Parity Doubling of Baryons in QCD Thermodynamics

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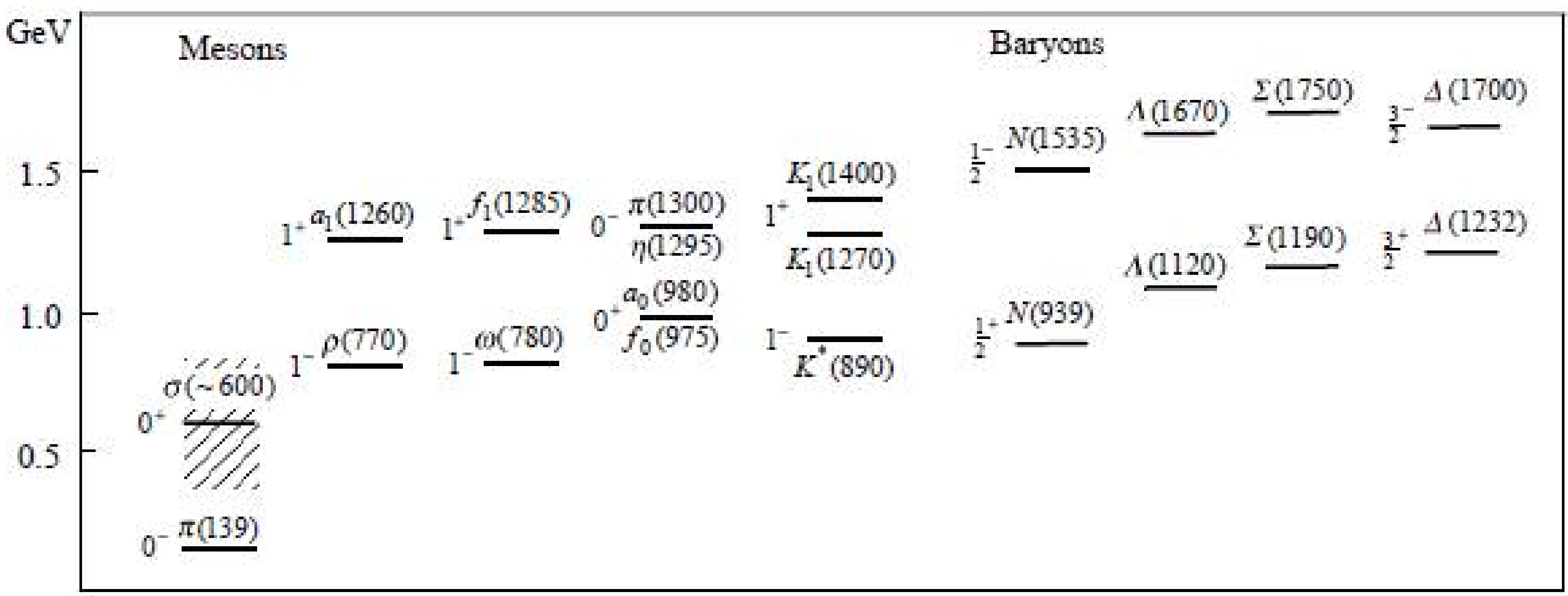
Spectra in a chirally broken world

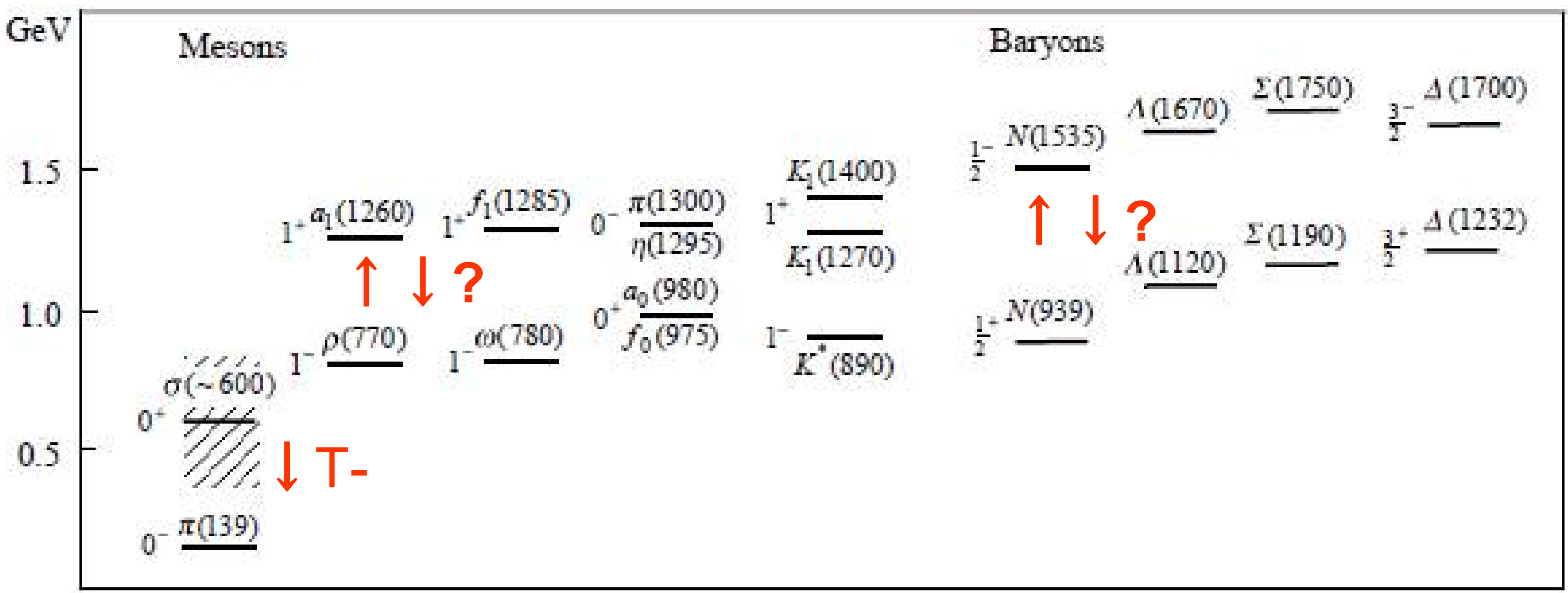
- Lowest pseudo-scalar mesons as NG bosons
- Mass splitting between positive and negative parity hadrons



Spectra in a chirally restored world

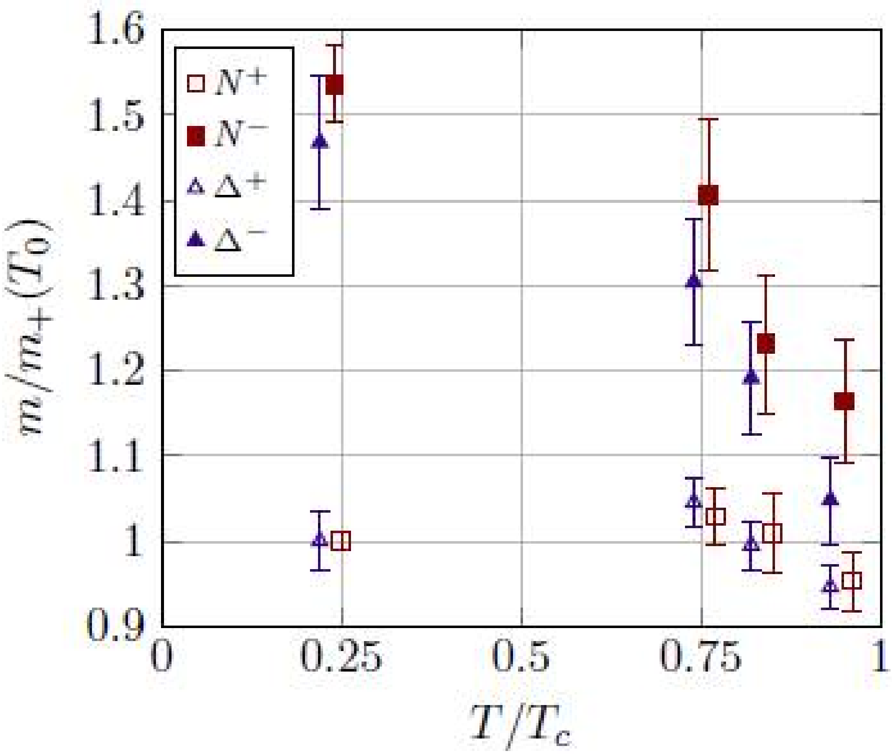
- ❑Lowest scalar meson → O(4) vector with pion
- ❑Parity partners degenerate → chiral partners

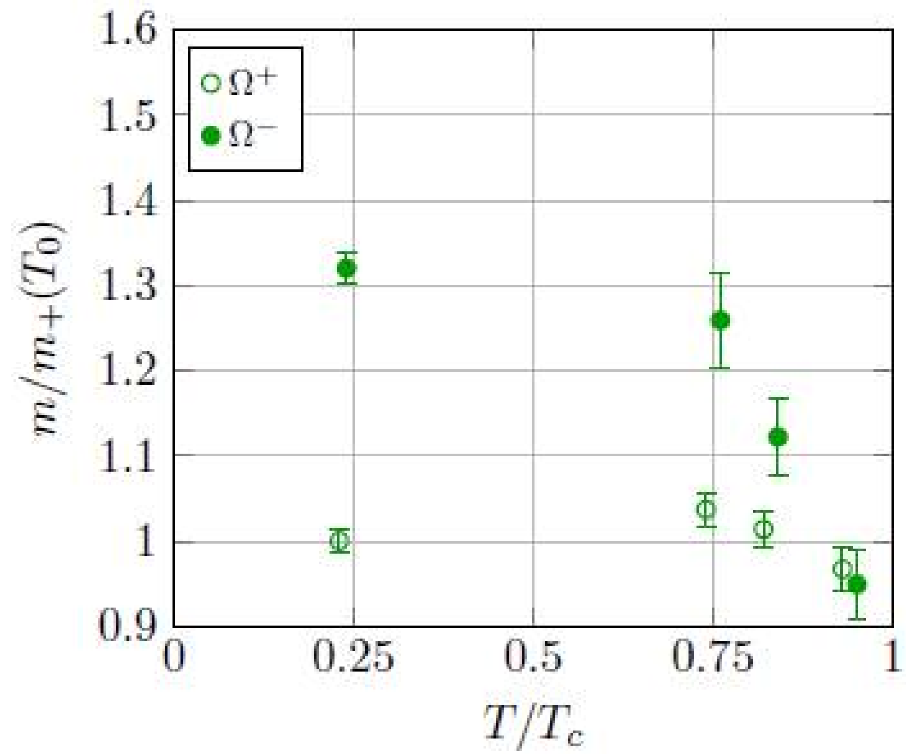
[mq ≈ 0: helicity eigenstates ≈ parity eigenstates]



Lattice QCD tells us ...

- Temporal correlations in baryonic channels
  [FASTSUM Coll., 2015-17: mpi≈400 MeV, mk≈500 MeV, Wilson fermions, Tch=185 MeV]





vs. Mn ≈ 3 x Mq

Nucleon mass vs. CSB

- Gell-Mann—Levy model/conventional LSM

$$\mathcal{L}_{\mathrm{GL}} = i\bar{N}\partial\!\!\!/ N - g\bar{N}(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})N + \mathcal{L}_{\mathrm{meson}}$$

$$\psi_L \to L\,\psi_L\,, \quad \psi_R \to R\,\psi_R \qquad\qquad m_N = g\langle\sigma\rangle$$

- When CS restored → massless nucleon

- How to introduce a mass term?

Non-SCB mass of nucleons

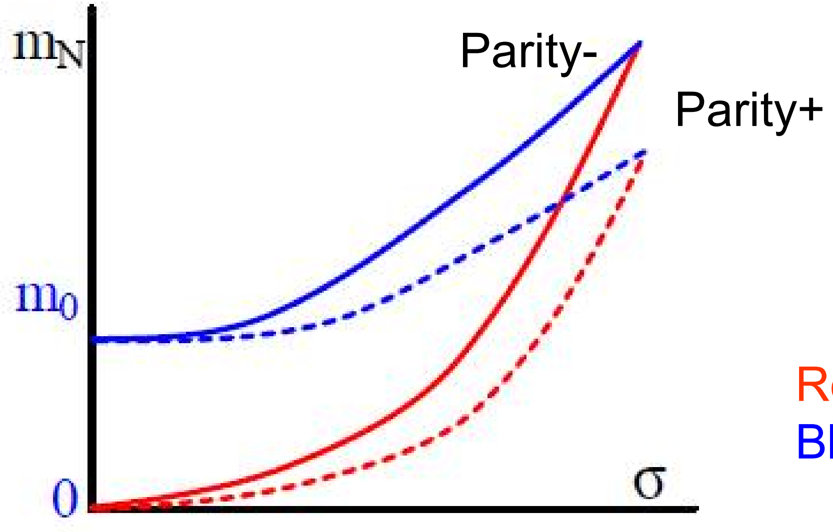
- SU(2) chiral transformation of 2 nucleons

  → how to assign 2 indep. rotation to them?

$$\psi_{1L} \to g_l \, \psi_{1L} \,, \quad \psi_{1R} \to g_r \, \psi_{1R} \;\sim\; \psi_{1L} : (1/2, 0) \quad \psi_{1R} : (0, 1/2)$$

$$\psi_{2L} \to g_r \, \psi_{2L} \,, \quad \psi_{2R} \to g_l \, \psi_{2R} \;\sim\; \psi_{2L} : (0, 1/2) \quad \psi_{2R} : (1/2, 0)$$

$$\mathcal{L}_m = m_0 \left(\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2 \right) \;\Rightarrow\; m_{N_\pm} = \frac{1}{2} \left[\sqrt{c_1 \sigma^2 + 4 m_0^2} \mp c_2 \sigma \right]$$



[DeTar-Kunihiro, 1989]

Red: standard
Blue: Mirror

Origin of the survival mass?

- Emergence of a scale in QCD → trace anomaly

$$\partial_\mu J^\mu = T^\mu_\mu \propto \langle H|G^2|H\rangle$$

- in hot matter [Miller, 2007: lattice QCD EoS]

$$\langle G^2\rangle_{T_{\rm chiral}} \simeq \frac{1}{2}\langle G^2\rangle_{T=0}$$

- in nuclear matter [Cohen et al. , 1995: Feynman-Hellmann theorem & low-density approx.]

$$\left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\mu\nu} \right\rangle_{\rho_N} - \left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\mu\nu} \right\rangle_{\rm vac} = -\frac{8}{9}(M_N - \sigma_N - S)\rho_N + \cdots$$

5% smaller

How large is m0?

- Vacuum: m0 = 270 – 460 MeV [DeTar-Kunihiro, Nemoto et al. , Gallas et al.]
- Finite m0: dominated by color-magnetic gluon
  - VEV of dilaton → m0 [CS et al.]
- Nuclear matter
  - Ground state: binding energy, normal NM density
  - Preferred m0 ≈ 500-800 MeV (w/ and w/o 4Q)

    [Zschiesche et al. 2007, Gallas et al. 2011]
- LQCD/FASTSUM: near Tch, zero chem.pot.

  m0(octet,decuplet) ≤ m+(T=0)

m0 ≈ a few Λ qcd

Mass difference: weak m0-dep.

Parity doubling of baryons

- ❑ Baryon octet and decuplet with finite m0
- ❑ Consistent with established phenomenology:
  - ✓ Gell-Mann-Okubo mass formula

$$\frac{3}{4}m_\Lambda + \frac{1}{4}m_\Sigma - \frac{1}{2}(m_N + m_\Xi) = 0$$

  - ✓ Gell-Mann's equal spacing rule

$$m_{\Sigma^*} - m_\Delta = m_{\Xi^*} - m_{\Sigma^*} = m_\Omega - m_{\Xi^*}$$

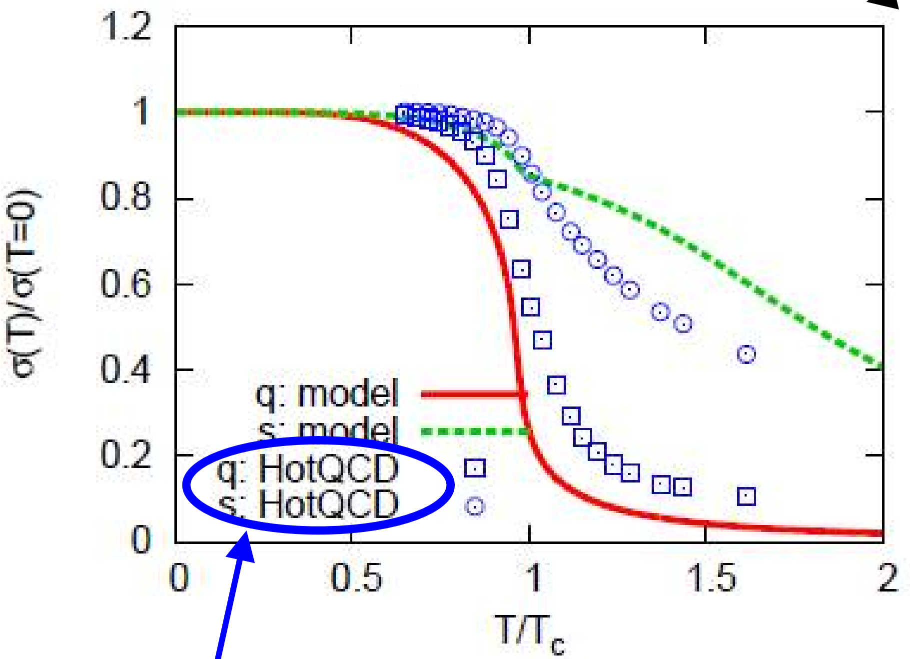
- ❑ Mass relations [CS, NPA ('18)]

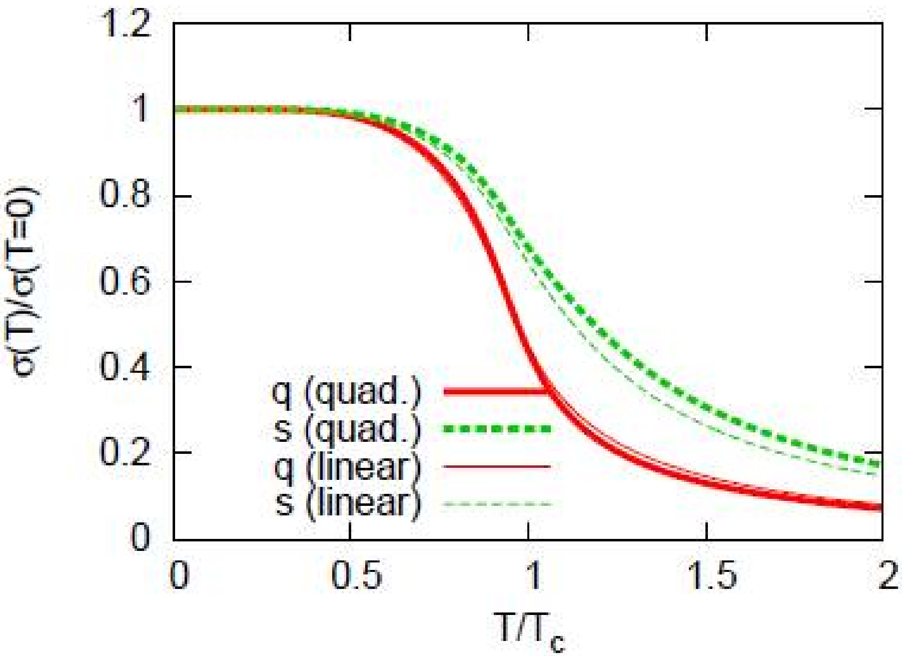
$$M_B(\sigma_q, \sigma_s; a, b, m_0)$$

Light-quark condensate Strange-quark condensate

Chiral condensates

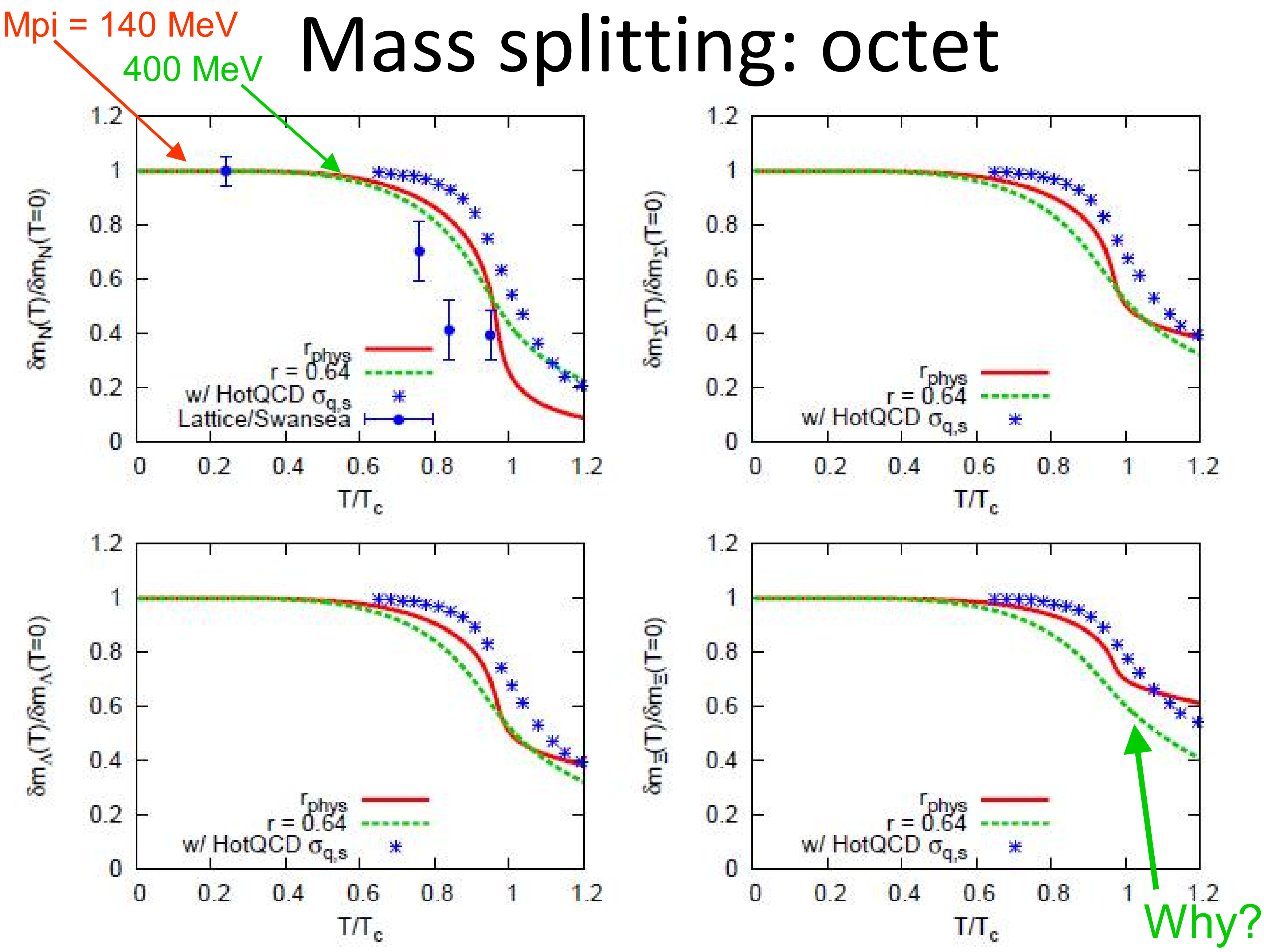
- Quark condensates from a model vs. LQCD
- Pion mass dependence: mpi = 140, 400 MeV



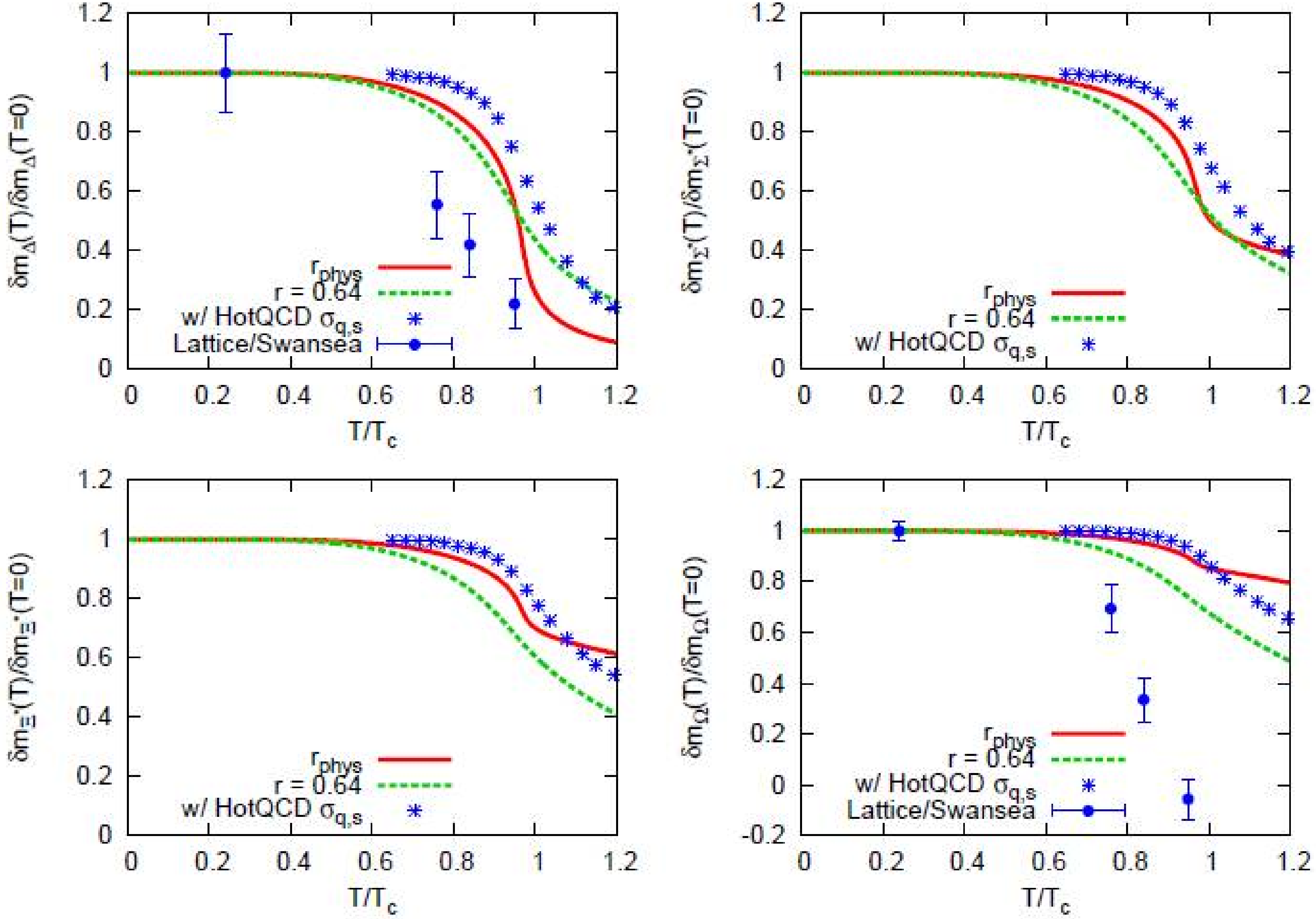


Lattice QCD w/ physical mpi

Mass splitting: octet



Mass splitting: decuplet



Remarks

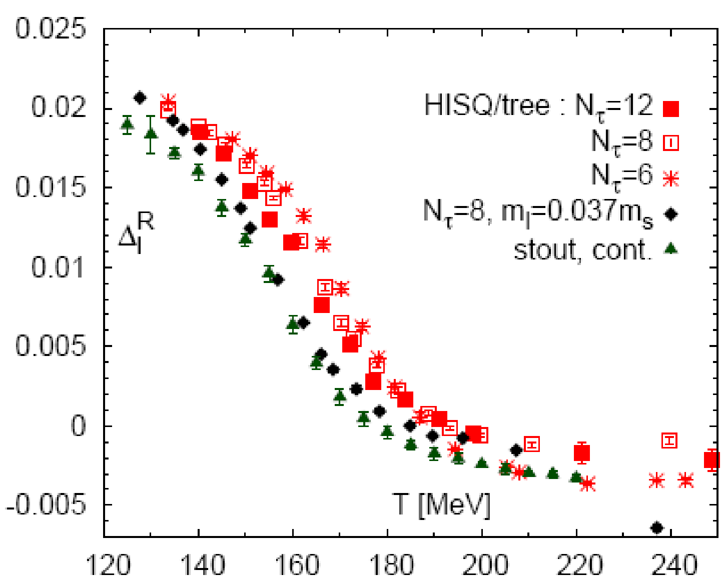
- Nucleons and deltas: δ m drops substantially.
- Much milder trend in hyperons: s-quark effect
- Heavier mpi → mk: δ m(u,d) ≈ δ m(s)
  - more explicit breaking but closer to SU(3)
  - FASTSUM's setup: SU(3) rather than SU(2+1)

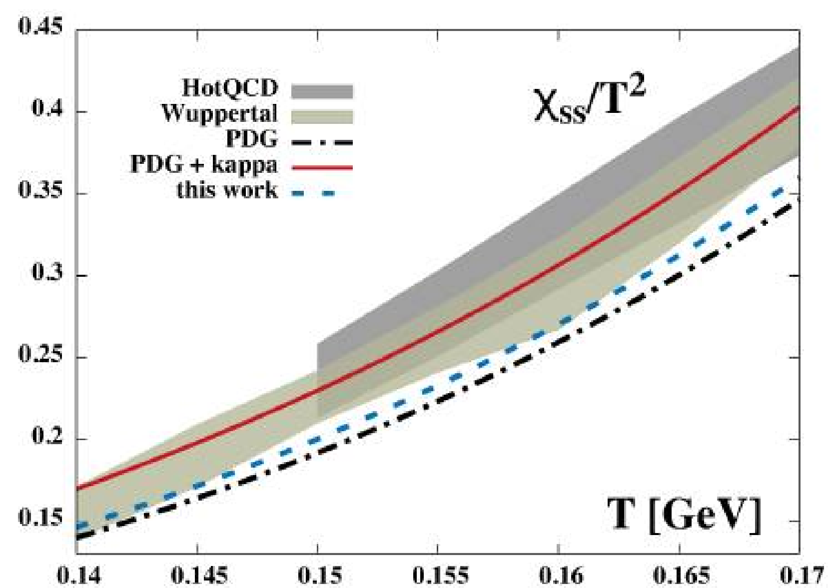
    → when mpi ↗, hyperon- δ m ↘ --- 1st order
  - Still, Omega-baryon mass needs to be understood.
  - Missing piece(s)? --- the onset of deconfinement
- Need simulations w/ physical mpi & other fermions (vs. Wilson)

Any imprint in EoS?

Signal of chiral symmetry restoration

- ❑Lattice QCD shows clearly <qqbar> dropping!
- ❑More deviation from HRG in higher-order fluctuations → Missing states? Interactions? and/or in-medium effects?





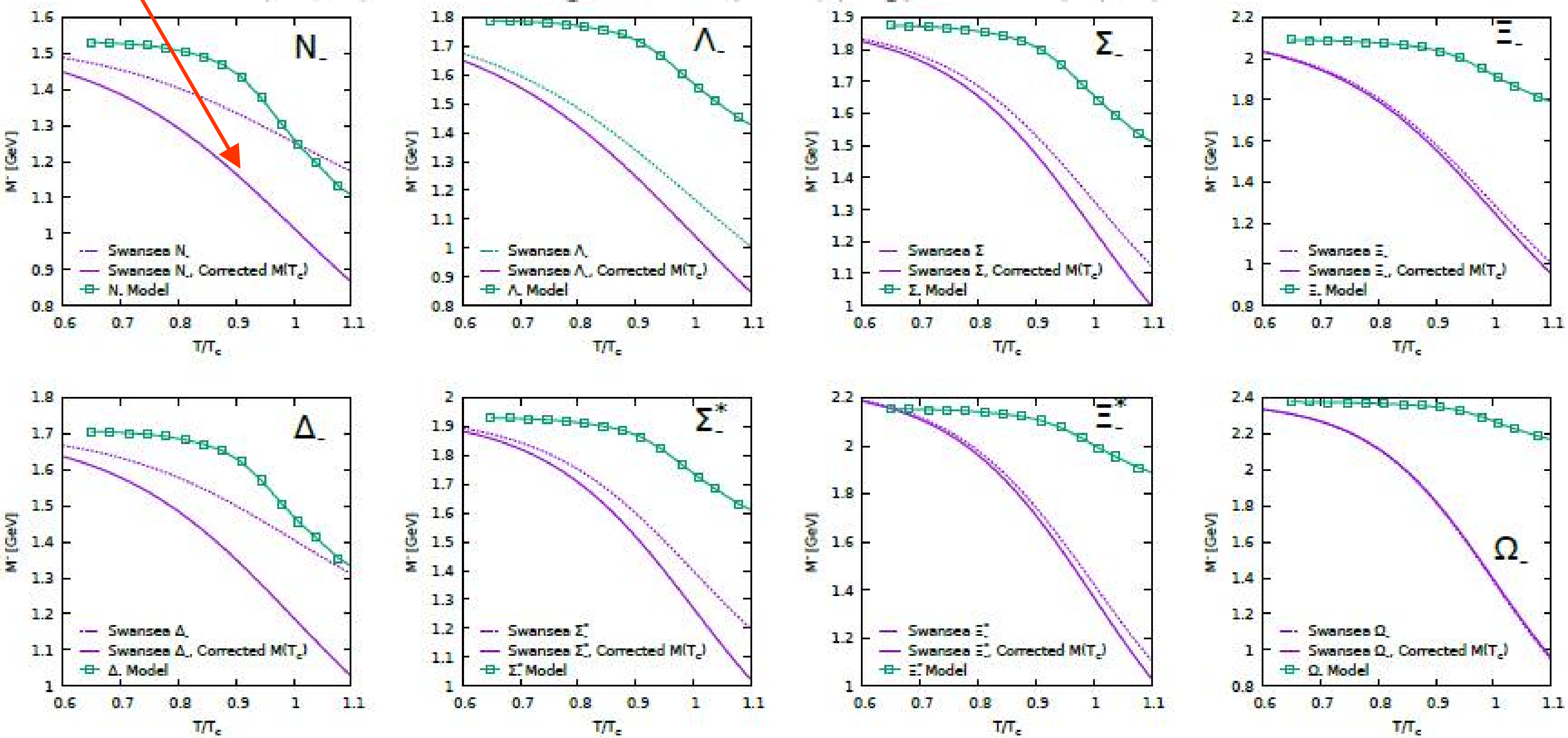
$$M_{-}^{\mathrm{lat}}(T_c) \times \frac{M_{+}^{\mathrm{PDG}}}{M_{+}^{\mathrm{lat}}}$$

In-medium HRG

- T-dep. motivated by Lattice findings [Aarts et al.]

$$M^{-}(T) = M^{-}(T=0)\omega(T,b) + M^{-}(T_c)(1-\omega(T,b))$$

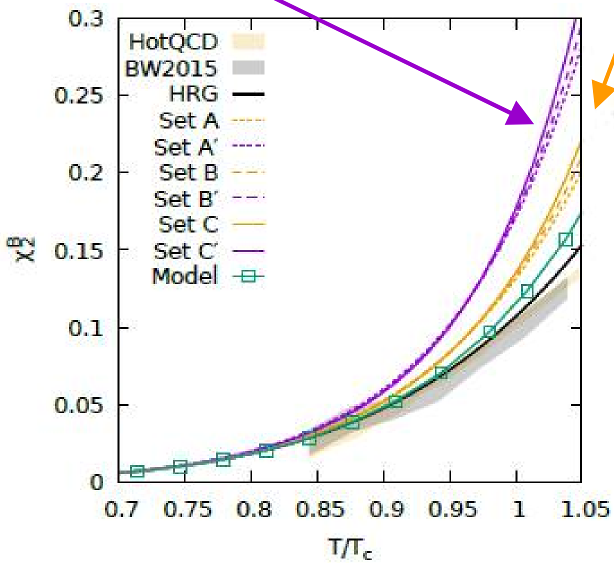
$$\omega(T,b) = \tanh[(1-T/T_c)/b]/\tanh(1/b)$$



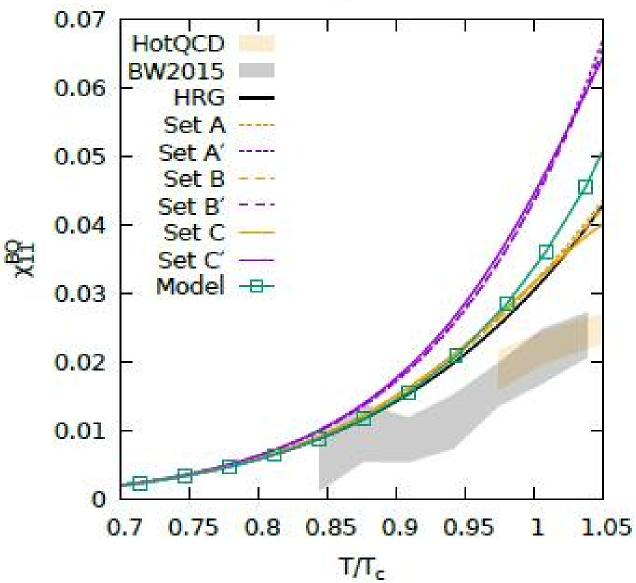
[Morita et al., arXiv:1711.10779 [hep-ph]] corrected $M_{-}^{\mathrm{lat}}(T_c)$

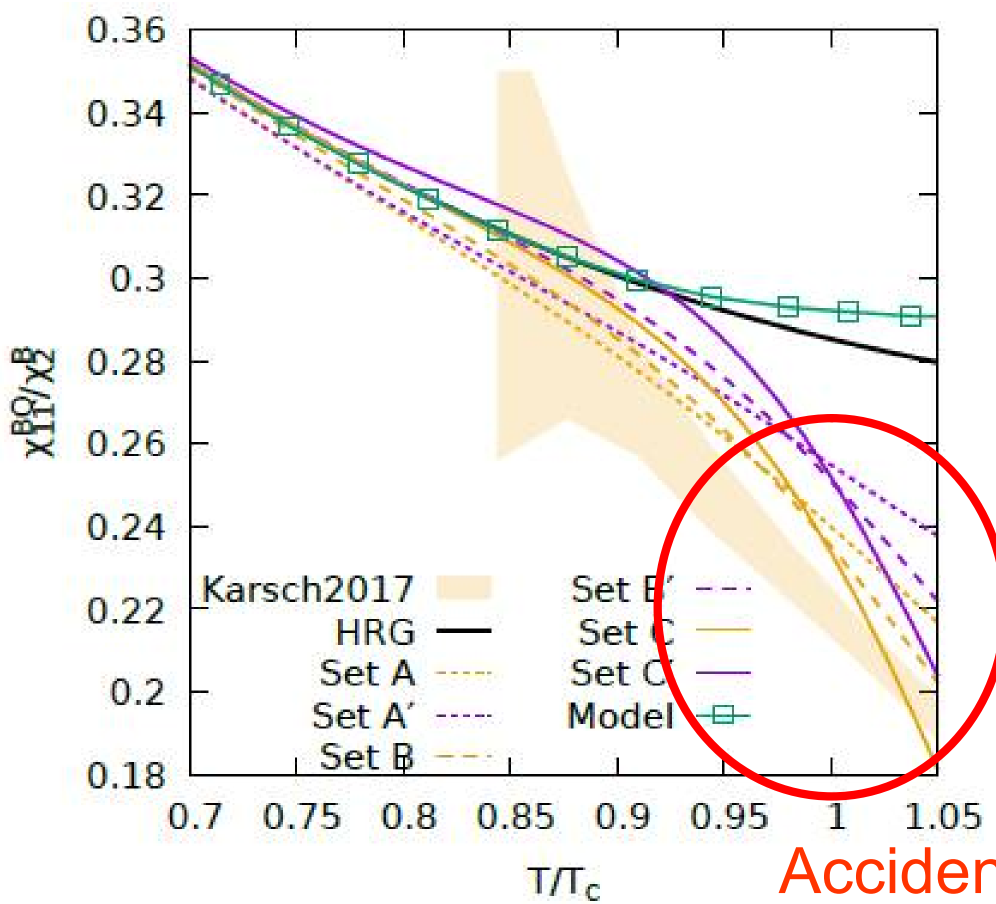
uncorrected

Fluctuations of net-baryon number



$$\chi_{ijk}^{BQS} \equiv \frac{\partial^{i+j+k}}{\partial^i(\mu_B/T)\partial^j(\mu_Q/T)\partial^k(\mu_S/T)} p(T,\mu_B,\mu_Q,\mu_S)/T^4$$





Accidental!

[Morita et al., arXiv:1711.10779 [hep-ph]]

What is missing? --- finite width

- Thermodynamics of broad resonances

→S matrix approach [Dashen, Ma and Bernstein, 1969]

- Grand canonical potential

$$\Omega = \Omega_0 + \Omega_{\rm int}$$

$$\Delta \ln Z = \int dE\, e^{-\beta E} \frac{1}{4\pi i} \mathrm{tr} \left[S^{-1} \frac{\overleftrightarrow{\partial}}{\partial E} S \right]_c$$

- Leading contribution: 2-body [Beth-Uhlenbech, 1937]

$$\Delta \ln Z = \int dE\, e^{-\beta E} \times \frac{1}{\pi} \frac{\partial}{\partial E} \mathrm{tr}\,(\delta_E)$$

Phase shift

Dynamical information

What is missing? --- finite width

- ❑K0*/ κ (800) meson: chiral partner of kaon

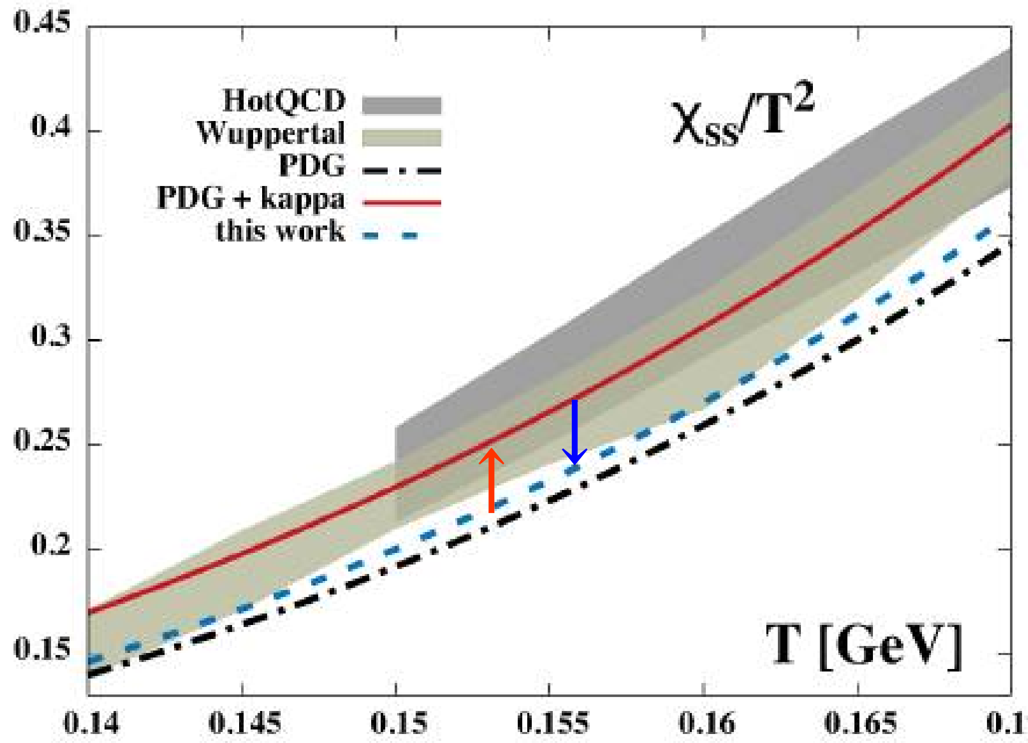
  NOTE: omitted from PDG summary table

- ❑S matrix approach [Friman et al. 2015]
  - ✓Empirical π -K phase shift from experiment

$$\Omega = \Omega_\pi + \Omega_K + \Omega_{\text{int}}$$

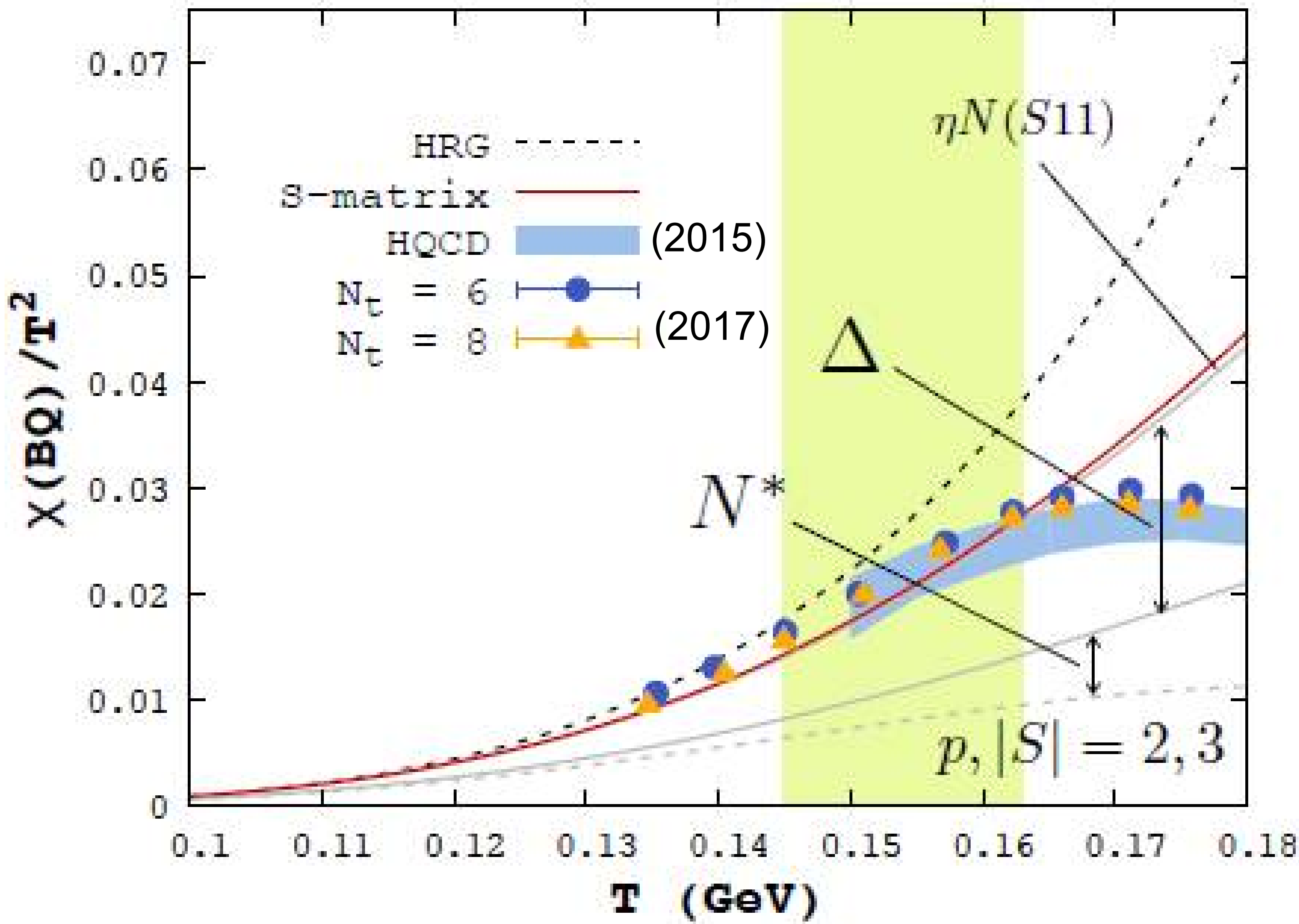
cf. HRG

$$\Omega = \Omega_\pi + \Omega_K + \Omega_{\text{res}}$$



Talk by Pok Man Lo [Lo et al., arXiv:1710.02711 [hep-ph]]

Pi-Nucleon system



Summary

- Emergent parity-doubling structure as a manifestation of restored chiral symmetry

Lessons:

- Naive “in-medium HRG” does not work.
- Effect of resonance widths – beyond HRG
- Survival mass ≈ chromo-magnetic sector

- Higher-lying states near QCD p.t.
- Interplay between CSB and confinement
- Toward more realistic description of QCD