Thermal dilepton production: current status and near and far time perspectives

Heavy Ion Meeting, 17 September 2020

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ÖAW AUSTRIAN ACADEMY OF SCIENCES

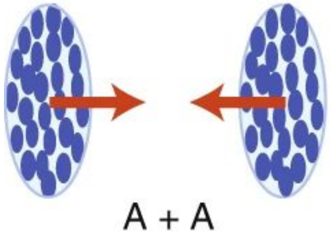
FTE NATIONALSTIFTUNG FORSCHUNG | TECHNOLOGIE | ENTWICKLUNG

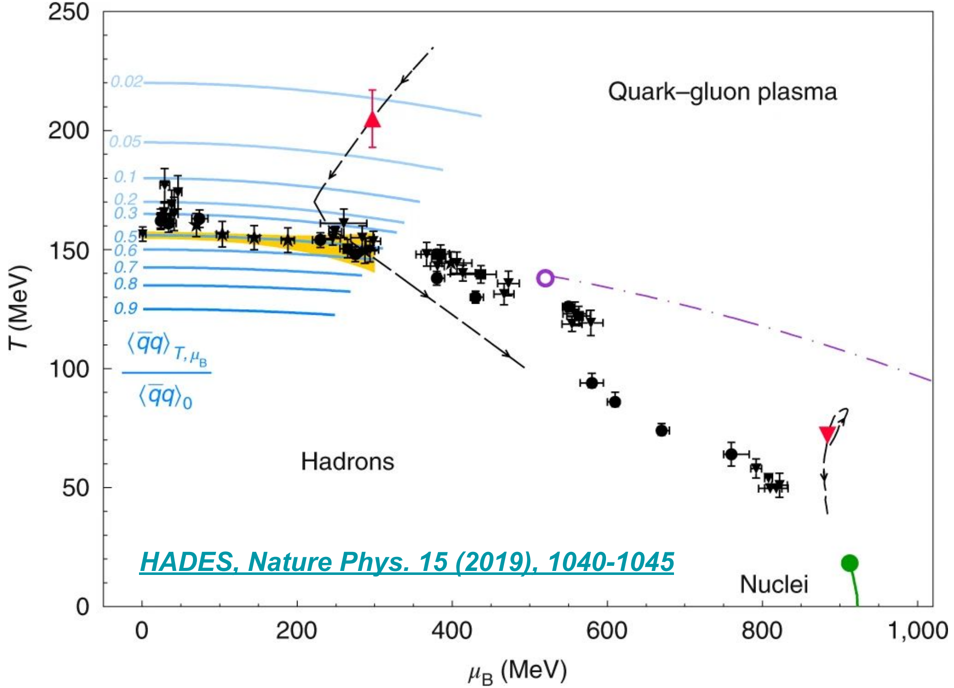
Outline

- Thermal radiation and dileptons
    - (Low-mass) dilepton sources and physics objectives
    - Experimental results (with focus on recent results from ALICE at the LHC)
- Upgrades and future heavy-ion experiments (at the LHC)

Michael Weber

Heavy-ion collisions and dileptons



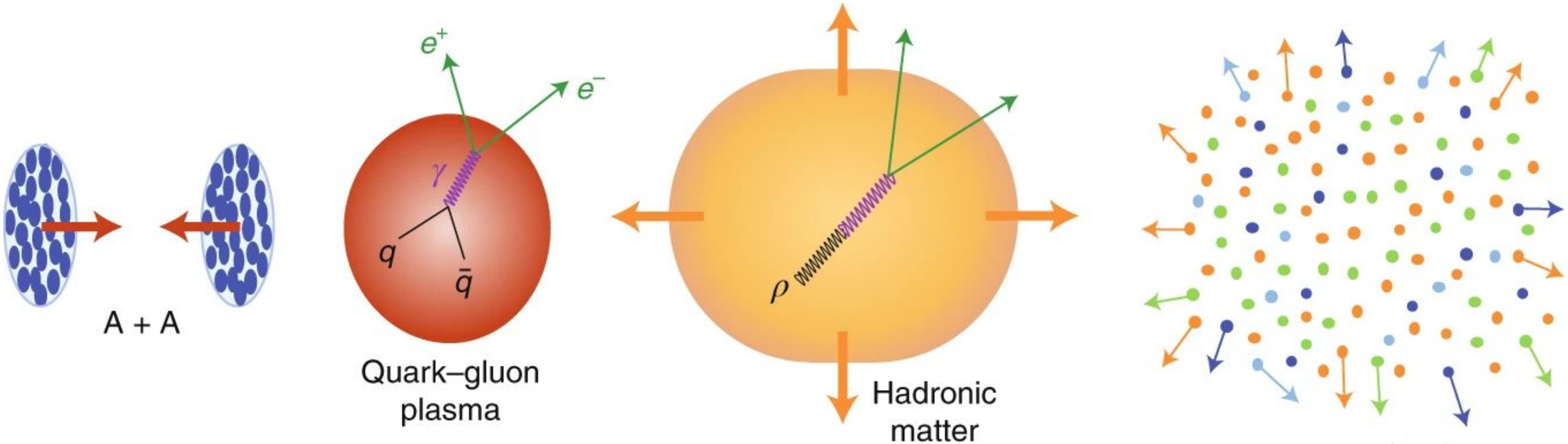


HADES, Nature Phys. 15 (2019), 1040-1045

Ultra-relativistic Heavy-Ion Collisions: **test QCD at high temperatures/densities**

- Phase transitions / Quark-Gluon Plasma (**QGP**)
- **Deconfinement**
- (Partial) restoration of **chiral symmetry**

Heavy-ion collisions and dileptons

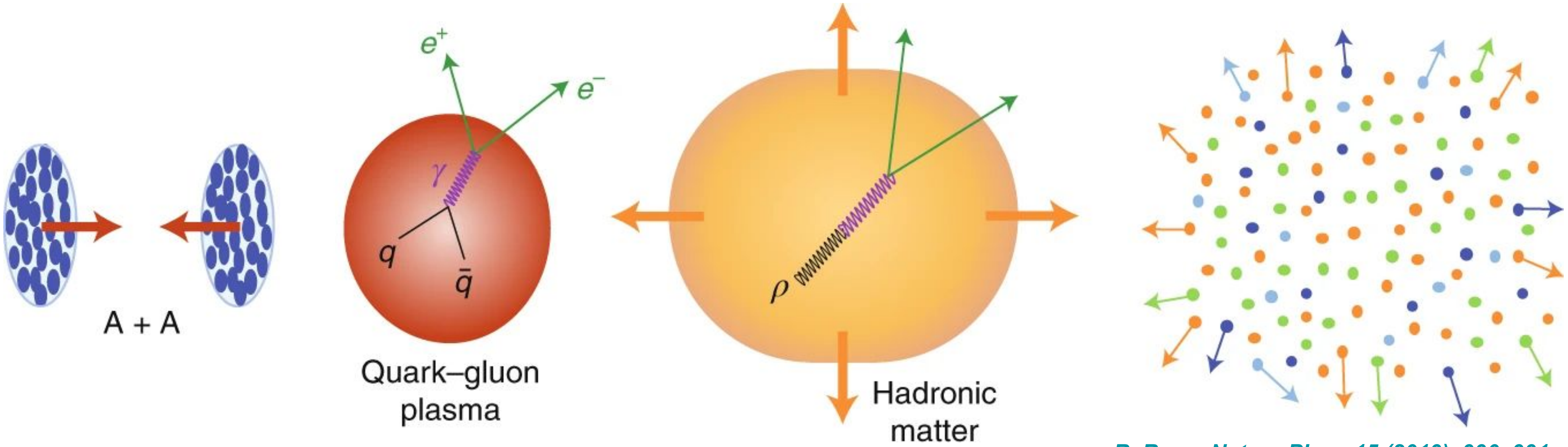


[R. Rapp, Nature Phys. 15 (2019), 990–991]

Measure photons or 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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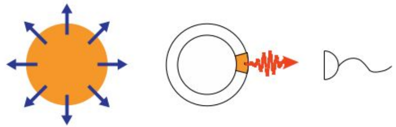
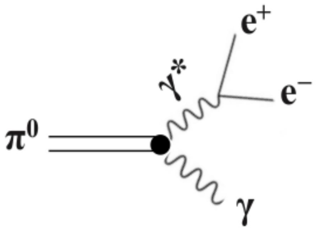
Measure photons or dileptons (e^+e^- or $\mu^+\mu^-$ pairs)

- Couple to EM current throughout the **full collision history**
- Very low interaction with QCD medium (**no strong interaction**)
- **Virtual photons:** invariant mass, no blue-shift of rapidly expanding system
- **Sensitive to** thermal radiation, vector meson spectral shape, production of heavy flavour (charm and beauty) hadrons, beyond SM particles with $J^{PC}=1^{--}$ (e.g. dark photons)

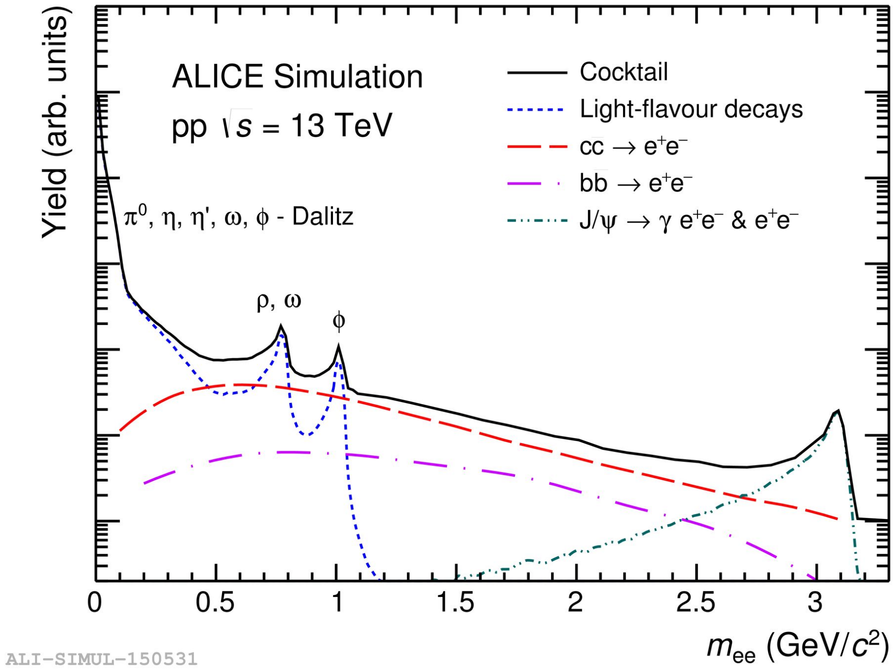


Dilepton sources - light flavour

- Dominating **low mass region** $m_{ee} < 1.1$ GeV/c^2



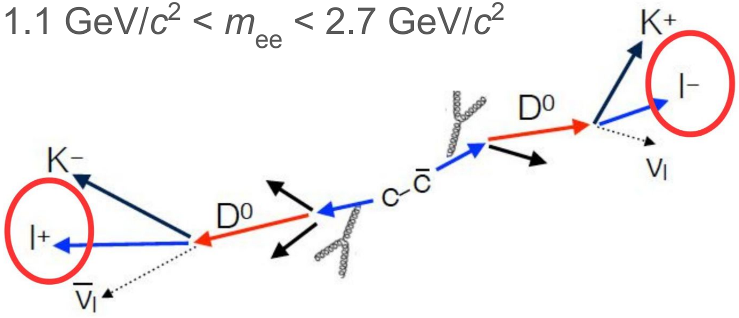
- Populated with **light neutral mesons** (π^0, η, η', ρ, ω and ϕ)
  - Decaying via Dalitz, or two body decays
- Connection to QCD chiral symmetry restoration expected at temperatures reached in UrHICs
  - **In-medium modification** of vector mesons: "ρ broadening" (see later slides)

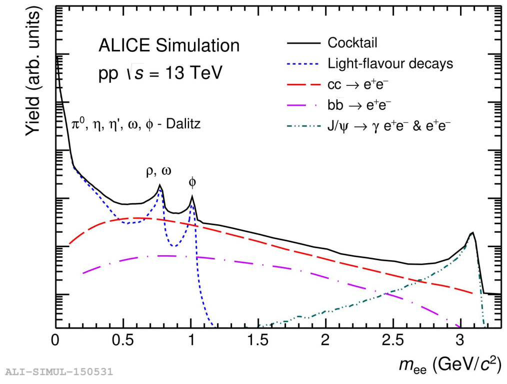


For dimuons only m > 0.2 GeV/c^2 accessible

Dilepton sources - heavy flavour

- Dominating **intermediate mass region** $1.1\ \mathrm{GeV}/c^2 < m_{ee} < 2.7\ \mathrm{GeV}/c^2$

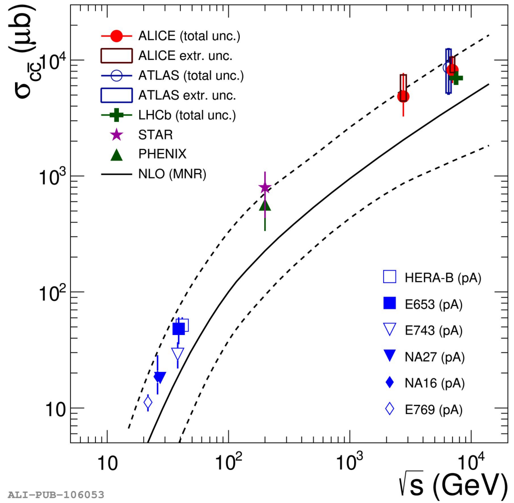




- In pp collisions: **measurement of $\sigma_{cc,bb}$**
  - Complementary to hadron measurements
  - Strongly increasing contribution with $\sqrt{s_{NN}}$

- In p-Pb collisions: cold nuclear matter effects
  - **Nuclear PDFs**

- Other “hard” sources (not discussed here): Prompt, Drell-Yan, and pre-equilibrium virtual photons



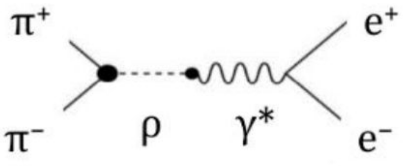
Dilepton sources - thermal

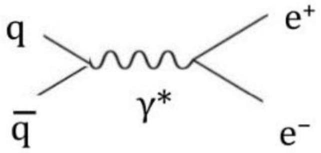
Thermal dilepton emission rate:

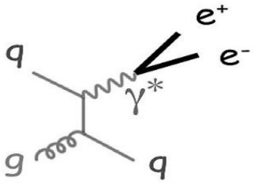
$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{\mathrm{EM}}^2 L(M)}{\pi^3 M^2} f^B(q_0;T)\, \boxed{\mathrm{Im}\Pi_{\mathrm{EM}}(M,q;\mu_B,T)}$$

hadrons

partons







Dilepton sources - thermal

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

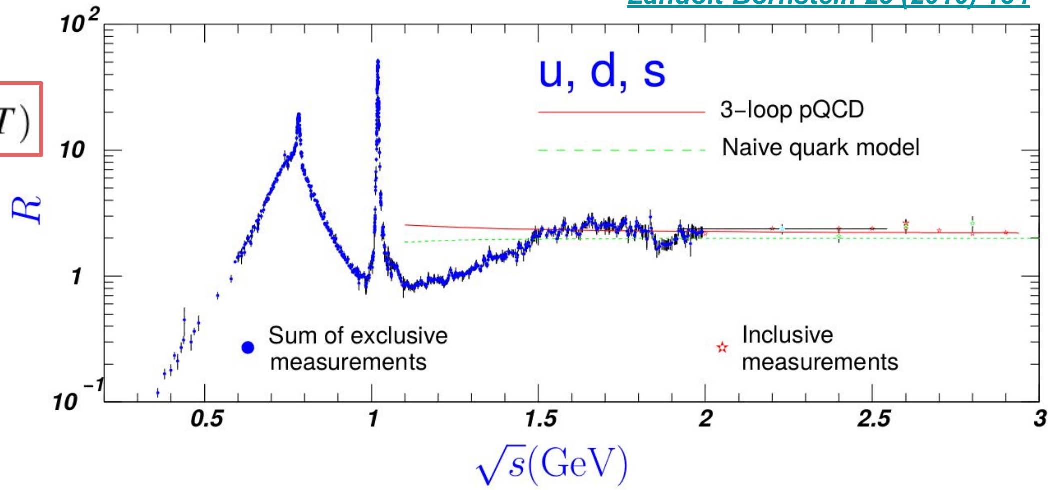
hadrons

$$j^\mu_{EM} = \sum_{V=\rho,\omega,\varphi} \frac{m_V^2}{g_V} V^\mu$$

partons

$$j^\mu_{EM} = \sum_{q=u,d,s} e_q \bar{q}\gamma^\mu q$$

Landolt-Bornstein 23 (2010) 134

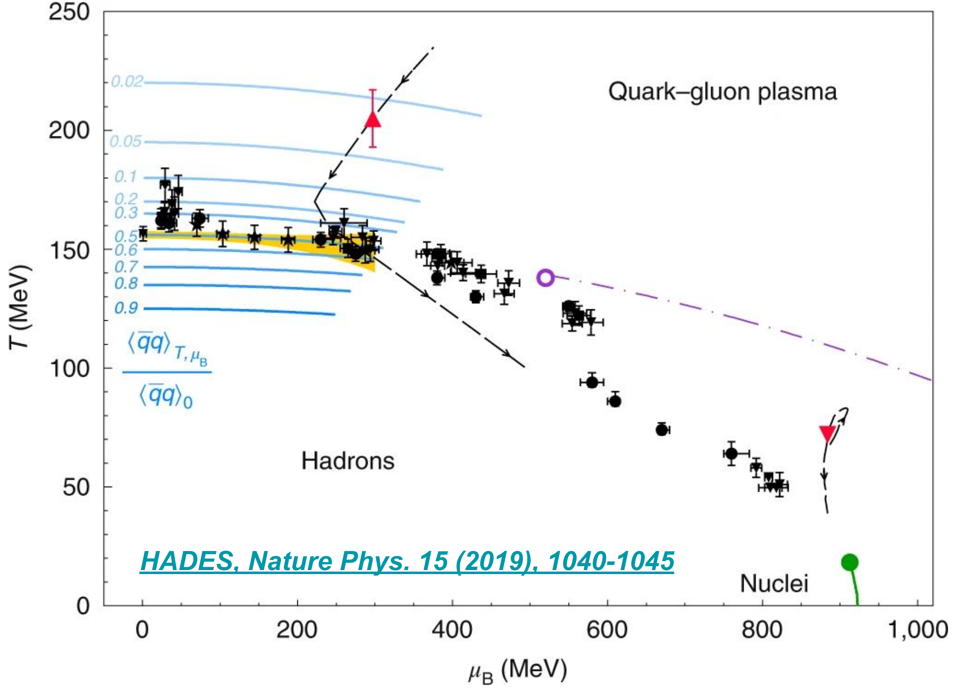


- **Vacuum**: EM spectral function well known from the e^+e^- annihilation cross section into hadrons / $\mu^+\mu^-$

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

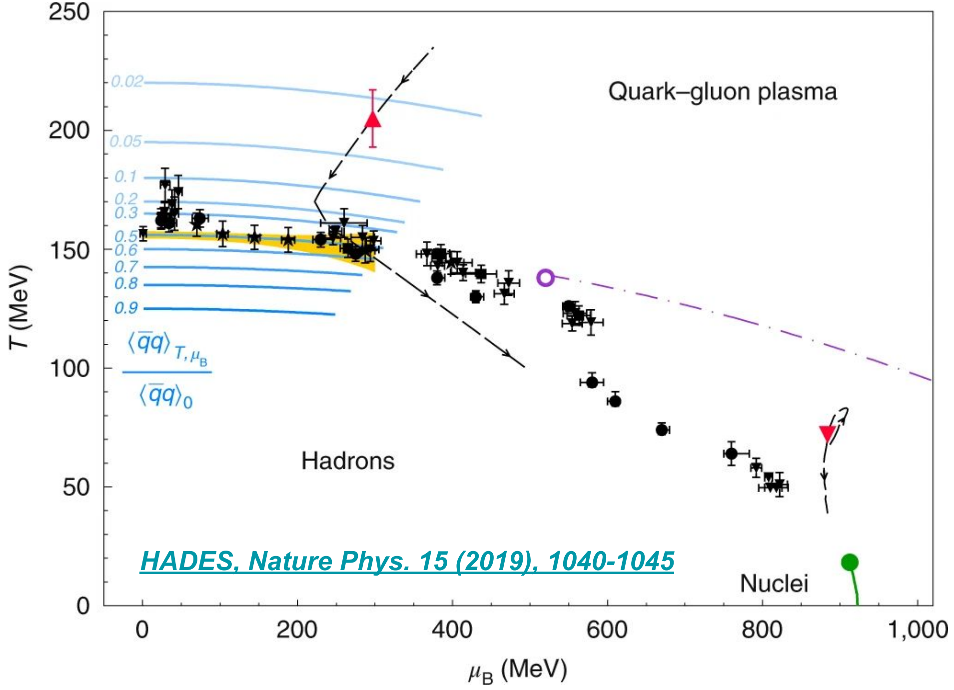
- **Medium:**
  - Below 1.5 GeV/c^2: **modification of vector meson spectral function**
    → signals (approach to) deconfinement and the **restoration of chiral symmetry?**
  - Above 1.5 GeV/c^2: **extraction of temperature** (and space-time evolution of thermal source)

Temperature evolution



- System evolution in the QCD phase diagram

Temperature evolution



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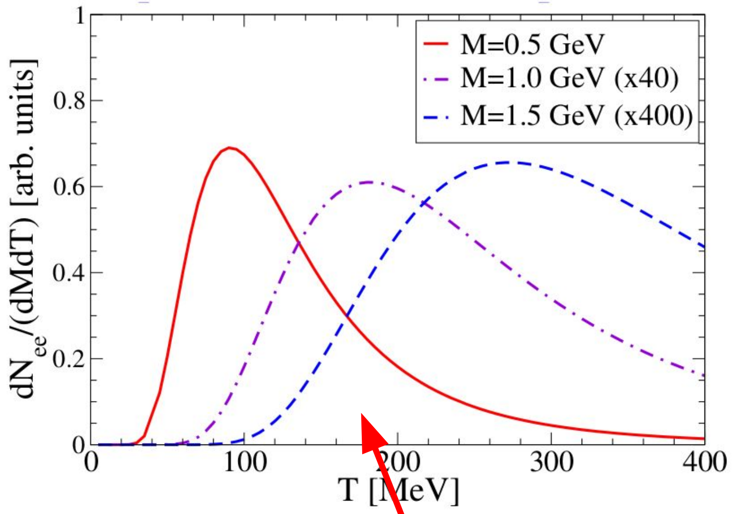
R. Rapp, Acta Phys. Pol. B 42, 2823 (2011)



- System evolution in the QCD phase diagram
- Temperature-differential dielectron emission:

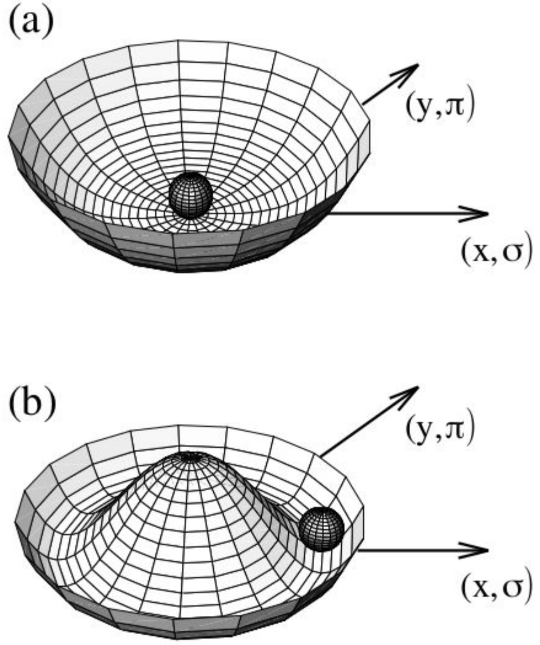
$$\frac{dN_{ee}}{dMdT} \propto \mathrm{Im}\, \Pi_{\mathrm{EM}}(M;T)\, \mathrm{e}^{-M/T}\, T^{-m}$$

- **Dilepton mass sensitive to system temperature (evolution)**

Partial restoration of chiral symmetry

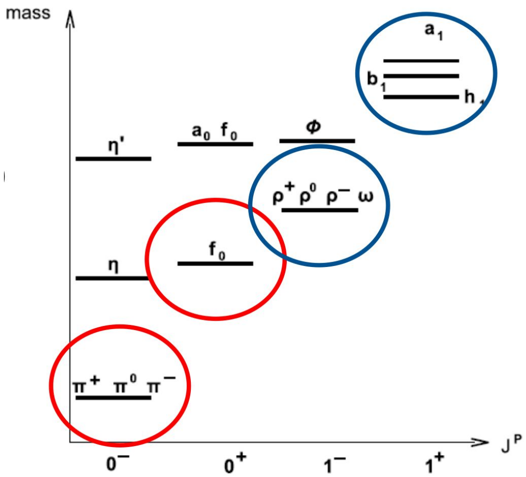
Chiral symmetry of QCD Lagrangian:

- Ground state breaks symmetry spontaneously



[V. Koch, Int.J.Mod.Phys. E6 (1997) 203-250]

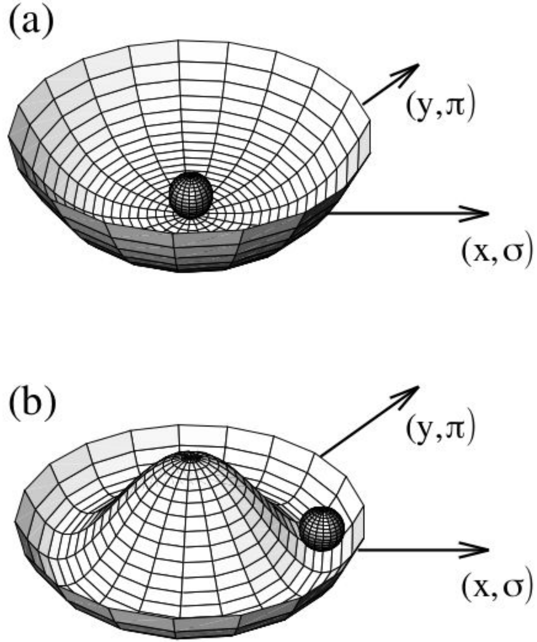
Partial restoration of chiral symmetry



Spontenous broken symmetry	
Heisenberg magnet	**QCD**
L rotational invariant	L chiral invariant
g.s. breaks symmetry: Magnetization	g.s. breaks symmetry: chiral condensate
Restoration for T > T_C	Restoration for high temperatures or densities

S. Leupold, Physics@FAIR, 2011

Chiral symmetry of QCD Lagrangian:
- Ground state breaks symmetry spontaneously
- Parity partners not degenerate



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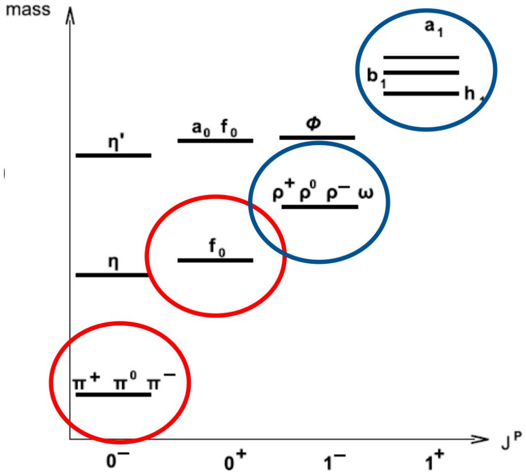

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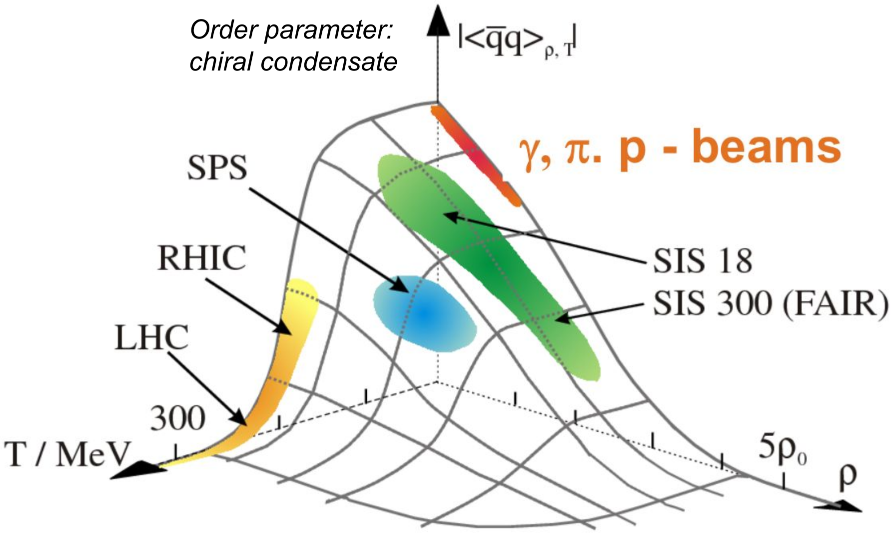

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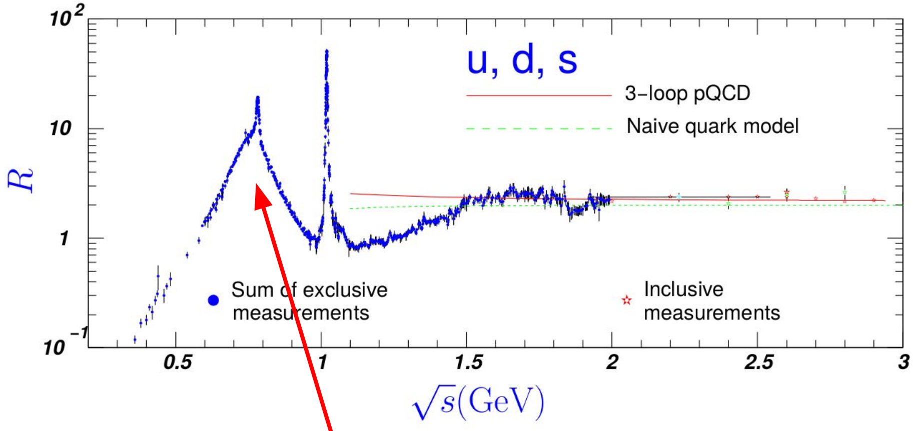

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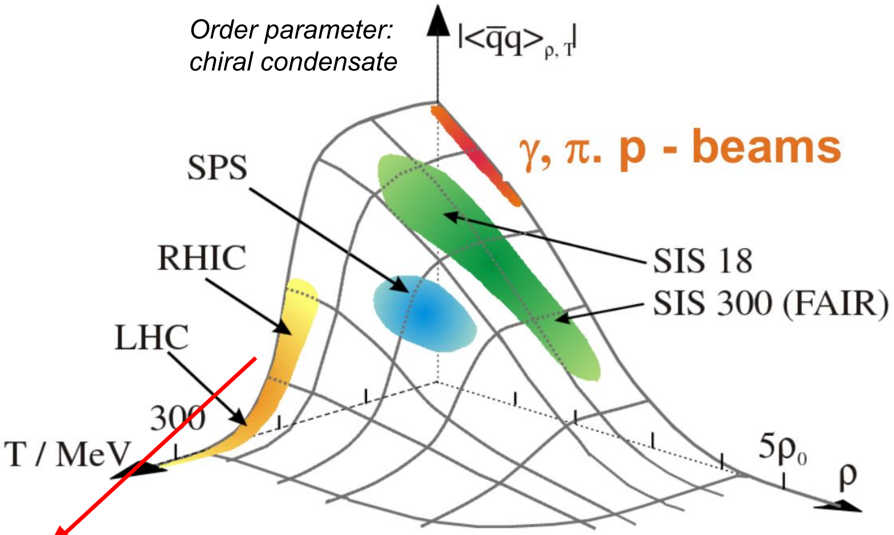
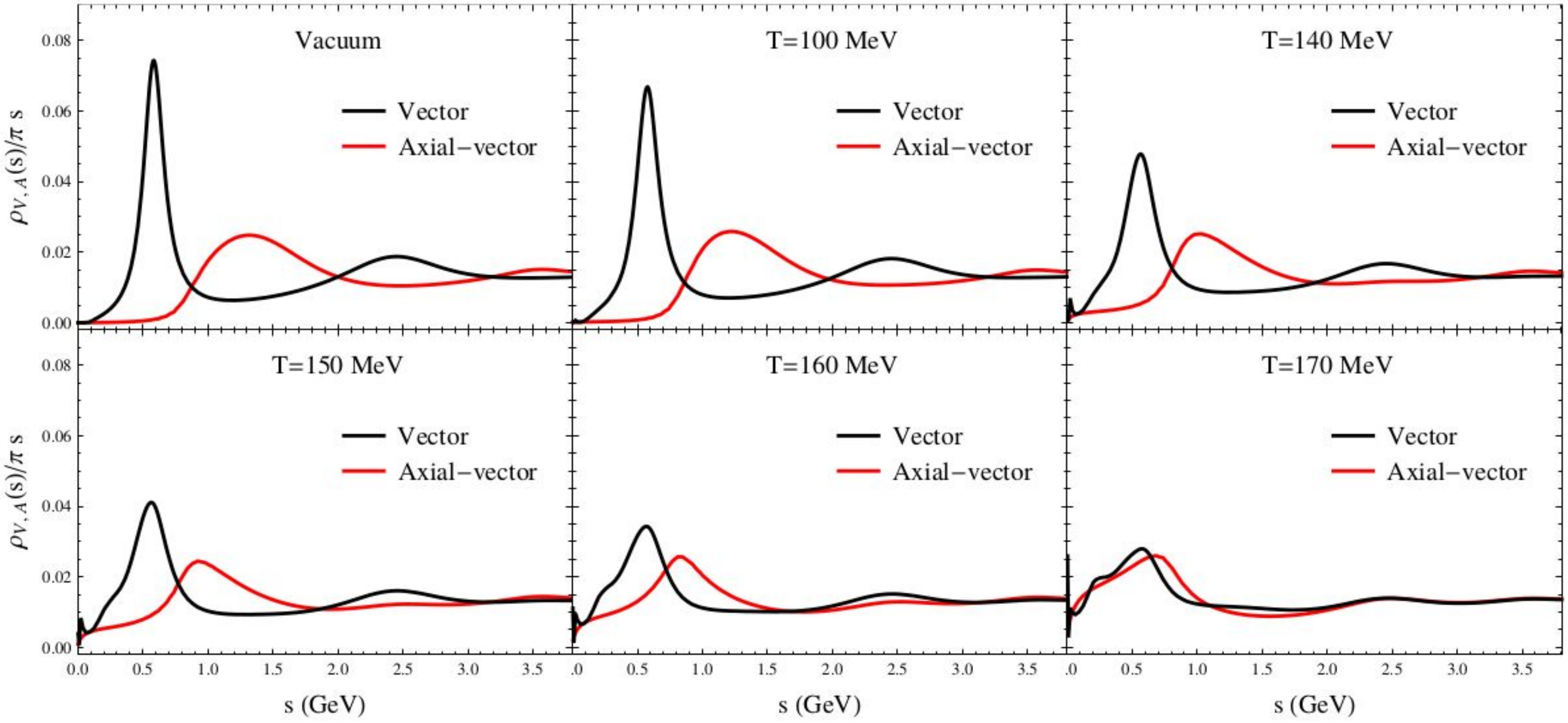


QCD sum rule:

$$\frac{1}{M^2}\int_0^\infty ds \frac{\rho_V(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) + \frac{m_q\langle\bar{q}q\rangle}{M^4} + \frac{1}{24M^4}\langle\frac{\alpha_s}{\pi}G^2_{\mu\nu}\rangle - \frac{56\pi\alpha_s}{81M^6}\langle\mathcal{O}_4^V\rangle \ldots$$

→ measurable in-medium modification of vector (and axial-vector) spectral function?

Partial restoration of chiral symmetry

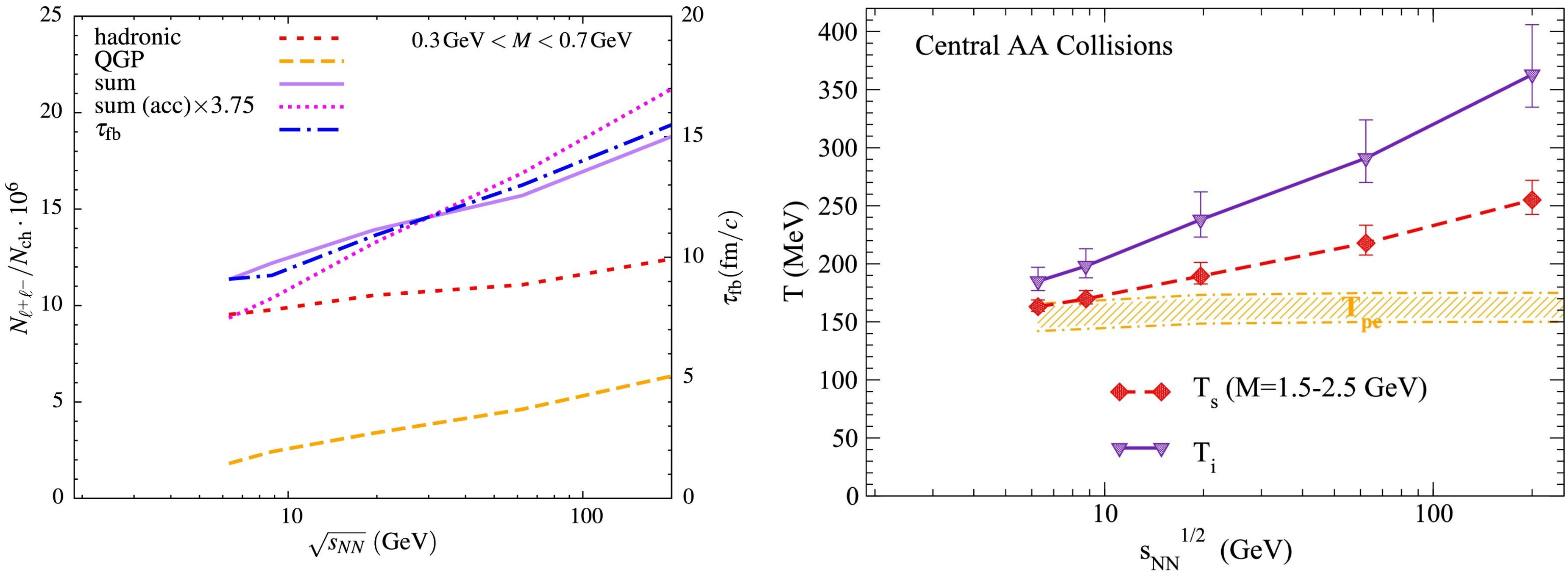


- **ρ-meson melting/broadening**
- Merging of vector and axial-vector spectral functions
- “Direct connection between dileptons and chiral restoration”

P.M. Hohler, R. Rapp, Phys.Lett.B731 (2014) 103-109

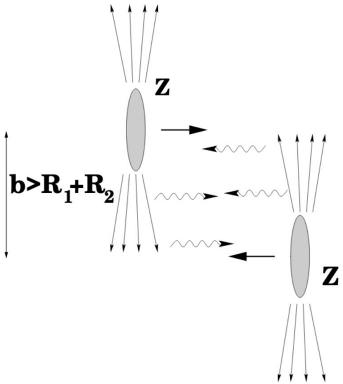
Summary: dileptons as thermometer and chronometer

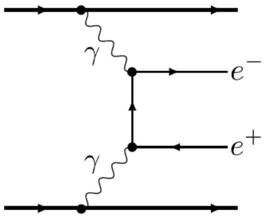
R. Rapp, H. van Hees, Phys.Lett. B 753, 586 (2016)



- Low-mass thermal radiation ("excess spectra") in m_{ee} = 0.3-0.7 GeV/c^2 **~ fireball lifetime**
- Inverse slope parameter (1.5-2.5 GeV/c^2) **~ initial temperature**

Dilepton sources - photoproduction

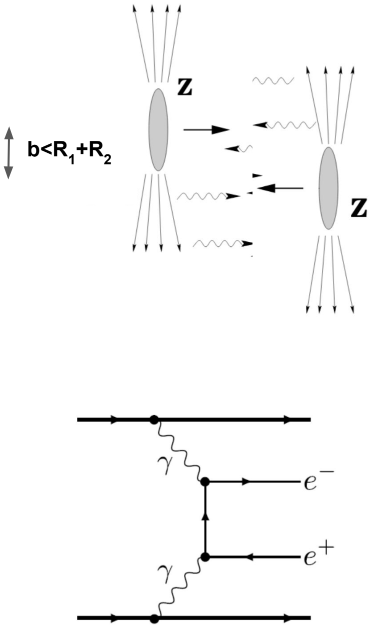


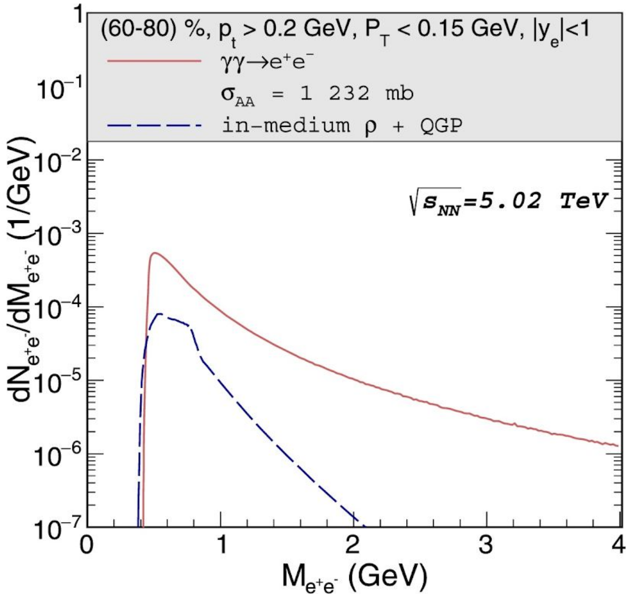


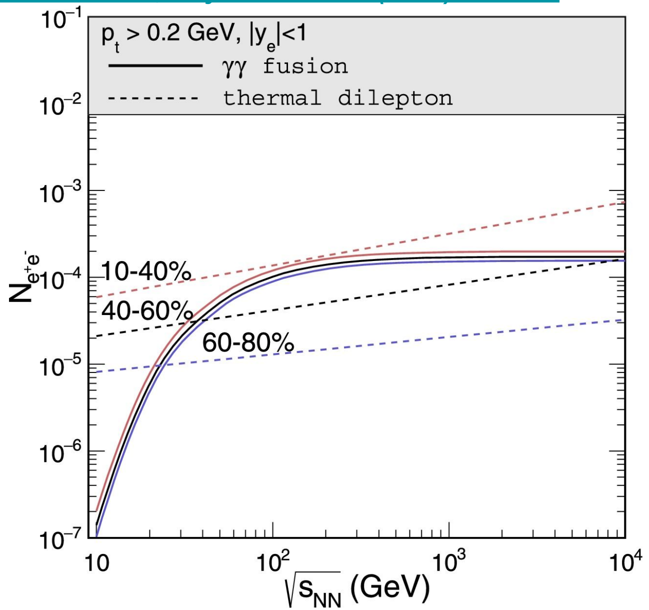
- EM field surrounding the fast moving nuclei can be treated as a **quasi-real photon flux**
- high cross section for **photon-photon interactions** (and photon-nucleus)

Dilepton sources - photoproduction

M. Klusek-Gawenda et al., Phys.Lett.B 790 (2019) 339-344





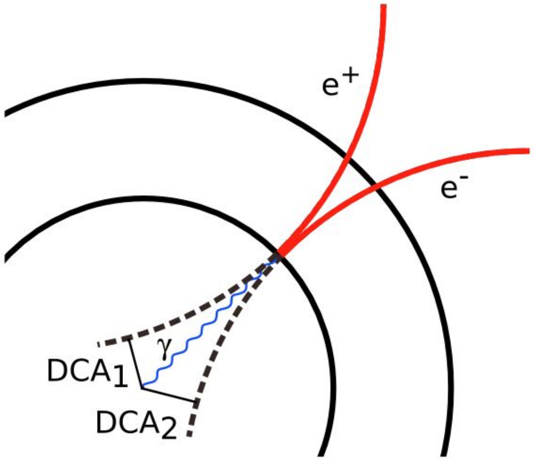


- EM field surrounding the fast moving nuclei can be treated as a **quasi-real photon flux**
- high cross section for **photon-photon interactions** (and photon-nucleus)
  - Dileptons with **low pair transverse momentum**
  - **Different scaling** with collision energy and centrality w.r.t. hadronic and thermal production

Experimental approach and challenges

Example: dielectrons

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



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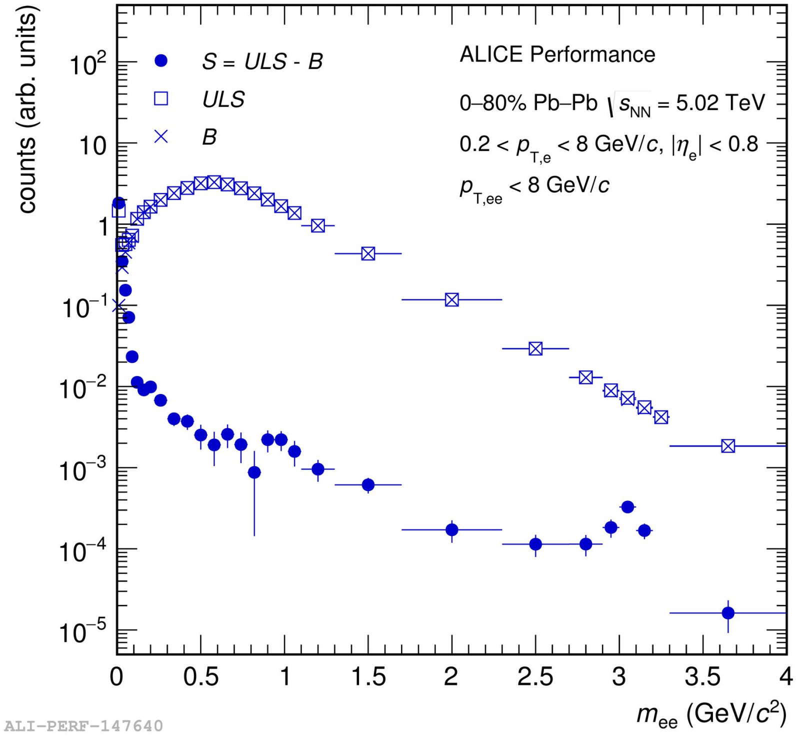
- Subtract **combinatorial background B**
  - S = ULS - B = R*LS
  - S/B ~ 10^{-3} in central Pb-Pb collisions



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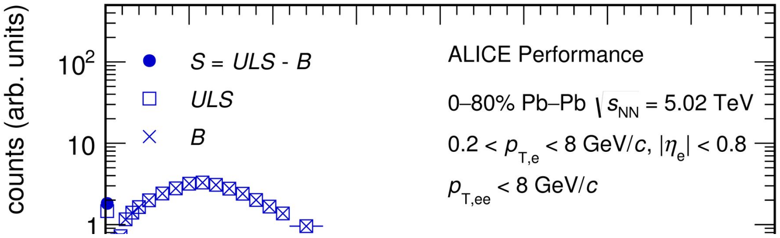

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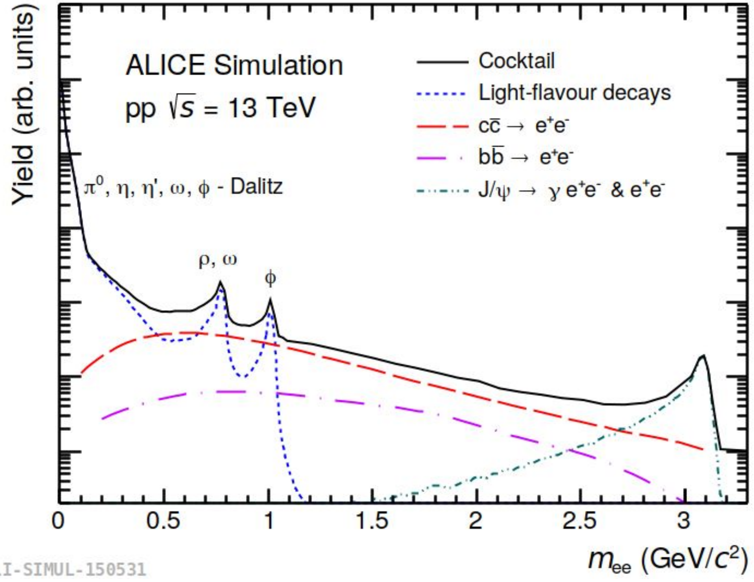


- Subtract “known” long-lived light- and heavy-flavour sources (“**cocktail**”)
  - Systematic uncertainties

Example at LHC - ALICE

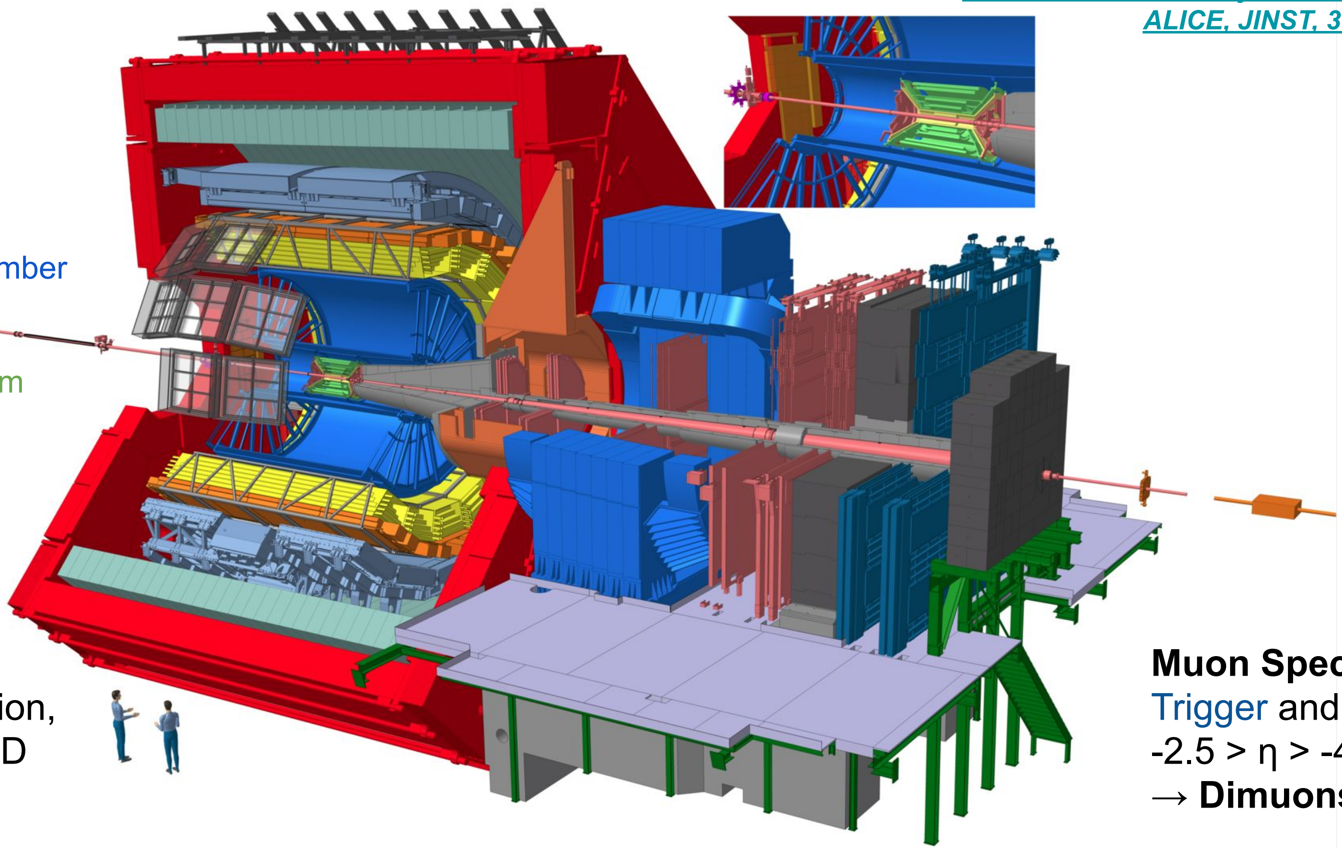
ALICE

[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

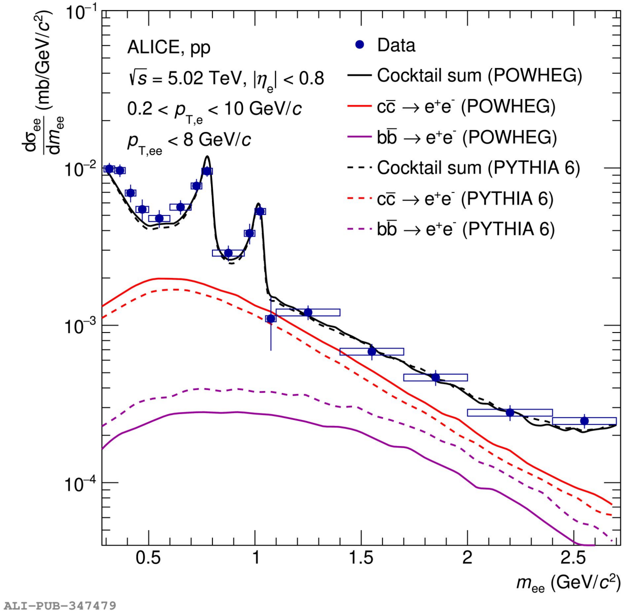


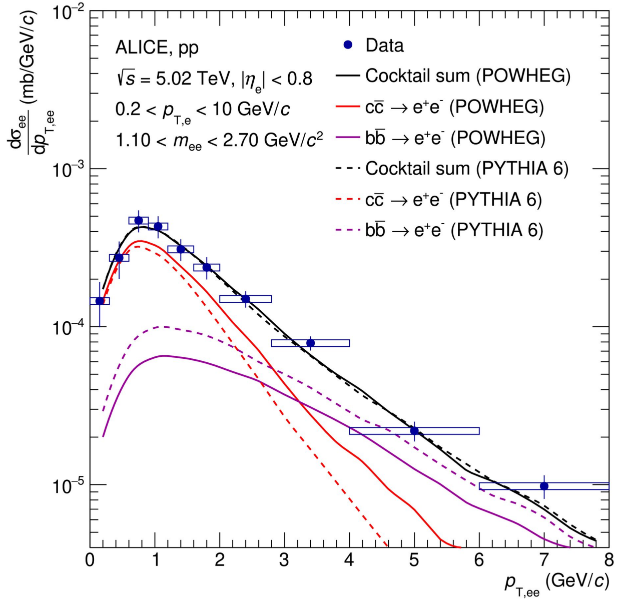
Central barrel:
Event characterization,
Vertex, Tracking, PID
$|\eta| < 0.9$
→ **Dielectrons**

Muon Spectrometer:
Trigger and Tracking
$-2.5 > \eta > -4$
→ **Dimuons**

Light and heavy flavour - ALICE pp

ALICE, arXiv:2005.11995 [nucl-ex]





- **Proper reference:** Data well described by “cocktail” of known hadronic sources within uncertainties

Light and heavy flavour - ALICE pp

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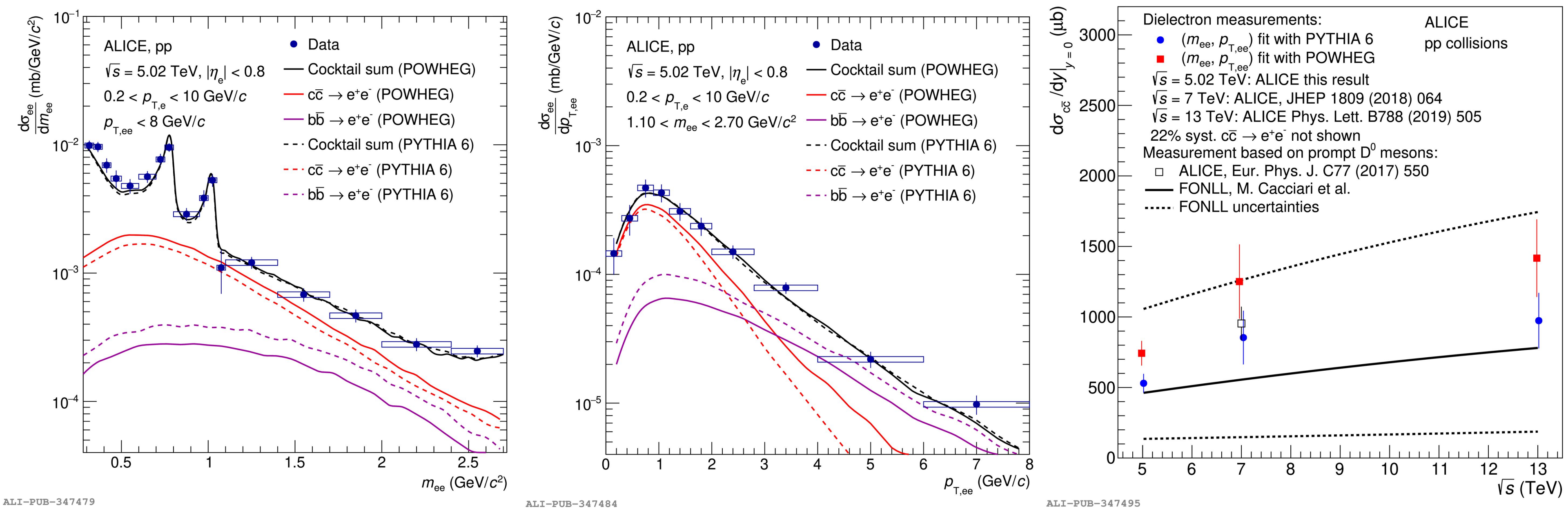
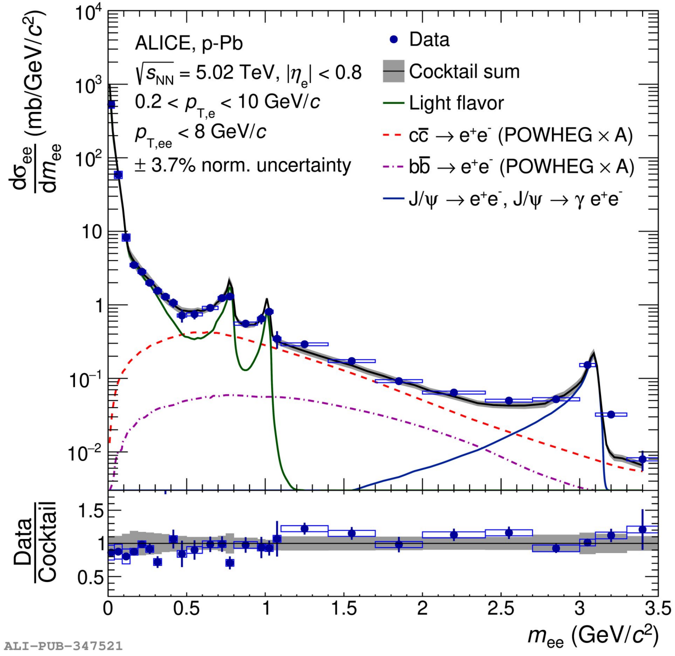


- **Proper reference:** Data well described by “cocktail” of known hadronic sources within uncertainties
- **Heavy flavour cross section:** extracted with 2D fit (m_{ee}, $p_{T,ee}$)
  - Compatible with hadron measurements
  - **Model dependence:** sensitivity to production mechanisms

Light and heavy flavour - ALICE p-Pb

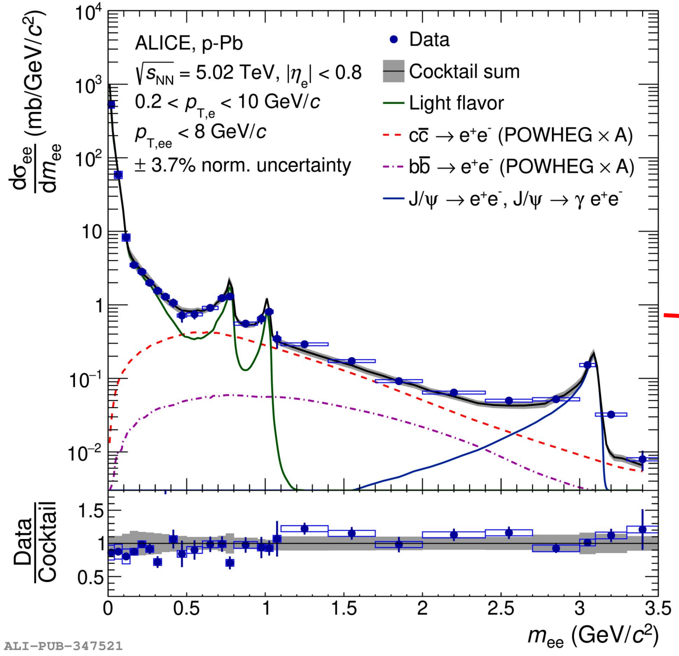
ALICE, arXiv:2005.11995 [nucl-ex]



- **Proper reference:** Data well described by “cocktail” of known hadronic sources within uncertainties
  - Scaling of heavy-flavour sources with *A* or number of binary collisions N_{coll}

Light and heavy flavour - ALICE p-Pb

ALICE, arXiv:2005.11995 [nucl-ex]



Nuclear modification factor:

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

pp results

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

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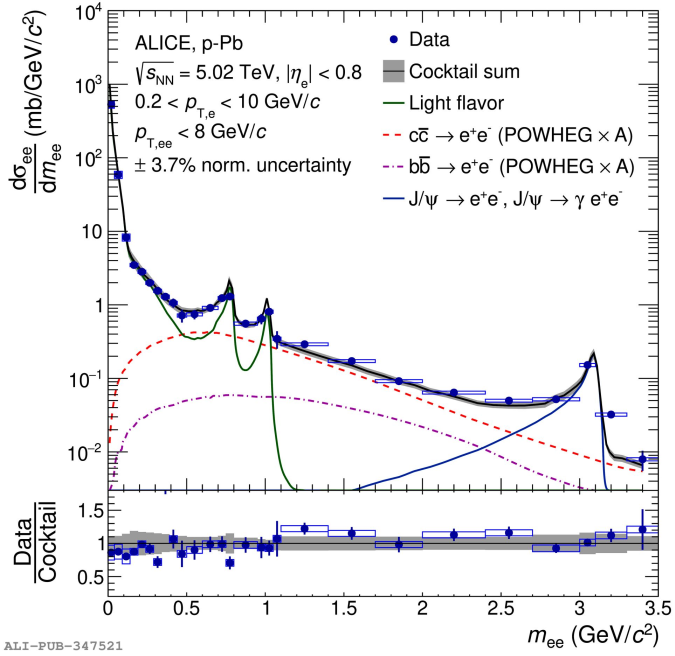
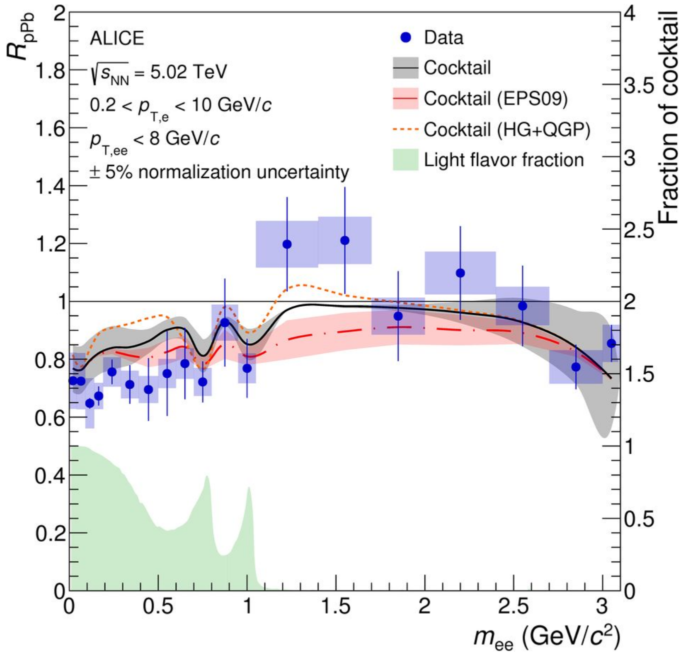
  - Scaling of heavy-flavour sources with *A* or number of binary collisions N_{coll}

Light and heavy flavour - ALICE p-Pb

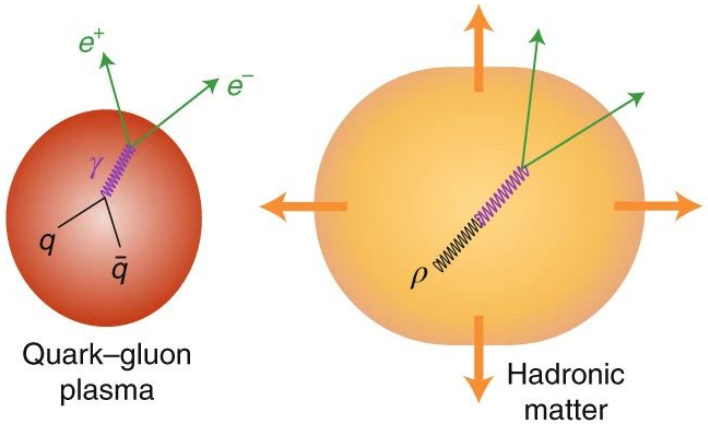
ALICE, arXiv:2005.11995 [nucl-ex]





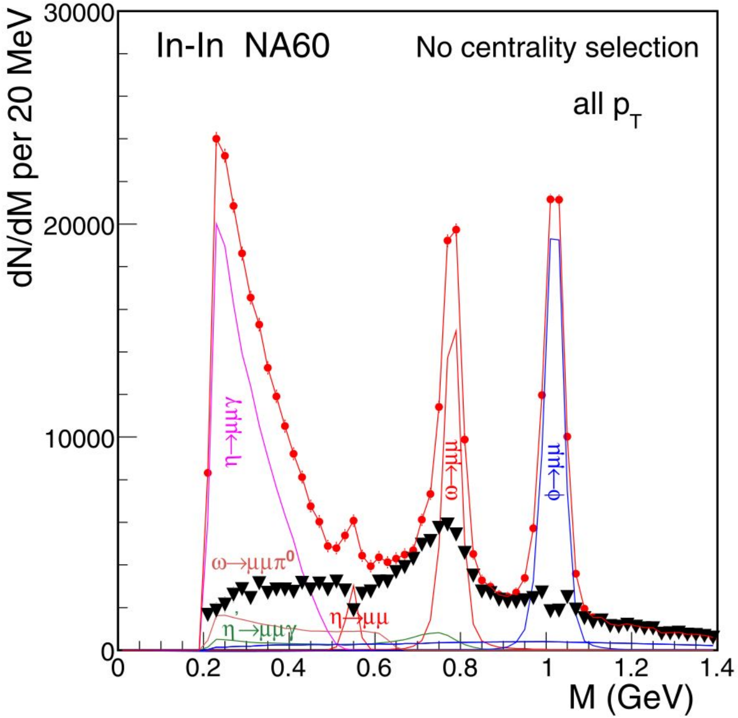
- **Proper reference:** Data well described by “cocktail” of known hadronic sources within uncertainties
- Current precision doesn’t allow for conclusions on potential **cold nuclear matter effects** (EPS09 nPDF) or **thermal radiation** (Rapp)

Thermal dilepton production



Thermal dilepton production - SPS

NA60, Eur.Phys.J.C 61 (2009) 711-720



- **Most precise heavy-ion dilepton results so far**

Thermal dilepton production - SPS

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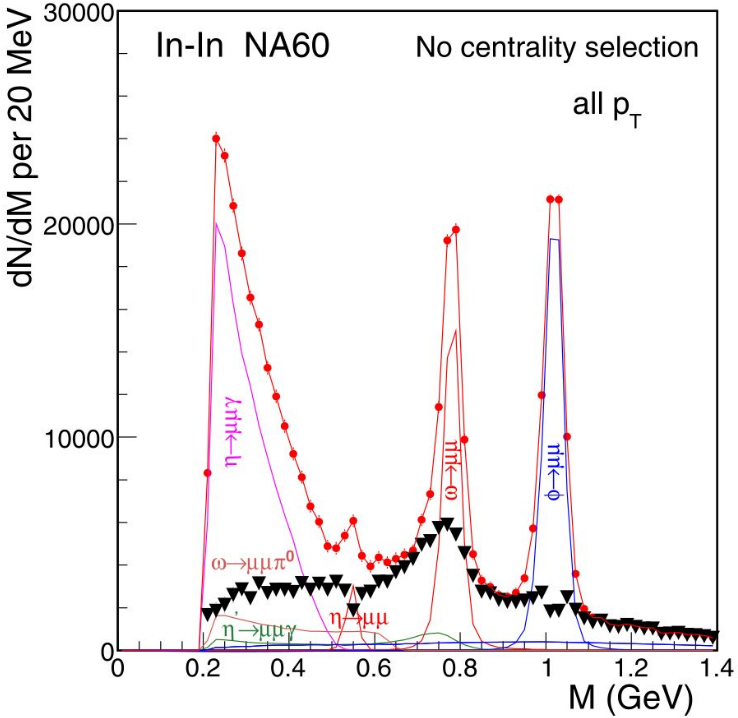
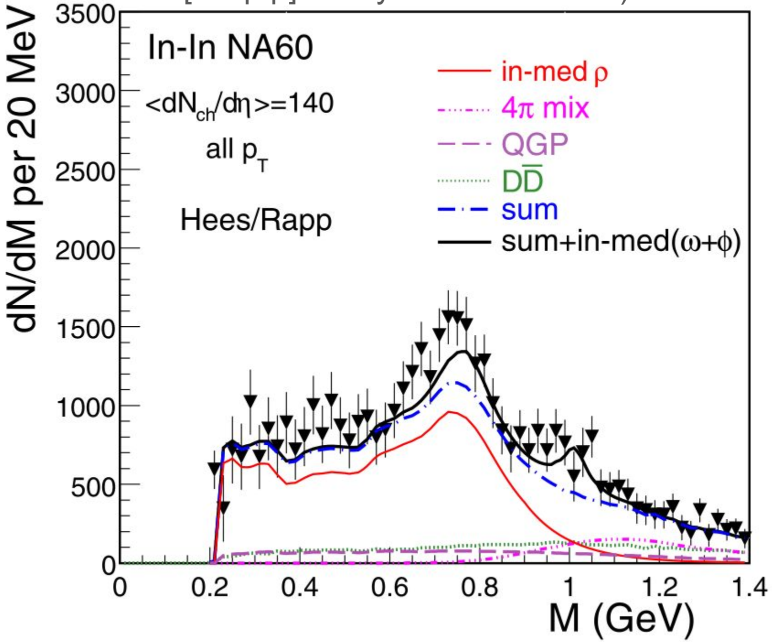


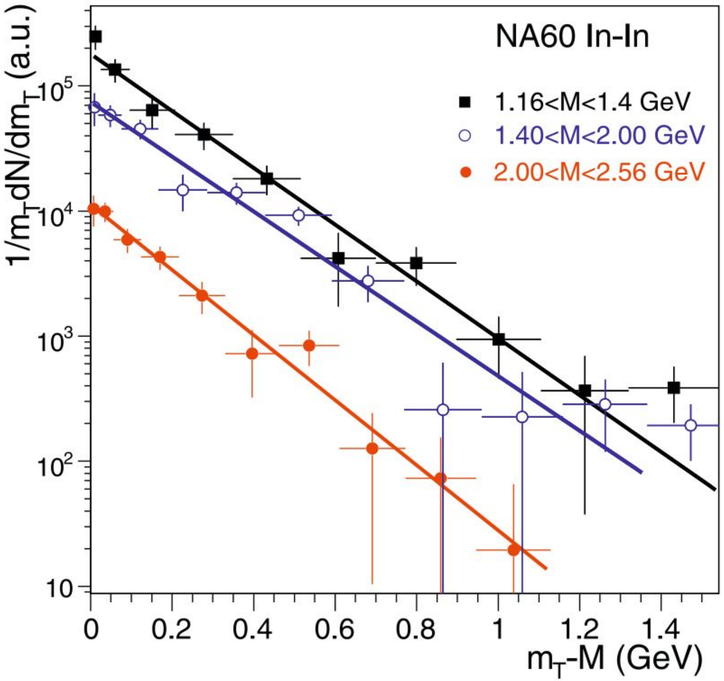
Excess (after subtraction of long-lived light- and [keep ρ] heavy-flavour sources)



- **Most precise heavy-ion dilepton results so far**
- Consistent with an **in-medium ρ spectral function** that, driven by the coupling to baryons, melts and approaches the one from qq annihilation in the vicinity of the phase transition

Thermal dilepton production - SPS

NA60, Eur.Phys.J.C 61 (2009) 711-720

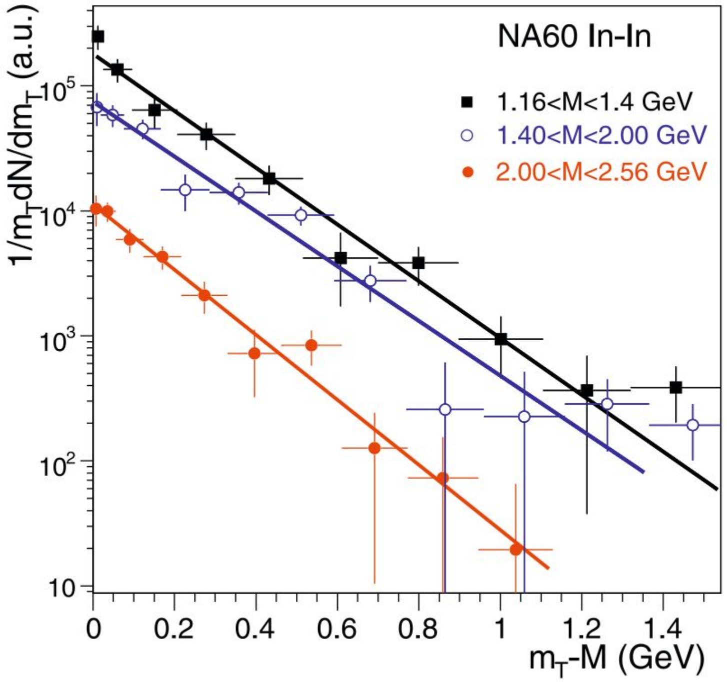


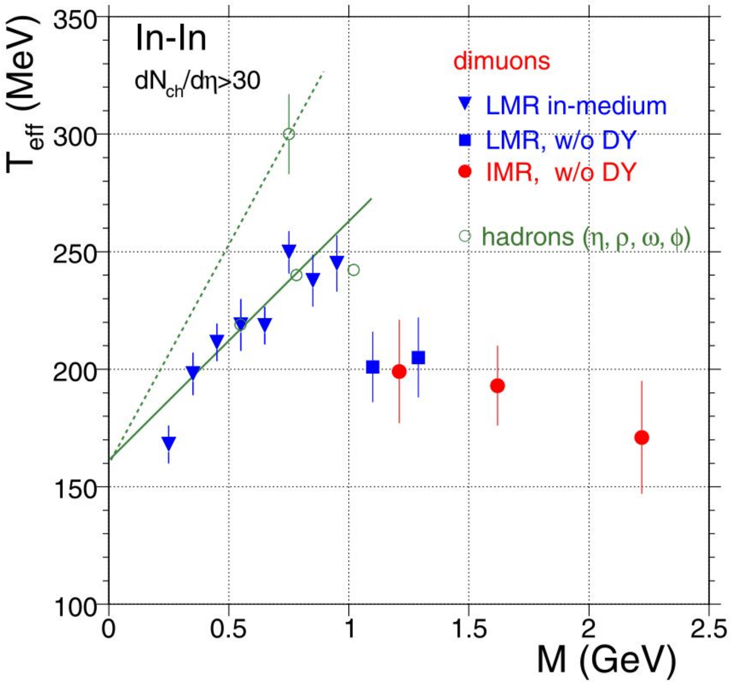
$$m_T^2 = m^2 + p_x^2 + p_y^2 = E^2 - p_z^2$$

- Fit to m_T spectra of excess yield (acceptance corrected) in different mass regions

Thermal dilepton production - SPS

NA60, Eur.Phys.J.C 61 (2009) 711-720

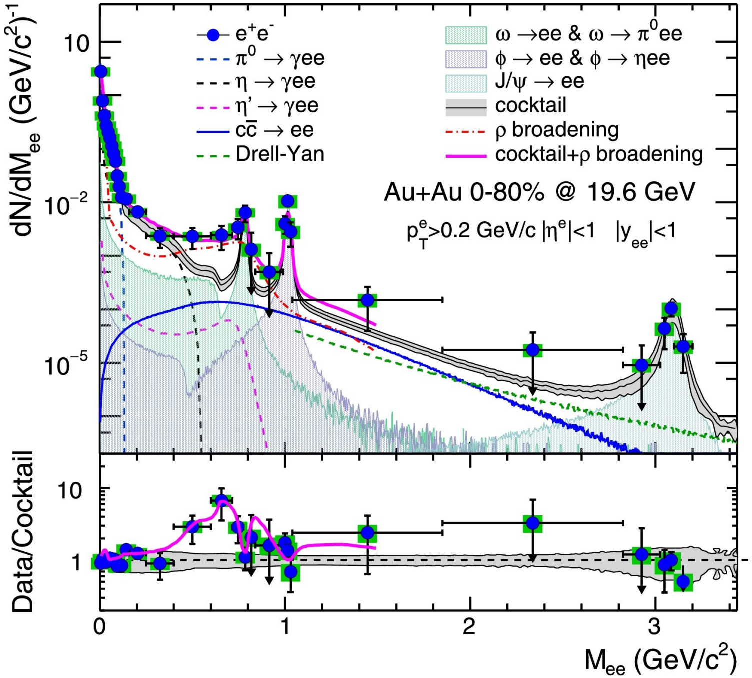




- Fit to m_T spectra of excess yield (acceptance corrected) in different mass regions
- No increase of the exponential inverse slope with mass
  → Insensitive to the expansion of the medium
  → **true measure of the average temperature (T_{eff} = 205 ± 12 MeV)**

Thermal dilepton production - RHIC

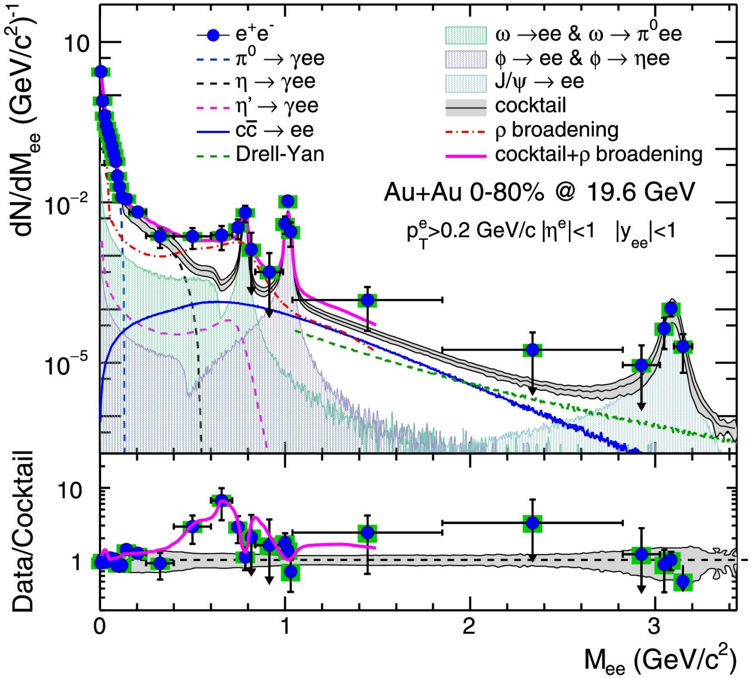
STAR, Phys.Lett.B 750 (2015) 64-71



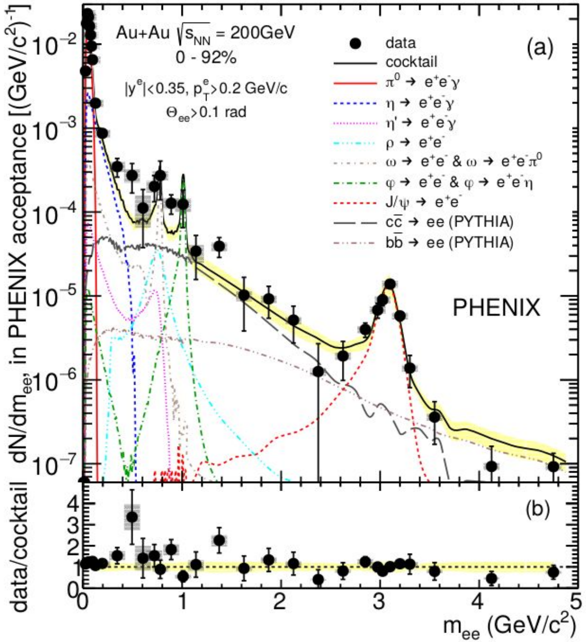
- **Excess in the low mass region**

Thermal dilepton production - RHIC

STAR, Phys.Lett.B 750 (2015) 64-71



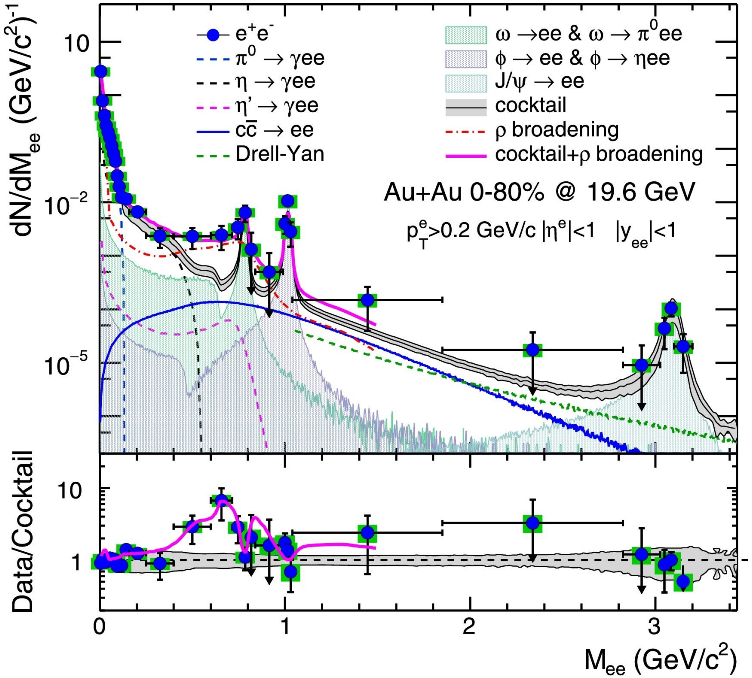
PHENIX, Phys.Rev.C 93 (2016) 1, 014904



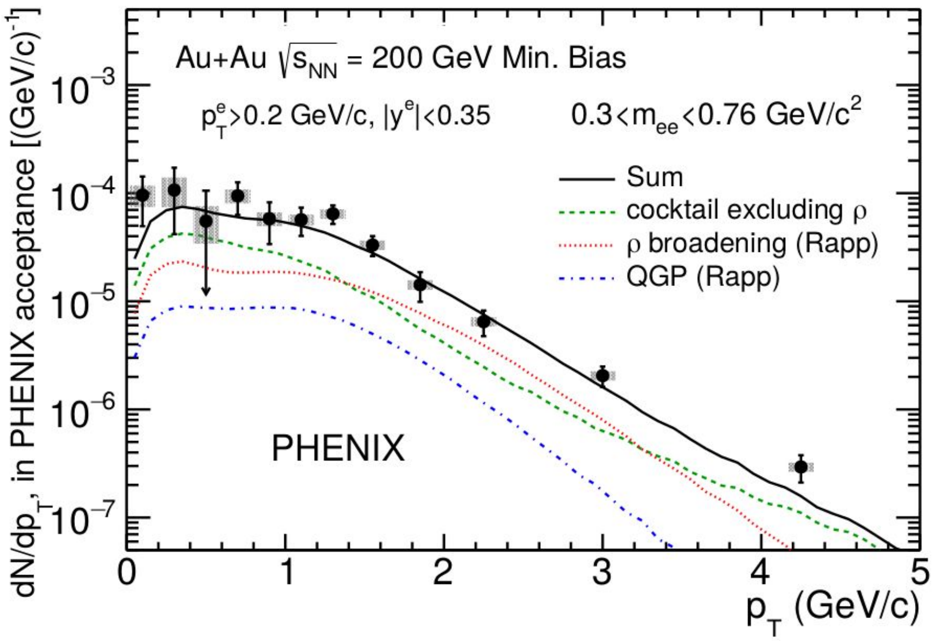
- **Excess in the low mass region** in the full RHIC beam energy range (19.6 - 200 GeV)

Thermal dilepton production - RHIC

STAR, Phys.Lett.B 750 (2015) 64-71



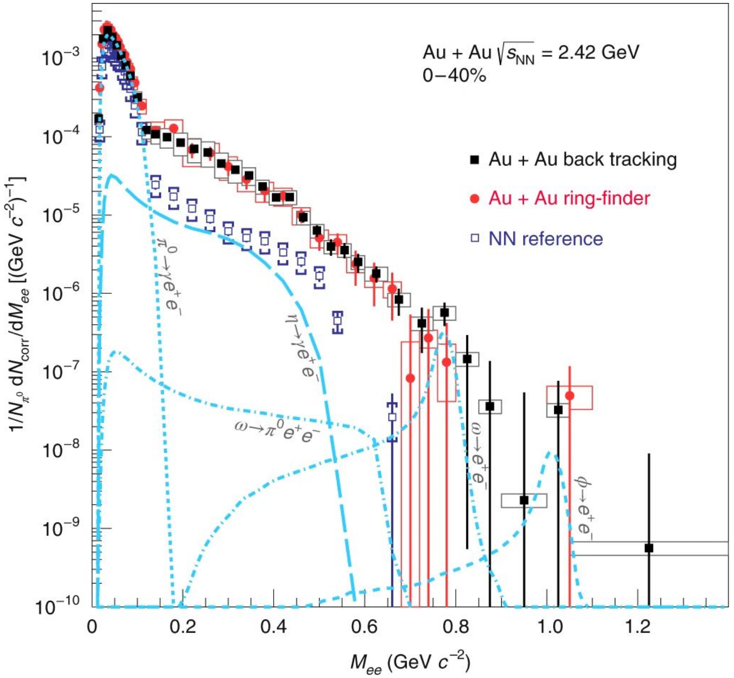
PHENIX, Phys.Rev.C 93 (2016) 1, 014904



- **Excess in the low mass region** in the full RHIC beam energy range (19.6 - 200 GeV)
- Compatible with **ρ broadening + QGP thermal radiation**

Thermal dilepton production - SIS

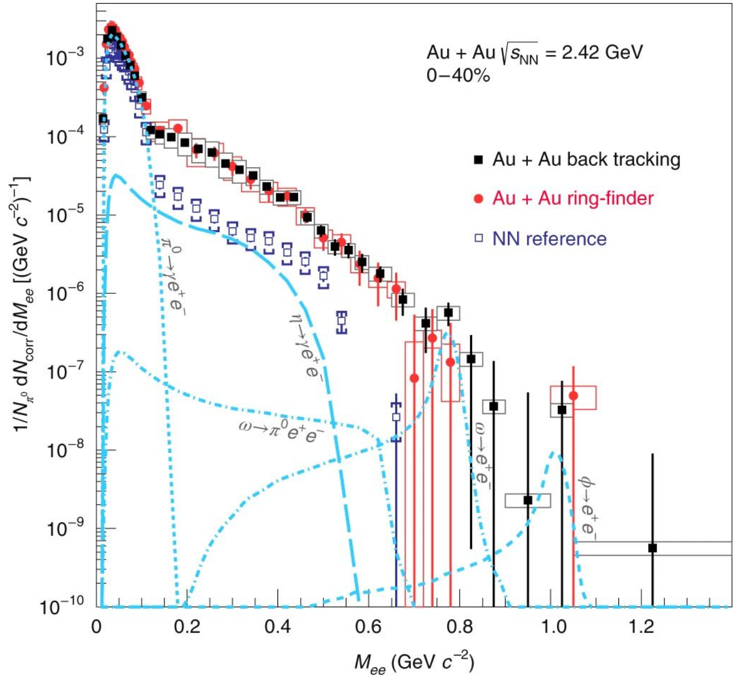
HADES, Nature Phys. 15 (2019), 1040-1045

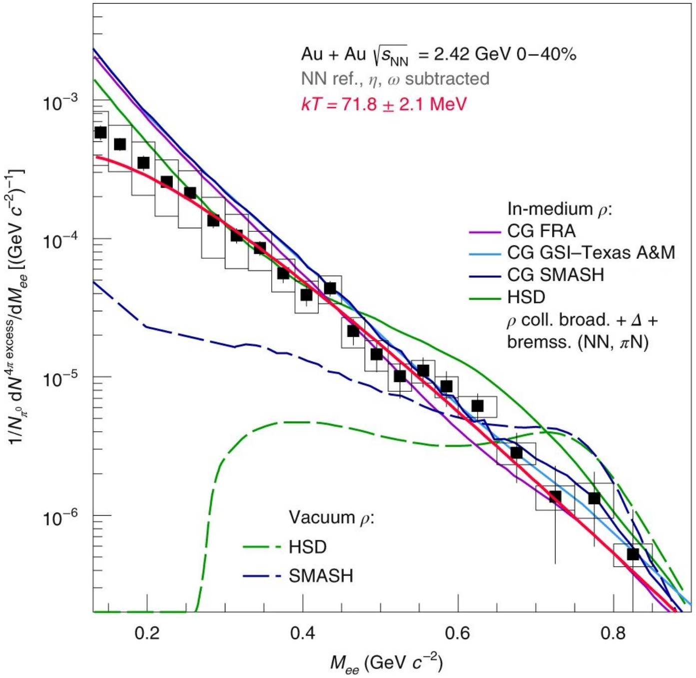


- Excess in the low mass region **also in the AGS/SIS energy range** (~2 GeV)

Thermal dilepton production - SIS

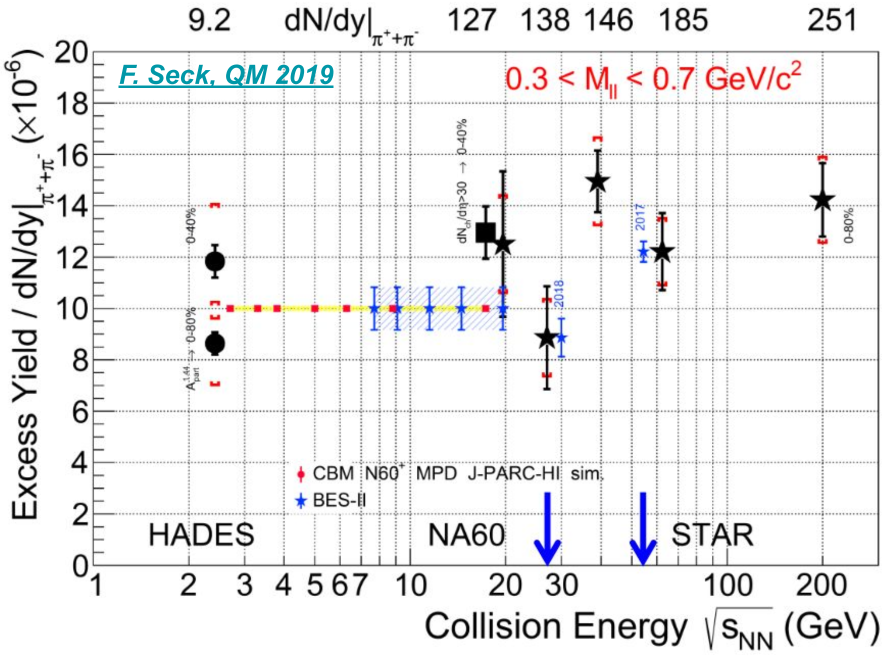
HADES, Nature Phys. 15 (2019), 1040-1045





- Excess in the low mass region **also in the AGS/SIS energy range** (~2 GeV)
- Compatible with **ρ broadening** (+ Bremsstrahlung)
- “evidence for a source of **temperature in excess of 70 MeV**”

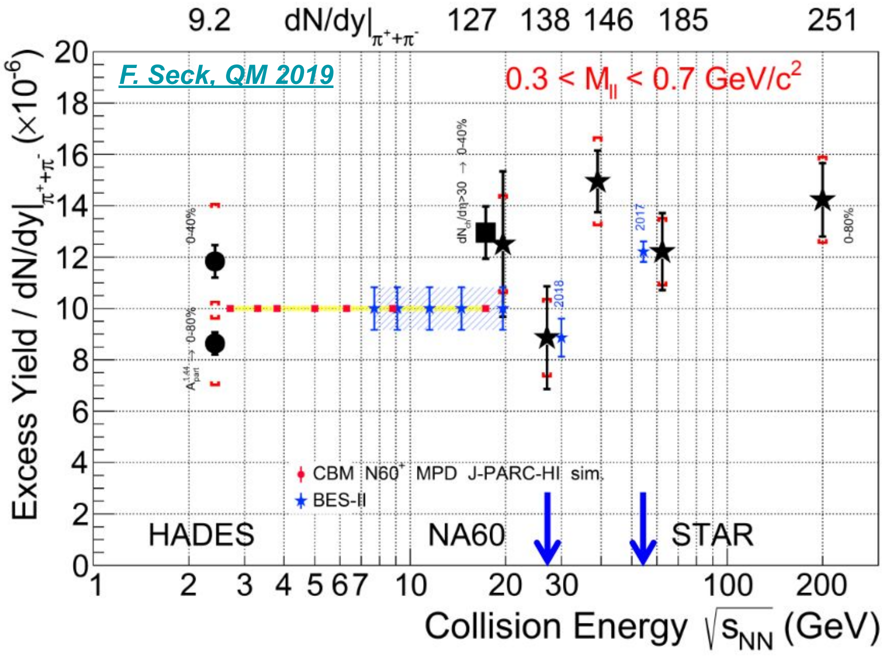
Thermal dilepton production - excitation function

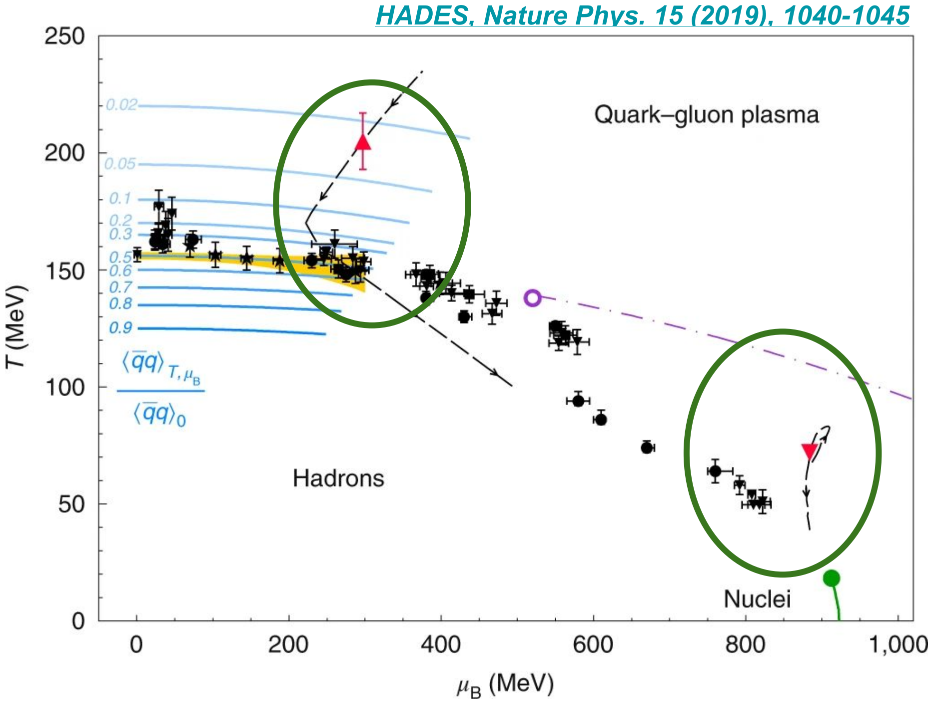


Existing measurements
Projections (RHIC)
Projections (FAIR, SPS, NICA, J-PARC)

- Excess in the low mass region as a function of collision energy (**chronometer**)

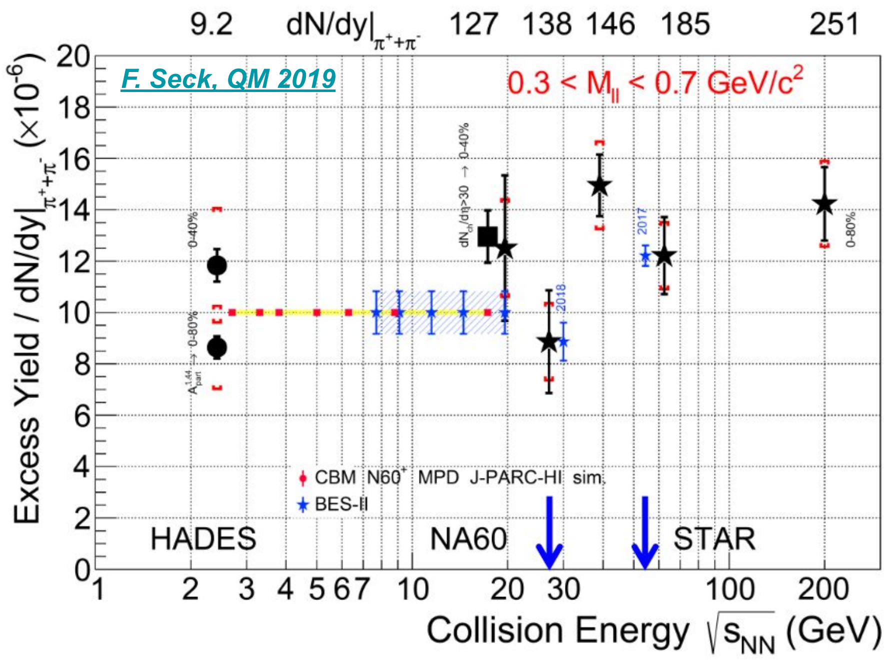
Thermal dilepton production - excitation function

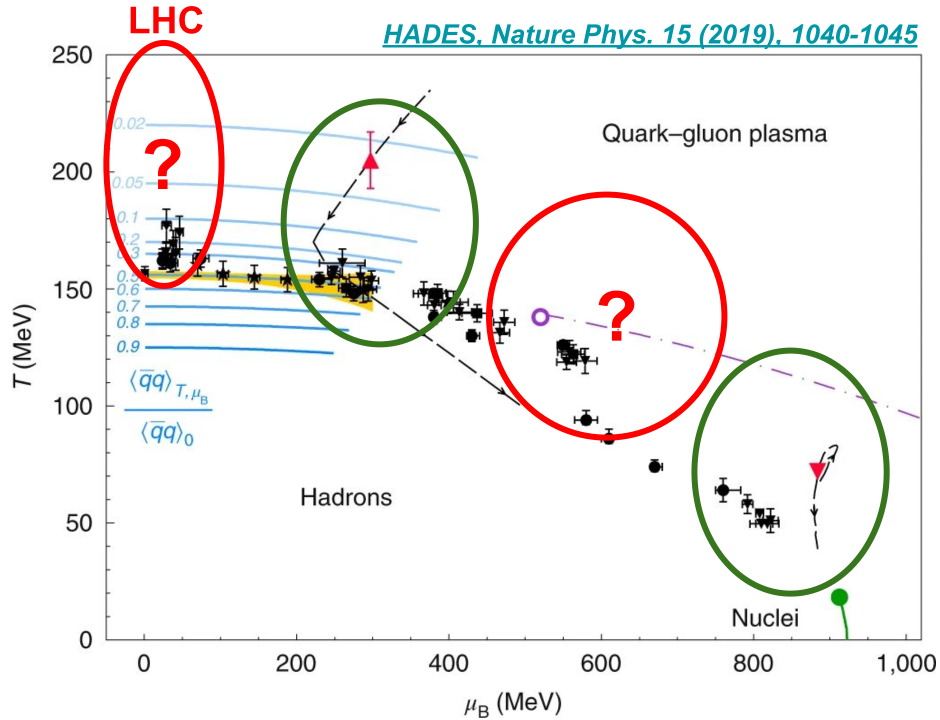




- Excess in the low mass region as a function of collision energy (**chronometer**)
- Extraction of effective temperature (**thermometer**)

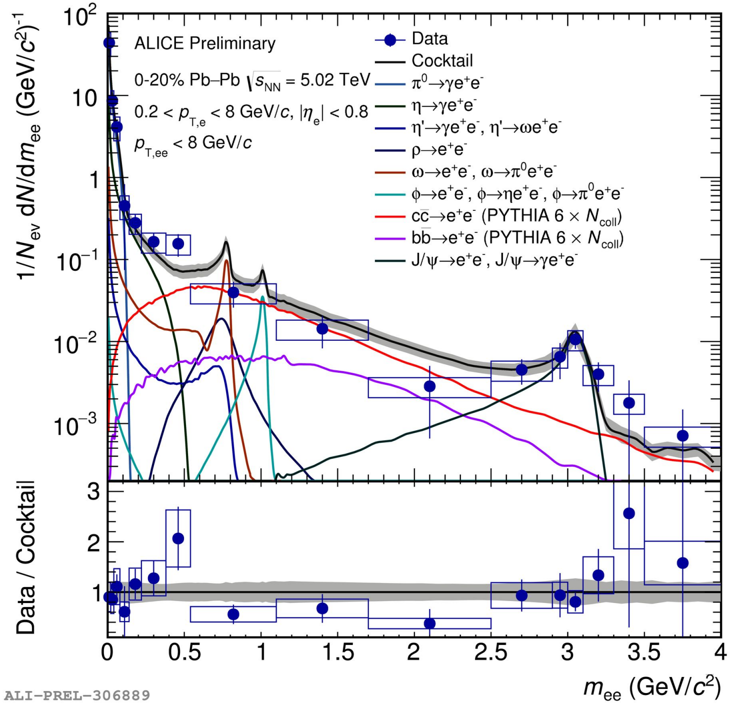
Thermal dilepton production - excitation function





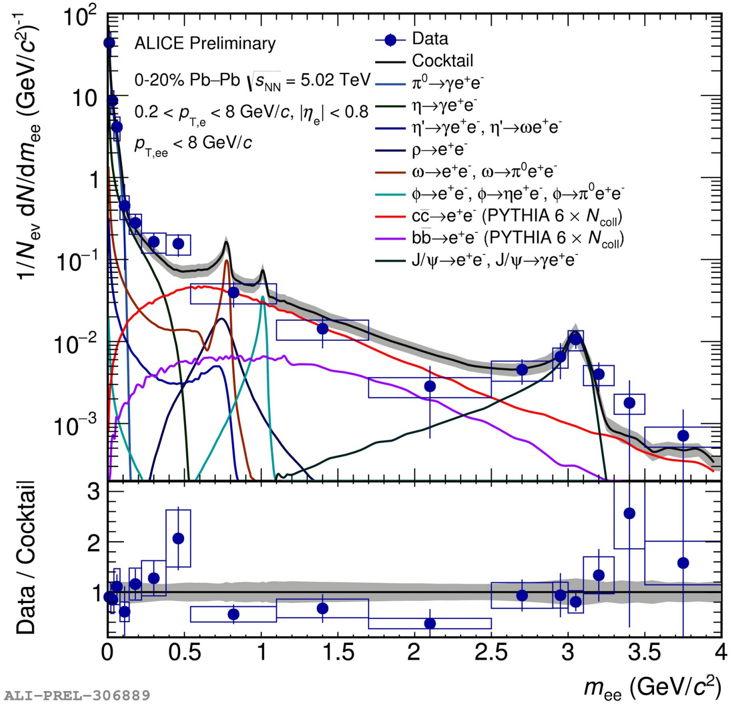
- Excess in the low mass region as a function of collision energy (**chronometer**)
- Extraction of effective temperature (**thermometer**)
- **Large uncharted territory on the QCD phase diagram**

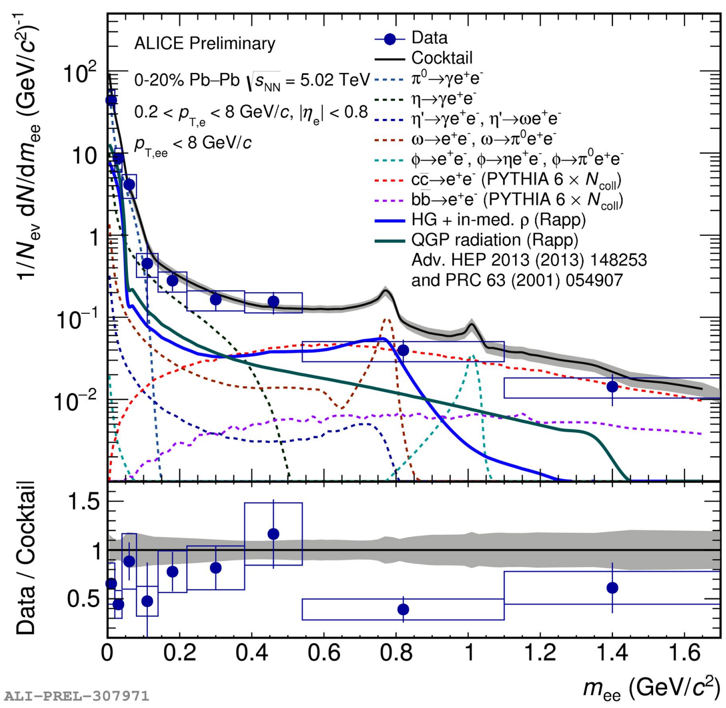
ALICE measurements - Dielectrons LHC Run 2



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

ALICE measurements - Dielectrons LHC Run 2



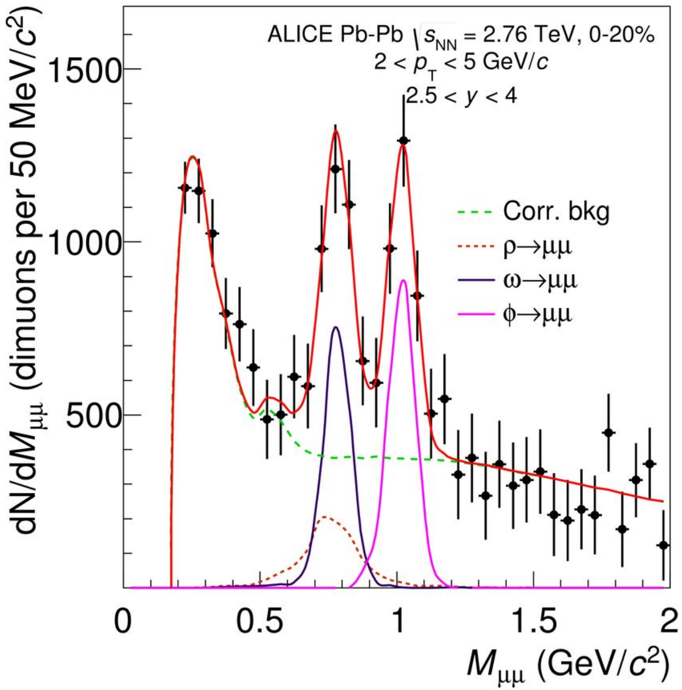


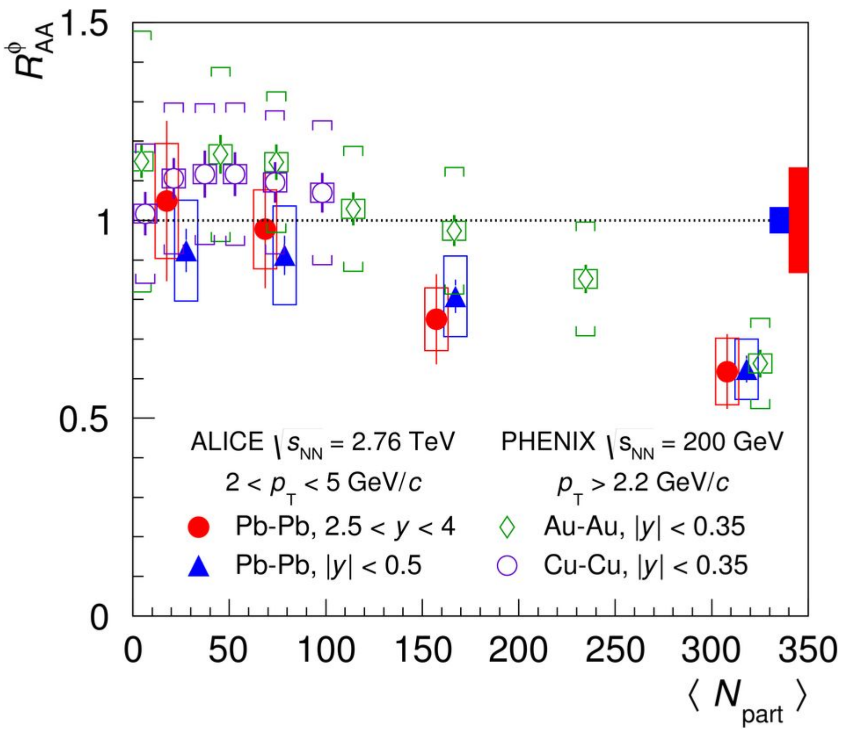
- **Central Pb-Pb collisions** (2015 data only)
- Still large uncertainties (analysis of 2018 data with ~10 times larger sample ongoing)
- Comparisons to **pure hadronic cocktail, nPDFs, and thermal scenarios** inconclusive so far

(similar conclusion from Run 1 data)

ALICE measurements - Dimuons

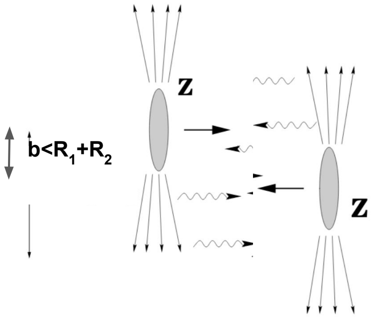
ALICE, Eur. Phys. J. C 78 (2018) 559

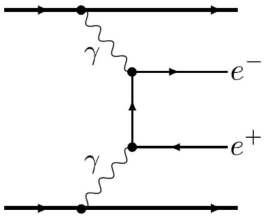




- **Limited background rejection at low p_T in LHC Run 1 and 2**
- Focus on vector meson production in pp and Pb-Pb collisions → **nuclear modification factor**

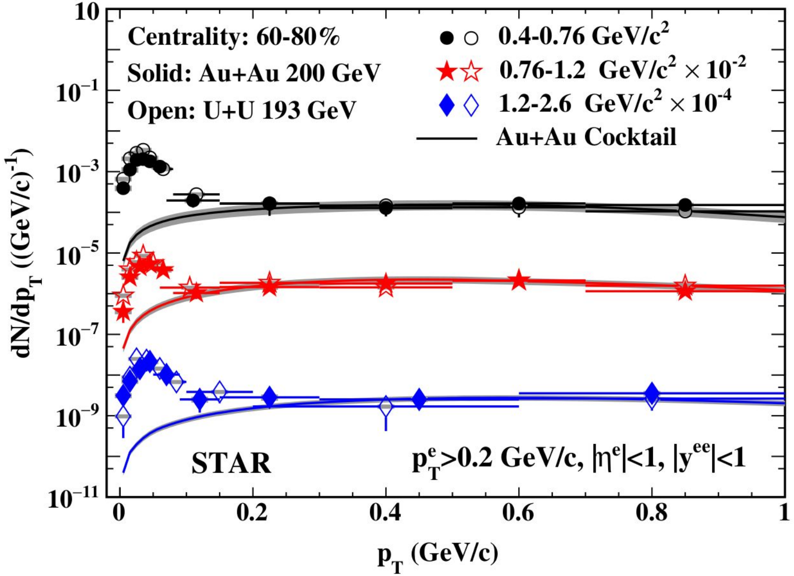
Photoproduction

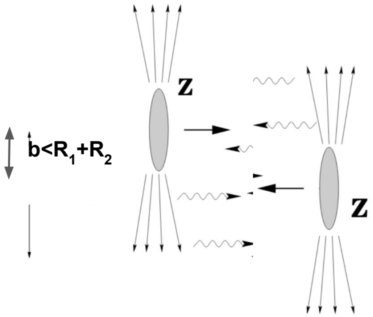


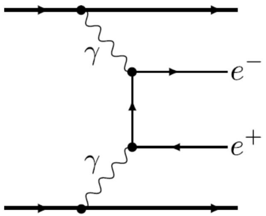


Photoproduction - STAR

STAR, Phys.Rev.Lett. 121 (2018) 13, 132301



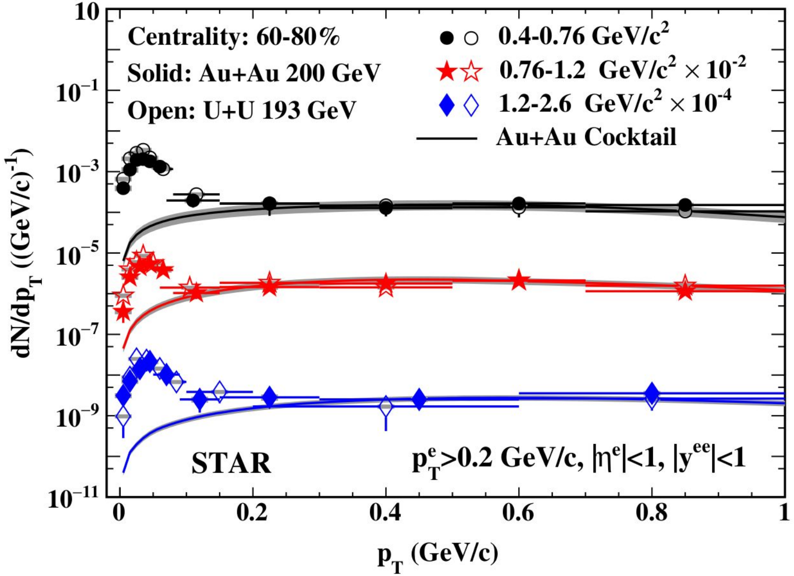


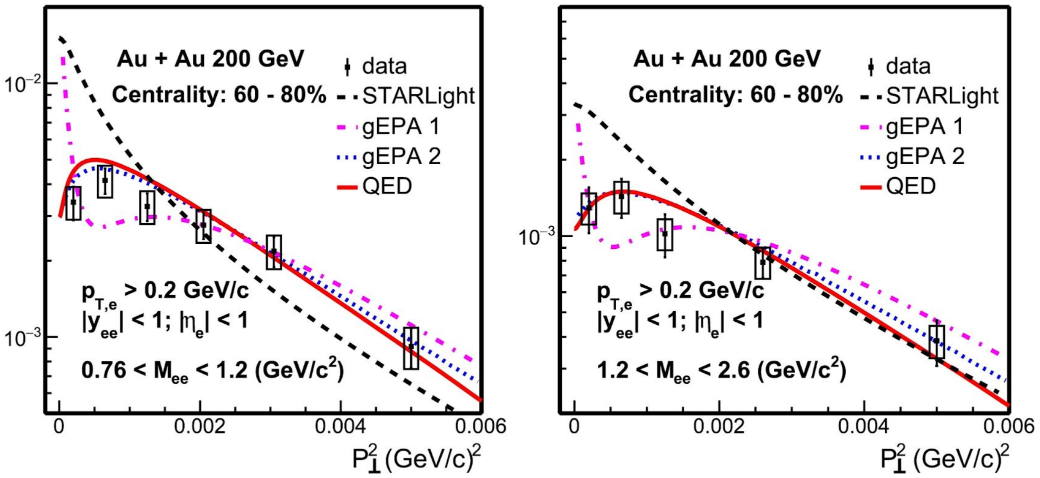


- **Excess e^+e^-** pair p_T distribution concentrates **below p_T~0.15 GeV/*c***
  - Evidence of **photon interactions in hadronic heavy ion collisions**

Photoproduction - STAR

[STAR, Phys.Rev.Lett. 121 (2018) 13, 132301](#)

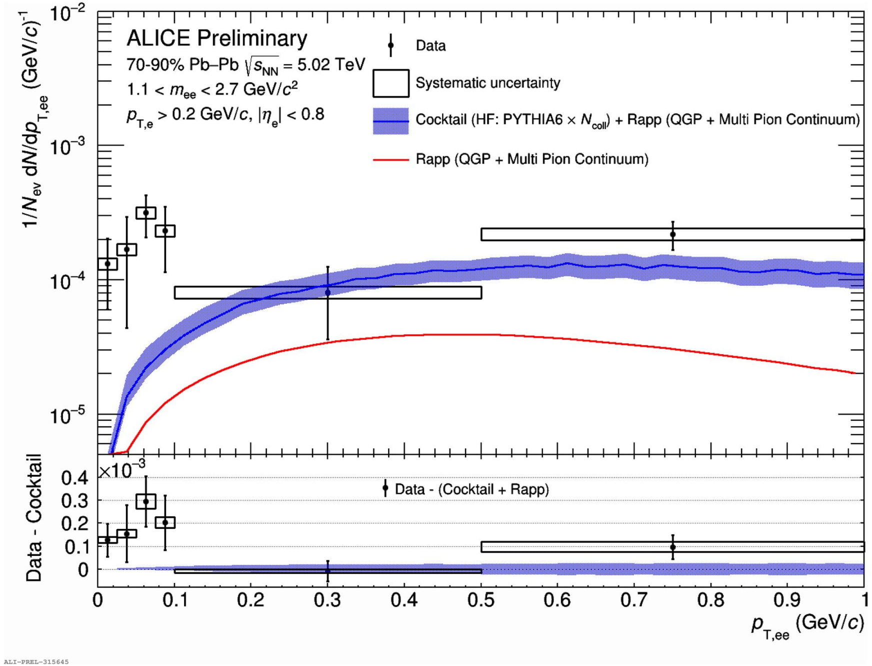




[W. Zha et al., Phys.Lett.B 800 (2020) 135089](#)

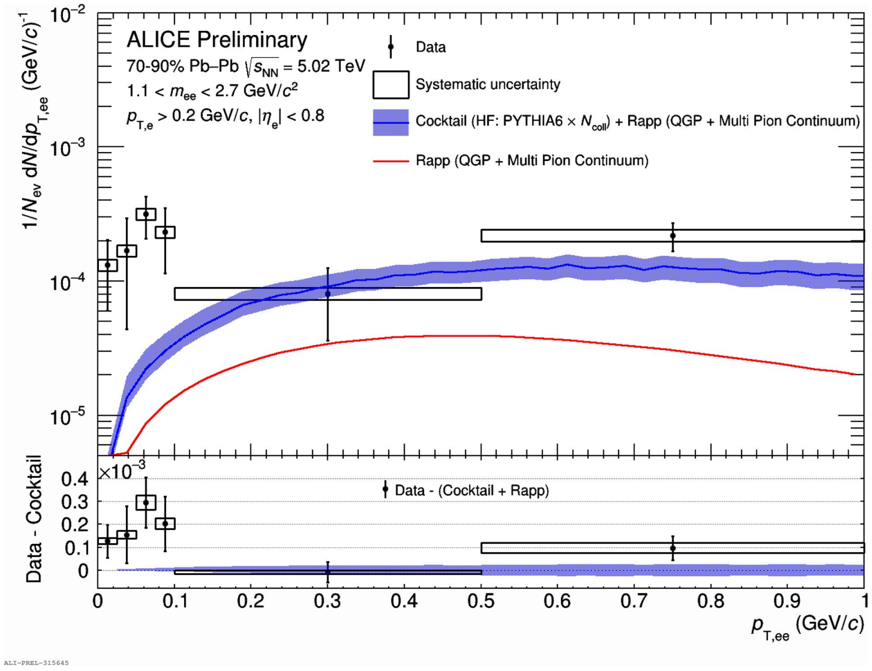
- **Excess e^+e^-** pair p_T distribution concentrates **below p_T~0.15 GeV/c**
  - Evidence of **photon interactions in hadronic heavy ion collisions**
- **p_T broadening w.r.t. UPC** (StarLight):
  - Importance of **impact parameter dependence** of initial electromagnetic field
  - **Additional effects?** See [S. Klein et al., arXiv:2003.02947 [hep-ph]](#) for a recent summary

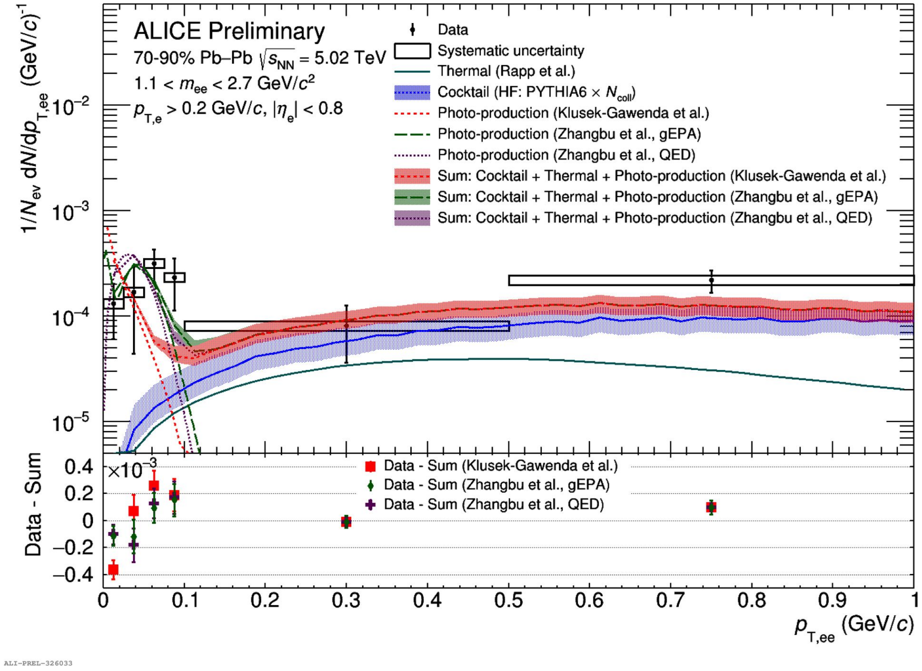
Photoproduction - ALICE



- Excess w.r.t. cocktail and thermal sources **at $p_{T,ee}$ < 0.1 GeV/c**

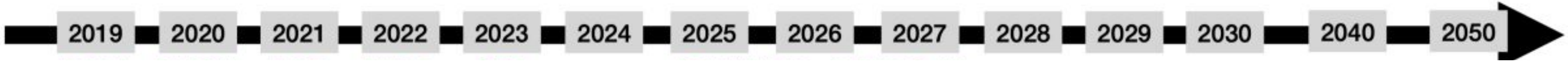
Photoproduction - ALICE





- Excess w.r.t. cocktail and thermal sources **at $p_{T,ee}$ < 0.1 GeV/c**
- **Compatible with photo-production models** (caveat: no resolution effects taken into account here)
- **Next steps:** increase statistics by factor of two by including 2018 data, event-plane dependence,...

The next decade



The next decade

ALICE

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

At the LHC (changes due to Covid not included here):

[***HL-LHC WG5 yellow report***]

Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

ALICE:

13 nb^{-1} Pb-Pb

0.6 pb^{-1} p-Pb

\+ pp

(***ALICE-PUBLIC-2020-005***)

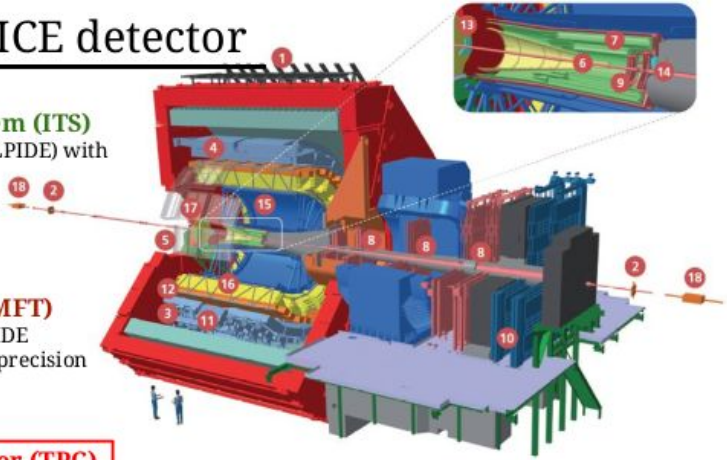
The next decade

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

Upgraded ALICE detector

New Inner Tracking System (ITS)
- monolithic CMOS sensors (ALPIDE) with very small material budget
- improved pointing precision

Muon Forward Tracker (MFT)
- new tracker based on ALPIDE
- improved MUON pointing precision



1 ACORDE | ALICE Cosmic Rays Detector
2 AD | ALICE Diffractive Detector
3 DCal | Di-jet Calorimeter
4 EMCal | Electromagnetic Calorimeter
5 HMPID | High Momentum Particle Identification Detector
6 ITS-IB | Inner Tracking System - Inner Barrel
7 ITS-OB | Inner Tracking System - Outer Barrel
8 MCH | Muon Tracking Chambers
9 MFT | Muon Forward Tracker
10 MID | Muon Identifier
11 PHOS / CPV | Photon Spectrometer
12 TOF | Time Of Flight
13 T0+A | Tzero + A
14 T0+C | Tzero + C
15 TPC | Time Projection Chamber
16 TRD | Transition Radiation Detector
17 V0+ | Vzero + Detector
18 ZDC | Zero Degree Calorimeter

Time Projection Chamber (TPC)
- New readout chambers using GEM technology
- New electronics for continuous readout (SAMPA)

Online Offline (O2) system
- new computing facility
- online tracking & data compression
- 50kHz PbPb event rate

New Trigger Detectors (FIT)
New Central Trigger Processor (CTP)
TOF, TRD: new readout electronics
PHOS, EMCAL, CPV, HMPID: improvement of readout rate

MUON ARM
- New electronics for Muon Chambers (SAMPA)
- New electronics for Muon Trigger

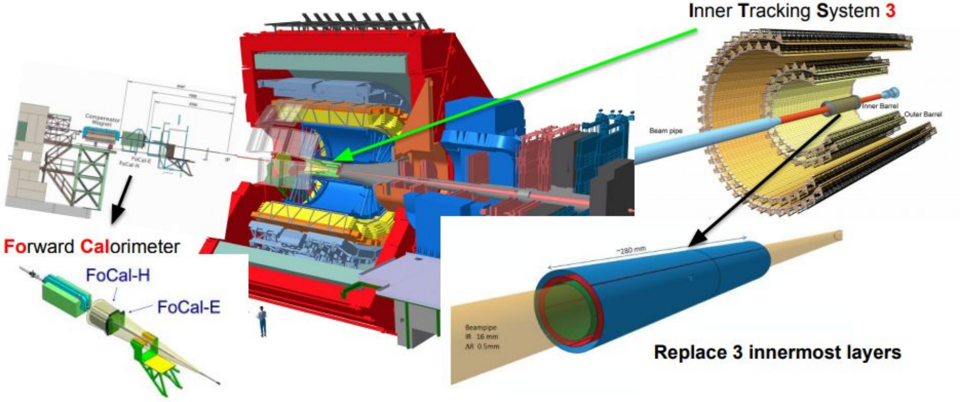
Common Projects:
- Common Readout Unit (CRU) for all detectors
- SAMPA common FE chip for TPC and Muon arm

5

O Vazquez Doce, LHCC open session Sep 2020

The next decade

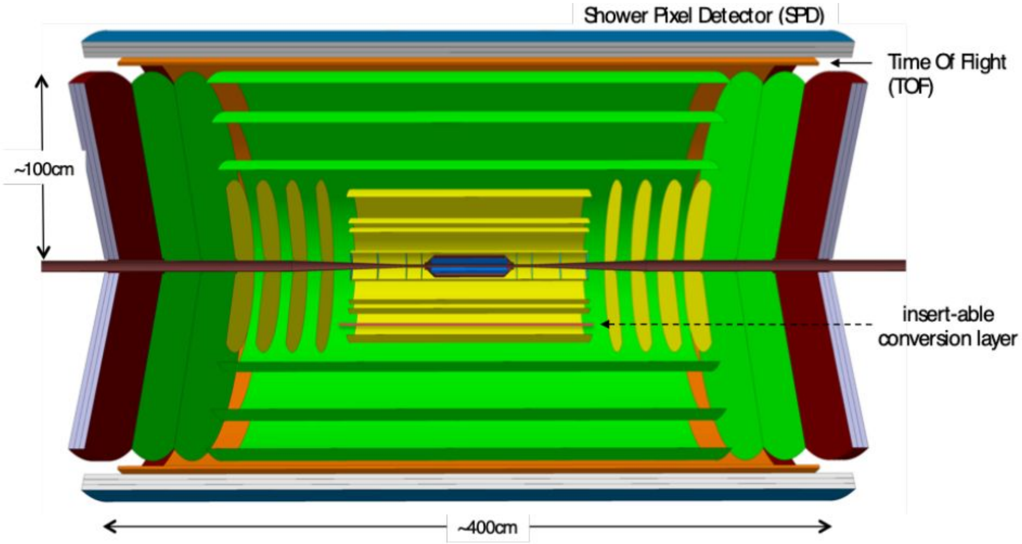
FoCal and ITS3:



[*A. Rossi, ICHEP 2020*]

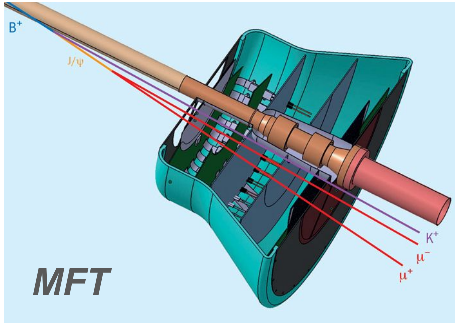
The next decade

A next generation heavy-ion experiment:



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

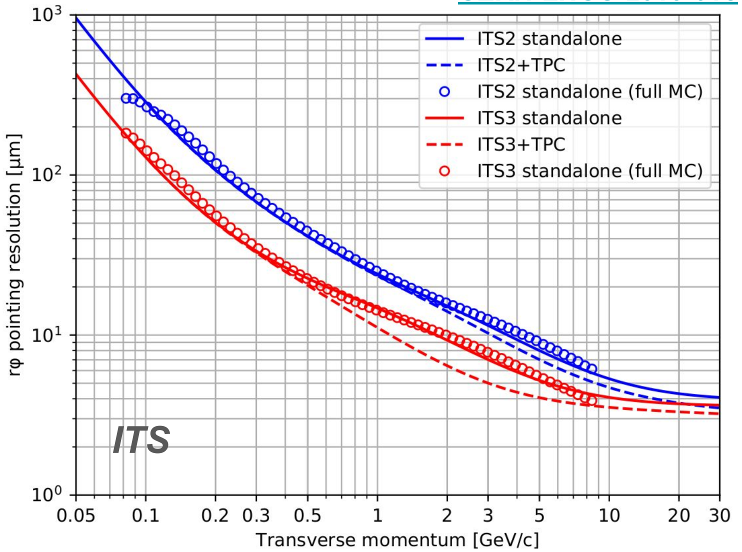
ALICE upgrades (Run 3 and 4) and dileptons



- **Dimuons:**
  - Vertexing by Muon Forward Tracker
  - Better mass resolution and reduced background

- **Dielectrons:**
  - Improved vertex resolution (ITS2, ITS3)
  - Reduced material budget (conversions)
  - Higher data acquisition rate (50 kHz)
  - Dedicated low B field run(s): improved efficiency at low p_T, better conversion rejection

CERN-LHCC-2019-018

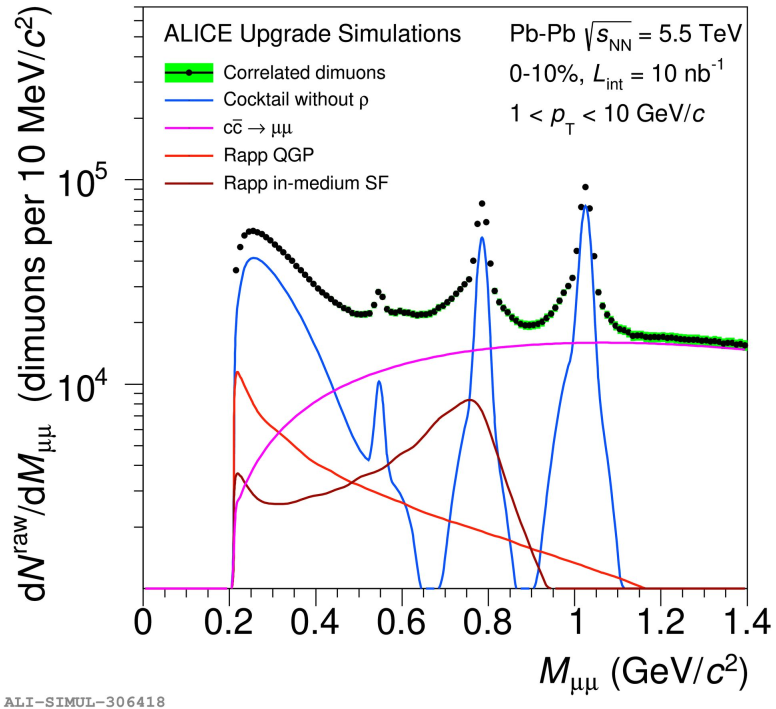


Inner layers	ITS1 (Run 1-2)	ITS2 (Run 3)	ITS3 (Run 4)
X/X_0	1.14%	0.38%	0.05%
innermost radius	39 mm	22 mm	18 mm
pixel size	50x425 μm^2	~27x29 μm^2	O(15x15 μm^2)

A. Rossi, ICHEP 2020

ALICE - Dimuons (Run 3)

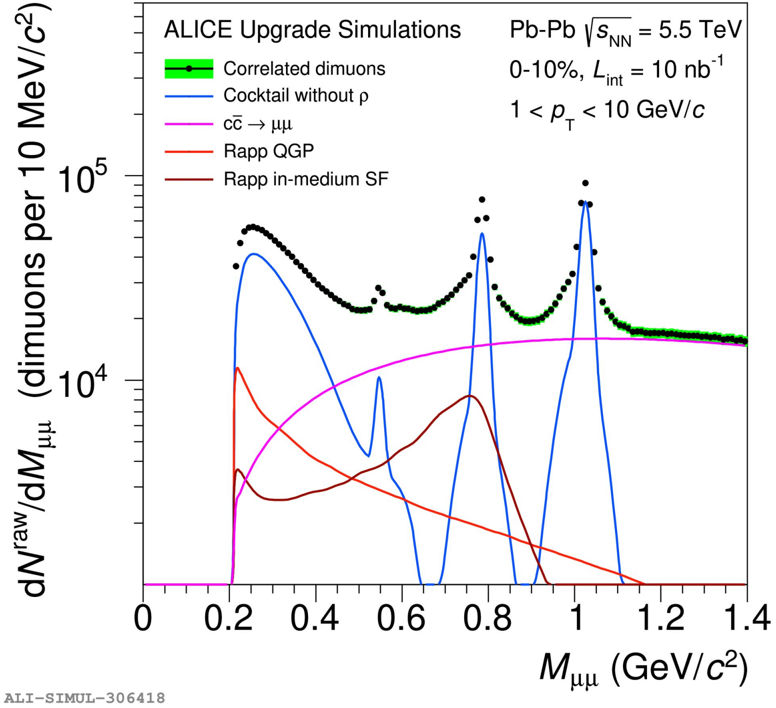
HL-LHC WG5 yellow report



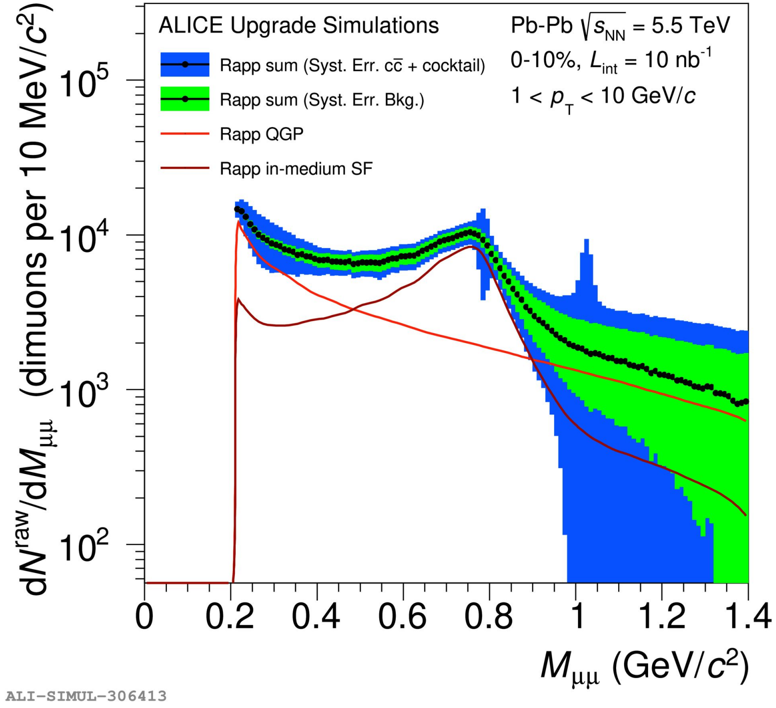
Not optimized to reduce contribution of heavy-flavour sources

ALICE - Dimuons (Run 3)

HL-LHC WG5 yellow report



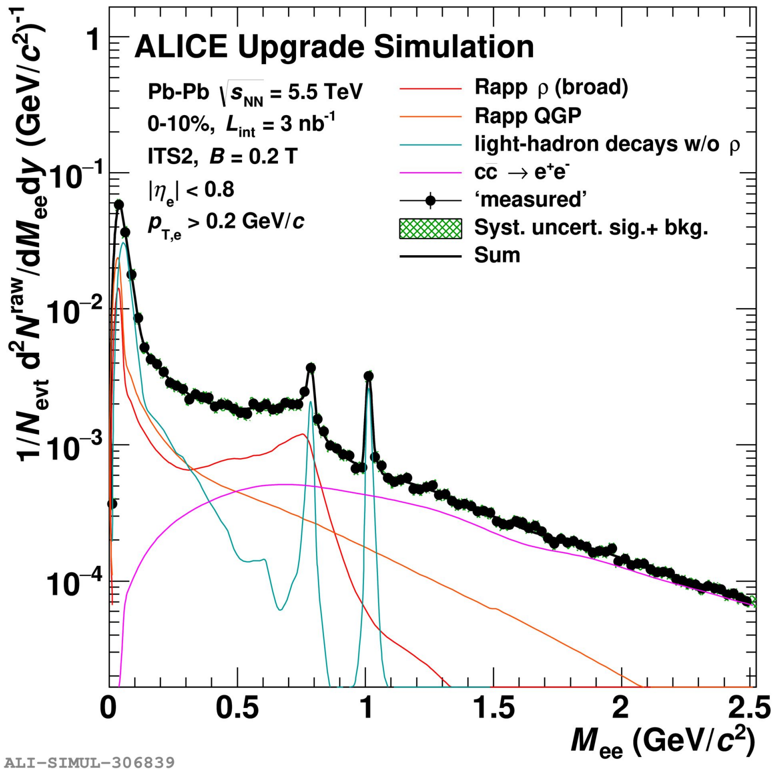
Not optimized to reduce contribution of heavy-flavour sources



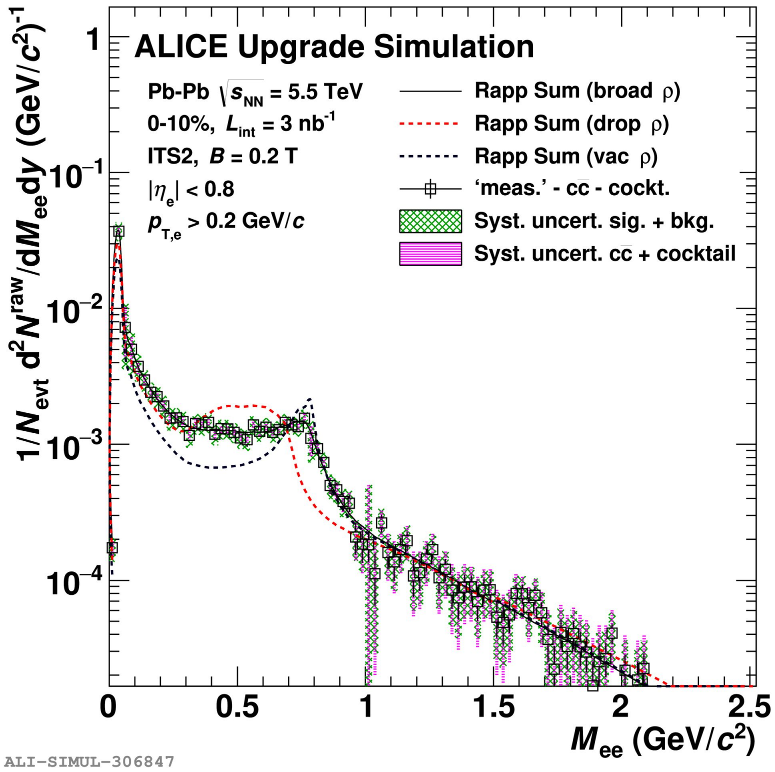
After subtraction of long-lived light- and (keep ρ) heavy-flavour sources
→ **measurement of ρ spectral shape**

ALICE - Dielectrons (Run 3)

HL-LHC WG5 yellow report



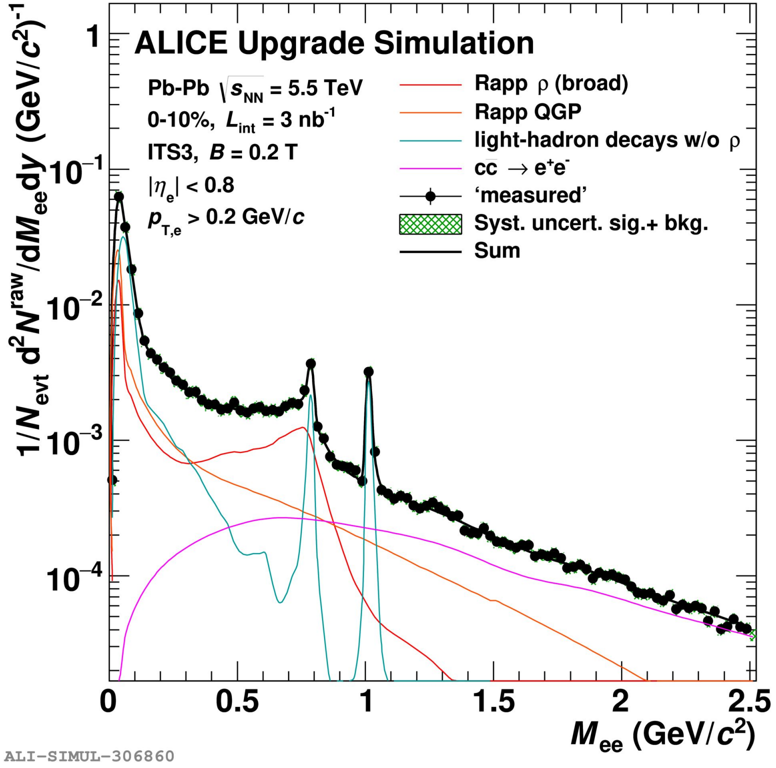
Applying cuts on the pair DCA to reduce contribution of heavy-flavour sources



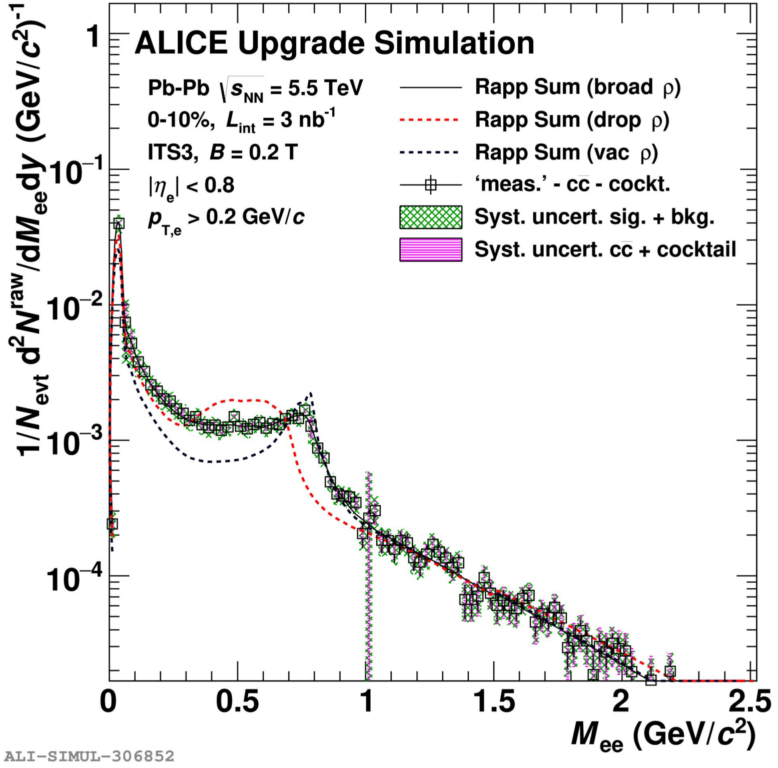
After subtraction of long-lived light- and (keep ρ) heavy-flavour sources
→ **measurement of ρ spectral shape**

ALICE - Dielectrons (Run 4)

CERN-LHCC-2019-018



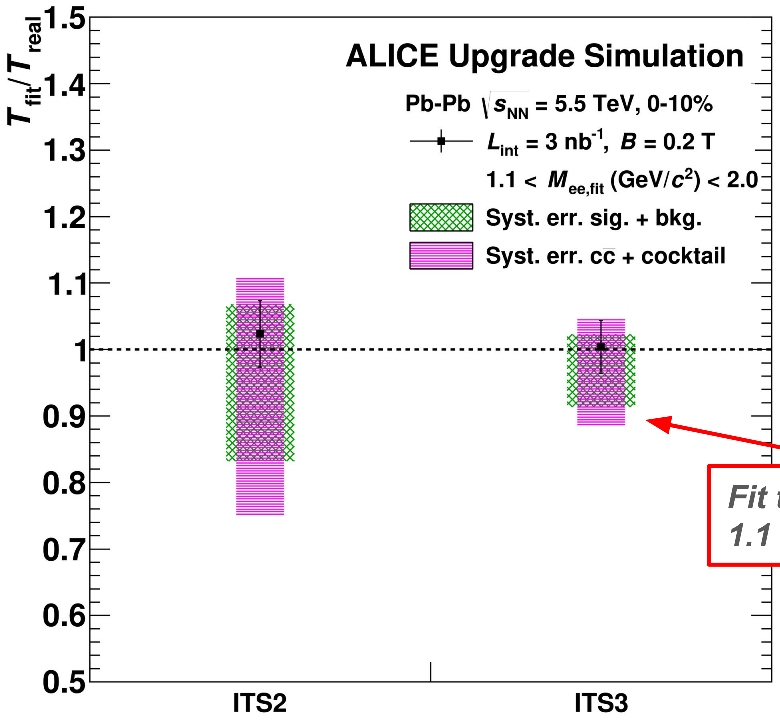
Applying cuts on the pair DCA to reduce contribution of heavy-flavour sources



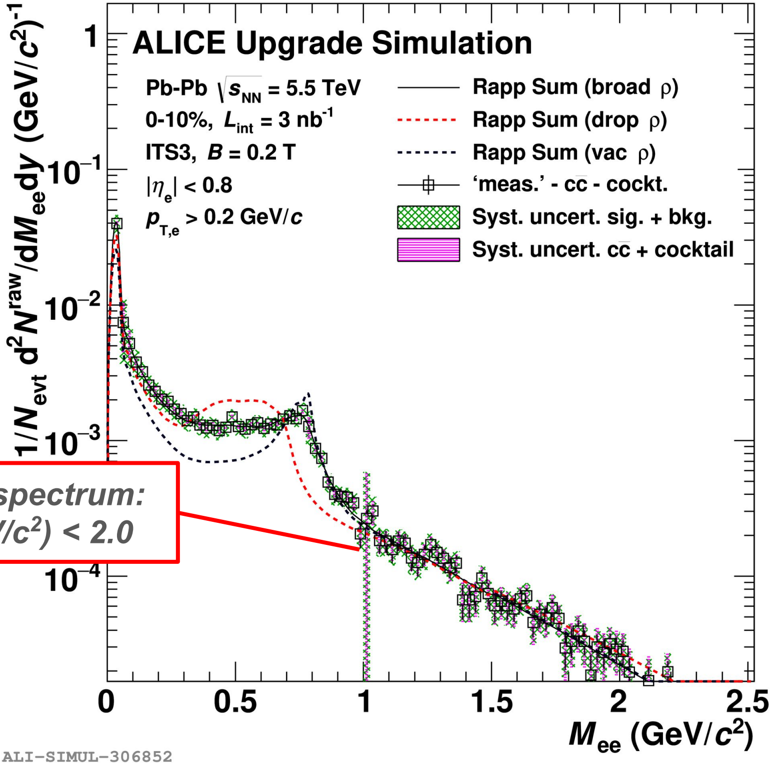
After subtraction of long-lived light- and (keep ρ) heavy-flavour sources
→ **reduction of stat./syst. uncertainties**

ALICE - Temperature extraction

CERN-LHCC-2019-018



ALI-SIMUL-306864



ALI-SIMUL-306852

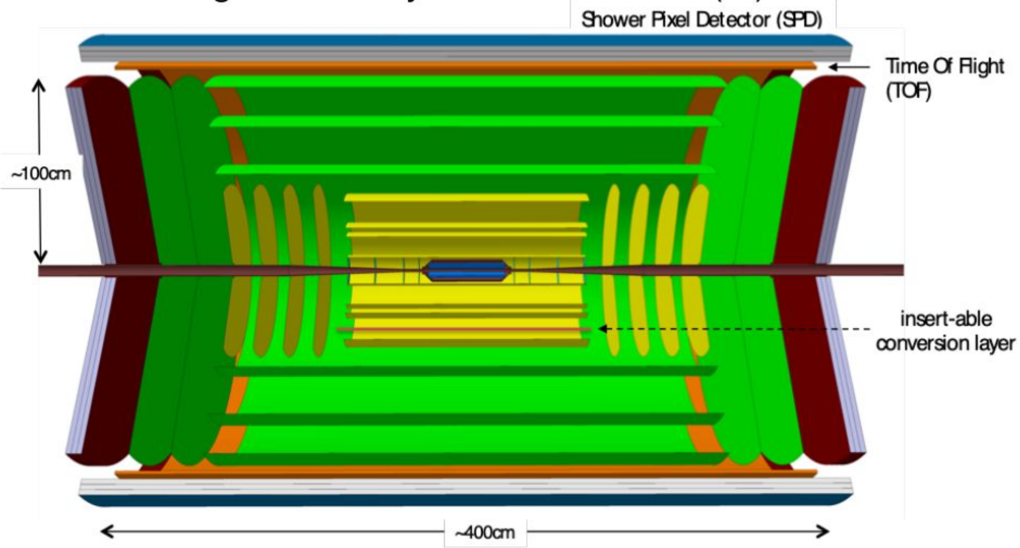
- **Temperature measurement at the LHC**
  - Heavy flavour uncertainties can be improved
- Large statistics will allow for **more differential measurements (p_T dependence, flow, polarization)**

Beyond 2030: ALICE 3

A next-generation LHC heavy-ion experiment

a thin, light, fast all-silicon tracking & PID detector

high luminosity with smaller ions (Ar)



Beyond 2030: ALICE 3

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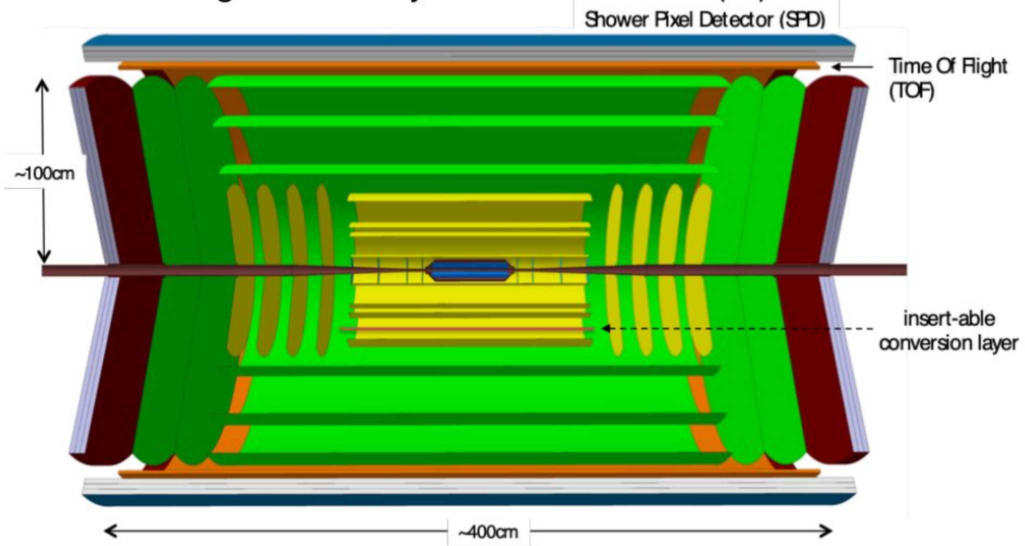
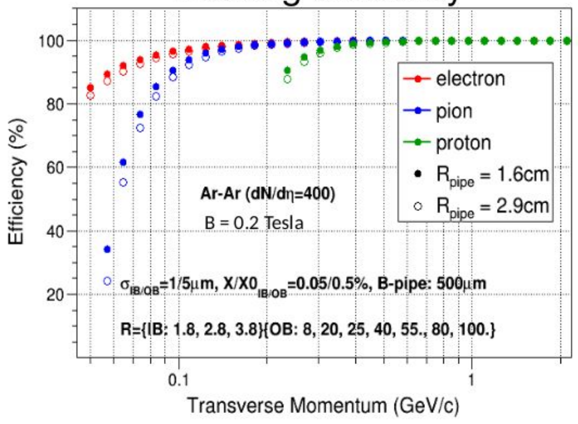


Tracking efficiency



Heavy-flavour and quarkonia

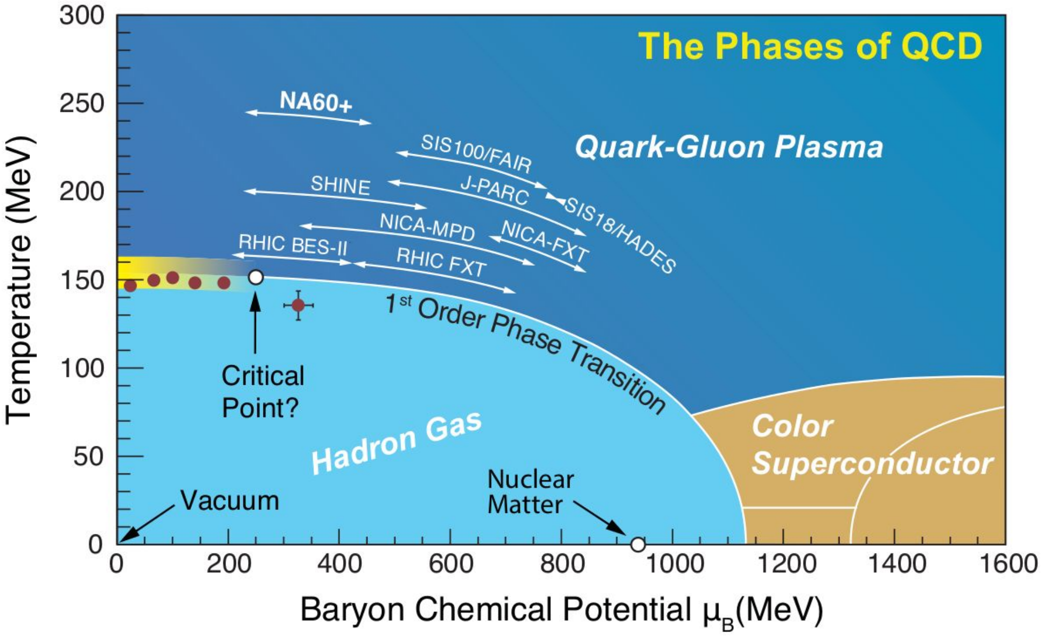
- Multiply Heavy Flavoured hadrons: Ξ_{cc}, Ω_{cc}, Ω_{ccc}
- Ultimate precision on B mesons at low p_T
- $\chi_{c1,2}$ states
- X, Y, Z charmonium-like states (e.g. X(3872))

Unique low material budget and low-p_T coverage

- Thermal radiation and electric conductivity
- Chiral symmetry restoration: modification of ρ, a_1
- Quantum statistics effects
- Condensate physics
- Soft Theorems

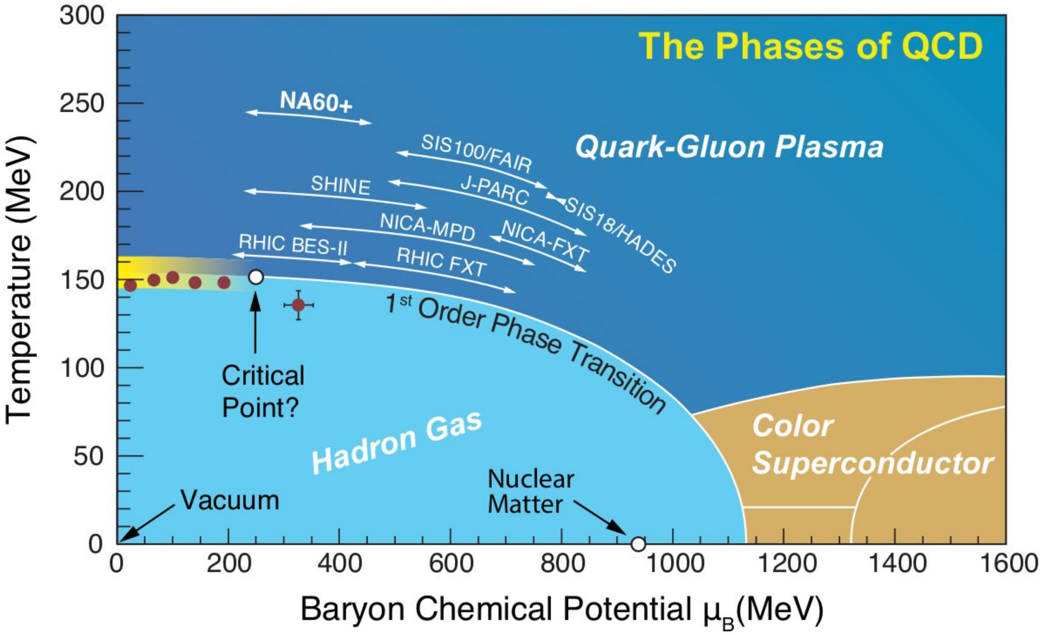
ALICE 3 workshop: 13.-15. Oct 2020

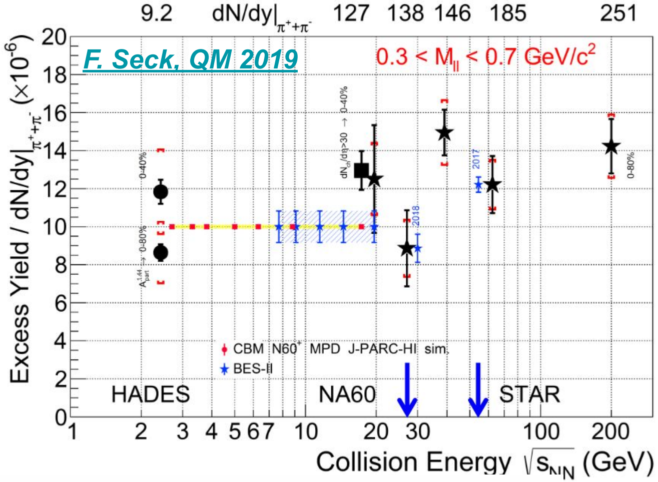
Other future opportunities: beam energy scan

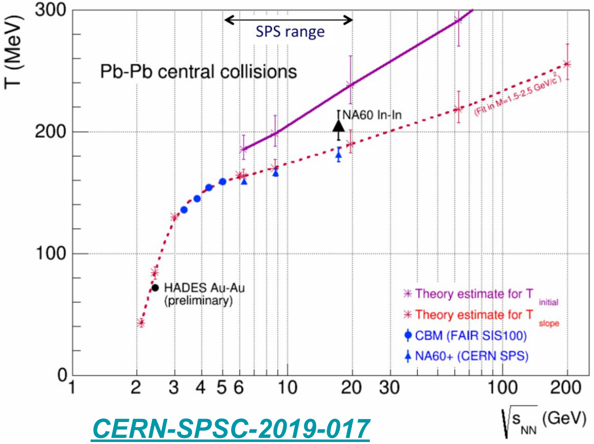


- Many new experiments covering a very wide μ_B region
  - NA60+, HADES/CBM, J-PARC, NICA, ...
- Reaching very high interaction rates → precision physics

Other future opportunities: beam energy scan







CERN-SPSC-2019-017

- Many new experiments covering a very wide μ_B region
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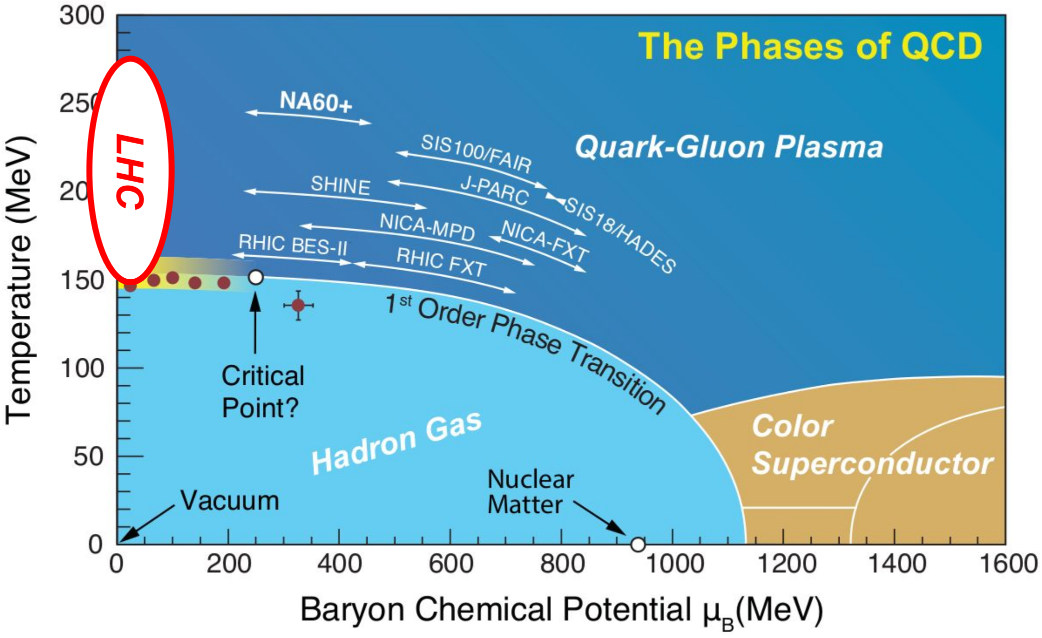
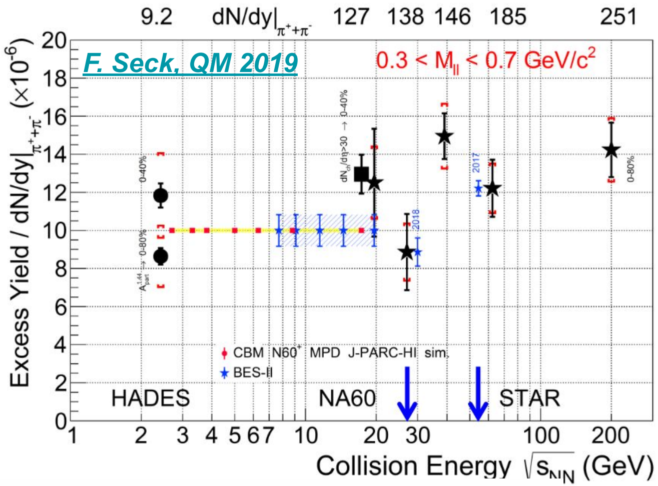
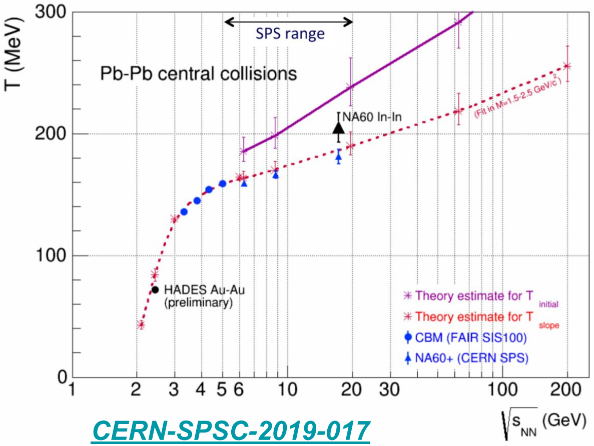
- **Goal: Caloric curve from thermal dileptons**

Other future opportunities: beam energy scan



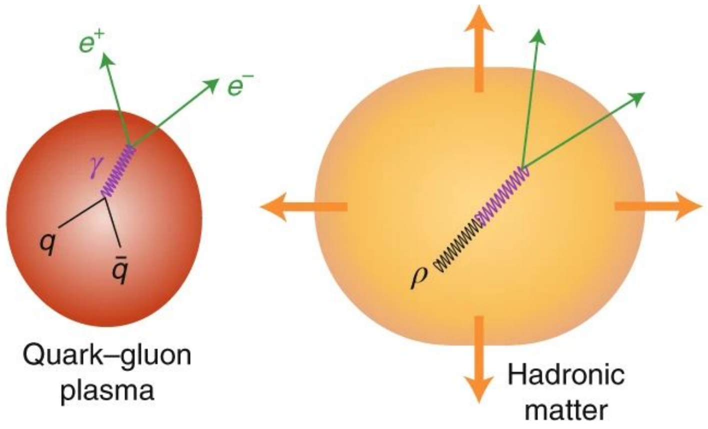




[CERN-SPSC-2019-017]

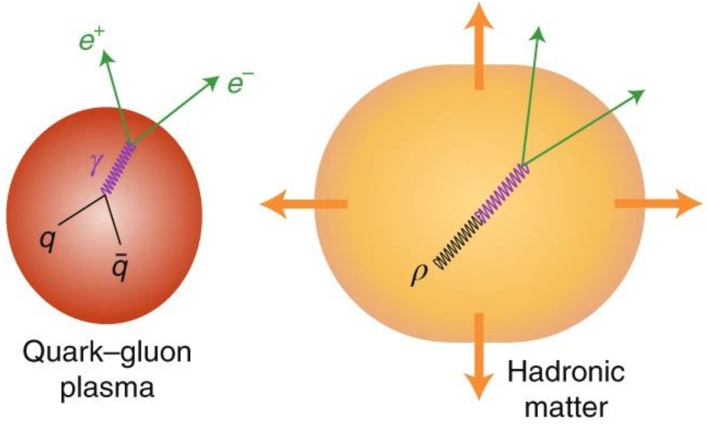
- Many new experiments covering a very wide μ_B region
  - NA60+, HADES/CBM, J-PARC, NICA, ...
- Reaching very high interaction rates → precision physics
- **Goal: Caloric curve from thermal dileptons**
- **At LHC: opportunities with LHCb after upgrades**

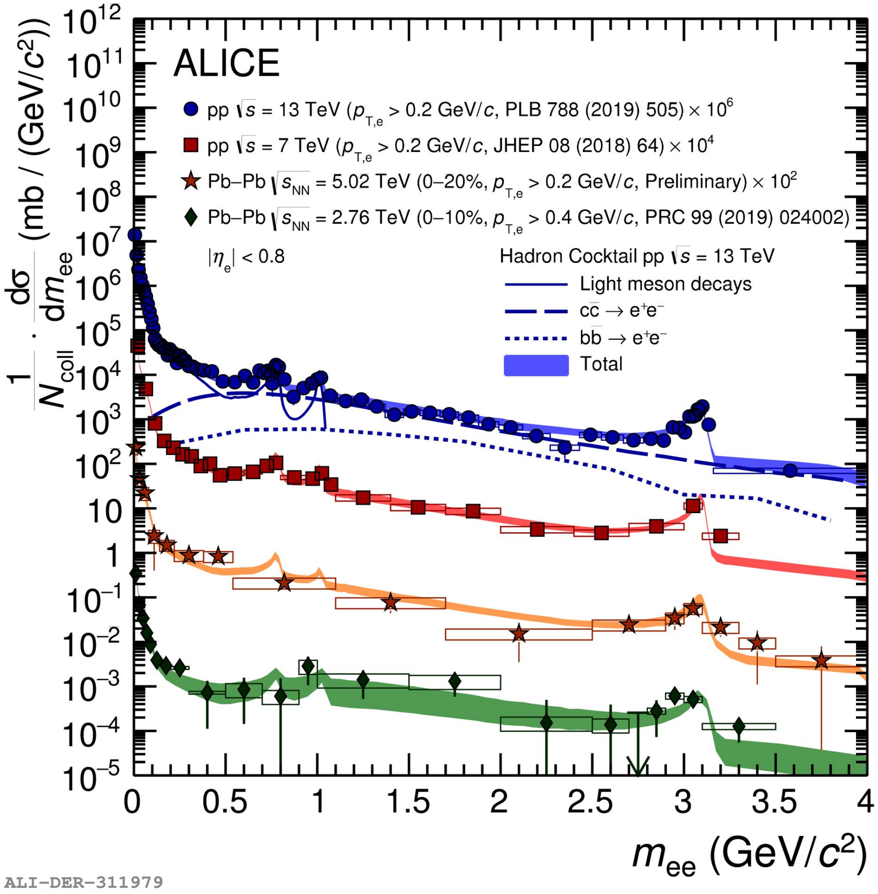
Summary



- **Study QCD phase diagram with dileptons:**
  - Temperature, space-time evolution, chiral symmetry

Summary



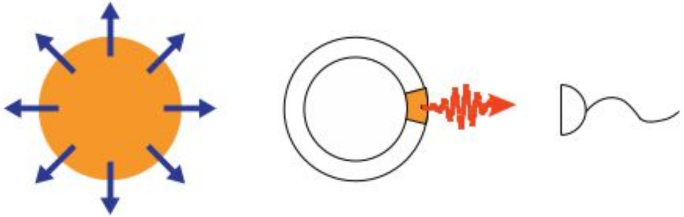


- **Study QCD phase diagram with dileptons:**
  - Temperature, space-time evolution, chiral symmetry
- **ALICE:** first results available, no conclusion yet on thermal dilepton production at the LHC
- **Great future ahead of us:**
  - LHC Run 3+
  - and more dilepton experiments/possibilities

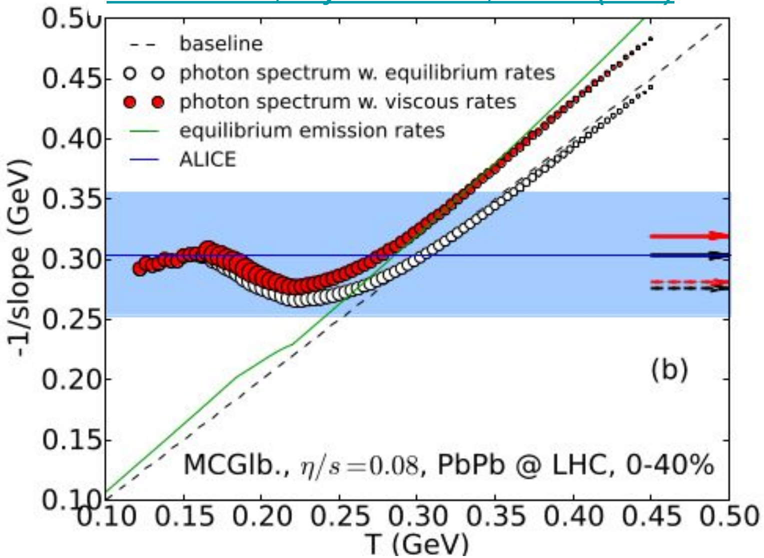
Thank you!

Backup

Real photons?



[C. Shen et al., Phys. Rev. C 89, 044910 (2014)]

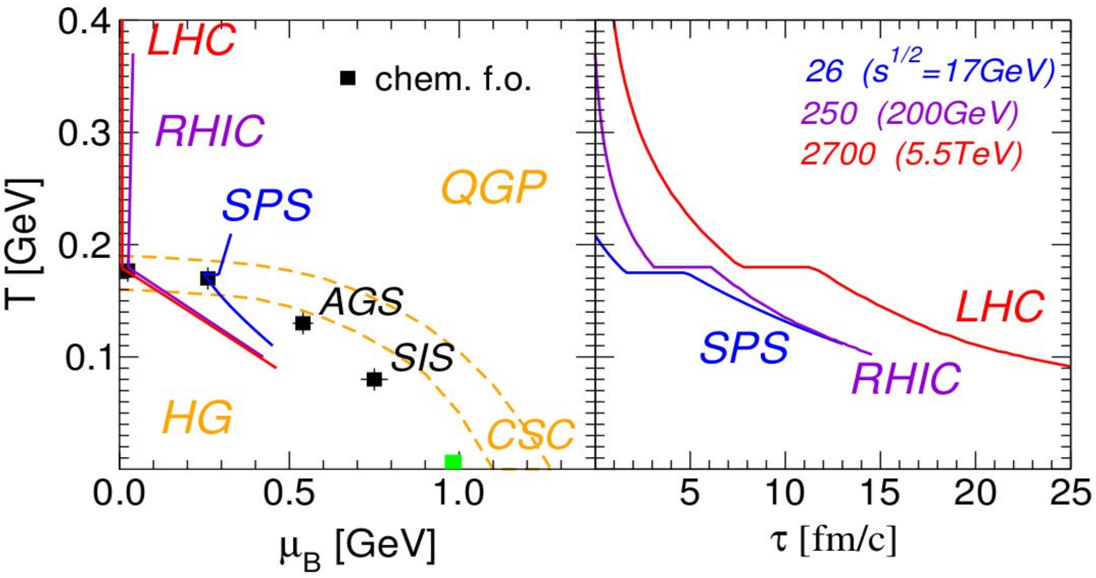


$$E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}}$$

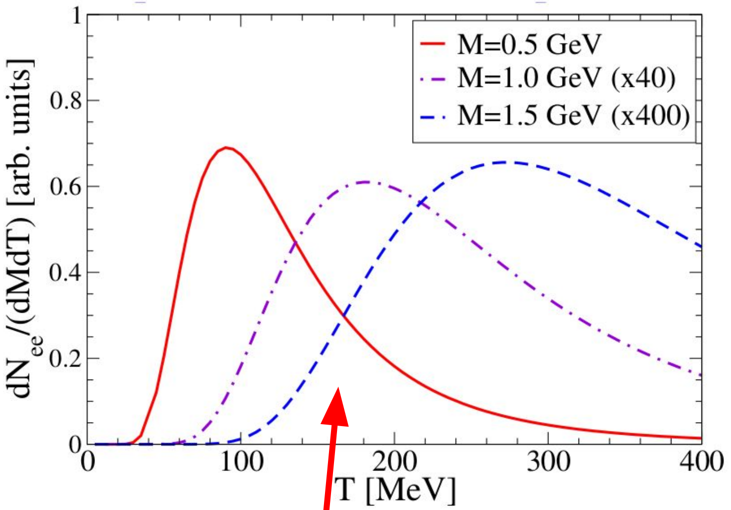
$$T_{\text{eff}} = \underbrace{\sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}}}_{2 \text{ for } \beta_{\text{flow}}=0.6} \times T$$

- Large blueshift at late times when $T \approx$ 150 - 200 MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

Temperature evolution and extraction



R. Rapp, Acta Phys. Pol. B 42, 2823 (2011)

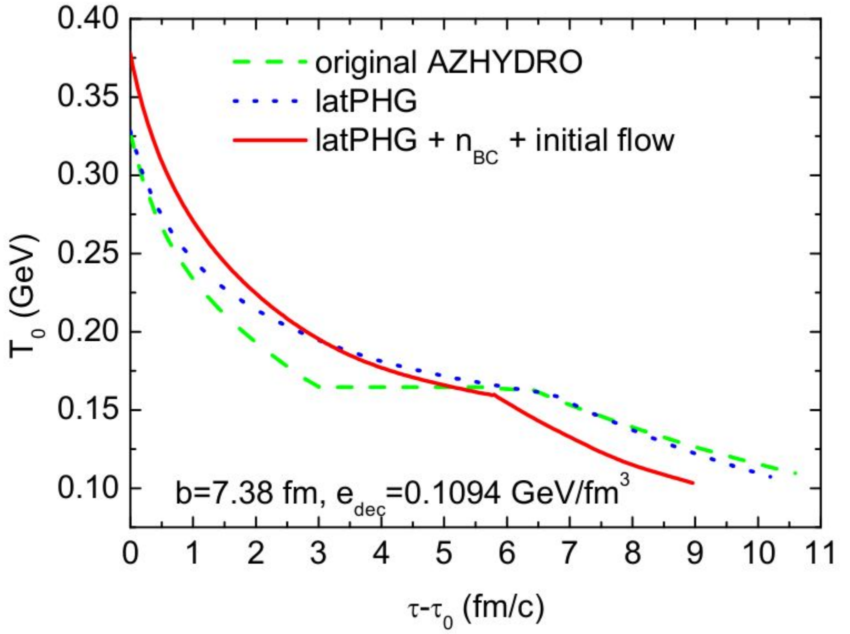


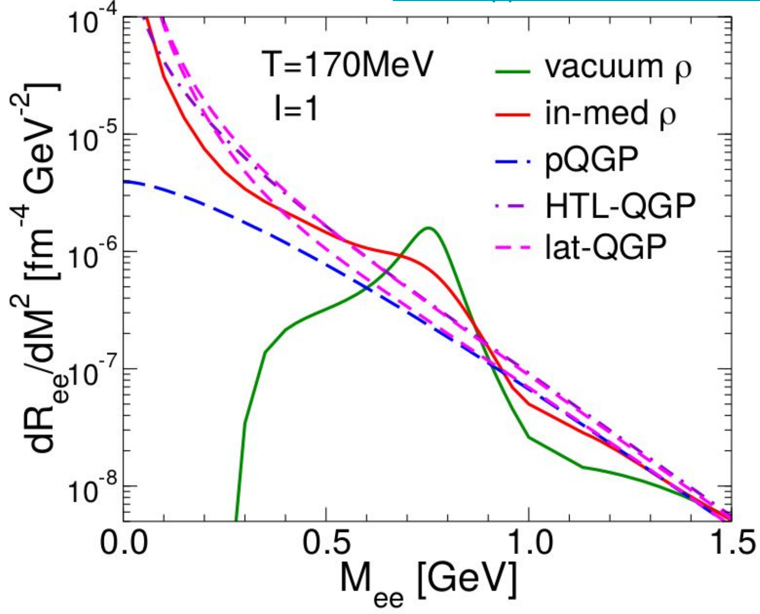
- Isentropic trajectories that the medium follows in the QCD phase diagram
- Temperature-differential dielectron emission:

$$\frac{dN_{ee}}{dMdT} \propto \mathrm{Im}\, \Pi_{\mathrm{EM}}(M;T)\, \mathrm{e}^{-M/T}\, T^{-m}$$

Partial restoration of chiral symmetry

Ralf Rapp, arXiv:1304.2309 [hep-ph]





- Space-time integral over the dilepton rate via relativistic hydrodynamics
- Switch between partonic and hadronic description at T = 170 MeV
  - **“Rho melting”**: hadronic emission rate similar to QGP rate at T = 170 MeV (not by construction), importance of baryon density (coupling to baryonic resonances)

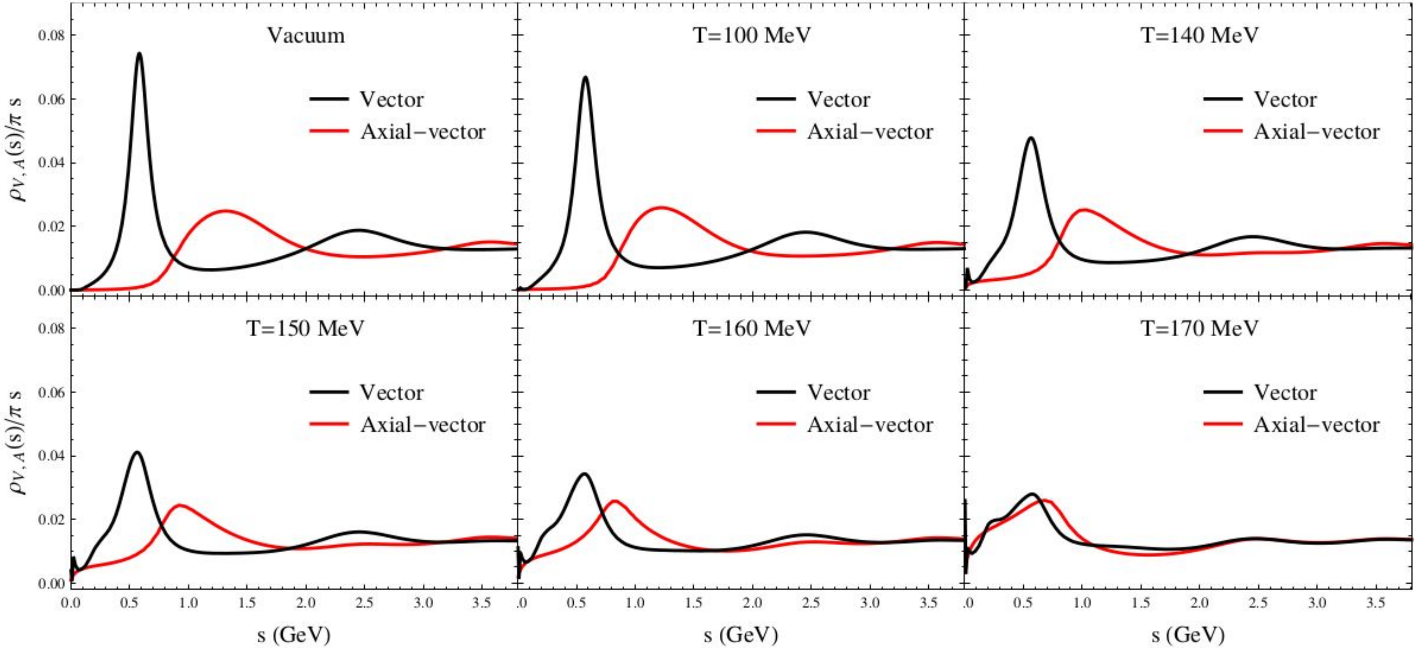
Partial restoration of chiral symmetry

Rho spectral function (constrained by low-energy measurements) + Ansatz for a1

- + QCD and Weinberg sum rules
- + Condensates from hadron resonance gas constrained by lattice QCD
- + Chiral mixing

[P.M. Hohler, R. Rapp, Phys.Lett.B731 (2014) 103-109]

quantitatively compatible with (approach to) chiral symmetry restoration



2.4 QCD + Weinberg Sum Rules

$$\frac{1}{M^2}\int_0^\infty ds \frac{\rho_V(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) + \frac{m_q\langle\bar{q}q\rangle}{M^4} + \frac{1}{24M^4}\langle\frac{\alpha_s}{\pi}G^2_{\mu\nu}\rangle - \frac{56\pi\alpha_s}{81M^6}\langle\mathcal{O}_4^V\rangle \ldots$$

[Hatsuda+Lee'91, Asakawa+Ko '93, Leupold et al '98, ...]

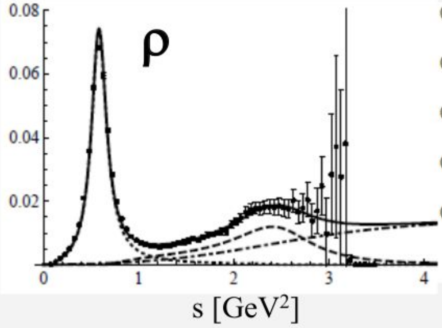
$$\int_0^\infty ds\, \frac{\Delta\rho(s)}{s} = f_\pi^2 \,,$$

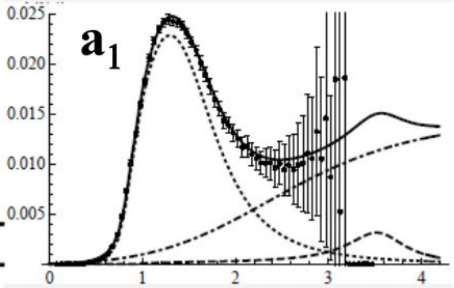
$$\int_0^\infty ds\, \Delta\rho(s) = f_\pi^2 m_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

$$\int_0^\infty ds s \Delta\rho(s) = -2\pi\alpha_s\langle\mathcal{O}_4^{SB}\rangle$$

$$\Delta\rho = \rho_V - \rho_A$$

[Weinberg '67, Das et al '67; Kapusta+Shuryak '94]

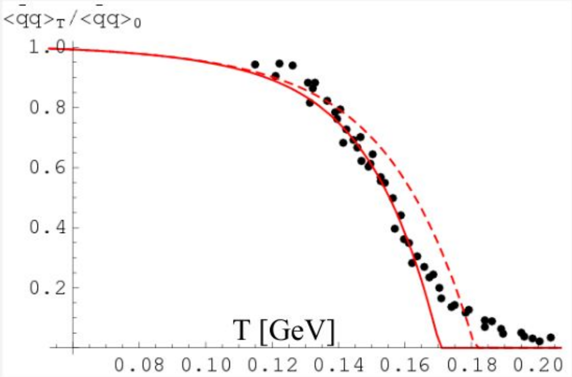




[Hoher+RR '12]

- accurately satisfied in **vacuum**
- **In Medium**:
  condensates from hadron resonance gas, constrained by lattice-QCD

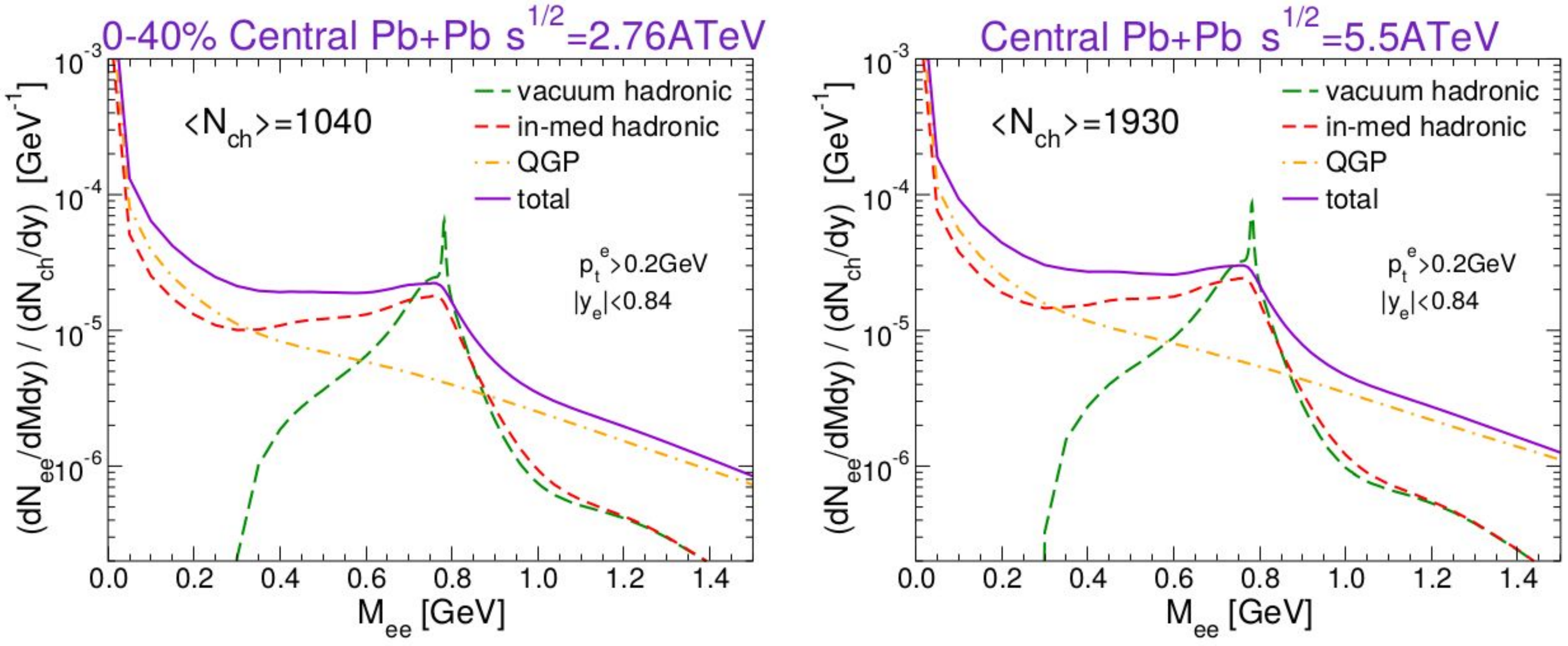
$$\langle\mathcal{O}\rangle_T \simeq \langle\mathcal{O}\rangle_0 + \sum_h d_h \int \frac{d^3k}{(2\pi)^3\, 2E_h}\langle h(\vec{k})|\mathcal{O}|h(\vec{k})\rangle n_h(E_h)$$



R. Rapp, ECT 2018*

LHC predictions

Ralf Rapp, arXiv:1304.2309 [hep-ph]

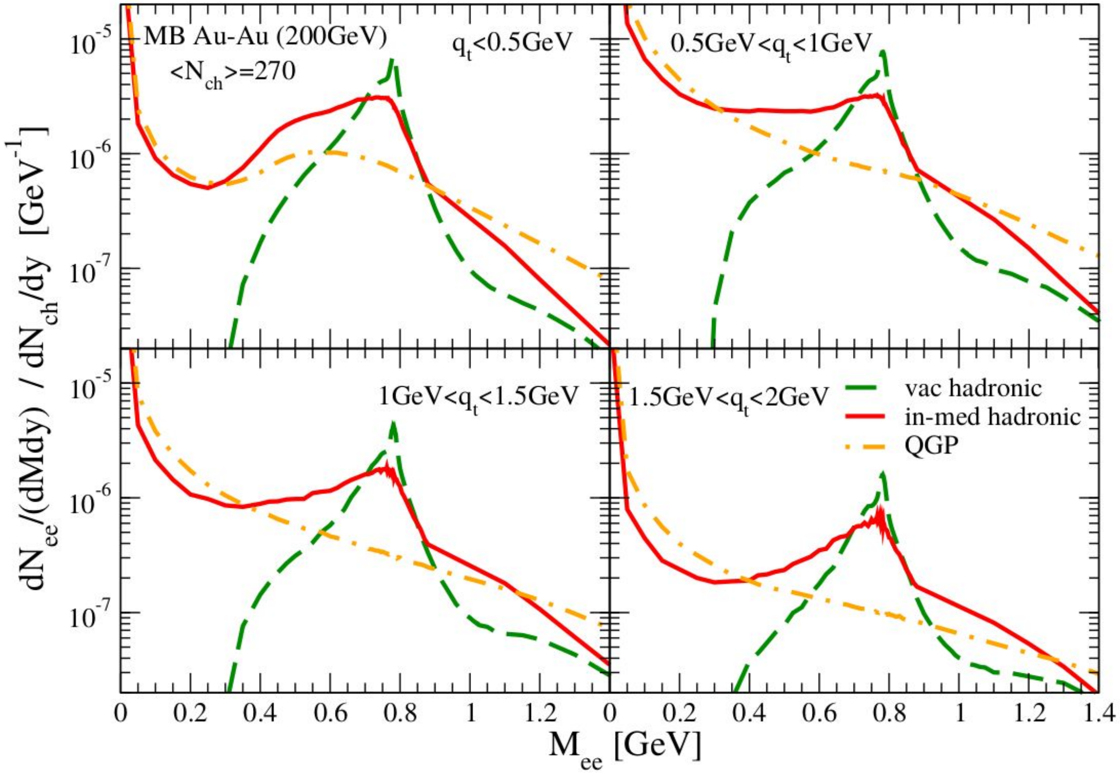


Chiral mixing

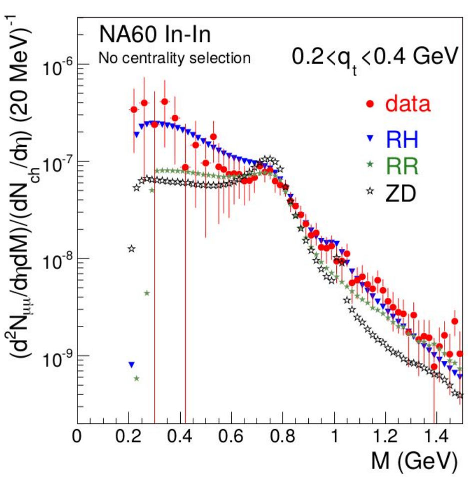
Ralf Rapp, arXiv:1304.2309 [hep-ph]

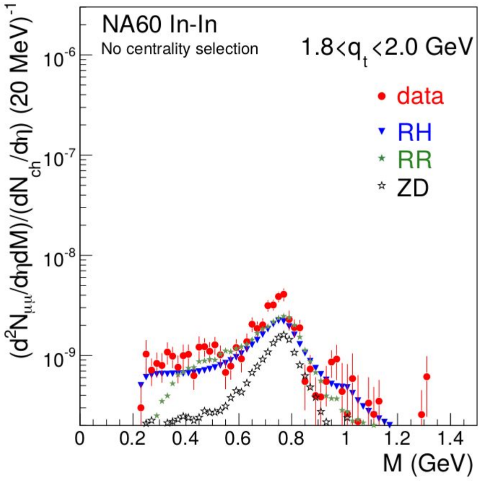
- **Chiral partners: ρ and a_1**
  - In vacuum symmetry broken, no coupling a_1 of to dileptons
  - In medium with T >> T_C **symmetry restored and partners mix**
- Maximum effect at the LHC by comparing no mixing vs. maximum mixing (no temperature dependence of chiral restoration)
  - Above 1 GeV/c^2 large background from thermal QGP radiation
  - **~20% effect**

- **enhance the signal from the hadronic phase**, e.g. by cutting on larger pair momenta
  - Larger transverse flow

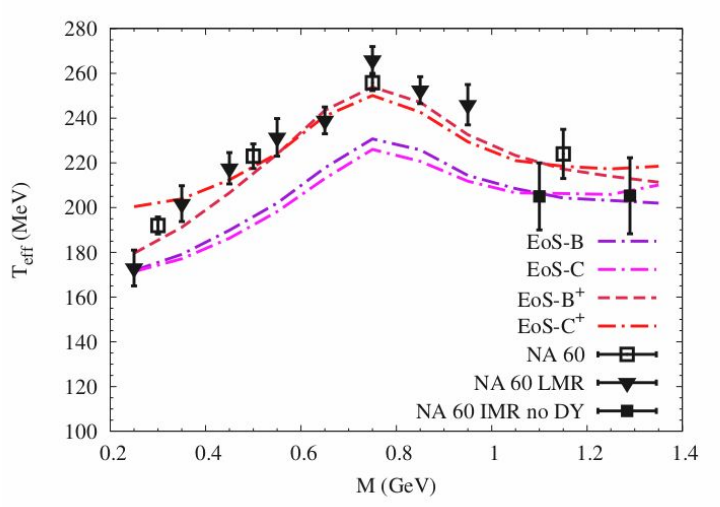


Differential measurments - transverse momentum





R. Rapp, J. Wambach, H. van Hees, Landolt-Bornstein 23 (2010) 134



R. Rapp, Acta Phys. Pol. B 42, 2823 (2011)

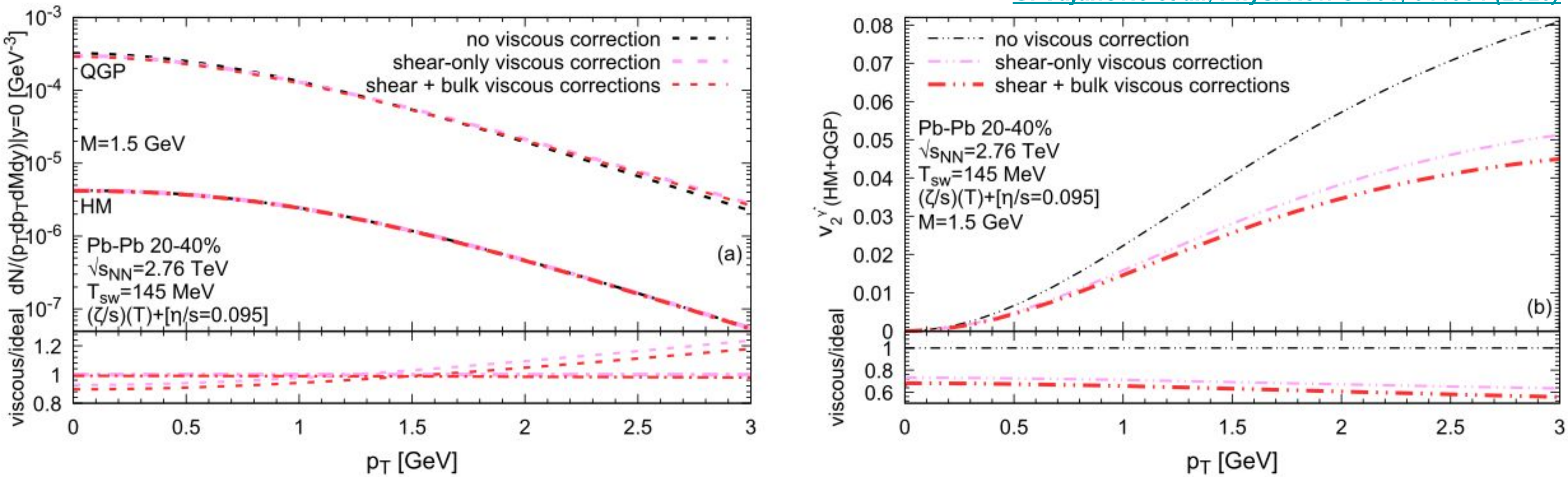
- Interesting features in mass spectra in different p_T bins, e.g. vanishing medium effects with increasing momentum
- Effective temperature (from transverse momentum spectra) as function of mass Sensitive to radial flow (barometer)

$$T_{\text{eff}} \simeq T + M\langle\beta\rangle^2$$

- Run 3/4: T_{eff} with a stat. precision of $\sigma(T_{\text{eff}})/T_{\text{eff}}$ = 1%   ALICE, J. Phys. G 41 (2014) 087001

Differential measurments - (elliptic) flow

[G. Vujanovic et al., Phys. Rev. C 101, 044904 (2020)](#)

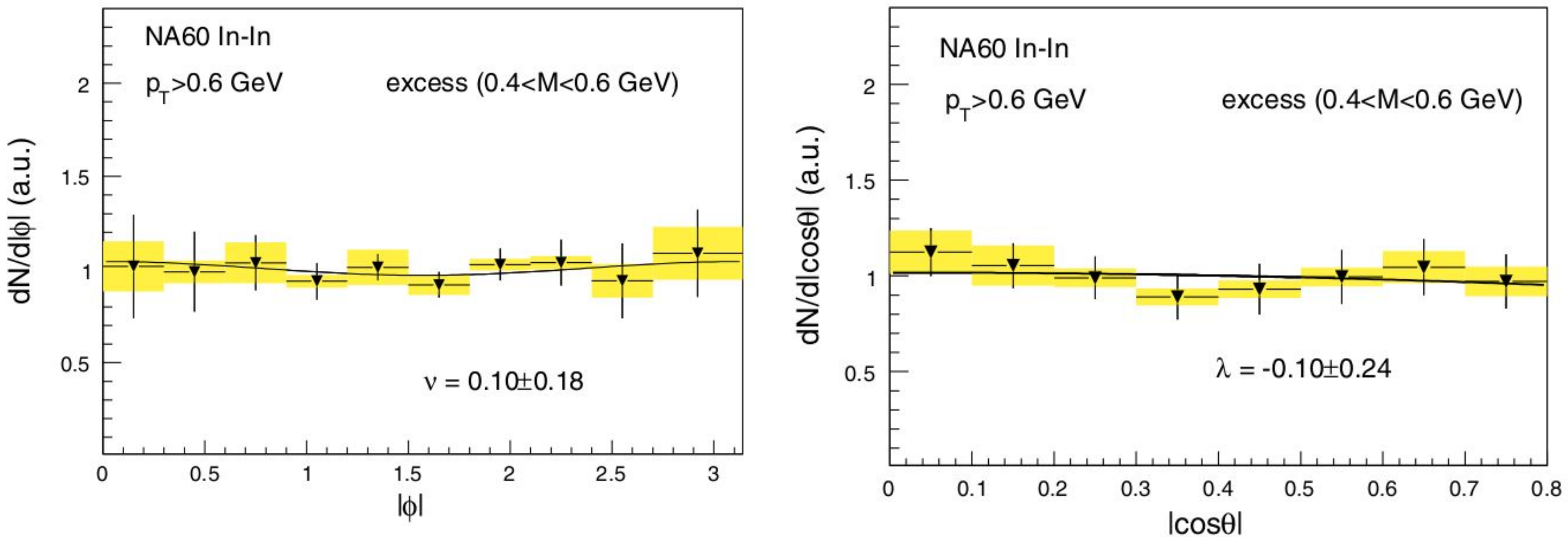


- Direct and clean access the medium properties and dynamics of early stage of the collisions (mass as proxy for temperature) → resolve "photon puzzle"?
- Sensitivity to shear and bulk viscosity (together with hadronic observables)

- Run 3/4 ALICE: 1% absolute stat. uncertainty [ALICE, J. Phys. G 41 (2014) 087001](#)

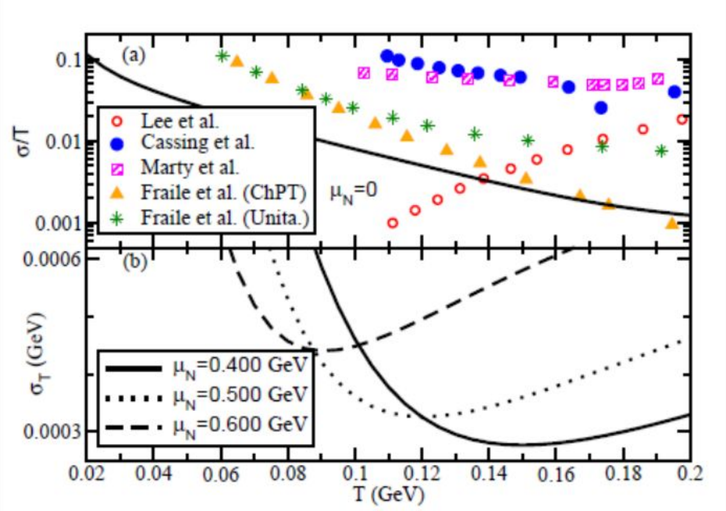
Differential measurments - polarization

NA60, Phys.Rev.Lett. 102 (2009) 222301

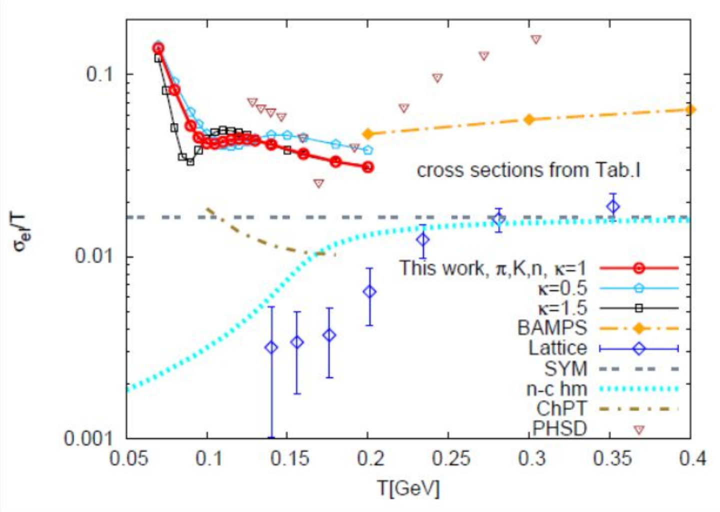


- Angular distribution of continuum dilepton pairs: $$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$
- Sensitive to photon source polarization (thermalization, gluon anisotropy, Drell-Yan,…)
- No estimate for Run 3/4 yet (NA60 used ~50k excess pairs)

Electric conductivity



[S. Ghosh ‘17]



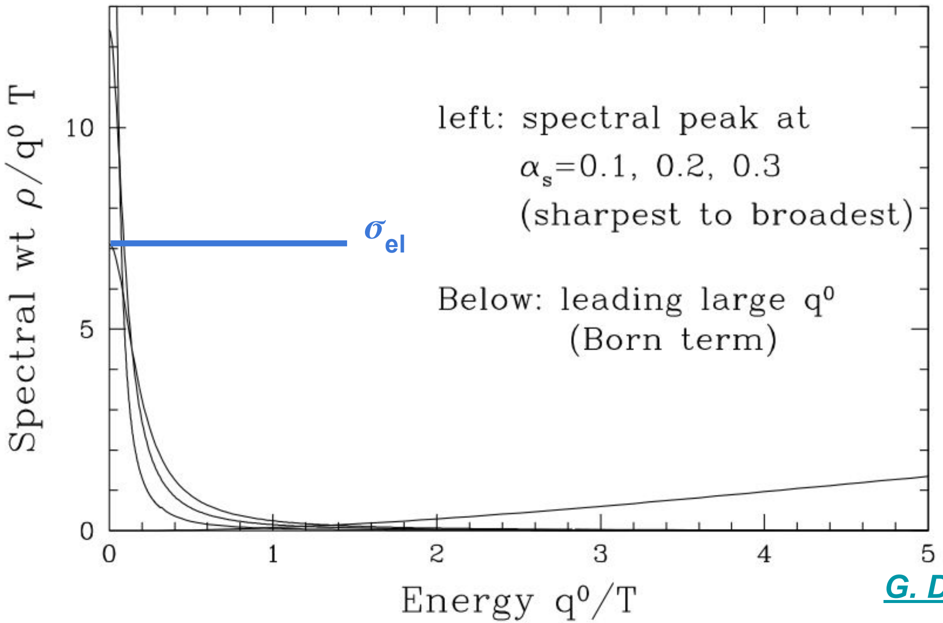
[Greif ‘17]

R. Rapp, ECT 2018*

- Large spread and interest in literature
- Connected to dilepton production via spectral function

$$\sigma_{EM}(T) = -\, e^2 \lim_{q_0 \to 0} \left[\partial/\partial q_0 \ \mathrm{Im}\, \Pi_{EM}(q_0, q=0; T) \right]$$

Electric conductivity



Need sensitivity down to very low p_T and mass

G. D. Moore and J.-M. Robert, arXiv:hep-ph/0607172

- Connected to dilepton production via spectral function

$$\sigma_{EM}(T) = - e^2 \lim_{q_0 \to 0} [\ \partial/\partial q_0 \ \mathrm{Im}\ \Pi_{EM}(q_0, q=0;T)\ ]$$

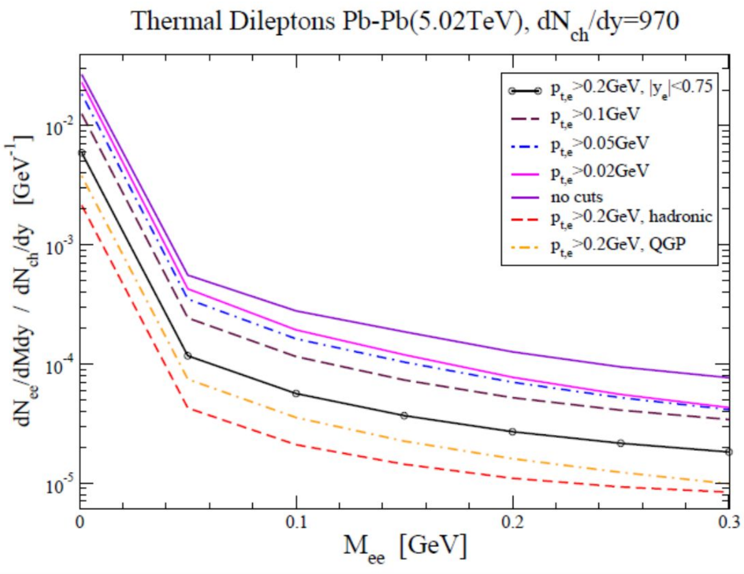
the transverse plane. For di-leptons, it would be interesting to find the spectrum below the temperature scale, $p_T \ll T$, because one is then sensitive to the transport peak which is characterized by electric conductivity. A detector with low-p_T coverage could lead to an excellent understanding of

S. Flörchinger, arXiv:1812.08122
and Slides ALICE-LMee workshop 2019

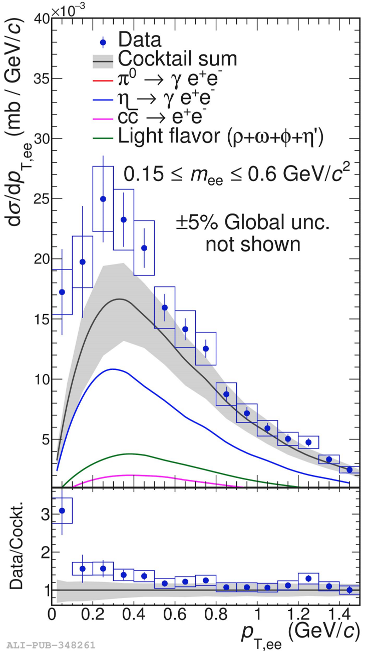
How low is low?

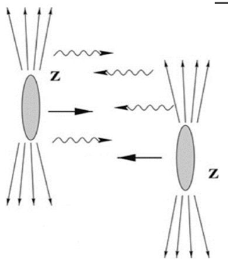
- Need quantitative theory input (discussions started)
- Efficiency at low invariant mass and pair p_T (see slides later)
- Background? Cocktail sources not important, but what about photoproduction?

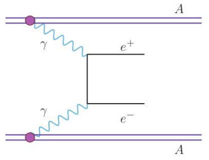
→ StarLight?

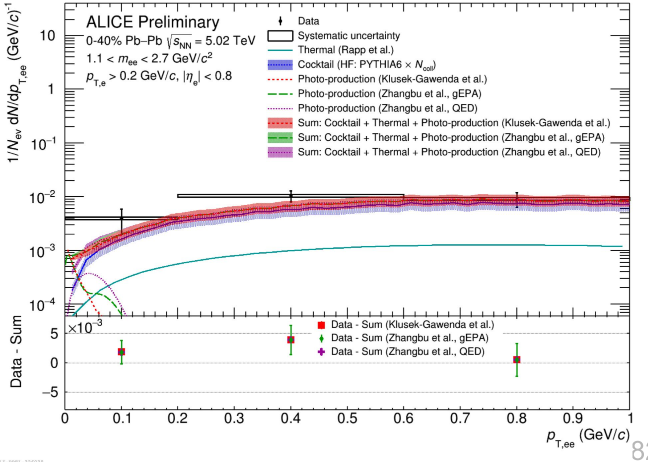


R. Rapp, ECT* 2018



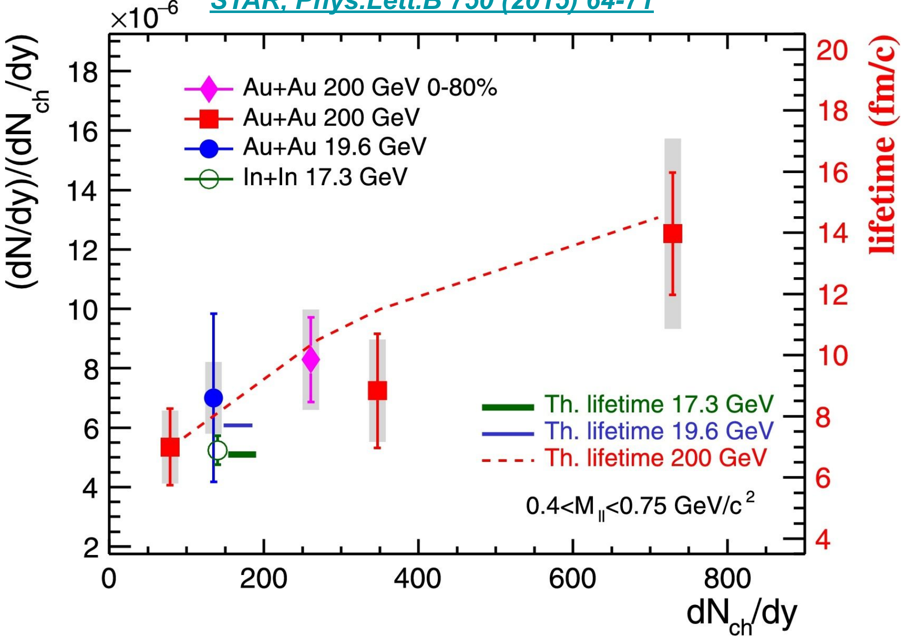




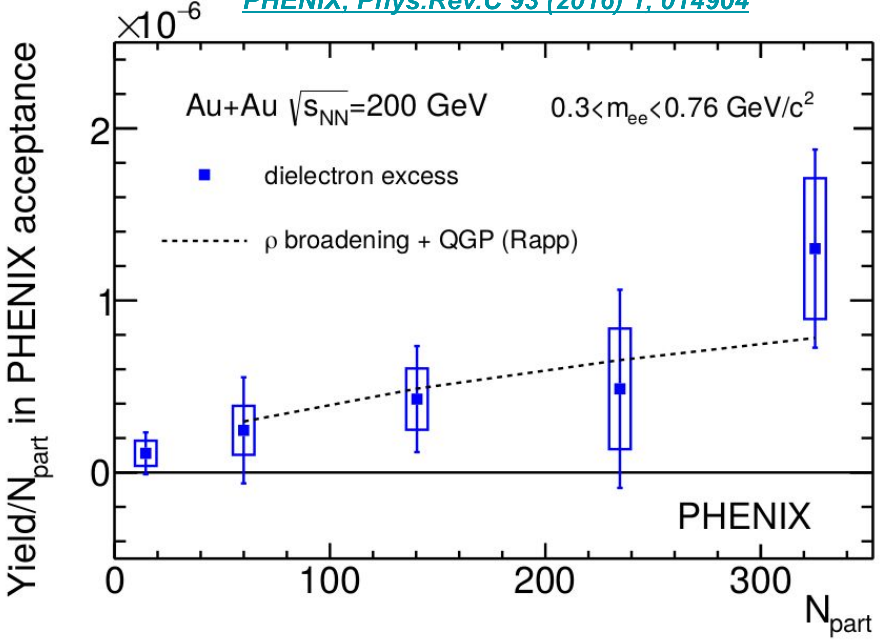


Thermal dilepton production - RHIC

STAR, Phys.Lett.B 750 (2015) 64-71



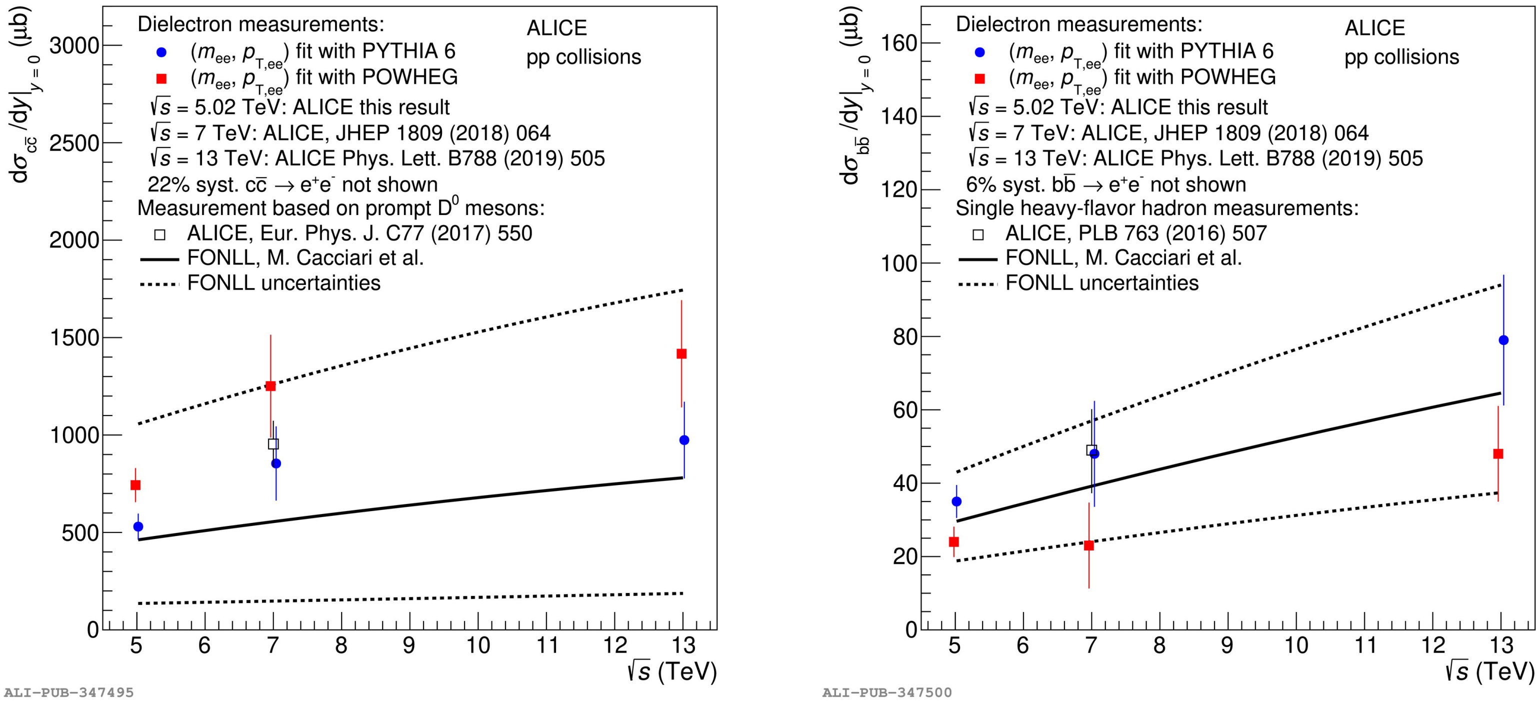
PHENIX, Phys.Rev.C 93 (2016) 1, 014904



- **Excess in the low mass region** in the full RHIC beam energy range (19.6 - 200 GeV)
- Compatible with **ρ broadening + QGP thermal radiation**
- Centrality dependent excess yield **(thermal lifetime)** in agreement with measurements

pp and p-Pb - ALICE

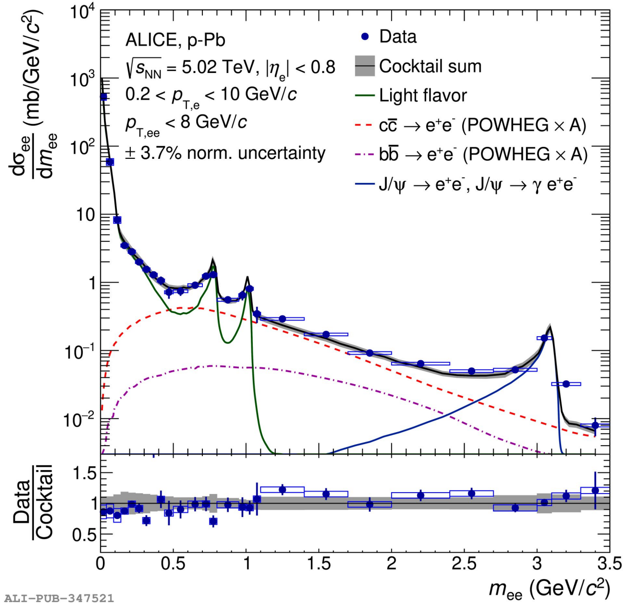
ALICE, arXiv:2005.11995 [nucl-ex]

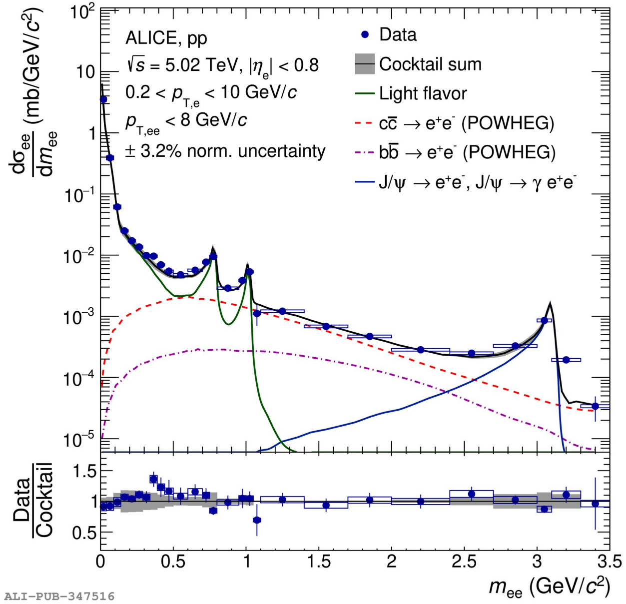


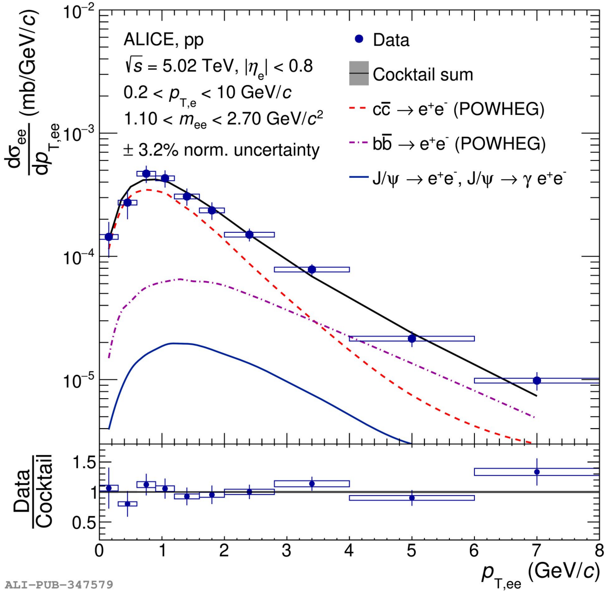
- **Heavy flavour cross section:** extracted with 2D fit (m_{ee}, $p_{T,ee}$)
  - Compatible with hadron measurements
  - Model dependence: sensitivity to production mechanisms

pp and p-Pb - ALICE

ALICE, arXiv:2005.11995 [nucl-ex]

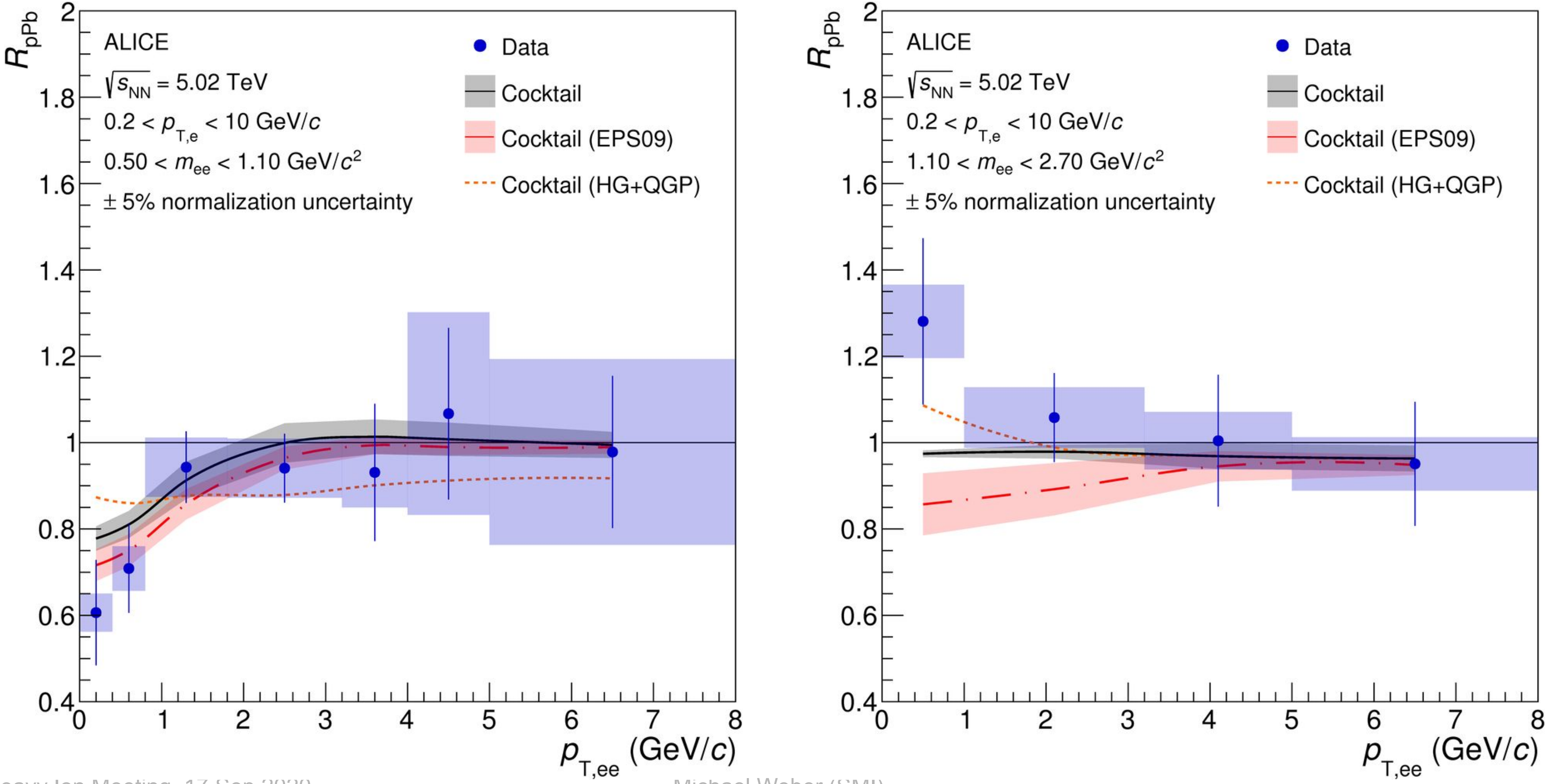




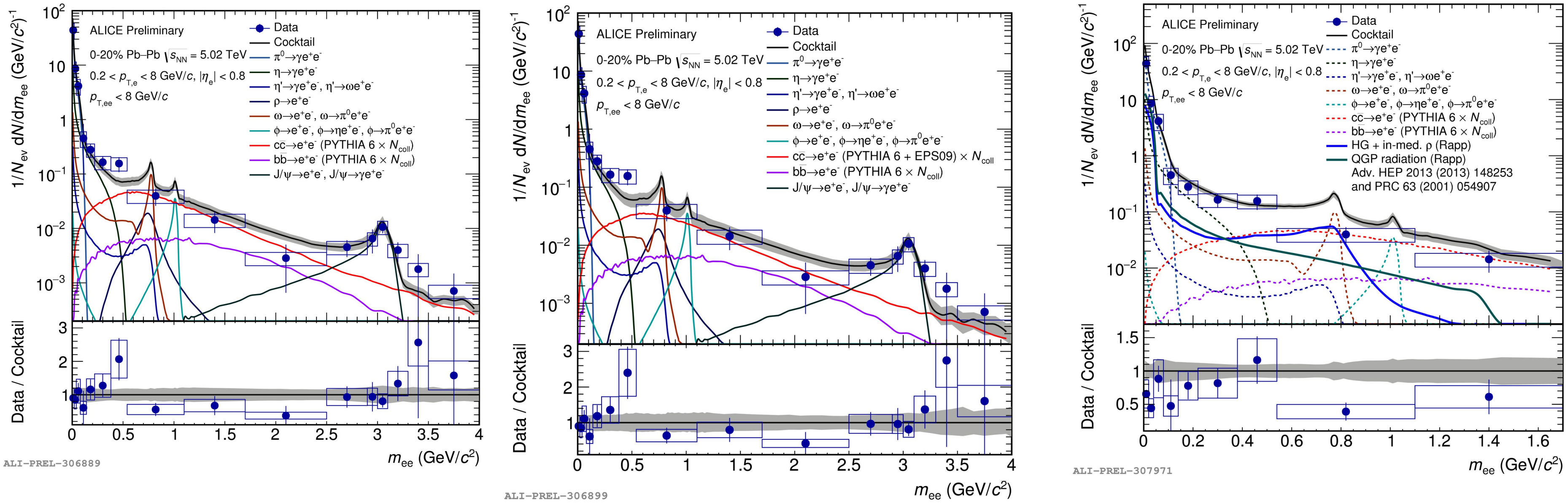


pp and p-Pb - ALICE

ALICE, arXiv:2005.11995 [nucl-ex]



ALICE measurements - Dielectrons Run 2



- **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

Distinguish prompt and non-prompt sources

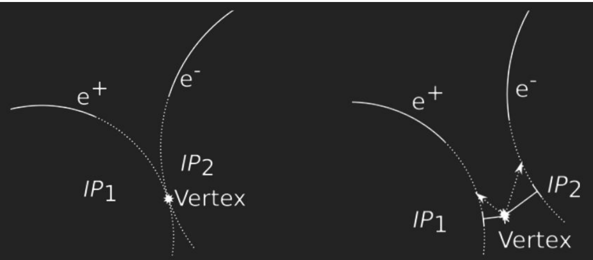


Figure 4: Schematic illustration of a prompt (left) and non-prompt (right) decay of a dielectron pair

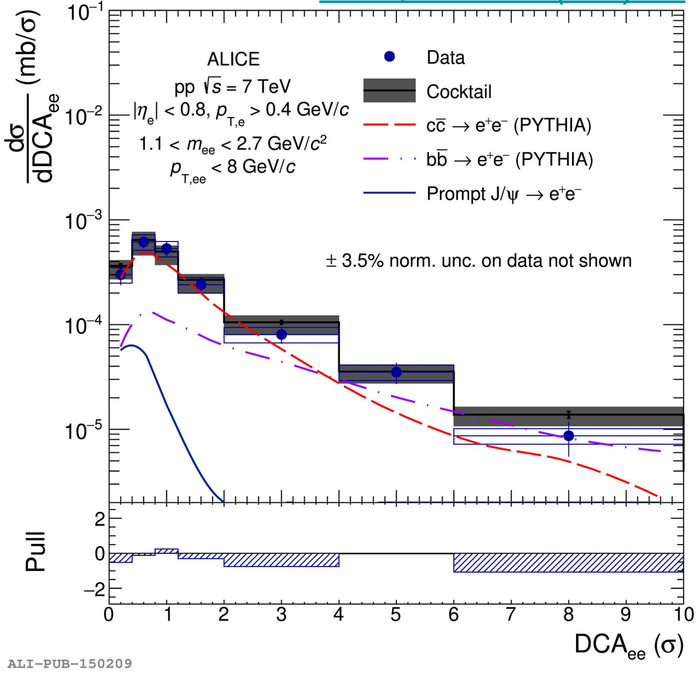
Calculate the distance-of-closest-approach for the dielectron pairs (DCA_{ee}) as the sum of the distance of the single electron tracks to the primary vertex, after normalising to the resolution:

$$\mathrm{DCA_{ee}} = \sqrt{\frac{\mathrm{DCA}_1^2 + \mathrm{DCA}_2^2}{2}}$$

Expectation: DCA_{ee}(prompt) < DCA_{ee}(charm) < DCA_{ee}(beauty)

S. Scheid, HP2020

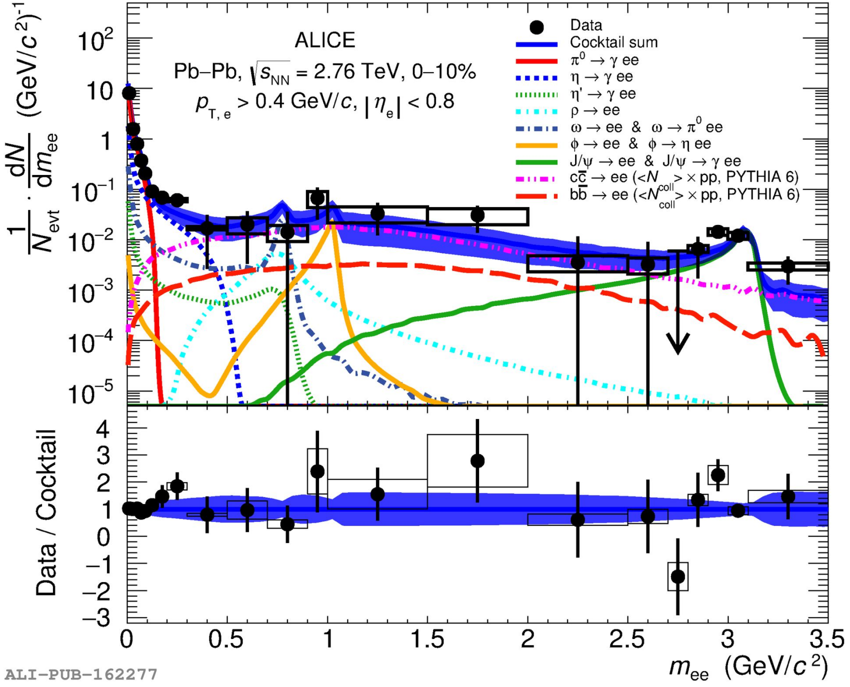
ALICE, JHEP 1809 (2018) 064

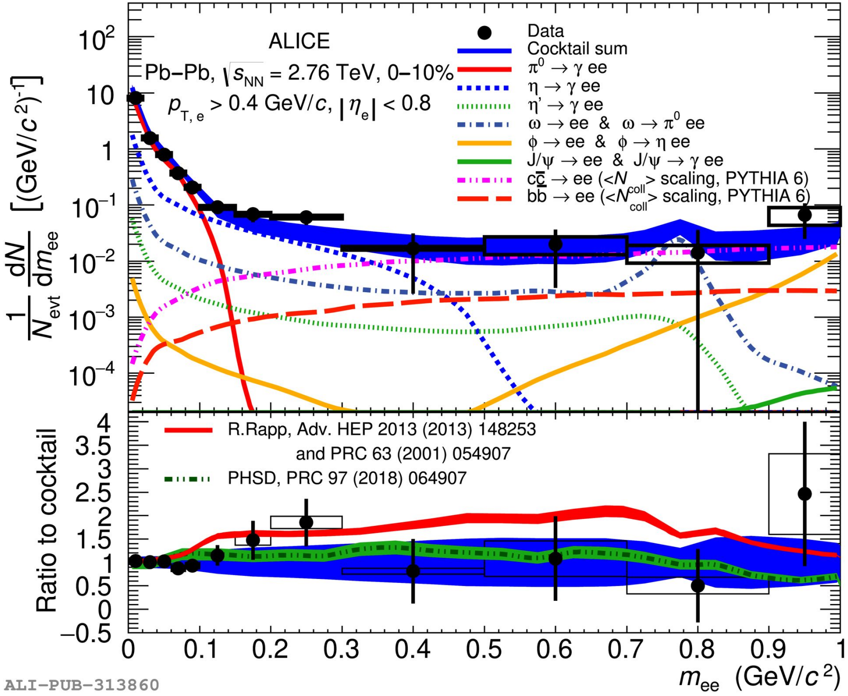


- Heavy-flavour hadrons have a **delayed decay**
  - D-meson cτ = 150-300 μm, B-meson cτ = 450 μm
- Can be used to **separate prompt and heavy flavour sources**
  → work in progress for p-Pb and Pb-Pb collisions

ALICE measurements - Dielectrons Run 1

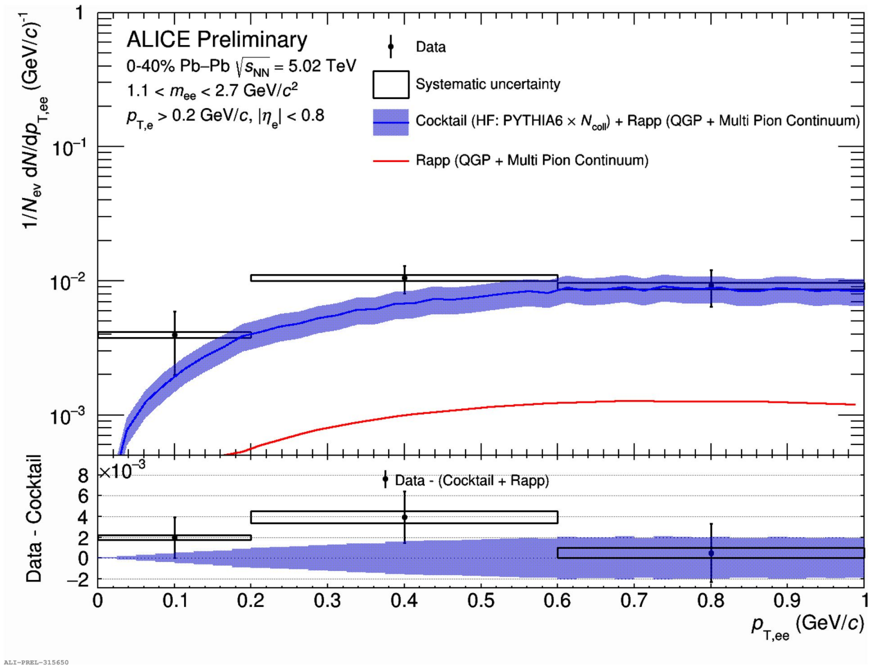
[ALICE, Phys. Rev. C 99, 024002 (2019)](#)

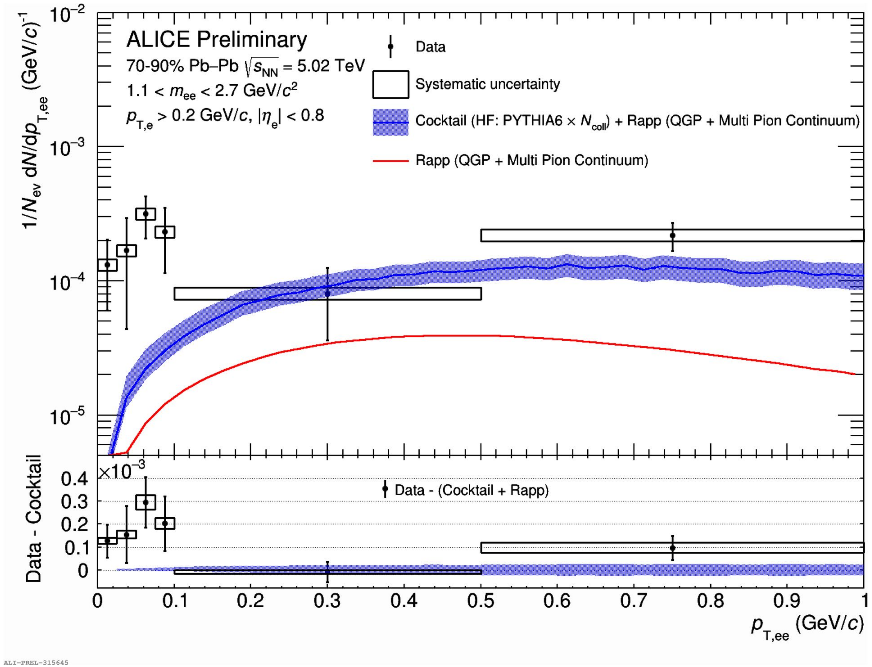




- **First low-mass/p_T dielectron measurement at the LHC**

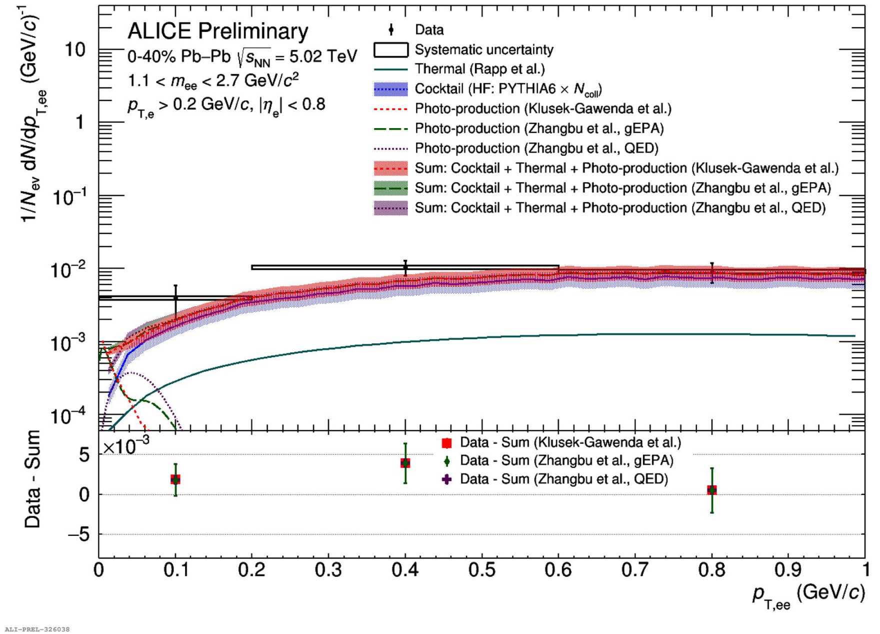
Photoproduction - ALICE

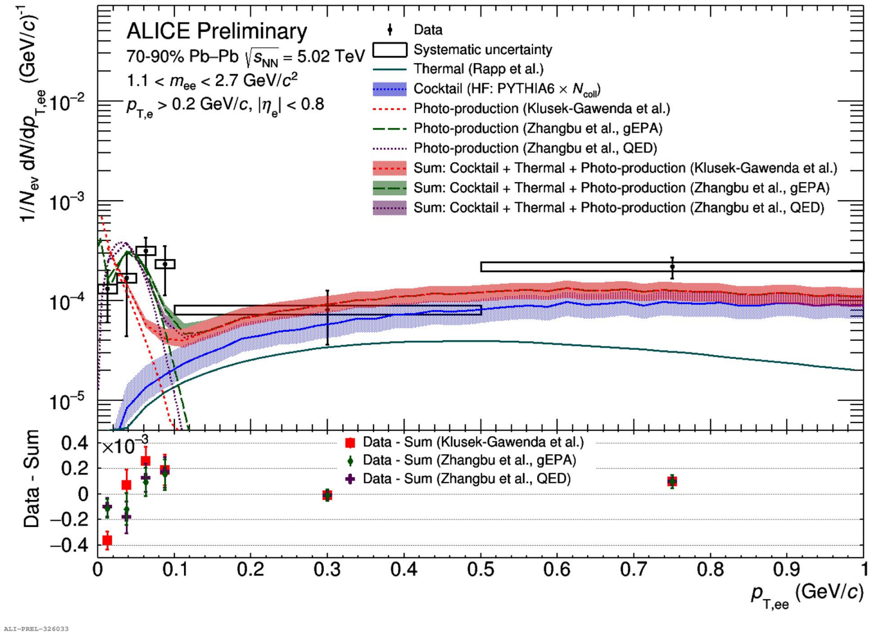




- Excess w.r.t. cocktail and thermal sources at $p_{T,ee}$ < 0.1 GeV/c

Photoproduction - ALICE

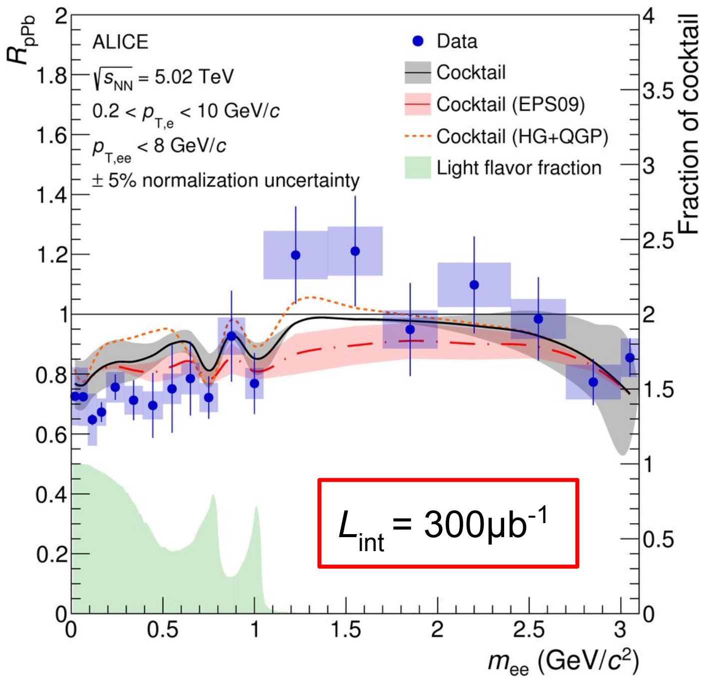




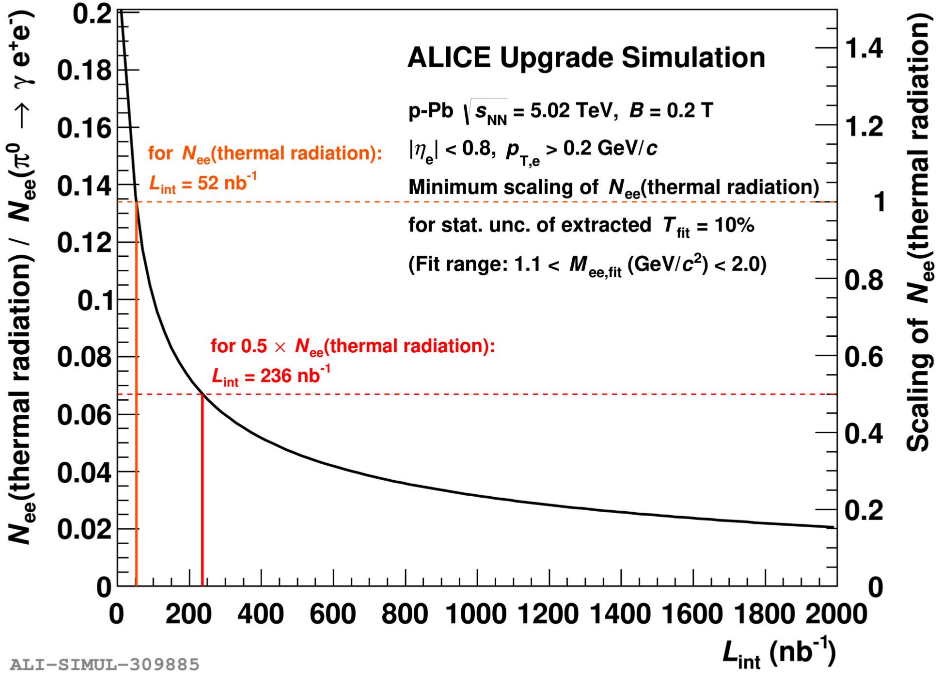
- Excess w.r.t. cocktail and thermal sources at $p_{T,ee}$ < 0.1 GeV/c
- Compatible with photo-production models (caveat: no resolution effects taken into account here)
- Next steps: increase statistics by factor of two by including 2018 data, event-plane dependence,...

Thermal radiation in small systems (p-Pb)?

ALICE, arXiv:2005.11995 [nucl-ex]



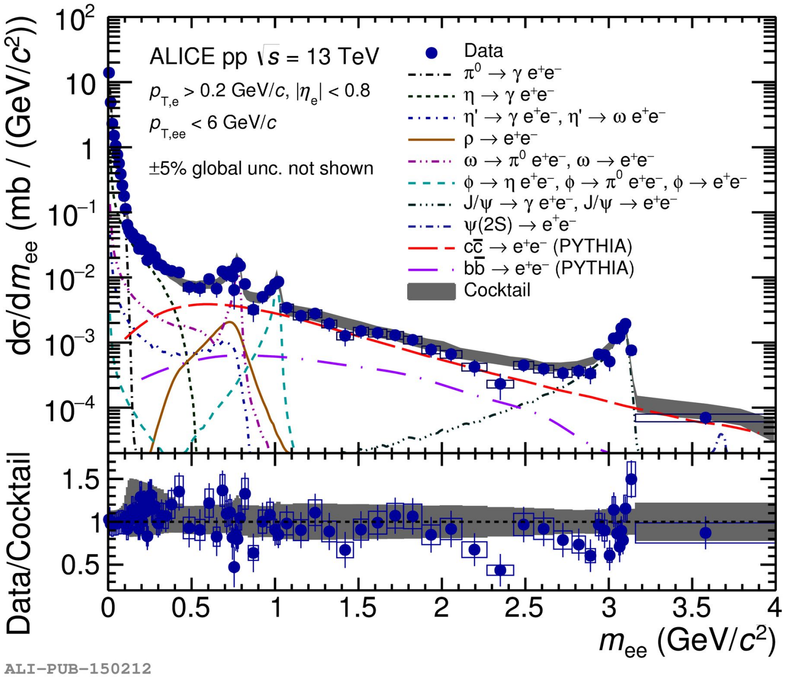
HL-LHC WG5 yellow report

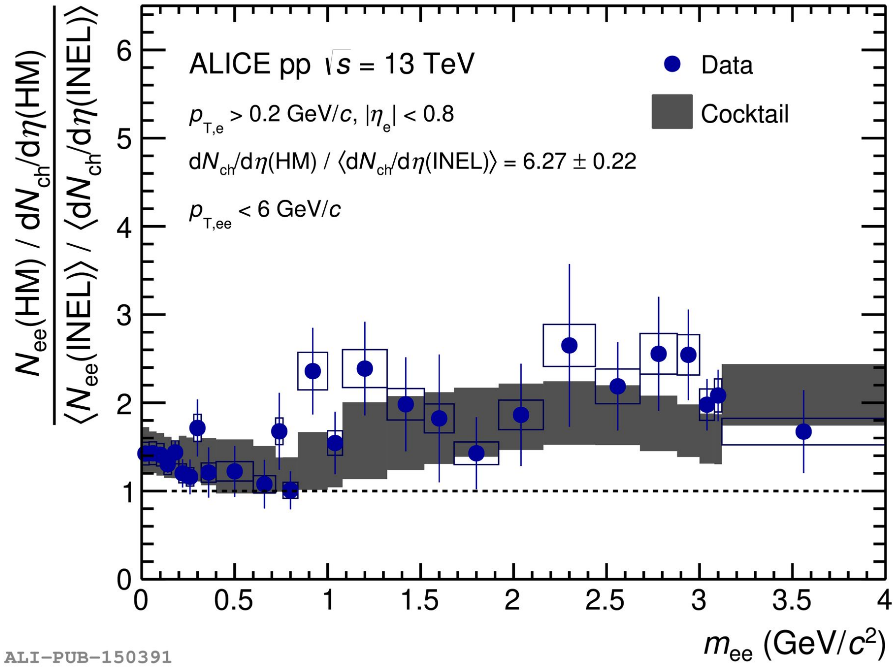


- Within uncertainties compatible with hadronic cocktail
- Need more statistics (Run 3 and beyond)
- Study multiplicity dependence (ongoing for Run 2)

Thermal radiation in small systems (pp)?

ALICE, Phys. Lett. B 788 (2019) 505





- Within uncertainties compatible with hadronic cocktail
- Need more statistics and reduce systematic uncertainties
- Extended pp programme in preparation: ***ALICE-PUBLIC-2020-005***

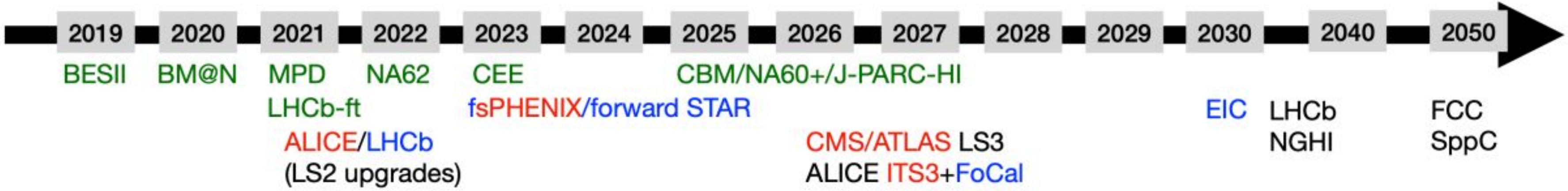
Future high-energy pp programme with ALICE

Measurement	ALICE uniqueness	Other experiments
Ω/π ratio vs. multiplicity	π, K, p PID $p_T > 0.15$ GeV/c mid-y	— *
Flow of π, K, p at high multiplicity	π, K, p PID $p_T > 0.15$ GeV/c mid-y $p_T < 0.5$ GeV/c crucial for mass ordering	CMS in Run 4 (with proposed timing layer) limited to $p_T > 0.4$ GeV/c at $\|\eta\| \approx 1.4$
h–jet recoil at high multiplicity	Charged jets $p_T^{jet} > 15$ GeV/c maximum sensitivity to jet ΔE at low p_T^{jet}	ATLAS and CMS (γ/Z–jet with $p_T^{jet} > 30$ GeV/c)
Nuclei and hypernuclei	$Z = 2$ nuclei PID $p_T > 0.8$ GeV/c	— *
p–hyperon(Y) and Y–Y interaction	π, K, p PID $p_T > 0.15$ GeV/c mid-y	—
B mesons	PID, B mesons $p_T > 0$ mid-y Reference for $p_T < 5$ GeV/c B R_{AA}	ATLAS and CMS ($p_T > 5$ GeV/c), LHCb (forward rapidity)
Jets and HF jets	Charged jets $p_T^{jet} > 10$ GeV/c Larger dead cone aperture at low radiator E	ATLAS and CMS ($p_T > 30$ GeV/c)
Charmonia	J/ψ, ψ(2S) $p_T > 0$ mid- and fwd-y, central-forward correlations	ATLAS and CMS ($p_T > 3$ GeV/c), LHCb (forward rapidity)
Low-mass central diffraction	π, K, p PID $p_T > 0.15$ GeV/c mid-y	LHCb (forward rapidity)
Low-mass dielectrons	e ID $p_T > 75$ MeV/c	—

* possible in CMS only in Run 4 and with extended running (several months per year) at low rate (min-bias readout rate CMS Run 4: < 250 kHz i.e. 2–4 times lower than ALICE).

The next decade

C. Loizides, arXiv:2007.00710 [nucl-ex]



At the LHC (changes due to Covid not included here):

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Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

ALICE:
13 nb^{-1} Pb-Pb
0.6 pb^{-1} p-Pb

\+ pp
(ALICE-PUBLIC-2020-005)

ALICE - Dielectrons (Run 3)

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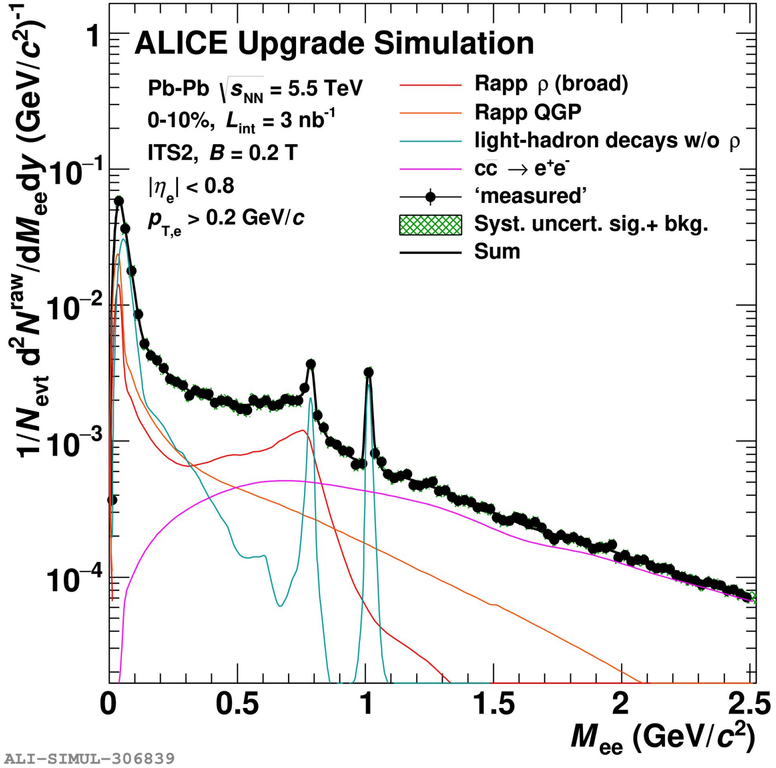

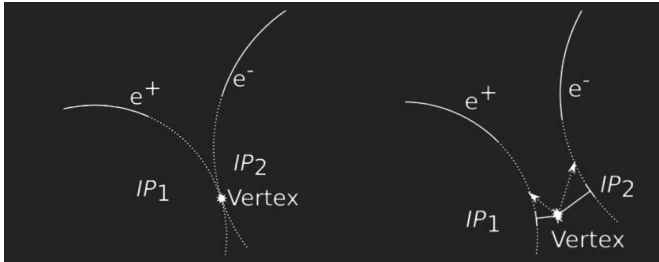

Figure 4: Schematic illustration of a prompt (left) and non-prompt (right) decay of a dielectron pair

Calculate the distance-of-closest-approach for the dielectron pairs (DCA_{ee}) as the sum of the distance of the single electron tracks to the primary vertex, after normalising to the resolution:

$$\mathrm{DCA_{ee}} = \sqrt{\frac{\mathrm{DCA}_1^2 + \mathrm{DCA}_2^2}{2}}$$

Expectation: DCA_{ee}(prompt) < DCA_{ee}(charm) < DCA_{ee}(beauty)

S. Scheid, HP2020

Applying cuts on the pair DCA to reduce contribution of heavy-flavour sources

ALICE - Dielectrons (Run 3)

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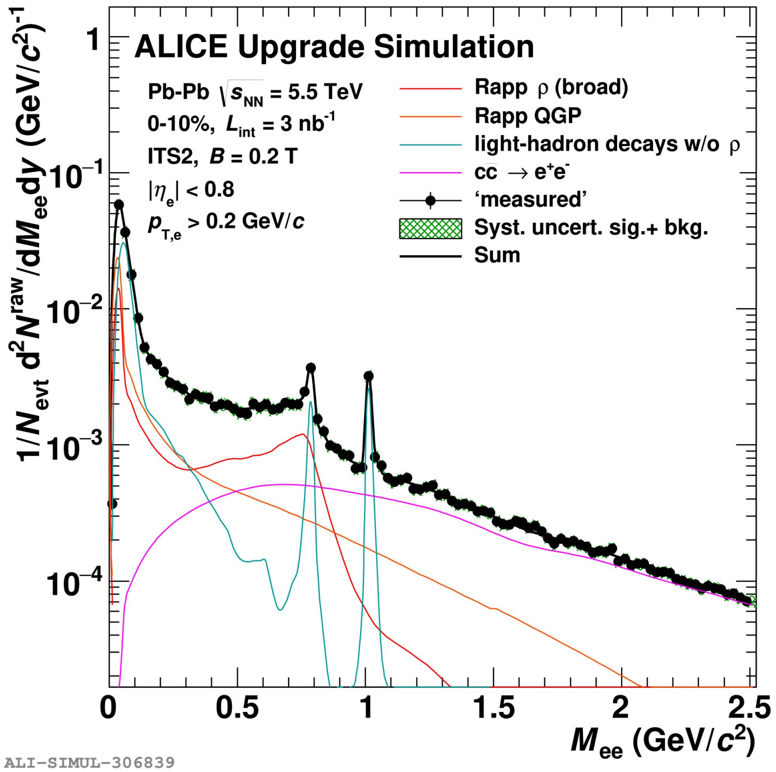
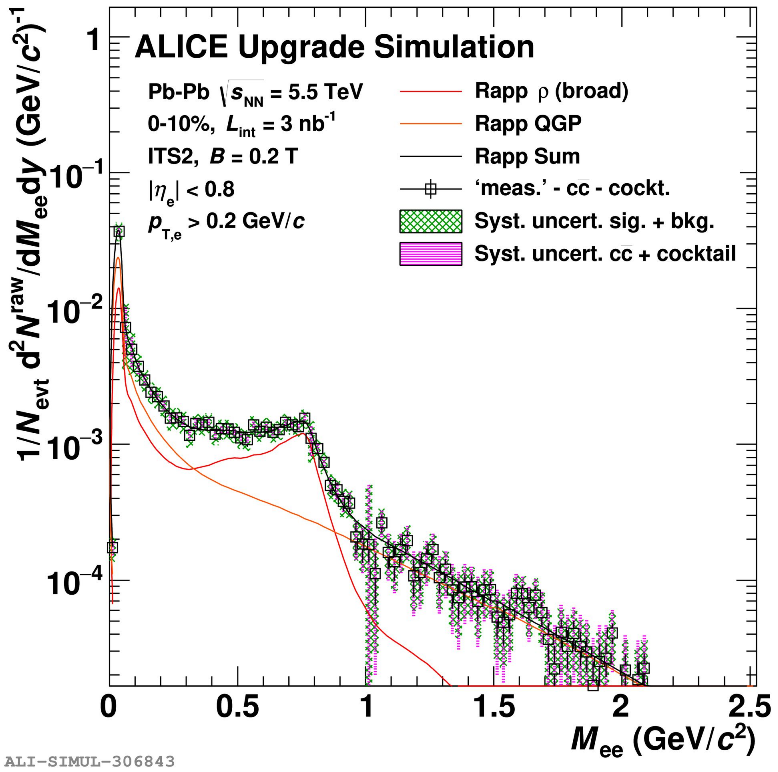


Applying cuts on the pair DCA to reduce contribution of heavy-flavour sources



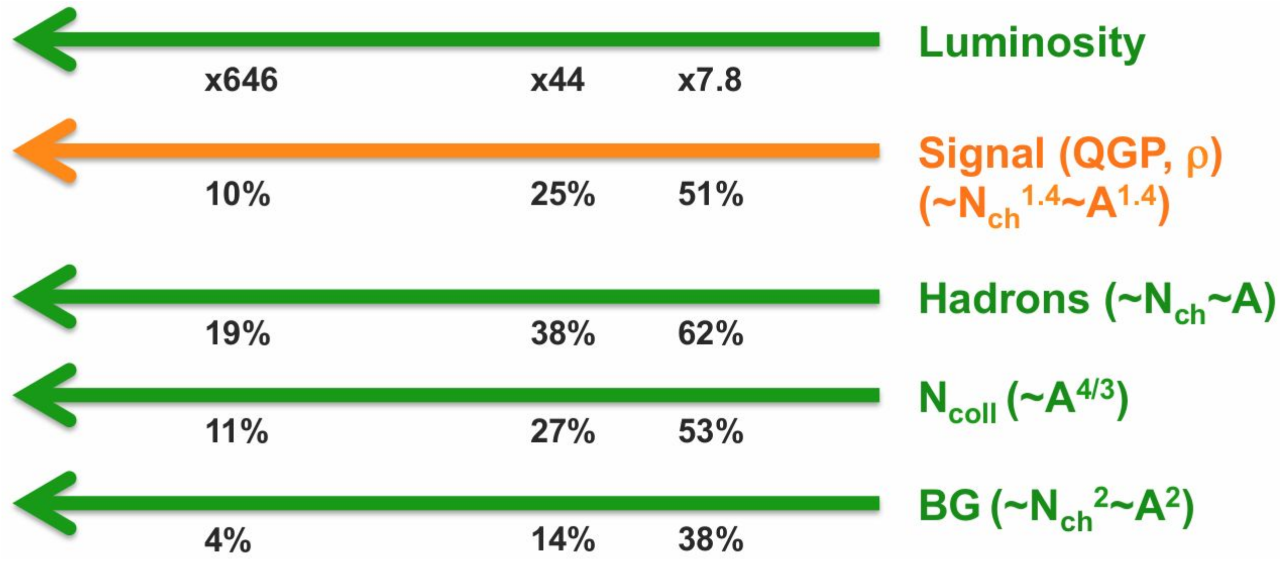
After subtraction of long-lived light- and (keep ρ) heavy-flavour sources

Other collision systems - luminosities and dileptons

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	5.67	7.8
$\langle L_{AA} \rangle$ cm^{-2}s^{-1}	4.54×10^{31}	2.45×10^{30}	1.69×10^{30}	1.68×10^{29}	2.95×10^{28}	3.8×10^{27}
$\langle L_{NN} \rangle$ cm^{-2}s^{-1}	1.16×10^{34}	3.93×10^{33}	2.71×10^{33}	1.02×10^{33}	4.91×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}$ dt/nb^{-1}	5.89×10^4	3180.	2190.	218.	38.2	4.92
$\int_{month} L_{NN}$ dt/pb^{-1}	1.51×10^4	5090.	3510.	1330.	636.	213.

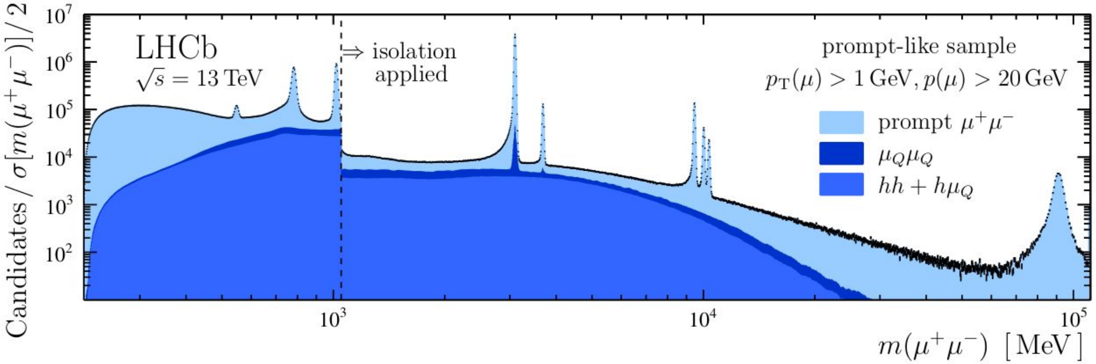
HL-LHC WG5 yellow report

Optimistic scenario



Other future opportunities: LHCb

LHCb, Phys. Rev. Lett. 120, 061801 (2018)

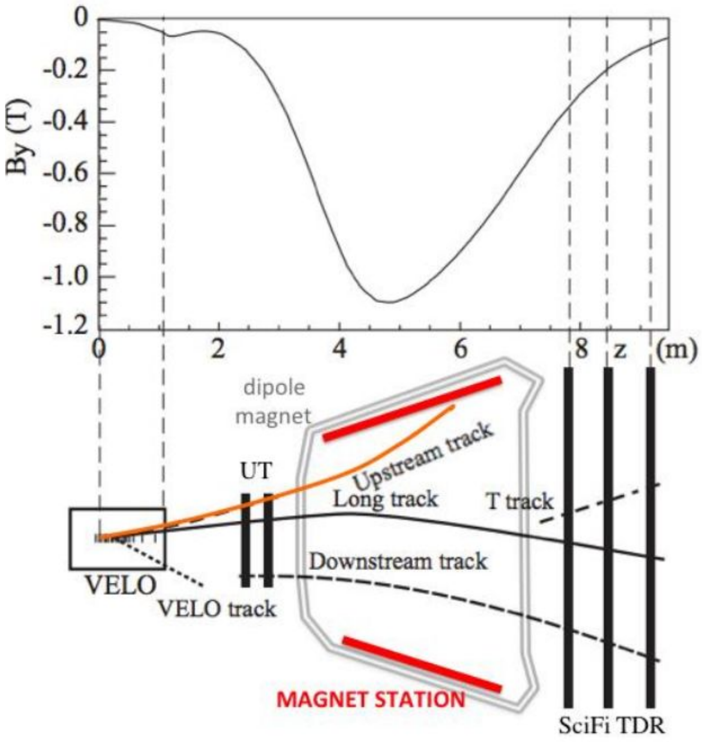


- PID and resolution limitations in momentum to be explored in detail
- Low multiplicity collisions only (no central heavy-ion collisions at the moment)

	LHCb	LHCb Upgrade I	LHCb Upgrade II
$\mathcal{L}_{instantaneous}$ ($cm^{-2}s^{-1}$)	4×10^{32}	2×10^{33}	$\mathbf{2 \times 10^{34}}$
Pile-up	1	6	**60**
b-hadron per evt.	0.003	0.02	**0.2**
c-hadron per evt.	0.04	0.22	**2**
light,long-lived per evt.	0.51	2.08	**21**

[LHCb-PUB-2014-027]

C. da Silva, Epiphany 2020



Planned magnet station for low momentum electron tracking