2016) 586
HADES Nature Phys. 15 (2019) 1040
NA60 EPJ C59 (2009) 607

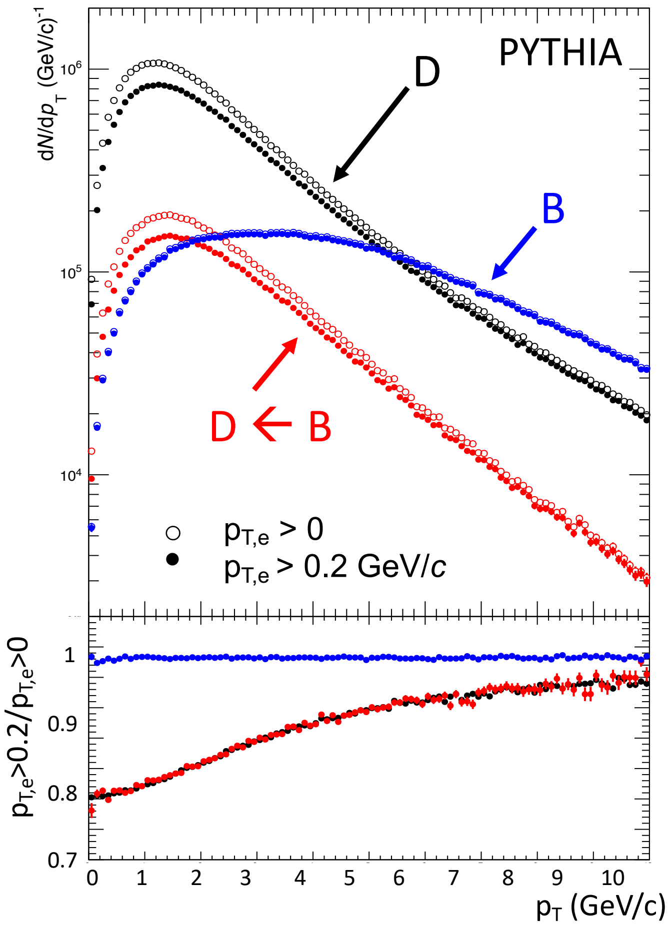


- Energy dependence of temperature measurement may reveal a plateau in the caloric curve, suggesting 1st order phase transition
- Systematic beam energy scan is important

Dielectrons from charm and beauty

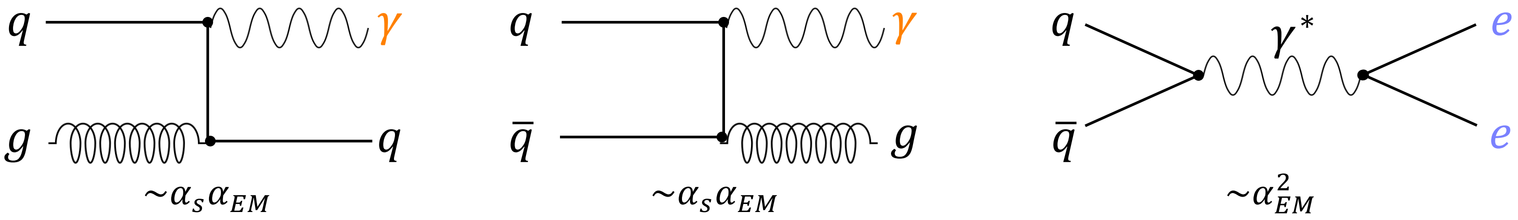


Typical single-electron low-$p_{T,e}$ cut preserves most of the heavy-flavour cross-section at mid-rapidity



Photons or dileptons

- 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 combinatorial background and **hadron decays**



- Photons integrate over space-time evolution, different collision stages **cannot be distinguished (aka *direct photon puzzle*)**
- Dielectrons do as well but **carry mass which can serve as a clock**