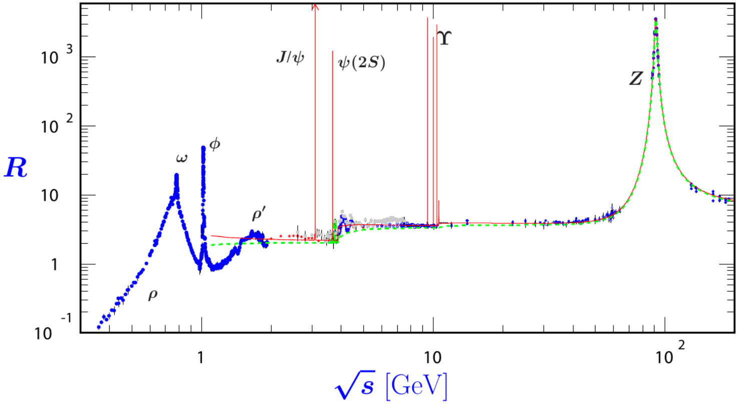
Quiz – Solutions

- 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!?!

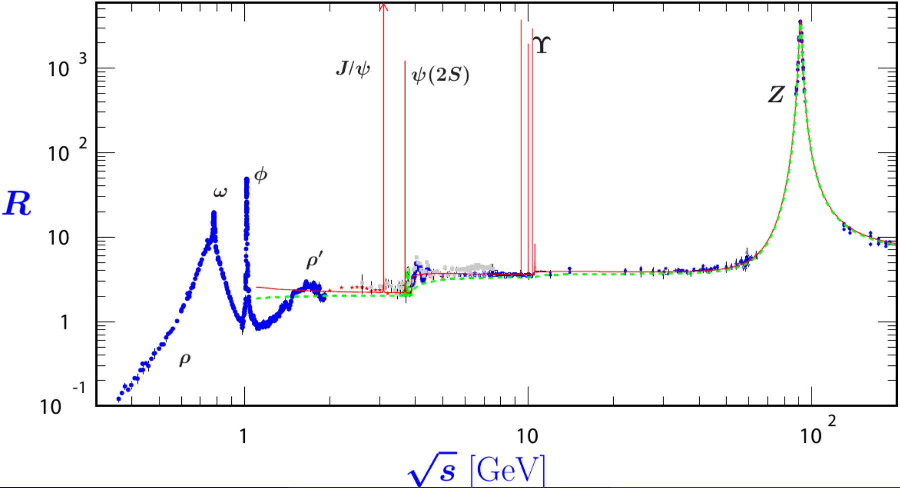
Quiz – Solutions

- 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
    - $\rho^0, \omega, \phi, \rho'$
    - charmonium states χ/ψ, ψ
    - bottomonium states Y
  - $\sqrt{s} \gtrsim m_Z$: additional contribution from weak neutral current (Z^0)



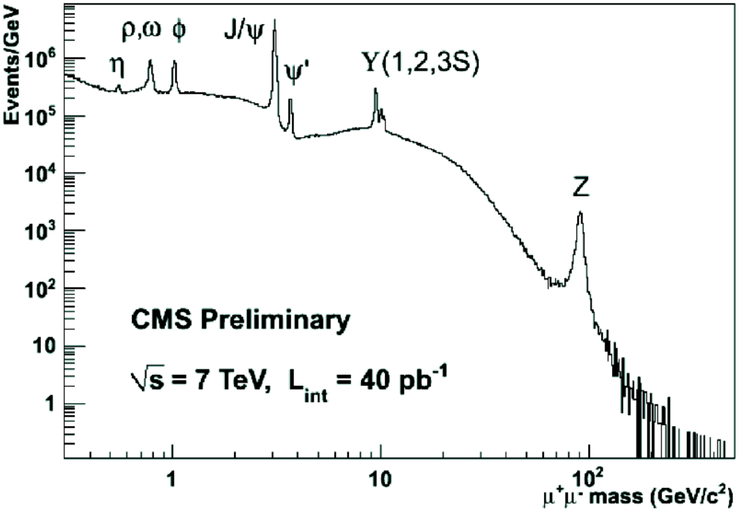
Quiz – Solutions

- 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 – Solutions

$\mu^+\mu^-$ spectrum at the LHC (from CMS collaboration)



Quiz – Solutions

- 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
- 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)

Quiz – Solutions

- What are anomalies? Are they always bad for models?
  - symmetry of a classical field theory that does not survive quantization
  - occurs, because radiative corrections (loop diagrams) must be regularized, but there's no symmetry-conserving regulator
  - only bad if symmetry is vital for the consistency of the model or on phenomenological grounds (empirically known conservation law)
  - "good" case: $\mathrm{U}(1)_A$ breaking in QCD/QED
  - predicts correct rate $\pi^0 \rightarrow \gamma\gamma$
  - Adler-Bell-Jackiw anomaly [Adl69, BJ69]
  - NB: here anomaly must shifted to axial-vector current since vector current important for em. and QCD gauge symmetry!

Quiz – Solutions

- 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
- 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!

Quiz – Solutions

- Why do we need effective hadronic models to theoretically study electromagnetic probes in HICs?
  - "fundamental" theory is QCD
  - so far we cannot solve confinement/bound-state problems to describe hadrons from first-principle QCD calculation
  - lQCD: can not calculate in-medium current-current correlator in the time-like region
- How do we constrain effective hadronic models theoretically?
  - use symmetries of underlying fundamental symmetry (QCD)
  - constraints from em. gauge invariance, χS, anomalies,...
- How do we determine all the parameters (couplings, masses, form factors) of the models?
  - use data on "elementary" hadron interactions and electrodynamics of hadrons

Quiz – Solutions

- What is left to be predicted from such models?
  - in-medium modifications of hadron-spectral properties/interactions
- What are the most important processes leading to medium modifications of the vector mesons' spectral functions?
  - modification of the "pion cloud"
  - direct baryon interactions (even at low *net*-baryon density!)
- What are the different dilepton sources that are important in UHICs?
  - Dalitz decay of mesons π^0, η (chiral anomalies!)
  - decay of light vector mesons, ρ, ω, ϕ

  $\Rightarrow$ observation of medium modifications of hadrons!
    - comparison of models with data (particularly NA60): vector-meson masses $\sim$ vacuum values but substantial broadening of mass spectra
    - data favor "melting-resonance scenario" over "dropping-mass scenario"
  - thermal dilepton radiation from QGP, particularly in IMR
  - decay of correlated $\mathrm{D}\overline{\mathrm{D}}$ decays; important "background" to emission from QGP in IMR!

Quiz – Solutions

- Which interesting information can be gained from investigating also $\ell^+\ell^-$-p_T spectra in addition to M spectra?
  - through blue shift of (virtual) photons $\Rightarrow$ weighted average radial flow over whole history of fireball evolution, not only from thermal-freezeout state as for hadrons
- What fundamental properties about the hot and dense medium produced in HICs have we inferred from $\ell^+\ell^-$ data so far?
  - all data compatible with χSR (no clear proof yet!)
  - kind of "quark-hardon duality" of hadronic dilepton production close to phase transition $T \simeq 160$-190 MeV
  - "resonance-melting scenario" of in-medium vector-meson modification favored compared to "dropping-mass scenario"

Bibliography I

[Adl69] S. L. Adler, Axial vector vertex in spinor electrodynamics, Phys. Rev. **177** (1969) 2426.
http://dx.doi.org/10.1103/PhysRev.177.2426

[BJ69] J. S. Bell, R. Jackiw, A PCAC puzzle: $\pi^0 \to \gamma\gamma$ in the sigma model, Nuovo Cim. A **60** (1969) 47.
http://dx.doi.org/10.1007/BF02823296