Electromagnetic Probes in Heavy-Ion Collisions I

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Outline

1. Plan of the Lectures
2. Electromagnetic Probes: Phenomenology
3. QCD and Chiral Symmetry
   - Chiral Symmetry
   - Chiral Symmetry and Hadron Phenomenology
   - Strongly interacting matter: QCD/hadronic models at finite T, μ
4. Fundamental theoretical tools
   - The McLerran-Toimela formula
   - QCD sum rules
5. Summary
6. References
7. Quiz + Solutions

Plan of the Lectures

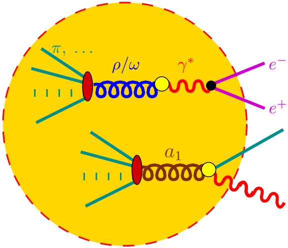
- Lecture I: Fundamentals (HvH)
  - QCD, chiral symmetry, and the relation with electromagnetic probes
  - basic phenomenology of dilepton signals
  - model independent approach: QCD sum rules
  - literature: [DGH92, FHK$^+$11, RW00, RWH09]
- Lecture II: Effective hadronic models (Sascha Vogel)
  - more on phenomenology of electromagnetic probes in HICs
  - (effective) Lagrangians for hadrons; QED of hadrons
  - Feynman rules; fundamental processes
  - literature: [Won94]

Plan of the Lectures

- Lecure III: P/HMBT and the NA60 experiment (HvH)
  - partonic and hadronic many-body theory
  - fireball model for the bulk evolution
  - understanding the NA60 dimuon measurement
  - literature: [RW00, RWH09, HR06, HR08]
- Lecture IV: Transport approach to dilepton production in HICs (SV)
  - basics of transport theory (UrQMD)
  - realistic description of the bulk evolution of the fireball
  - the shining method for electromagnetic probes
  - direct experimental check for chiral symmetry restoration?
  - Literature: [BBB+98, PSB+08, SSV+09, SSBS11]

Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: only e. m. interactions
- reflect whole "history" of collision
- chance to see chiral symm. rest. directly?



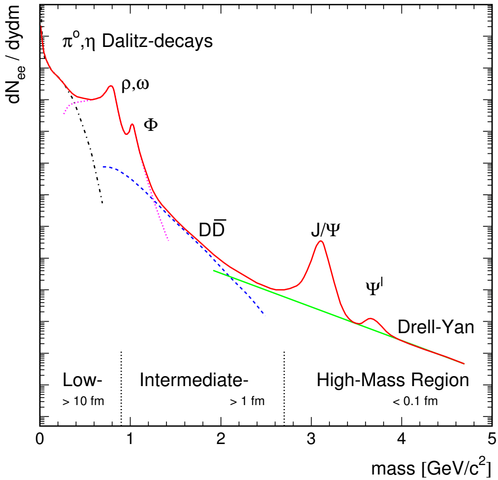
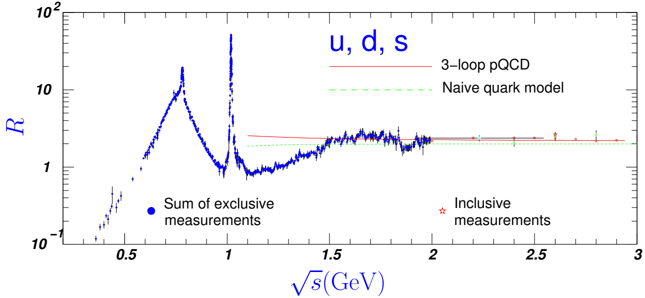


Fig. by A. Drees (from [RW00])

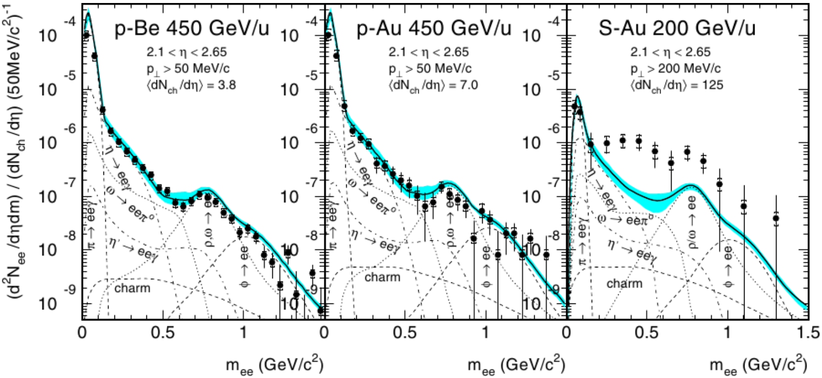
Vacuum Baseline: $e^+e^- \to$ hadrons



$$R := \frac{\sigma_{e^+e^- \to \text{hadrons}}}{\sigma_{e^+e^- \to \mu^+\mu^-}}$$

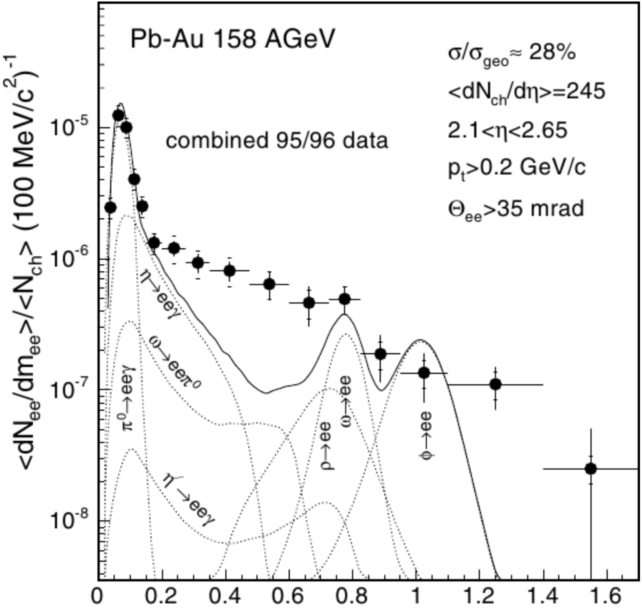
- probes all hadrons with quantum numbers of γ^*
- $R_{\text{QM}} = N_c \sum_{f=u,d,s} Q_f^2 = 3 \times [(2/3)^2 + (-1/3)^2 + (-1/3)^2] = 2$
- Our aim pp $\to \ell^+\ell^-$, pA $\to \ell^+\ell^-$, AA $\to \ell^+\ell^-$ $\ell = \text{e}, \mu$
- see also Theory Lecture II by Sascha!

The CERES findings: Dilepton enhancement



- pp (pBe): "elementary reactions"; baseline (mandatory to understand first!)
- pA: "cold nuclear matter effects"; next step (important as baseline for other observables like "J/ψ suppression")
- AA: "medium effects"; hope to learn something about in-medium properties of vector mesons, fundamental QCD properties

The CERES findings: Dilepton enhancement



QCD and ("accidental") Symmetries

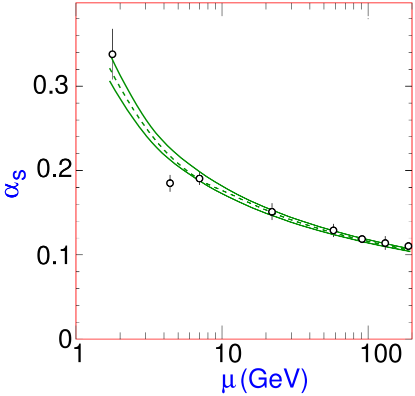
- Theory for strong interactions: QCD

$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \overline{\psi}(\mathrm{i}\not{D} - \hat{M})\psi$$

- Particle content:
  - ψ: Quarks, including flavor- and color degrees of freedom, $\hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) =$ current quark masses
  - A_μ^a: gluons, gauge bosons of $\text{SU}(3)_{\text{color}}$
- Symmetries
  - fundamental building block: local $\text{SU}(3)_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry ($\hat{M} \to 0$)
  - dilation symmetry (scale invariance for $\hat{M} \to 0$)

Features of QCD

- asymptotically free: at large momentum transfers $\alpha_s \to 0$
- running from renormalization group:
  Nobel prize 2004 for Gross, Wilczek, Politzer



- quarks and gluons confined in hadrons
- theoretically not fully understood (nonperturbative phenomenon!)
- need of effective hadronic models at low energies: (Chiral) symmetry!

Chiral Symmetry

- Consider only light u, d quarks
- iso-spin 1/2 doublet: $\psi = \begin{pmatrix} u \\ d \end{pmatrix} = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$
- NB: ψ has three "indices": Dirac spinor, color, flavor iso-spin!
- γ matrices: $\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}\mathbb{1}$, $\gamma_5 := \mathrm{i}\gamma_0\gamma_1\gamma_2\gamma_3$, $\gamma_5\gamma_\mu = -\gamma_\mu\gamma_5$, $\gamma_5^\dagger = \gamma_5$, $\gamma_5^2 = \mathbb{1}$
- Diracology of left and right-handed components

$$\psi_L = \frac{\mathbb{1} - \gamma_5}{2}\psi = P_L\psi, \quad \psi_R = \frac{\mathbb{1} + \gamma_5}{2}\psi = P_R\psi,$$

$$P_R^2 = P_L^2 = \mathbb{1}, \quad P_R P_L = P_L P_R = 0, P_{L/R}\gamma_5 = \gamma_5 P_{L/R} = -P_{L/R}$$

$$P_{L/R}\gamma_\mu = \gamma_\mu P_{R/L}, \quad \overline{P_L\psi} = \overline{\psi}P_R, \quad \overline{P_R\psi} = \overline{\psi}P_L$$

$$\overline{\psi}\gamma_\mu\psi = \overline{\psi_L}\gamma_\mu\psi_L + \overline{\psi_R}\gamma_\mu\psi_R, \quad \overline{\psi}\psi = \overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L$$

- $\overline{\psi} := \psi^\dagger\gamma_0$, $\overline{\gamma_5\psi} = \psi^\dagger\gamma_5^\dagger\gamma_0 = -\overline{\psi}\gamma_5$
- in the massless limit ($m_u = m_d = 0$)

$$\mathscr{L}_{u,d} = \overline{\psi}\mathrm{i}\not{D}\psi = \overline{\psi_L}\mathrm{i}\not{D}\psi_L + \overline{\psi_R}\mathrm{i}\not{D}\psi_R$$

Chiral Symmetry

- in the massless limit ($m_u = m_d = 0$)
- a lot of global chiral symmetries:
  - change of independent phases for left and right components:

$$\psi_L(x) \to \exp(\mathrm{i}\phi_L)\psi_L(x), \quad \psi_R(x) \to \exp(\mathrm{i}\phi_R)\psi_R(x)$$

  - symmetry group $\mathrm{U}(1)_L \times \mathrm{U}(1)_R$
  - independent "iso-spin rotations"

$$\psi_L(x) \to \exp(\mathrm{i}\vec{\alpha}_L \cdot \vec{T})\psi_L(x), \quad \psi_R(x) \to \exp(\mathrm{i}\vec{\alpha}_R \cdot \vec{T})\psi_R(x)$$

  - $\vec{T} = \vec{\tau}/2$, $\vec{\tau}$: Pauli matrices; symmetry group $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$
- alternative notation scalar-pseudoscalar phases/iso-spin rotations

$$\psi \to \exp(\mathrm{i}\phi_s)\psi, \quad \psi \to \exp(\mathrm{i}\gamma_5\phi_a)\psi$$

$$\psi \to \exp(\mathrm{i}\vec{\alpha}_V \cdot \vec{T})\psi, \quad \psi \to \exp(\mathrm{i}\gamma_5\vec{\alpha}_A \cdot \vec{T})\psi$$

- Caveat: Symmetry group is NOT $\mathrm{U}(1)_s \times \mathrm{U}(1)_a$ or $\mathrm{SU}(2)_V \times \mathrm{SU}(2)_A$
- $\mathrm{U}(1)_s$ and $\mathrm{SU}(2)_V$ are subgroups that are symmetries even if $m_u = m_d \neq 0 \Rightarrow$ Heisenberg's iso-spin symmetry!

Currents: relation to mesons

- based on [Koc97, Sch03, Din11]
- Noether: each global symmetry leads to a
- from chiral symmetries

$$j_s^\mu = \overline{\psi}\gamma^\mu\psi, \quad j_a^\mu = \overline{\psi}\gamma^\mu\gamma_5\psi$$
$$\vec{j}_V^\mu = \overline{\psi}\gamma^\mu\vec{T}\psi, \quad \vec{j}_A^\mu = \overline{\psi}\gamma^\mu\gamma_5\vec{T}\psi$$

- Link to mesons: Build Lorentz-invariant objects with corresponding quantum numbers
  - σ: $\overline{\psi}\psi$ (scalar and iso-scalar)
  - π's: $\mathrm{i}\overline{\psi}\vec{T}\gamma_5\psi$ (pseudoscalar and iso-vector)
  - ρ's: $\overline{\psi}\gamma_\mu\vec{T}\psi$ (vector and iso-vector)
  - a_1's: $\overline{\psi}\gamma_\mu\gamma_5\vec{T}\psi$ (axialvector and iso-axialvector)
- in nature: σ and π's; ρ's and a_1's do not have same mass!
- reason: QCD ground state not symmetric under pseudoscalar and pseudovector trafos since $\left\langle \mathrm{vac} \middle| \overline{\psi}\psi \middle| \mathrm{vac} \right\rangle \neq 0$

E.m. Current: relation to mesons

- $Q = t_3 + Y/2$, t_3: iso-spin-3-comp, $Y = s + c + b + t + B$
  - quarks: $t_{3u} = -t_{3d} = 1/2$, $t_{3c} = t_{3s} = t_{3t} = t_{3b} = 0$, $Y_u = Y_d = 1/3$, $Y_c = Y_t = 4/3$, $Y_s = Y_b = -2/3$, $B_f = 1/3$, $Q_u = Q_c = Q_t = 2/3$, $Q_d = Q_s = Q_b = -1/3$
- electromagnetic current of quarks (including sum over 3 colors!)

$$J^{\mu}_{\text{em}} = \sum_f \overline{\psi}_f (\hat{T}_3 + \hat{Y}/2) \psi_f = \sum_f Q_f \overline{\psi_f} \gamma^\mu \psi_f = \frac{2}{3} \overline{u} \gamma^\mu u - \frac{1}{3} (\overline{d} \gamma^\mu d + \overline{s} \gamma^\mu s)$$

- split into flavor-iso-spin states:

$$\begin{aligned} &\omega \quad (T=0) : j^{\mu}_{\text{em}\omega} = 1/6(\overline{u}\gamma^\mu u + \overline{d}\gamma^\mu d) \\ &\phi \quad (T=0) : j^{\mu}_{\text{em}\phi} = -1/3 \overline{s}\gamma^\mu s \\ &\rho^0 \quad (T=1) : j^{\mu}_{\text{em}\rho} = 1/2(\overline{u}\gamma^\mu u - \overline{d}\gamma^\mu d) \end{aligned}$$

- expressed in normalized hadronic basis

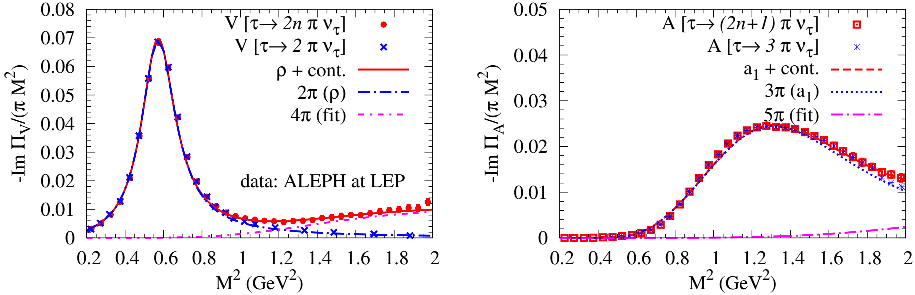
$$j^{\mu}_{\text{em}} = \frac{1}{\sqrt{2}} \left[\frac{\overline{u}\gamma^\mu u - \overline{d}\gamma^\mu d}{\sqrt{2}} + \frac{1}{3} \frac{\overline{u}\gamma^\mu u + \overline{d}\gamma^\mu d}{\sqrt{2}} - \frac{\sqrt{2}}{3} \overline{s}\gamma^\mu s \right]$$

Spontaneous symmetry breaking

- spontaneously broken symmetry: ground state not symmetric
- vacuum necessarily degenerate
- vacuum invariant under scalar and vector transformations: $\mathrm{U}(1)_L \times \mathrm{U}(1)_R$ broken to $\mathrm{U}(1)_s$; $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ broken to $\mathrm{SU}(2)_V$
- for each broken symmetry massless scalar Goldstone boson
- there are three pions which are very light compared to other hadrons (finite masses due to explicit breaking through m_u, m_d!)
- but no pseudoscalar isoscalar light particle! ($m_\eta \simeq 548\,\mathrm{MeV}$)
- reason: $\mathrm{U}(1)_a$ anomaly
    - axialscalar symmetry doesn't survive quantization!
    - good for explanation of correct decay rate for $\pi_0 \to \gamma\gamma$
    - axialscalar current not conserved $\partial_\mu j_a^\mu = 3/8 \alpha_s \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$
- explicit breaking due to quark masses
    - can be treated perturbatively $\Rightarrow$ chiral perturbation theory
    - axial-vector current only approximately conserved $\Rightarrow$ PCAC
    - a lot of low-energy properties of hadrons derivable

Most accurate experiment related to χSB

- weak decay $\tau \rightarrow \nu + n \cdot \pi$
- weak interactions: currents $\propto j_V^\mu - j_A^\mu$
  - ew. sector in standard model: gauged+Higgsed chiral model $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
  - no anomaly in gauge symmetry due to particle content!
- n even: must go through vector current
  n odd: must go through axialvector current

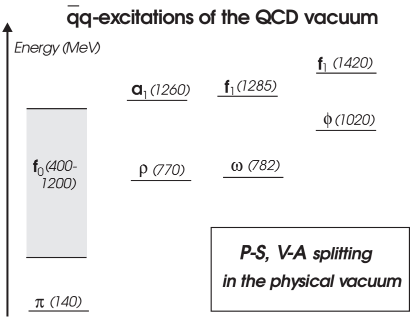


NB: Fate of QCD's Scaling Symmetry

- classical field theory: continuous symmetry $\Rightarrow$ conserved current
- $\hat{M} \to 0 \Rightarrow$ dilatation (or scale) symmetry
  - $x \to \lambda x, \quad \psi \to \lambda^{-3/2}\psi, \quad A_\mu^a \to \lambda^{-1} A_\mu^a$
  - dilatation current:
    $j_D^\mu = x_\nu \Theta^{\mu\nu}$
  - Scale invariance does not survive quantization ("Trace" Anomaly)
    $\partial_\mu j_D^\mu = {\Theta_\mu}^\mu = -\frac{\beta(\alpha_s)}{4\alpha_s} A_{\mu\nu}^a A^{a\mu\nu}$
  - $\beta(\alpha_s)$: Gell-Mann-Low function, rules the running of the coupling with renormalization scale
  - Not a "bug" but a feature: hadrons get most of their mass from it!

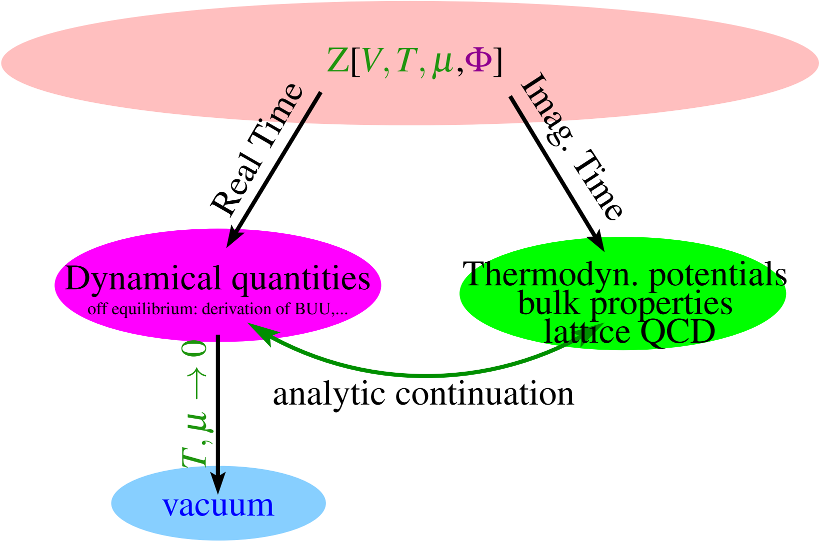
Phenomenology from Chiral Symmetry

- Use (approximate) chiral symmetry to build effective models
- Ward identities
  - PCAC: $\left\langle 0 \middle| \partial^\mu j^k_{A\mu} \middle| \pi^j(\vec{k}) \right\rangle = \mathrm{i} F_\pi^2 m_\pi^2 \delta^{kj}$
  - $m_\pi^2 F_\pi^2 = -(m_u + m_d) \left\langle 0 \left| \overline{u} u \right| 0 \right\rangle$
    (Gell-Mann-Oakes-Renner relation)
- Spontaneous breaking causes splitting of chiral partners:



Finite Temperature/Density: Idealized theory picture

- partition sum: $Z(V, T, \mu_q, \Phi) = \mathrm{Tr}\{\exp[-(\mathbf{H}[\Phi] - \mu_q \mathbf{N})/T]\}$



[CSHY85, Lv87, LeB96, KG06]

Finite Temperature

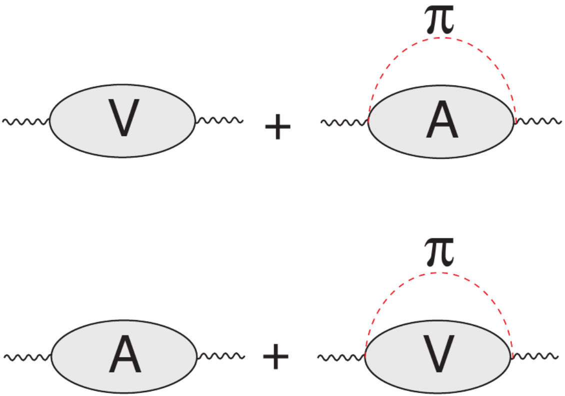
- Asymptotic freedom
  - quark condensate melts at high enough temperatures/densities
- all bulk properties from partition sum:

$$Z(V,T,\mu_q) = \mathrm{Tr}\{\exp[-(\mathbf{H} - \mu_q \mathbf{N})/T]\}$$

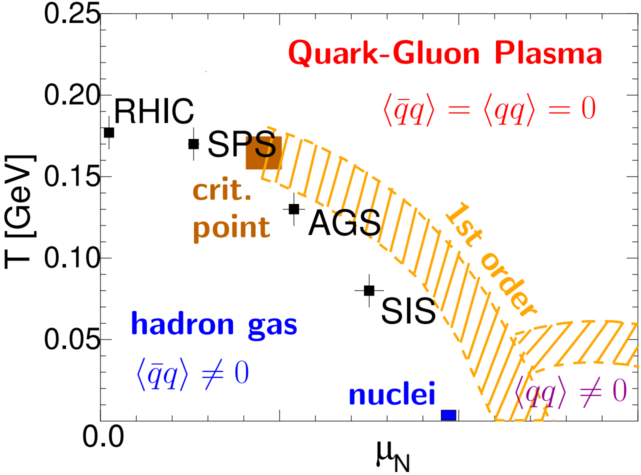
- Free energy: $\Omega = -\frac{T}{V} \ln Z = -P$
- Quark condensate: $\left\langle \overline{\psi}_q \psi_q \right\rangle_{T,\mu_q} = \frac{V}{T} \frac{\partial P}{\partial m_q}$
- Lattice QCD (at $\mu_q = 0$)
  - chiral symmetry $\Leftrightarrow \langle \overline{\psi} \psi \rangle$
  - deconfinement transition $\Leftrightarrow$ Polyakov Loop $\mathrm{tr} \left\langle P \exp(\mathrm{i} \int_0^\beta \mathrm{d}\tau A^0) \right\rangle$
  - Chiral symmetry restoration and deconfinement transition at same T_c

Vector-Axialvector Mixing in the Medium

- in the medium: vector-axialvector currents mix
- due to thermal pions
- possible mechanism for χSR!
- in low-density/temperature approximation: model independent
- see [DEI90a, DEI90b, UBW02, SYZ96, SYZ97]



The QCD Phase Diagram



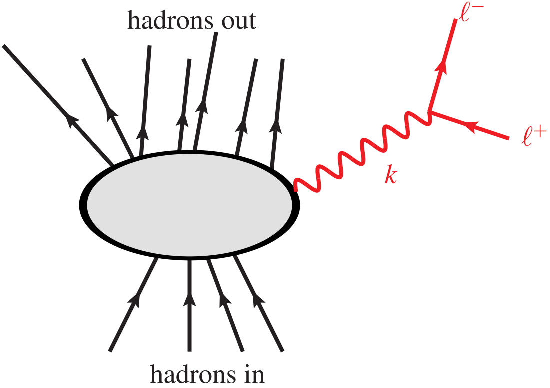
The McLerran-Toimela formula

- radiation of dileptons from thermalized strongly interacting particles
- dileptons escape fireball without any final-state interactions
- calculation exact concerning strong interactions
- leading-order $\mathcal{O}(\alpha^2)$ in QED

$$\mathbf{H}_{\text{em}} = e \int \mathrm{d}^3\vec{x}\, \mathbf{J}_\mu(t,\vec{x}) A^\mu(t,\vec{x}), \quad A^\mu(t,\vec{x}) = \frac{\epsilon^\mu}{2\omega V} \exp(ik \cdot x)$$

- $\mathbf{J}_\mu$: exact Heisenberg em. current operator of quarks or hadrons
- $e = \sqrt{4\pi\alpha}$, $\alpha \simeq 1/137$

The McLerran-Toimela formula



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

$$S_{f'i} = \left\langle f \left| \int \mathrm{d}^4 x \, \mathbf{J}_\mu(x) \right| i \right\rangle D_\gamma^{\mu\nu}(x, x') e \overline{u}_\ell(x') \gamma_\mu v_\ell(x')$$

The McLerran-Toimela formula

- Fourier transformation: energy-momentum conservation
  $|f'\rangle = |f, \ell^+ \ell^-(k)\rangle$

$$S_{fi} = T_{fi}(2\pi)^4 \delta^{(4)}(P_f + k - P_i)$$

- Fermi's trick: Rate

$$R_{f'i} = \frac{|S_{f'i}|^2}{\tau V} = (2\pi)^4 \delta^{(4)}(P_f + k - P_i) |T_{f'i}|^2$$

- summing over $|f\rangle$ and polarizations of dilepton states
- averaging over initial hadron states: heat bath (grand canonical)

$$\boldsymbol{\rho} = \frac{1}{Z} \exp[-\beta(\mathbf{H}_{\text{QCD}} - \mu_B \mathbf{Q}_{\text{baryon}})]$$

The McLerran-Toimela formula

- result (derivation see [GK91], Appendices)

$$\frac{\mathrm{d}R_{ll}}{\mathrm{d}^4 k} = -\frac{\alpha^2}{3\pi^3} \frac{k^2 + 2m_\ell^2}{(k^2)^2} \sqrt{1 - \frac{4m_\ell^2}{k^2}} g_{\mu\nu} n_B(k^0) \, \mathrm{Im} \, \Pi^{\mu\nu}_{\text{ret}}(k)$$

- em. current-current correlator

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

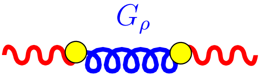
- in principle measureable: in linear response approximation Green's function for lepton current running through medium
- $k^2 = M^2 > 0$ invariant mass of dilepton
- probing medium with photons: same correlator for $k^2 = M^2 = 0$
- then correlator $\Leftrightarrow$ dielectric function $\epsilon(\omega)$ in electrodynamics!

The McLerran-Toimela formula

- for real photons

$$\omega \frac{\mathrm{d}R}{\mathrm{d}^3 \vec{k}} = -\frac{\alpha g_{\mu\nu}}{2\pi^2} \operatorname{Im} \Pi^{\mu\nu}_{\text{ret}}(k), \quad \omega = k^0 = |\vec{k}|$$

- NB: Phenomenological effective hadronic model: vector-meson dominance model
- em. current $\propto V^\mu$ (with $V \in \{\rho, \omega, \phi\}$)

$\Sigma^{\gamma}_{\mu\nu} =$ 

- Dilepton/photon rates: $\propto A_V = -2 \operatorname{Im} D_V^{(\text{ret})}$ (vector-meson spectral function!)
- measuring in-medium vector-meson spectral function!?!
- $\rightarrow$ Lecture III

QCD Sum rules

- based on [LPM98]
- calculate current correlator, e.g., the vector part of the em. current

$$j_\mu = \frac{1}{2}(\overline{u}\gamma_\mu u - \overline{d}\gamma_\mu d)$$

- corresponds to the ρ meson!
- use pQCD to determine correlator

$$\Pi_{\mu\nu}(k) = \left(g_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}\right)\Pi(k^2)$$

  in deep spacelike region, $Q^2 = -k^2 \gg \Lambda_{\text{QCD}}$
- related to time-like region $\Rightarrow$ sum rule

$$\Pi(k^2) = \Pi(0) + cQ^2 + \frac{Q^4}{\pi}\int_0^\infty \mathrm{d}s \frac{\operatorname{Im}\Pi(s)}{s^2(s+Q^2-\mathrm{i}\epsilon)}$$

- dispersion relation: spectral function $\operatorname{Im}\Pi$!

QCD Sum rules

- left-hand side of sum rule
- pQCD + chiral models for baryon-pion interactions [see, e.g., [DGH92]]

$$R(Q^2) := \frac{\Pi(k^2=-Q^2)}{Q^2} = -\frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right)\ln\left(\frac{Q^2}{\mu^2}\right) + \frac{1}{Q^4} m_q \langle \overline{q} q \rangle + \frac{1}{24 Q^4}\left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu}\right\rangle - \frac{112}{81 Q^6}\kappa \langle \overline{q} q \rangle^2$$

- additional cold-nuclear matter contributions

$$\Delta R(Q^2) = \frac{m_N}{4Q^4} A_2 \rho_N - \frac{5 m_N^3}{12 Q^6} A_4 \rho_N$$

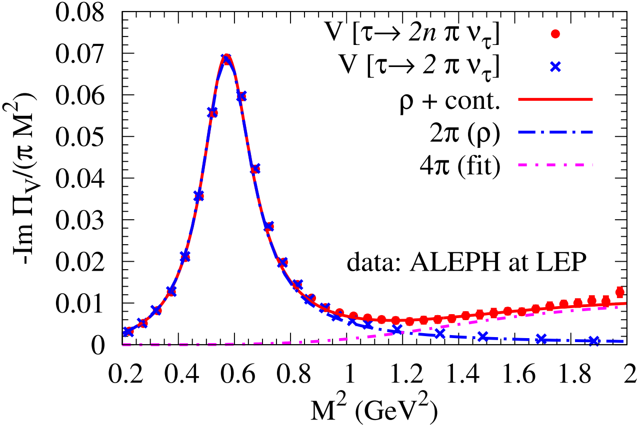
- $A_{2,4}$ from parton-distribution functions
- also condensates corrected

$$\langle \overline{q} q \rangle = \langle \overline{q} q \rangle_{\text{vac}} + \frac{\sigma_N}{2 m_q} \rho_N,$$

$$\left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu}\right\rangle = \left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu}\right\rangle_{\text{vac}} - \frac{8}{9} m_N^{(0)} \rho_N$$

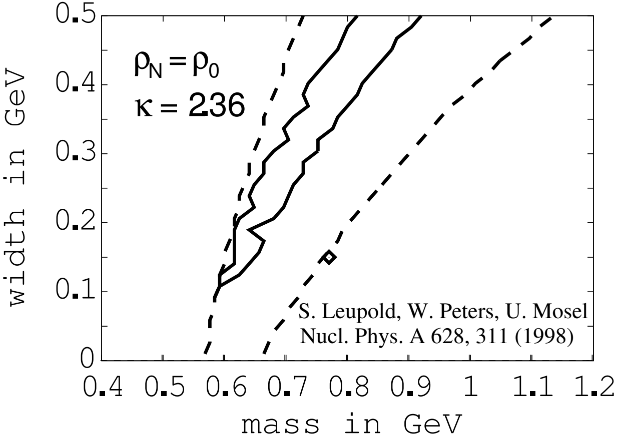
QCD Sum rules

- right-hand side of sum rule
- use hadronic models to fit measured vector-current correlator
- e.g., ALEPH/OPAL data of $\tau \to \nu + 2n\pi$



QCD Sum rules

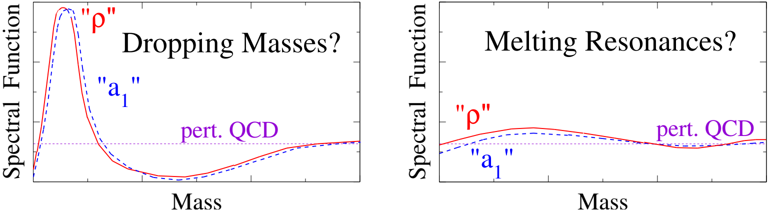
- typical result from [LPM98]



- possible medium effects on ρ meson
  - dropping mass, unchanged/small width
  - unchanged mass, broadened spectrum (large width)

Scenarios for chiral symmetry restoration

- hadron spectrum must become degenerate between chiral partners



- models alone of little help (realization of χS not unique!)
  - "vector manifestation" $\rho_{\text{long}} = \chi$ partner of $\pi \Rightarrow$ dropping mass
  - "standard realization" $\rho = \chi$ partner of a_1, extreme broadening $+$ little mass shifts
- theory "shopping list"
  - effective hadronic models (well constrained in vacuum!)
  - and concise evaluation in the medium!
  - models for fireball evolution
  - must include partonic $\rightarrow$ phase transition $\rightarrow$ hadronic evolution
- precise $\ell^+\ell^-$ (γ) data from HICs mandatory!

Summary

- Motivation for dilepton measurements in HICs
  - leptons are penetrating probes
  - invariant-mass spectra of $\ell^+\ell^-$ undistorted by FSIs
  - give spectral properties of electromagnetic current correlator
  - related to vector-meson spectral function
  - related to (approximate) chiral symmetry $\Leftrightarrow$ chiral phase transition
  - chiral-symmetry restoration (perhaps) observable!?!
  - one key obsevation in HICs:
    enhancement of dileptons in low-mass region compared to pp collisions
- QCD and chiral symmetry
  - fundamental symmetry: local color-gauge symmetry $\mathrm{SU}(3)_c$
  - a lot of "accidental" global symmetries in light-quark sector
    - chiral and scaling symmetry in light-quark sector
    - $\mathrm{U}(1)_A$ symmetry and scaling symmetry anomalously broken
    - axialvector-iso-vector symmetry spontaneously broken
    - pions as Goldstone bosons
    - slightly explicitly broken by light-quark masses

Summary

- Fundamental results from theory
  - Dilepton spectrum $\Leftrightarrow$ em. current-correlation function
  - model-independent approach: QCD sum rules
    - relate pQCD + measurable condensates at $Q^2 = -q^2 \gg \Lambda^2$ to measureable spectral functions at $q^2 = s > 0$
    - dropping mass and resonance melting as mechanism for χSR possible
    - cannot be decided theoretically from first principles
- Need for
  - hadronic effective models in vacuum and in medium
  - evolution models of fireball (quantum transport, QMD, hydrodynamics)
  - high-precision dilepton data

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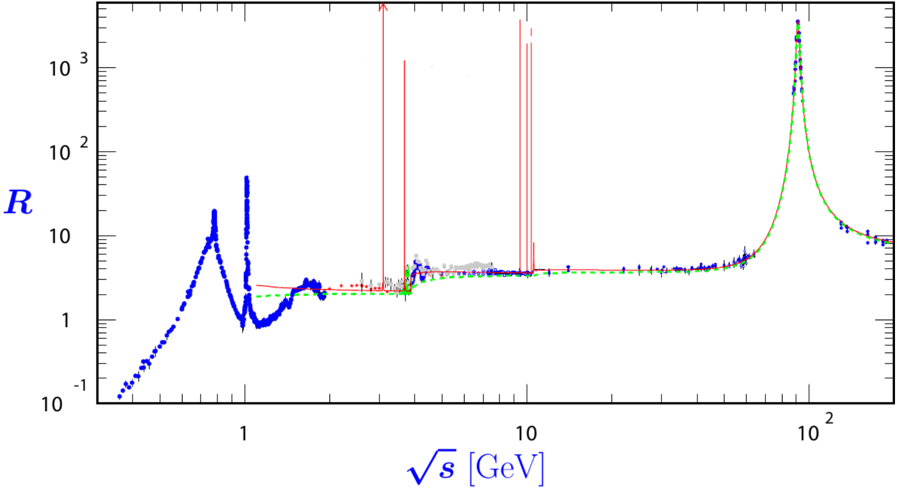
Quiz

- Why do we want to measure dileptons in HICs?
- What are the peaks in the following figure of $R_{e^+e^- \to \text{hadrons}}$?
- Can you explain the horizontal lines (values: 2, 3.333, 3.667)?



Quiz

- What are the "fundamental" and "accidental" symmetries of QCD?
- What's chiral symmetry?
- Why is it (intuitively) only true for massless quarks?
- What's the main consequence of spontaneous symmetry breaking?
- What's the main meaning of the McLerran-Toimela formula?
- Can one decide from first principles, whether χSR is caused by "dropping hadron masses" or "resonance melting"?

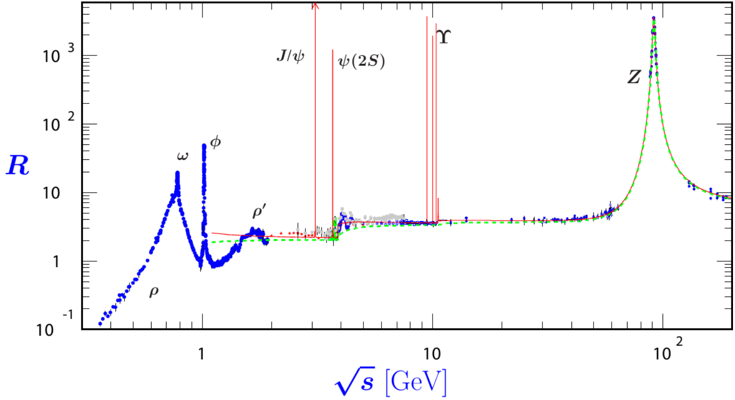
SOLUTIONS

Quiz

- Why do we want to measure dileptons in HICs?
  - $\ell^+\ell^-$ penetrating probes, unaffected by final-state interactions
  - shine through for all times of fireball evolution
  - probe not only dilute regions but also hot/dense interior of the medium
  - invariant-mass spectra probe em. current correlator of partons/hadrons
  - directly related to vector-meson properties (in the medium!)
  - directly related to vector current $\Rightarrow$ χSR!?!

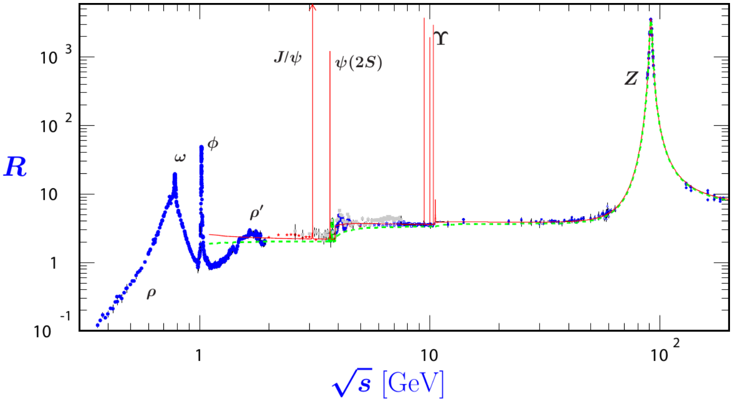
Quiz

- What are the peaks in the following figure of $R_{e^+e^- \to \text{hadrons}}$?
  - $\sqrt{s} < m_Z$: hadron resonances in the QED cross section
    - ρ^0, ω, ϕ, ρ'
    - charmonium states χ/ψ, ψ
    - bottomonium states Υ
  - $\sqrt{s} \gtrsim m_Z$: additional contribution from weak neutral current (Z^0)



Quiz

- Can you explain the horizontal lines (values: 2, 3.333, 3.667)?
  - the dashed green lines are $R_{\text{quark model}} = N_c \sum_f Q_f^2$ (sum runs over quarks with $\sqrt{s} > 2m_f$)
  - the red solid lines include QCD corrections up to three loops



Quiz

- What are the "fundamental" and "accidental" symmetries of QCD?
  - fundamental: gauged color symmetry $\Rightarrow$ gluons as gauge bosons
  - accidental: in limit $m_q \to 0$ chiral $\mathrm{U}(1)_L \times \mathrm{U}(1)_R \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ and scale (dilation) symmetry
  - $\mathrm{U}(1)_A$ and scale symmetry anomalously broken
  - $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ spontaneously broken to $\mathrm{SU}(2)_V$
  - χ symmetry also explicitly broken by quark masses
- What's chiral symmetry?
  - independent symmetries for left-handed and right-handed parts of fermions
- Why is it (intuitively) only true for massless quarks?
  - for massless quarks: left/right-handed the same as states with good helicity $\mp 1/2$
  - massive particles $\Rightarrow$ can always boost to frame where helicity is flipped

Quiz

- What's the main phenomenological consequence of spontaneous symmetry breaking?
  - the appearance of as many massless Goldstone bosons as there are symmetry operations that change the vacuum
    (but not the corresponding lowest energy eigenvalue)
- What's the main meaning of the McLerran-Toimela formula?
  - dilepton or photon production rate from an equilibrated medium
  - connects these production rates with em. current correlator
  - (approximate) validity of vector-meson dominance $\Rightarrow$
    direct relation of rates with in-med. VM spectral functions

Quiz

- Can one decide from first principles, whether χSR is caused by dropping hadron masses or "resonance melting"?
  - constraints from QCD (and chiral) sum rules admit both dropping VM (ρ) masses or "melting" (broadening)
  - chiral symmetry makes model-independent predictions only for on-shell self-energies at (very) low momenta
  - medium modifications only model independent in the low density/temperature limit
  - need for hadronic models: realization of chiral symmetry not unique; different models predict also either broadening (usual Wigner-Weyl manifestation) or dropping masses (vector manifestation in hidden-local symmetry)
- We need high-precision dilepton data from HIC experiments and good hadronic models to make a case for χSR!