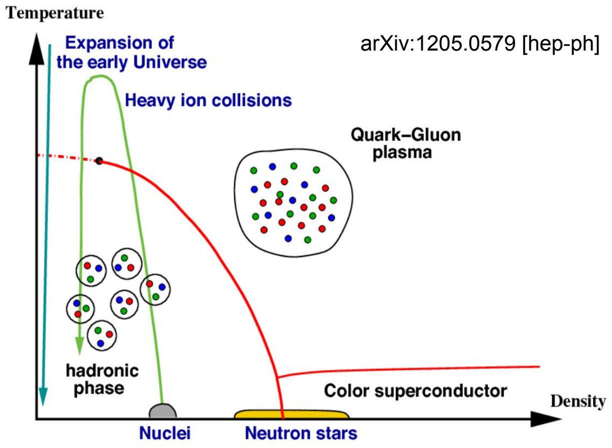
Chiral Symmetry Restoration in Heavy Ion Collisions (?)

(with dileptons and other tools)

Otón Vázquez Doce
Excellence Cluster Universe (TU-Munich)
Workshop Quantum Foundations, Frascati (Roma), November 30, 2017

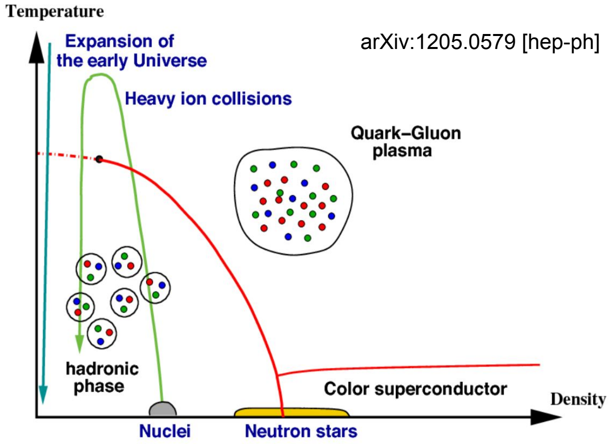
Heavy ion collisions in the QCD phase diagram

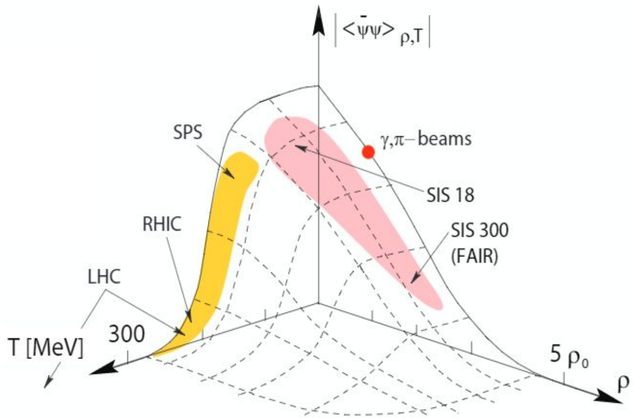


- High number of nucleons + small space + high energy
- The temperature in heavy ion collisions exceed 2×10^{12} K

- Heavy ion collision experiments allow to study a **deconfined phase of matter** and go back in time to the very early moments of the history of the Universe
  $T_c \sim 170$ MeV (T=1 MeV $\sim 10^{10}$K)

Heavy ion collisions in the QCD phase diagram





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- At high T/density: new state of strongly interacting matter.
- Lattice QCD calculation predict **chiral symmetry restoration at T ≲ deconfinement** phase transition

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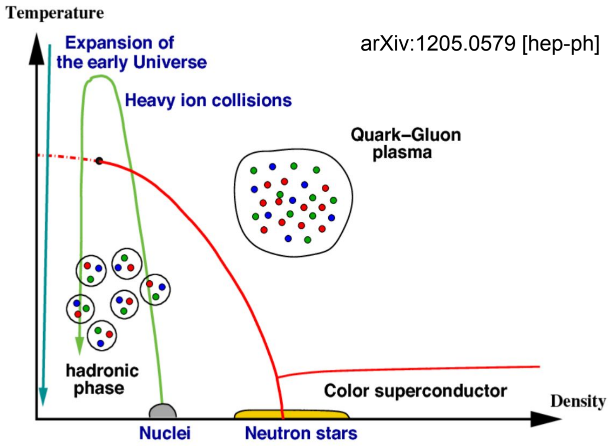

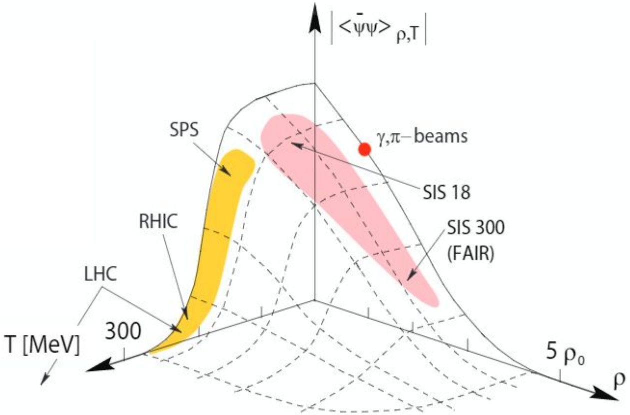

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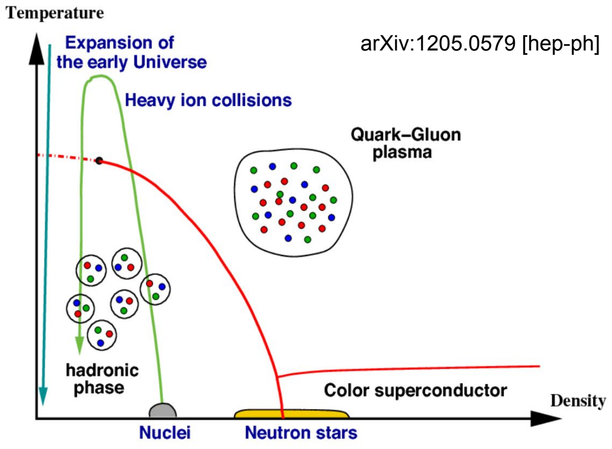

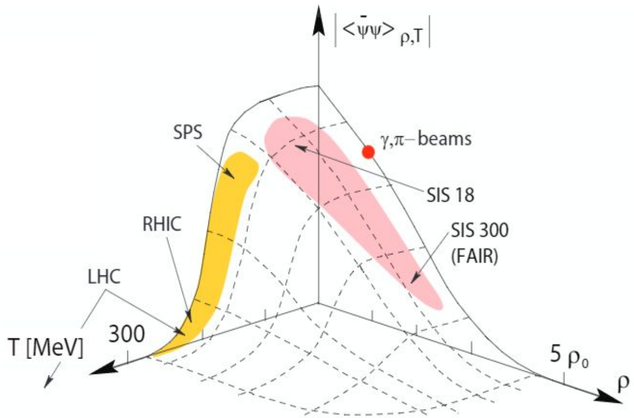

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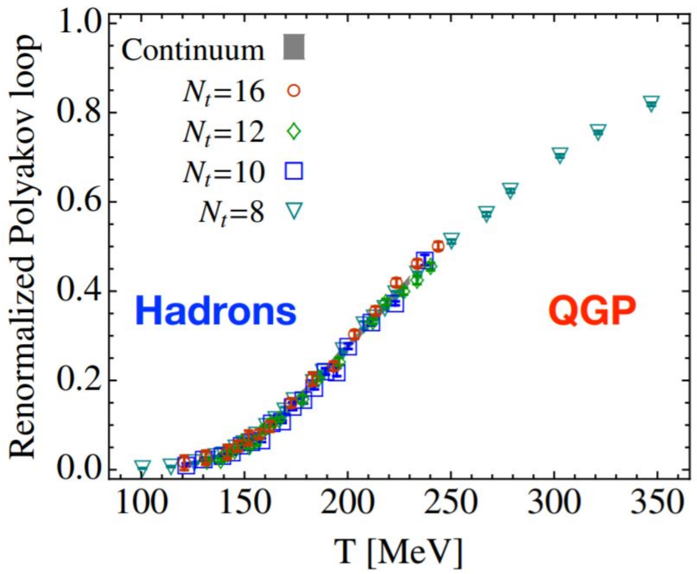
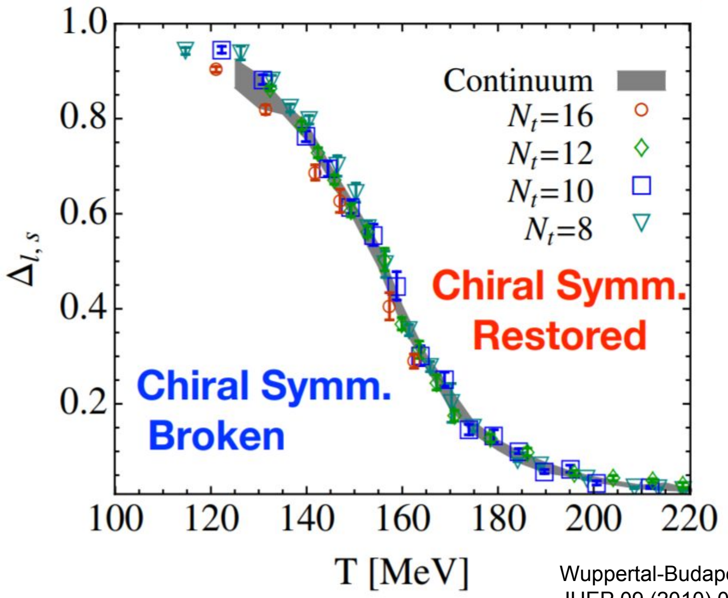
Heavy Ion Collisions at the **LHC**: μ_B=0:
directly comparable with Lattice QCD

Predicted QCD Phase Transitions

Order parameter of deconfinement



Order parameter of chiral symmetry

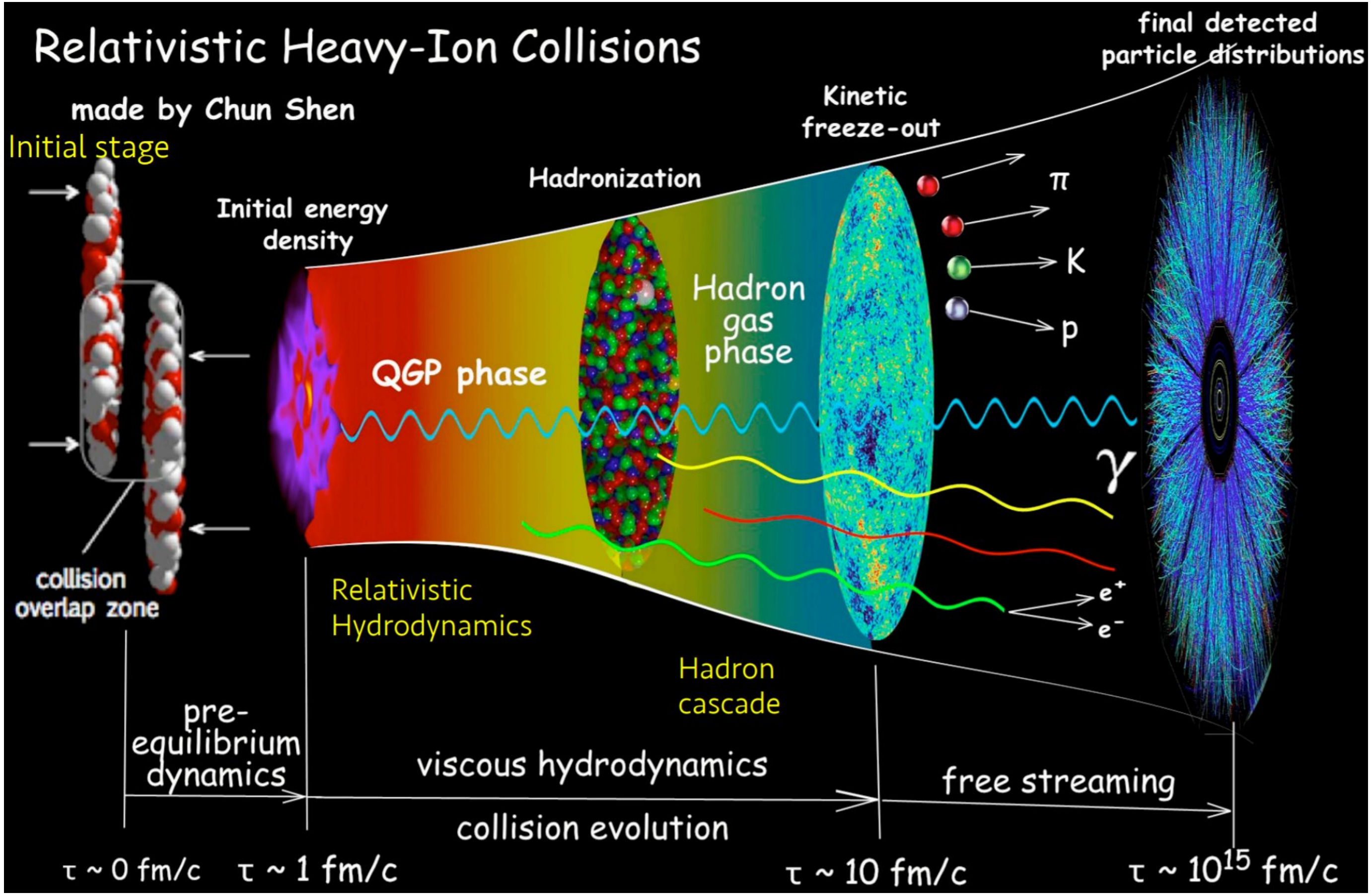


Wuppertal-Budapest Collaboration
JHEP 09 (2010) 073

Lattice QCD predicts **two phase transitions to occur at similar temperatures**

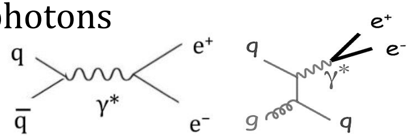
- **Deconfinement** → Quark Gluon Plasma
- **Chiral symmetry restoration** → effect on hadron masses

Heavy ion collisions

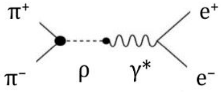


Dielectrons in HIC

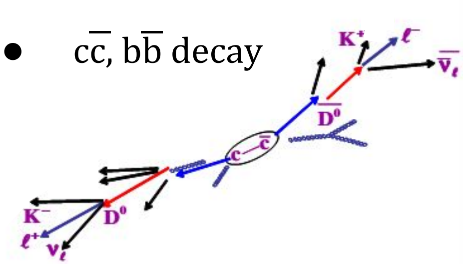
- Initial hard scattering: Drell-Yan (at LHC important from m_{ee}> 10 GeV/c^2)
- Thermal virtual photons
  - From QGP



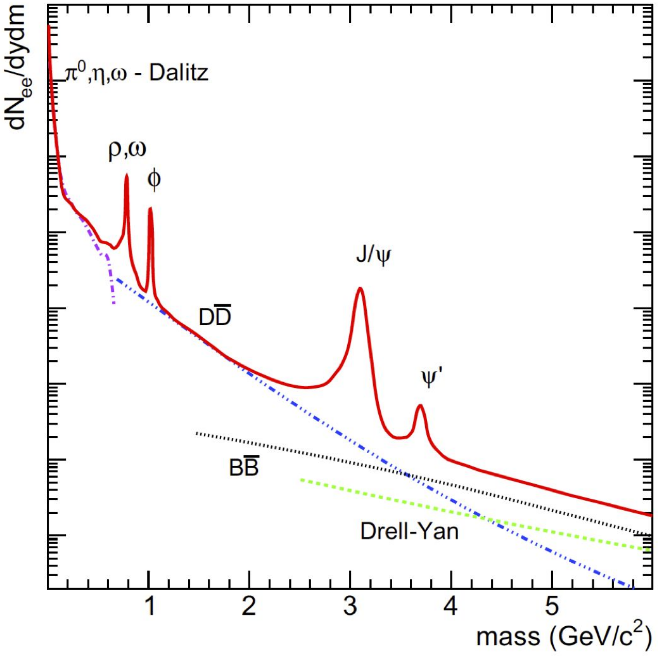
  - From hadron gas



- Hadron decays
- $c\bar{c}$, $b\bar{b}$ decay



A. Drees, Nucl. Phys. A830 (2009) 435



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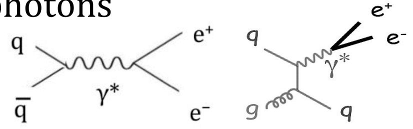

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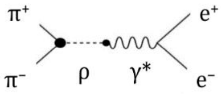

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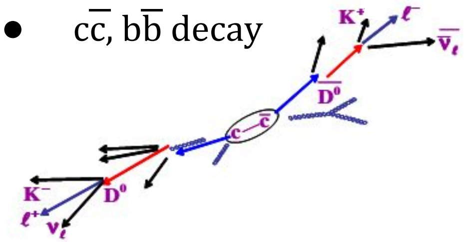

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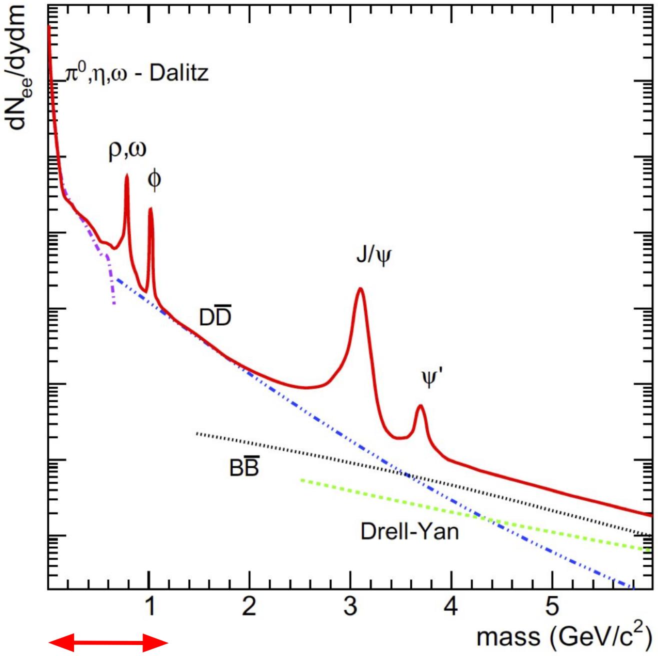

- In-medium **modification of vector mesons**
  - Connected to chiral symmetry restoration?
- **Thermal radiation**: quasi-real virtual photons (p_T>1GeV/c)

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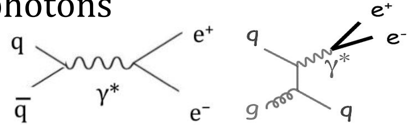

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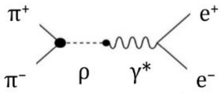

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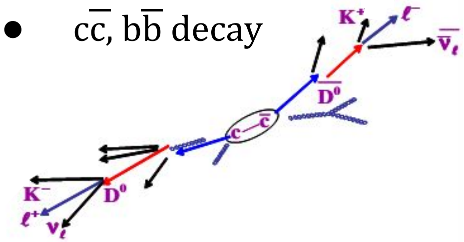

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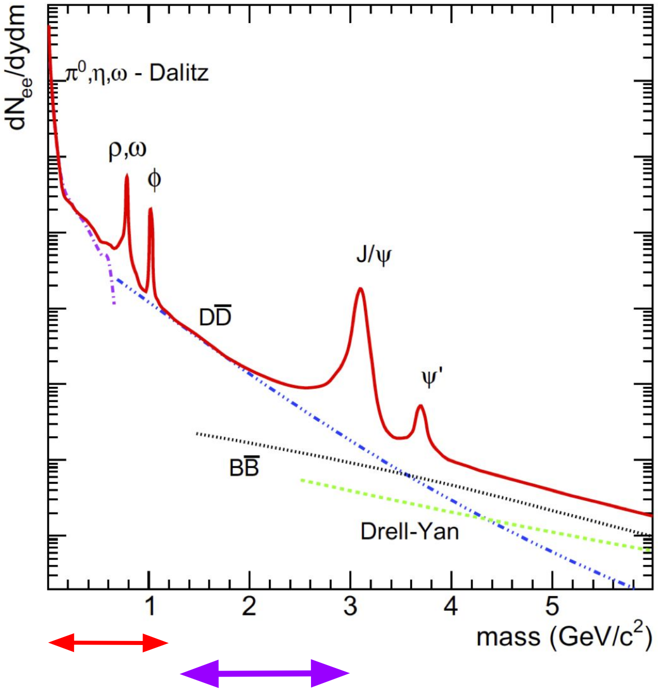

- vector mesons in medium, virtual direct photons
- **Thermal radiation from the QGP**
  $dN/dm_{ee} \sim \exp(-m_{ee}/T)$ (no Doppler shift from expanding medium)

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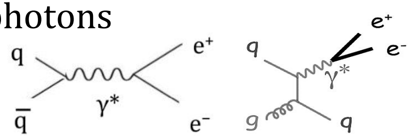

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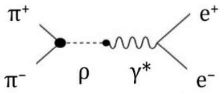

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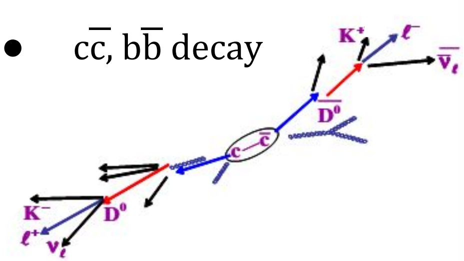

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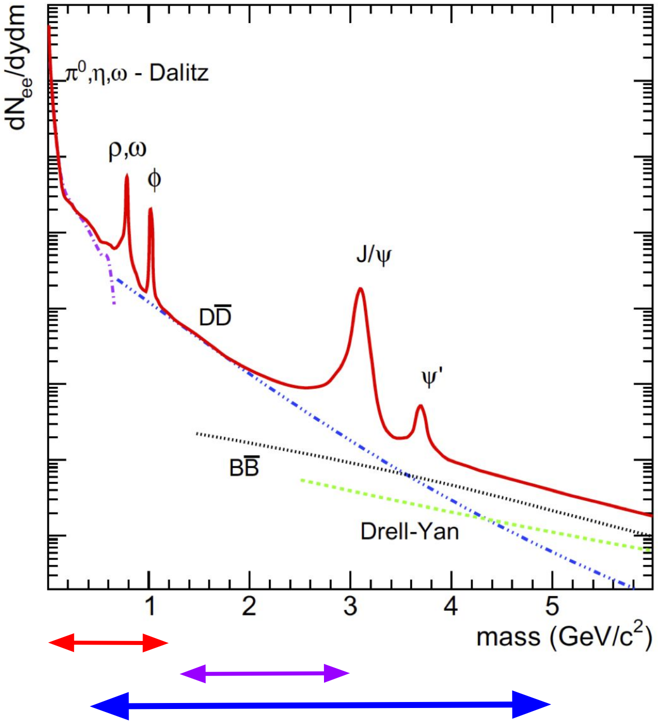


- vector mesons in medium, virtual direct photons
- Thermal radiation from the QGP
- **Semileptonic decays of open charm and beauty**
  - Heavy flavour cross sections
  - Heavy flavour production mechanism

Dominant from low mass at the LHC!

Probes for Chiral Symmetry restoration in HIC

- Requirement: carry hadron spectral properties from (T, ρ_B) to detectors
  - relate to hadrons in medium
  - leave medium without final state interaction

- Dileptons from vector meson decays

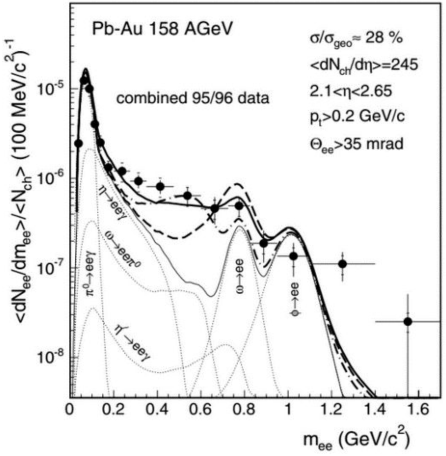
	m [MeV]	Γ_{tot} [MeV]	τ [fm]	BR→ee
ρ	770	150	1.3	4.7×10^{-5}
ω	782	8.6	23	7.2×10^{-5}
ϕ	1020	4.4	44	3.0×10^{-4}

Best candidate: ρ meson

- short lived (compare to τmedium = 10 fm/c)
- decay (and regeneration) in medium
- properties of in-medium ρ and of medium itself not well known

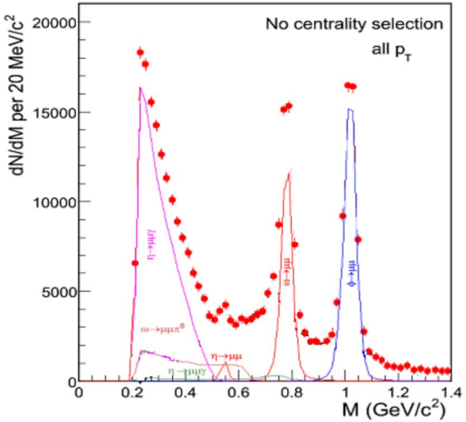
Dileptons before the LHC

CERES @ CERN SPS
Pb-Au $\sqrt{s_{NN}}$=17 GeV
- M_{ee} excess in the ρ region



Eur. Phys. J. C 41, 475–513 (2005)

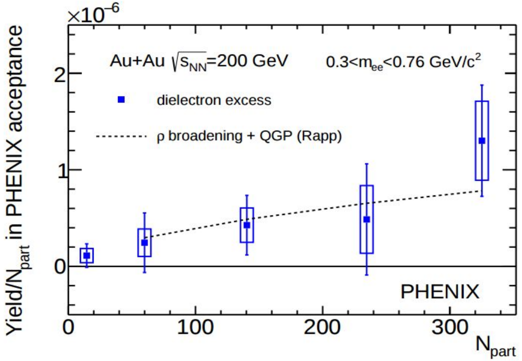
NA60 @ CERN SPS
In-In $\sqrt{s_{NN}}$=17 GeV
- Excess spectrum in low mass dimuons.



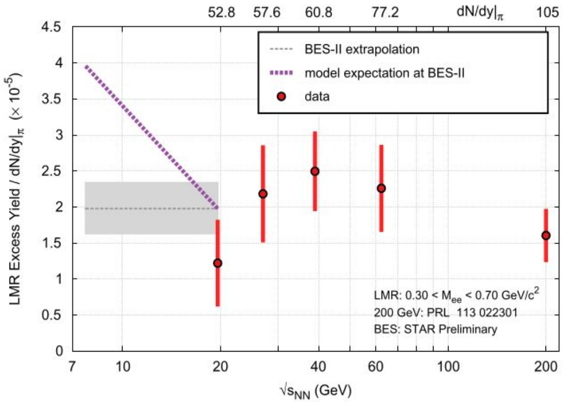
PRL 96, 162302 (2006)

PHENIX @ RHIC
Au-Au √sNN=200 GeV
- Centrality dependence of the LMR excess

arXiv:1509.04667



STAR @ RHIC
Au-Au $\sqrt{s_{NN}}$=200 GeV
- Energy scan of LMR excess



arXiv_1409.5675

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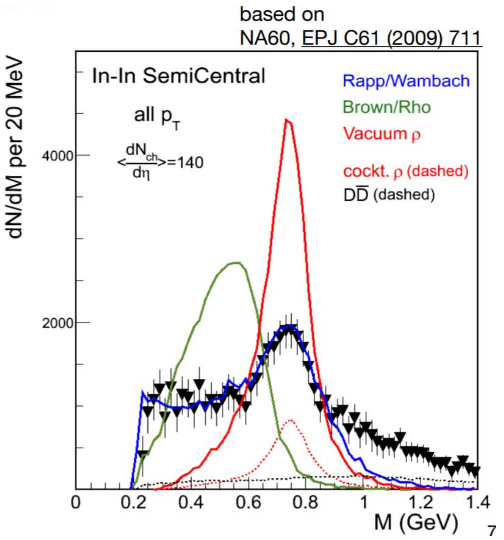
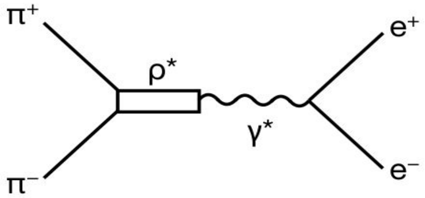


NA60 @ CERN SPS
In-In $\sqrt{s_{NN}}$=17 GeV

- Low mass enhancement due to ππ annihilation?
 Spectral shape dominated by ρ meson



- **Vacuum ρ**
  - Vacuum values of width and mass

- **In-medium ρ**
  - Brown-Rho scaling
    - **Dropping masses** as chiral symmetry is restored
  - Rapp-Wambach melting resonances
    - hadronic collision **broadening of spectral function**
    - small contribution from the QGP (qq annihilation) in the form of thermal radiation
    - Only indirectly related to CSR
    - **Data consistent with broadening**

- From STAR+PHENIX @ RHIC:
  - No strong E dependence: ρ coupling to baryons (total baryon density nearly constant)
  - Low mass region dielectron elliptic flow consistent with hadron v_2 (late emission).

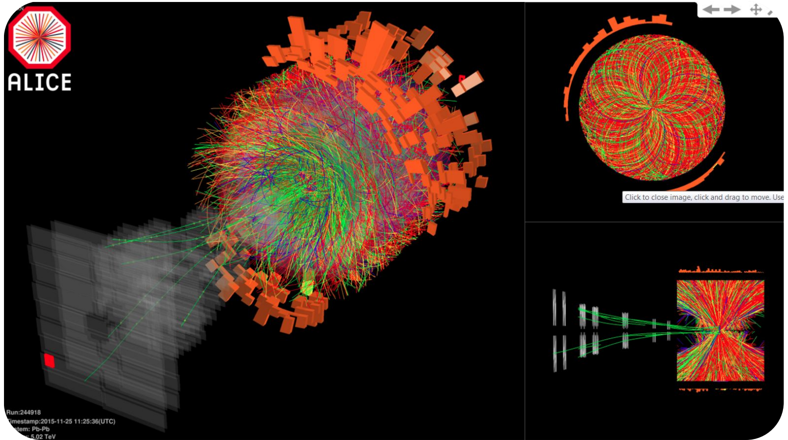
The ALICE experiment at the LHC

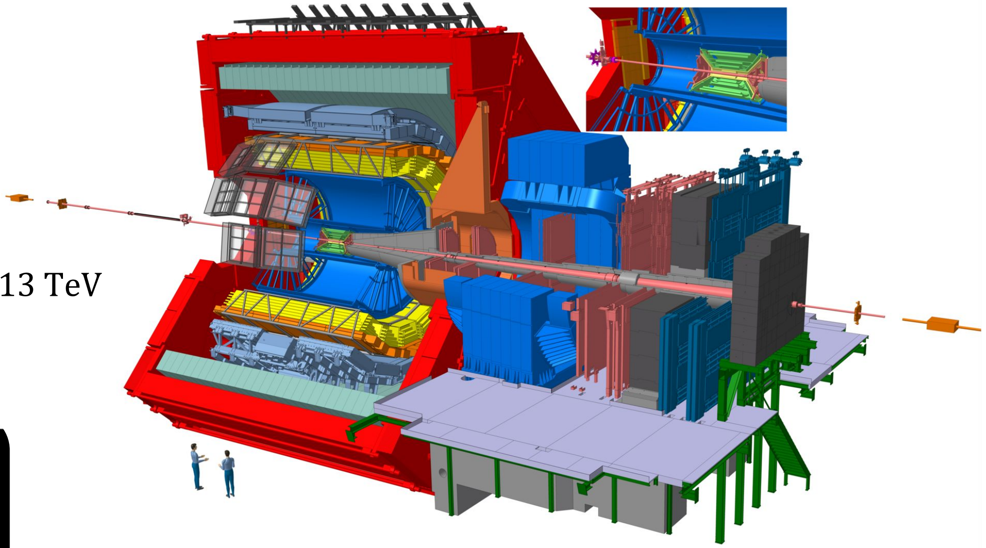
A Large **I**on **C**ollider **E**xperiment

- Investigate the QGP properties in Pb-Pb collisions at the LHC

Collected data by ALICE during Run-1 and Run-2

- pp collisions $\sqrt{s}$ = 2.76 TeV, 5.02 TeV, 7 TeV, 8 TeV, 13 TeV
- p-Pb collisions $\sqrt{s_{NN}}$= 5.02 TeV, 8.16 TeV
- **Pb-Pb** collisions $\sqrt{s_{NN}}$ = **2.76 TeV, 5.02TeV**





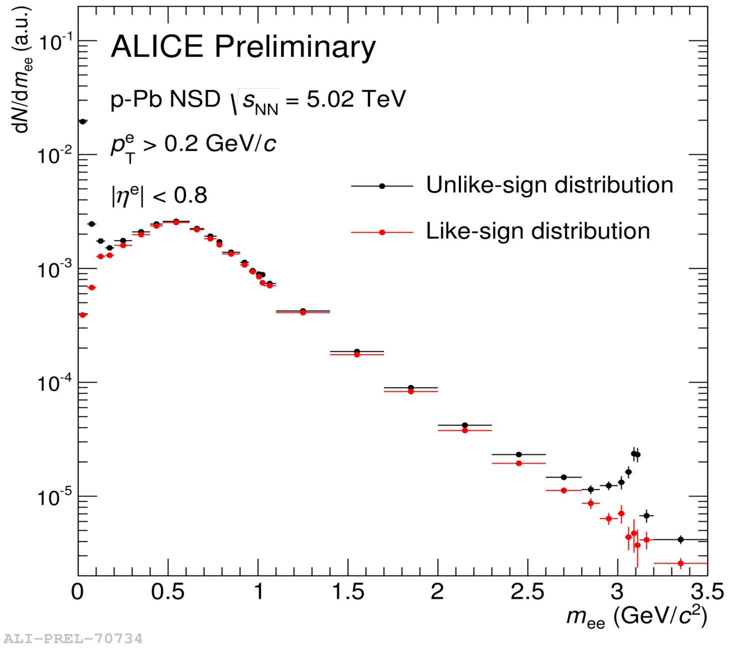
Dielectron signal extraction

Raw yield $N^{+-} \rightarrow$ **"ULS" = Signal** + $B_{combinatorial}$

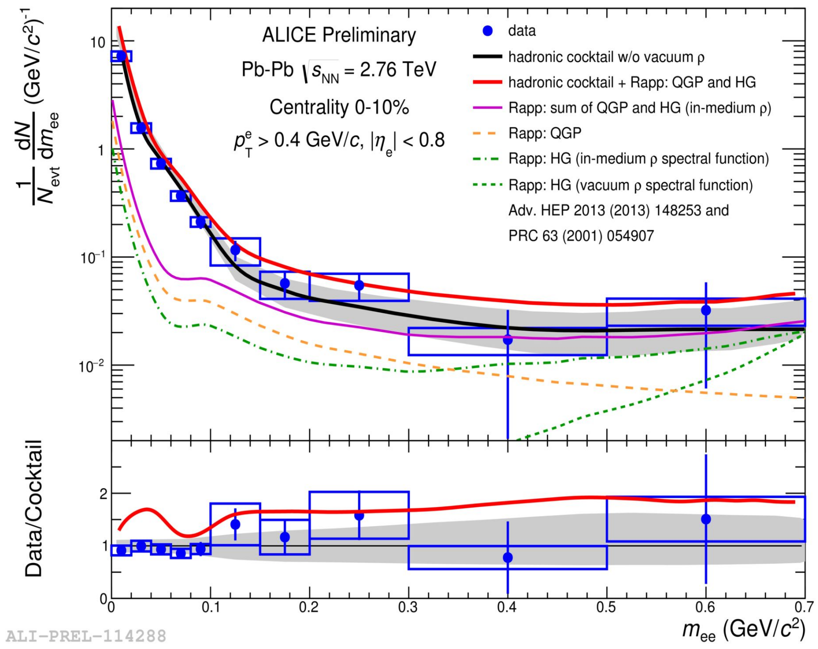
"LS" = $B_{combinatorial}$ = $B_{correlated}$ + $B_{uncorrelate}$

Correlated background: e. g. double Dalitz decay, jets.

Uncorrelated background: random electron combinations



ALICE preliminary results: Pb-Pb $\sqrt{s_{NN}}$= 2.76 TeV



LHC Run-1 data (2011): 18 M events 0-10% cent.

→ **Data** vs hadronic cocktail + (**QGP**+**HG**) **radiation**

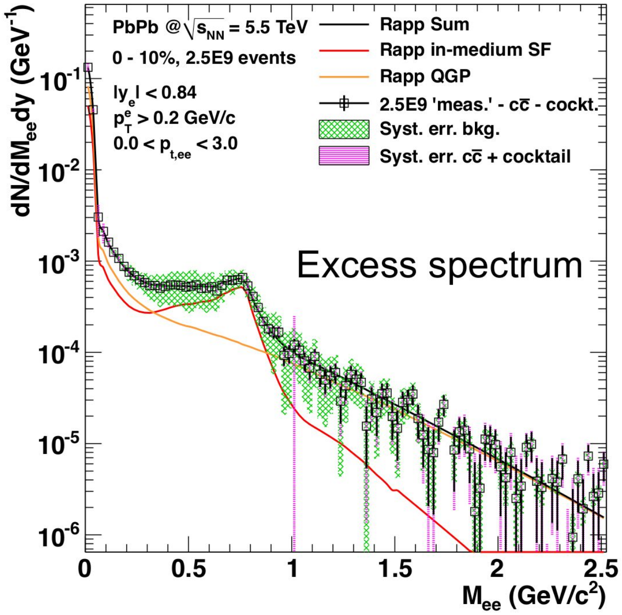
- Cocktail without vacuum ρ and ω
- HG include in-medium modified ρ and ω spectral function
- QGP: expanding fireball model with T_C = 170 MeV

R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253

R. Rapp, Phys. Rev. C63 (2001) 054907

- No sensitivity yet for possible thermal radiations from QGP and hadron gas
- Run-2 analysis and especially Run-3 (upgrades) will allow significant measurements

ALICE upgrade for Run-3: dielectrons



J. Phys. G 41 (2014) 087002

Upgrade of the central tracking system (ITS and TPC)

- Reduced material budget(**x4**)
- improved vertex resolution (**x3**)
- higher readout rate (**x100** for the TPC)
- Increase low m_T acceptance with low B (0.2 T) run

● Vertex-cut reduce heavy flavour contribution

● **Precise measurement of the effective temperature at early times** become feasible

● **Access to ρ in-medium spectral function** → Unique measurement at $\mu_B \sim 0$

Exponential fit for m_{ee}>1.1GeV/c^2

$$dN/dm_{ee} \sim e^{-m/T}$$

slope **precision ±10% stat ±10-20% syst**

pp collisions @13TeV: baseline...and high multiplicity events effects

nature physics

LETTERS

PUBLISHED ONLINE: 24 APRIL 2017 | DOI: 10.1038/NPHYS4111

OPEN

Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions

ALICE Collaboration†

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ALICE

Excellence Cluster Universe

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First dielectron analysis of high multiplicity events in pp

New phenomena in high multiplicity pp events?

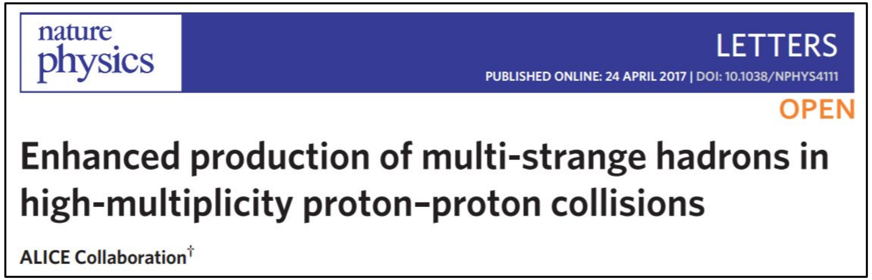
- Production / destruction of ρ meson, direct photons, open heavy flavour… ?

- Idea: produce a ratio of (uncorrected) dielectron spectra:

$$\frac{N_{ee}(\mathrm{HM})/\langle N_{ch}(\mathrm{HM})\rangle}{N_{ee}(\mathrm{MB})/\langle N_{ch}(\mathrm{MB})\rangle}$$

- Naive expectation (for light flavour): signal ~ N_{ch}

pp collisions @13TeV: baseline...and high multiplicity events effects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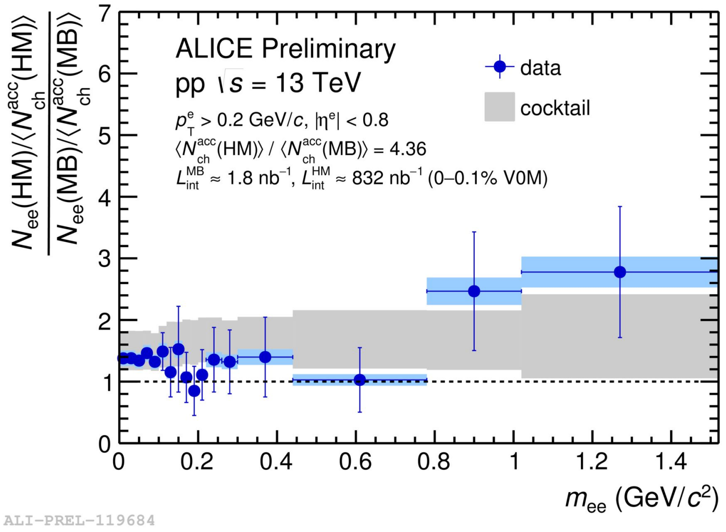
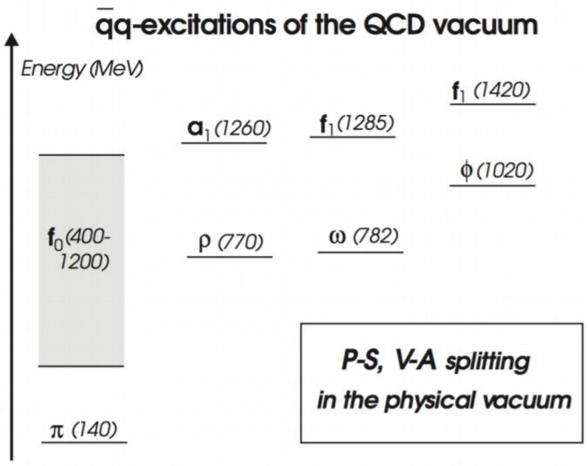
- Intermediate mass: in **agreement with D-meson enhancement from pp @ 7 TeV**
  - **Low mass: ratio > 1 due to change of hadron p_T** spectrum and acceptance cut
  - Analysis of more data (x5) is ongoing



Chiral Symmetry Restoration: Chiral partners

- Chiral Symmetry breaking causes mass difference for chiral partners (e.g. 500 MeV between ρ and a1)



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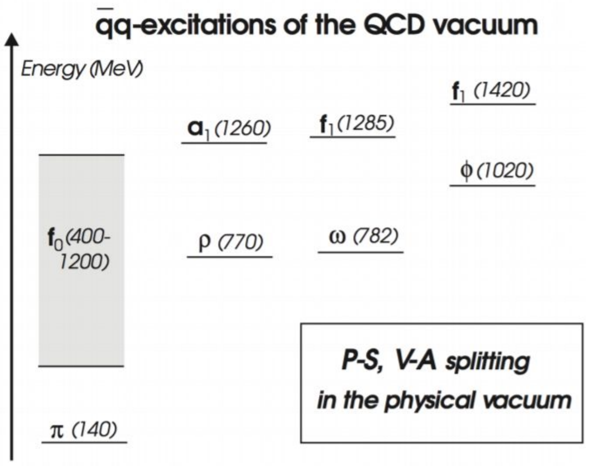
  - ρ broadening confirmed at RHIC, but do not need chiral symmetry to cause “collisional” broadening
  - Evidence for restoration at most indirect



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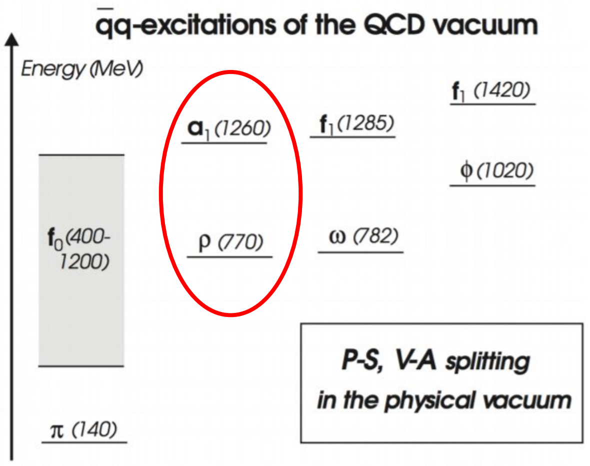
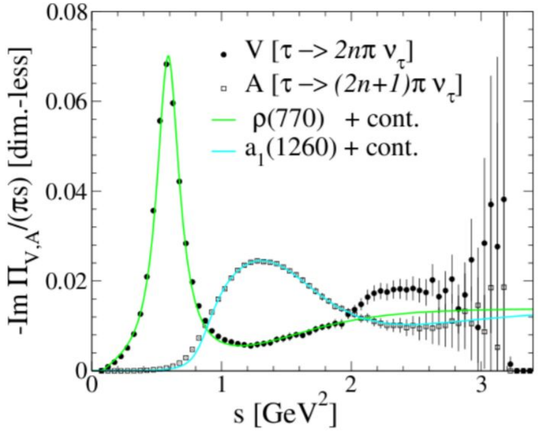
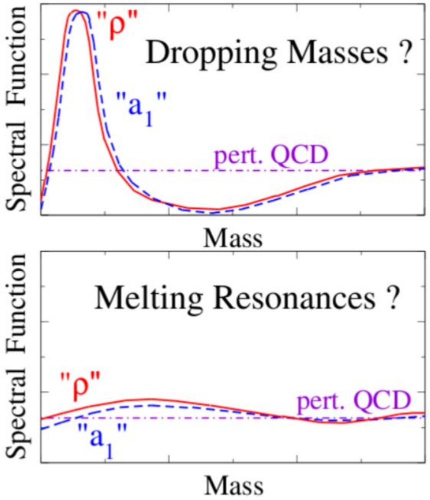


- Whatever the scenario is for ρ (broadening, dropping mass):
  - **When Chiral Symmetry is restored: chiral partners degenerate**





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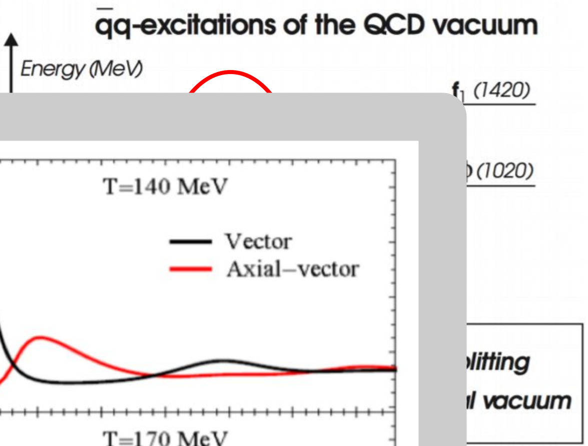
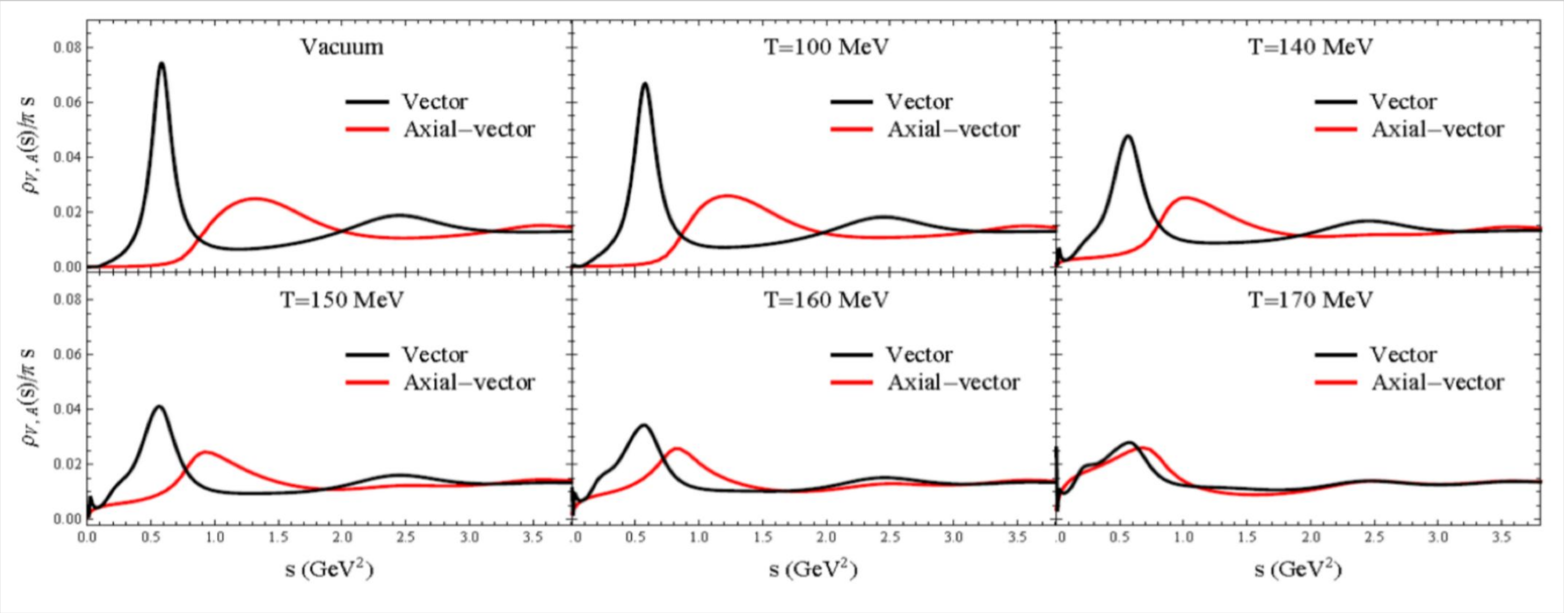
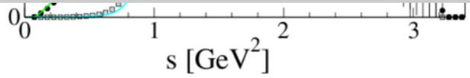
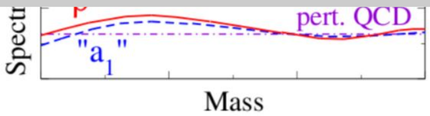
- Chiral Symmetry breaking causes mass difference for chiral partners (e.g. 500 MeV between ρ and a1)









ALICE experiment summary

Low-mass dielectrons measurements are been performed with ALICE at the LHC in all collision systems:

- Pb-Pb Run-1:
  - No sensitivity for excess in the ρ region yet

- Run-2 analysis ongoing.
  - Employ MVA methods to improve signal efficiencies and purities
  - **Study dielectron production for the first time in pp High Multiplicity events.**

ALICE will implement major tracking hardware upgrades: ITS and TPC from the upcoming Run-3

- Independent & complementary measurement of temperature in different mass regions
- Precise measurement of the **effective temperature at early times** become feasible
- **Access to ρ in-medium spectral function → Unique measurement at μ_B~0**