Catalytic effects of monopole in QCD

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Topics of my research

- **Catalytic effects of monopoles at the zero temperature.**

  I started this project with A. Di Giacomo in 2014.

  Details of this research are in the article, **M. H., arXiv: 1807.04808**.

  I have already submitted it to PRD, and the answer from a referee is major revision.

- **Catalytic effects of monopoles in the finite temperature.**

  I extend the research project at the zero temperature to the finite temperature.

  I investigate the catalytic effects of monopoles on the phase transitions of the quark confinement and chiral symmetry breaking.

- **Monopoles and instantons under the strong magnetic fields.**

  Collaborators: C. Bonati, M. D'Elia, and F. Negro, University of Pisa

Purpose of this research

- **We want to show that monopoles condensing in the QCD vacuum closely relate to instantons, and chiral symmetry breaking.**
- **We add monopoles by a monopole creation operator in SU(3) quenched configurations** [C. Bonati, et al., PRD 85 (2012) 065001]**.**
- **We use the overlap fermions which preserve the chiral symmetry in the lattice gauge theory, as an analytical tool.**

  [R. G. Edwards, et al., PRD 61 (2000) 074504; **L. Giusti, et al., JHEP 11 (2003) 023**; L. Del Debbio, et al., PRL 94 (2005) 032003; L. Del Debbio, et al., JHEP 02 (2004) 003]
- **We estimate the effects of the additional monopoles on the physical observables.**

Monopole effects

We have already demonstrated the results as follows:

(1) Monopoles make instantons. [A. Di Giacomo and M. H. PRD 91 (2015) 054512]

(2) In random matrix theory, the low-lying eigenvalues of the overlap Dirac operator are not affected by the additional monopoles.

The chiral condensate decreases by increasing the values of monopole charges. [A. Di Giacomo, M. H., and F. Pucci, Proc. Sci., CD15 (2015) 127]

(3) The light quark masses become heavy by increasing the values of monopole charges. [Preliminary results: A. Di Giacomo and M. H., Proc. Sci., Lat2015 (2015) 313]

However, the results (1) and (2) are obtained using the lattice of one value of the lattice spacing and small volume. Moreover, statistical samples of the result (3) are not enough.

Catalytic effects of monopoles in QCD

- Therefore, I improve the previous research using the lattice of the larger volume and the finer lattice spacing, and increasing the number of statistical samples.
- I show that the catalytic effects of monopoles in QCD as follows [**arXiv: 1807.04808**]:

  (i) The decay constants of the pseudoscalar increase.

  (ii) The values of the chiral condensate decrease.

  (iii) The masses of the light quarks and the pseudoscalar increase.

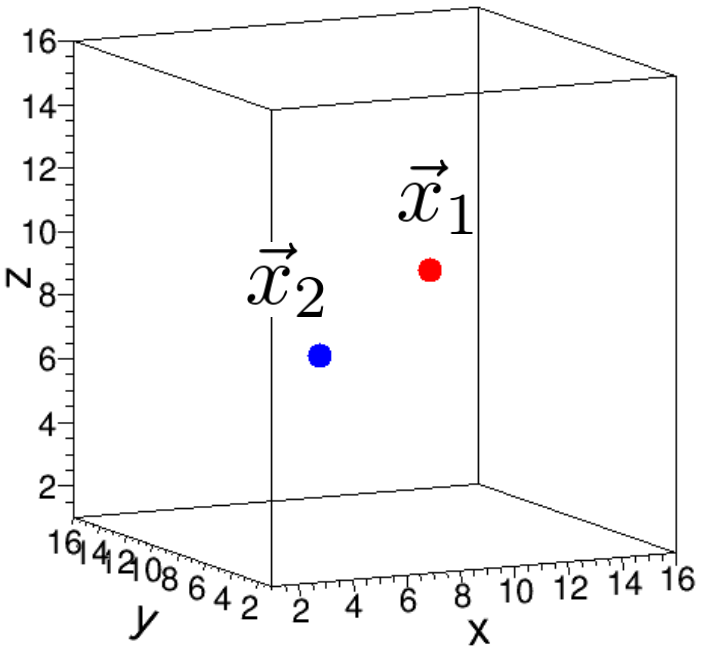
  (iv) The decay width of the charged pion becomes wider and the lifetime of the charged pion becomes shorter.

  These are the catalytic effects of the Adriano monopole.

Additional monopoles

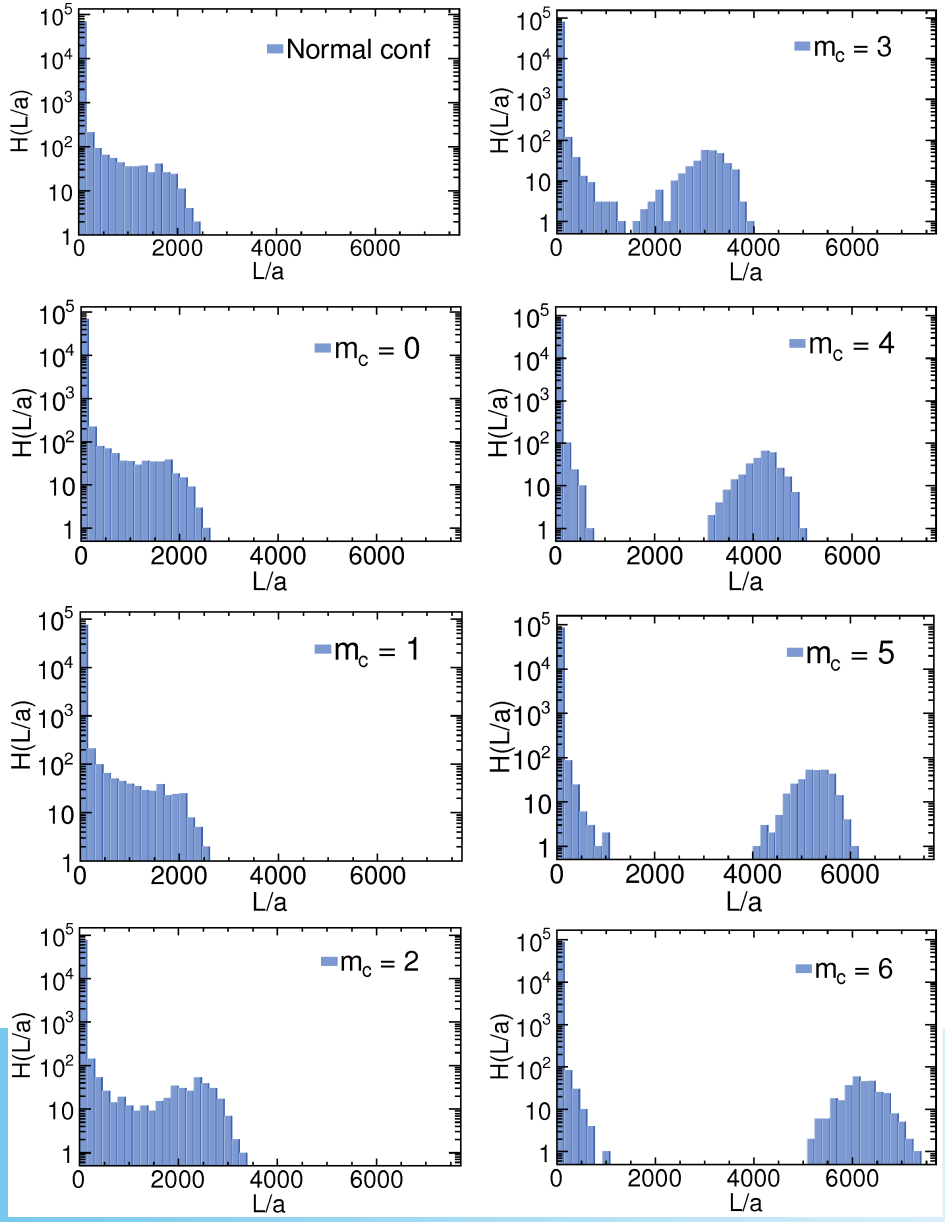
- **The monopole creation operator** [C. Bonati, et al., PRD 85 (2012) 065001]
- **The locations of the additional monopole and anti-monopole**

$$\mathbf{V} = \mathbf{16^3 \times 32}$$



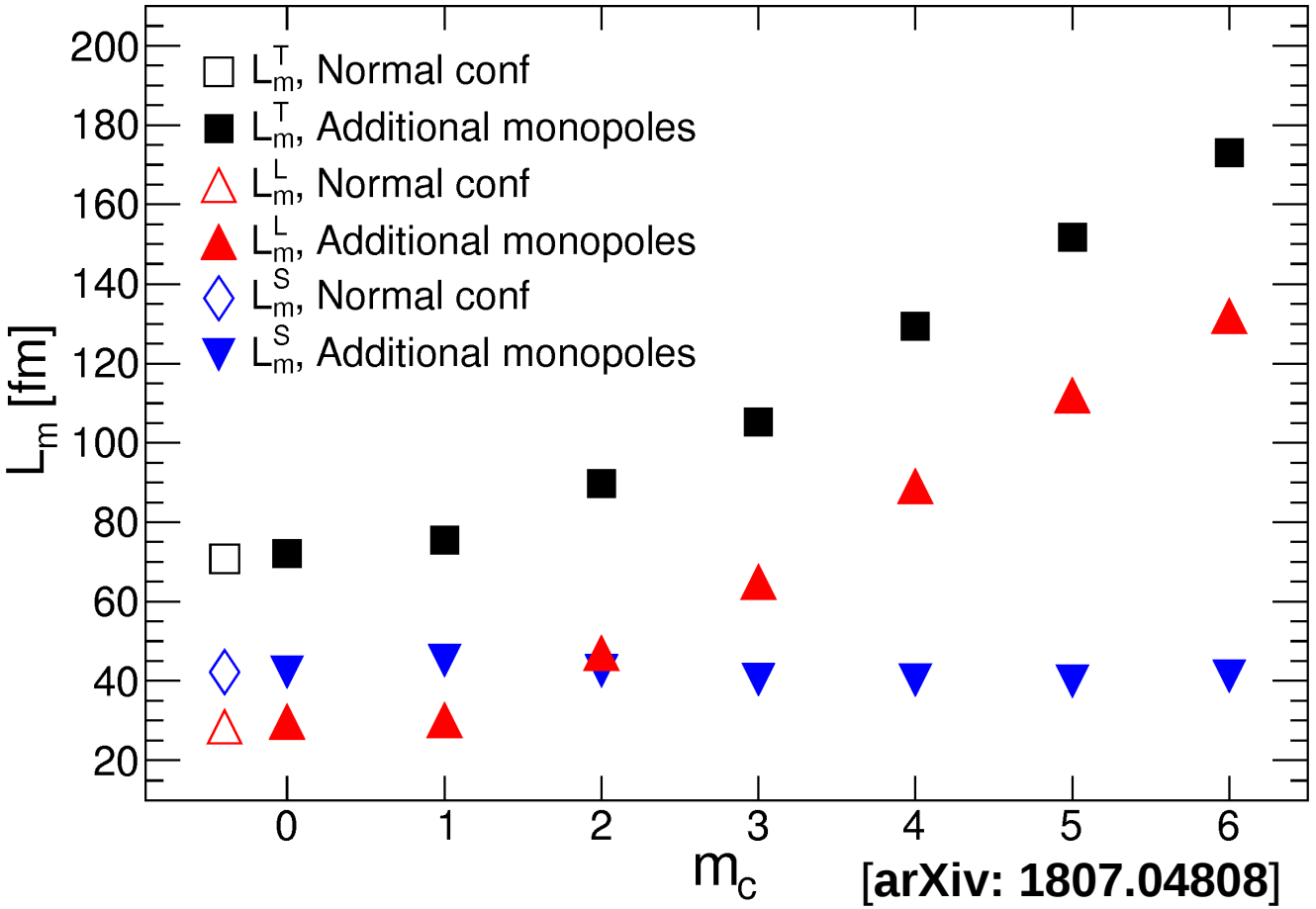
$$D = |\vec{x}_1 - \vec{x}_2| \approx 1.1 \ [\mathrm{fm}]$$

- **The check on the additional monopoles** [arXiv: 1807.04808]



The length of monopole loops

The monopole creation operator makes only the long monopole loops which relate with the quark confinement.



[arXiv: 1807.04808]

The overlap Dirac operator

- **We use the technique of the epsilon regime of QCD to calculate the overlap Dirac operator from the gauge links of the configurations** [L. Giusti, et al., Com. Phys. Comm. 153 (2003) 31, etc]**.**
- We approximate the sign function by the Chebyshev polynomials.
- We then solve eigenvalue problems $\mathbf{D}(\rho)|\psi_\mathbf{i}\rangle = \lambda_\mathbf{i}|\psi_\mathbf{i}\rangle$ using by the subroutines (ARPACK).
- Almost all computational times are spent for the computations of the eigenvalue problems.
- We compute *O*(100) pairs of low-lying eigenvalues and eigenvectors, and save them in storage elements of the JLDG.
- The lattice spacing is computed from the analytic interpolation [S. Necco, et al., NPB 622 (2002) 328]. The Sommer scale is $r_0 = 0.5$ [fm].
- **There are zero modes (topological charges) in the spectra of the eigenvalues.**

Supercomputers

NEC, SX-ACE

(CMC and RCNP, Osaka Univ.)

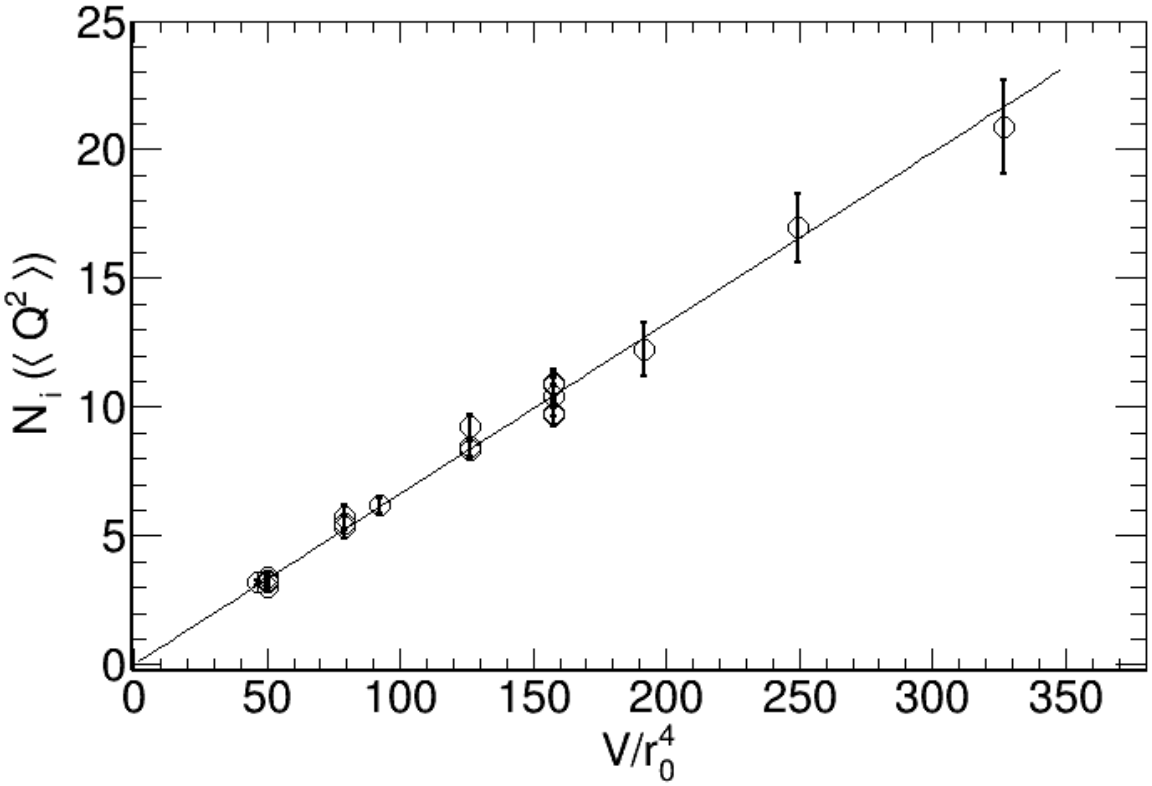
- **Vector processors**
- 1CPU / 1-node
- 4-core / 1-node
- Total node: 1536
- Memory: 64GB / 1-node
- Performance:
  276 Gflops / 1-node

Instantons

- The topological charge **Q** is defined as follows: $\mathbf{Q = n_+ - n_-}$.
- We suppose that the Atiyah–Singer index theorem,
  $\mathbf{n_+}$**:** The number of instantons of the ***positive charge*****.**
  $\mathbf{n_-}$**:** The number of instantons of the ***negative charge*****.**
- However, we never observed the numbers of zero modes of the positive chirality and the negative chirality in the same configuration at the same time.
- Therefore, we make a hypothesis and check the consistency.
- **We have shown that the total number of instantons and anti-instantons N_i can be calculated from the average square of the topological charges** [A. Di Giacomo and M. H. PRD 91 (2015) 054512]**:** $\mathbf{N_i = \langle Q^2 \rangle}$

Instanton density

- To confirm our supposition, we evaluate the instanton density, by fitting the linear function.



$$2\rho_i r_0^4 = 6.673(14) \times 10^{-2}$$

$$\mathbf{B = -0.02(0.1) = 0,\ \chi^2/d.o.f = 20.4/21.0}$$

- **The instanton density is**

$$\rho_{\mathbf{i}} =$$

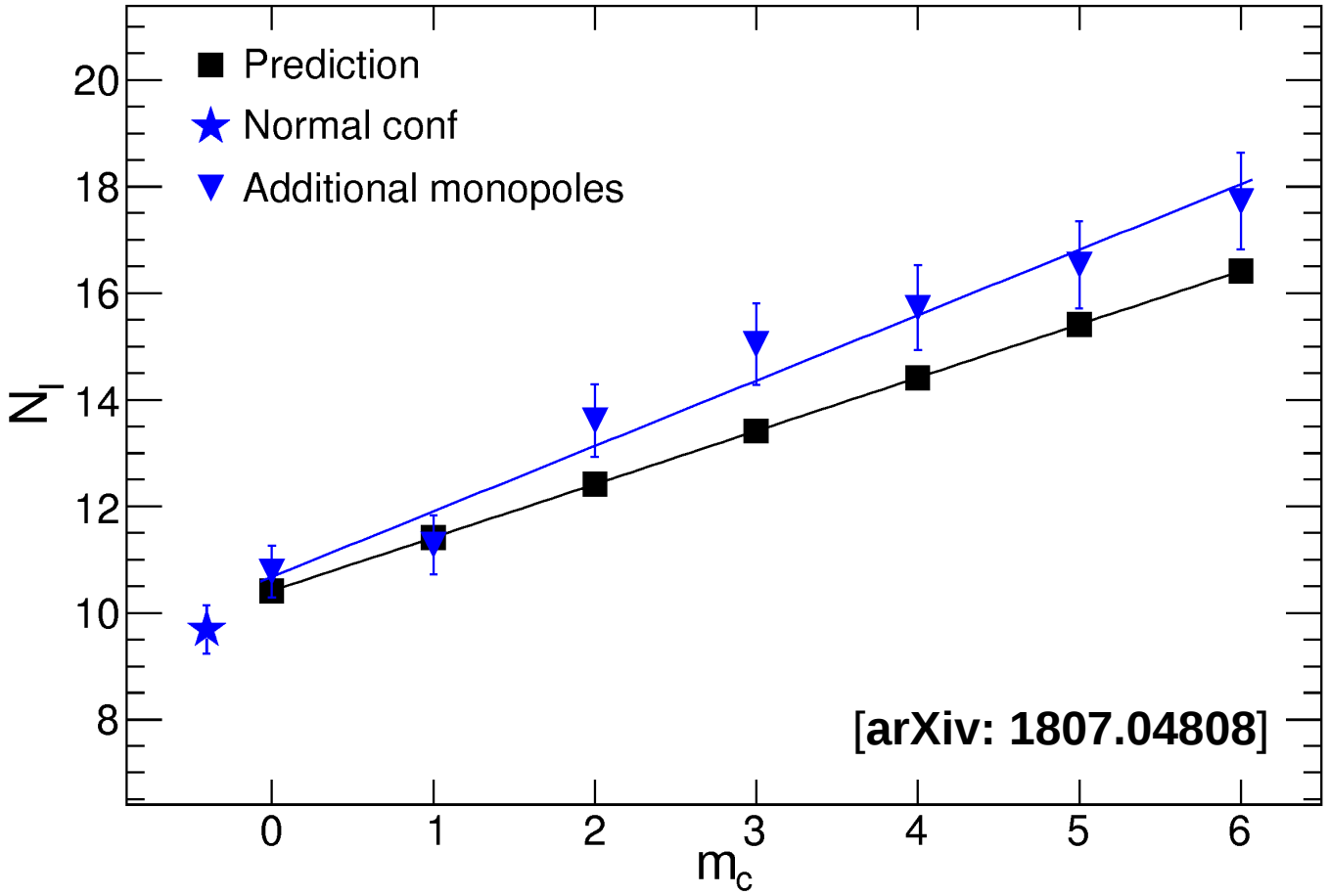
$$\mathbf{8.09(17) \times 10^{-4}\ [GeV^4]}.$$

- **The prediction from the instanton liquid model is as follows:** [E. V. Shuryak, NPB 203 (1982) 93]**:**

$$\mathbf{n}_c = 8 \times 10^{-4}\ [\mathbf{GeV}^4]$$

- **We can properly calculate the total number of instantons and anti-instantons from the square of the topological charges.**

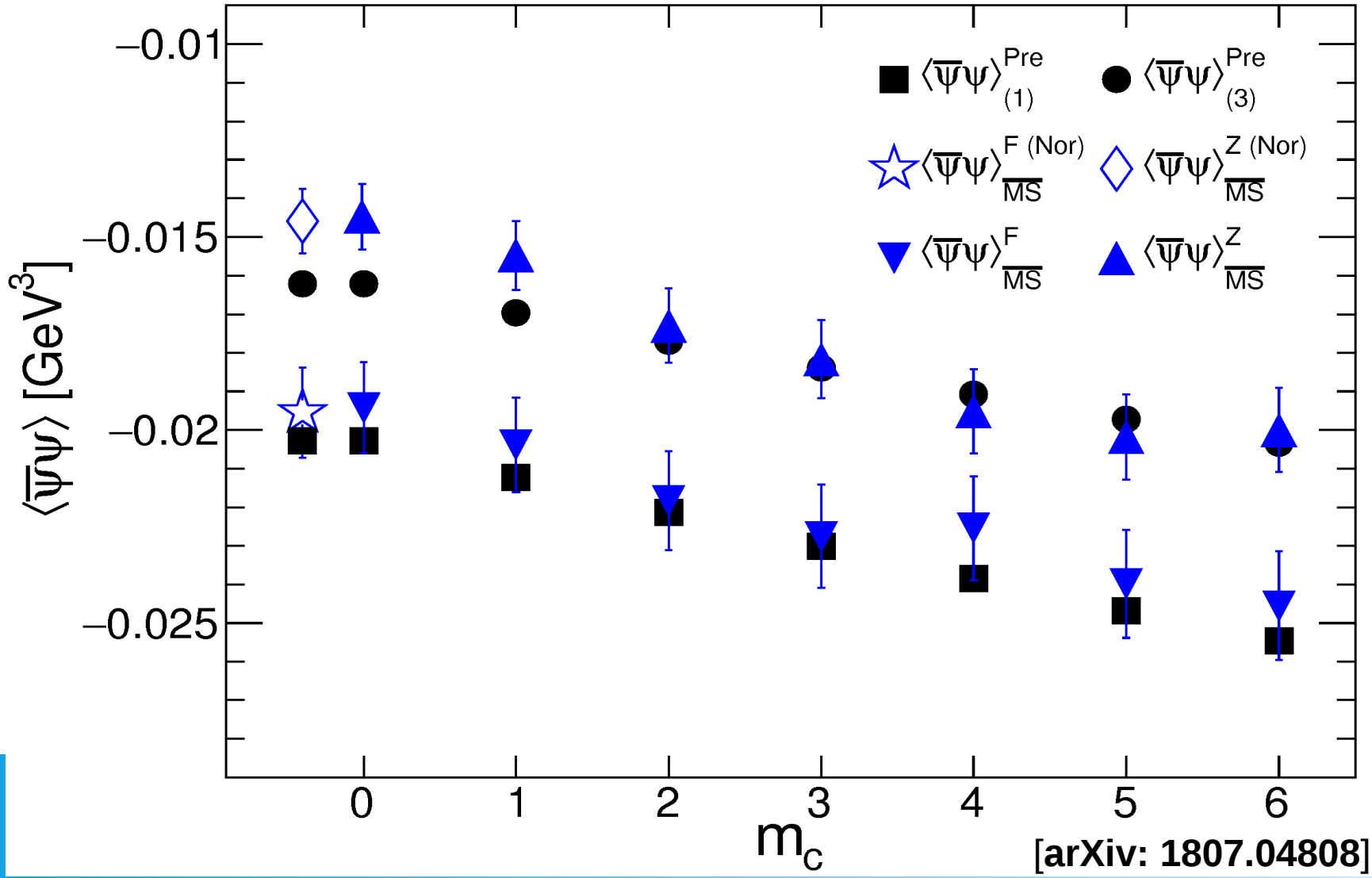
Instantons and monopoles



The total number of instantons and anti-instantons increases by increasing the values of the magnetic charges of moonpolse and anti-monopoles; **thus the additional monopoles and anti-monopoles make instantons and anti-instantons**.

The chiral condensate

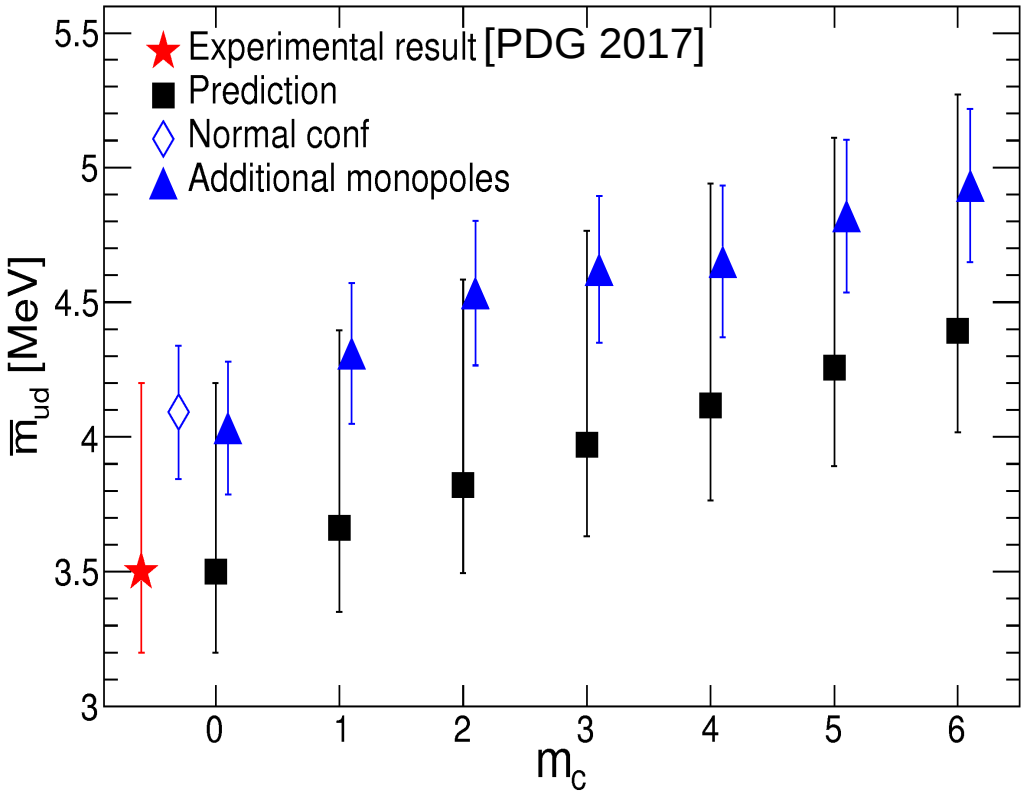
- **The physical observables are calculated from the correlation functions of the operators.**

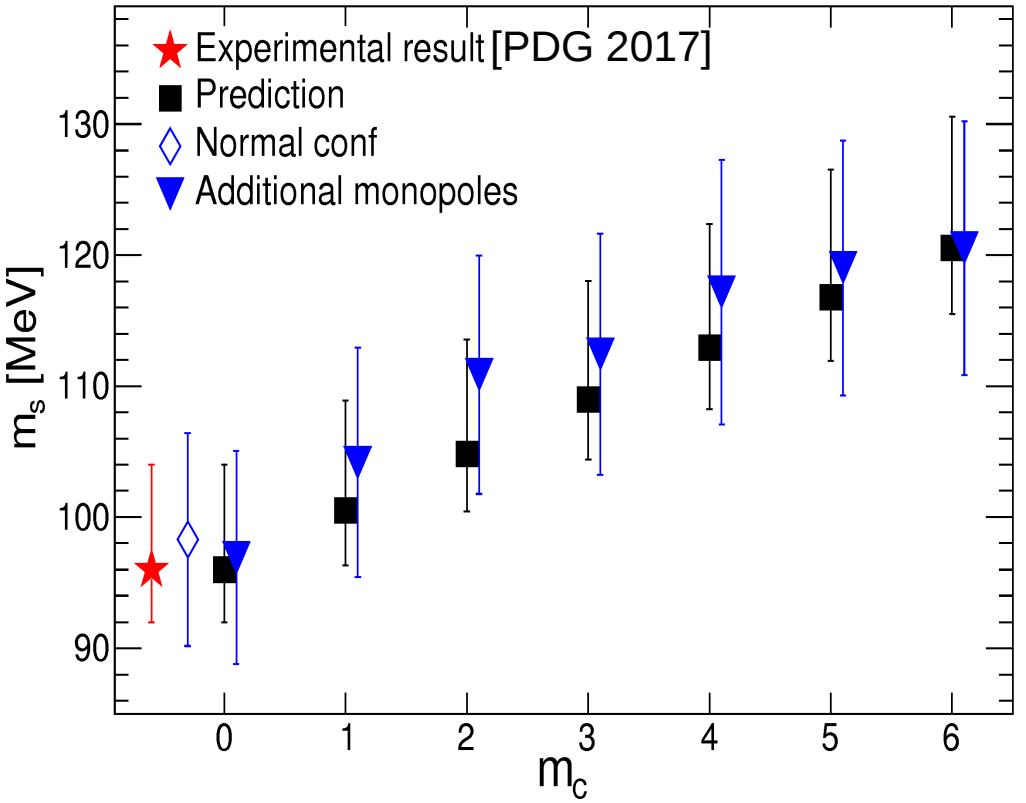


[arXiv: 1807.04808]

The light quark masses

The renormalized light quark masses increases with increasing the values of the magnetic charges. [arXiv: 1807.04808]

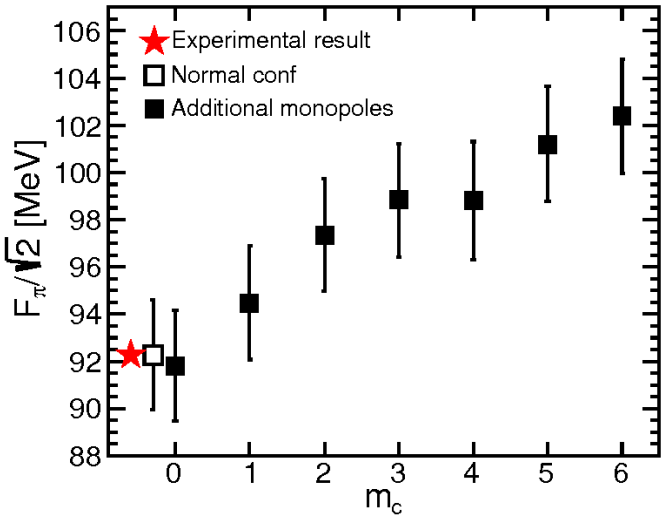


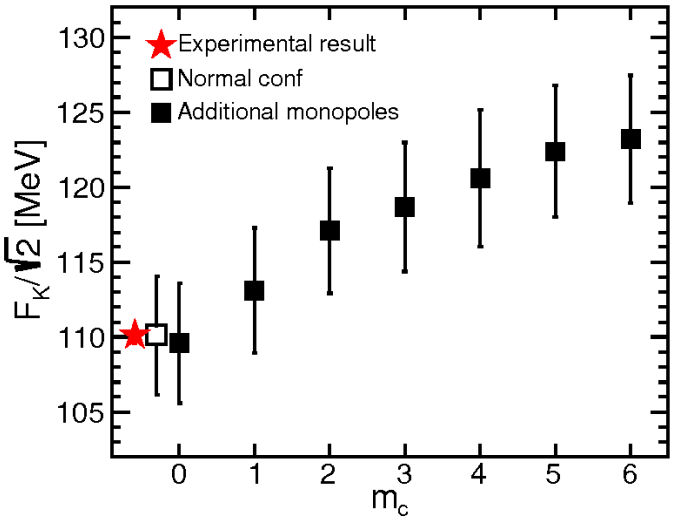


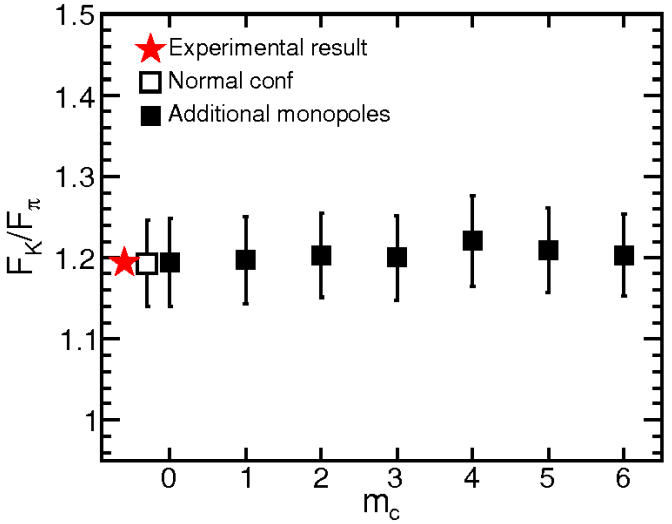
The numerical results of the light quark masses are evaluated in the $\overline{MS}$-scheme at 2 [GeV].

The decay constants and masses

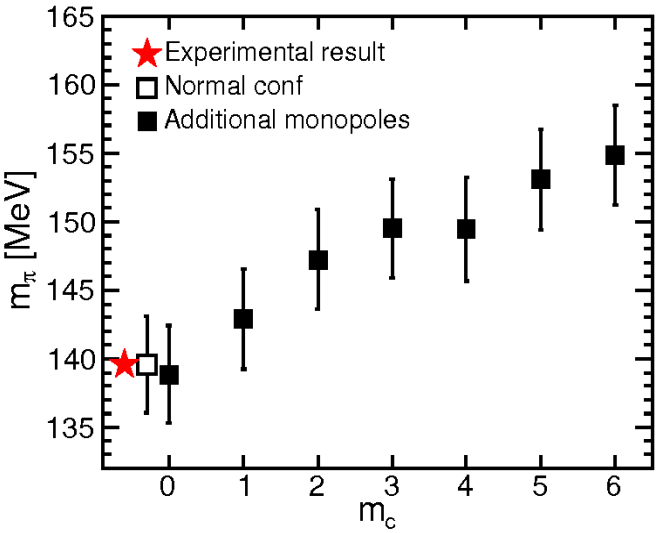
- **The decay constants of the pion and the kaon [arXiv: 1807.04808]**

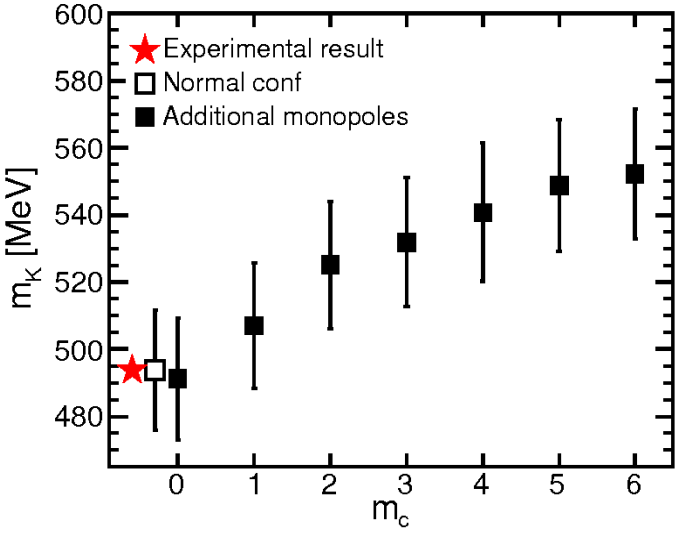


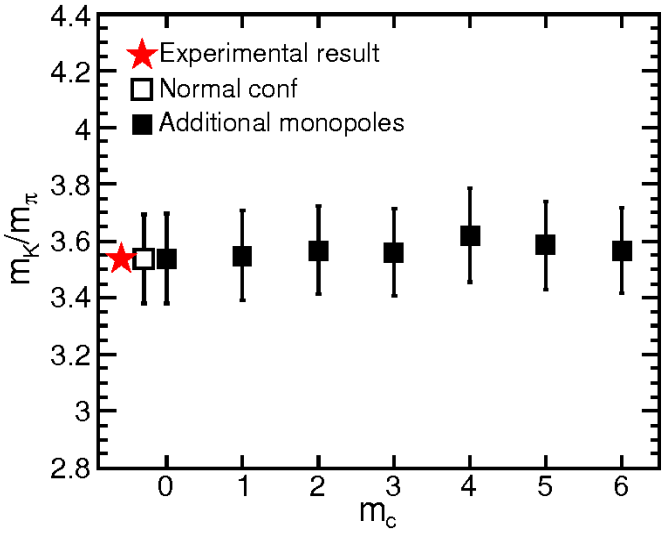




- **The masses of the pion and the kaon [arXiv: 1807.04808]**



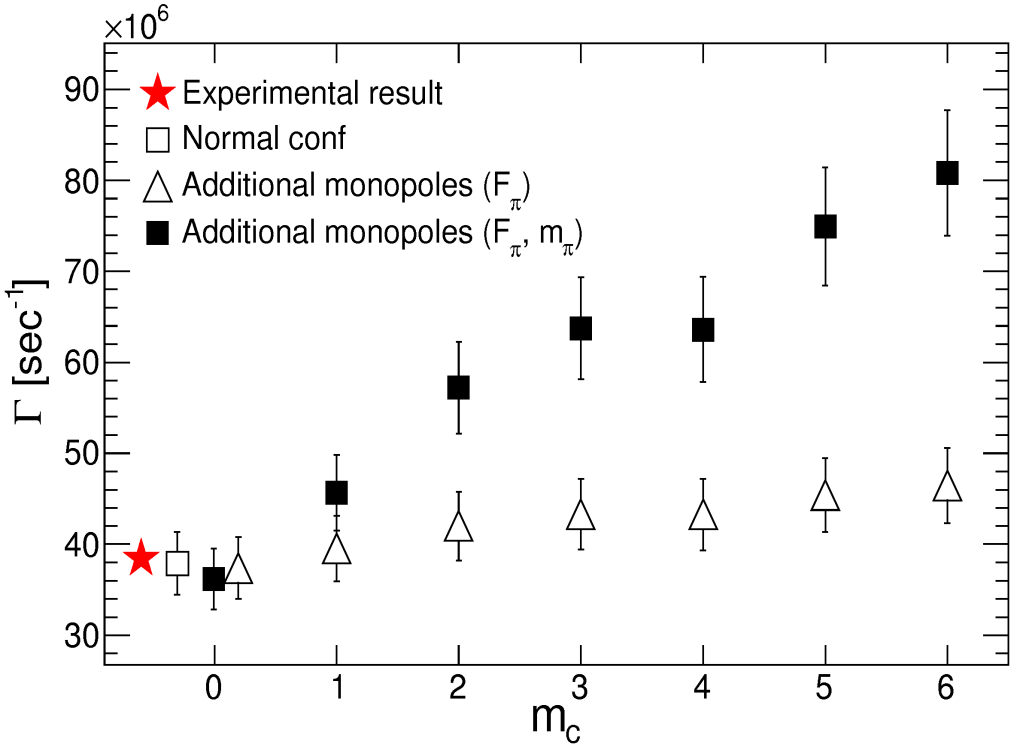




The experimental results are taken from [PDG 2017].

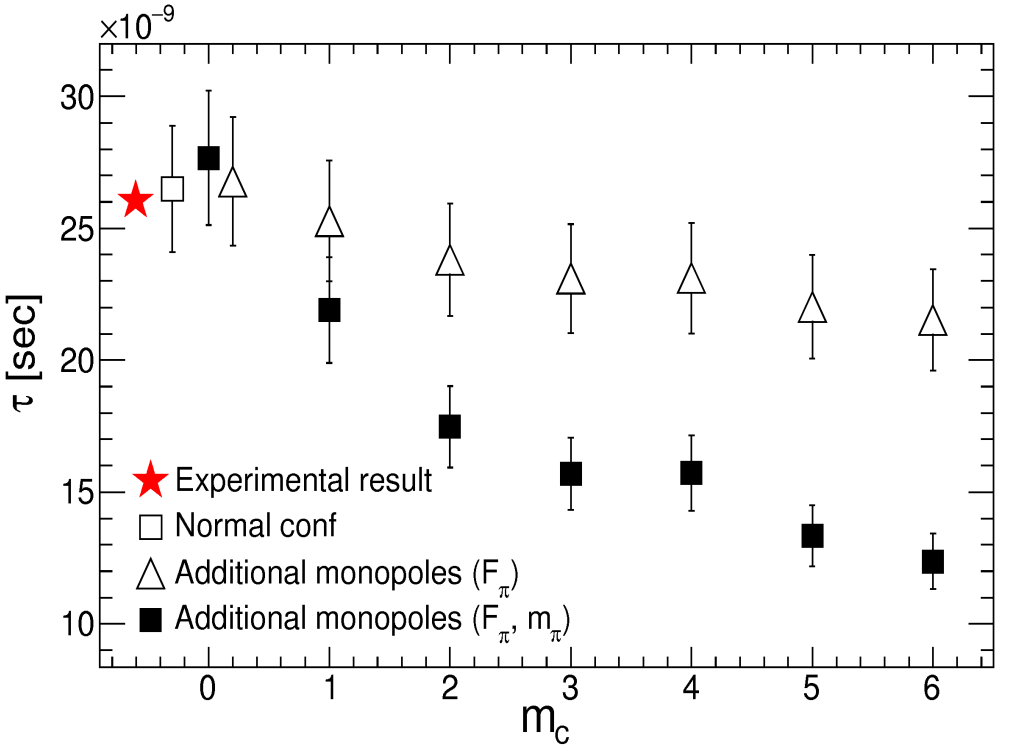
The decay width and the lifetime

- **The decay width Γ of the charged pion becomes wider by increasing the values of magnetic charges.**



[arXiv: 1807.04808]

- **The lifetime τ of the charged pion becomes shorter by increasing the values of the magnetic charges.**



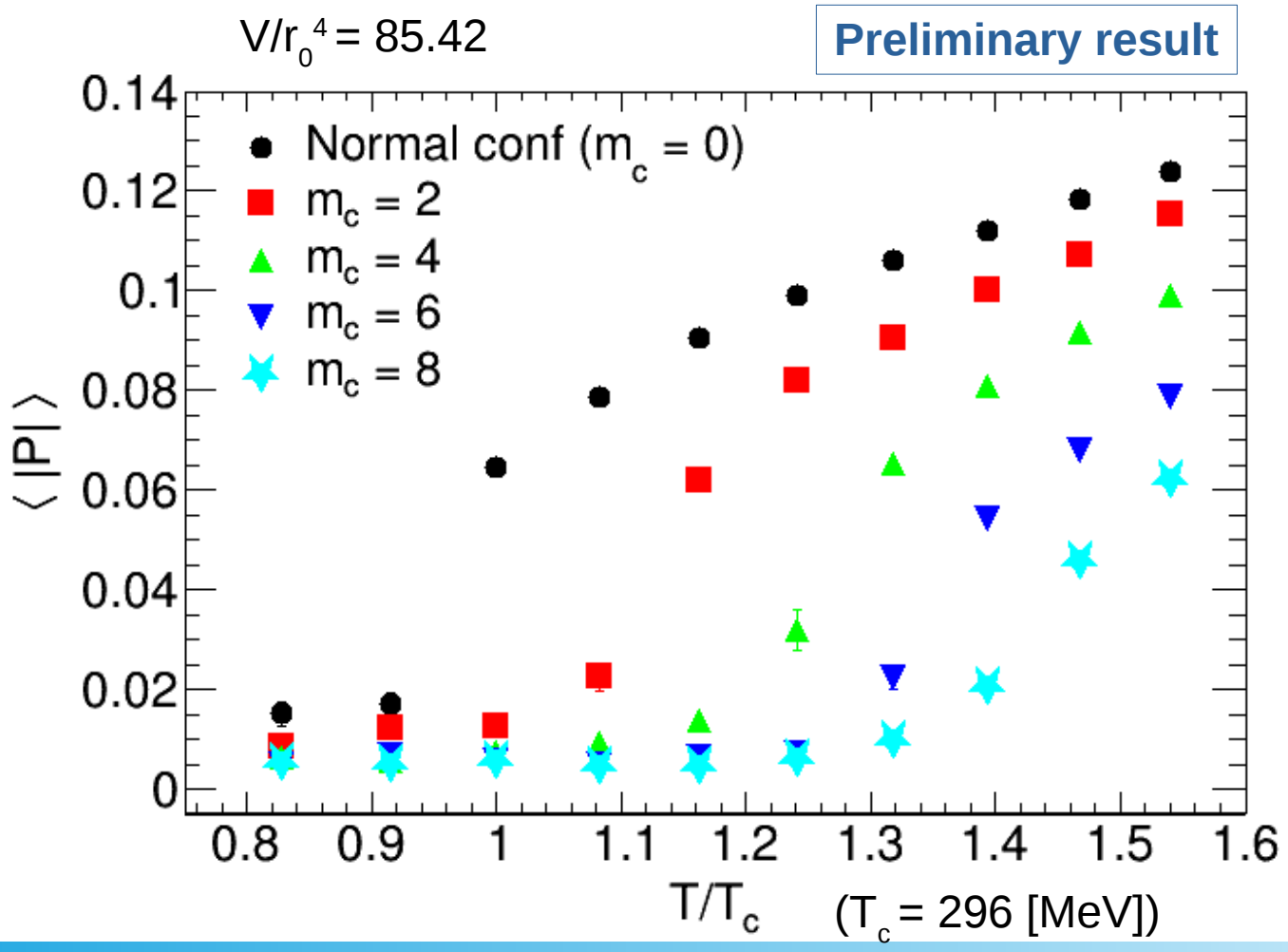
[arXiv: 1807.04808]

The catalytic effects of monopoles in the finite temperature

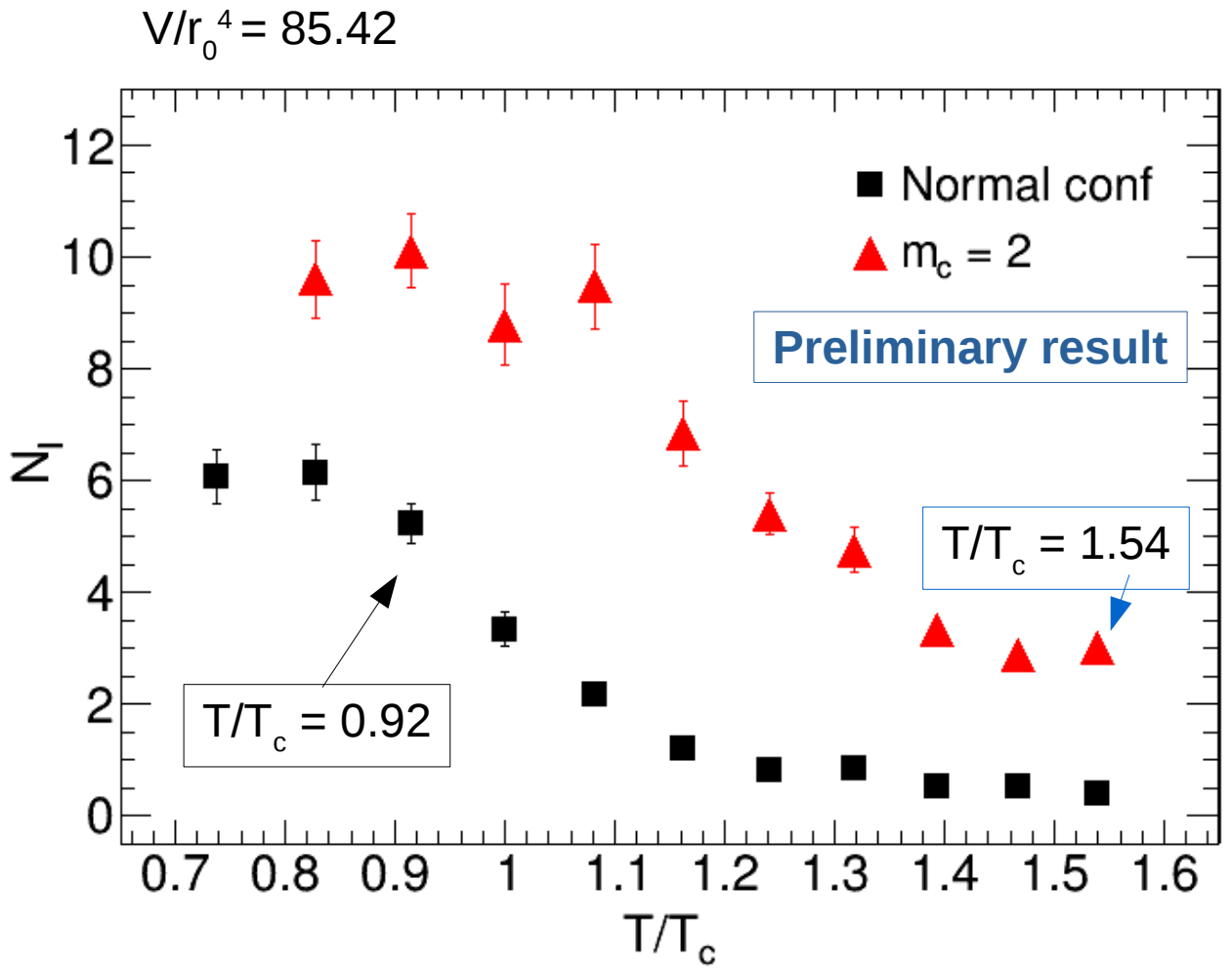
- I want to show that the additional monopoles relate to the phase transitions of the quark confinement and the chiral symmetry breaking.
- I add the monopole and anti-monopole to the configurations of the finite temperature, varying the magnetic charges.
- First, I calculate the absolute value of the Polyakov loop as the order parameter of the quark confinement.
- Next, I compute the total number of instantons and anti-instantons from the expectation values of the square of the topological charges.
- I compute the spectrum density of the low-lying eigenvalues of the overlap Dirac operator.

The phase transition of the quark confinement

The critical temperature rises by increasing the values of the magnetic charges.



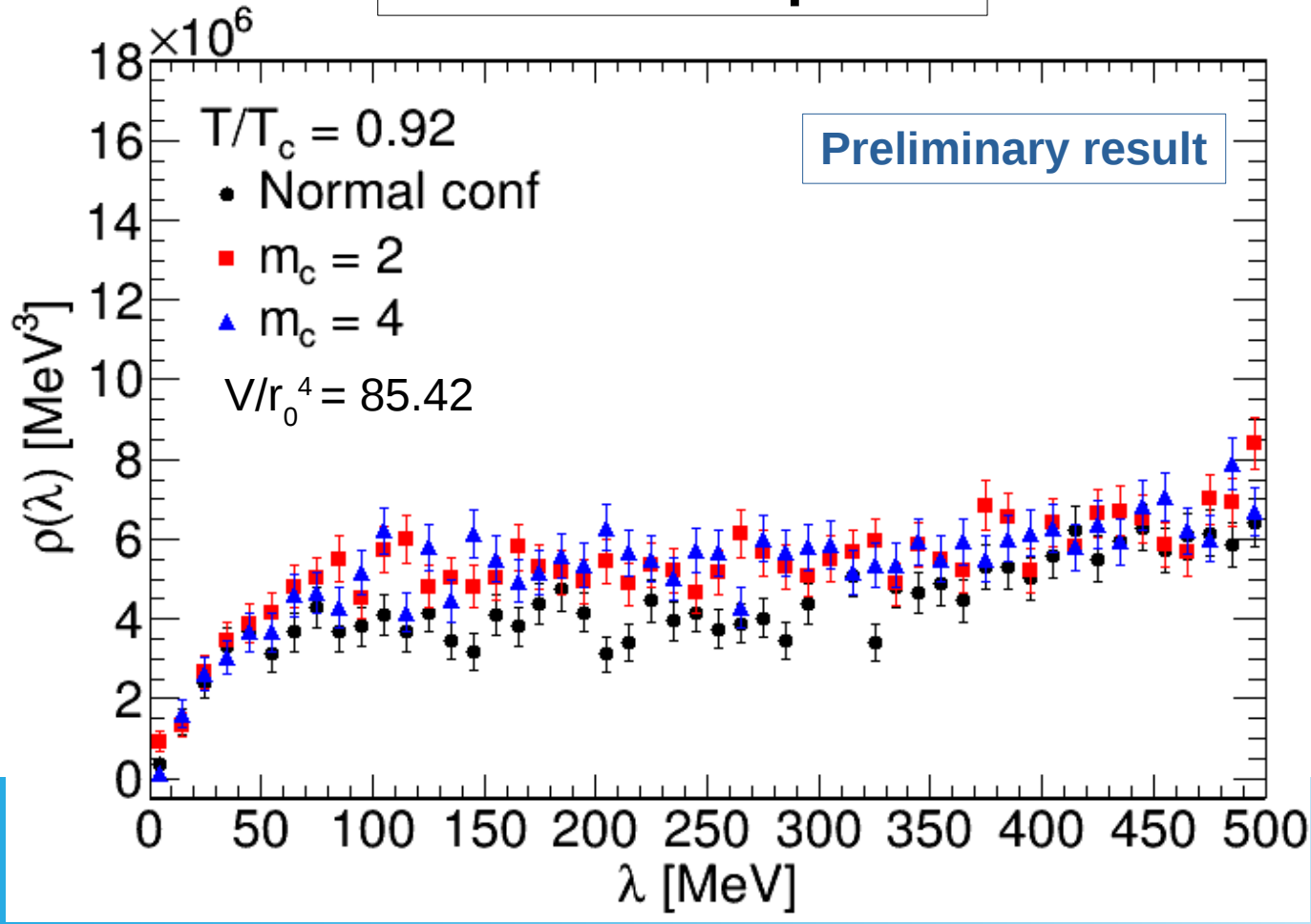
The number of instantons and anti-instantons



The spectrum density in the confinement phase

The spectrum density of low-lying eigenvalues of the overlap Dirac operator increases with increasing the values of the magnetic charges. [A. Di Giacomo, M. H., and F. Pucci, Proc. Sci., CD15 (2015) 127]

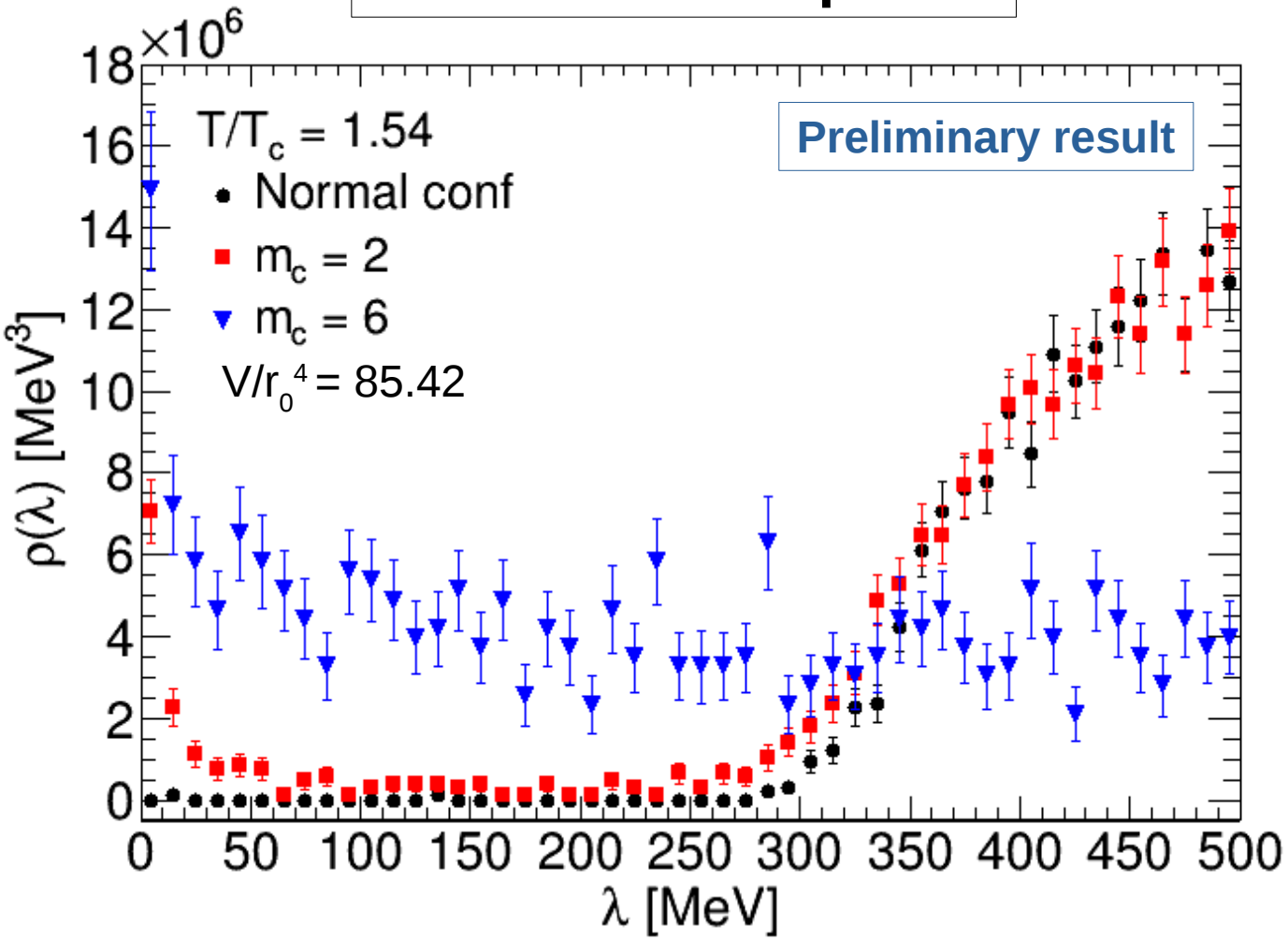
Confinement phase



The spectrum density in the deconfinement phase

The restoration of the chiral symmetry breaking would not occur by increasing the values of the magnetic charges.

Deconfinement phase



The conclusions

- **I introduced the catalytic effects of monopoles at the zero temperature and the finite temperature.**
- **In the study of zero temperature, I have shown that the chiral condensate decreases, the decay constants increase, and the masses of the light quarks and pseudoscalar increase. Finally, I have demonstrated that the decay width becomes wider and the lifetime becomes shorter.**
- **In the study of the finite temperature, the critical temperature would rise. The restoration of the chiral symmetry breaking would not occur due to the catalytic effects of the Adriano monopole.**