Dileptons and Photons

Messengers from strongly interacting matter under extreme conditions

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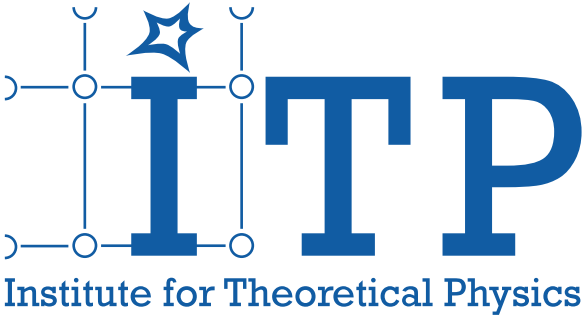
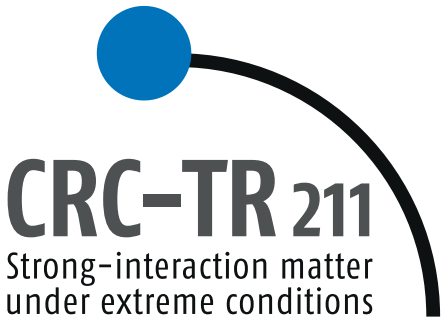




Outline

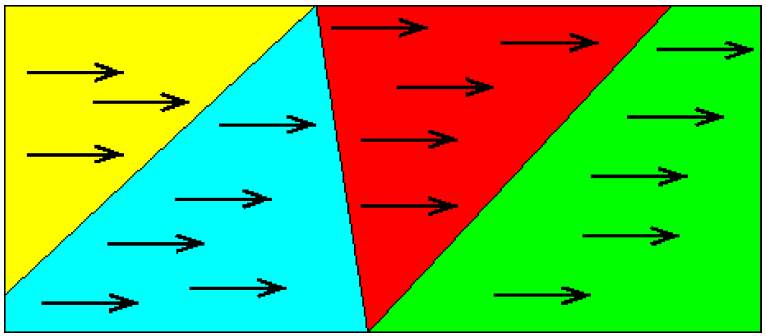
The Beauty of Nature: Symmetries

Symmetry of Natural Laws and Conservation Laws

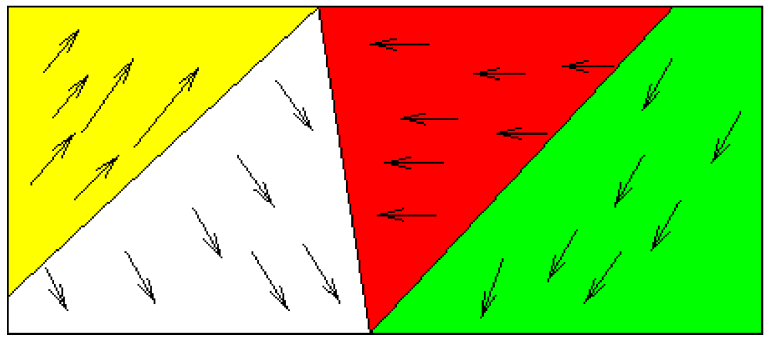
- Emmy Noether: symmetries $\Leftrightarrow$ conservation laws
  - Equation of motion unchanged under symmetry transformation $\Leftrightarrow$ conserved quantity
- Example 1: Natural Laws do not change with time (equations look the same at any time) $\Rightarrow$ Conservation of Energy
- Example 2: Natural Laws do not change with position (equations of motion look the same at any place) $\Rightarrow$ Conservation of momentum

Spontaneous Symmetry Breaking

- Equations symmetric, but not the state of lowest energy
- more than one state with lowest energy ⇒
  massless (quasi-)particles: Nambu-Goldstone bosons
- Conservation law still true, but symmetry not realized
- example: rotating a piece of iron, no change of laws for atoms
- permanent magnet ⇒ magnetization specifies a direction
- magnetization ⇔ order parameter for rotational symmetry
- state not symmetric ($\vec{M} \neq 0$) ⇒ spontaneously broken phase
- Heating the magnet ⇒ looses magnetization
- Phase transition ⇒ symmetry restored $\vec{M} = 0$



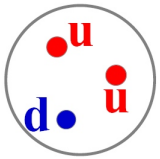
heating ⇒



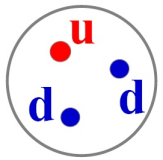
Elementary Particles and the Standard Model

Subatomic particles

- electrons are elementary
- atomic nucleus is composed of nucleons (protons and neutrons)
- nucleons made of up and down quarks

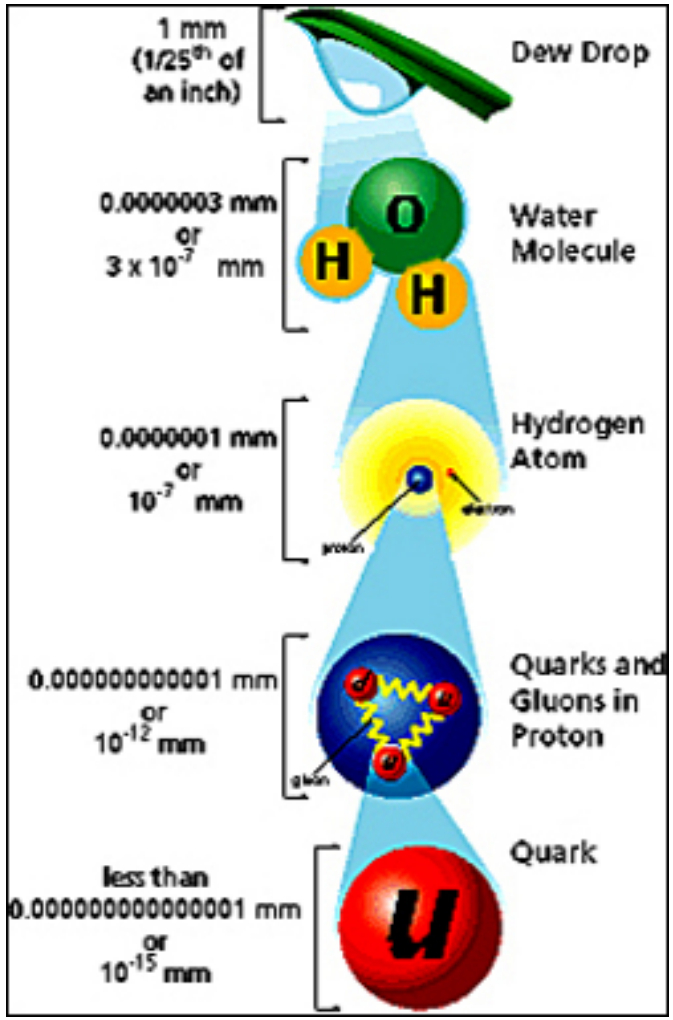


proton = (uud)



neutron = (udd)

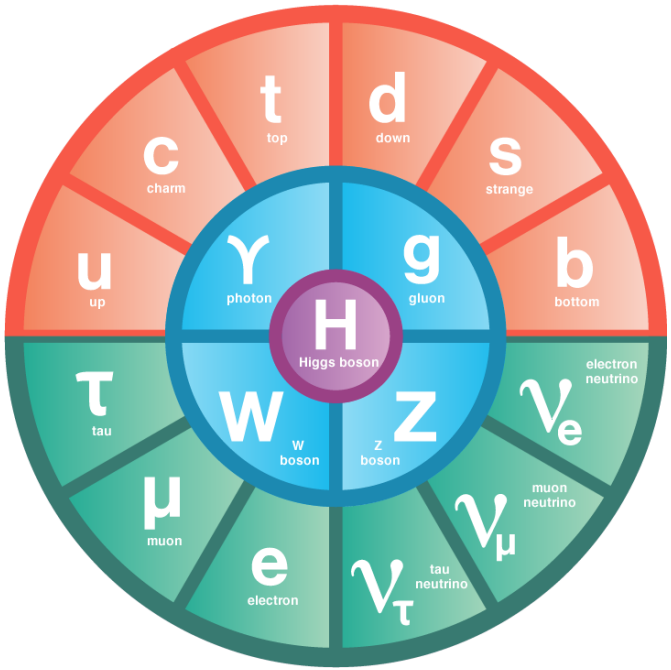
- up quark: charge $+2/3$, mass $m_{\mathrm{u}} = 3\,\mathrm{MeV}/c^2$
  down quark: charge $-1/3$, mass $m_{\mathrm{d}} = 6\,\mathrm{MeV}/c^2$
  electron: charge -1, mass $m_{\mathrm{e}} = 0.5\,\mathrm{MeV}/c^2$
- BUT: nucleon mass $m_{\mathrm{p}} \simeq m_{\mathrm{n}} = 940\,\mathrm{MeV}/c^2$



[http://www.particlecentral.com/particle_page.html]

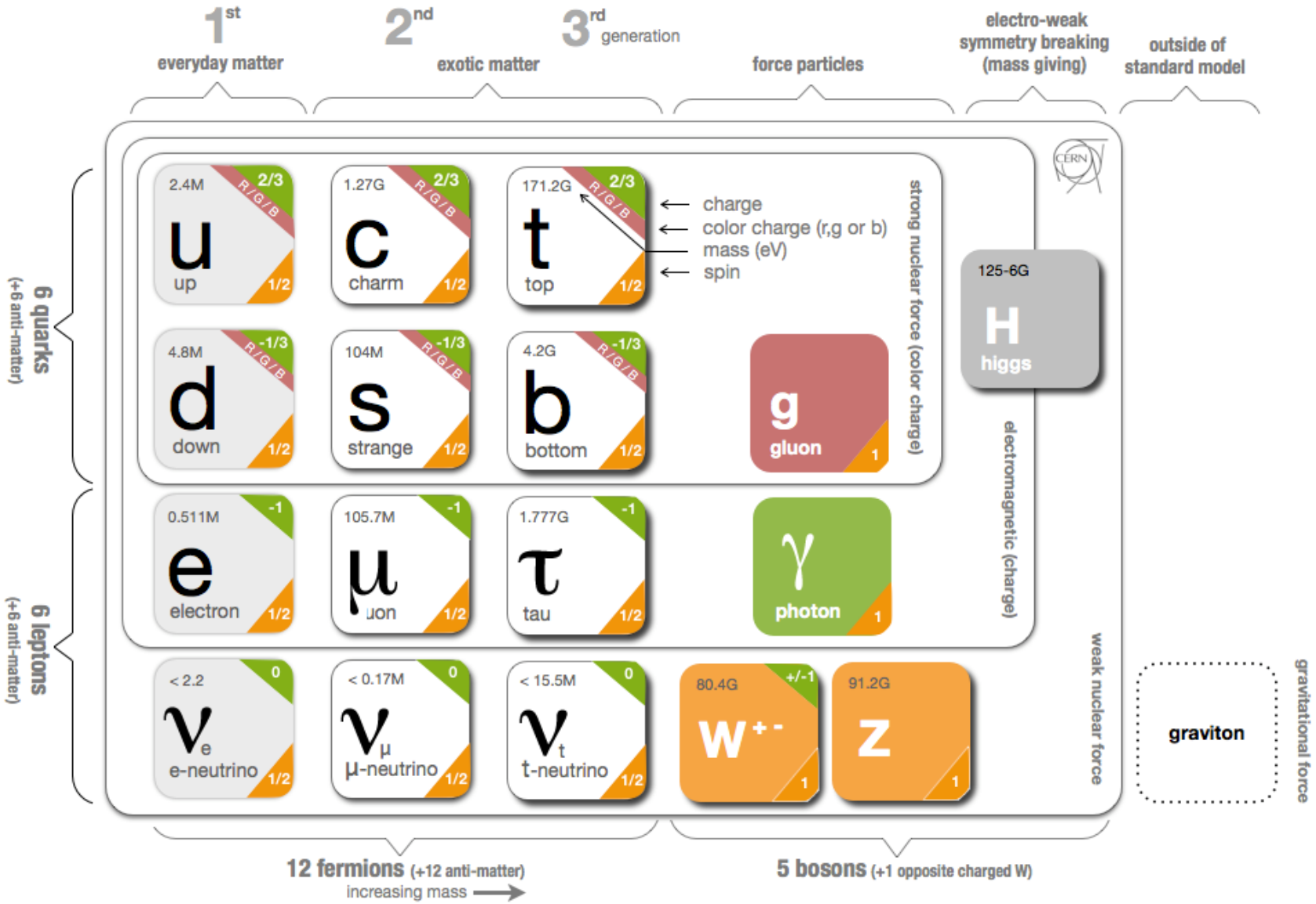
Elementary Particles and Fundamental Interactions

- What holds the particles together (forming matter)?
- Fundamental forces or interactions
- Laws ruled by (local gauge) symmetries!
  $\Rightarrow$ Standard Model of elementary particle physics
- e.g. electric charge conserved $\Leftrightarrow$ "Force Carrier" (wave fields $\longleftrightarrow$ particles) for electromagnetic interaction Photon



- strong interaction: QCD, $SU(3)_{color}$
  interaction of quarks via gluons
- electroweak interaction: QFD,
  $SU(2)_{wiso} \times U(1)_{hyper}$ "Higgsed" to $U(1)_{em}$
  interaction of quarks and leptons via
  massive $W_{\pm}$, Z_0 and γ
  Higgs field $\langle H \rangle_0 \neq 0$:
  provides all "elementary masses"
  Higgs-field excitations: massive spin-0
  Higgs boson (discovered in 2012)

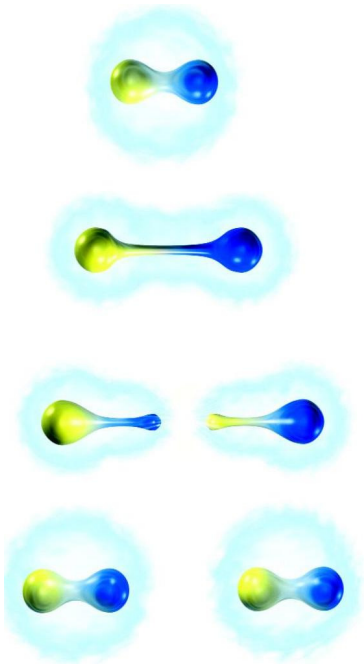
The standard model in a nutshell: particles and forces



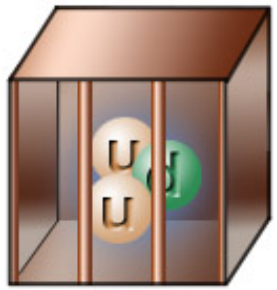
[graphics from http://www.isgtw.org/spotlight/go-particle-quest-first-cern-hackfest]

Quantum Chromo Dynamics

- no free quarks and gluons seen!
- always confined in color-less objects
- hadrons: baryons (qqq) and mesons ($q\bar{q}$)
- trying to free q and $\bar{q}$ from a meson:



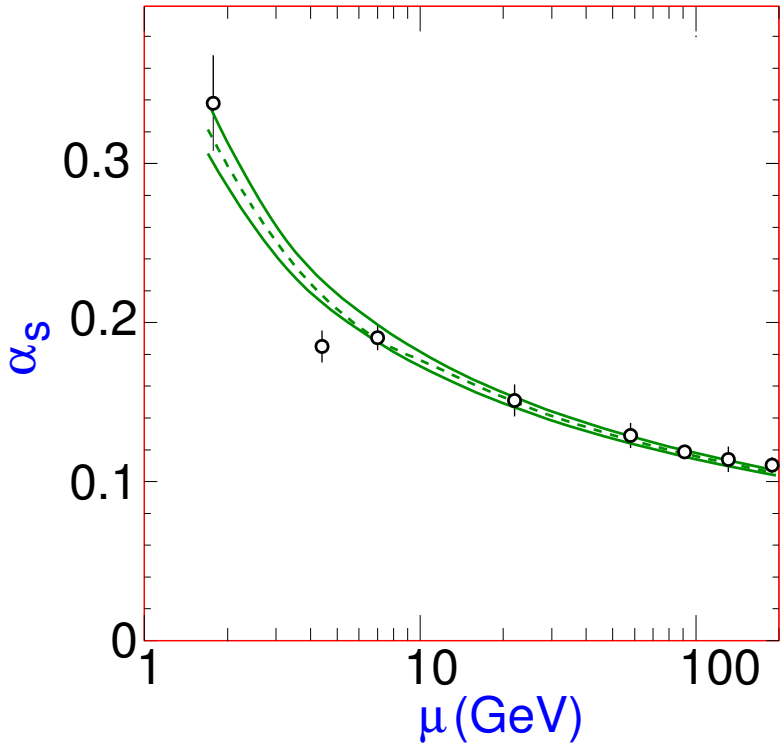
- interaction becomes very strong at large distances
- rather create new hadrons than breaking colored objects free!



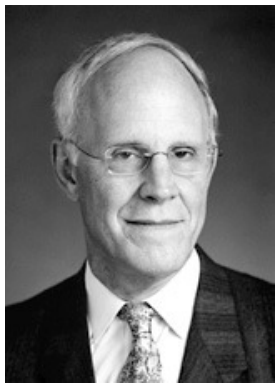
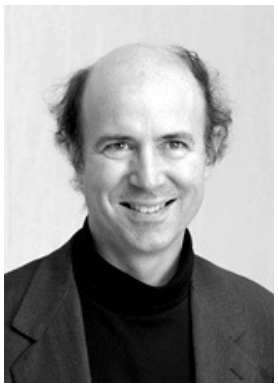
- quarks confined in hadrons
- 1973: Gross and Wilczek, Politzer
- build theory based on color symmetry!
- force becomes stronger for longer distances/low collision energies
- reason: force carriers themselves have color

Quantum Chromo Dynamics

- from color symmetry of quarks (color charge conserved)
- force carriers: gluons (spin 1)
- matter particles: quarks (spin 1/2)
- theory called Quantum Chromo Dynamics (QCD)
  (Greek: chromos=color)
- force becomes weaker at small distances/high energy
- "asymptotic freedom" (from perturbative QCD)



Nobel prize in physics 2004:


Gross, Wilczek, Politzer

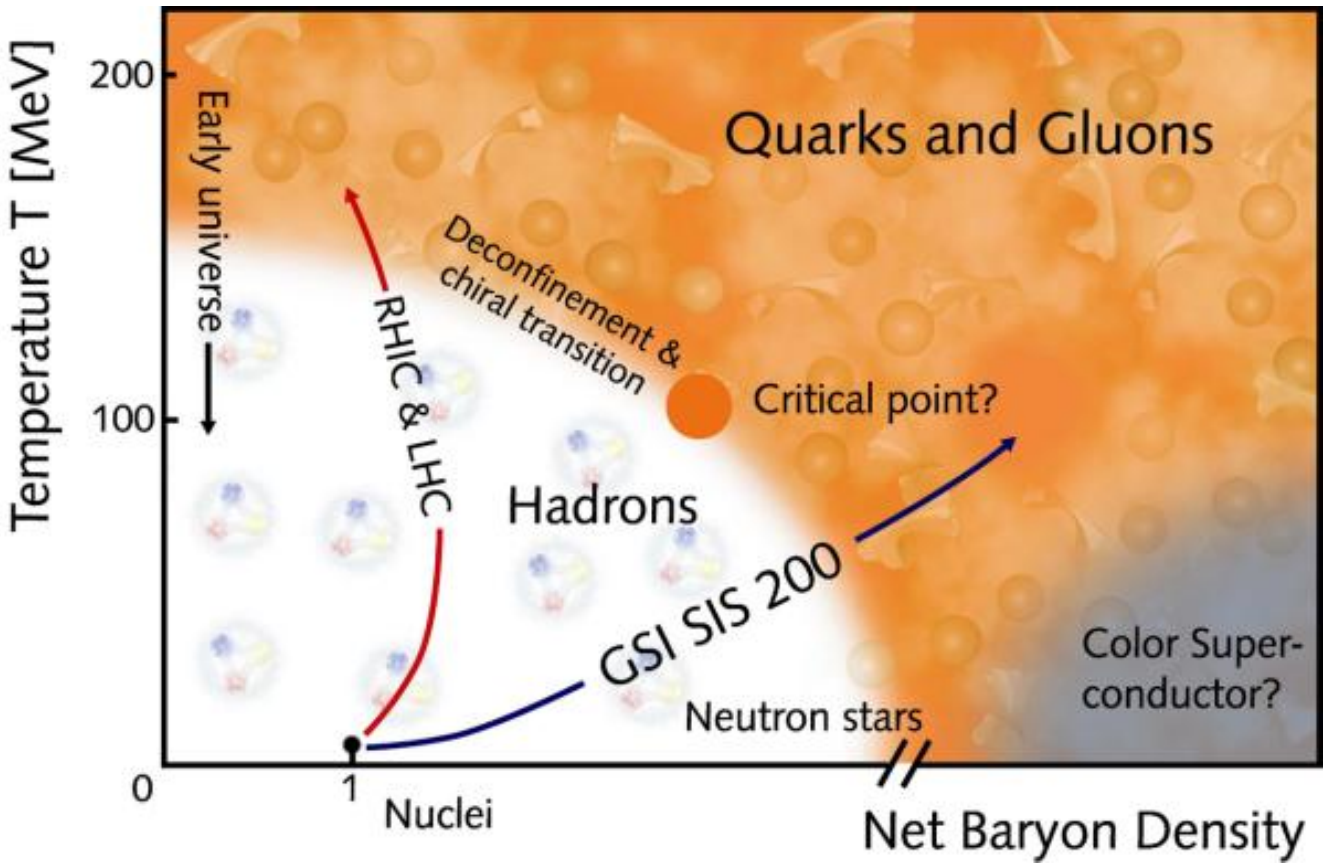
"Accidental" Symmetries of QCD

- chiral symmetry
  - light-quark sector: $m_q \ll m_{\text{had}} \Rightarrow$ approximate chiral symmetry
  - strong interaction: $\langle \overline{q} q \rangle_{\text{vac}} \neq 0$ (quark condensate)
  - chiral symmetry spontaneously broken (order parameter = quark condensate)
  - pions (pseudo-)Nambu-Goldstone modes: $m_\pi^2 f_\pi^2 = -m_q \langle \overline{q} q \rangle_{\text{vac}}$
- scaling symmetry
  - classical field theory: in limit of massless quarks no scale
  - symmetry under scale transformations
  - Noether: trace of energy-momentum tensor $T^\mu{}_\mu = 0$
  - quantization: need to introduce renormalization scale
  - scale invariance broken explicitly by quantization (anomaly)
  - $\langle T^\mu{}_\mu \rangle \neq 0$; $\propto$ gluon condensate + $m_{\text{q}} \times$ quark condensate
  - $\langle \text{nucleon} | T^\mu{}_\mu | \text{nucleon} \rangle = m^2_{\text{nucleon}}$ [Rob17]

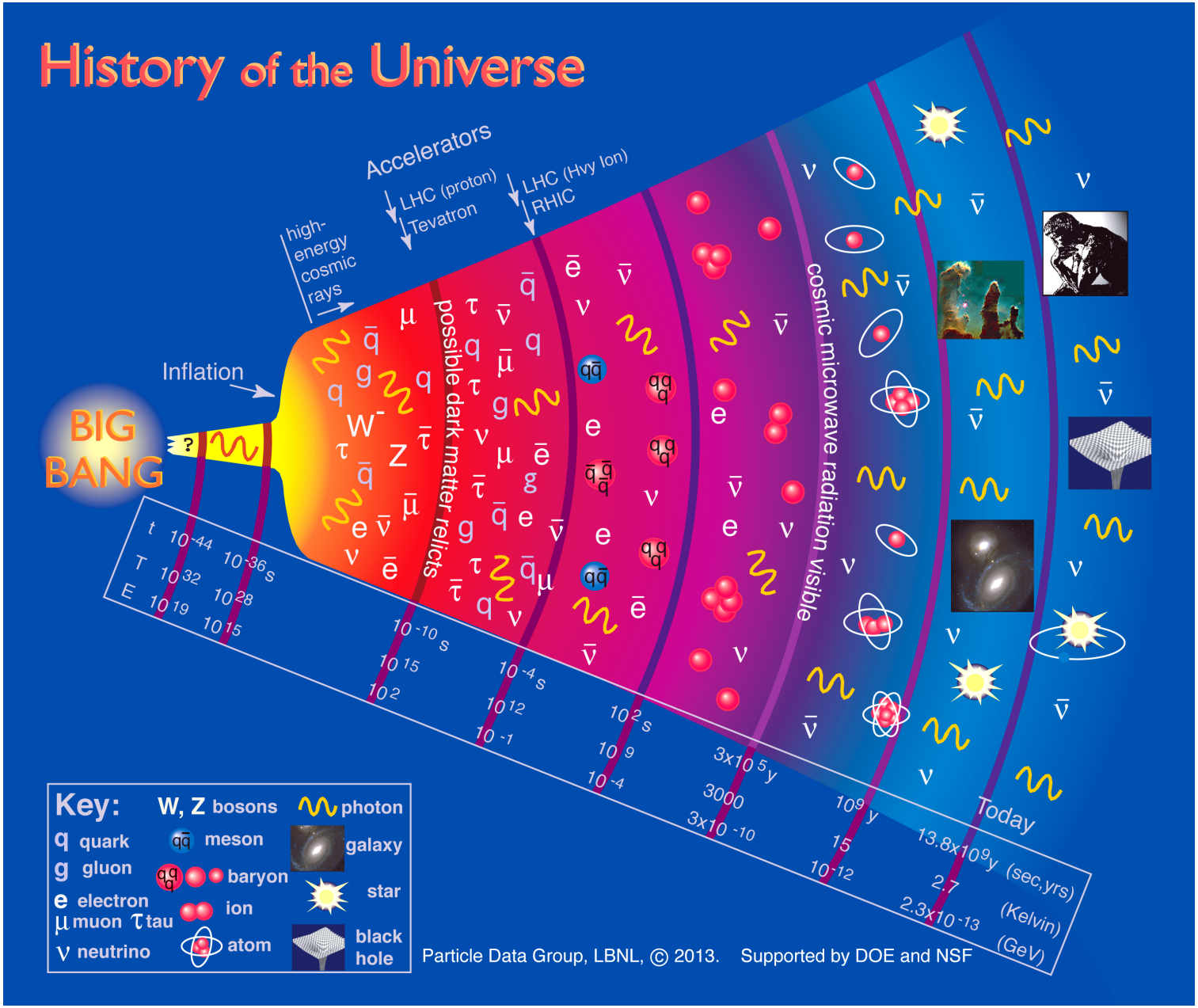
Heavy-Ion Collisions and the Quark-Gluon Plasma

QCD Phase diagram

- lots of quarks and gluons close together
- dense and hot environment ⇒ strong force becomes weaker!
- quarks and gluons move freely in medium ⇒ quark-gluon plasma (QGP)
- QCD at high temperatures and densities
- $\bar{q}q$ condensate disolves (phase transition/cross over!)
- chiral symmetry restored

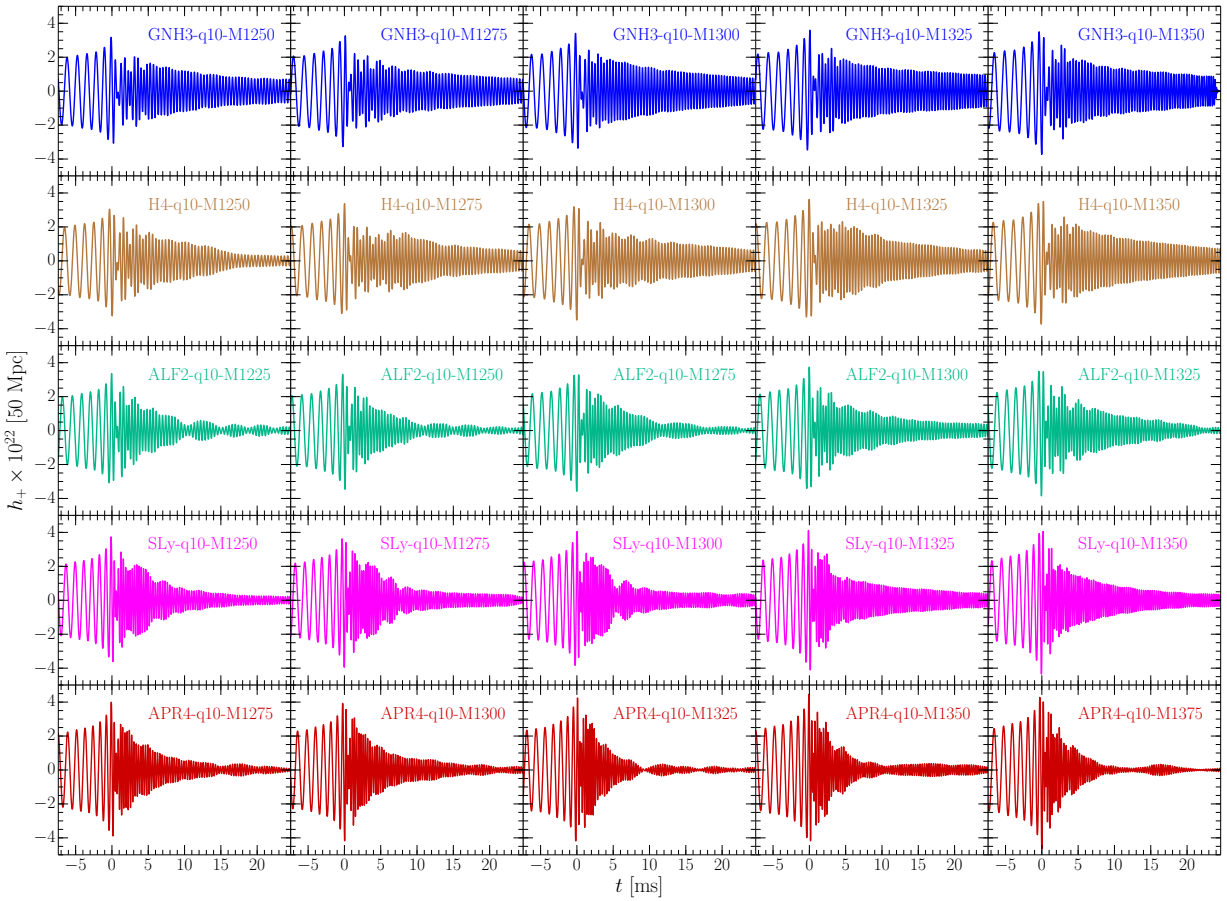


Evolution of the Universe



Neutron Stars and Neutron-Star mergers

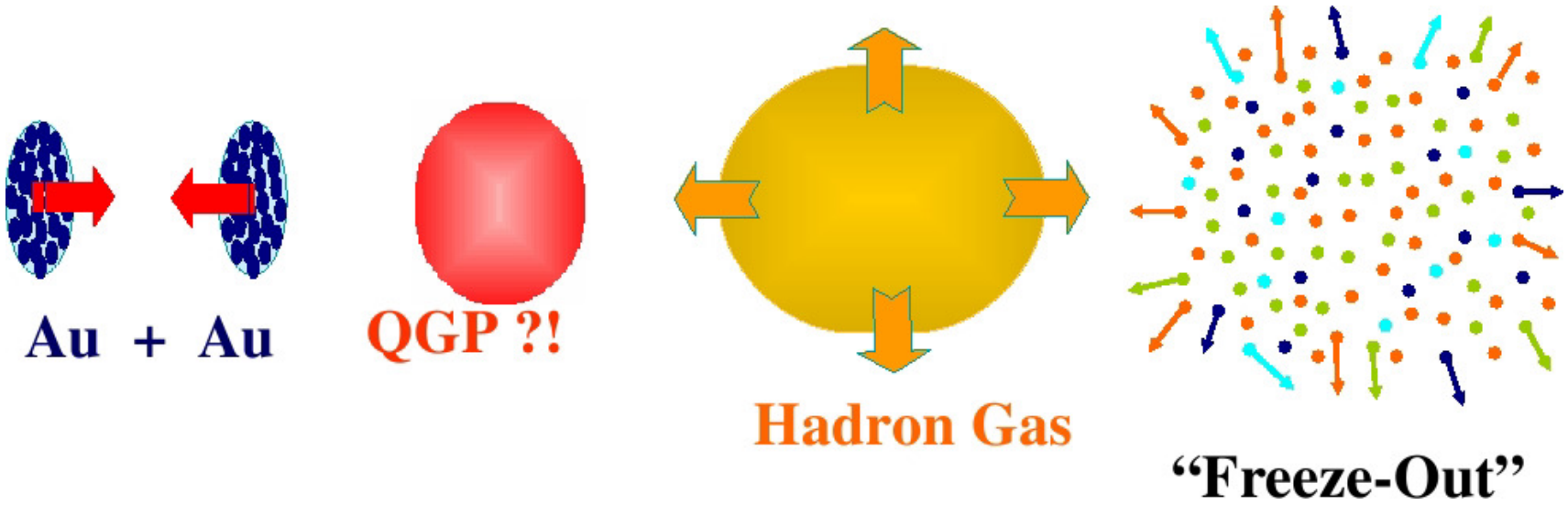
- neutron stars: cool dense matter $n = 2\text{-}3 n_0$)
- neutron-star mergers: two neutron stars circling around each other
  - loose energy through gravitational wave emission
  - crash together dectable graviational waves (LIGO/VIRGO)
  - details of wave form $\Leftrightarrow$ QCD equation of state!



GR simulation from K. Takami, L. Rezzolla, and L. Baiotti (2015); (review: [BR17])

Ultra-relativistic heavy-ion collisions

- highly energetic collisions of (heavy) nuclei
- many collisions of partons inside the nucleons
- creation of many particles ⇒ hot and dense fireball
- generation of the Quark-Gluon Plasma (QGP)?
- properties of QGP and/or compressed baryonic matter?
- signatures of 1st-order phase transition (critical end point)?

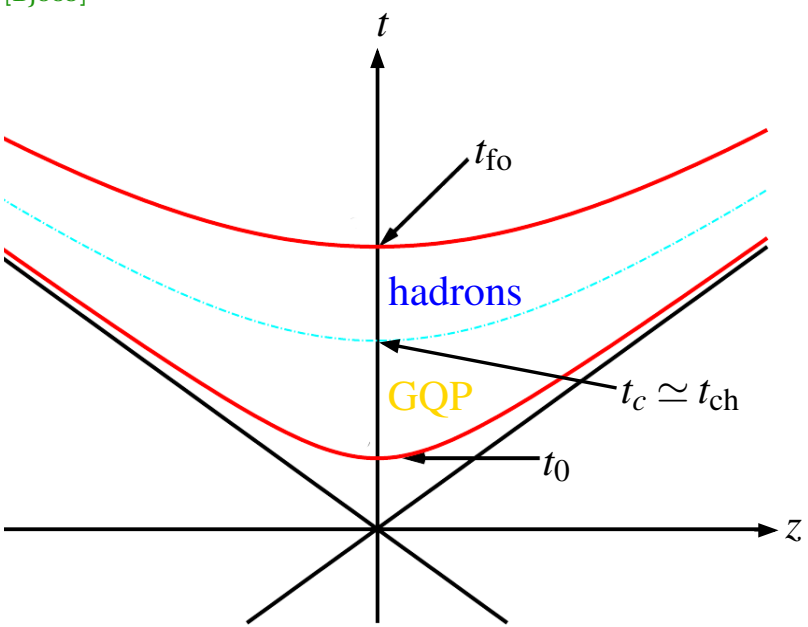


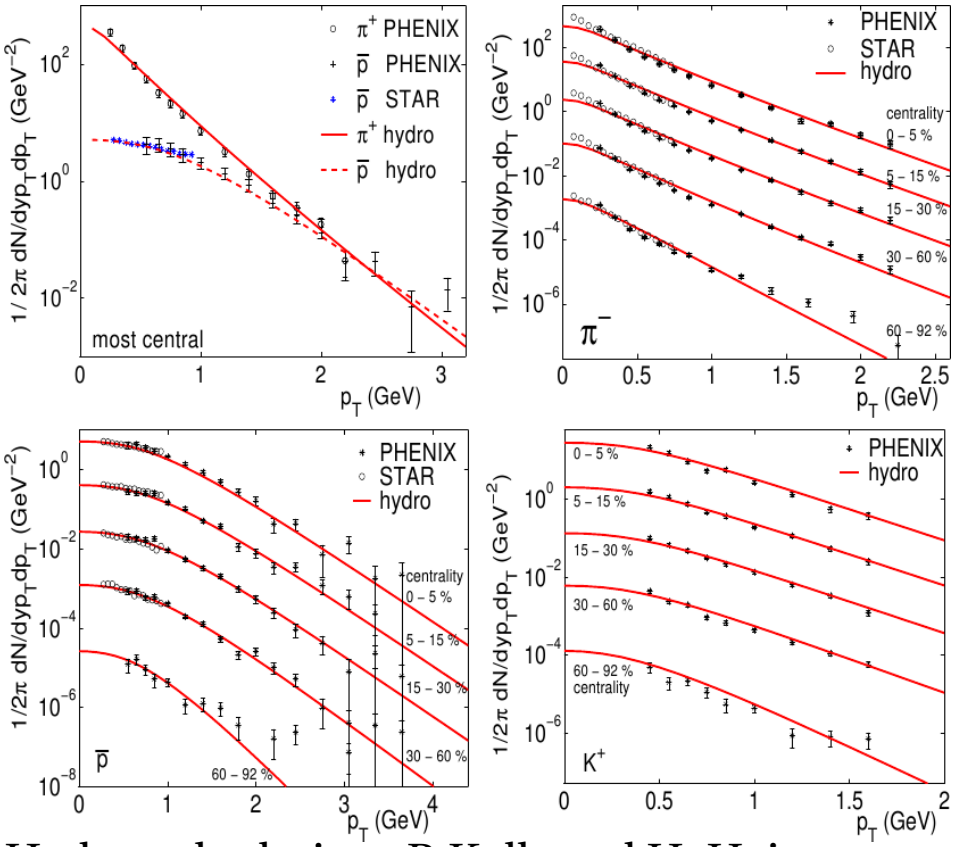
Collective flow of the fireball (Hydrodynamics)

- (nearly) ideal fluid in local thermal equilibrium
- hydrodynamical model for ultra-relativistic heavy-ion collisions
  - after short formation time ($t_0 \lesssim 1$ fm/c)
  - QGP in local thermal equilibrium $\longrightarrow$ hadronization at $T_{\rm pc} \simeq 150$-160 MeV
  - chemical freeze-out: (inelastic collisions cease) $T_{\rm ch} \simeq 150$-160 MeV
  - thermal freeze-out: (also elastic scatterings cease) $T \sim 100$ MeV

Bjorken: boost-invariant solution

[Bjo83]

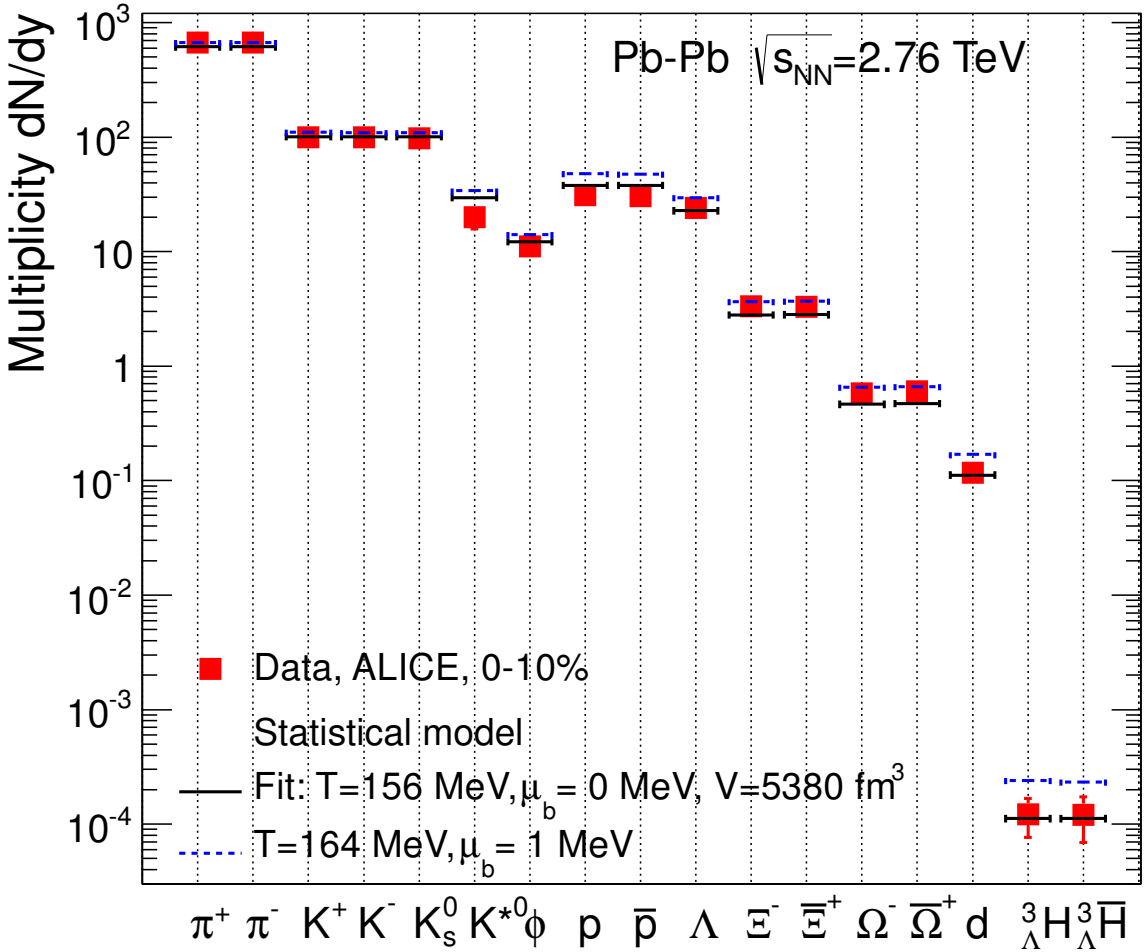




Hydro calculation: P. Kolb and U. Heinz [KH03]

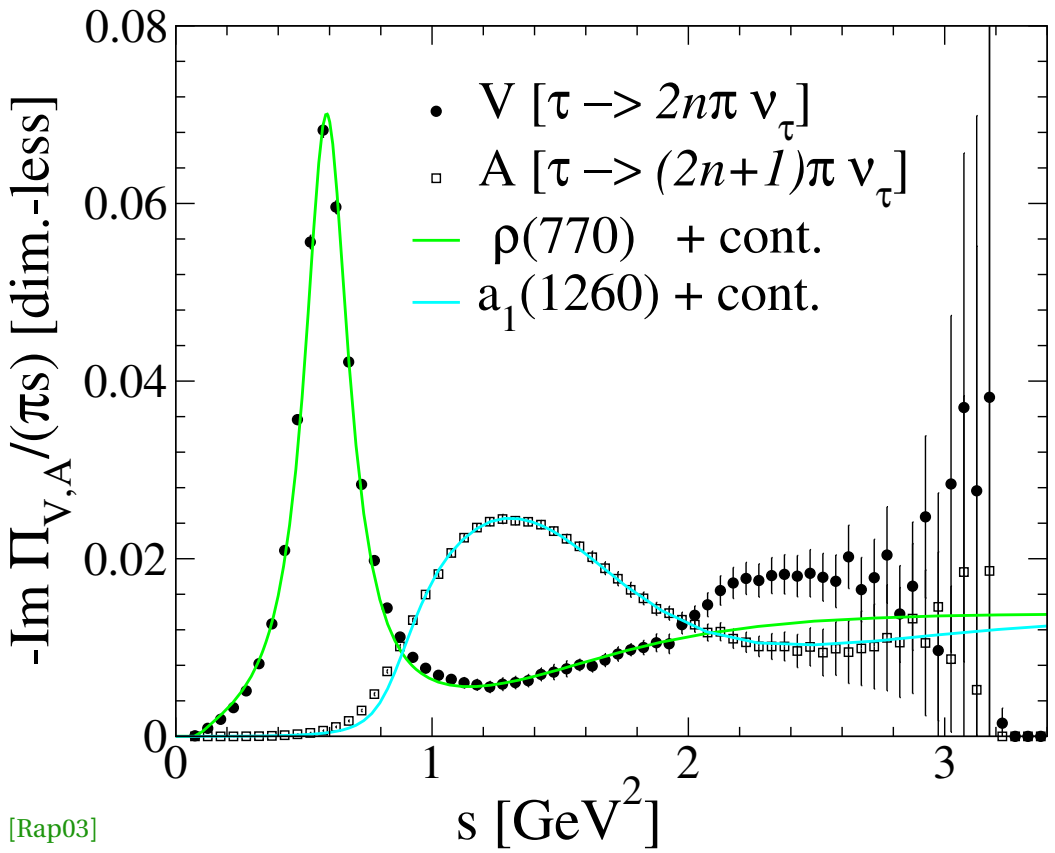
Chemical freeze-out: Statistical hadronization model

- hadron abundancies: can be described by (grand-)canonical hadron-resonance-gas model ($T_{\rm ch} \simeq T_{\rm pc}$, $\mu_{\rm B} = 0$)
- even light (anti-hyper-)nuclei follow the systematics!

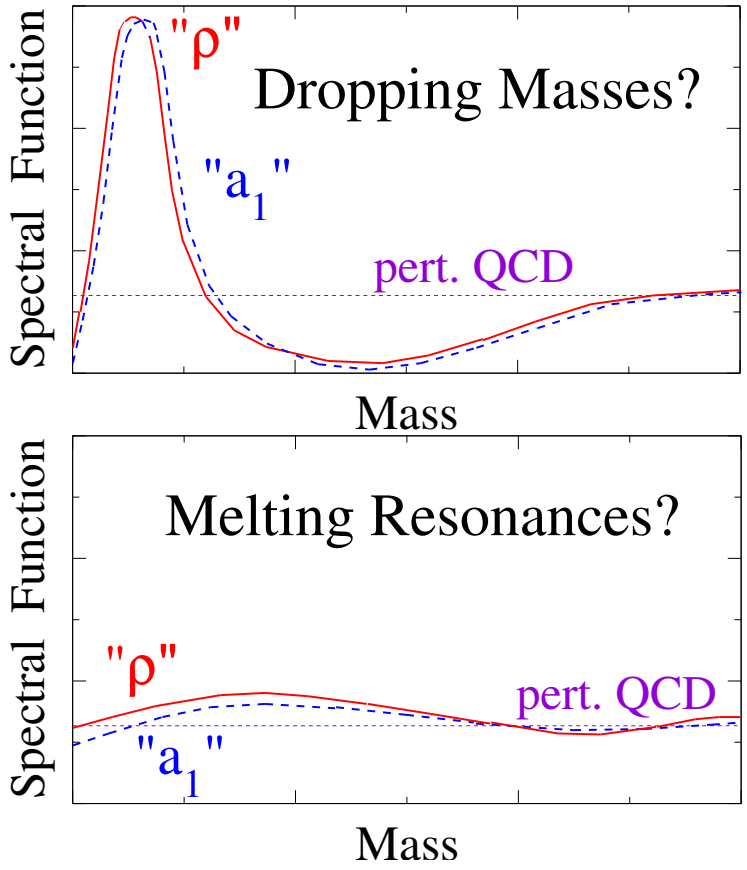


thermal hadronization model: J. Stachel et al [SABMR14]

Vector Mesons and chiral symmetry



[Rap03]

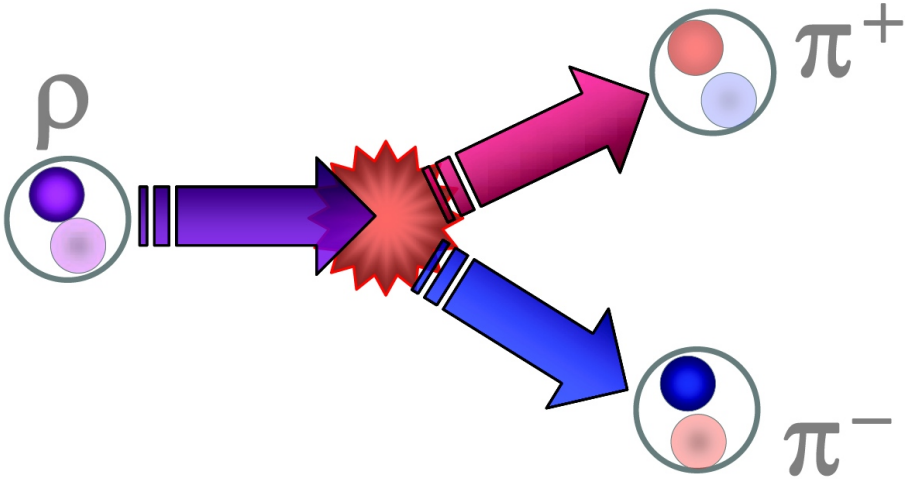


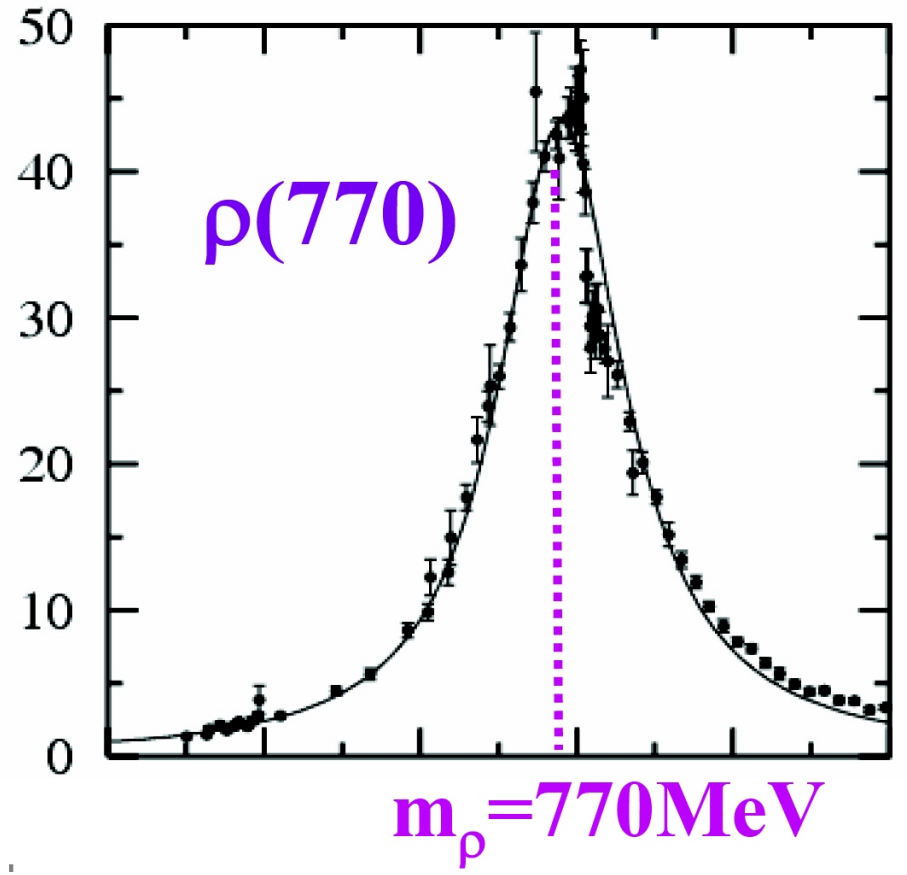
[Rap05]

- at high enough temperatures and or densities: melting of $\langle \bar{q}q \rangle$
- $\Rightarrow$ spontaneous breaking of chiral symmetry supended
- $\Rightarrow$ chiral phase transition; chiral-symmetry restoration (χSR)
- which scenario is right? microscopic mechanisms behind χSR?

The ρ meson in the vacuum

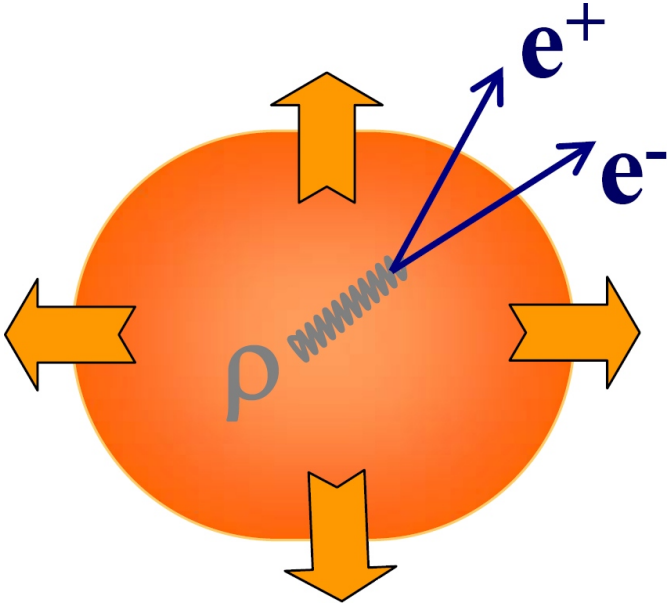
- mass of the ρ mesons: $m_\rho = 770\,\mathrm{MeV}/c^2$
- $m_\rho \approx 2M_{\text{constituent quarks}}$
- its lifetime is about $1.3\,\mathrm{fm}/c = 3.3 \cdot 10^{-24}\mathrm{sec}$
- It decays inside the hot and dense matter!





The ρ meson in the fireball

- how to measure the ρ mass inside the fireball?
  - could look at the decay pions
  - energy-momentum conservation $\Leftrightarrow$ ρ mass
  - but pions interact strongly with the "junk" around them $\Rightarrow$ Signal gets destroyed!
- solution: rarely the ρ's decay into an e^+e^- or $\mu^+\mu^-$ pair ("dileptons")
- Fermi's golden rule (in medium): dilepton rate
  $\propto \eta_{\mu\nu}\,\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{em}}(M_{\ell^+\ell^-}, \vec{q}_{\ell^+\ell^-}) f_{\mathrm{B}}(u_\mu q^\mu)$ (u^μ: four-velocity of fluid cell)
- $\Pi^{\mu\nu}_{\mathrm{em}}$ em. current-current correlation function
- large contribution from hadronic vector current
- spectral properties of light vector mesons (ρ, ω, ϕ)

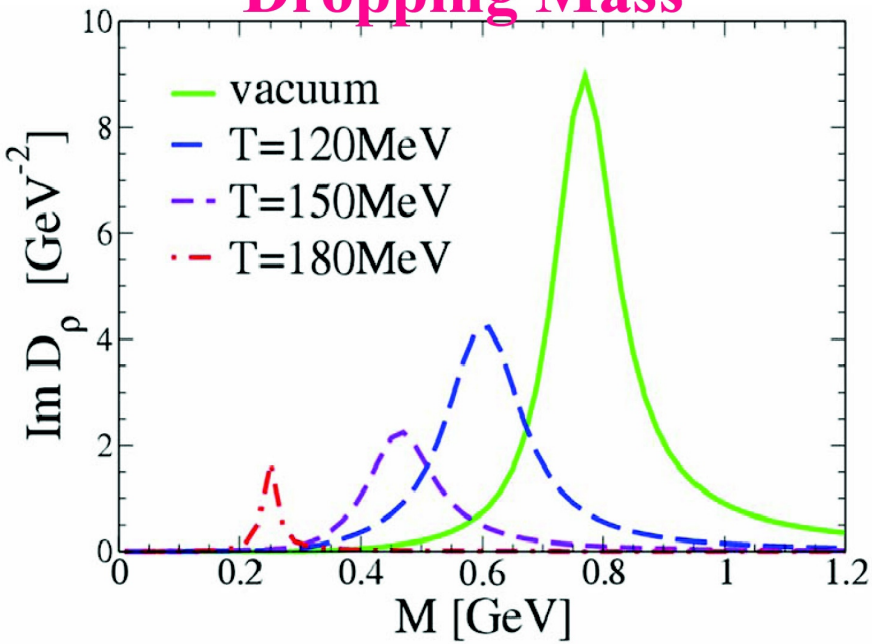


- $e^\pm$ and $\mu^\pm$ are leptons
- they do not interact strongly
- signal undistorted
- get the mass of the ρ inside the fireball

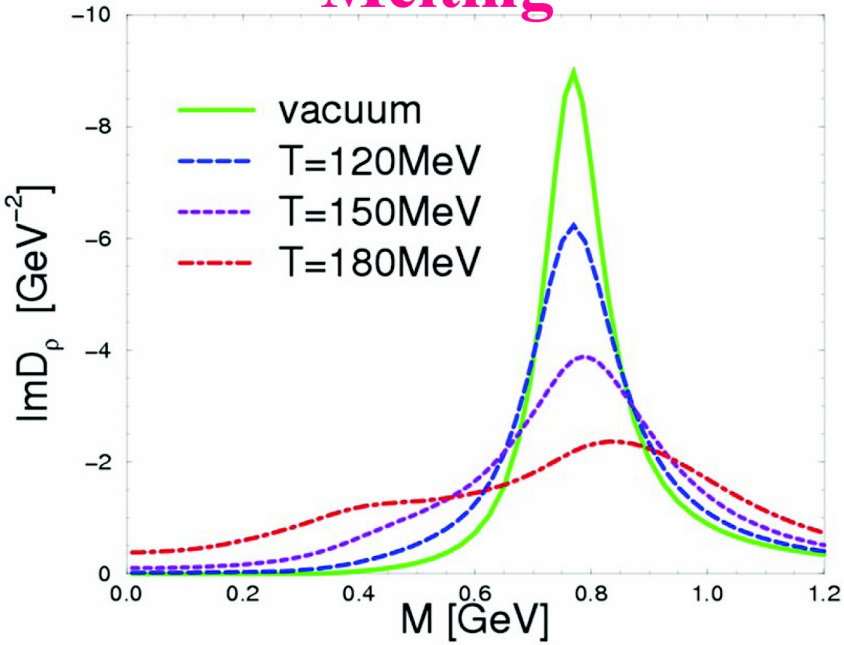
Predictions from chiral models

- chiral symmetry in hadronic models can be realized in different ways
- some lead to "dropping ρ mass" ($m_{\rm had} \propto \langle \bar{\rm q}{\rm q} \rangle_{\rm vac}$)
- quark condensate melts, not much else happens to the ρ
- other models ρ result in a broad mass distribution ("melting ρ")
- mass contribution from trace anomaly (gluons)
  (gluon condensate doesn't melt according to lattice QCD)

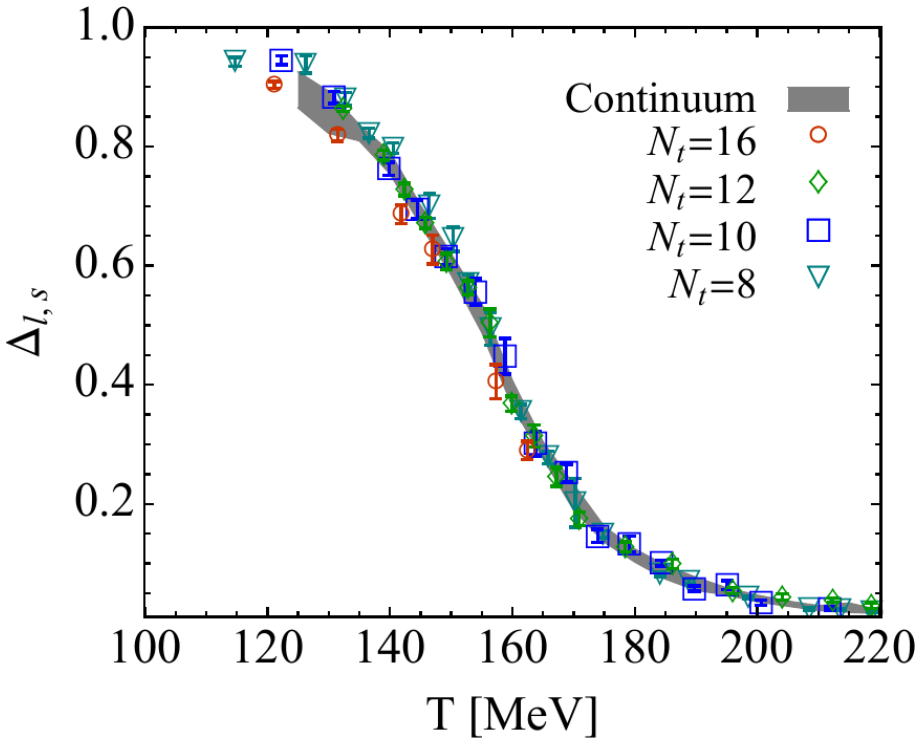
"Dropping Mass"



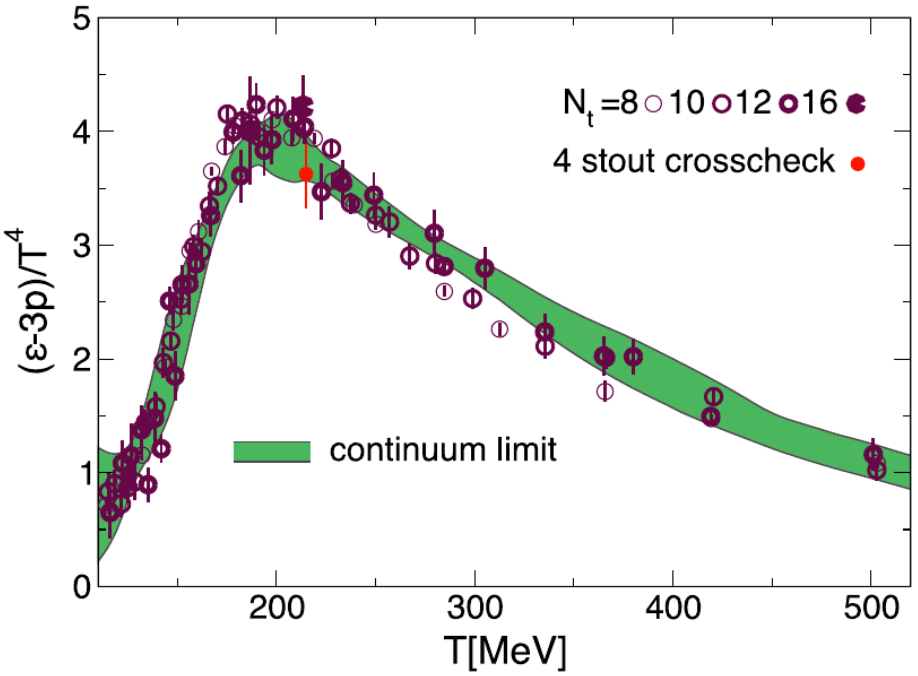
"Melting"



Quark Condensate and Trace from Lattice QCD



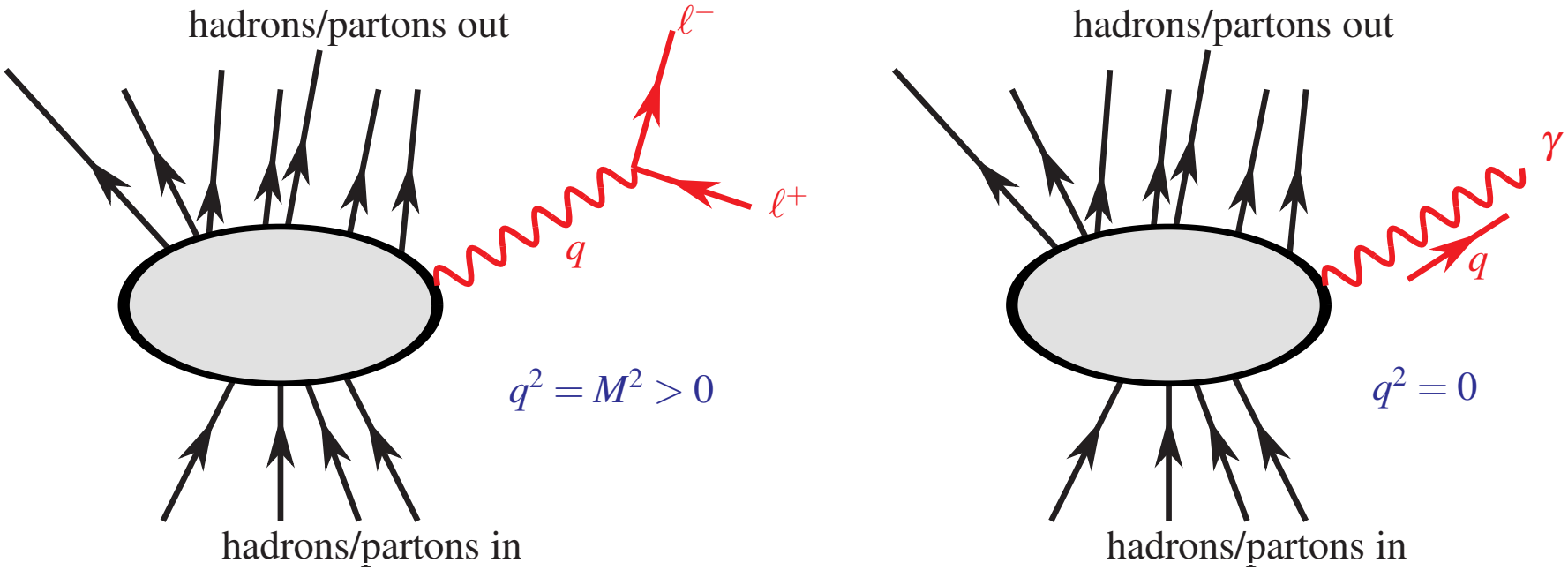
[BEF+11]



[BFH+14]

Electromagnetic Probes in Heavy-Ion Collisions

The McLerran-Toimela formula



- Fermi's golden rule $\Rightarrow$ transition-matrix element for process $|i\rangle \rightarrow \left|f'\right\rangle = \left|f\right\rangle + |\ell^+\ell^-(k)\rangle$
- QED Feynman rules

The McLerran-Toimela formula

- result (derivation see [GK91], Appendices)

$$\frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{q^2+2m_\ell^2}{(k^2)^2}\sqrt{1-\frac{4m_\ell^2}{k^2}}\,\eta_{\mu\nu}\,\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{ret}}(M,\vec{q})\,n_{\mathrm{B}}(u\cdot q)$$

- spectral and thermal information!
- $M^2 = q\cdot q$: invariant mass/$\vec{q}$ momentum of dilepton
- u: four-velocity of fluid cell $\Rightarrow$ Doppler effect on $\vec{p}$ and p_T spectra!
- electromagnetic current-current correlator

$$\mathrm{i}\Pi^{\mu\nu}_{\mathrm{ret}}(q) := \int \mathrm{d}^4x\ \exp(\mathrm{i}q\cdot x)\left\langle\left[\mathbf{J}^\mu_{\mathrm{em}}(x),\mathbf{J}^\nu_{\mathrm{em}}(0)\right]\right\rangle_{T,\mu_B}\Theta(x^0)$$

- written in (local) restframe of the medium
- probing medium with photons: same correlator for $q\cdot q = M^2 = 0$
- then correlator $\Leftrightarrow$ dielectric function $\epsilon(\omega)$ of electrodynamics!

$$\omega\frac{\mathrm{d}N_\gamma}{d^4x\,\mathrm{d}^3\vec{q}} = -\frac{\alpha\eta_{\mu\nu}}{2\pi^2}\,\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{ret}}(q^0,\vec{q})\,n_{\mathrm{B}}(u\cdot q),\quad q^0=\omega=|\vec{k}|$$

Radiation from thermal QGP: $q\bar{q}$ annihilation

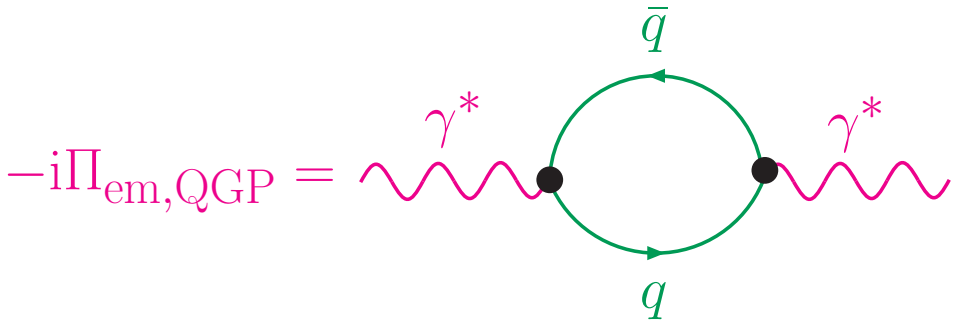
- General: McLerran-Toimela formula

$$\frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{q^2+2m_\ell^2}{(k^2)^2}\sqrt{1-\frac{4m_\ell^2}{k^2}}\,\eta_{\mu\nu}\,\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{ret}}(M,\vec{q})\,n_{\mathrm{B}}(u\cdot q)$$

- i enumerates partonic/hadronic sources of em. currents
- in-medium em. current-current correlation function

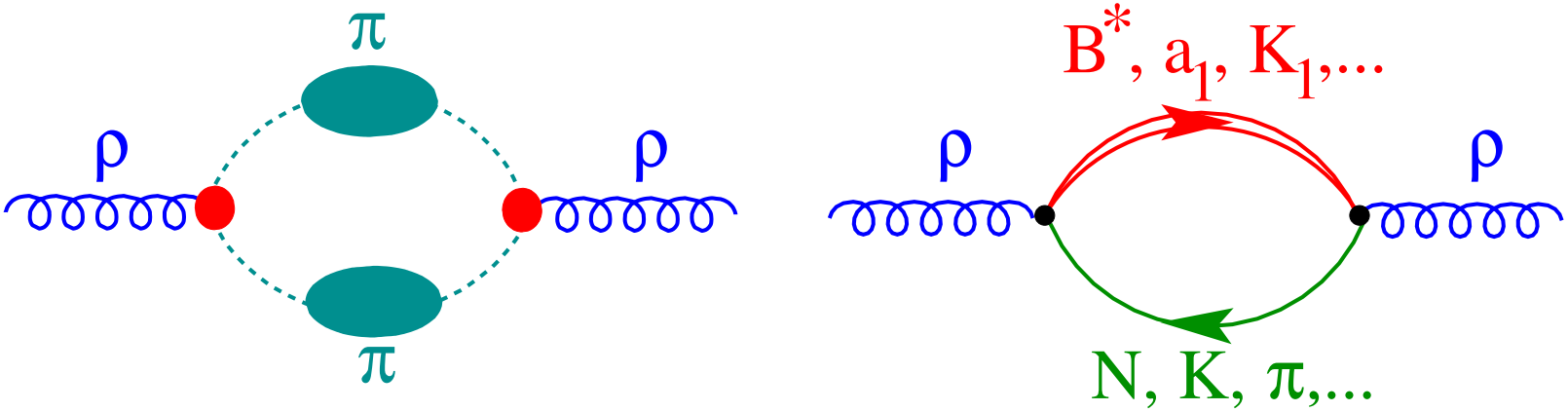
$$\mathrm{i}\Pi^{\mu\nu}_{\mathrm{ret}}(q) := \int \mathrm{d}^4x\ \exp(\mathrm{i}q\cdot x)\left\langle\left[\mathbf{J}^\mu_{\mathrm{em}}(x),\mathbf{J}^\nu_{\mathrm{em}}(0)\right]\right\rangle_{T,\mu_B}\Theta(x^0)$$

- Feynman diagrams: photon polarization
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved em. current-current correlator



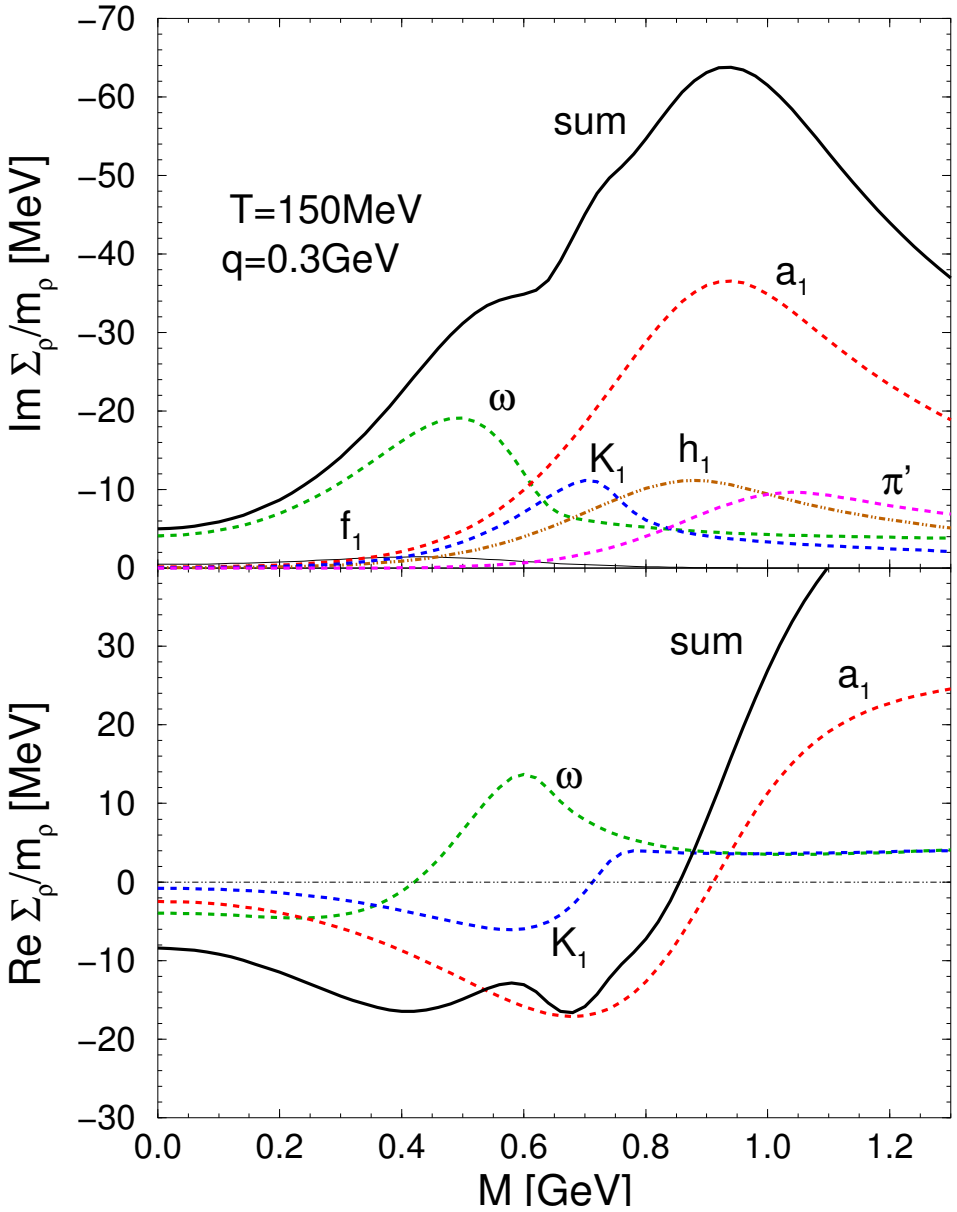
Hadronic many-body theory

- hadronic many-body theory (HMBT) of vector mesons
  [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...]
- $\pi\pi$ interactions and hadronic excitations
- effective hadronic models, implementing symmetries
- good approximation: vector-meson dominance, $J^\mu_{\rm em} \propto \rho^\mu, \omega^\mu, \phi^\mu$
- dilepton/photon rates then $\propto \mathrm{Im}\, D_{\rm VM}$ (VM-spectral functions)
- parameters fixed by phenomenology
  (photon absorption at nucleons and nuclei, $\pi N \to \rho N$)
- evaluated at finite temperature and density
- self-energies $\Rightarrow$ mass shift and broadening in the medium



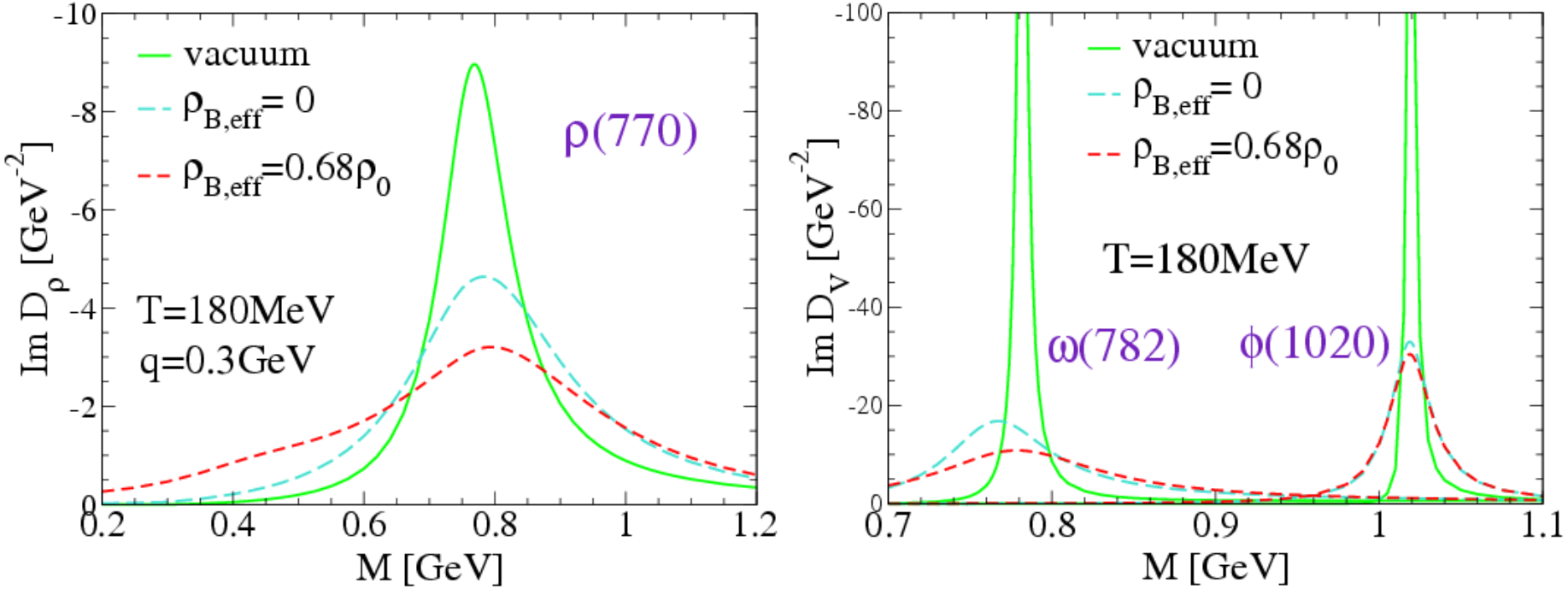
- Baryons important, even at low **net** baryon density $n_B - n_{\overline{B}}$
- reason: $n_B + n_{\overline{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



[RG99]

In-medium spectral functions and baryon effects

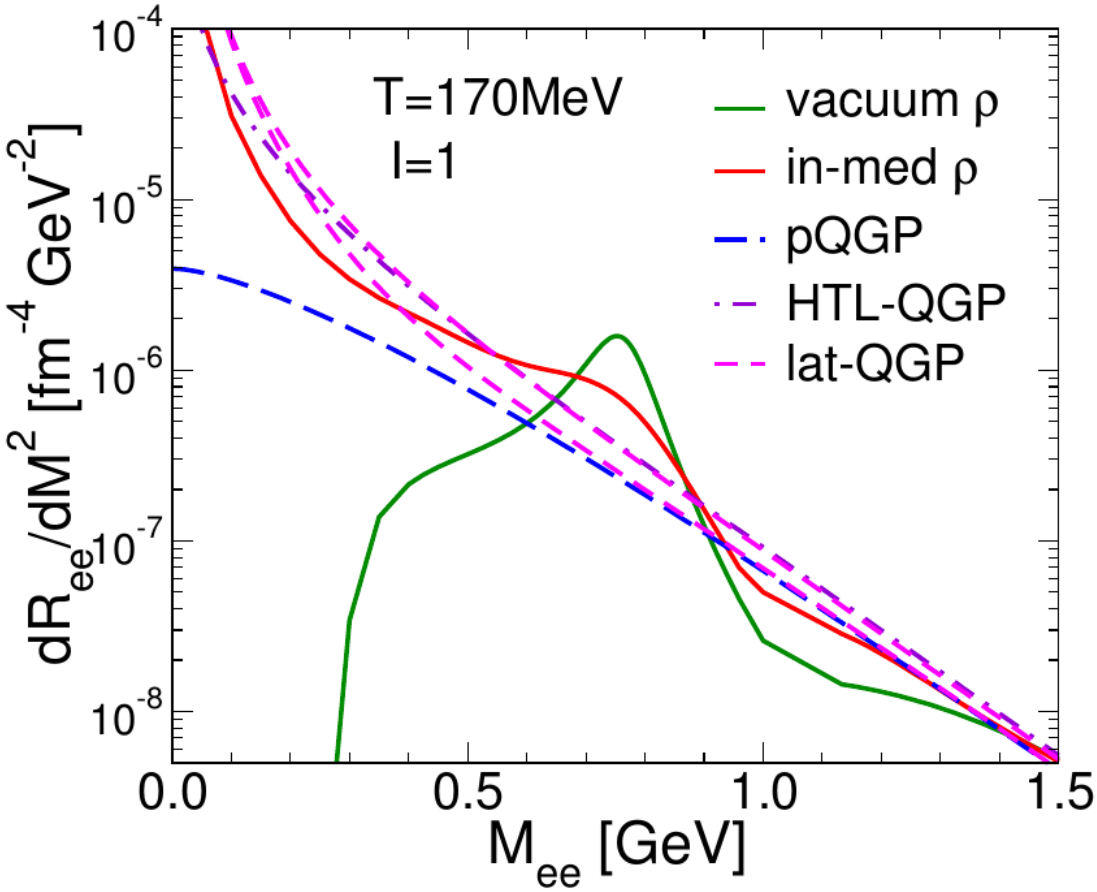


[RW99]

- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

Dilepton rates: Hadron gas ⟷ QGP

- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?



[Rap13]

Bulk evolution with transport and coarse graining

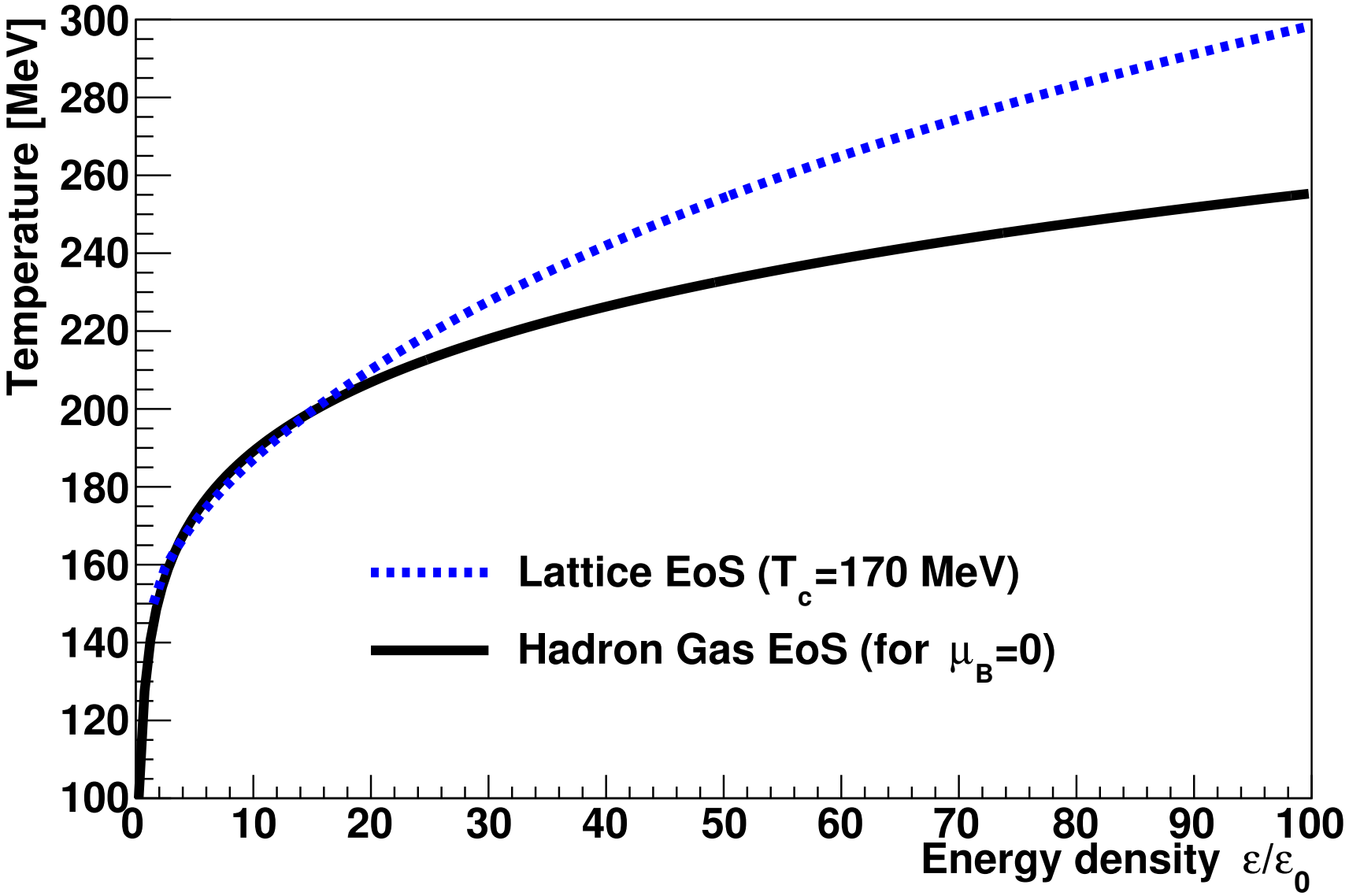
- established transport models for bulk evolution
  - e.g., UrQMD, GiBUU, BAMPS, (p)HSD,...
  - solve Boltzmann equation for hadrons and/or partons
- dilemma: need medium-modified dilepton/photon emission rates
- usually available only in equilibrium QFT calculations
- one way out:
  - UrQMD transport for entire bulk evolution
    $\Rightarrow$ use coarse graining in space-time cells $\Rightarrow$ extract $T, \mu_B, \mu_\pi, \ldots$
    $\Rightarrow$ use equilibrium rates locally
  - fit temperature, chemical potentials, flow-velocity field
    from anisotropic energy-momentum tensor [FMRS13]

$$T^{\mu\nu} = (\epsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu$$

  - thermal rates from partonic/hadronic QFT become applicable
- work with Stephan Endress (PhD Thesis) and Marcus Bleicher

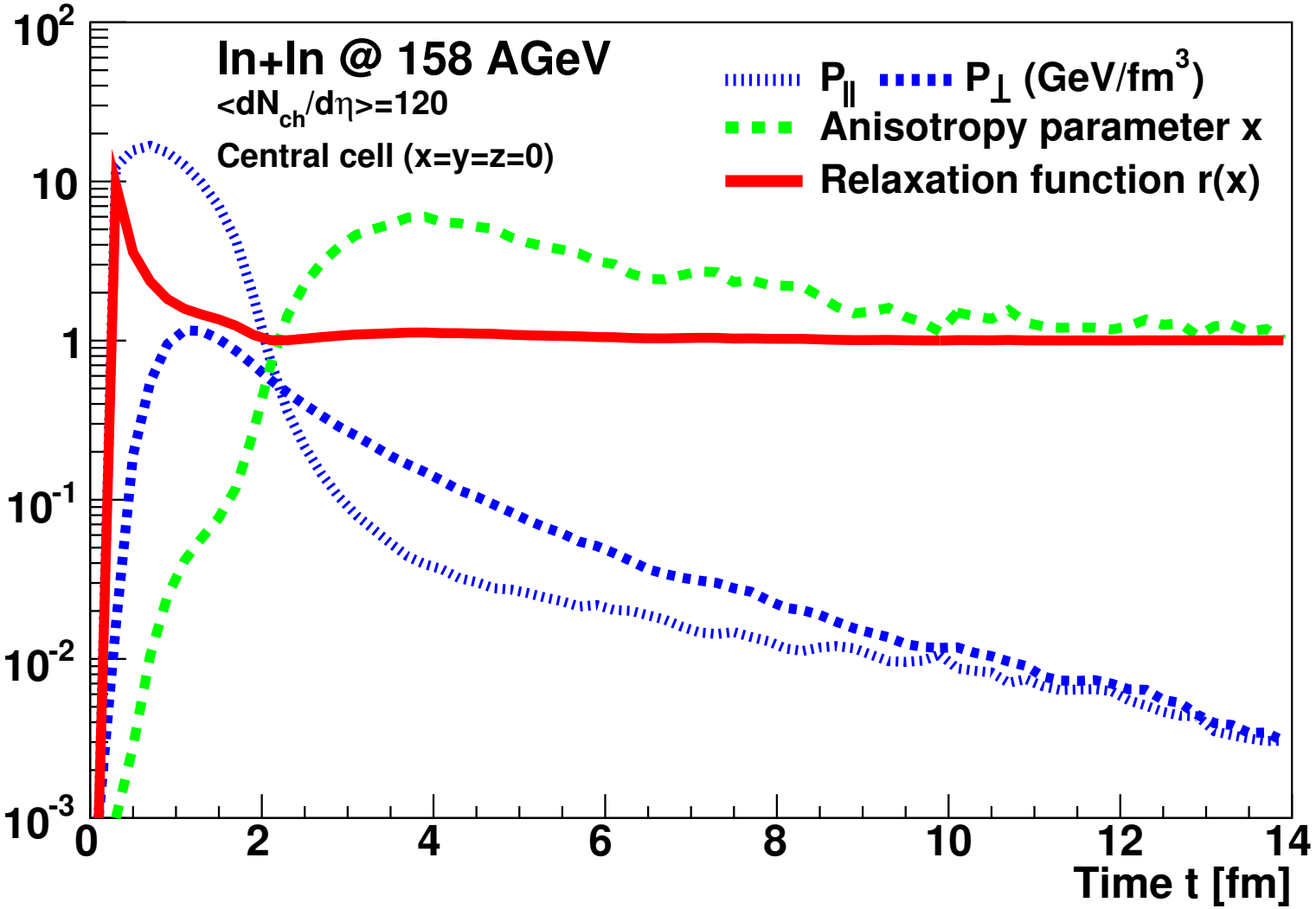
Coarse-grained UrQMD (CGUrQMD)

- $T_c = 170$ MeV; $T > T_c \Rightarrow$ lattice EoS; $T < T_c \Rightarrow$ HRG EoS



Coarse-grained UrQMD (CGUrQMD)

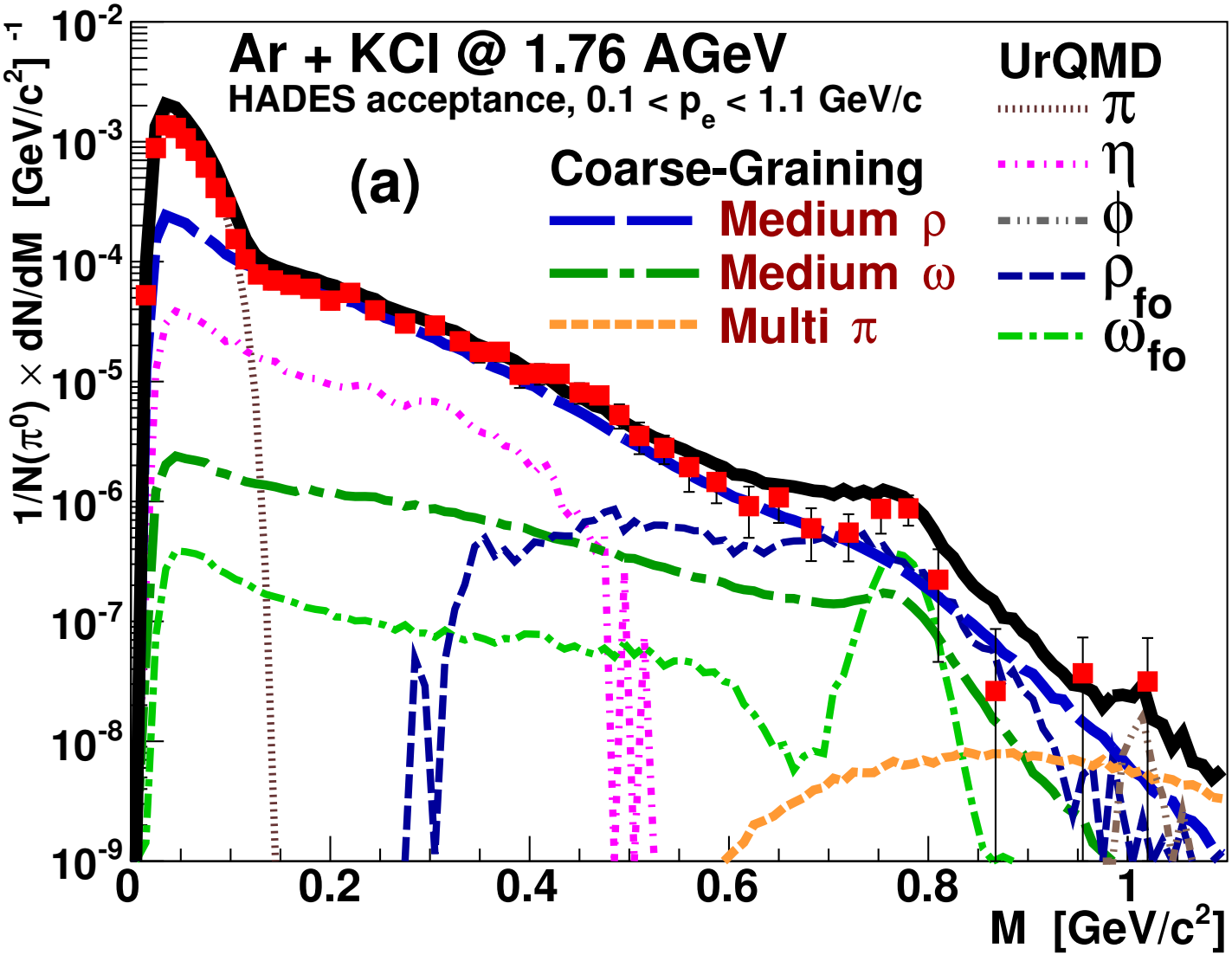
- pressure anisotropy (for In+In @ SPS; NA60)



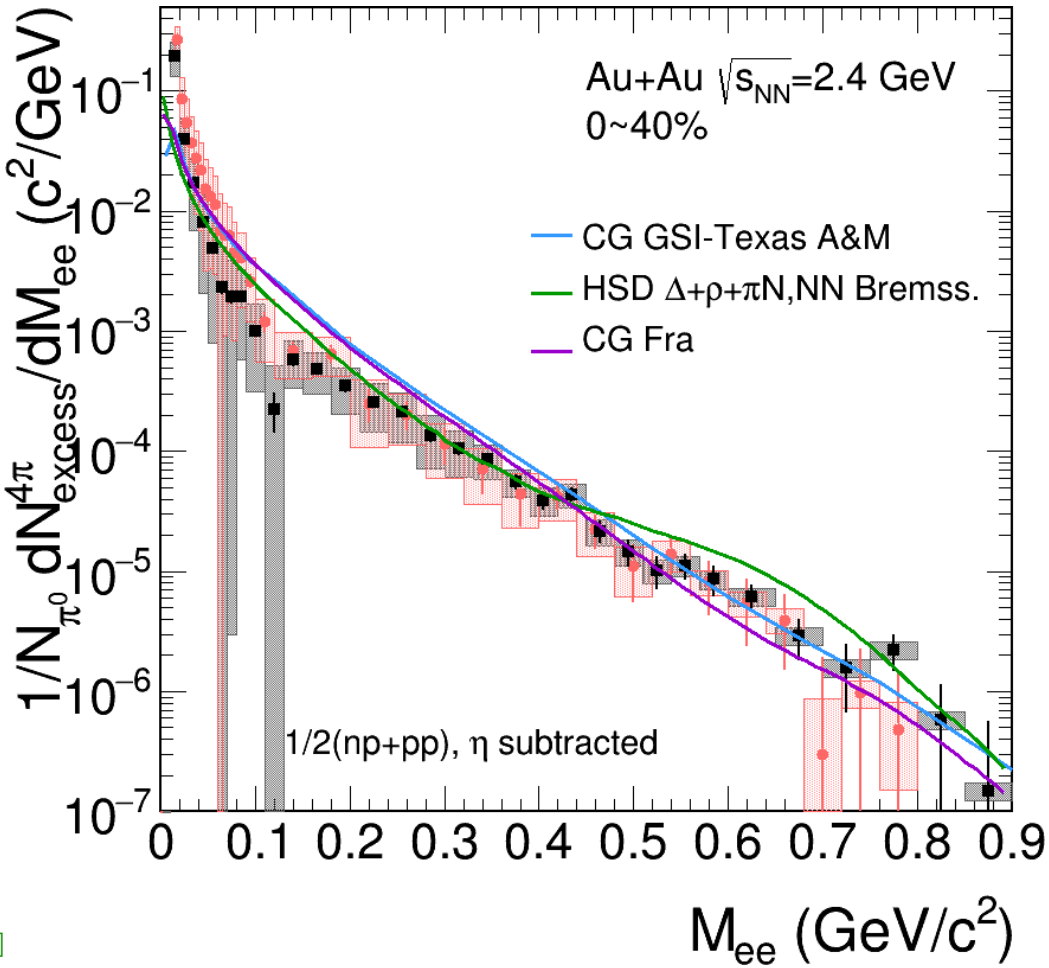
Dielectrons (SIS/HADES)

CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates



CGUrQMD: Au+Au (1.23 *A*GeV) (SIS/HADES)



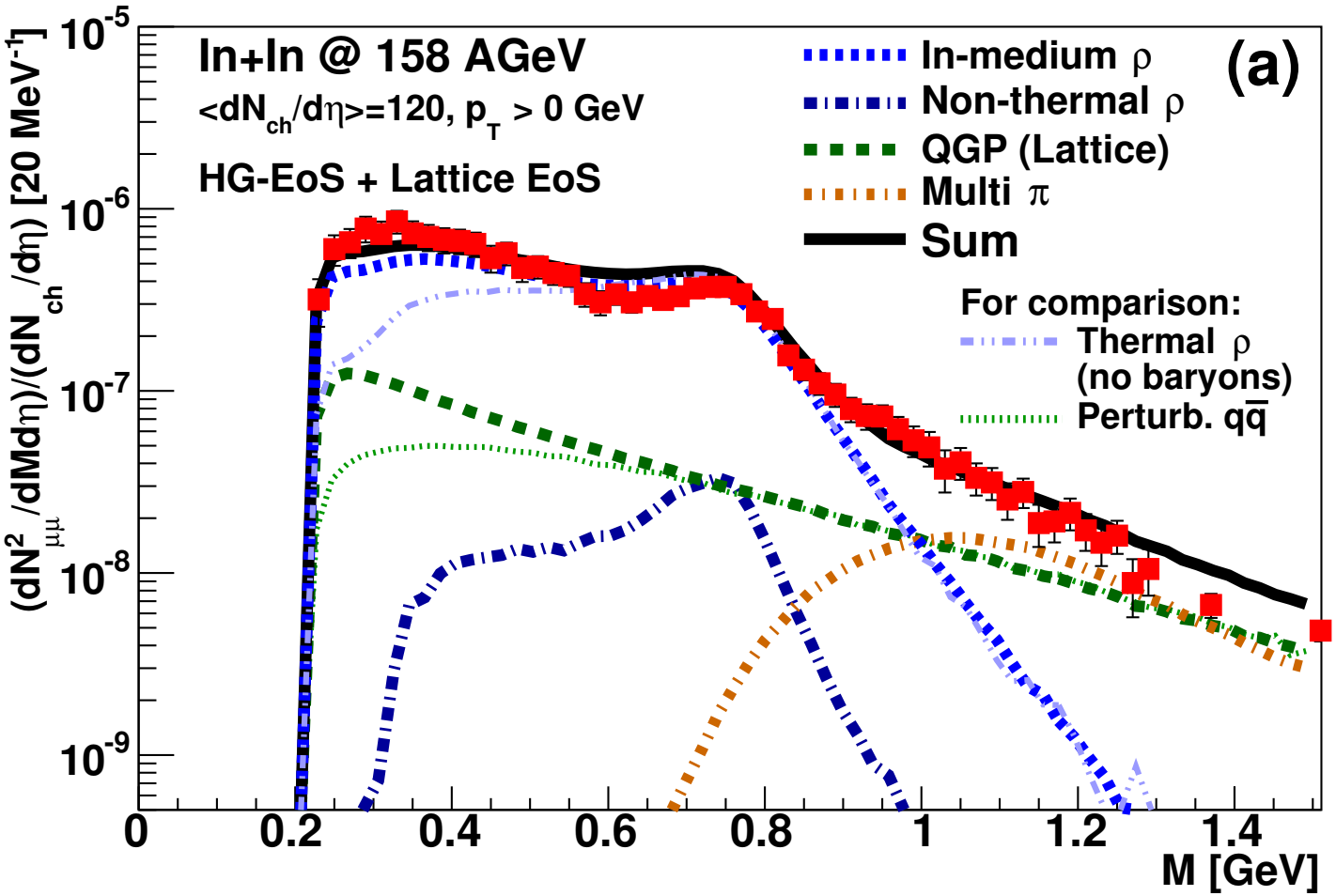
[T. Galatyuk, Quark Matter 2017 talk]

- good agreement between models and data
- consistency between two independent coarse-grained-UrQMD simulations
- based on same Rapp-Wambach in-medium rates

Dimuons (SPS/NA60)

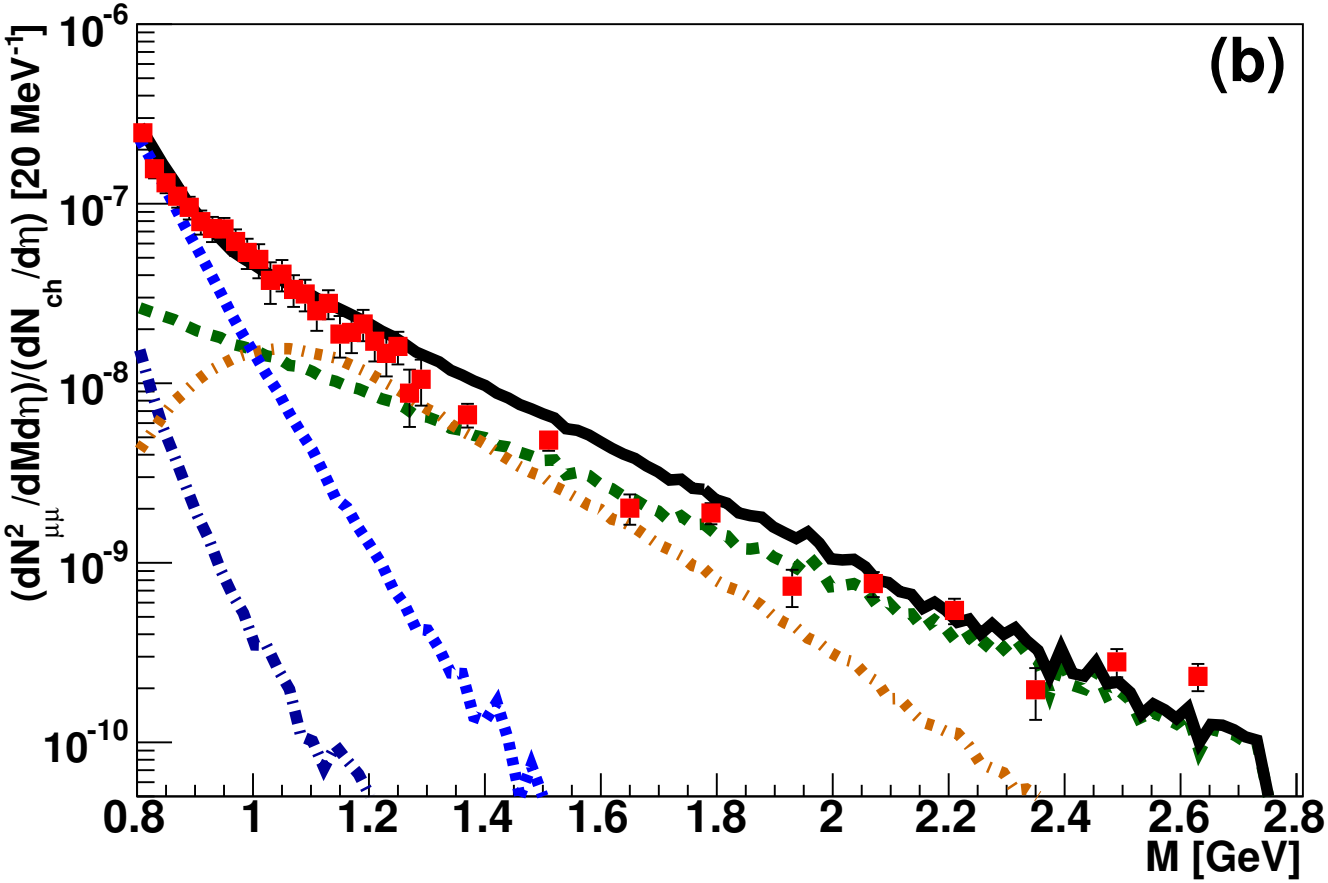
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \to \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



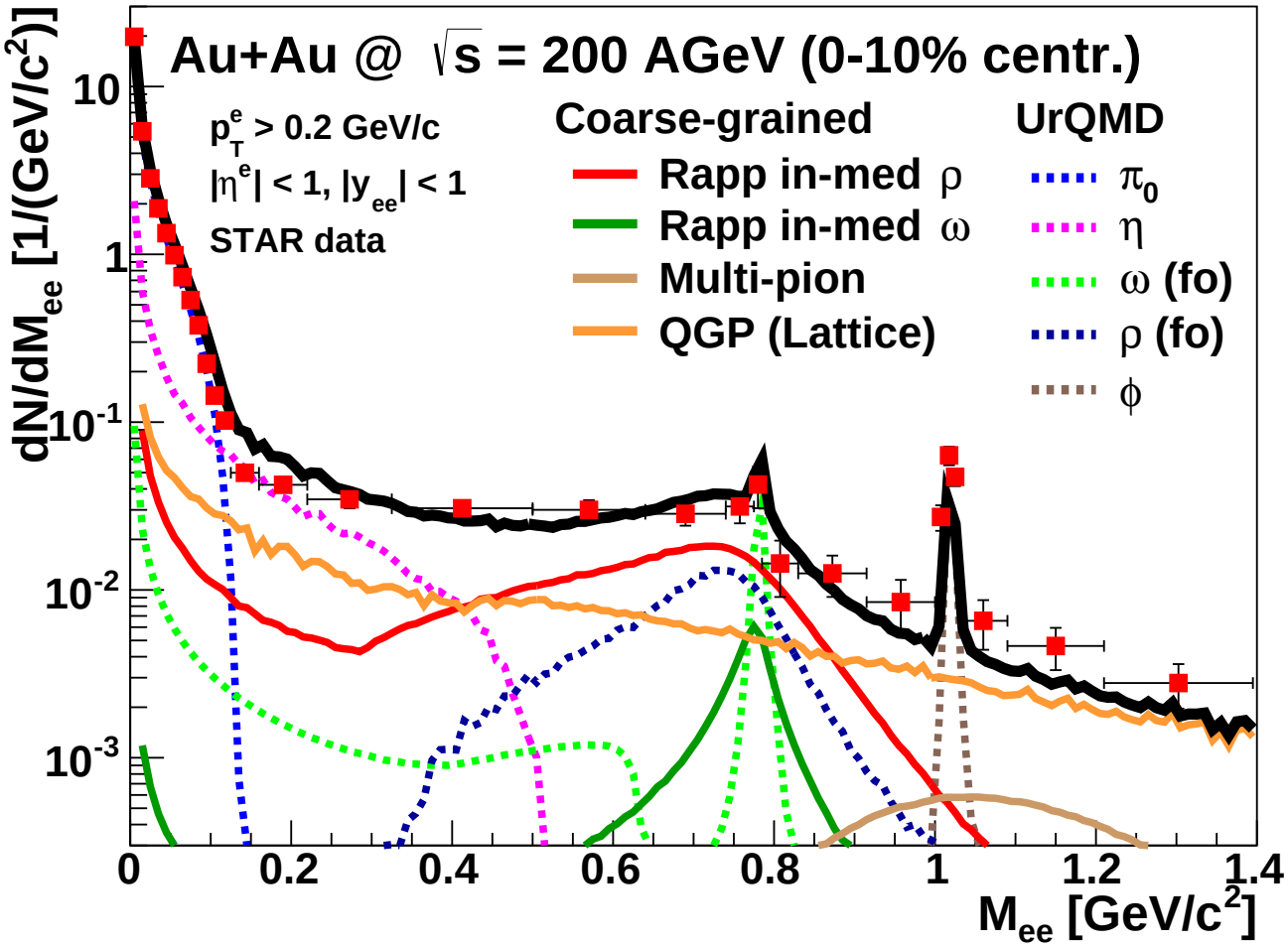
CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \to \mu^+\mu^-$ (NA60) [EHWB15]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- higher IMR: provides averaged true temperature
  $\langle T \rangle_{1.5\,\mathrm{GeV} \lesssim M \lesssim 2.4\,\mathrm{GeV}} = 205\text{-}230\,\mathrm{MeV}$
- clearly above $T_c \simeq 150\text{-}160\,\mathrm{MeV}$
  (no blueshifts in the invariant-mass spectra!)

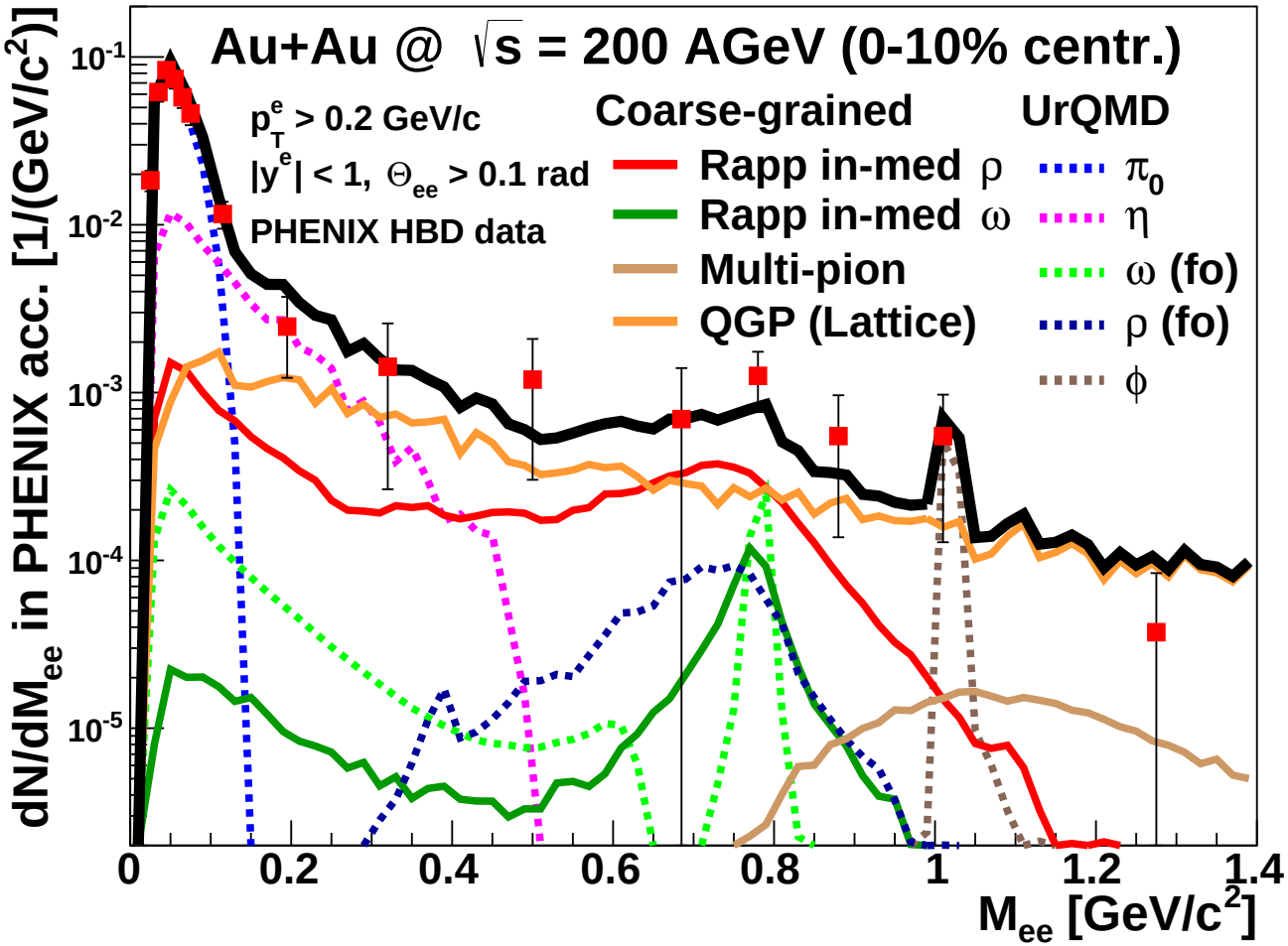


Dielectrons at RHIC

CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$) (RHIC/STAR)

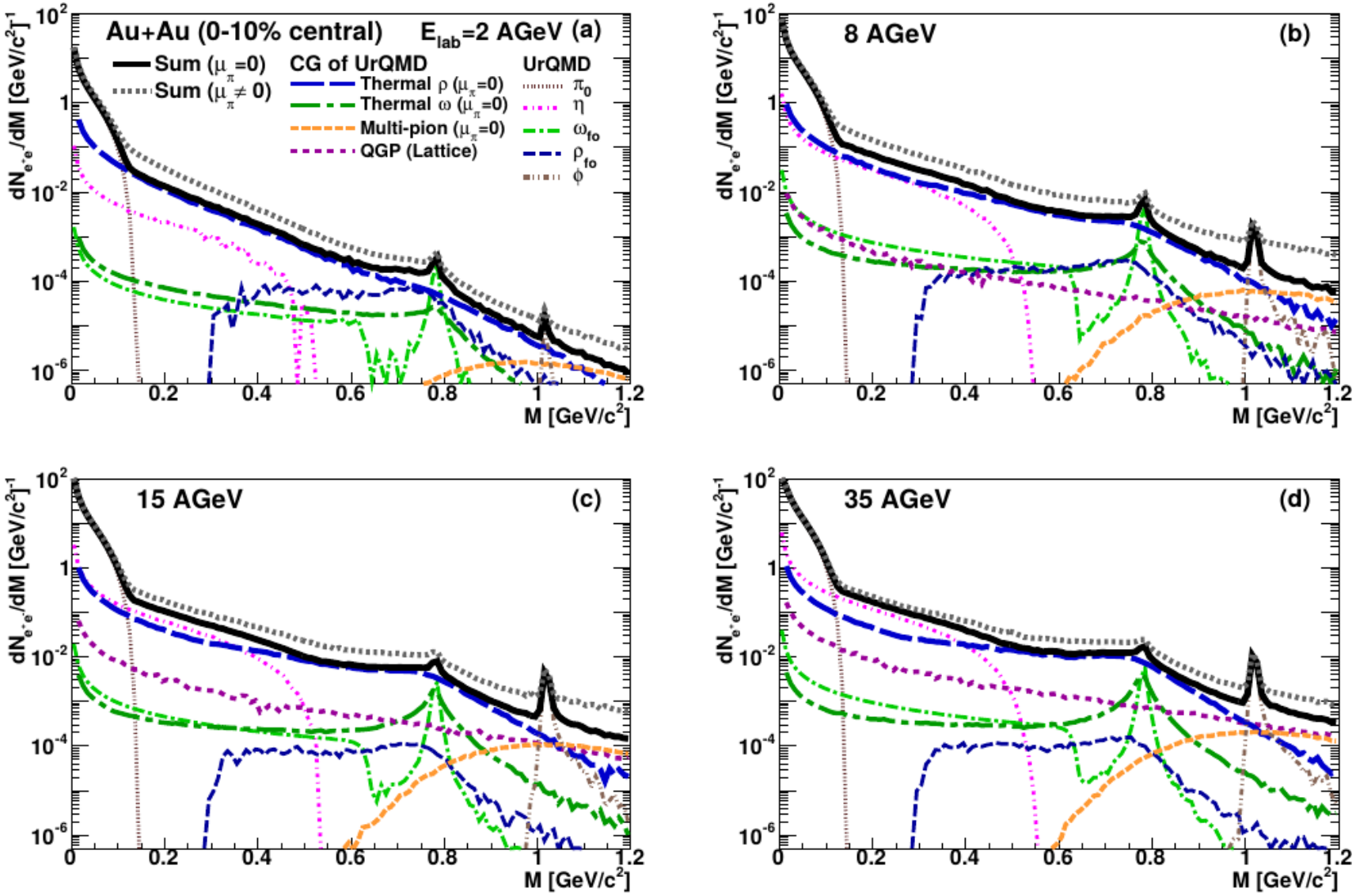


CGUrQMD: Au+Au ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$) (RHIC/PHENIX)



Dielectrons at RHIC-BES/FAIR/NICA

CGUrQMD: Au+Au ($E_{\mathrm{lab}} = 2$-$35\,A\mathrm{GeV}$)



NB: also photon spectra [EHB16b]

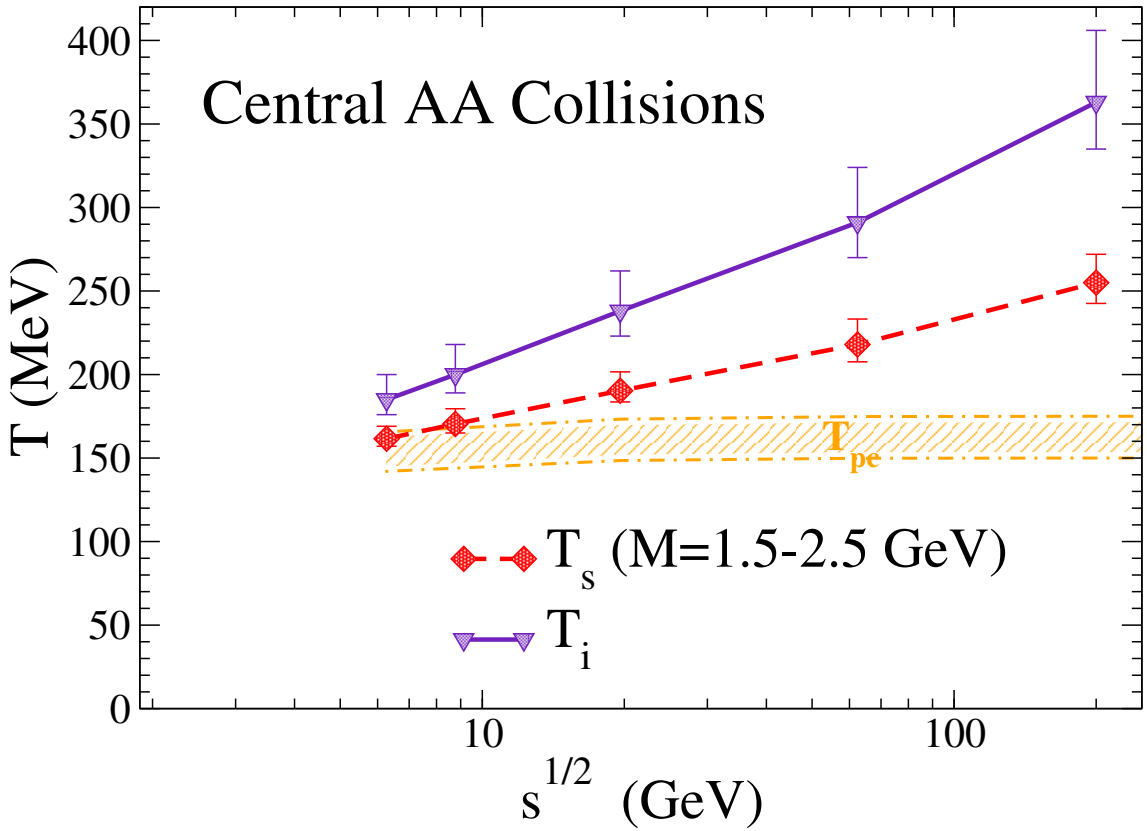
Signatures of the QCD-phase structure?

QCD phase structure from em. probes?

- hadronic observables like p_T spectra:
  "snapshot" of the stage after kinetic freezeout
- particle abundancies: chemical freezeout
- em. probes: emitted during the whole medium evolution
  life time of the medium $\Rightarrow$ "four-volume of the fireball"
- use CGUrQMD to study system-size dependence
- study AA collisions for different A [EHWB15]
- "excitation functions":
  systematics of $\ell^+\ell^-$ (and γ) emission vs. beam energy [EHB16b, RH16]
  similar study in [GHR+16]
- caveat: phase transition not really implemented!!!

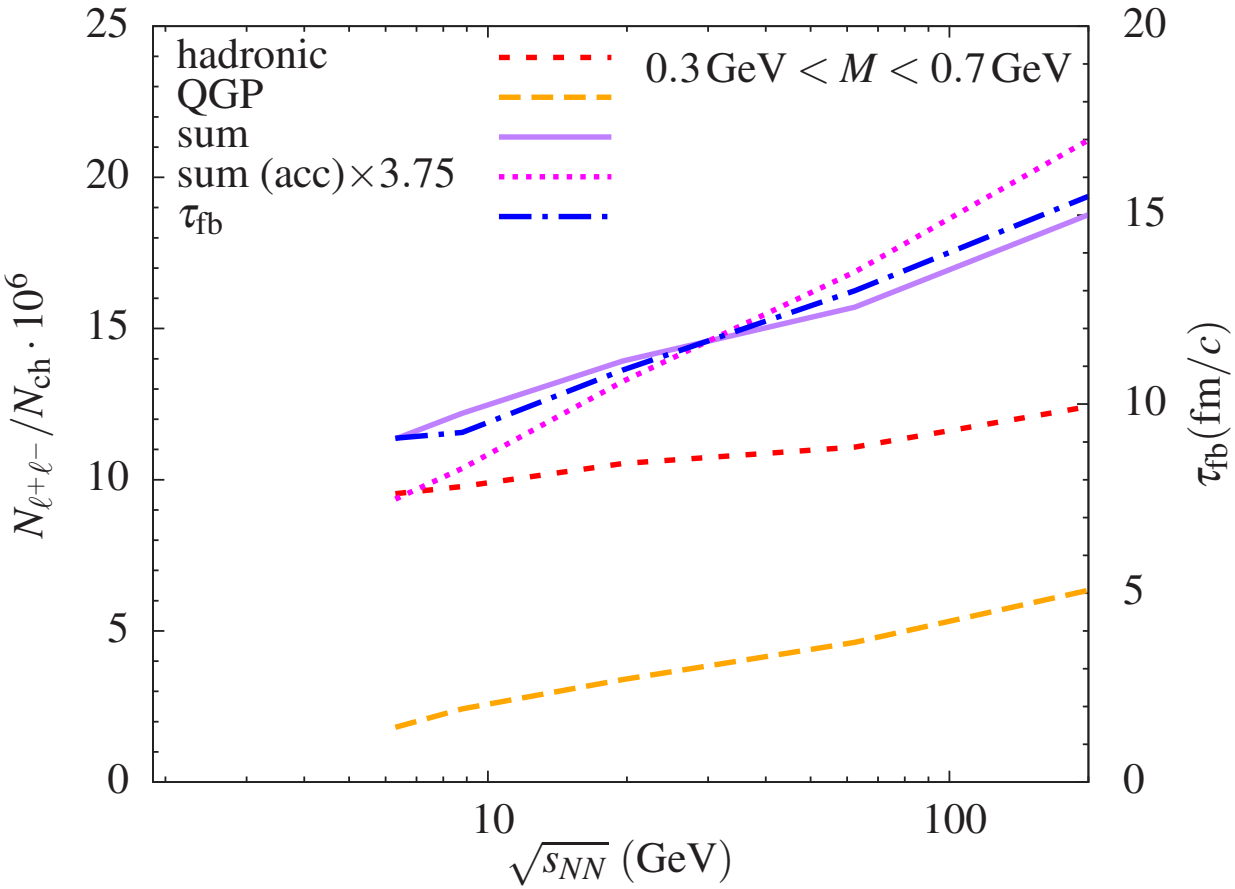
Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16, EHB16a]
- invariant-mass slope in IMR ⇒ invariant "mean temperature"!
- no blue shift from radial flow as in p_T/m_T spectra!



Dilepton systematics in the beam-energy scan

- thermal-fireball model [RH16]
- beam-energy scan at RHIC and lower energies at FAIR and
- dilepton yield as fireball-lifetime clock



Conclusions

- extremely hot and/or dense strongly interacting matter
- in Nature
  - few micro-seconds after big bang
    (no "finger prints" left in cosmic microwave background)
  - neutron stars, neutron-star mergers, supernovae
    exciting new possibilities through gravitational waves @ LIGO/VIRGO
    and em. waves at various wave lengths ("multi-messenger astronomy")
- in the laboratory: (ultra-)relativistic heavy-ion collisions
- phase structure of QCD matter (ruled by symmetries of the Standard Model)
- origin of hadron masses?
- electromagnetic probes in heavy-ion collisions
  - produced over entire history of fireball evolution
  - for them medium transparent
  - allow to observe mass spectra of in-medium vector mesons
  - thermometer and clock for fireball
  - more detailed insight into phase diagram in "beam-energy scan"
    (ongoing at RHIC and at future FAIR and NICA)?

Thank you!

- collaborators over the years

  Jörn Knoll (GSI Darmstadt, PhD advisor)
  Ralf Rapp (Texas A&M University, College Station, Texas)
  Min He (Texas A&M University, College Station, Texas)
  Ulrich Mosel (Justus Liebig University Giessen)
  Fabian Eichstädt (Justus Liebig University Giessen)
  Janus Weil (Justus Liebig University Giessen/Goethe University Frankfurt)
  Carsten Greiner (Goethe University Frankfurt)
  Marcus Bleicher (Goethe University/FIAS Frankfurt)
  Stephan Endres (Goethe University/FIAS Frankfurt)
  Kai Gallmeister (Justus Liebig University Giessen/Goethe University Frankfurt)
  Christian Wesp (Goethe University)
  Alex Meistrenko (Goethe University)
  Julian Schmitt (Goethe University)
  Benjamin Schüller (Goethe University)

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