# Hadrons under extreme conditions

Gert Aarts

Swansea University (& ECT*)

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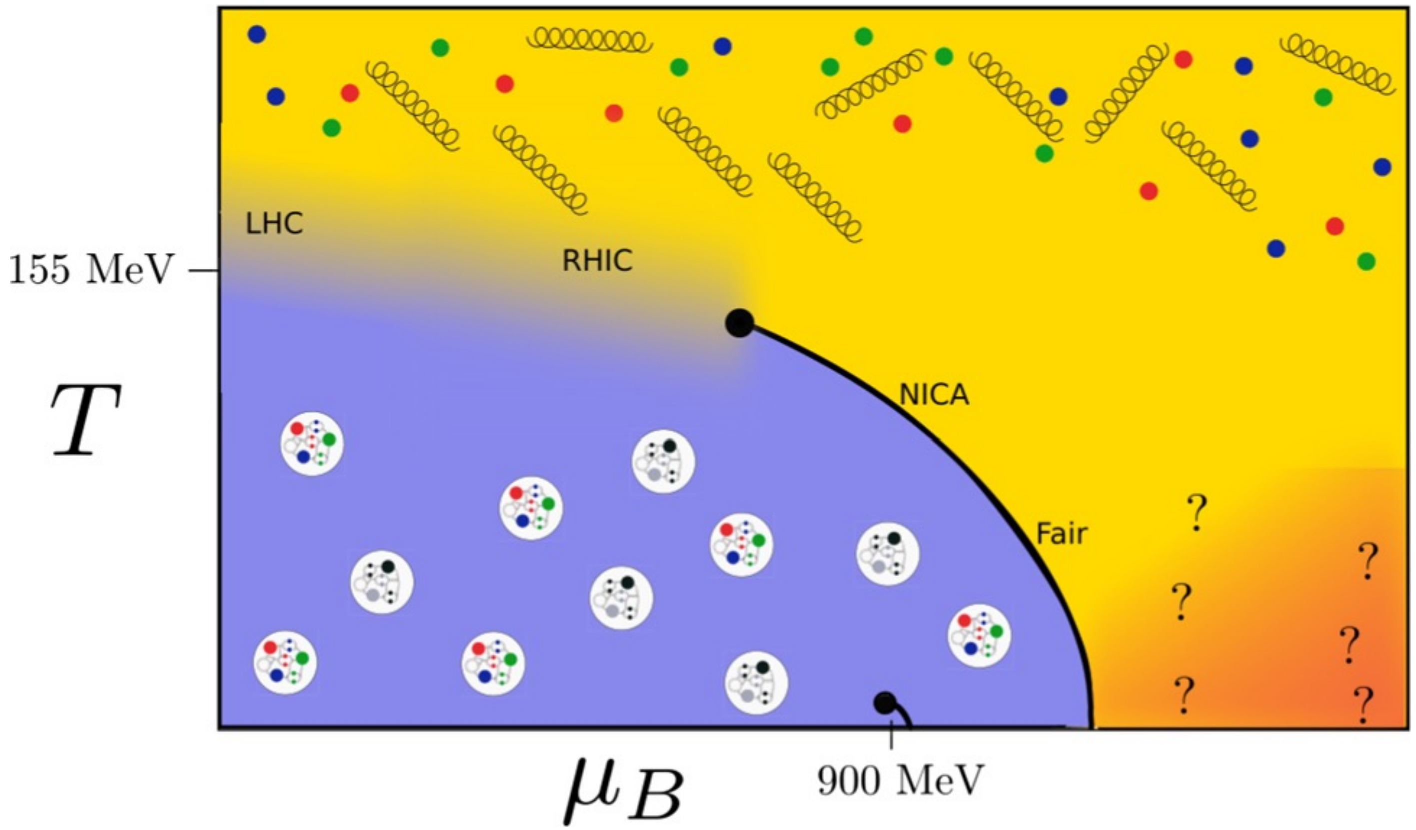
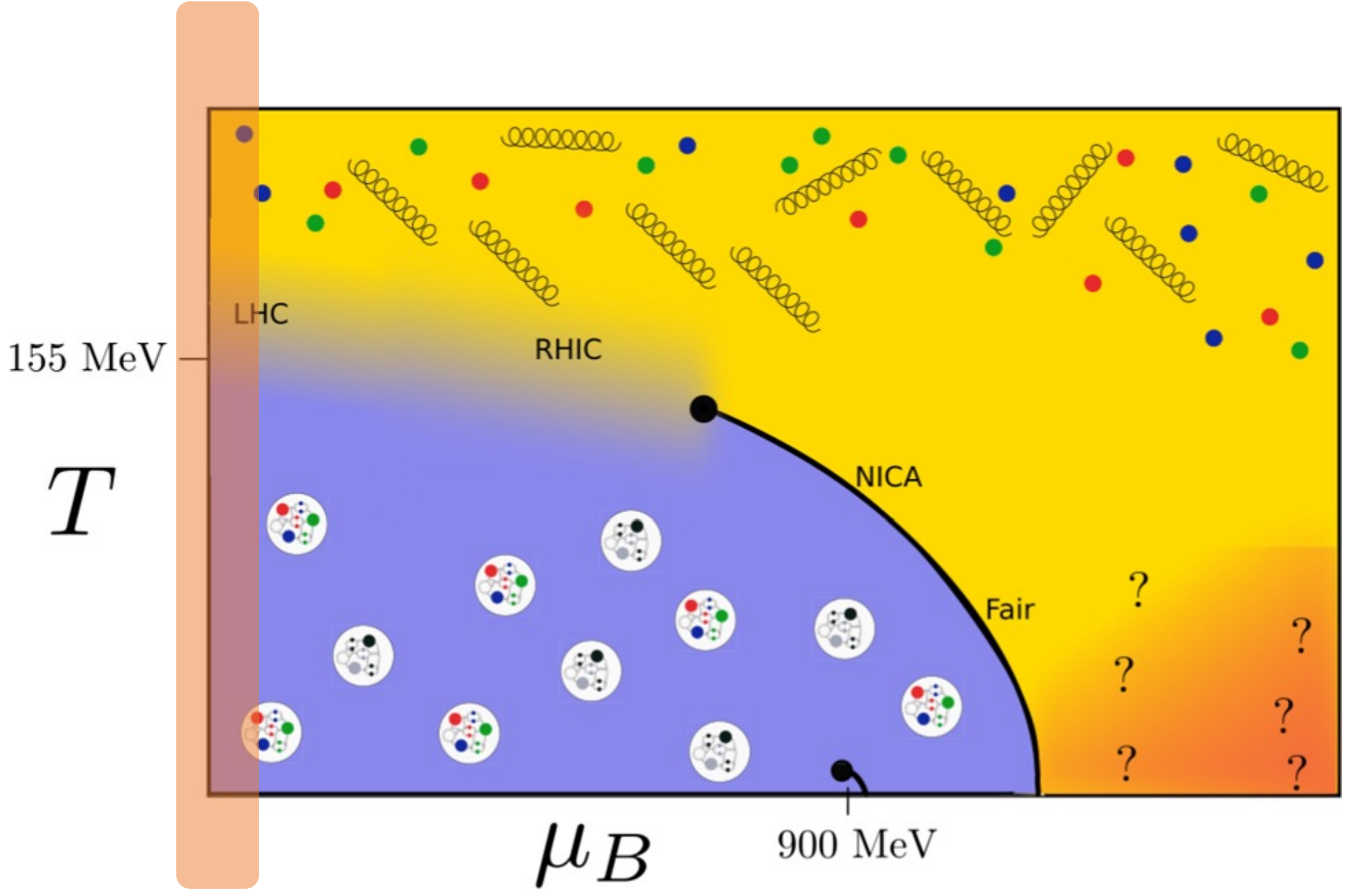
# QCD phase diagram (sketch)



# Thermal transition: what happens to hadrons?

- (de)confinement
- chiral symmetry
- heavy quarks



# Outline

- FASTSUM lattice collaboration
- spectroscopy at finite temperature: anisotropic lattices, many temperatures
- **$D$ and $D_s$ mesons in the hadronic phase**
- **spin ½ charmed baryons in the hadronic phase**
- summary

# FASTSUM lattice QCD collaboration

**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, Antonio Smecca

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

…

EPJA 60 (2024) 59, 2209.14681, PRD 105 (2022) 034504, PRD 99 (2019) 074503, JHEP 06 (2017) 034, ………..,  PRL 106 (2011) 061602

# Spectroscopy in thermal LQCD


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

- 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

PRD 105 (2022) 034504
2209.14681

# Anisotropic thermal LQCD: fixed scale approach

- $N_f = 2 + 1$ Wilson-type quarks, light quarks still heavier than in nature
- Generation 2L: $m_\pi = 239(1)$ MeV

| $a_\tau$ [fm] | $a_\tau^{-1}$ [GeV] | $\xi = a_s/a_\tau$ | $a_s$ [fm] | $m_\pi$ [MeV] | $T_{\rm pc}^{\bar{\psi}\psi}$ [MeV] |
|---|---|---|---|---|---|
| 0.03246(7) | 6.079(13) | 3.453(6) | 0.1121(3) | 239(1) | 167(2)(1) |

| $N_\tau$ | 128 | 64 | 56 | 48 | 40 | 36 | 32 | 28 | 24 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| $T$ [MeV] | 47 | 95 | 109 | 127 | 152 | 169 | 190 | 217 | 253 | 304 |
| $N_{\rm cfg}$ | 1024 | 1041 | 1042 | 1123 | 1102 | 1119 | 1090 | 1031 | 1016 | 1030 |

many ensembles, both below and above $T_{pc} = 167(3)$ MeV
unique setup in lattice community, especially with regard to hadronic phase

# $D_{(s)}$ and $D^*_{(s)}$ mesons

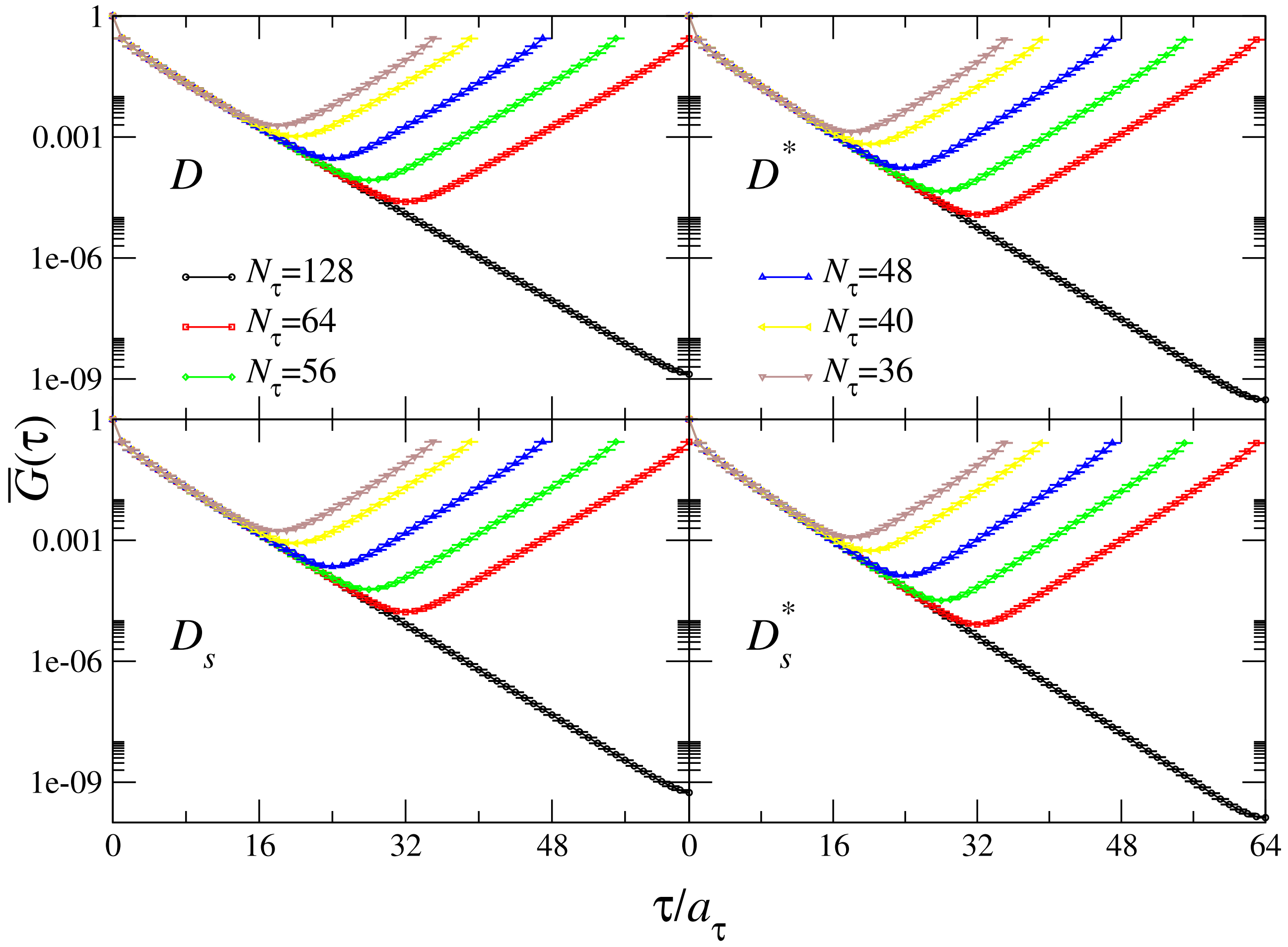
- correlators at various temperatures
- dominant signal is exponential decay

$$G(\tau) \sim \exp(-m\tau)$$

- periodic at finite temperature

$$G(1/T - \tau) = G(\tau)$$

- how to detect thermal effects?



# How to assess thermal effects?

- two origins of thermal effects: *kinematical* and *dynamical*
- consider spectral relation

$$G(\tau, \mathbf{p}; T) = \int_0^\infty \frac{d\omega}{2\pi} K(\tau, \omega; T) \rho(\omega, \mathbf{p}; T) \qquad K(\tau, \omega; T) = \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

- *kinematical*: kernel $K$ depends on $T$, related to geometry of lattice
- *dynamical*: spectral function $\rho$, in-medium effects ⟹ interesting physics!

how to disentangle the two

# Ratios of ratios of correlators at different $T$'s

- standard ratios $G(\tau;T_1)/G(\tau;T_2)$ suffer from periodicity effect
- proposal: two-step comparison
- divide out dominant effect of ground state at all temperatures

  using model correlator with parameters determined at reference temperature $T_0$

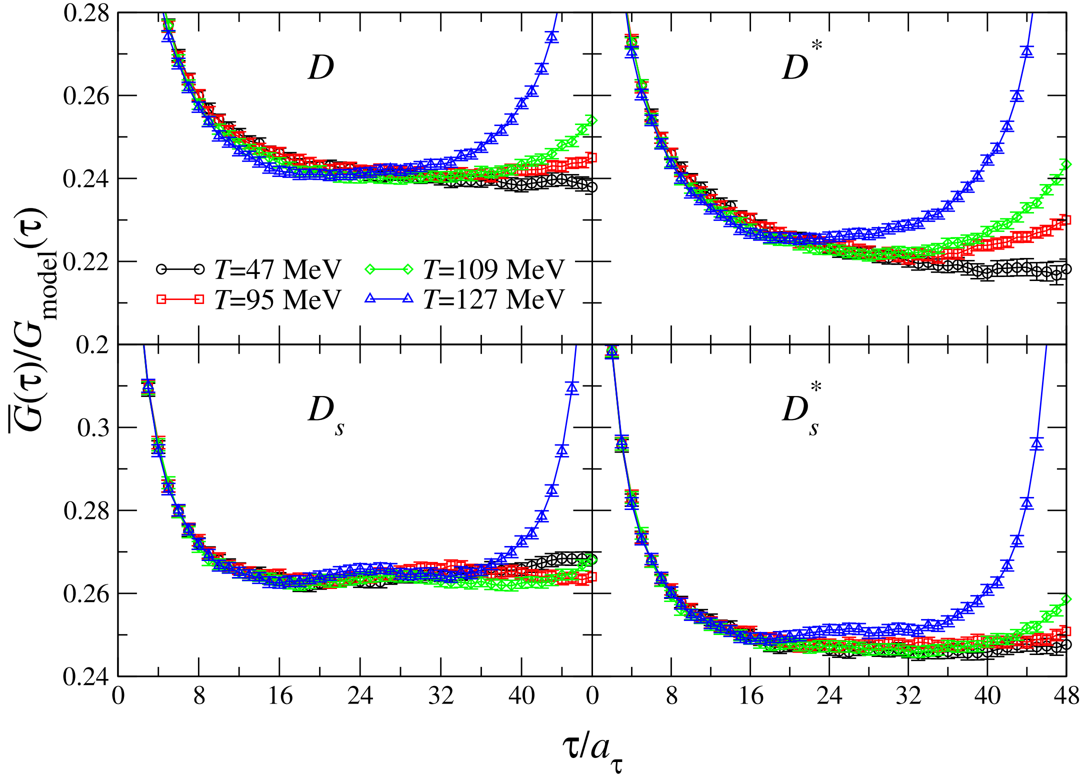
$$G_{\rm model}(\tau;T,T_0) = A(T_0)\frac{\cosh[M(T_0)(\tau-1/2T)]}{\sinh[M(T_0)/2T]}$$

- divide out kinematical effect out by taking double ratio

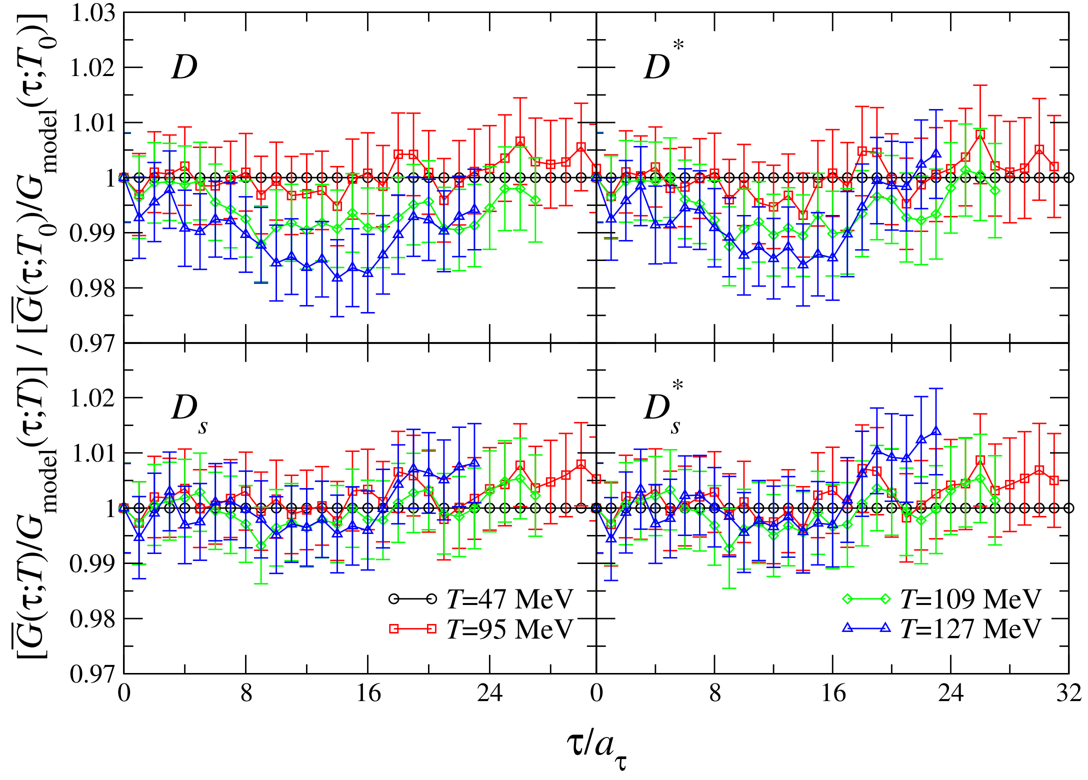
$$\frac{G(\tau;T)}{G_{\rm model}(\tau;T,T_0)} \Bigg/ \frac{G(\tau;T_0)}{G_{\rm model}(\tau;T_0,T_0)}$$

# $D_{(s)}$ and $D^*_{(s)}$ channels: up to $T = 127$ MeV

- ratio and double ratio in hadronic phase, using $T_0 = 47$ MeV




single ratio: plateau for larger $\tau$

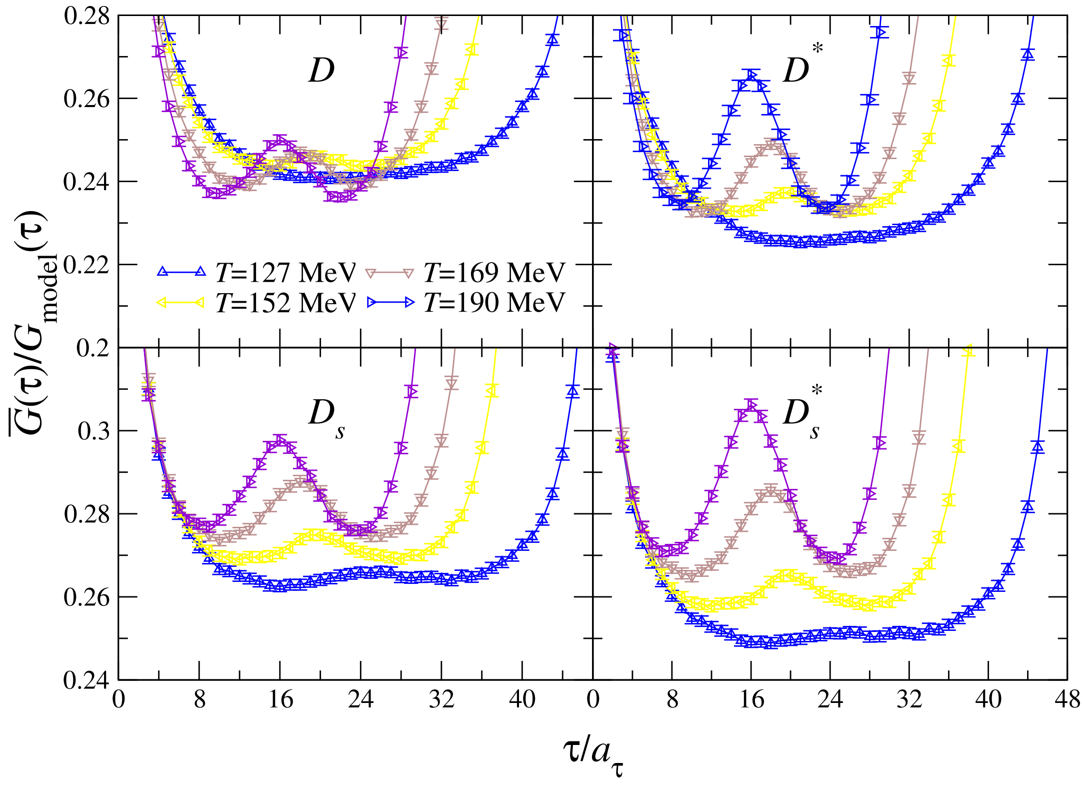



$$\frac{G(\tau;T)}{G_{\rm model}(\tau;T,T_0)} \Big/ \frac{G(\tau;T_0)}{G_{\rm model}(\tau;T_0,T_0)}$$

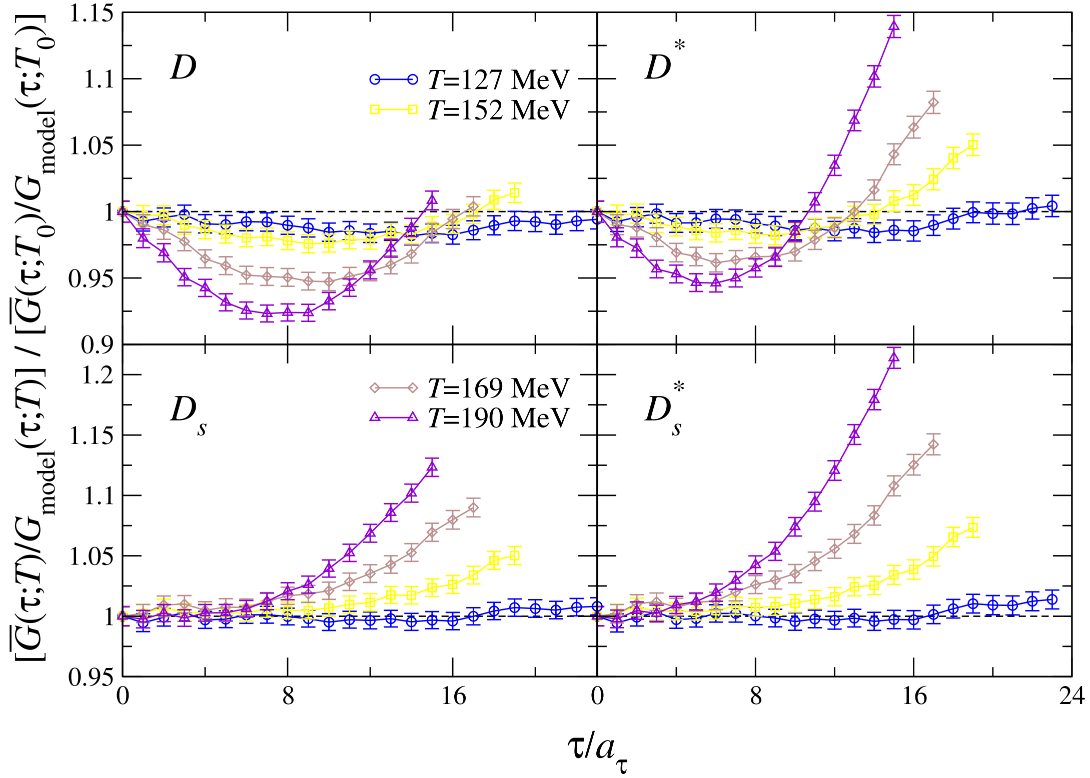
double ratio: deviations from reference $T_0 <$ 1-2%

# $D_{(s)}$ and $D^*_{(s)}$ channels: up to $T = 190$ MeV

- ratio and double ratio at higher temperatures, using $T_0 = 47$ MeV




single ratio: stronger deviations




$$\frac{G(\tau;T)}{G_{\text{model}}(\tau;T,T_0)} \Big/ \frac{G(\tau;T_0)}{G_{\text{model}}(\tau;T_0,T_0)}$$

double ratio: deviations of 10-15%

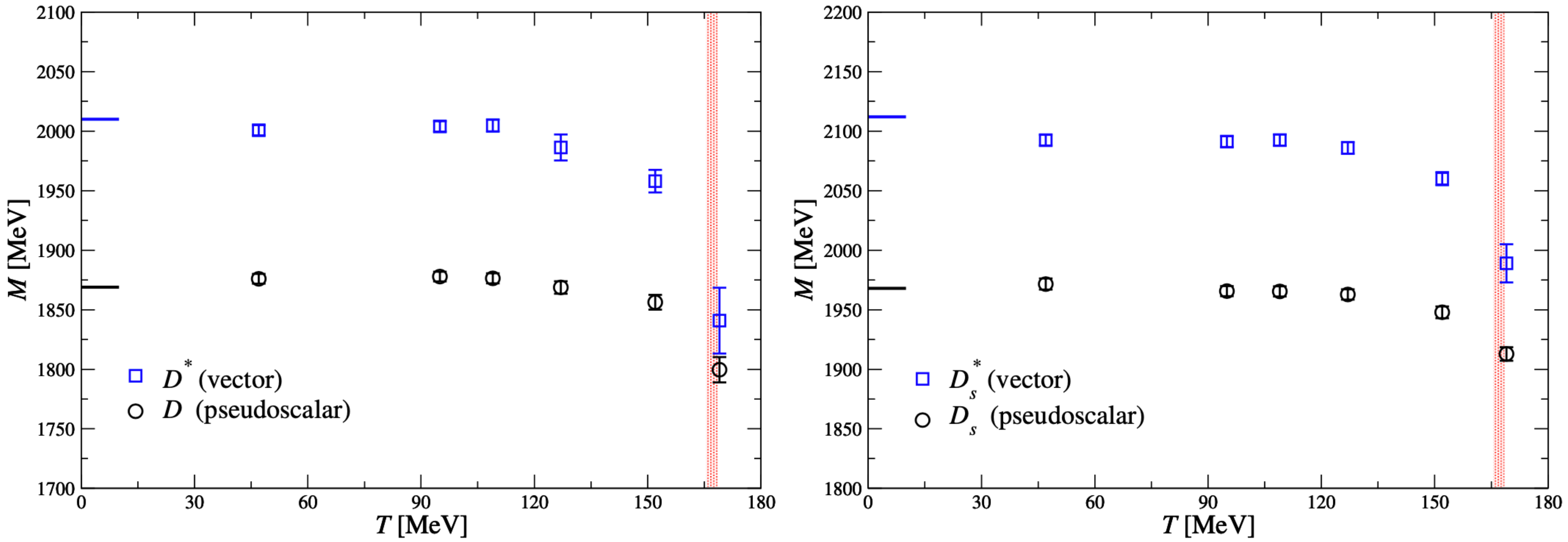
# $D_{(s)}$ and $D^*_{(s)}$ channels: double ratios

- double ratio shows no temperature dependence up to at least $T = 127$ MeV
- deviation from 1 less than 1-2%, within error
- suggests absence of thermal effects: carry out mass fits to confirm

- temperature dependence clearly visible at $T = 152$ MeV
- strong temperature dependence in quark-gluon plasma
- small characteristic wiggles can be modelled with reduced mass (not shown)
- large thermal effects cannot be absorbed in this way

→ perform mass fits up to $T = 169$ MeV – recall that $T_{pc} = 167(3)$ MeV

# $D_{(s)}$ and $D^*_{(s)}$: thermal ground state masses



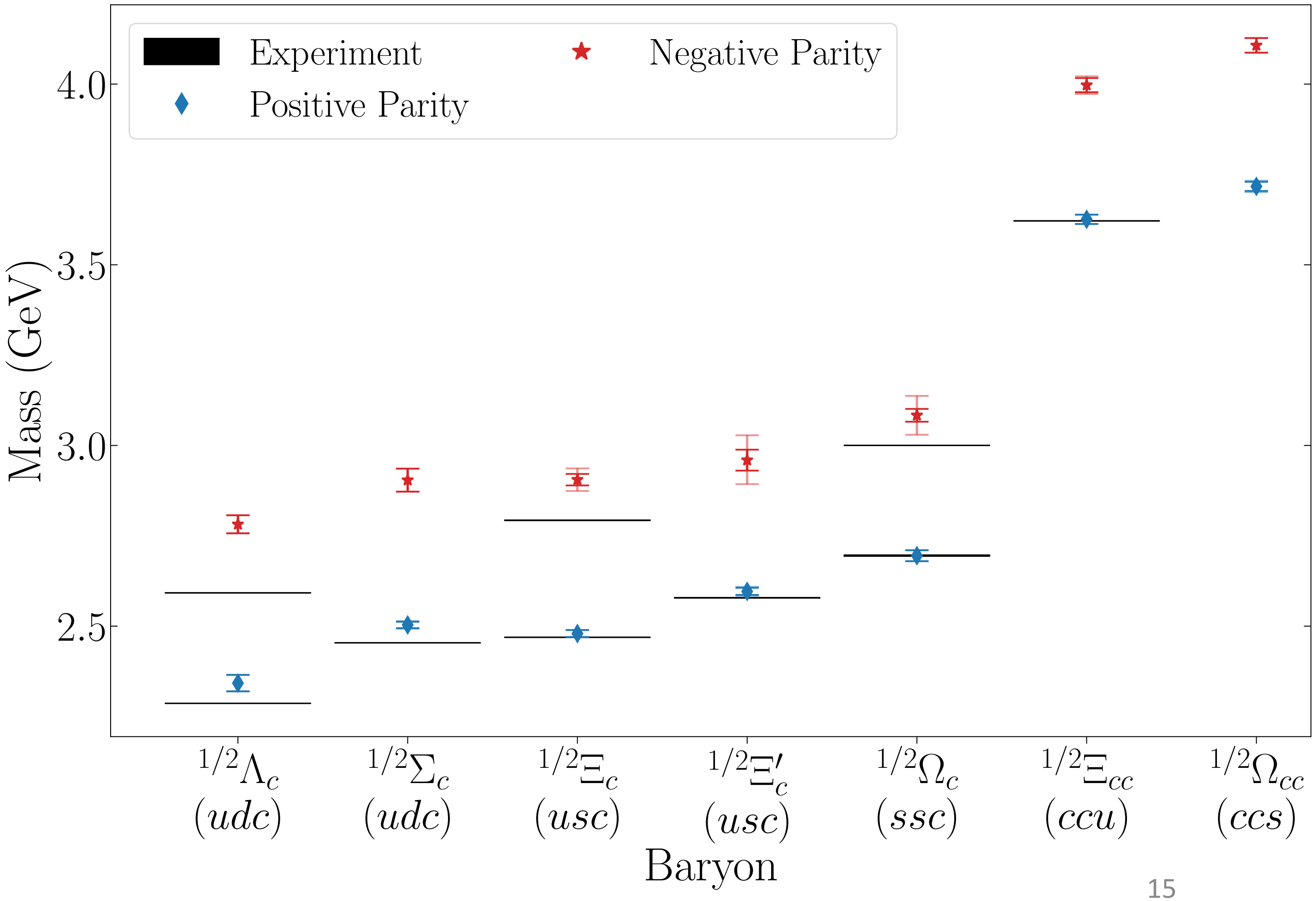

| | $J^P$ | PDG | $T$[MeV]= 47 | 95 | 109 | 127 | 152 | 169 |
|---|---|---|---|---|---|---|---|---|
| $D$ | $0^-$ | 1869.65(5) | 1876(4) | 1878(4) | 1876(4) | 1869(5) | 1856(6) | 1800(11) |
| $D^*$ | $1^-$ | 2010.26(5) | 2001(4) | 2004(4) | 2005(5) | 1986(11) | 1958(9) | 1841(28) |
| $D_s$ | $0^-$ | 1968.34(7) | 1972(5) | 1966(4) | 1965(4) | 1963(4) | 1948(5) | 1913(6) |
| $D_s^*$ | $1^-$ | 2112.2(4) | 2092(4) | 2091(5) | 2092(5) | 2086(5) | 2060(6) | 1989(16) |

# Spin ½ charmed baryons

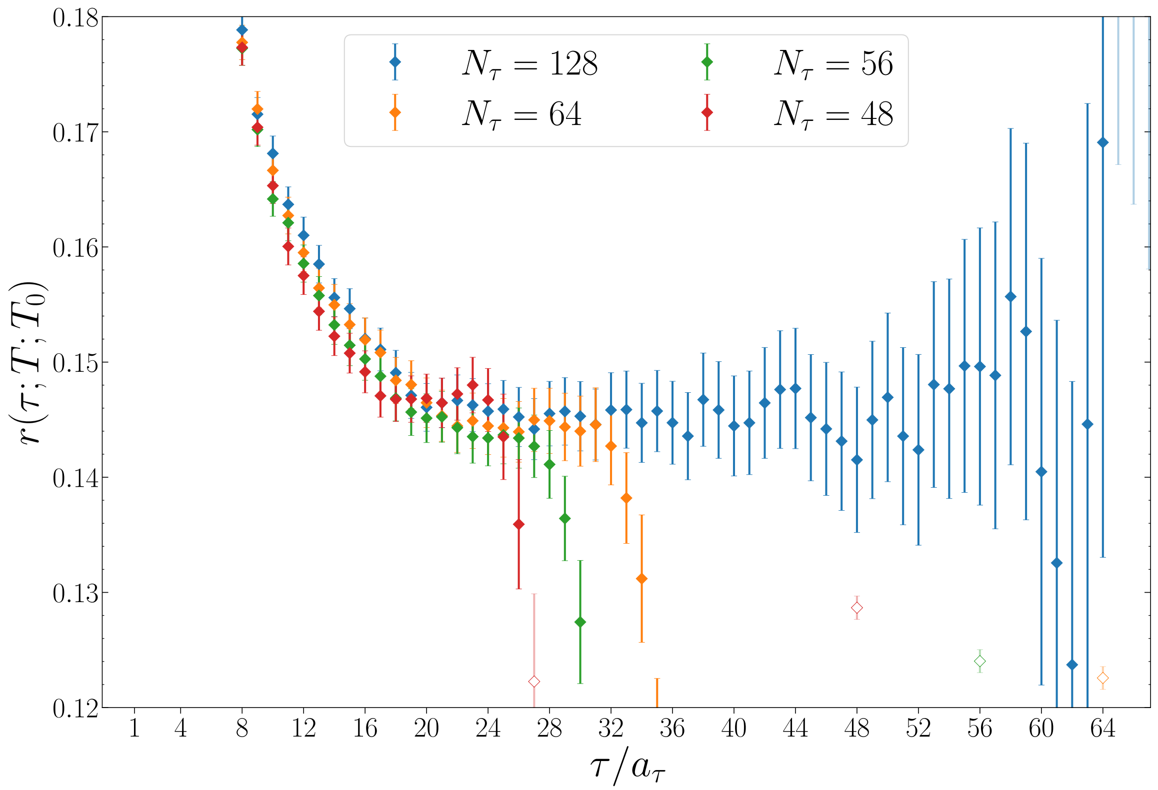
- similar analysis as for mesons
- fit ground state at $T_0 = 47$ MeV
- pos. and neg. parity states

note:

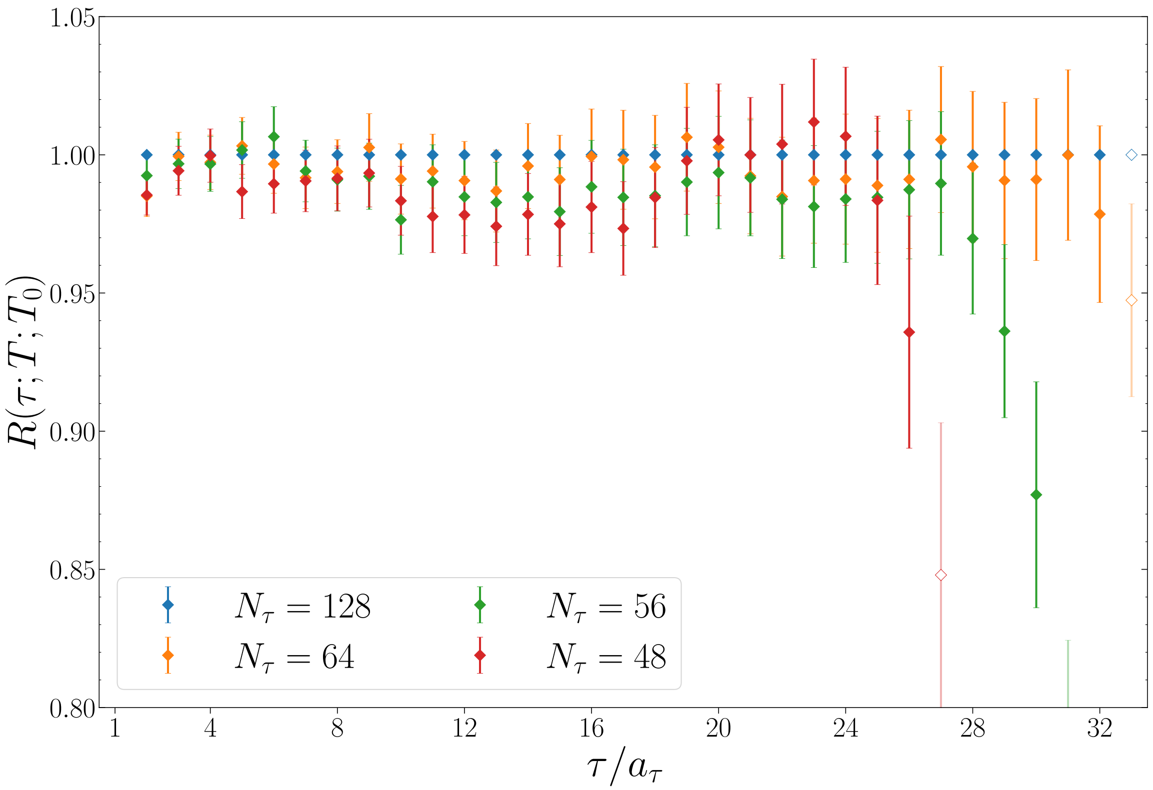
- lattices not designed for high precision in vacuum



# Spin ½ $\Sigma_c(udc)$ baryon: (double) ratios

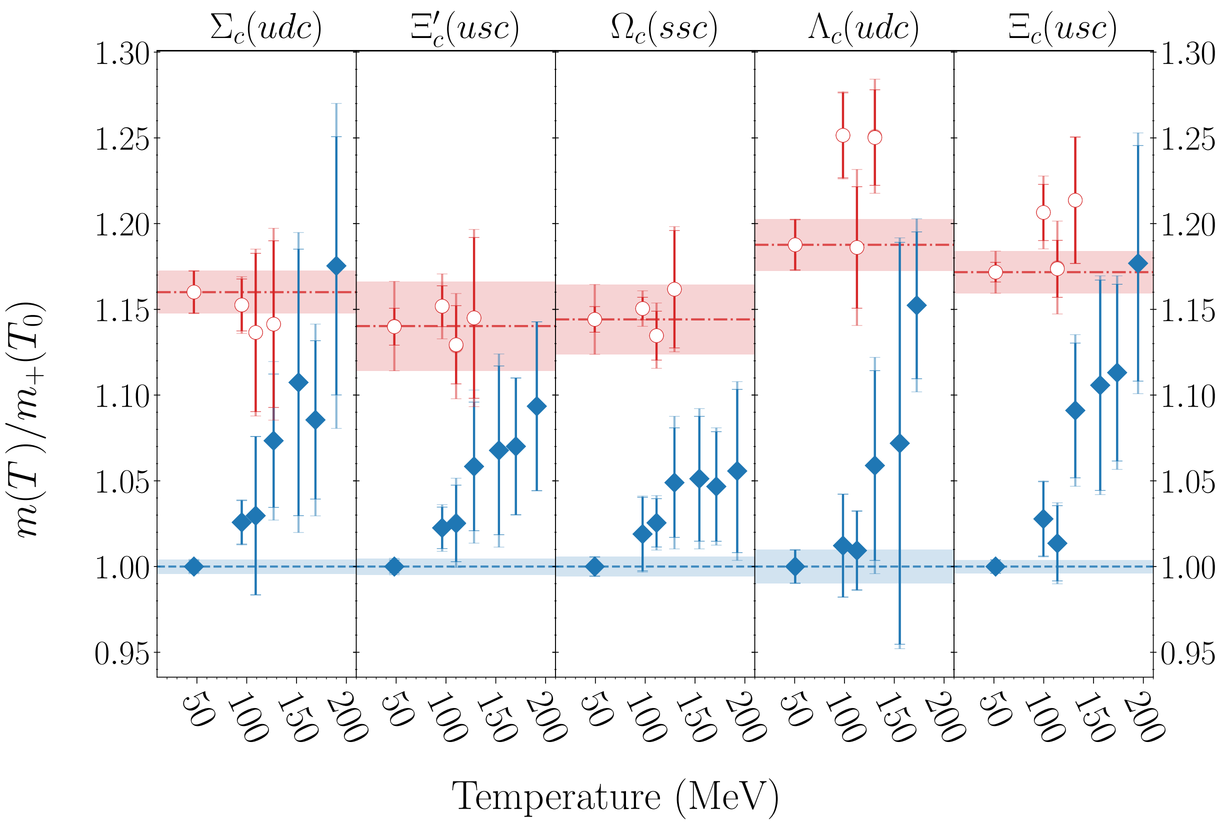


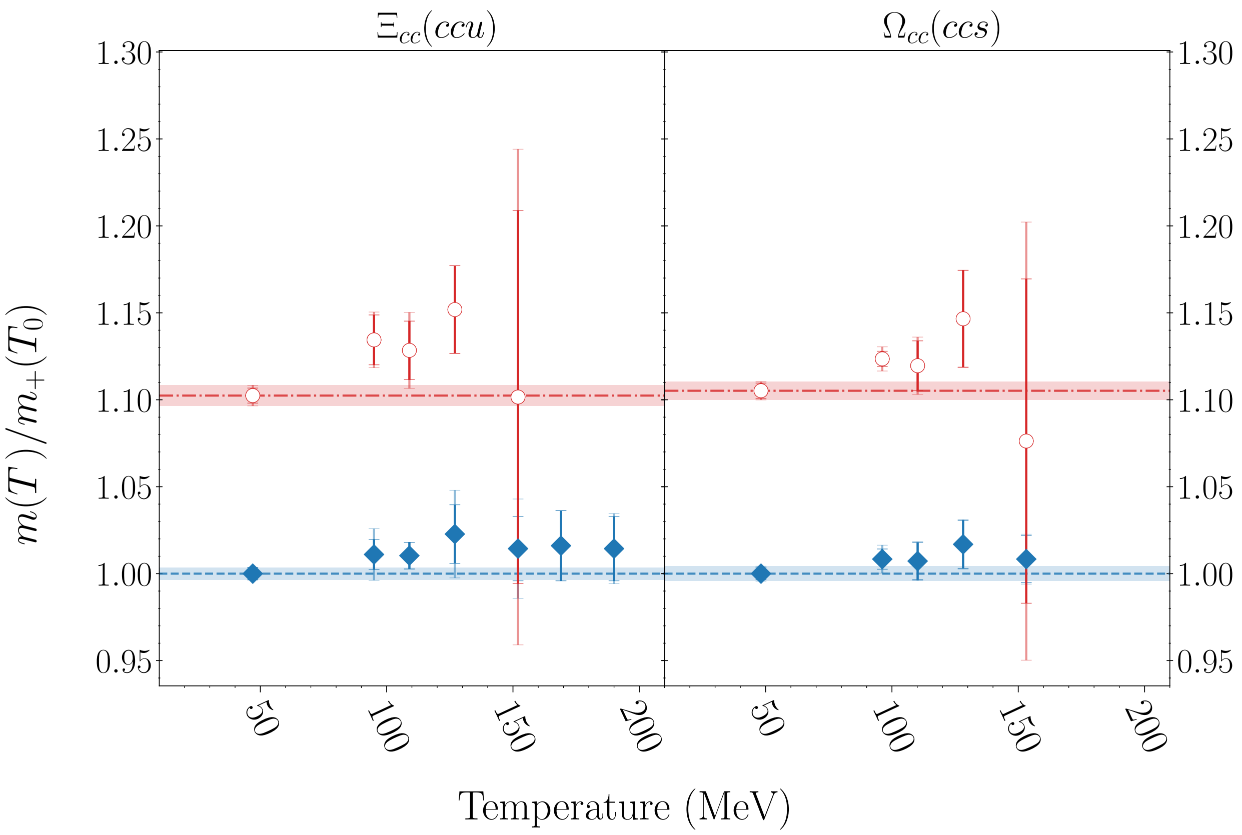

single ratio: plateau




double ratio: small deviations

# Spin ½ charmed baryon spectrum at finite $T$




single-charm
pos and neg parity

less clean signal
compared to mesons

double-charm
pos and neg parity

# Baryons: parity doubling and chiral symmetry

- 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** $\leftrightarrows$ **parity doubling**

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

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

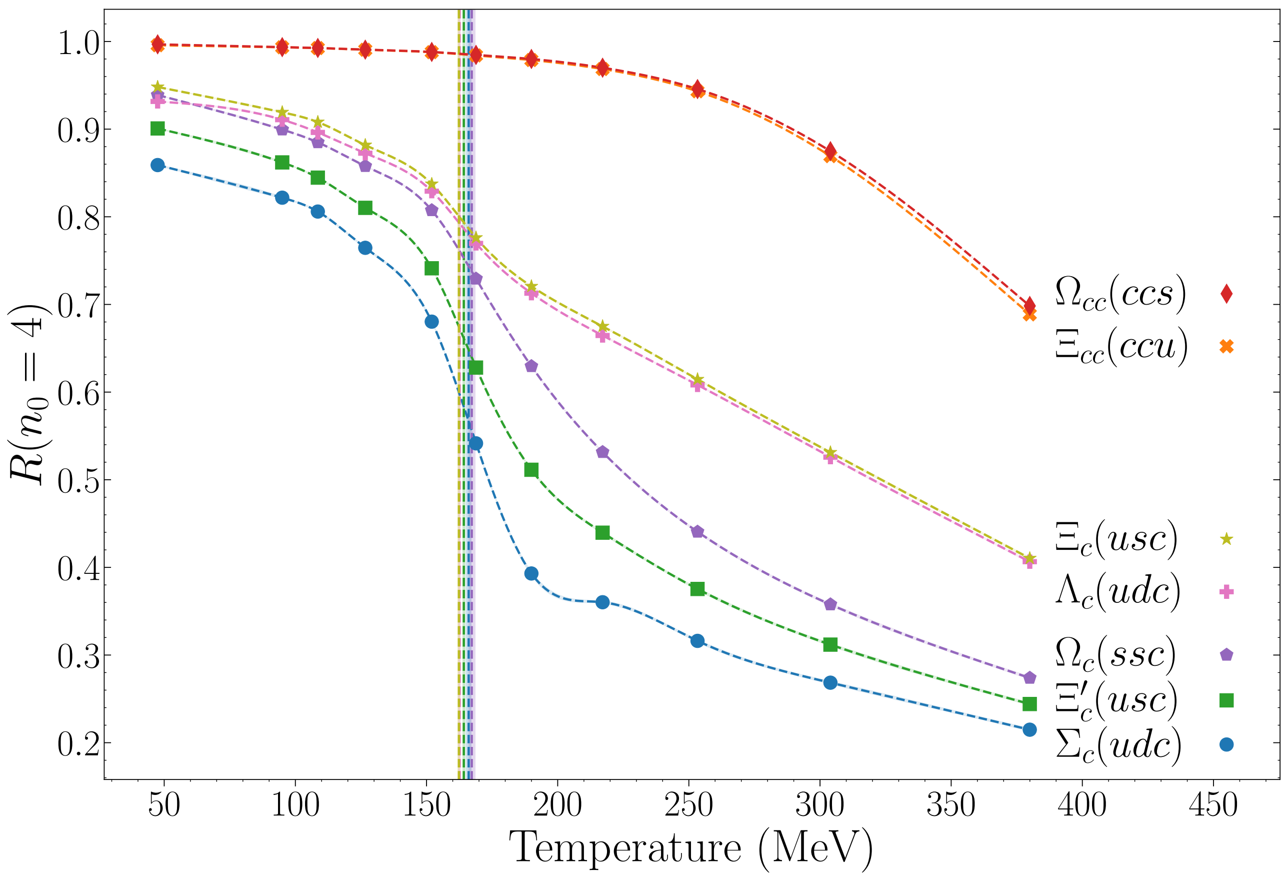
- if parity doubling: $R = 0$
- if ~~parity doubling~~, and ground state dominates, with $m_+ \gg m_-$ : $R = 1$

# Charmed baryons and parity doubling

- charm mass is not small
- chiral symmetry explicitly broken

nevertheless

- thermal transition visible in $R$ ratio via inflection point
- single-charm states ordered by flavour multiplet at high $T$




| S | C | Inflection point (MeV) | |
|---|---|---|---|
| 0 | 1 | $\Sigma_c\,(udc)$ 166.1(1.0) | $\Lambda_c\,(udc)$ 162.6(5) |
| −1 | 1 | $\Xi'_c\,(usc)$ 164.2(6) | $\Xi_c\,(usc)$ 162.3(4) |
| −2 | 1 | $\Omega_c\,(ssc)$ 167.2(1.3) | |

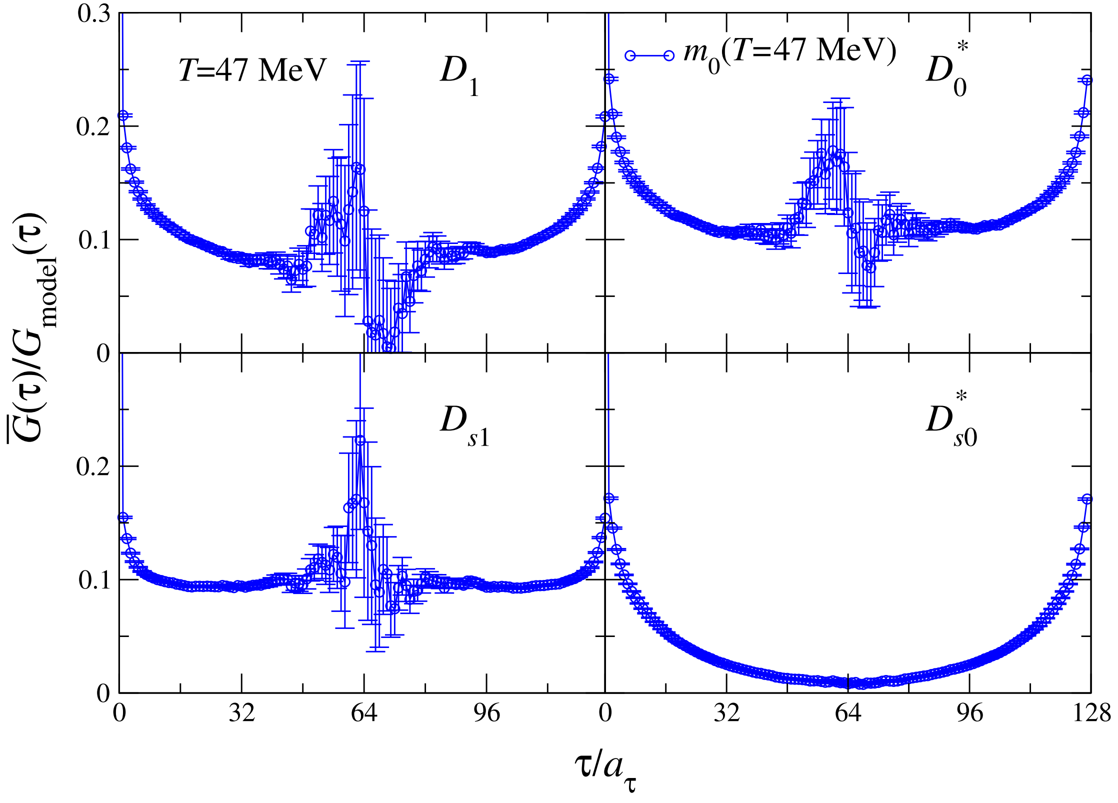
$T_{pc} = 167(3)$ MeV

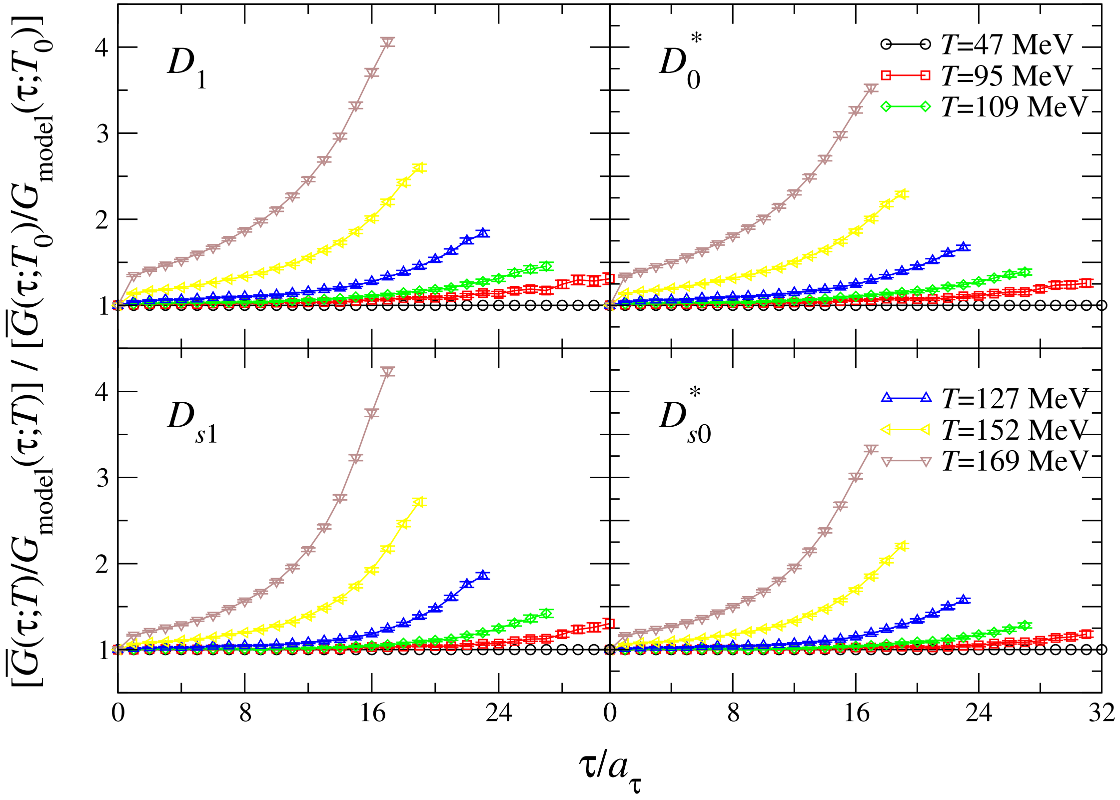
# Summary: hadrons at finite temperature

- FASTSUM: spectral properties in thermal QCD on anisotropic lattices
- approaching thermal crossover: thermal modification of hadrons
- here: $D_{(s)}$ mesons and spin ½ charmed baryons in the hadronic phase
- $D_{(s)}$ mesons in pseudoscalar and vector channels: temperature dependence well controlled, reduced mass close to transition
- spin ½ charmed baryons: increasing mass close to transition but more noisy
  chiral symmetry restoration for light quarks visible in correlators

# Backup slides

# What about axial-vector and scalar channels?




ground states harder to determine with these fits

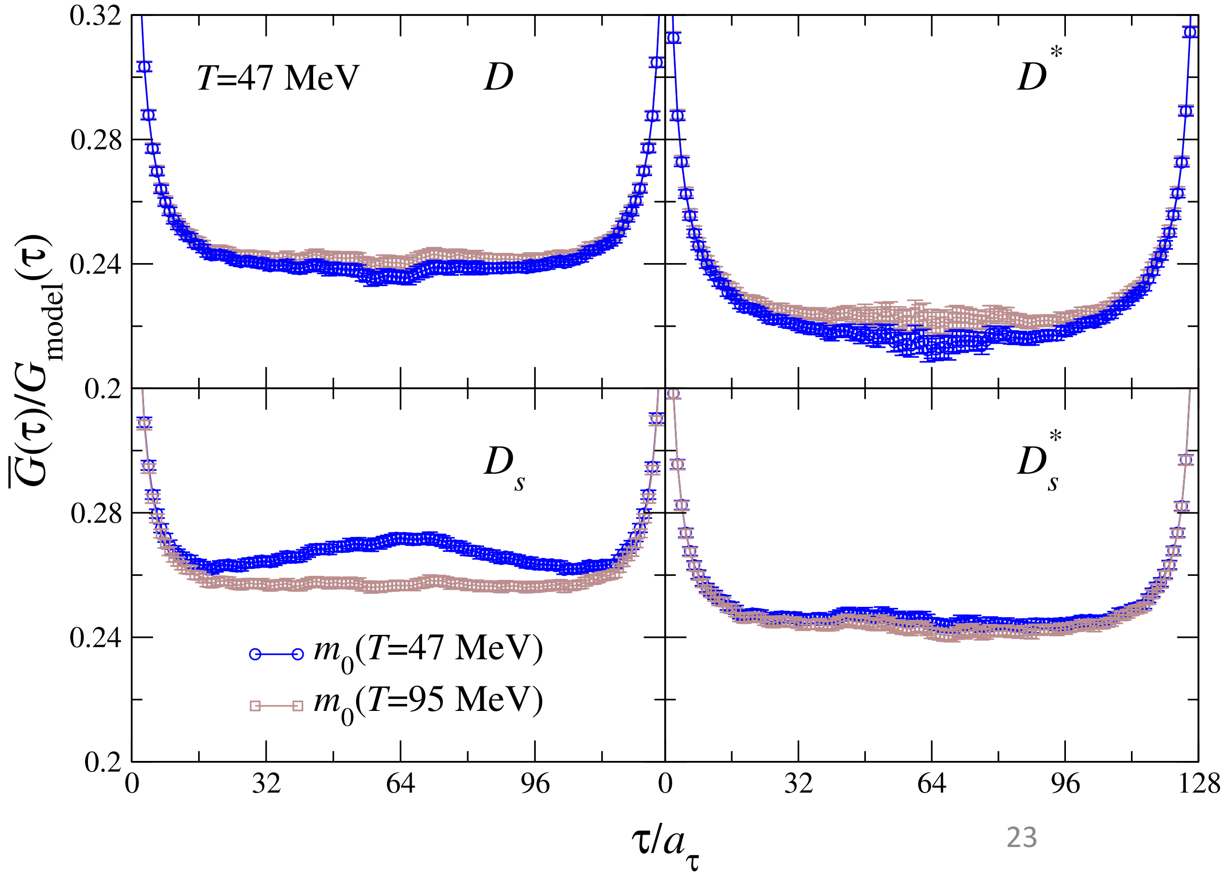
double ratio shows strong temperature dependence throughout the hadronic phase

# $D_{(s)}$ and $D^*_{(s)}$ channels: step 1a

$G(\tau; T_0)/G_{\text{model}}(\tau; T_0)$

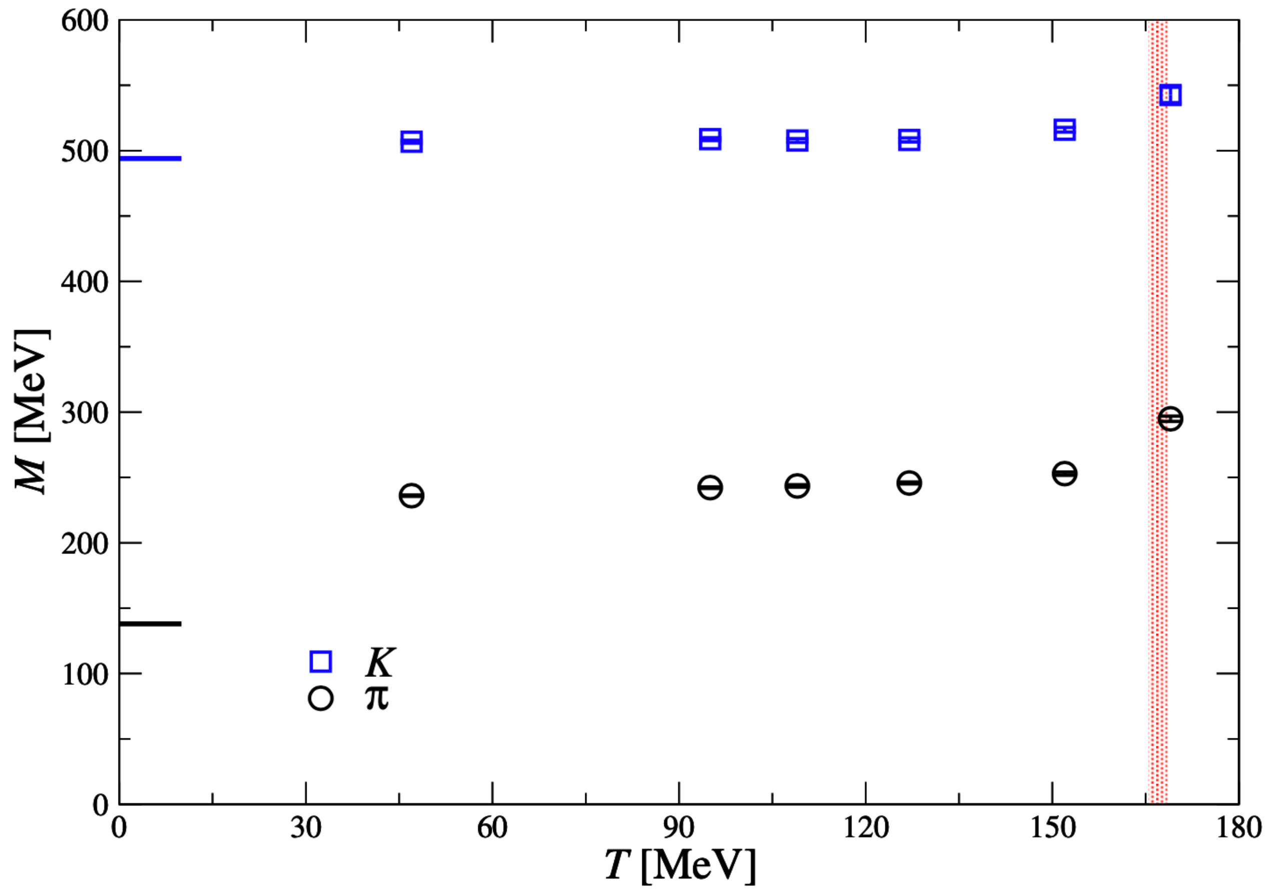
- divide out ground state decay at the lowest temperature, using $T_0 = 47, 95$ MeV
- plateau indicates accurate determination of ground state mass

| | | $J^P$ | PDG [MeV] | $a_\tau M$ | $M$ [MeV] |
|---|---|---|---|---|---|
| $D$ | pseudoscalar | $0^-$ | 1869.65(5) | 0.3086(1) | 1876(4) |
| $D^*$ | vector | $1^-$ | 2010.26(5) | 0.3291(1) | 2001(4) |
| $D_0^*$ | scalar | $0^+$ | 2300(19) | 0.3656(14) | 2222(10) |
| $D_1$ | axial-vector | $1^+$ | 2420.8(5) | 0.3823(70) | 2325(43) |
| $D_s$ | pseudoscalar | $0^-$ | 1968.34(7) | 0.3243(3) | 1972(5) |
| $D_s^*$ | vector | $1^-$ | 2112.2(4) | 0.3442(1) | 2092(4) |
| $D_{s0}^*$ | scalar | $0^+$ | 2317.8(5) | 0.3479(46) | 2115(29) |
| $D_{s1}$ | axial-vector | $1^+$ | 2459.5(6) | 0.4132(2) | 2512(6) |



# Light quarks: pion and kaon

- states have substantial width
- also thermal effects in pion and kaon masses
- possibility for intricate temperature-dependent interplay



# Poor man's reconstructed correlator

aside:

- similar to what is known as *reconstructed correlator*
- requires complete spectral function at reference temperature $T_0$
- this approach only relies on a (standard) ground state fit at $T_0$
- very little input required: robust procedure

- conclusion is identical:

  if the double ratio is not equal to '1', spectral content has changed with temperature