Electromagnetic Probes in Heavy-Ion Collisions I

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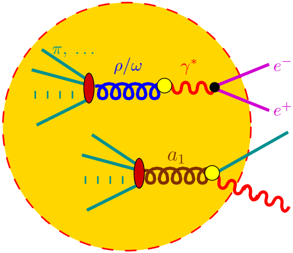
Outline

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]
- Lecure II: P/HMBT and dilepton experiments (HADES and NA60)
  - partonic and hadronic many-body theory
  - fireball model for the bulk evolution
  - di-muons at the SPS@CERN (NA60)
  - literature: [RW00, RWH09, HR06, HR08]

Why Electromagnetic Probes?

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



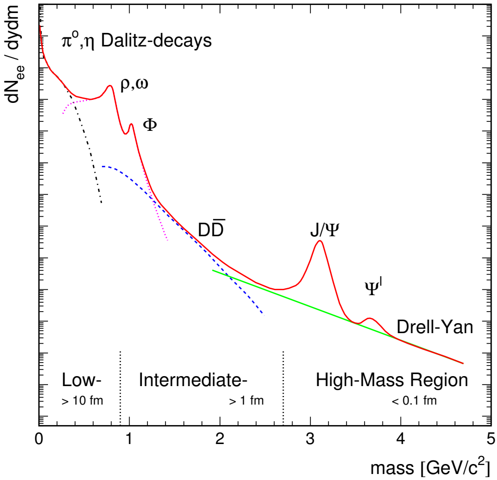
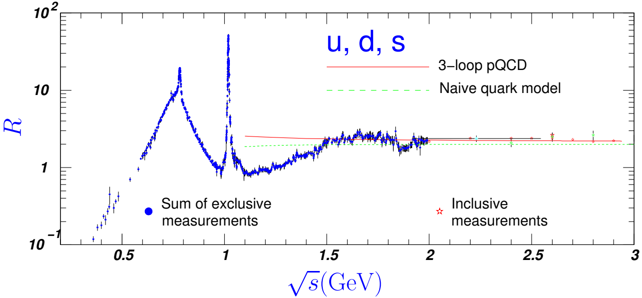


Fig. by A. Drees (from [RW00])

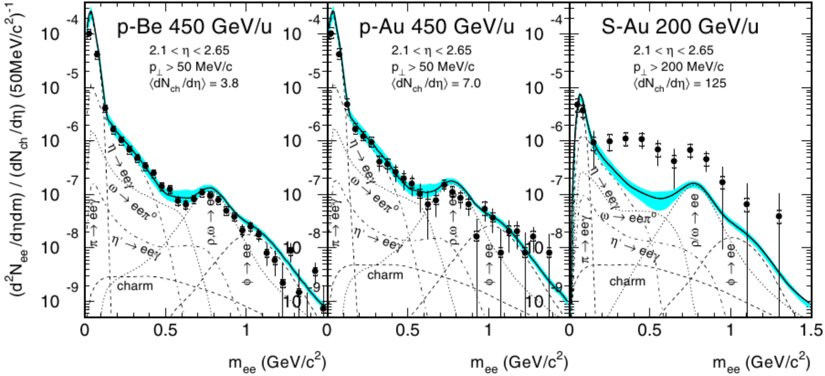
Vacuum Baseline: $e^+e^- \to$ hadrons



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

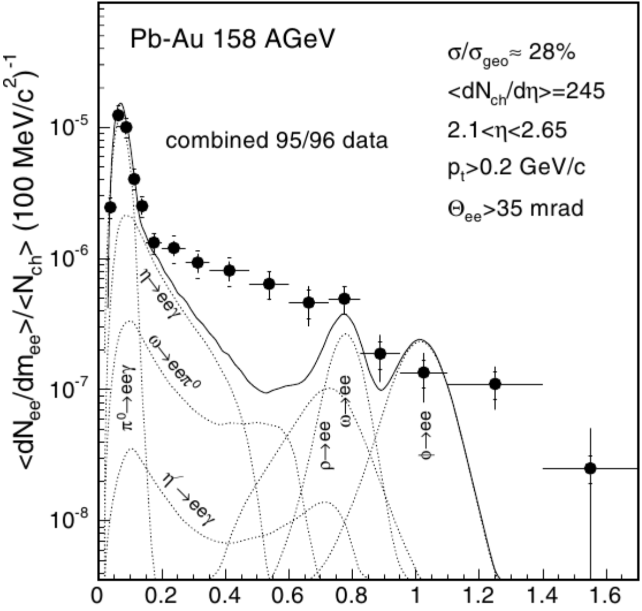
- probes all hadrons with quantum numbers of γ^*
- $R_{\mathrm{QM}} = N_c \sum_{f=u,d,s} Q_f^2 = 3 \times [(2/3)^2 + (-1/3)^2 + (-1/3)^2] = 2$
- Our aim $\mathrm{pp} \to \ell^+\ell^-$, $\mathrm{pA} \to \ell^+\ell^-$, $\mathrm{AA} \to \ell^+\ell^-$ $\ell = \mathrm{e}, \mu$
- see also Theory Lecture II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

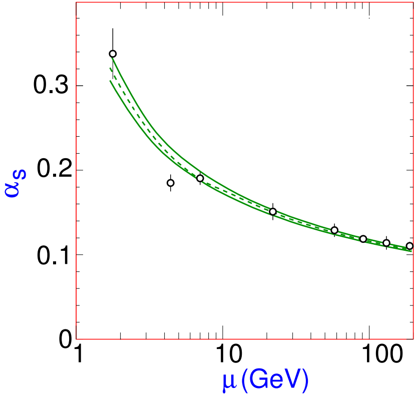
- Theory for strong interactions: QCD

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

- 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 ($\hat{M} \rightarrow 0$)
  - dilation symmetry (scale invariance for $\hat{M} \rightarrow 0$)

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

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

- $\mathrm{U}(1)_s$ 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 conserved quantity
- 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 $\langle \text{vac} | \overline{\psi}\psi | \text{vac} \rangle \neq 0$

Electromagnetic 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!)

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

- split into flavor-iso-spin states:

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

- expressed in normalized hadronic basis

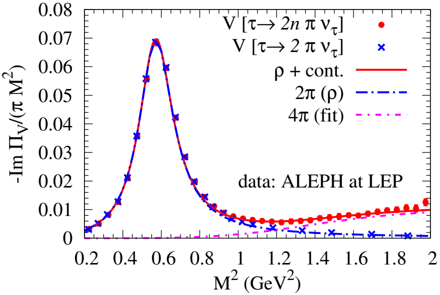
$$j^\mu_{\text{em}} = \frac{1}{\sqrt{2}} \left[\frac{\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d}{\sqrt{2}} + \frac{1}{3} \frac{\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d}{\sqrt{2}} - \frac{\sqrt{2}}{3} \bar{s}\gamma^\mu s \right]$$

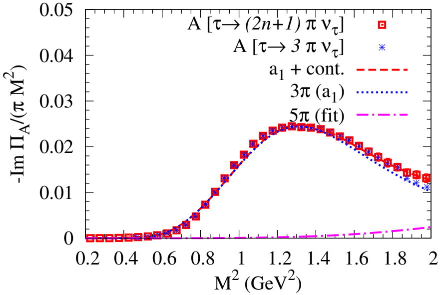
Spontaneous symmetry breaking

- spontaneously broken symmetry: ground state not symmetric
- vacuum necessarily degenerate
- vacuum invariant under scalar and vector transformations: $U(1)_L \times U(1)_R$ broken to $U(1)_s$; $SU(2)_L \times SU(2)_R$ broken to $SU(2)_V$
- 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! ($m_\eta \simeq 548$ MeV)
- reason: $U(1)_a$ anomaly
  - axialscalar symmetry does not 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



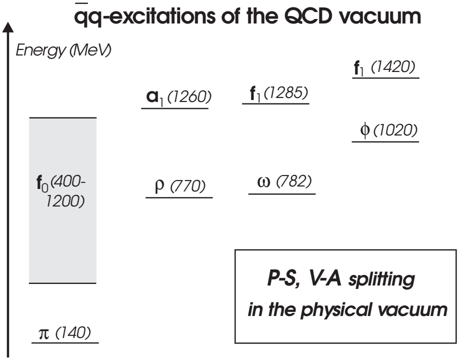


NB: Fate of QCD's Scaling Symmetry

- classical field theory: continuous symmetry $\Rightarrow$ conserved current
- $\hat{M} \rightarrow 0 \Rightarrow$ dilatation (or scale) symmetry
  - $x \rightarrow \lambda x, \quad \psi \rightarrow \lambda^{-3/2} \psi, \quad A_\mu^a \rightarrow \lambda^{-1} A_\mu^a$
  - 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!

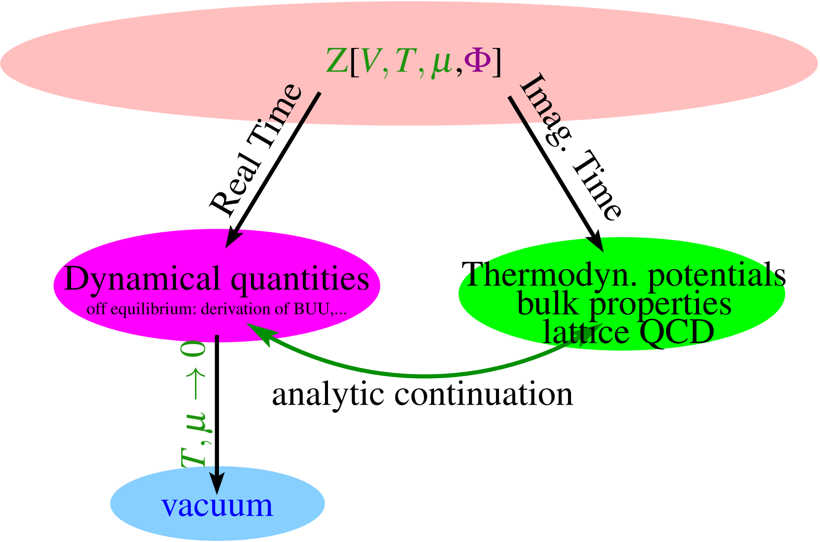
Phenomenology from Chiral Symmetry

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



Finite Temperature/Density: Idealized theory picture

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



[CSHY85, Lv87, LeB96, KG06]

Finite Temperature

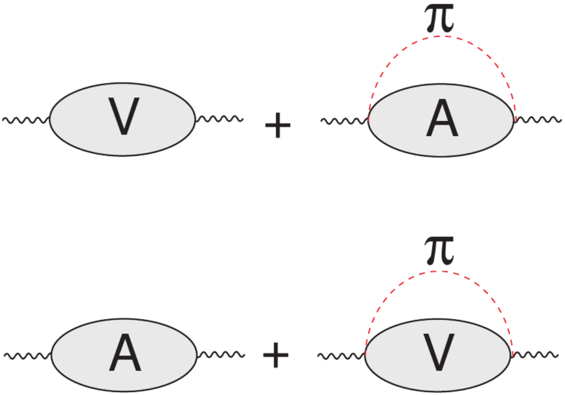
- Asymptotic freedom
  - quark condensate melts at high enough temperatures/densities
- all bulk properties from partition sum:

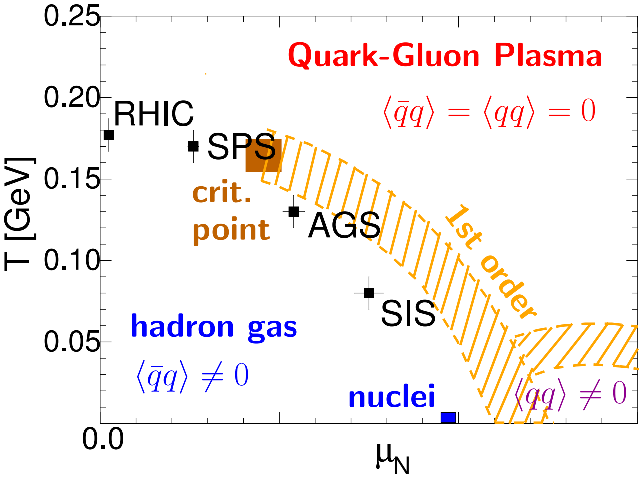
$$Z(V, T, \mu_q) = \mathrm{Tr}\{\exp[-(\mathrm{H} - \mu_q \mathrm{N})/T]\}$$

- 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]





Quark-Gluon Plasma
$\langle \bar{q}q \rangle = \langle qq \rangle = 0$
RHIC
SPS
crit. point
AGS
1st order
SIS
hadron gas
$\langle \bar{q}q \rangle \neq 0$
nuclei
$\langle qq \rangle \neq 0$
T [GeV]
0.25
0.20
0.15
0.10
0.05
0.0
μ_N

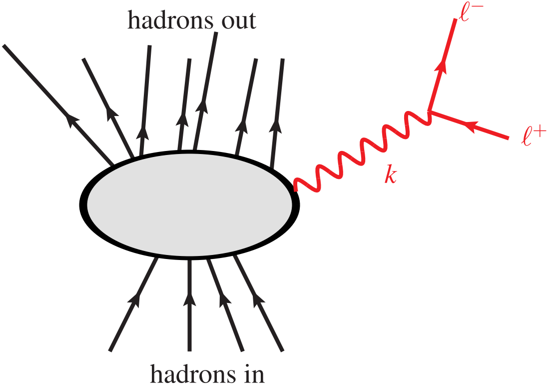
The McLerran-Toimela formula

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

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

- J_μ: 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 ⇒ transition-matrix element for process $|i\rangle \rightarrow |f'\rangle = |f\rangle + |\ell^+\ell^-(k)\rangle$
- QED Feynman rules

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

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)

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

The McLerran-Toimela formula

- result (derivation see [GK91], Appendices)

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

- em. current-current correlator

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

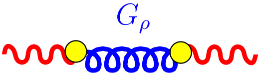
- in principle measureable: in linear response approximation Green's function for lepton current running through medium
- $k^2 = M^2 > 0$ invariant mass of dilepton
- probing medium with photons: same correlator for $k^2 = M^2 = 0$
- then correlator $\Leftrightarrow$ dielectric function $\varepsilon(\omega)$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

The McLerran-Toimela formula

- for real photons

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

- 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 II

QCD Sum rules

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

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

- 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

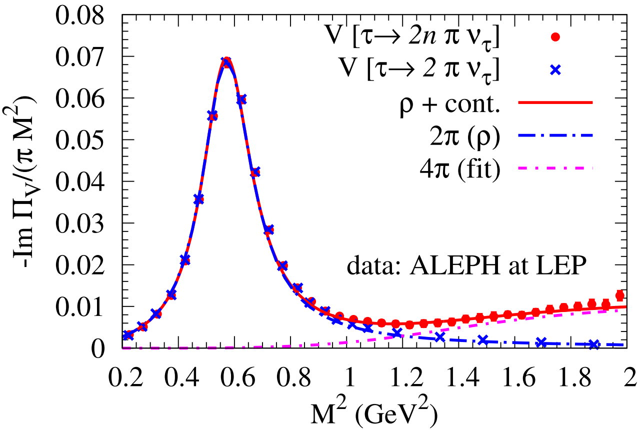
$$\Delta R(Q^2) = \frac{m_N}{4Q^4} A_2 \rho_N - \frac{5 m_N^3}{12 Q^6} A_4 \rho_N$$

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

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

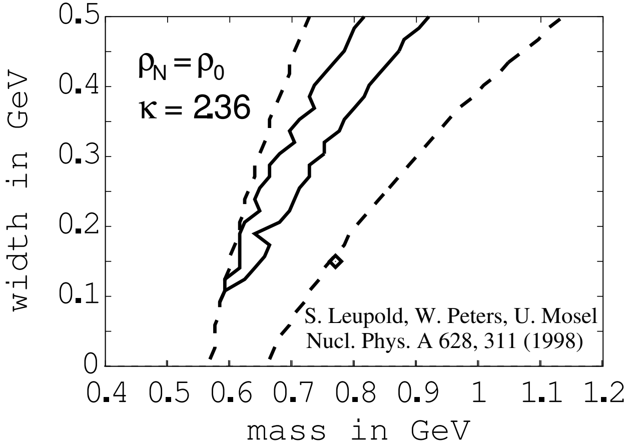
$$\left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu} \right\rangle = \left\langle \frac{\alpha_s}{\pi} F^a_{\mu\nu} F^{a\mu\nu} \right\rangle_{\text{vac}} - \frac{8}{9} m_N^{(0)} \rho_N$$

- 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

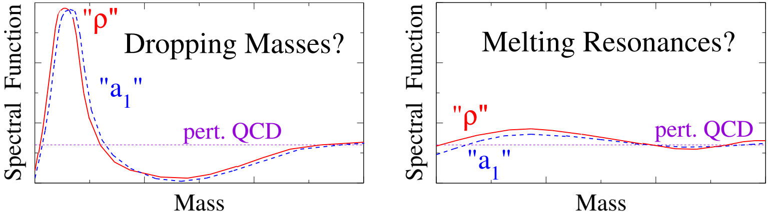
- typical result from [LPM98]



- 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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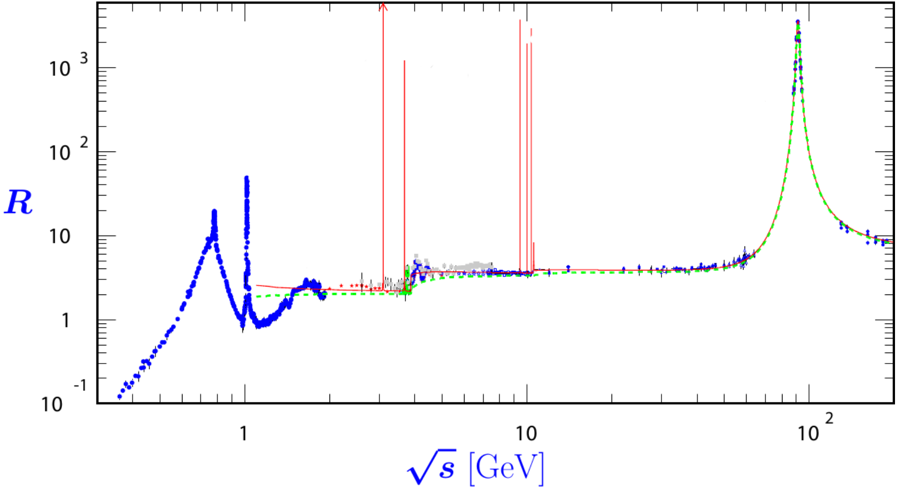
Quiz

- 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”?