

Thermal QCD phase transition and its scaling window from Wilson twisted mass fermions



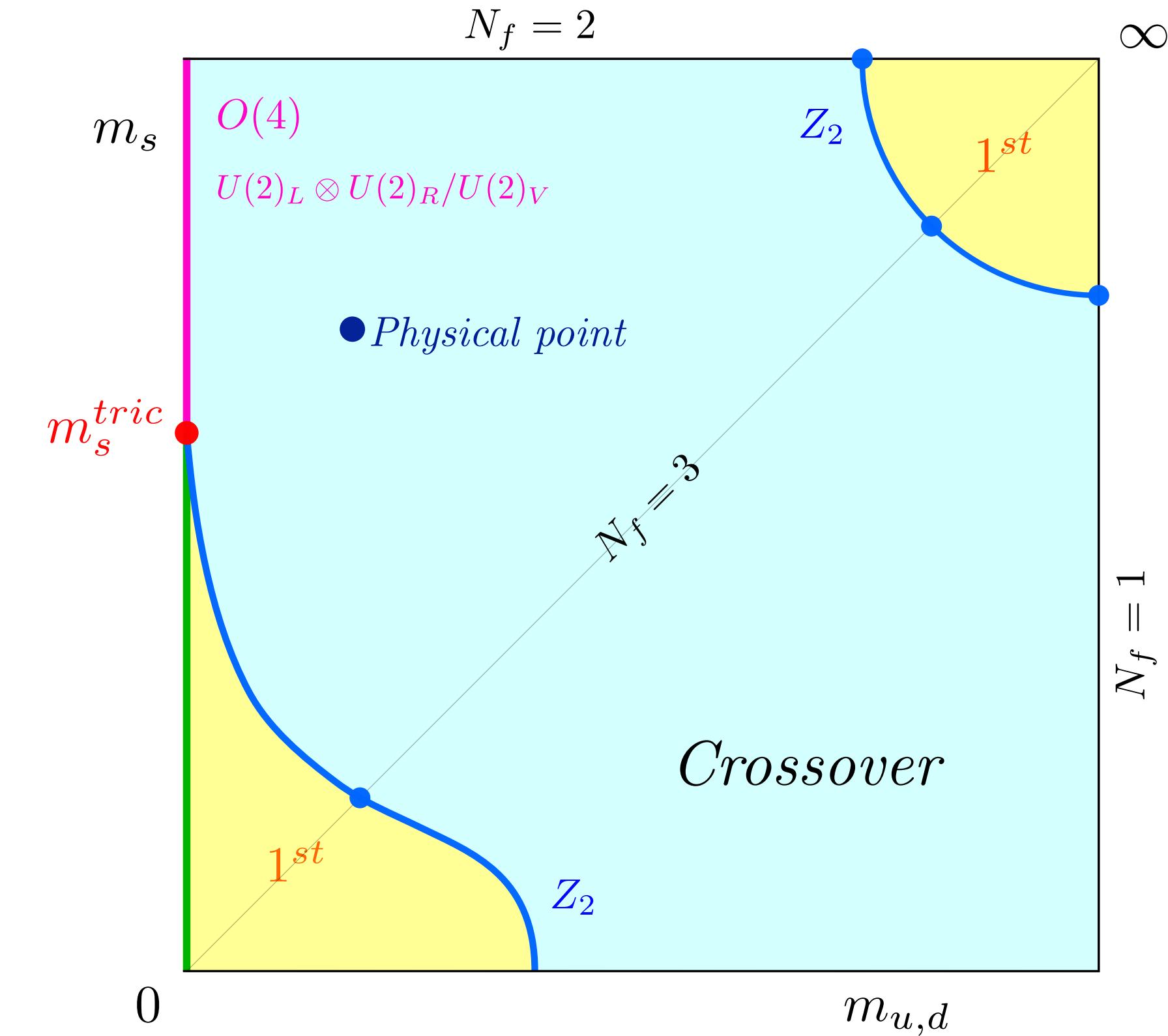
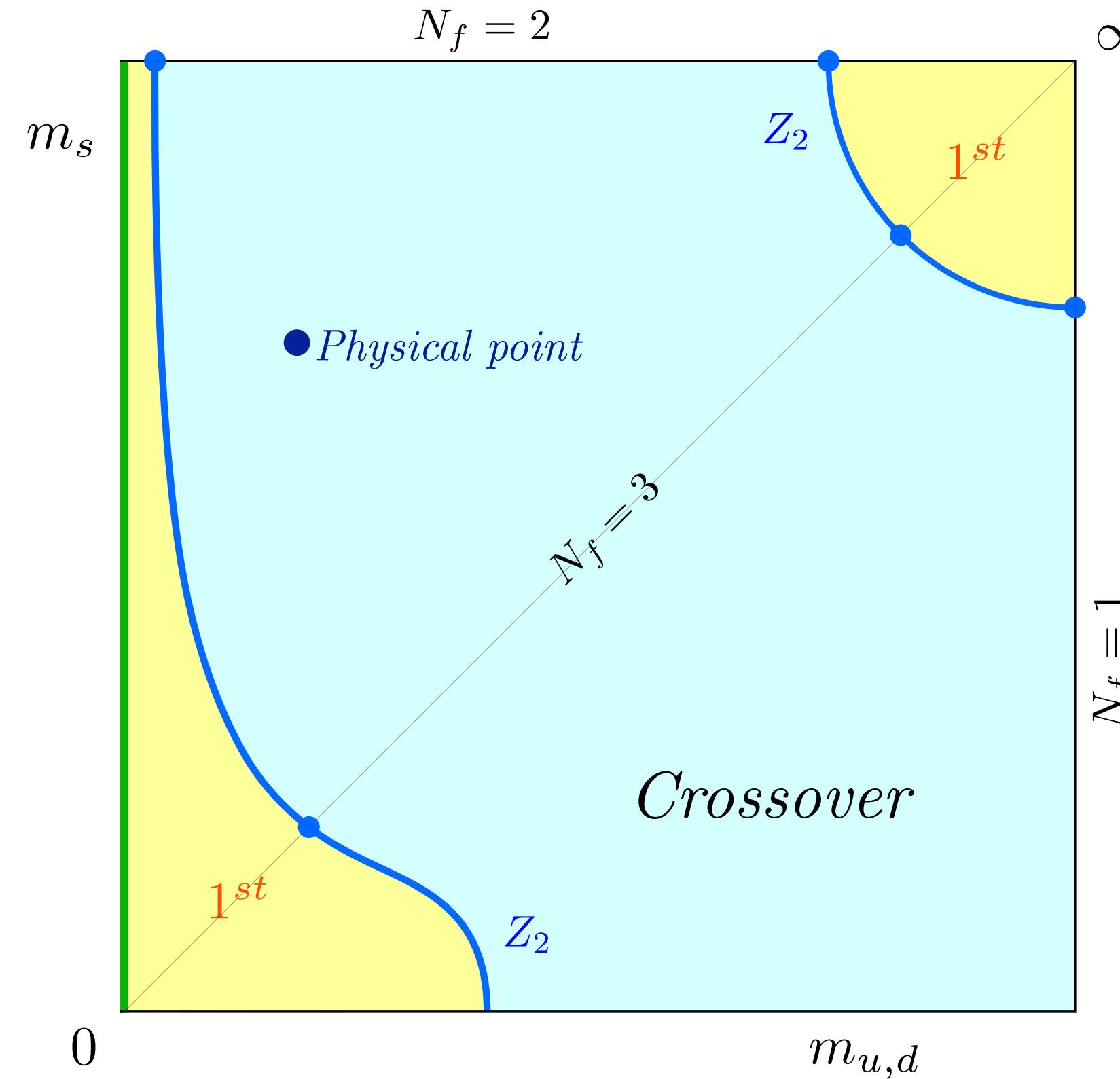
Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE



A.Yu. Kotov, M.P. Lombardo, A. Trunin / arXiv:2105.09842

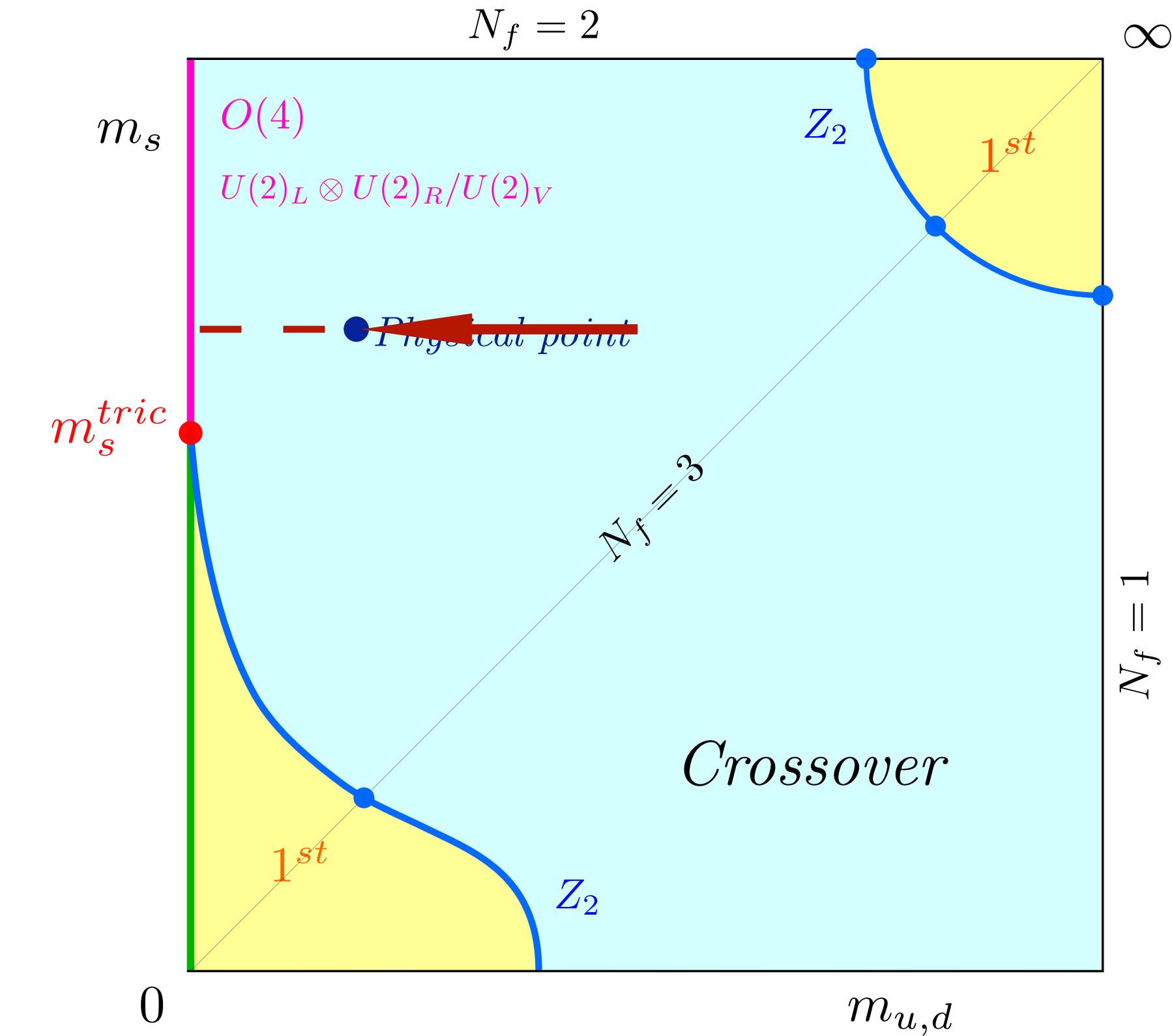
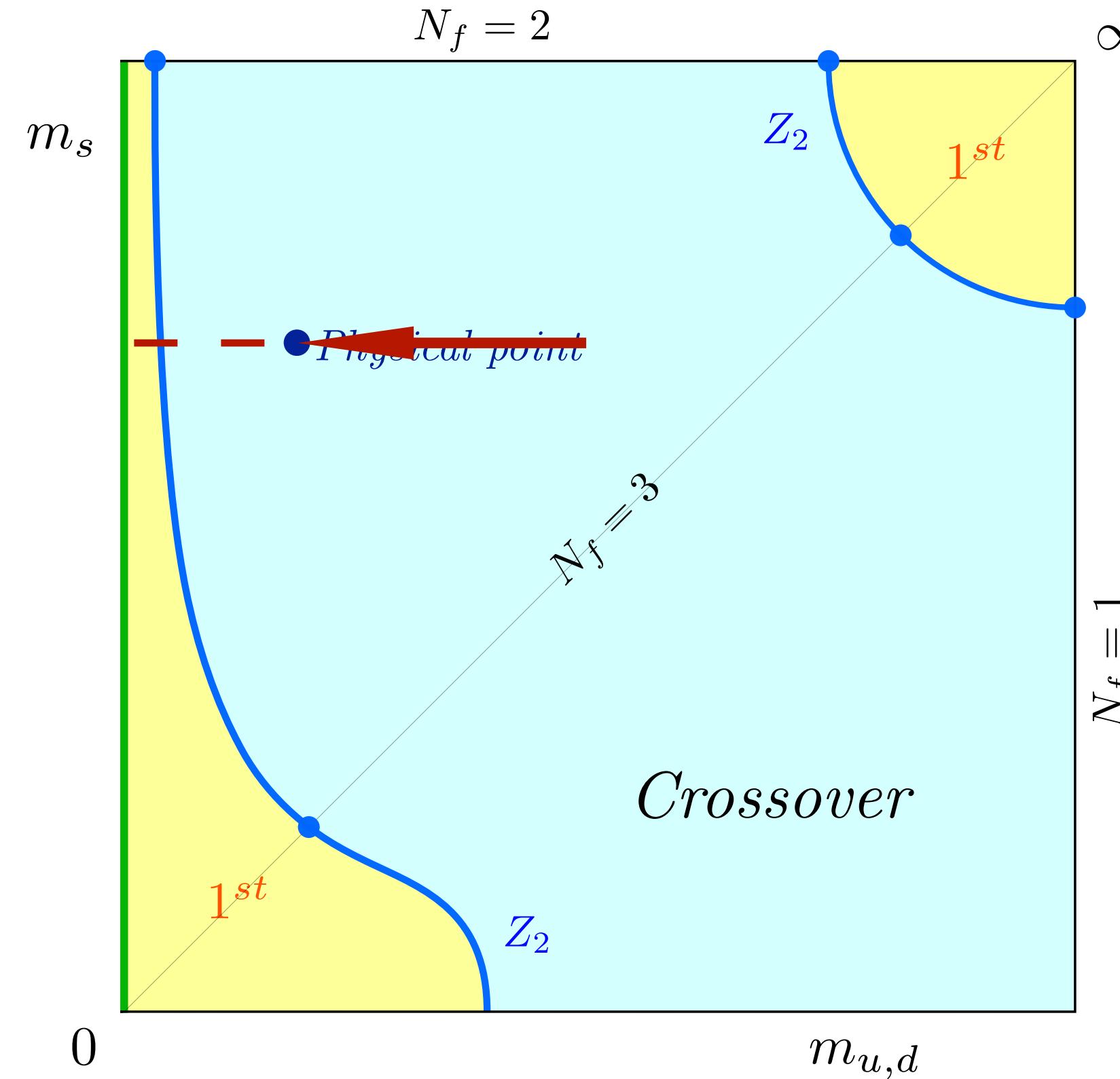
vConf2021

QCD at various m_q : Columbia plot



[F. Cuteri et al., 2021]

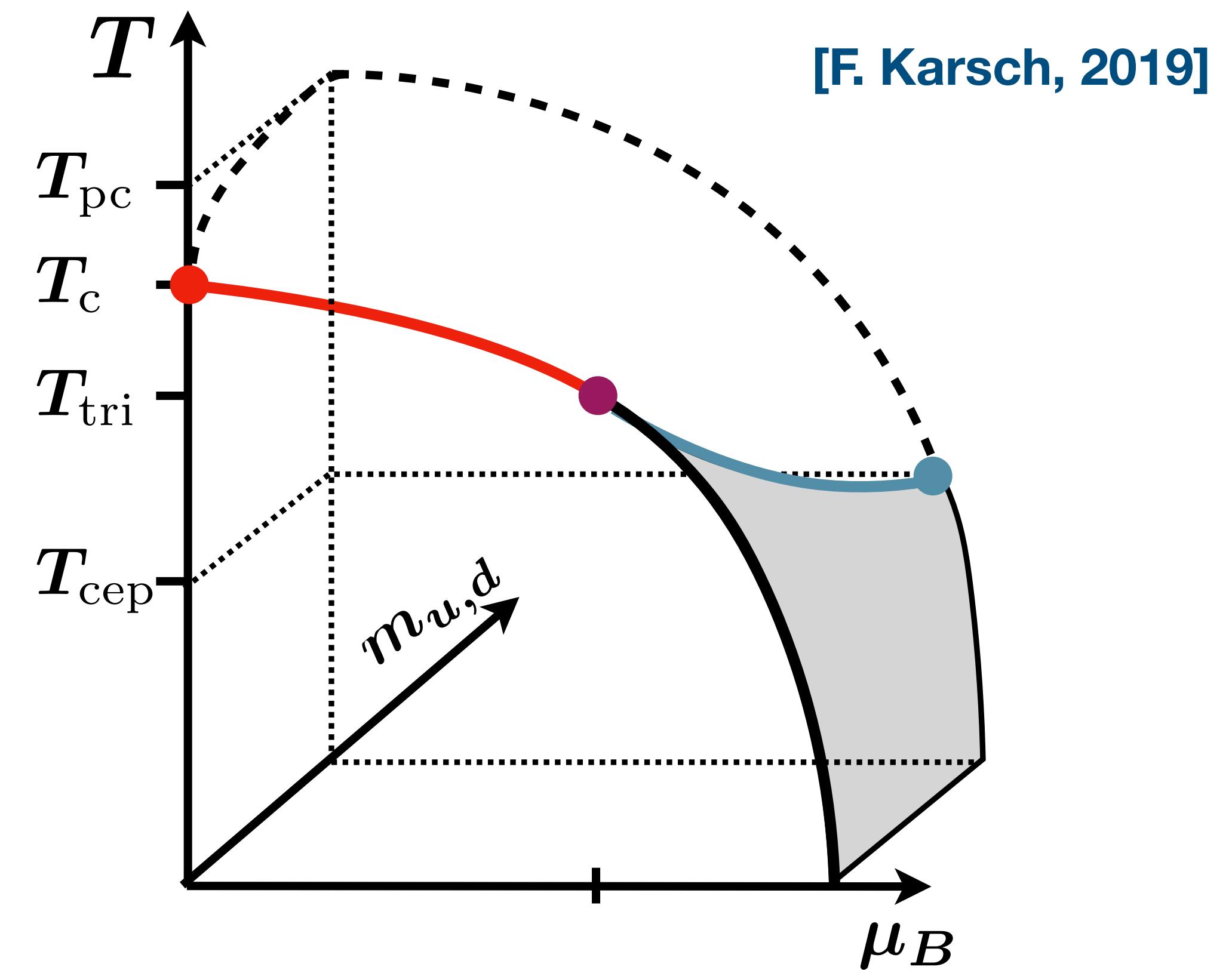
QCD at various m_q : Columbia plot



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Related to the effective restoration of anomalous $U_A(1)$ symmetry

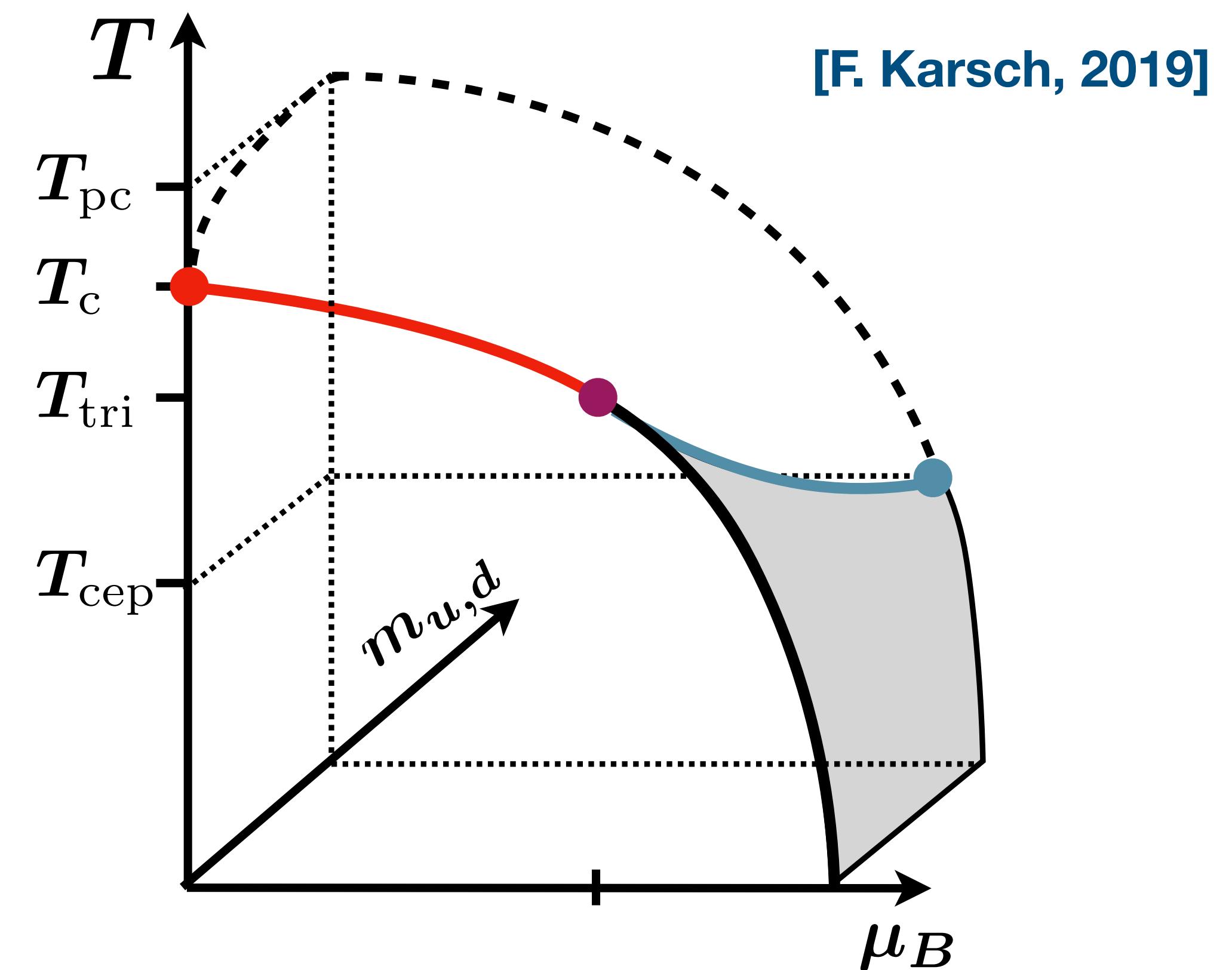
QCD in the chiral limit $m_u = m_d \rightarrow 0$



QCD in the chiral limit $m_u = m_d \rightarrow 0$

- Effective restoration of the $U_A(1)$ symmetry
- Upper bound on CEP at nonzero baryon μ_B :

$$T_{\text{CEP}} < T_{\text{tri}} < T_c(m_{u,d} \rightarrow 0)$$



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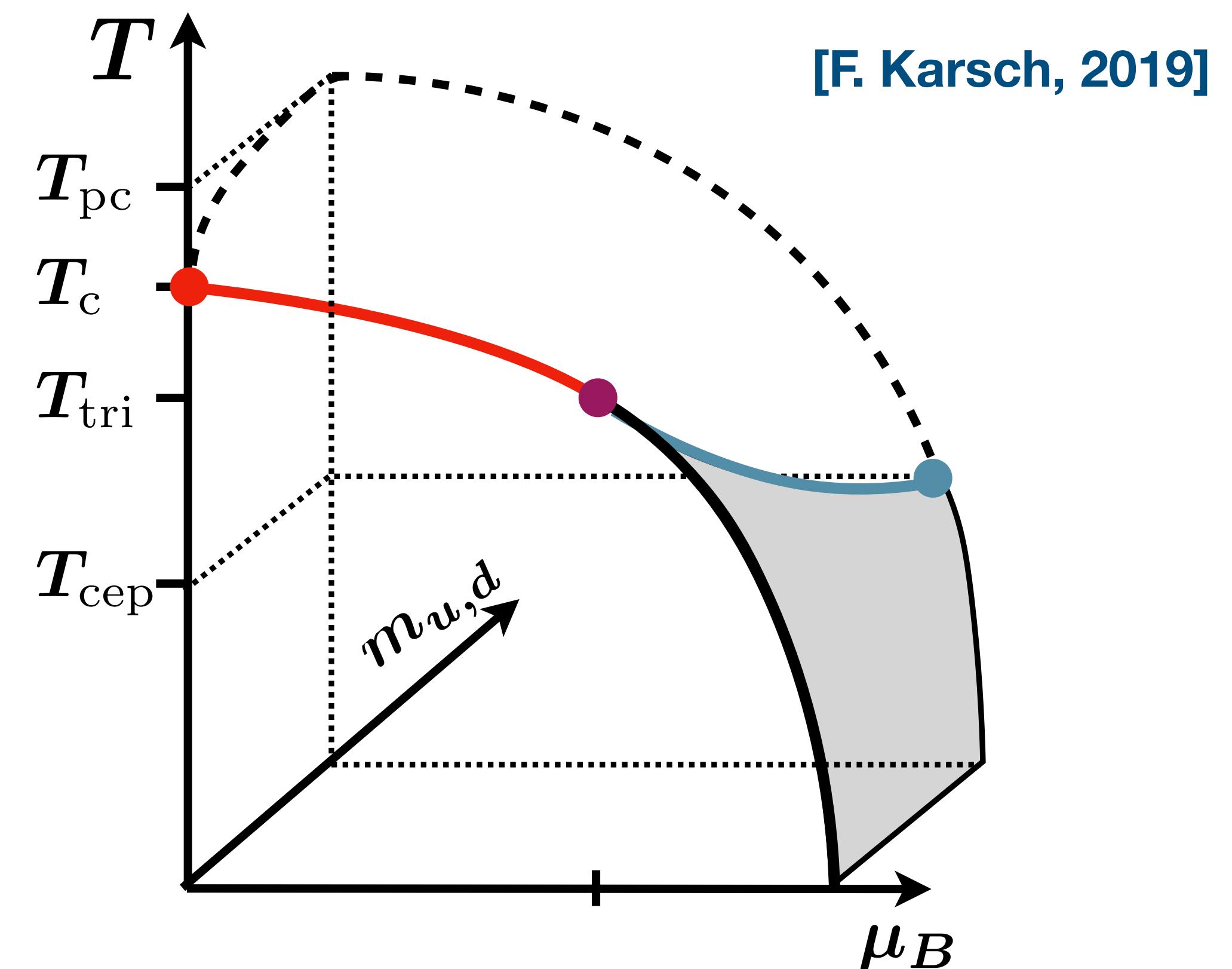
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- T_c for $m_{u,d} \rightarrow 0$
- Scaling properties:

nature/universality class of the transition for $m_{u,d} \rightarrow 0$



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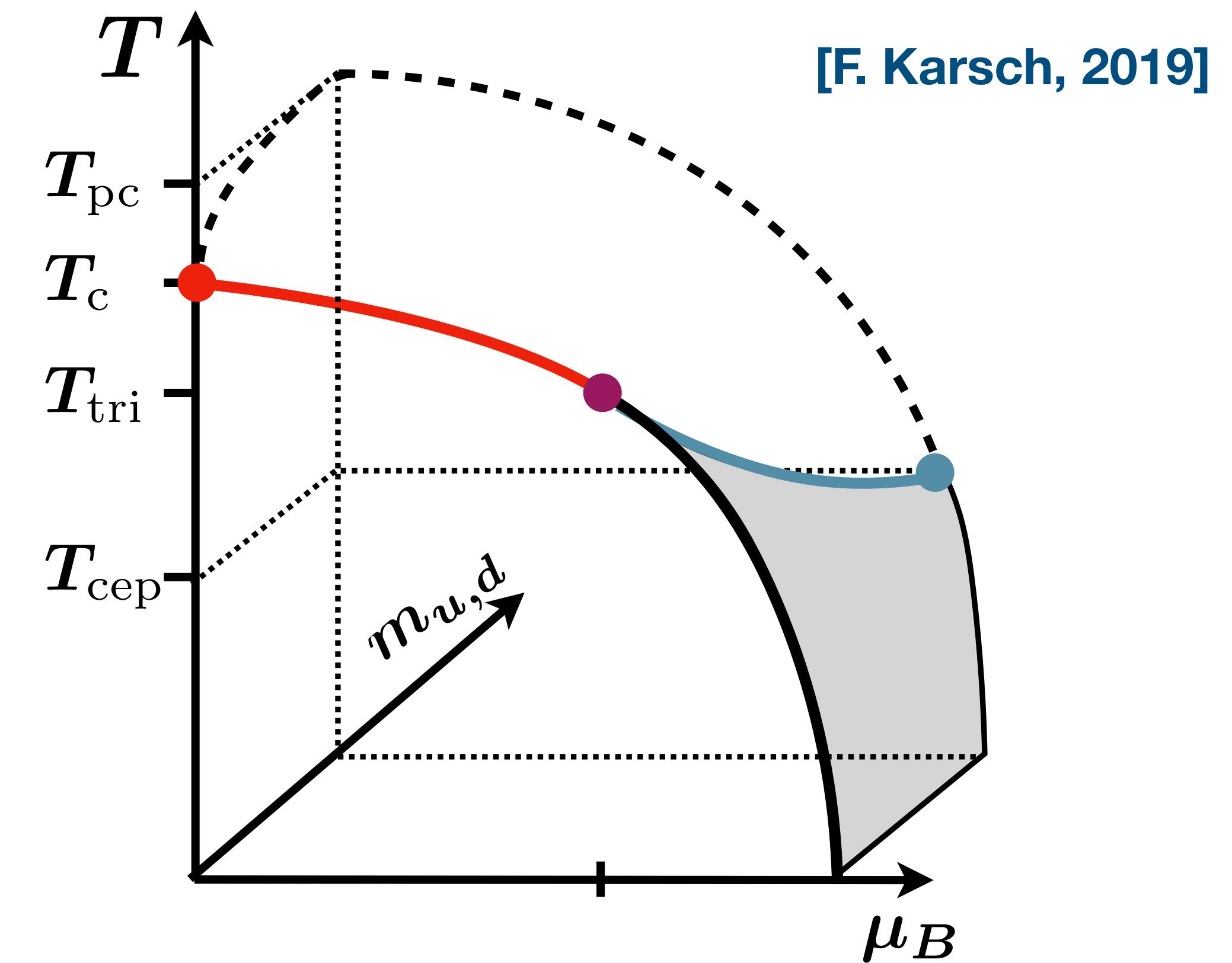
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Simulations:

- $N_f = 2 + 1 + 1$ twisted mass Wilson fermions for several $m_\pi \in [140 : 380]$ MeV

Observables and Equation of State

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- Chiral condensate $\langle \bar{\psi} \psi \rangle$:

$$\text{EoS: } \langle \bar{\psi} \psi \rangle = A h^{1/\delta} f(x) + \dots, \quad h \equiv m, \quad x = t/h^{1/\beta\delta}$$

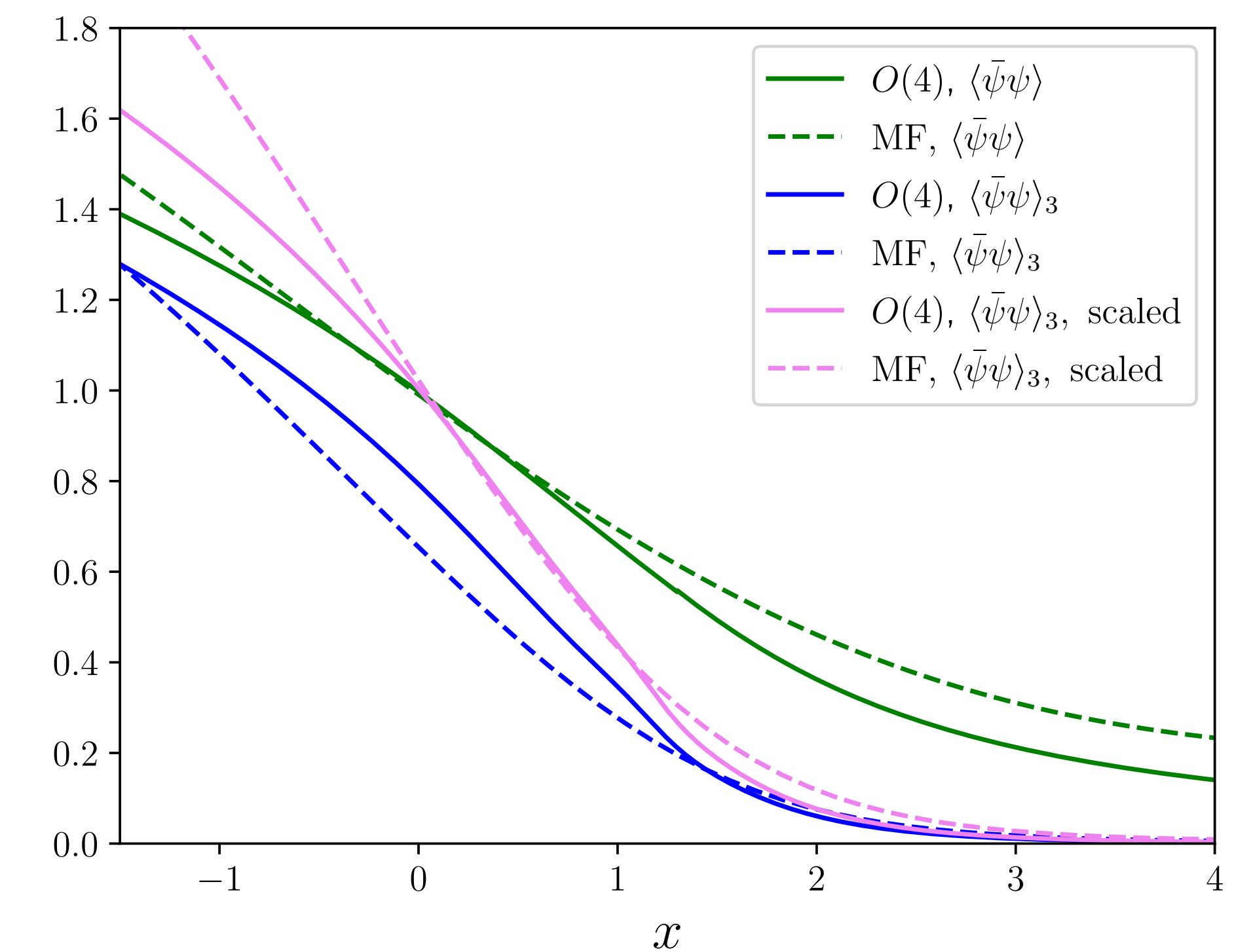
- Chiral susceptibility $\chi = \partial \langle \bar{\psi} \psi \rangle / \partial m$

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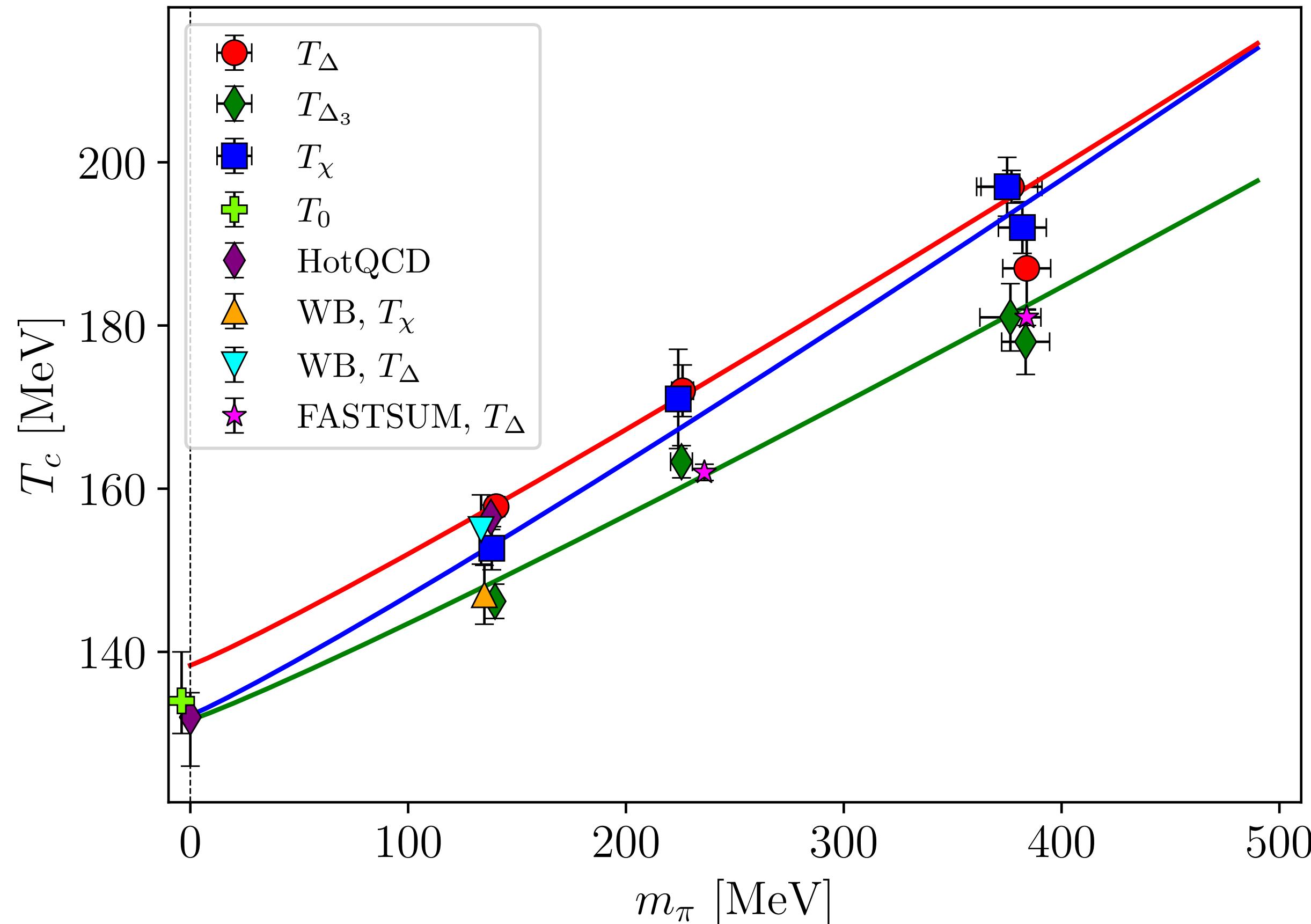
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- Chiral susceptibility $\chi = \partial \langle \bar{\psi}\psi \rangle / \partial m$
- New order parameter: $\langle \bar{\psi}\psi \rangle_3 = \langle \bar{\psi}\psi \rangle - m\chi$
[W.Unger, 2010]
 - terms $\sim m$ cancel: divergences/regular
 - $\sim m^3$ (symmetric phase)
 - $\langle \bar{\psi}\psi \rangle_3 \sim t^{-\gamma-2\beta\delta}$ vs $\langle \bar{\psi}\psi \rangle \sim t^{-\gamma}$ as $t \rightarrow \infty$



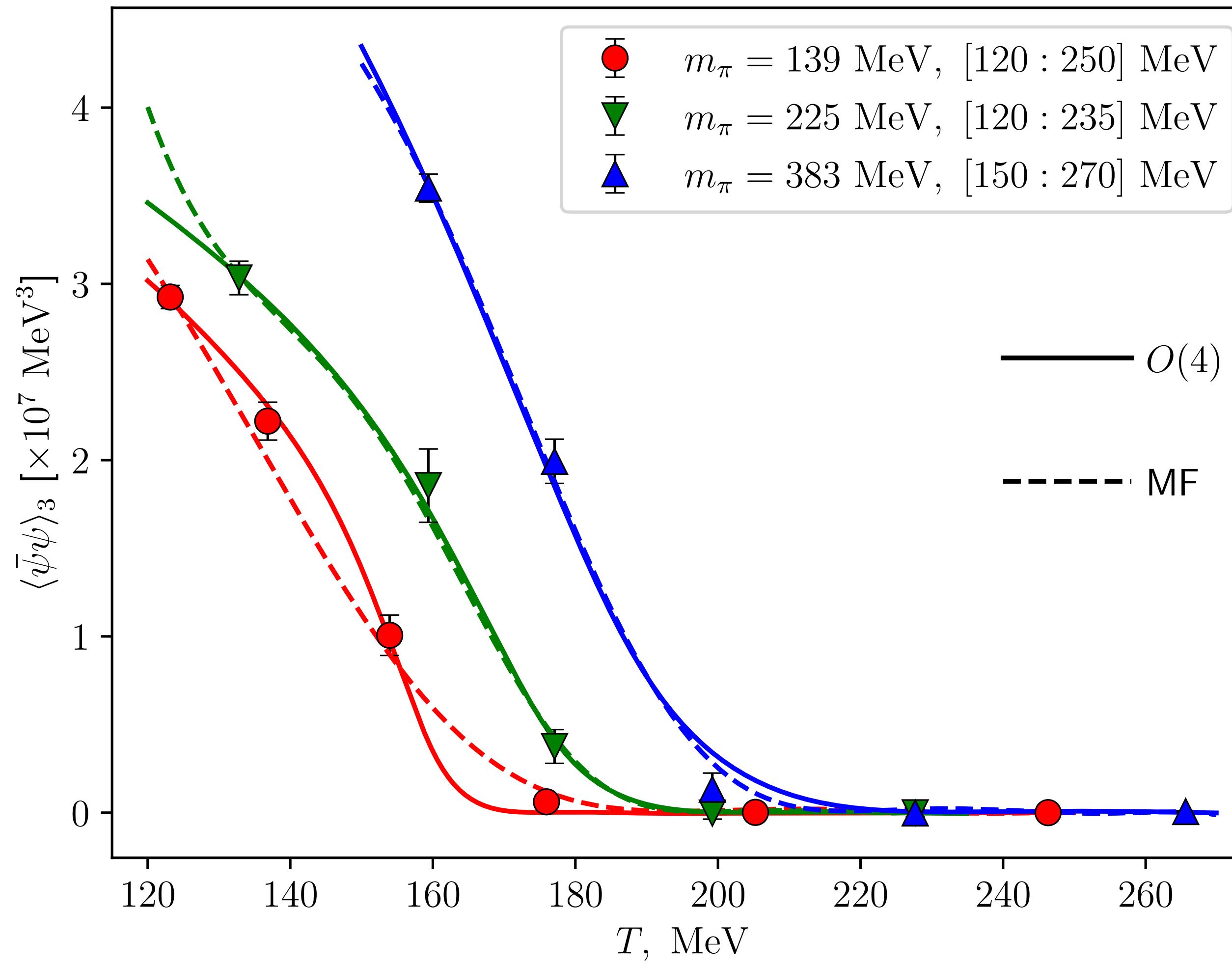
Critical temperature and the chiral limit



	$T(m_\pi = 139 \text{ MeV})$ [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)

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

O(4) vs mean field

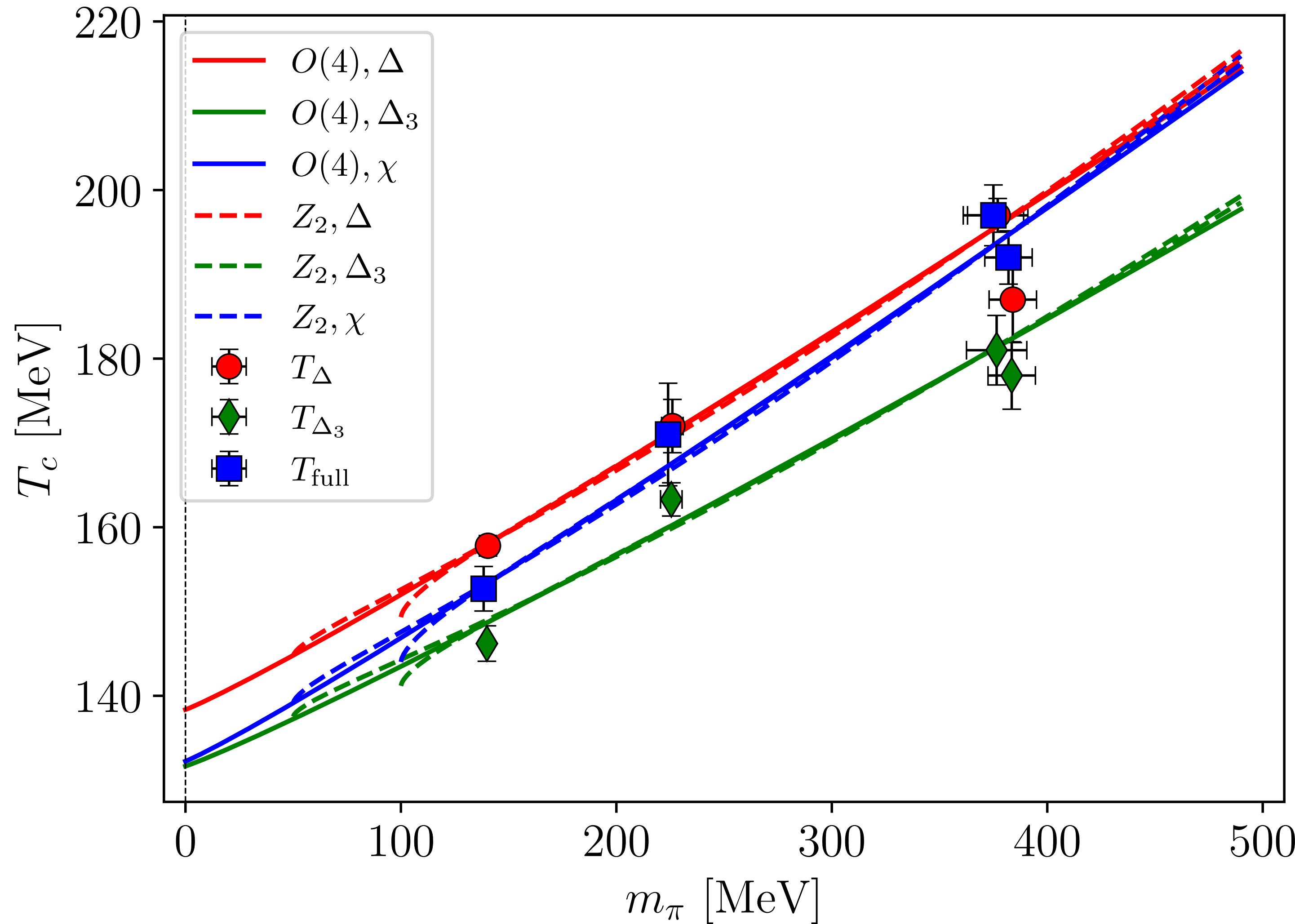


Mild tension between
data and MF for
 $m_\pi=139 \text{ MeV}$

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

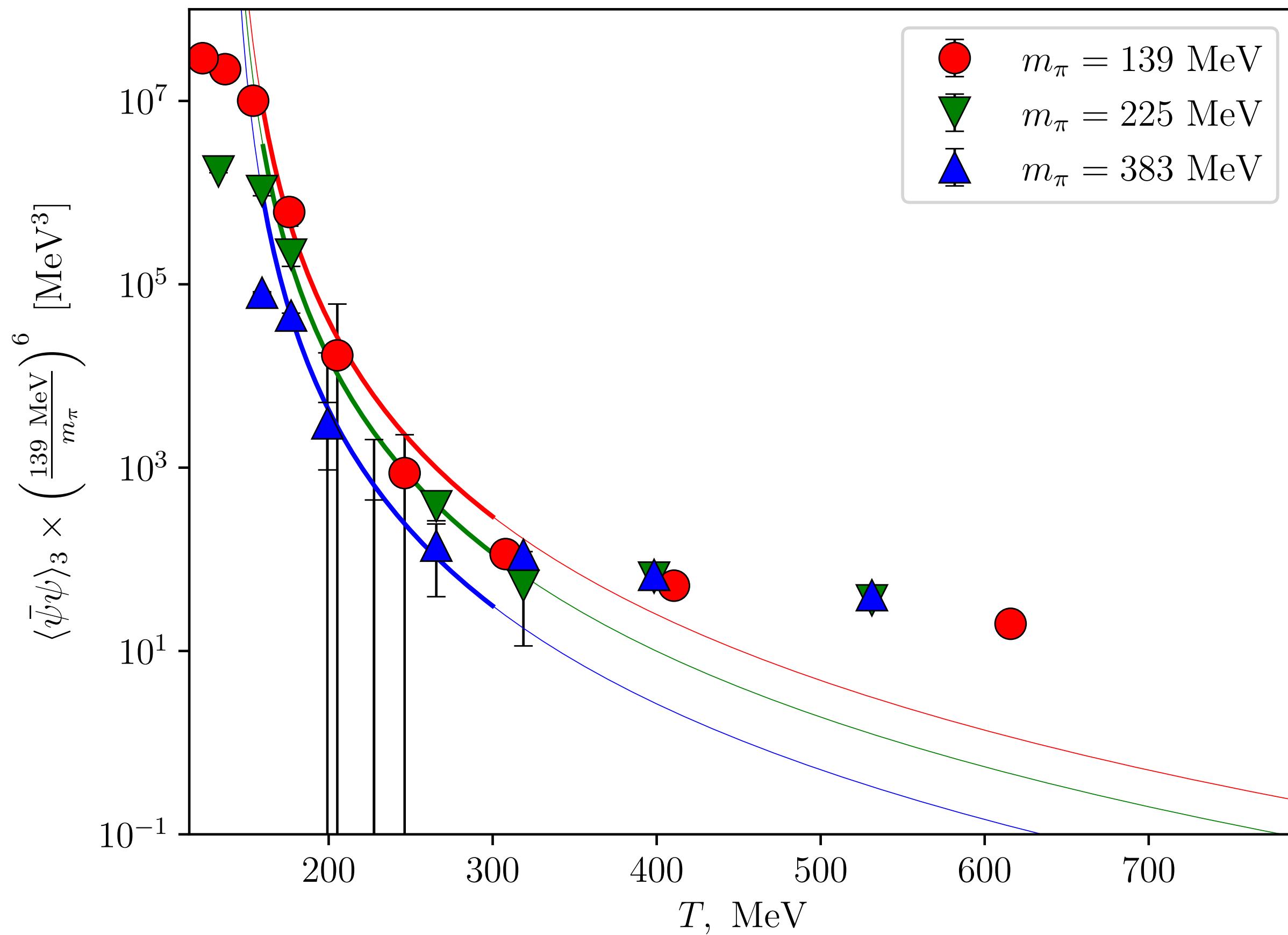
$m_\pi \text{ [MeV]}$	$T_0 \text{ [MeV]}$
139	142(2)
225	159(3)
383	174(2)

Z_2 scaling



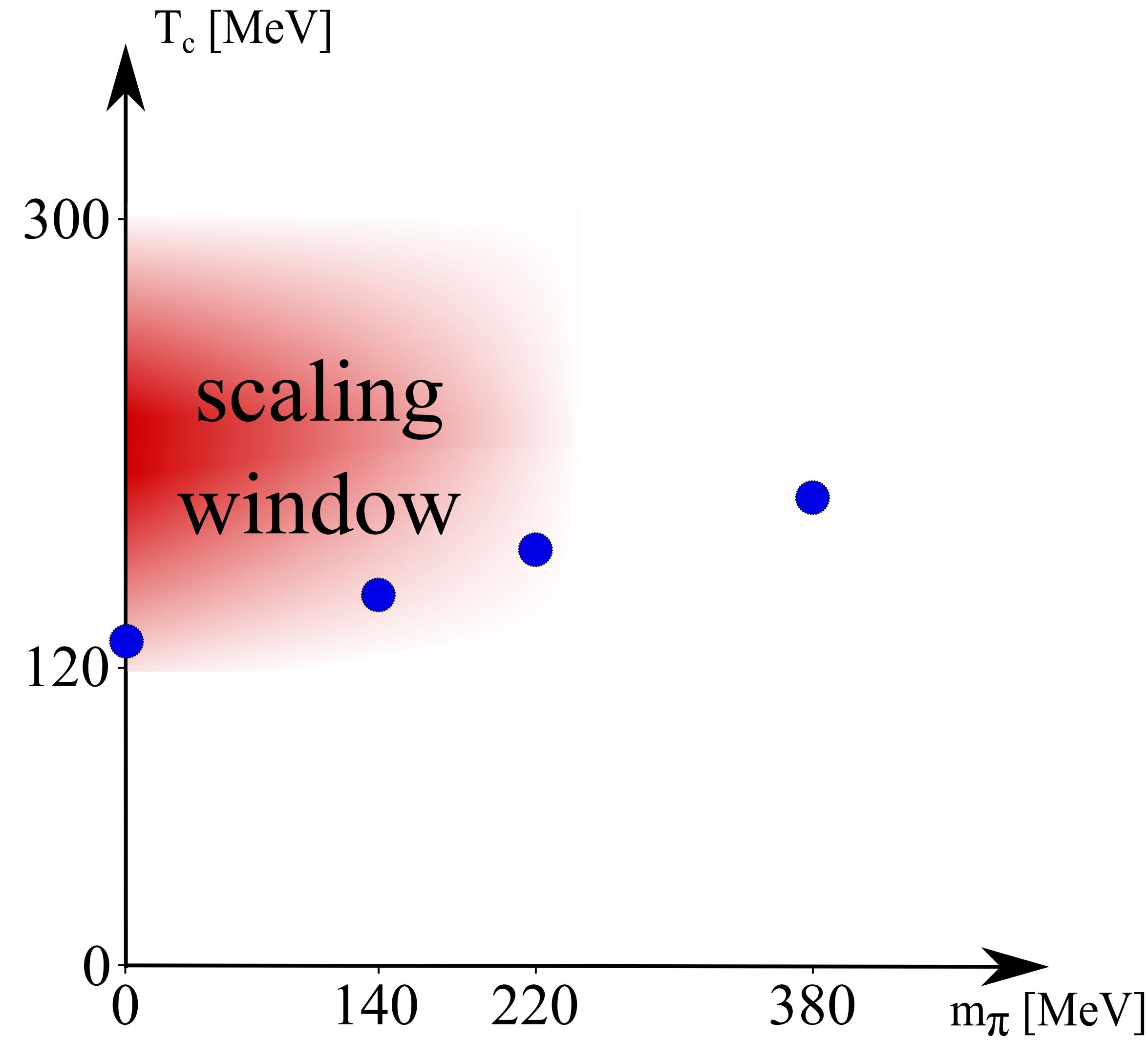
Can also describe data
for $m_\pi^c \in [0, m_{\text{phys}}]$

Large temperature behaviour



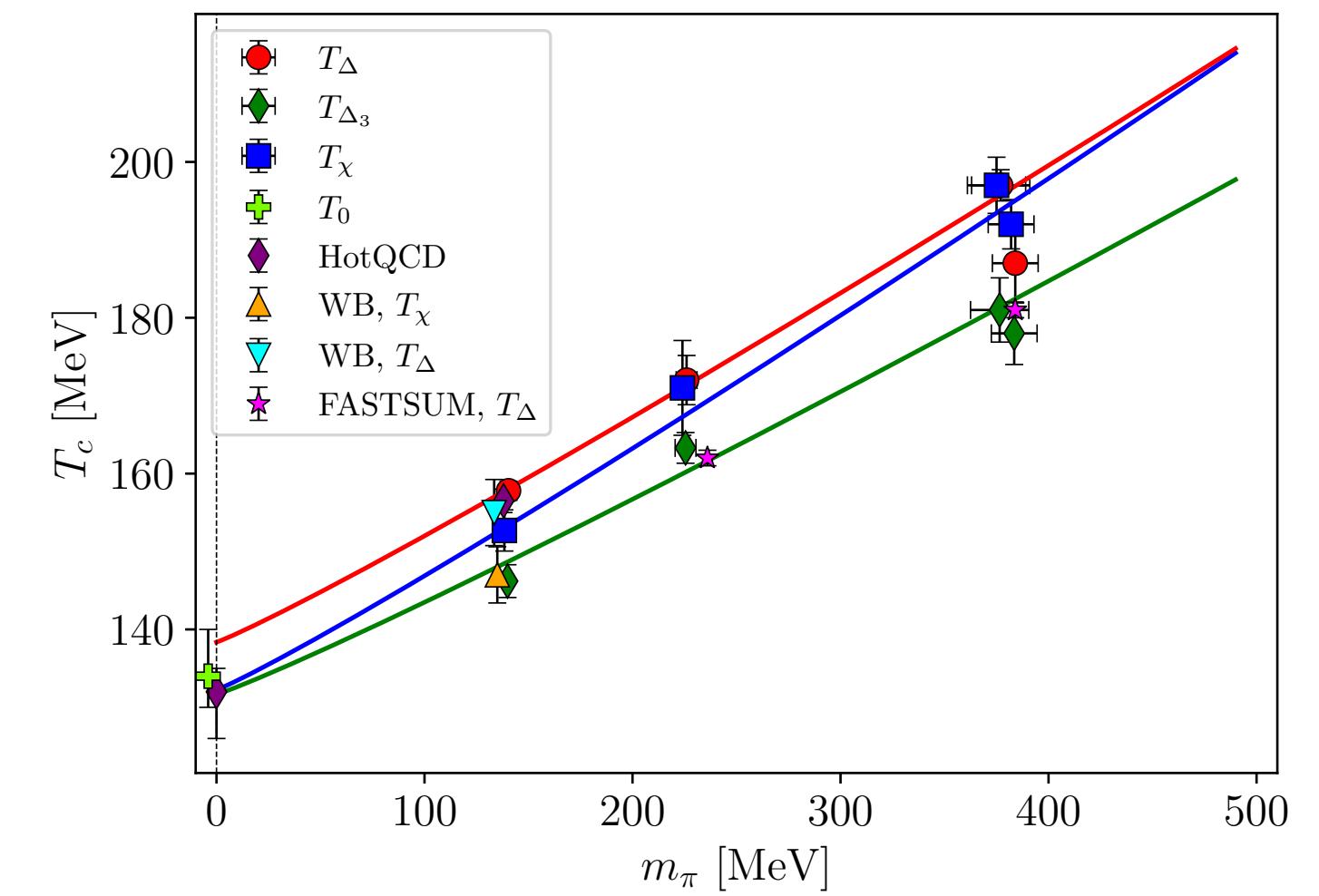
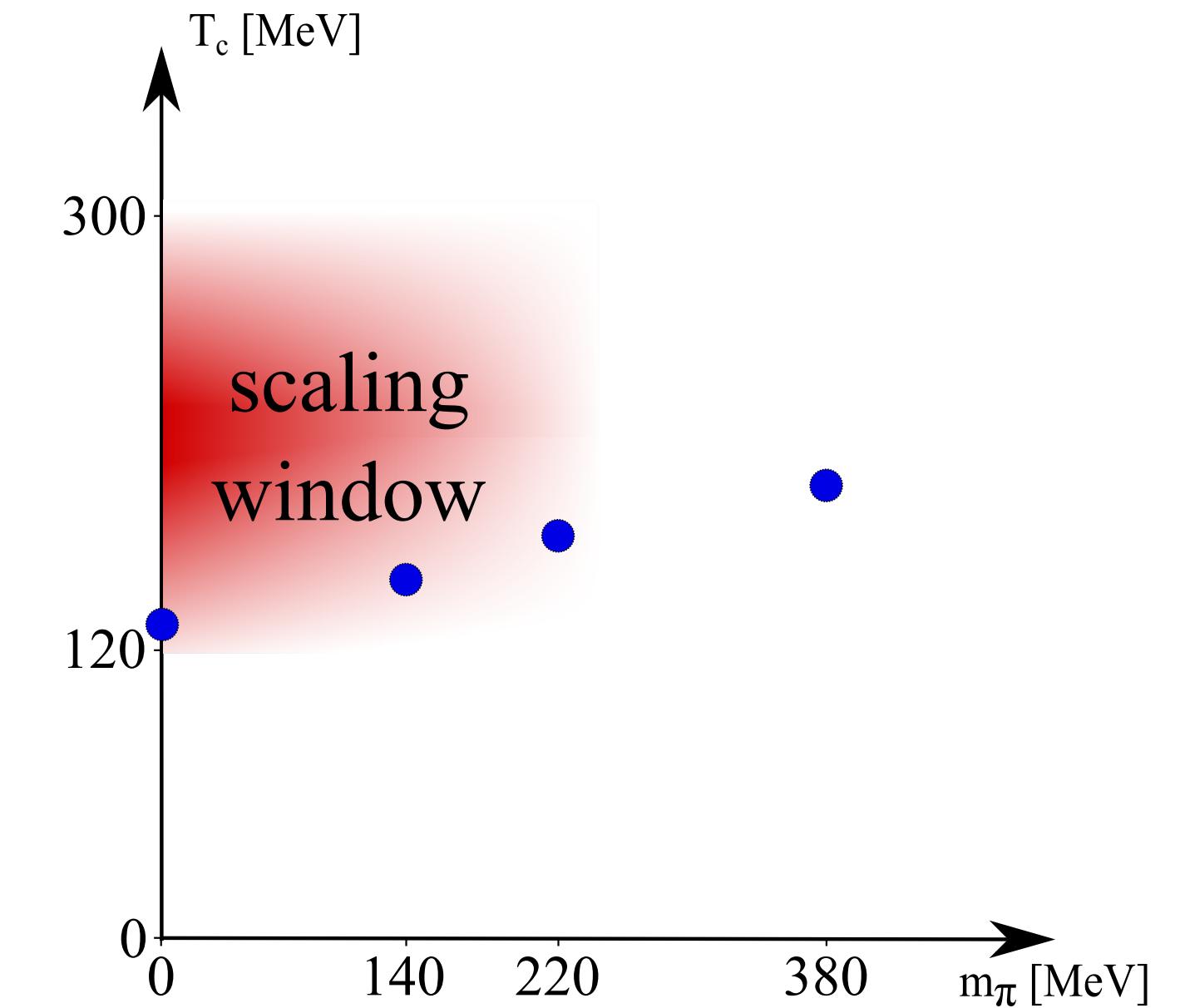
- O(4): $\langle \bar{\psi} \psi \rangle_3 \sim t^{-\gamma - 2\beta\delta}$
- Griffith analyticity: $\langle \bar{\psi} \psi \rangle_3 \sim m^3 \sim m_\pi^6$
- $T \sim 300 \text{ MeV}$

Scaling window



Conclusions

- $\langle \bar{\psi} \psi \rangle_3 = \langle \bar{\psi} \psi \rangle - m\chi$ is useful to study scaling
- $T_0 = 134^{+6}_{-4}$ MeV in the chiral limit
- $O(4)$ scaling for $m_\pi \lesssim 140$ MeV, $T \in [120, 300]$ MeV
- Z_2 scaling with any $m_\pi \lesssim 140$ MeV cannot be excluded
- $T \geq 300$ MeV: leading order Griffith analyticity



BACKUP

Lattice setup

- $N_f = 2 + 1 + 1$ twisted mass Wilson fermions at maximal twist

- Fixed scale approach: $a = \text{fixed}$, $T \leftrightarrow N_t$
- Based on ETMC T=0 parameters

[C. Alexandrou et al., 2018]

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)