EXPLORING THE PHASE DIAGRAM WITH ELECTROMAGNETIC PROBES

ALBERICA TOIA
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6^{TH} EUROPEAN NUCLEAR PHYSICS CONFERENCE
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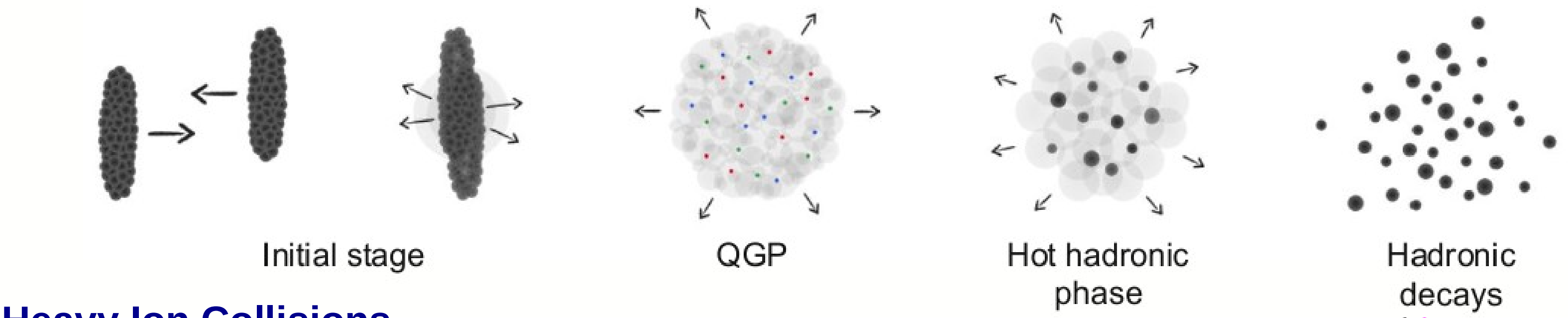
EXPERIMENTAL ACCESS TO PHASE DIAGRAM



Heavy Ion Collisions

- create hot and dense matter in the lab
- The properties of the initial state can be inferred from the properties of the particles in the final state.
- Observation: Freeze-out points map the phase diagram
- Variation of collision energy allows to study different regions

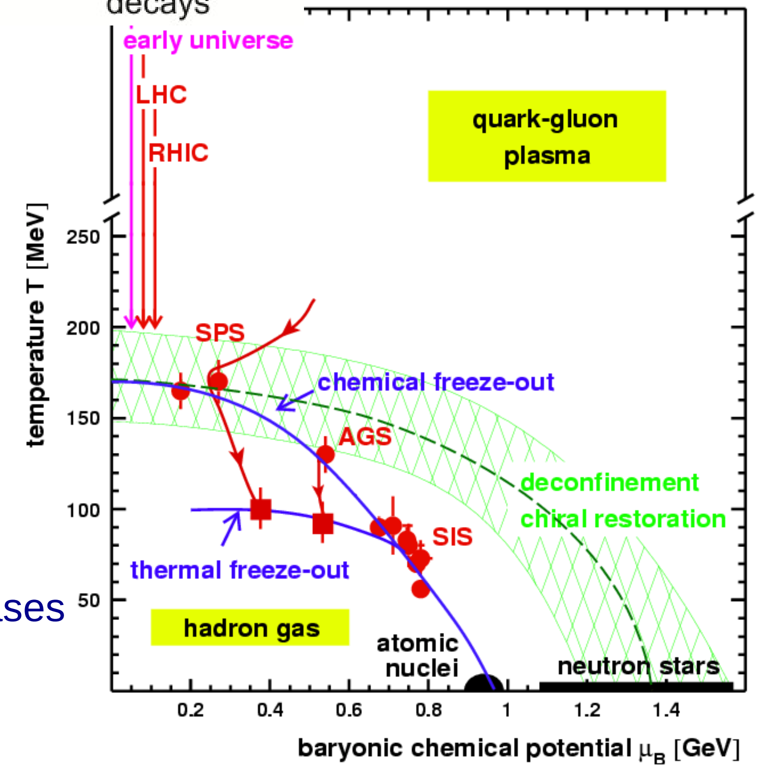
At very high temperature:

- N of baryons = N of antibaryons, situation similar to **early universe**
- L-QCD: at T_C ~155 MeV crossover transition hadronic matter → **QGP**
- LHC, RHIC

At high baryon density:

- N of baryons >> N of antibaryons , densities like in **neutron star cores**
- L-QCD not applicable, models predict phase transitions and exotic phases
- BES-RHIC, CERN SPS, FAIR, NICA

Phase Diagram



WHAT WE CAN LEARN FROM DILEPTONS

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2})$$

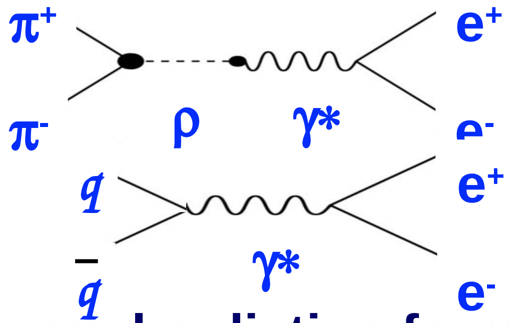
γ*→ee decay

EM correlator ***Medium property***

Boltzmann factor ***temperature***

Hadronic contribution Vector Meson Dominance → **Medium modification of meson Chiral restoration**

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V(M) \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right)N_c\sum_{q=u,d,s}(e_q)^2 \end{cases}$$



qq annihilation → **Thermal radiation from partonic phase (QGP)**

From emission rate of dilepton, one can decode

- **medium effect on the EM correlator**
- **temperature of the medium**

RELATION BETWEEN PHOTONS AND DILEPTONS

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

Emission rate of (virtual) photon per volume

$$q_0\frac{dR_{\gamma^*}}{d^3q} = -\frac{\alpha}{2\pi^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T).$$

Relation between them — **Prob. $\gamma^* \rightarrow l^+l^-$**

$$q_0\frac{dR_{ll}}{dM^2d^3q} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}q_0\frac{dR_{\gamma^*}}{d^3q}$$

Dilepton — **virtual photon**

This relation holds for the yield after space-time integral

Virtual photon emission rate can be determined from dilepton emission rate

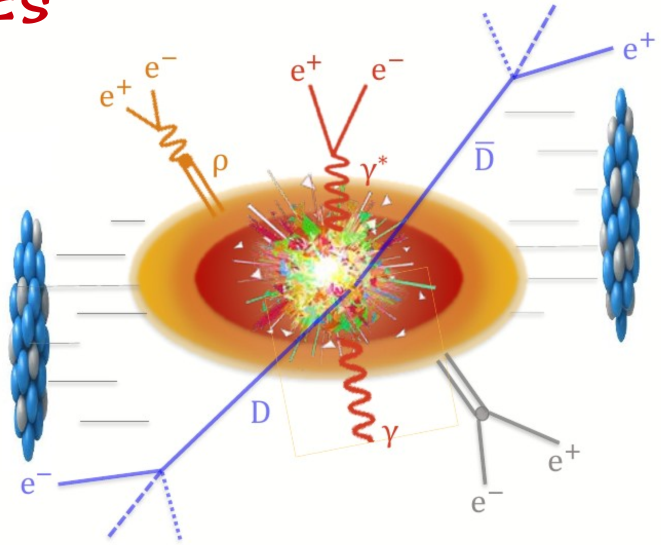
$$q_0\frac{dn_{\gamma^*}}{d^3q} \simeq \frac{3\pi}{\alpha}M^2q_0\frac{dn_{ll}}{d^3qdM^2} = \frac{3\pi}{2\alpha}Mq_0\frac{dn_{ll}}{d^3qdM}.$$

$M \times dN_{ee}/dM$ gives virtual photon yield

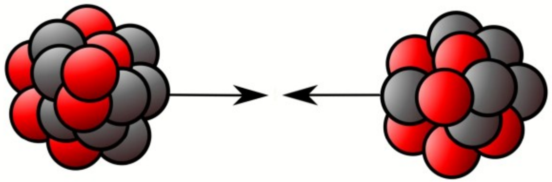
For $M \rightarrow 0$, $n_{\gamma}^* \rightarrow n_{\gamma}$(real) real photon emission rate can also be determined

ELECTROMAGNETIC PROBES

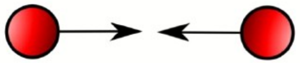
•**Photons and Dileptons**
unique probe:
• Produced at all stages of collision
• with negligible final-state interactions
→ Keep the information about their production mechanism
• Information must be deconvoluted



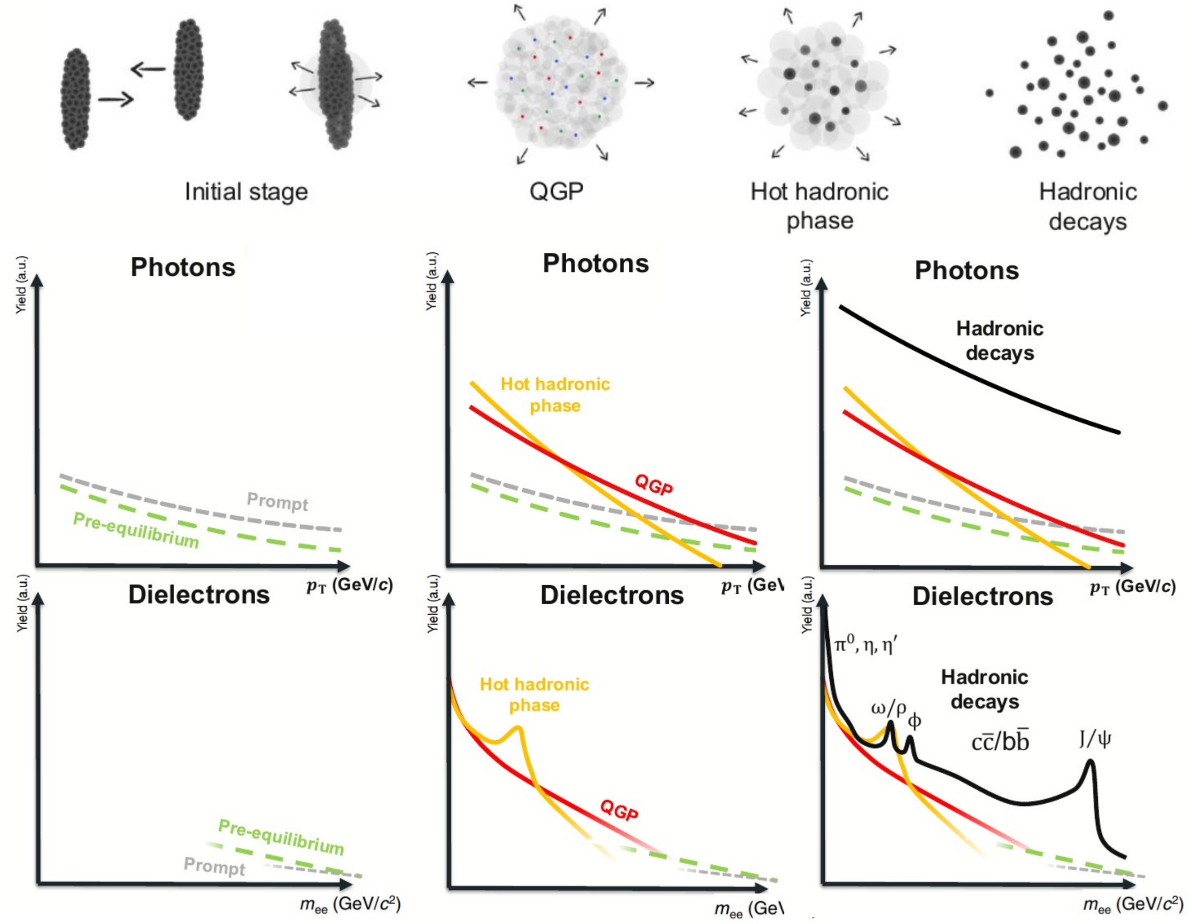
Pb−Pb collisions:
• Chiral-symmetry restoration: modification of vector mesons
• Thermal radiation throughout the medium evolution
• Decorrelation of heavy-flavor pairs in the medium
• Constrain the space-time evolution of the collision



pp collisions:
• Establish new analysis techniques (high stat., better S/B)
• Vacuum baseline for Pb−Pb studies
• Heavy-flavor, direct photons, Drell−Yan
• Search for new physics (Onset of thermal radiation, dark photons)



•Photons and dileptons across collision stages



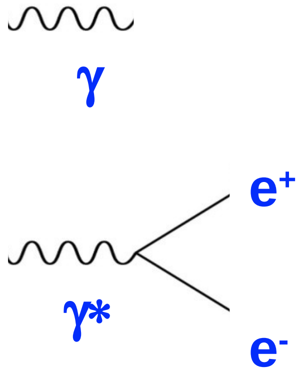
• **Contributions to EM spectrum**

Initial stage of the collision
- Prompt: Drell−Yan & hard scatterings
- Pre-equilibrium contributions

Thermal radiation from the medium
- Quark-Gluon Plasma (QGP)
- Hot hadronic phase

Hadronic decays
- Large combinatorial & physical backgrounds

→ Additional separation with invariant mass of dielectrons

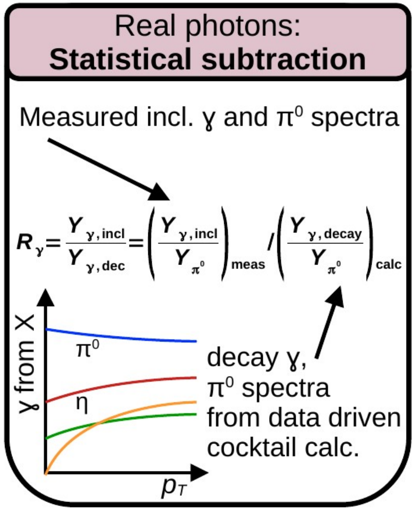


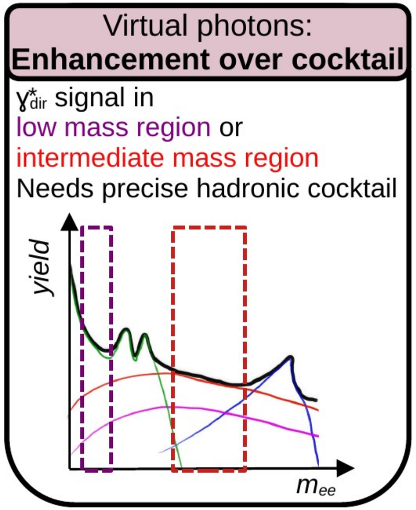
PHOTONS

Photon Reconstruction

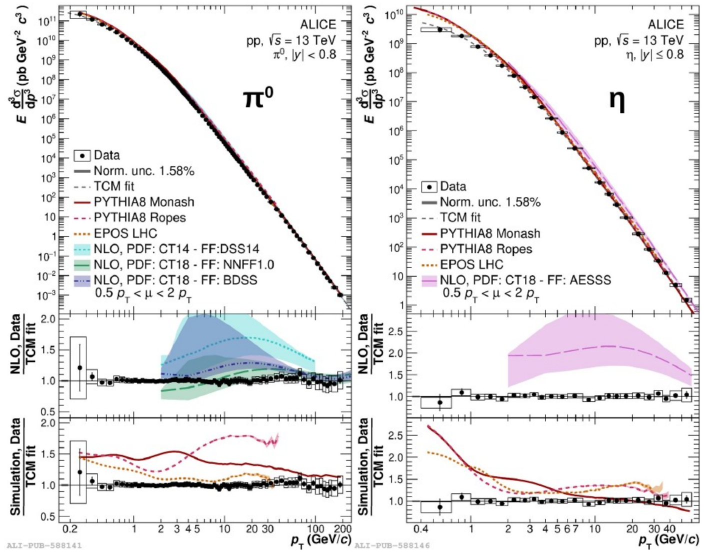
- **Real Photons**
  Calorimetry
  Statistical subtraction of hadronc sources

- **Virtual Photons (→ Dileptons)**
  Source of real photon should also emit virtual photon (e+e- pair)
  - Reduce hadron decay background
  - photon ID, energy resolution, etc
  - Use M, p_T, ϕ
  - Reduce the yield (~ $\alpha/3\pi$ ~ 1/1000)

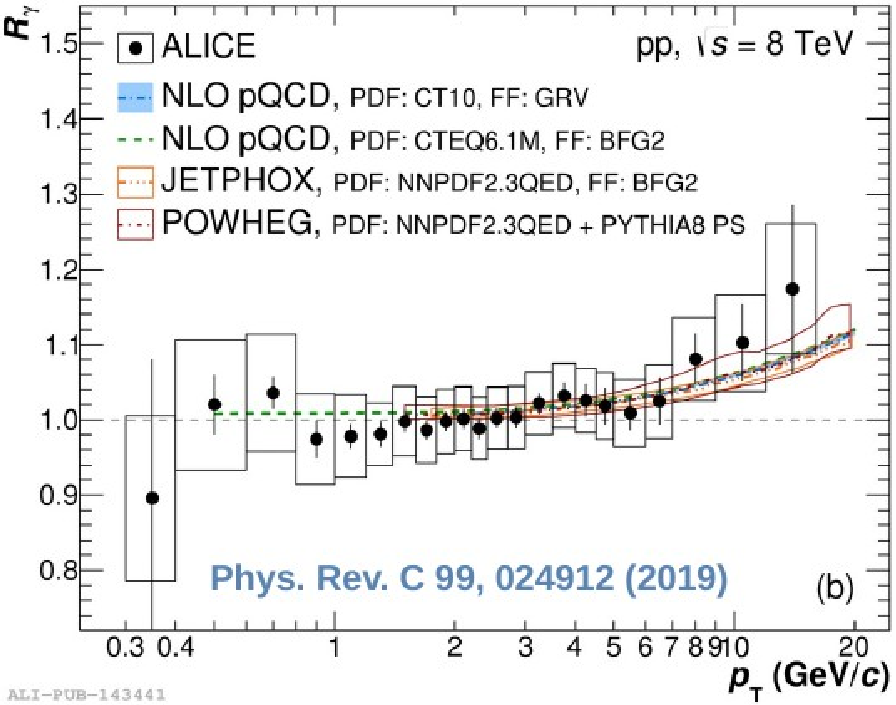




ALICE: REAL DIRECT PHOTONS



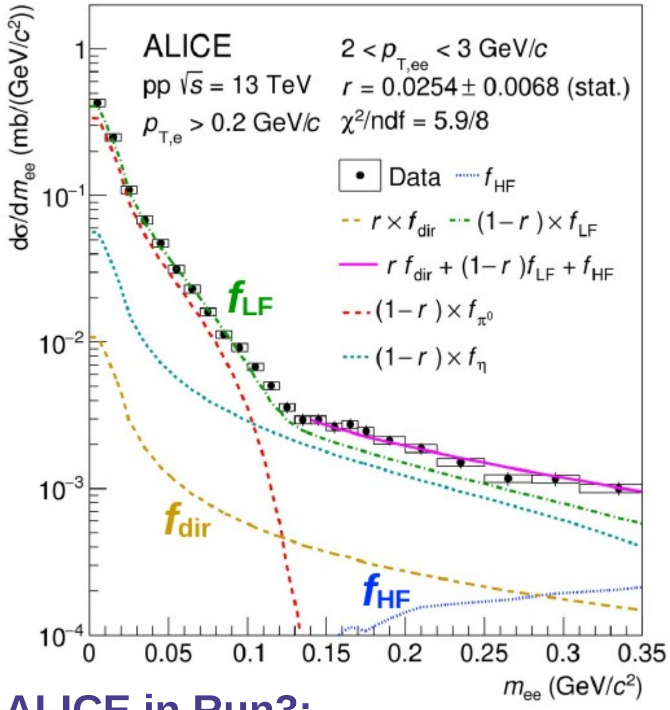
$$R_\gamma = \frac{Y_{\gamma,\mathrm{incl}}}{Y_{\gamma,\mathrm{dec}}} = \left(\frac{Y_{\gamma,\mathrm{incl}}}{Y_{\pi^0}}\right)_{\mathrm{meas}} / \left(\frac{Y_{\gamma,\mathrm{decay}}}{Y_{\pi^0}}\right)_{\mathrm{sim}}$$



Inclusive spectra (Multiplicity dependence)
Combination of 8 (6) different rec. techniques for π0 (η)
Unprecedent large pT coverage and small uncertainties
Thermal photons in pp?
Signal of < 2% expected at LHC energies
→ Issue: Large decay photon background
→ No significant ɣdir signal for pT < 10 GeV/c

arXiv: 2411.09560

ALICE: VIRTUAL DIRECT PHOTONS



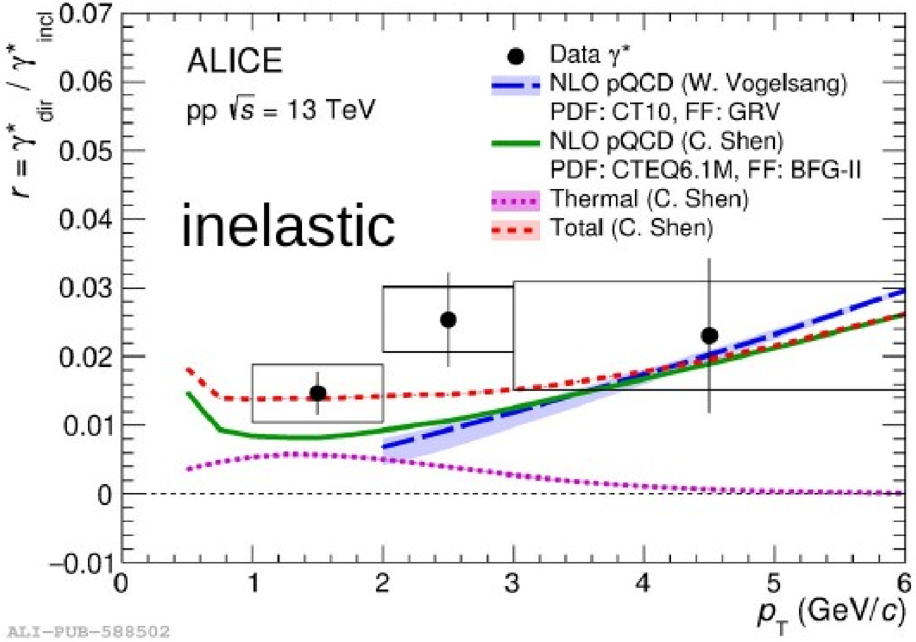
$$r\, f_{dir} + (1-r)\, f_{LF} + f_{HF}$$

$$r = \left.\frac{\gamma^*_{dir}}{\gamma^*_{incl}}\right|_{m_{ee}\to 0} = \frac{\gamma_{dir}}{\gamma_{incl}}$$

Significant direct-photon fraction above $m_{\pi 0}$

Model calculations with and without thermal contribution agree with data

pQCD calculation in high-multiplicity from scaled inelastic result



ALICE in Run3:

readout (TPC) x100 (PbPb) x1000 (pp)

pointing resolution (ITS2) improved

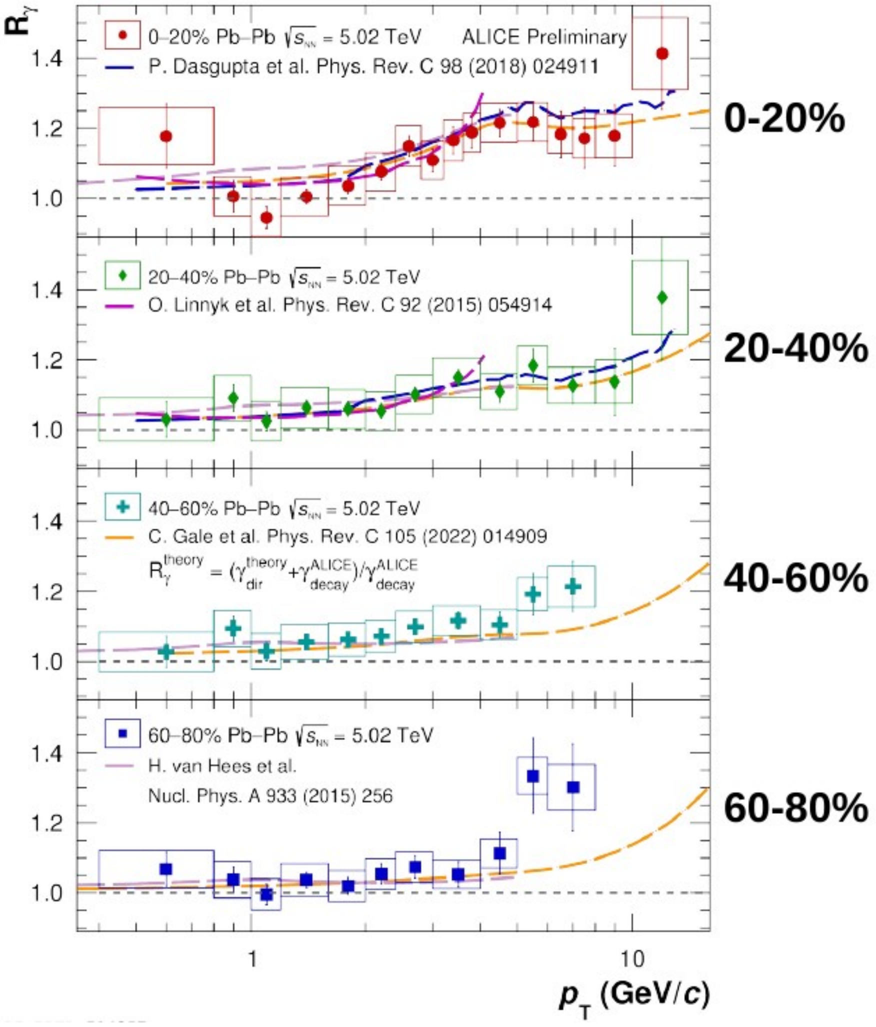
Dielectron spectra in pp, √s = 13 TeV for inelastic and high-multiplicity

Direct photons accessible via template fit (ɣ* dir + Light flavor + Heavy flavor)

arXiv: 2411.14366

DIRECT PHOTONS IN AA

REAL



REAL

Consistent with model predictions

No significant thermal photon contribution

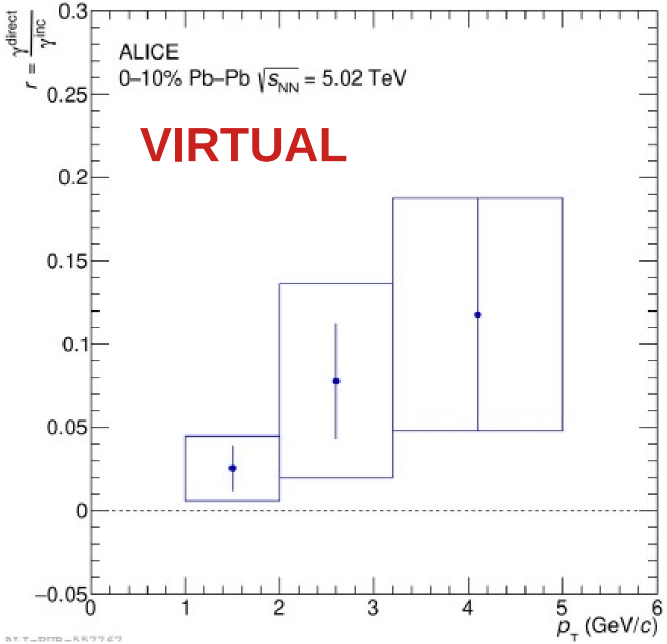
VIRTUAL

Sensitive to radiation from QGP and HRG in IMR and LMR

Significant ɣ dir extracted

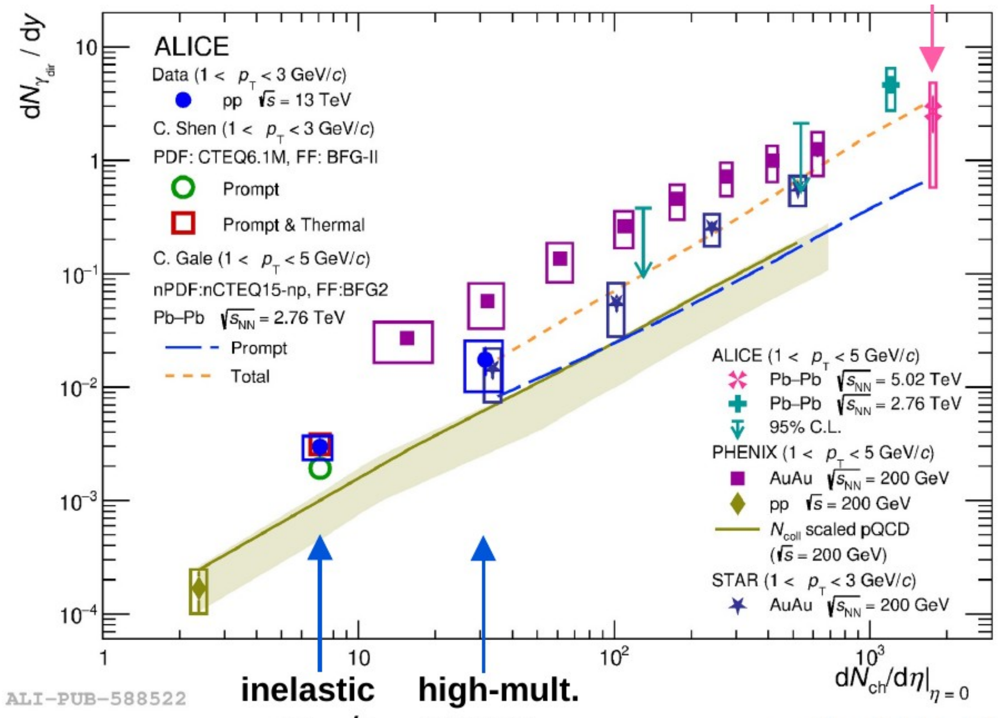
Model prediction agrees with data

Higher statistical precision needed



arXiv: 2308.16704

DIRECT PHOTONS VS MULTIPLICITY



arXiv: 2411.14366

ALICE pp results compared to:

- AuAu √sNN = 200 GeV (STAR)

similar yield in peripheral AuAu and high mult. pp

- AuAu √sNN = 200 GeV (PHENIX)

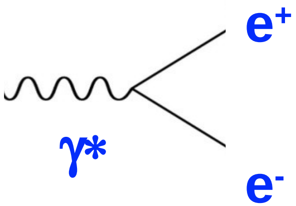
larger yield in peripheral AuAu compared to high mult. pp

ALICE Pb–Pb results:

- Agree with both PHENIX and STAR

ALICE Pb–Pb, $\sqrt{s_{NN}}$ = 2.76 TeV: Phys. Lett. B 754 (2016)
ALICE Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV: arXiv: 2308.16704
PHENIX pp, √s = 200 GeV: Phys. Rev. Lett. 123 (2019)
PHENIX N_{coll} scaled pQCD: Phys. Rev. C 107 (2023)
STAR AuAu $\sqrt{s_{NN}}$ = 200 GeV: Phys. Lett. B 770 (2017)
PHENIX AuAu $\sqrt{s_{NN}}$ = 200 GeV: Phys. Rev. Lett. 123 (2019)
C. Shen, pp √s = 13 TeV: Phys. Rev. C 95 (2017)
C. Gale, Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV: Phys. Rev. C 105 (2022)

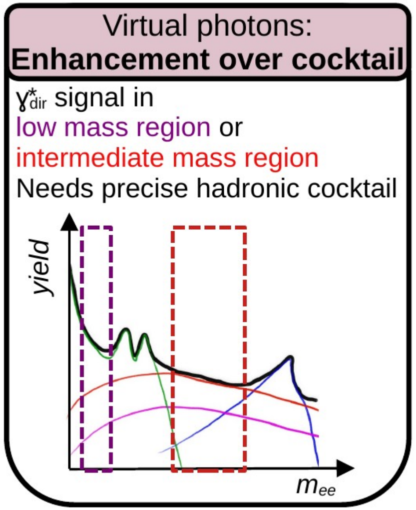
arXiv:2411.14366



DILEPTONS

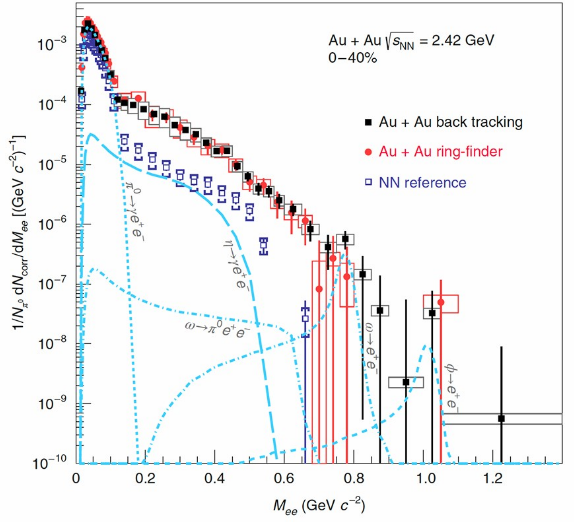
Dilepton Reconstruction

- **Virtual Photons (→ Dileptons)**
- Electron / muon ID
- Use M, p_T, ϕ
- Pair: make all combinations
- Combinatorial background

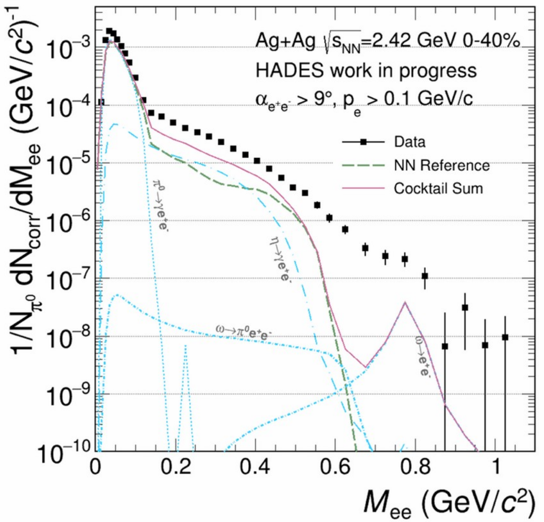


HADES

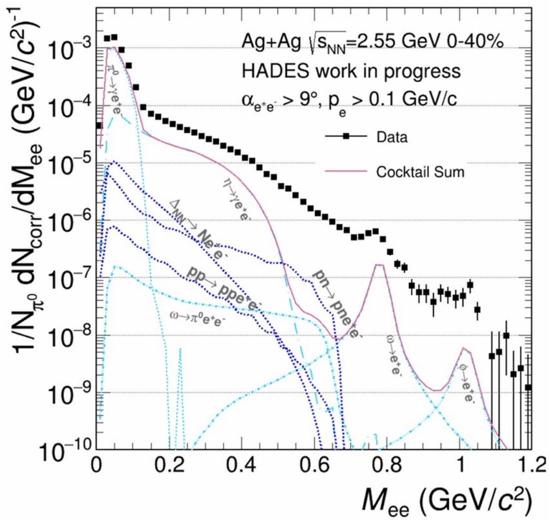
Au+Au at 2.42 GeV



Ag+Ag at 2.42 GeV



Ag+Ag at 2.55 GeV

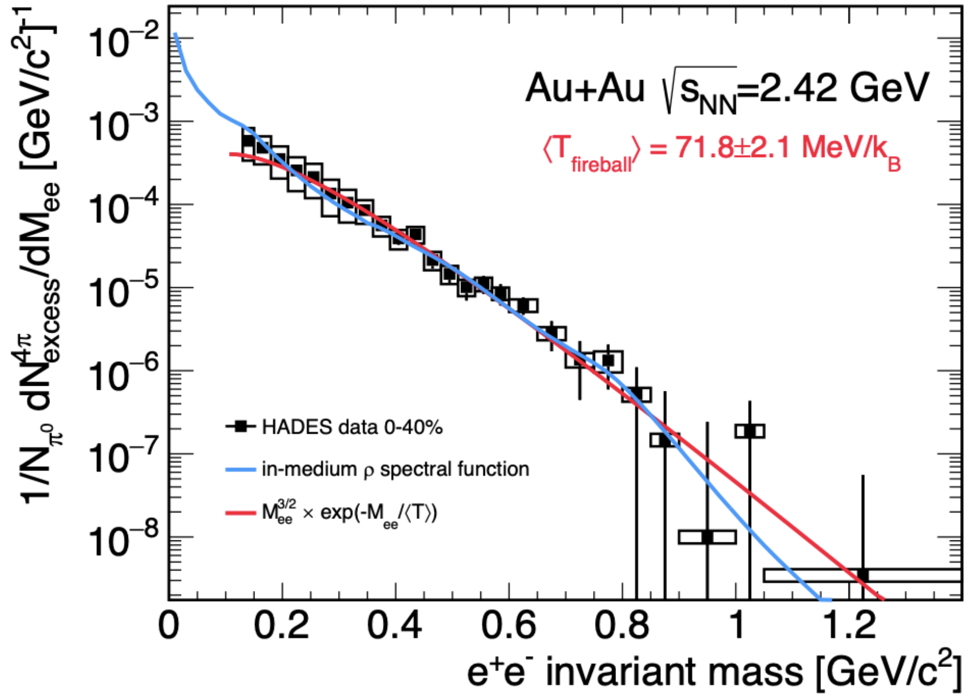


Strong isospin effect → **needs to measure NN reference**

Clear excess visible above contributions from initial NN reference and freeze-out cocktail

HADES, Nature Phys. 15 (2019) 1040

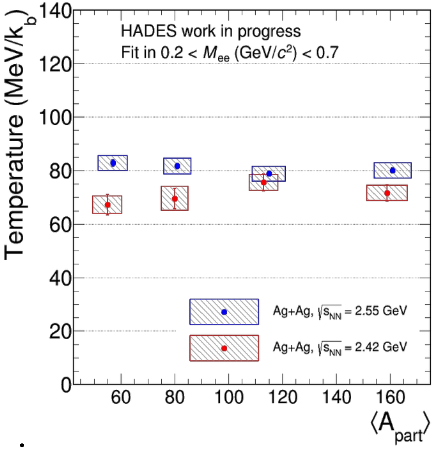
HADES

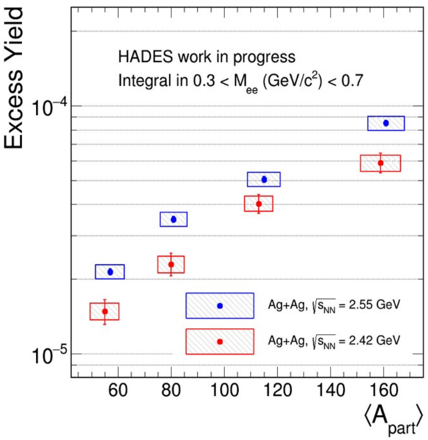


Thermal excess radiation established at HADES
-meson peak undergoes a strong broadening in medium
in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies
Baryonic effects are crucial

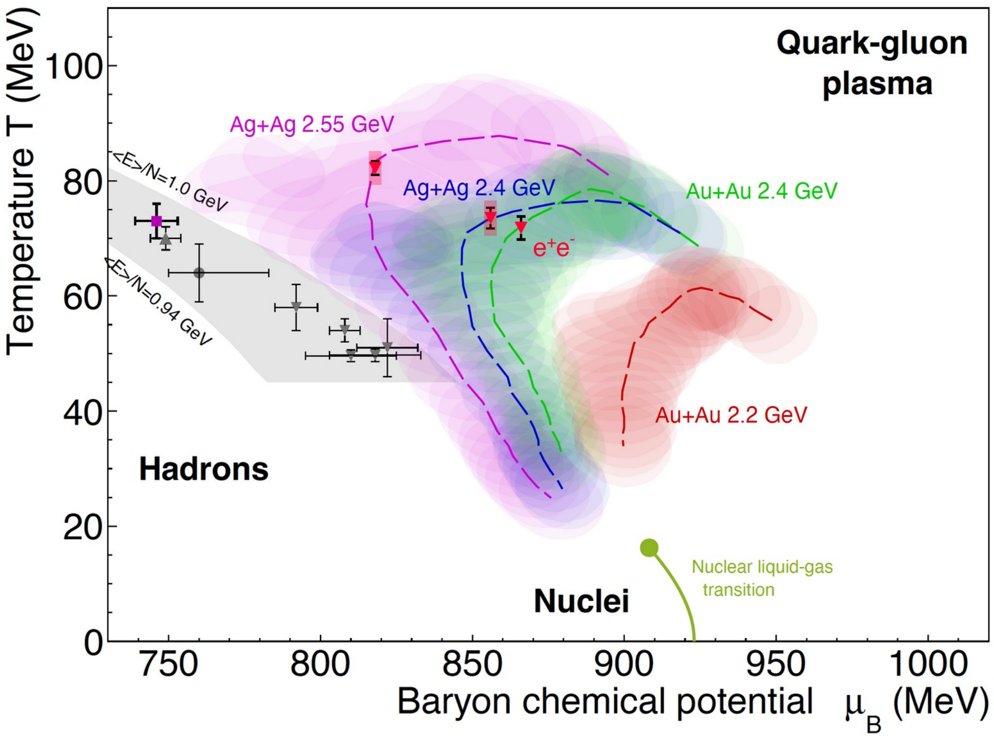
Excess yields after background subtraction of dielectron pairs originating from thermal radiation
→ Well described by coarse-grained UrQMD calculation
→ Temperature extracted via fit

System size, centrality, energy dependence of excess yield





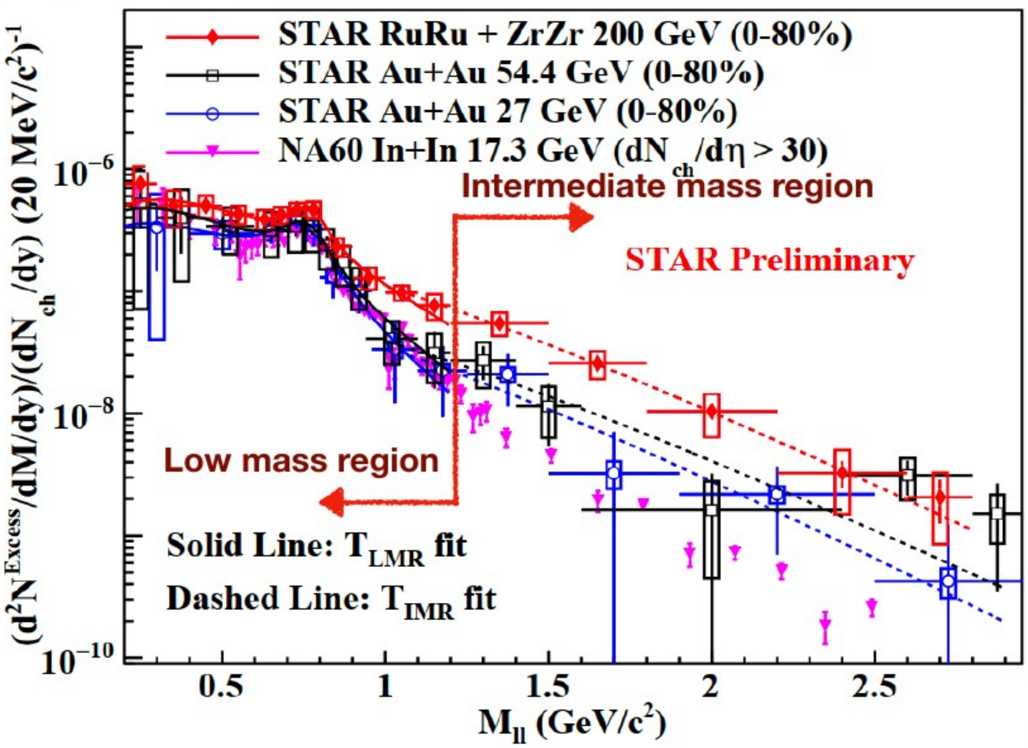
HADES



FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au2.4 GeV data: HADES
Nature Phys. 15(2019) 1040
EPJA 52 (2016) 5, 131
PRC 106 (2022) 1, 014904
Ag+Ag data: HADES preliminary
figure: F. Seck, T. Galatyuk

Measurements of average fireball temperatures in AgAg and AuAu collisions at different √sNN
→ **Trajectories based on coarse-grained UrQMD calculations**
Temperatures well above freezeout region based on SHM

STAR

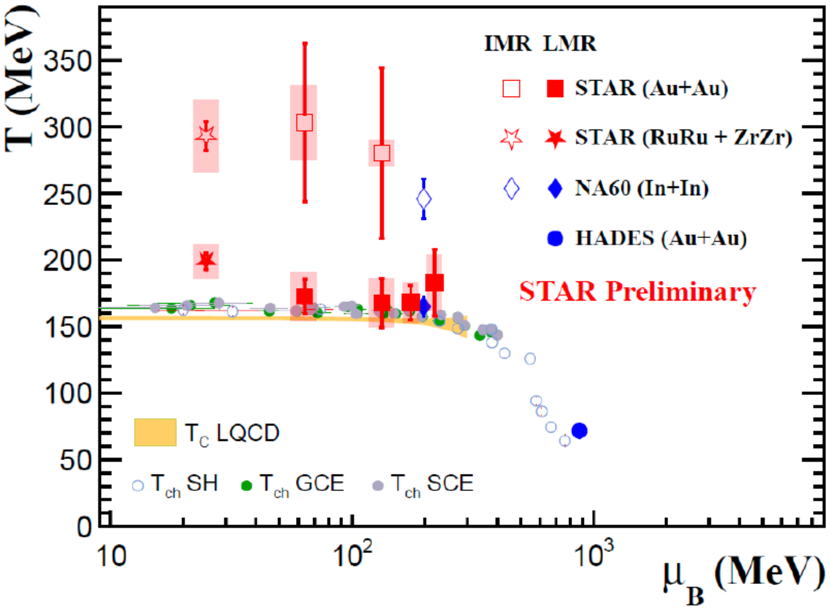


Measurements of dielectron excess from BES-II and isobar runs

Temperature extraction in

LMR: $(a \times BW + b \times M^{3/2}) \times e^{-m/T}$

IMR: $M^{3/2} \times e^{-m/T}$

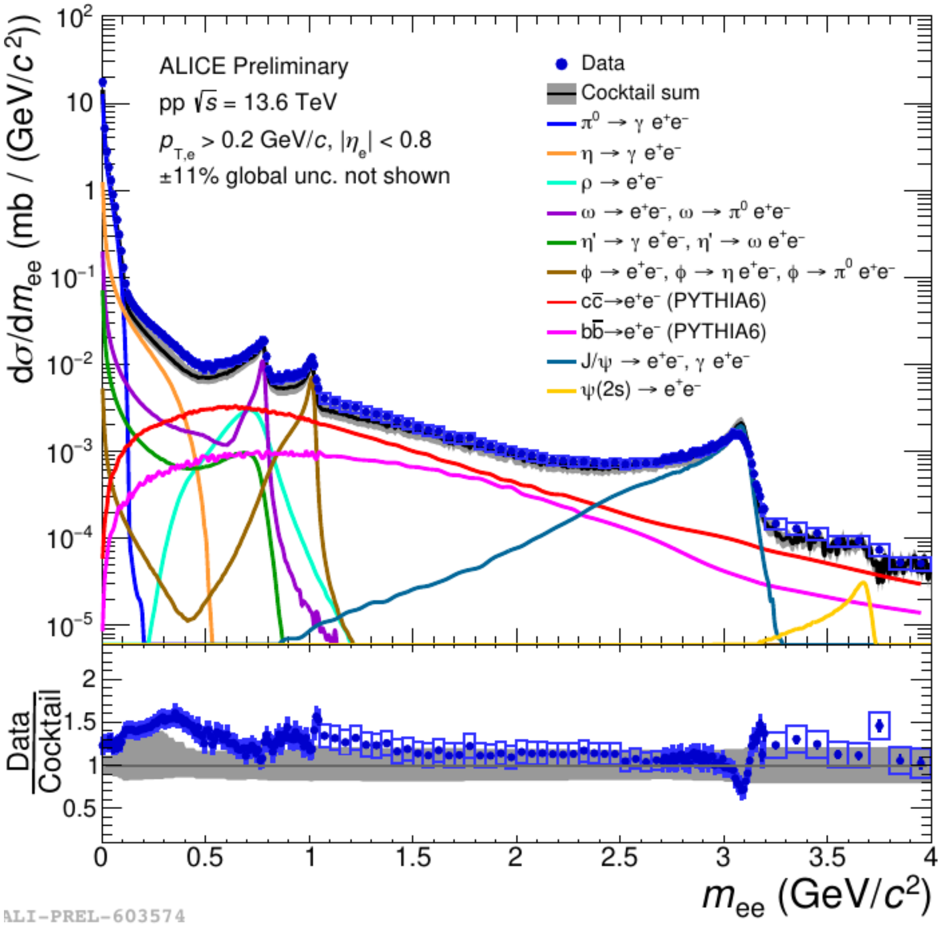


LMR:

→ BES-II results consistent with Tpc

→ Slightly higher T for 200 GeV AuAu data (Contribution from QGP?)

IMR: Consistent higher than LMR results



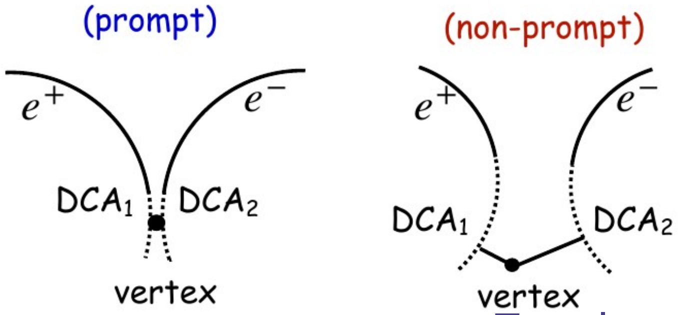
ALICE in Run3:
readout (TPC) x100 (PbPb) x1000 (pp)
pointing resolution (ITS2) improved

RHIC to LHC: ten times more charm
Dominant source of background
→ Modified by shadowing and medium interactions
→ Significant uncertainties related to estimation of Cocktail
Experimental means of background estimation necessary

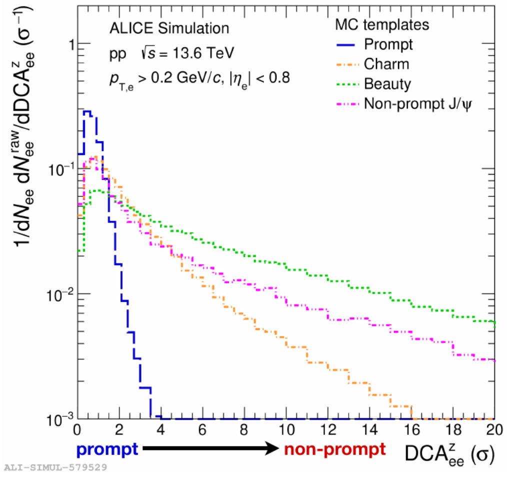
Data compared to hadronic cocktail calculations
Dominated by systematic (correlated) uncertainties
Overall good agreement of data and cocktail within uncertainties

ALCE DCA

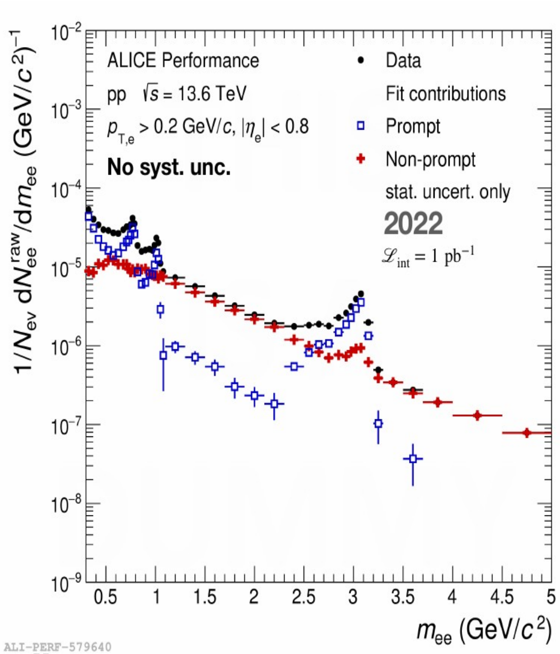
Heavy-flavour hadrons have a finite decay length
ITS 2 upgrade improved pointing resolution by factor 2–5

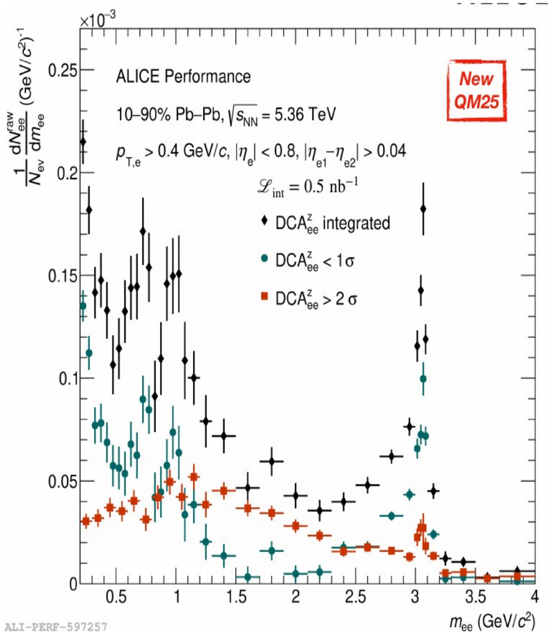


In pp and AuAu
Spectra separated via topological fit
→ Prompt spectrum exhibits all expected features of the resonance structure
→ Non-prompt spectrum shows broad structure with a small contribution of non-prompt J/ψ

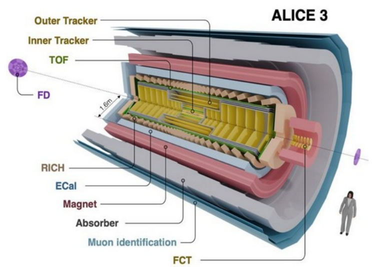


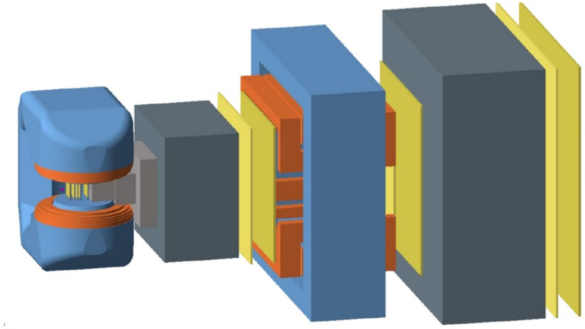
Template from MC for different sources
Parameterise data in mass slices to unfold spectrum and isolate prompt contributions
Data can be well described by template sum

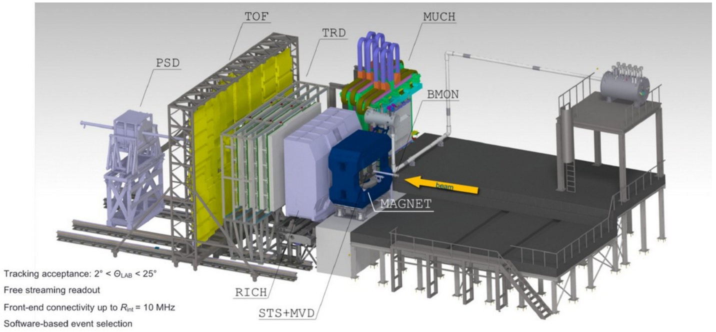




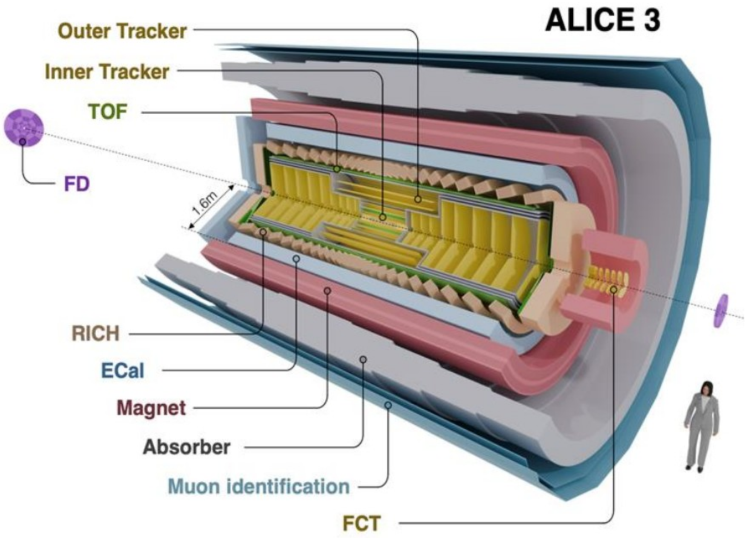
THE FUTURE


ALICE 3
Outer Tracker
Inner Tracker
TOF
FD
RICH
ECal
Magnet
Absorber
Muon identification
FCT




TOF
MUCH
TRD
PSD
BMON
MAGNET
RICH
STS+MVD
Tracking acceptance: 2° < Θ_LAB < 25°
Free streaming readout
Front-end connectivity up to R_int = 10 MHz
Software-based event selection

ALICE 3



√sNN ~ 5 TeV (LHC)

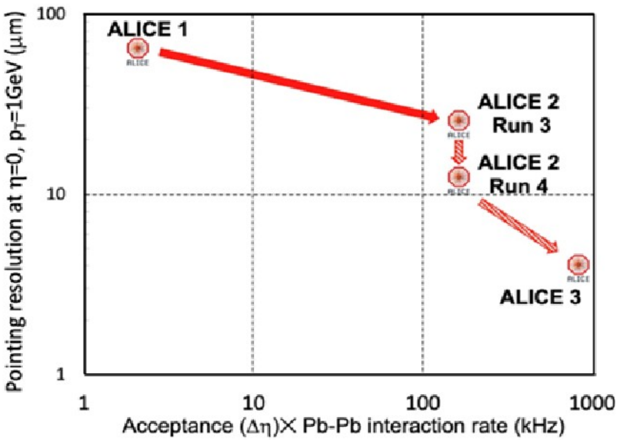
Measurement of thermal dielectrons

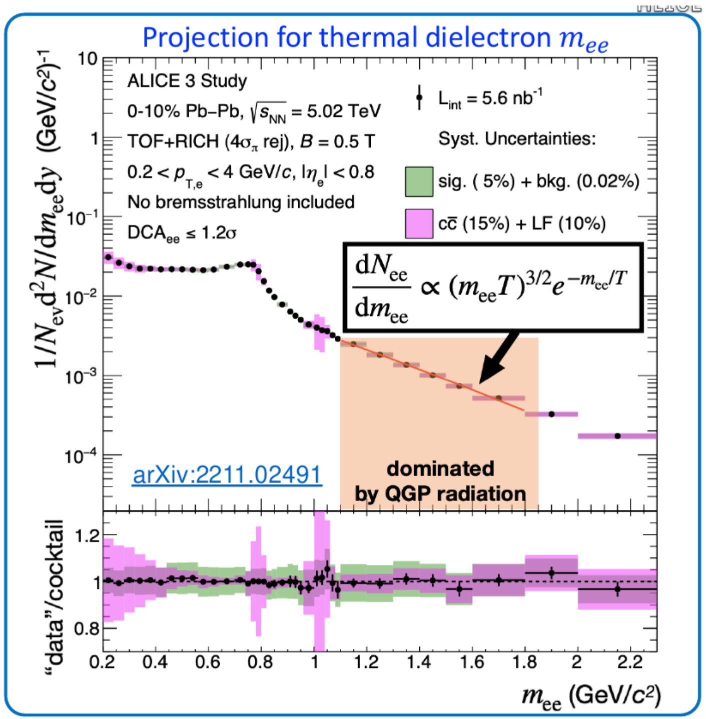
→ QGP temperature and evolution

→ Chiral symmetry restoration

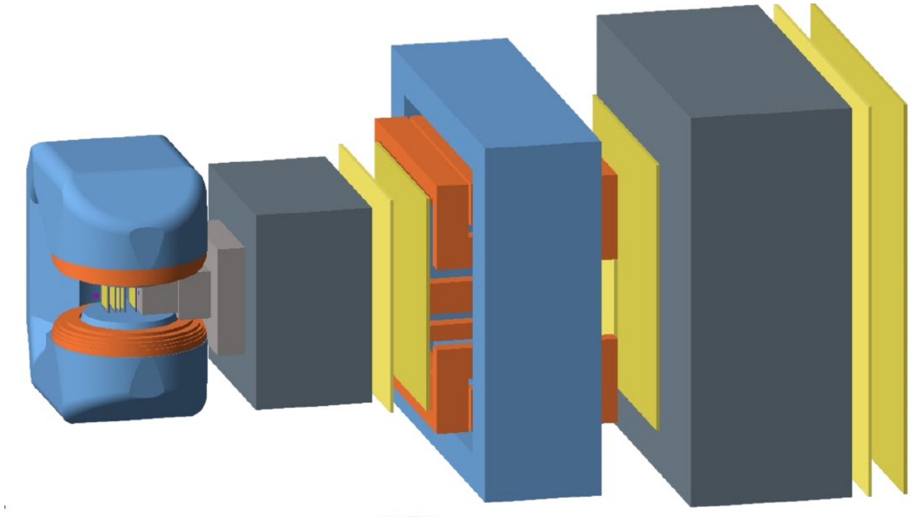
→ Dielectron v2

→ Preequilibrium radiation



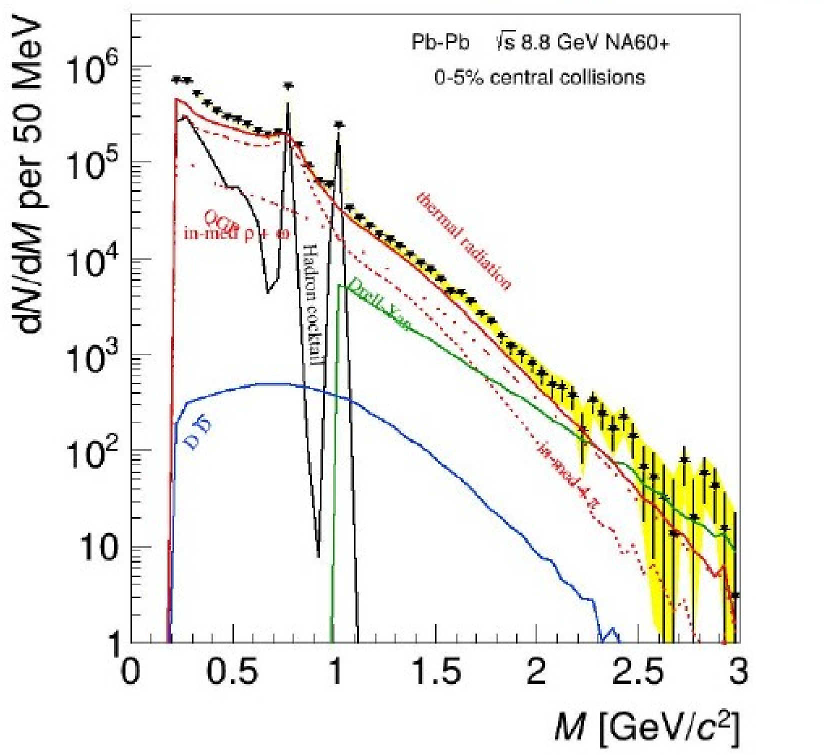


NA60+



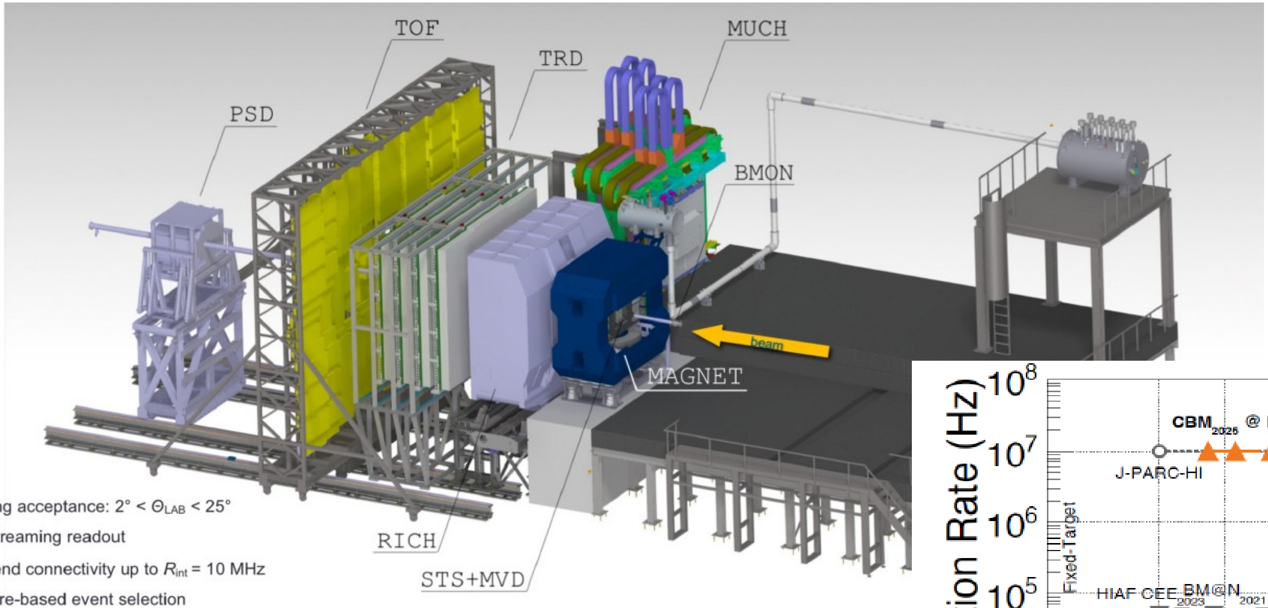
√sNN ~ 6 - 17 GeV (SPS)
Measurement of thermal dimuons
→ Fireball lifetime
→ Chiral symmetry restoration
→ 1st order phase transition
→ Thermal dimuon v2

6×10^{11} Pb on target (1 month)



√sNN ~ 3 – 5 GeV (SIS100)

CBM



Tracking acceptance: $2° < \Theta_{LAB} < 25°$

Free streaming readout

Front-end connectivity up to R_{int} = 10 MHz

Software-based event selection

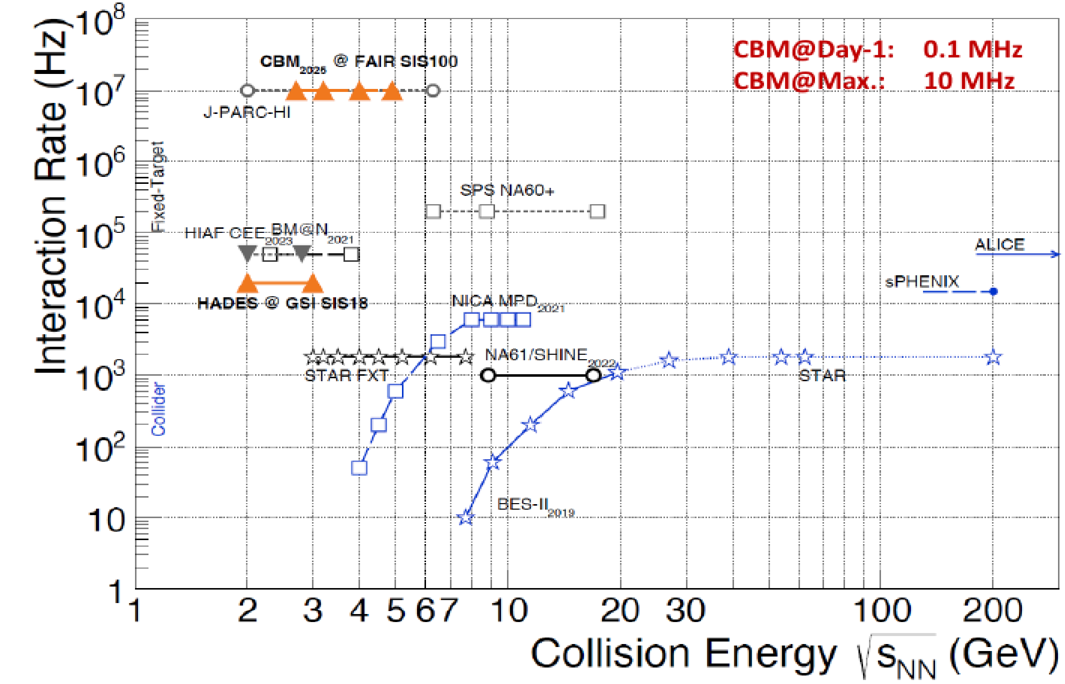
Challenges for detector:
- high granularity
- low material budget
- **Fast, radiation hard** detectors & front-end electronics

Free-streaming readout and online event reconstruction

Experimental requirements:
- High multiplicity collisions, O(1000) particles/collision
- High event rates, up to 10^7 Hz Au+Au collisions
- High precision measurements, complex decay topology

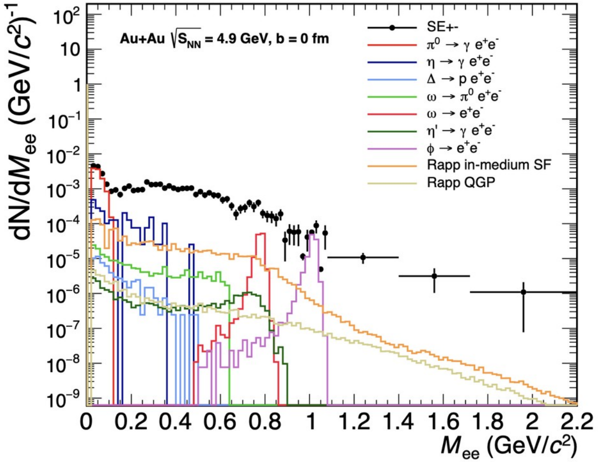
spatial resolution → $\Delta p/p$ = 1 − 2% (B=1T)

tracking efficiency >97% for primary tr

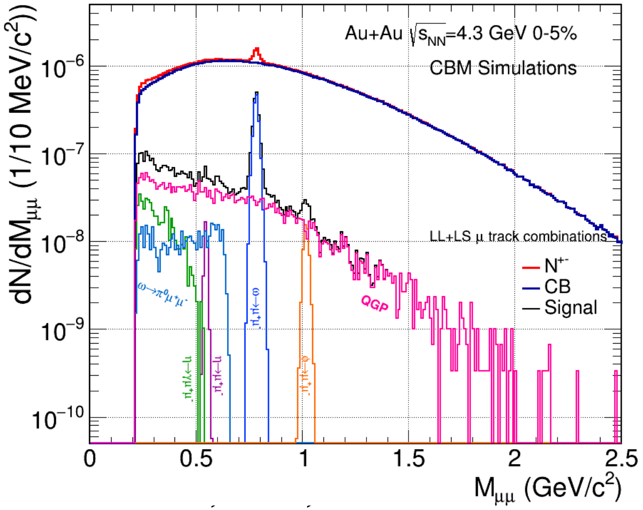


DLEPTONS IN CBM

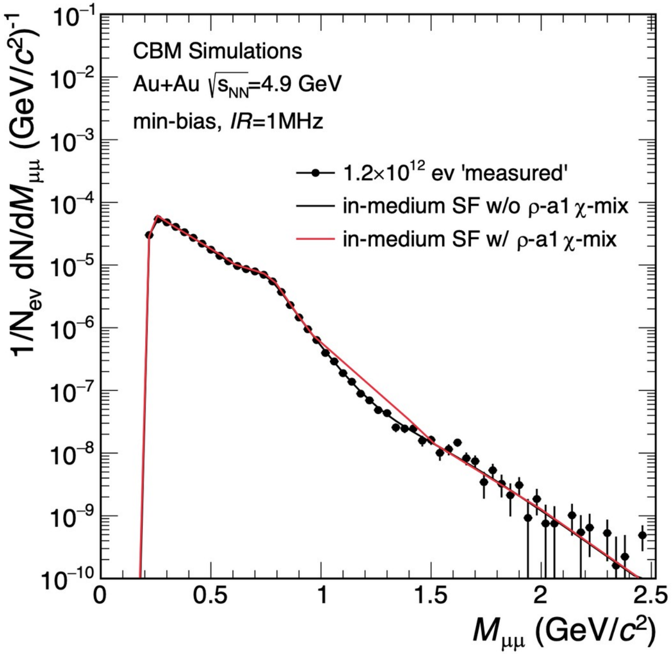
ELECTRONS



MUONS

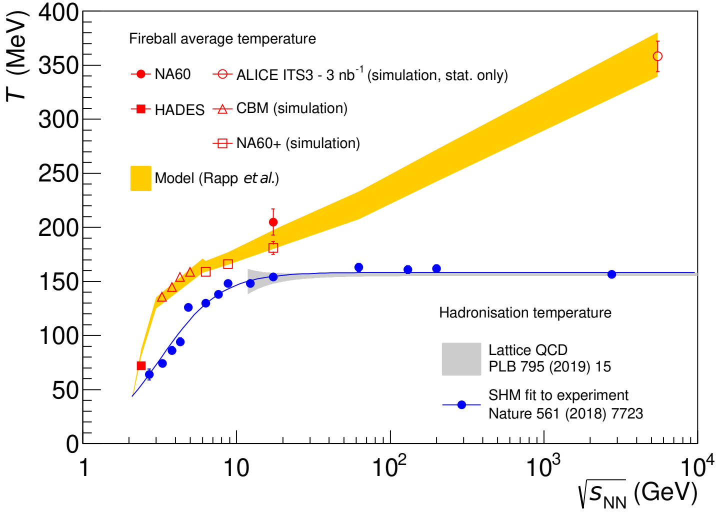


Cocktail Subtraction
based on contributins
measured in pp, dp collisions



Yield of ρ-a1
→ signature of chiral symmetry

Measurement at different energies
→ caloric curve
→ phase transition



CONCLUSIONS

EM probes (photons and dileptons): unique access to Temperature, full evolution of the system
Challenging measurement: cocktail, background and low branching ratio

DIRECT PHOTONS
New data from STAR and PHENIX on direct photon production
First significant data from ALICE
→ PHENIX data in agreement with previous measurements of direct photon yield and ow
→ Universal scaling of yields with $(dN_{ch}/d\eta)^{-\alpha}$
→ Unresolved tension in measurement of yields and scaling slope
The direct photon puzzle persists... and becomes more puzzling
Main experimental challenge
→ Resolve ambiguity between measurements
→ Input from LHC measurements
→ Dielectron v2 in intermediate-mass to access early ow

DILEPTONS
Dielectron measurements over broad range of collision energies
→ Temperature measurements by HADES and STAR
mapping out the phase diagram and caloric curve
Promising new data from the upgraded ALICE detector from Run 3

More data to come from future experiments!

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