Thermal QCD and chiral symmetry

Gert Aarts

Swansea University & ECT*

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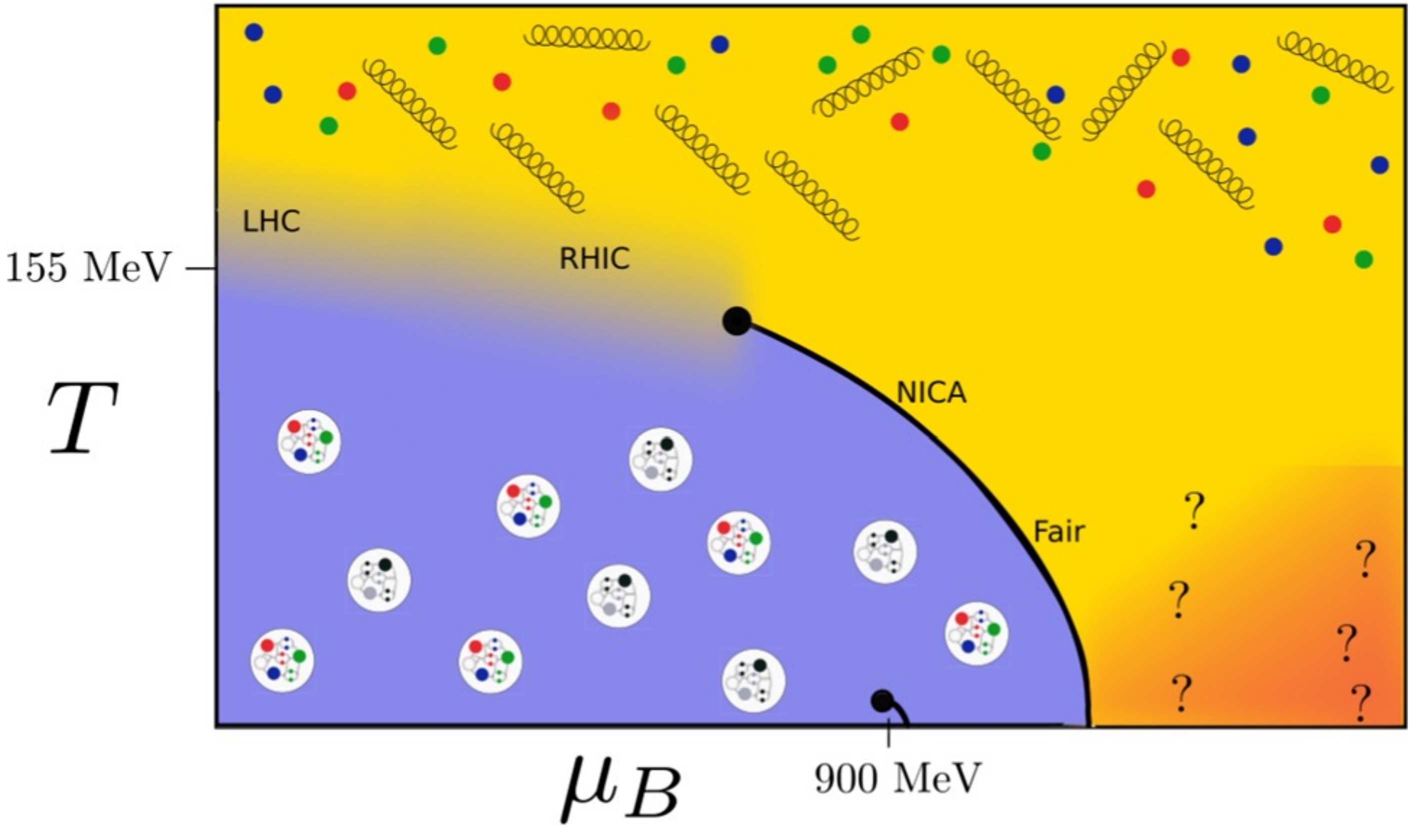
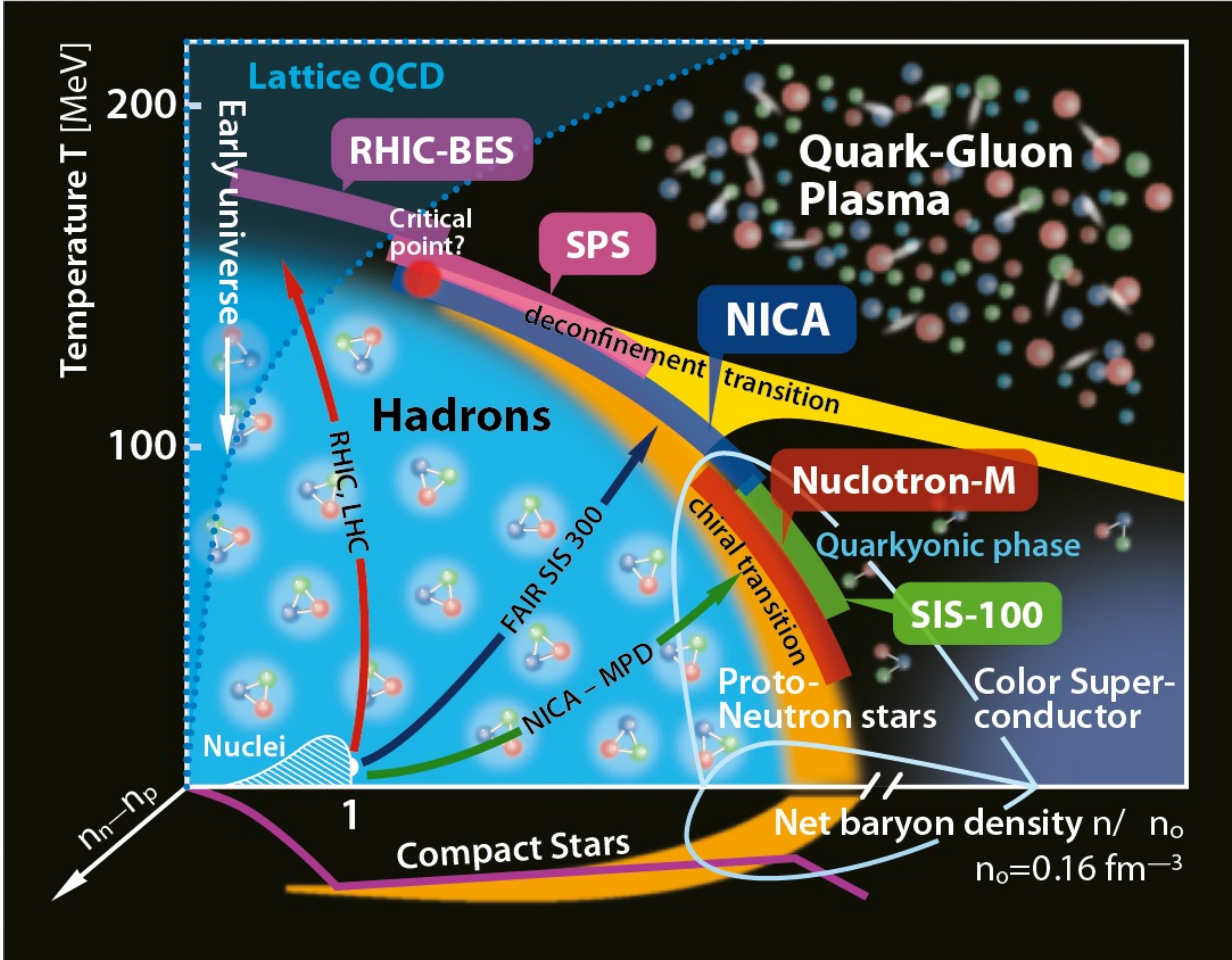
QCD phase diagram (conjecture)



QCD phase diagram: experimental and observational probes

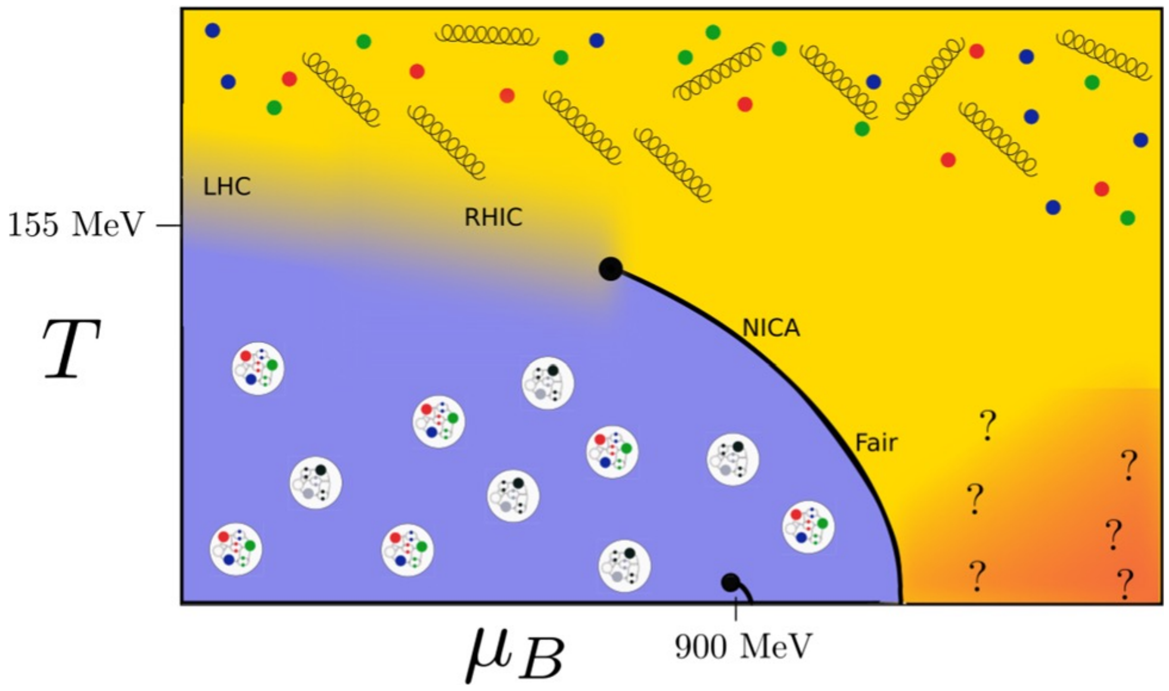
heavy-ion collision experiments:
RHIC, LHC, FAIR, NICA



Outline

- thermal transition
- chiral symmetry
- baryons
- mesons
- bonus: D mesons

Thermal transition



Thermal transition is a crossover

absence of global symmetries and related order parameters

chiral symmetry:

- massless limit: order parameter = chiral condensate
- explicitly broken by nonzero quark masses

observables linked to chiral symmetry used to show transition is a thermal crossover

i.e. no non-analytic behaviour in free energy (Fodor et al, *Nature* 2006)

- (pseudo)critical temperature not uniquely defined, depends on observable

FASTSUM: PRD 105 (2022) 034504

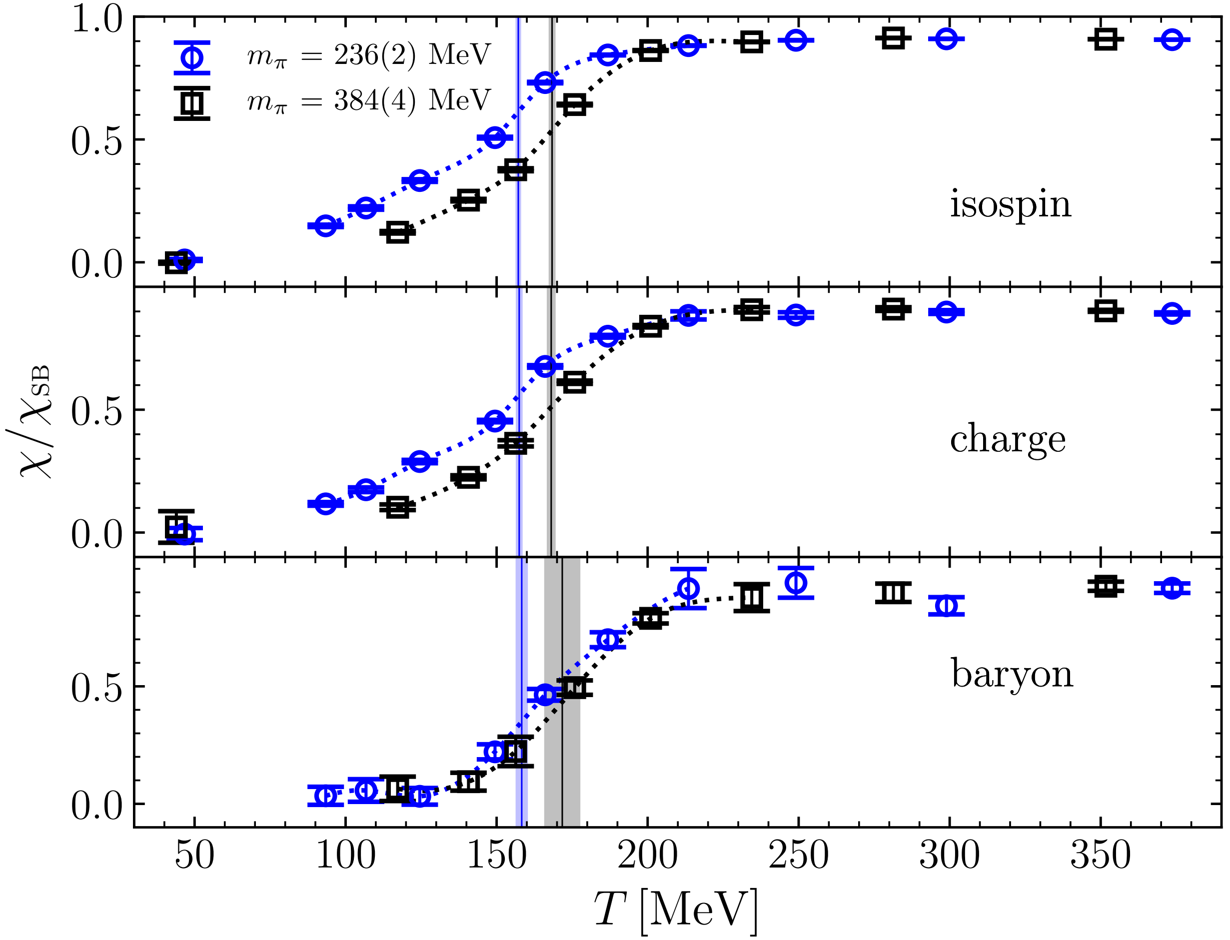
Transition details depend on light quark masses

susceptibilities χ/χ_{SB} :

- fluctuations of isospin number, electrical charge and baryon number

- two values of light quark masses (or pion mass)

- lighter quarks → lower T_{pc}



Pseudo-critical temperature

- most precise results obtained with staggered quarks at the physical point, in the continuum limit, using chiral susceptibility as observable

- $T_{pc} = 158.0(6)$ MeV
  [Budapest-Wuppertal, PRL 125 (2020) 052001]

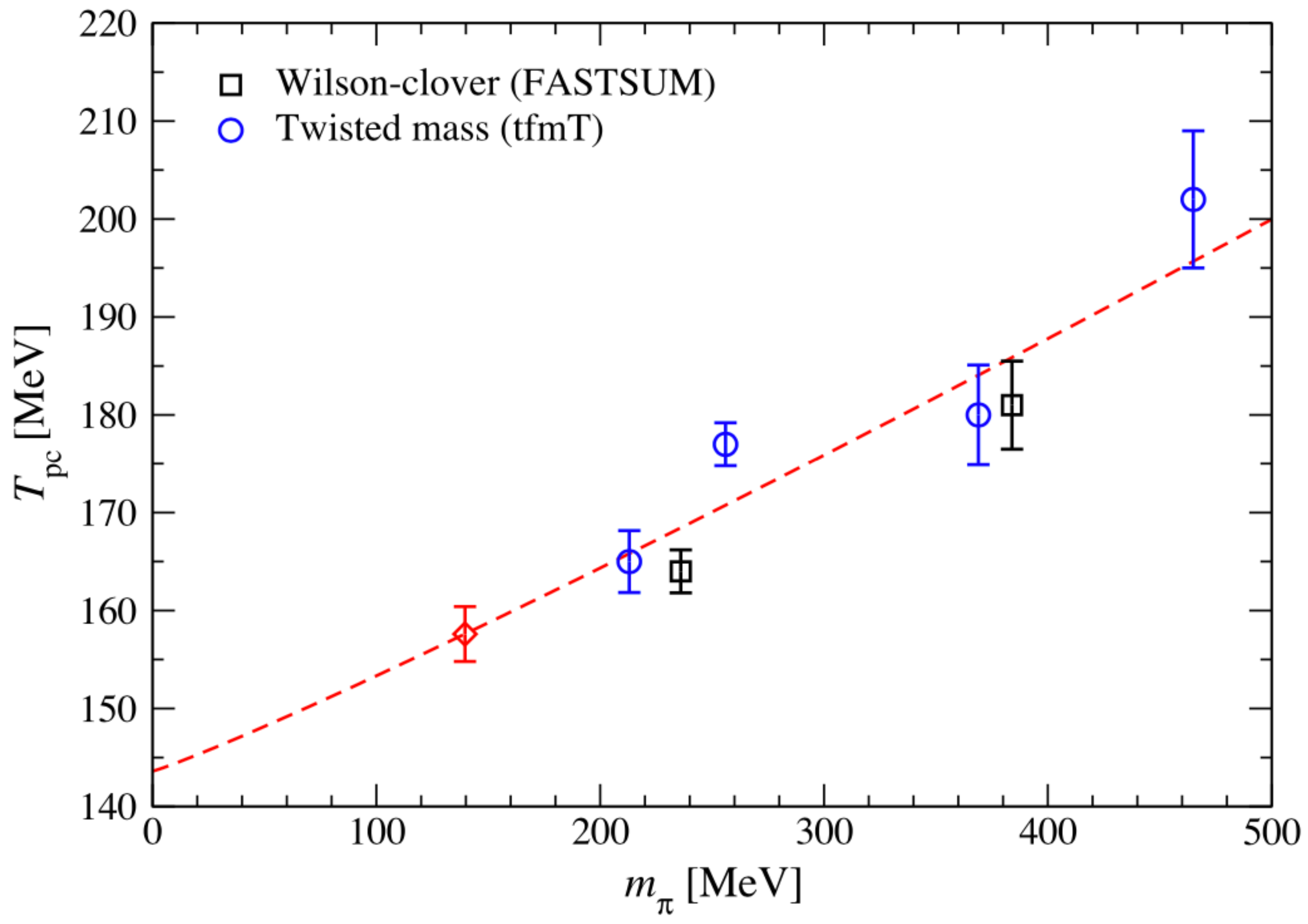
- $T_{pc} = 156.5(1.5)$ MeV
  [HotQCD, PLB 795 (2019) 15]

Pseudo-critical temperature vs pion mass

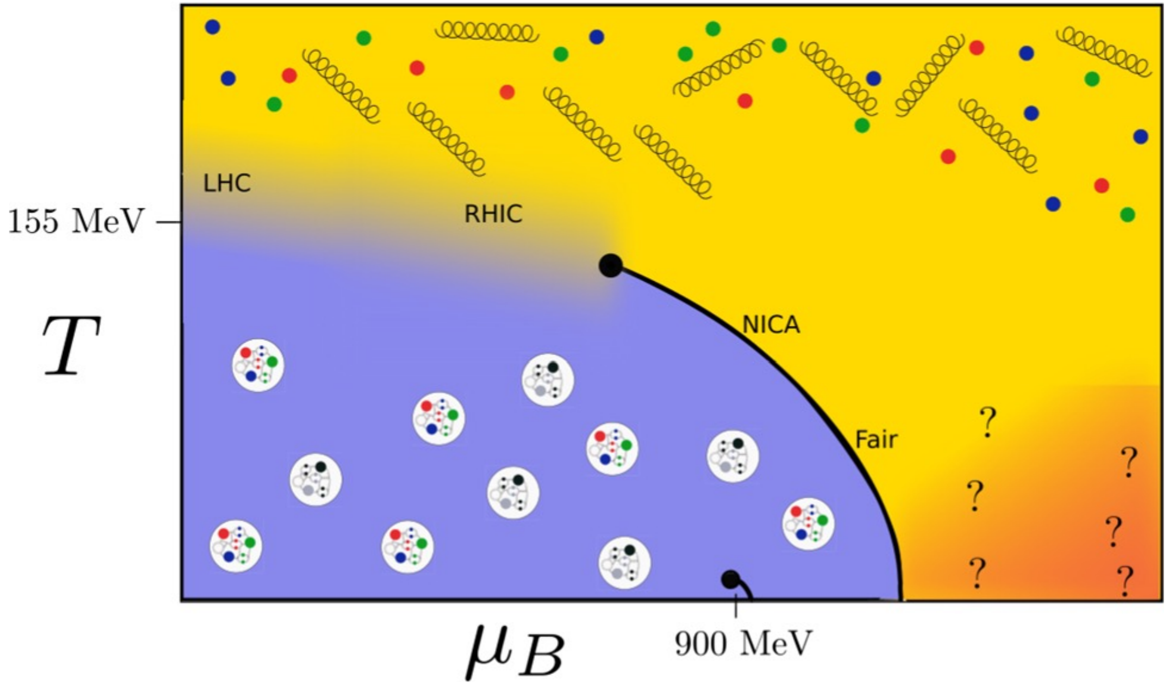
- Wilson quarks: pion not yet at physical value
- no continuum limit
- steady progress using Wilson-clover and twisted mass fermions

Extrapolation to physical point:

➢ $T_{pc} = 158(3)$ MeV



Thermal transition: what happens to hadrons?



Chiral symmetry: beyond thermodynamics

- how does chiral symmetry restoration affect hadrons / quarks?
- manifestations of chiral symmetry restoration in hadronic medium?
- impact on heavy-ion physics and interpretation of data?
- compare and contrast with effective models

FASTSUM collaboration

FASTSUM's aim is to compute spectral quantities (masses, widths, spectral functions, transport, …) at nonzero temperature, in hadronic phase and quark-gluon plasma

GA, Chris Allton, Tim Burns, Simon Hands, Benjamin Jaeger, Seyong Kim, Maria-Paola Lombardo, Sinead Ryan, Jonivar Skullerud

Pietro Giudice, Jonas Glesaaen, Alexander Nikolaev, Ryan Bignell

Ale Amato, Davide de Boni, Kristi Praki, Sergio Chaves

…

PRD105 (2022) 034504, PRD99 (2019) 074503, JHEP 06 (2017) 034, in preparation

Spectroscopy in thermal LQCD

- Euclidean lattice formulation: compact time direction $T = 1/(a_\tau N_\tau)$
- need many time slices (N_τ) to study temporal quantities (spectrum)

- use anisotropic lattices, with $a_\tau \ll a_s$
- FASTSUM: fixed lattice spacing (no continuum limit)
- follow HadSpec action and tuning
- fine temporal lattice, $a_s/a_\tau \sim 3.45$, $a_\tau^{-1} \sim$ 6 GeV

- $N_f = 2 + 1$ Wilson-type quarks, light quarks still heavier than in nature
- Gen2: $m_\pi = 384(4)$ MeV, Gen2L: $m_\pi = 236(2)(4)$ MeV

PRD 105 (2022) 034504

Anisotropic thermal LQCD: fixed scale approach

$m_\pi = 384(4)$ MeV

Generation 2, $24^3 \times N_\tau$			
N_τ	T [MeV]	T/T_c	N_{cfg}
128[a]	44	0.24	305
48[b]	117	0.63	251
40	141	0.76	502
36	156	0.84	501
32	176	0.95	1000
28	201	1.09	1001
24	235	1.27	1002
20	281	1.52	1000
16	352	1.90	1000

two sets of many ensembles
both below and above T_{pc}

$m_\pi = 236(2)(4)$ MeV

Generation 2L, $32^3 \times N_\tau$		
N_τ	T [MeV]	N_{cfg}
128	47	1024
64	94	1041
56	107	1042
48	125	1123
40	150	1102
36	167	1119
32	187	1090
28	214	1031
24	250	1016
20	300	1030
16	375	1102

Chiral symmetry

- chiral symmetry spontaneously and explicitly broken in QCD vacuum
- pion π is pseudo-Goldstone boson
- chiral symmetry restored at high T

  (influence of nonzero quark mass becomes negligible as well)

- degeneracies expected in channels related by symmetry

→ mesons: $SU(2)_L$ x $SU(2)_R$, e.g. vector and axial-vector channel (ρ and a_1)

→ baryons: parity doubling

- while this is expected from symmetry, actual realisation is determined by dynamics

Baryons: parity doubling

- positive and negative parity states non-degenerate in vacuum

  example: $m_N = m_+ = 939$ MeV, $m_{N*} = m_- = 1535$ MeV

- exact statement: chiral symmetry unbroken ⇆ parity doubling

- in lattice QCD: at the level of the correlator (no need to identify states, etc)
- quasi-order parameter:

$$R = \sum_\tau \frac{G_+(\tau) - G_-(\tau)}{G_+(\tau) + G_-(\tau)}$$

- if parity doubling: $R = 0$
- if ~~parity doubling~~, and ground state dominates, with $m_+ \gg m_-$: $R = 1$

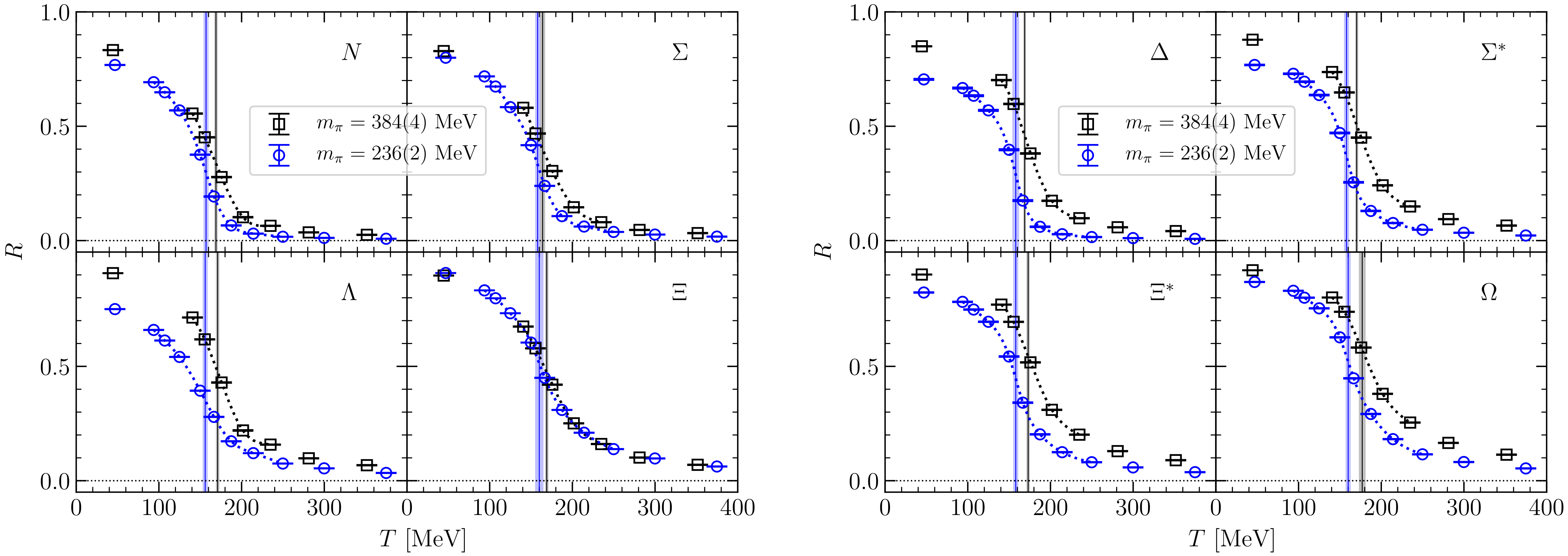
Baryons: parity doubling

- study for all baryons made of u, d, s quarks

- strangeness $|S| = 0, 1, 2, 3$

- octet (spin 1/2): N, Σ, Λ, Ξ
- decuplet (spin 3/2): $\Delta, \Sigma^*, \Xi^*, \Omega$

Degeneracy from correlators: quasi-order parameter



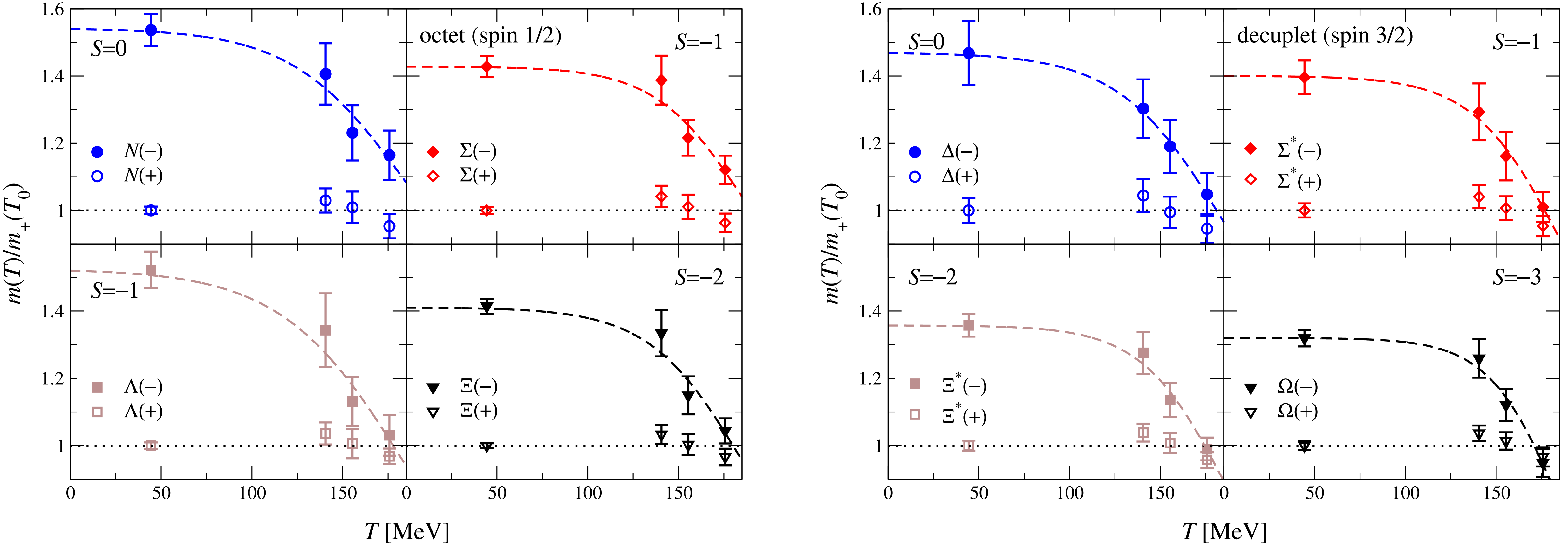
integrated correlator (a)symmetry: from $R \sim 1$ at $T = 0$ to $R \sim 0$ at $T \gg T_{pc}$

inflection points (vertical bands) in agreement with T_{pc} from chiral condensate

Baryons: parity doubling

- thermal transition is a crossover, not a sharp phase transition
- onset of degeneracy already visible in hadronic phase?
- precursor to chiral symmetry restoration
- study +/- parity ground states below T_{pc}

Baryons: parity doubling emerges



mass of negative parity states is reduced, approximate degeneracy at T_{pc}

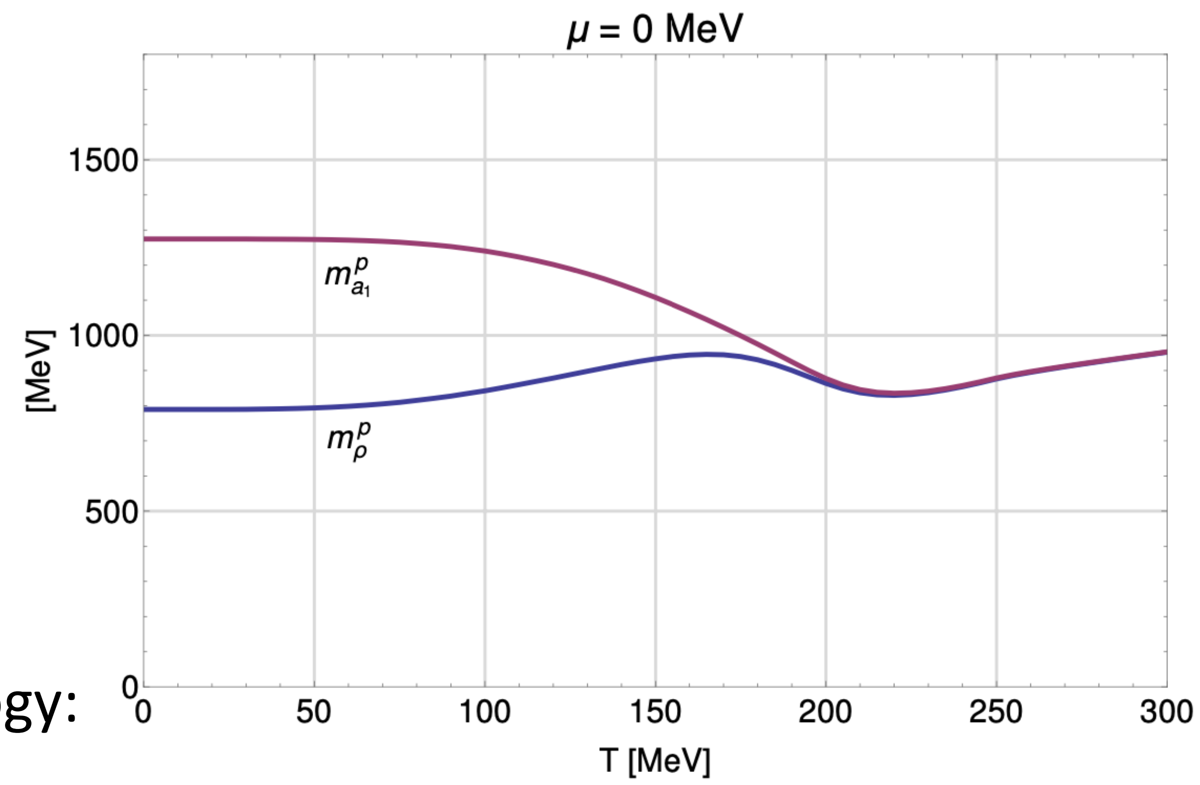
Baryons: parity doubling

- + parity masses independent of temperature (within error)
- - parity masses come down
- near-degeneracy at crossover
- general principle expected, realisation depends on QCD dynamics

- implications for heavy-ion physics: in-medium hadron resonance gas
- results are used to benchmark so-called parity doublet models

Mesons: temperature dependence

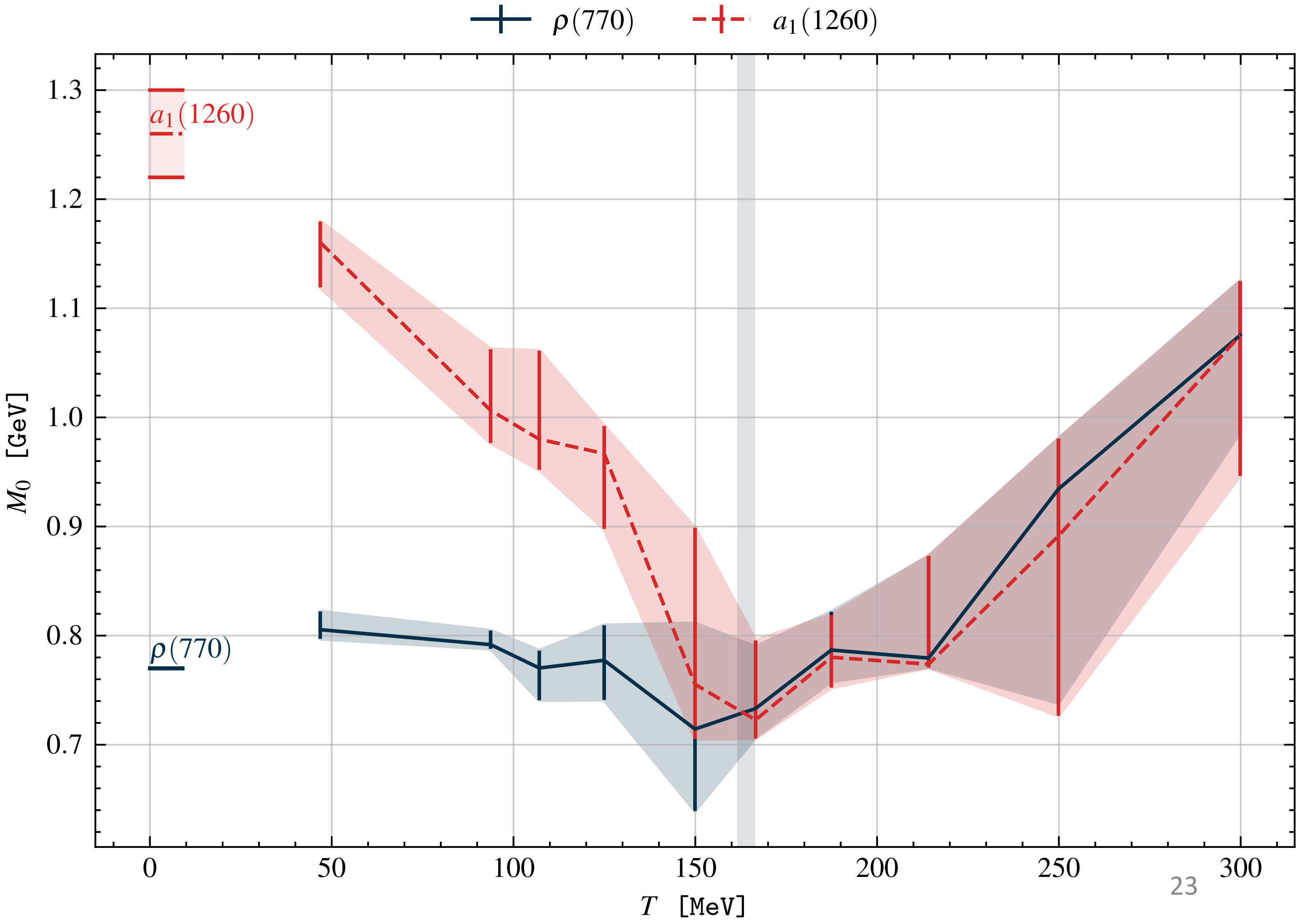
- same game can be played for mesons
- surprisingly a bit more involved
- vector/axial-vector degeneracy: ρ and a_1
- very relevant for heavy-ion phenomenology: dilepton and photon production
- studied extensively in effective models



Example model calculation
Rennecke et al, PRD 95 (2017) 036020

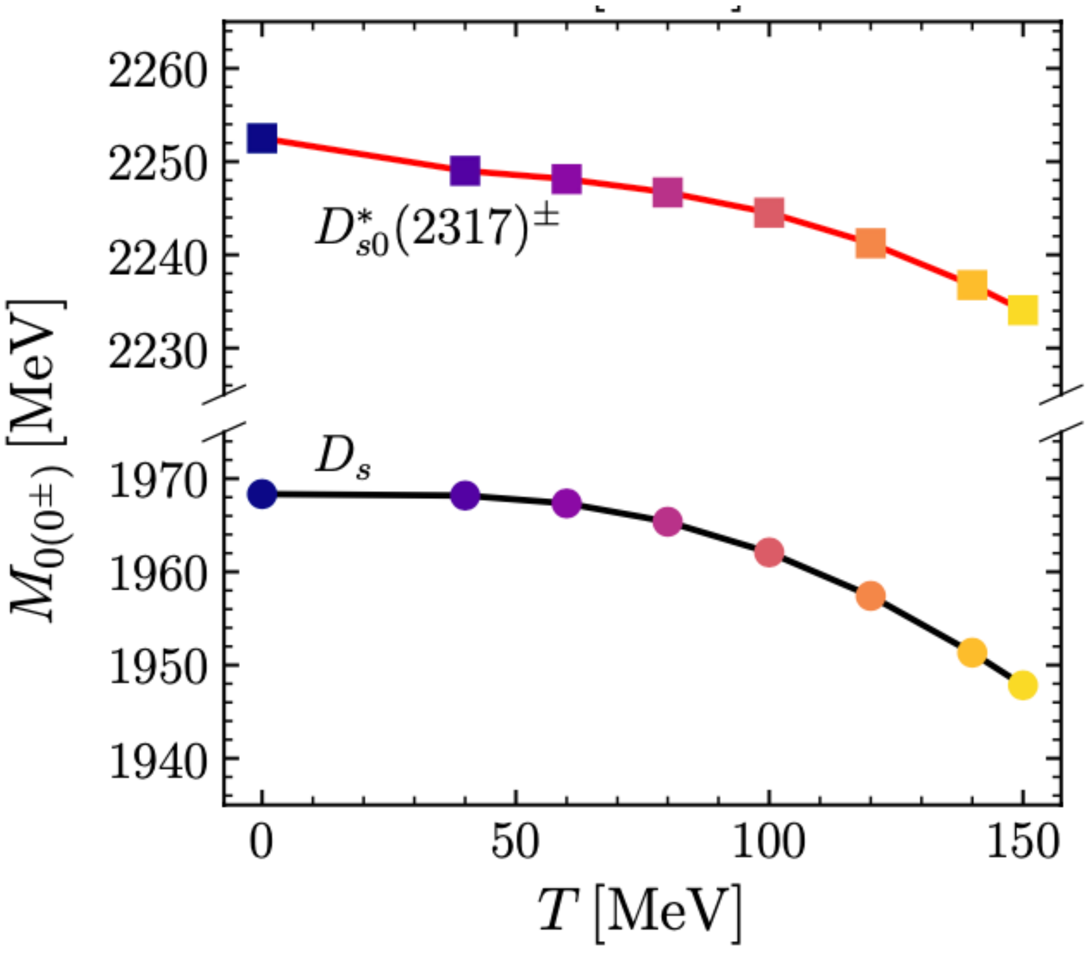
Light mesons: vector/axial-vector degeneracy

- ρ/a_1 degeneracy emerges at thermal transition
- signal above transition cannot be trusted but indicates degeneracy
- preliminary



Bonus: thermal *D* mesons

- interest for heavy-ion physics
- time evolution of open charm
- medium effects in hadronic gas



Example model calculation: Tolos et al, PLB 806 (2020) 135464

FASTSUM: Chaves et al, in preparation

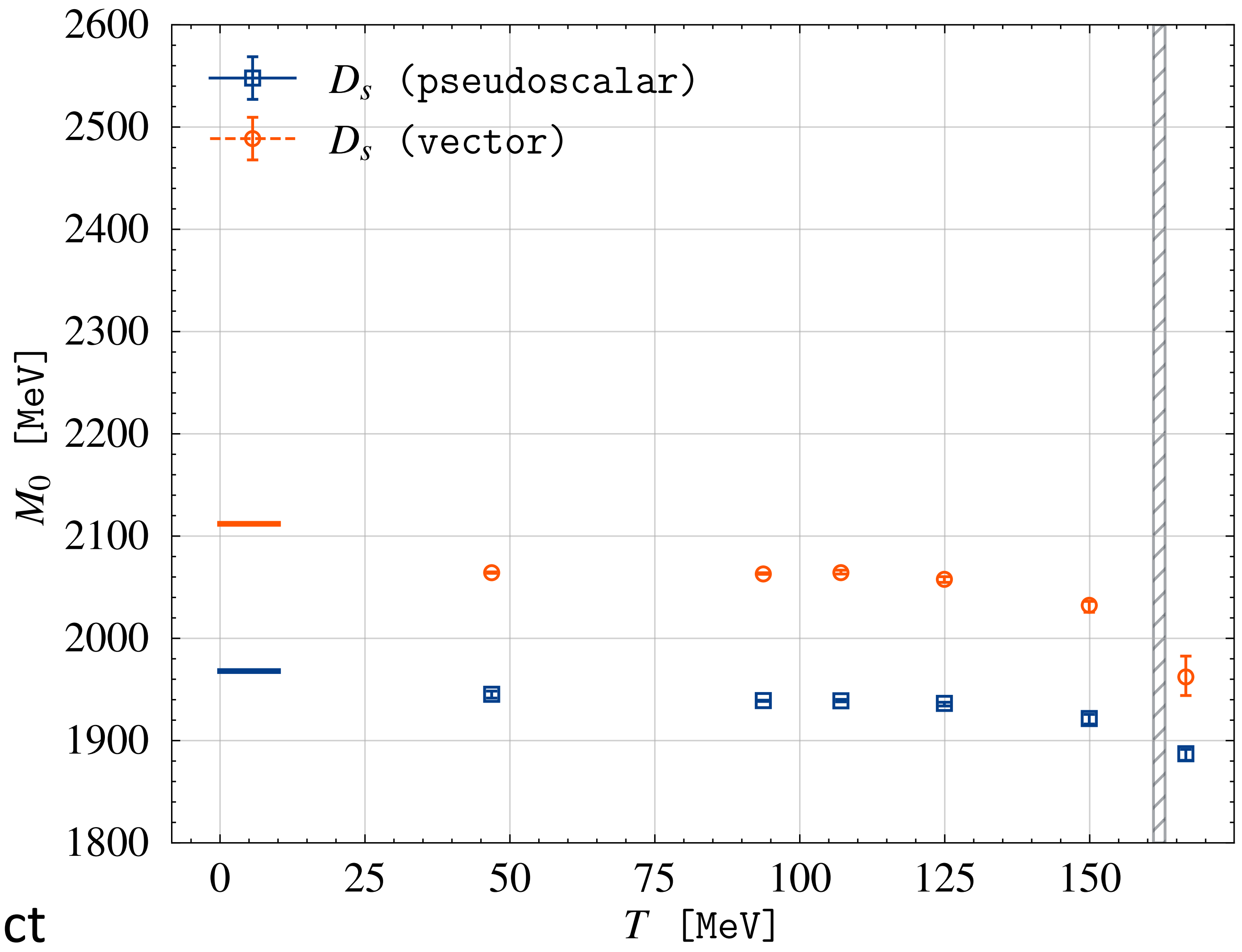
Thermal *D* mesons: pseudoscalar and vector

- PS and V channels described by simple pole Ansatz
- extensive mass fits

assumption as T increases:

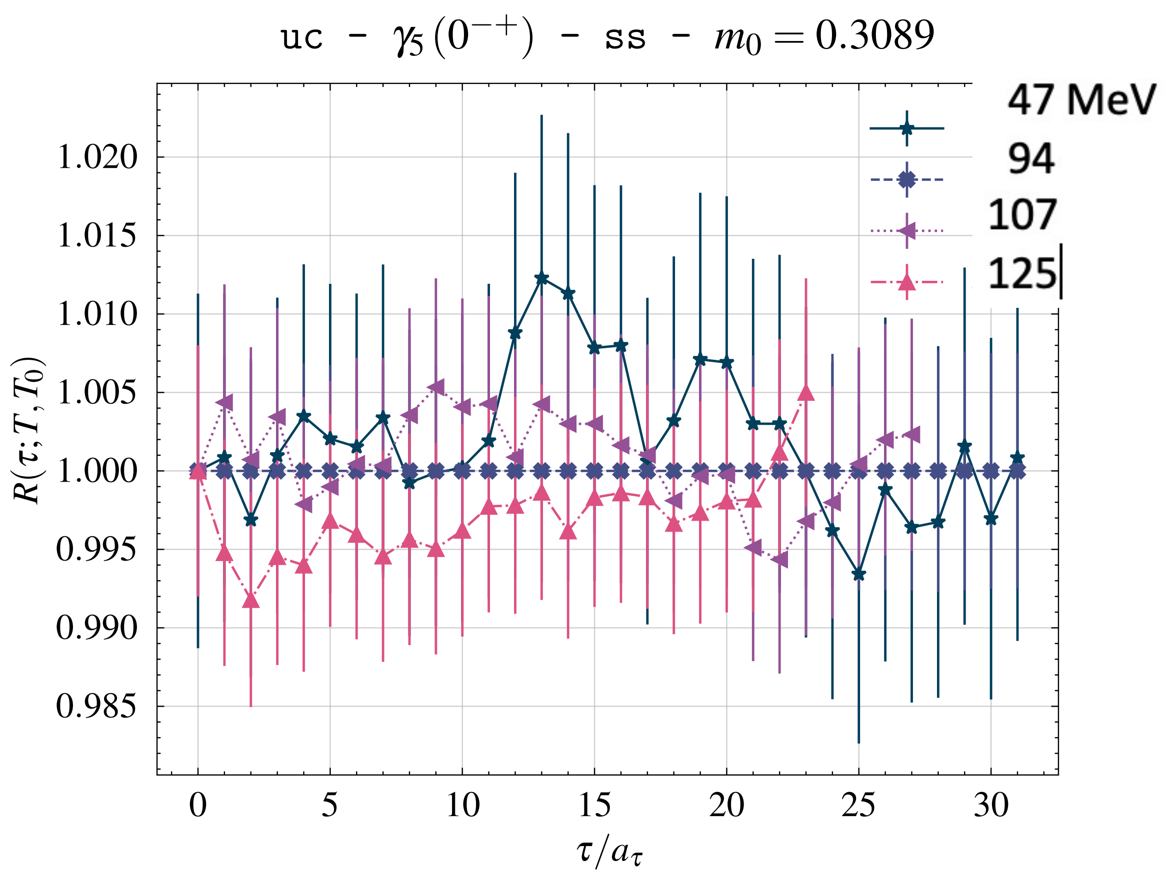
- in-medium modification captured by temperature-dependent mass

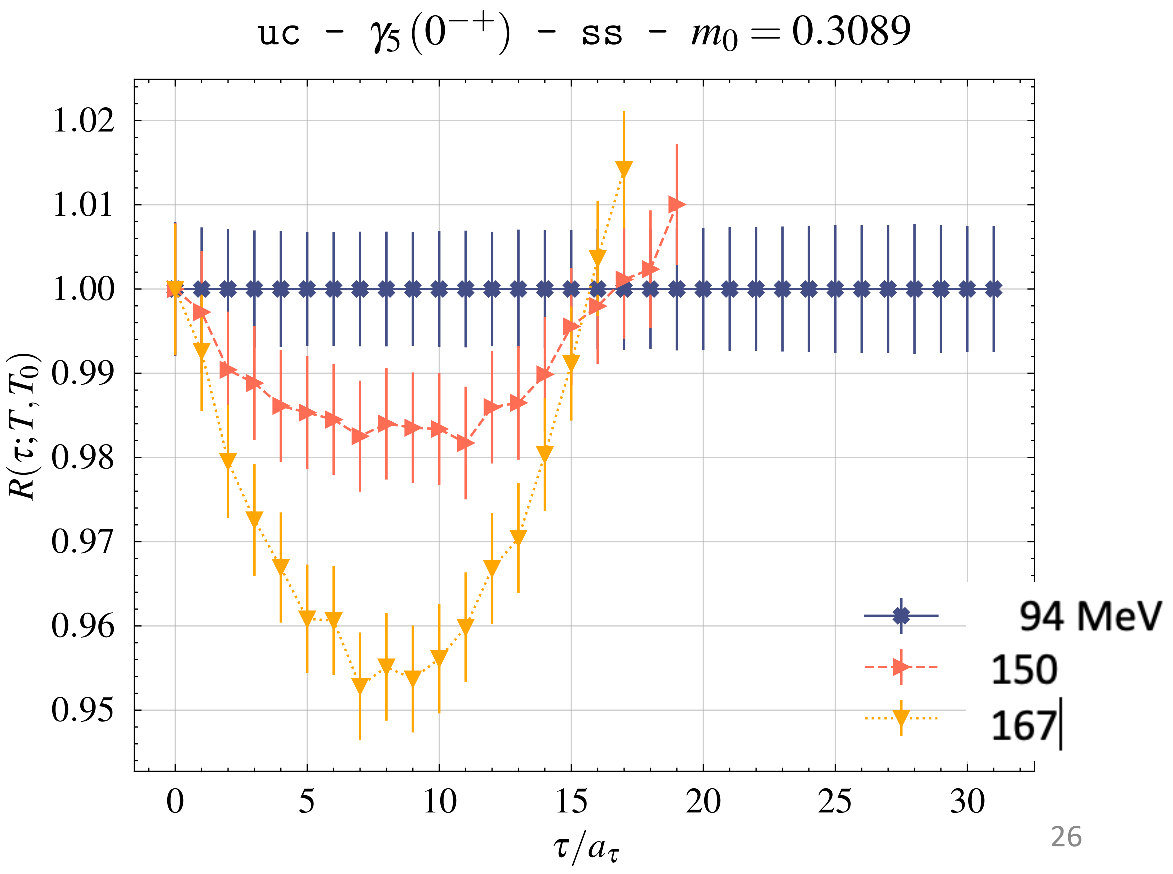
- small – O(50 MeV) – but noticeable effect



Thermal D mesons: pseudoscalar and vector

- results supported by direct comparison of correlators – no fitting assumptions needed
- ratio of correlators at temperature T with benchmark correlator at $T = 94$ MeV

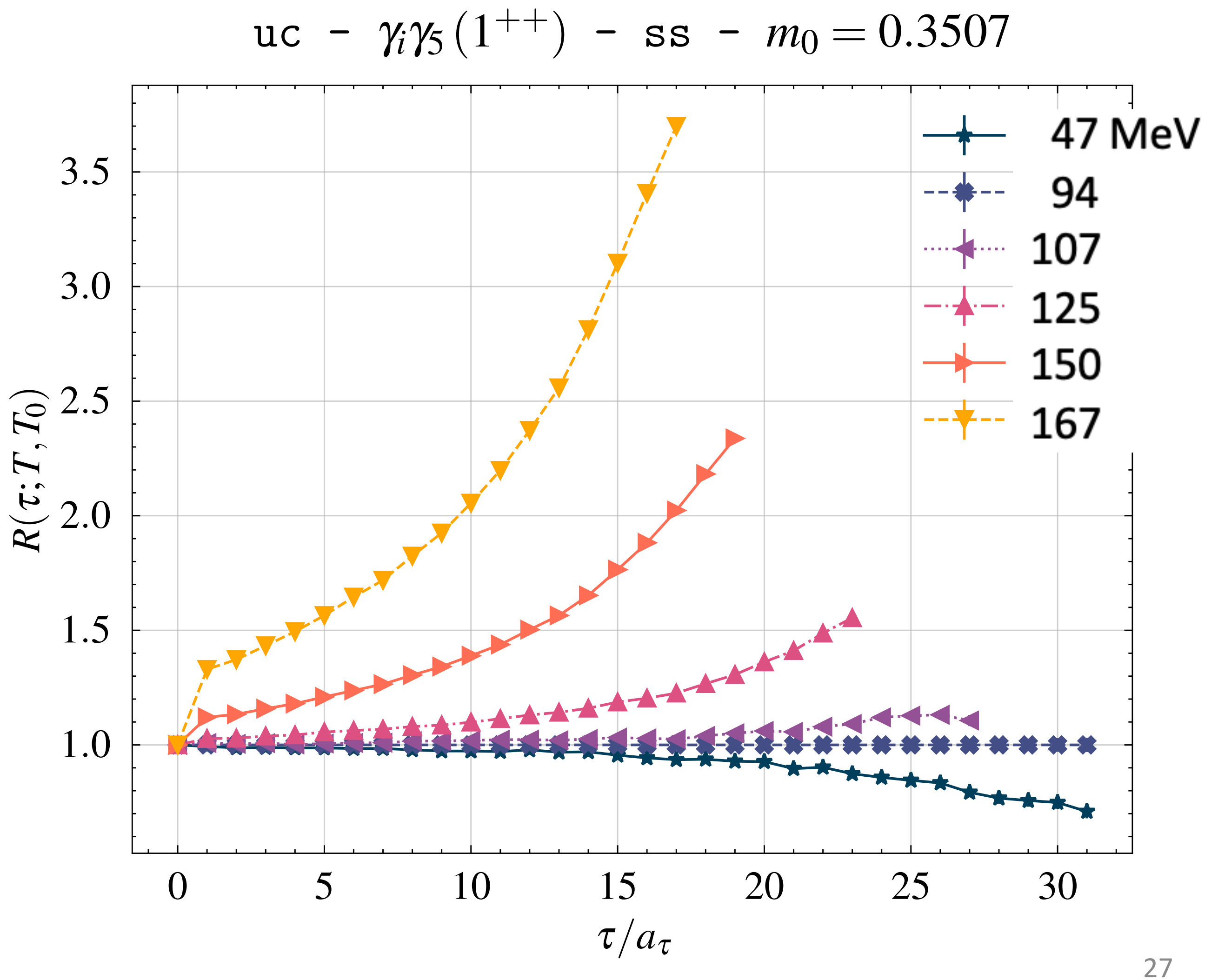




FASTSUM: Chaves et al, in preparation

Thermal *D* mesons: axial-vector and scalar

- not true in axial-vector and scalar channels
- strong T dependence throughout hadronic phase
- needs further understanding
- models/threshold effects/ large widths/…



Summary

- thermal transition is a crossover
- chiral symmetry plays essential role
- used to study properties of thermal crossover, incl most precise estimates of T_{pc}
- going beyond thermodynamics: emerging degeneracies in spectrum

  - baryons and parity doubling
  - mesons and chiral partners

- new lattice data in hadronic phase: precursor to chiral symmetry restoration
- compare with effective model descriptions/understanding at $T = 0$