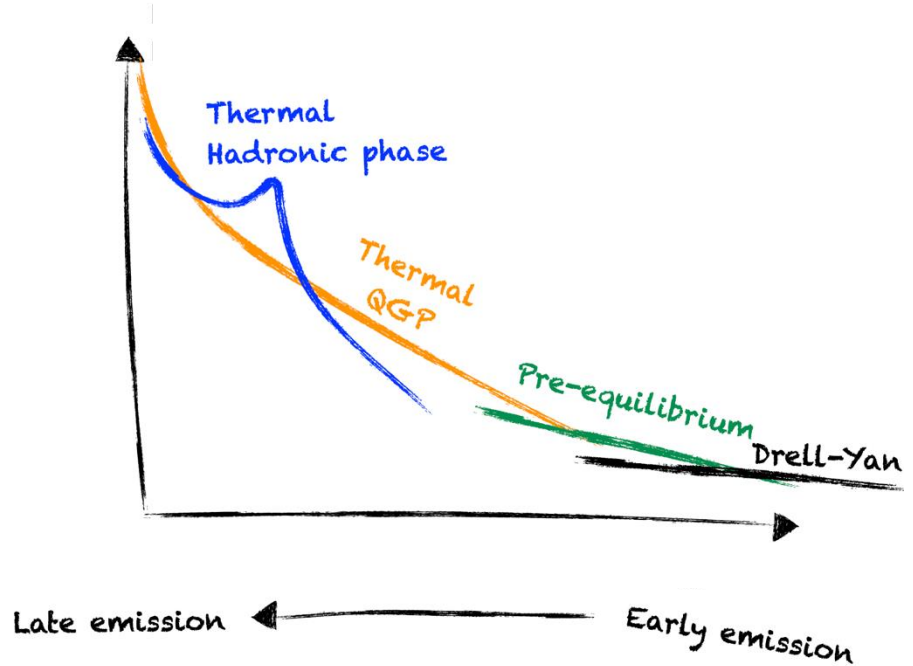


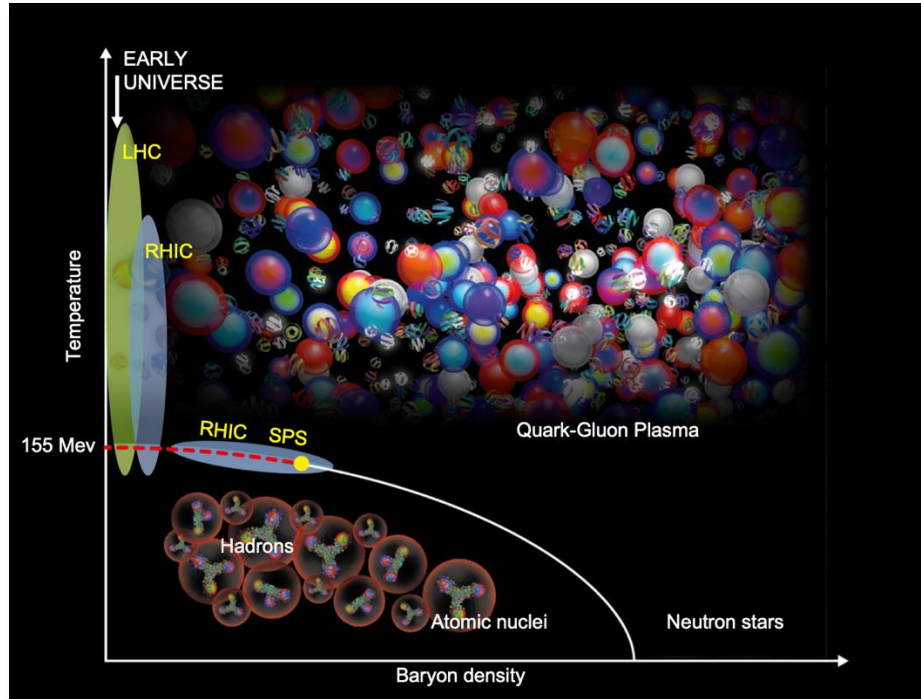


Beyond chemical freeze-out

Harald Appelshäuser
Goethe University Frankfurt



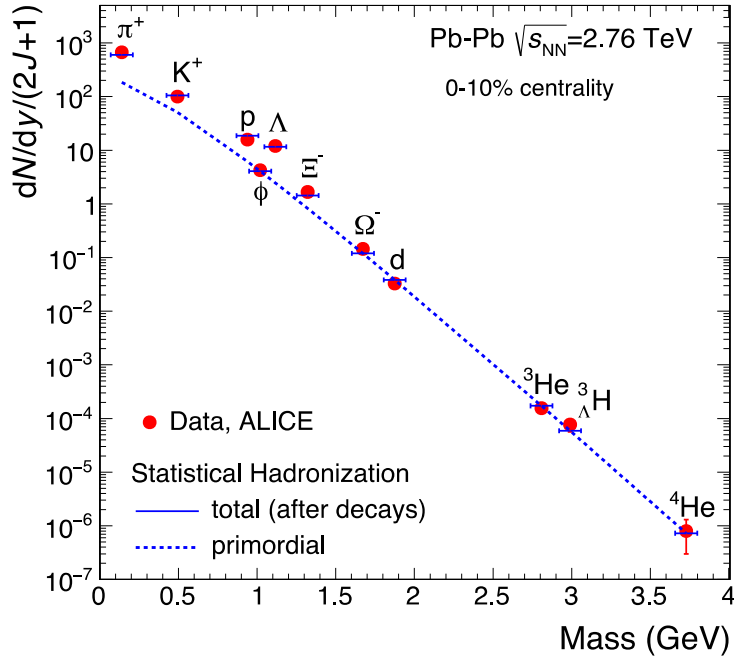
Quark Gluon Plasma - the playground of QCD



- Lattice QCD predicts state of deconfined QCD matter at high temperatures – QGP
- Governed the fate of the early universe in the first few microseconds
- Can be produced in heavy ion collisions (HICs) but for not quite as long

Final state hadrons

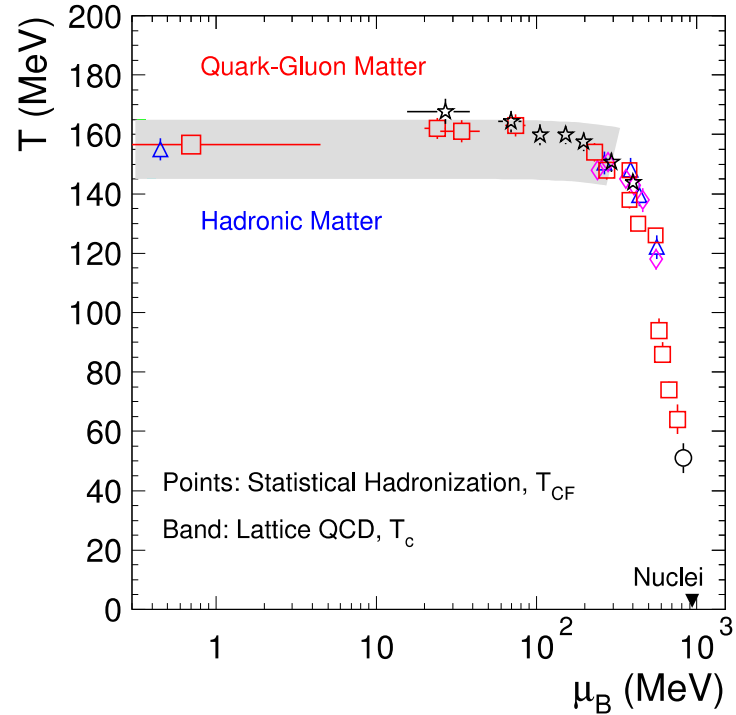
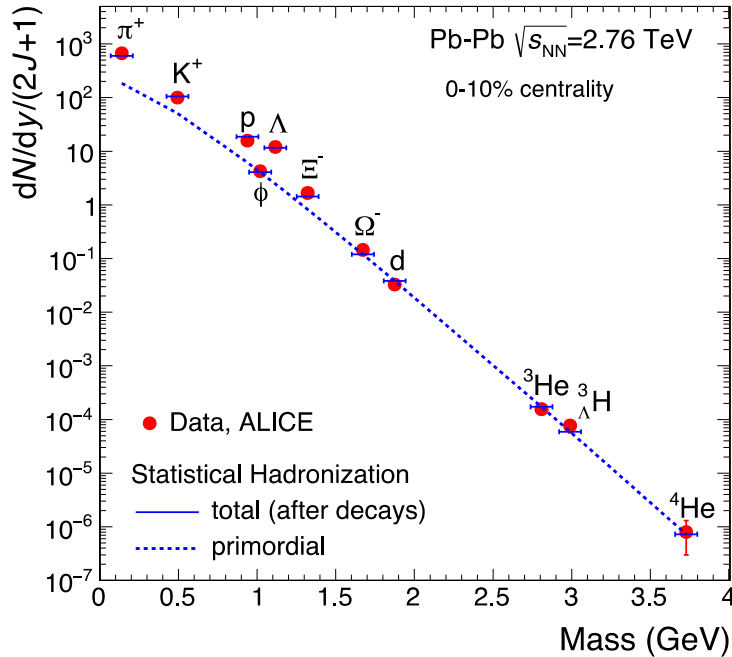
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel,
Nature 561 (2018) no.7723, 321



- final state hadrons reflect **equilibrium state at T_c**

Final state hadrons

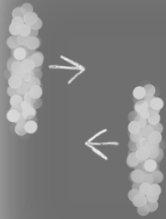
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel,
Nature 561 (2018) no.7723, 321



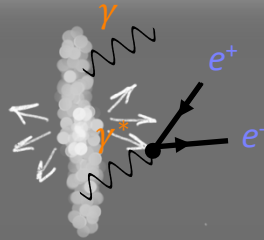
- final state hadrons reflect **equilibrium state at T_c**

Photons and dileptons

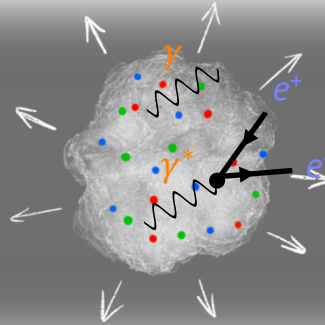
- are produced **at all stages** of the collision
- leave the system **without strong FSI** – **soft but penetrating**
 - messengers of **QGP properties**



**hard scattering,
pre-equilibrium**



thermal QGP
($T > T_c$)



thermal hadronic
($T < T_c$)
hadronic decays

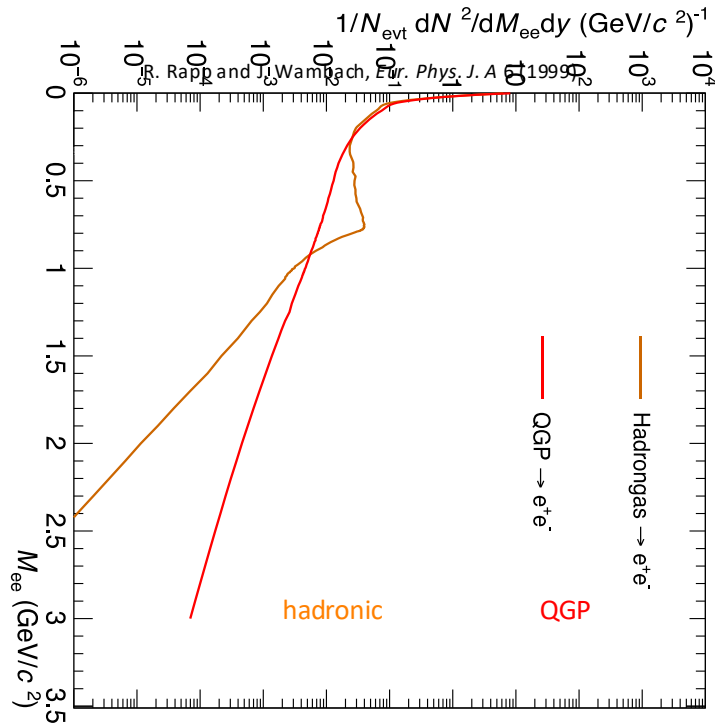
$\pi, \eta, \eta', \omega, \rho, \phi, J/\psi, c\bar{c}, b\bar{b}$

Dileptons

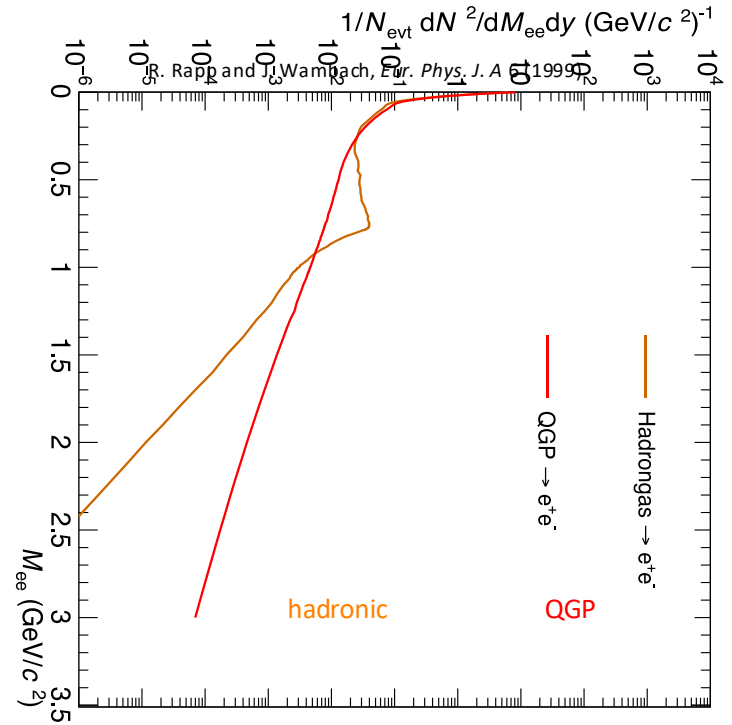
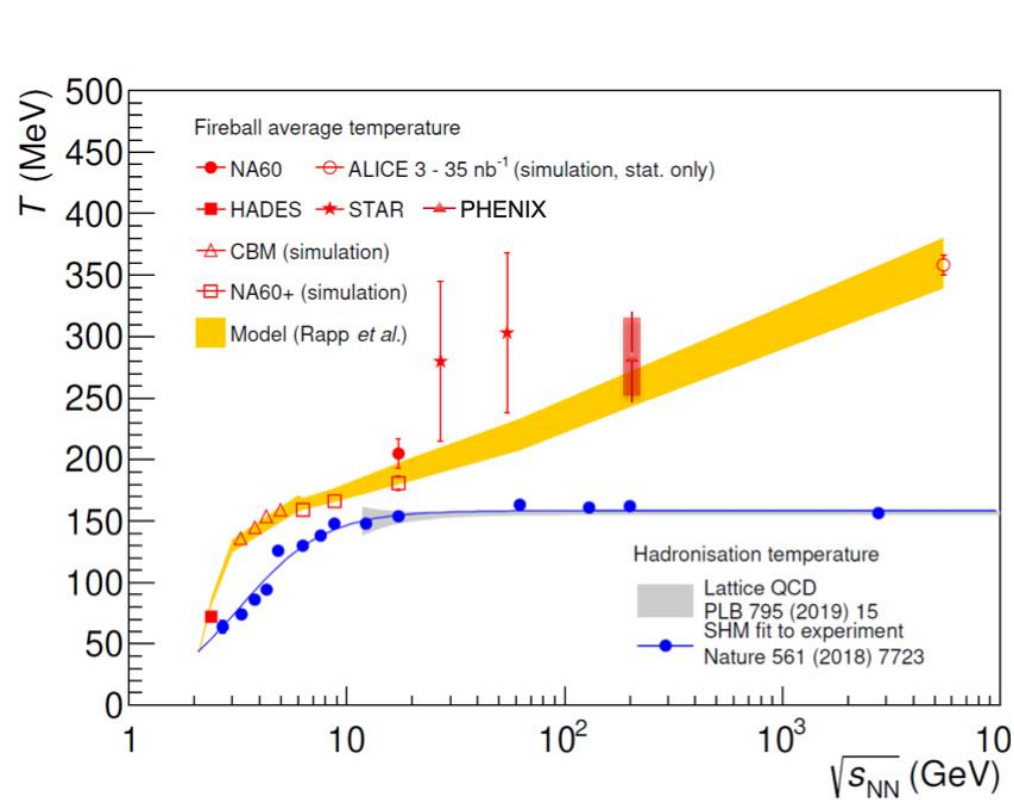
- dilepton yield: space-time integral over **thermal emission rate**:

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

- 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

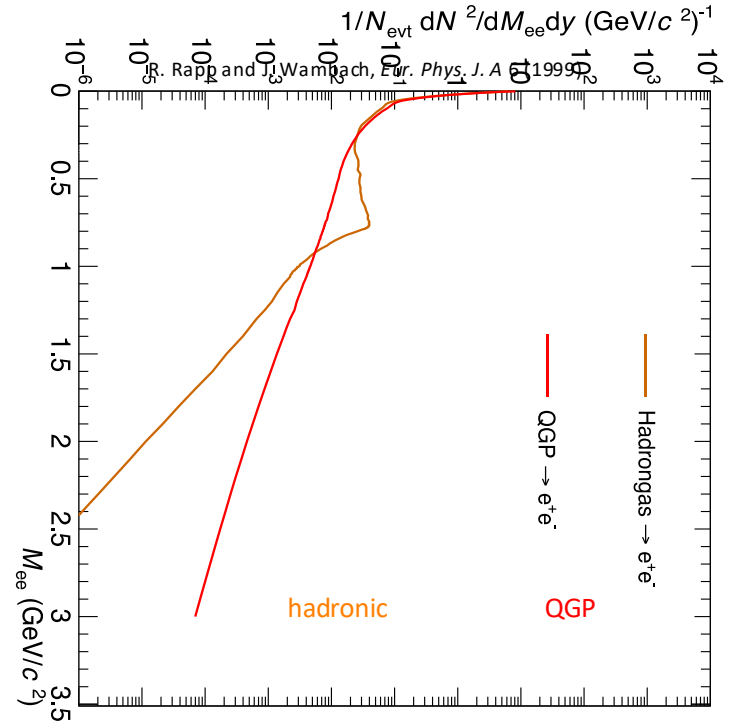


Dielectrons at the LHC



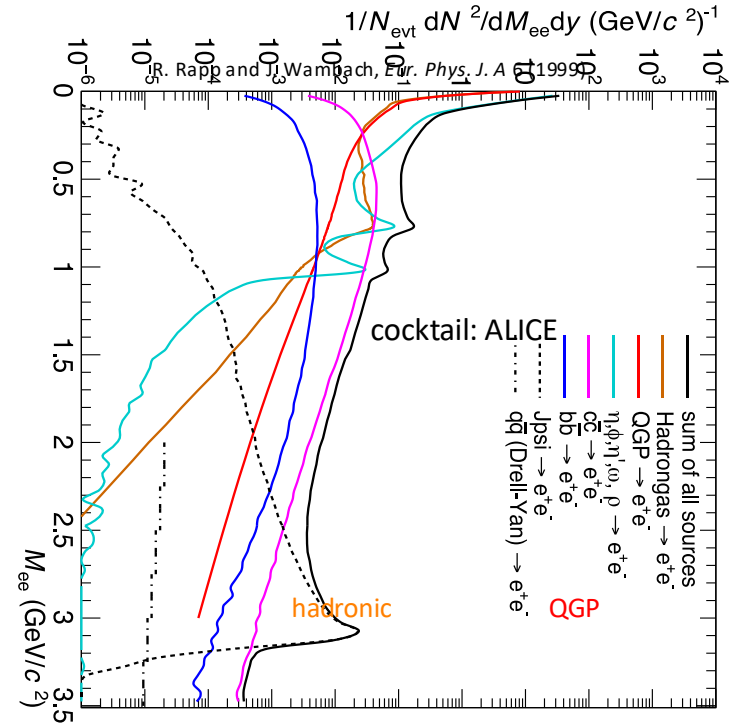
Dielectrons at the LHC

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



Dielectrons at the LHC

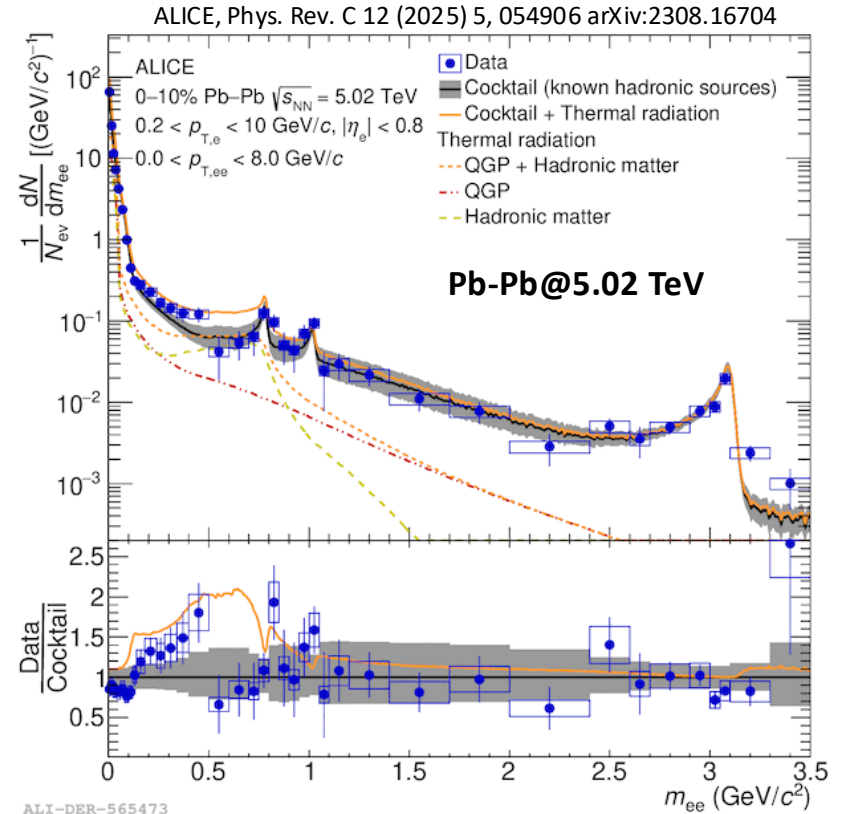
- Pb-Pb at the LHC produces the **largest, hottest and longest-lived QGP**, but
- Large combinatorial and **physical backgrounds**
- In the **Intermediate Mass Region (IMR)** (1–2.5 GeV/c²):
 - thermal $e^+e^-/HF \leq 10\%$
 - heavy-flavor contribution must be known with great precision



Dielectrons in Pb-Pb – Run 2

Pb-Pb results from Run 2:

- Indication for **low-mass enhancement**
- **Cocktail:** HF based on EPS09 and HFE R_{AA}
 - Possible QGP contribution in the IMR **not resolvable** within systematic and statistical uncertainties

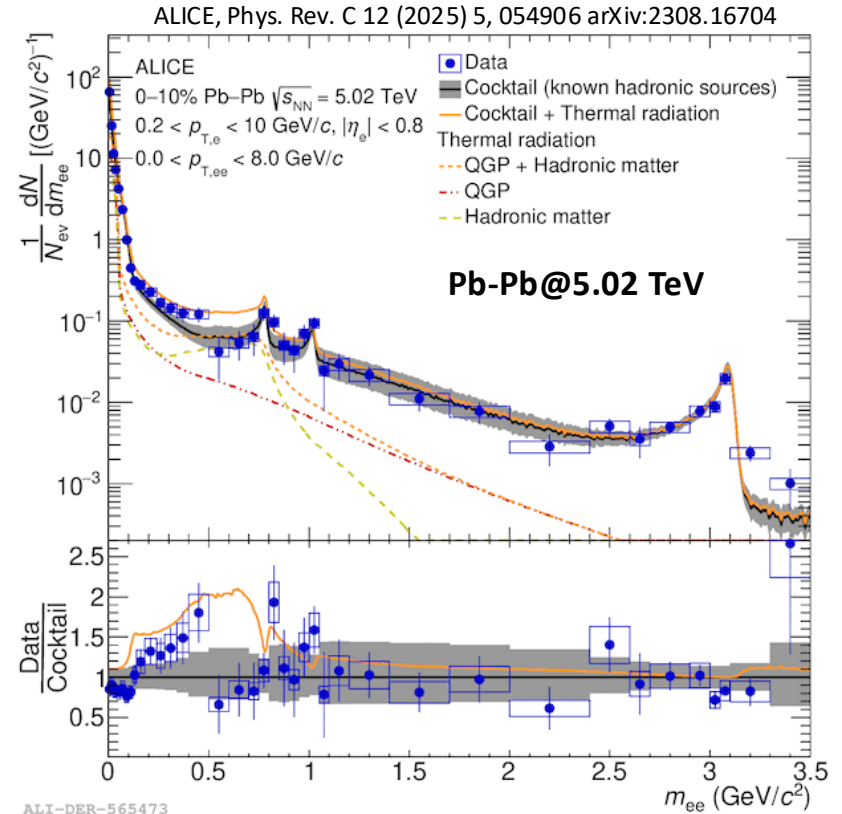


Dielectrons in Pb-Pb – Run 2

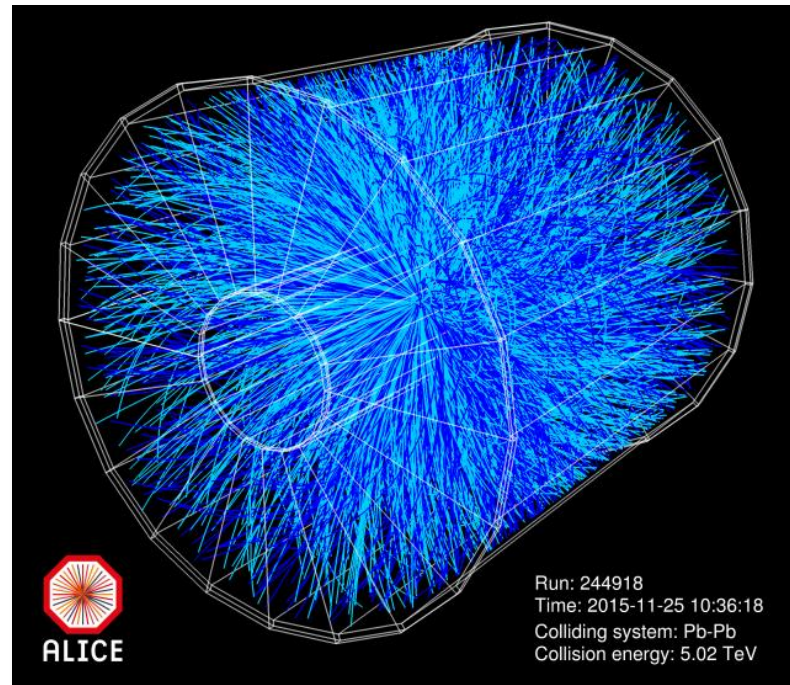
Pb-Pb results from Run 2:

- Indication for **low-mass enhancement**
- **Cocktail:** HF based on EPS09 and HFE R_{AA}
 - Possible QGP contribution in the IMR **not resolvable** within systematic and statistical uncertainties
- Measurement of thermal QGP dielectrons at the LHC requires **much more statistics** and a **cocktail-independent approach** via **precise tagging of secondary electrons** from HF decays

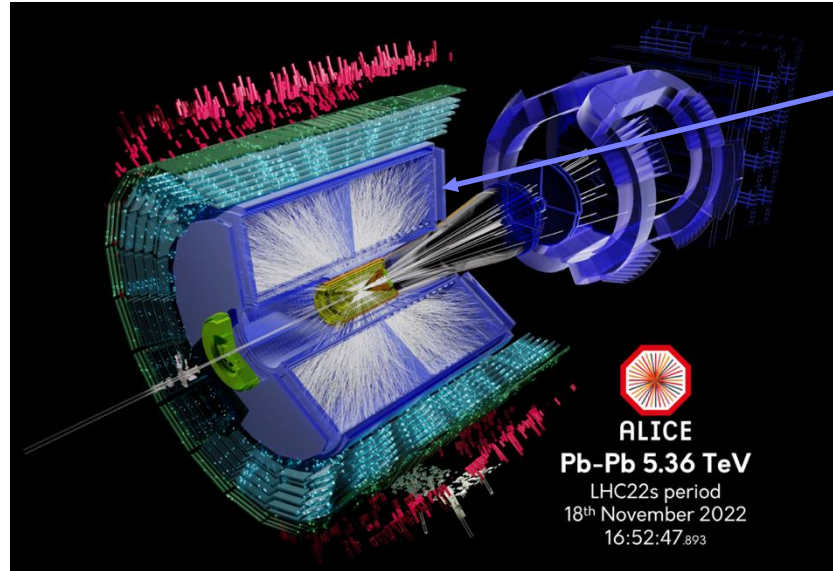
→ Upgrade TPC and ITS



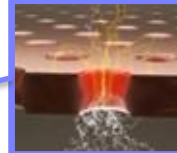
The ALICE TPC



ALICE 2 in Run 3

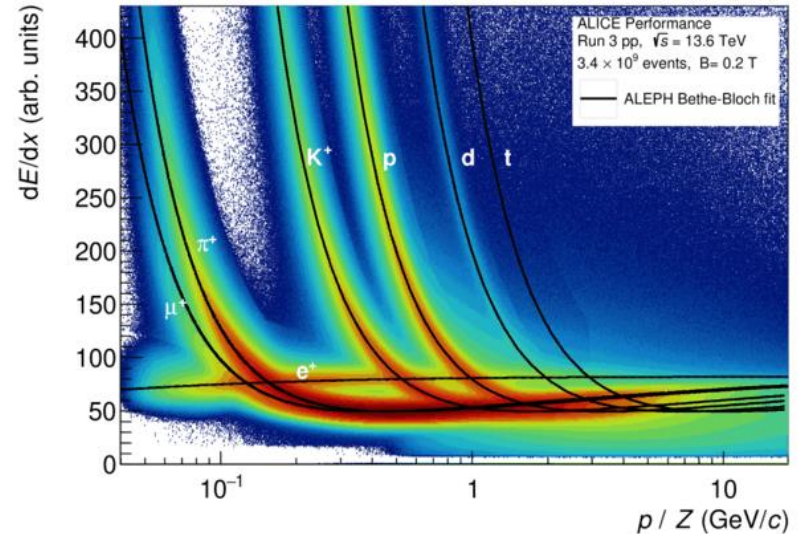


ALICE, *JINST* 19 (2024) P05062, arXiv:2302.01238



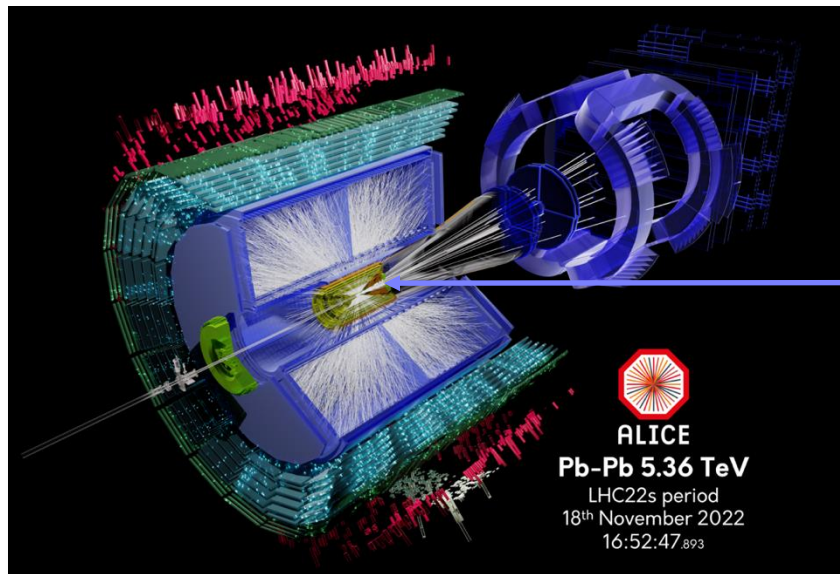
New TPC readout system

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

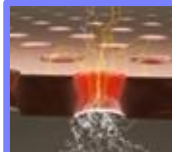


ALI-PERF-629735

ALICE 2 in Run 3



ALICE, *JINST* 19 (2024) P05062, arXiv:2302.01238



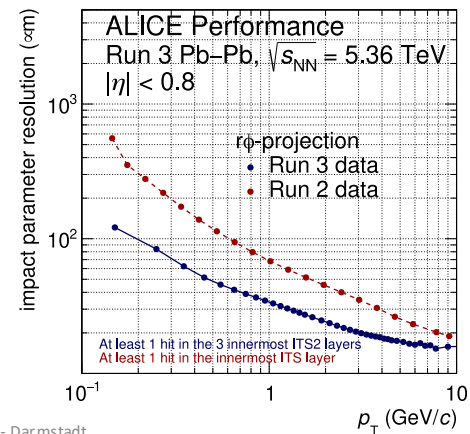
New TPC readout system

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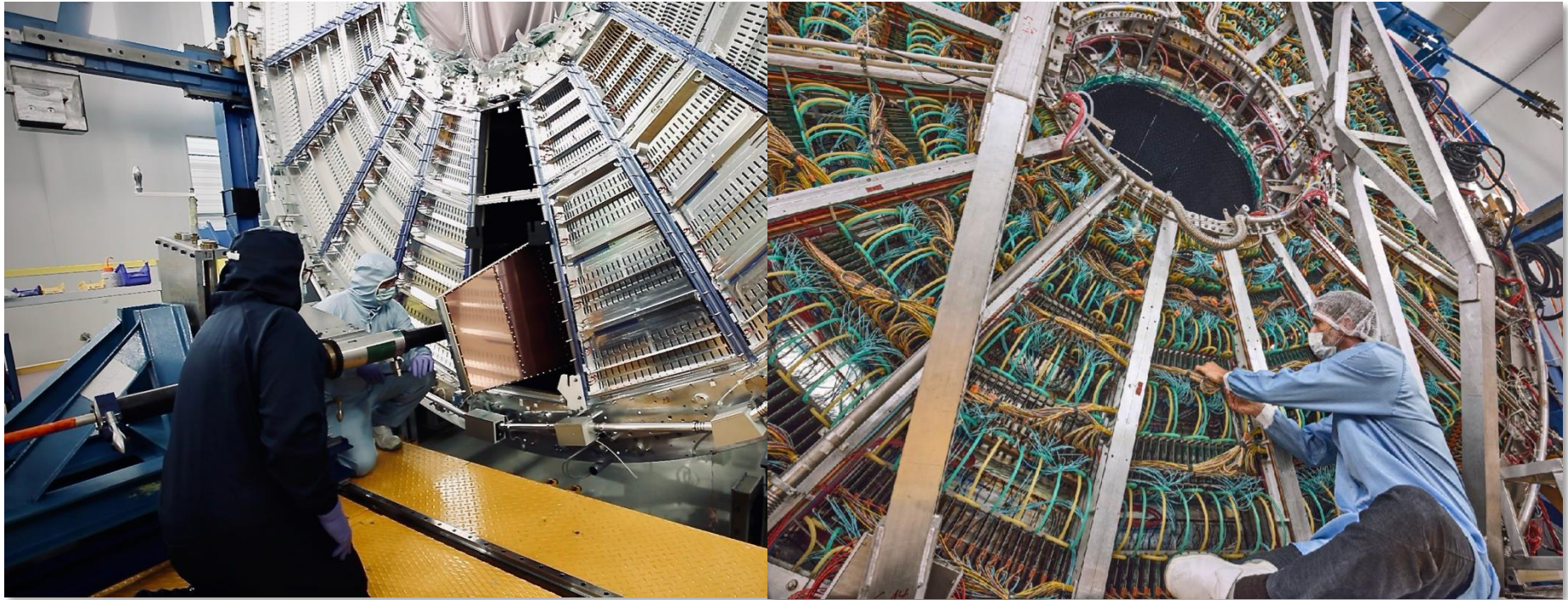


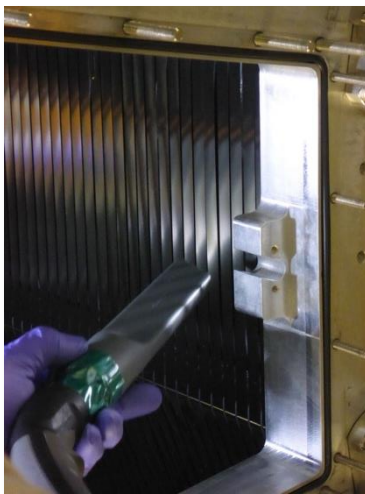
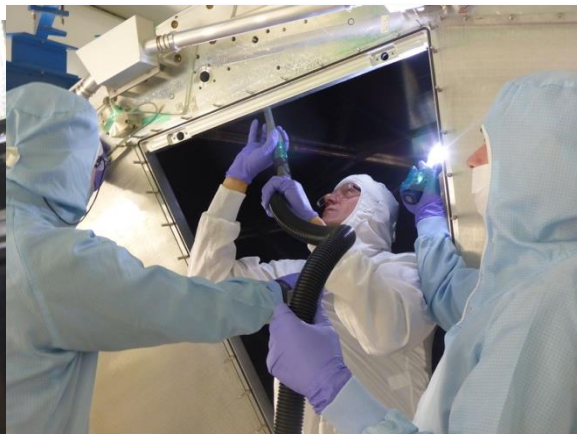
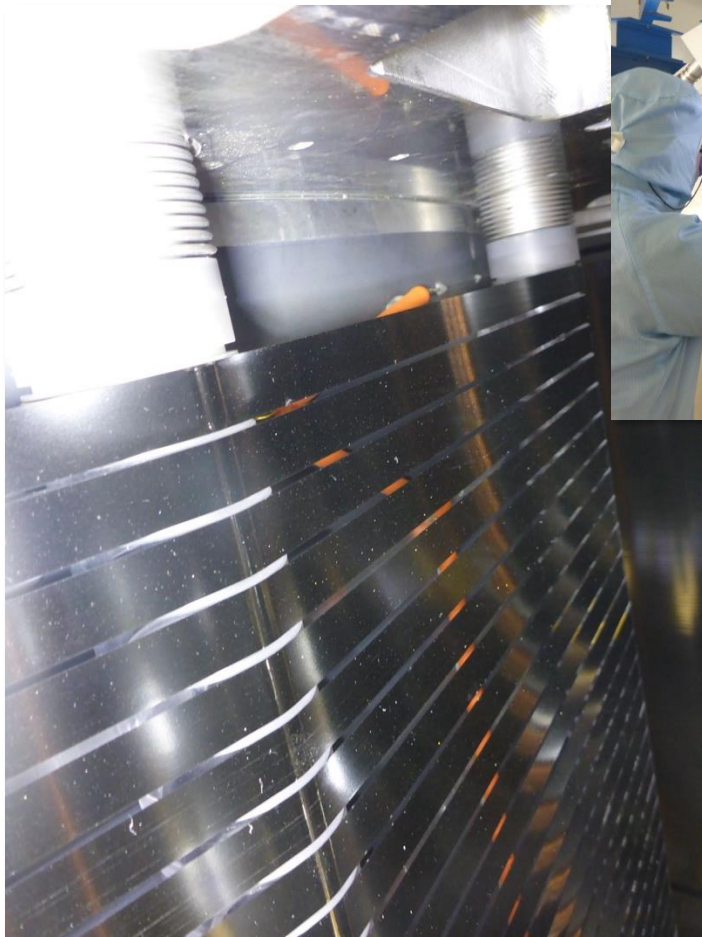
New Inner Tracking System (ITS2)

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



TPC Upgrade 2019





The ALICE TPC

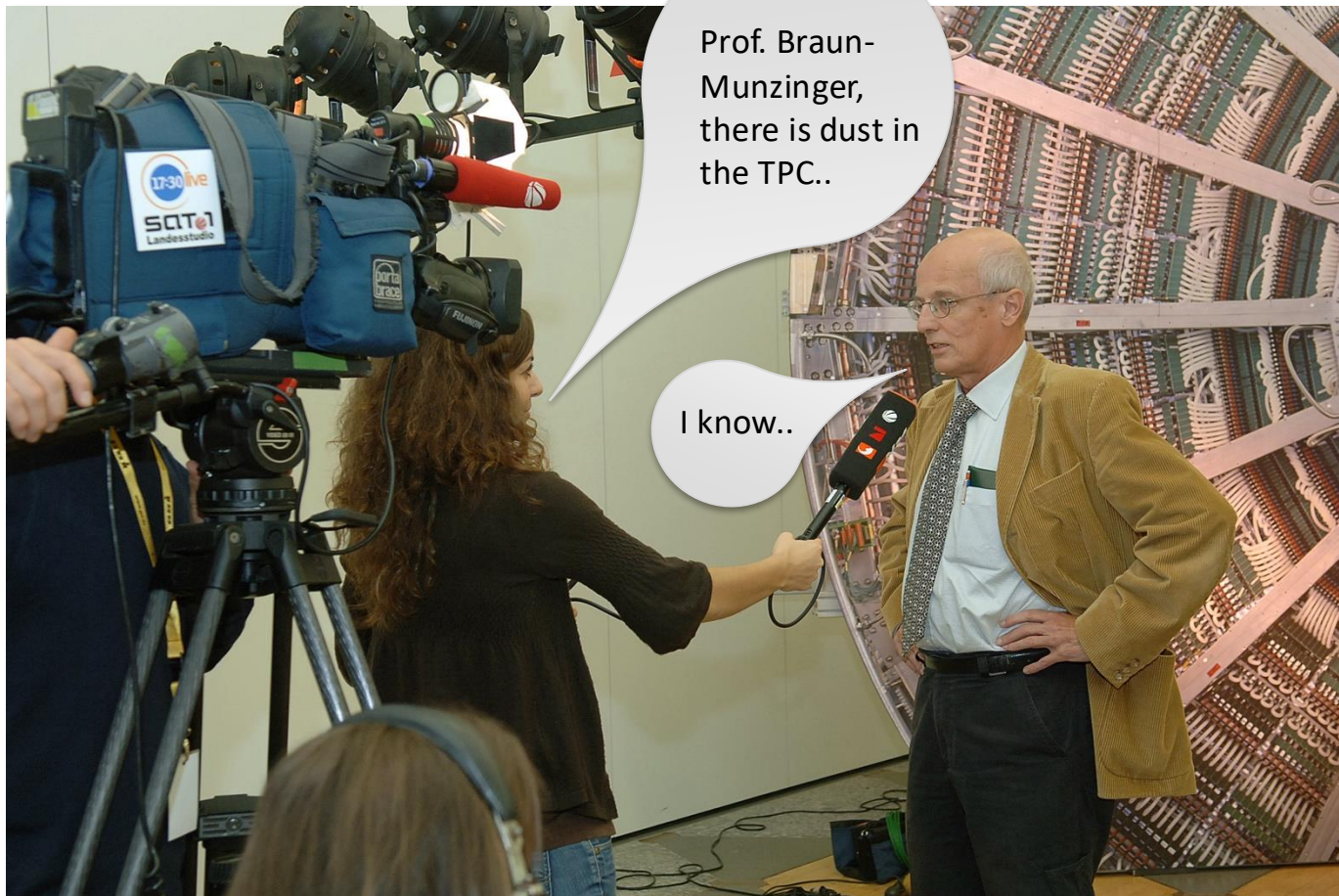


The ALICE TPC

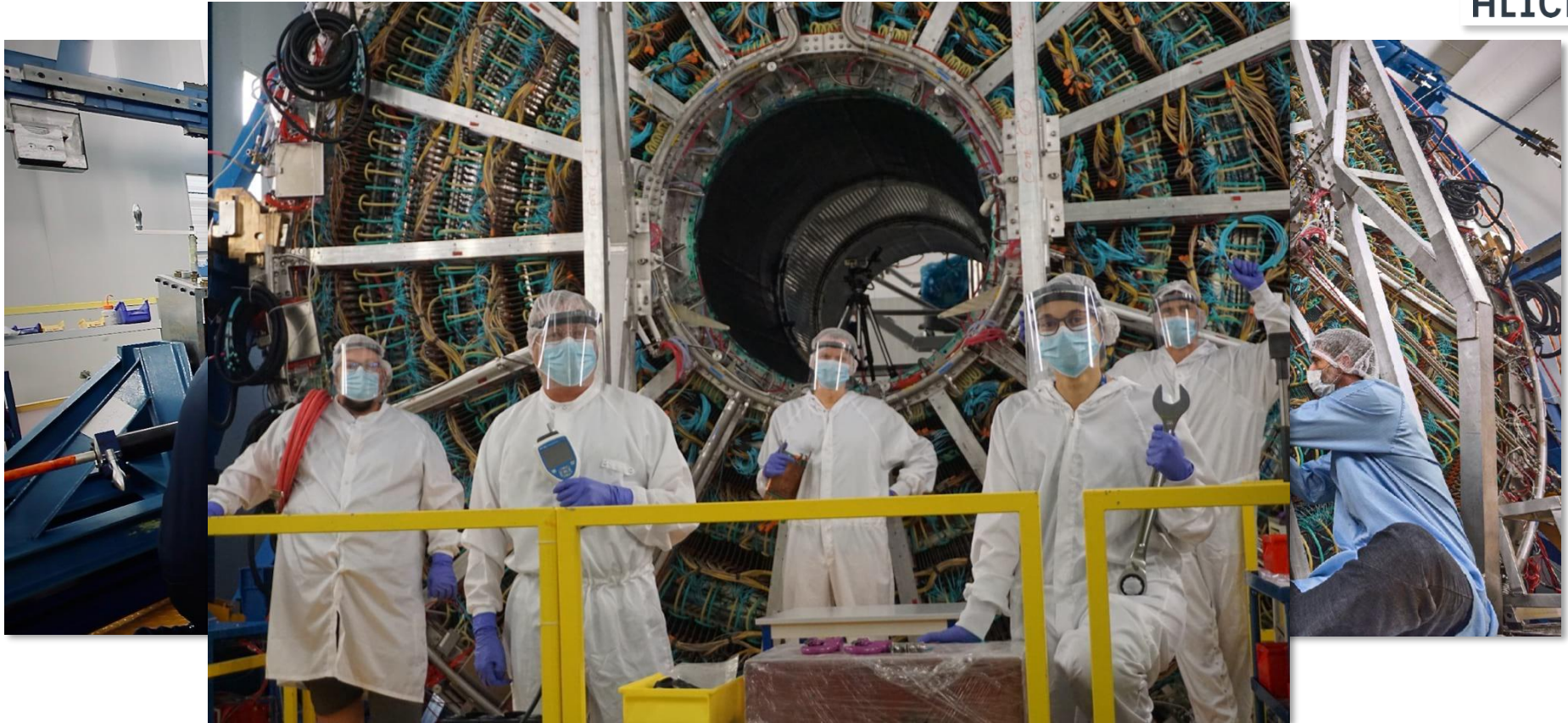


The ALICE TPC

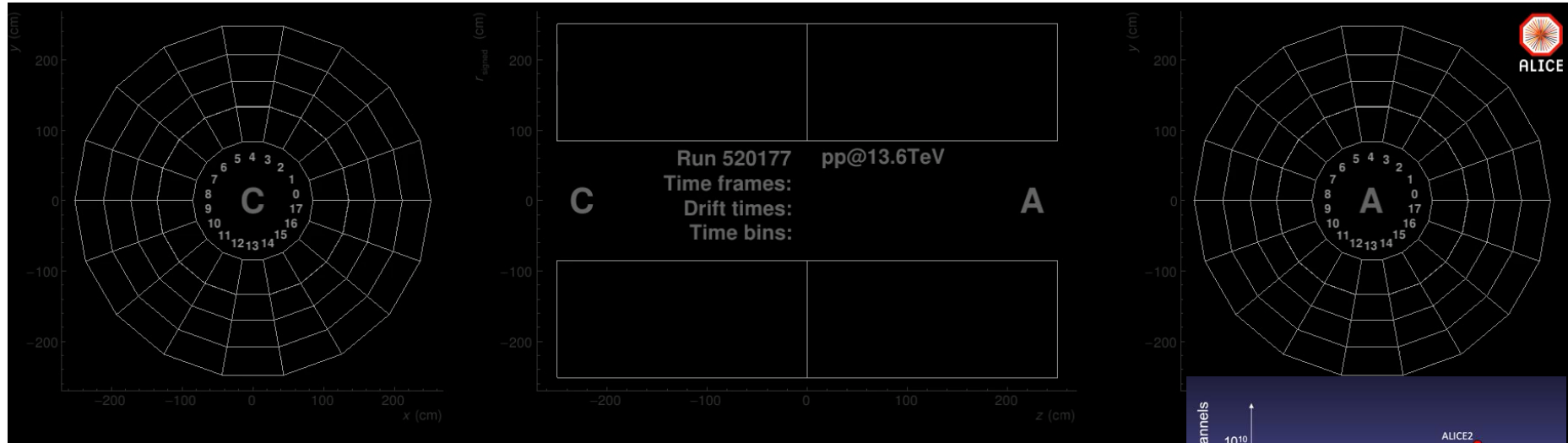




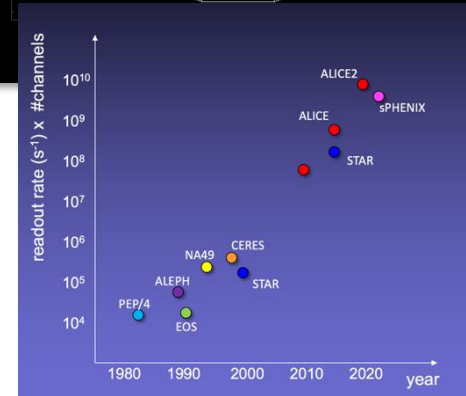
Mission accomplished 2020



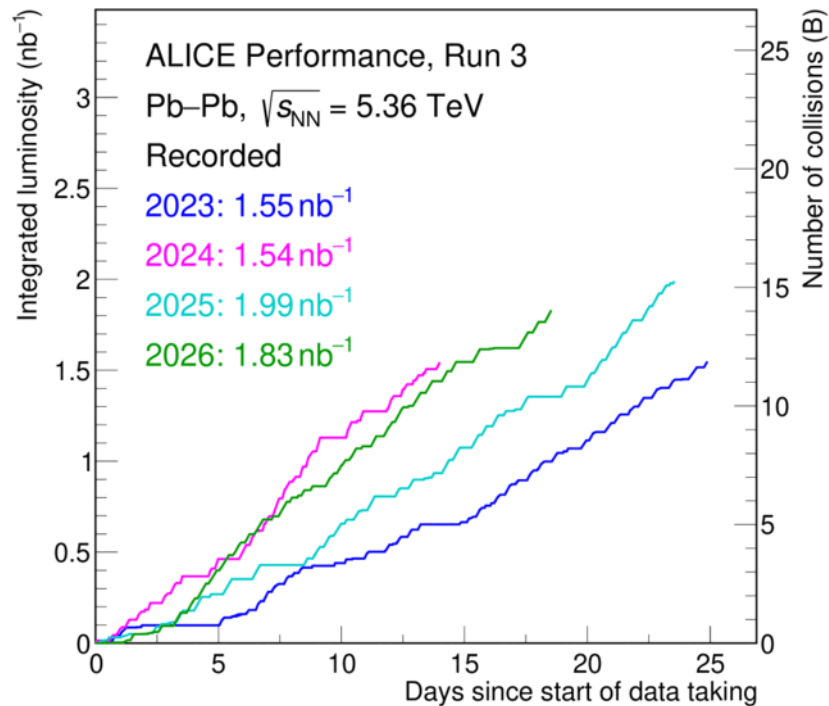
ALICE TPC in continuous readout



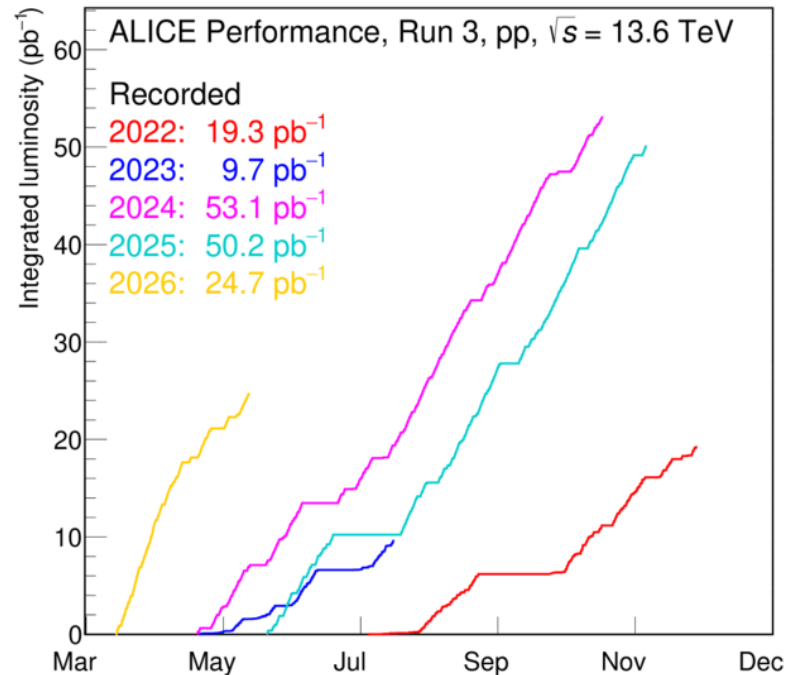
- up to **50 kHz** in Pb-Pb
- up to **1 MHz** in pp
- data rate off detector **3.5 TB/s**
- after online reco **200 GB/s** to disk



ALICE 2 in Run 3



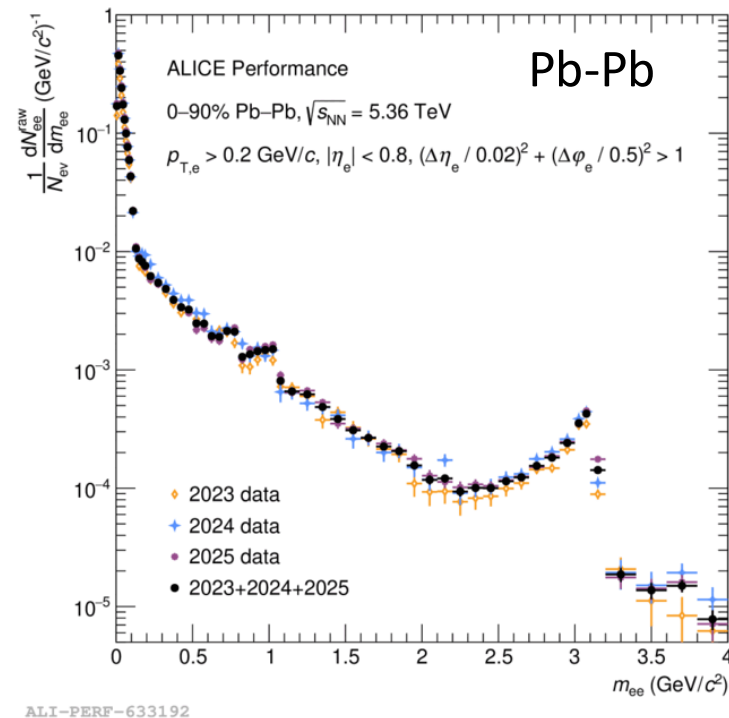
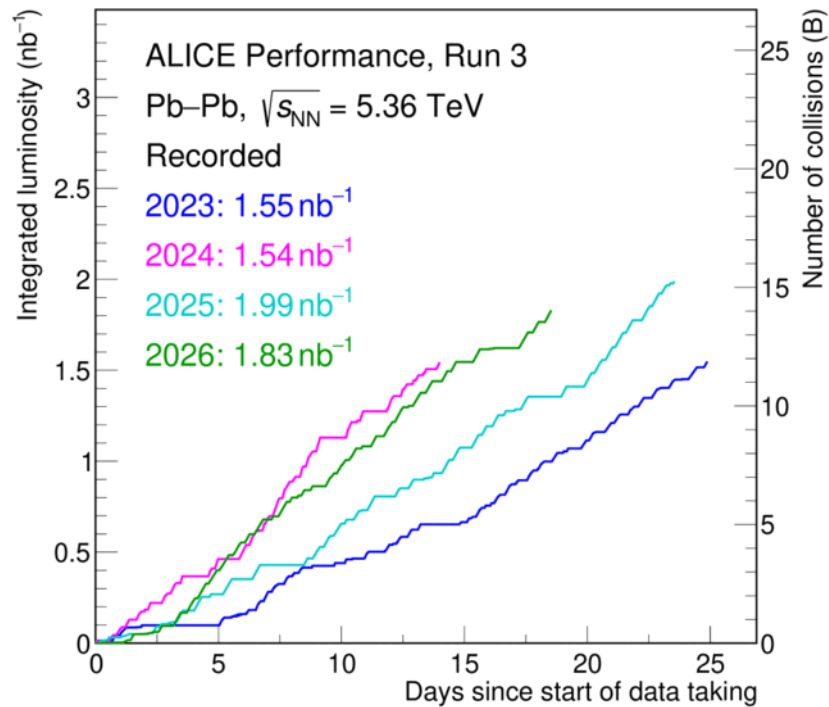
ALI-PERF-634120



ALI-PERF-630176

- 6.9 nb⁻¹ achieved in Pb-Pb → factor >100 compared to Run1
- 157 pb⁻¹ achieved in pp → factor >1000 compared to Run1

ALICE 2 in Run 3

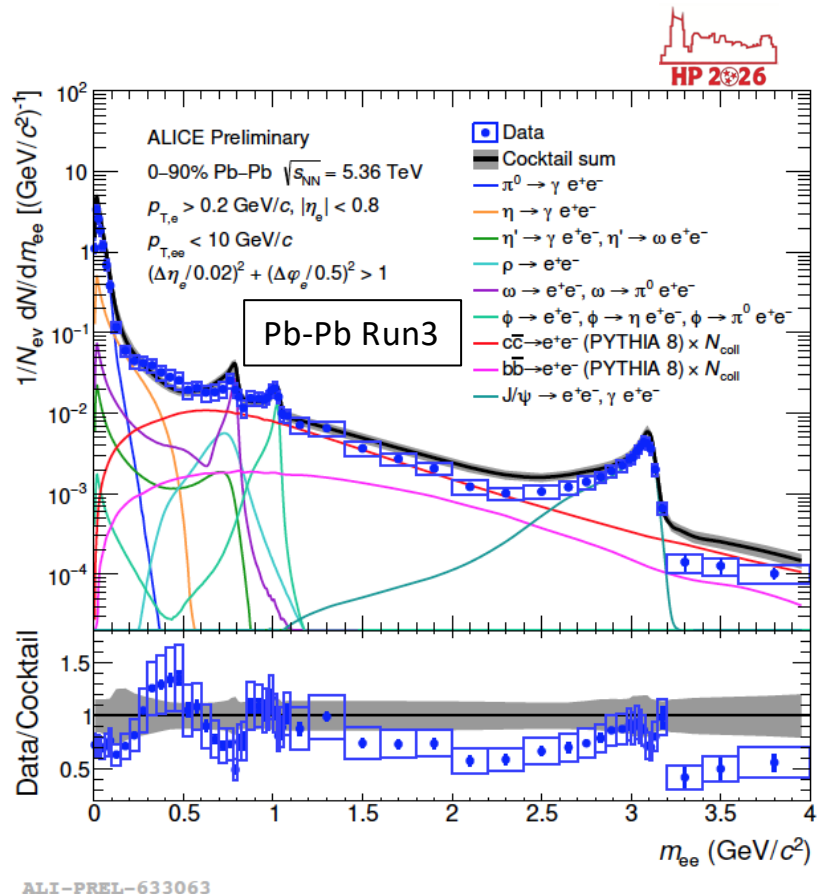


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ALICE 2 in Run 3

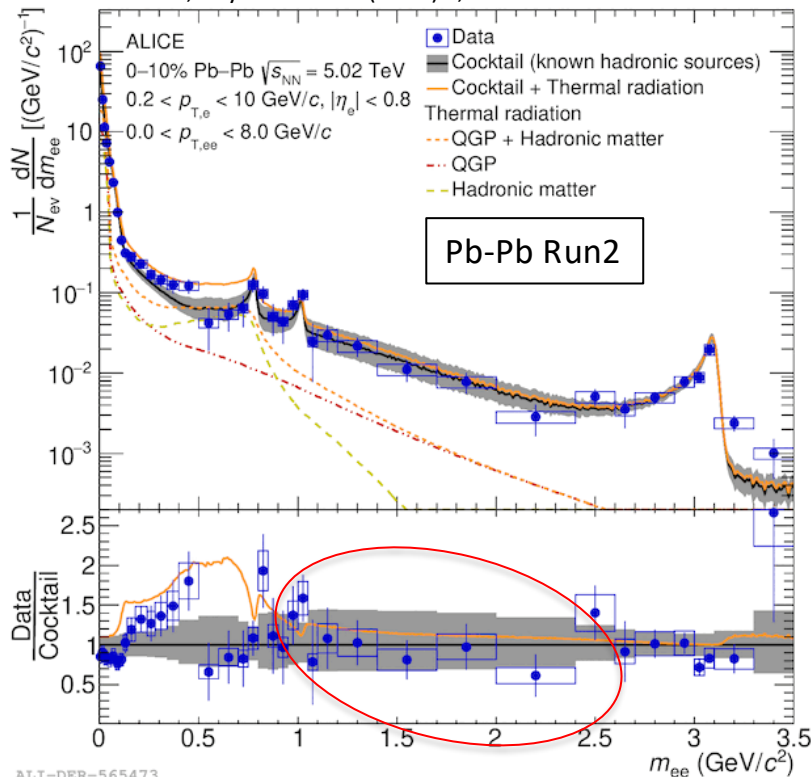
Pb-Pb results from Run 3:

- First preliminary Pb-Pb result from Run 3 (2025 data only)
- **Low-mass enhancement** compatible with Run2
- **HF suppression in IMR**

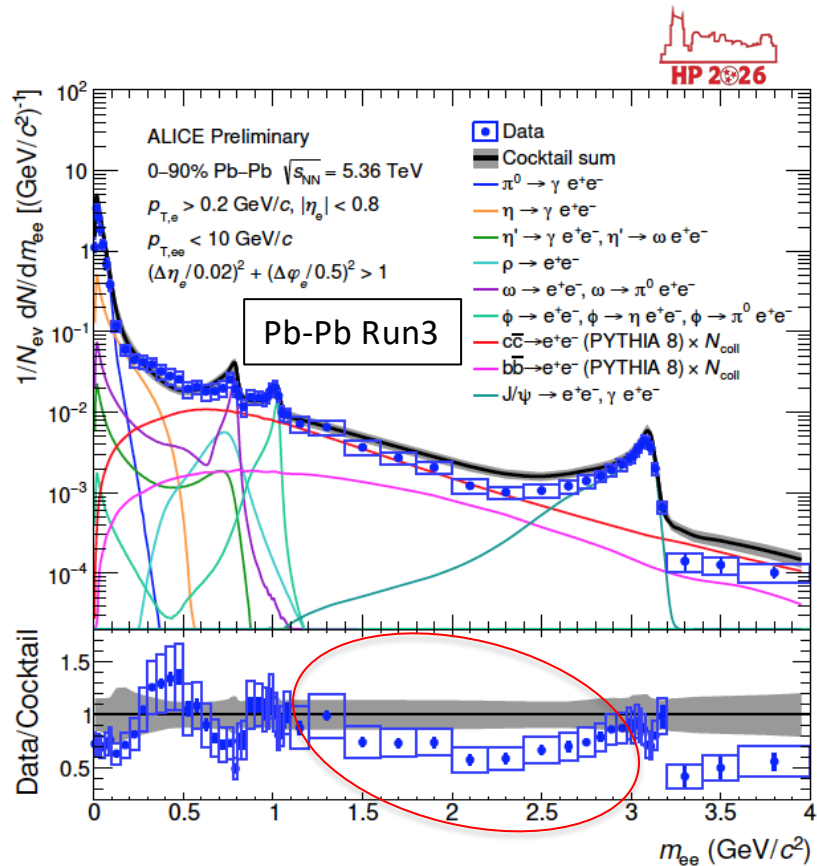


ALICE 2 in Run 3

ALICE, Phys. Rev. C 12 (2025) 5, 054906 arXiv:2308.16704

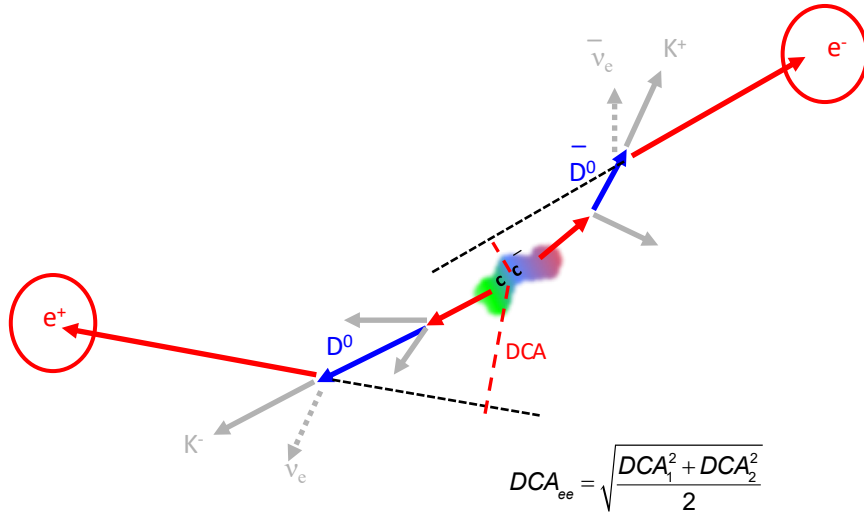


ALI-DER-565473



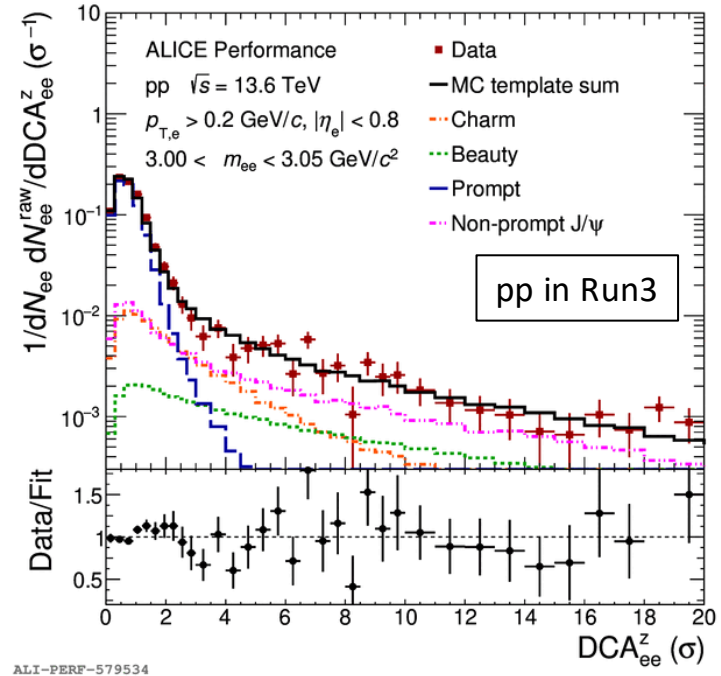
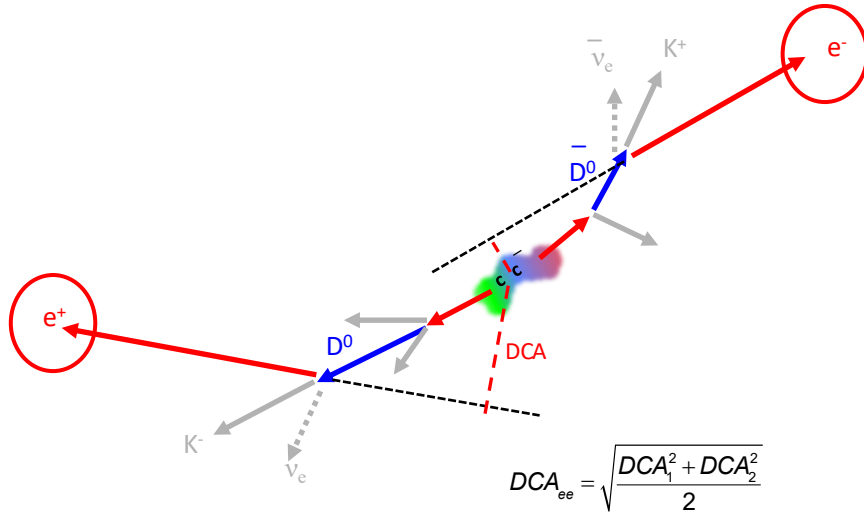
• Dielectrons at the LHC: precision era has begun

Topological separation of dielectron sources



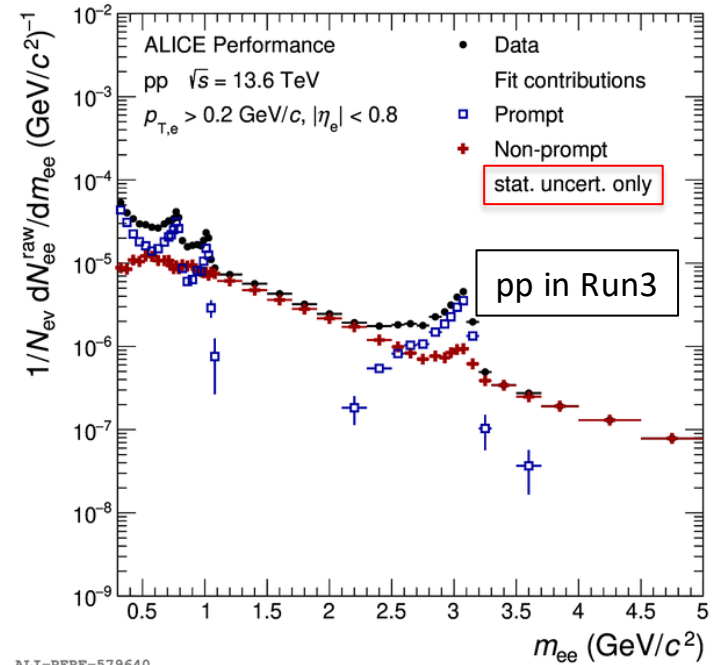
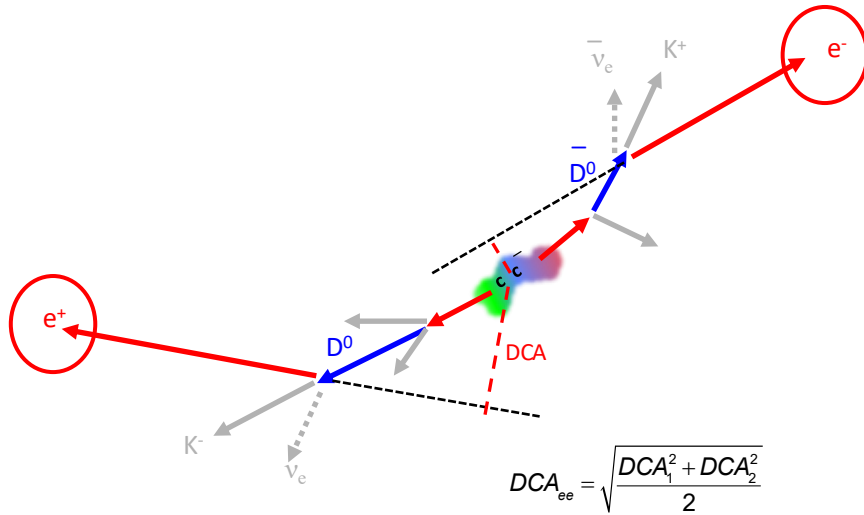
- DCA_{ee} allows separation of prompt from delayed dielectron sources

Topological separation of dielectron sources



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

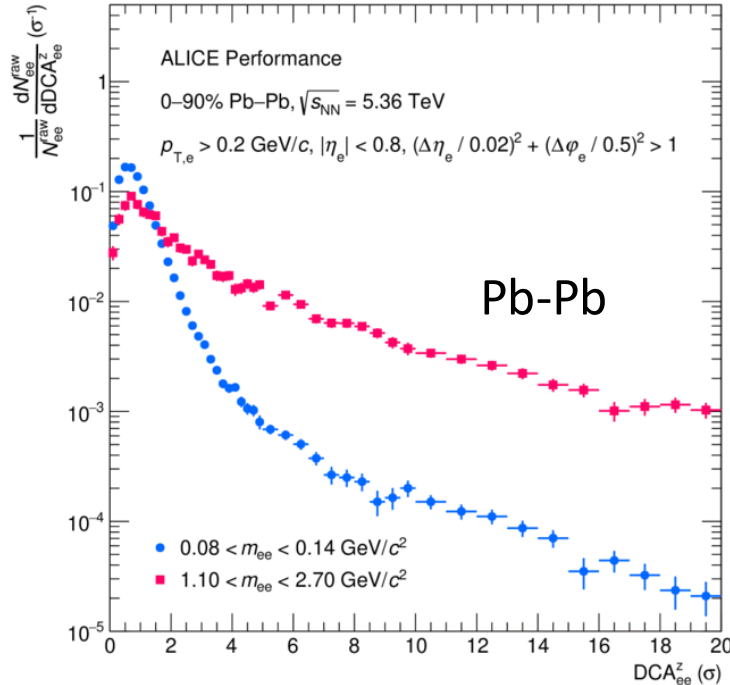
Topological separation of dielectron sources



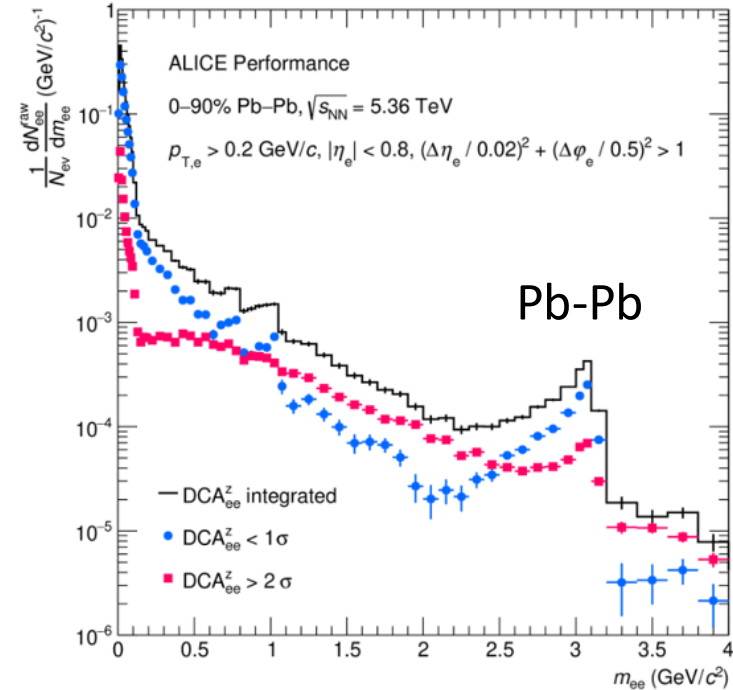
ALI-CONF-579640

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

ALICE2 – dielectrons in Run 3



ALI-PERF-633222



ALI-PERF-633227

- DCA_{ee} allows separation of prompt from delayed dielectron sources
- Next step: extract thermal signal and QGP temperature in intermediate-mass region

T from IMR dileptons

- Early system is gluon dominated at the LHC

$$\tau(gg \rightarrow gg) \ll \tau(gg \rightarrow q\bar{q})$$

- If quarks are suppressed, so is EM radiation

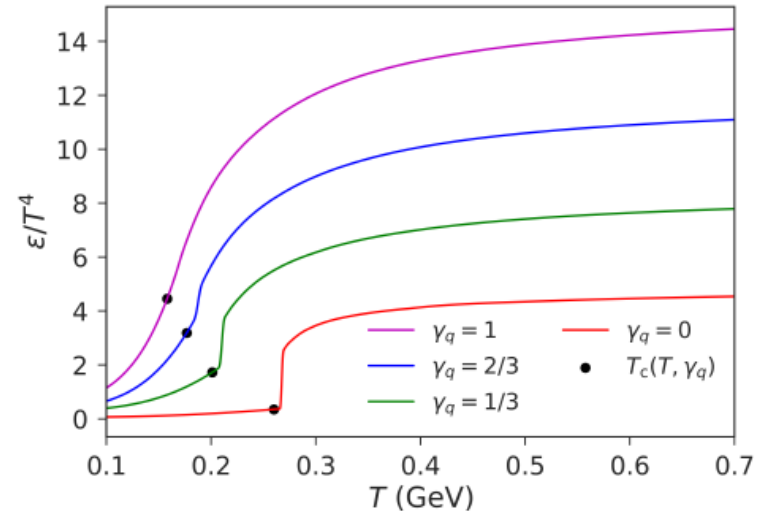
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- Quark undersaturation changes EoS

A. Gordeev, S. Bass, B. Müller, J.F. Paquet, PRC 113, 014906 (2026)

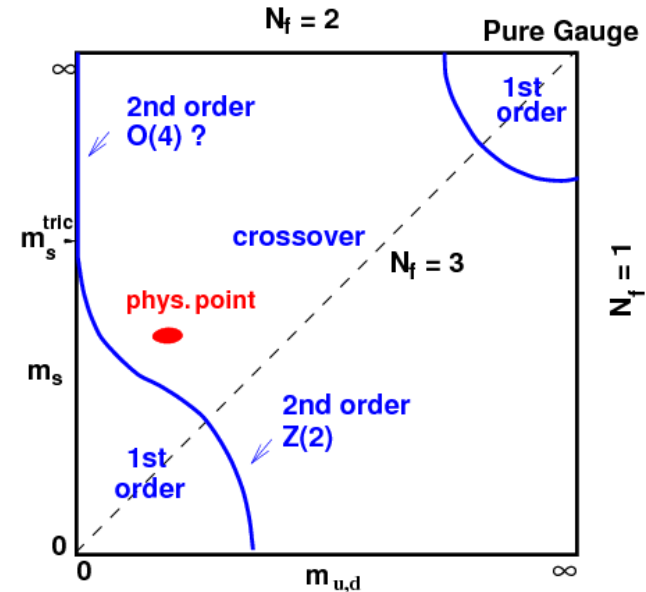


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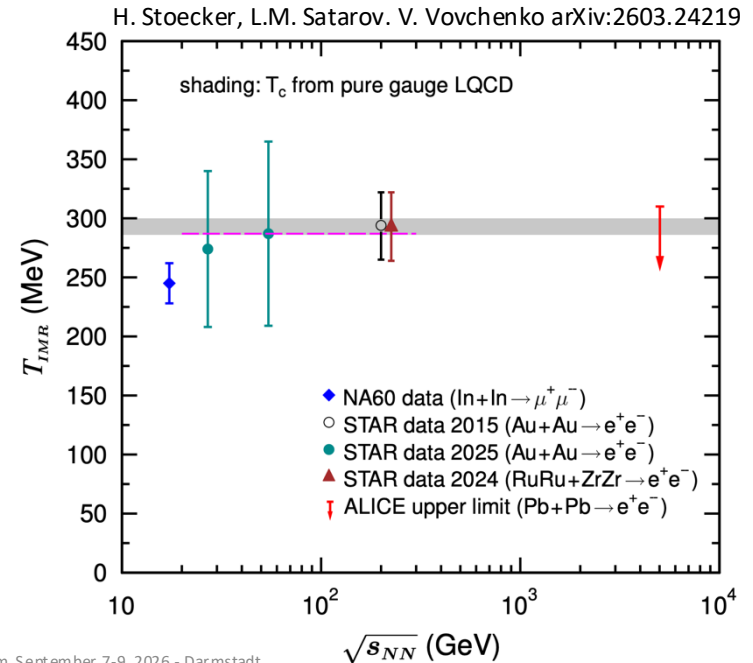
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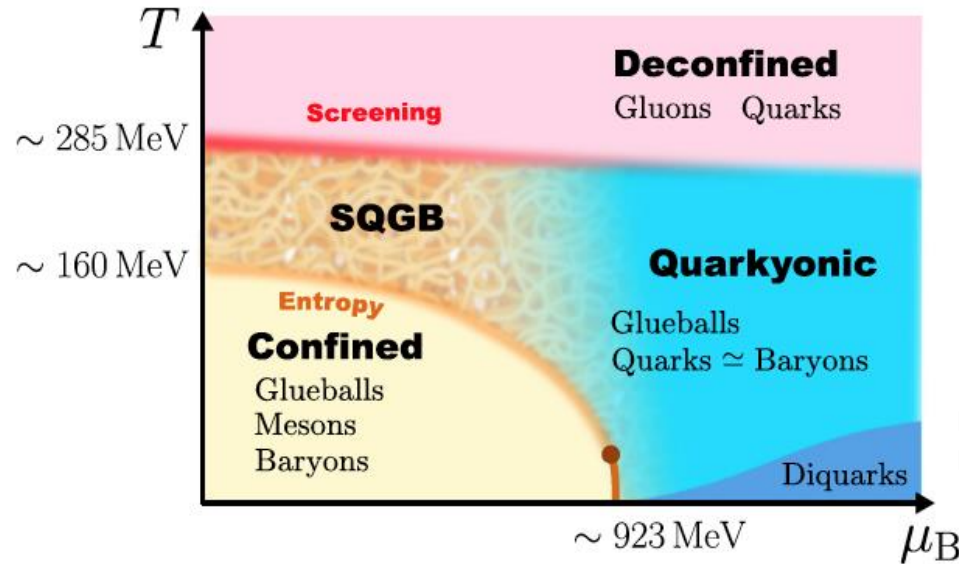
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- Quark undersaturation changes EoS
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- EM emission is favored from mixed phase $\rightarrow$ plateau of „early temperature“?



New QCD phases

- Distinct quark and gluon crossovers can be a real feature of QCD

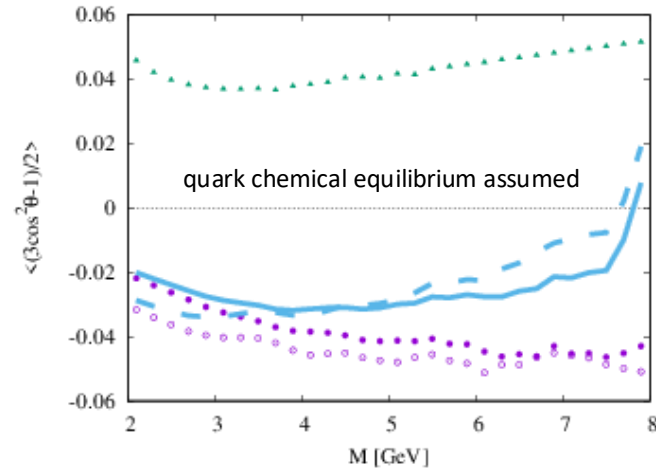
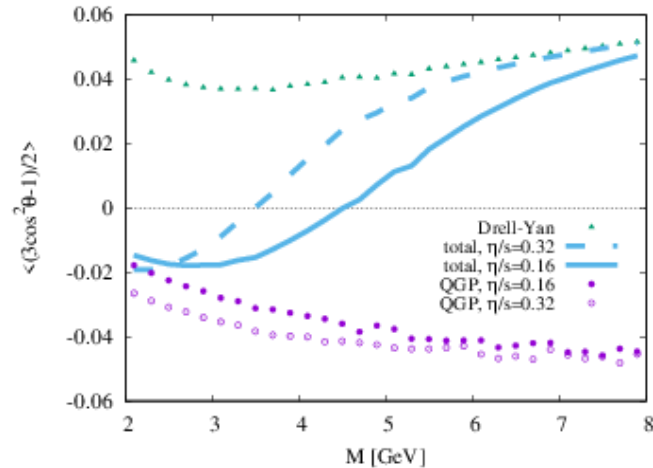


Fujimoto, Fukushima, Hidaka, McLerran
Phys. Rev. D112, 074006 (2025)

- SQGB: stringy quarks with thermal excitations, but confined

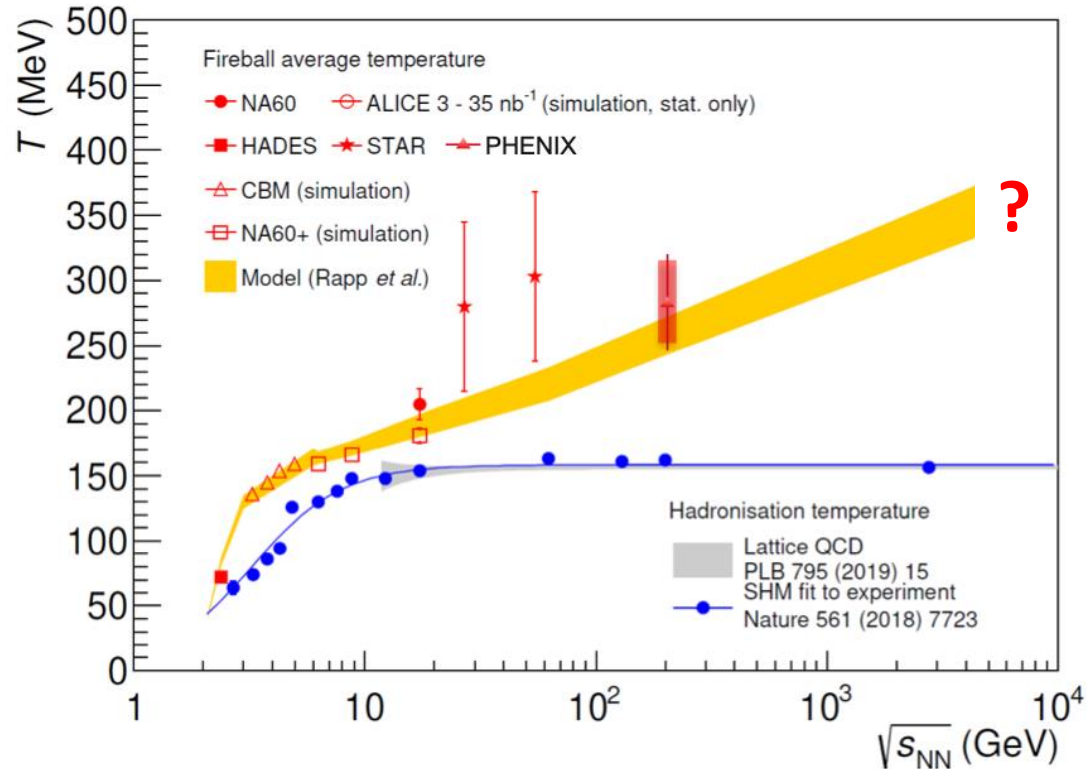
Test of quark equilibration - polarization

- Dilepton polarization signals the degree of quark equilibration



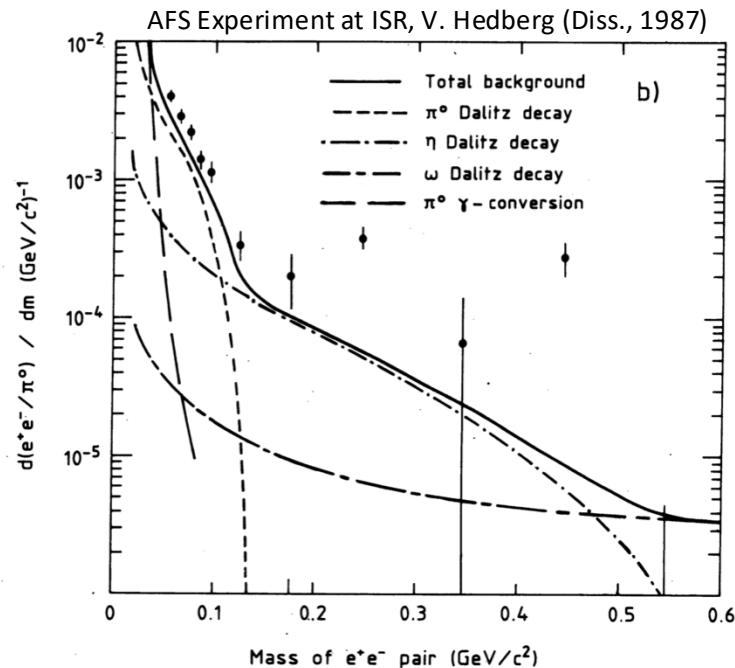
- Zero-crossing characteristic for quark underpopulation and relaxation time

T from IMR dileptons at the LHC



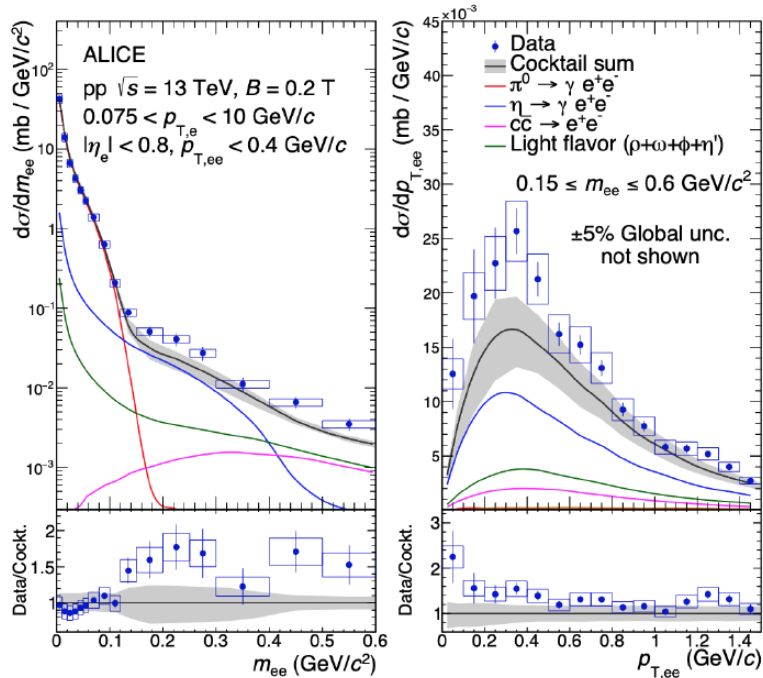
The cold case - ,anomalous‘ radiation in small systems

- **Direct soft photon excess** over hadronic decays observed in πp , $K p$, μp , pp , p -Be at different energies and kinematic ranges
- **Hadronic Bremsstrahlung** could not account for it
- Relation to **Low's theorem**
- Indications of excess also observed in the **virtual photon sector: e^+e^-**

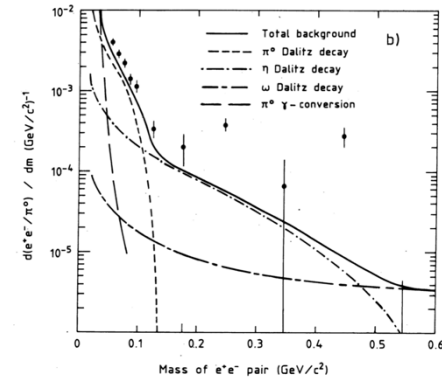


Run2: pp at 13 TeV with low B-field

ALICE, *Phys.Rev.Lett.* 127 (2021) 4, 042302



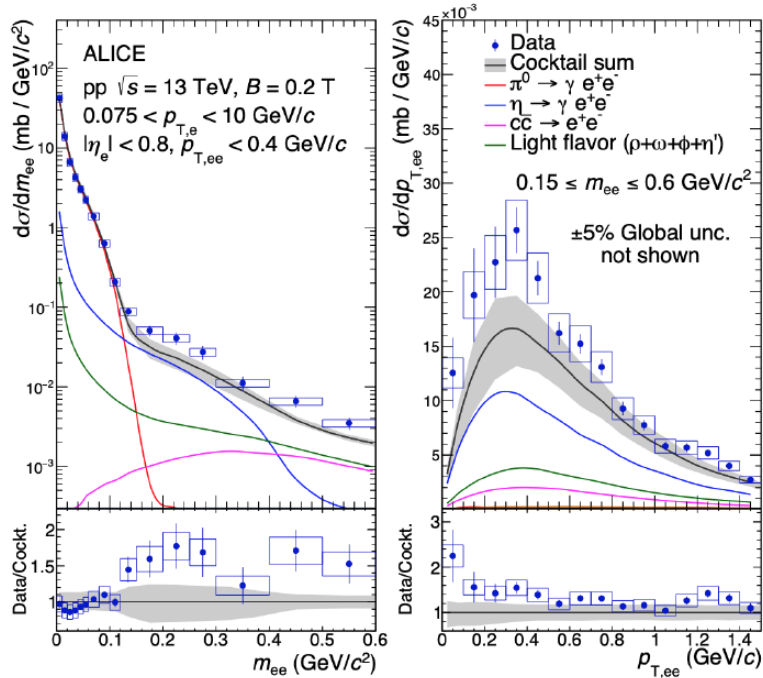
- Dielectron **enhancement over hadronic cocktail** observed in $m_\pi < m_{ee} < 0.5 \text{ GeV}/c^2$
- Reminiscent of low-mass enhancement from AFS at ISR



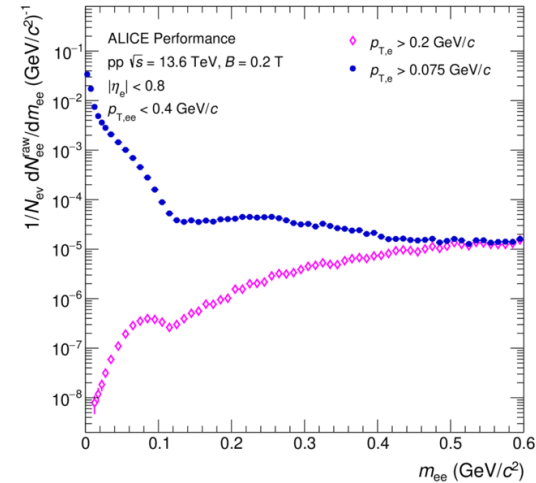
- Uncertainties do not allow yet firm conclusion

Run3: high-statistics pp with low B-field

ALICE, *Phys.Rev.Lett.* 127 (2021) 4, 042302



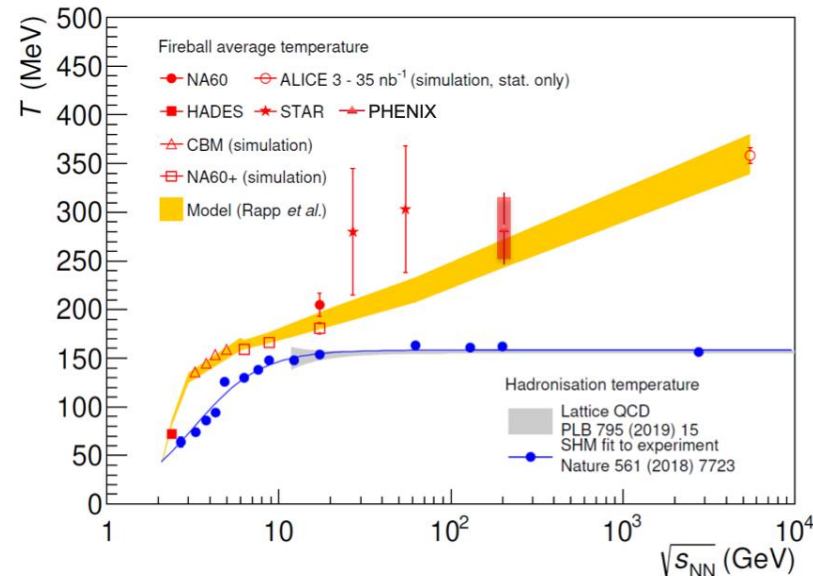
- Dielectron **enhancement over hadronic cocktail** observed in $m_\pi < m_{ee} < 0.5$ GeV/c²



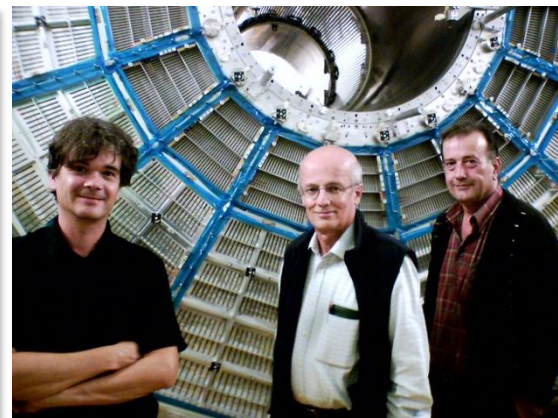
- ALICE high-statistics data at low B from Run3 now available to close the case

Summary

- Dileptons are unique probes to study the early phase of heavy ion collisions
- The upgraded ALICE detector will allow us to study the phase structure of QCD at the LHC
- Future opportunities with ALICE3 – see Raphaelles talk



Erice 1998



Happy Birthday Peter!

