

# Spectral quantities in thermal QCD: a progress report from the FASTSUM collaboration

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# Matter under extreme conditions

a current challenge in thermal lattice QCD:

- go beyond thermodynamics: spectroscopy
- fate of hadrons at finite temperature
- manifestations of chiral symmetry restoration
- phenomenology and heavy-ion collisions
- flavour dependent observables
- ...

from simulation perspective: more exploratory than thermodynamics

- not yet with physical quarks
- not yet in continuum limit

# Outline

- FASTSUM ensembles
- towards lighter pions
- fluctuations and chiral properties
- baryons and parity doubling
- summary

for further results, see two following talks by

- Aleksandr Nikolaev, on  $\mathcal{O}(\mu^2)$  corrections to the light meson spectrum
- Sam Offler, on bottomonium

# FASTSUM collaboration

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recent work:

JHEP 06 (2017) 034

[arXiv:1703.09246 [hep-lat]]

EPJ WoC 171 (2018) 14005

[arXiv:1710.00566 [hep-lat]]

PoS LATTICE2018 (2018) 183

[arXiv:1812.08151 [hep-lat]]

PRD 99 (2019) 074503

[arXiv:1812.07393 [hep-lat]]

# FASTSUM ensembles

- $N_f = 2 + 1$  dynamical quark flavours, Wilson-clover
- anisotropic lattice,  $\xi = a_s/a_\tau \approx 3.5$ , many time slices
- ⇒ good for spectroscopy
- tuning of anisotropy and ensembles\* at  $T = 0$  from HadSpec collaboration
- fixed lattice spacing,  $a_\tau^{-1} \approx 6$  GeV
- fixed anisotropy,  $\xi \approx 3.5$
- light quarks,  $m_q \rightarrow m_{ud}$ , strange quark  $m_s$  physical

	$a_s$ [fm]	$a_\tau$ [fm]	$a_\tau^{-1}$ [GeV]	$\xi = a_s/a_\tau$	$N_s$	$m_\pi$ [MeV]	$m_\pi L$
Gen 2	0.1227(8)	0.0350(2)	5.63(4)	3.5	24	384(4)	5.7
Gen 2L	0.1136(6)	0.0330(2)	5.997(34)	3.453(6)	32	236(2)	4.3

# FASTSUM ensembles

$N_\tau$	128*	40	36	32	28	24	20	16
$T$ [MeV]	44	141	156	176	201	235	281	352
$T/T_c$	0.24	0.76	0.84	0.95	1.09	1.27	1.52	1.90
$N_{\text{cfg}}$	139	501	501	1000	1001	1001	1000	1001

Gen 2 ensembles,  $m_\pi = 384$  MeV, lattice size  $24^3 \times N_\tau$

$N_\tau$	256*	128	64	56	48	40	36
$T$ [MeV]	23	47	94	107	125	150	167
$N_{\text{cfg}}$	750	300	500	500	500	500	500
$N_\tau$	32	28	24	20	16	12	8
$T$ [MeV]	187	214	250	300	375	500	750
$N_{\text{cfg}}$	500	1000	1000	1000	1000	1000	1000

Gen 2L ensembles,  $m_\pi = 236$  MeV, lattice size  $32^3 \times N_\tau$

the lower temperatures with  $N_{\text{cfg}} = 500$  are currently being upgraded to 1000

# FASTSUM status

multi-year project, with essential contributions by

- Jonas Glesaaen (especially code development)
- Ben Jäger (especially code development, simulations)
- Liang-Kai Wu (simulations)
- Aleksandr Nikolaev (analysis, simulations, theory)
- . . .

code: modification of OpenQCD

*J. Glesaaen & B. Jäger, openQCD-FASTSUM, [doi.org/10.5281/zenodo.2216356](https://doi.org/10.5281/zenodo.2216356)*

*J. Glesaaen, openqcd-hadspec, [doi.org/10.5281/zenodo.2217028](https://doi.org/10.5281/zenodo.2217028)*

(include anisotropy, stout-smearing, stand-alone spectroscopy)

# Fluctuations and chiral properties

- thermodynamics usually studied with staggered quarks
- we are interested in spectroscopy
- but need to understand thermodynamics to determine thermal crossover properties

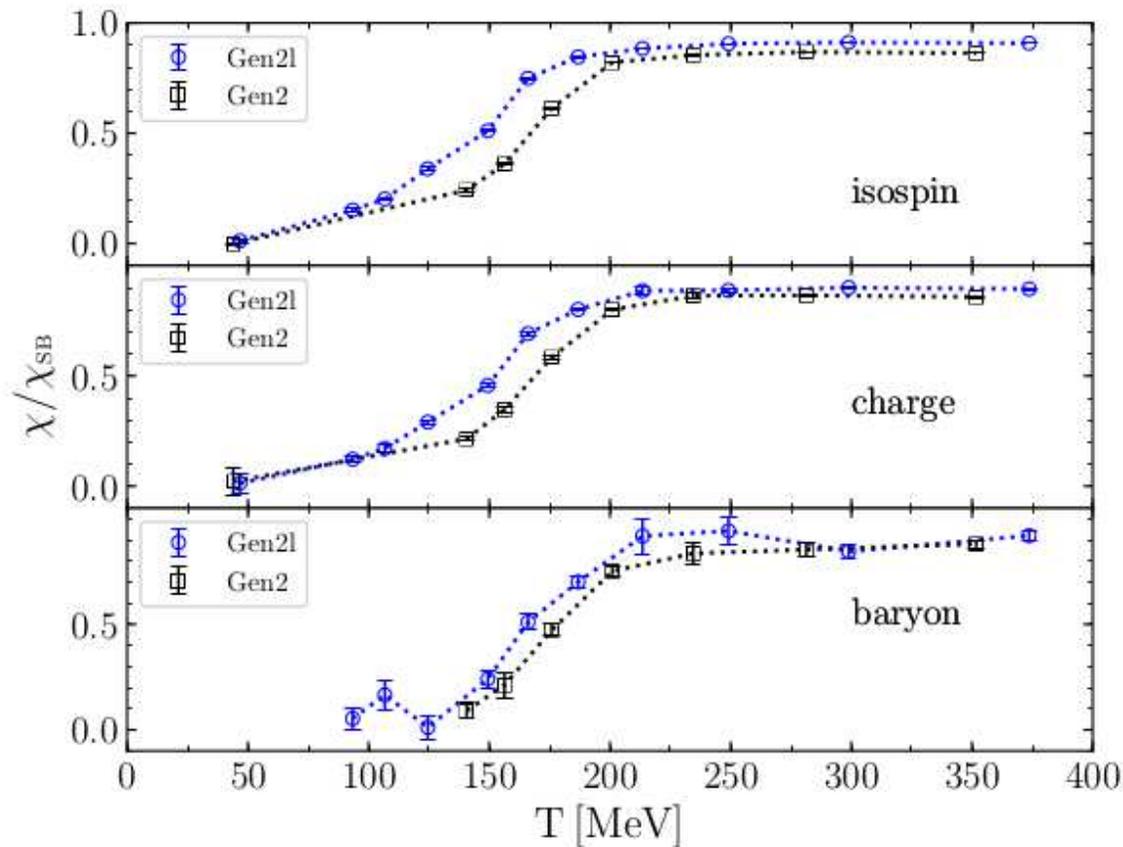
⇒ thermal crossover with Wilson fermions

- transition temperature depends on observable
- expectation: shift of pseudo-critical temperatures to lower values as  $m_\pi$  is reduced

everything is *preliminary!*

# Susceptibilities

fluctuations of isospin, electric charge and baryon number



$$T_{infl} \simeq 169 \text{ MeV}$$

(Gen 2)

$$T_{infl} \simeq 157 \text{ MeV}$$

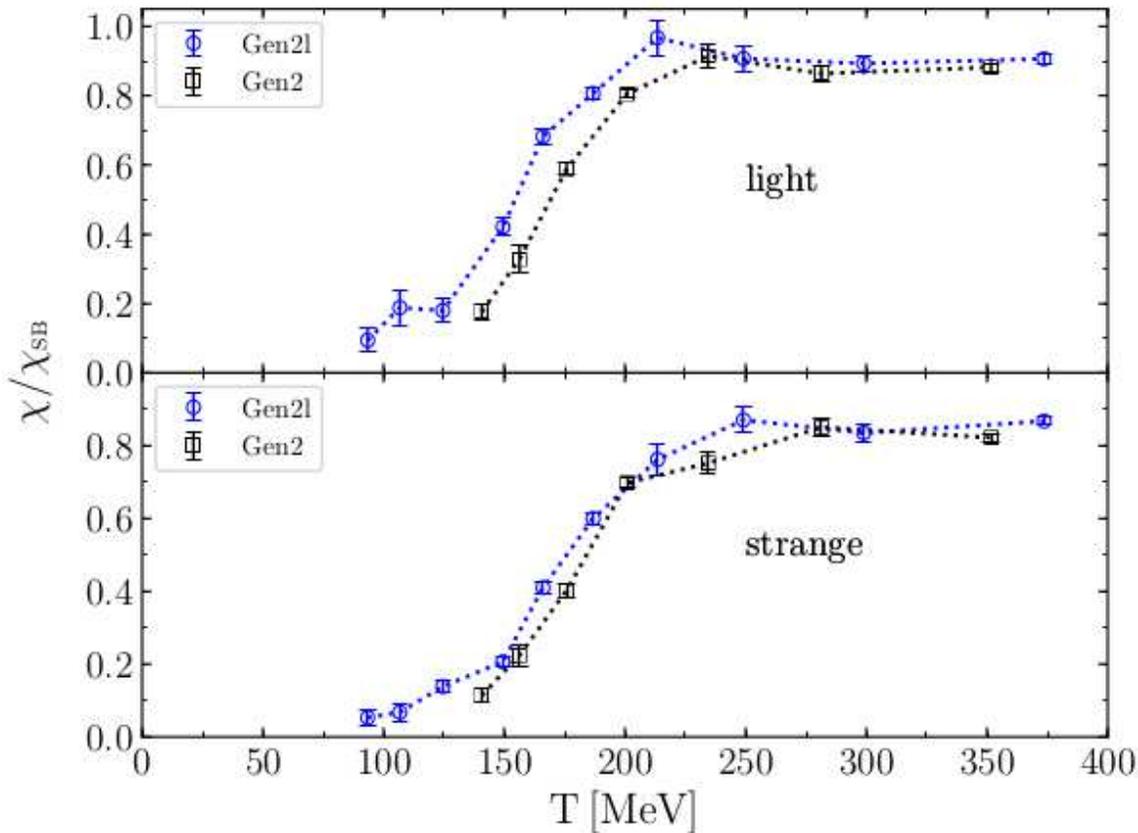
(Gen 2L)

$\chi/\chi_{SB}$ , normalised with massless, lattice Stefan-Boltzmann result

- temperature of inflection point indication of crossover

# Susceptibilities

fluctuations of light and strange quark number



light quark number:

$$T_{\text{infl}} \simeq 164 \text{ MeV}$$

(Gen 2)

$$T_{\text{infl}} \simeq 154 \text{ MeV}$$

(Gen 2L)

strange quark number:

$$T_{\text{infl}} \simeq 184 \text{ MeV}$$

(Gen 2)

$$T_{\text{infl}} \simeq 161 \text{ MeV}$$

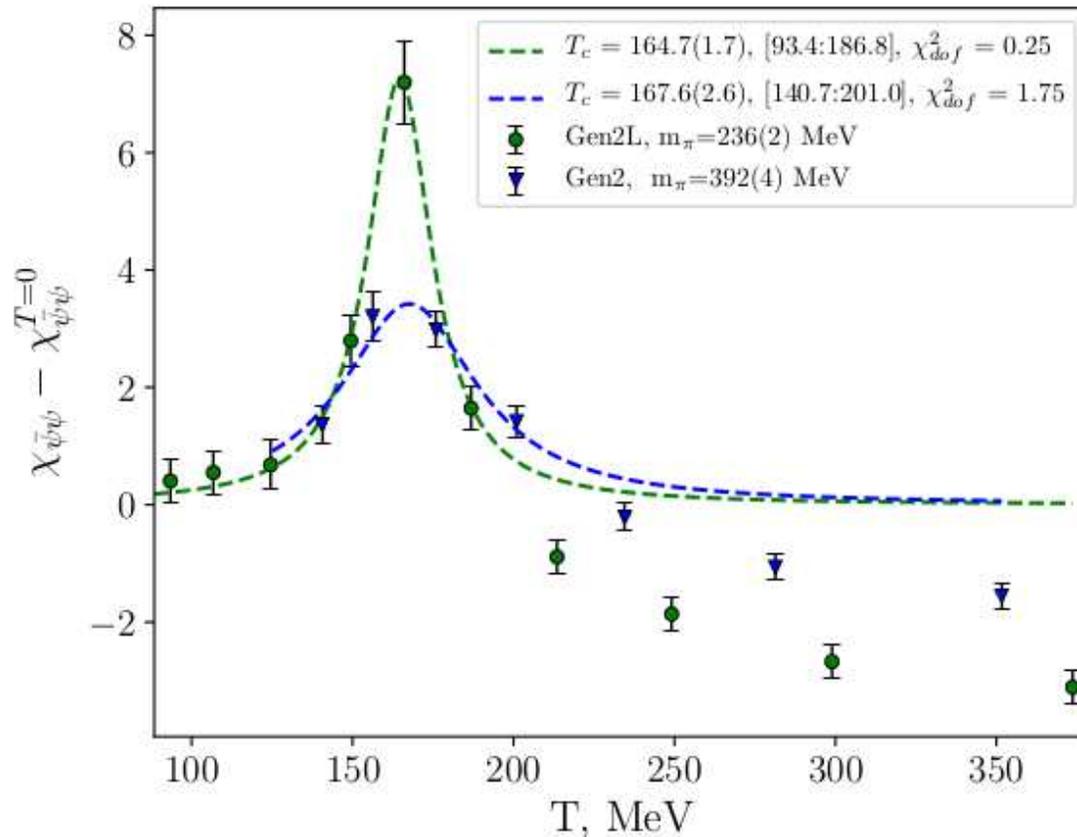
(Gen 2L)

$\chi/\chi_{SB}$ , normalised with massless, lattice Stefan-Boltzmann result

- temperature of inflection point indication of crossover

# Chiral susceptibility

- fixed scale approach
- additive + multiplicative renormalisation  $T$  independent



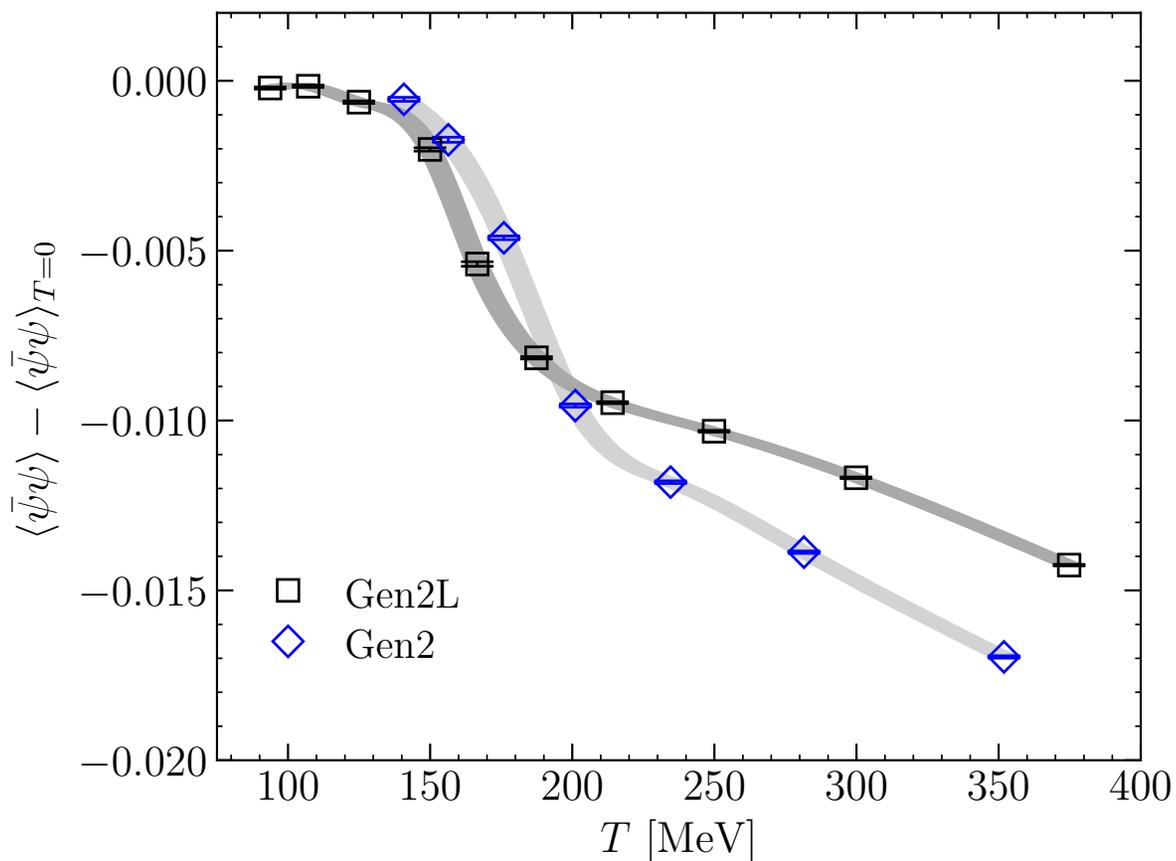
$T_{\text{infl}} \simeq 167 \text{ MeV}$   
(Gen 2)

$T_{\text{infl}} \simeq 165 \text{ MeV}$   
(Gen 2L)

- more pronounced peak

# Chiral condensate

- fixed scale approach
- additive + multiplicative renormalisation  $T$  independent

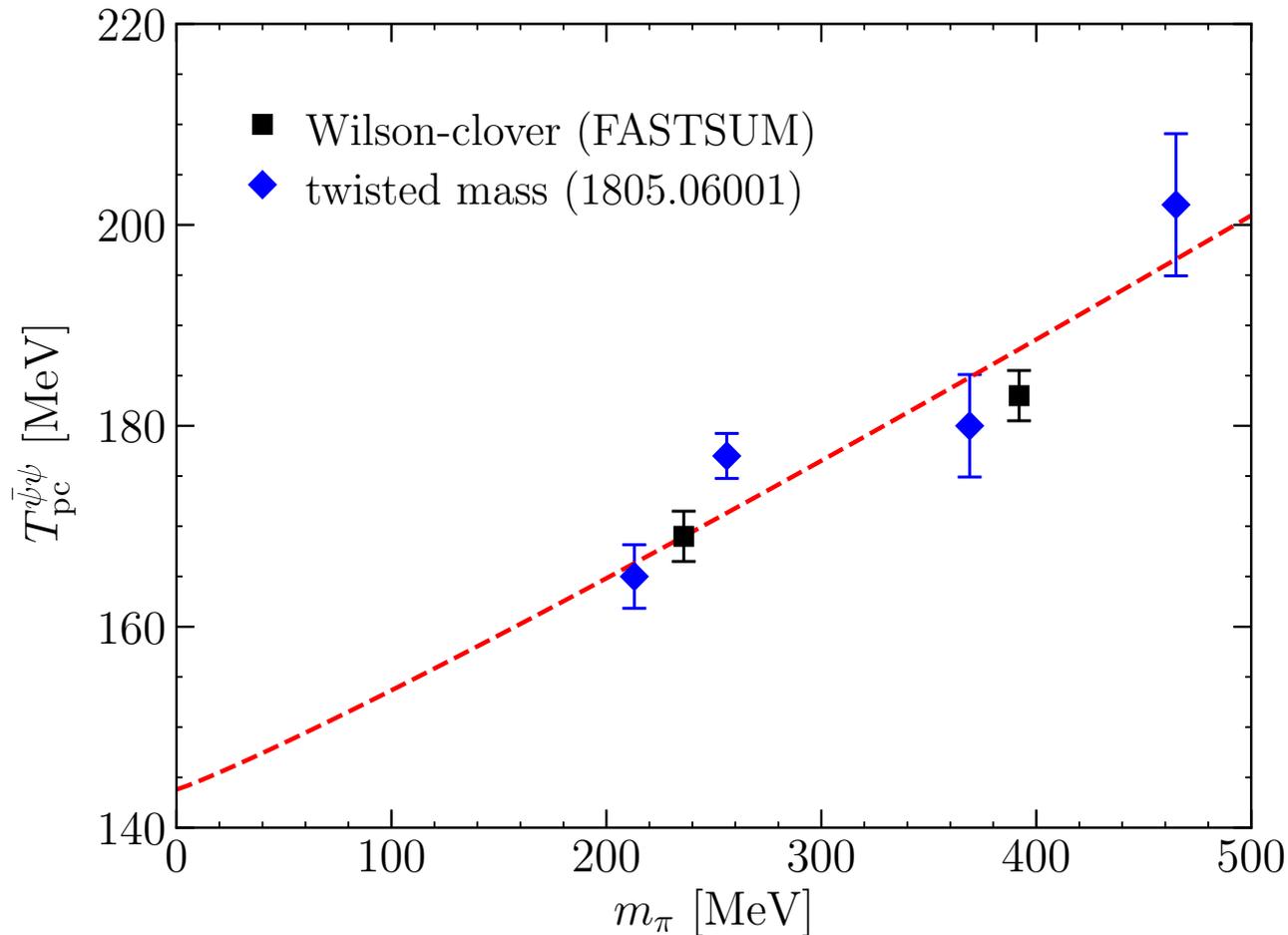


$T_{\text{infl}} \simeq 182 \text{ MeV}$   
(Gen 2)

$T_{\text{infl}} \simeq 168 \text{ MeV}$   
(Gen 2L)

# Chiral condensate

$T_{pc}$  from inflection point, compare with twisted mass fermions  
1805.06001 Lombardo et al



consistency between different Wilson-type formulations

# Baryons and parity doubling

baryons come in pairs, related by parity

- positive/negative parity operators:  $PO_{\pm}(\tau, \mathbf{x}) = \pm O_{\pm}(\tau, -\mathbf{x})$
- in Nature the corresponding states are not degenerate:  
no parity doubling

- example: nucleon groundstate

$$\text{positive parity: } m_{+} = m_N = 0.939 \text{ GeV}$$

$$\text{negative parity: } m_{-} = m_{N^*} = 1.535 \text{ GeV}$$

- absence of parity doubling is directly related to chiral symmetry breaking

# Parity doubling and chiral symmetry

construct quasi-order parameter

- study correlator ratio

Datta, Gupta, Mathur et al

JHEP 1302 (2013) 145 [1212.2927]

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

- no parity doubling and  $m_- \gg m_+$ :  $R(\tau) = 1$
- parity doubling:  $R(\tau) = 0$

by construction:  $R(1/T - \tau) = -R(\tau)$  and  $R(1/2T) = 0$

- integrated ratio
- ⇒ quasi-order parameter

$$R = \frac{\sum_n R(\tau_n) / \sigma^2(\tau_n)}{\sum_n 1 / \sigma^2(\tau_n)}$$

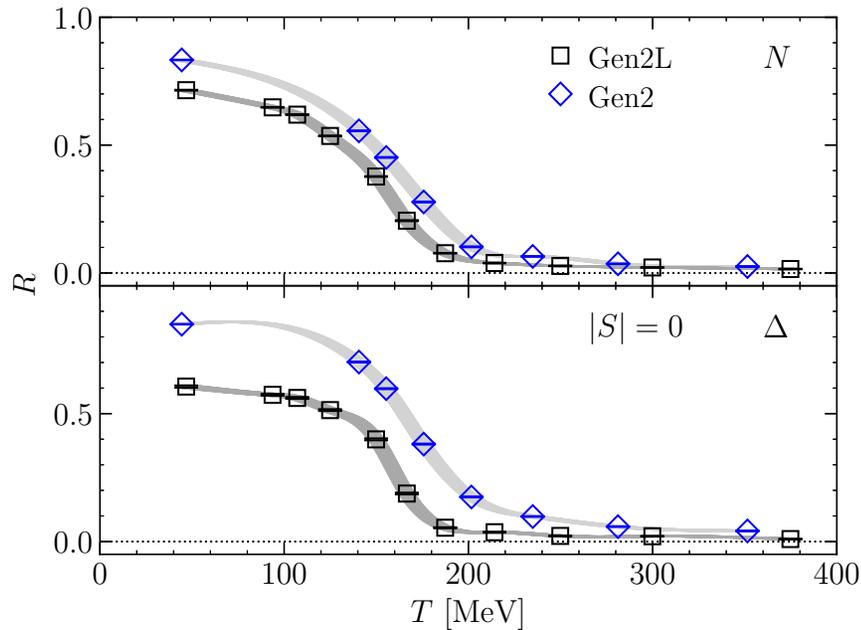
GA et al, PRD 92 (2015) 014503, JHEP 06 (2017) 034

PRD 99 (2019) 074503

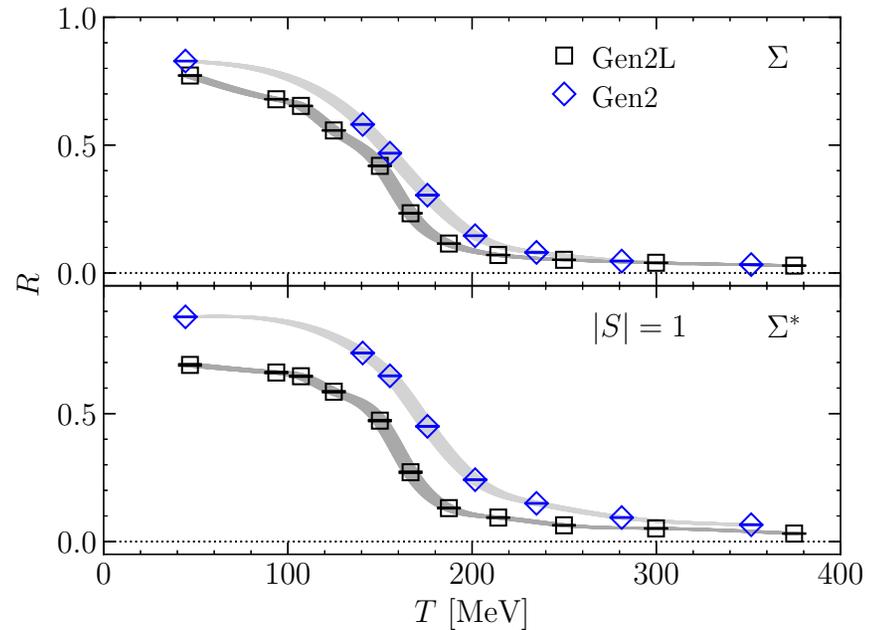
# Parity doubling for light baryons

quasi-order parameter for parity doubling  $R$

- constructed from euclidean baryonic lattice correlator
- $R = \mathcal{O}(1)$  in vacuum  $\Leftrightarrow R = 0$  with full chiral symmetry



$S = 0$



$S = -1$

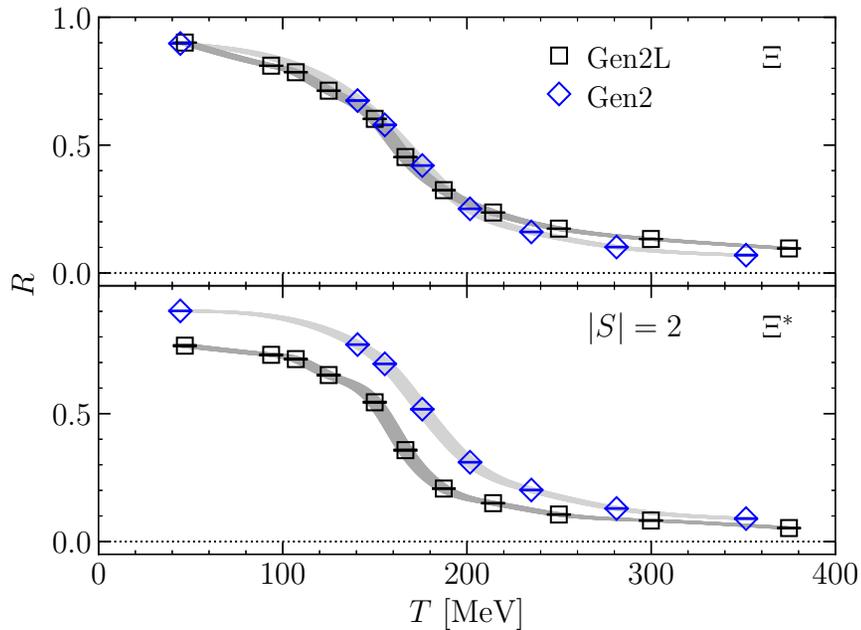
$T_{\text{infl}} \simeq 169 \text{ MeV}$  (Gen 2)

$\simeq 159 \text{ MeV}$  (Gen 2L)

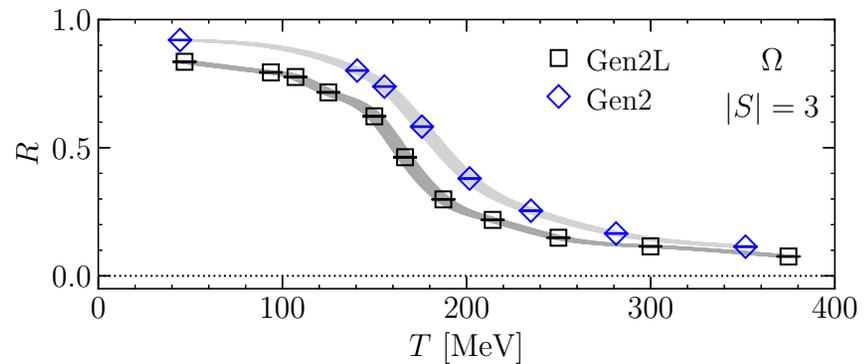
# Parity doubling for light baryons

quasi-order parameter for parity doubling  $R$

- constructed from euclidean baryonic lattice correlator
- $R = \mathcal{O}(1)$  in vacuum  $\Leftrightarrow R = 0$  with full chiral symmetry



$$S = -2$$



$$S = -3$$

Gen 2L: essentially no strangeness dependence in  $T_{\text{inf}}$

# Masses of pos/neg parity groundstates

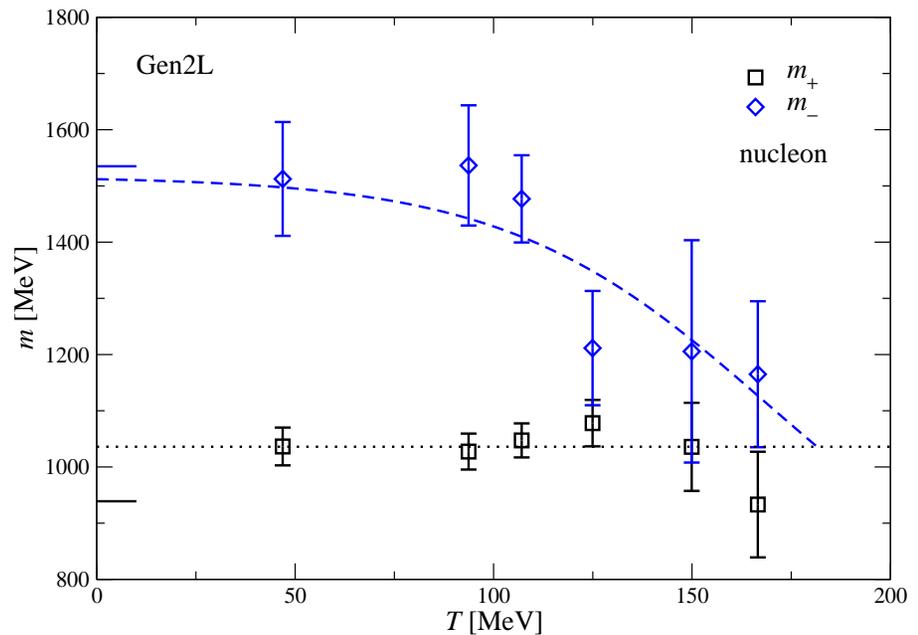
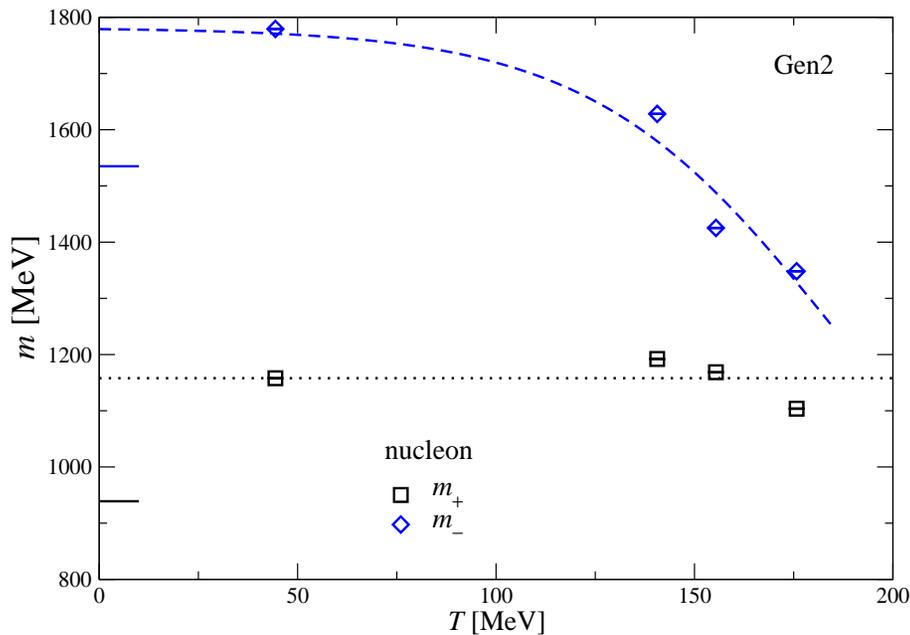
physics in the hadron gas: medium-dependent baryon masses

- relevant for heavy-ion phenomenology
- strongly interacting hadronic gas
- after hadronisation but before freezeout

in hadronic phase:

extract masses using conventional methods

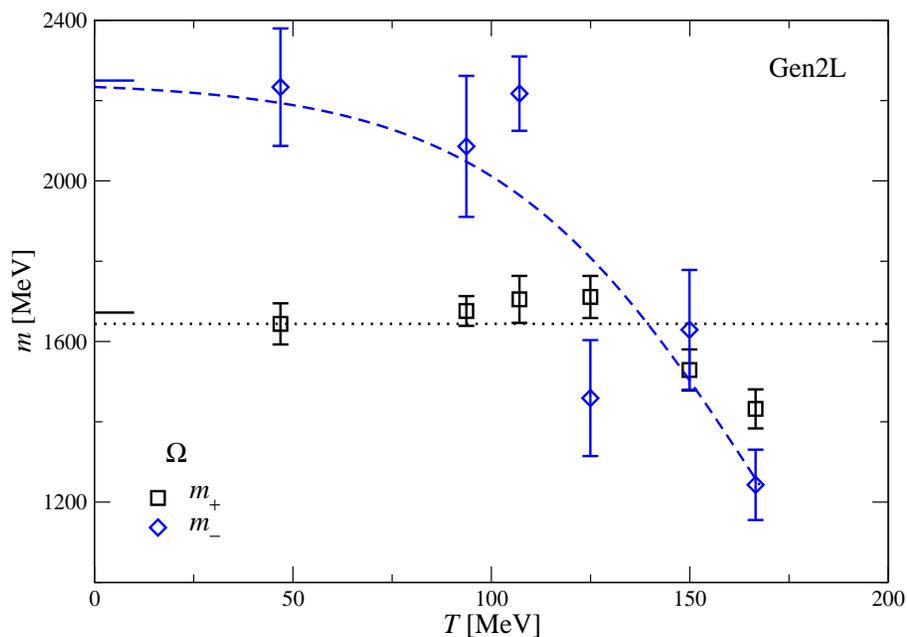
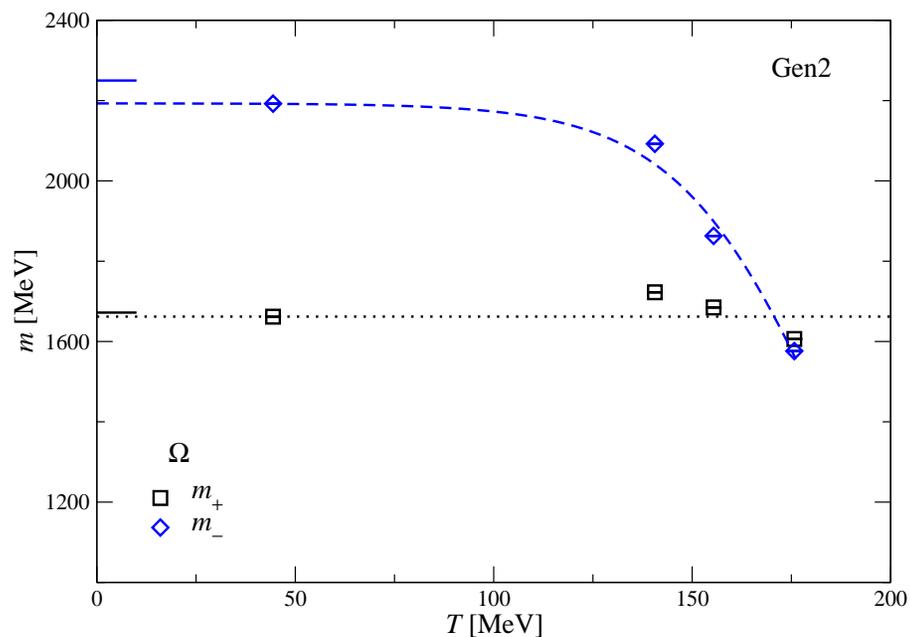
# Nucleons in the hadronic phase: Gen2 vs Gen2L



in Gen2L:

- masses at  $T = 0$  closer to PDG values
- error bars substantially larger
- nevertheless, pos-parity masses nearly  $T$  independent
- neg-parity masses reduced as  $T$  increases

# $\Omega$ in the hadronic phase: Gen2 vs Gen2L



in Gen2L:

- strange quark mass already close to physical value
- error bars substantially larger
- nevertheless, pos-parity masses nearly  $T$  independent
- neg-parity masses reduced as  $T$  increases

# Summary

- FASTSUM anisotropic  $N_f = 2 + 1$  ensembles
- towards physical quark masses
- properties of the chiral crossover with Wilson fermions

Generation 2  $\Rightarrow$  Generation 2L

$$m_\pi = 384(4) \text{ MeV} \Rightarrow 236(2) \text{ MeV}$$

- shift of pseudocritical temperatures to lower values (as expected) from a wide range of observables linked to chiral symmetry
- consistent with twisted mass fermions
- baryonic spectrum in hadronic phase, in-medium effects