Fluctuations and correlations of baryonic chiral partners

Michał Marczenko

University of Wrocław

Koch, MM, Redlich, Sasaki, arXiv:2308.15794

Zimányi School 2023

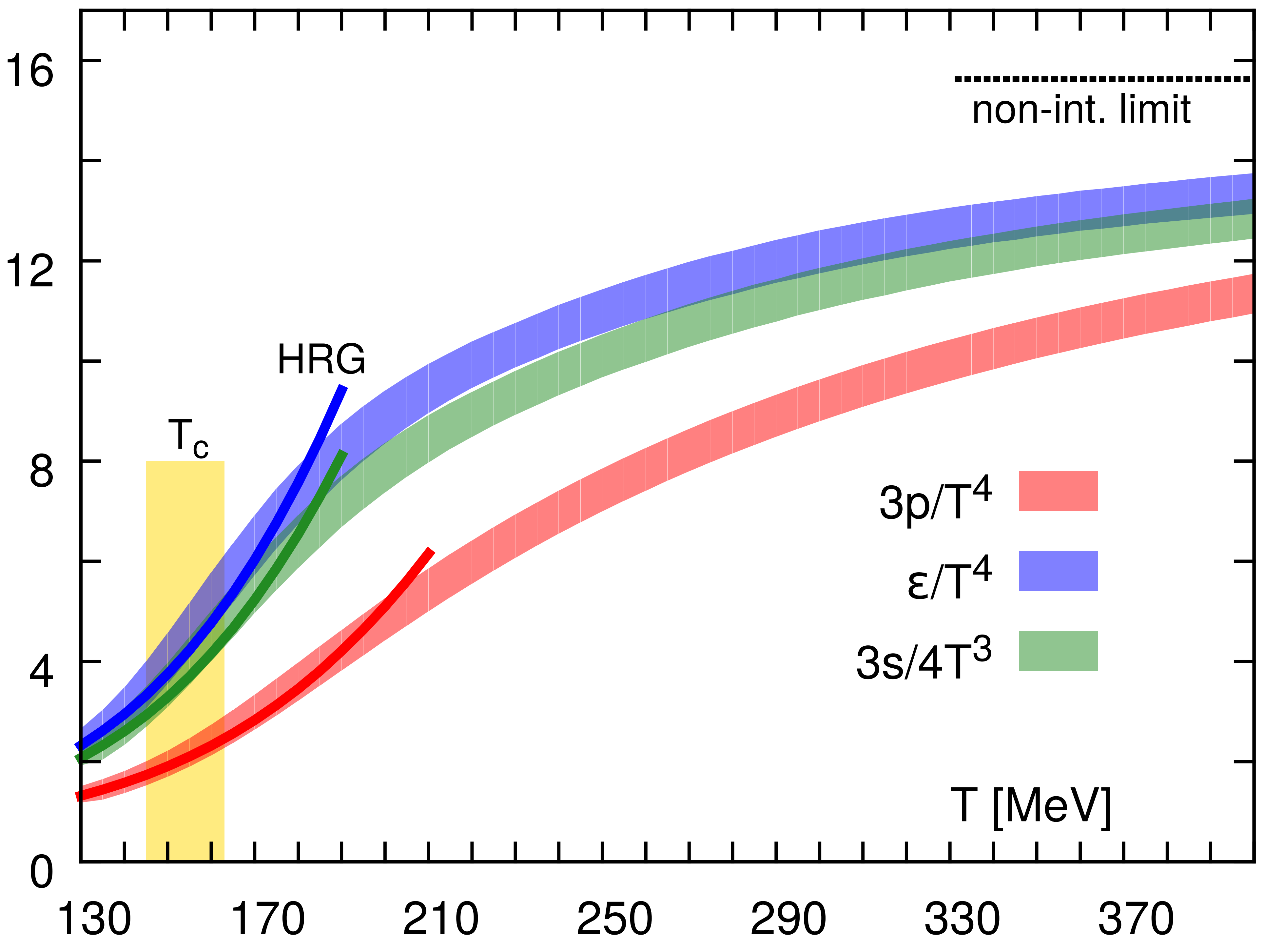
Uniwersytet Wrocławski

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

CSSF
INCUBATOR OF SCIENTIFIC EXCELLENCE

Lattice QCD vs Hadron Resonance Gas

HotQCD, 2014

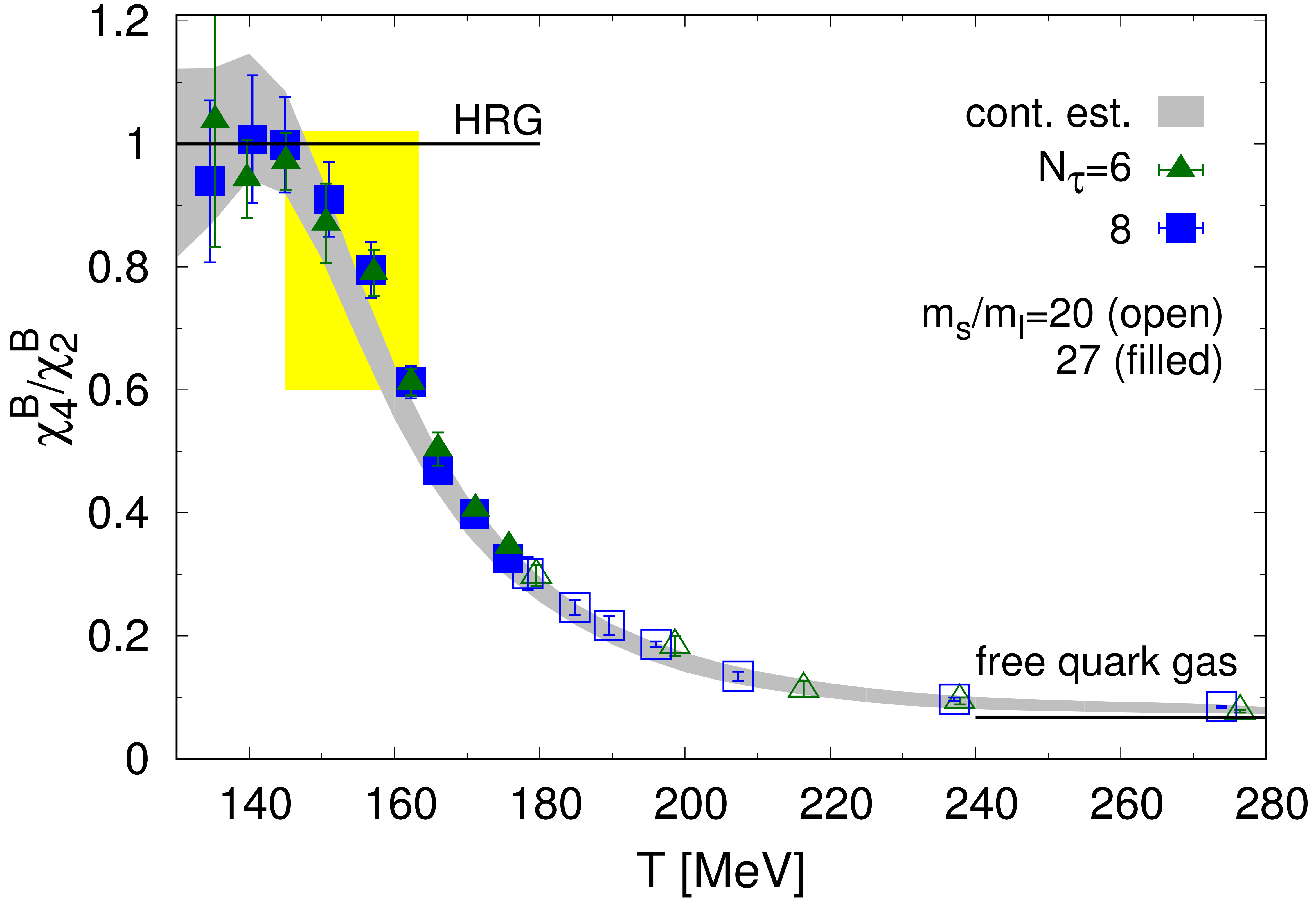


Pressure in the HRG model

$$P^{\mathrm{HRG}} = \sum_{i \in \mathrm{had}} P^{\mathrm{id}}\left(T, \mu_i; m_i\right)$$

Agreement with LQCD EoS up to $\simeq T_c$

HotQCD, 2017

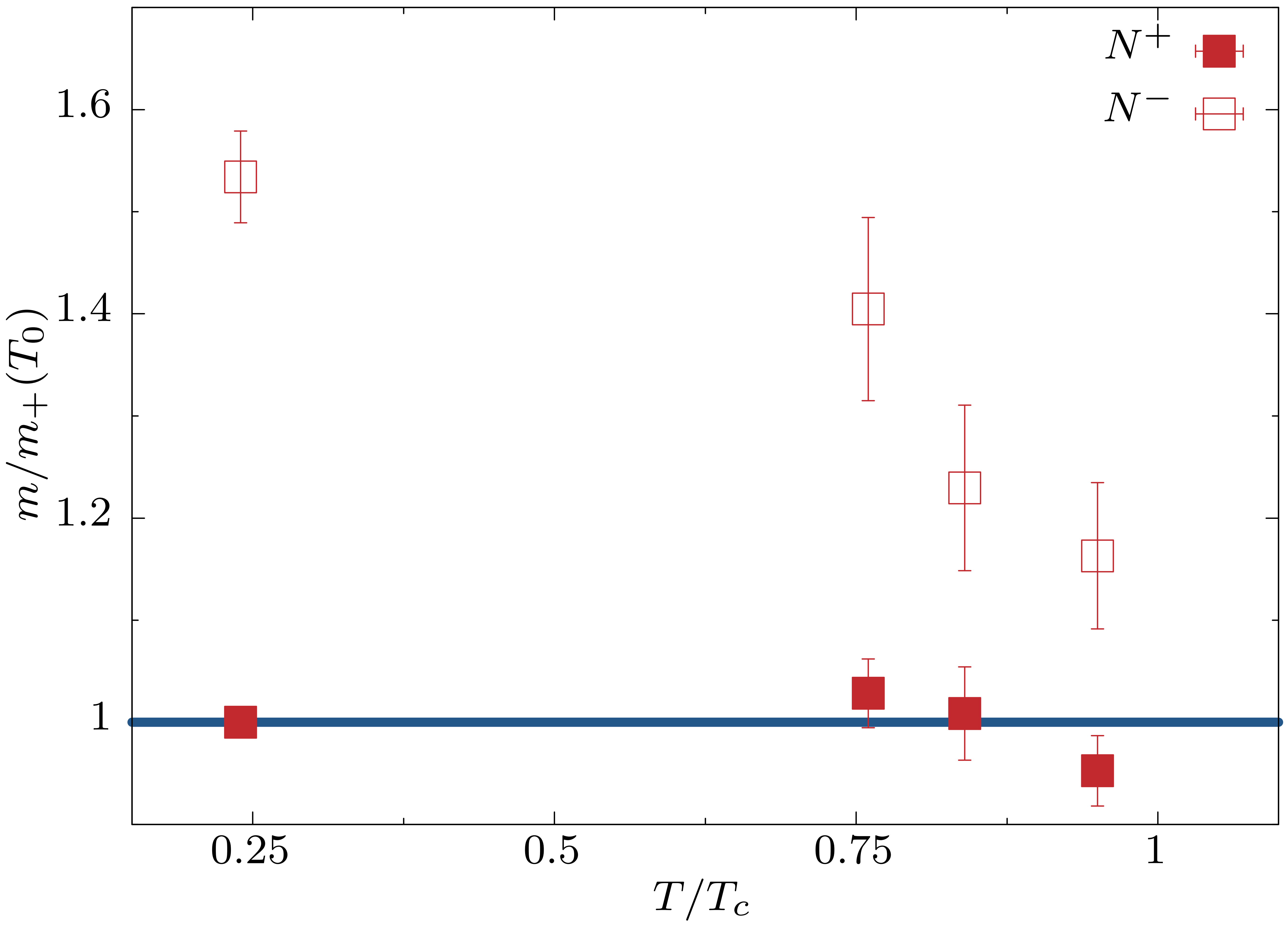


Taylor expansion of LQCD EoS

$$\frac{P}{T^4} = \sum_{k=0}^{\infty} \left(\frac{\mu_B}{T}\right)^k \frac{\chi_k^B}{k!}, \text{ where } \chi_k^B = \frac{\partial^k P/T^4}{\partial\left(\mu_B/T\right)^k}$$

Kurtosis: $\frac{\chi_4^B}{\chi_2^B} \sim B^2$: breakdown $\sim T_c$: changeover to QGP

Parity Doubling in Lattice QCD Aarts et al, 2017, 2019



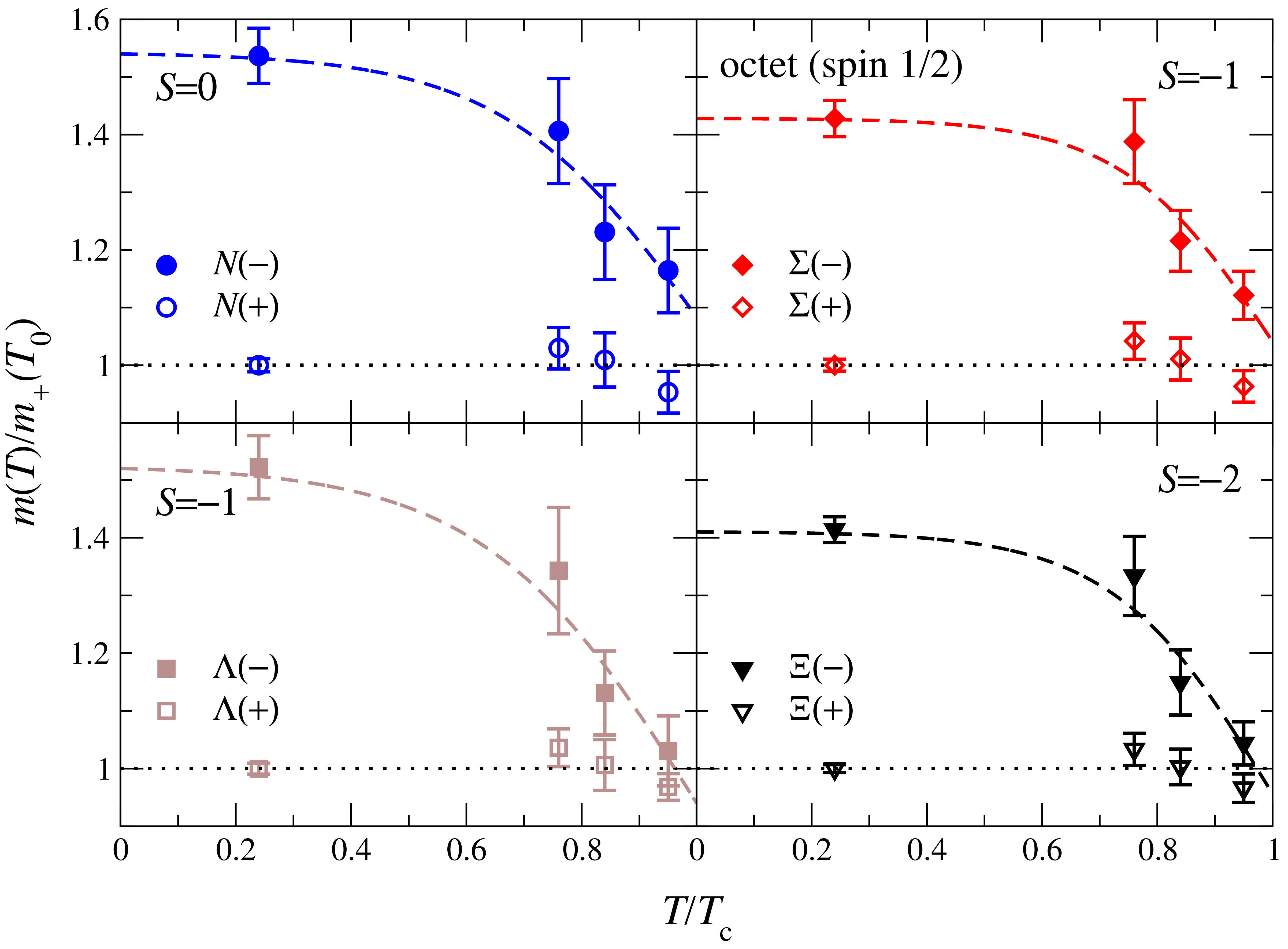
- N^+ nucleon stays nearly unchanged
- N^- chiral partner drops mass towards T_c
- Chiral partners $N^\pm$ degenerate at T_c
- Chiral parents stay massive

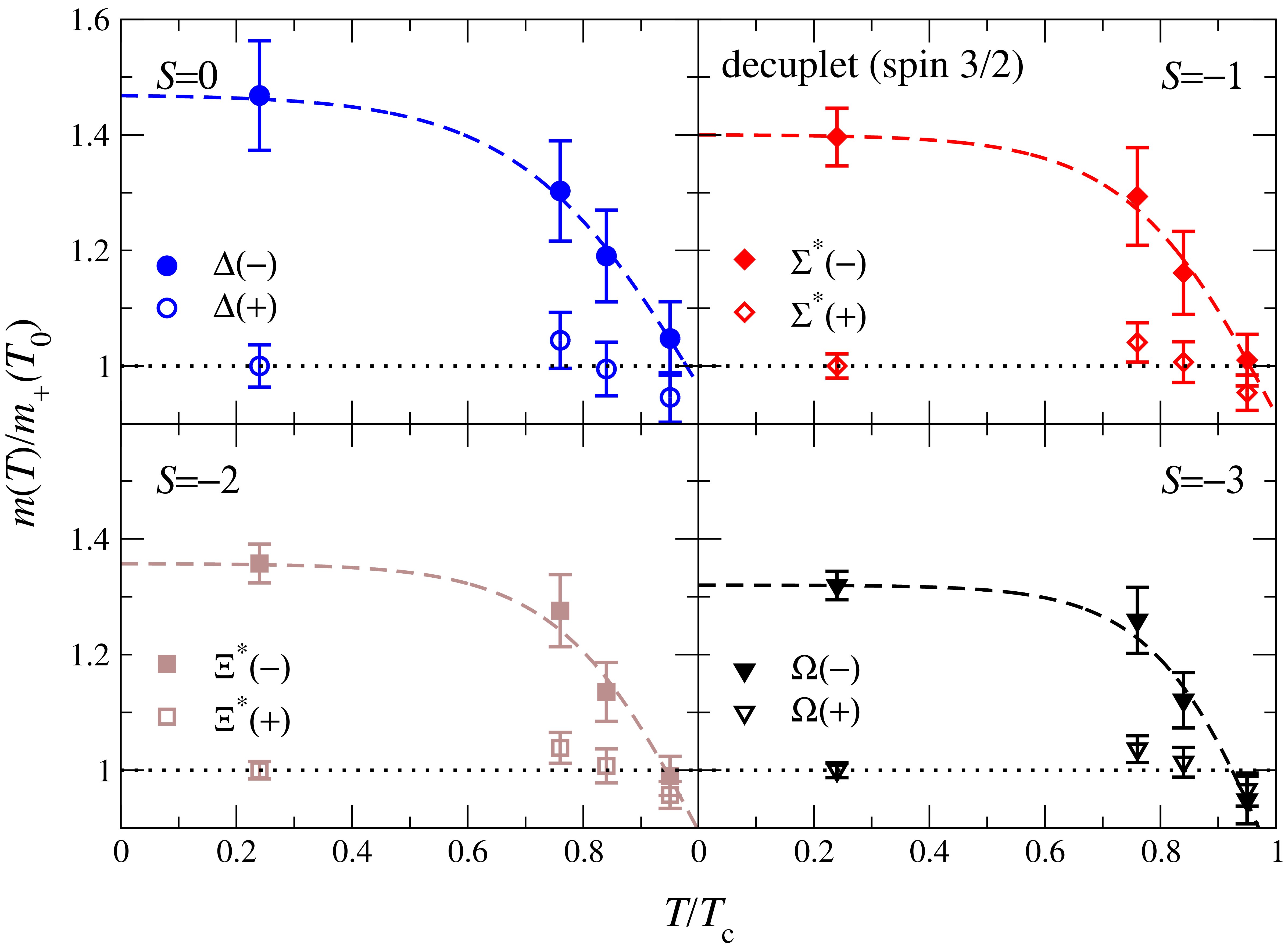
Imprint of chiral symmetry restoration in the baryonic sector

LQCD results still obtained with heavy m_π far from continuum limit

Imprint of chiral symmetry restoration in the baryonic sector

Aarts et al, 2019





In-Medium Hadron Resonance Gas

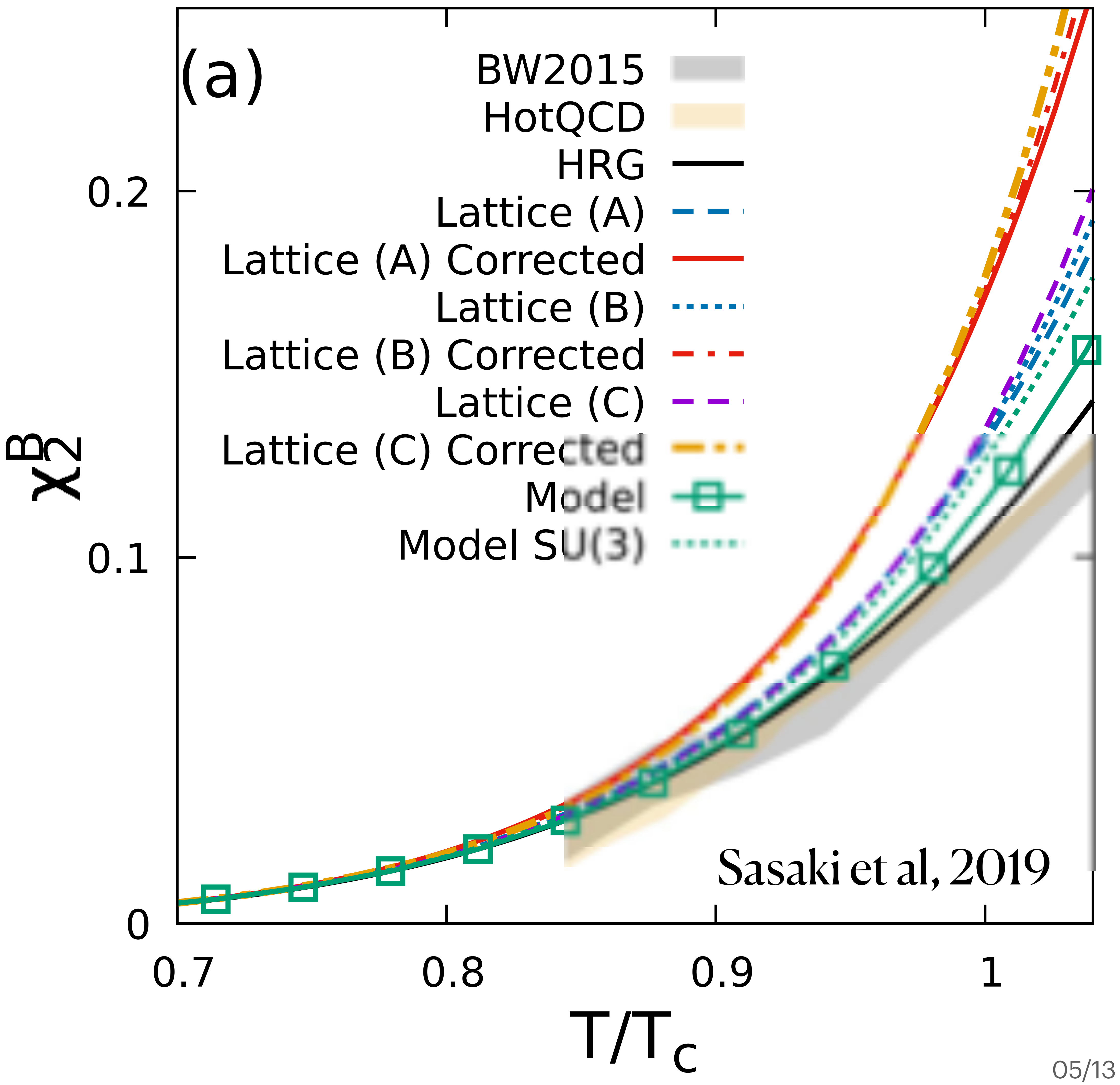
Susceptibilities are sensitive probes of chiral dynamics

$$\chi_2^B = \frac{\partial^2 P/T^4}{\partial(\mu_B/T)^2} = \frac{1}{VT^3} C_2^B$$

Fluctuations with chiral in-medium baryon masses

Too large fluctuations

Correlations between parity partners



For multiplicity $N_B = N_+ + N_-$ Net-baryon number: $\langle N_B \rangle = \langle N_+ \rangle + \langle N_- \rangle$

Second-order fluctuations of the net-baryon number:

$$\langle \delta N_B \delta N_B \rangle = \langle (\delta N_+)^2 \rangle + \langle (\delta N_-)^2 \rangle + 2\langle \delta N_+ \delta N_- \rangle$$

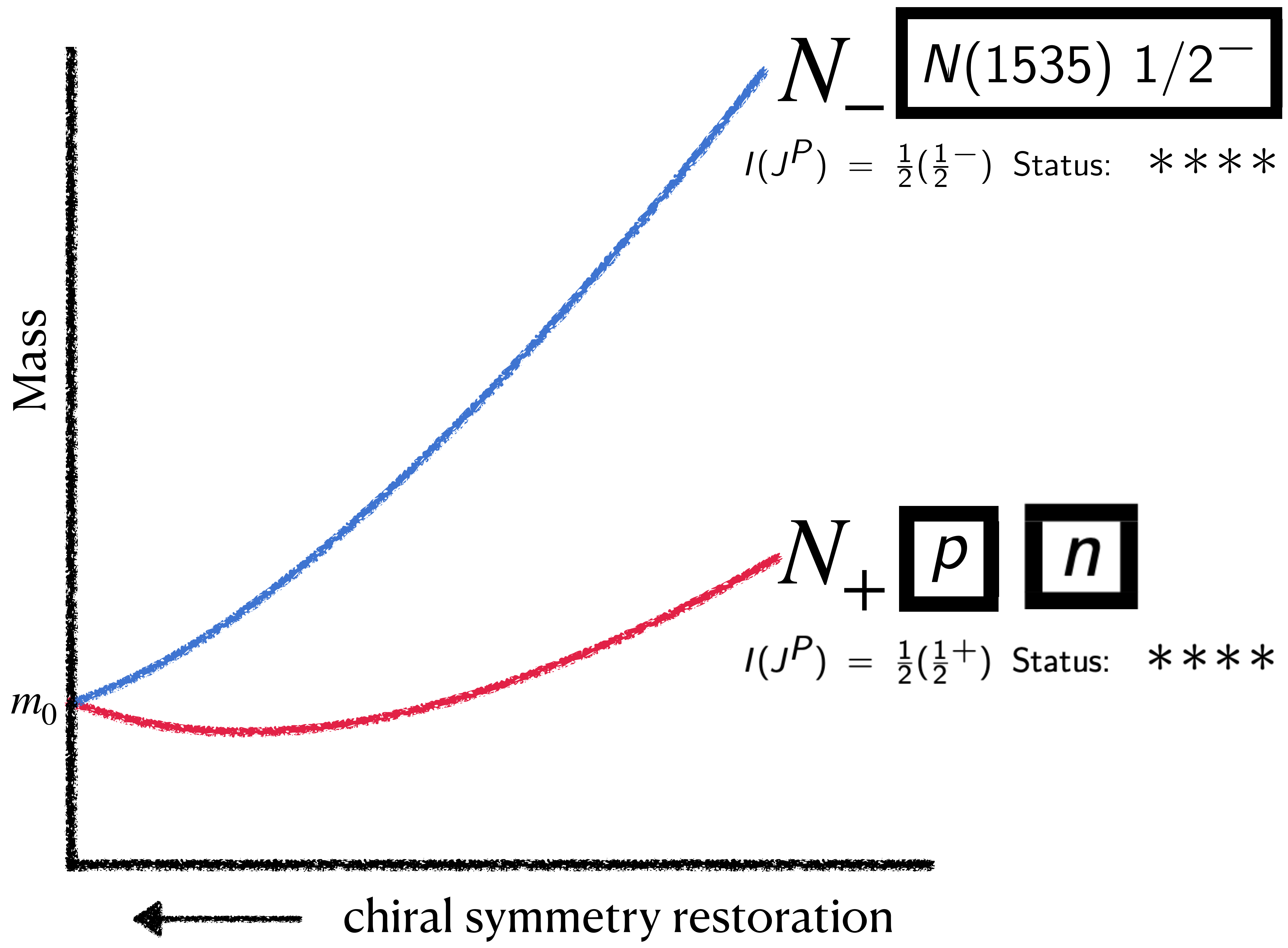
$$\langle \delta N_\alpha \delta N_\beta \rangle = VT^3 \chi_n^{\alpha\beta} \quad \longleftrightarrow \quad \chi_2^{\alpha\beta} = \frac{d^2 P/T^4}{d(\mu_\alpha/T)d(\mu_\beta/T)}$$

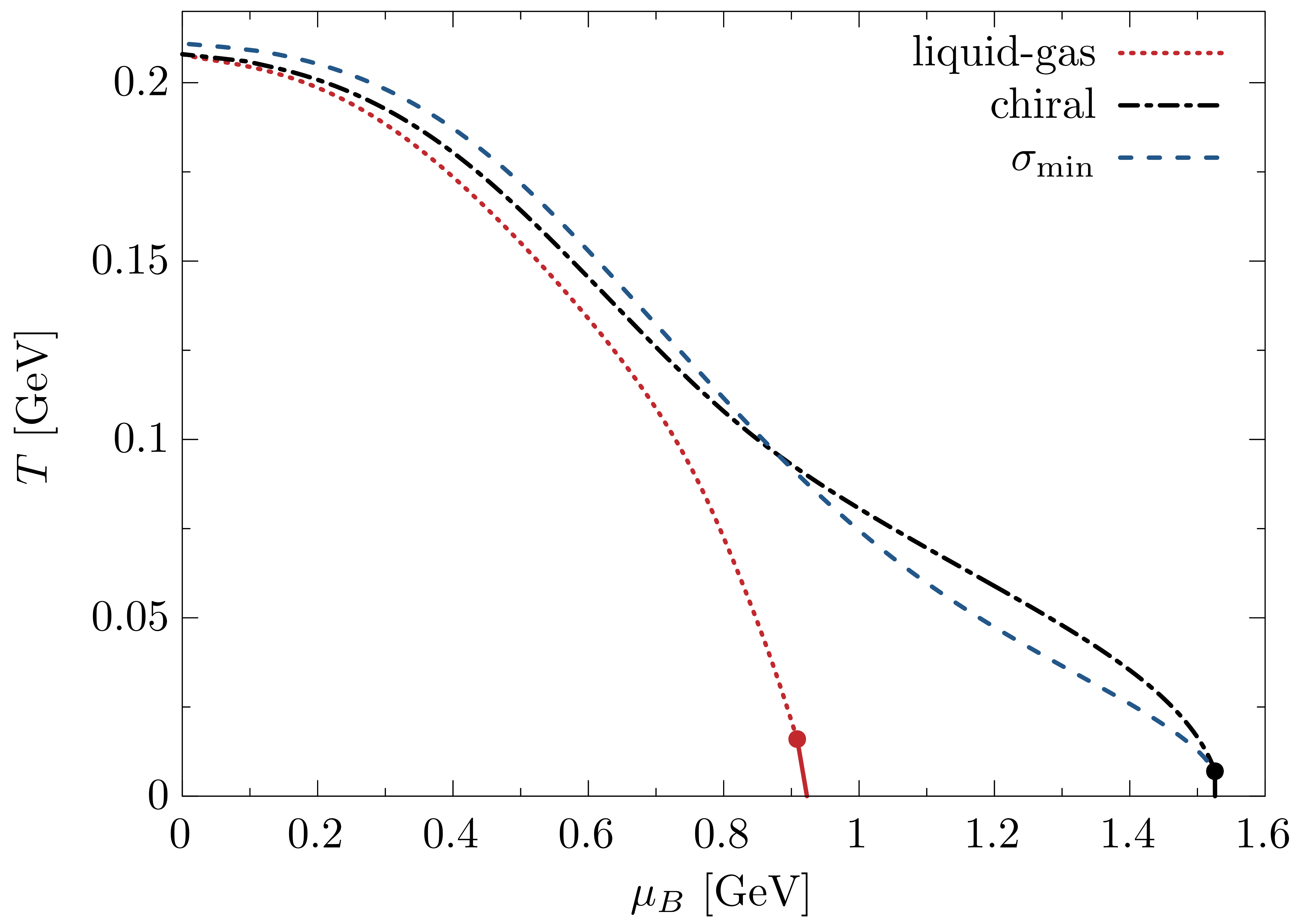
$$\chi_2^B = \chi_2^{++} + \chi_2^{--} + 2\chi_2^{+-}$$

- What are the individual contributions of parity partners N_+ and N_-?
- What is the strength and sign of the correlation χ_2^{+-}?
- Is net-proton a good proxy for net-baryon fluctuations? $\chi_2^B = \chi_2^{++} + \cancel{\chi_2^{--} + 2\chi_2^{+-}}$

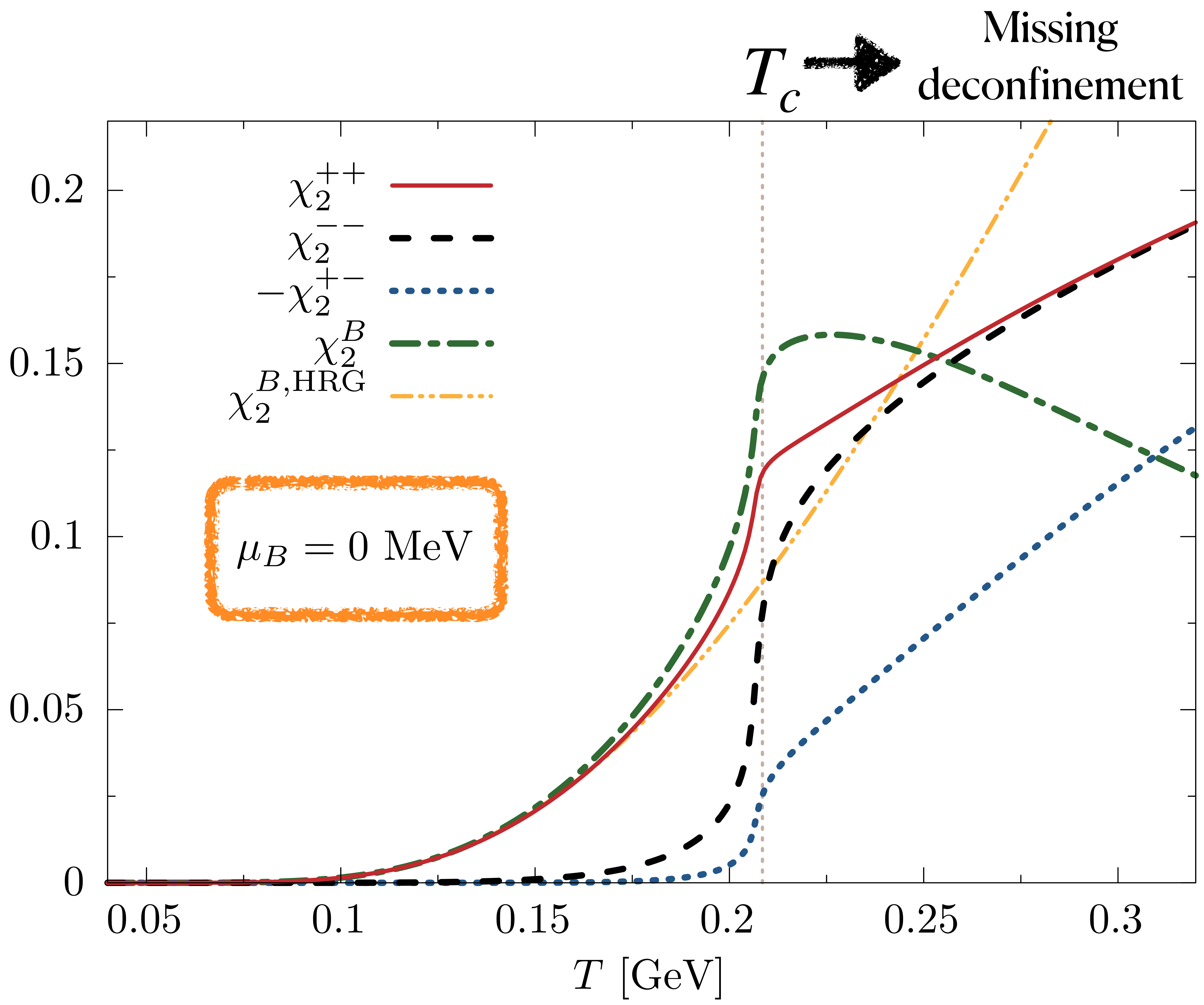
Model a'la DeTar, Kunihiro 1989 $\longrightarrow \mathscr{L}_{\text{mass}} \sim m_0 \left(\bar{\psi}_1 \gamma_5 \psi_2 + \bar{\psi}_2 \gamma_5 \psi_1\right)$

$$M_{\pm} = \frac{1}{2}\left(\sqrt{4m_0^2 + a^2\sigma^2} \mp b\sigma\right) \xrightarrow{\sigma \to 0} m_0$$





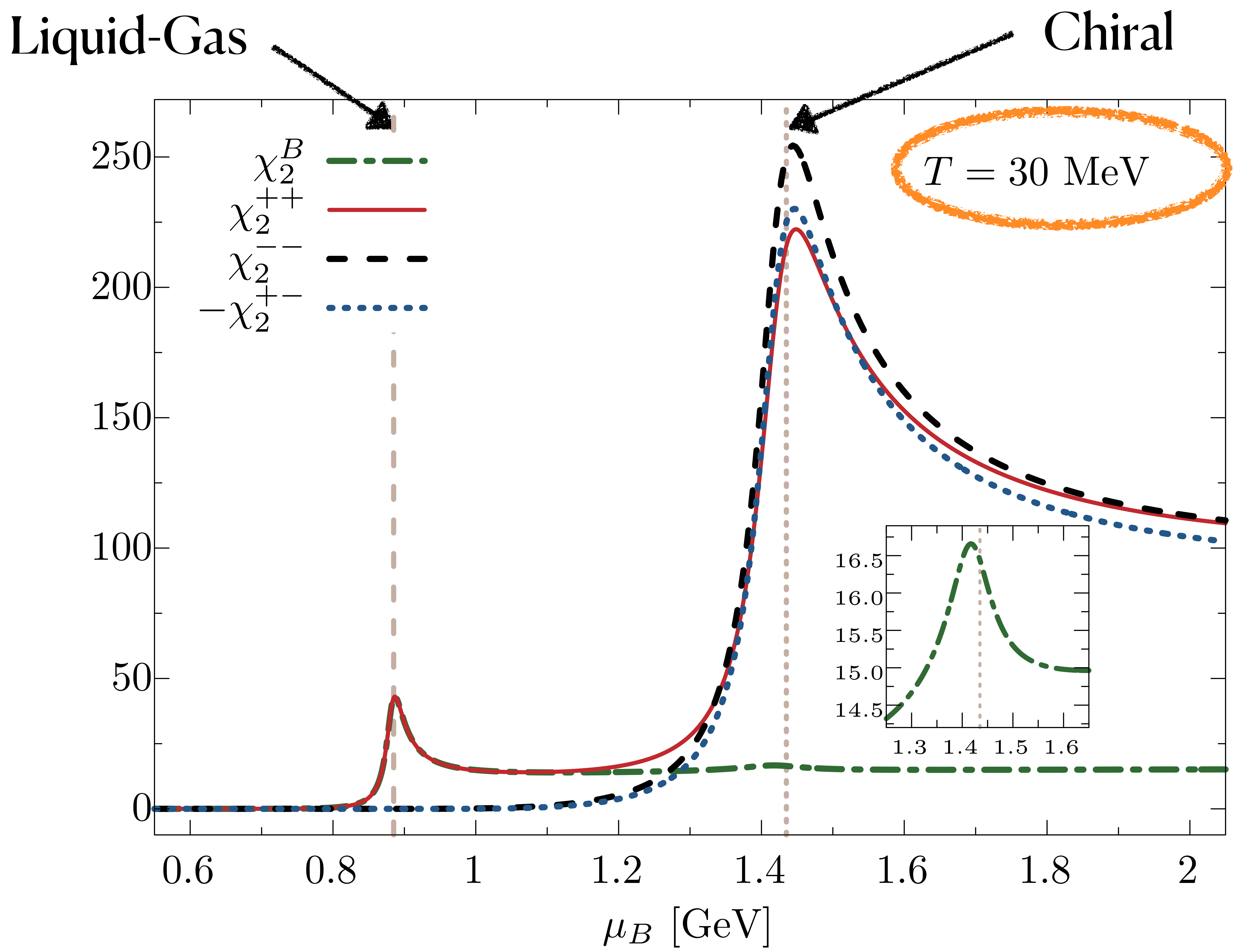
Fluctuations of chiral partners near crossover at $\mu_B = 0$

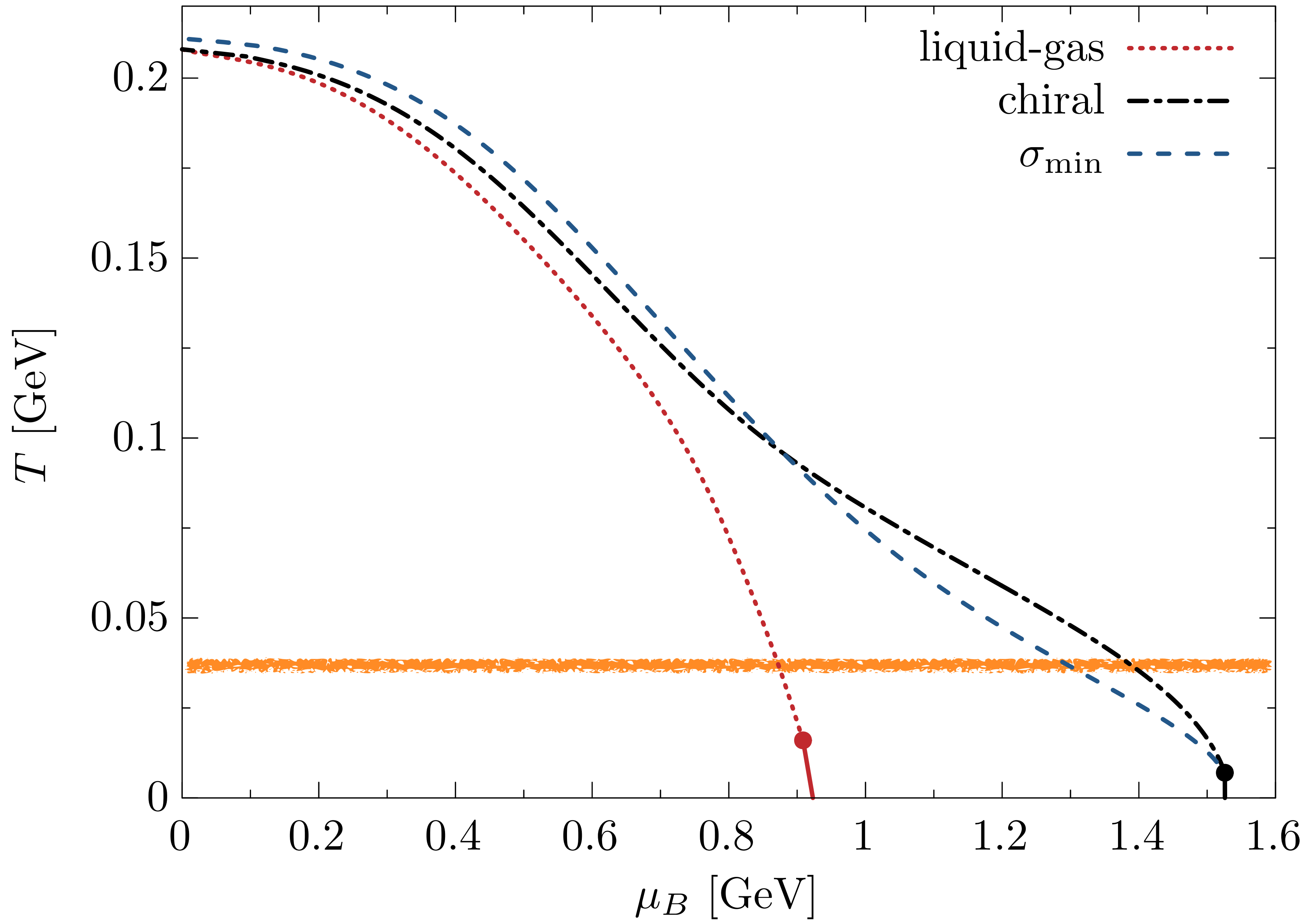


- χ_2^B dominated by nucleon (positive parity)
- N^- relevant only around T_c
- χ_2^{+-} relevant only around T_c and negative
- χ_2^{+-} more negative with repulsive interactions

Net-baryon number fluctuations sensitive to an interplay between repulsive interactions and chiral in-medium baryon masses

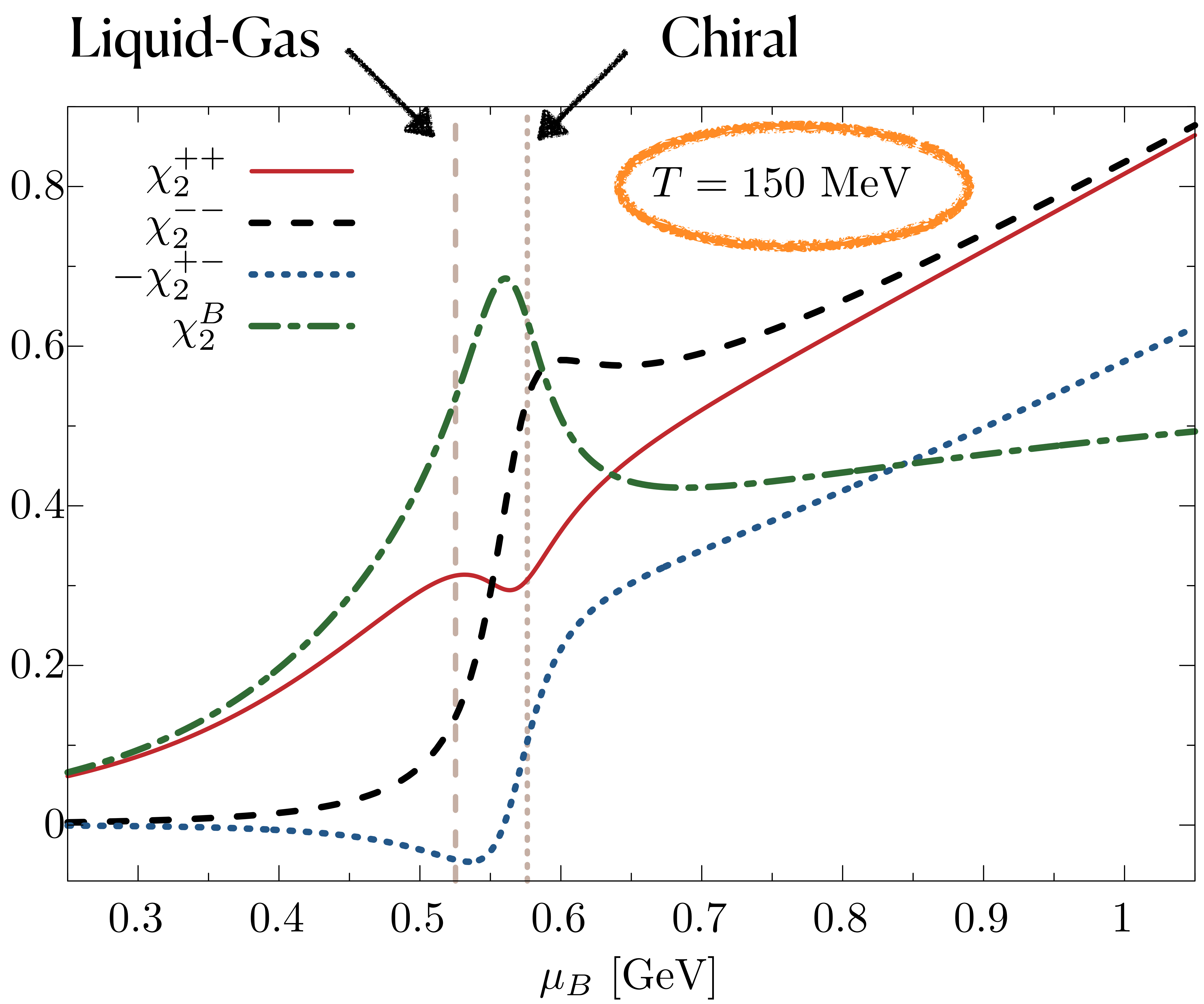
Fluctuations at liquid-gas and chiral transitions

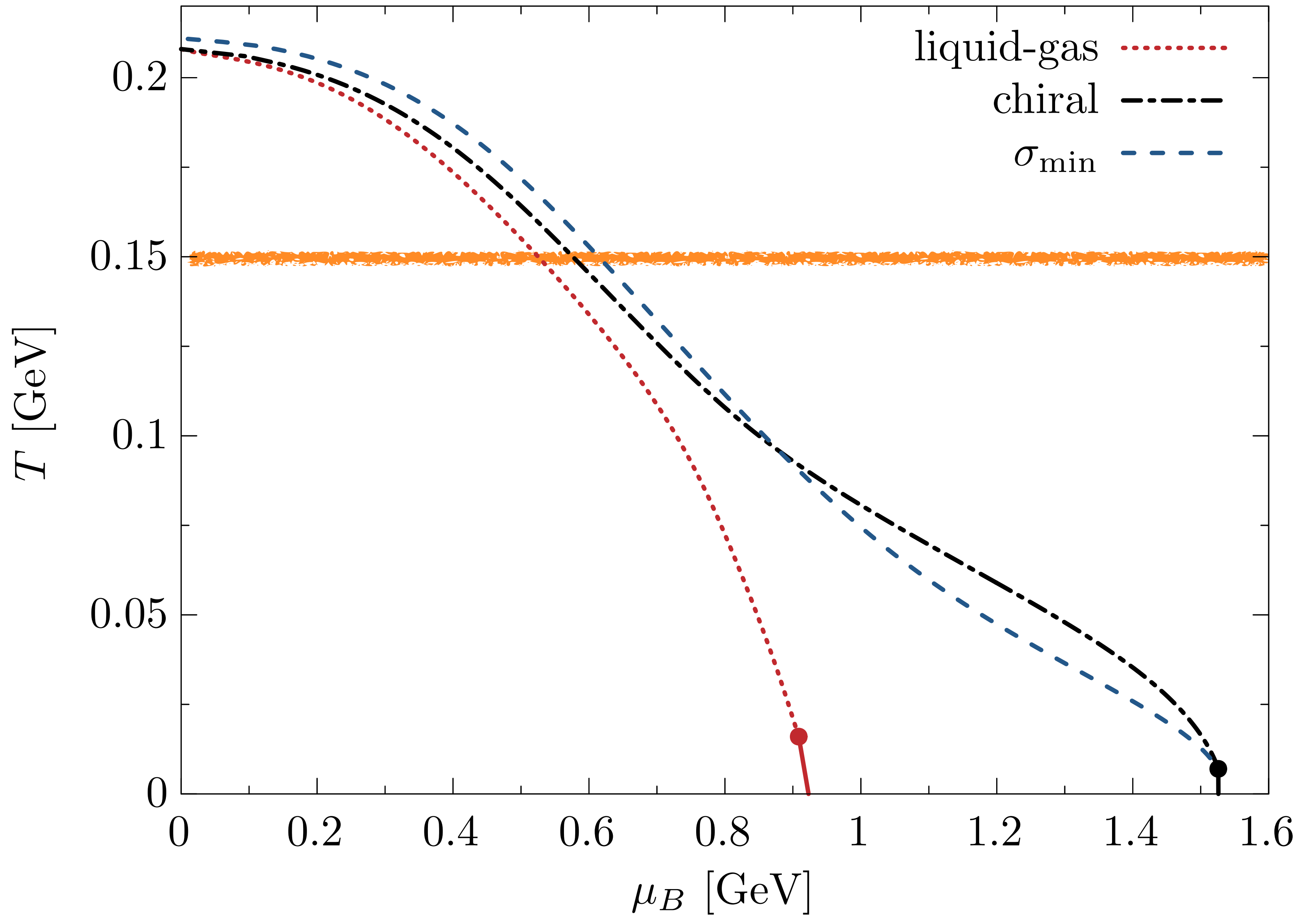




$$\chi_2^B = \chi_2^{++} + \chi_2^{--} + 2\chi_2^{+-}$$

Increasing T ⟶ peaks getting closer





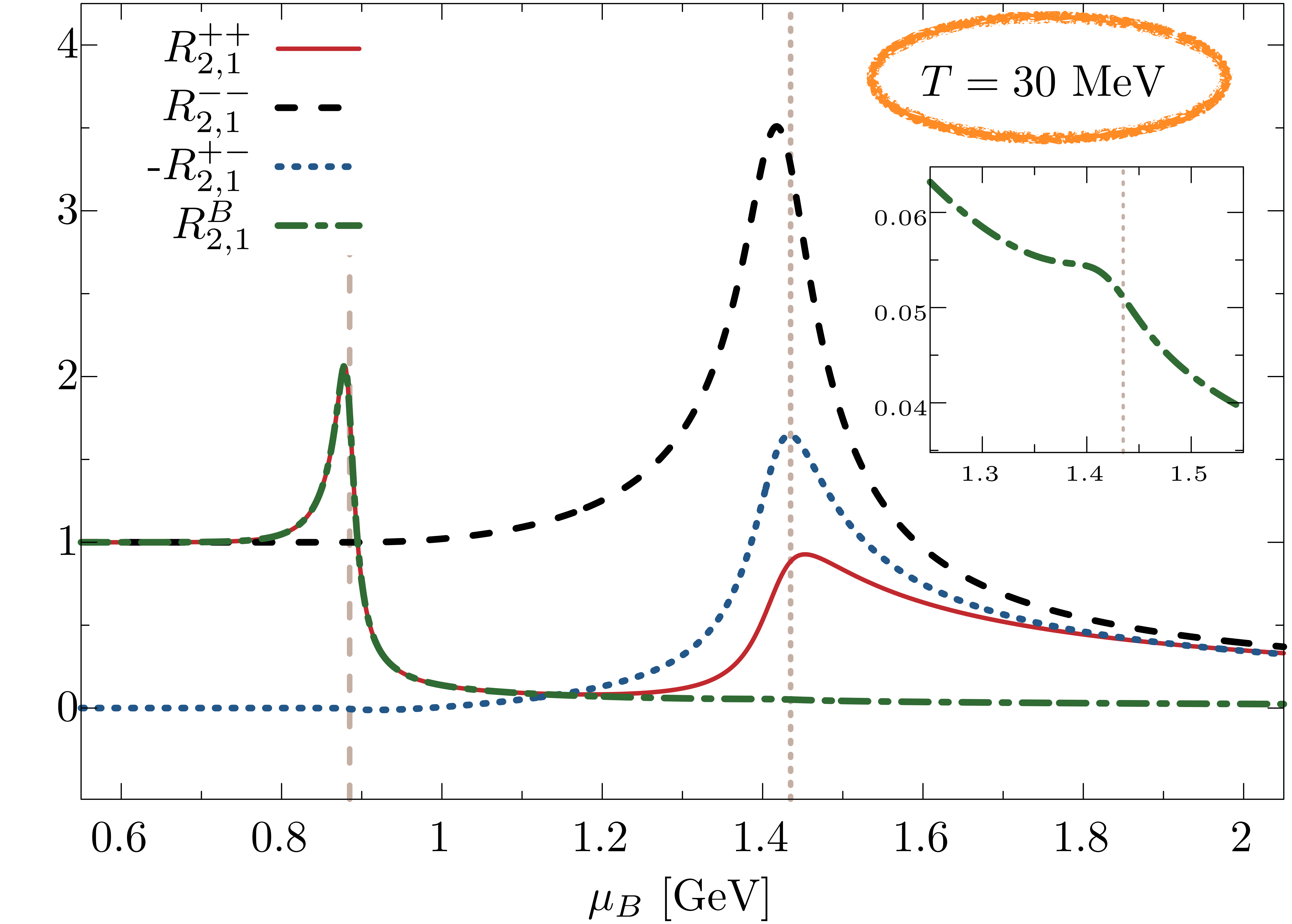
- Qualitative difference of χ_2^{++} and χ_2^{--}
- Stronger signal left in χ_2^{B}

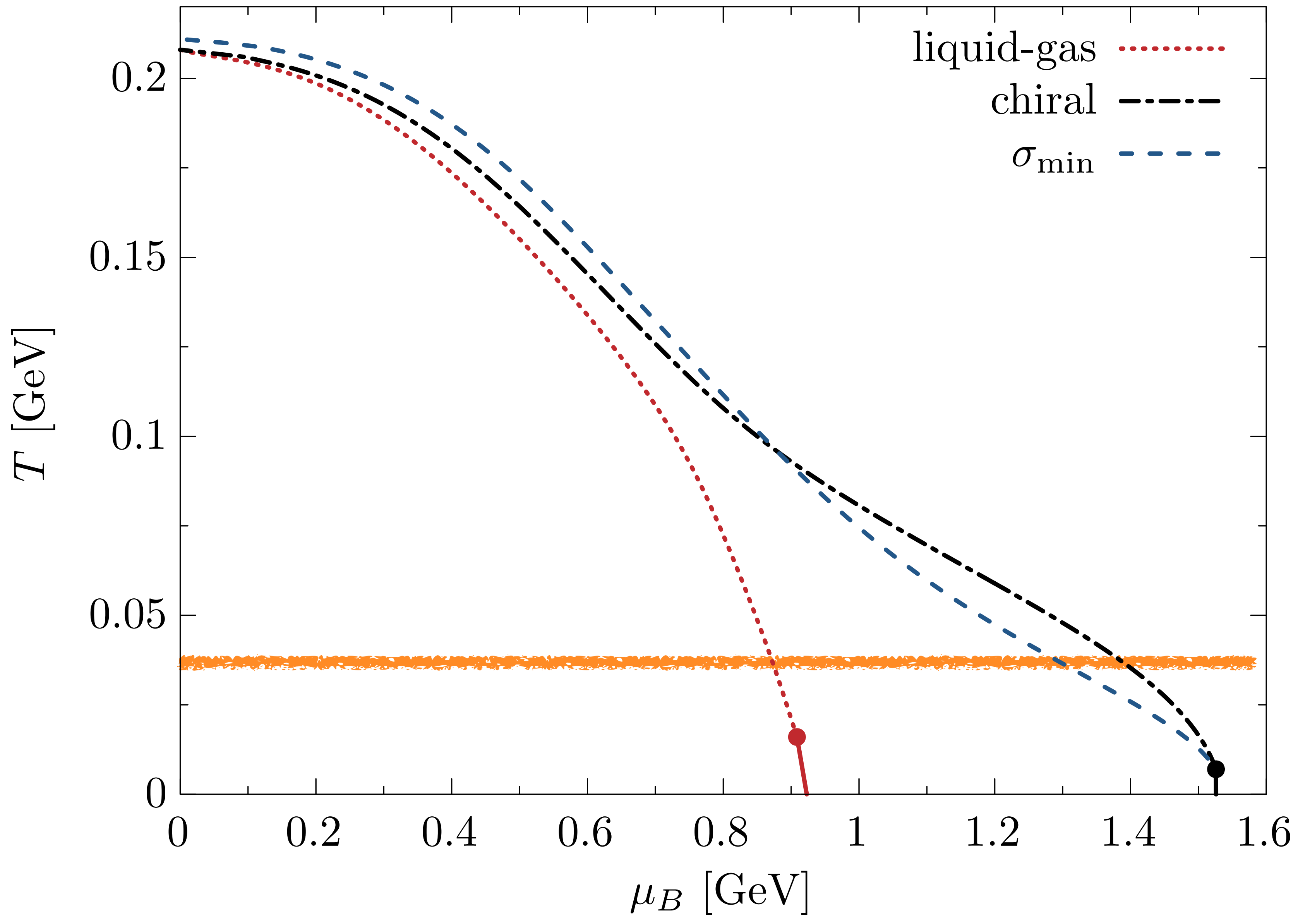
Cumulants $C_n \sim V$

$\downarrow$

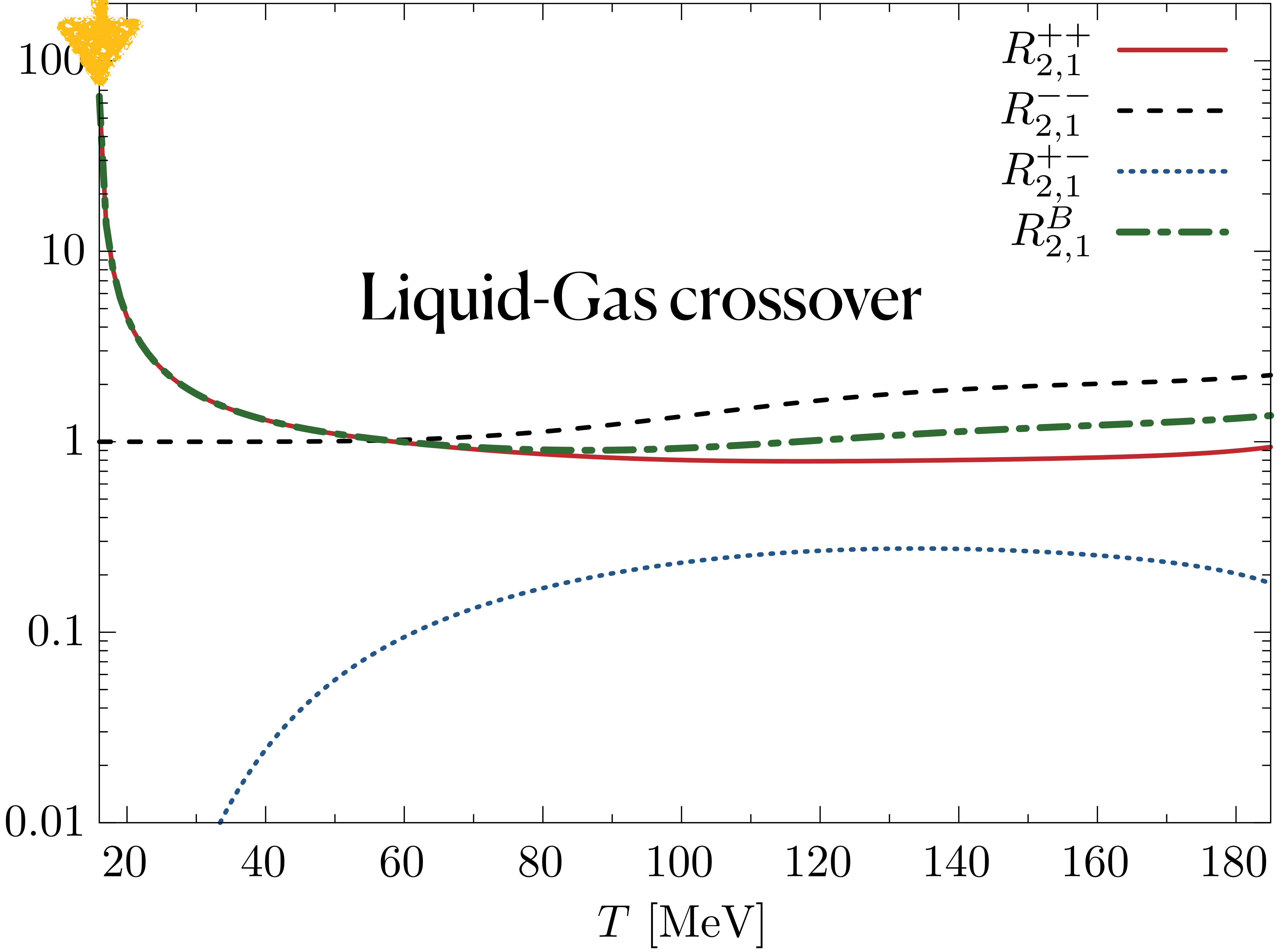
volume cancels in ratios

$$R_{2,1}^{\alpha\beta} \equiv \frac{C_2^{\alpha\beta}}{\sqrt{C_1^\alpha C_1^\beta}} = \frac{\chi_2^{\alpha\beta}}{\sqrt{\chi_1^\alpha \chi_1^\beta}} = \frac{\sigma^2}{M}$$

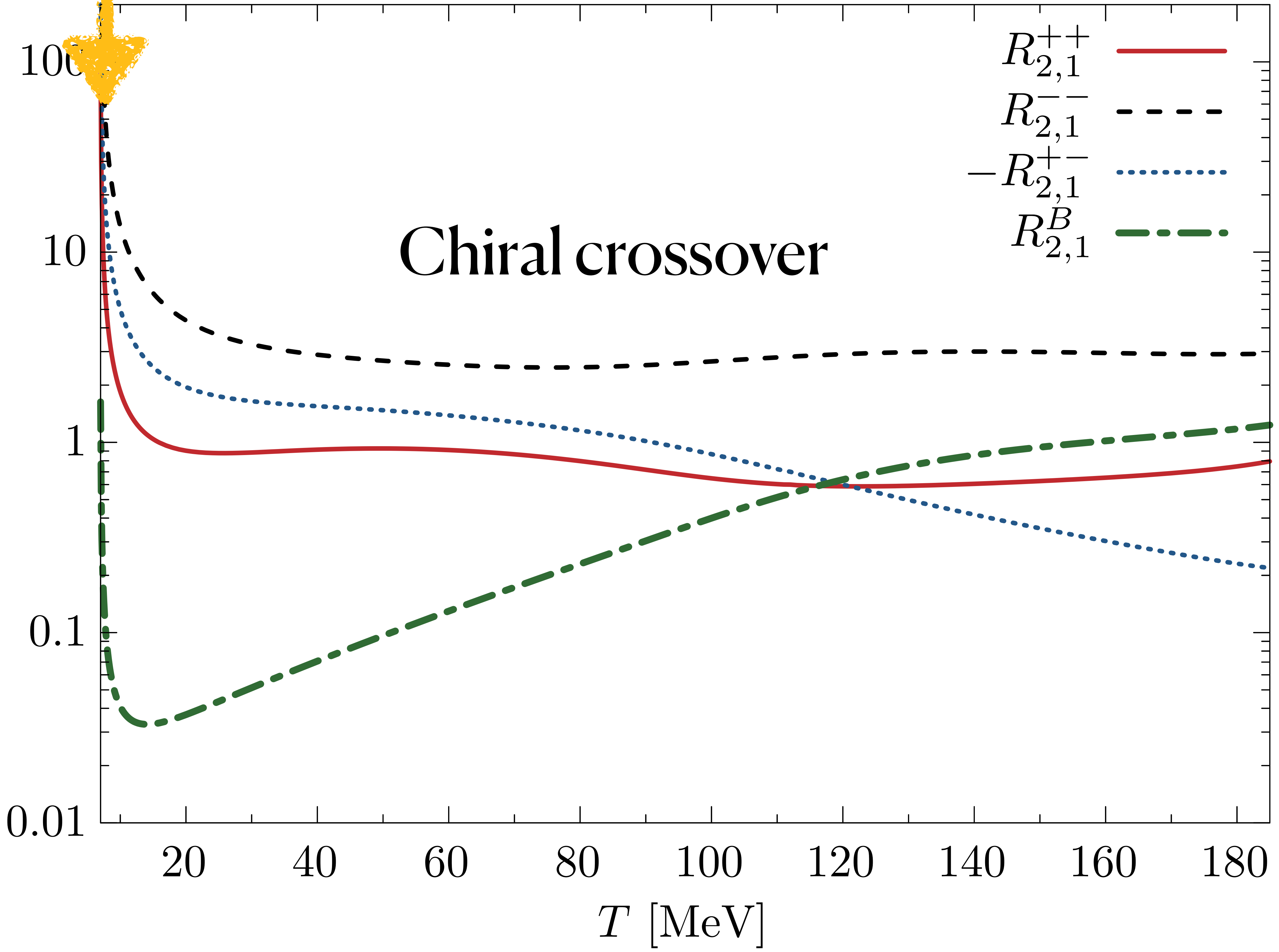




Liquid-Gas CP



Chiral CP



Fluctuations dominated by positive parity

Net-baryon ~ Net-nucleon

Presence of chiral partners + correlations

Net-baryon ≪ Net-nucleon

Summary

Negative correlations between baryonic chiral partners

χ_2^{proton} may not reflect χ_2^B at the chiral phase boundary

Interesting to calculate $\chi_2^{++}, \chi_2^{--}, \chi_2^{+-}$ in other non-perturbative approaches

Thank You

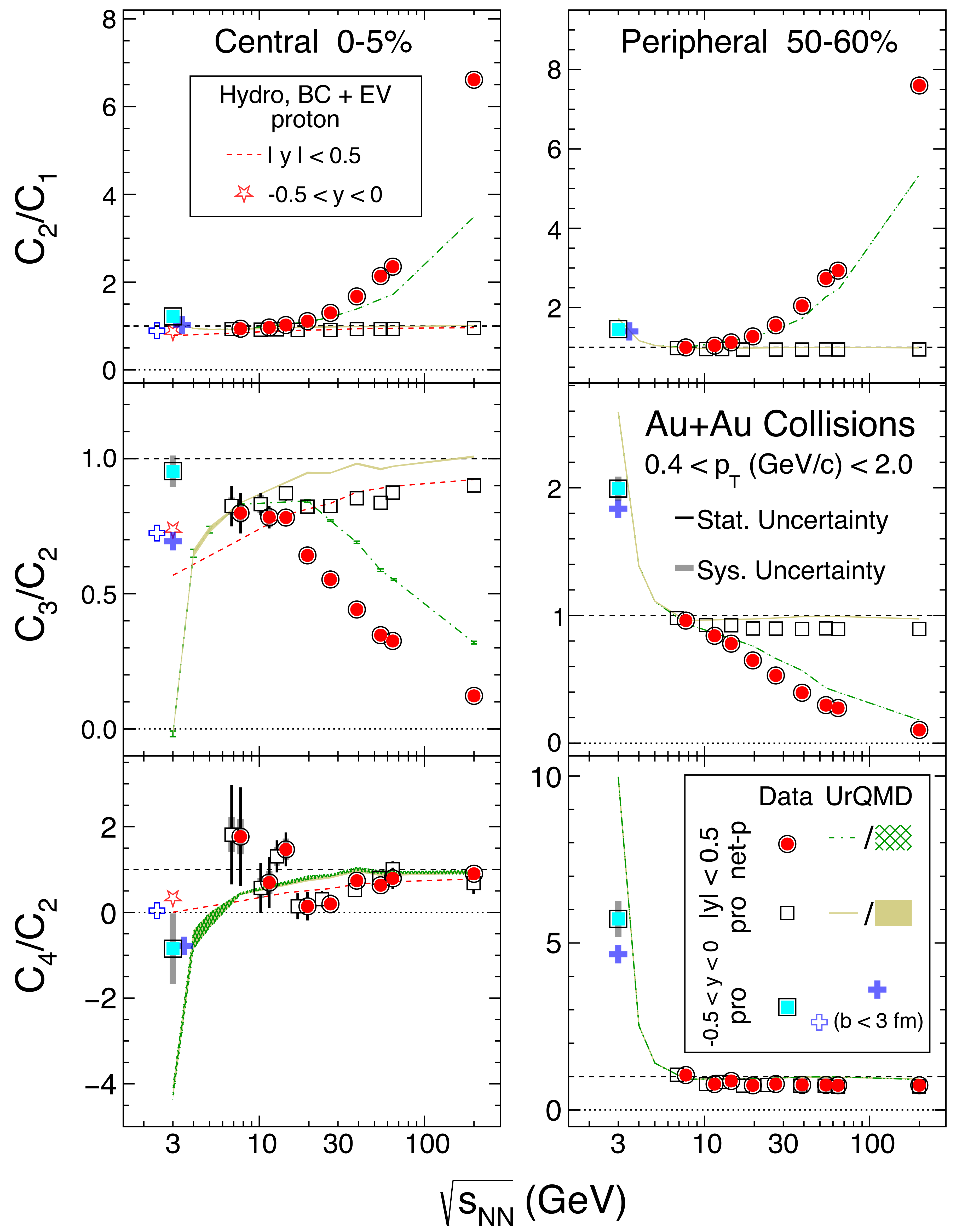
Cumulants vs Susceptibilities

Mean: M	$\langle N_B \rangle$	C_1
Variance: σ^2	$\langle (\delta N_B)^2 \rangle$	C_2
Skewness: S	$\langle (\delta N_B)^3 \rangle / \sigma^3$	$C_3/C_2^{3/2}$
Kurtosis: K	$\langle (\delta N_B)^4 \rangle / \sigma^3 - 3$	C_4/C_2^2

$$C_n \equiv VT^3 \frac{d^nP/T^4}{d\left(\mu_B/T\right)^n}\Bigg|_T \quad \longleftrightarrow \quad \chi_n^B \equiv \frac{d^nP/T^4}{d(\mu_B/T)^n}\Bigg|_T$$

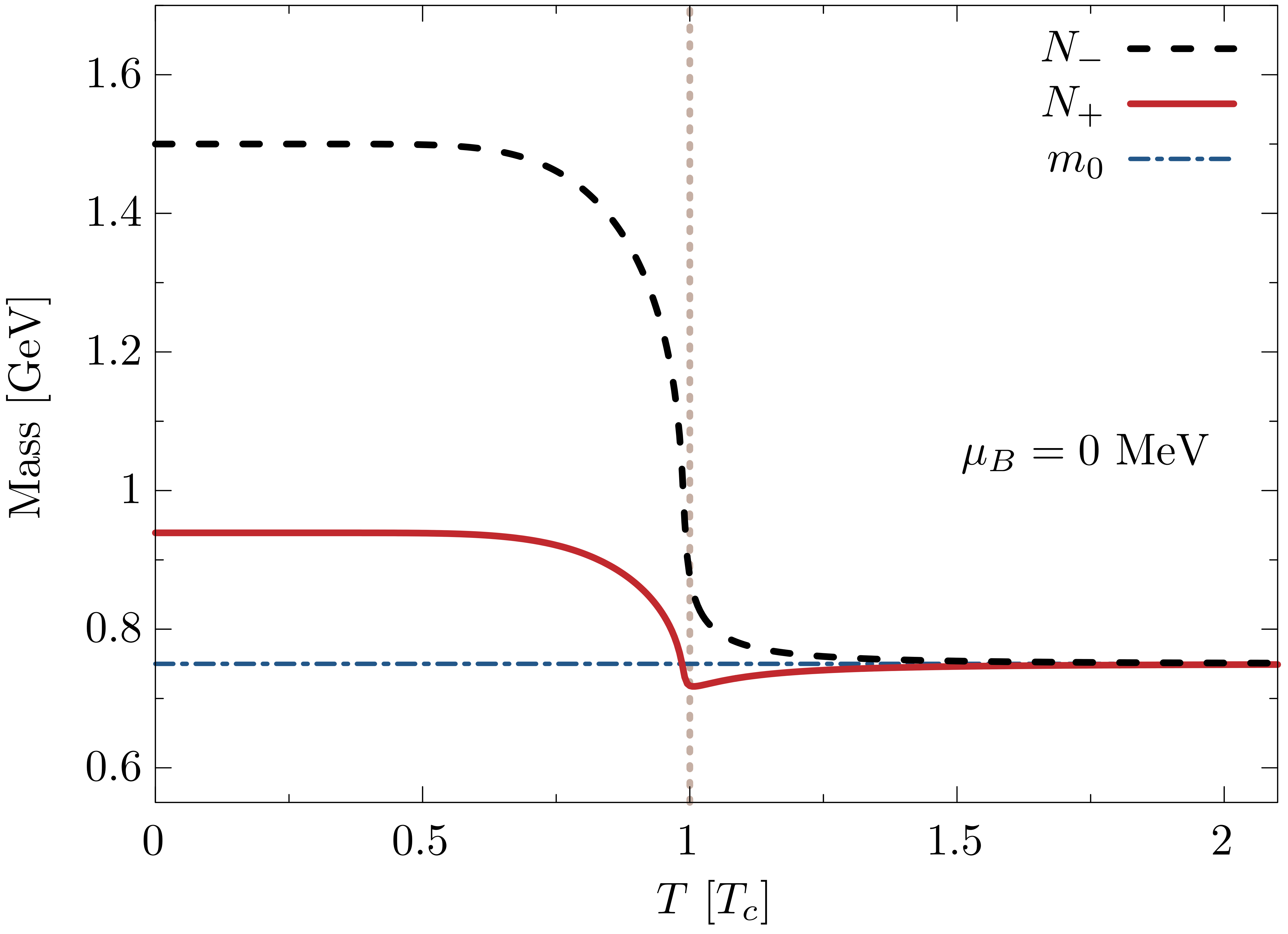
$$\boxed{C_n = VT^3\chi_n^B}$$

STAR, 2023

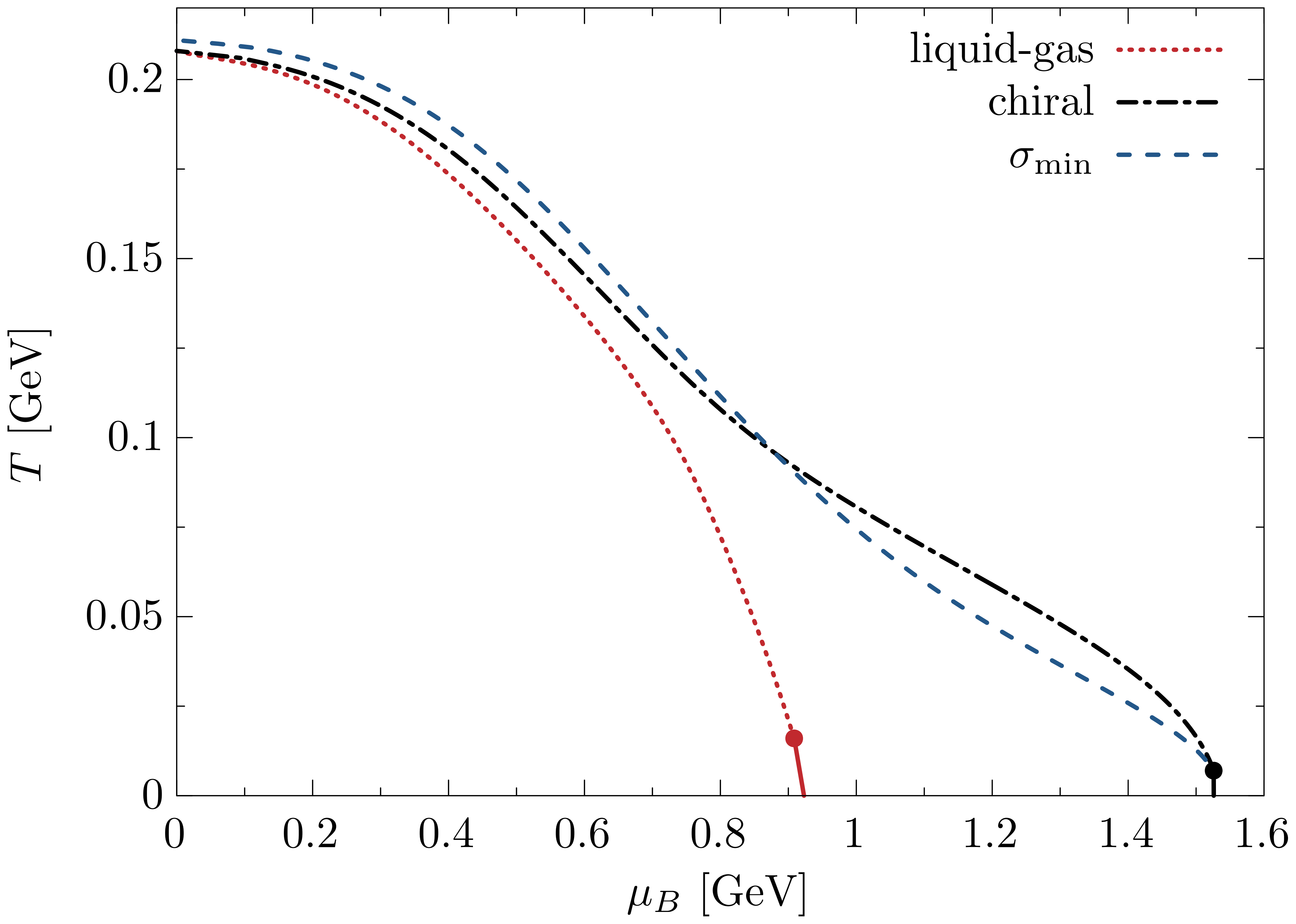


Chiral Criticality in Parity Doubling Model

In-medium masses

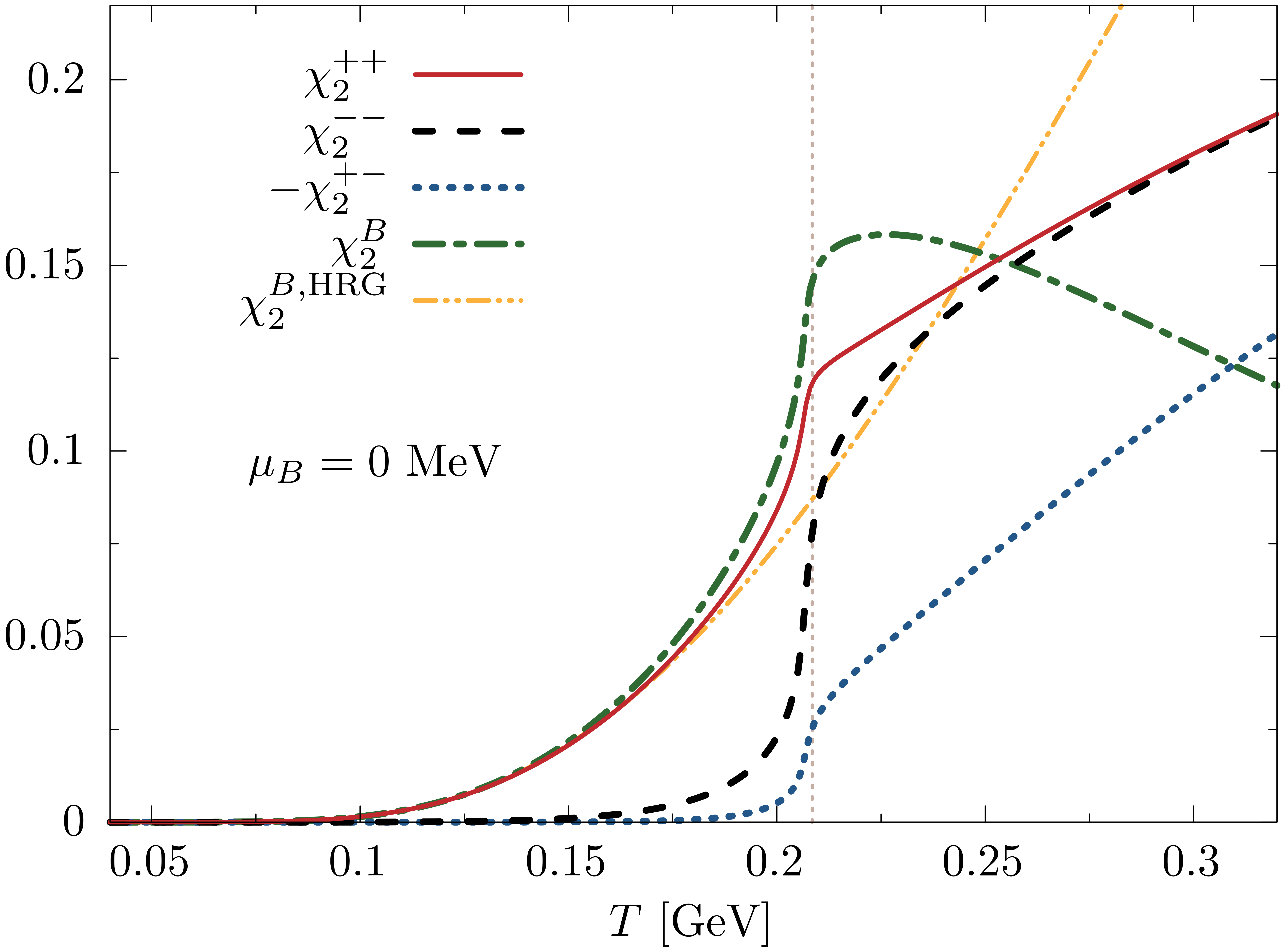


Phase diagram with liquid gas and chiral PTs

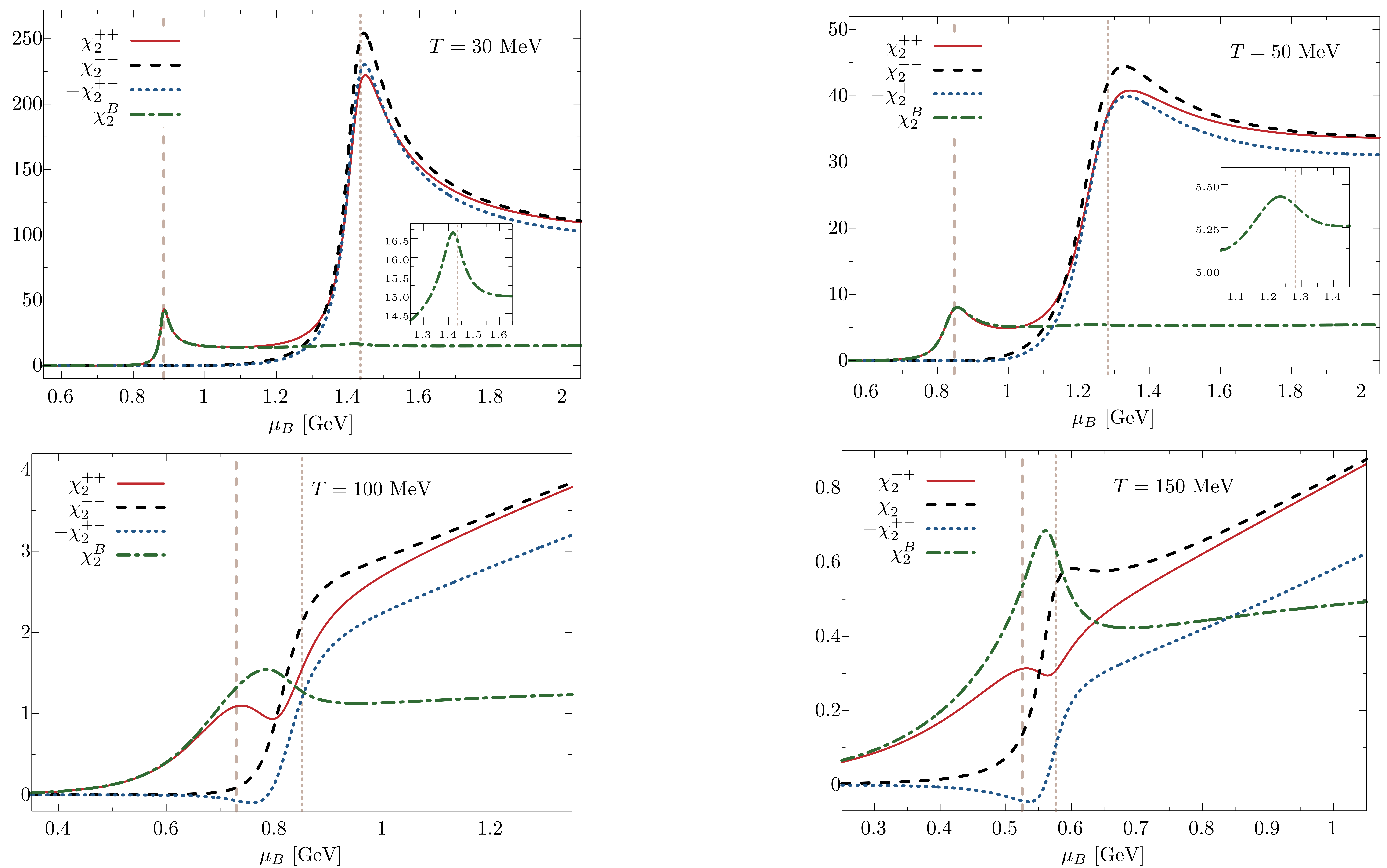


- M_- monotonically decreases
- M_+ has a minimum at $\sigma_{\mathrm{min}} = 2\dfrac{b}{a}\dfrac{m_0}{\sqrt{a^2 - b^2}}$

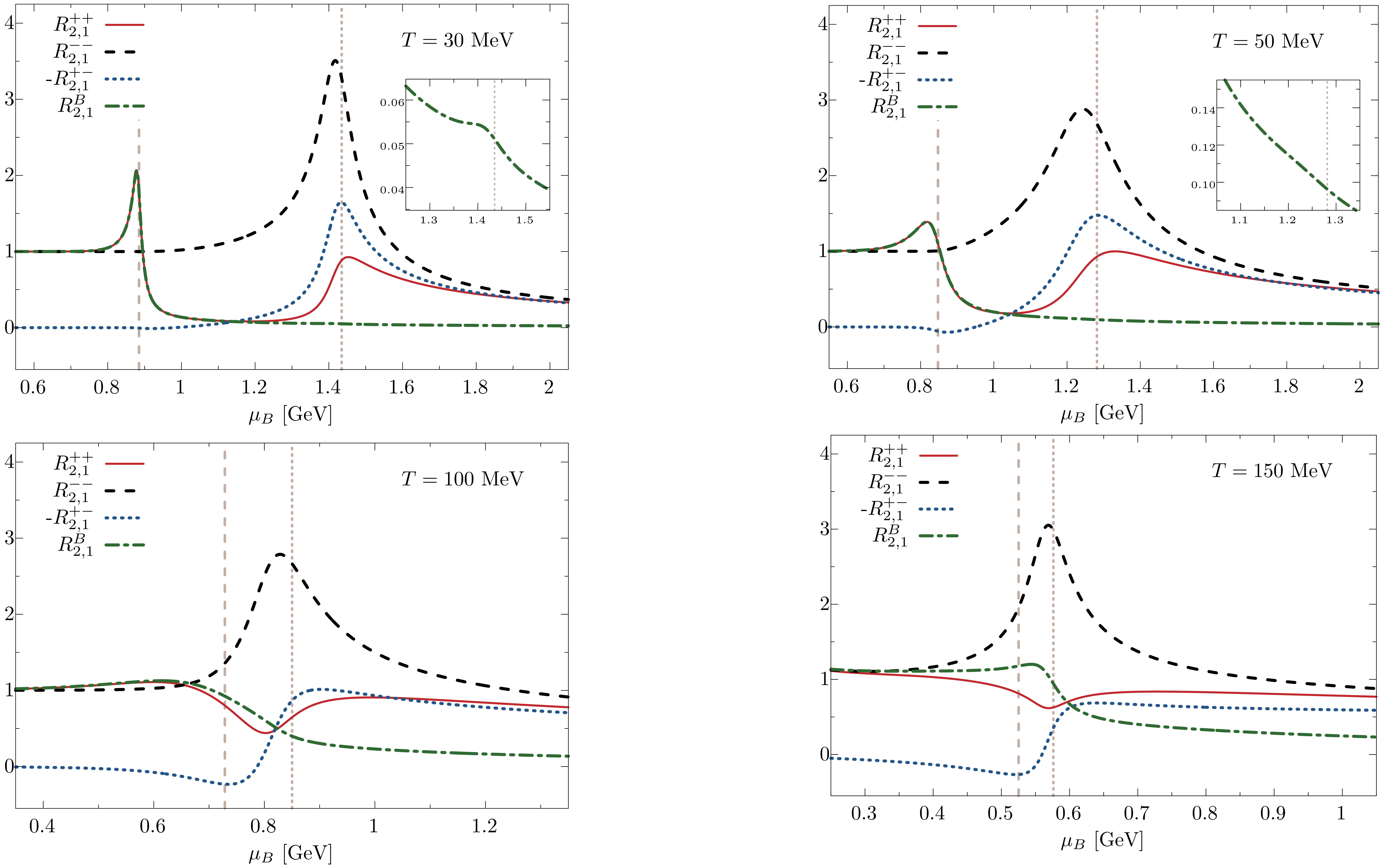
- Position of σ_{min} closely related to the chiral phase transition

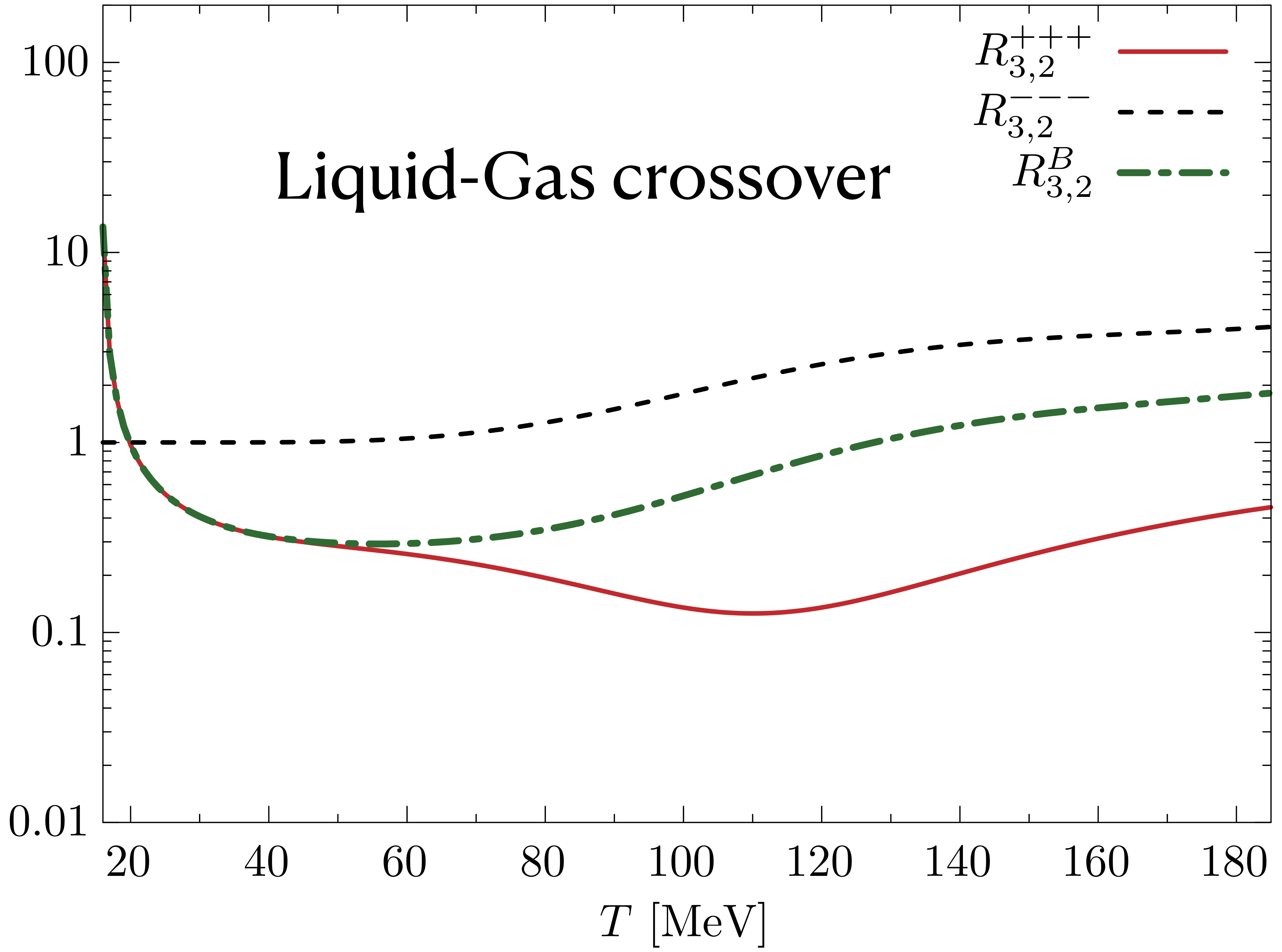


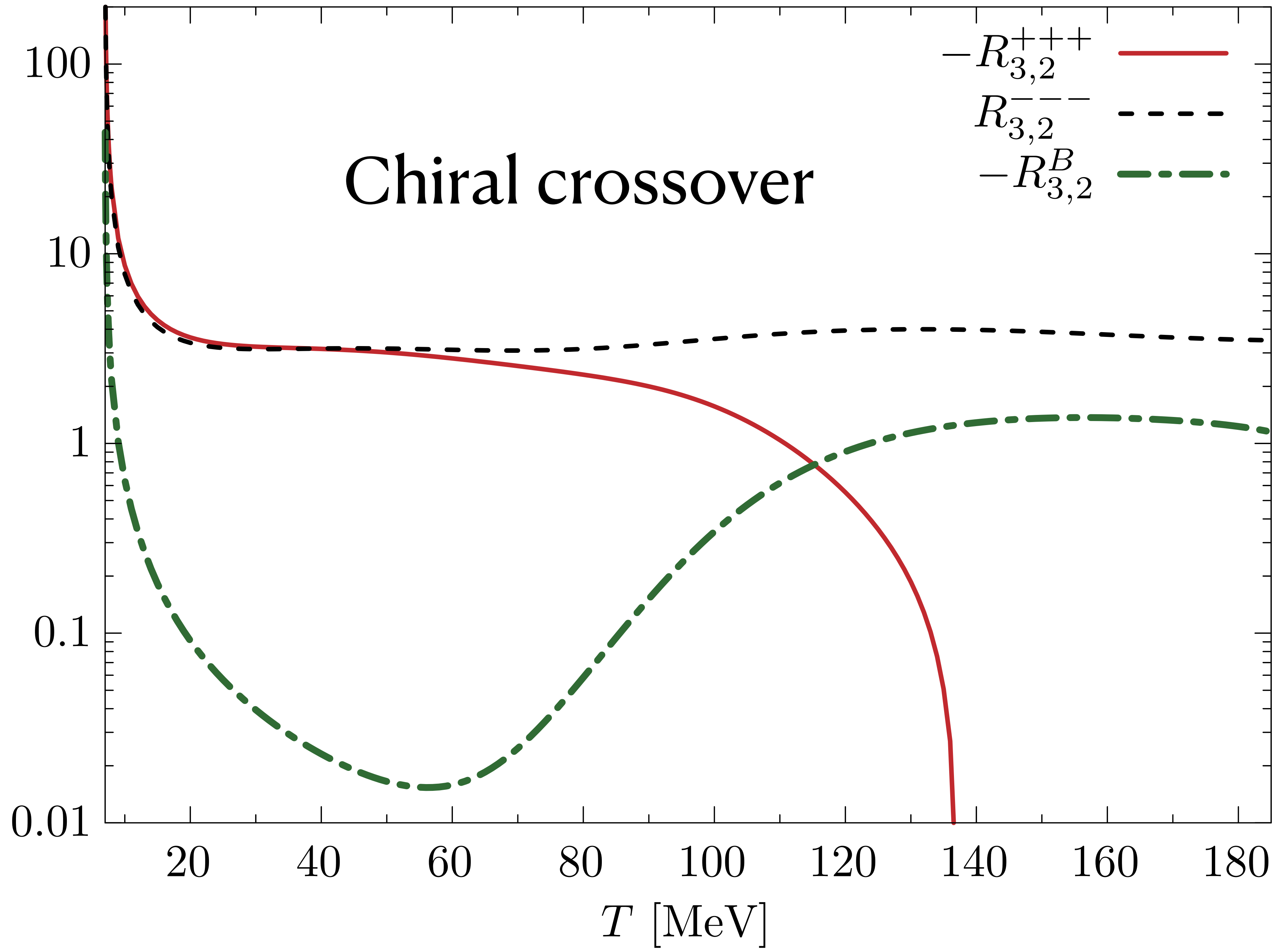
χ_2^{++}
χ_2^{--}
$-\chi_2^{+-}$
χ_2^{B}
$\chi_2^{B,\mathrm{HRG}}$
$\mu_B = 0$ MeV
0
0.05
0.1
0.15
0.2
0.05
0.1
0.15
0.2
0.25
0.3
T [GeV]



χ_2^{++}
χ_2^{--}
$-\chi_2^{+-}$
χ_2^{B}
$T = 30$ MeV
$T = 50$ MeV
$T = 100$ MeV
$T = 150$ MeV
μ_B [GeV]

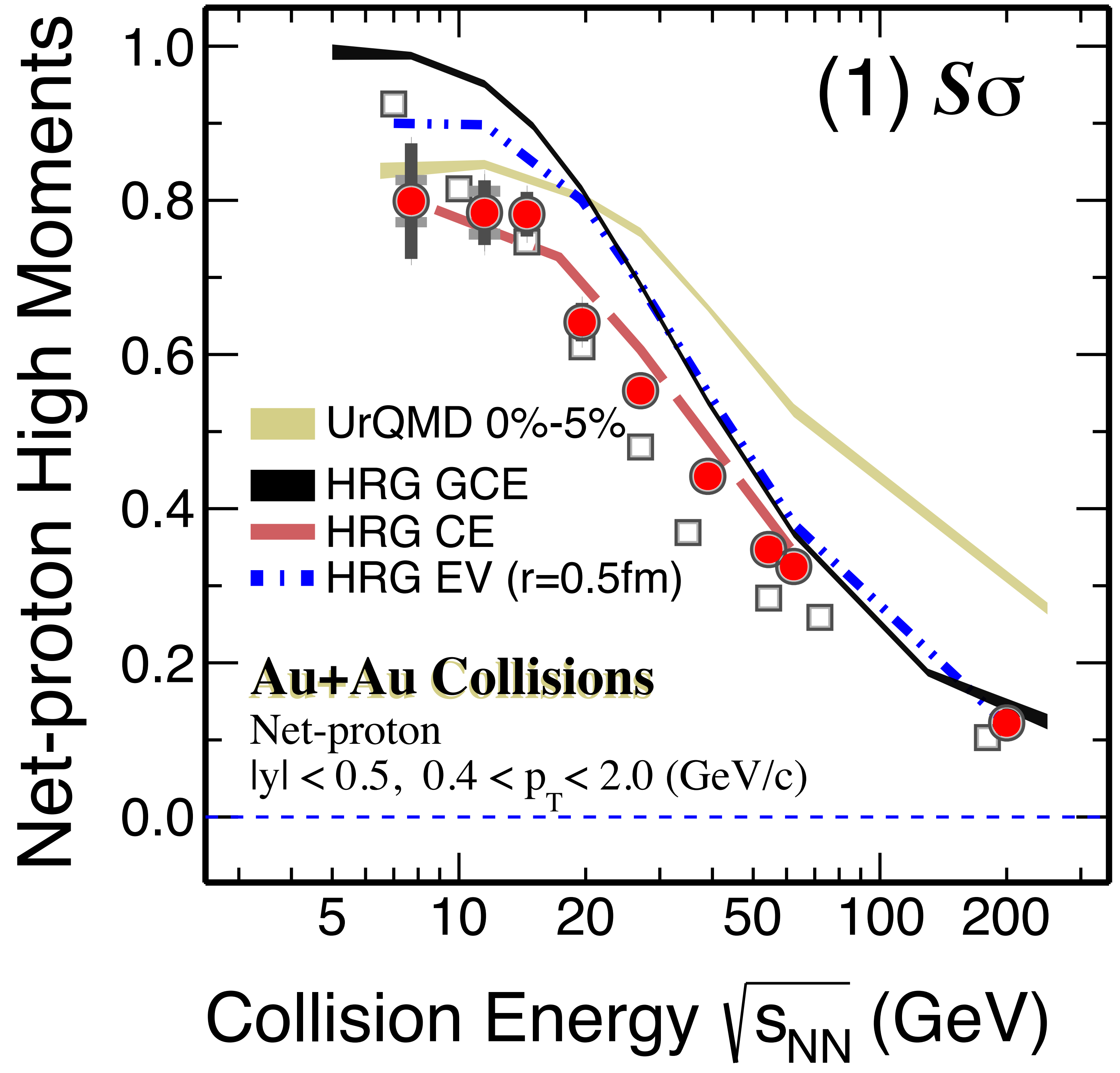

$R^{++}_{2,1}$
$R^{--}_{2,1}$
$-R^{+-}_{2,1}$
$R^{B}_{2,1}$
$T = 30$ MeV
μ_B [GeV]
$R^{++}_{2,1}$
$R^{--}_{2,1}$
$-R^{+-}_{2,1}$
$R^{B}_{2,1}$
$T = 50$ MeV
μ_B [GeV]
$R^{++}_{2,1}$
$R^{--}_{2,1}$
$-R^{+-}_{2,1}$
$R^{B}_{2,1}$
$T = 100$ MeV
μ_B [GeV]
$R^{++}_{2,1}$
$R^{--}_{2,1}$
$-R^{+-}_{2,1}$
$R^{B}_{2,1}$
$T = 150$ MeV
μ_B [GeV]





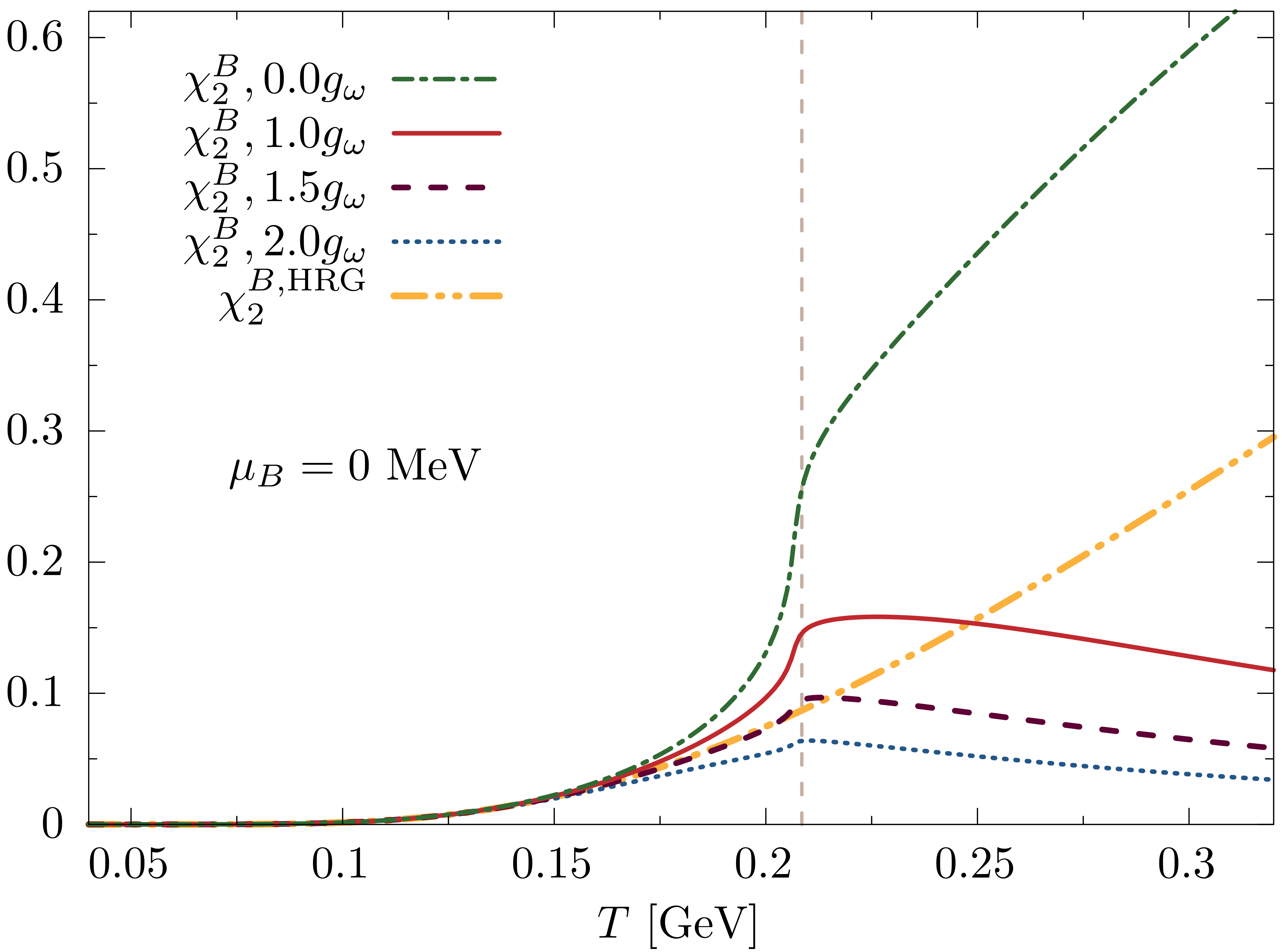
$$R^{\alpha\alpha\alpha}_{3,2} \equiv \frac{C^{\alpha\alpha}_3}{C^{\alpha\alpha}_2} = \frac{\chi^{\alpha\alpha}_3}{\chi^{\alpha\alpha}_2} = S\sigma$$

STAR, 2021



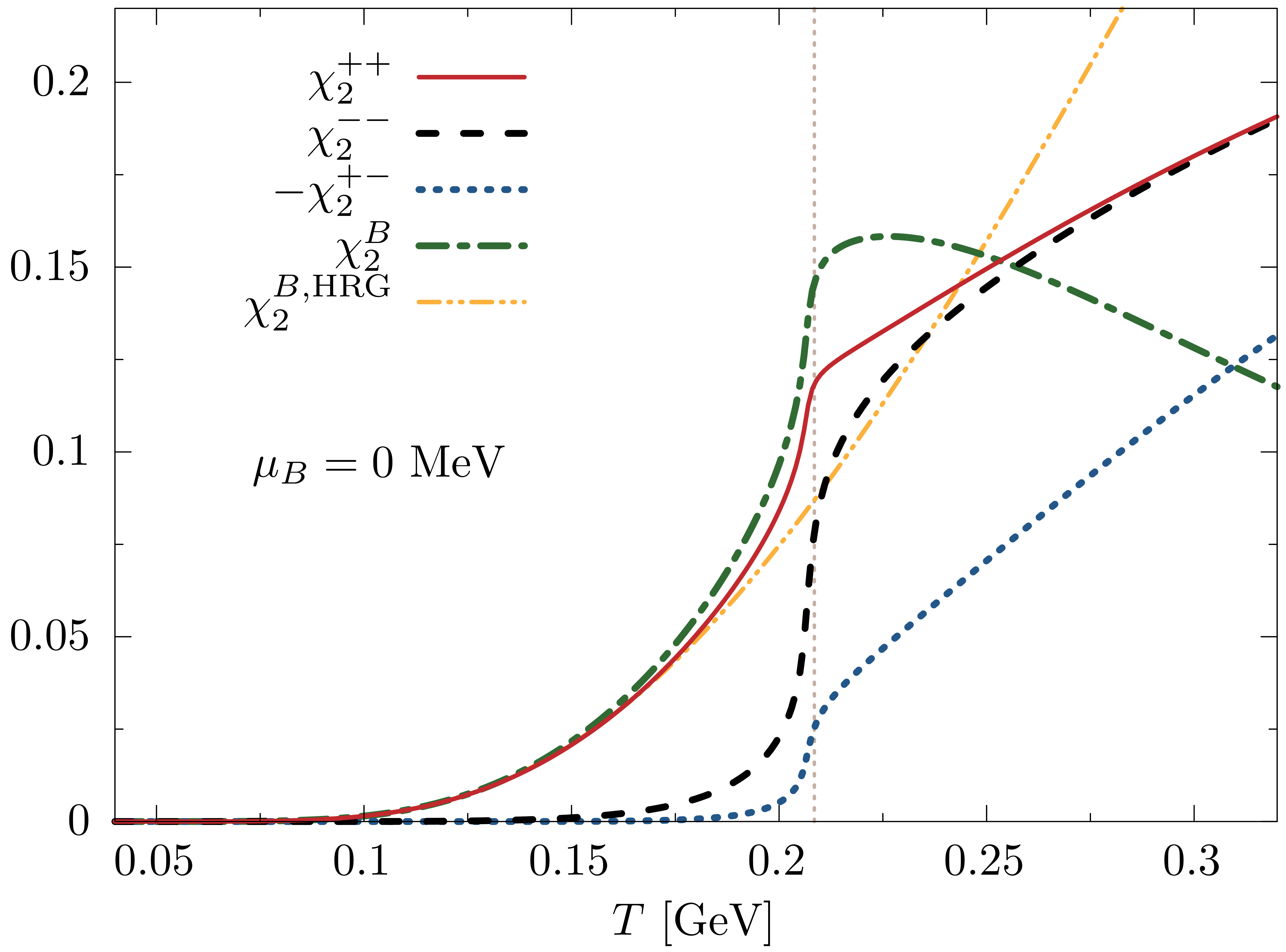
Influence of the strength of the repulsive interactions

- Clear suppression of fluctuations with an increasing repulsive vector interactions
- Increase of fluctuations due to in-medium chiral masses is reduced via negative correlations
- With particular repulsion strength, fluctuations are pushed down to HRG results with vacuum masses



Fluctuations of chiral partners near crossover at $\mu_B = 0$

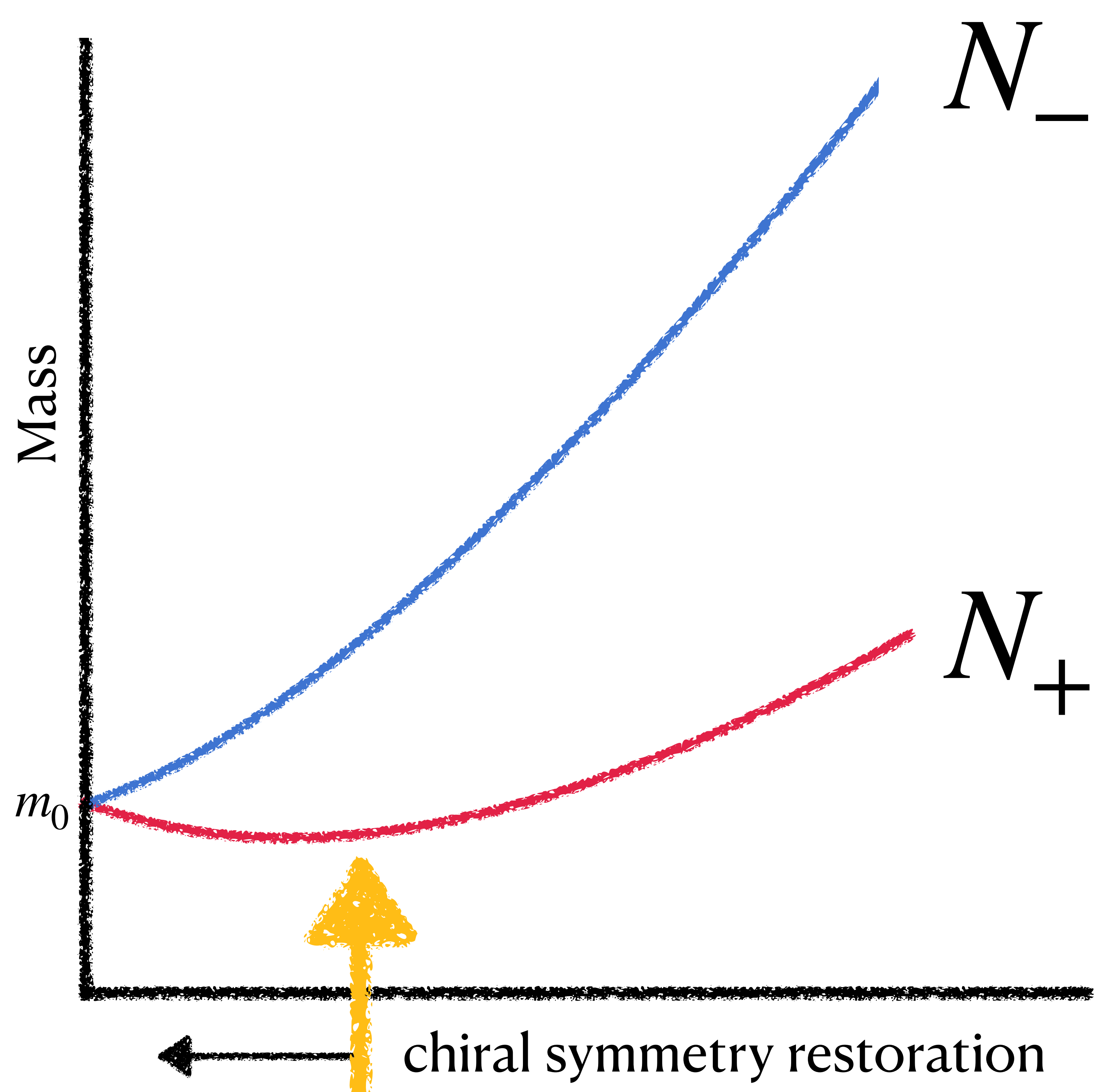
T_c → Missing deconfinement

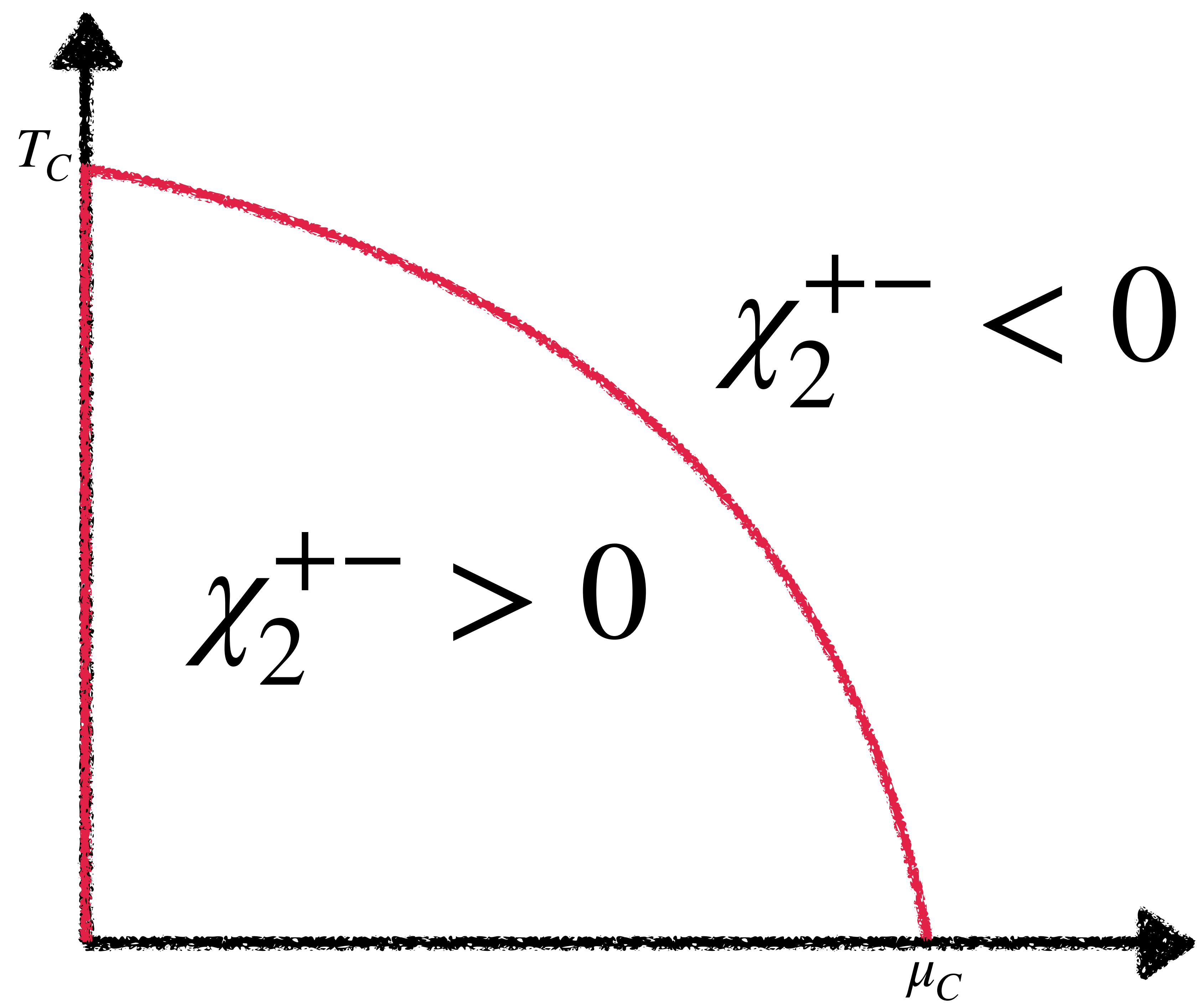


- Overall fluctuations dominated by net-nucleon at $\mu_B = 0$
- Contributions of N_- relevant only in the vicinity of T_c
- Correlations of N_+ and N_- provide negative contribution and set in only near T_c

Net-baryon number fluctuations sensitive to an interplay between repulsive interactions and chiral in-medium baryon masses

Idealized behavior of the correlator $\longrightarrow$ no repulsive forces





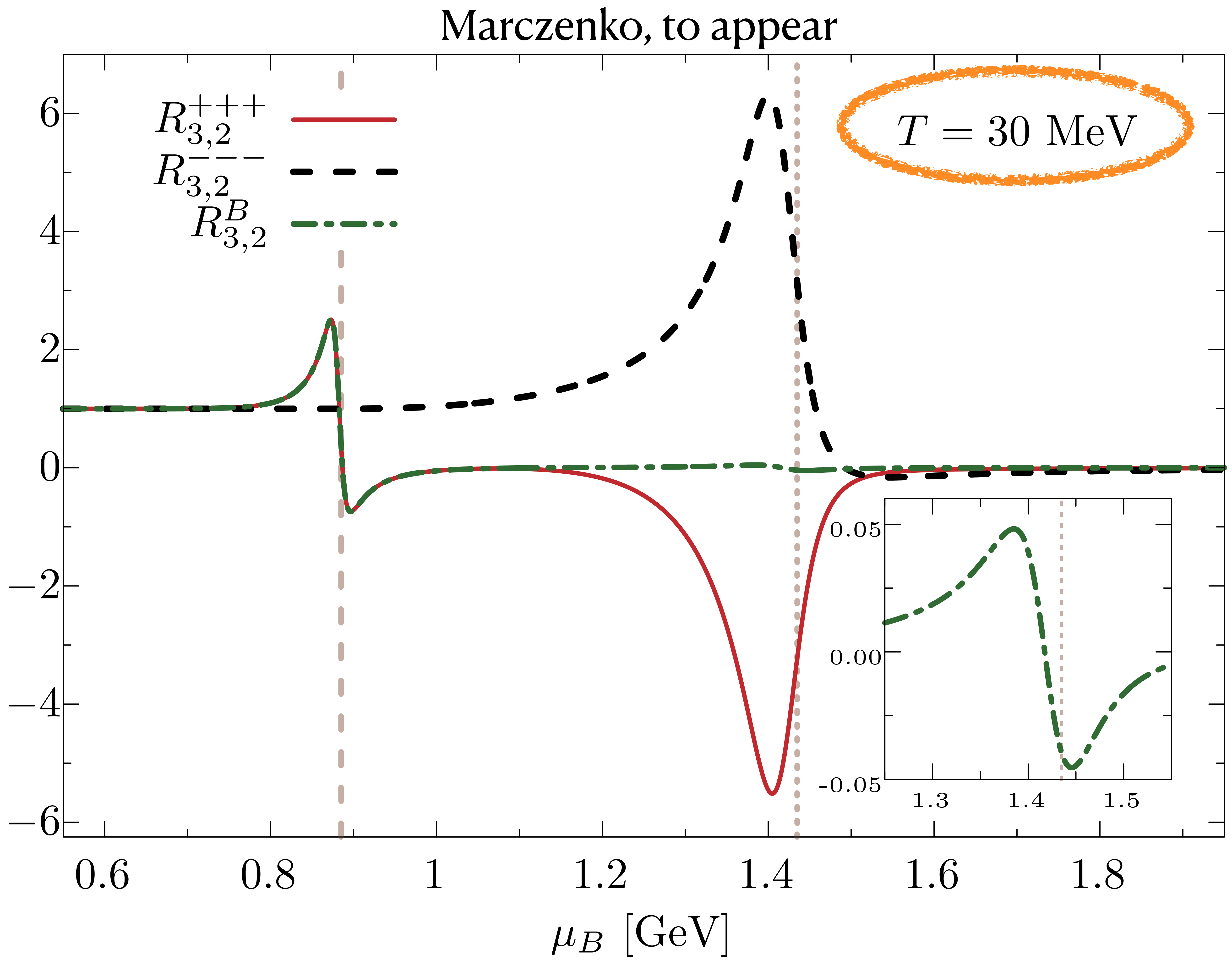
Min of M_+

$$\chi_2^{+-} \sim \frac{\partial m_+}{\partial \sigma} \frac{\partial m_-}{\partial \sigma}$$

$\longrightarrow$ but also repulsion

Change of the sign of χ_2^{+-} linked to the chiral phase boundary $\longrightarrow$ interesting quantity to calculate in LQCD

Higher-Order Fluctuations of Parity Partners



Consider $R_{3,2}^{+}$, $R_{3,2}^{-}$, $R_{3,2}^{B}$, where

$$R_{3,2}^{\alpha} \equiv \frac{C_3^{\alpha\alpha}}{C_2^{\alpha\alpha}} = \frac{\chi_3^{\alpha\alpha}}{\chi_2^{\alpha\alpha}} = S\sigma$$

- Very different properties of positive and negative parity partners fluctuation ratios $R_{3,2}^{\alpha}$
- Essentially different from the fluctuations of net baryon number
- Proton number $\neq$ baryon number fluctuation ratios