Chiral Separation Effect and Kondo effect in finite-density SU(2) gauge theory

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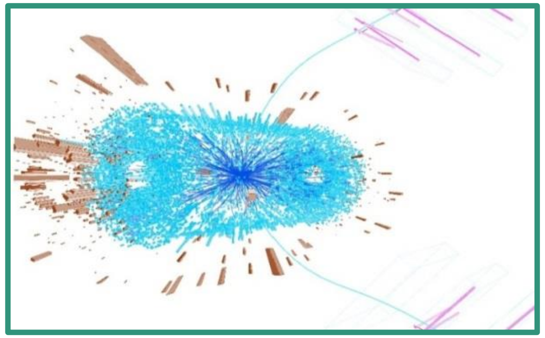
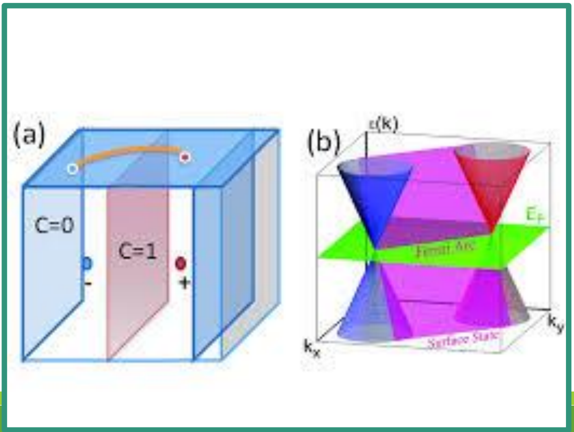
Why chiral plasmas?

Collective motion of chiral fermions



- **High-energy physics:**
  - ✓ Quark-gluon plasma
  - ✓ Neutrinos/leptons in Early Universe
  - ✓ Neutrinos in supernovae cores (l_{free}~1cm)
- **Condensed matter physics:**
  - ✓ Liquid He_3 [G. Volovik]
  - ✓ Weyl semimetals
  - ✓ Topological insulators

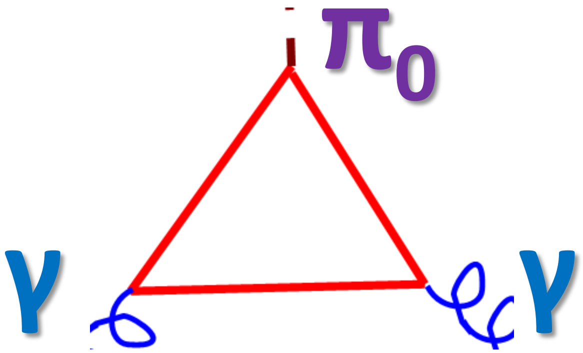


Chiral anomaly [Adler-Bell-Jackiw 1969]

Classical action $S = \bar{\psi}\gamma_\mu\left(\partial_\mu - iA_\mu\right)\psi$

invariant under chiral rotations

$$\psi \to e^{i\gamma_5\theta}\psi \qquad \gamma_5\gamma_\mu + \gamma_\mu\gamma_5 = 0$$

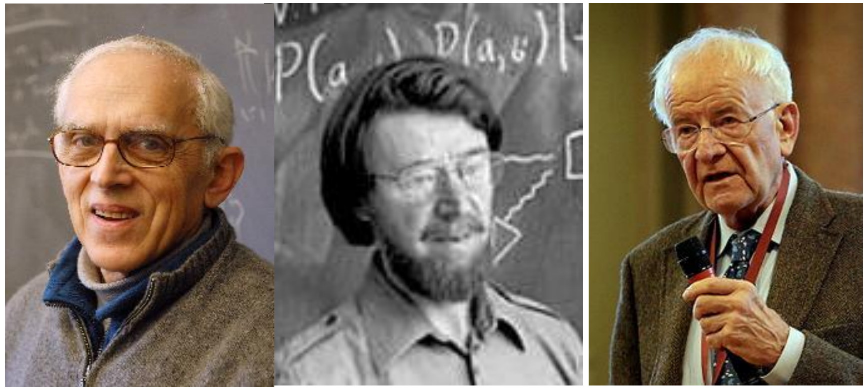


Corresponding conserved current: axial current

$$j_\mu^A = \bar{\psi}\gamma_5\gamma_\mu\psi$$

Upon quantization, one finds

$$\partial_\mu j_\mu^A = \frac{1}{2\pi^2}\vec{E}\cdot\vec{B}$$



Anomalous transport

Axial anomaly

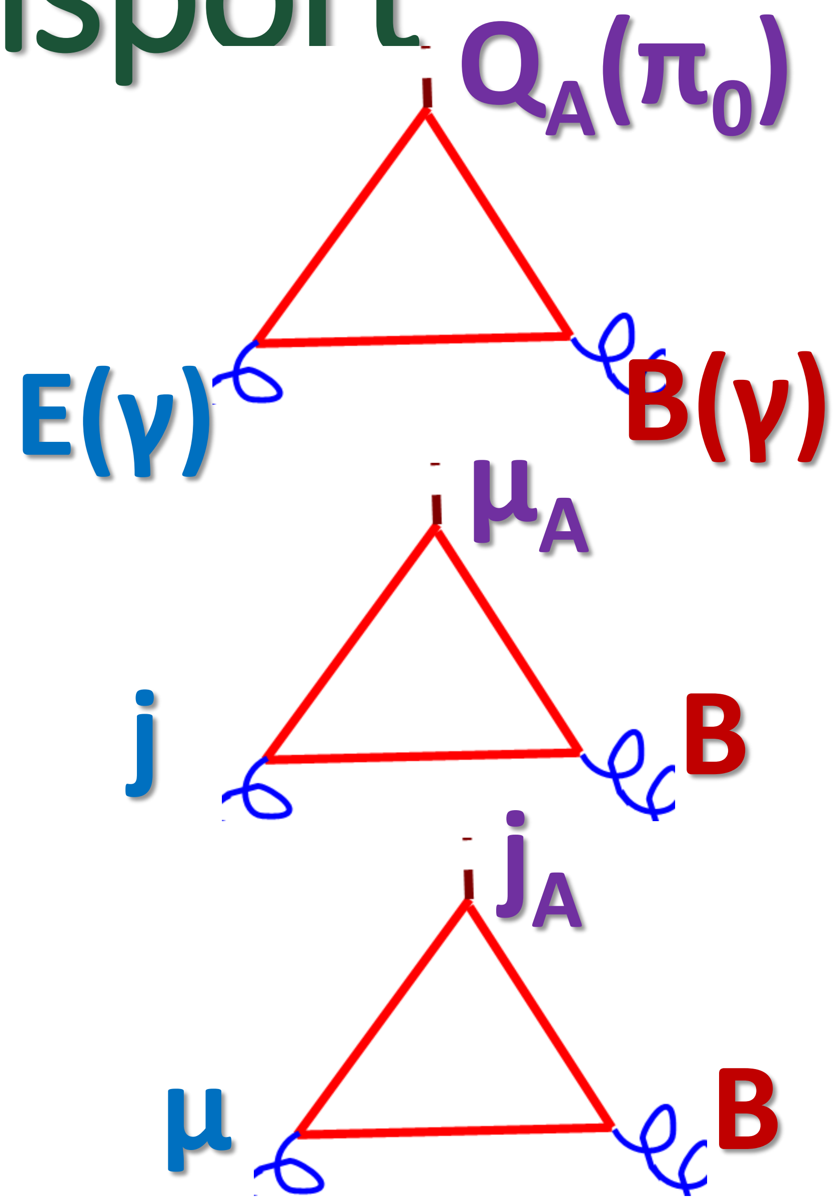
$$\partial_\mu j_\mu^A = \frac{1}{2\pi^2}\vec{E}\cdot\vec{B}$$

Chiral Magnetic Effect

$$\vec{j} = \frac{\mu_A \vec{B}}{2\pi^2}$$

Chiral Separation Effect

$$\vec{j}_A = \frac{\mu \vec{B}}{2\pi^2}$$



Anomalous transport and heavy ions

Ideal hydro

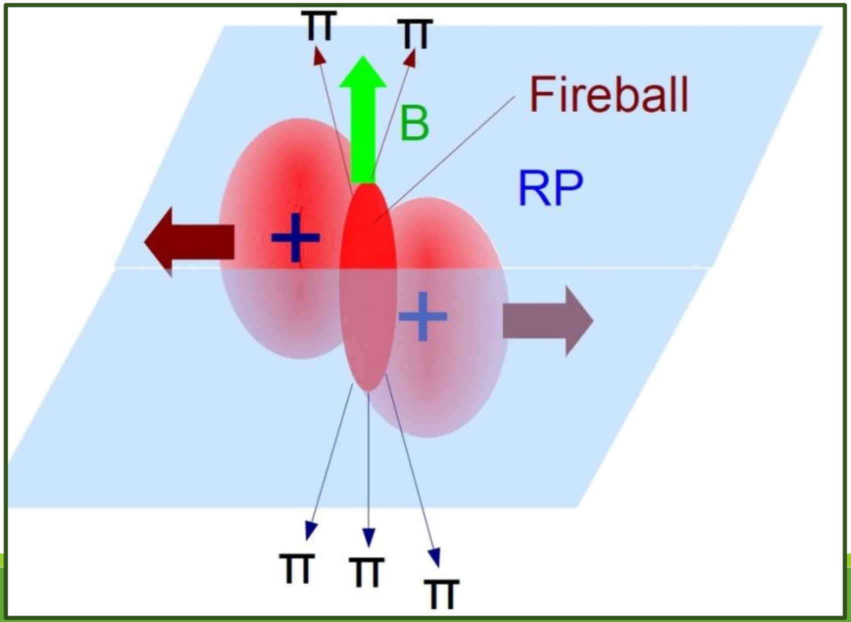
Viscous hydro

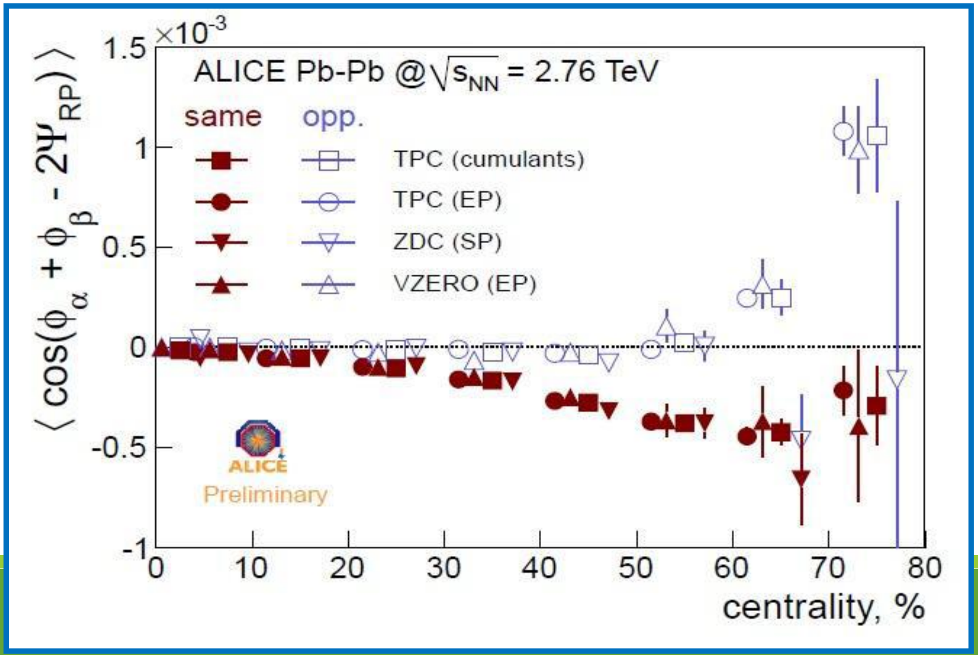
Anomalous hydro

Elliptic flow

Parity-odd fluctuations

Isobar run RHIC 2018 – results this September!





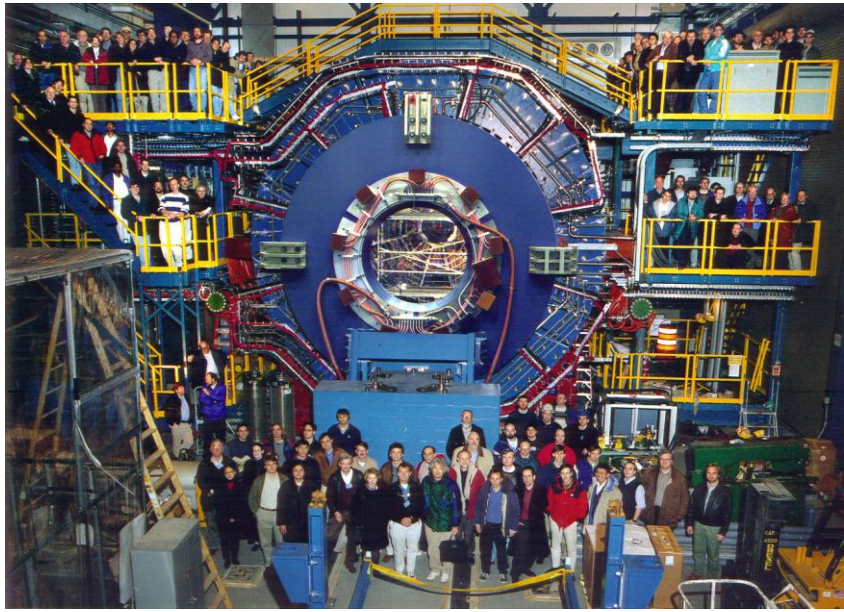
https://indico.bnl.gov/event/12758/

Anomalous transport and heavy ions

In order to better control the influence of signal and backgrounds, the STAR Collaboration performed a blind analysis of a large data sample of approximately 3.8 billion isobar collisions of 9644Ru+9644Ru and 9640Zr+9640Zr at sNN−−−√=200 GeV. ….

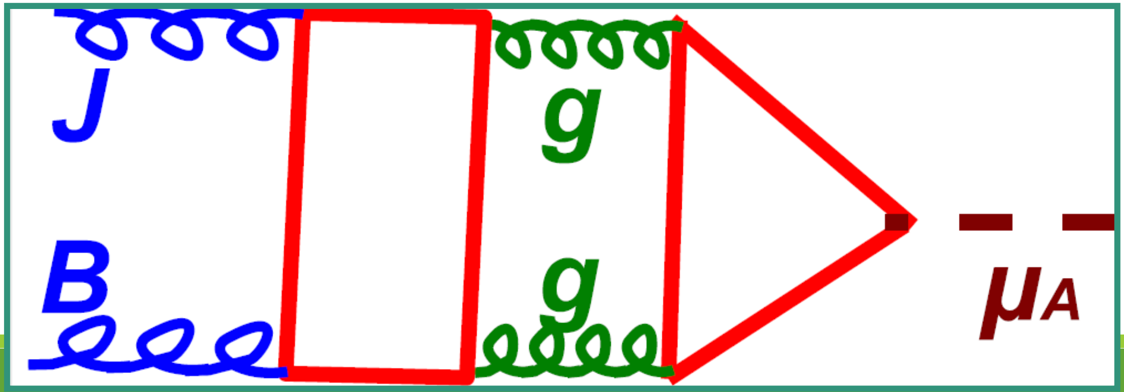
No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

[STAR Collaboration, ArXiv:2109.00131]



Anomalous transport coefficients

- Input for hydrodynamic simulations of HICs
- Get unknown corrections in real QCD
- Due to broken chiral symmetry [PB'1312.1843]
- Perturbatively [Miransky 1304.4606] [Gursoy 1407.3282]
- Due to influence of heavy quark flavors [Suenaga 2012.15173]



Anomalous transport coefficients

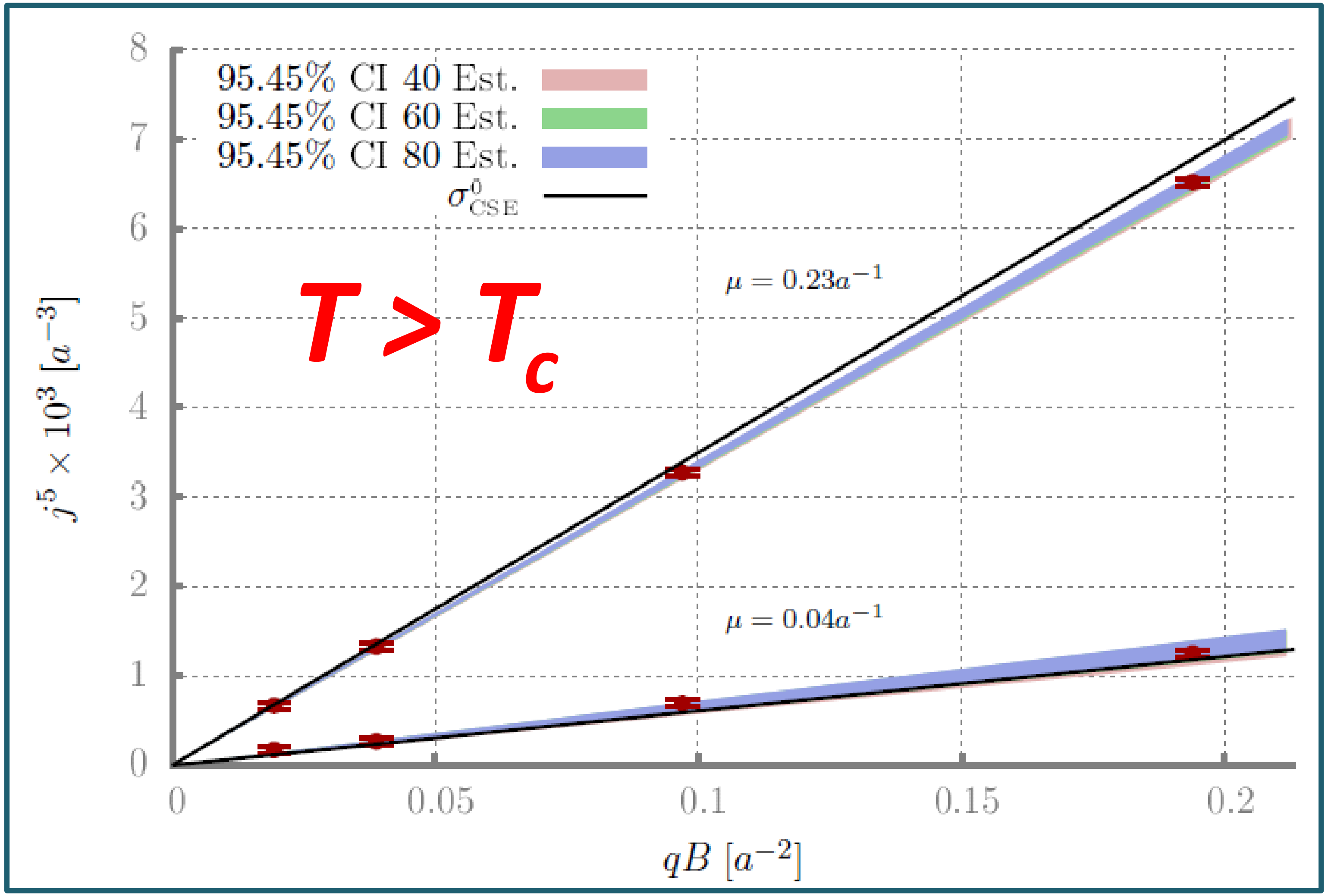
Lattice studies so far:

- [Yamamoto'1105.0385]: ~20% of Chiral Magnetic Effect
- [Braguta et al' 1401.8095]: ~5% of Chiral Vortical Effect

- So far hydro simulations with free-fermion transport coefficients only
- Lattice conclusions can question the hydro interpretation of RHIC results

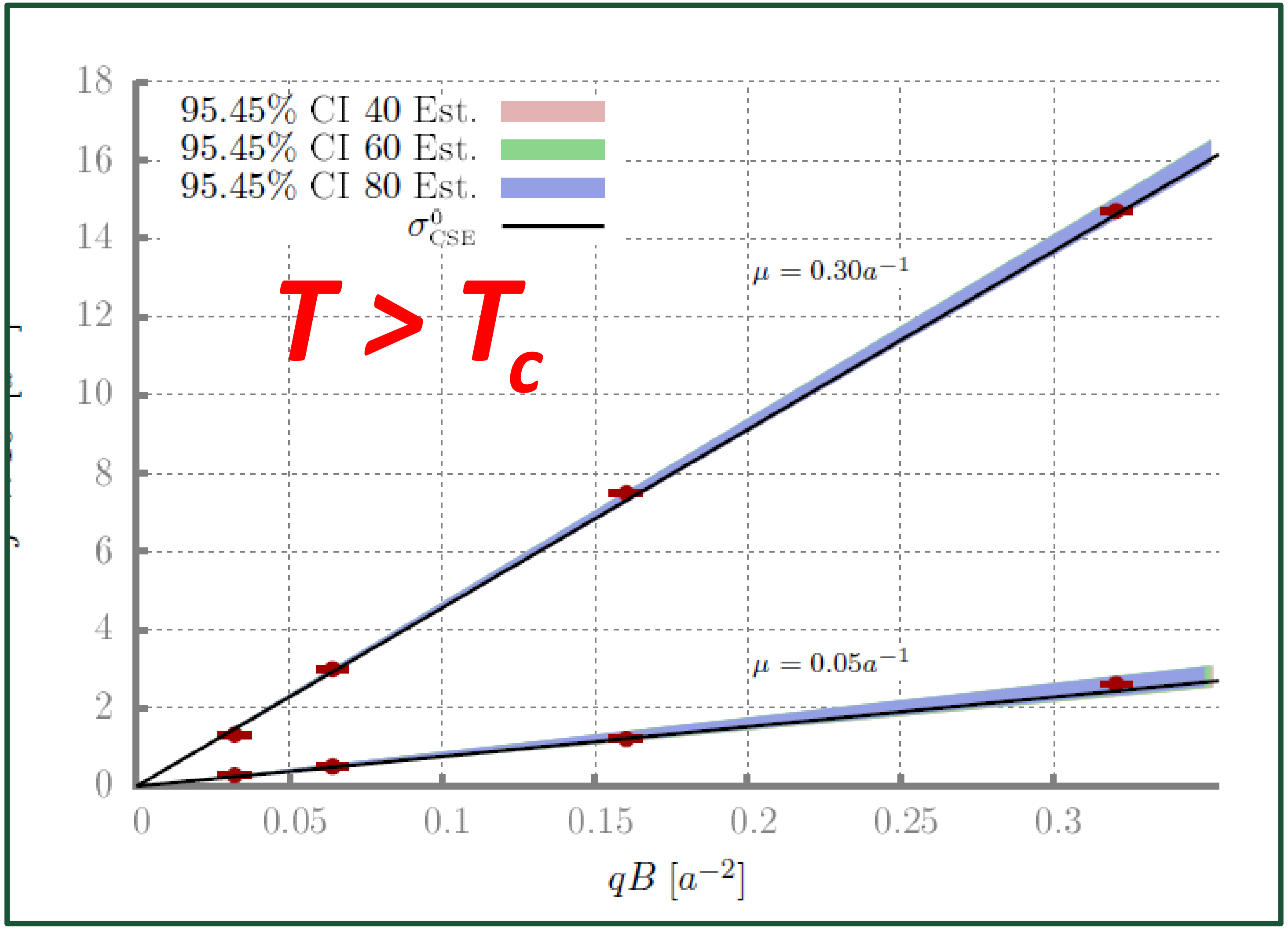
BUT: Wilson-Dirac/Quenched overlap/non-conserved currents/energy-momentum

Pure SU(3)gauge theory



[PB, M. Puhr, ArXiv: 1611.07263]

Pure SU(3)gauge theory



[PB, M. Puhr, ArXiv: 1611.07263]

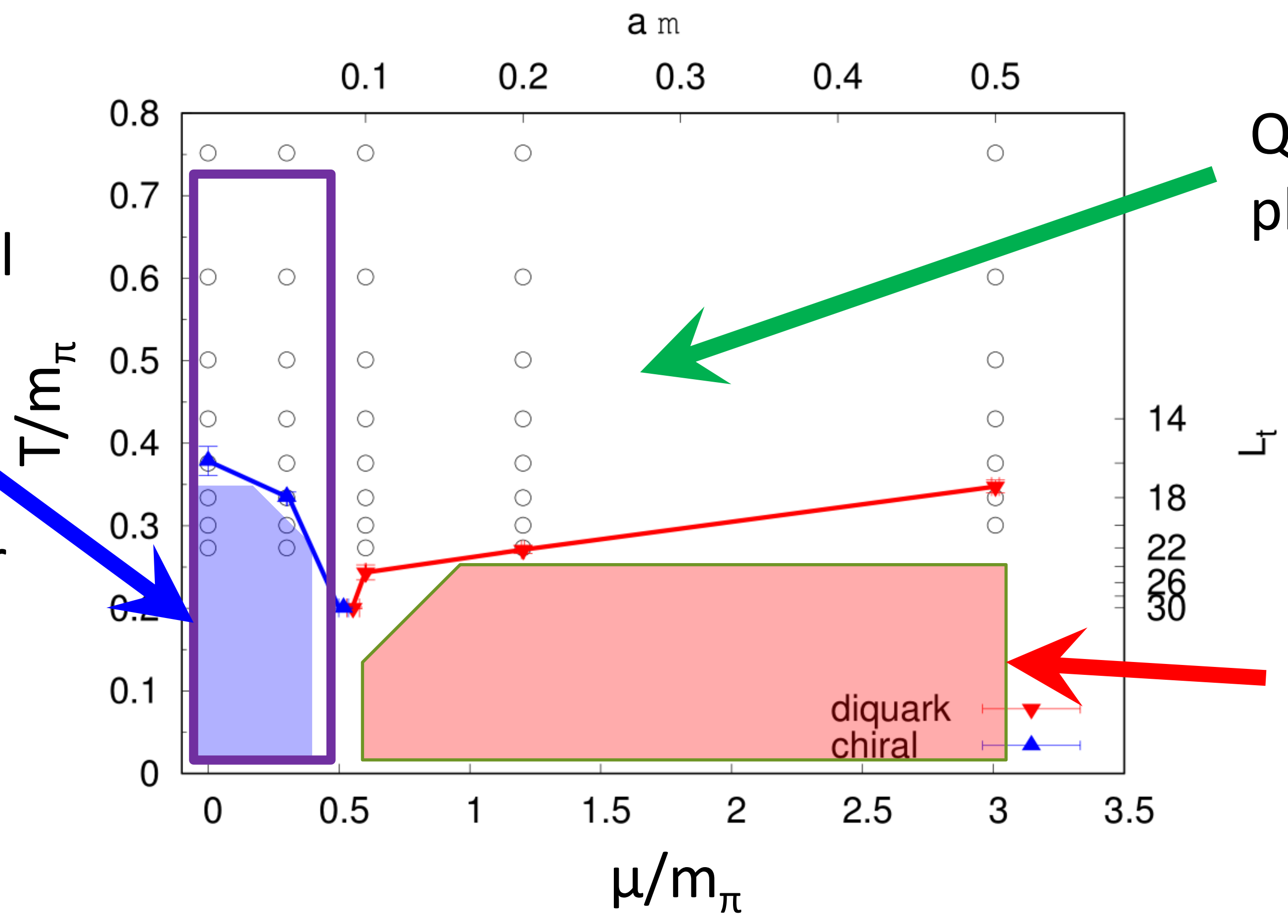
CSE with dynamical fermions

- What can be the order of magnitude of corrections?
- Sign problem in full QCD ⇒ use SU(2) gauge theory, no sign problem
- Features confinement-deconfinement crossover and χSB, QCD-like dynamics at small $\mu < m_\pi/2$.
- Diquark condensation at $\mu > m_\pi/2$, absent in real QCD

Phase diagram of SU(2) gauge theory

QCD-like low-temperature phase, broken chiral symmetry, pion excitations

Qualitatively similar to QCD !!!



Quark-gluon plasma phase

Diquark condensation phase, absent in QCD

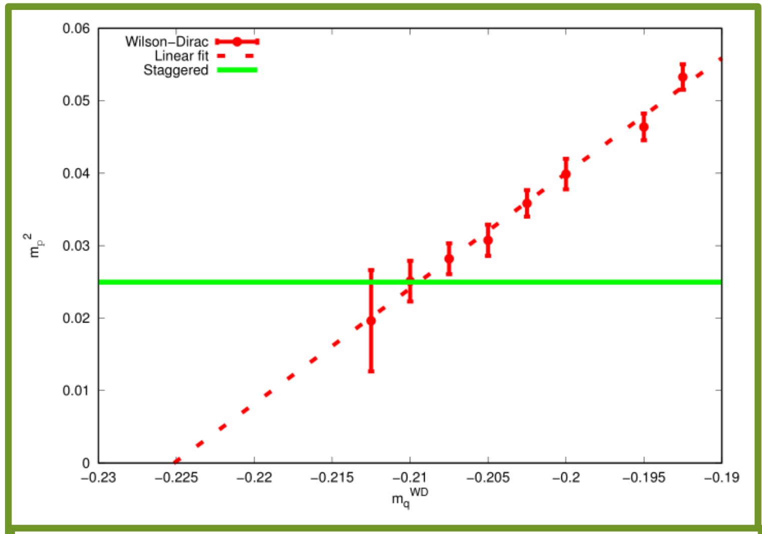
Lattice setup: sea quarks & gauge action

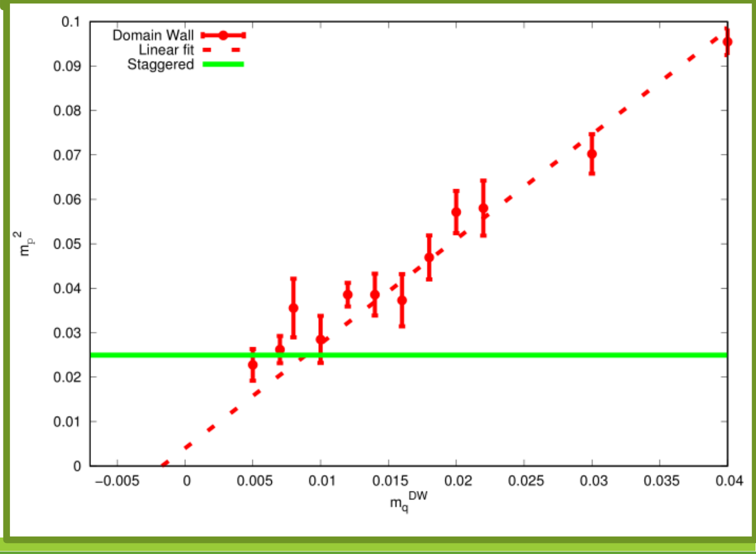
- $N_f=2$ light flavours with $m_u=m_d = 0.005$, pion mass $m_\pi = 0.158$
- Rooted staggered sea quarks
- Tadpole-improved gauge action
- Spatial lattice sizes $L_s=24$ and $L_s=30$
- Single gauge coupling = single lattice spa
- Temporal lattice sizes $L_t=4 \ldots 26$
- Standard Hybrid Monte Carlo
- Acceleration using **GPUs**

- Small diquark source term added for low temperatures to facilitate diquark condensation

Lattice setup: valence quarks

- Wilson-Dirac and Domain-Wall valence quarks
- HYP-smeared gauge links in the Dirac operator: reduces additive mass renormalization and lattice artifacts
- Better quality of signal than for staggered quarks
- Bare mass for Wilson-Dirac/Domain-Wall quarks tuned to match the pion mass calculated with sea quarks
- GMOR relation works with good precision





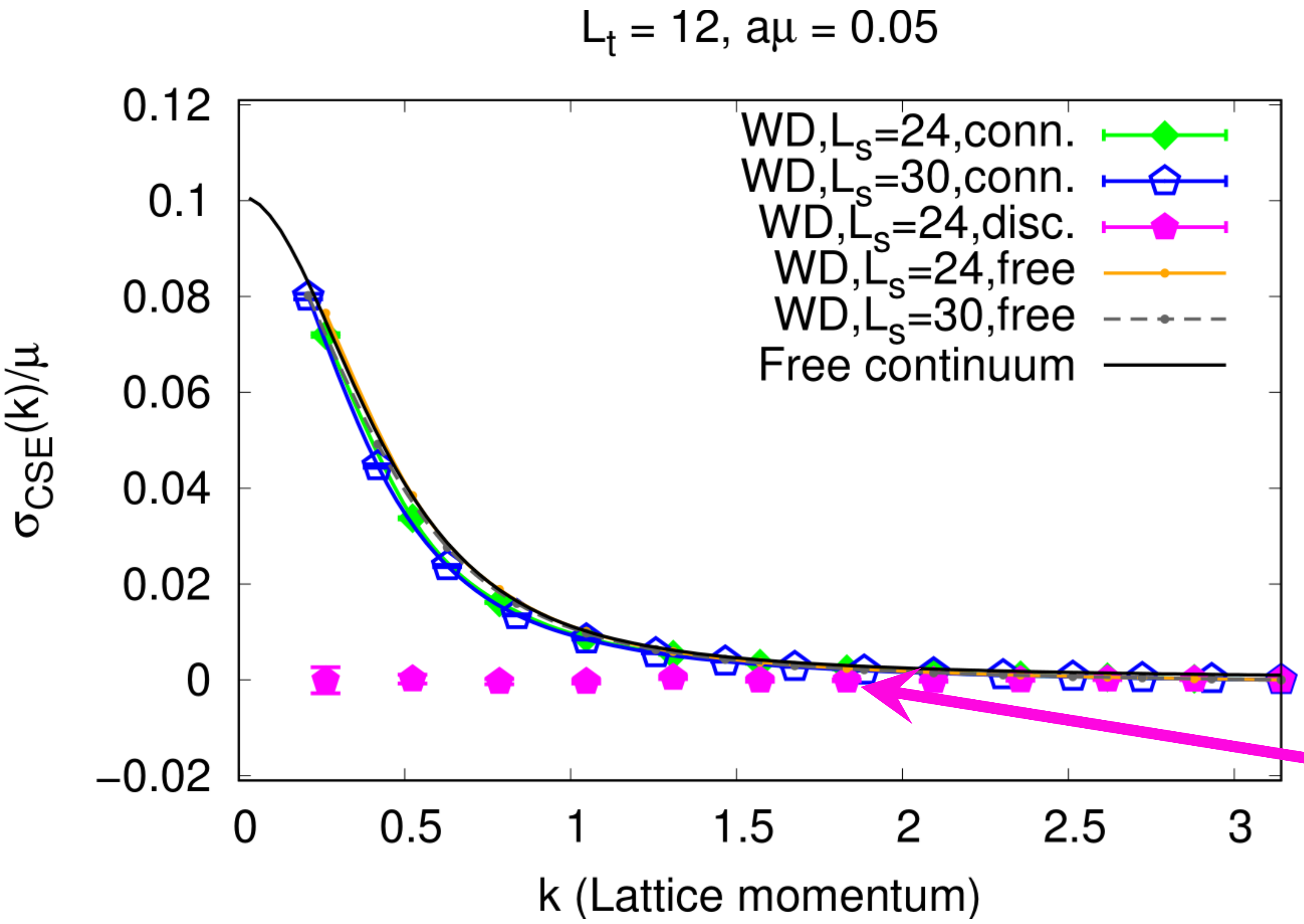
Measuring the CSE

- Sign problem even in SU(2) gauge theory at finite μ and magnetic field
- We use linear response approximation w.r.t. magnetic field

$$\vec{j}_A = \sigma_{CSE}(\mu, T)\ \vec{B}$$

$$\langle j_1^A(k_3)\, j_2^V(-k_3)\rangle = \sigma_{\mathrm{CSE}}\, k_3$$

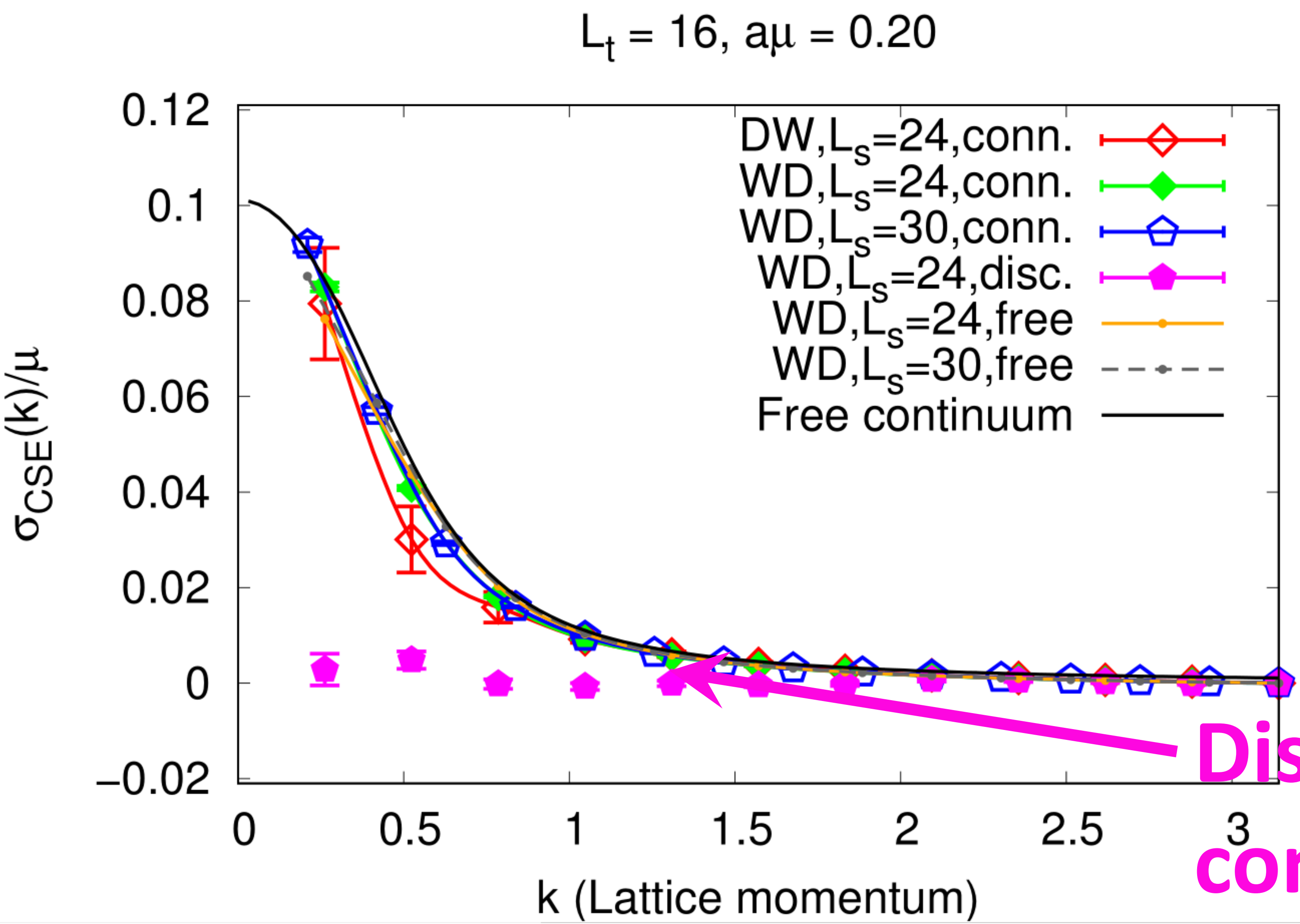
Numerical results



High T, Small μ

Disconnected contribution

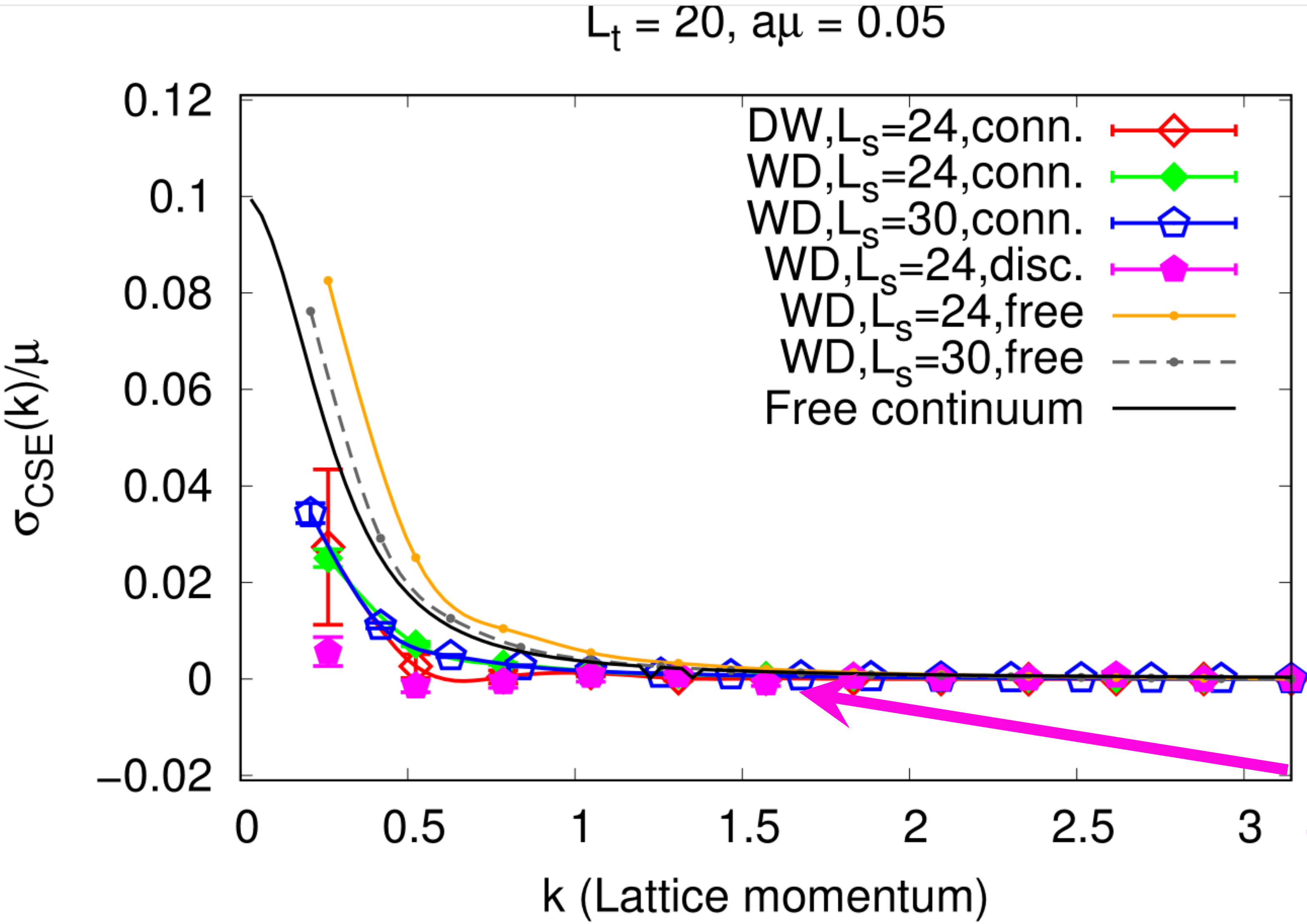
Numerical results



Critical T, Large μ

Disconnected contribution

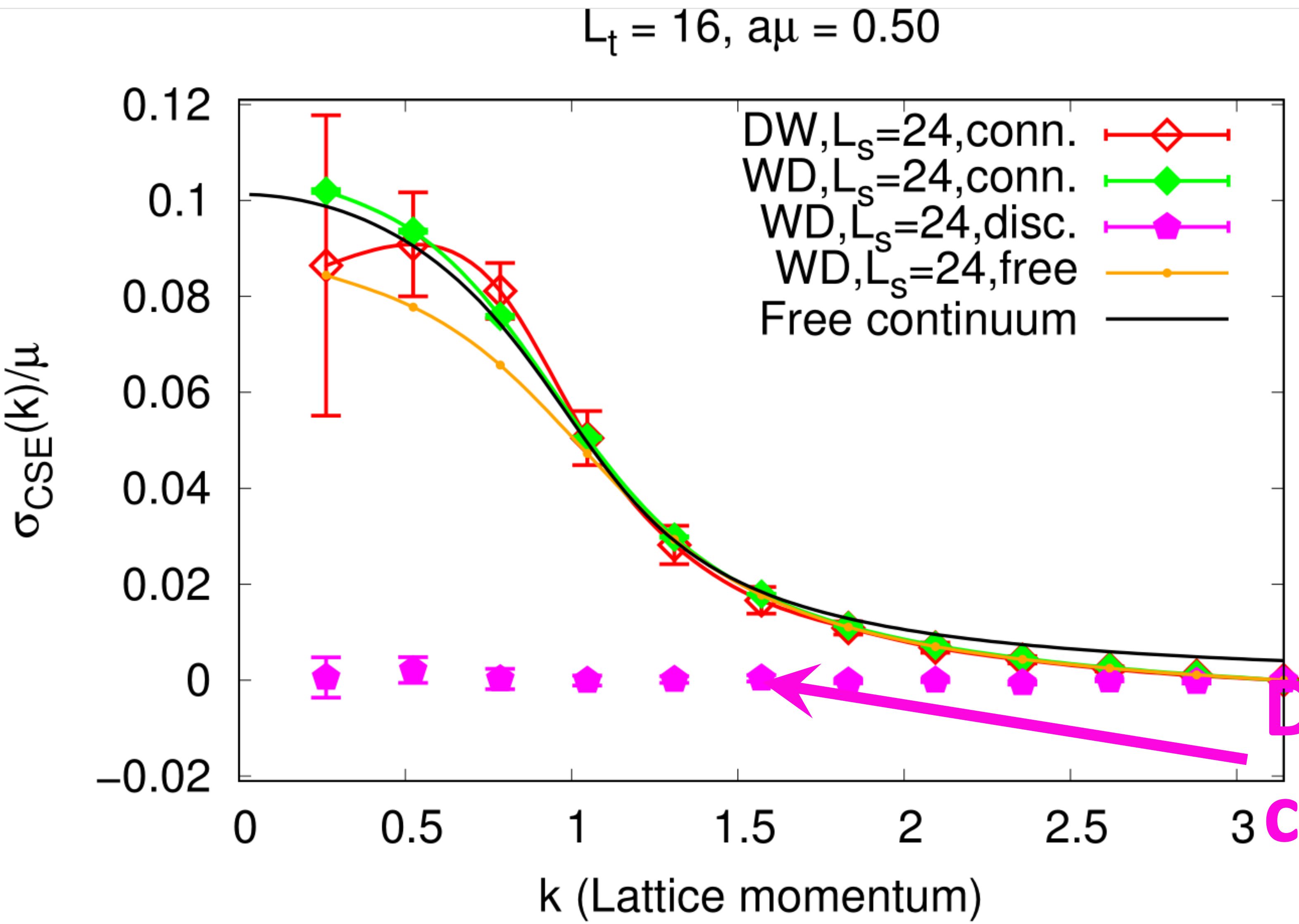
Numerical results



Low T, Small μ

Disconnected contribution

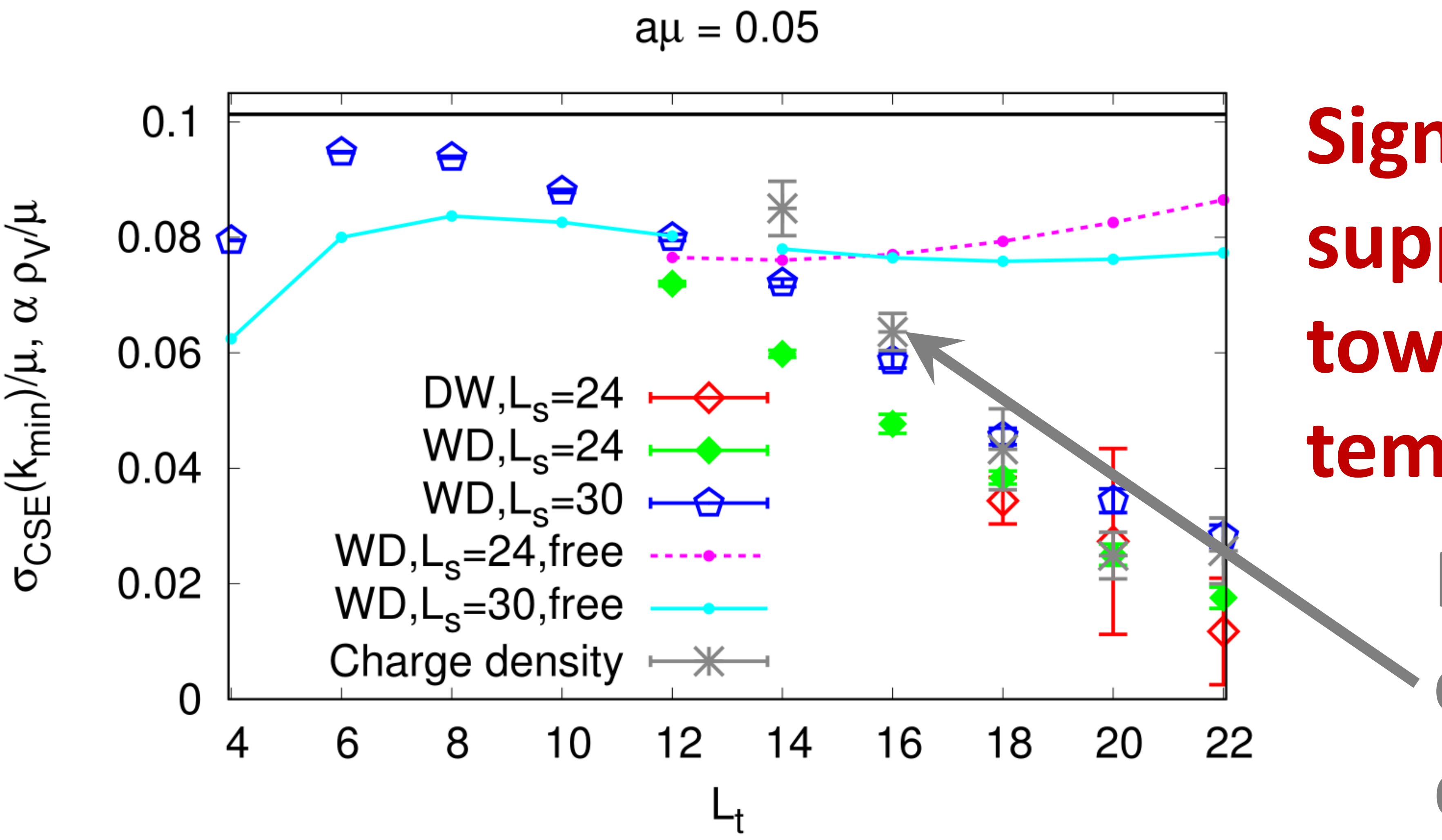
Numerical results



Critical T, Large μ

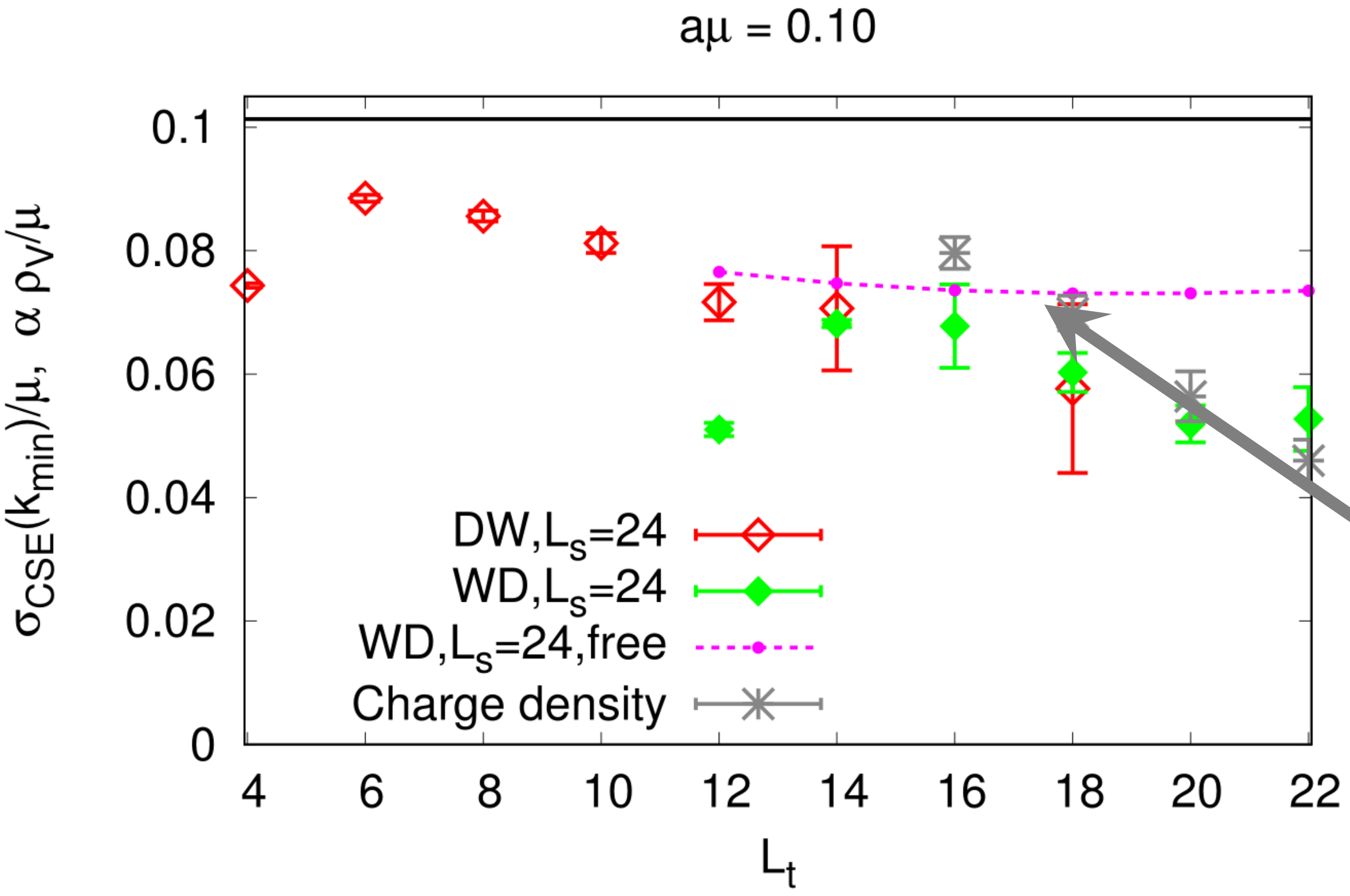
Disconnected contribution

σ_{CSE} vs temperature, low μ



Significant suppression towards low temperatures!

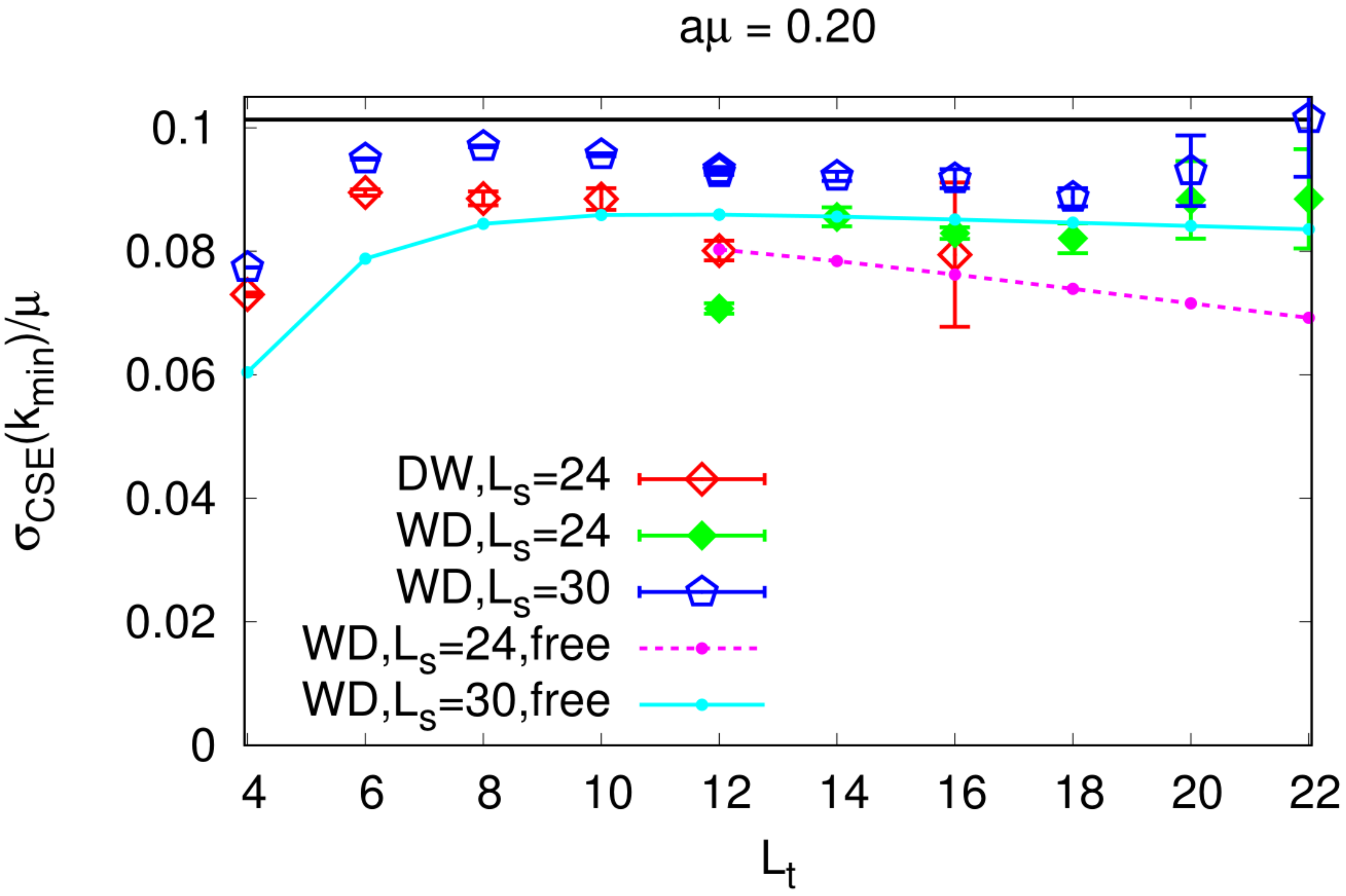
σ_{CSE} vs temperature, medium μ



Data moving closer to the free fermion results

Rescaled charge density (same coefficient)

σ_{CSE} vs temperature, large μ



Data quite close to the free fermion results

Describing CSE suppression

- ChPT result for flavor-non-singlet axial current [Avdoshkin,Sadofyev,Zakharov' 1712.01256]:

$$\vec{j}^{\,a}_A = \frac{N_c \mathrm{Tr}\,(Q)}{(2\pi f_\pi)^2}\, \rho^a_V\, \vec{B}$$

- We work with flavor-singlet axial current, has different status in ChPT
- Singlet and non-singlet currents become similar at large Nc
- Phenomenological formula works well in the low-T, low-μ regime even for singlet axial current in SU(2) gauge theory

Disconnected contribution appears to be small!

$$\sigma_{CSE}(\mu, T) = \alpha\, \rho_V(\mu, T)$$

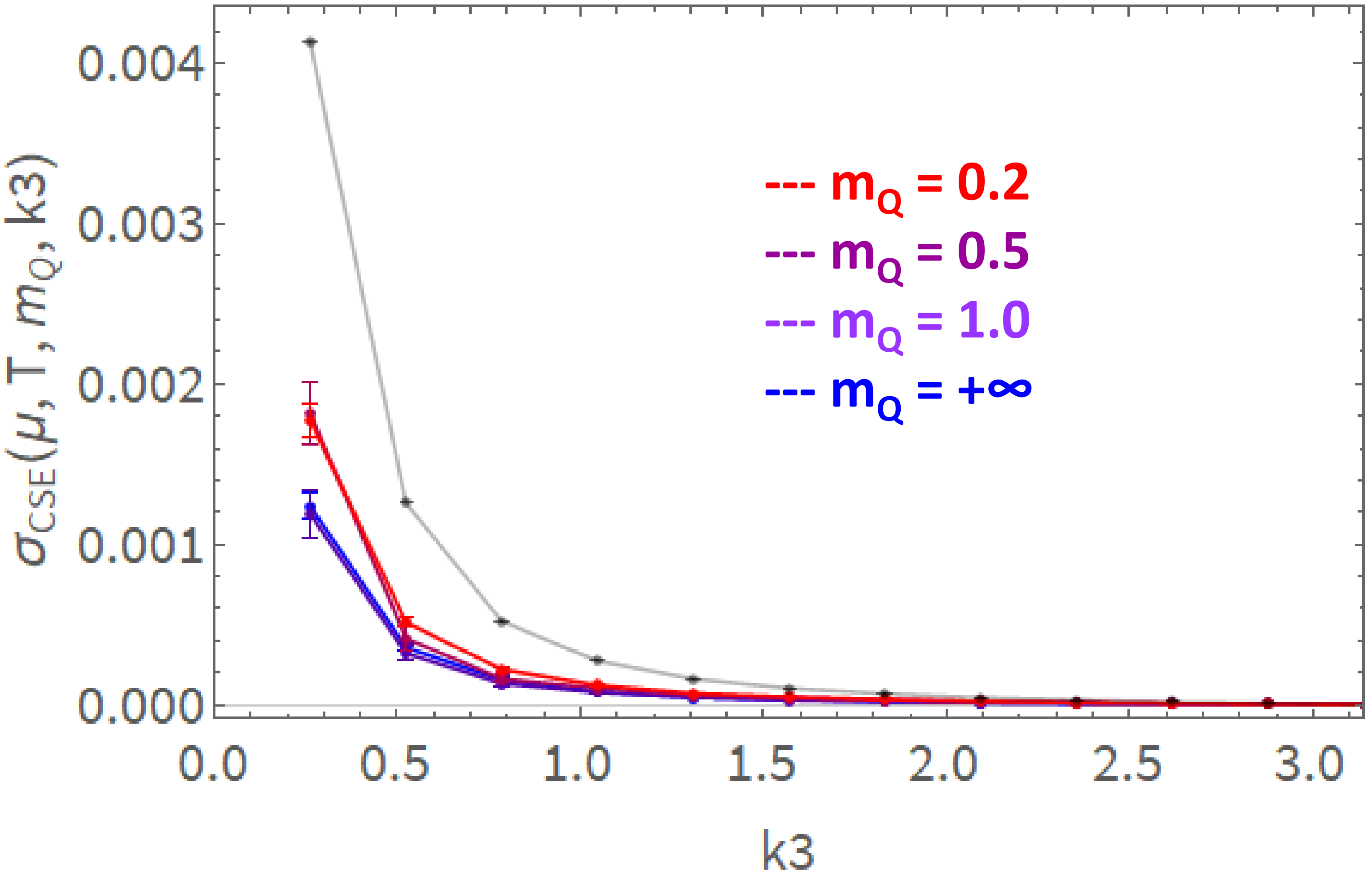
Kondo effect in non-Abelian gauge theory

- **Suppression of an interesting effect feels somewhat unfortunate…**
- **Is there something that can enhance the CSE?**
- **Yes, QCD Kondo Effect [Suenaga et al., 2012.15173]**

Kondo effect in non-Abelian gauge theory

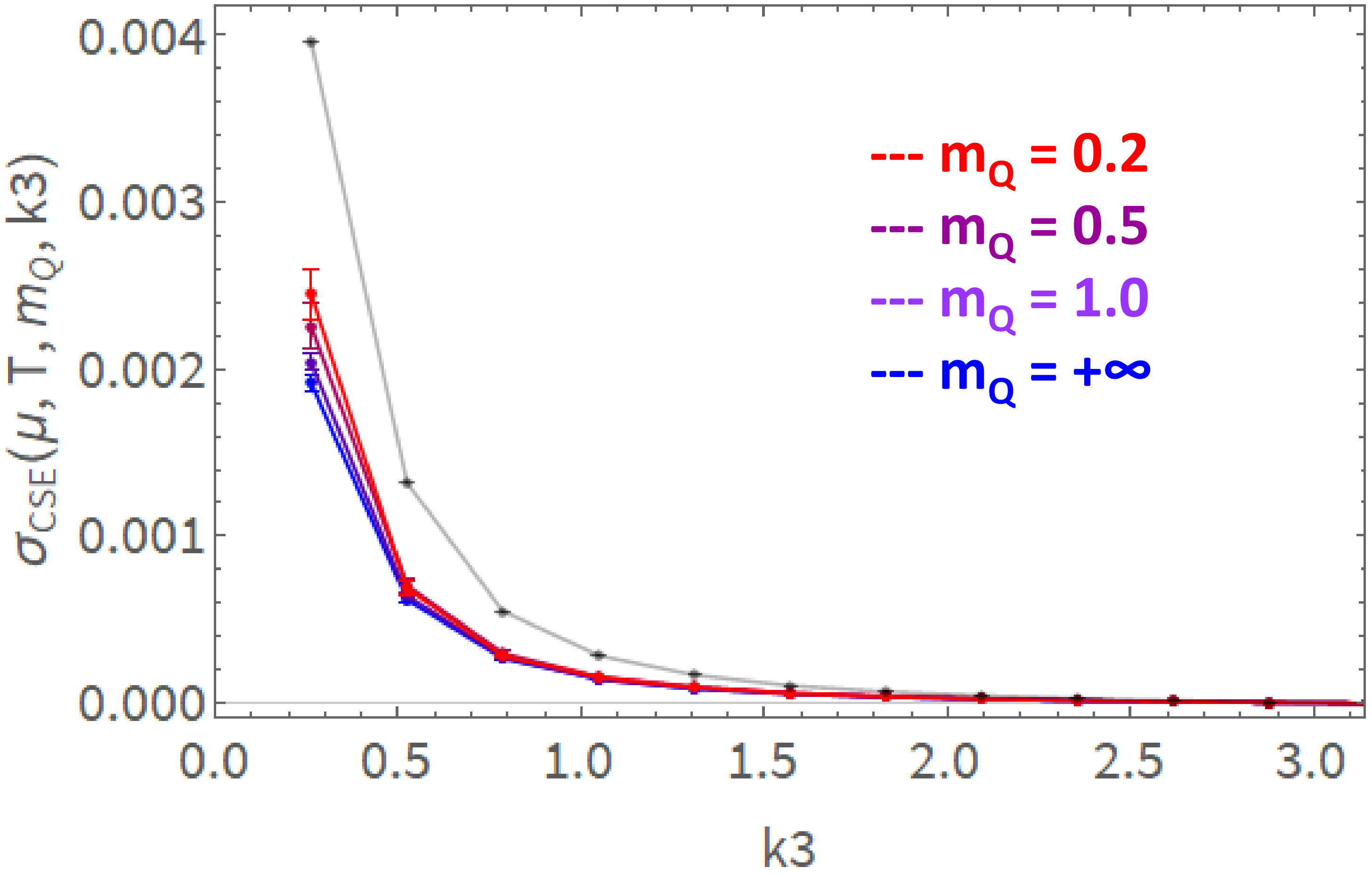
- **Kondo effect: scattering of light fermion near a Fermi surface off a heavy fermion of mass M enhanced as *log(M)***
- **Mean-field approach for QCD [Yasui,Suzuki,Itakura, 1604.07208]: spontaneous emergence of Kondo condensate** $\langle \bar{Q} q \rangle$
- **Suppresses low-T, finite-μ conductivity [Yasui,Ozaki, 1710.03434]**
- **But… CSE is enhanced [Suenaga,Araki,Suzuki,Yasui, 2012.15173]**
- **We only consider CSE of light quarks**

Numerical results for CSE in Nf=2+1 SU(2) LGT



- **Lt=20, low-temperature regime**
- **CSE enhanced by more than 30% for *m_Q=0.2 a***

Numerical results for CSE in Nf=2+1 SU(2) LGT



- Lt=18, a bit higher temperature
- Enhancement not so large
- Not a conventional Kondo, Fermi surface not well-defined

Conclusions

- CSE close to free-quark result at high temperatures and/or high densities
- Significant suppression at low temperatures and low densities
- σ_{CSE} approximately proportional to charge density rather than chemical potential
- Similar to ChPT calculation of [Avdoshkin,Sadofyev,Zakharov' 1712.01256] for axial non-flavor-singlet current, although non-singlet and singlet axial currents are physically quite different
- CSE can be enhanced in the presence of additional fermion flavors – signature of Kondo effect
- Next step: conductivity at finite density with heavy quarks