Electromagnetic radiation from hot nuclear matter

Science Coffee, Lund, 15 December 2020

Michael Weber

ÖAW AUSTRIAN ACADEMY OF SCIENCES
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Outline:

- **Objectives:** Chiral symmetry and temperature of QCD matter
- **Method:** Thermal dielectron production with ALICE at the CERN-LHC
- **Accomplished:** Understand your background
- **Future:** Expected performance with ALICE and next-generation particle detectors

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The origin of mass

Nucleon mass: 1% from quark mass (Higgs mechanism) → 99% from the strong interaction (QCD)

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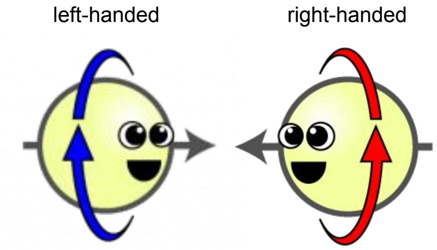

Strong interaction is blind to chirality, BUT...

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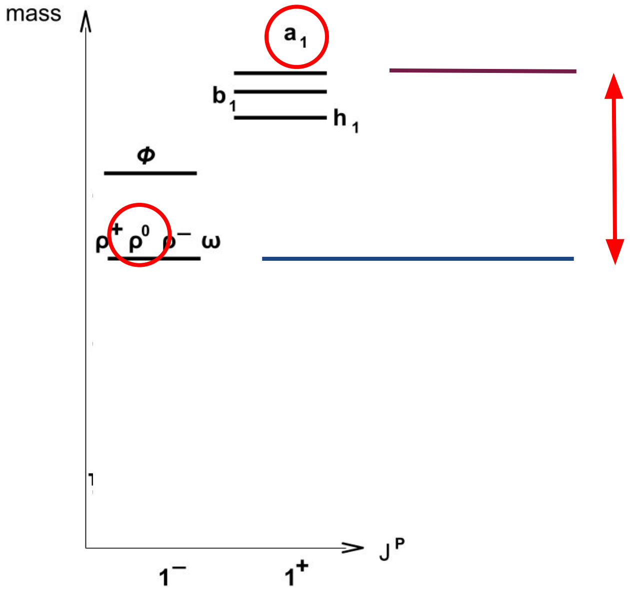

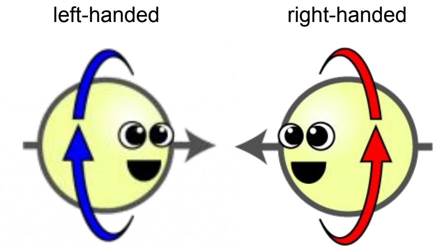

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Spontaneously broken: chiral symmetry

- Hadrons with different parity do **not have same mass**

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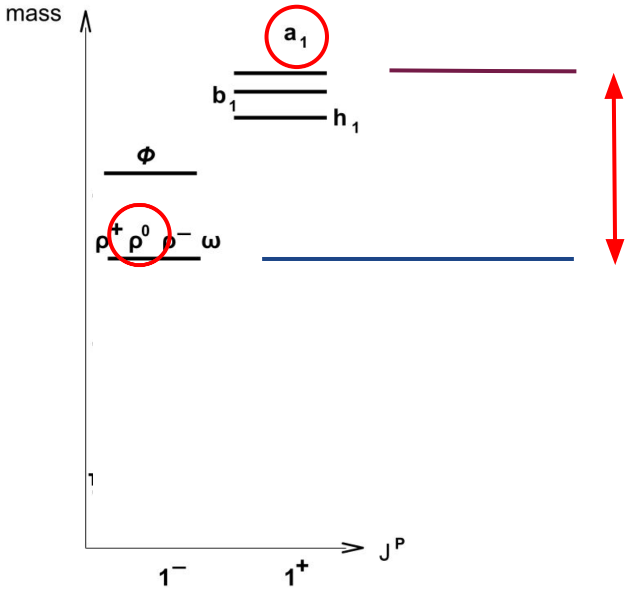

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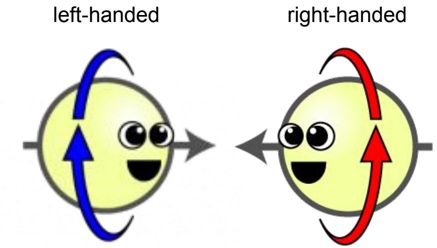

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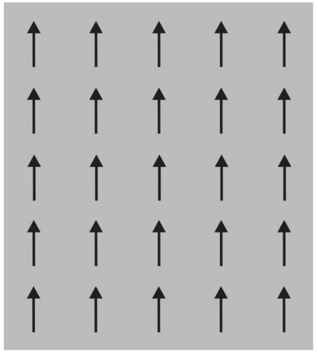
Compare to magnet:

$$H_{\text{int}} = g \sum_{i \neq j} \vec{s}_i \cdot \vec{s}_j$$

interaction between microscopic magnetic dipoles (spins)
does not prefer any direction, BUT the ground state:



with magnetization M (order parameter)

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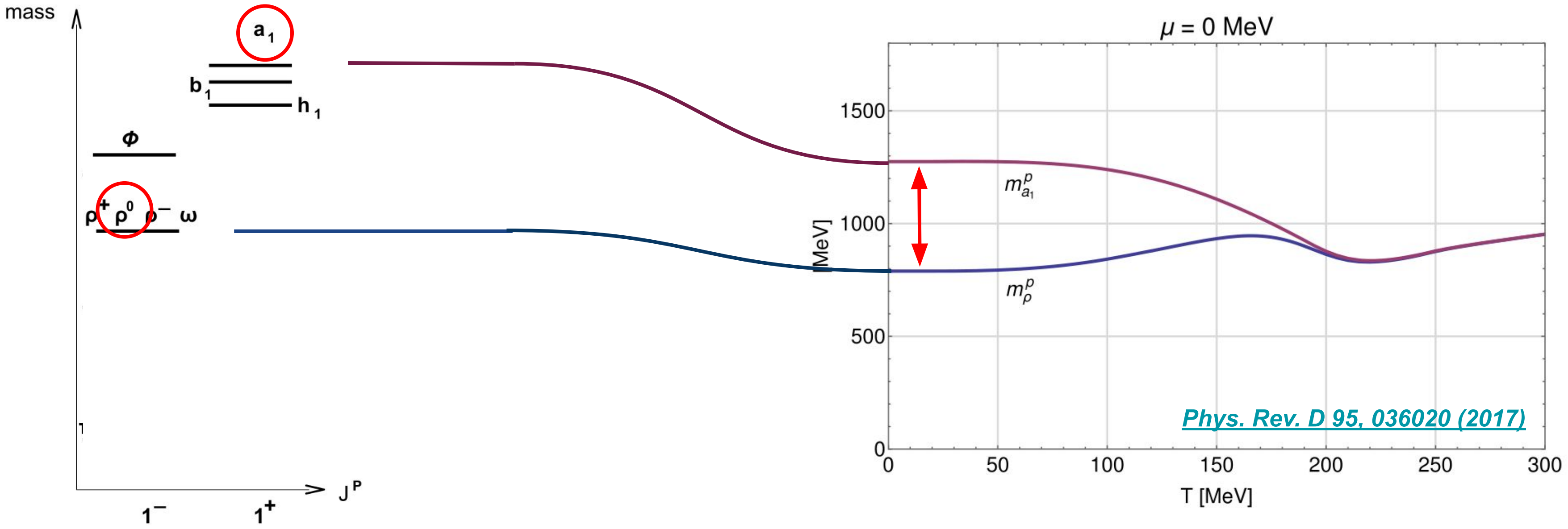

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Unique test of fundamental QCD property:

- **Change order parameter → change temperature**

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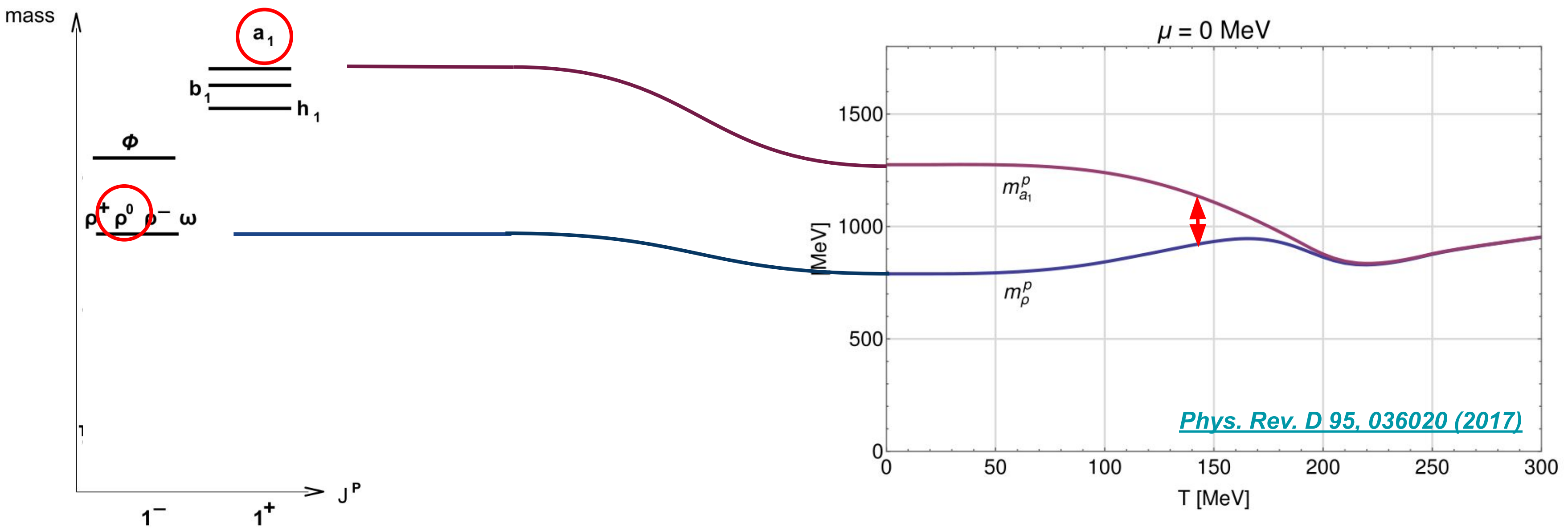

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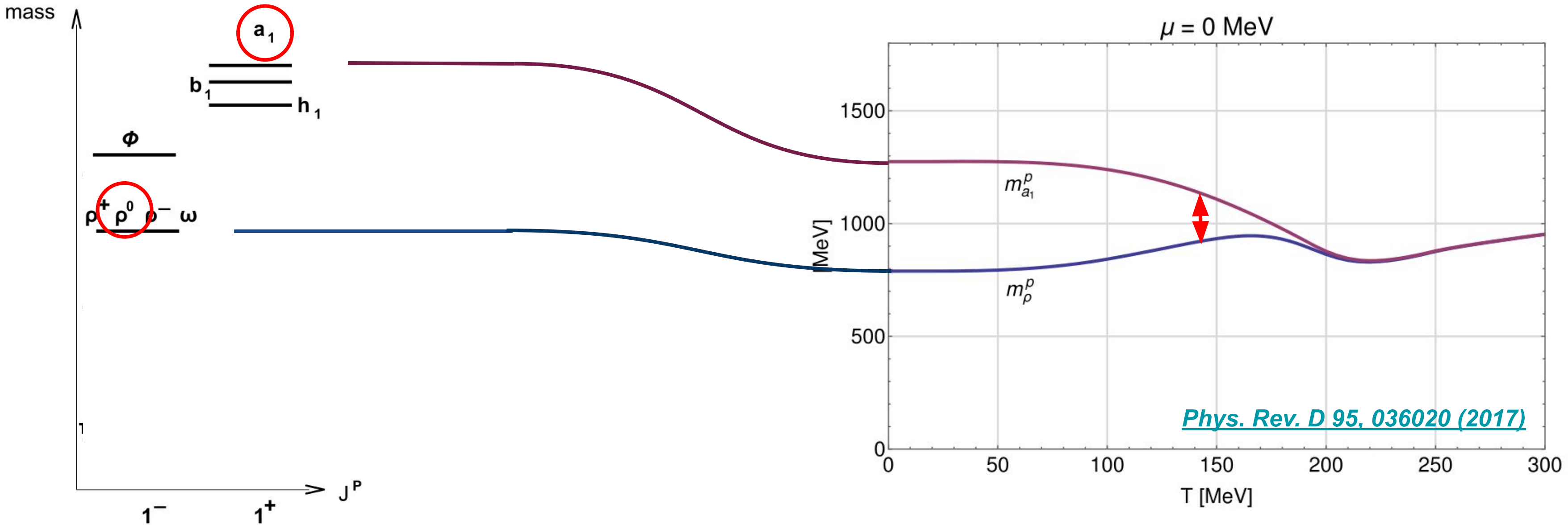

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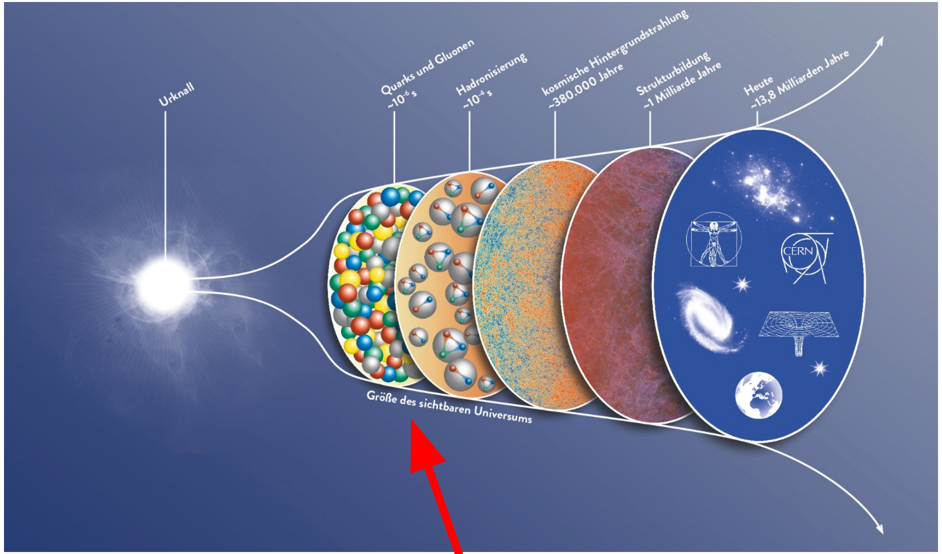
Unique test of fundamental QCD property:

- **Change order parameter → change temperature**
- **Symmetry restoration at high temperatures**
- Experimental proof
  - Measure hadron properties (**spectral functions**)
  - Measure **temperature of QCD matter**

Putting into context



Phase transition in early universe
(quarks→hadrons)

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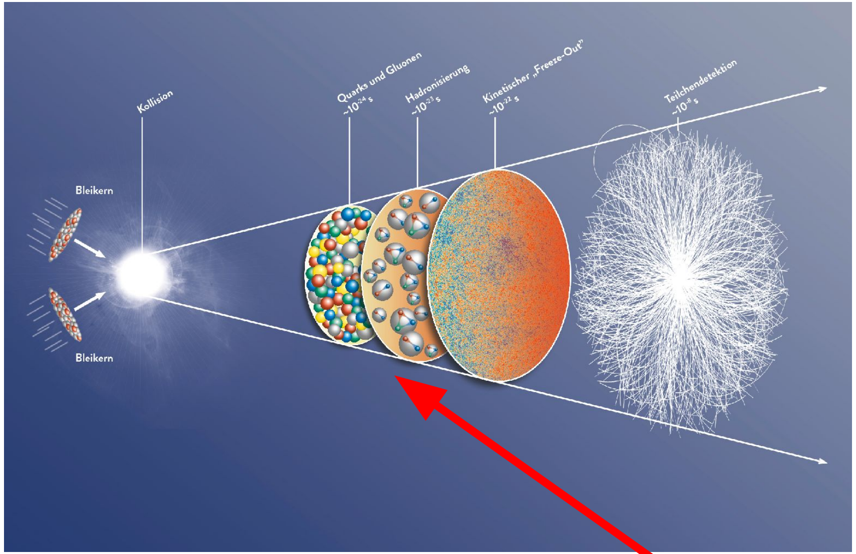

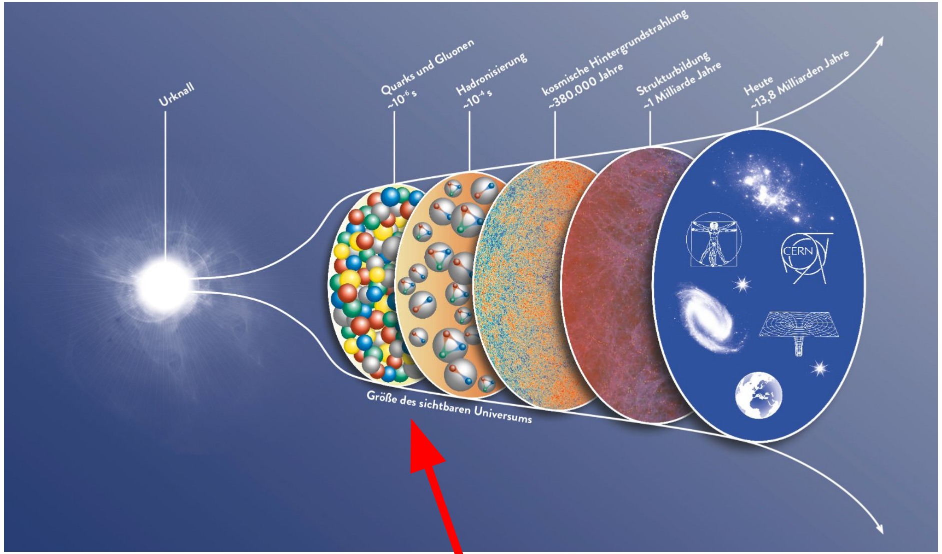

Use heavy-ion collisions

Phase transition in early universe (quarks→hadrons)

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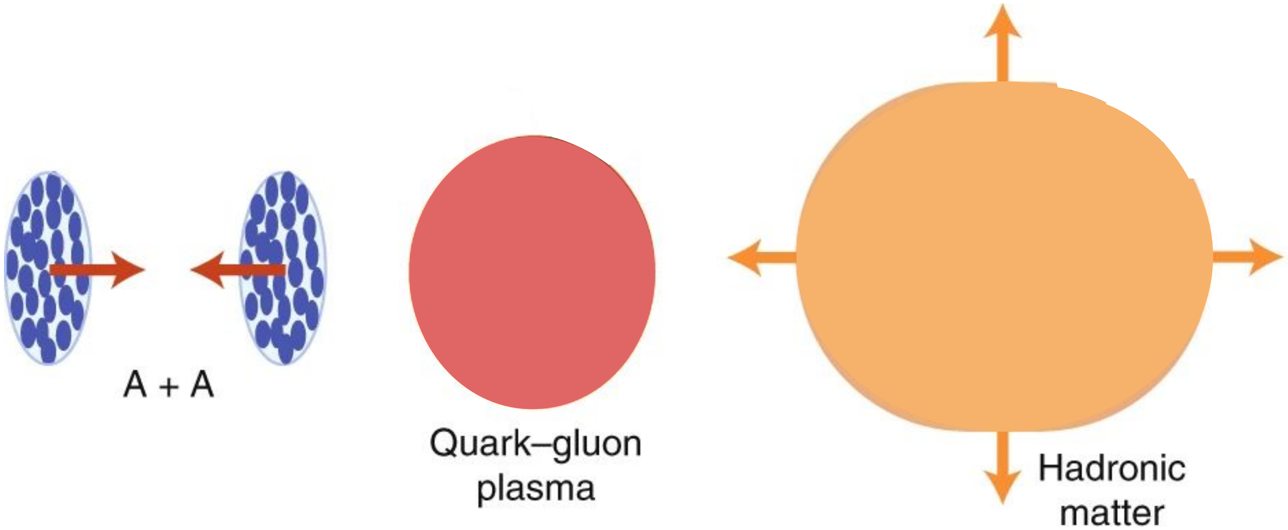
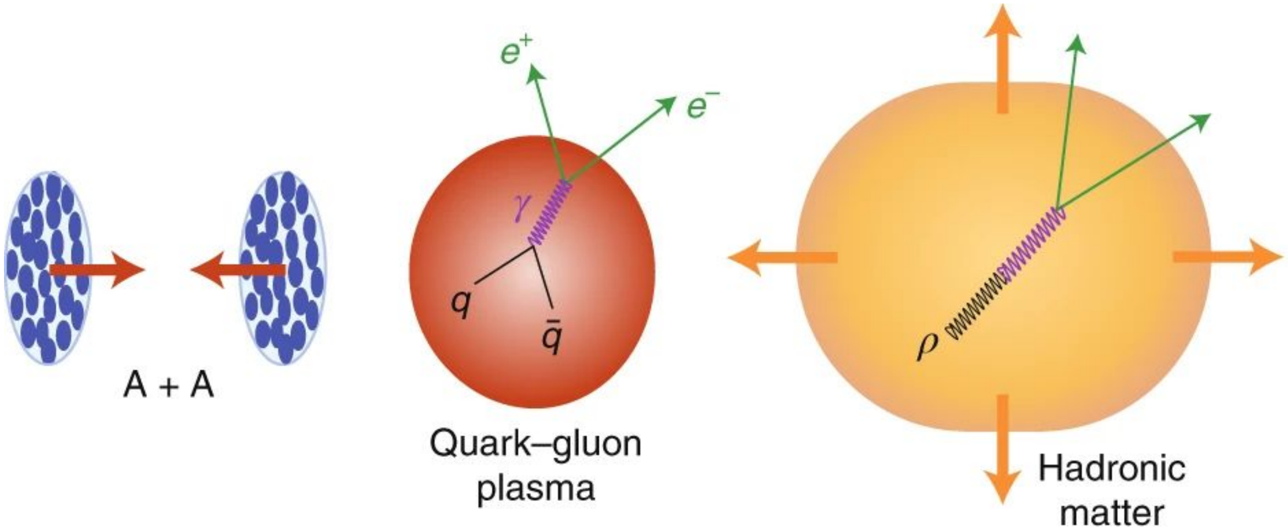
Heavy-ion collisions and dileptons



Degrees of freedom: *quarks, gluons* *hadrons*

Heavy-ion collisions and dileptons



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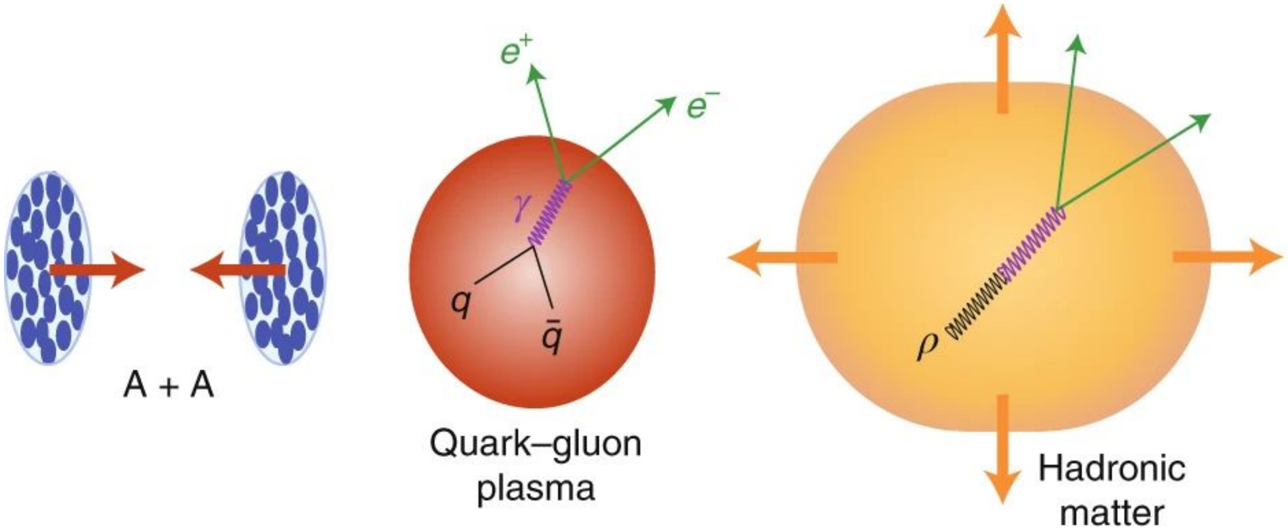
Strategy: measure dileptons (e^+e^- or $\mu^+\mu^-$ pairs)

- Couple to EM current throughout the **full collision history**
- Very low interaction with QCD medium (**no strong interaction**)

Heavy-ion collisions and dileptons



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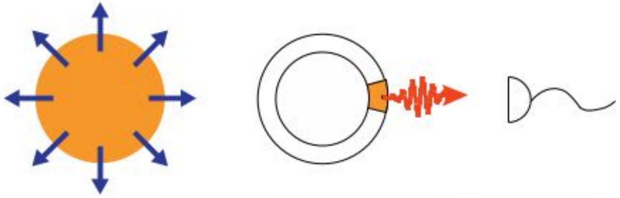
- **Virtual photons:** invariant mass, no blue-shift of rapidly expanding system
- **Bonus:** Also sensitive to **BSM particle decays (dark photons)**



Thermal dilepton production

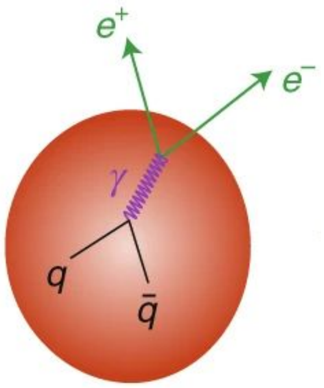
Thermal dilepton emission rate:

Electromagnetic spectral function

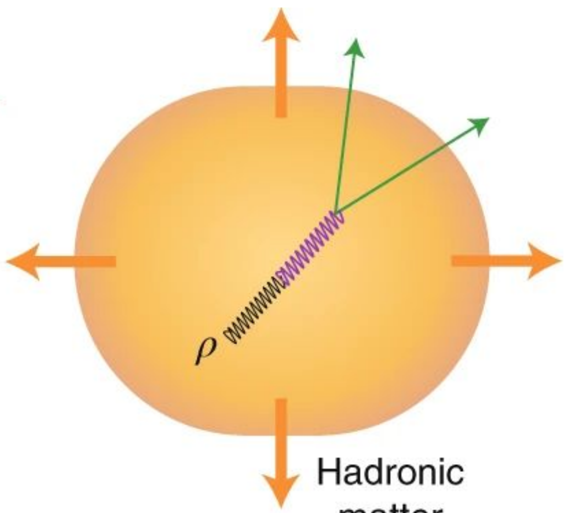
$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{EM}^2 L(M)}{\pi^3 M^2} f^B(q_0;T)\, \boxed{\mathrm{Im}\Pi_{EM}(M,q;\mu_B,T)}$$

quarks, gluons

hadrons



Quark–gluon plasma



Hadronic matter

Thermal dilepton production

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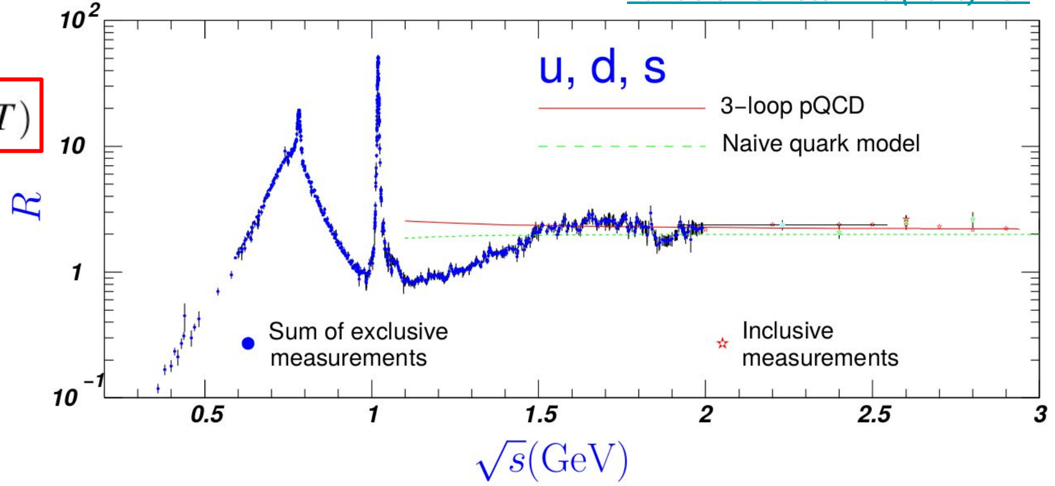
Landolt-Bornstein 23 (2010) 134



- **Vacuum**: EM spectral function well known from the e^+e^- annihilation cross section into hadrons / $\mu^+\mu^-$

$$R = -\frac{12\pi}{s} \mathrm{Im}\Pi_{EM}$$

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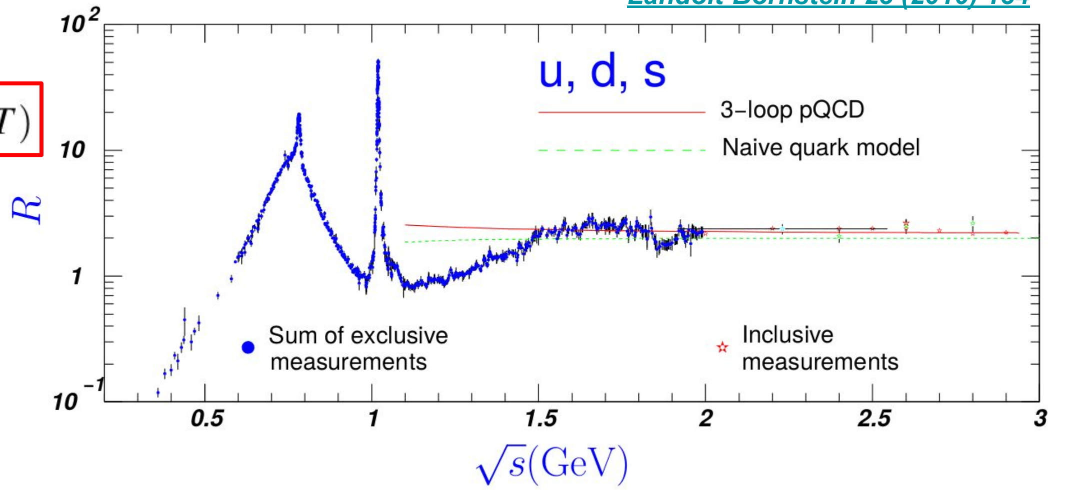


- **Vacuum**: EM spectral function well known from the e^+e^- annihilation cross section into hadrons / $\mu^+\mu^-$

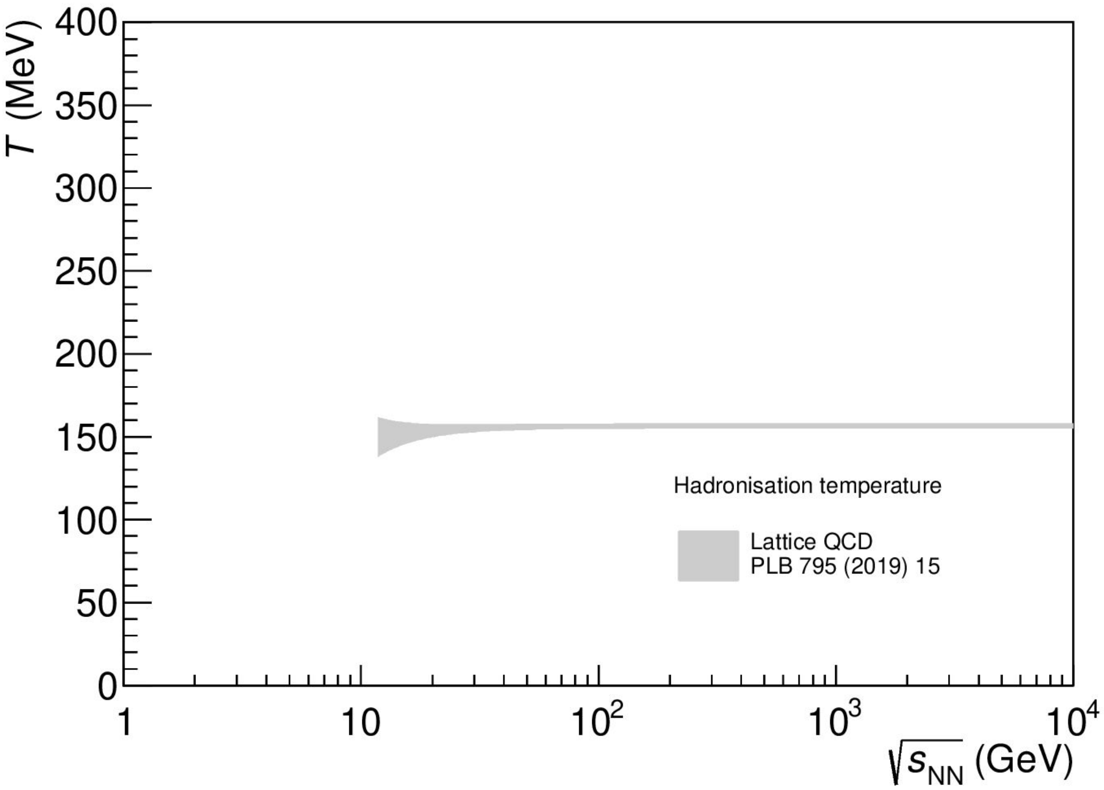
$$R = -\frac{12\pi}{s} \mathrm{Im}\Pi_{EM}$$

- **Medium:**
  - Below 1.5 GeV/c^2: measure **in-medium rho spectral function**
  - Above 1.5 GeV/c^2: **extraction of temperature** (and space-time evolution of thermal source)

Relevant temperatures in heavy-ion collisions

Why important?

- ***System temperature*** **> critical temperature?**



Lattice QCD, Phys. Lett. B 795 (2019) 15

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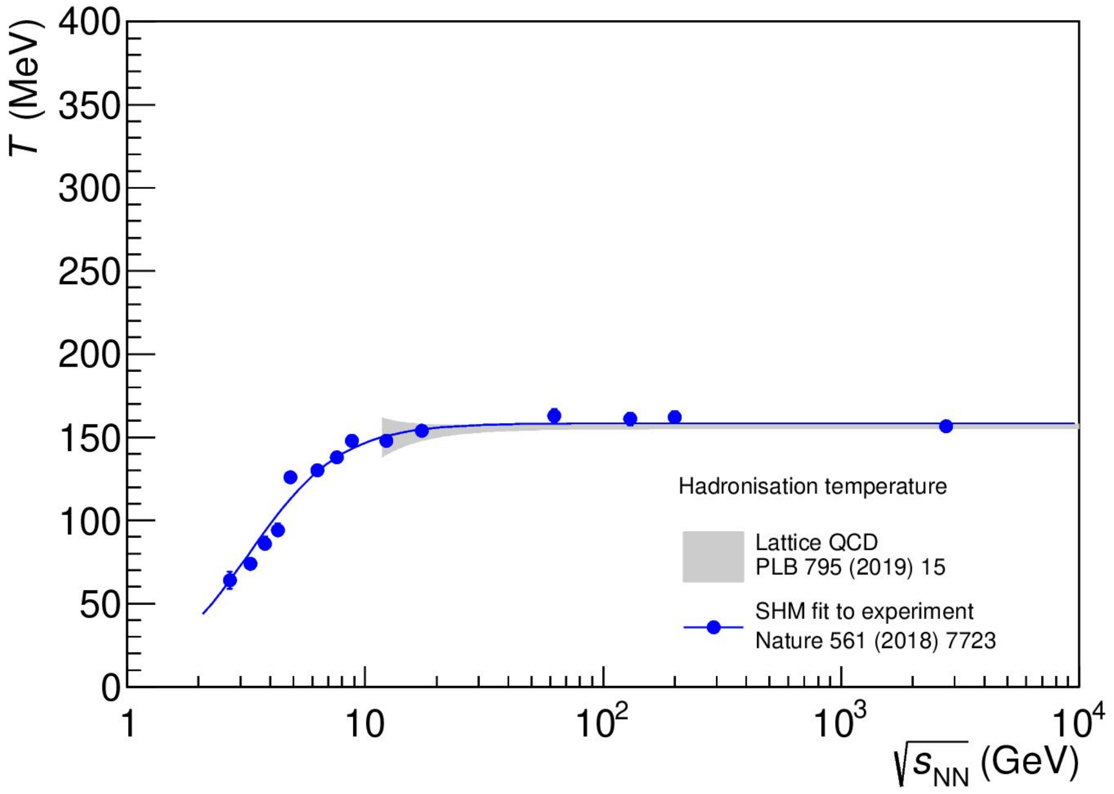

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[SHM, Nature 561 (2018) 7723, 321-330](#)

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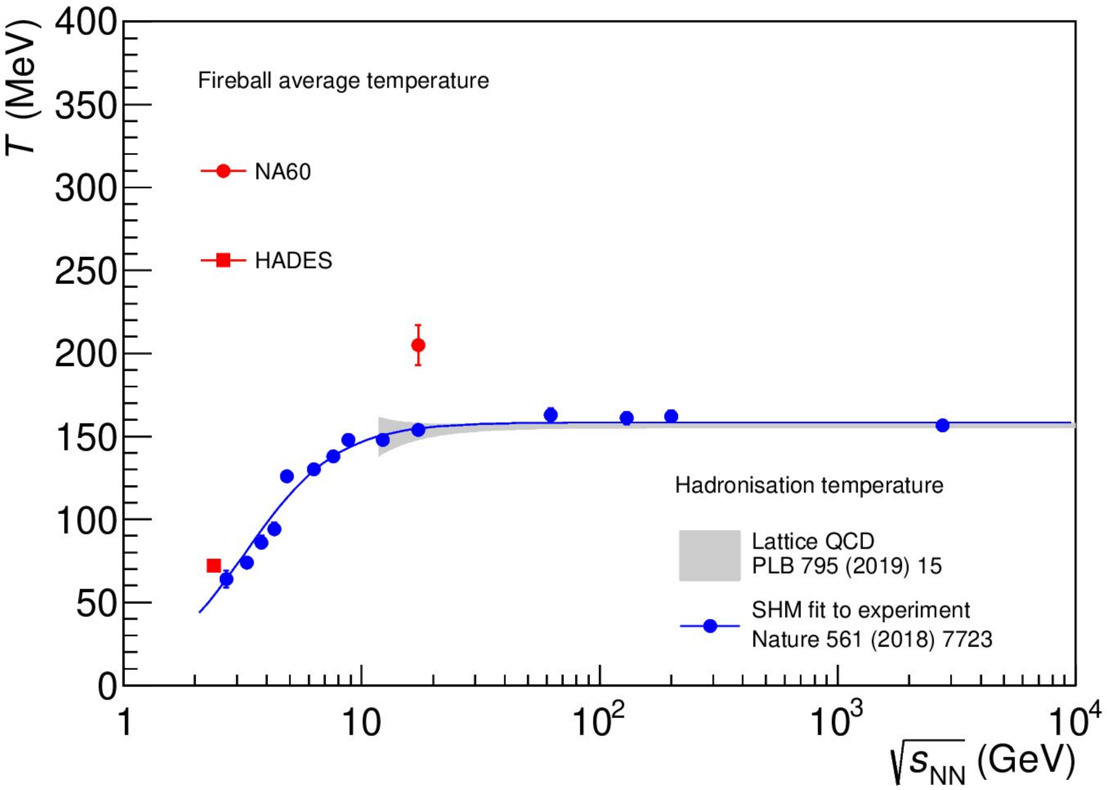

NA60, AIP Conf.Proc. 1322 (2010) 1, 1-10
HADES, Nature Physics 15 (2019) 10, 1040-1045
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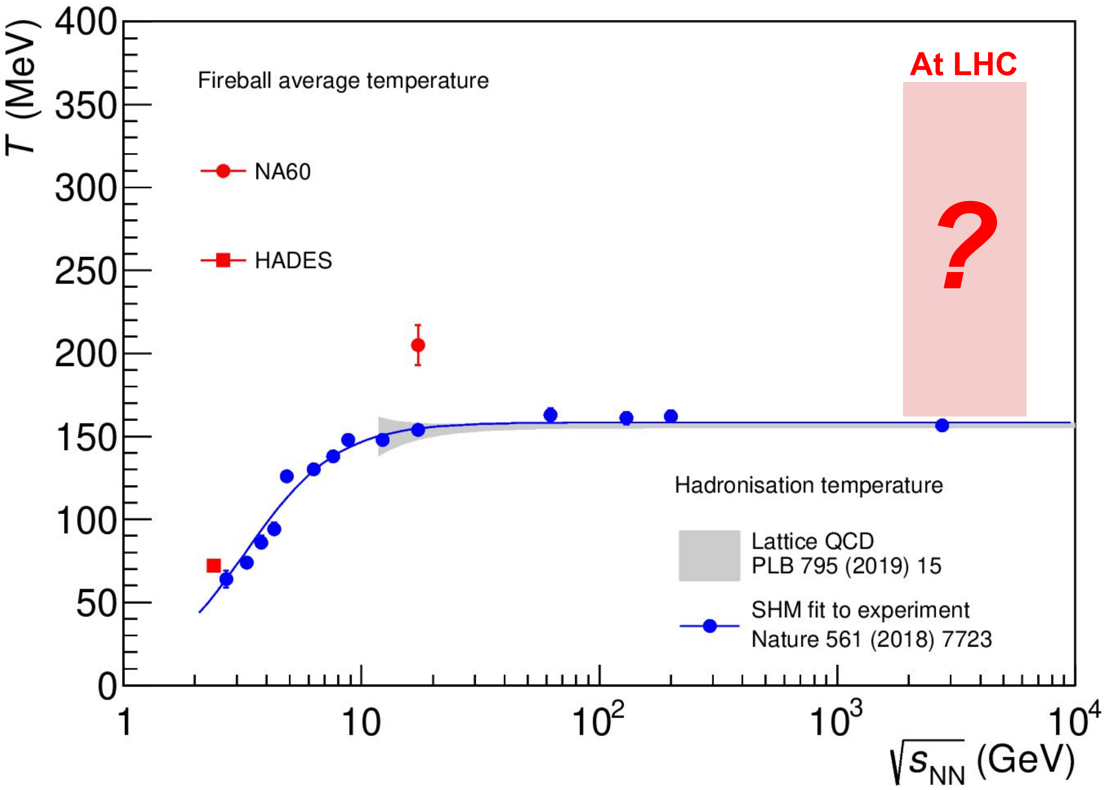
Goal:

- high precision measurements vs collision energy ranging over three orders of magnitude

Strategy:

- **Last five years:**
  - Optimize analysis
  - Understand background(s)
- **Next ten years:**
  - Optimize detector
  - Measure temperature and vector meson spectral function



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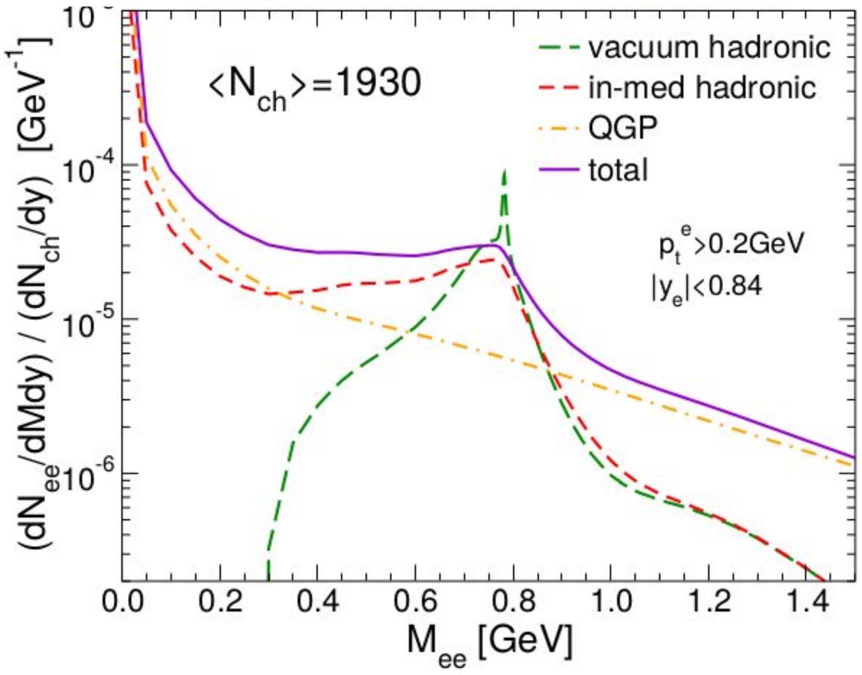
What to expect at the LHC

[Ralf Rapp, arXiv:1304.2309 [hep-ph]]



- In-medium modified rho spectral function → **restoration of chiral symmetry**

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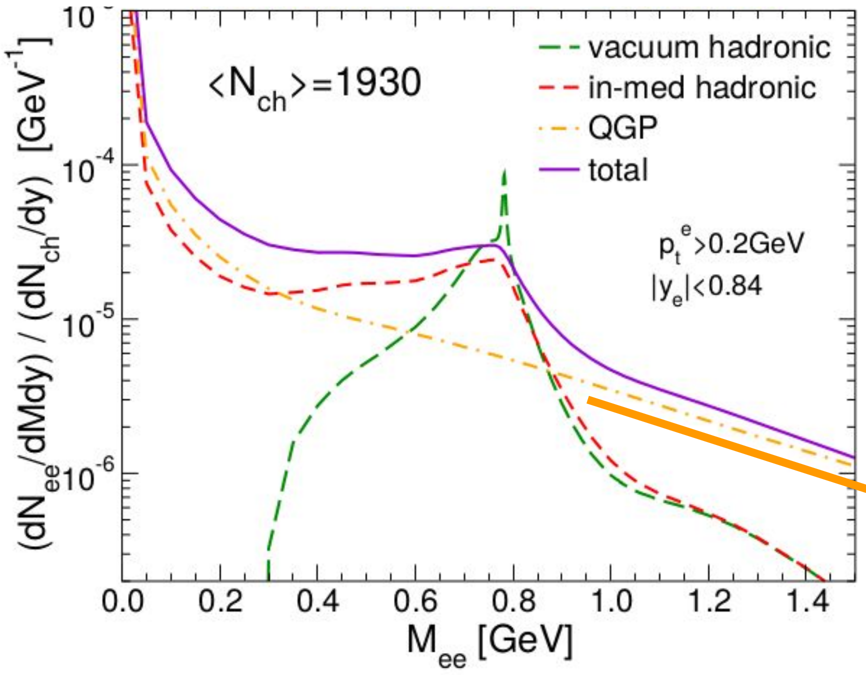
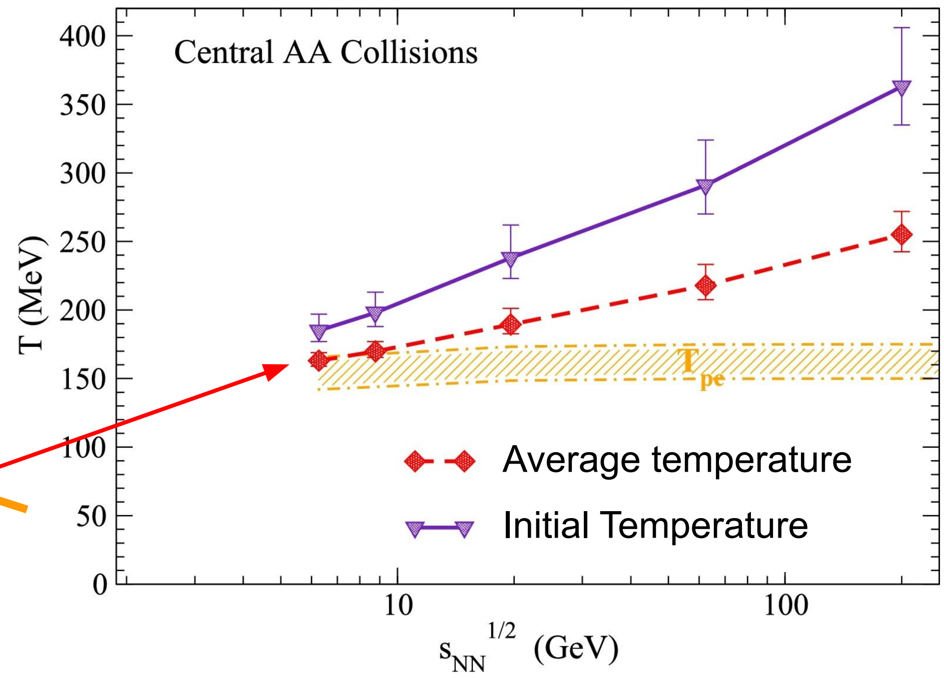


R. Rapp, H. van Hees, Phys.Lett. B 753, 586 (2016)



- In-medium modified rho spectral function → **restoration of chiral symmetry**
- Inverse slope parameter of dilepton invariant mass → **average and initial temperature**

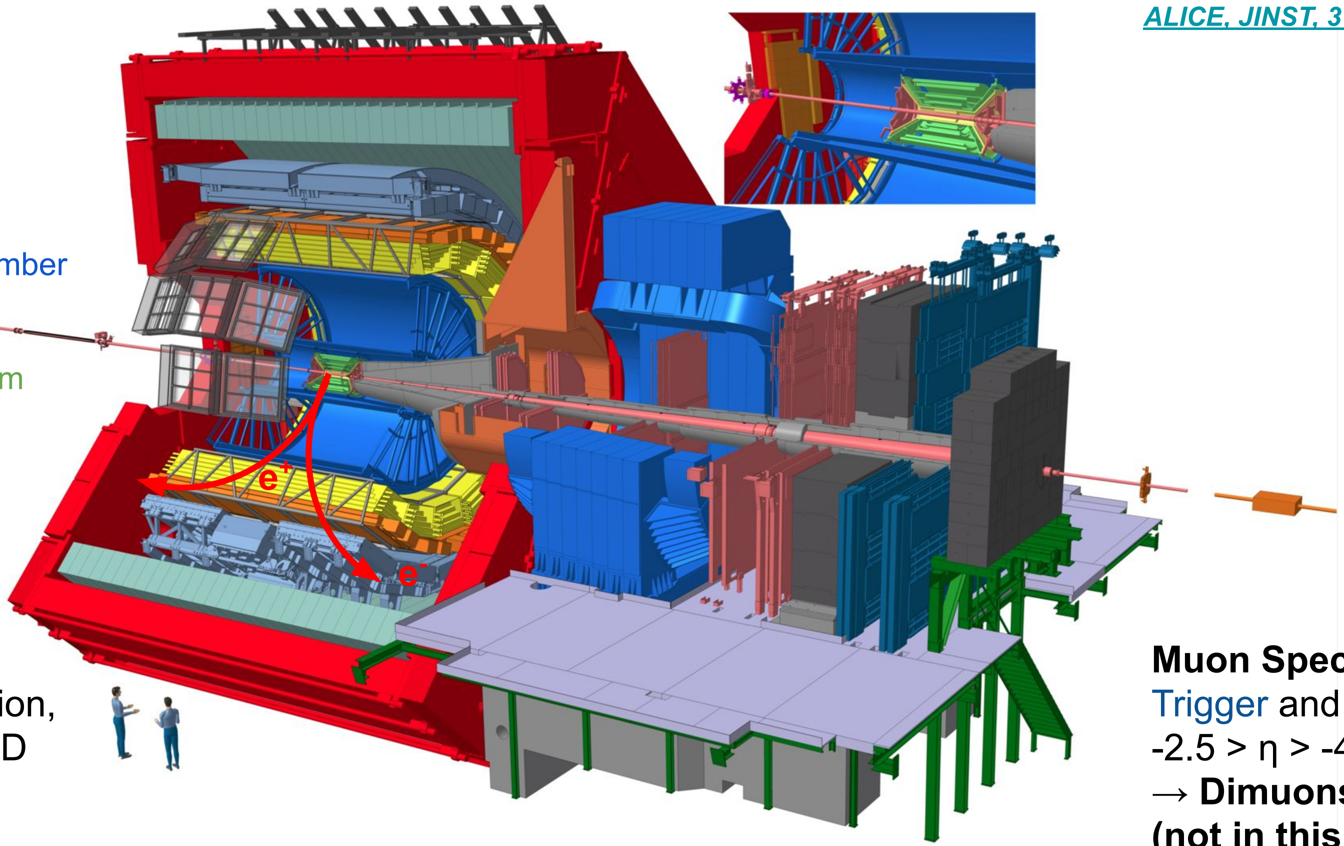
Experimental setup: ALICE at the CERN-LHC

ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044
ALICE, JINST, 3 (2008), S08002

Detector:
Length: 26 meters
Height: 16 meters
Weight: 10,000 ton

Time-Of-Flight
Time Projection Chamber

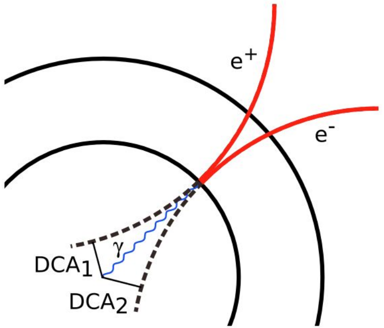
Inner Tracking System
V0, T0



Central barrel:
Event characterization,
Vertex, Tracking, PID
$|\eta| < 0.9$
→ **Dielectrons**

Muon Spectrometer:
Trigger and Tracking
$-2.5 > \eta > -4$
→ **Dimuons**
(not in this talk)

Experimental approach and challenges

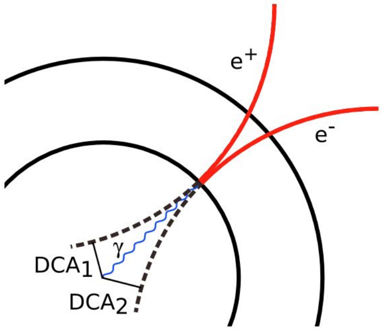


Method: dielectrons with ALICE at the LHC

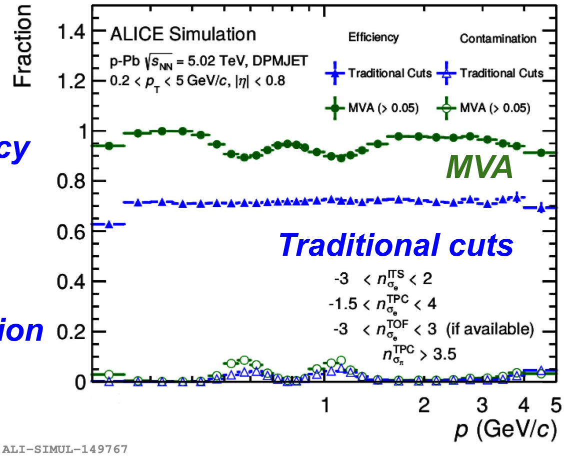
- Identify electrons/positrons
  - Minimize hadron contamination
- Pair electrons and positrons in one event
  - Major contribution from **photon conversion** in detector material

Experimental approach and challenges

CERN-THESIS-2019-261
CERN-THESIS-2018-034



Applying Machine Learning techniques (BDTs, Neural Networks):



Improve electron efficiency

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CERN-THESIS-2019-261
CERN-THESIS-2018-034

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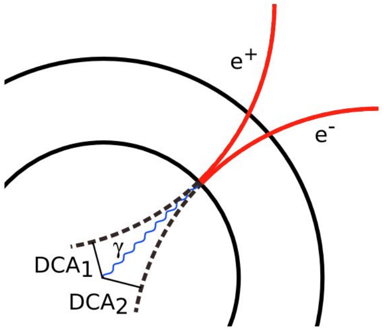
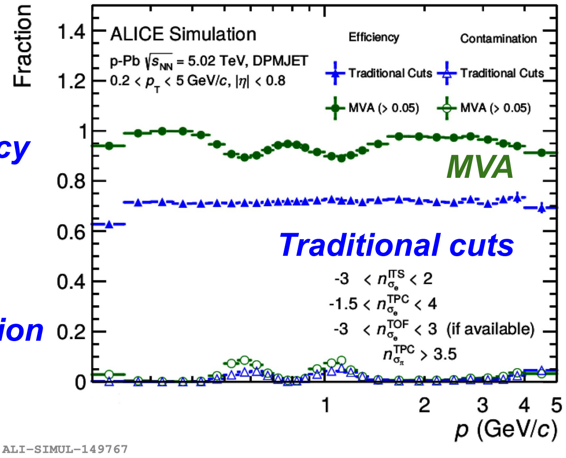


Efficiency

Contamination



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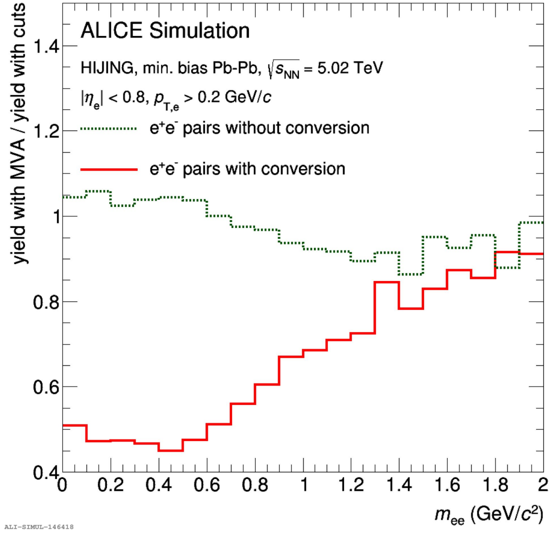

Improve conversion rejection

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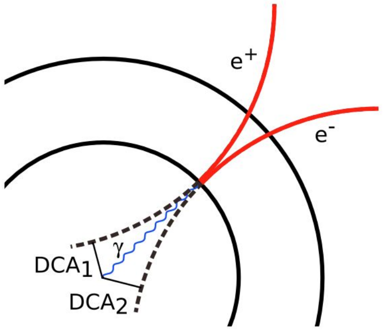

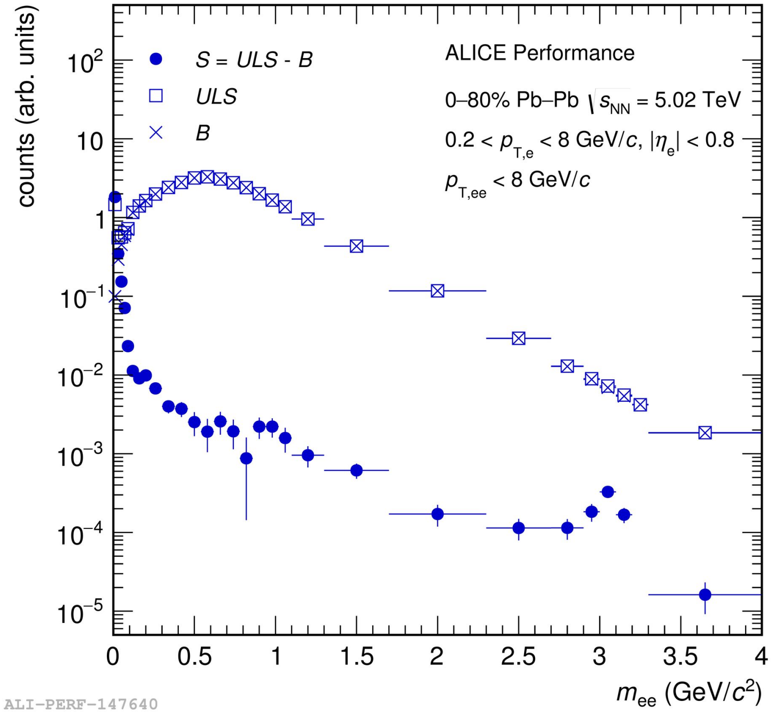

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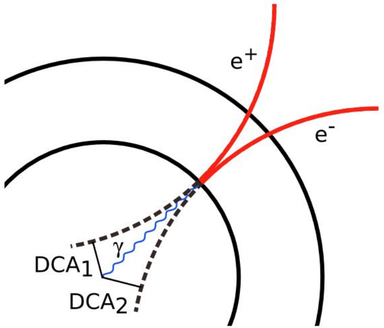
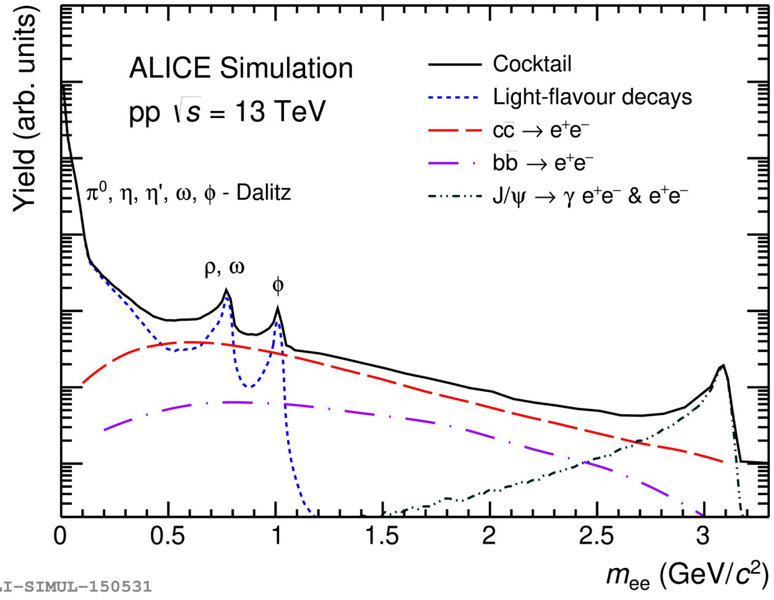
- Subtract **combinatorial background B**
  - S/B ~ 10^{-3} in Pb-Pb collisions

Experimental approach and challenges





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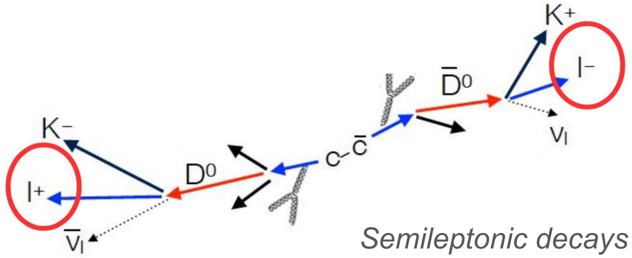
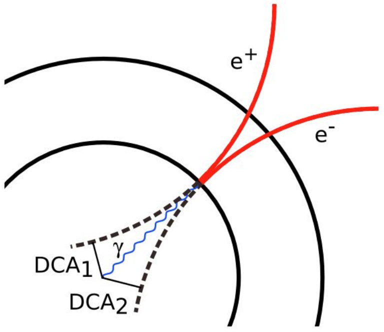
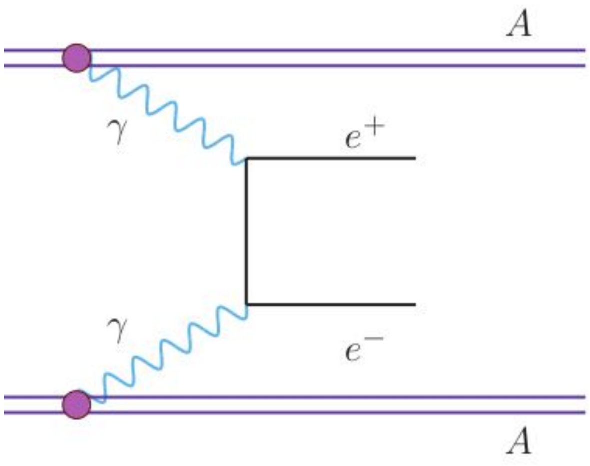
- Subtract “known” long-lived light- and heavy-flavour sources (“**cocktail**”)
  - **Step 1:** Reference systems → pp and p-Pb collisions



Semileptonic decays of charm/beauty hadrons (cτ ~ O(100μm))

Experimental approach and challenges





Method: dielectrons with ALICE at the LHC

- Identify electrons/positrons
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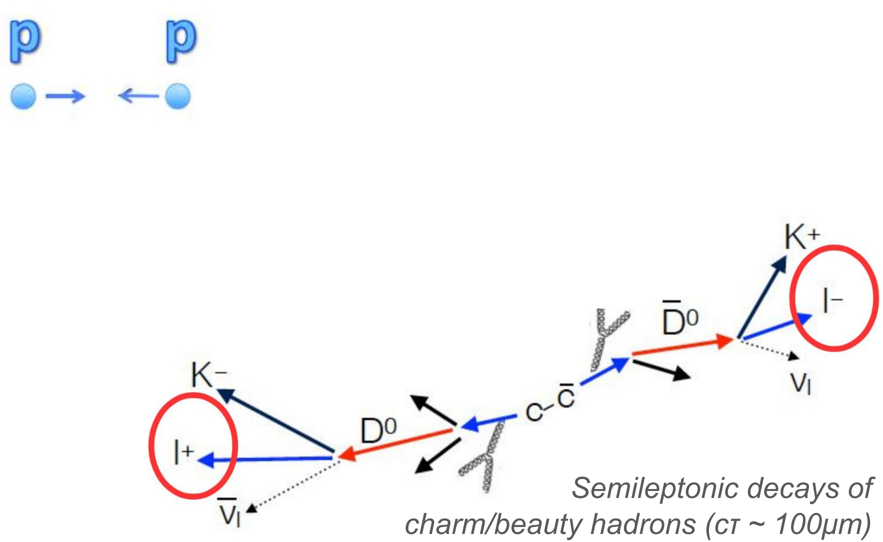
- Pair electrons and positrons in one event
  - Major contribution from **photon conversion** in detector material

- Subtract **combinatorial background B**
  - S/B ~ 10^{-3} in Pb-Pb collisions

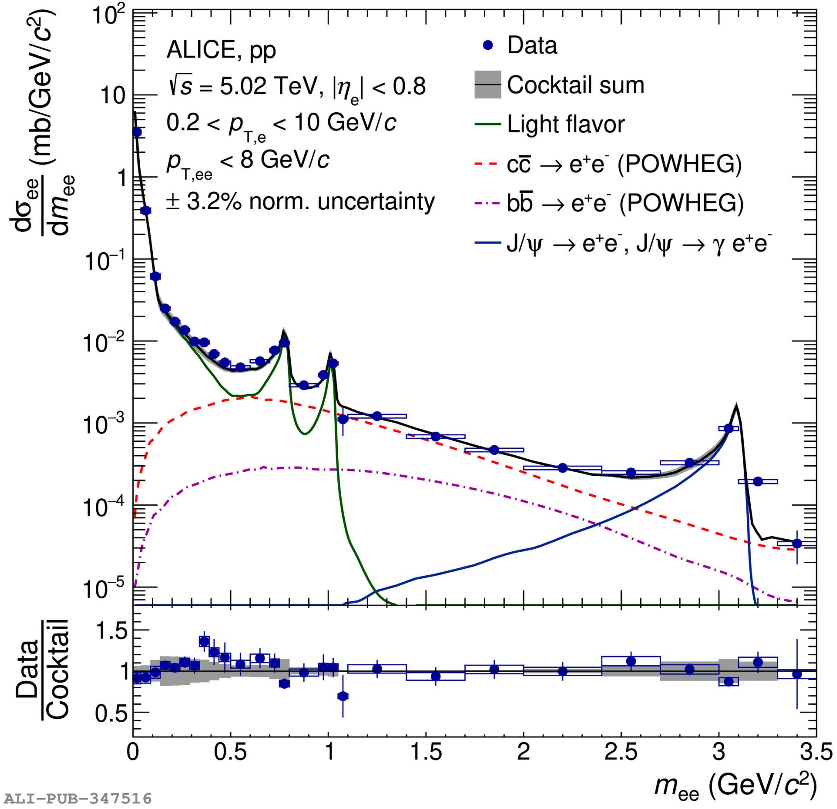
- Subtract “known” long-lived light- and heavy-flavour sources (“**cocktail**”) as well **QED dielectron production**
  - **Step 1:** Reference systems → pp and p-Pb collisions
  - **Step 2:** Peripheral Pb-Pb collisions

Understanding “hadronic sources”

[ALICE, arXiv:2005.11995 [nucl-ex]]



Semileptonic decays of charm/beauty hadrons (cτ ~ 100μm)



- Understand production and decay of **light and heavy flavour hadrons**

Understanding “hadronic sources”

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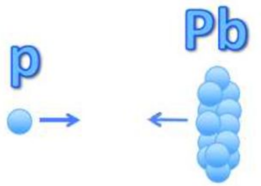
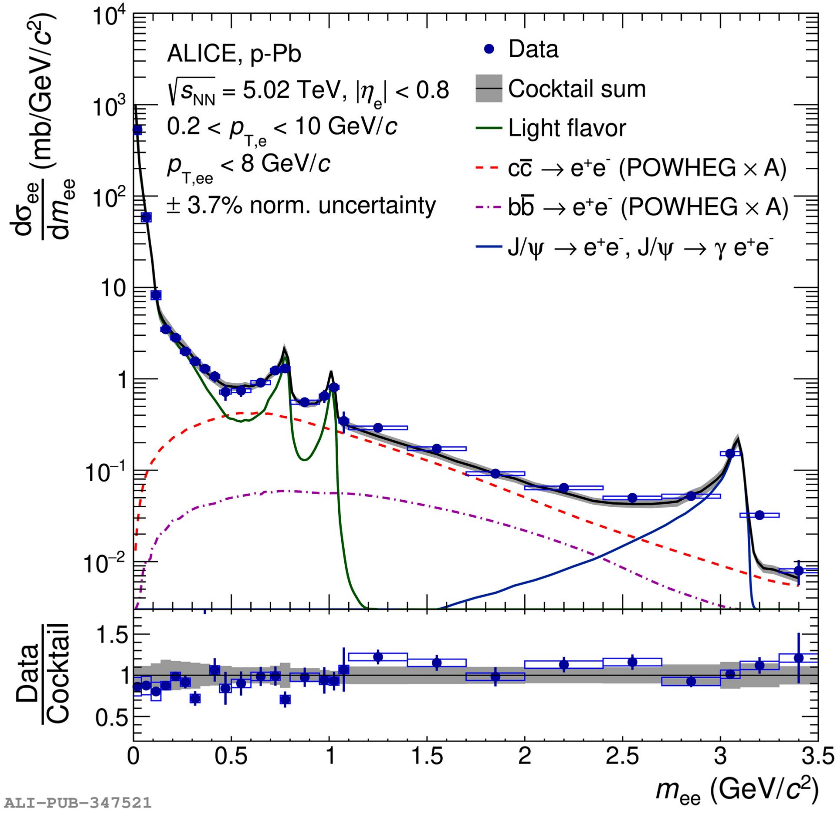
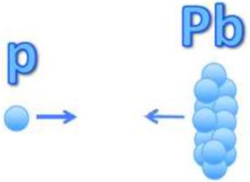




- Understand production and decay of **light and heavy flavour hadrons**
- Understand **modifications not related to hot QCD matter**

Understanding “hadronic sources”

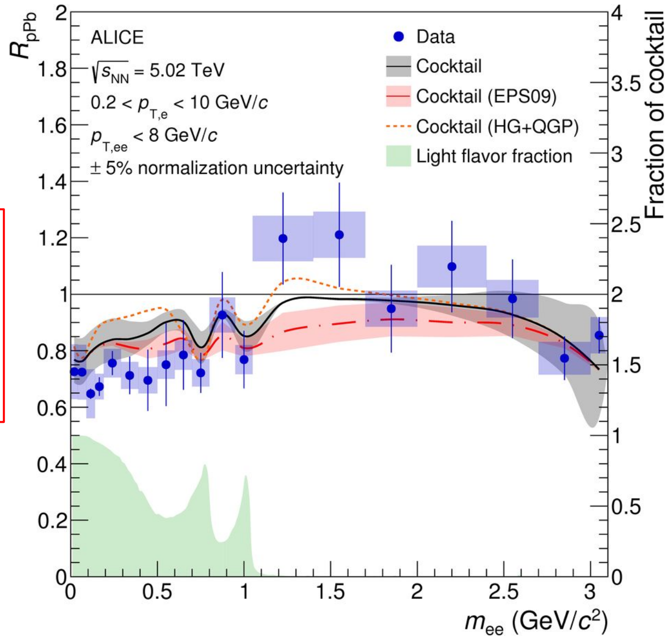
[ALICE, arXiv:2005.11995 [nucl-ex]](#)

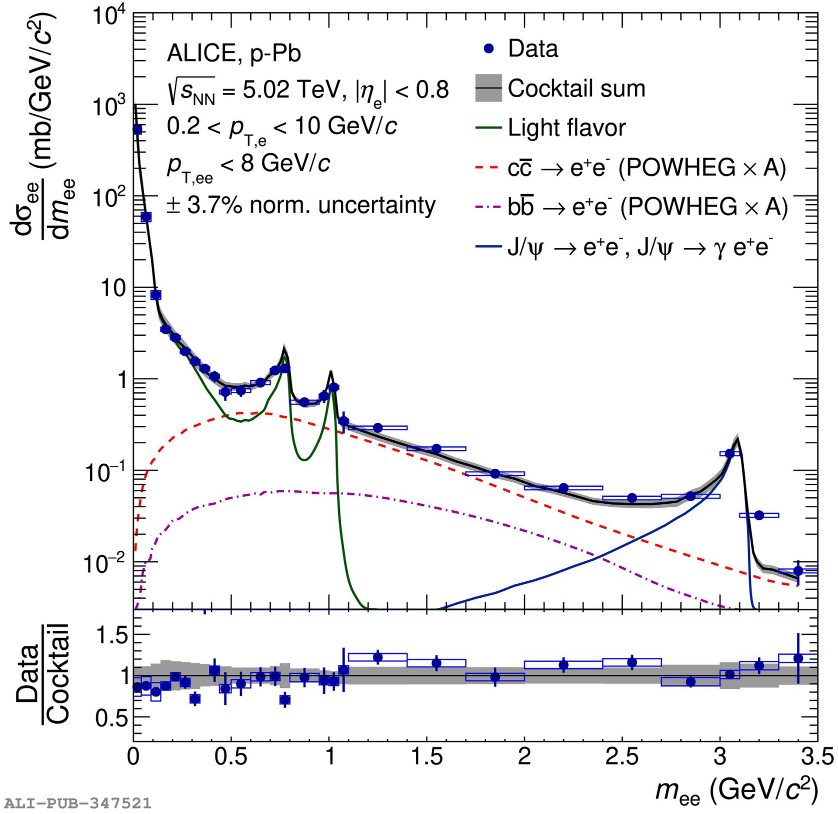


Nuclear modification factor:

$$R_{\mathrm{pPb}}(m_{\mathrm{ee}}) = \frac{1}{A}\frac{\mathrm{d}\sigma^{\mathrm{pPb}}_{\mathrm{ee}}/\mathrm{d}m_{\mathrm{ee}}}{\mathrm{d}\sigma^{\mathrm{pp}}_{\mathrm{ee}}/\mathrm{d}m_{\mathrm{ee}}}$$

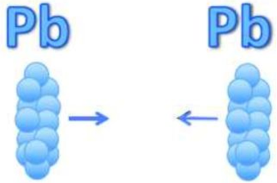
R_{pPb} = 1, if p-Pb simple superposition of pp/pn collisions

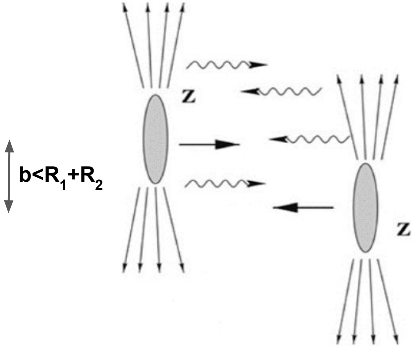


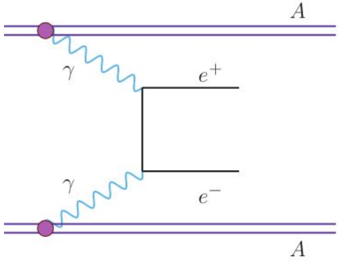


- Understand production and decay of **light and heavy flavour hadrons**
- Understand **modifications not related to hot QCD matter**
- **Thermal radiation in small systems?**

Understanding “QED sources”

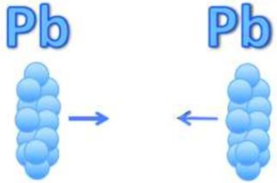


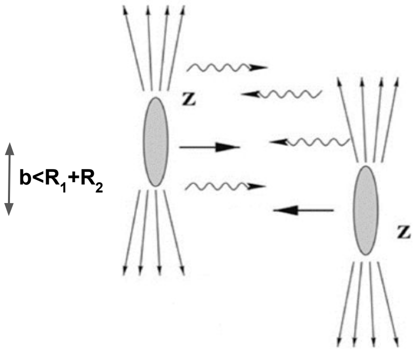


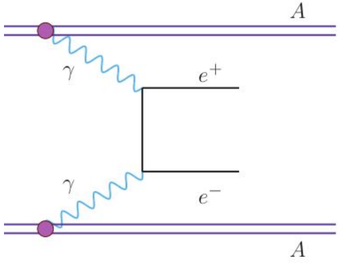


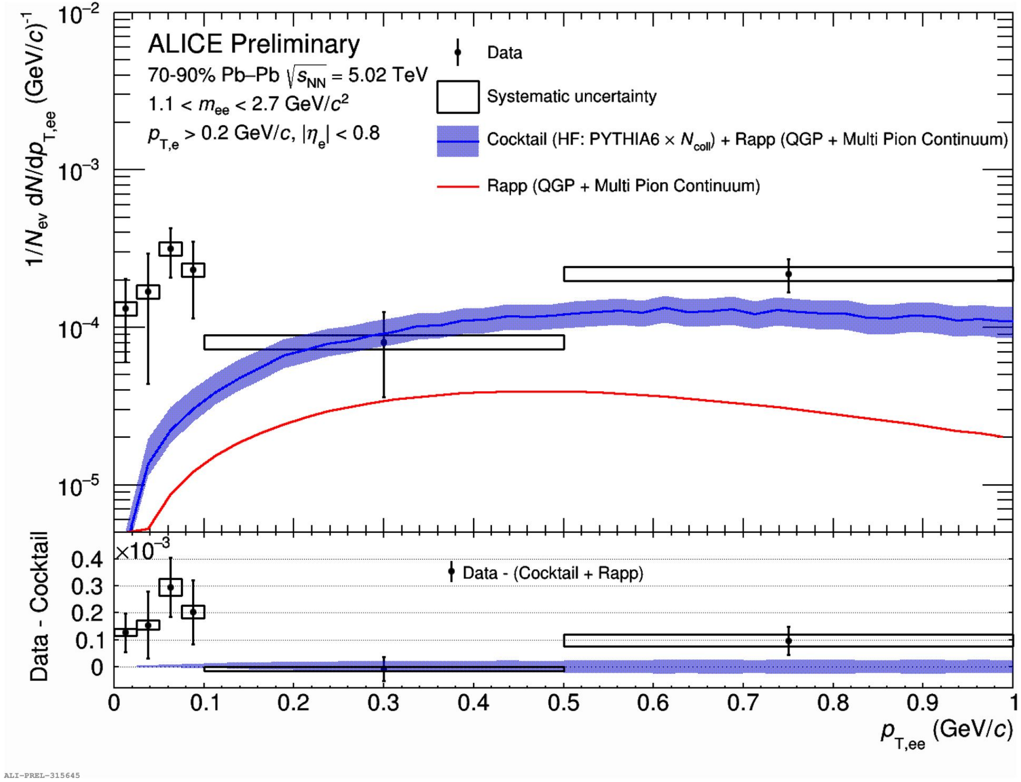
Understanding “QED sources”

[arXiv:1909.02508 [nucl-ex]](https://arxiv.org/abs/1909.02508)





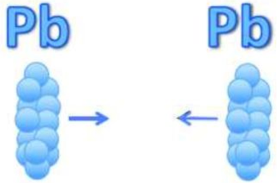


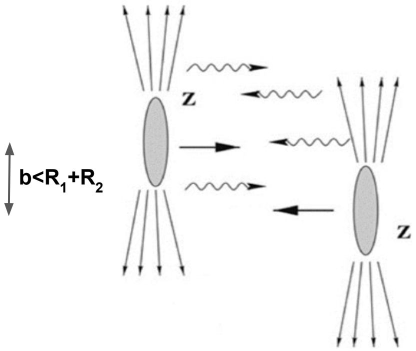


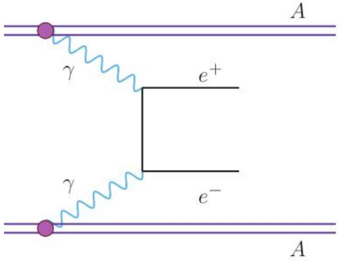
- **Excess of dielectrons** over hadronic cocktail

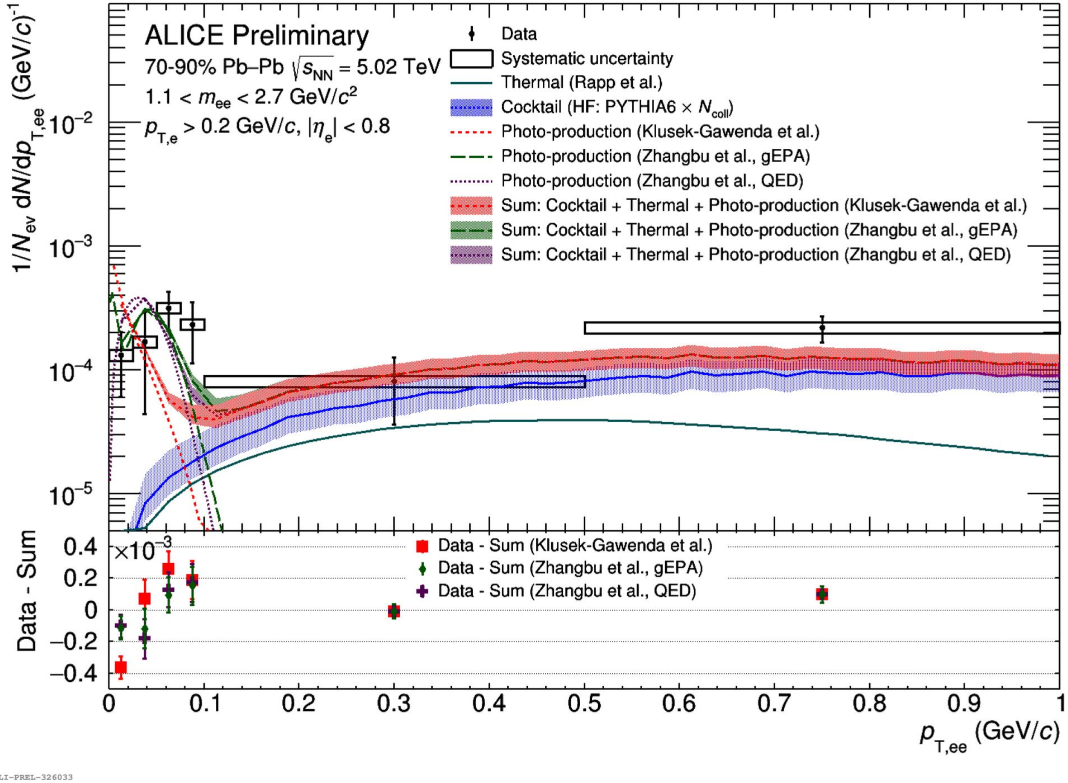
Understanding “QED sources”

arXiv:1909.02508 [nucl-ex]









- **Excess of dielectrons** over hadronic cocktail
  → **Continuum dilepton photo-production in Pb-Pb collisions at the LHC with nuclear overlap**

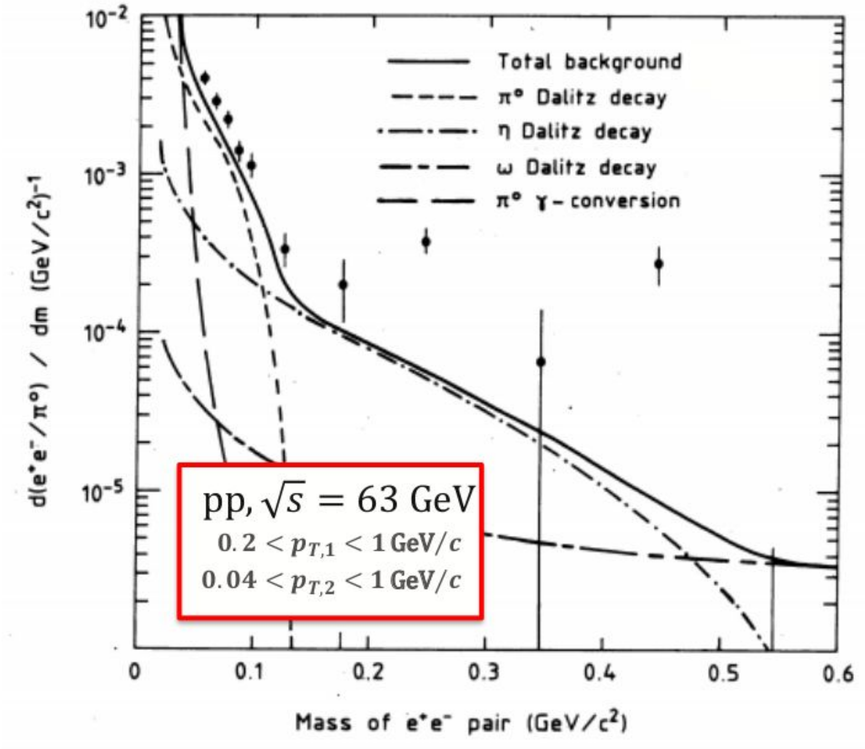
'Anomalous' dileptons in pp collisions

CERN ISR – AFS (1987):

- **Excess of dielectrons** over expectation from known hadronic sources in a 'elementary' collision system
  → Similar effects also observed in real-photon channel

Low-mass region (LMR) excess:

- 0.05 GeV/c^2 < m_{ee} < 0.6 GeV/c^2
- $p_{T,ee}$ < 1 GeV/c
  → **No other experiment could probe this region**



V. Hedberg, PhD thesis, Lund (1987)

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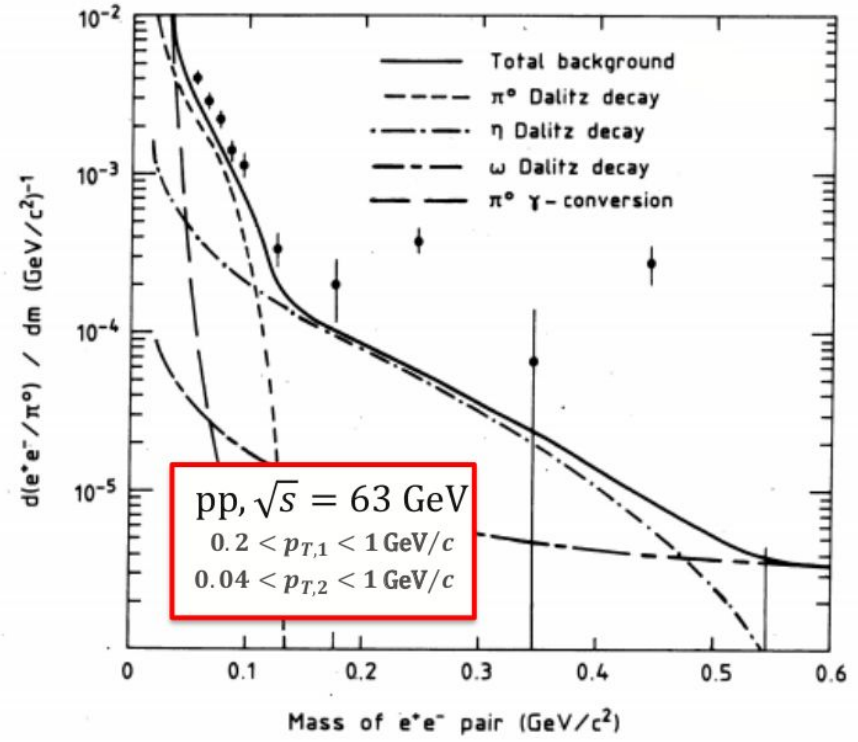
  → **No other experiment could probe this region**

Dedicated low B-field campaign (B = 0.5 T → 0.2 T):

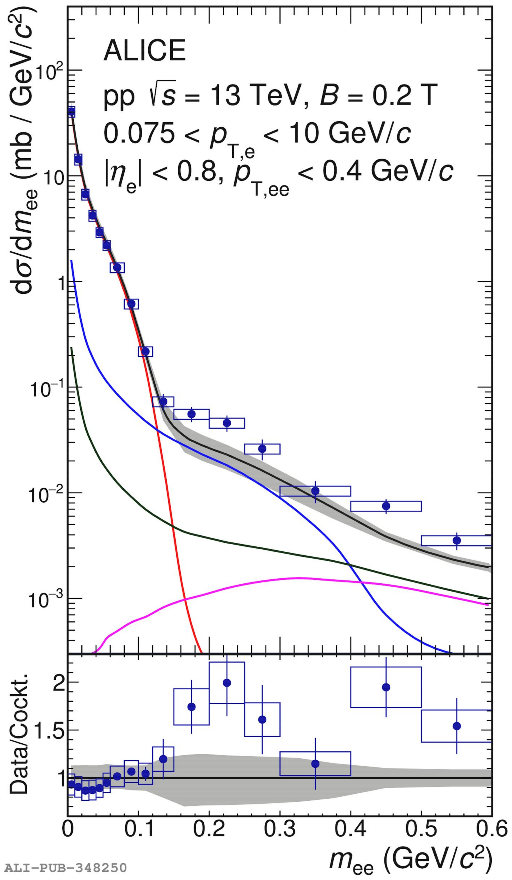
- Electron selection down to p_T > 0.075 GeV/c
- Better TOF acceptance & conversion rejection
  → **Allows ALICE to challenge the AFS measurement**



V. Hedberg, PhD thesis, Lund (1987)

Soft dielectrons in pp collisions at the LHC

arXiv:2005.14522 [nucl-ex]



- **Enhancement also observed at LHC energies**
  - 0.14 GeV/c^2 < m_{ee} < 0.6 GeV/c^2
  - $p_{T,ee}$ < 0.4 GeV/c

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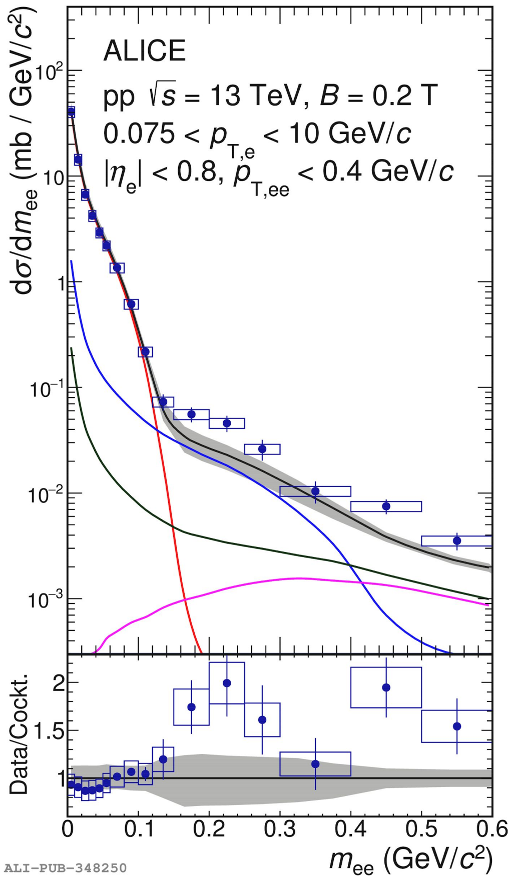

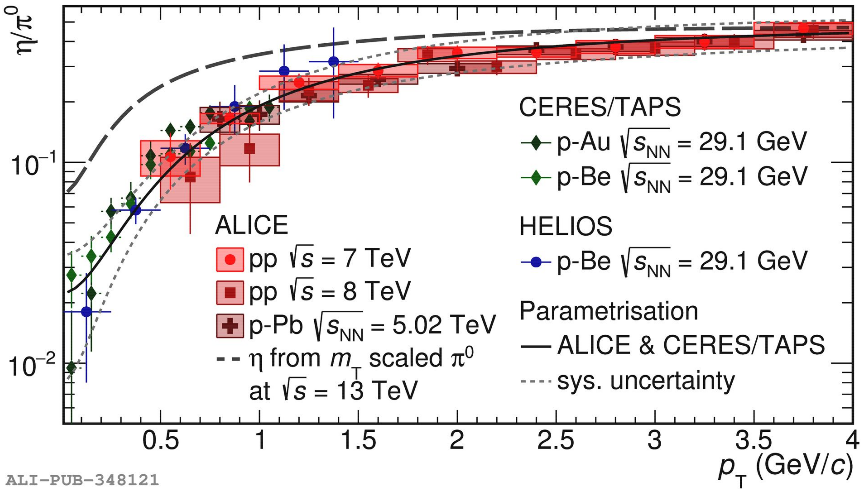

- **Enhancement also observed at LHC energies**
  - $0.14 \text{ GeV}/c^2 < m_{ee} < 0.6 \text{ GeV}/c^2$
  - $p_{T,ee} < 0.4$ GeV/c
- **η contribution dominating source of the cocktail uncertainties**
  - ALICE measurement only down to $p_T < 0.4$ GeV/c
  - m_T scaling overshoots η at low p_T
    → CERES/TAPS measurement used to constrain low p_T
    Eur.Phys.J.C 4 (1998) 249-257

Soft dielectrons in pp collisions at the LHC

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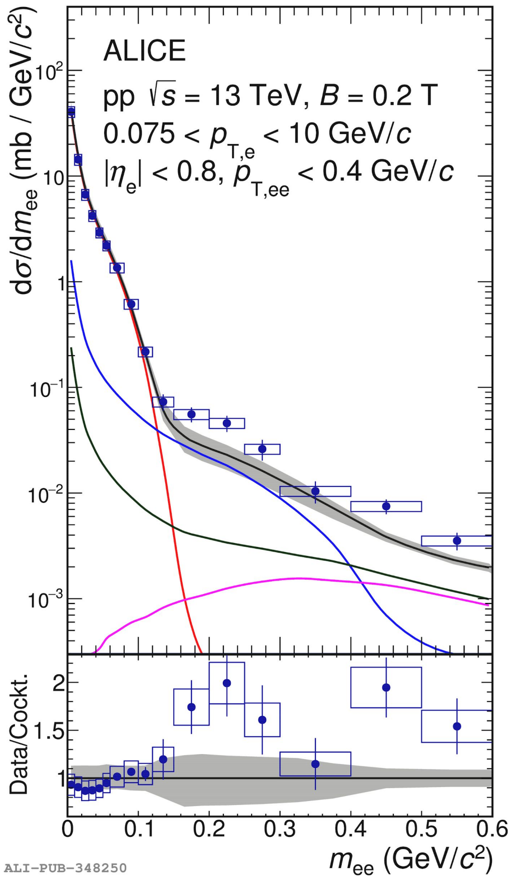
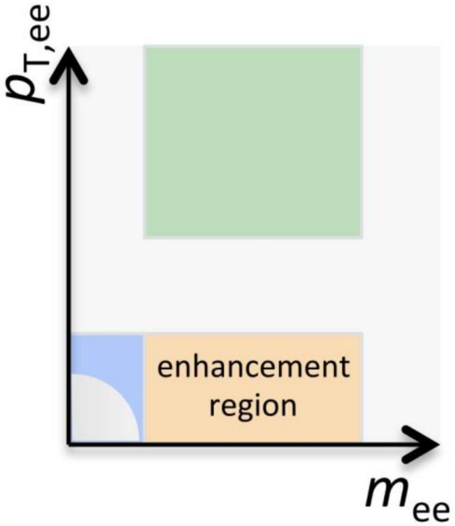
ALICE





- Enhancement also observed at LHC energies
- Study control regions and multiplicity dependence

Soft dielectrons in pp collisions at the LHC

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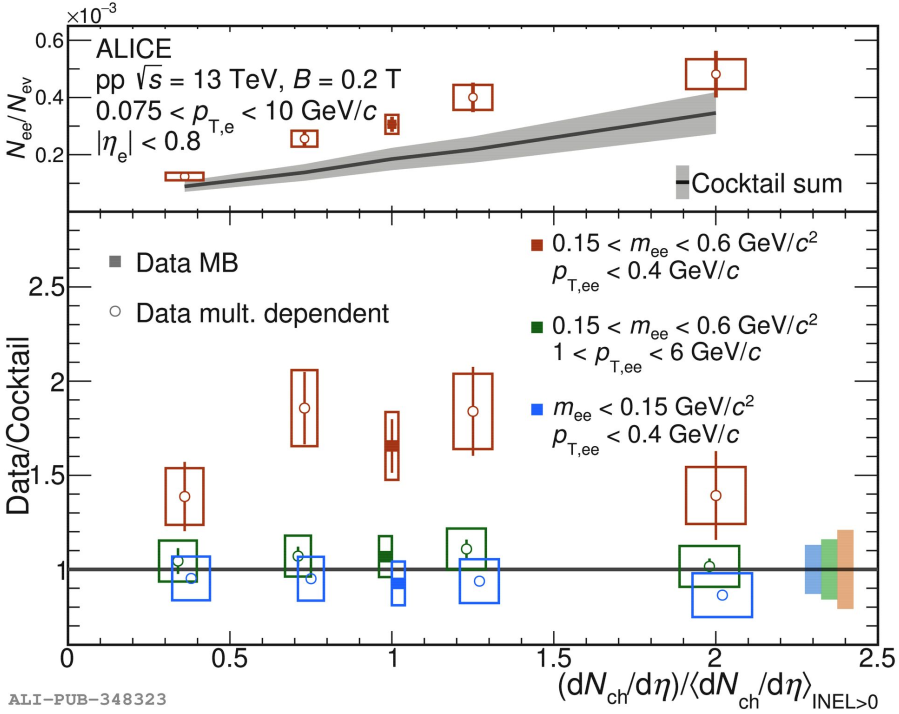
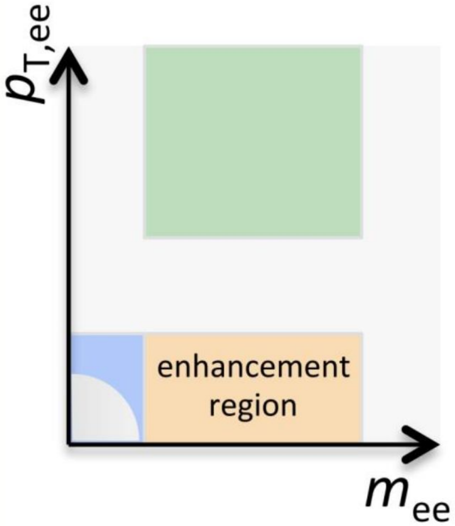
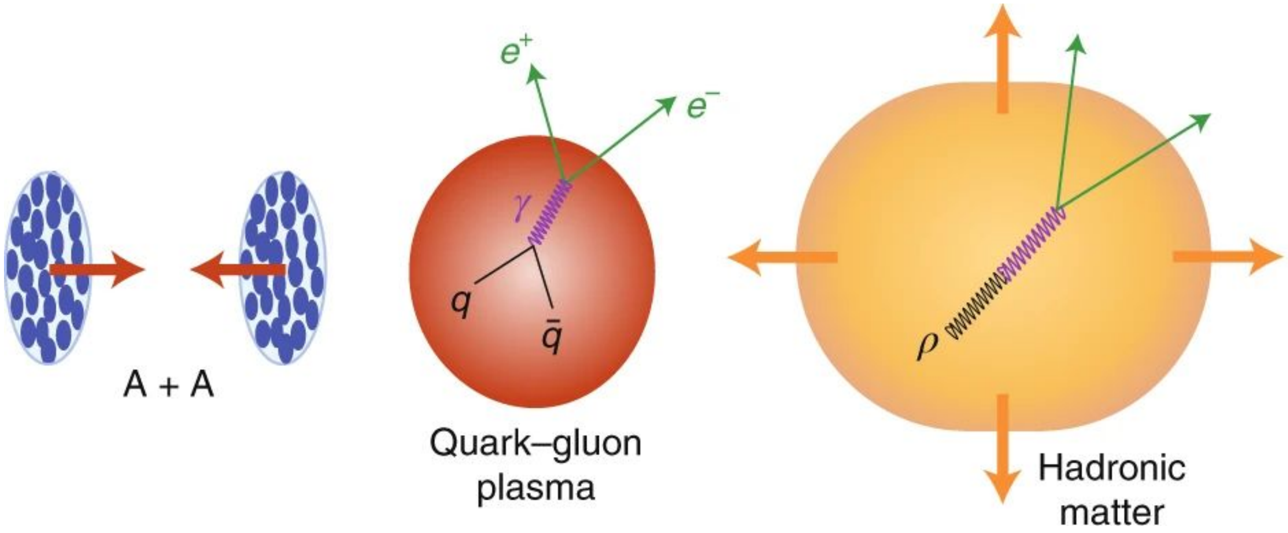




- **Enhancement also observed at LHC energies**
- **Study control regions and multiplicity dependence**
  → No excess at lower m_{ee} or higher $p_{T,ee}$
  → No clear multiplicity dependence within uncertainties
- **Most consistent with linear scaling**
  → **Future ALICE pp programme:** Large MB data set with an integrated luminosity of about **3 pb^{-1} (factor 300)**

ALICE-PUBLIC-2020-005

Status: thermal radiation in Pb-Pb collisions at LHC



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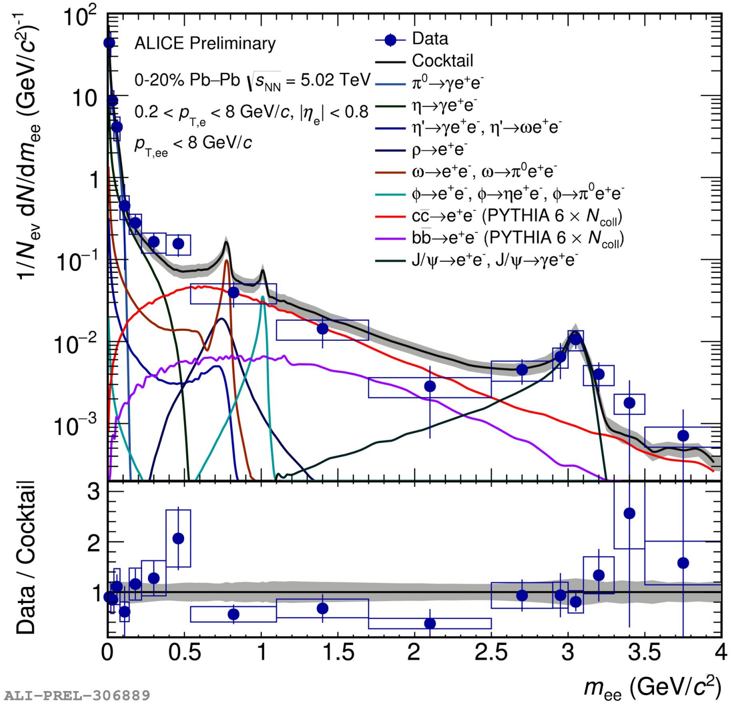

- **Central Pb-Pb collisions** (2015 data only)
- Still large uncertainties (analysis of 2018 data with ~10 times larger sample ongoing)

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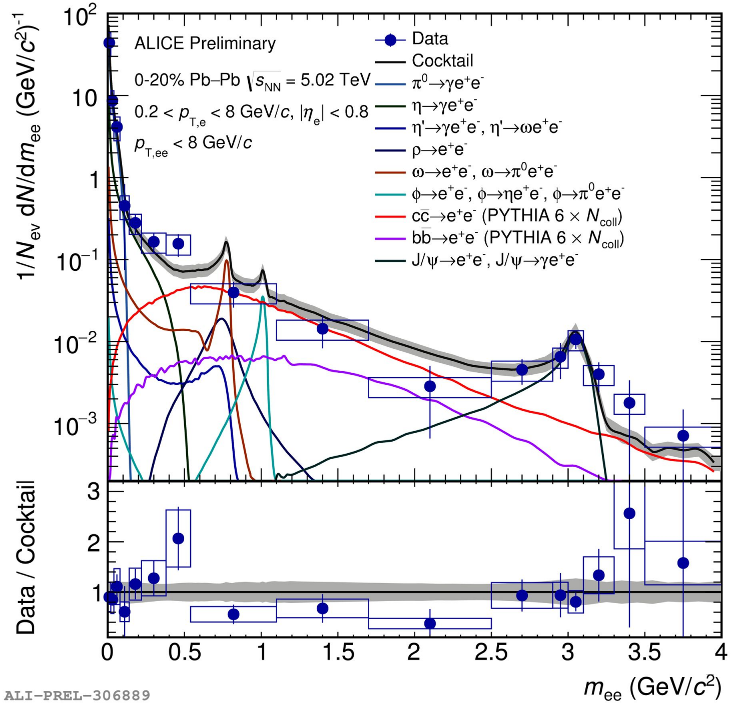
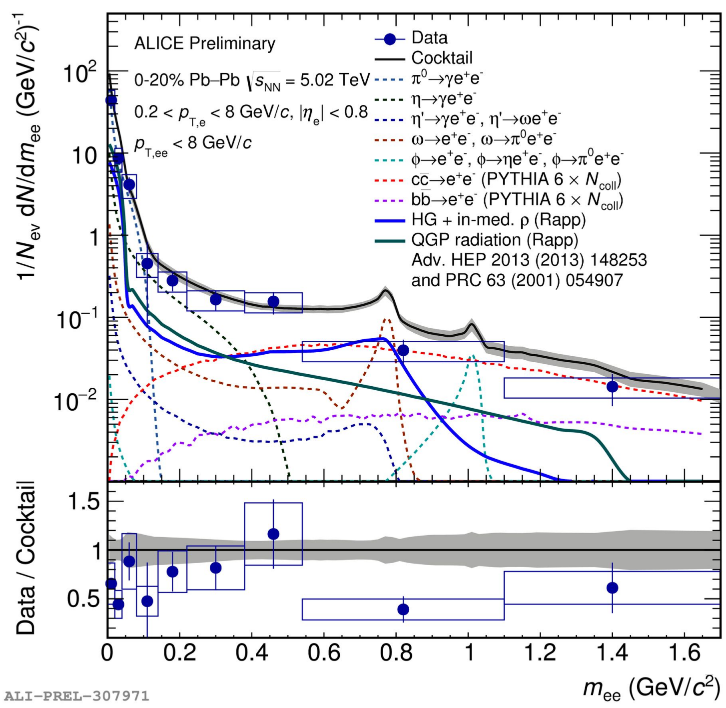


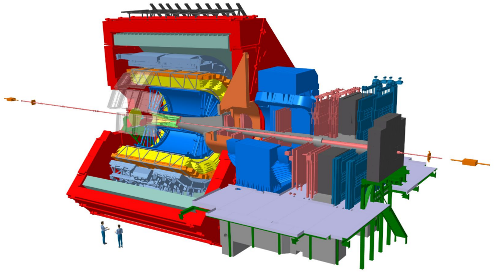


- **Central Pb-Pb collisions** (2015 data only)
- Still large uncertainties (analysis of 2018 data with ~10 times larger sample ongoing)
- Comparisons to **pure hadronic cocktail, nPDFs, and thermal scenarios** inconclusive so far

(similar conclusion from Run 1 data)

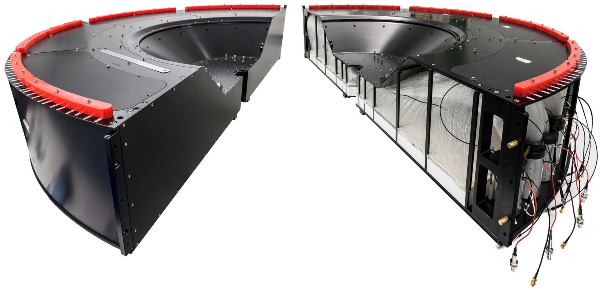
The next decade

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2040 2050



Major ALICE upgrade

- *Continuous (triggerless) data taking*
- *TPC readout: MWPC -> GEM*
- *New inner tracking system (ITS2)*
- *New event characterization detectors (FIT)*



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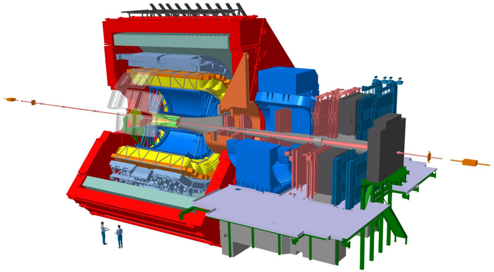

dileptons

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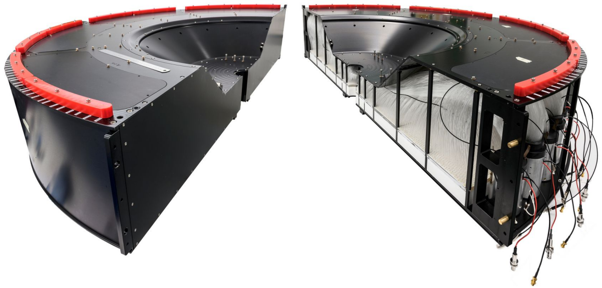
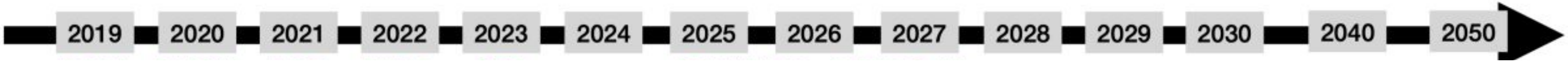
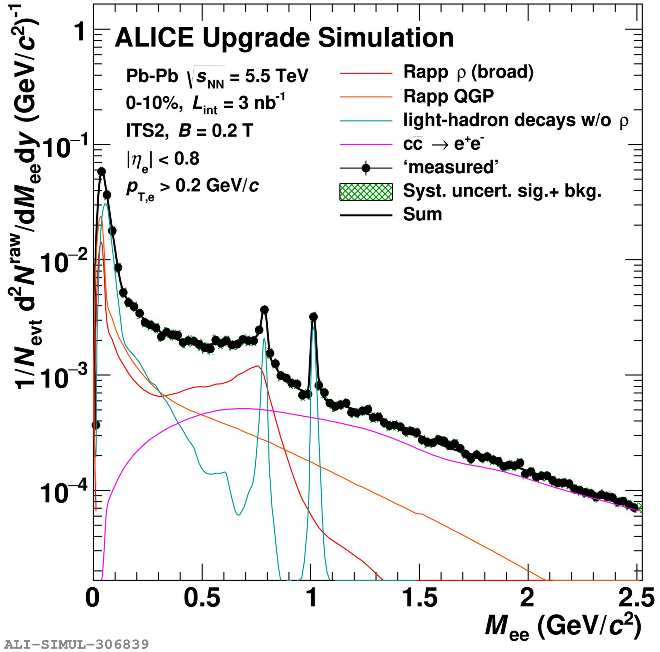


- Improved **pointing resolution (x3)**
- Reduced material budget (**less photon conversions**)
- More **statistics (up to x100)**
- Dedicated **low B field run(s)**: improved efficiency at low p_T, better conversion rejection

Physics performance with ITS2

[HL-LHC WG5 yellow report](#)

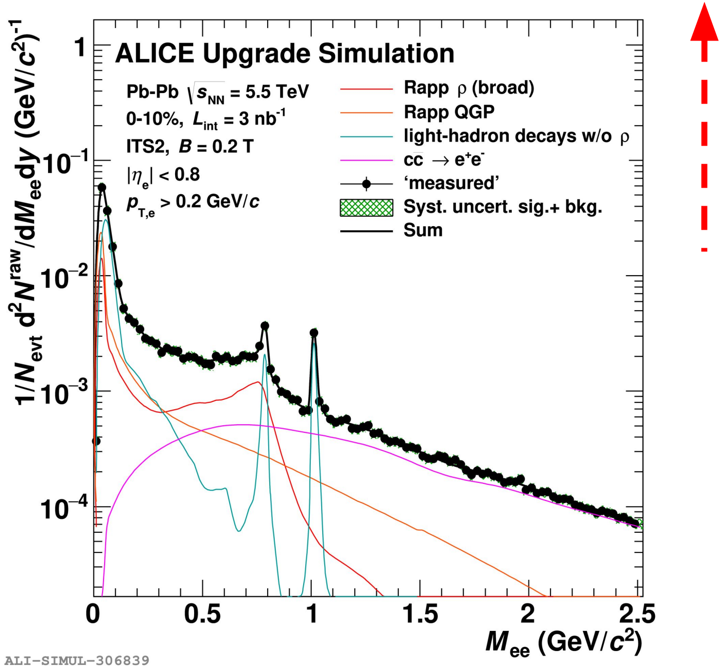




Invariant mass of dielectrons + "cocktail"

Physics performance with ITS2

HL-LHC WG5 yellow report



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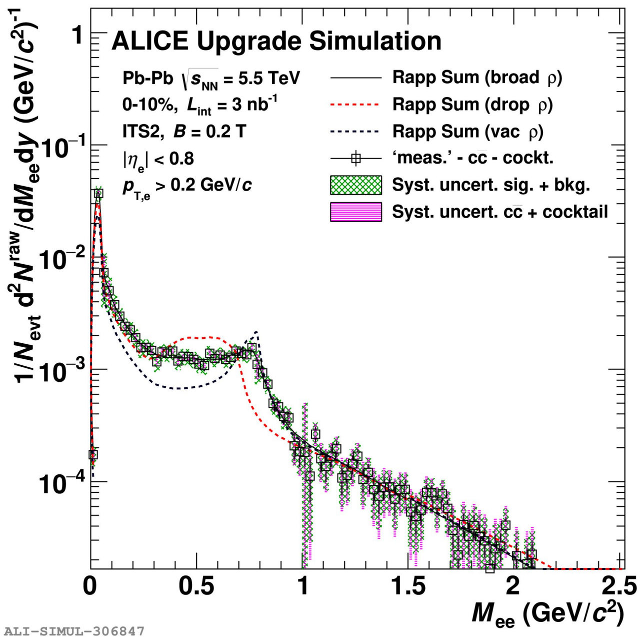

Excess spectrum

→ **first measurement of ρ spectral shape**

→ **first measurement of temperature**

The next decade

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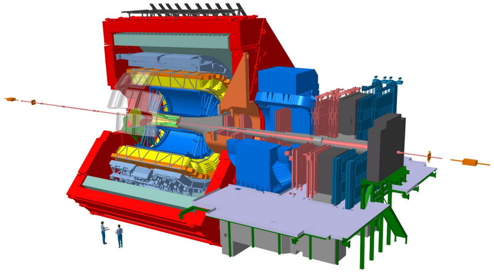

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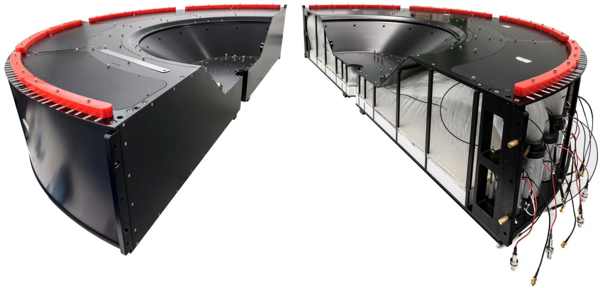
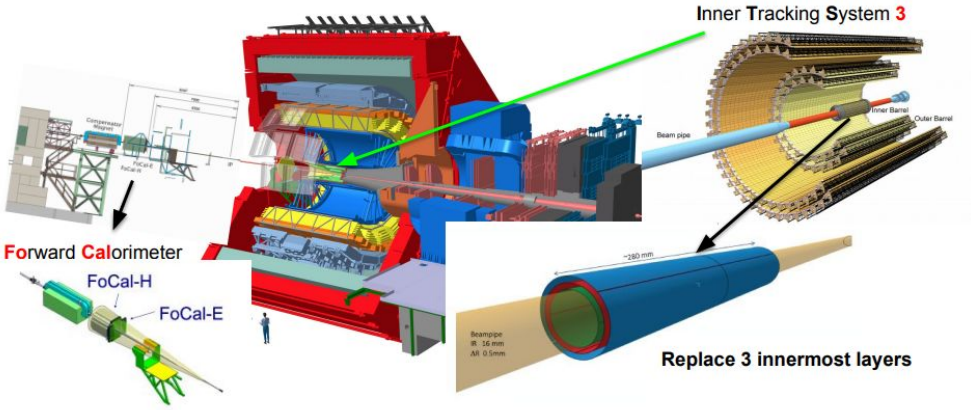
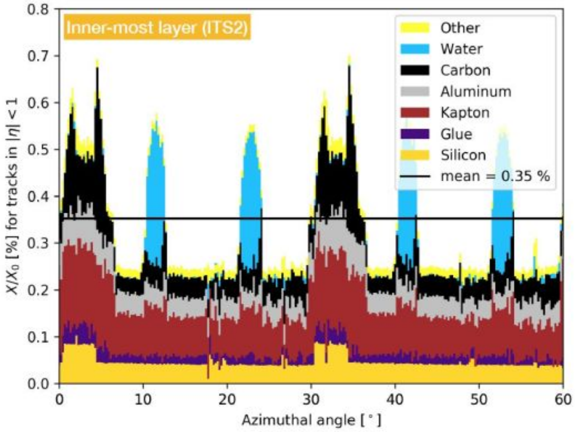


FoCal and ITS3



Towards a massless detector



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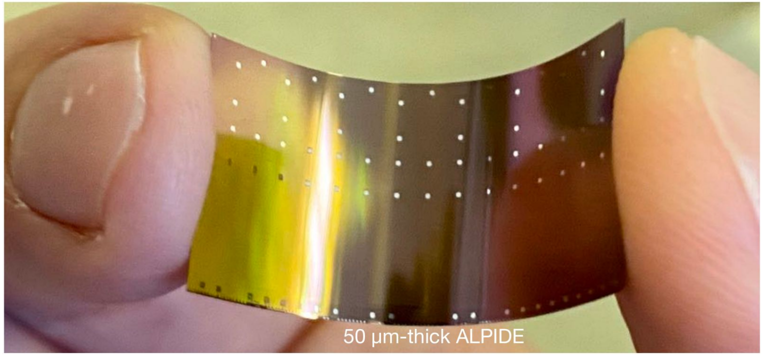
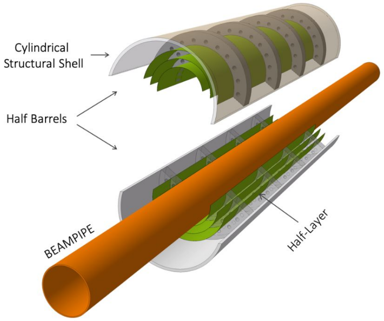
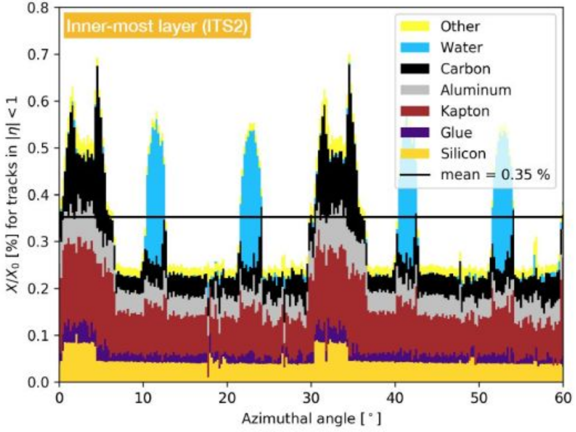
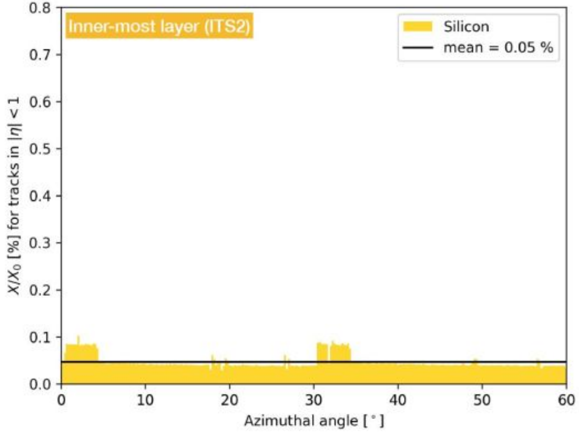




- Exchange inner 3 ITS layers with truly cylindrical Si-pixel layers based on ultra-thin, curved sensors (based on ALPIDE developed for ITS2):
  - Reduce **material budget from 0.35% X/X_0 to ≈ 0.05% X/X_0** and remove its inhomogeneities





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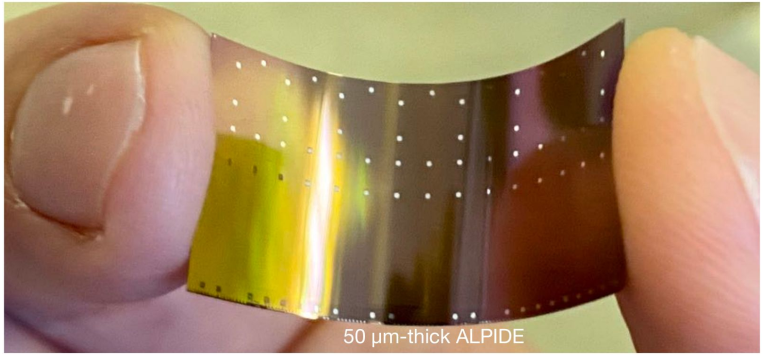
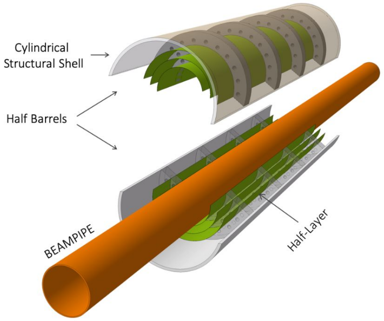
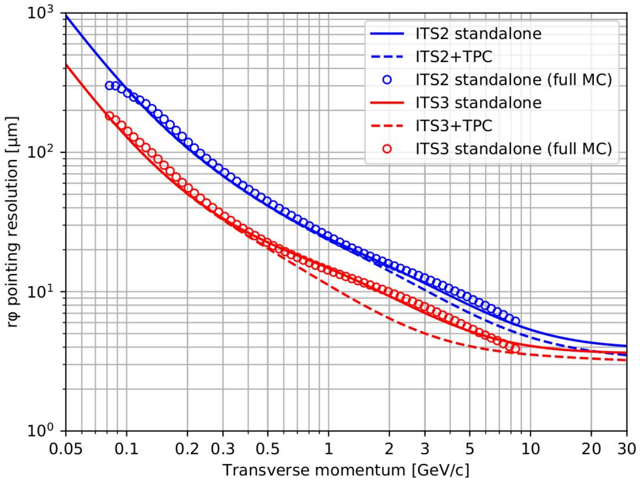




CERN-LHCC-2019-018

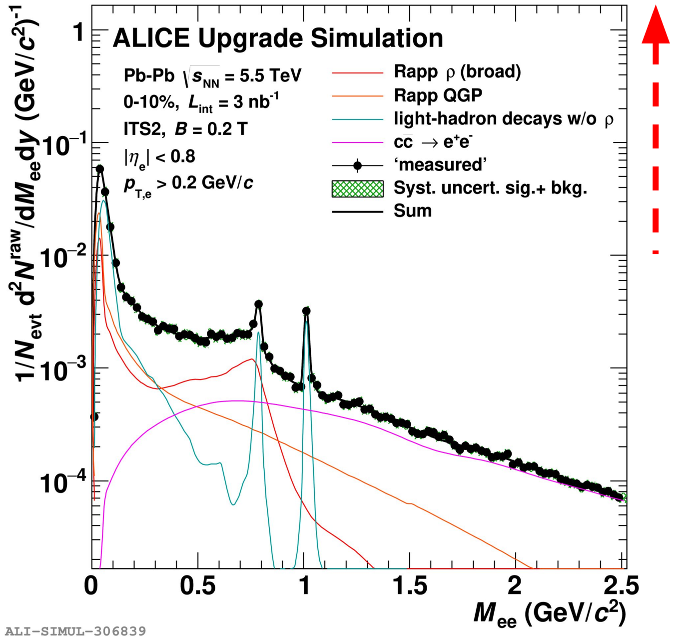
Inner layers	ITS1 (Run 1-2)	ITS2 (Run 3)	ITS3 (Run 4)
X/X_0	1.14%	0.38%	0.05%
innermost radius	39 mm	22 mm	18 mm
pixel size	50x425 μm^2	~27x29 μm^2	O(15x15 μm^2)

- Exchange inner 3 ITS layers with truly cylindrical Si-pixel layers based on ultra-thin, curved sensors (based on ALPIDE developed for ITS2):
  - Reduce **material budget from 0.35% X/X_0 to ≈ 0.05% X/X_0** and remove its inhomogeneities
- Move layers closer to the primary vertex, innermost layer at **R = 1.8 cm** (new beam-bipe with inner radius R = 1.6 cm)
  - **Improves pointing resolution by a factor ~3**

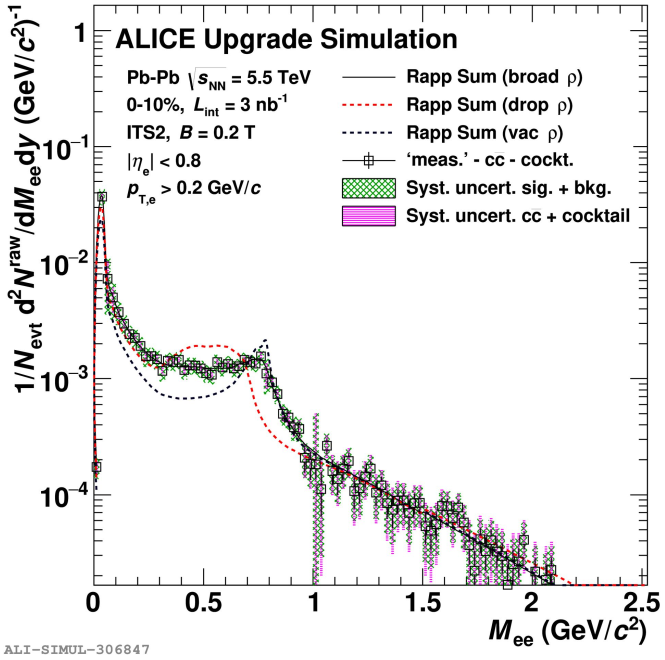


Physics performance with ITS2

[HL-LHC WG5 yellow report](#)



Invariant mass of dielectrons + "cocktail"



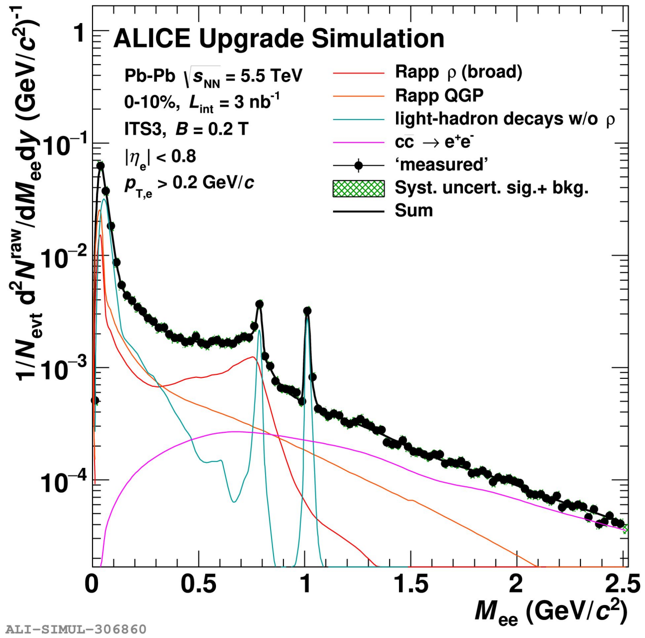
Excess spectrum

→ **first measurement of ρ spectral shape**

→ **first measurement of temperature**

Physics performance with ITS3

CERN-LHCC-2019-018



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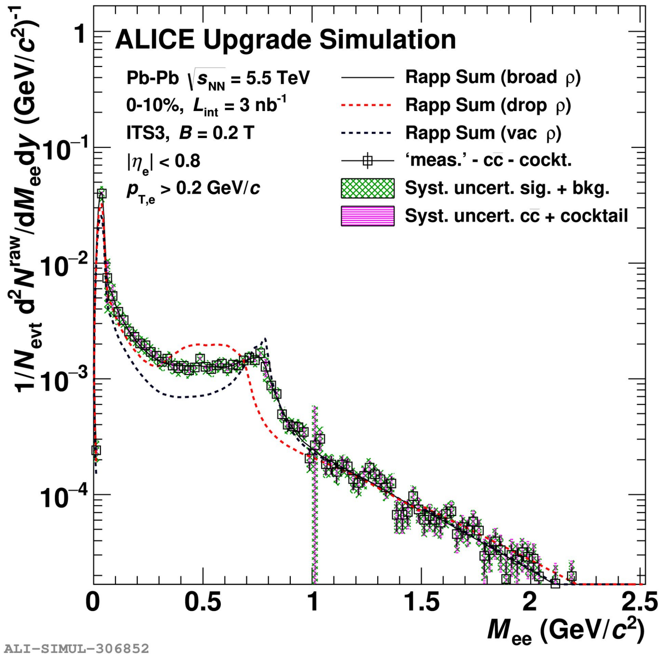
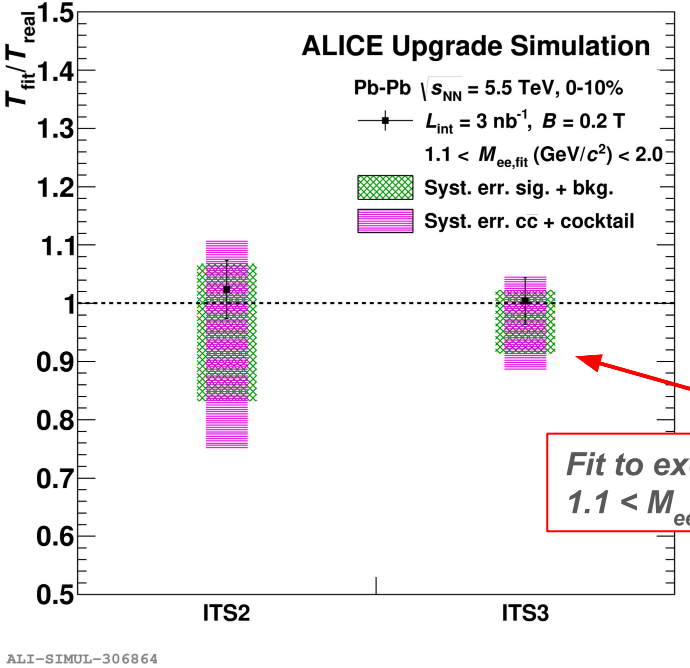
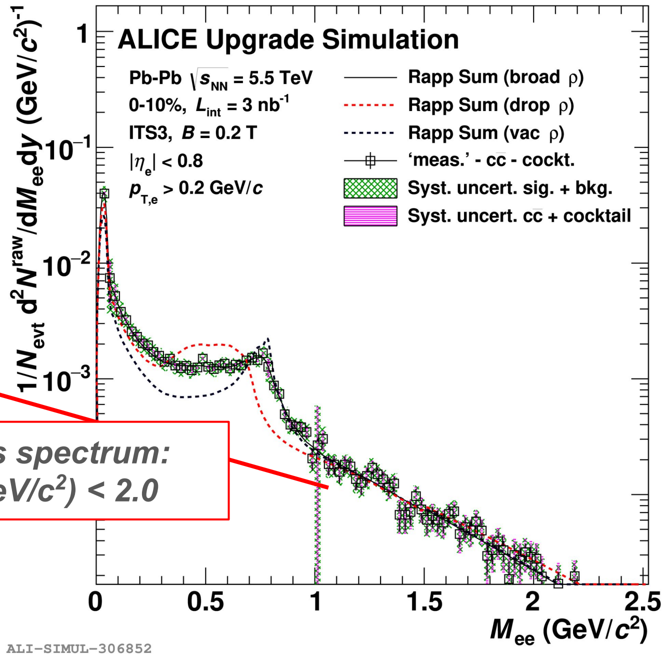


Excess spectrum
→ **Improved measurement of ρ spectral shape**

Physics performance with ITS3

CERN-LHCC-2019-018





Fit to excess spectrum:
1.1 < M_{ee} (GeV/c^2) < 2.0

Excess spectrum
→ **Improved measurement of ρ spectral shape**
→ **Improved temperature measurement**
→ **Differential measurements (p_T, flow, polarization)**

Putting into the big picture

Why important?

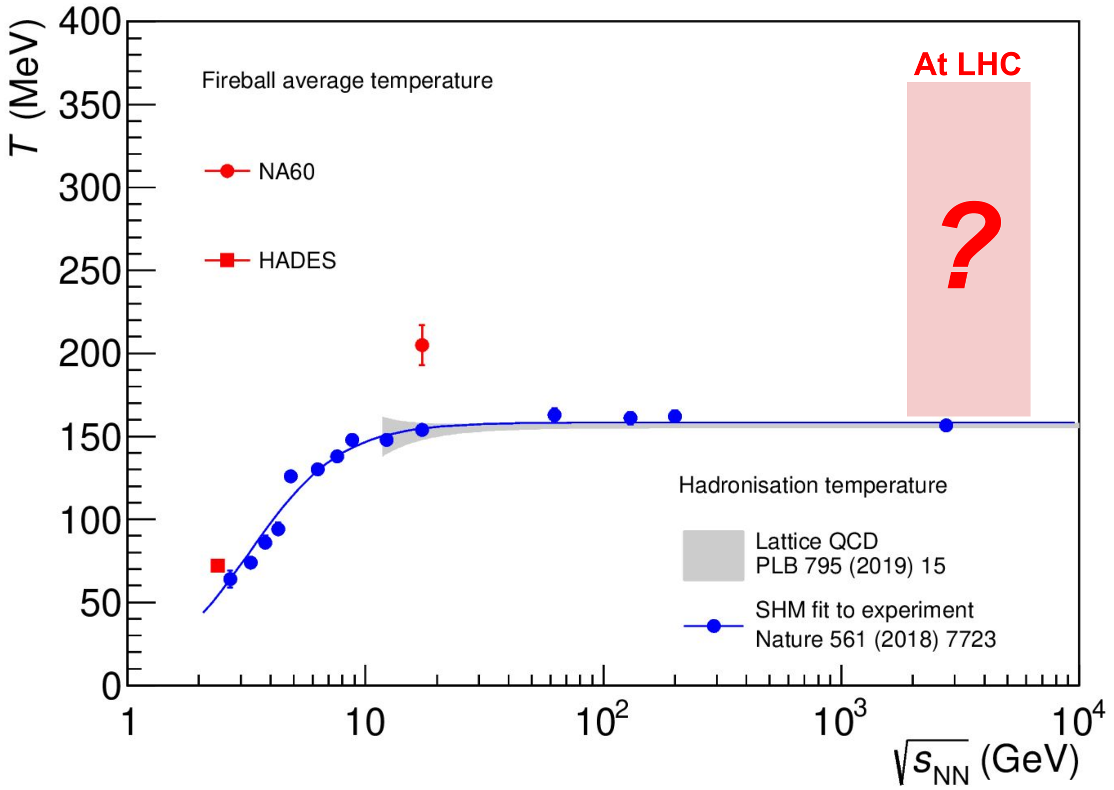
- ***System temperature* > critical temperature?**
- Experimentally established: saturation in the **chemical freeze-out temperature (after/at hadronisation)**
- **Initial/average temperature**: largely unmeasured, predicted to exceed **critical temperature**

Goal:

- high precision measurements vs collision energy ranging over three orders of magnitude

Strategy:

- **Last five years:** understand hadronic “background” in pp and p-Pb collisions, first feasibility studies in heavy-ion collisions
- **Next ten years:** measure T, vector meson spectral functions (and much more)



NA60, AIP Conf.Proc. 1322 (2010) 1, 1-10
HADES, Nature Physics 15 (2019) 10, 1040-1045
Lattice QCD, Phys. Lett. B 795 (2019) 15
SHM, Nature 561 (2018) 7723, 321-330

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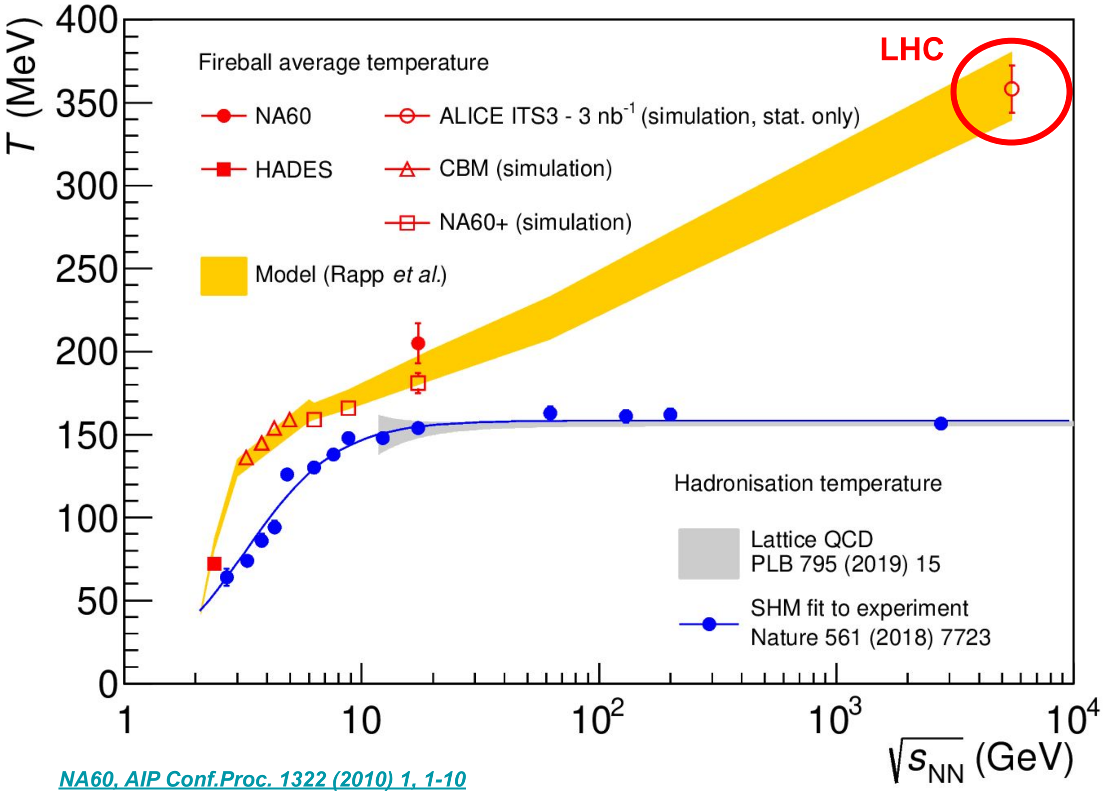
→ measuring the hottest temperature ever achieved by mankind



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CBM, Nucl. Phys. A 982 (2019) 163
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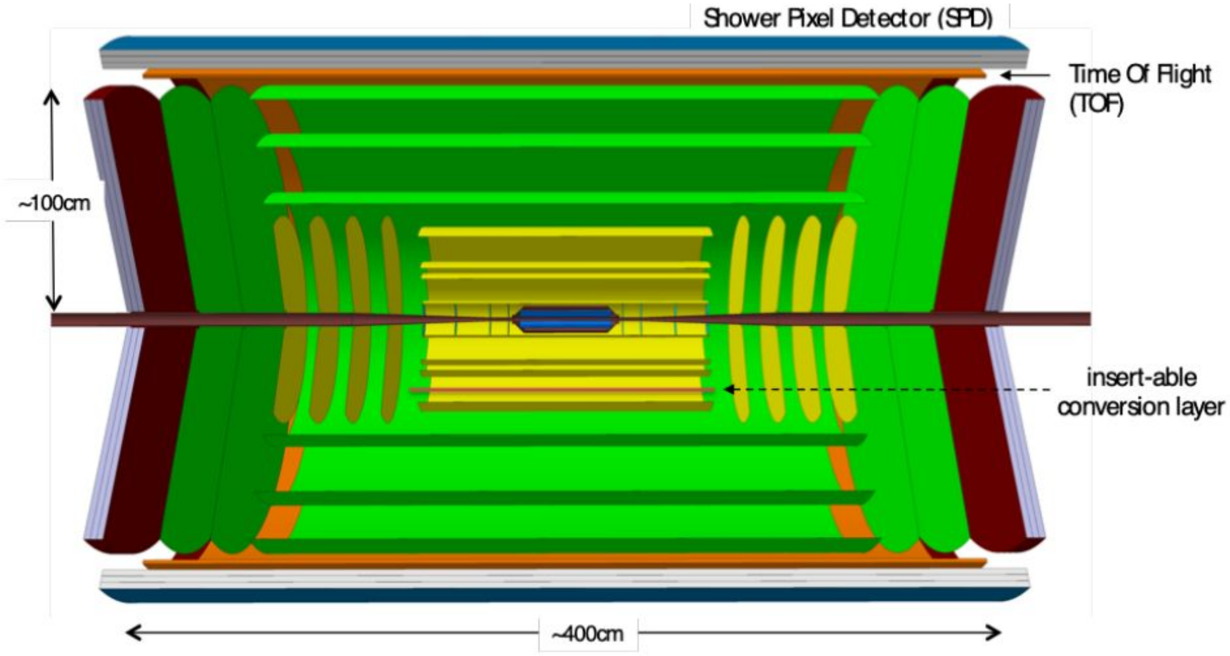
SHM, Nature 561 (2018) 7723, 321-330

Bright future at the LHC

[arXiv:1902.01211 [physics.ins-det]](arXiv:1902.01211)



Heavy-ion physics after 2030:

- Construct the **ultimate soft dilepton and photon detector** (based on ITS3 technology): $p \sim 1/R_{Nucleus} \sim 10$ *MeV/c*

Bright future at the LHC

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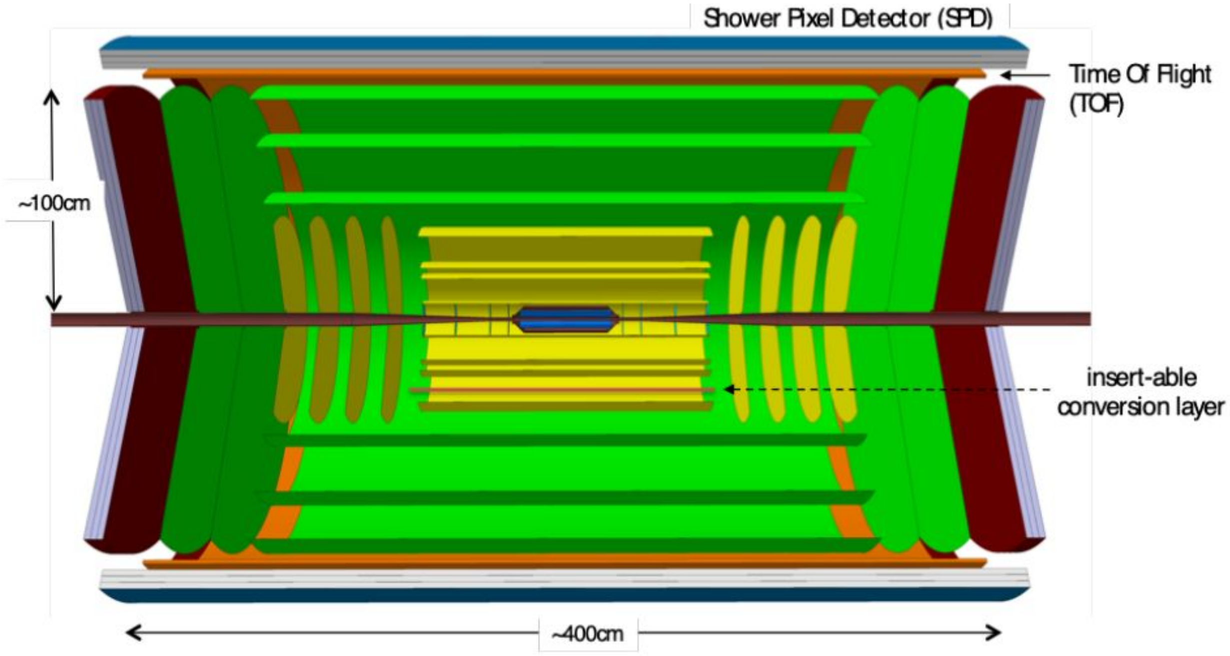

Key properties

- **ultra-low material budget** for low p_T tracking
  - X/X_0 ~ 0.05 % / layer
- **fast** to sample large luminosity
  - 50 - 100x Run 3/4
- **large acceptance**
  - $|\eta| < 4 \Rightarrow \Delta\eta = 8$ (total)
  - $|\eta| < \sim 1.4$ (central barrel)
- **excellent spatial resolution** for tracking and vertexing
  - innermost layers: $\sigma < 3$ µm
  - outer layers: $\sigma \sim 5$ µm
- **precise time measurement** for particle identification
  - $\sigma \sim 20$ ps

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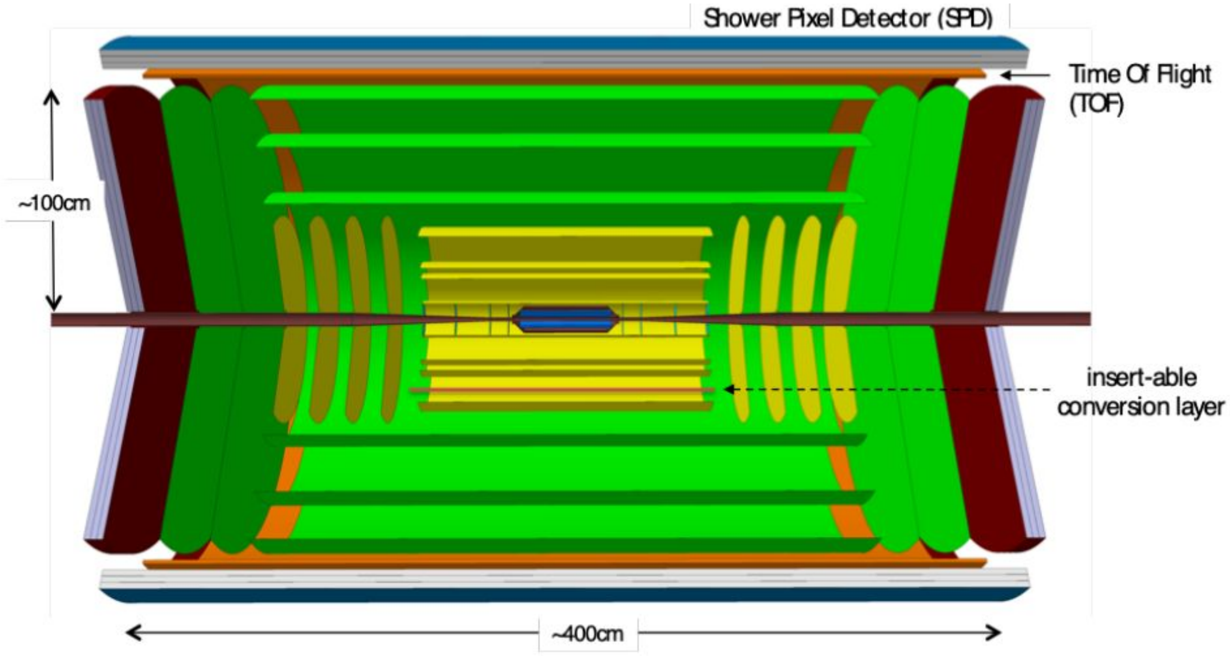

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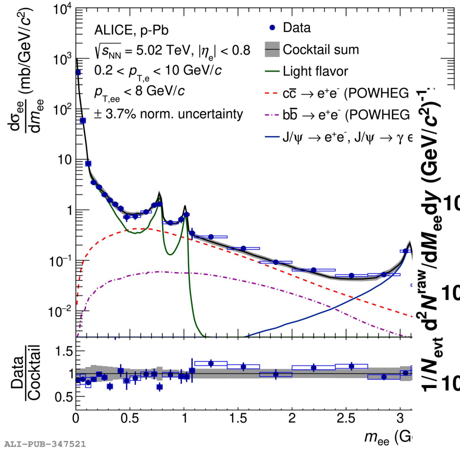
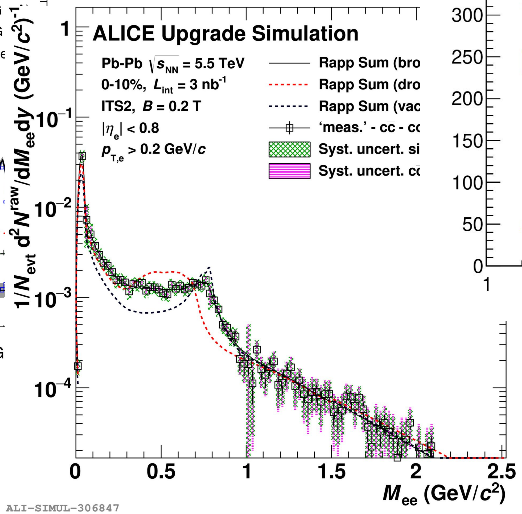
Heavy-ion physics after 2030:

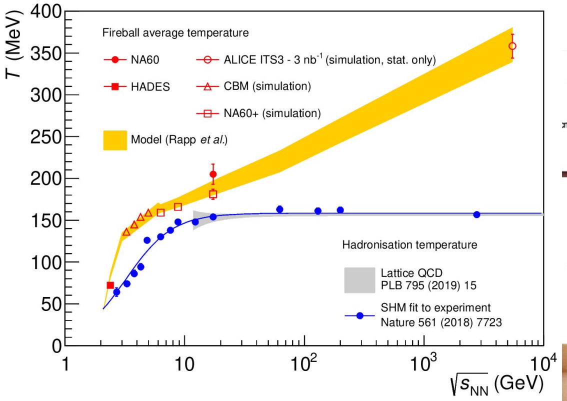
- Construct the **ultimate soft dilepton and photon detector** (based on ITS3 technology): $p \sim 1/R_{Nucleus} \sim 10$ *MeV/c*
- **Precision measurement** of EM radiation multi-differentially and down to lowest momenta, e.g. **electric conductivity**
- **BSM physics**

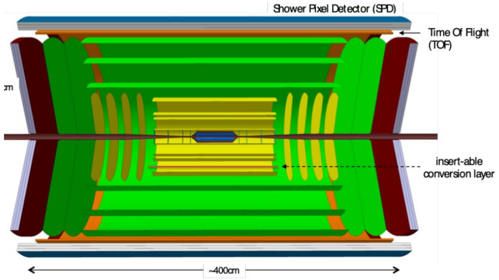
→ **Letter of Intent planned for end 2021**

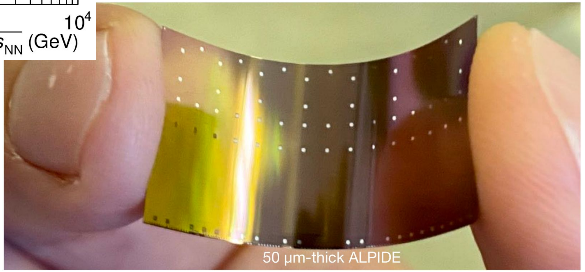
Summary











- **Objectives:** Chiral symmetry and temperature of QCD matter
- **Method:** Thermal dilepton production with ALICE at the CERN-LHC
- **Accomplished:** Understand your background (+ excess at low transverse momenta in pp)
- **Future:** Expected performance with ALICE and next-generation particle detectors

Thank you!