QCD phase transition for various number of flavours

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A.Yu. Kotov, M.P. Lombardo and A. Trunin, *Phys.Lett.B* 823 (2021) 136749
A.Yu. Kotov, M.P. Lombardo and A. Trunin, *Symmetry* 13 (2021) 10, 1833

Outline

- QCD phase transition from $N_f=2$ till the onset of conformal window
- $N_f=2+1$ with strange quark mass as an interpolator between $N_f=2$ and $N_f=3$
- $N_f=2+1+1$(physical strange and charm, various m_π)
  - scaling behaviour
  - new order parameter
  - thresholds in QGP

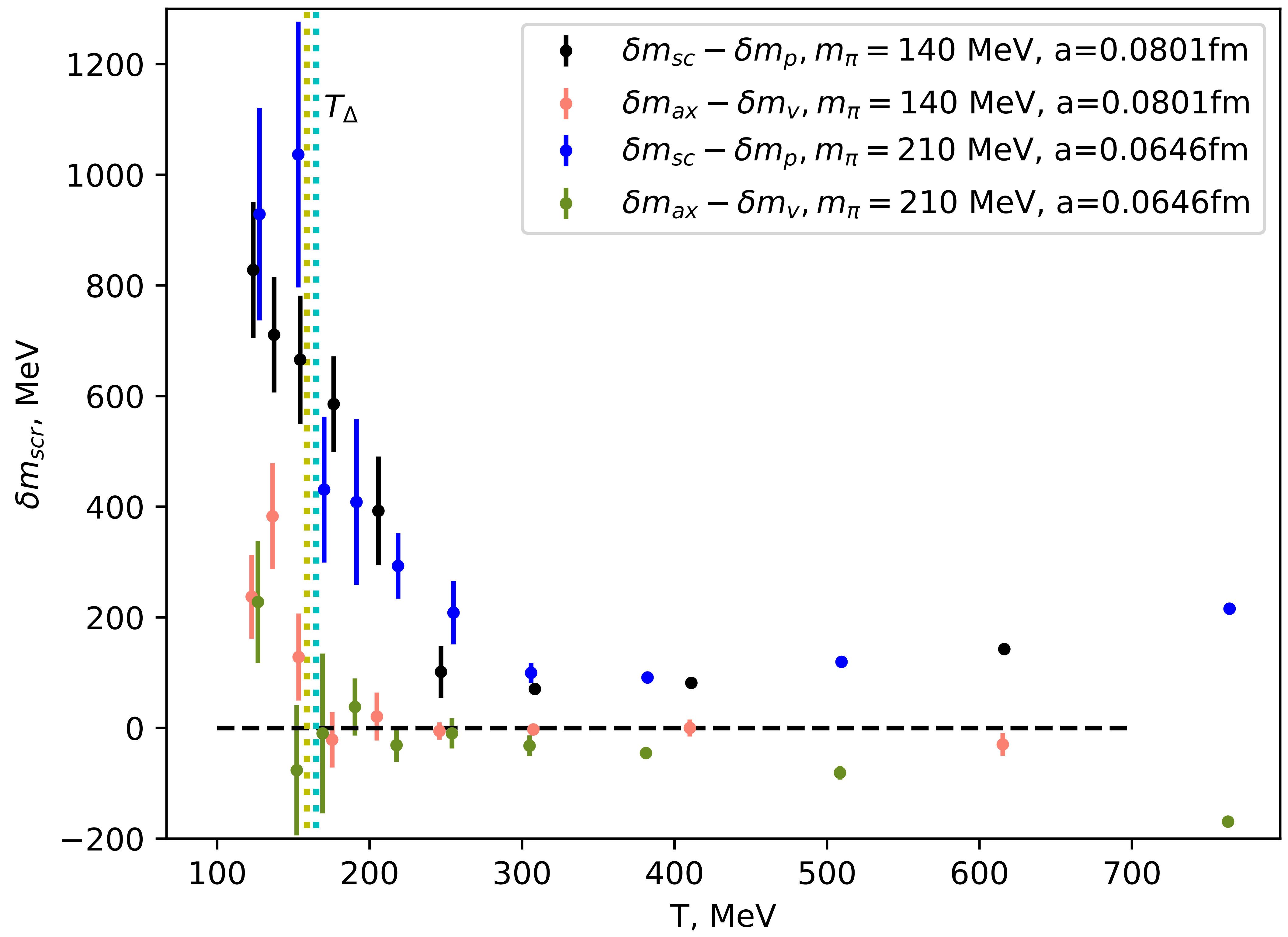
Symmetries of QCD

$$L_{\text{QCD}} = \bar{\psi}_L \not{D} \psi_L + \bar{\psi}_R \not{D} \psi_R + m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) + \text{gauge part}$$

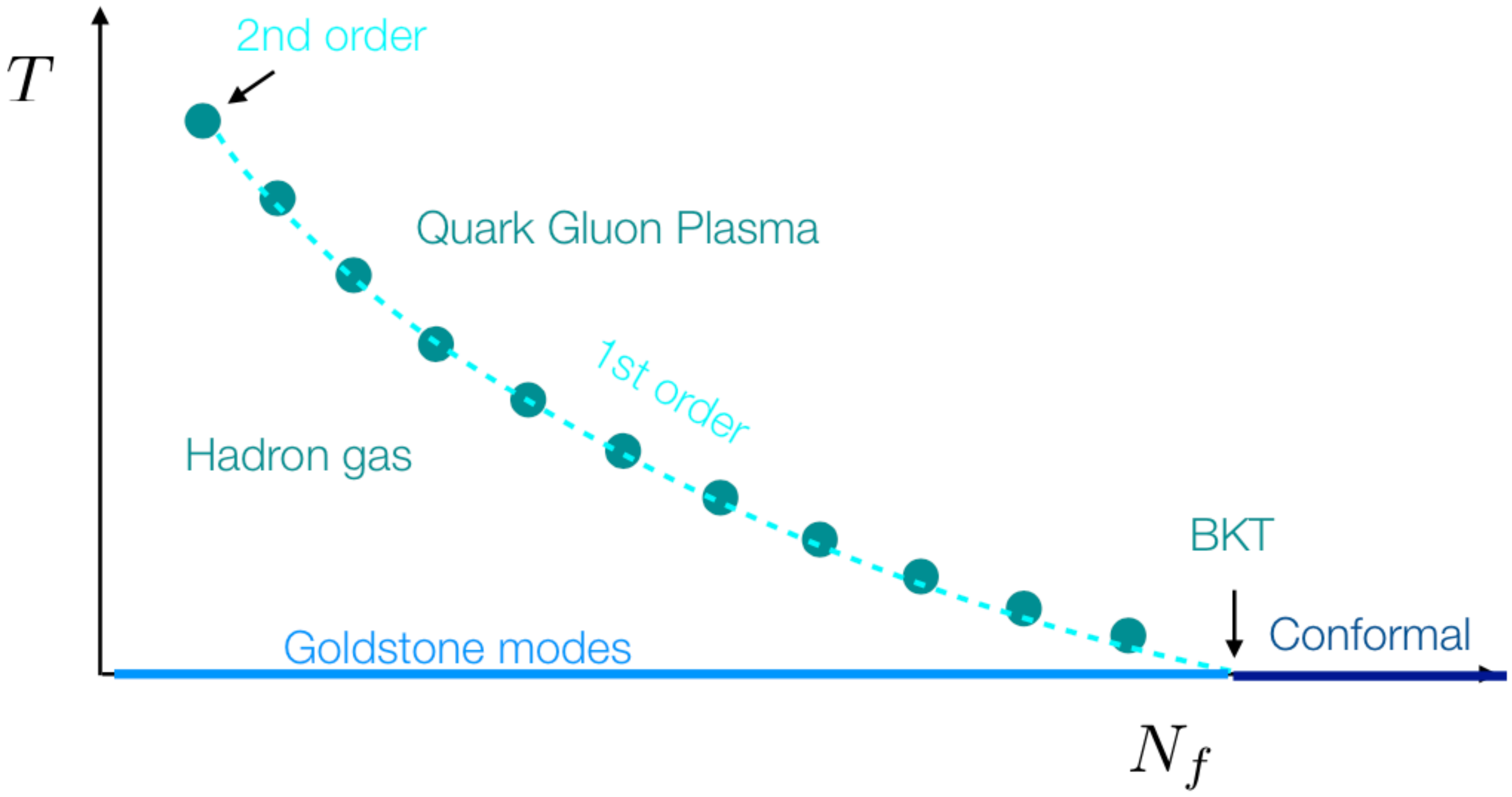
Symmetry at m=0: $SU_L(N) \times SU_R(N) \times U_V(1) \times U_A(1)$

Spontaneously broken to $SU_V(N)$ — Baryon number — Broken by anomaly

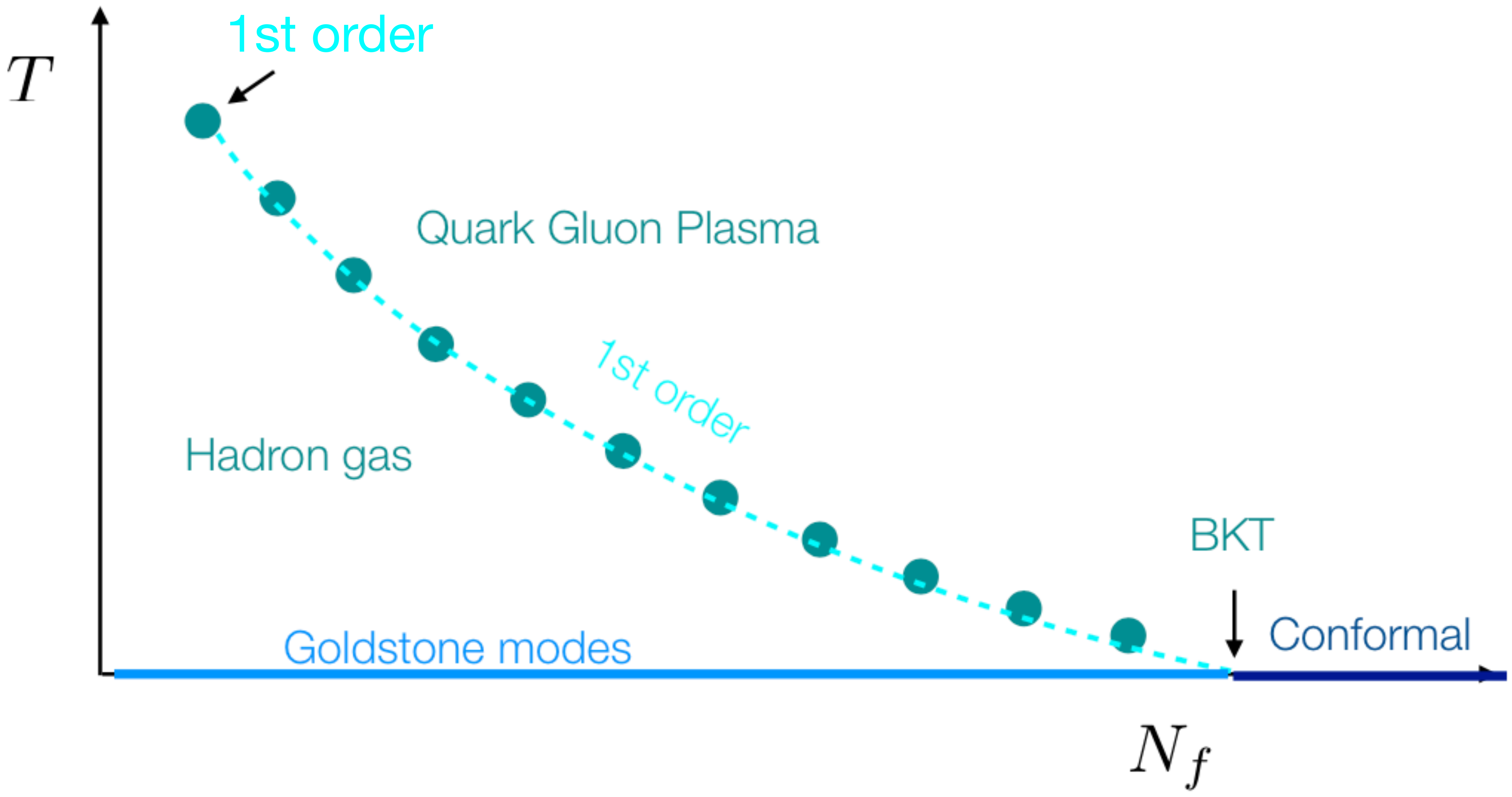
- Imprint on hadron spectrum
  - Goldstone bosons
  - Symmetry partners
- Restoration at finite temperature
- Nature of the QCD phase transition for various N



Scenarios for thermal phase transition

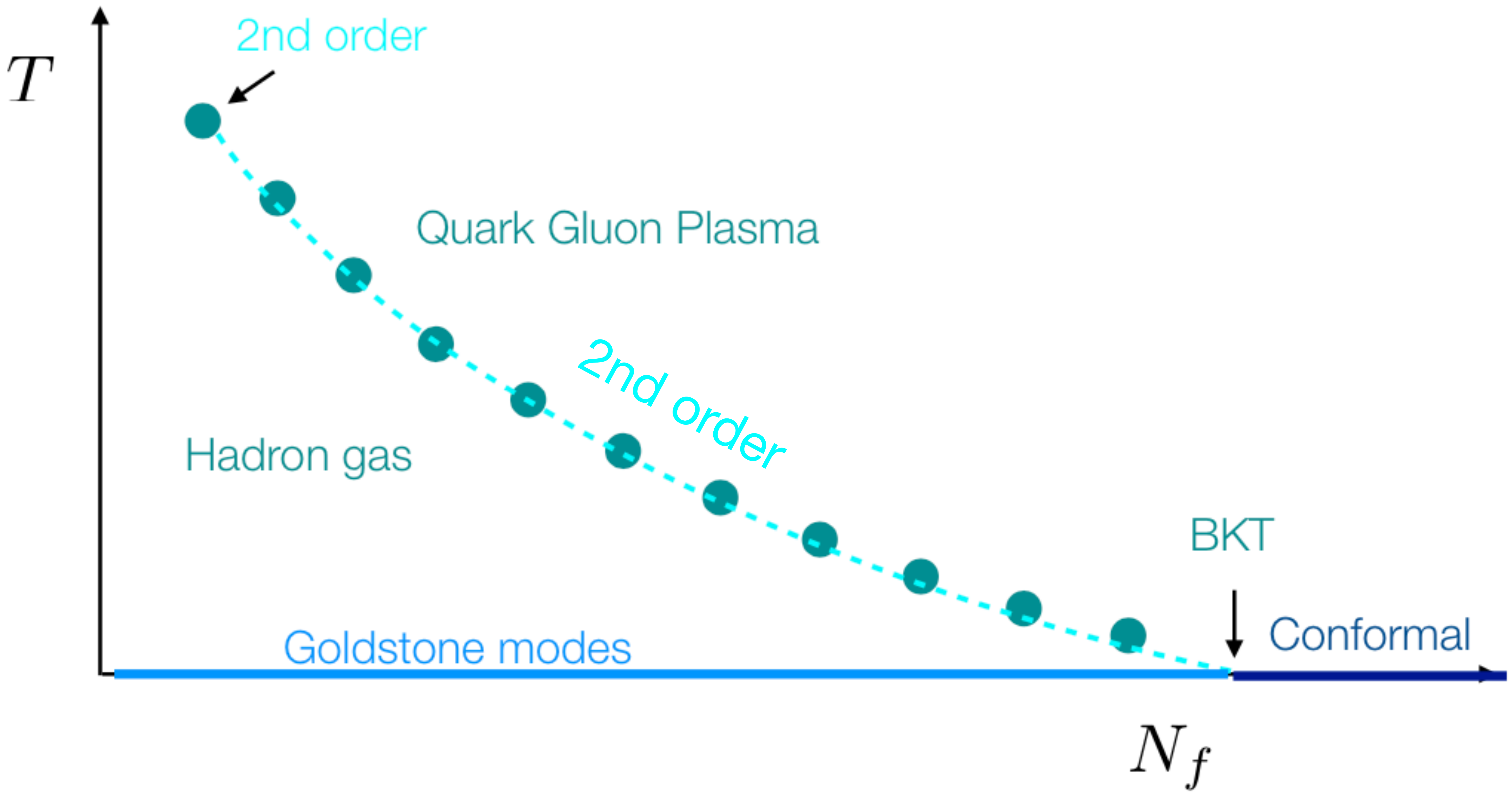


Scenarios for thermal phase transition



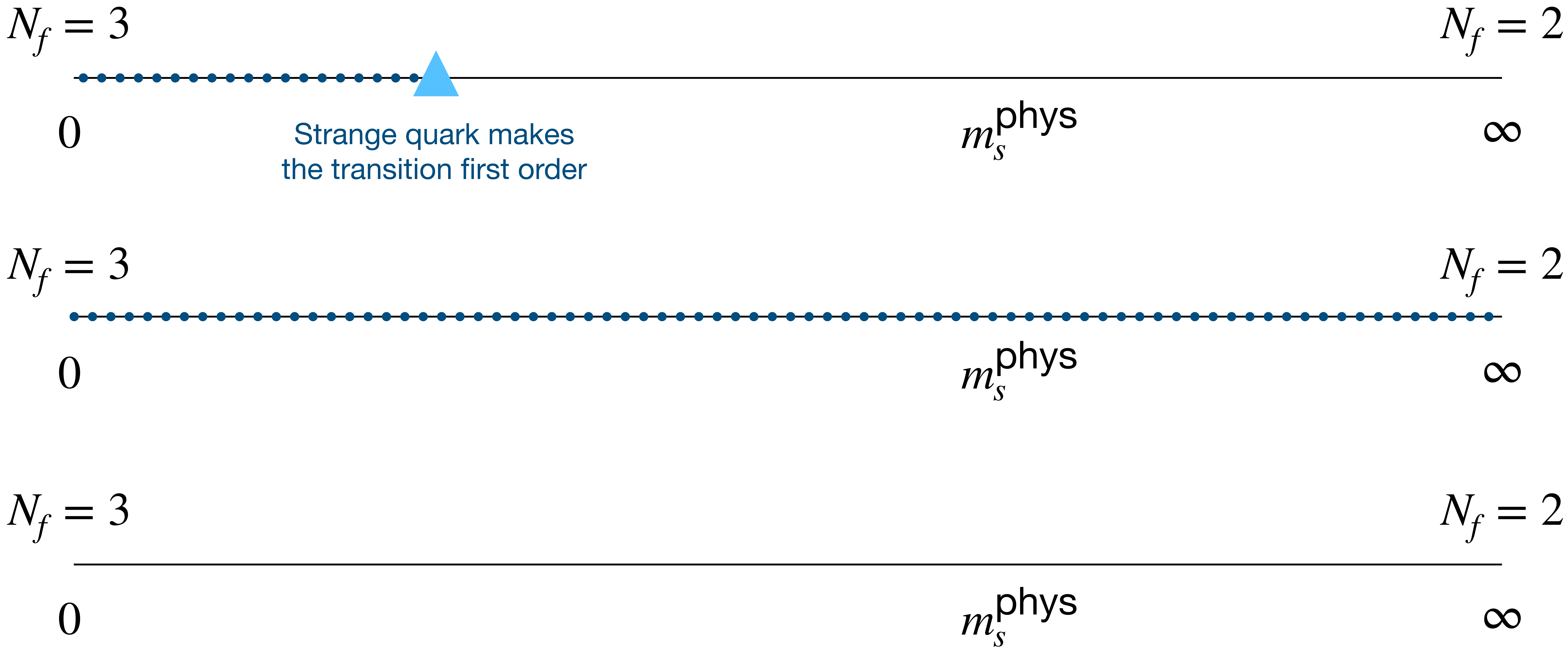
Scenarios for thermal phase transition

[Cuteri, Philipsen, Sciarra, 2021]

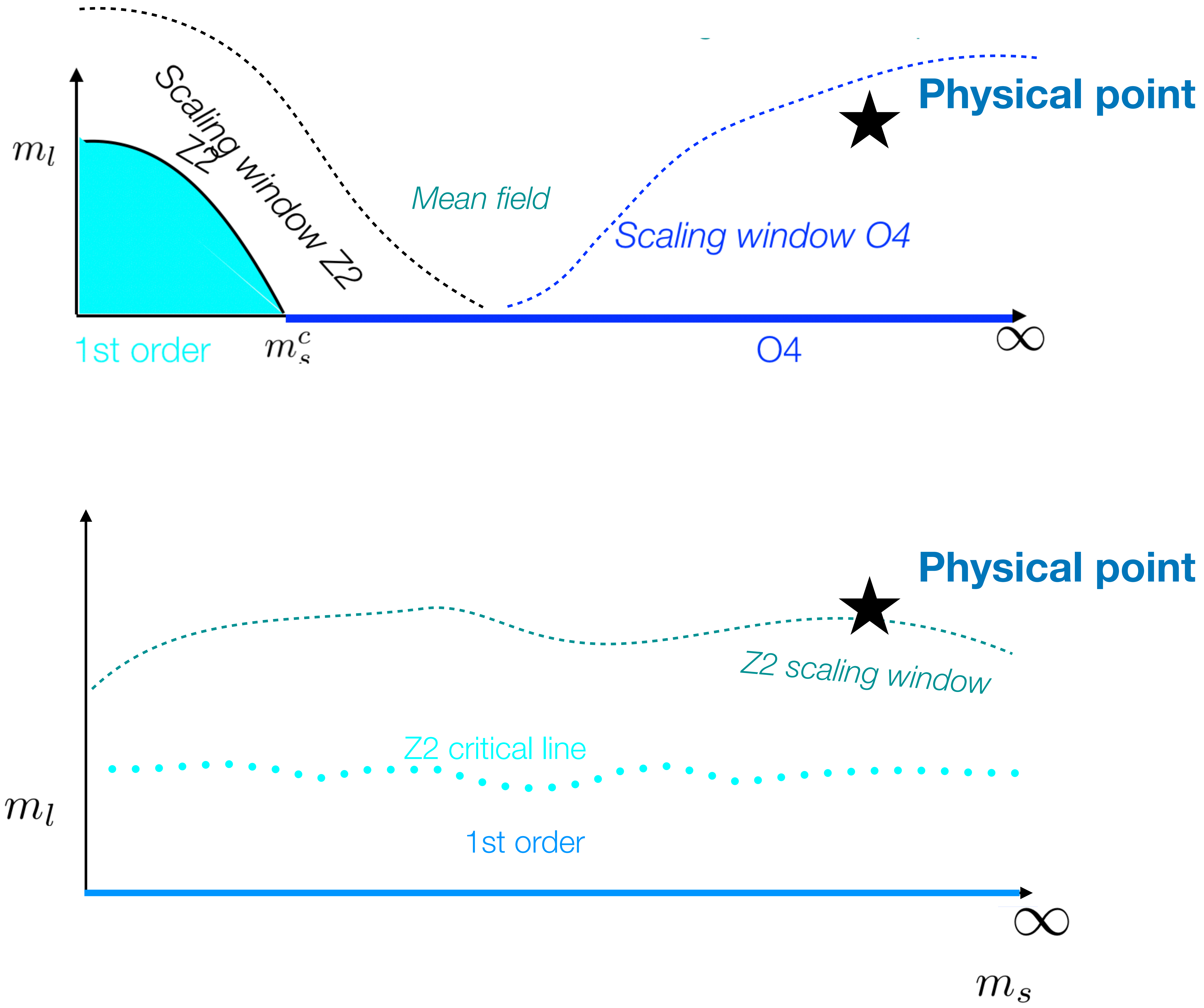


Between Nf=2 and Nf=3

Strange quark mass as an interpolator



Scaling windows



Our ensembles

$N_f = 2 + 1 + 1$ Wilson twisted mass fermions

$m_\pi^{\text{phys}} < m_\pi < 380$ MeV

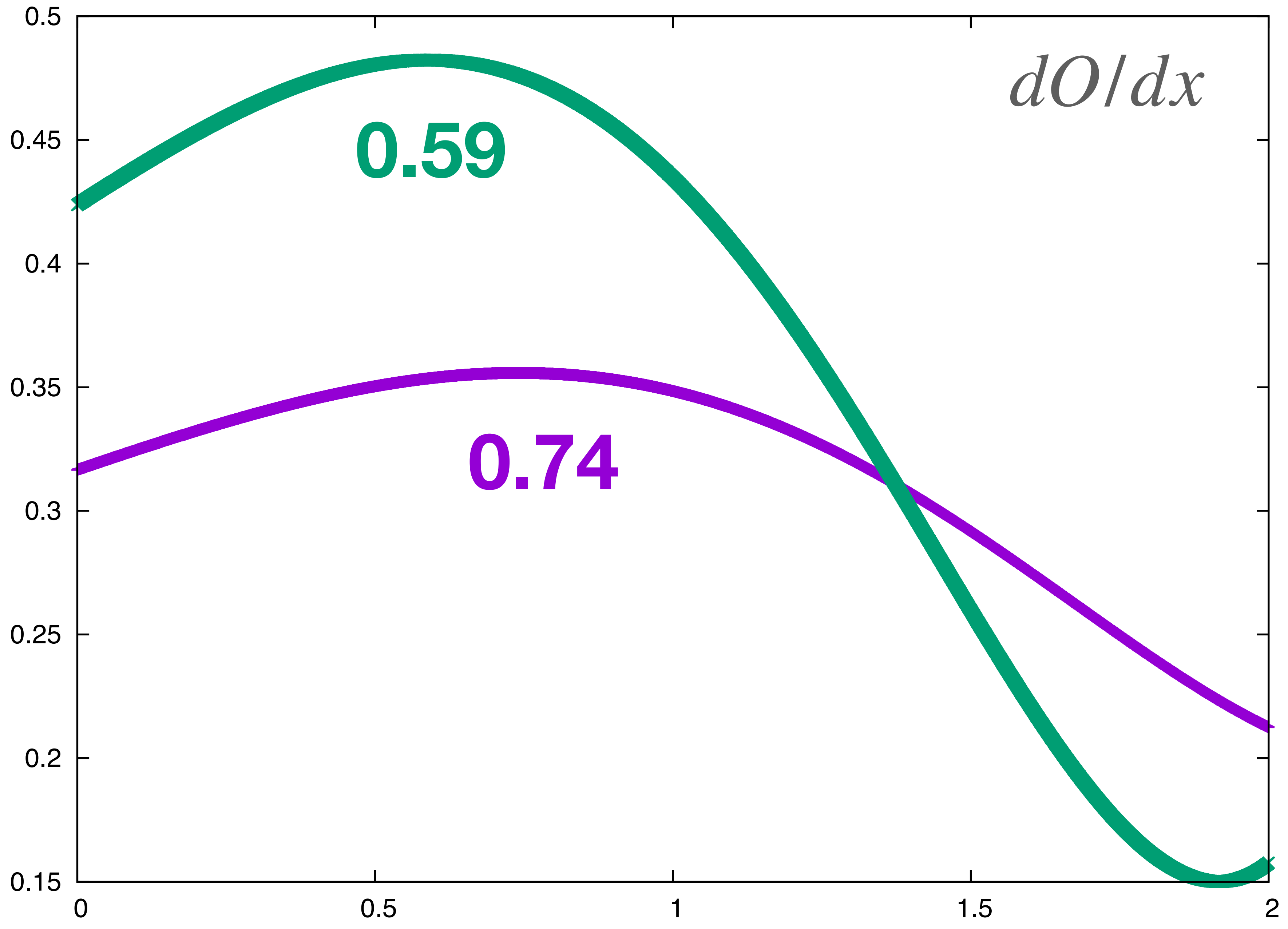
0.06 fm $\lesssim a \lesssim 0.08$ fm

Fixed scale approach $a =$ const

m_π [MeV]	**a [fm]**
139.7(3)	0.0801(4)
225(5)	0.0619(18)
383(11)	0.0619(18)
376(14)	0.0815(30)

New order parameter

- Chiral condensate $\langle\bar{\psi}\psi\rangle$ has large linear in m contributions (divergence, regular)
- $\langle\bar{\psi}\psi\rangle_3 = \langle\bar{\psi}\psi\rangle - m\chi$ is free from linear terms in mass [W. Unger, 2010]
- **EoS**: $\langle\bar{\psi}\psi\rangle = Ah^{1/\delta}f(x) + \ldots, \quad h \equiv m, \quad x = t/h^{1/\beta\delta}$



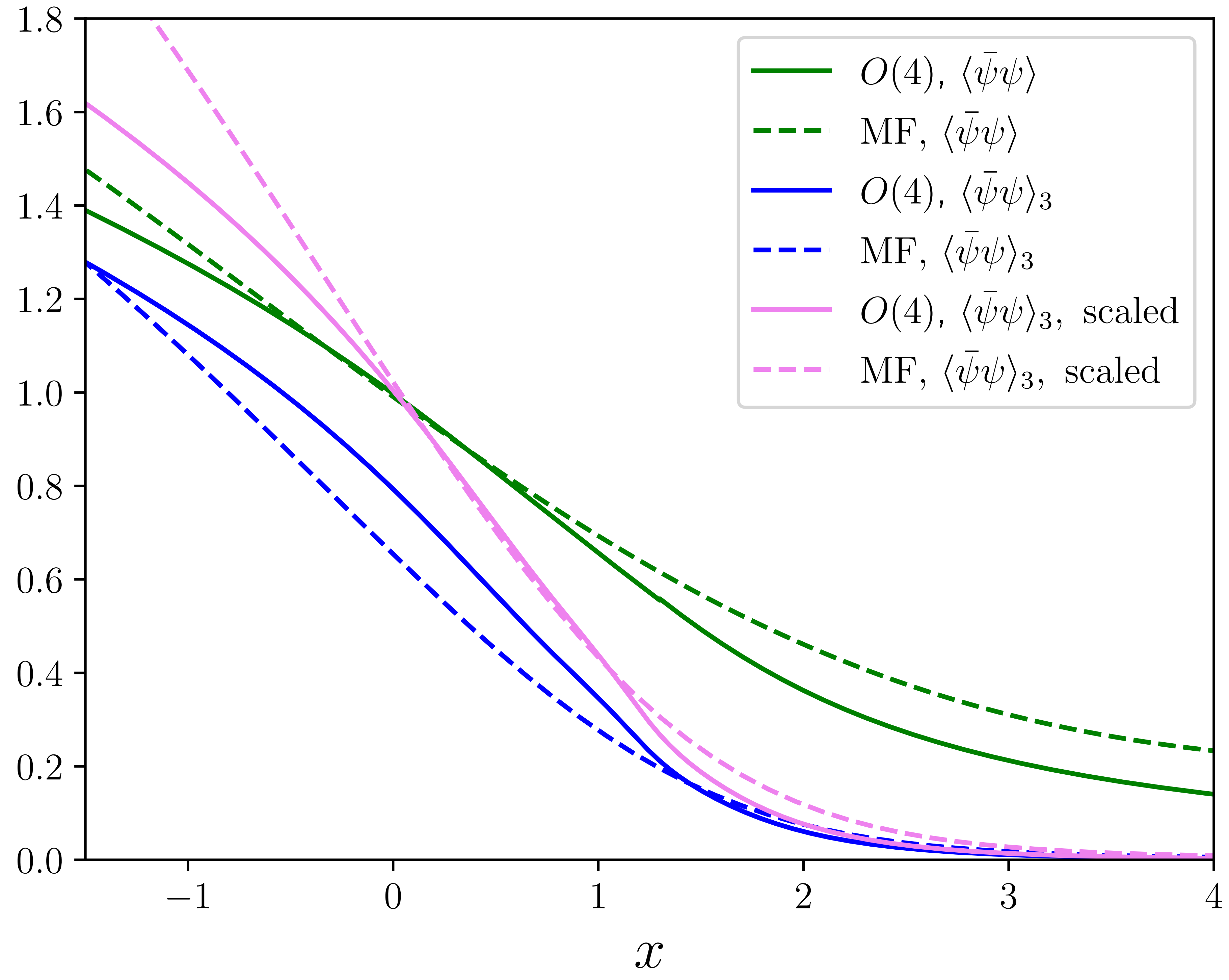
Observable	χ	$\bar{\psi}\psi$	O
k_s	1.35(3)	0.74(4)	0.59(1)

$$T_c = T_0 + Ak_s m_\pi^{2/\beta\delta}$$

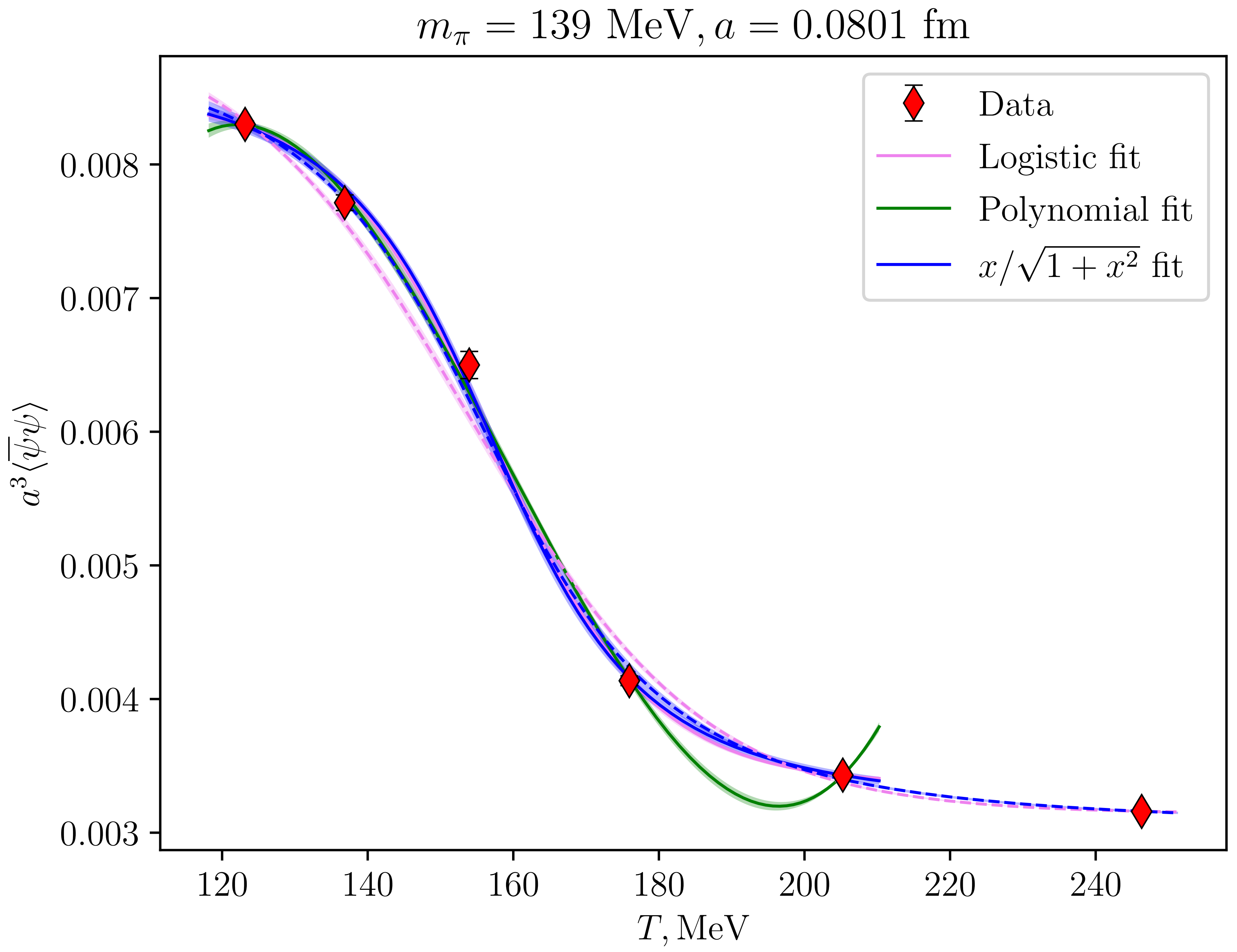
New order parameter

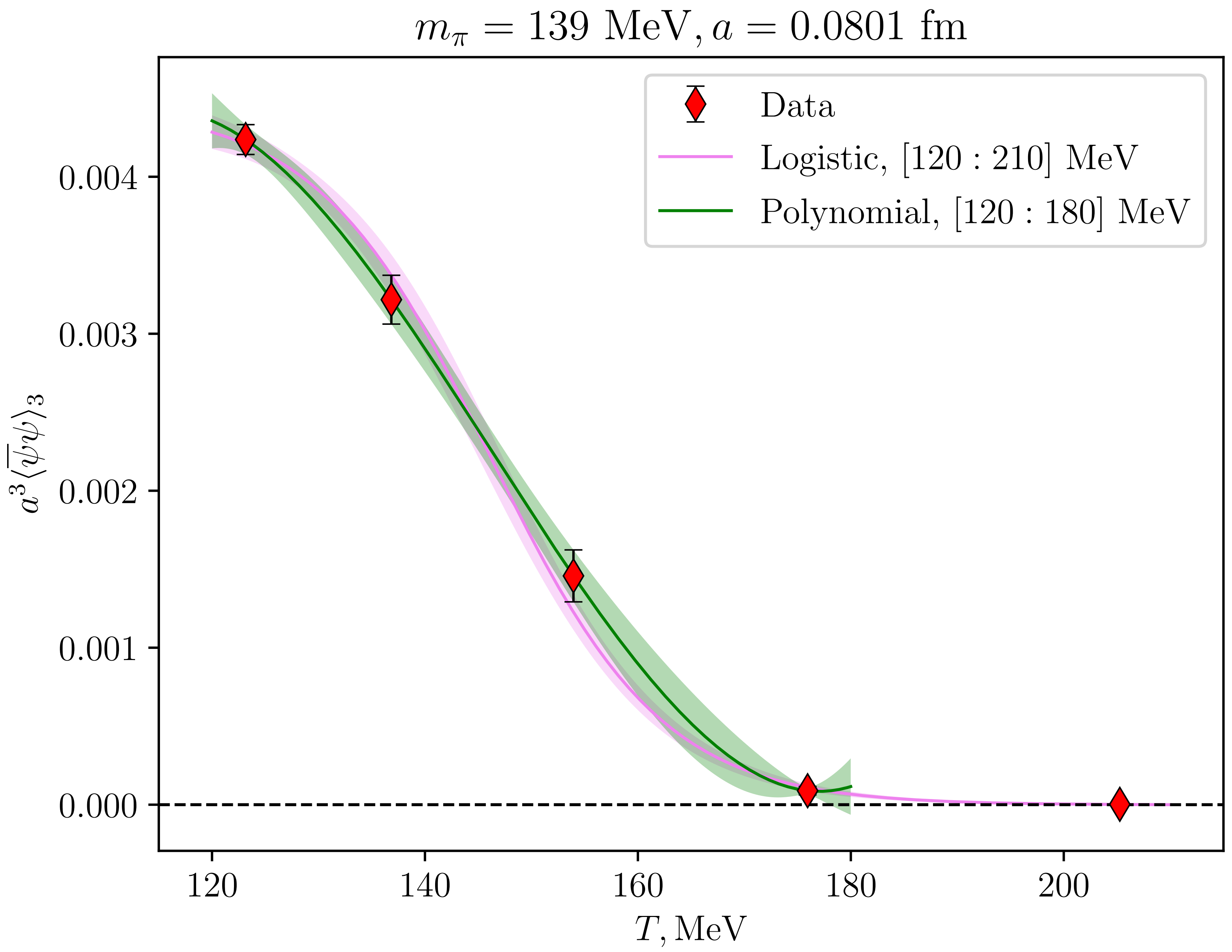
New order parameter: $\langle\bar{\psi}\psi\rangle_3 = \langle\bar{\psi}\psi\rangle - m\chi$

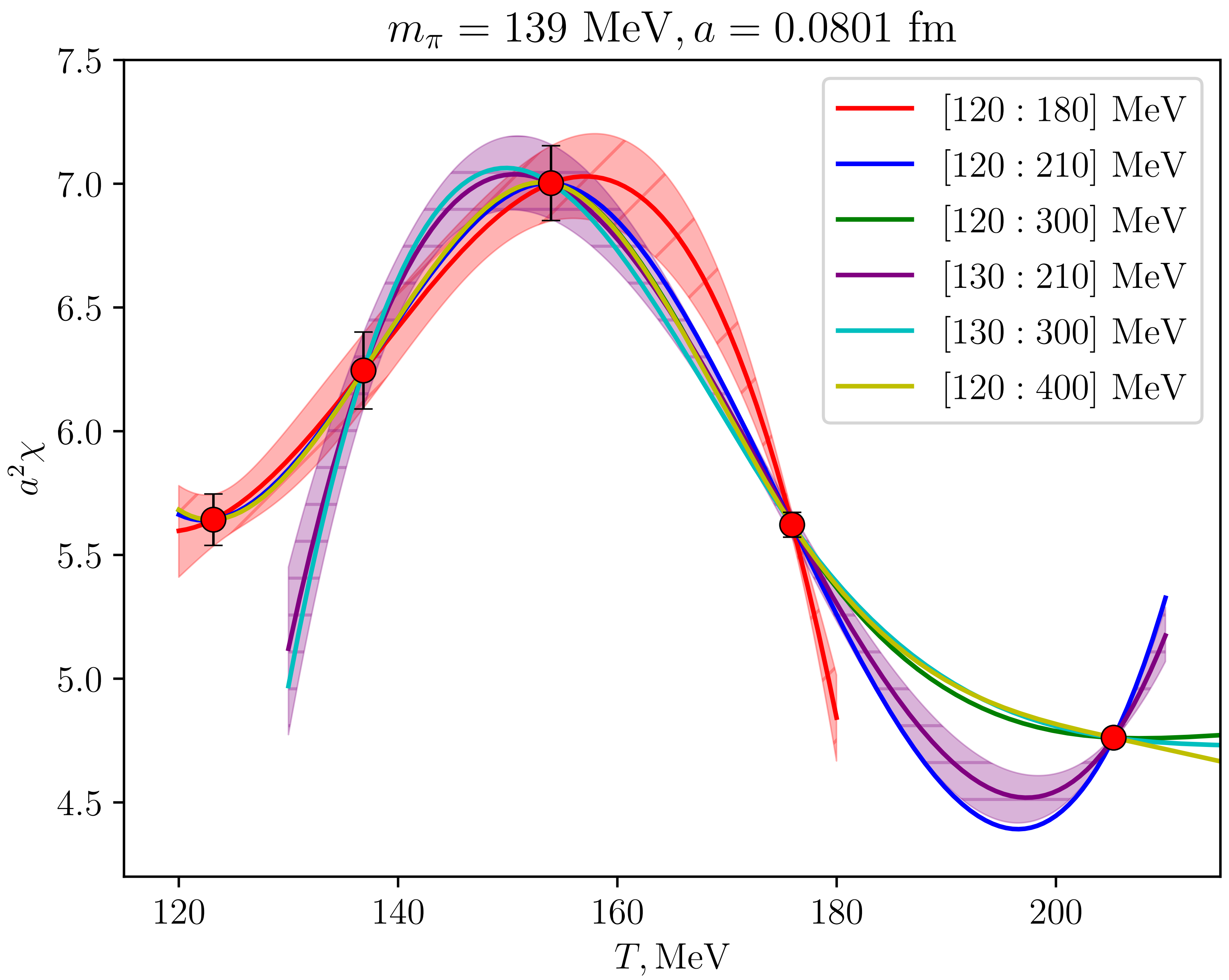
- terms $\sim m$ cancel: divergences/regular
- $\sim m^3$ (symmetric phase)
- $\langle\bar{\psi}\psi\rangle_3 \sim t^{-\gamma-2\beta\delta}$ vs $\langle\bar{\psi}\psi\rangle \sim t^{-\gamma}$ as $t \to \infty$



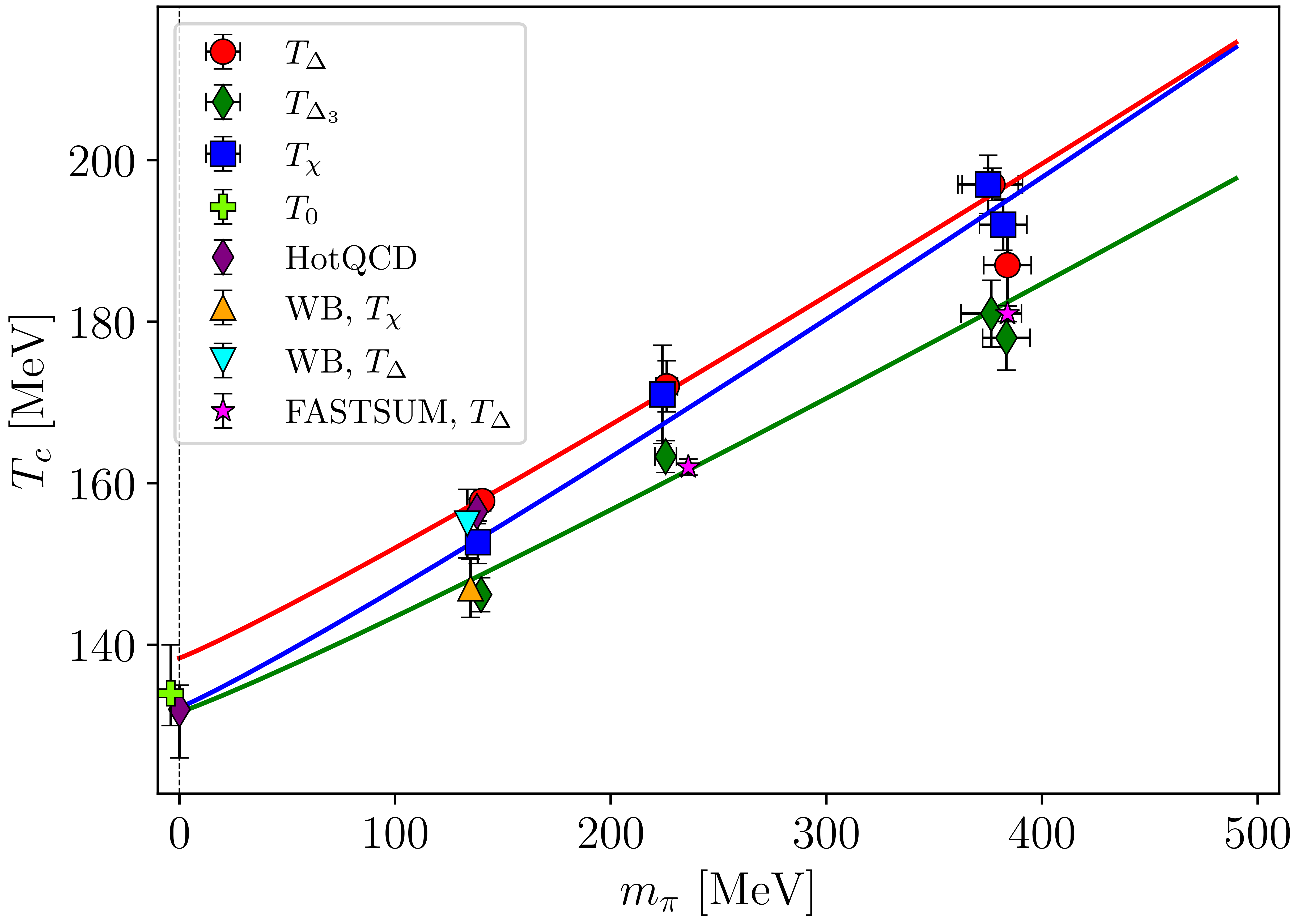
Physical pion mass







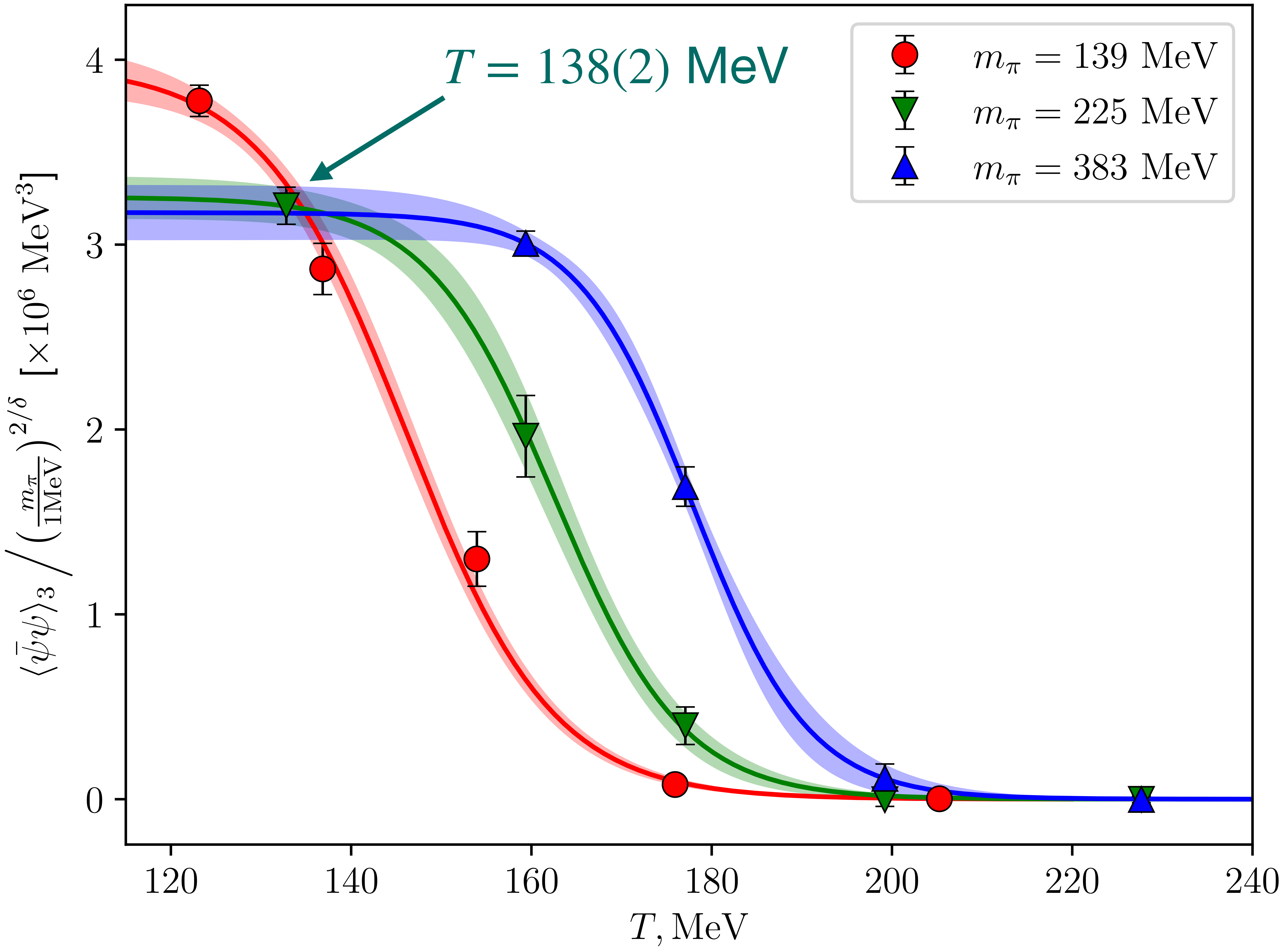
Critical temperature and chiral extrapolation



	$T(m_\pi = 139$ MeV) [MeV]	$T(m_\pi = 0)$ [MeV]
$\langle\bar\psi\psi\rangle$	157.8(12)	138(2)
χ	153(3)	132(4)
$\langle\bar\psi\psi\rangle_3$	146(2)	132(3)

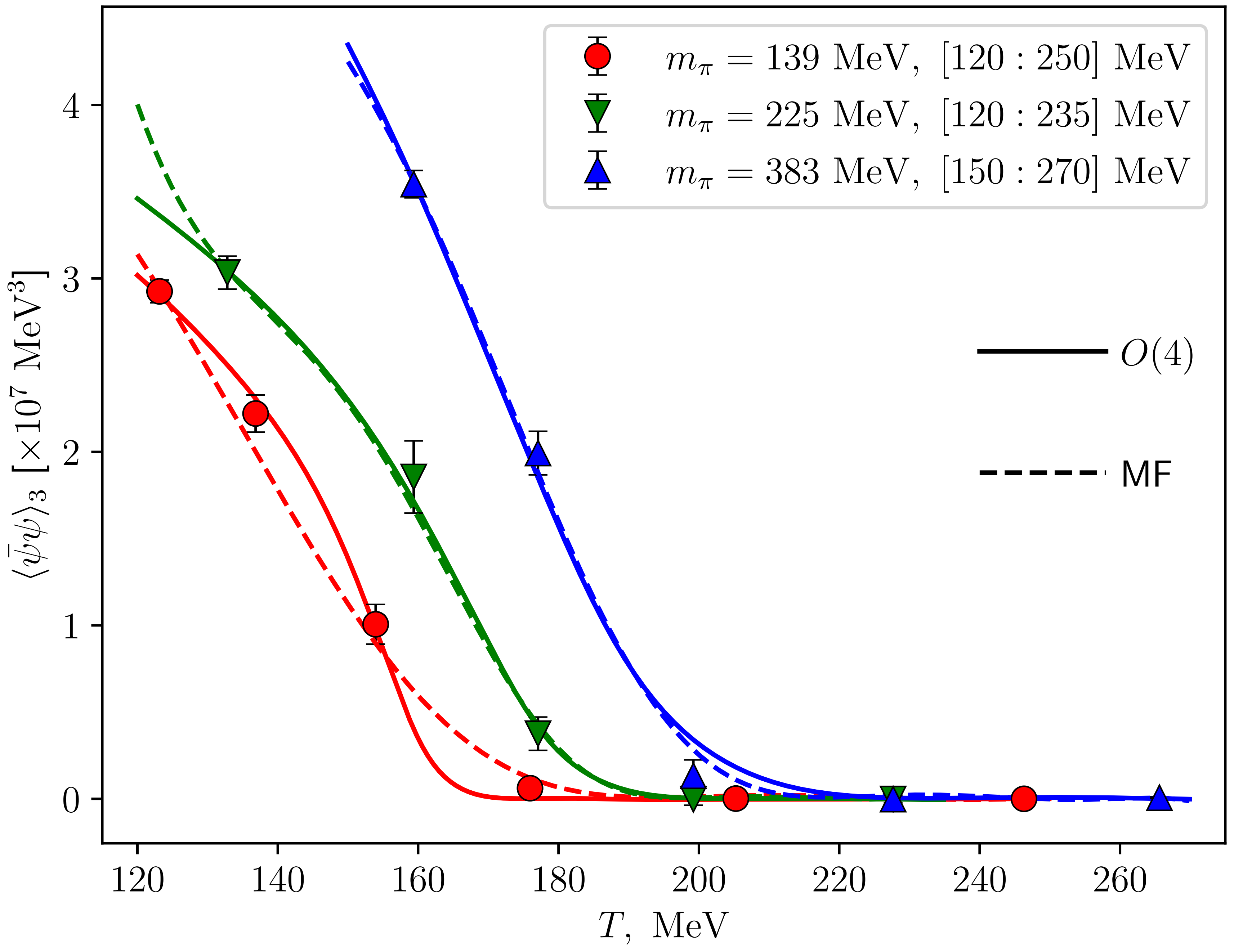
$$T_0 = 134^{+6}_{-4}\text{ MeV}$$

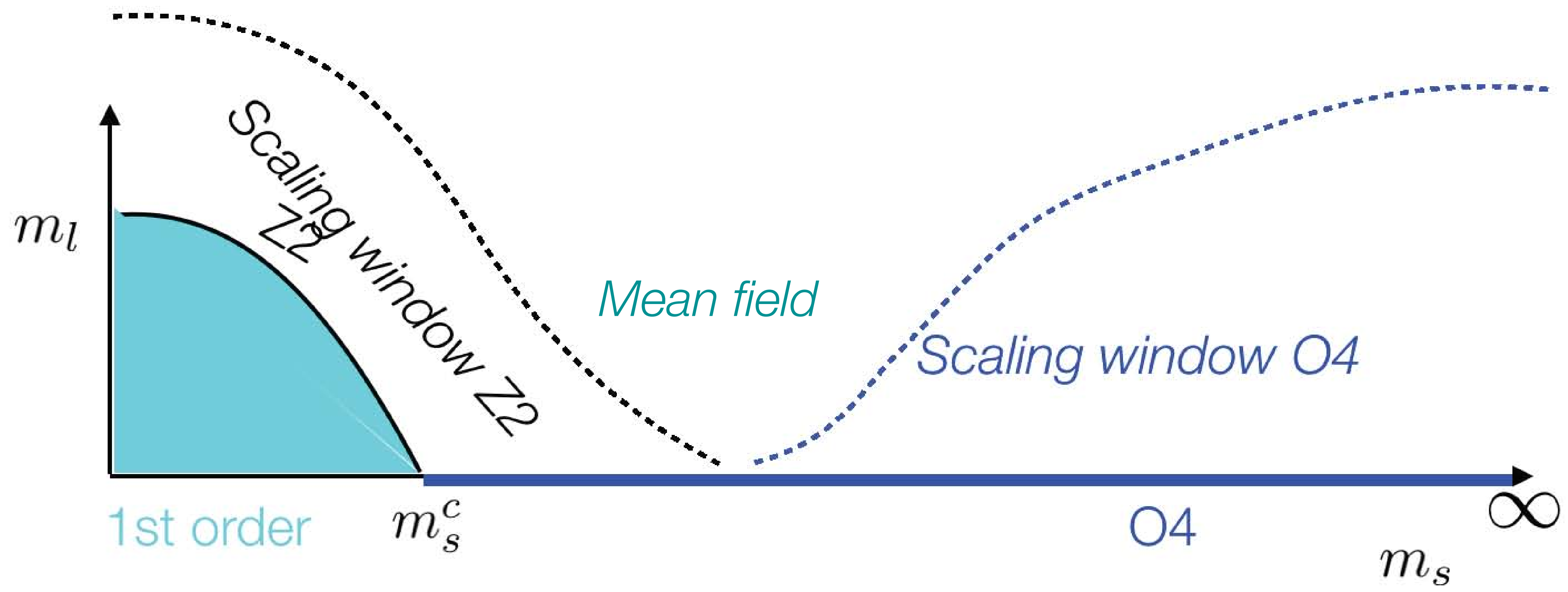
Scaling of $\langle \bar{\psi}\psi \rangle_3$



$$\frac{\langle \bar{\psi}\psi \rangle_3}{m^{1/\delta}} \sim \frac{\langle \bar{\psi}\psi \rangle_3}{m_\pi^{2/\delta}} = \text{const at t=0}$$

O(4) vs mean field

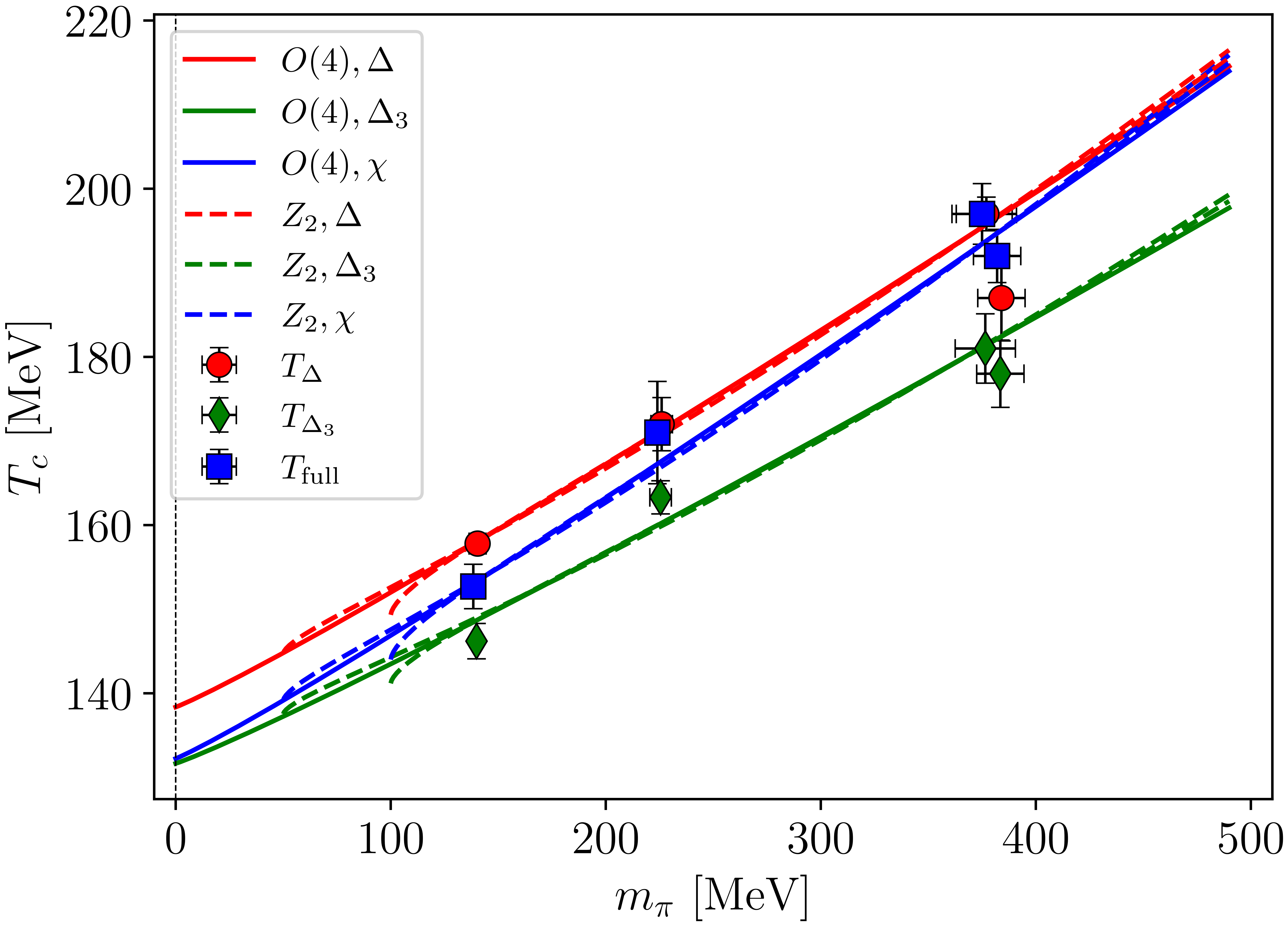




m_π [MeV]	T_0 [MeV]
139	142(2)
225	159(3)
383	174(2)

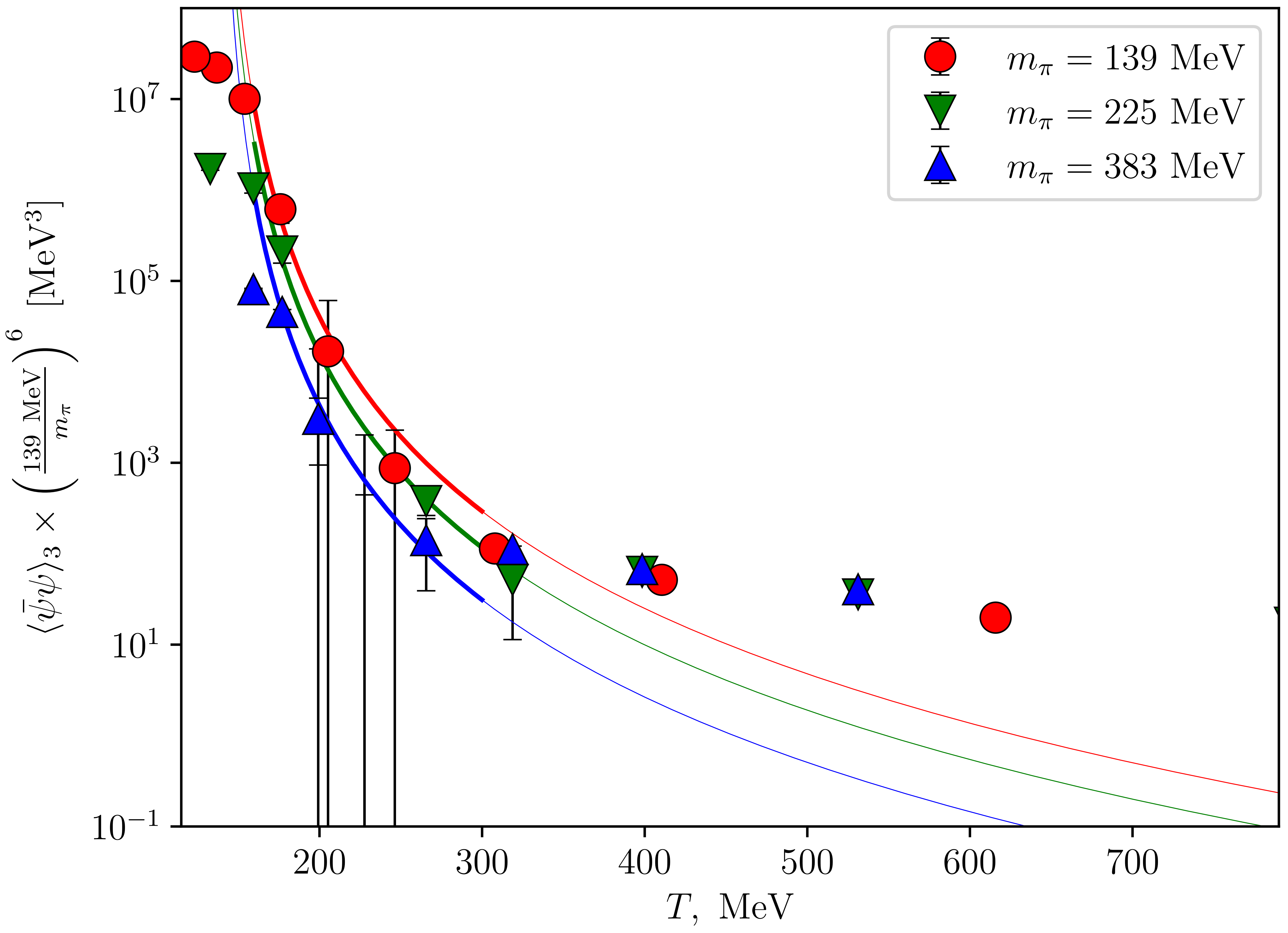
Mild tension between data and MF for m_π=139 MeV

Z_2 scaling



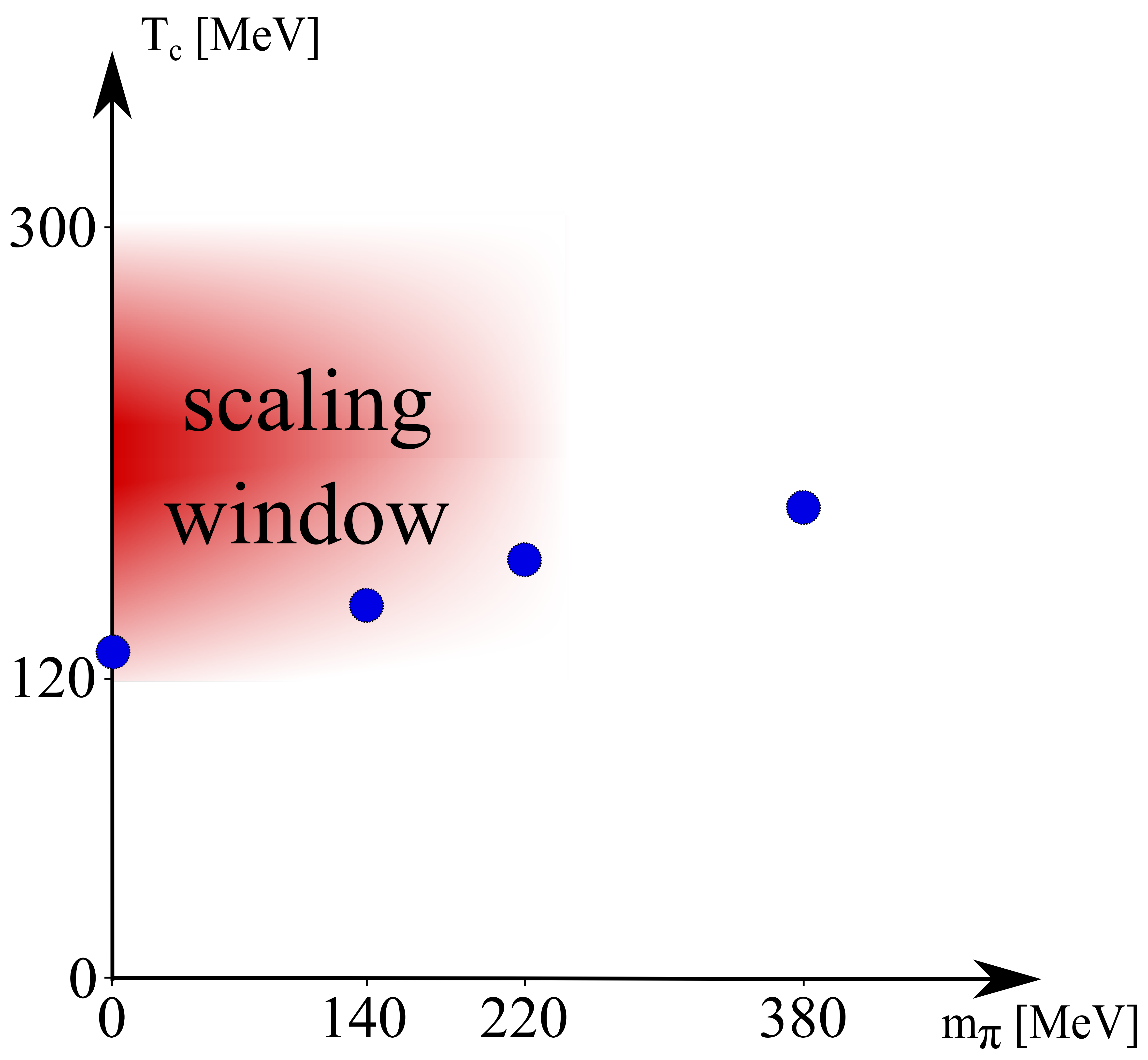
Can also describe data for $m_\pi^c \in [0, m_{\text{phys}}]$

Large temperature behaviour

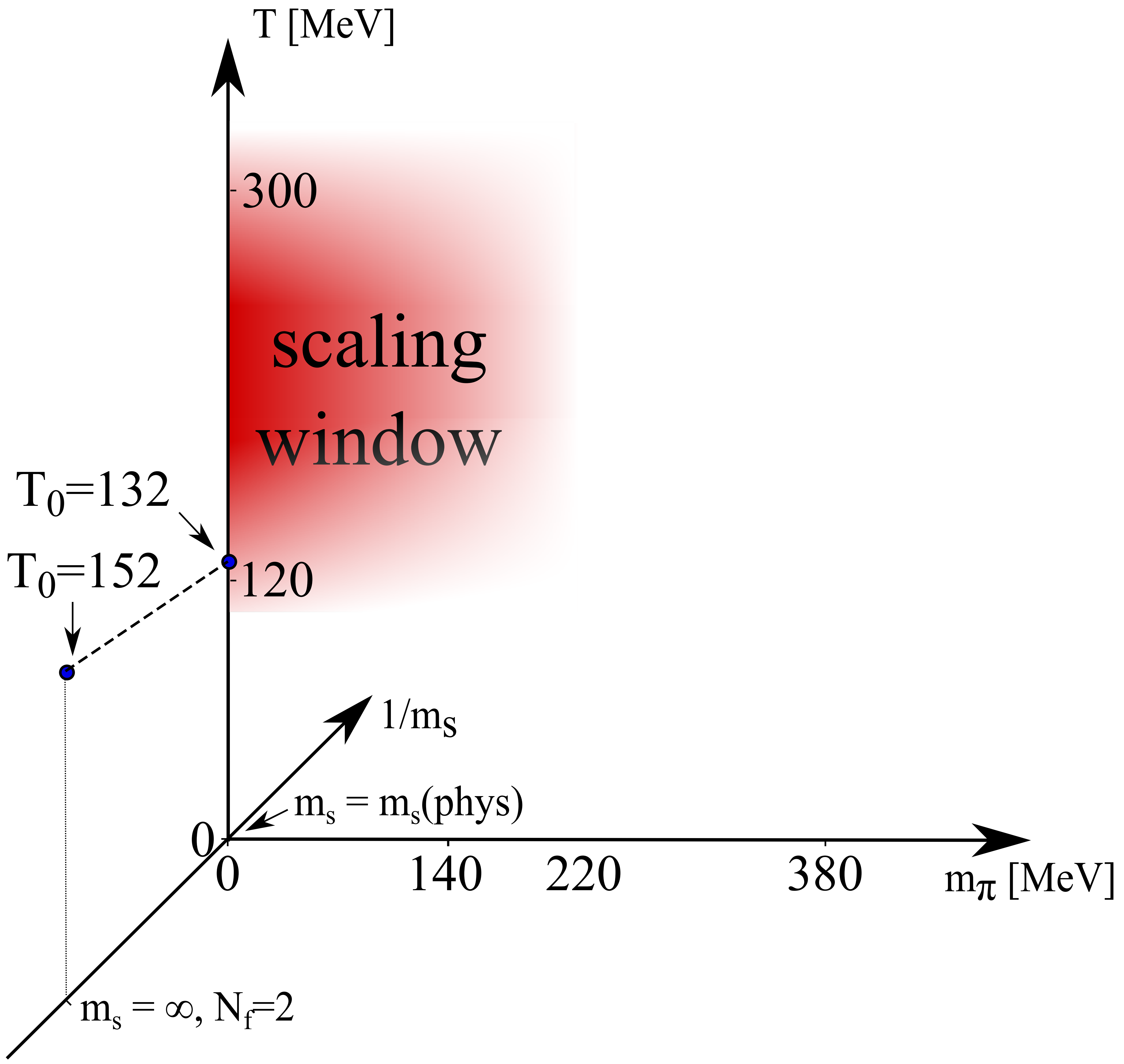


- O(4): $\langle\bar\psi\psi\rangle_3 \sim t^{-\gamma-2\beta\delta}$
- Griffith analyticity: $\langle\bar\psi\psi\rangle_3 \sim m^3 \sim m_\pi^6$
- $T \sim 300$ MeV

Sketch of possible phase diagram, 2D



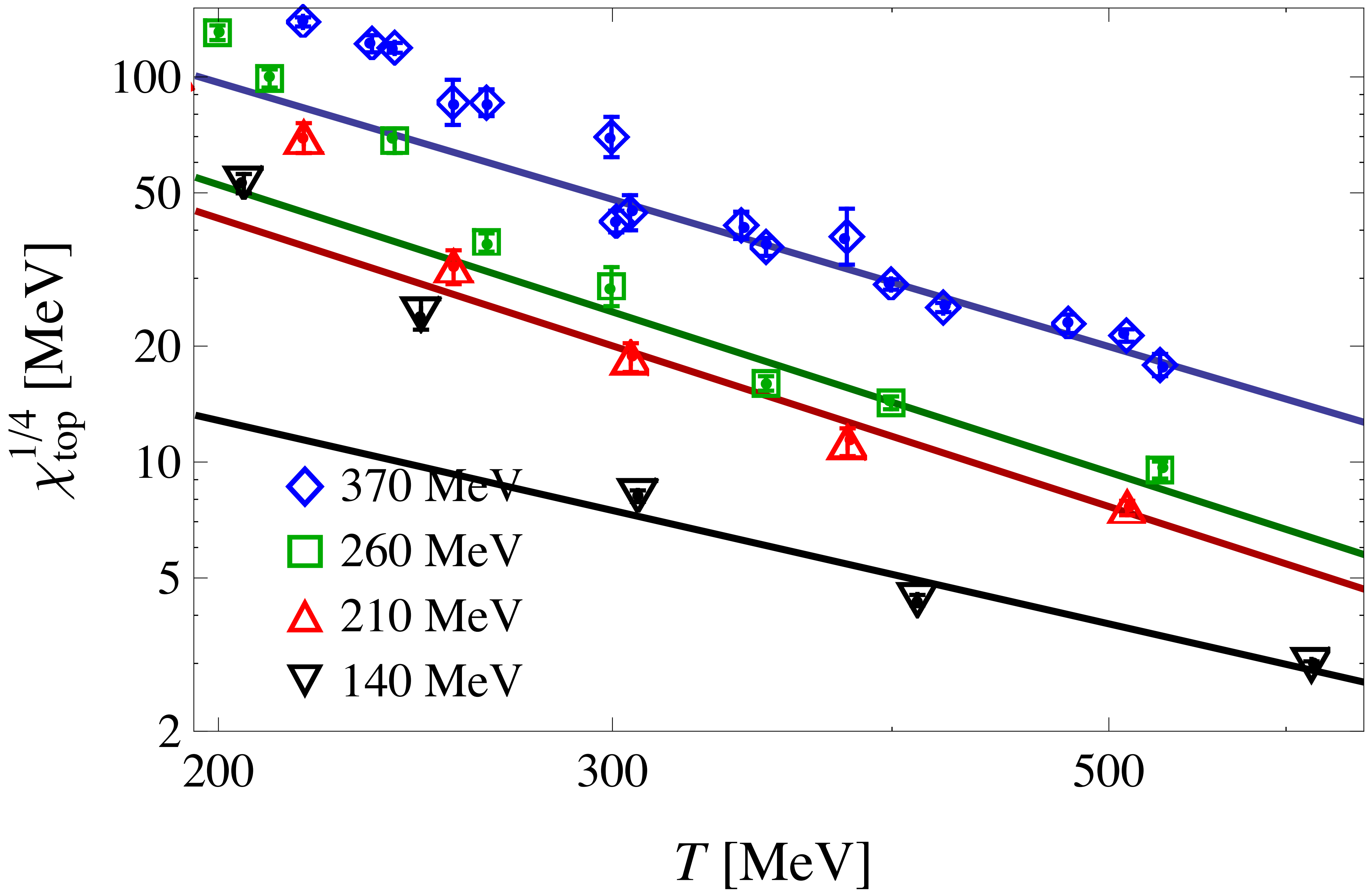
Sketch of possible phase diagram, 3D



Beyond the scaling behaviour

- $T \sim 300$ MeV: scaling behaviour ⇔ leading order Griffith analyticity
- Coincides with the onset of DIGA behaviour [Burger et al., 2018]
- Thresholds in QGP:

[Glozman, 2019][Alexandru, Horvath, 2019]
[Cardinali, D'Elia, Pasqui, 2021]



Conclusions

Consistency with O(4) scaling for light pions $m_\pi \lesssim m_\pi^{\text{phys}}$ and temperatures T<300 MeV
Order parameter $\langle\bar{\psi}\psi\rangle_3 = \langle\bar{\psi}\psi\rangle - m\chi$

$T = 134^{+6}_{-4}$ MeV in the chiral limit

From
- Scaling of pseudocritical temperatures
- Scaling of $\langle\bar{\psi}\psi\rangle_3$
- Fit to the Equation of State

T=300 MeV is close to the onset of DIGA behaviour, thresholds in QGP