A new paradigm for Quantum Chromodynamics in the infrared?

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LPTMC seminar

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Collaboration with Matthieu Tissier at LPTMC

+ Julien Serreau at APC, Université Paris-Cité
+ Marcela Peláez (former PhD at LPTMC) & Nicolás Wschebor, Universidad de la República, Montevideo, Uruguay

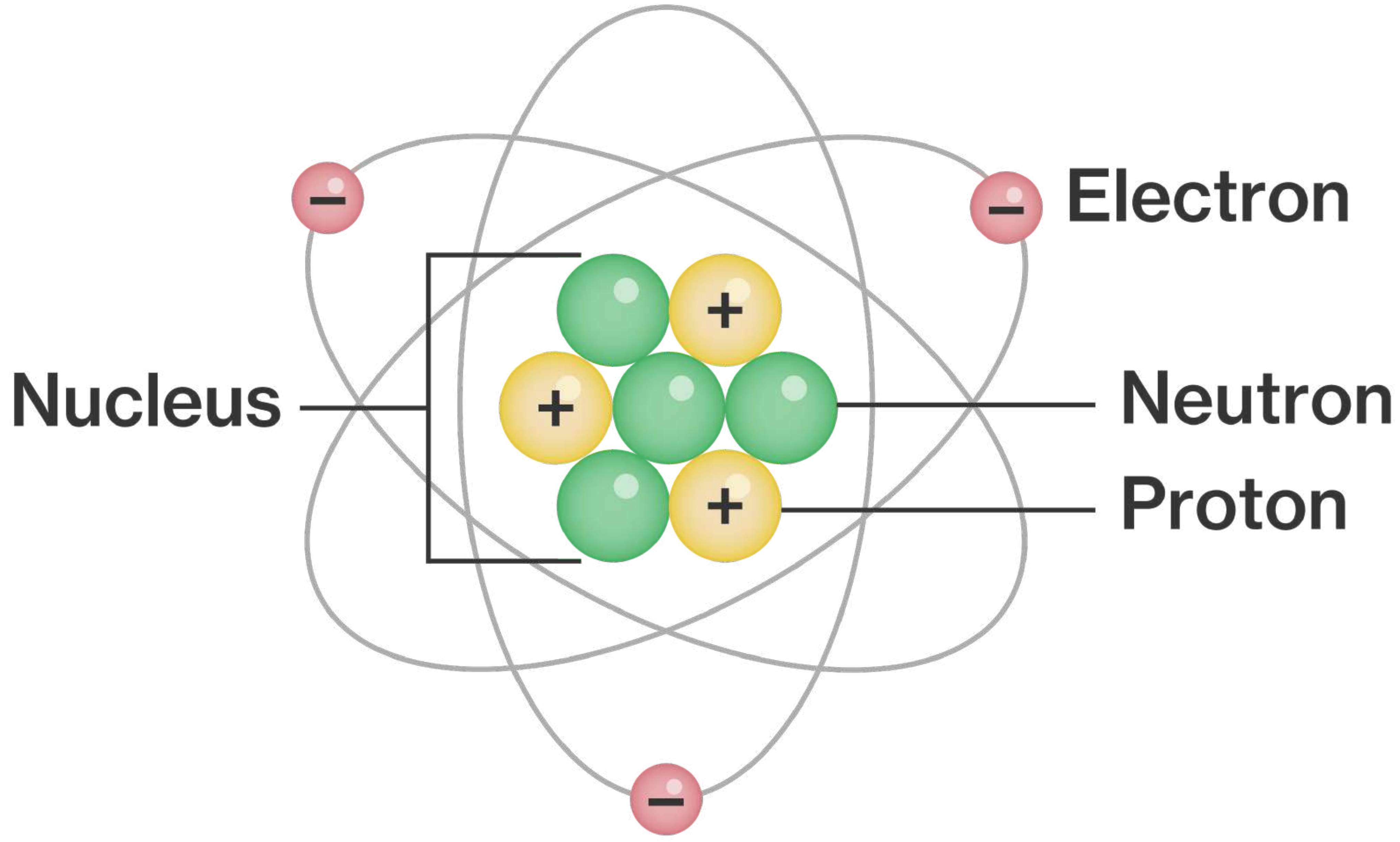
Quantum Chromodynamics describes a strongly correlated system.

Our activity benefits from ideas and techniques borrowed from condensed matter and statistical physics.

The strong interaction

One of the fundamental forces of Nature.

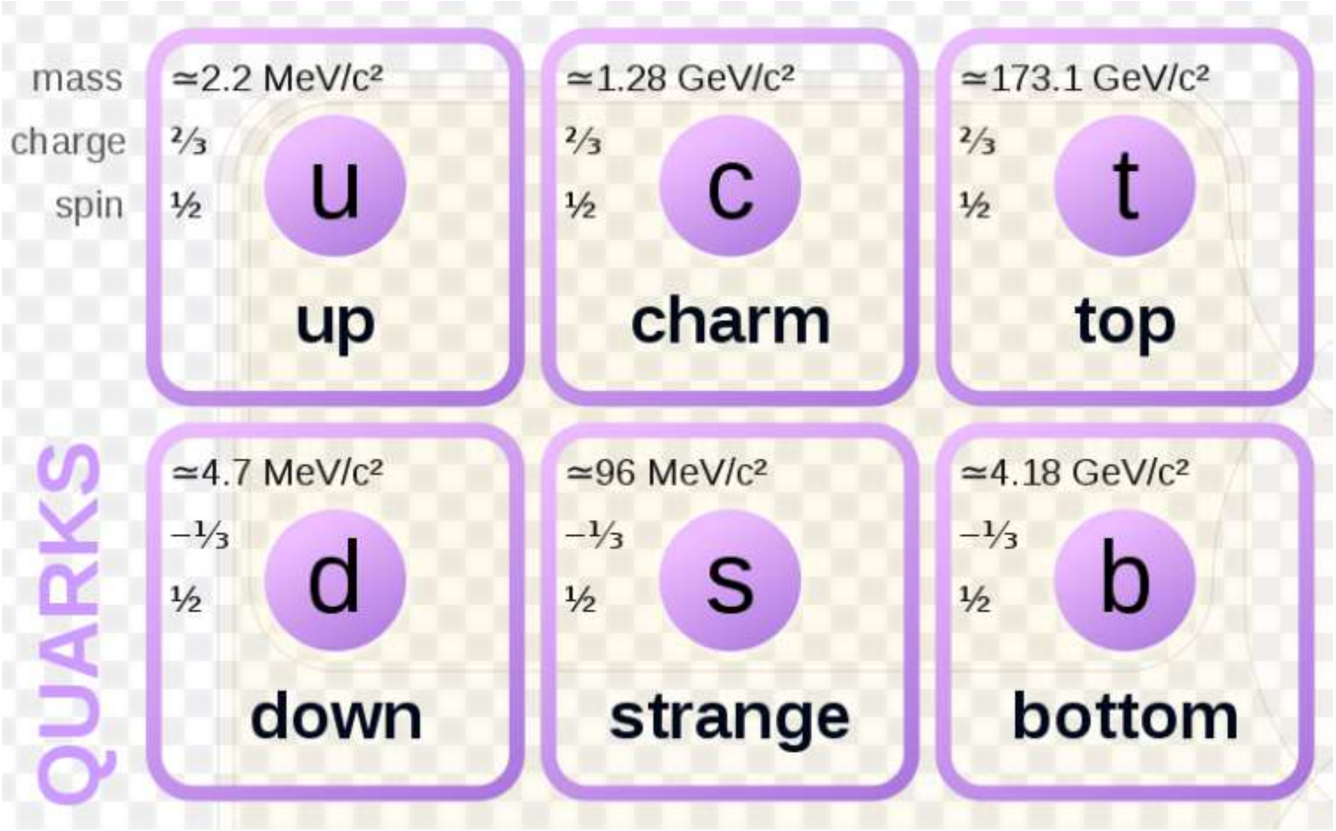
Ties protons and neutrons inside nuclei despite the repulsive electromagnetic forces between the protons.



Hadrons, quarks and gluons

The particles subjected to the strong interaction are called hadrons: protons, neutrons, pions, …

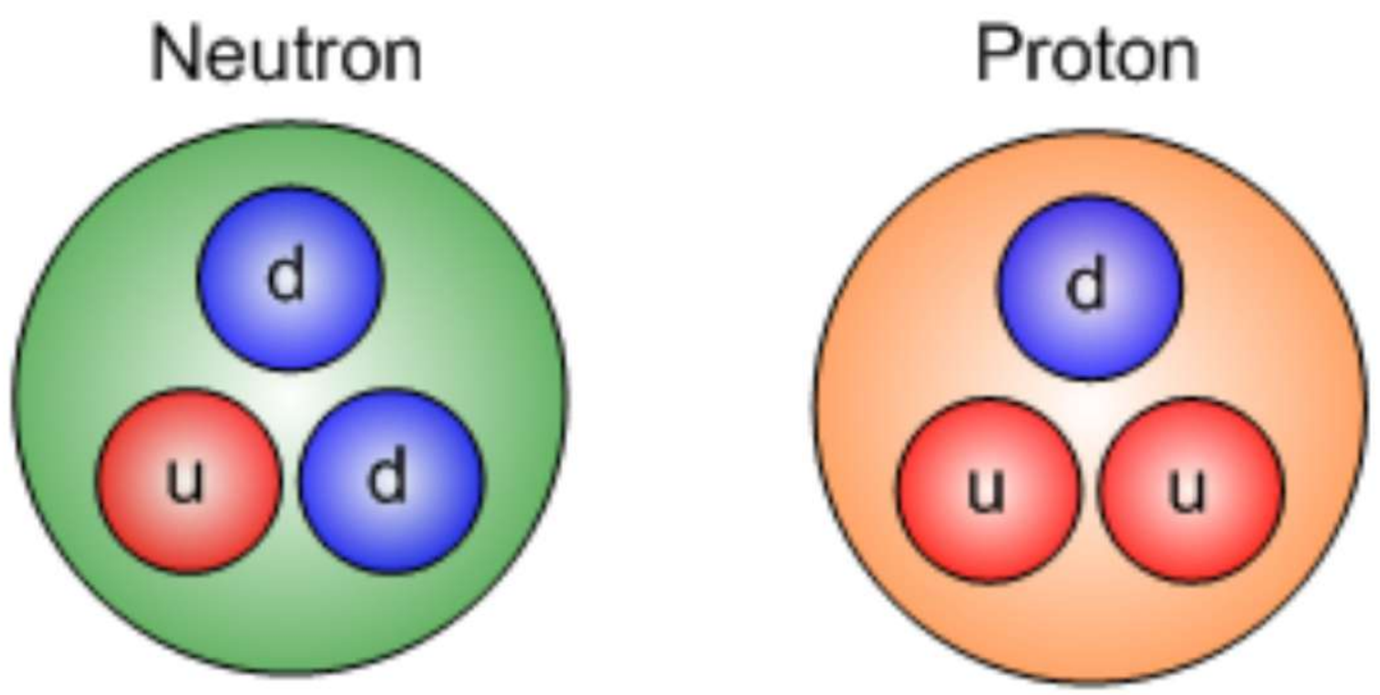
Our current understanding is that these are composite particles made of more elementary ones, the quarks.



The quarks interact via the exchange of gluons, pretty much like electrons exchange photons.

Two big mysteries of the hadronic world

1. Under normal conditions, quarks are never observed: they are said to be confined within hadrons.



2. The physical properties of these hadrons seem to have little to do with those of their constituent quarks taken individually.

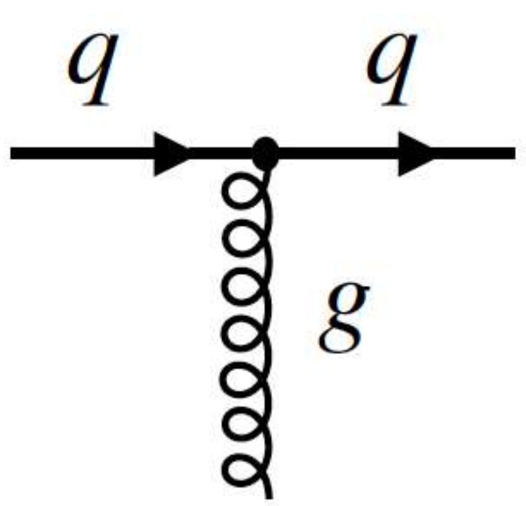
Ex: Proton mass is ~ 10^9 eV while u- and d-quark masses are just a few 10^6 eV.
Mass generation mechanism more effective than the Higgs mechanism!

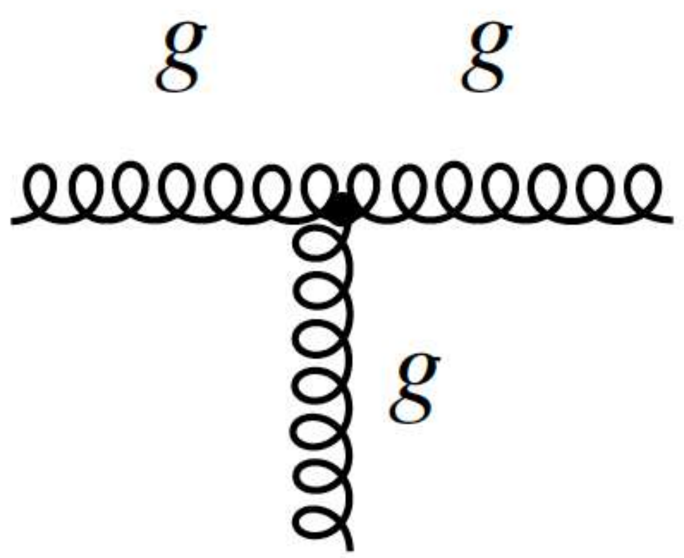
Quantum Chromodynamics

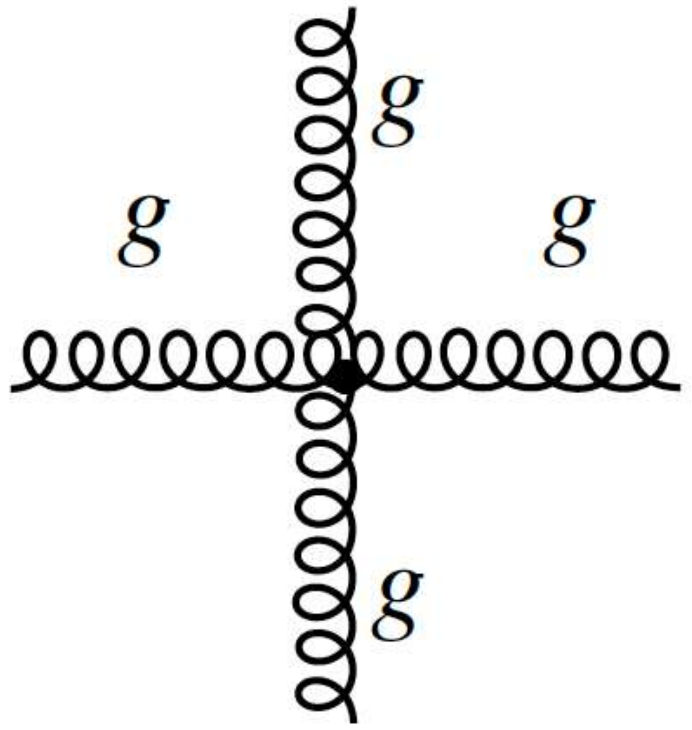
These mysteries should be solved within Quantum Chromodynamics (QCD), the accepted fundamental theory for strong interactions.

Gauge theory constructed in a way similar to Quantum Electrodynamics (QED): quarks carry a new type of charge dubbed as color and interact via the exchange of quanta of a gauge field known as gluons.

Major difference with QED: gluons carry color and hence self-interact.

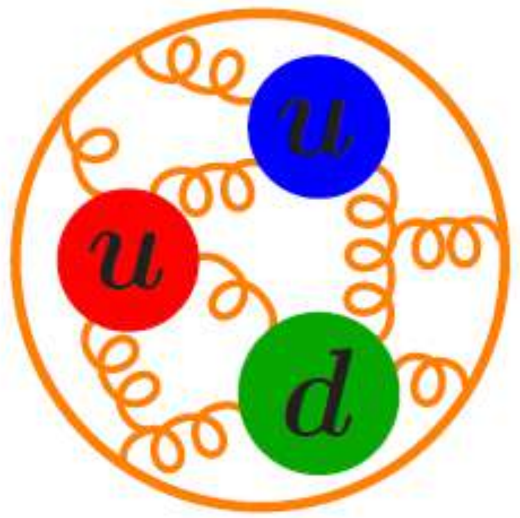




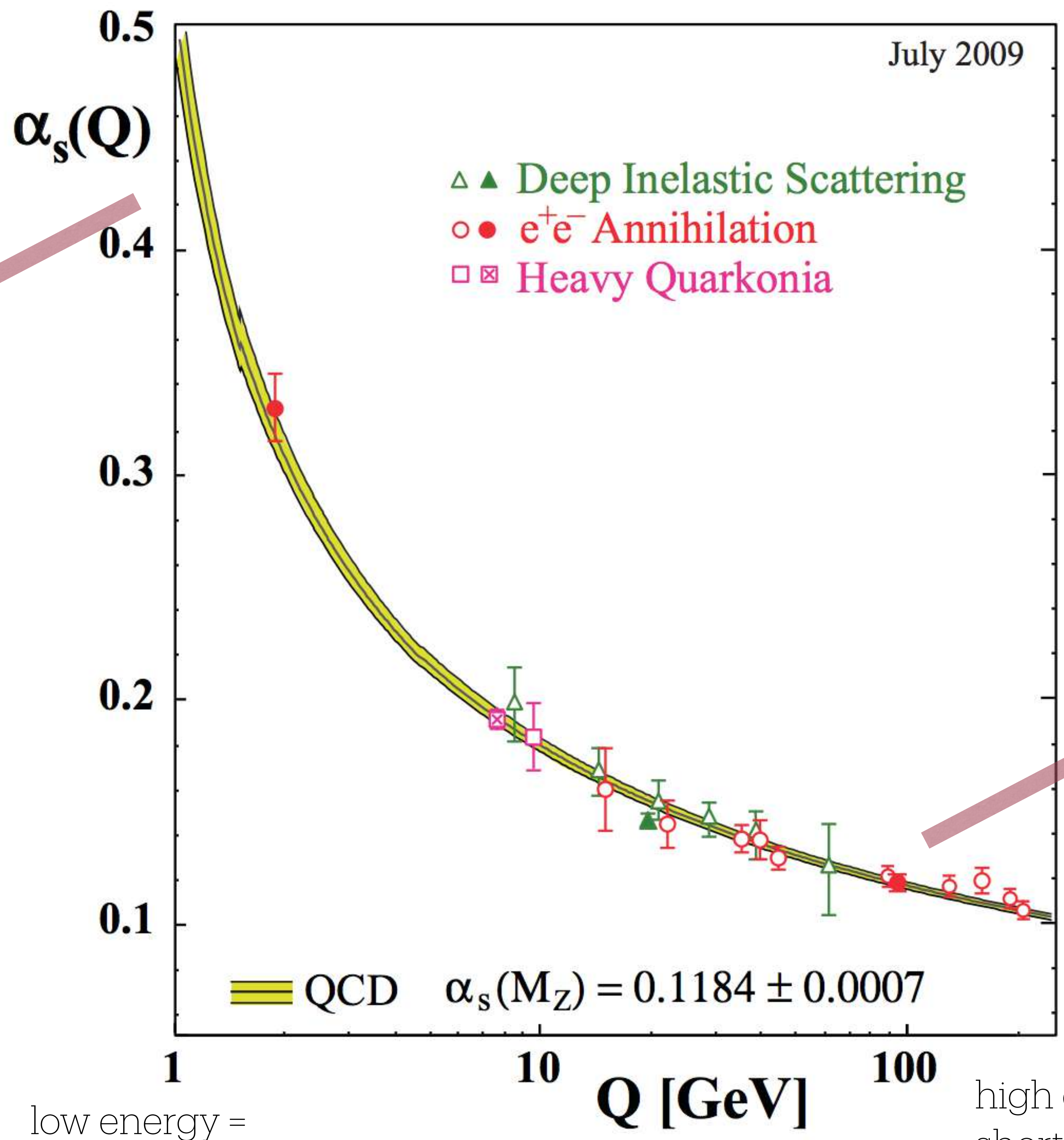


Intensity of the interaction:
strong coupling $\alpha_S(Q)$

Strong coupling



large $\alpha_S(Q)$: other approaches needed



small $\alpha_S(Q)$: perturbative techniques available

low energy = large distance

high energy = short distance

Some of the challenges

Hadronic structure:
How do quarks and gluons conspire to give hadrons their physical properties?

Confinement:
Why do quarks confine in the first place?

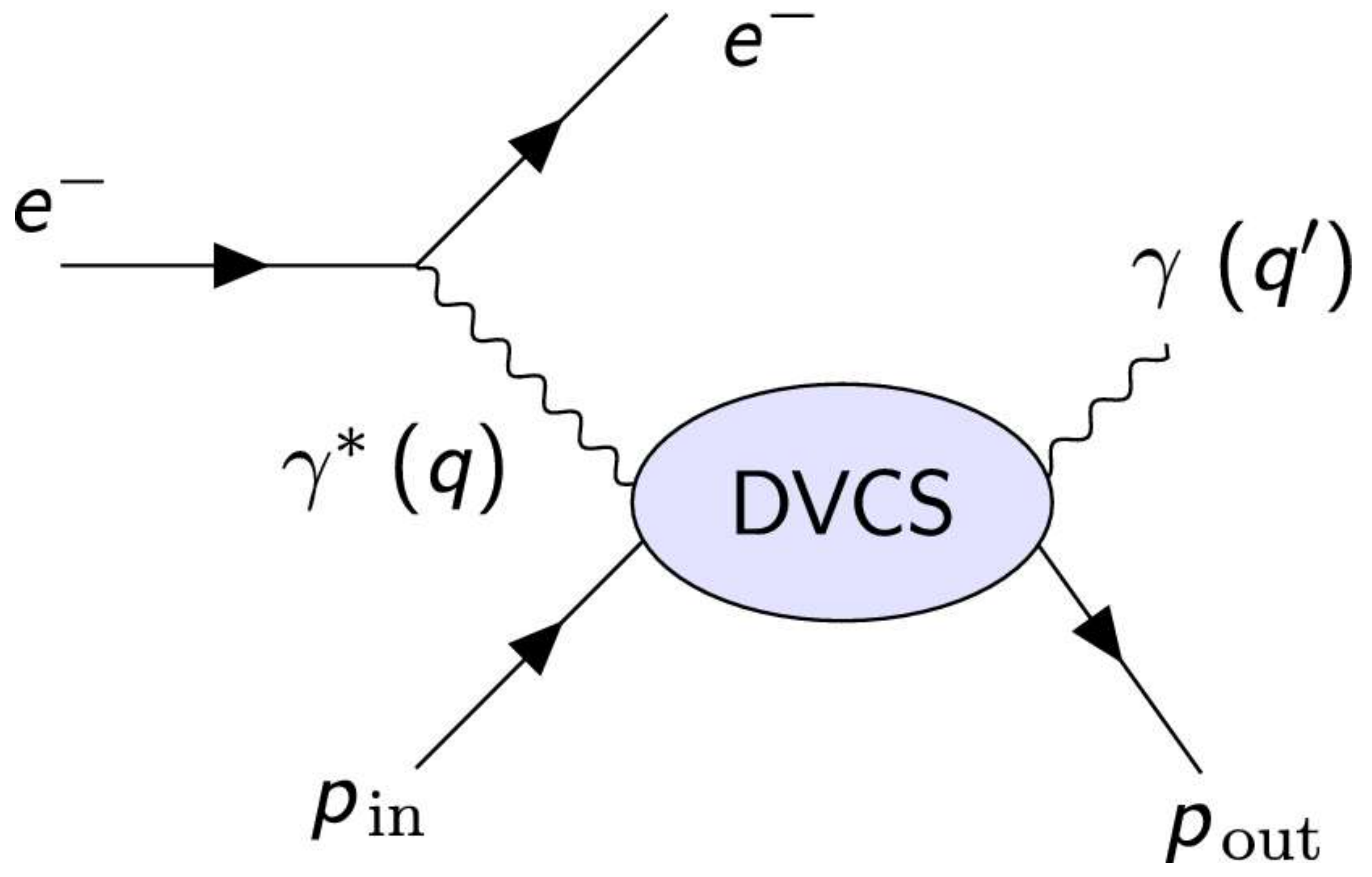
High energy regime:
What happens at high energies? Do quarks deconfine?

These questions mobilize both experimental and theoretical effort.

From the experimental side …

Scattering experiments

Scattering of some simple probe (electron, ...) off an hadron in order to probe its internal structure:



Observable = hard part x soft part

Measured — Computable perturbatively — Extracted from data

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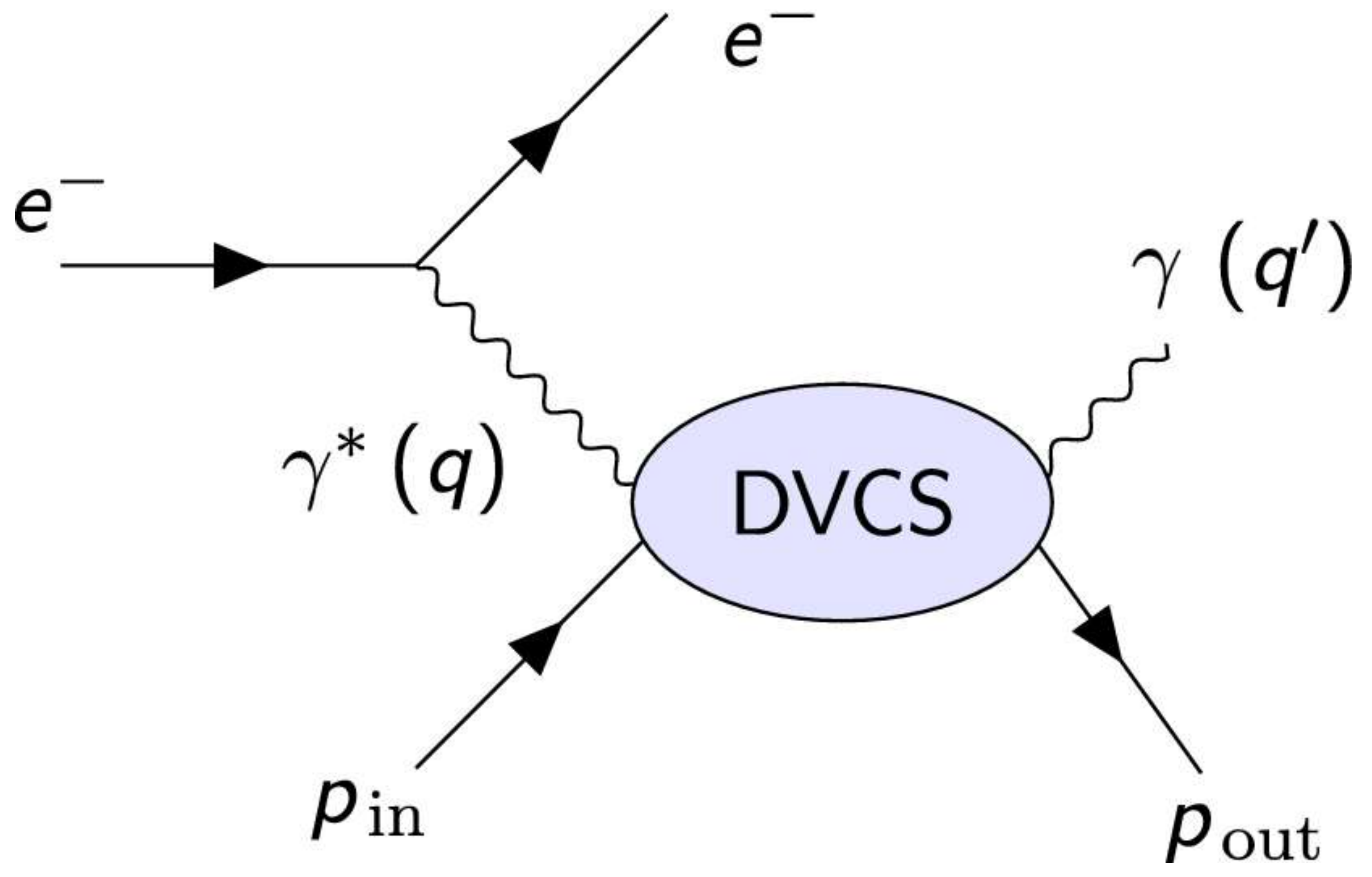

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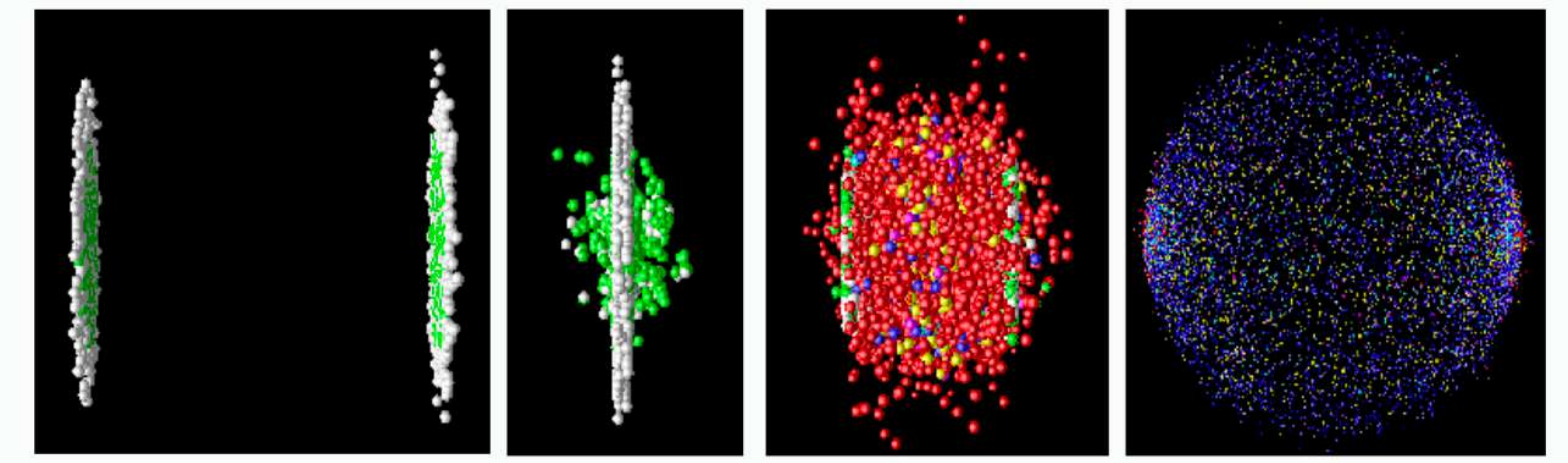
The soft part contains universal information about the distribution of quarks (and gluons) within the hadrons.

Can be used to:

- predict the outcome of other scattering processes;
- understand the physical properties of the hadrons from those of their constituents.

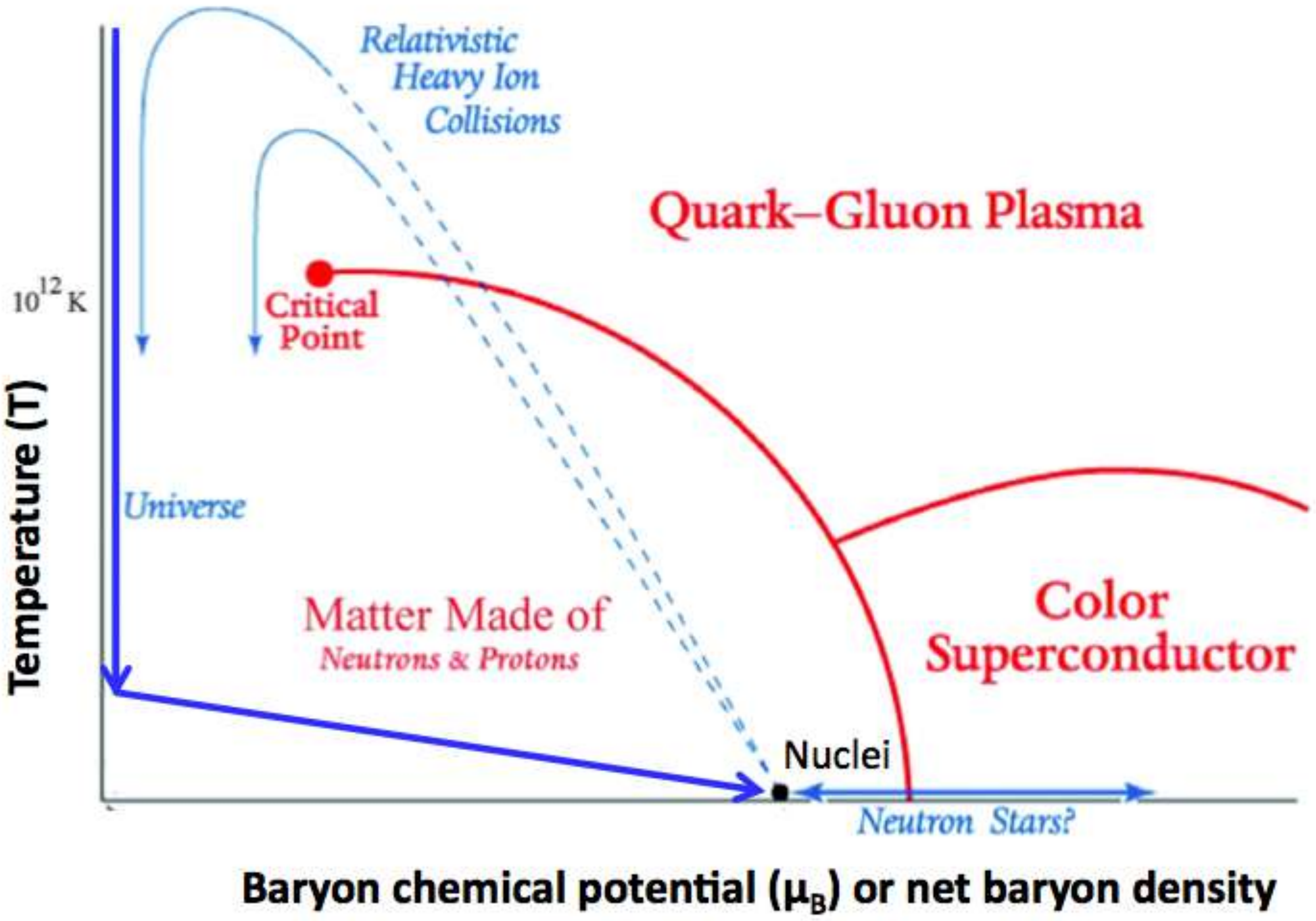
High energy collision experiments

Collisions of ultra-relativistic heavy nuclei in view of exploring the high energy regime of the theory.



In particular, one aims at forcing the quarks into a deconfined state of matter known as the quark-gluon plasma.

QCD phase diagram



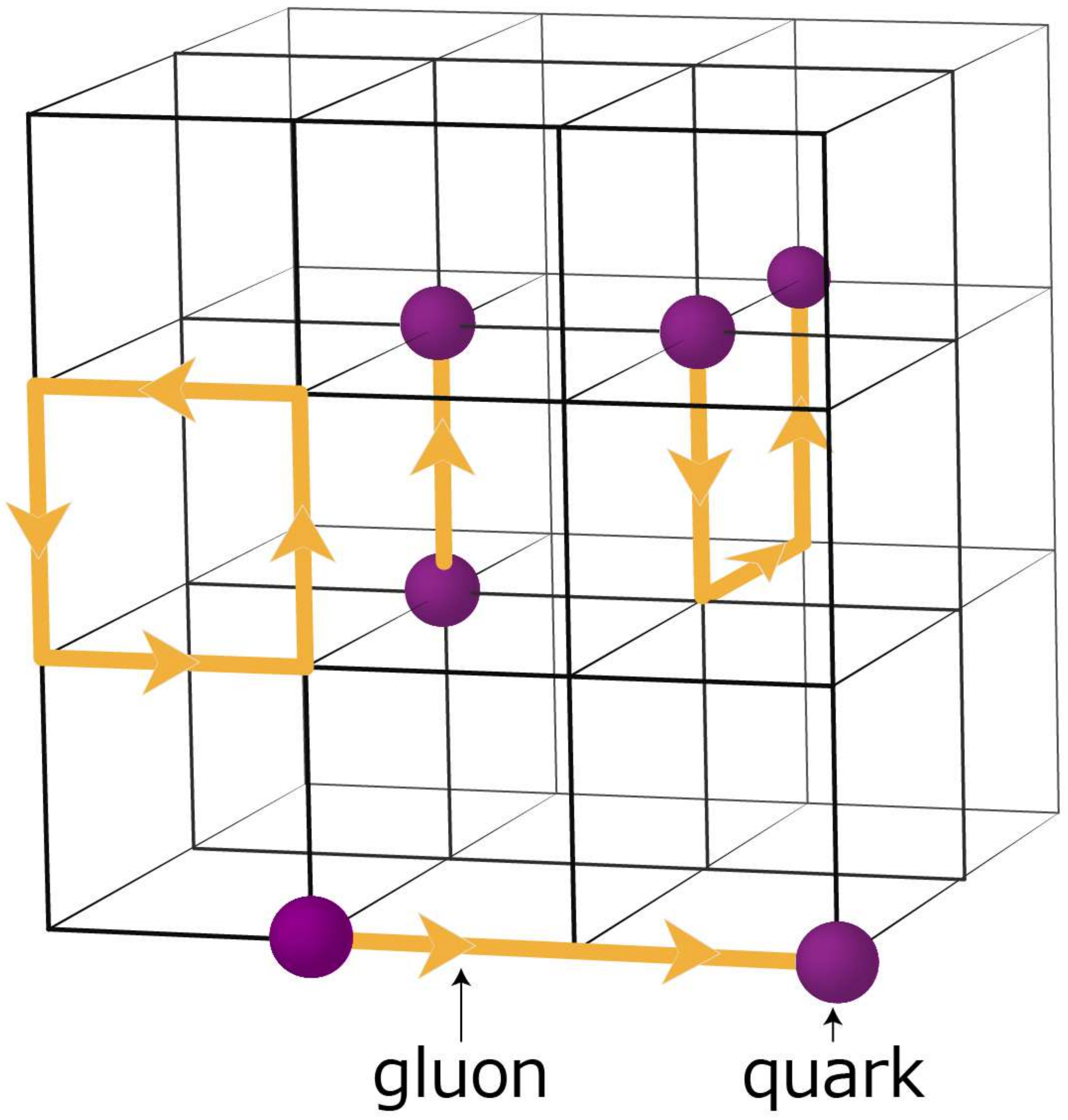
From the theory side …

Numerical simulations of QCD

The QCD functional integral
(partition function)

$$Z = \int \mathcal{D}A\mathcal{D}\psi\mathcal{D}\bar{\psi}\, e^{-S_{\mathrm{QCD}}[A,\psi,\bar{\psi}]}$$

is discretized and evaluated on a "lattice",
using statistical Monte-Carlo algorithms.

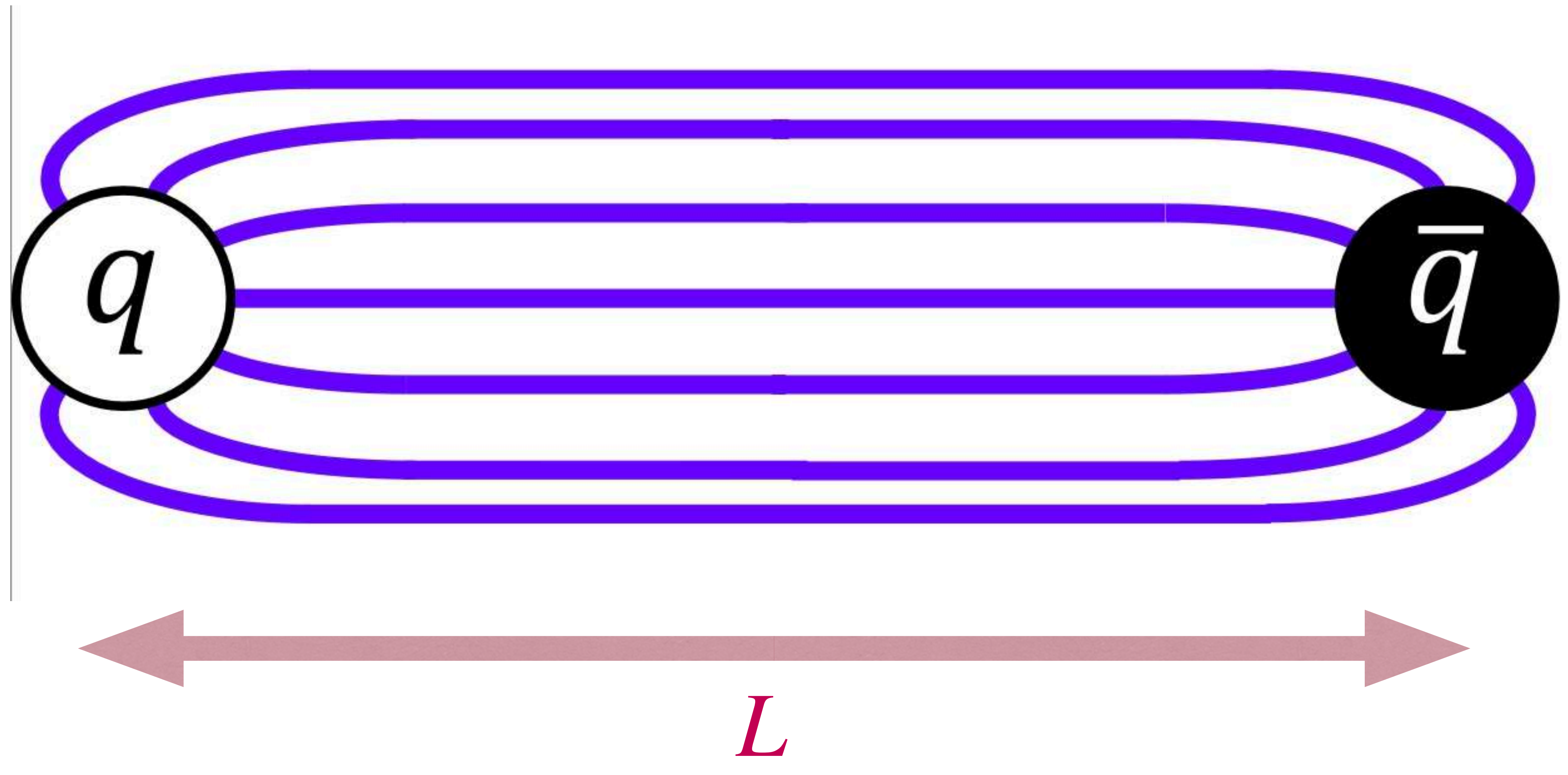


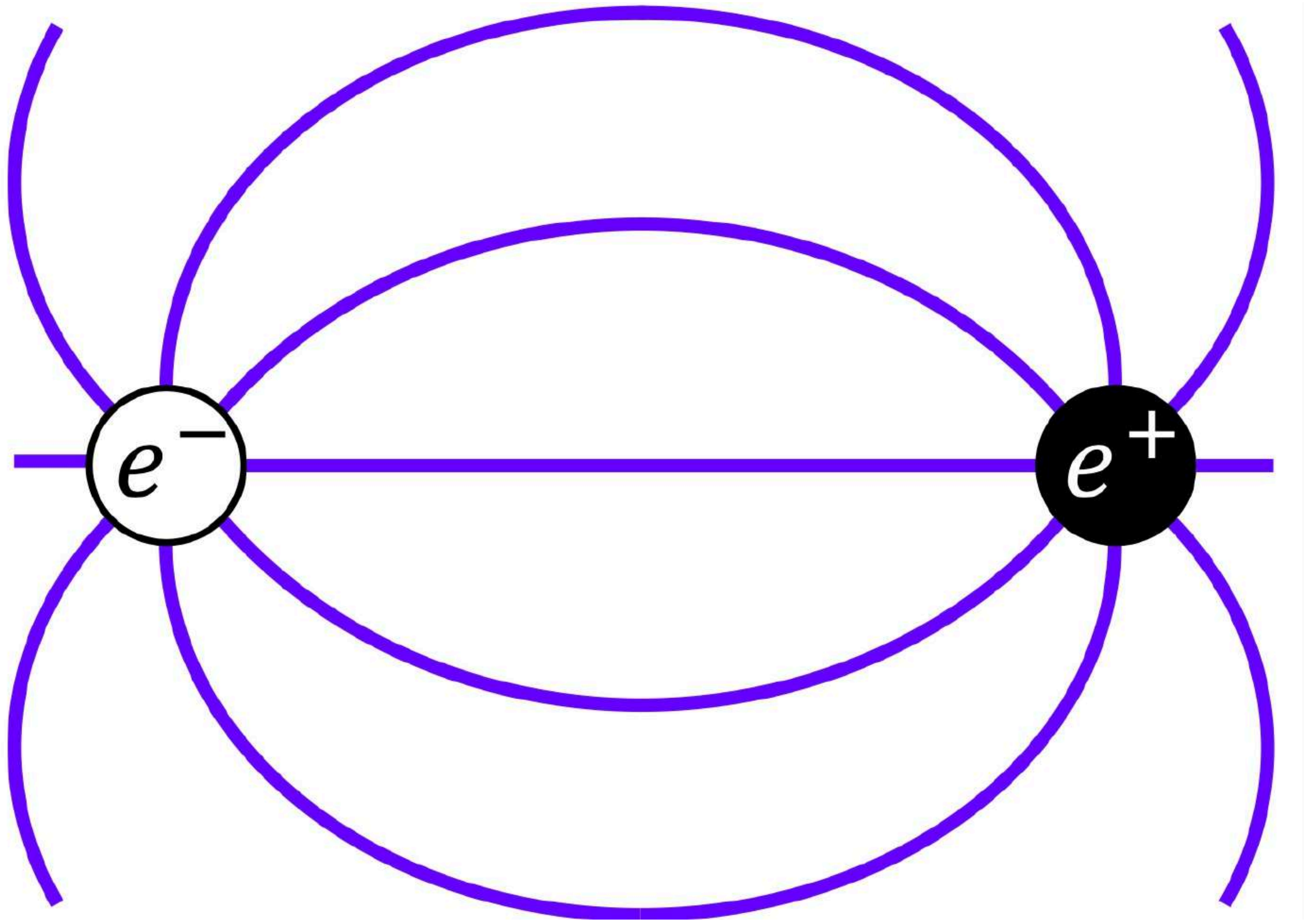
Immense source of knowledge about QCD.

The confining force between quarks

The lattice can for instance evaluate the "chromo-electric" force $F_{q\bar{q}}$ between a quark and an antiquark separated by a distance L.

Found to be radically different from, say, the electric force $F_{e^-e^+}$ between an electron and a positron.



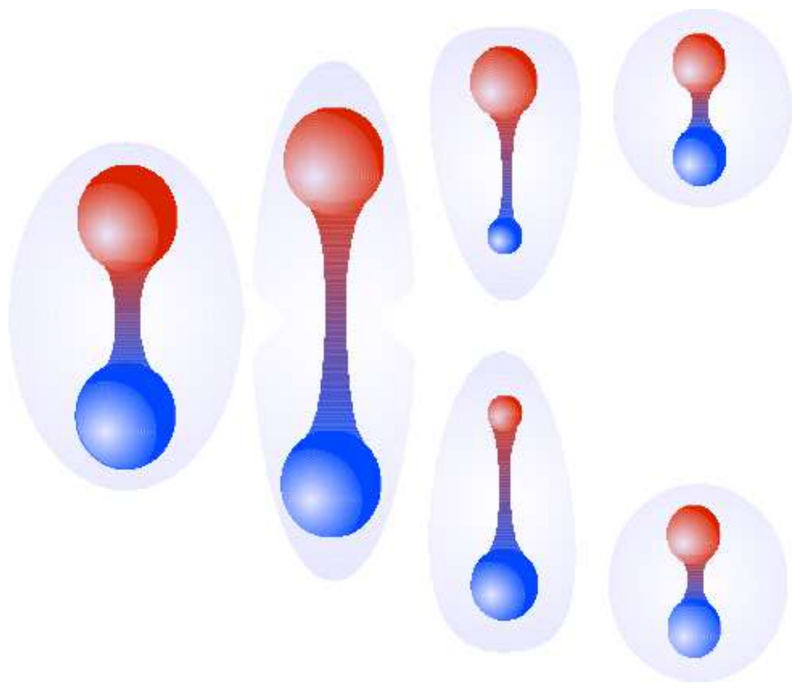


The confining force between quarks

$F_{q\bar{q}}$ is found not to depend on the separation L. It is essentially a constant, known as the string tension, of the order of (440 MeV)^2.

In normal units, this is "just" the weight of a small truck ~ 10^5 N. But applied over the scale of the hadron (~ 10^-15 m), this gives an enormous pressure of 10^35 Pa!

Other consequence: as one tries to separate the quark-antiquark pair, the mechanical work brought to the systems is very rapidly enough to create a new pair.



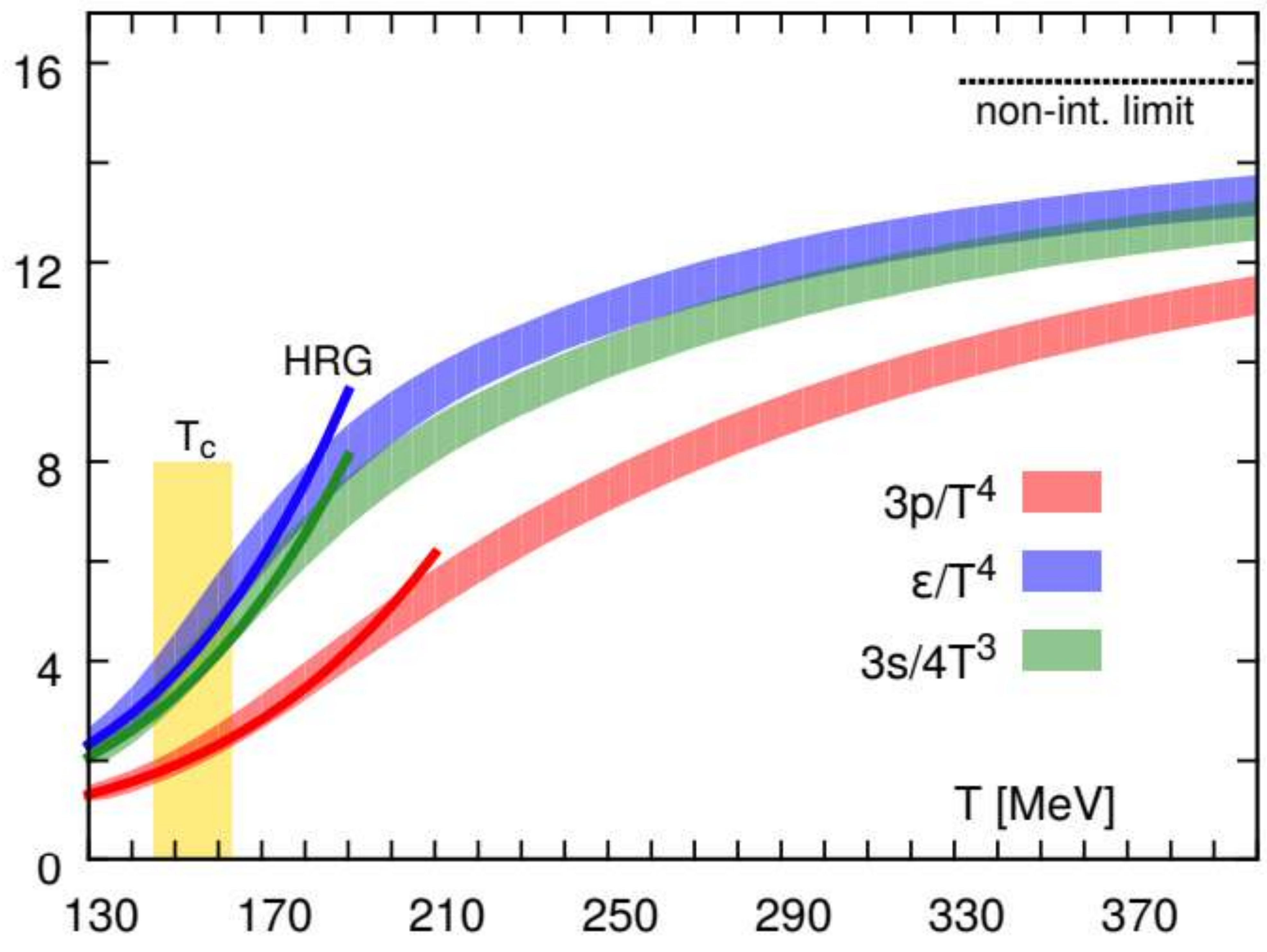
Essentially impossible to pull apart a quark from an hadron in the vacuum.

The deconfinement transition

What happens as one brings energy into the system, for instance by contact with a thermostat?

The strong coupling decreases and so does the string tension. It becomes simpler and simpler to separate a quark from an antiquark.

In the high temperature limit, one actually expects a deconfined phase of matter where quarks are liberated.



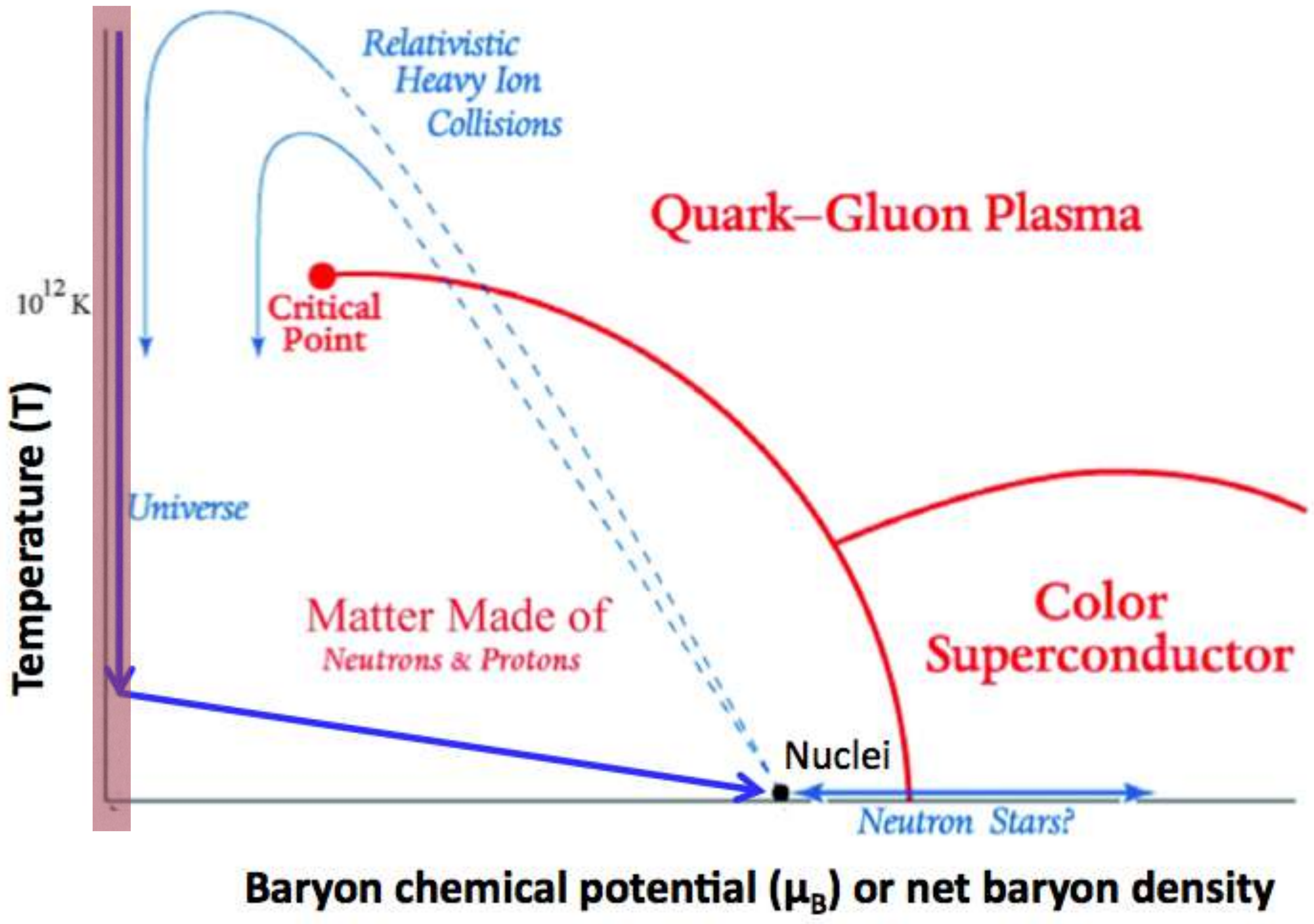
Tc~ 150 MeV of the order of 10^12 K

Limitations of the lattice simulations

Monte-Carlo simulations require a statistical interpretation of the functional integral

$$Z = \int \mathcal{D}A\mathcal{D}\psi\mathcal{D}\bar{\psi}\, e^{-S_{\mathrm{QCD}}[A,\psi,\bar{\psi}]}$$

and thus a real action.



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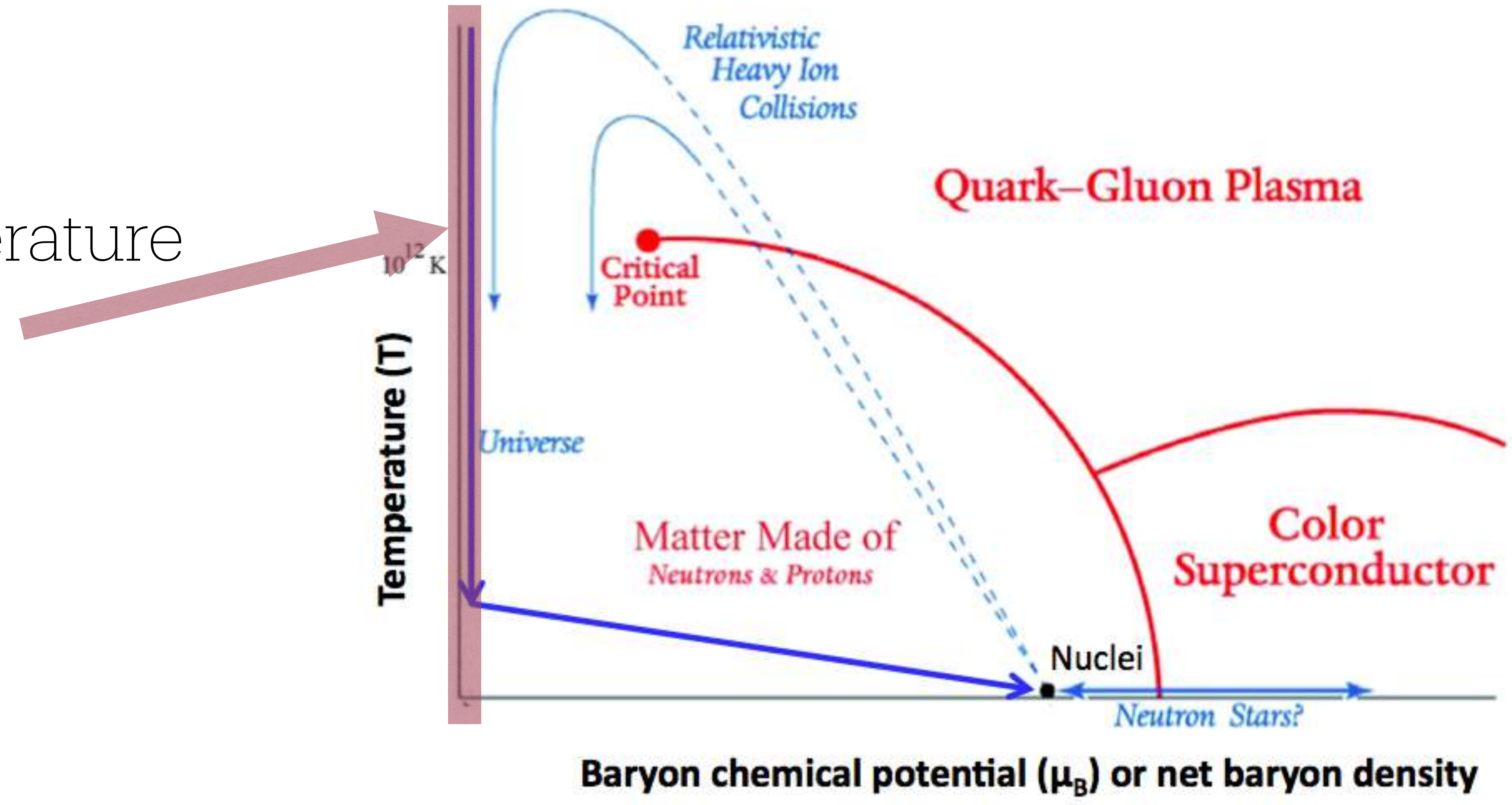

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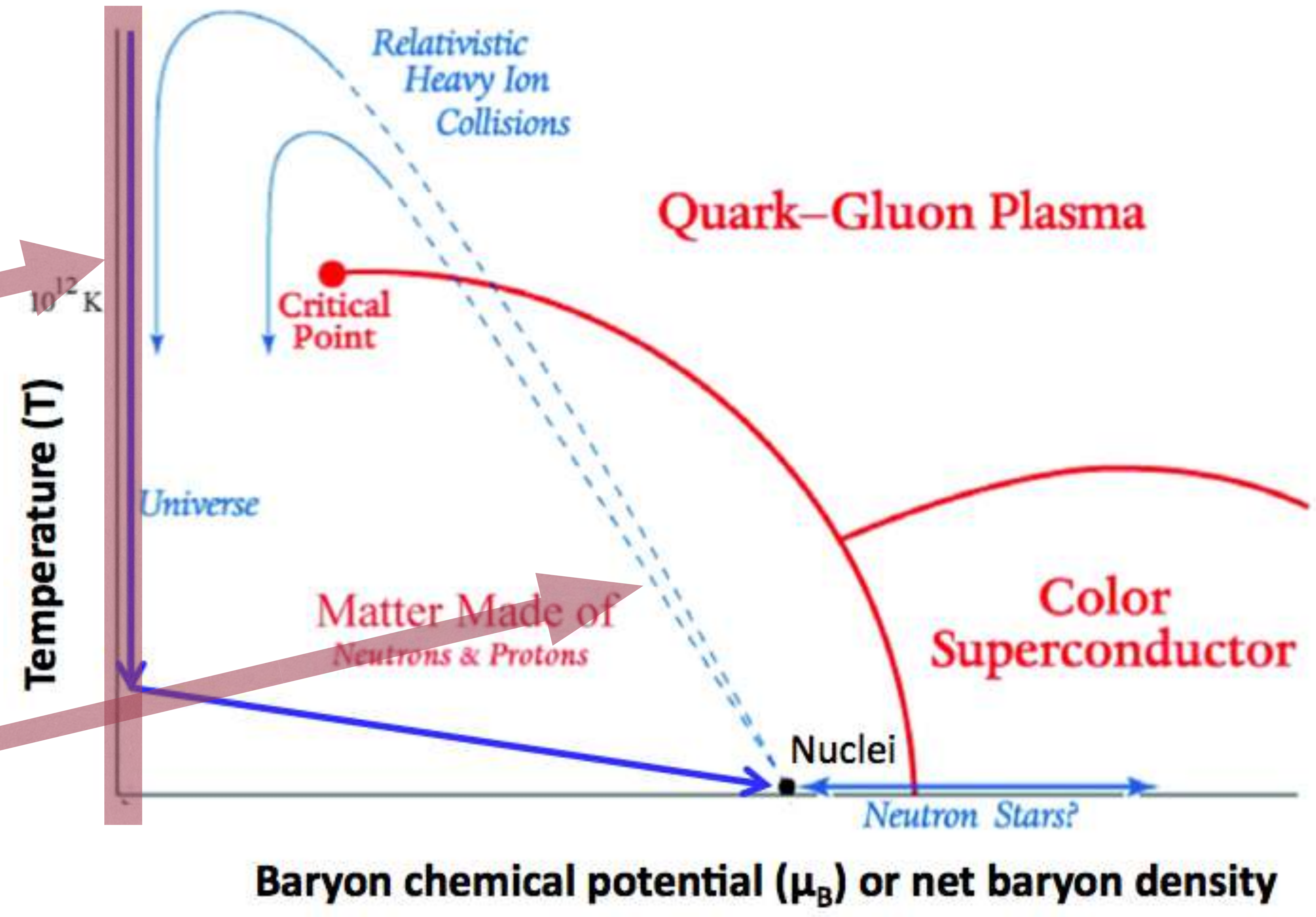
But in many other cases, the action is complex and Monte-Carlo techniques become inapplicable: "sign problem."



Beyond the numerical simulations?

Compute correlation functions instead

$[\,\chi = A, \psi, \bar{\psi}\,]$

$$\langle \chi_1 \cdots \chi_n \rangle \propto \int \mathcal{D}\chi \, \chi_1 \cdots \chi_n \, e^{-S_{\text{QCD}}[\chi]}$$

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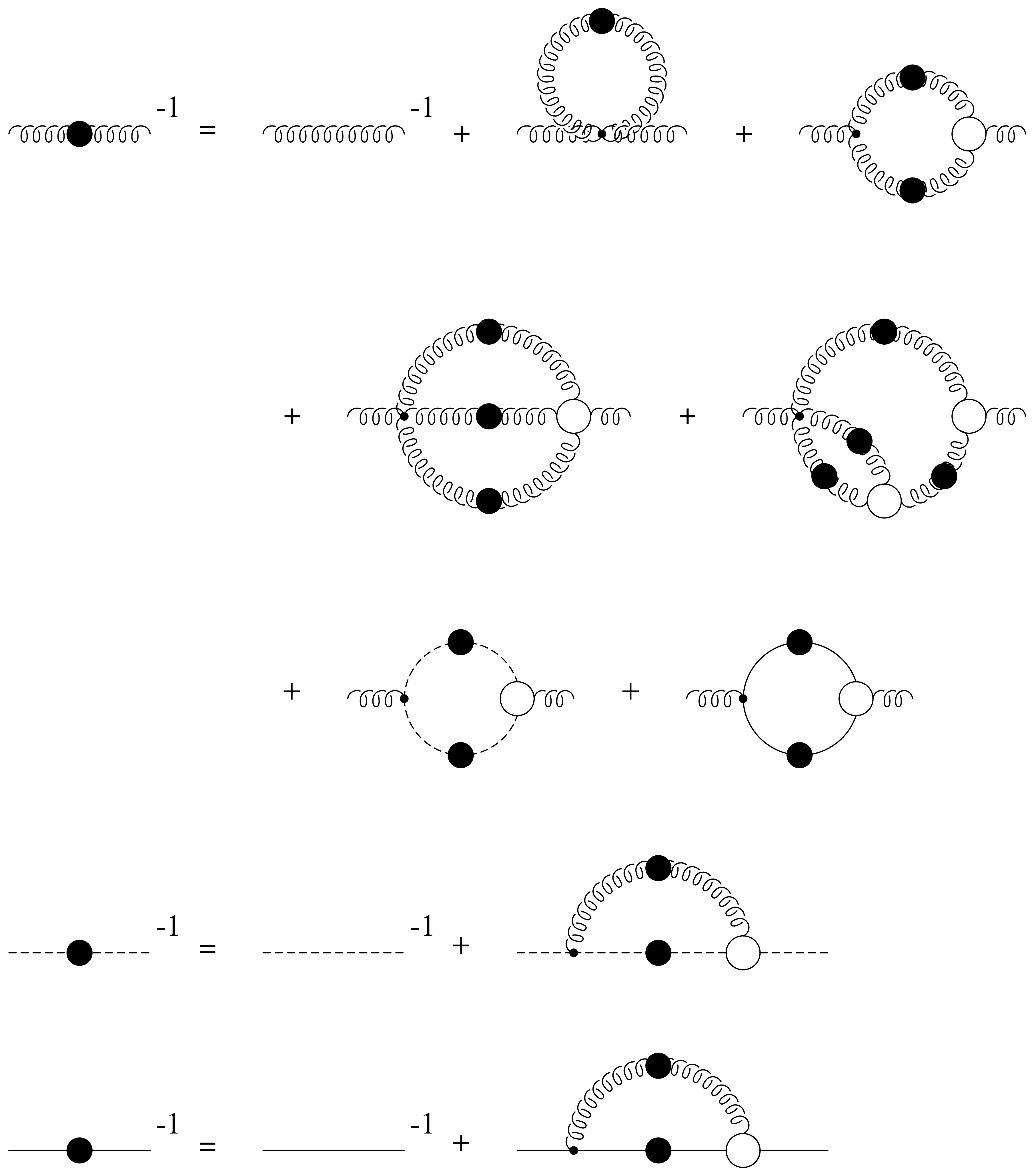
Solutions to integro-differential equations
so no statistical interpretation needed.



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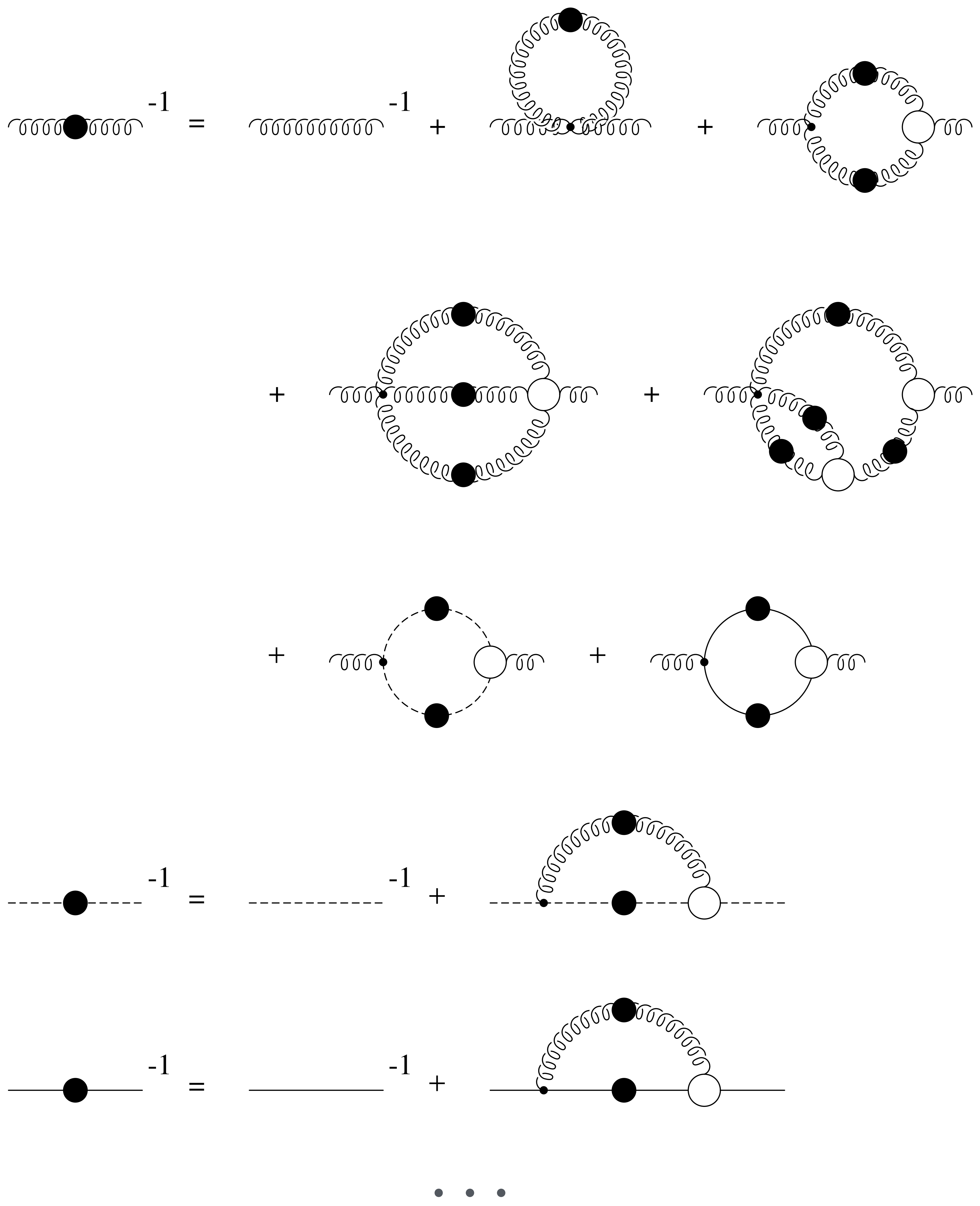
Infinite tower of equations that needs to be truncated.



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Infinite tower of equations that
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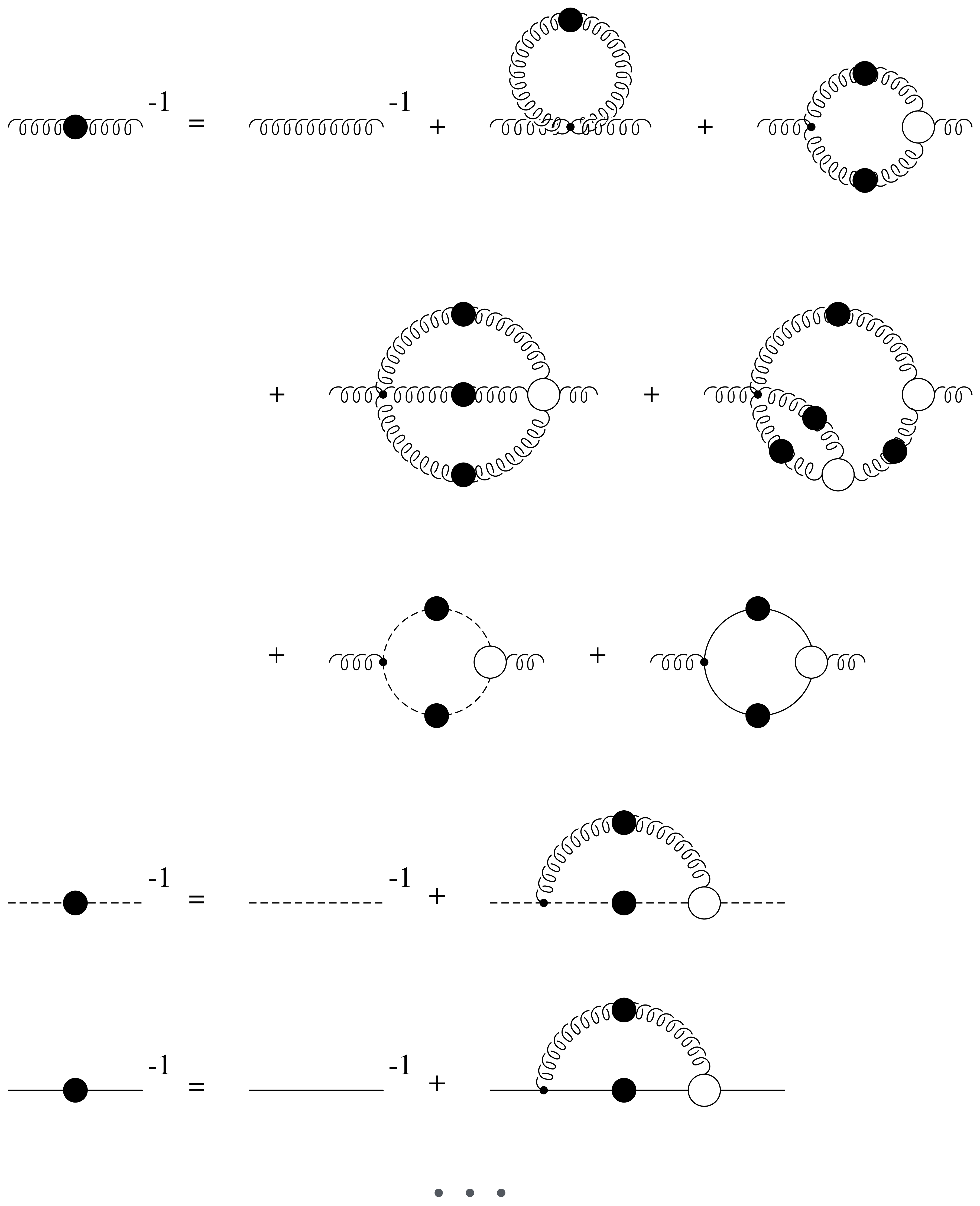
At low energies, no systematic truncation
and thus no real control over the error.



Could one imagine a third possible way into low energy QCD that allows one to circumvent some of the limitations of the lattice simulations while providing a better control over the error?

We believe that some of the results obtained over these past 20 years in the lattice simulations point at that possibility.

This talk aims at reporting our progress towards this goal.
[M. Peláez, U. Reinosa, J. Serreau, M. Tissier, N. Wschebor, Rept. Prog.Phys. 84 (2021)]

Outline

I. Motivation ✓

II. Quarks and gluons in the infrared

III. The Curci-Ferrari model

IV. Probing the QCD phase diagram from the CF model

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Quarks and gluons in the ultraviolet

QCD is a gauge theory:

$$S_{QCD} = \int d^4x \left\{ -\frac{1}{2}\mathrm{tr}\, F_{\mu\nu} F^{\mu\nu} + \bar{\psi}_f \left(i\gamma^\mu \partial_\mu + g\,\gamma^\mu A_\mu - m_f \right) \psi_f \right\}, \quad \alpha_S = \frac{g^2}{4\pi}$$

with $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu - ig\,[A_\mu, A_\nu]$ the gluon field-strength tensor.

Its action is invariant under gauge transformations:

$$\psi \to U\psi \equiv \psi^U \quad \text{and} \quad A_\mu \to U A_\mu U^\dagger + \frac{i}{g} U \partial_\mu U^\dagger \equiv A_\mu^U$$

Express a redundancy in the description:

(ψ, A_μ) is physically equivalent to (ψ^U, A_μ^U).

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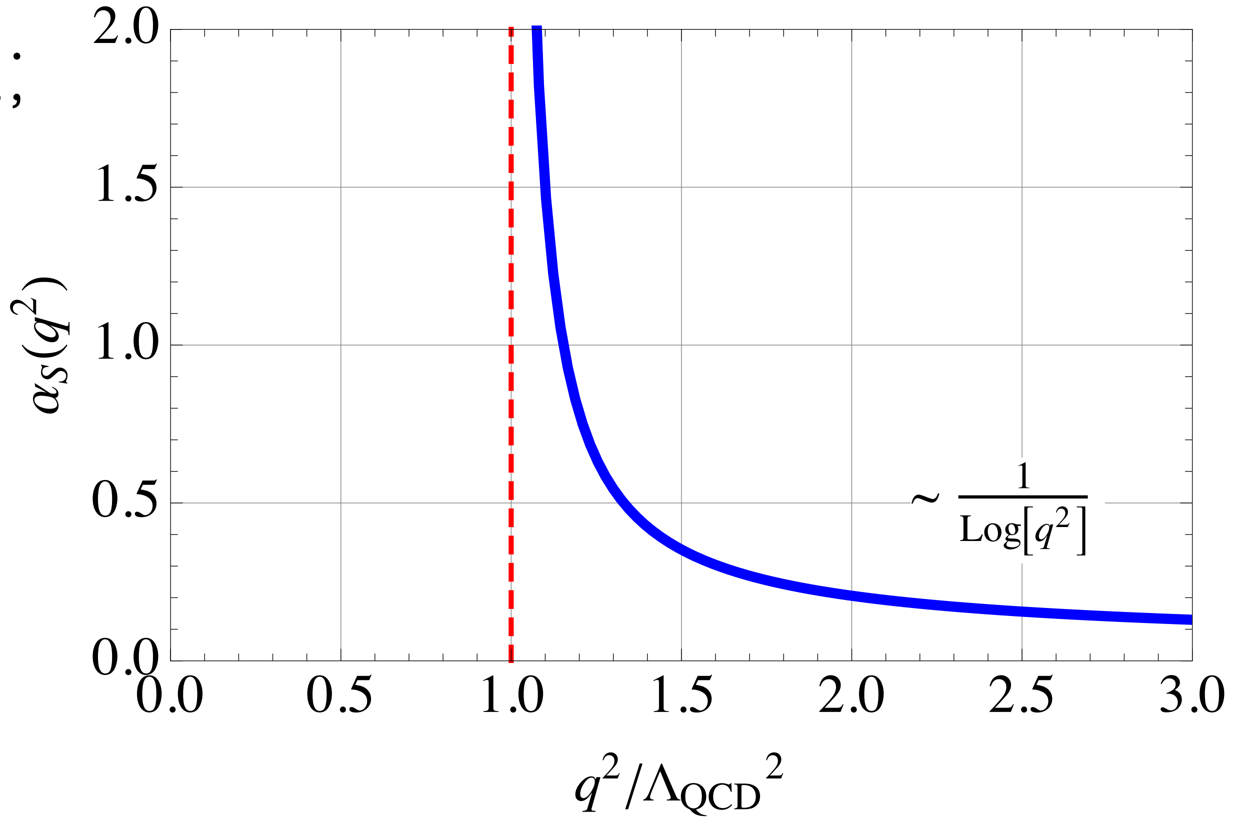
1. no gluonic mass term in the microscopic (ultraviolet) action;
2. all colored fields are universally coupled in the ultraviolet;
3. the theory is asymptotically free in the ultraviolet.



Quarks and gluons in the infrared

What do these properties become at low energies?

To answer one needs access to the exact correlation functions of the theory

$$\langle AA \rangle, \quad \langle \psi\bar{\psi} \rangle, \quad \langle AAA \rangle, \quad \langle A\psi\bar{\psi} \rangle, \quad \ldots$$

Two-point functions tell how quarks and gluon propagate and higher-point functions tell how quarks and gluons interact with each other.

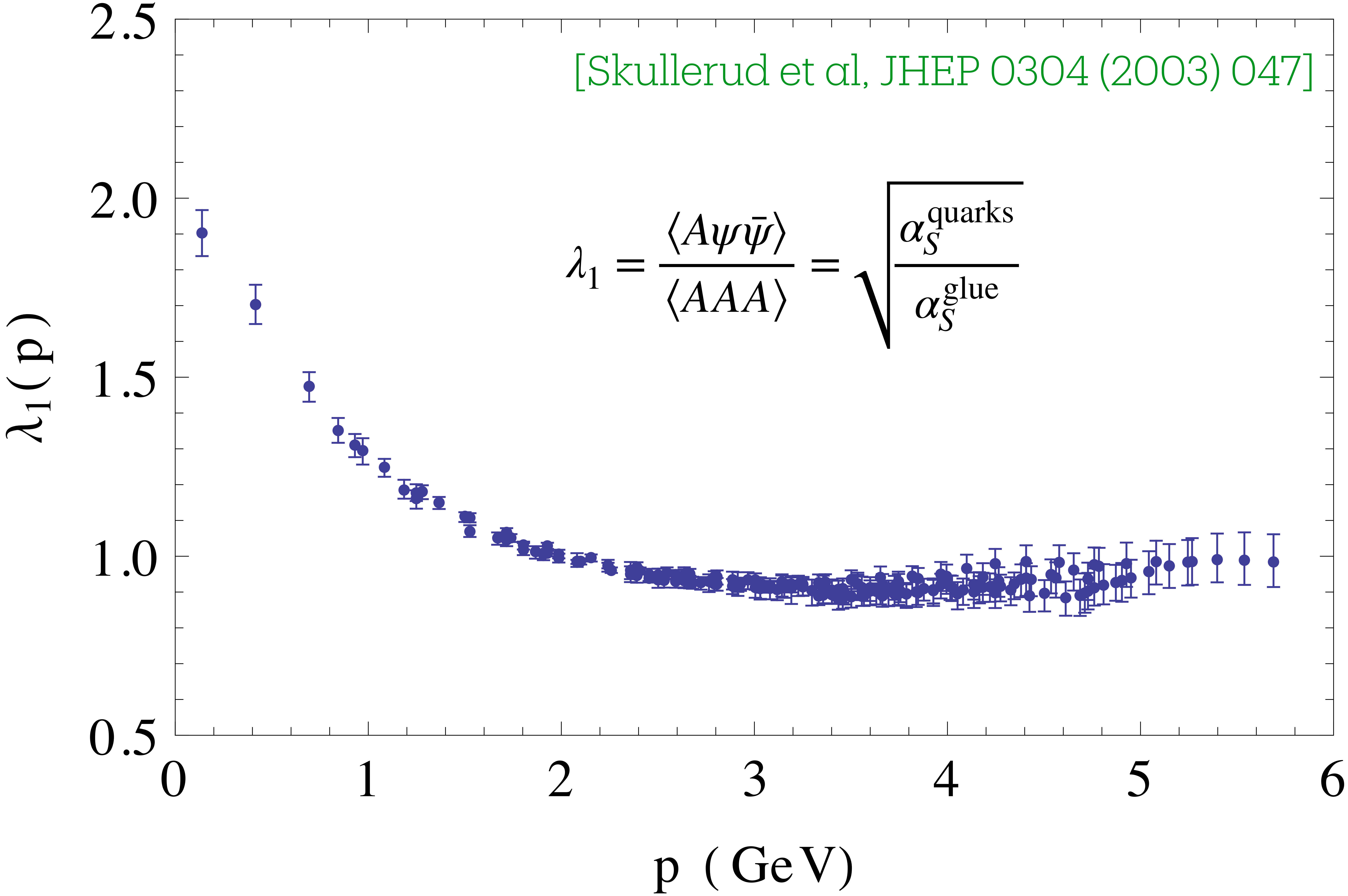
Quarks and gluons in the infrared

Subtle point: the definition of correlation functions requires fixing the gauge.

From now on: all correlators shown will be those of the Landau gauge $\partial_\mu A_\mu = 0$.

Good news: the Landau gauge can be easily implemented on the lattice.

(Non-)universality of the coupling



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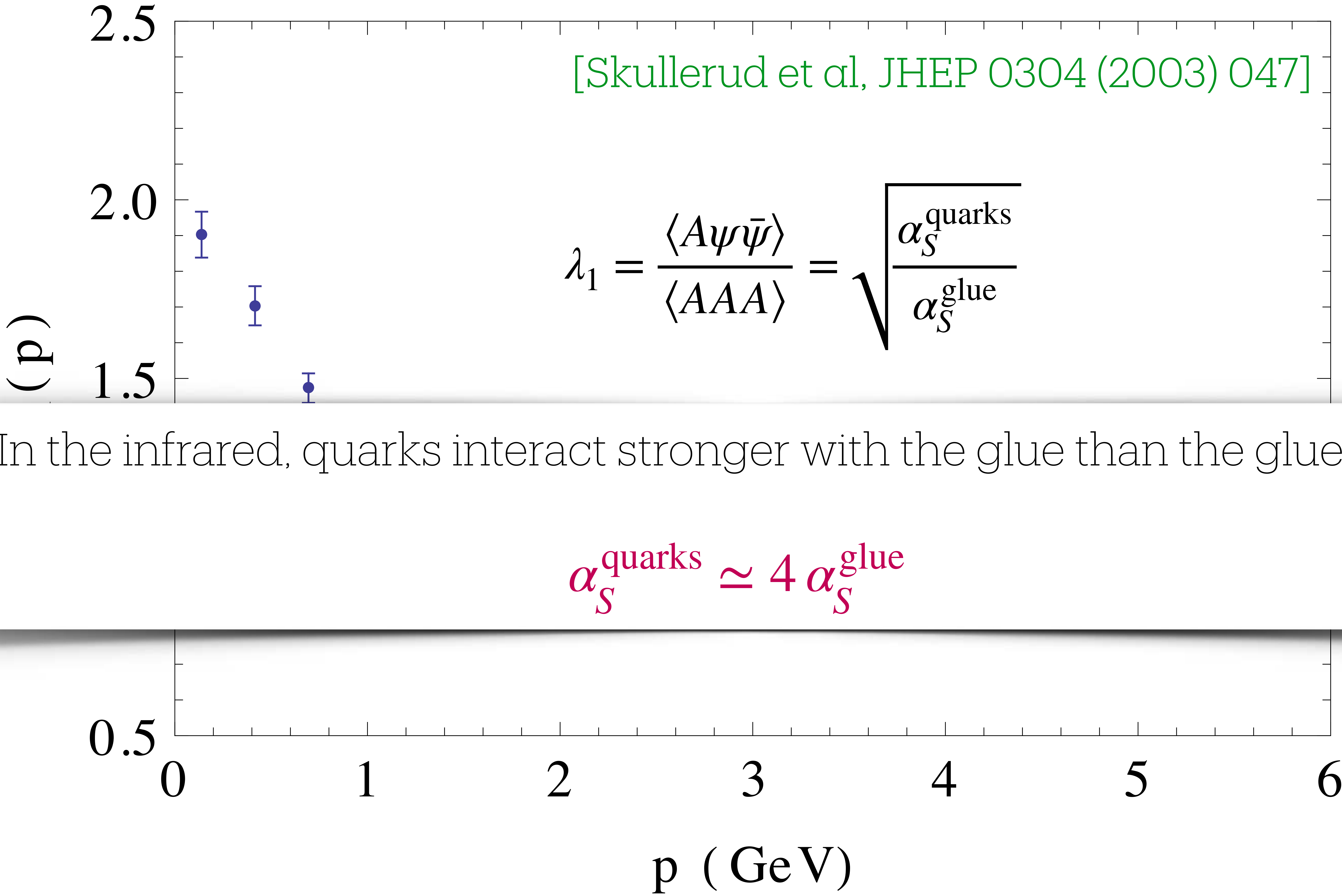

In the infrared, quarks interact stronger with the glue than the glue itself!

$$\alpha_S^{\text{quarks}} \simeq 4\,\alpha_S^{\text{glue}}$$

Coupling strength in the glue sector

Since the couplings are ordered in the infrared, it is interesting to look at the smallest of them, α_S^{glue}.

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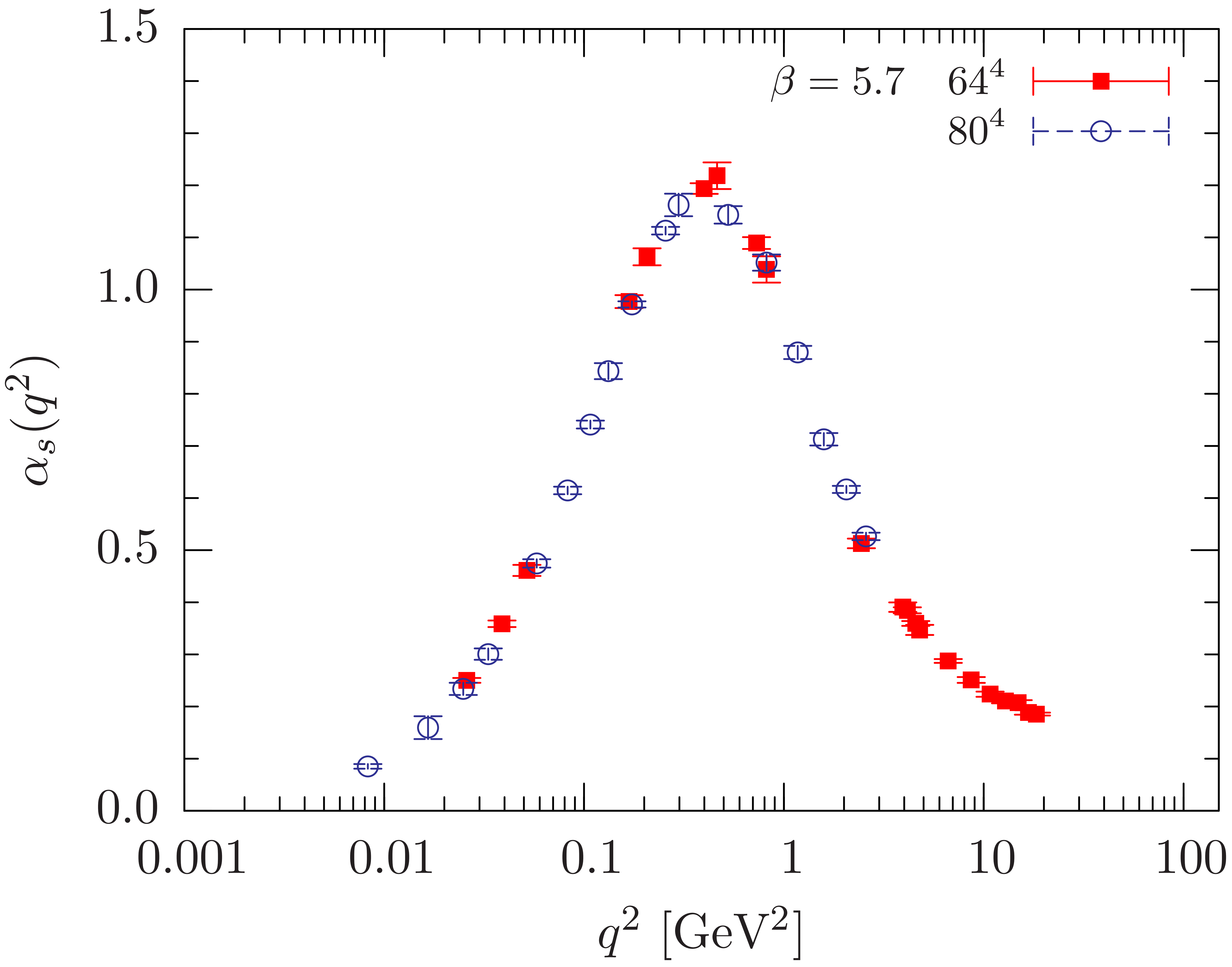

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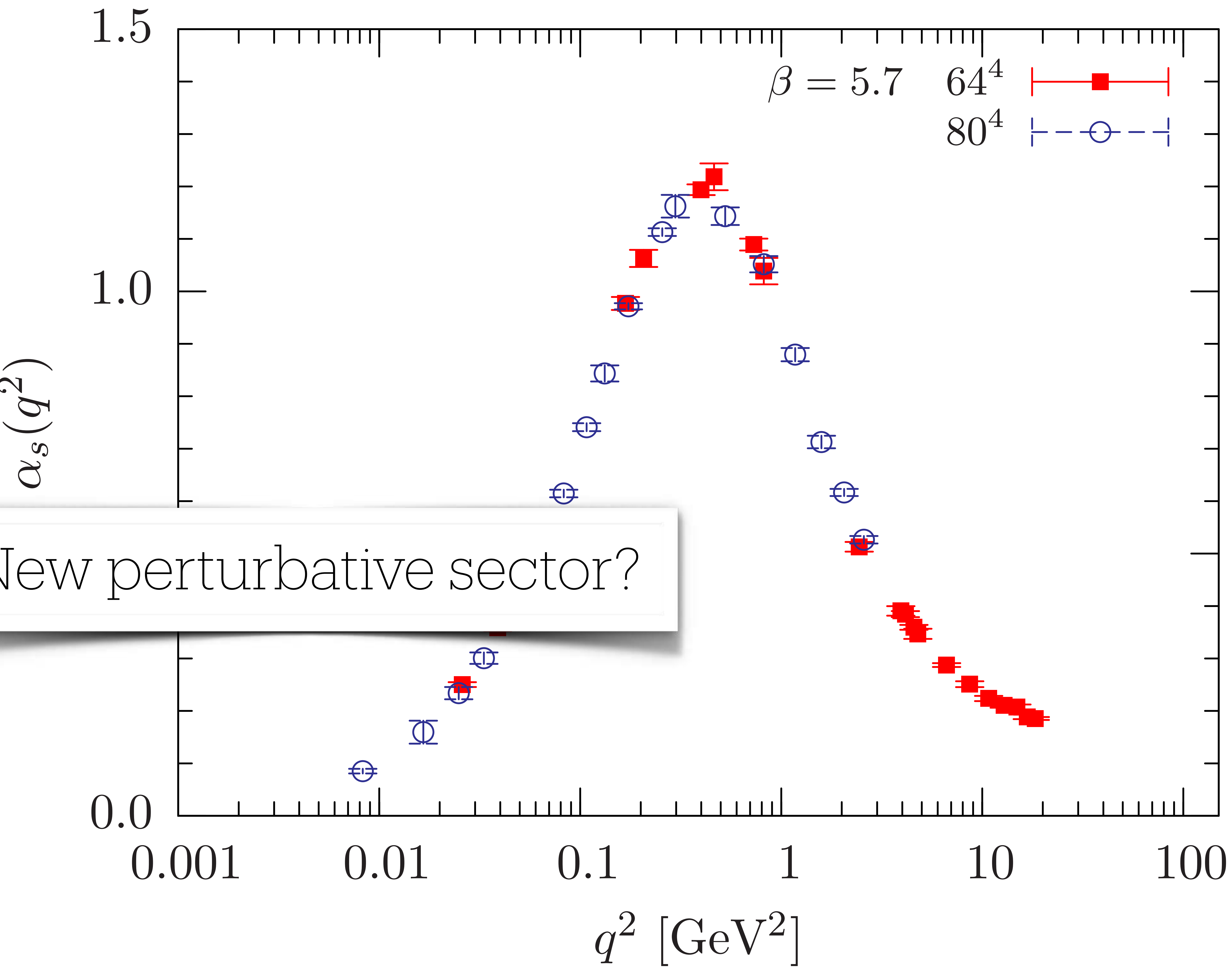

New perturbative sector?

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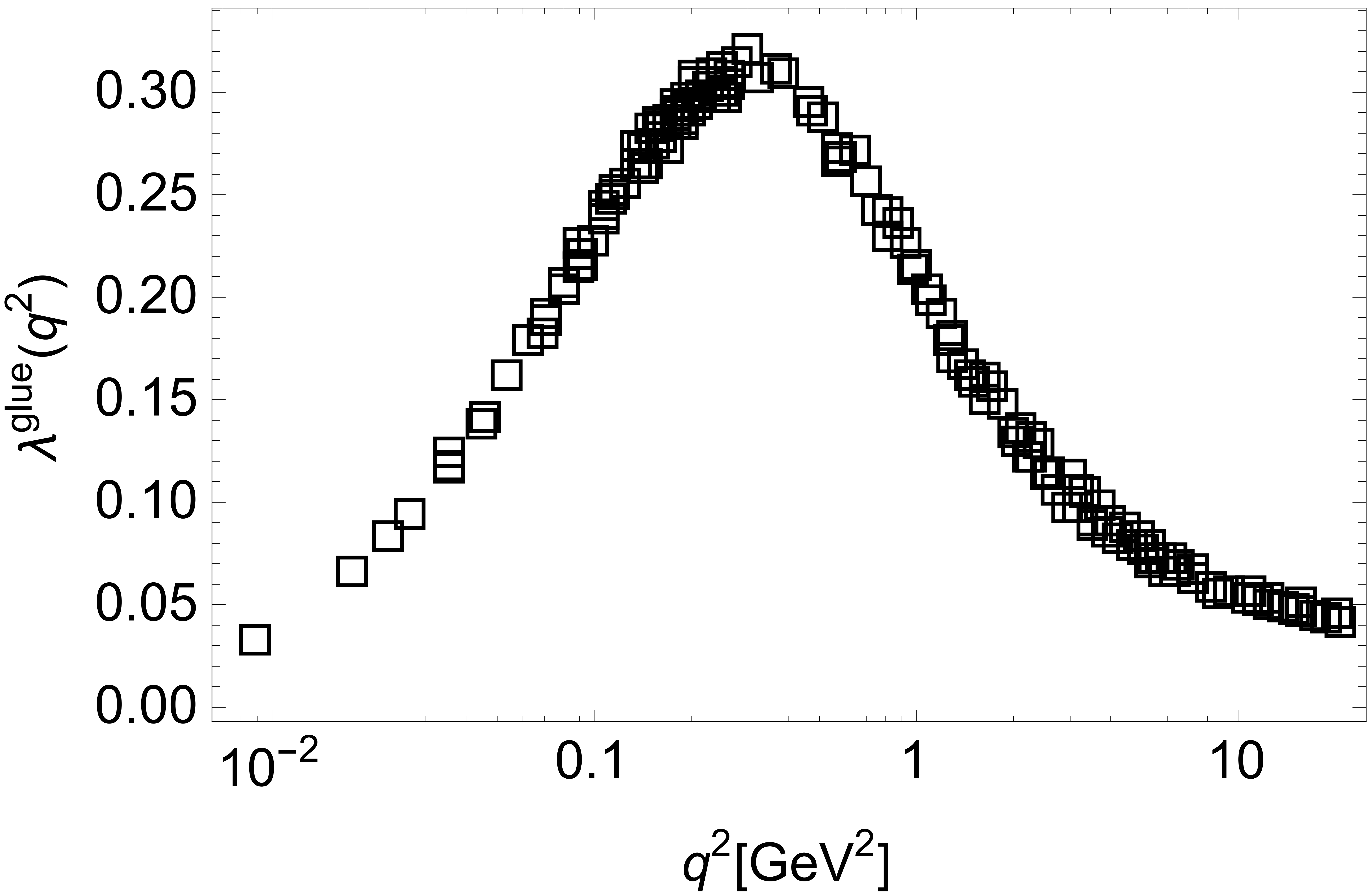

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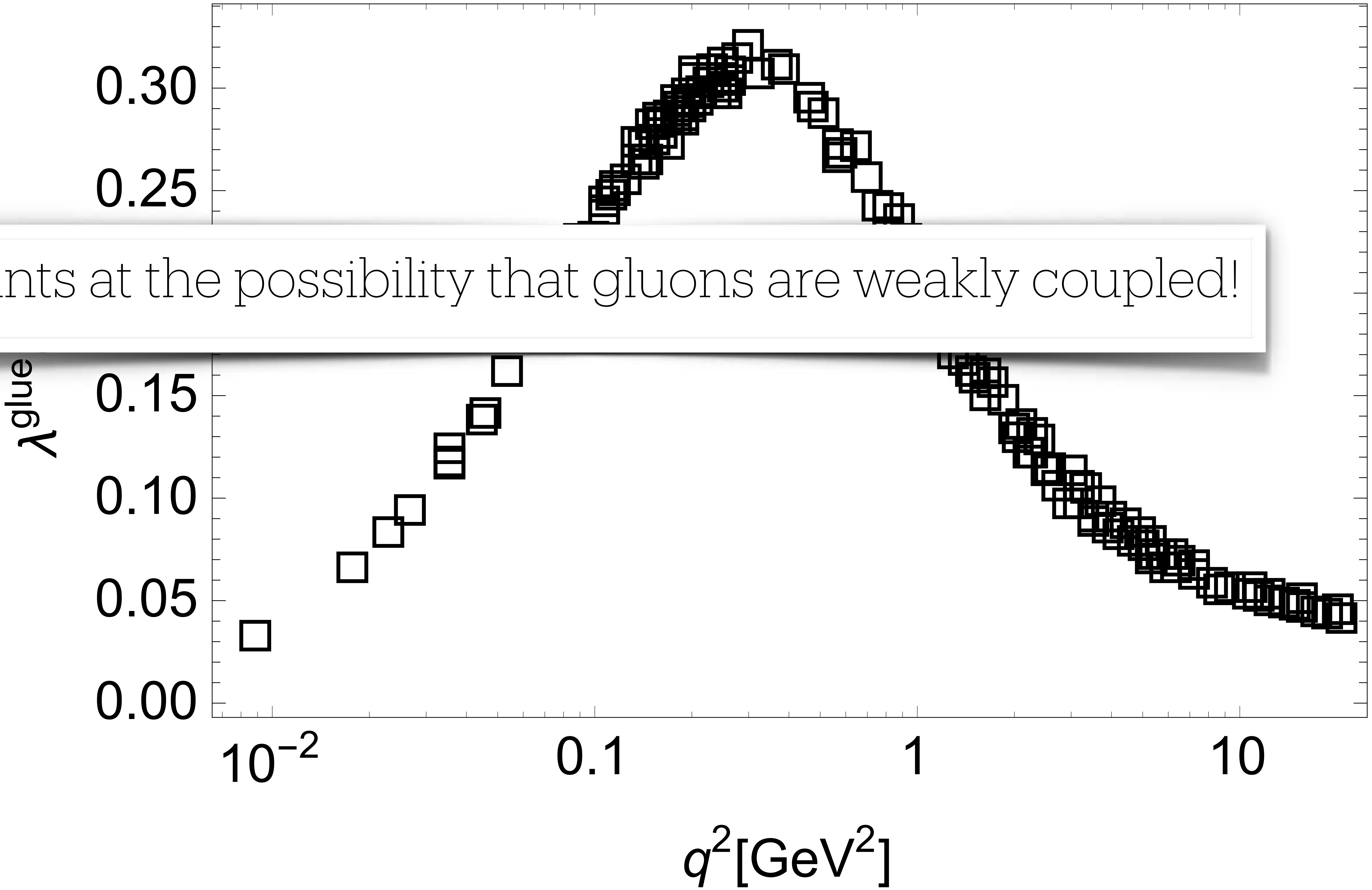

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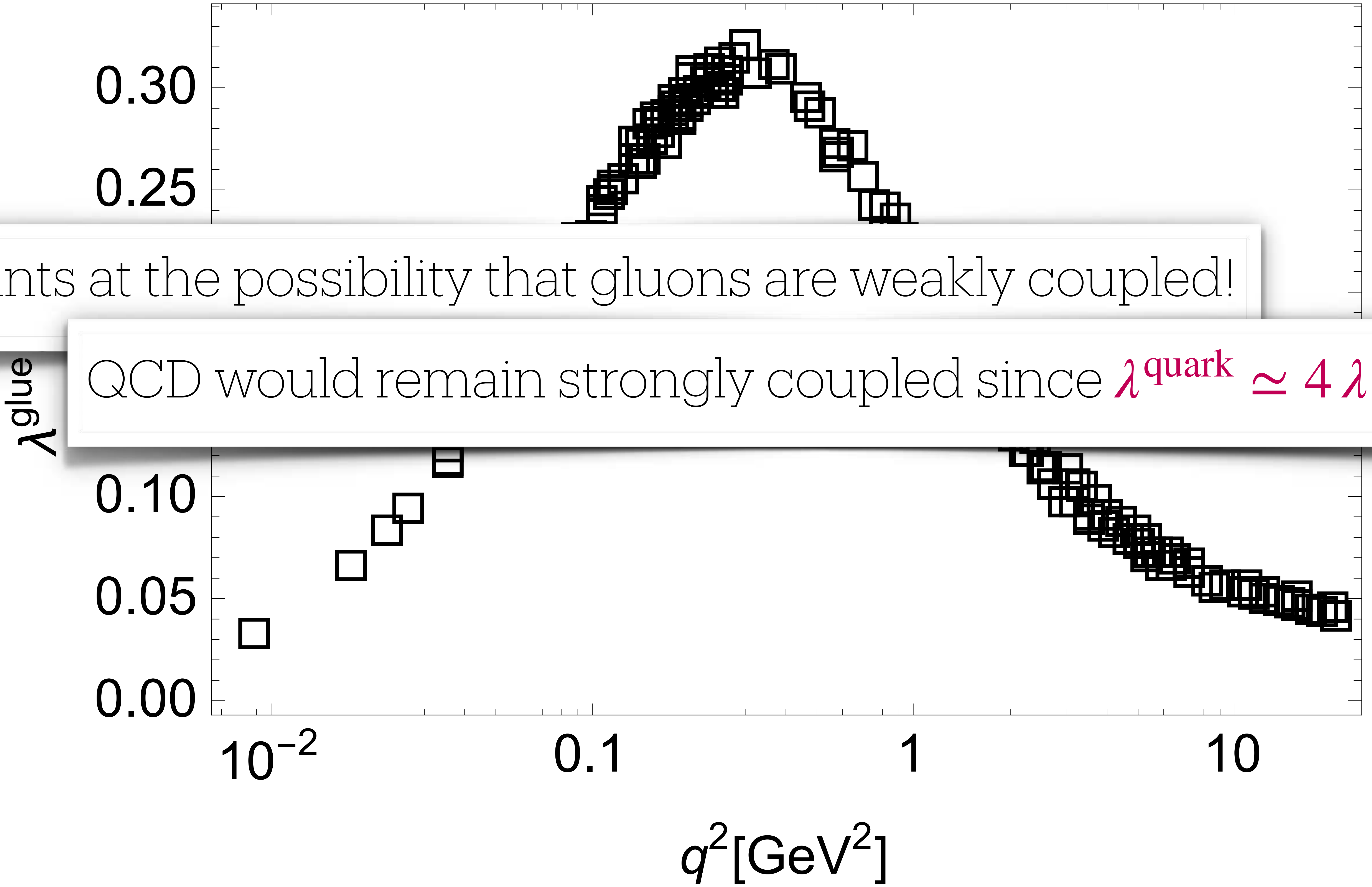

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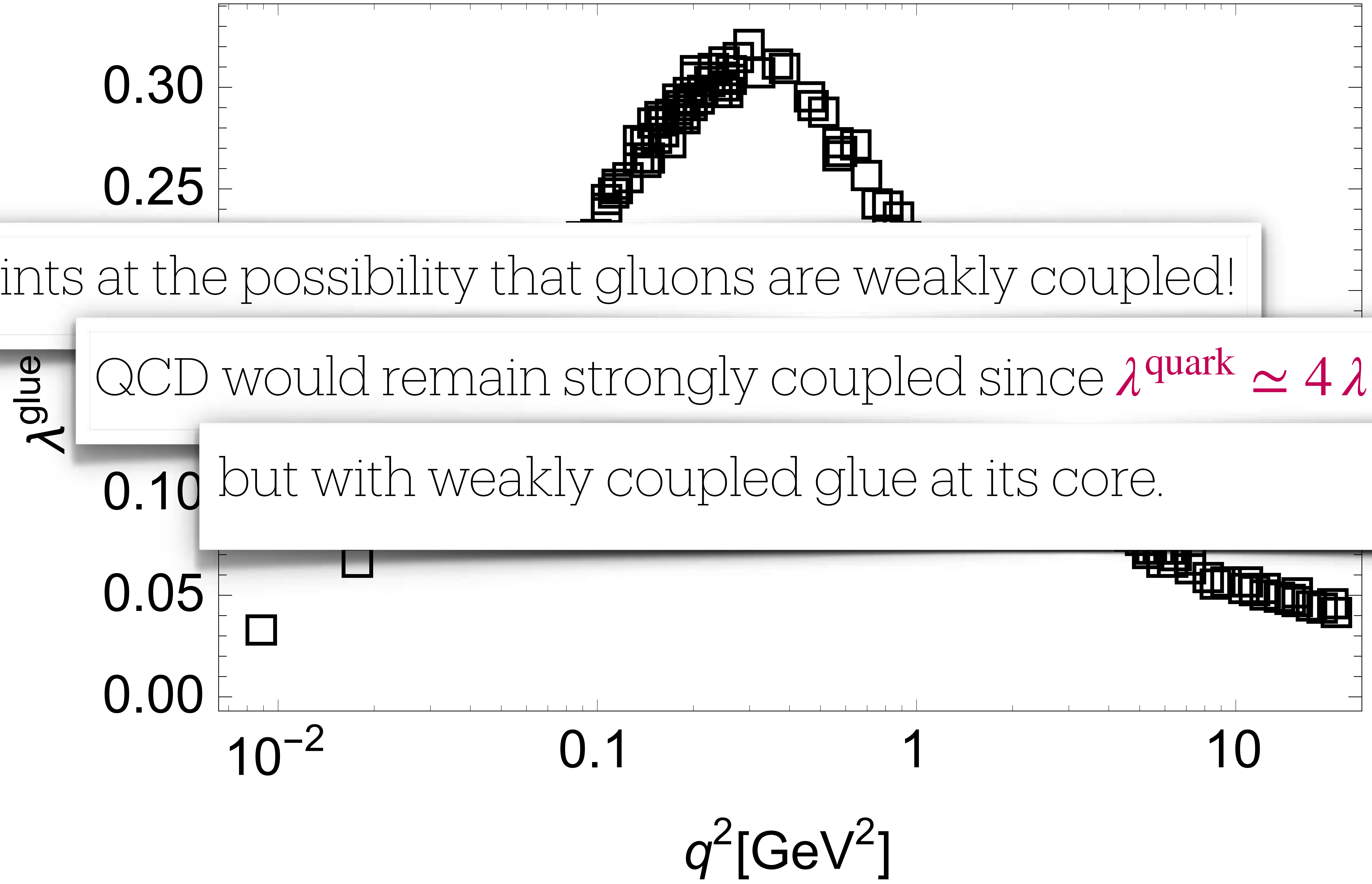

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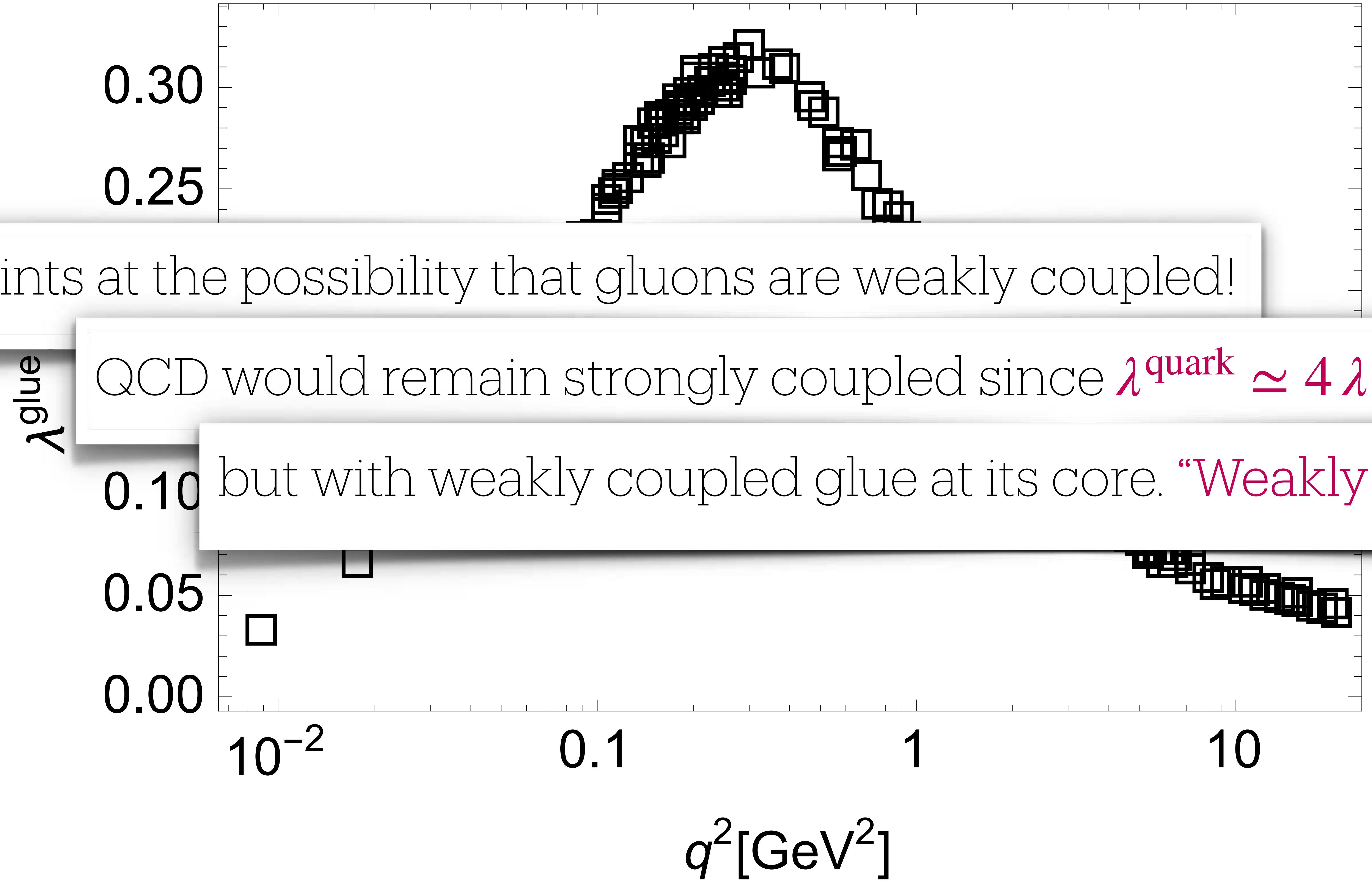

Hints at the possibility that gluons are weakly coupled!

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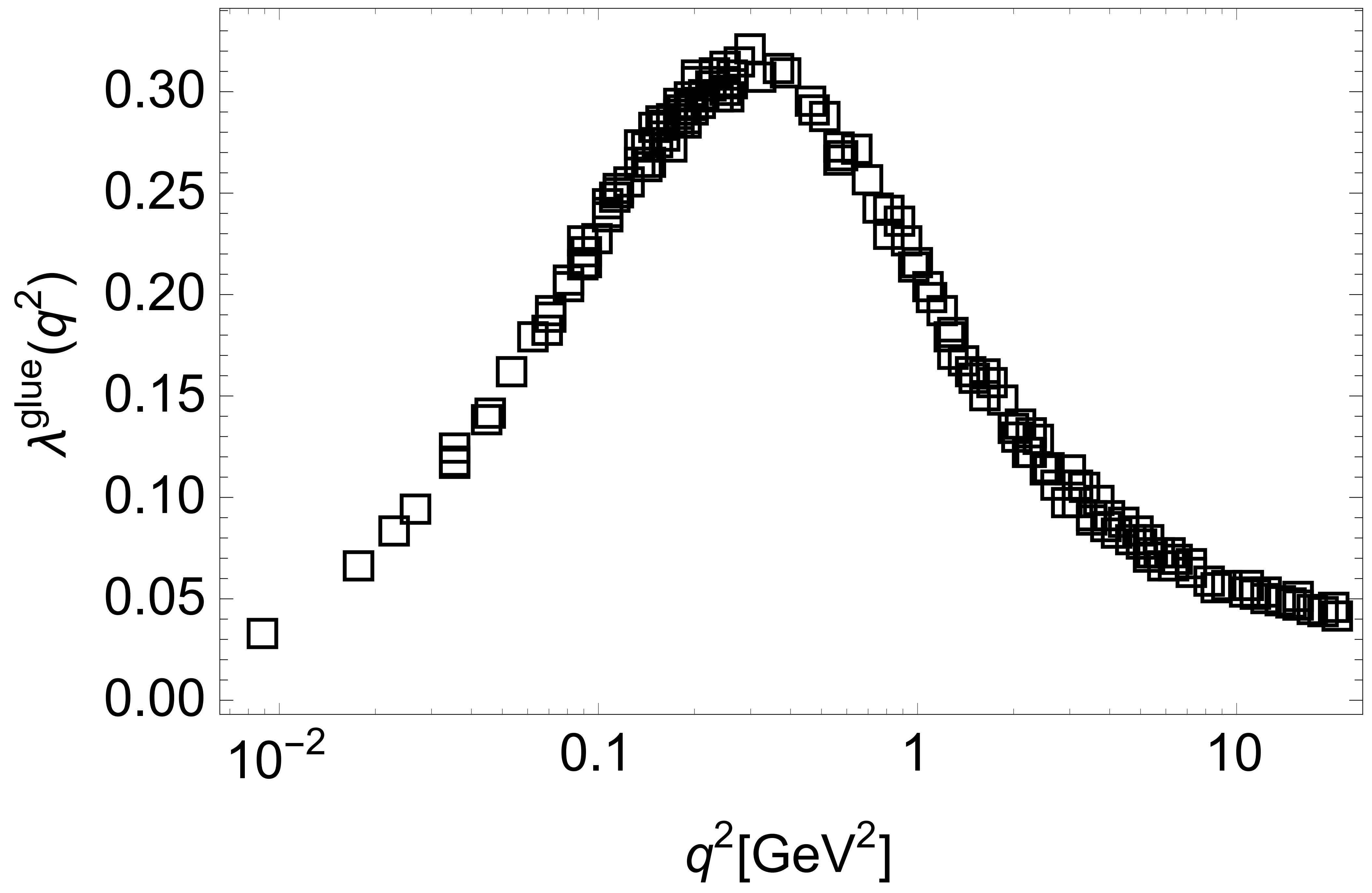
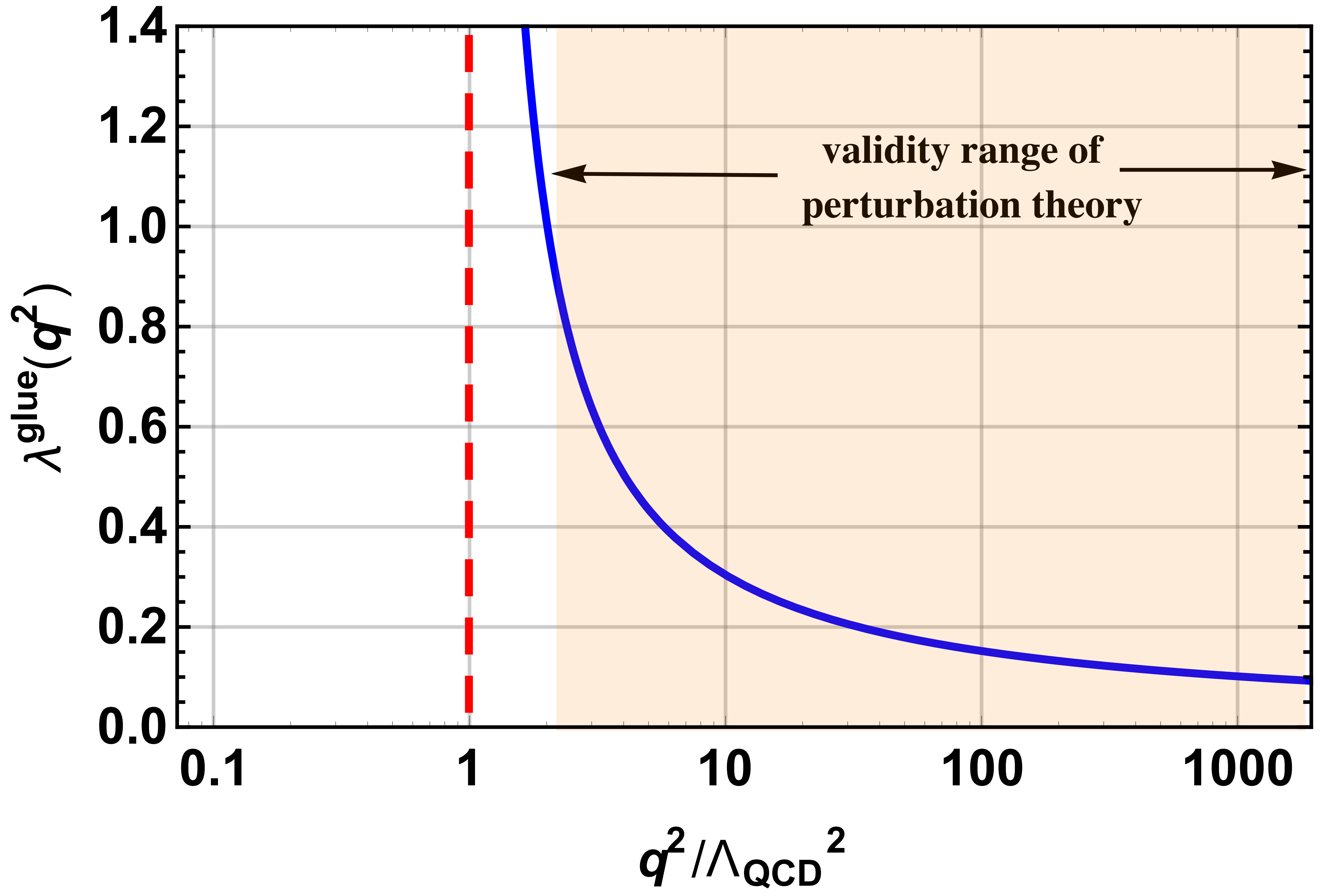
but with weakly coupled glue at its core. "Weakly coupled glue" scenario.

But wait ...

We have two seemingly contradictory pictures for the glue sector.





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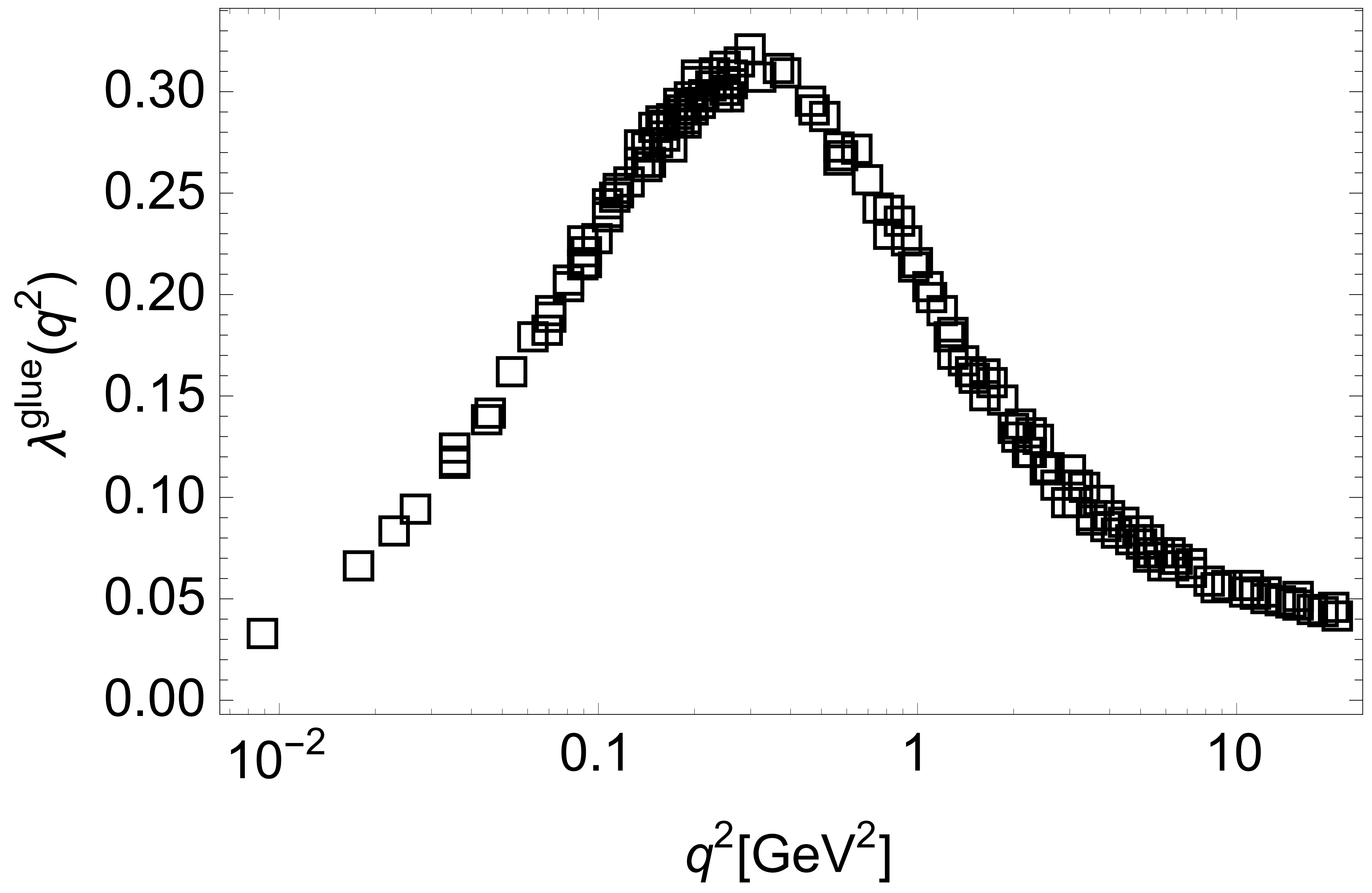

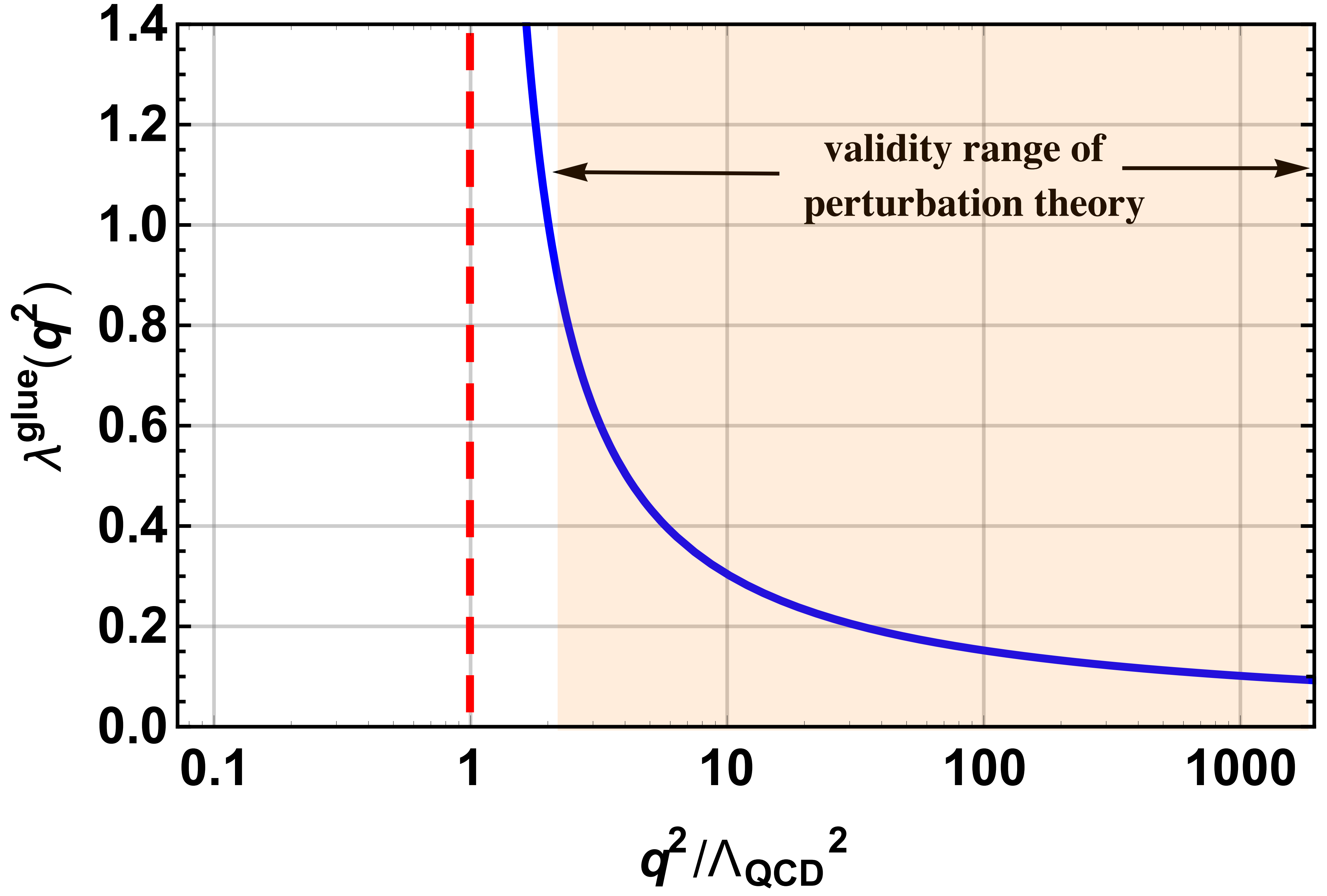

According to the first, perturbation theory is valid over all scales.

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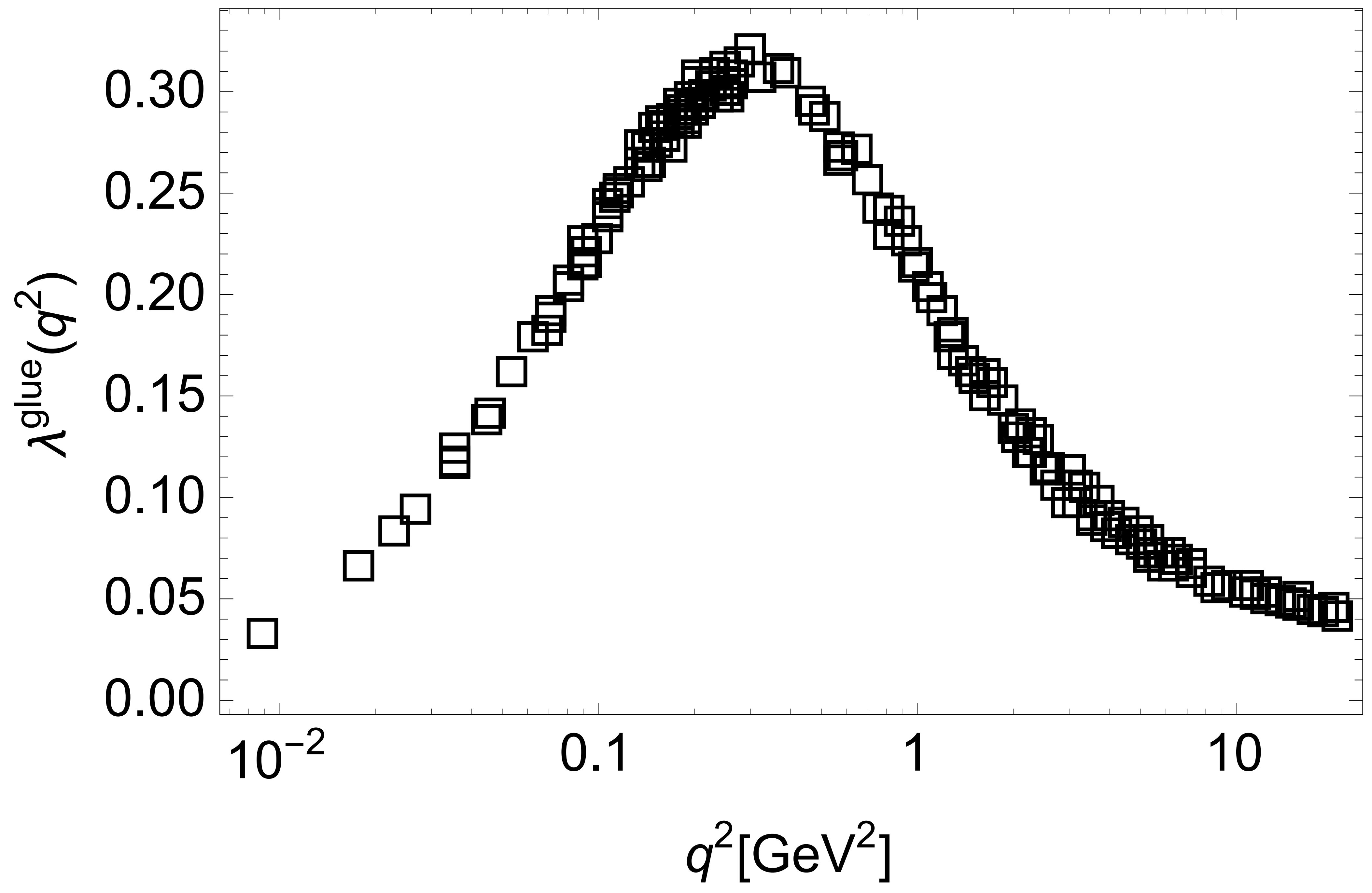

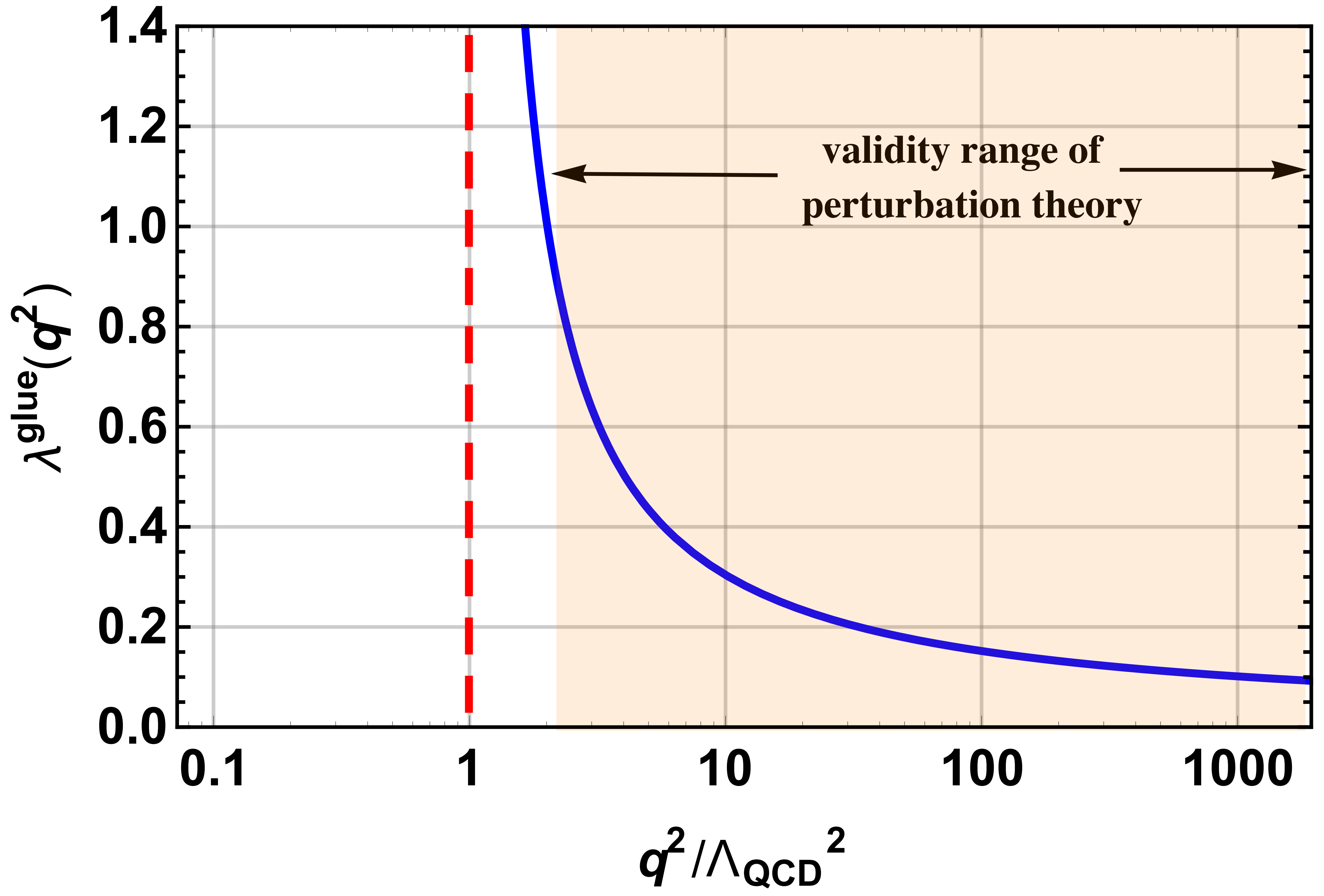

According to the first, perturbation theory is valid over all scales.

According to the second, perturbation theory predicts its own failure.

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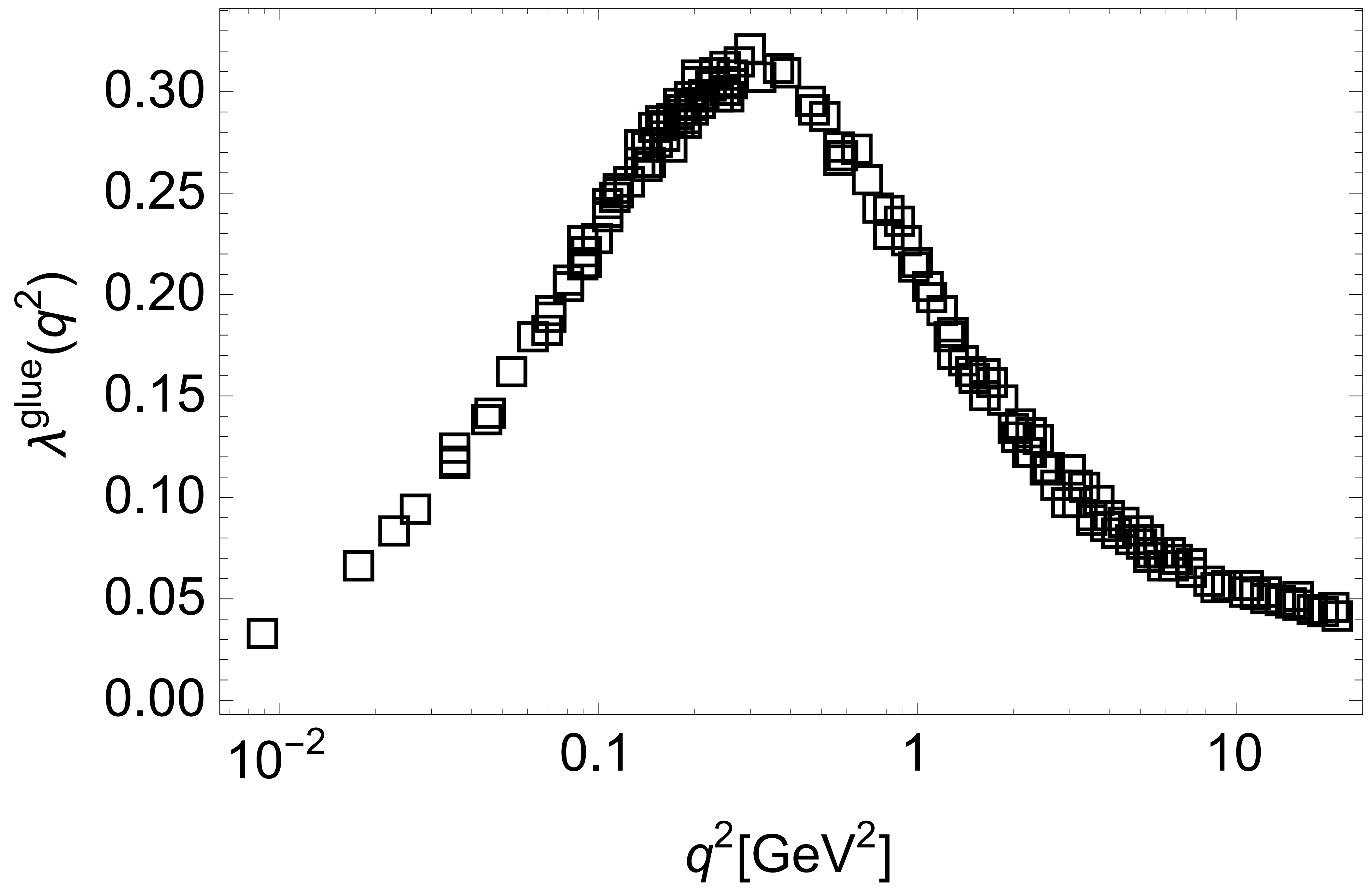

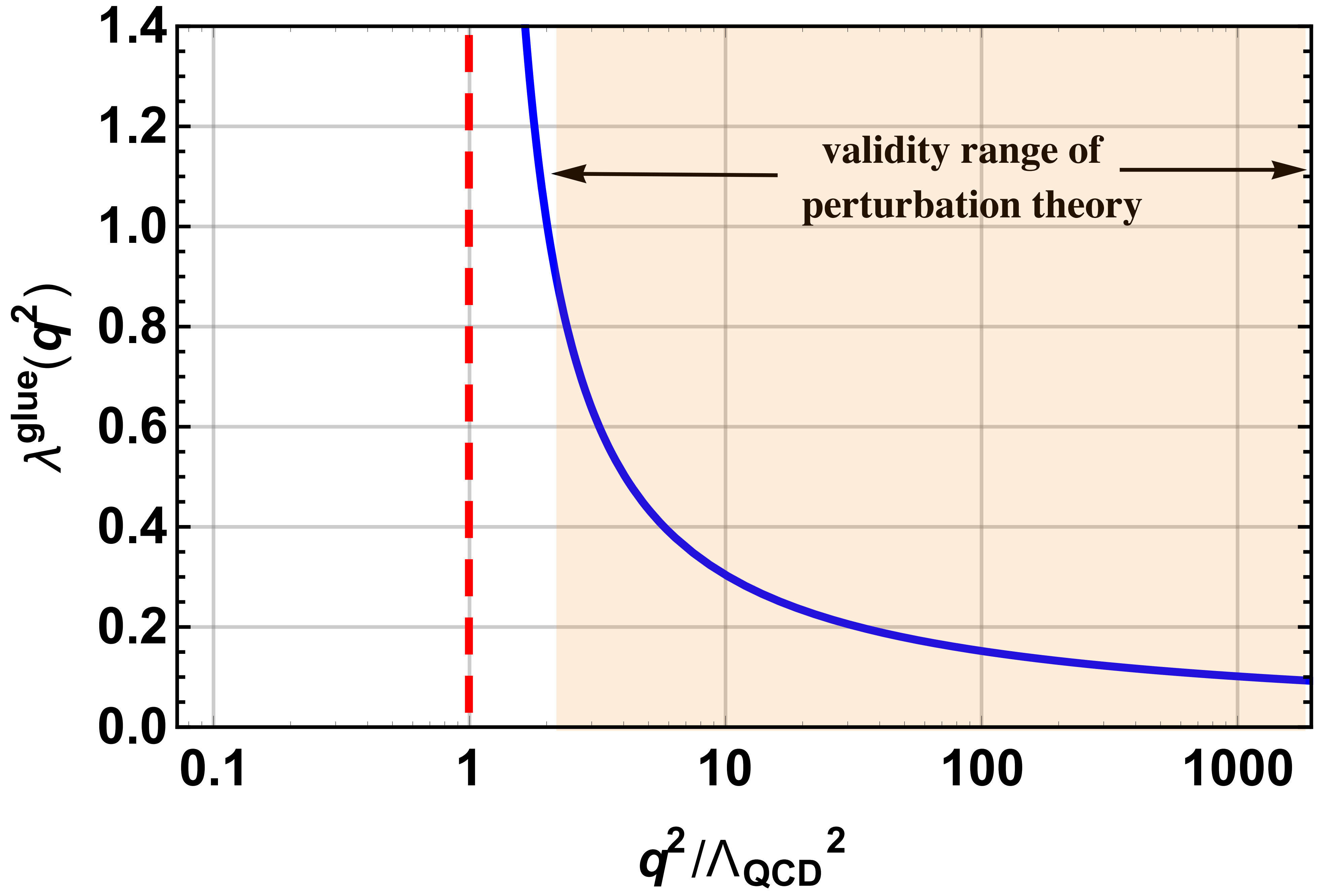

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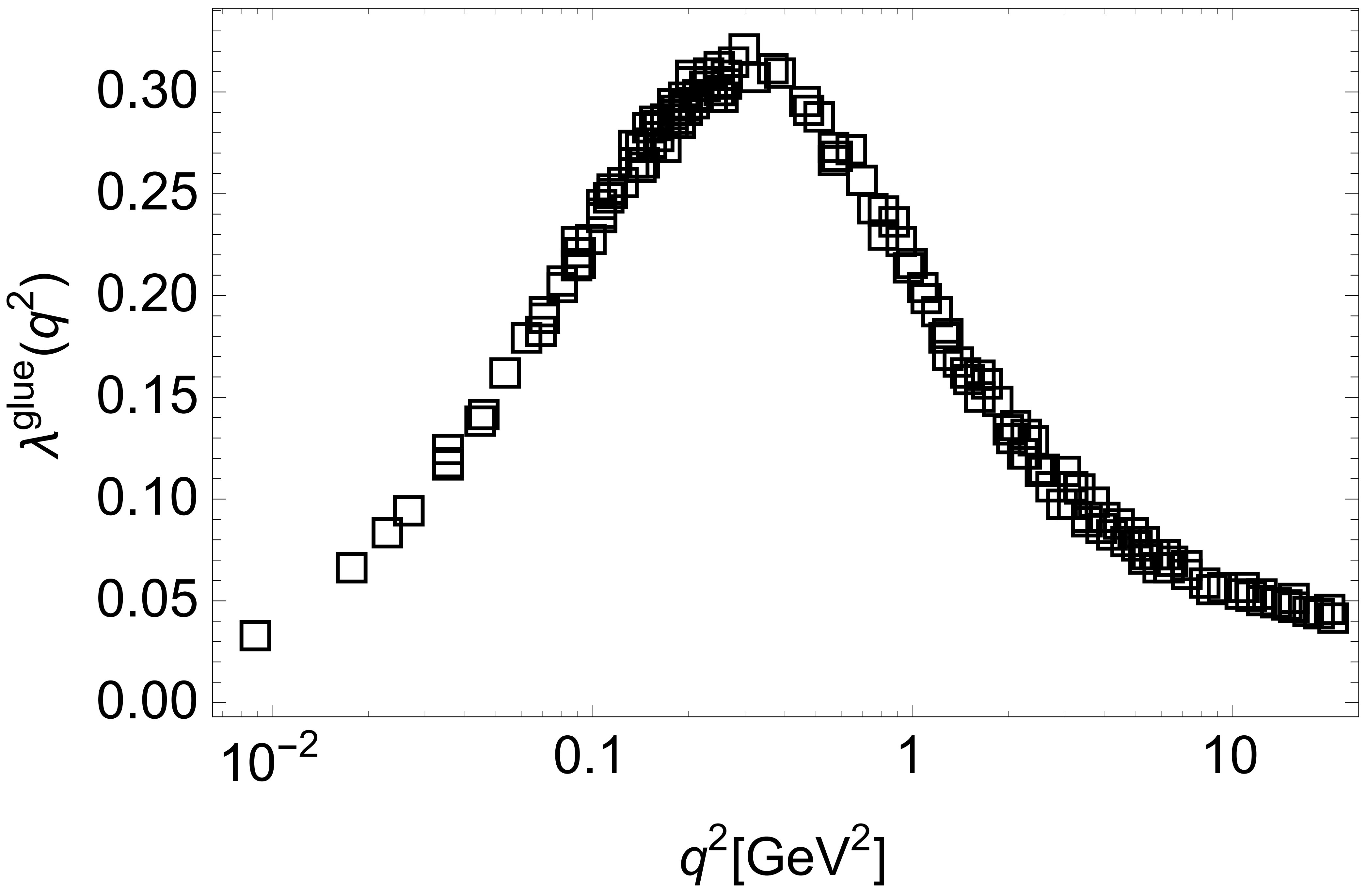
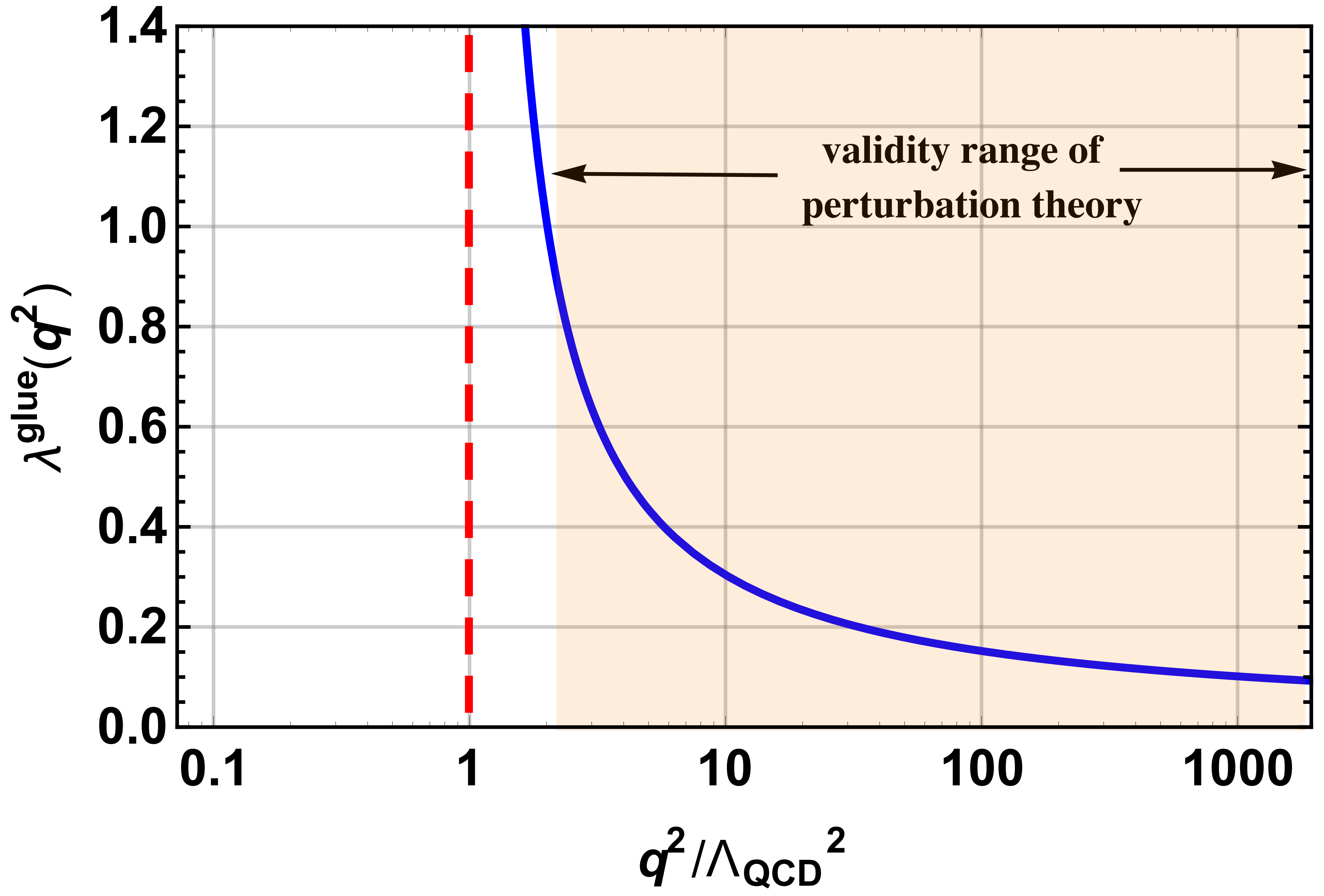




Yet, the first is the outcome of a first-principle lattice calculation.

The second actually results from an uncontrolled implementation of the gauge fixing.

Gauge fixing

To set up the perturbative expansion in the Landau gauge,
one should in principle consider:

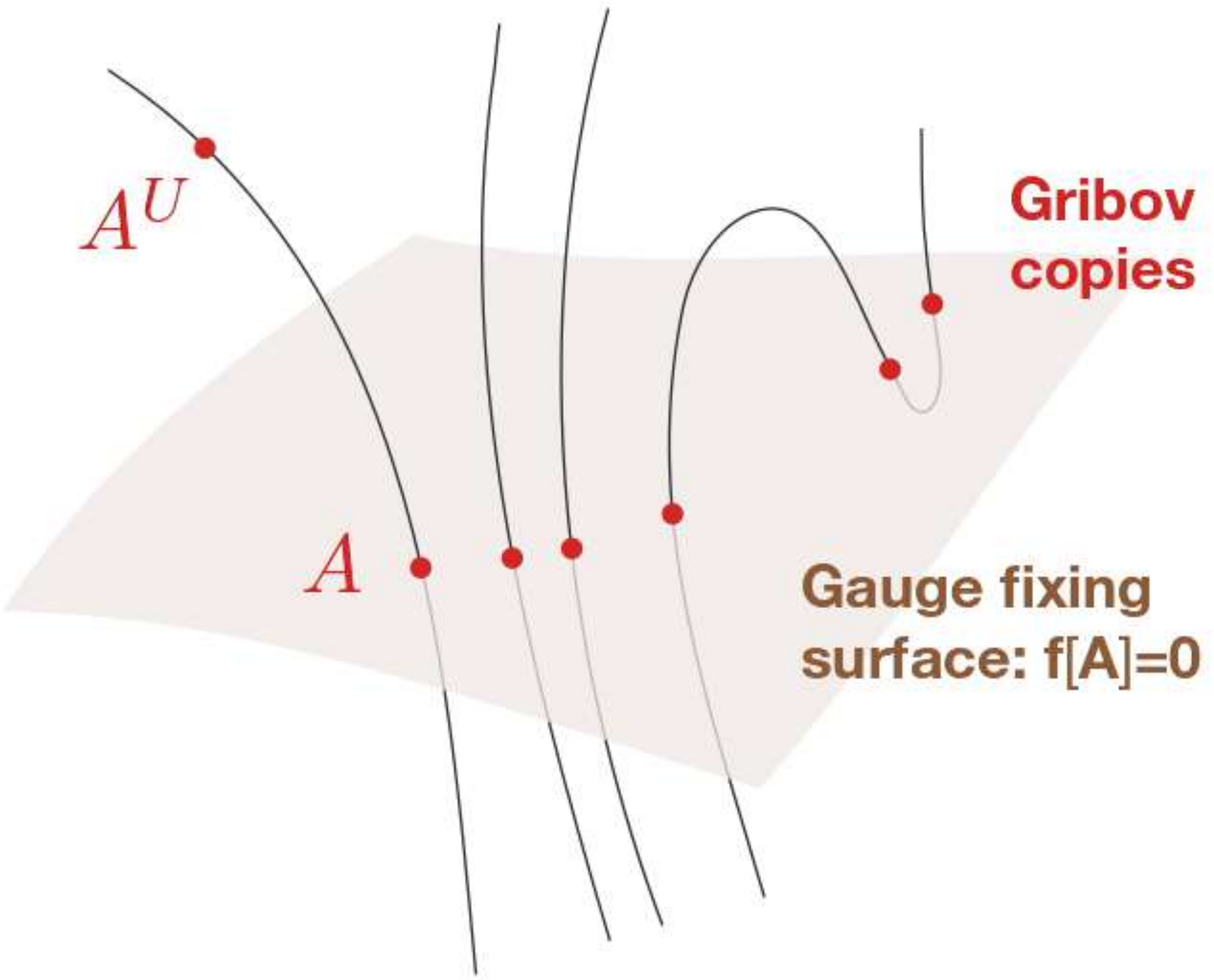
$$S_{\text{QCD}}[A, \psi, \bar{\psi}] \quad \text{with} \quad \partial_\mu A_\mu = 0$$

In practice, however, one uses the Faddeev-Popov action

$$S_{\text{FP}} = S_{\text{QCD}} + 2\int_x \text{tr}\,\left\{ ih\,\partial_\mu A_\mu + \partial_\mu \bar{c}\left(\partial_\mu c - ig[A_\mu, c]\right)\right\}$$

These two ways of proceeding are often thought to be equivalent.
They are not!

Gauge fixing



Indeed, the Faddeev-Popov construction relies on a mathematically incorrect assumption.

Gribov copy problem or ambiguity.

In fact:

- at high energies, the FP construction is seen to hold;
- At low energies, we have tangible evidence that it does not.

Scaling vs decoupling solutions

When the FP action is taken seriously at all scales, one deduces a specific behavior for the correlation functions in the infrared.

Scaling solution:

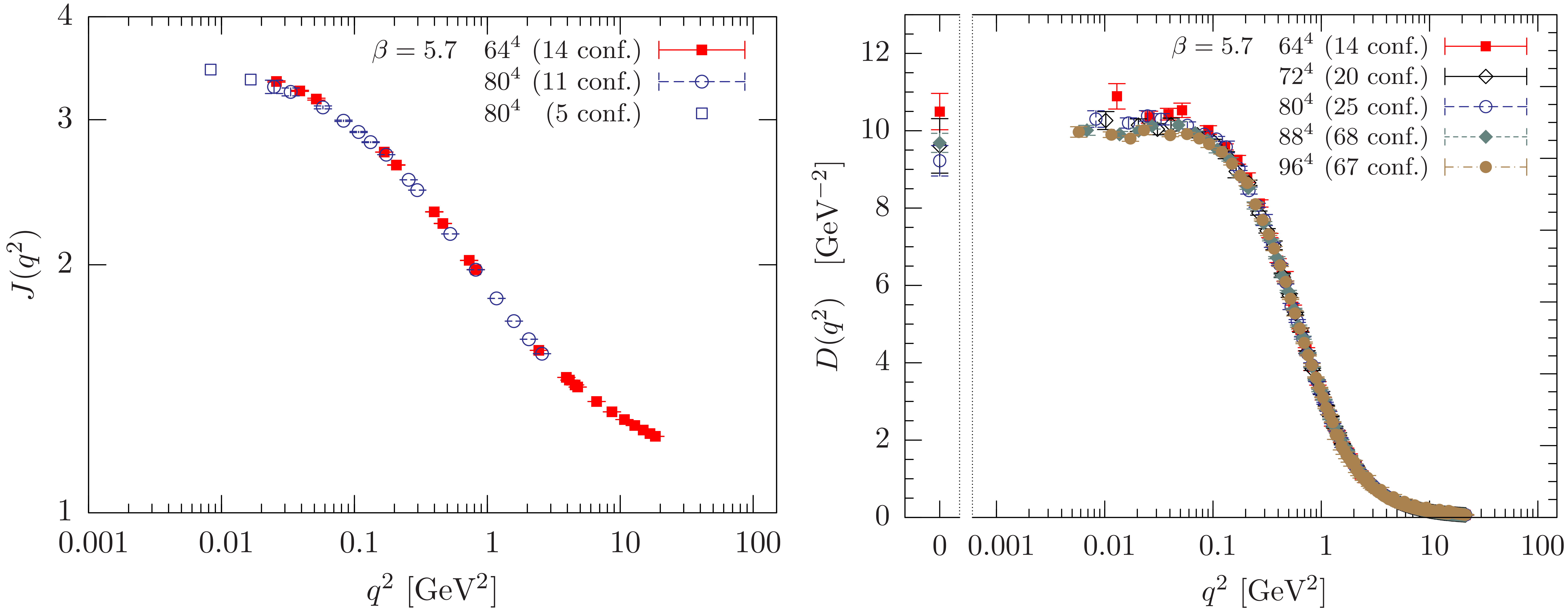
$$J(q^2) \equiv q^2 \langle c(-q)\bar{c}(q)\rangle \to \infty$$

as $q \to \infty$

$$D(q^2) \equiv \langle A(-q)\bar{A}(q)\rangle \to 0$$

Scaling vs decoupling solutions

At odds with the decoupling solution found on the lattice:



[I.L. Bogolubsky, E.M. Ilgenfritz, M. Müller-Preussker, A. Sternbeck, PLB 676, 69 (2009)]

Scaling vs decoupling solutions

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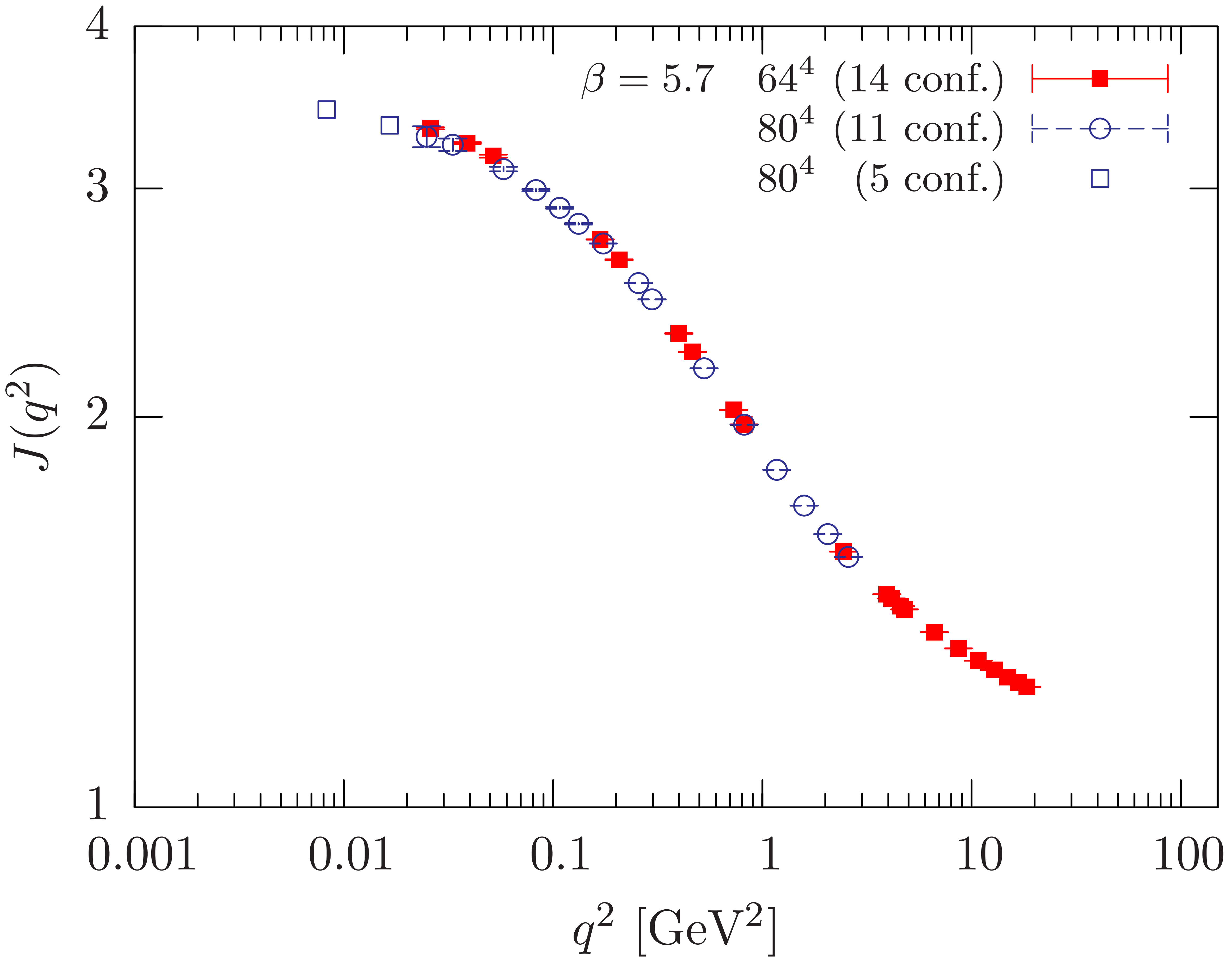
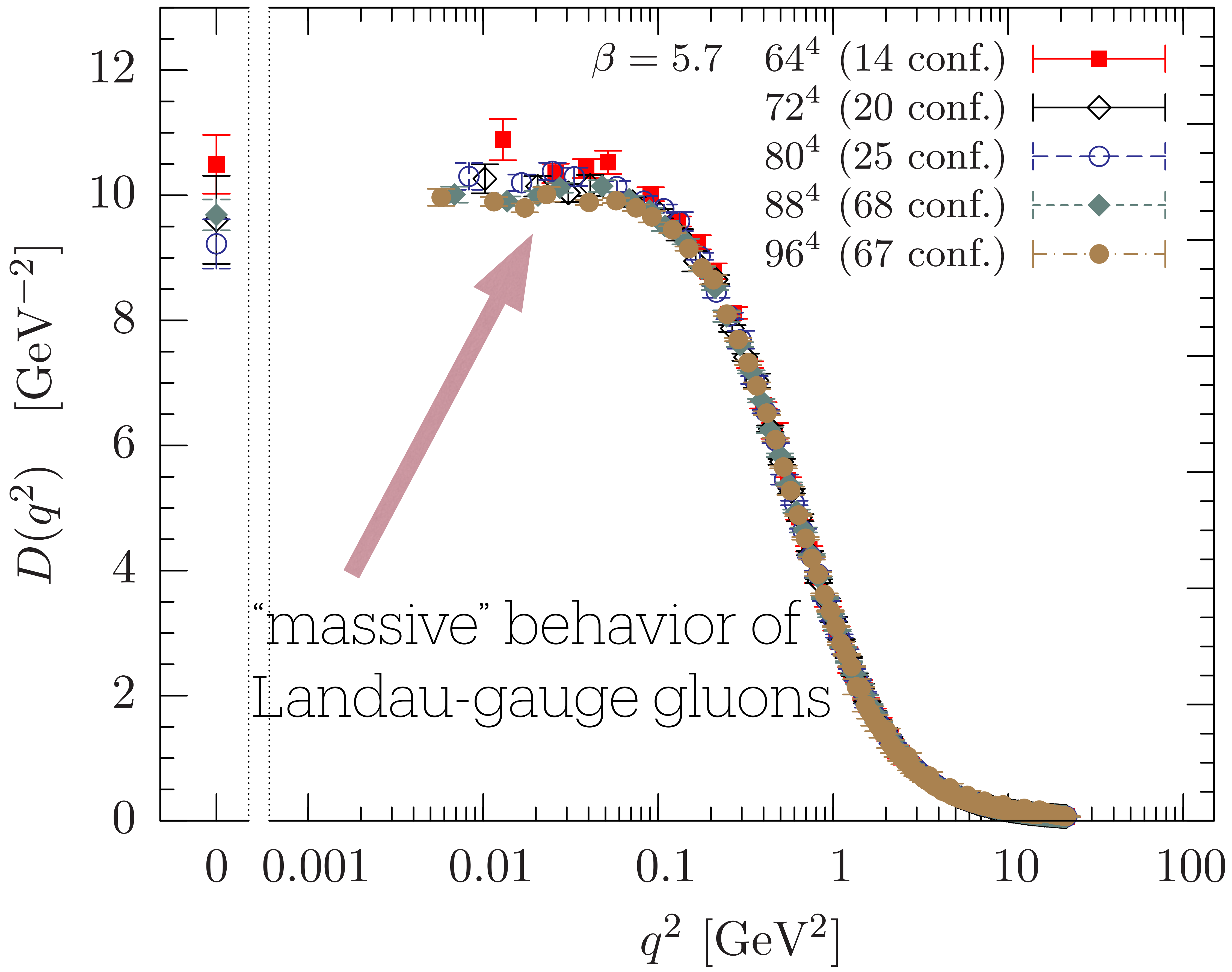
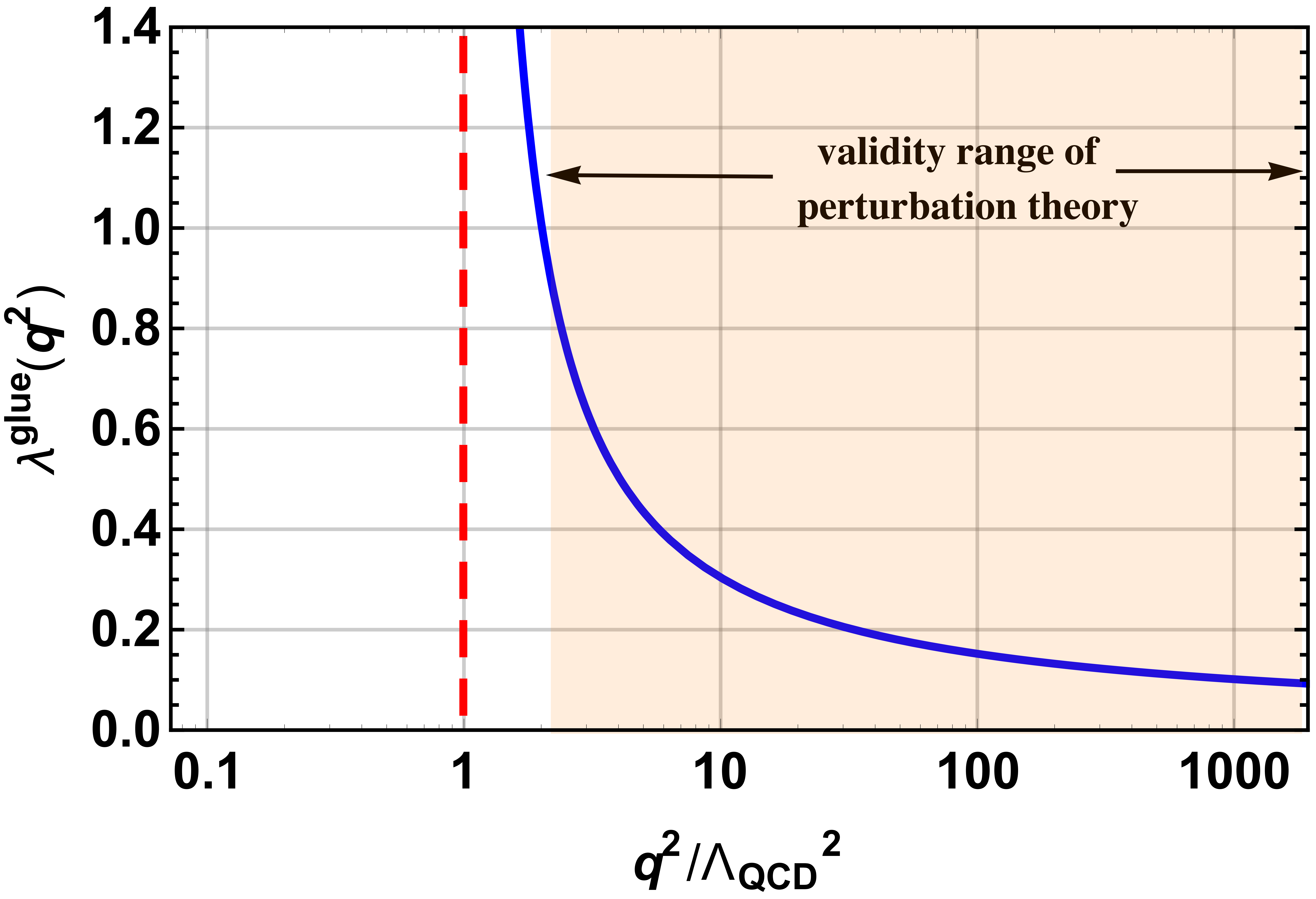


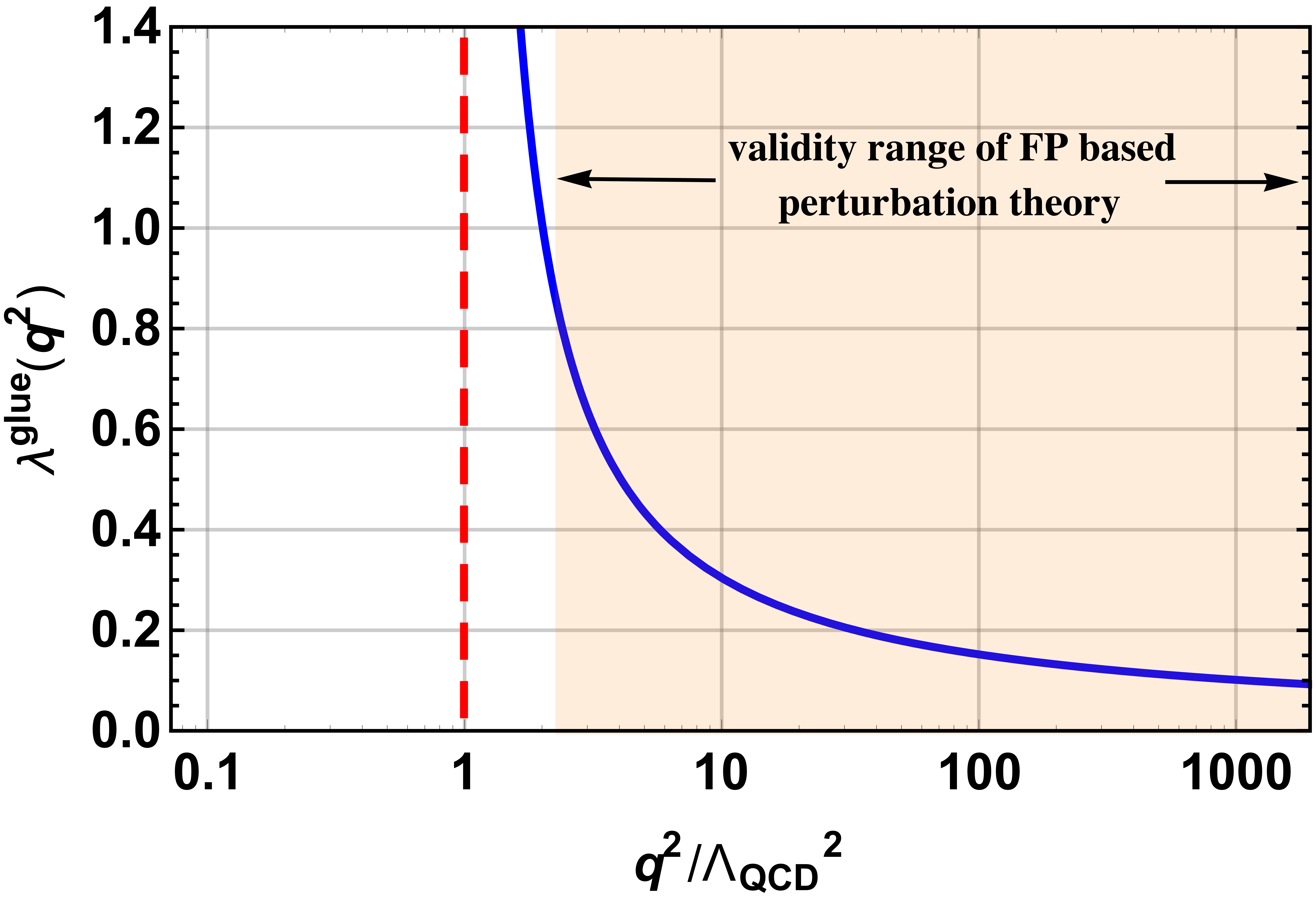


[I.L. Bogolubsky, E.M. Ilgenfritz, M. Müller-Preussker, A. Sternbeck, PLB 676, 69 (2009)]

Weakly coupled glue scenario



Weakly coupled glue scenario



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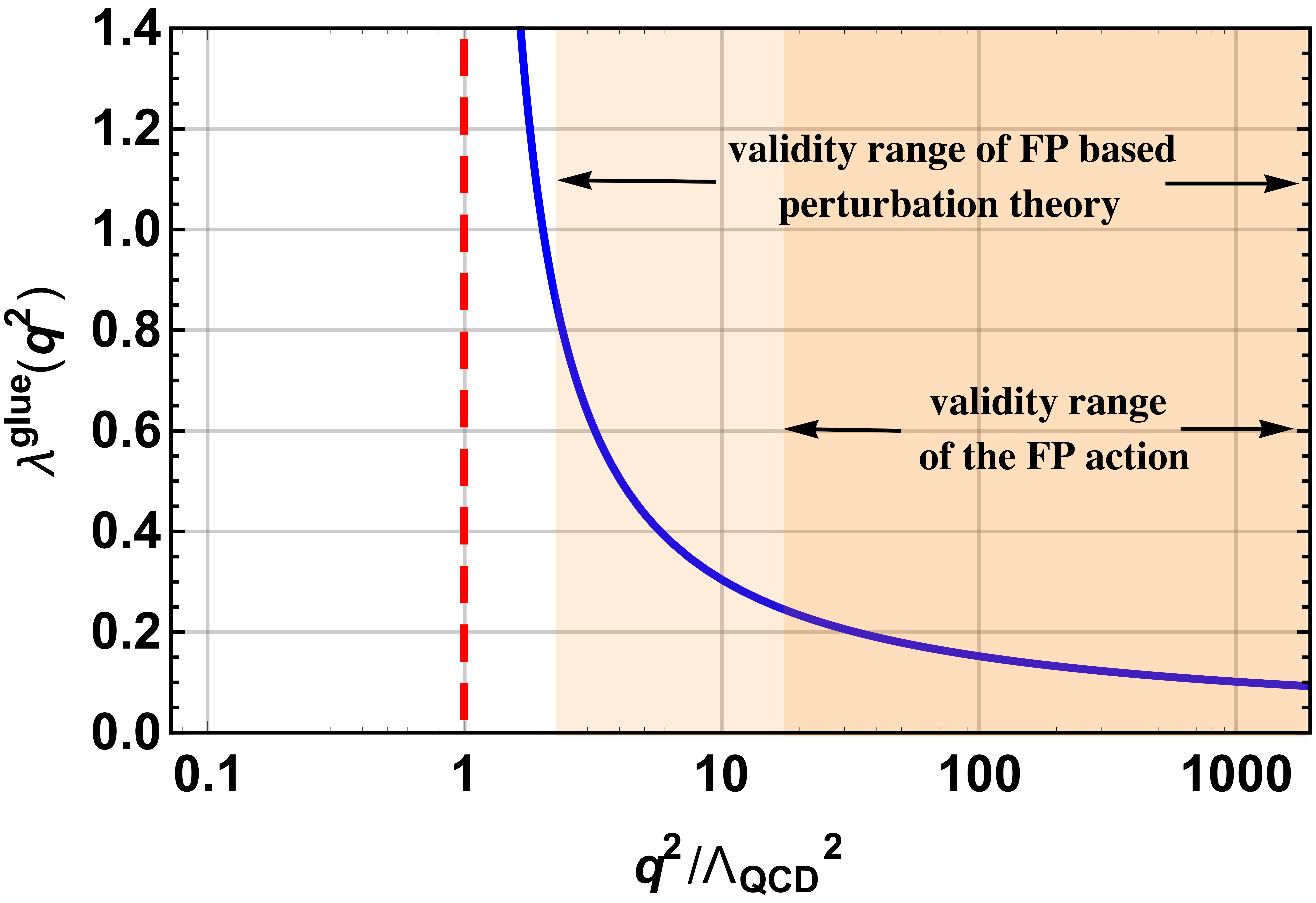

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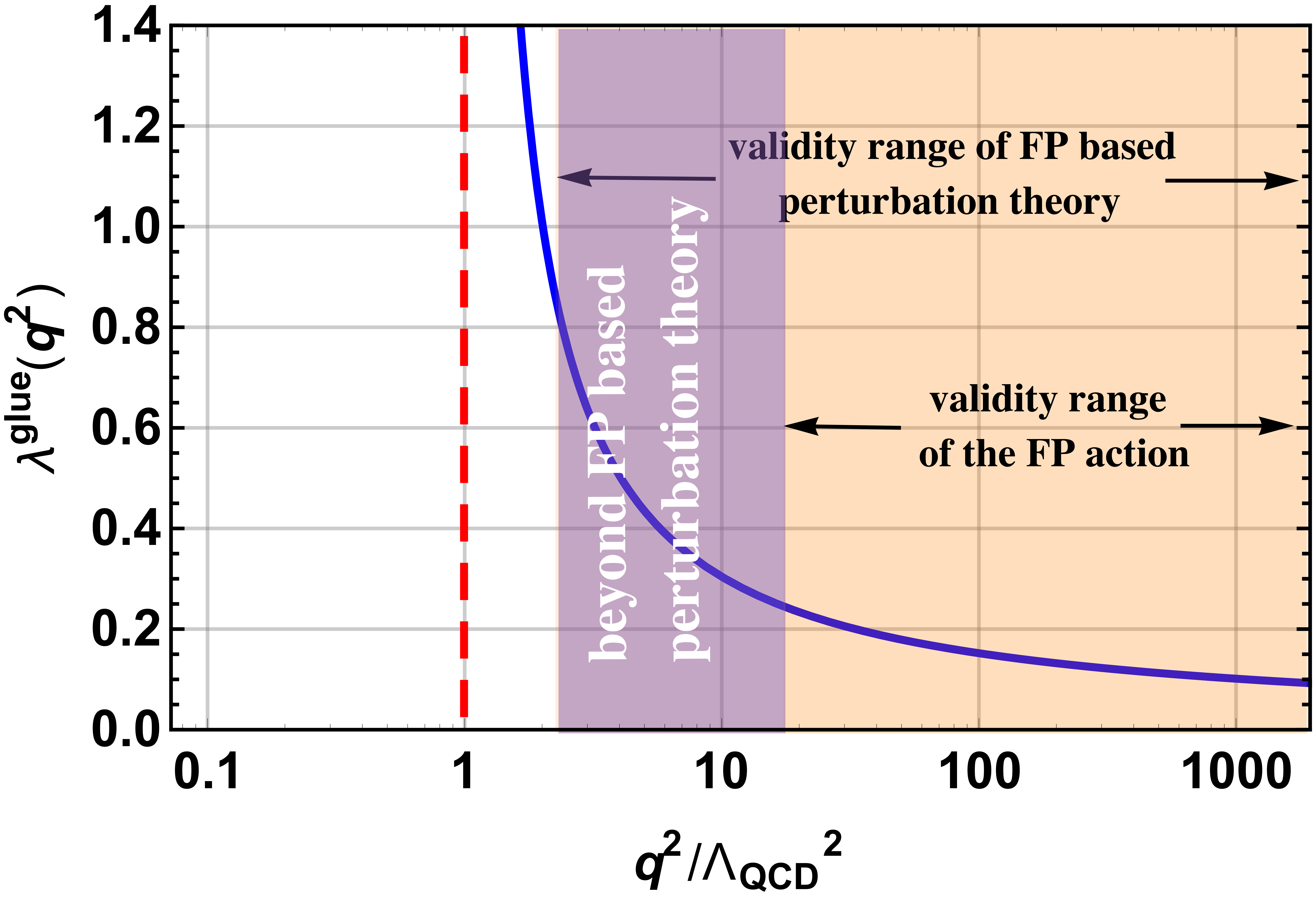

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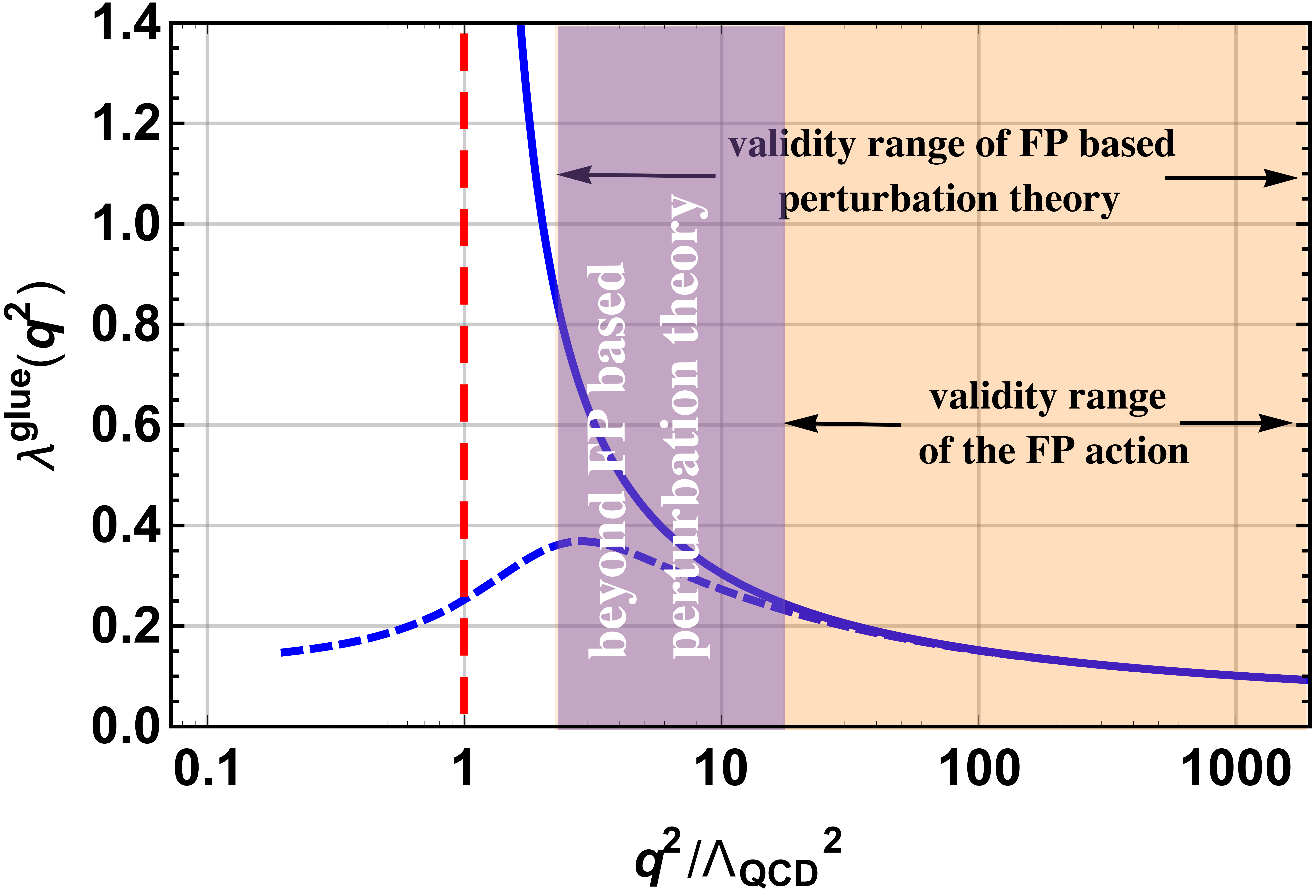


Beyond the Faddeev-Popov action?

How to find the appropriate extension of the Faddeev-Popov action?

- first-principle approach: not known;
- semi-first-principle approach: Gribov-Zwanziger framework;
- phenomenological approach: add new operators to the Faddeev-Popov action and constraint their couplings or even discard them using experiments/numerical simulations.

I. Motivation ✓

II. Quarks and gluons in the infrared ✓

III. The Curci-Ferrari model

IV. Probing the QCD phase diagram from the CF model

The Curci-Ferrari model

The Curci-Ferrari model is one example of such phenomenological extension:

$$S_{CF} = S_{QCD} + \underbrace{2\int_x \mathrm{tr}\left(ih\partial_\mu A_\mu + \partial_\mu \bar{c} D_\mu c\right)}_{\text{incomplete FP gauge-fixing}} + \underbrace{\int_x m^2\, \mathrm{tr}\, A_\mu^2}_{\text{IR, pheno term}}$$

Please, bear in mind that:

- pheno approach motivated by the decoupling behavior as observed on the lattice. No ambition to provide the final answer to the gauge-fixing problem.

- still, the model is renormalizable and thus predictive. Once the mass is fixed, its predictions can be compared to experiments or to simulations of QCD.

A frequent confusion

The Curci-Ferrari model is often confused with Proca theory which amounts to adding a mass term prior to fixing the gauge:

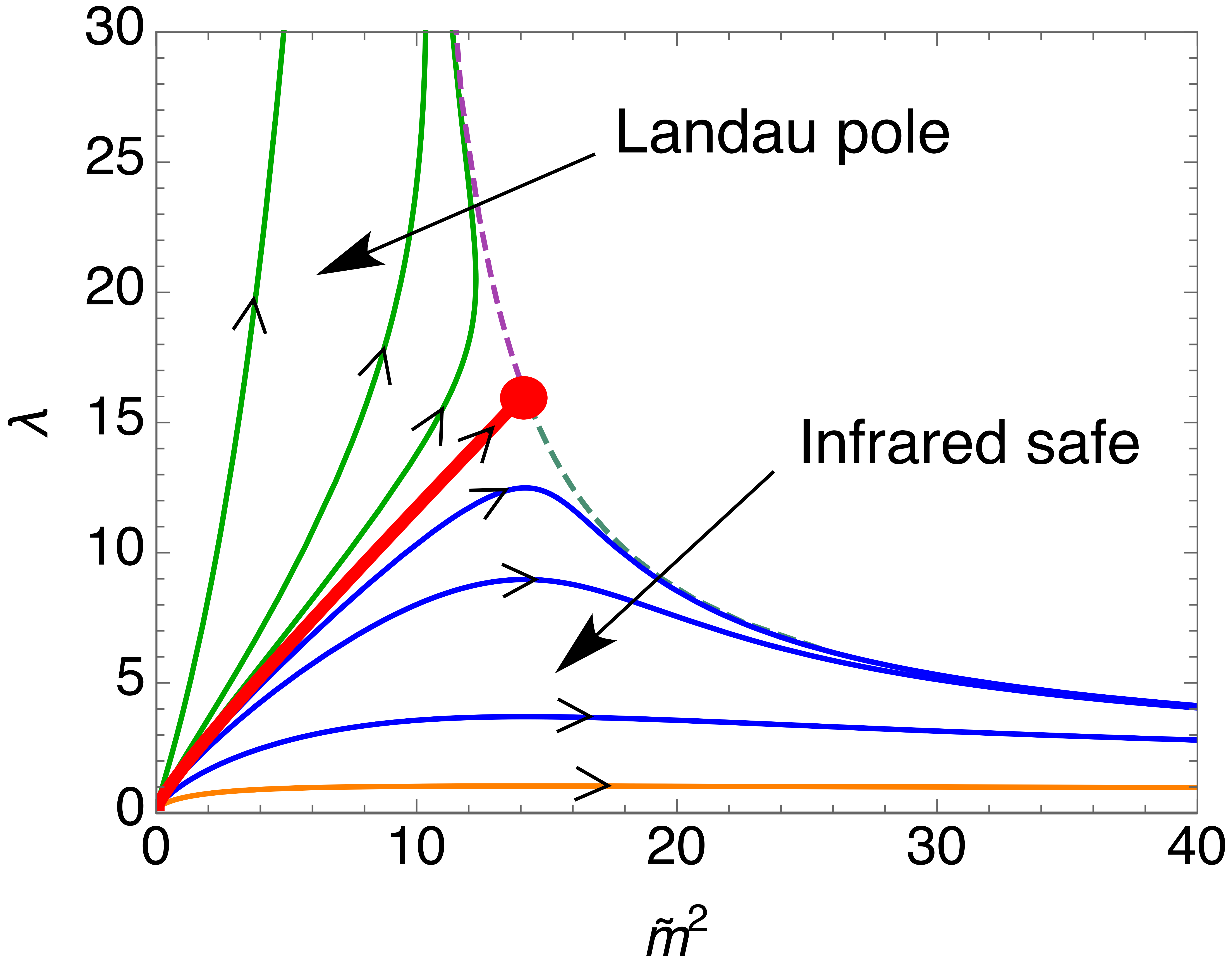
$$S_{Proca} = S_{QCD} + \int_x m^2 \, \mathrm{tr} \, A_\mu^2 \quad \text{vs} \quad S_{CF} = S_{FP} + \int_x m^2 \, \mathrm{tr} \, A_\mu^2$$

Quite different models actually!

Non-renormalizable	Renormalizable
Breaks gauge symmetry	Gauge symmetry broken by FP
Modifies a fundamental theory	Models the missing terms beyond FP

Flow diagram of the Curci-Ferrari model

Main attractive feature: its renormalization group flow



Good candidate for testing the weakly coupled glue scenario.

Testing the weakly coupled glue scenario

We use the quark masses as a tunable external parameter to progressively include more and more layers of complexity.

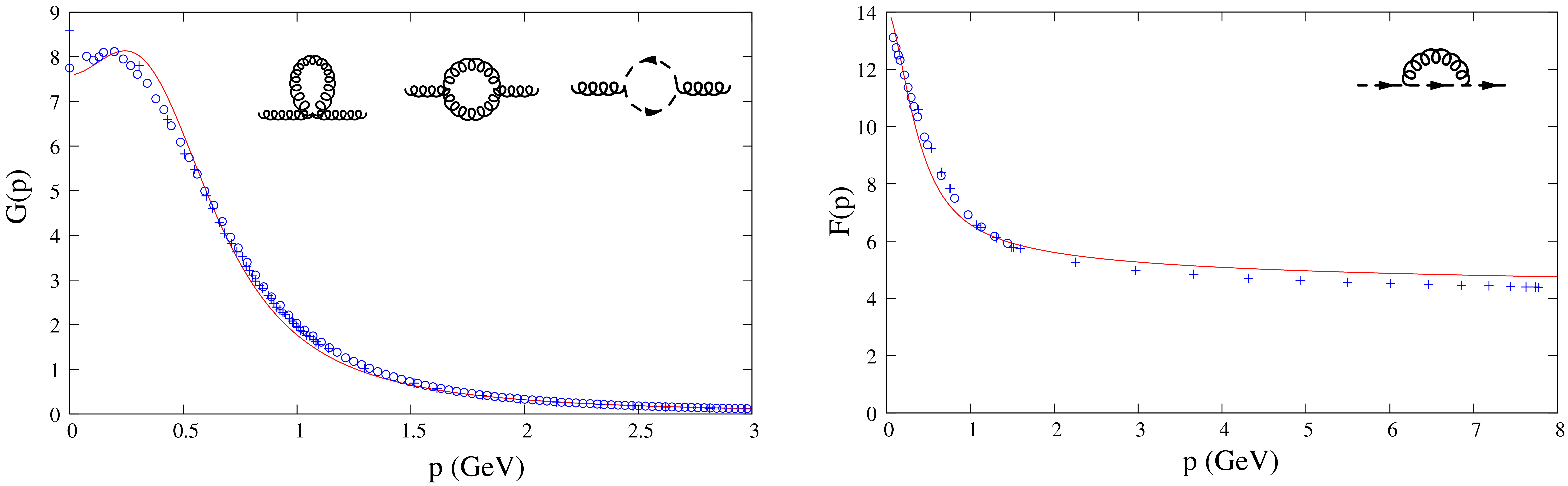
Infinite quark masses: only gluons are present.
Perturbation theory should apply.

Large quark masses: small departure from the previous case.
Perturbation theory should also apply.

Physical quark masses: the actual QCD case.
Perturbation theory is not applicable but we should be able to exploit the weakly coupled glue hypothesis.

Infinite quark masses 

First one-loop calculations of the gluon and ghost propagators in the CF model and comparisons to Landau gauge lattice data by Tissier and Wschebor in 2010:

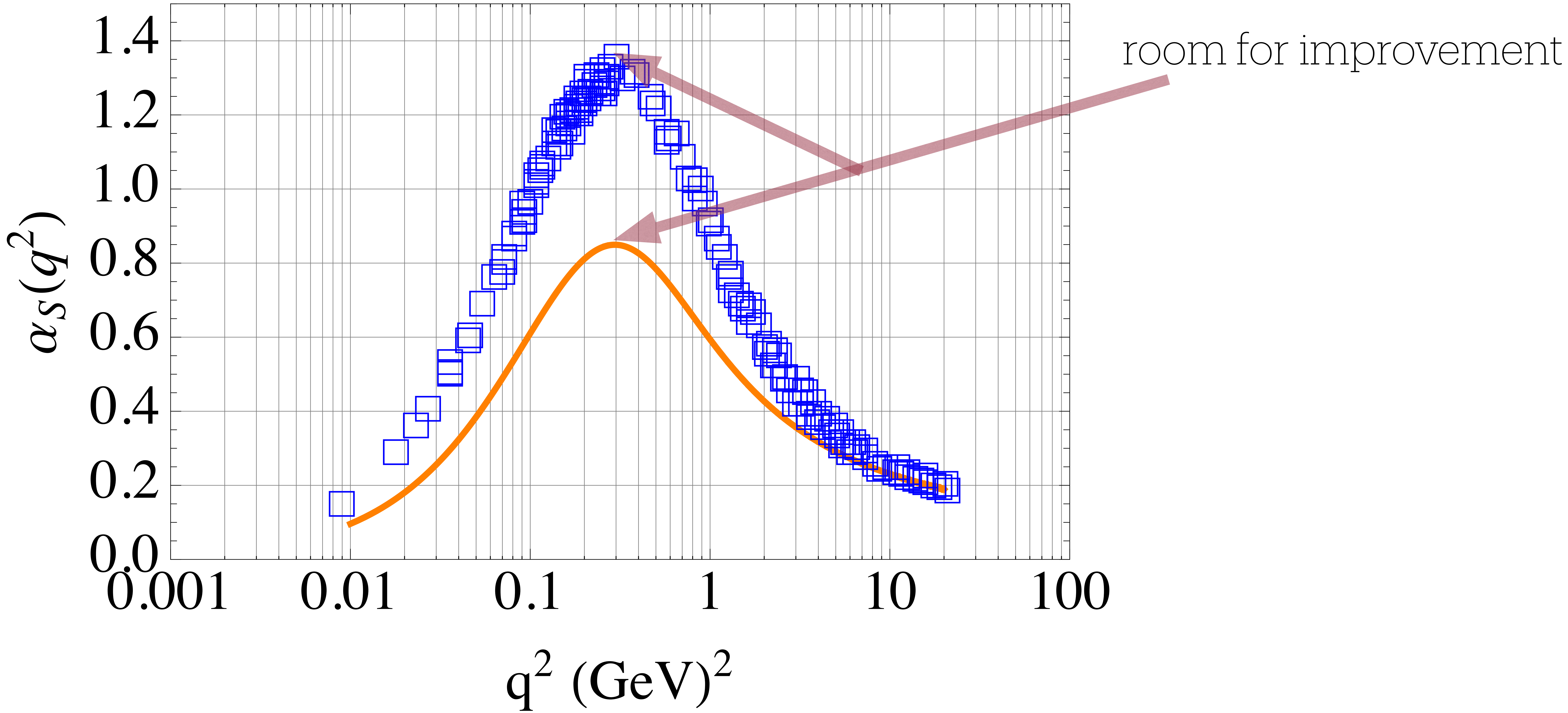


[Tissier and Wschebor, Phys. Rev. D82 (2010) & Phys. Rev. D84 (2011)]

m ~ 500 MeV

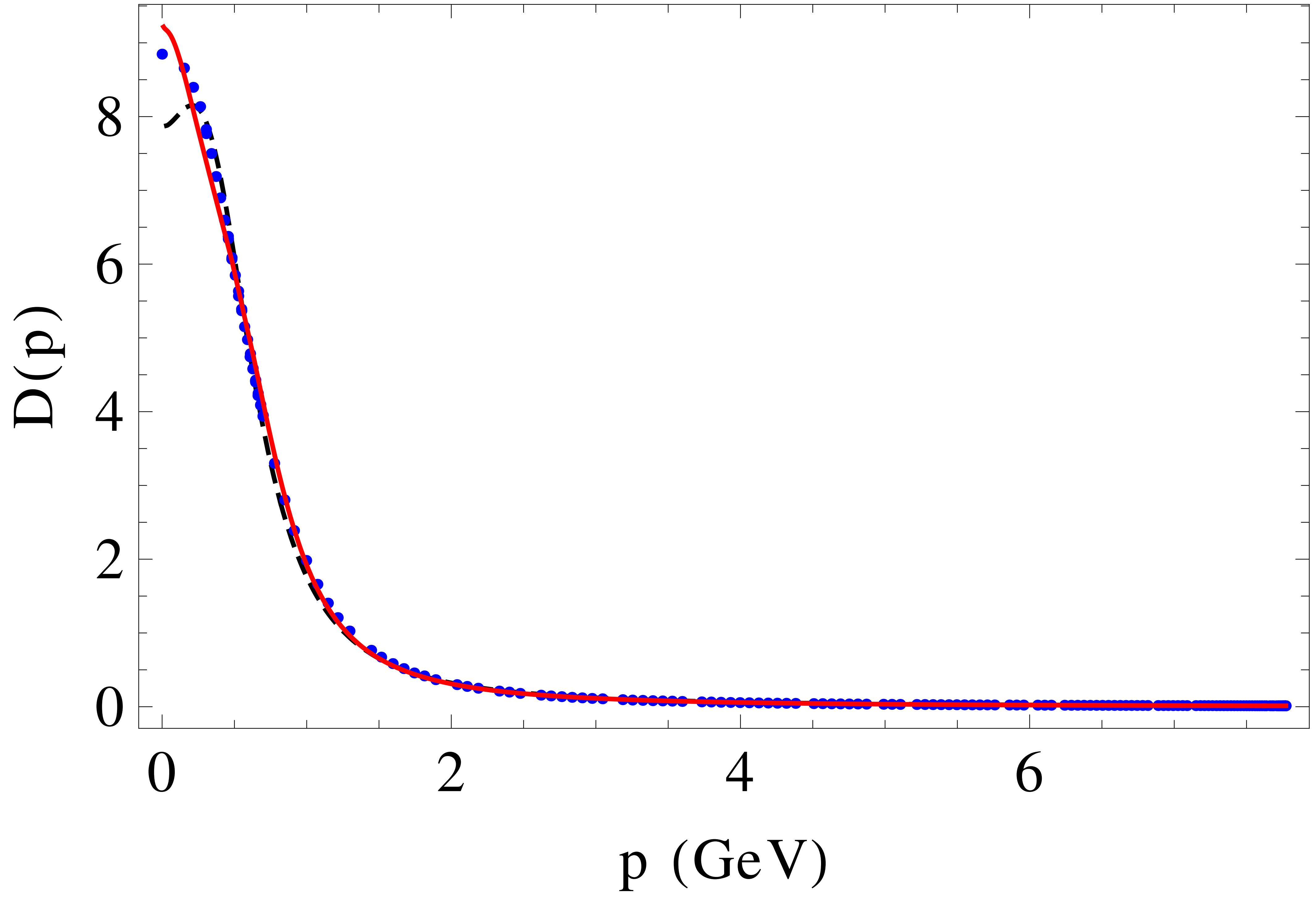
Infinite quark masses

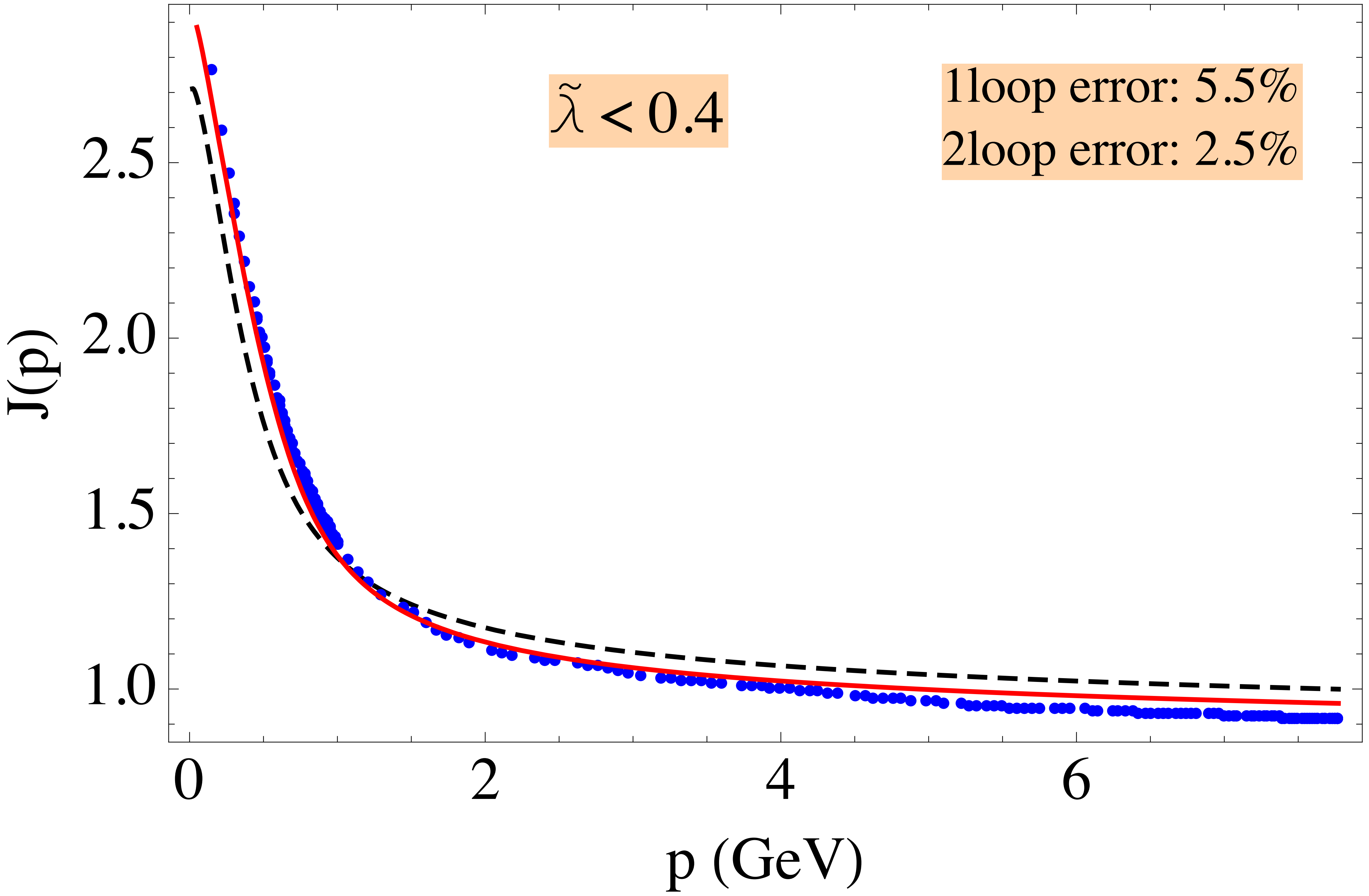
One-loop running coupling:



Infinite quark masses 

Two loop calculation is more involved (19 diagrams) but doable:

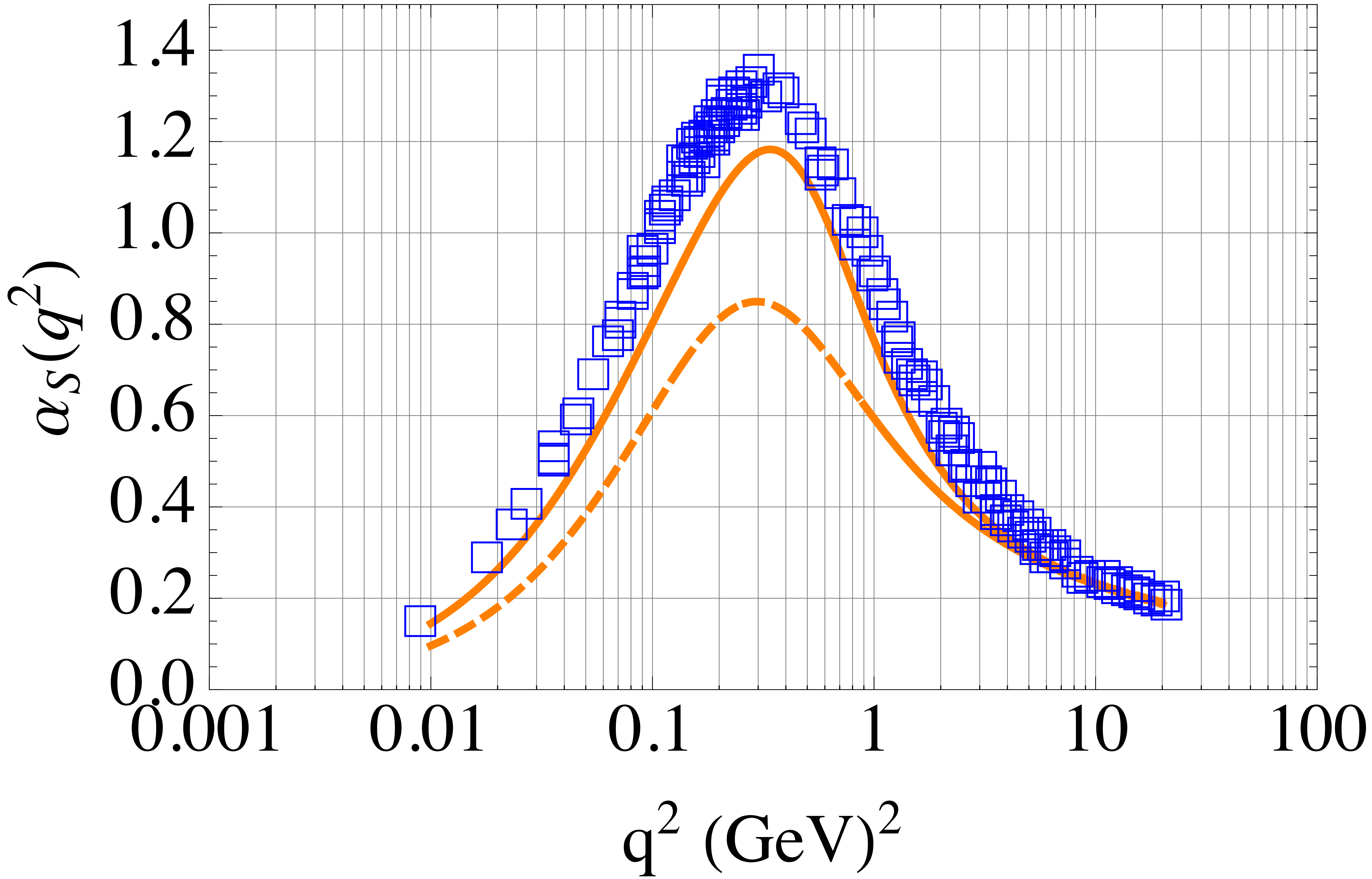




[J.A. Gracey, M. Peláez, U. Reinosa, M. Tissier, Phys. Rev. D100 (2019)]

Infinite quark masses

Two-loop running coupling:



Large quark masses 

In addition to the gluon and ghost propagators we have now access to the form factors of the quark propagator:

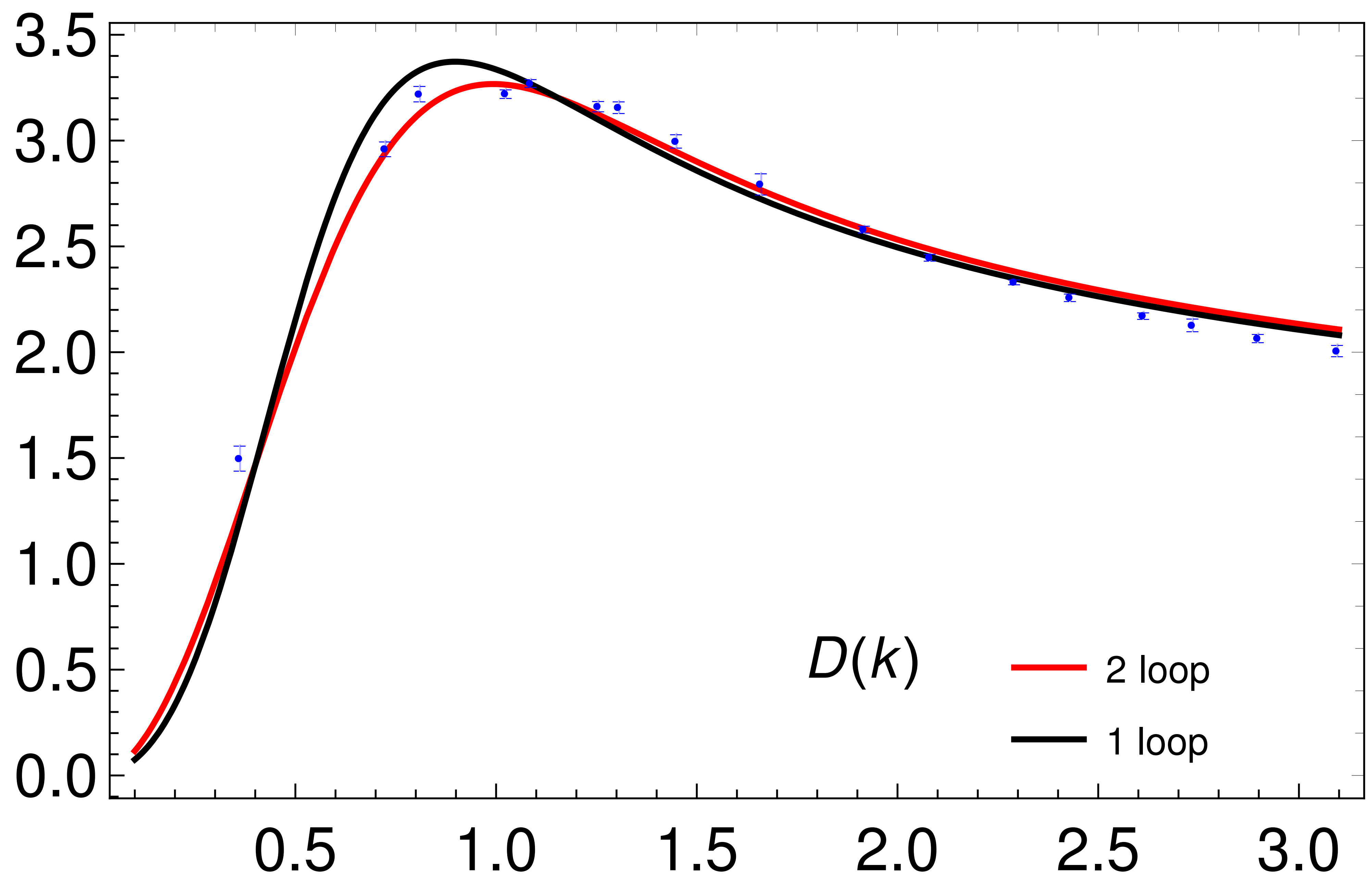
$$S(q) = \langle \psi \bar{\psi} \rangle = \frac{Z(q^2)}{i\gamma_\mu q_\mu + M(q^2)}$$

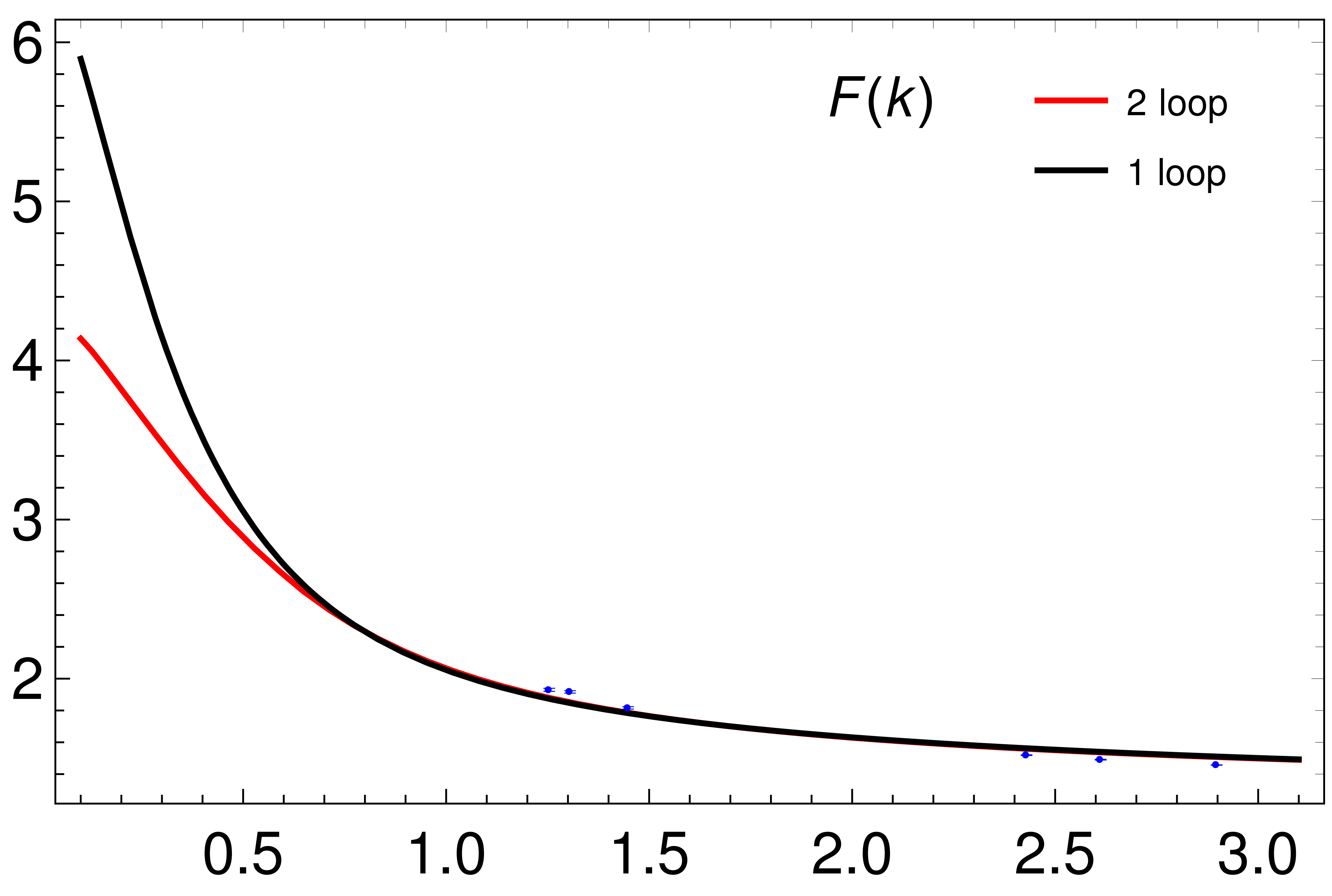
Quark dressing function $Z(q^2)$ and quark mass function $M(q^2)$.

Evaluated at one- and two-loop orders of the perturbative expansion.

Large quark masses 

The glue sector is still pretty well described by the perturbative CF model:

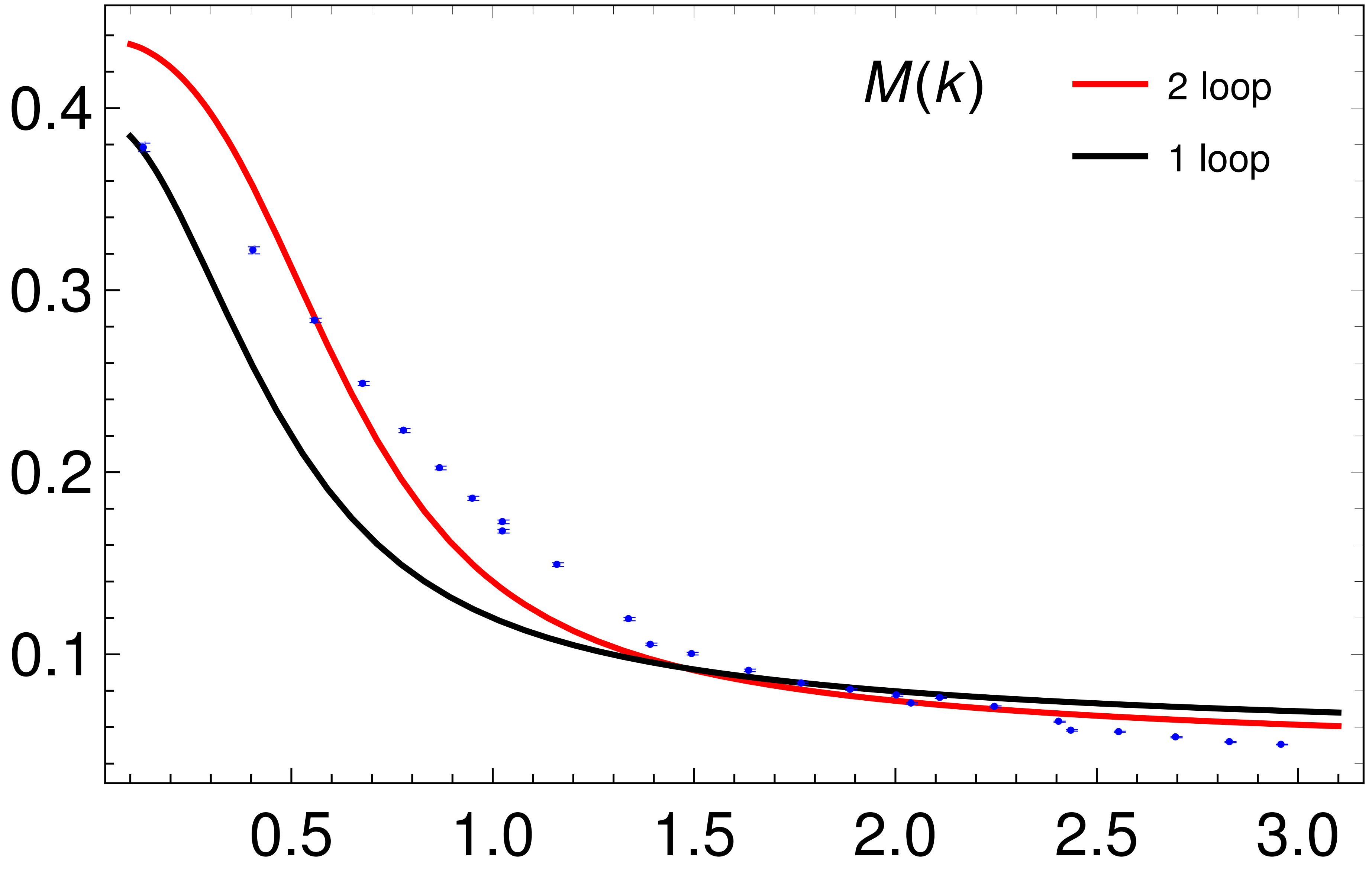


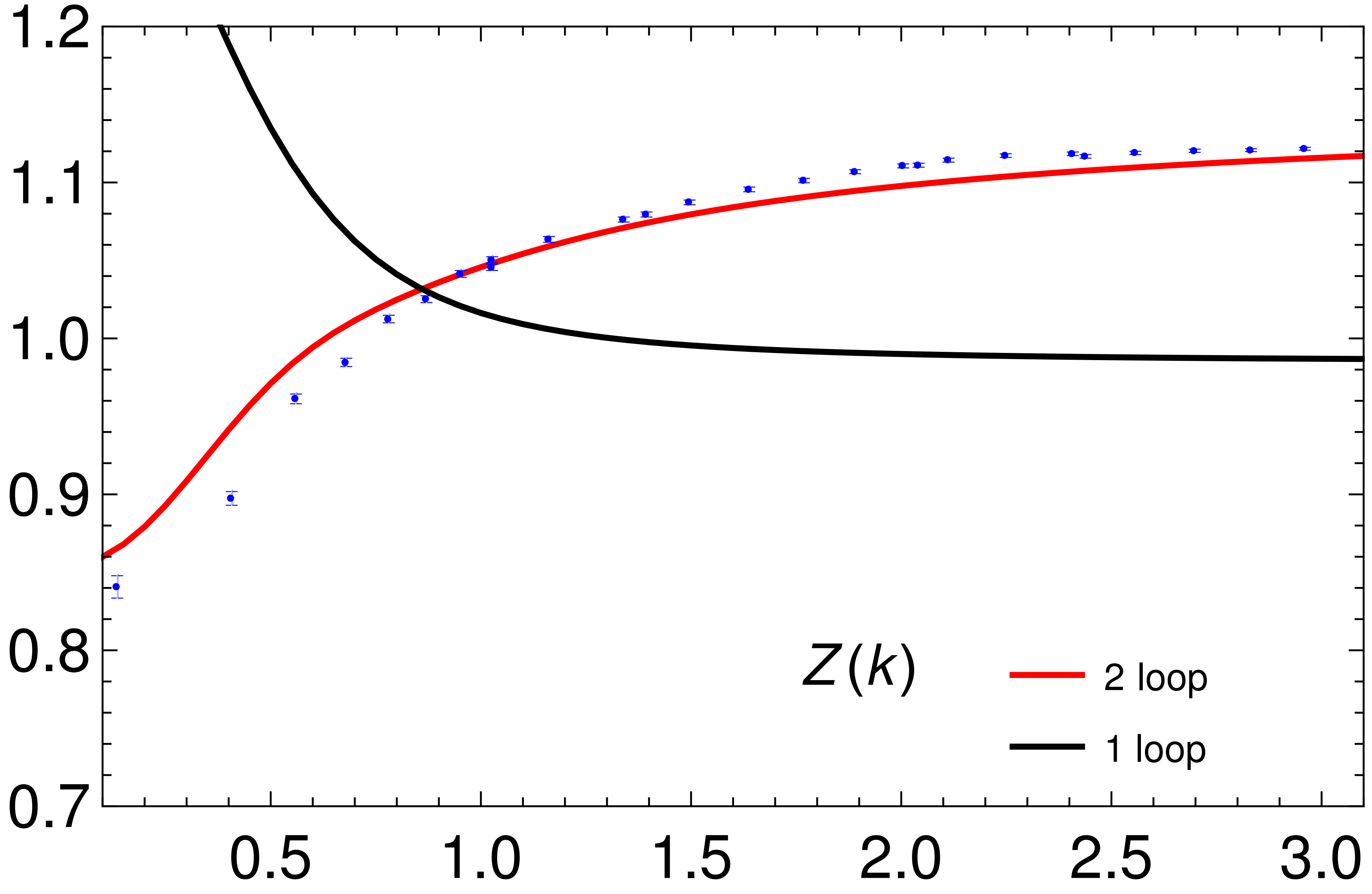


[N. Barrios, J.A. Gracey, M. Peláez, U. Reinosa, Phys. Rev. D104 (2021)]

Large quark masses 

The perturbative CF model also accounts for the quark form factors:





NB: this is not a trivial result since the quark dressing function $Z(q^2)$ is only accurately reproduced starting at two-loop order.

Physical quark masses 

The perturbative CF model is doomed to fail for at least two reasons:

- even though $\lambda^{\text{glue}} \simeq 0.3$ is perturbatively small, $\lambda^{\text{quark}} \simeq 1.2$ is not;

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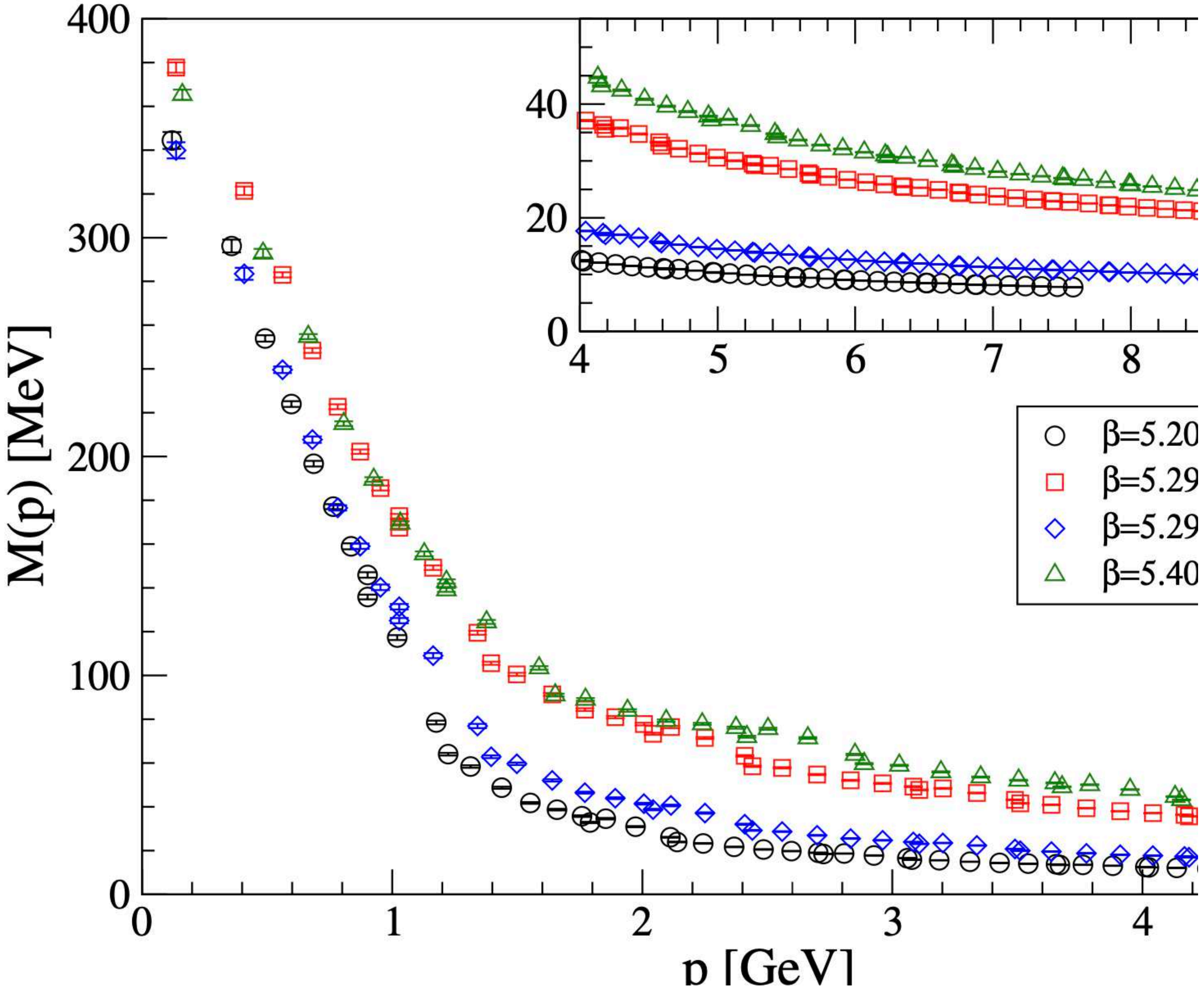

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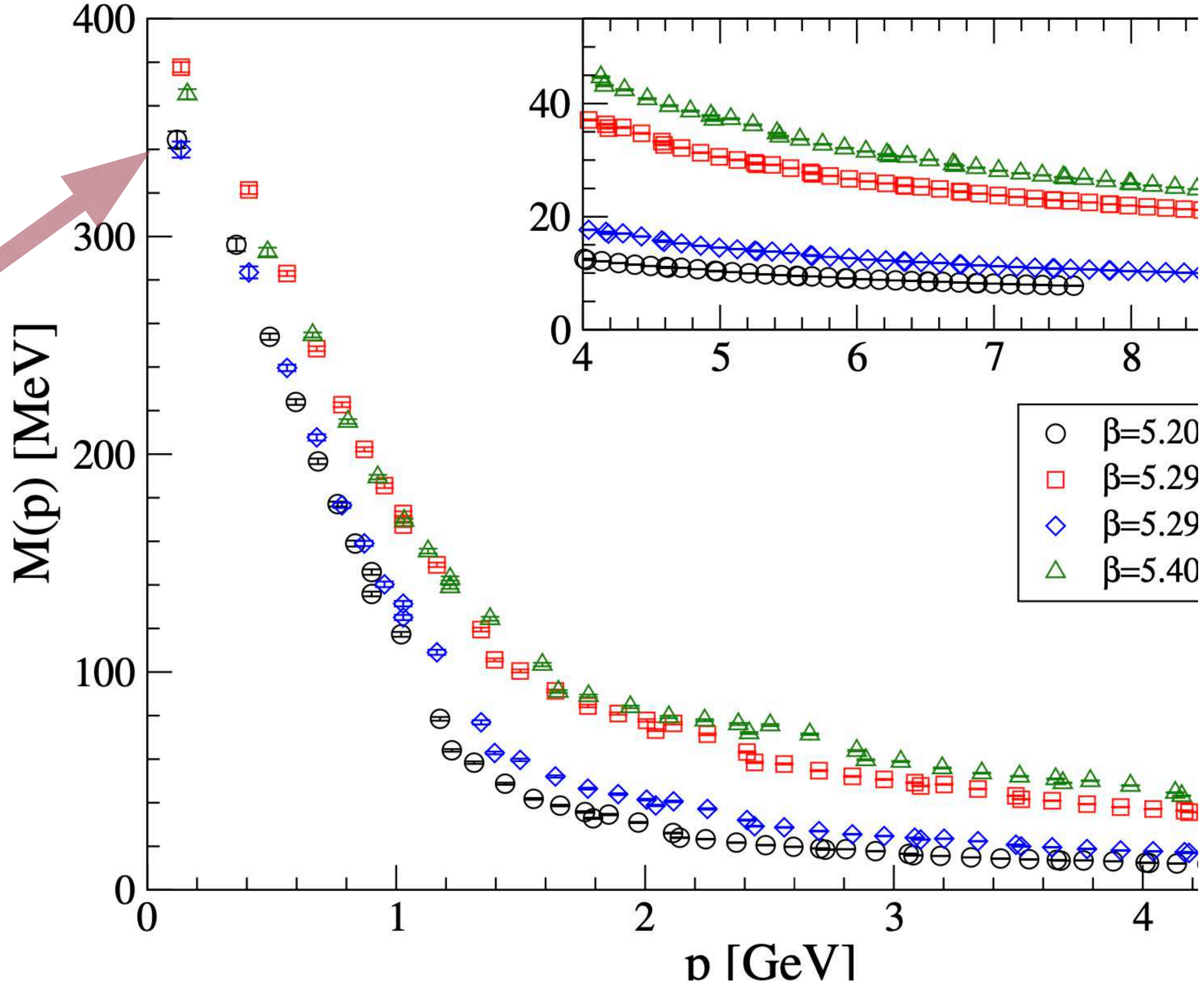


Spontaneous breaking of chiral symmetry

Physical quark masses 

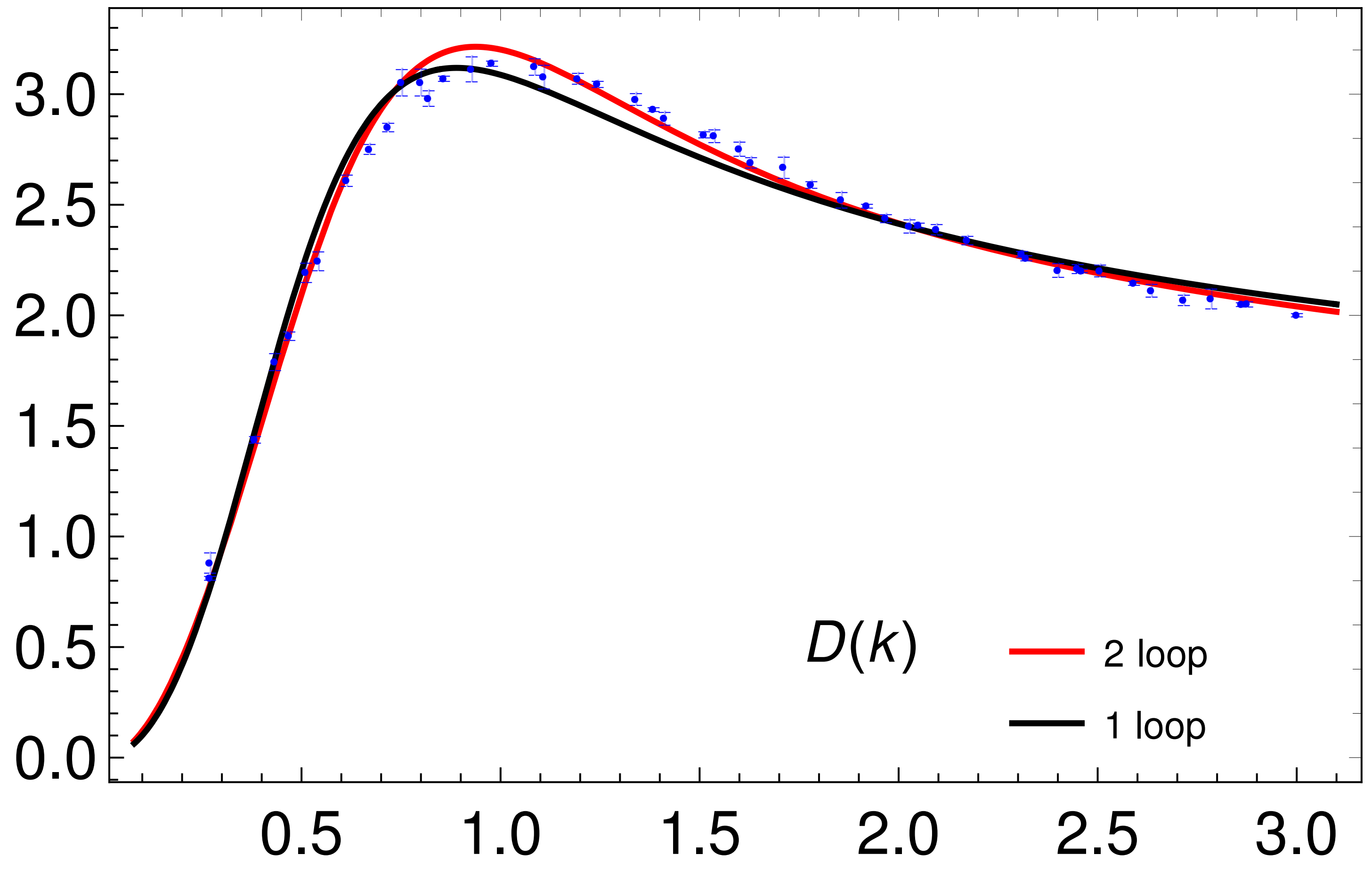
This does not mean that the CF model should be abandoned, however, since

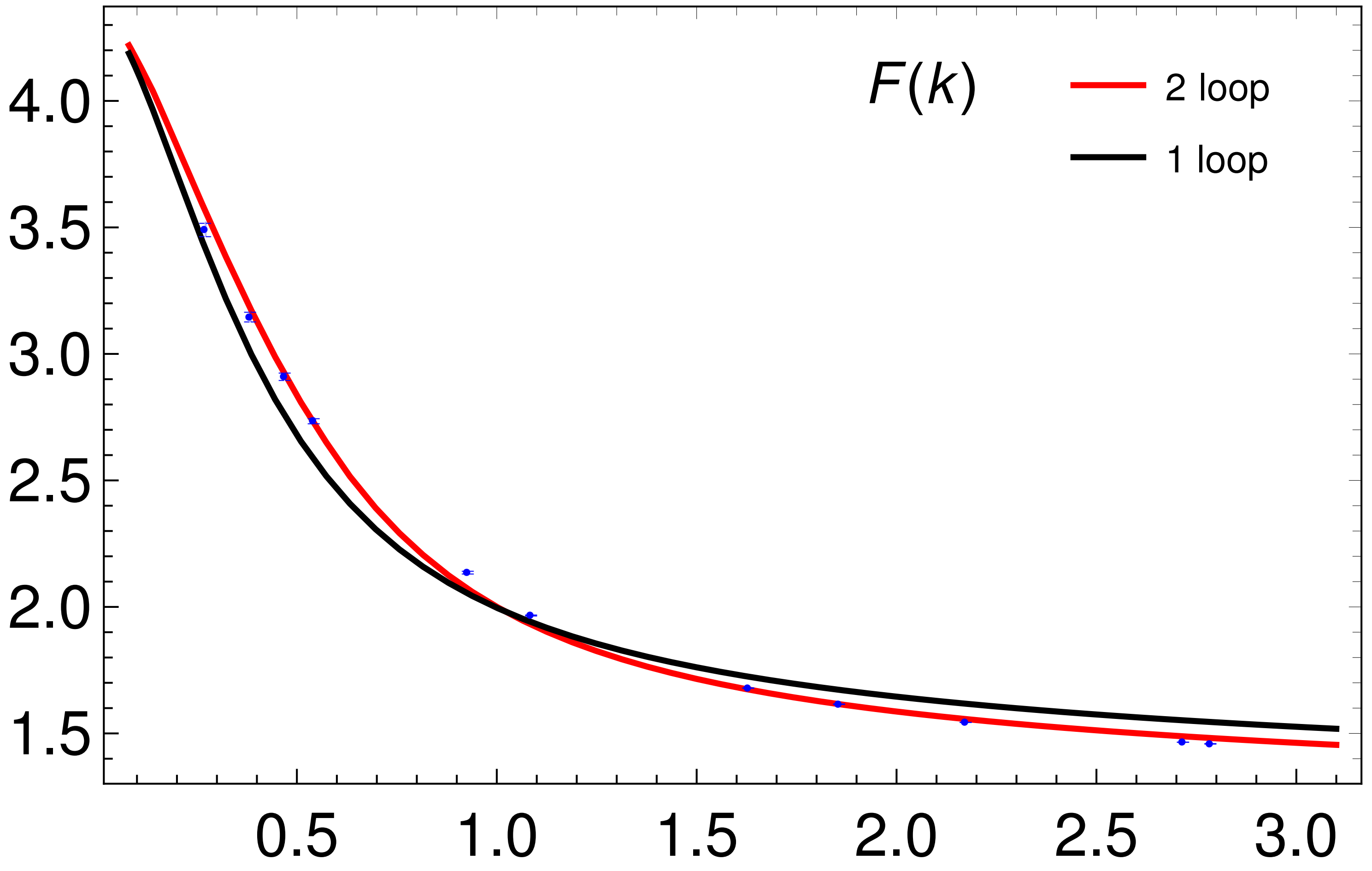
- quantities that are little impacted by chiral symmetry breaking could still admit a perturbative description within the CF model;

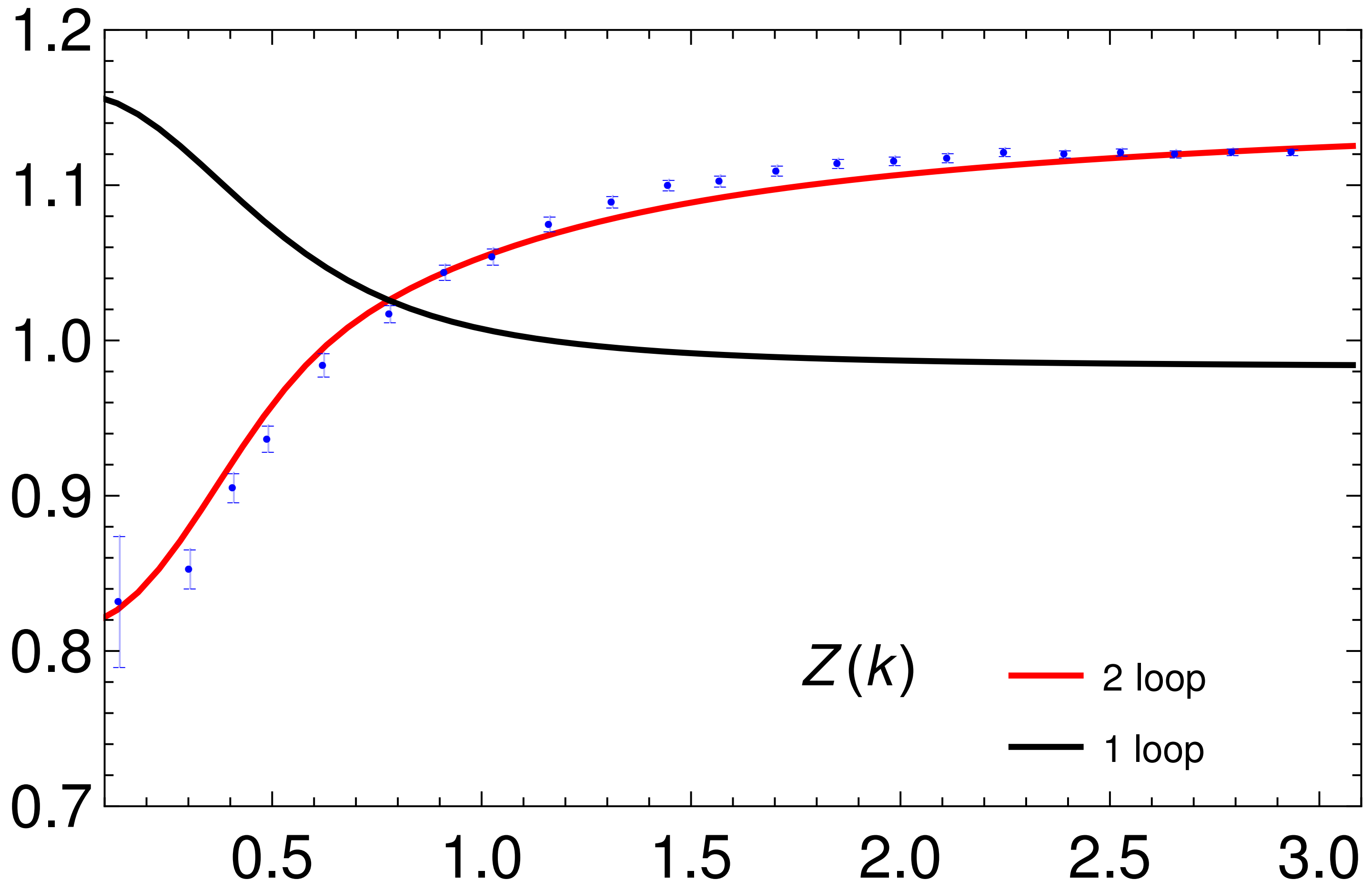
- quantities that are governed by chiral symmetry could still admit a good description within the CF model, beyond perturbation theory.

Physical quark masses 

The perturbative CF model is still good at describing quantities that are not directly impacted by chiral symmetry breaking:



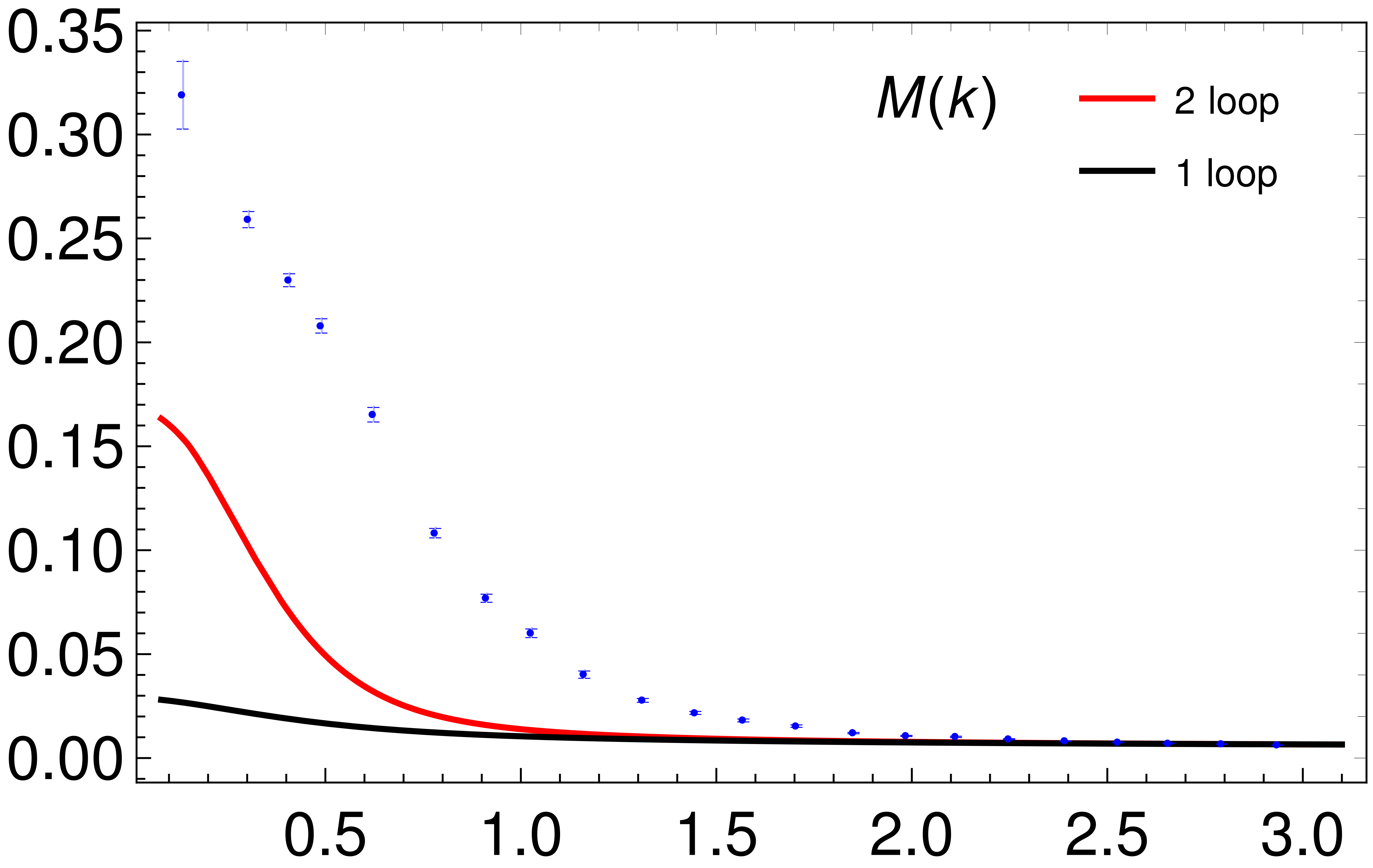




[N. Barrios, J.A. Gracey, M. Peláez, U. Reinosa, Phys. Rev. D104 (2021)]

Physical quark masses

As expected, the quark mass function is poorly reproduced perturbatively:



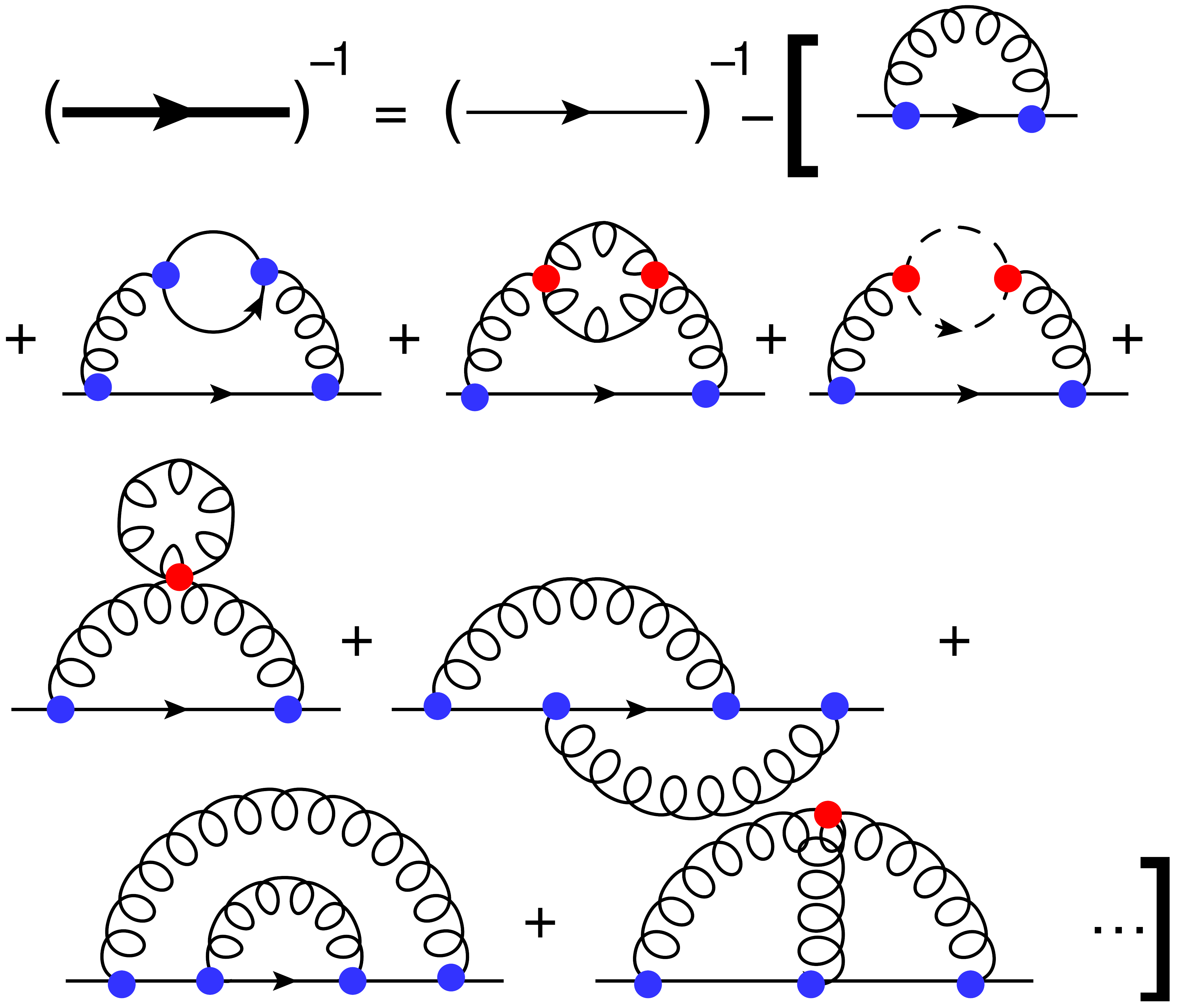
Calls for a non-perturbative treatment.

Physical quark masses 

How do we decide which diagrams dominate the quark propagator when the coupling is not small?

It seems that we are back to the old truncation problem.

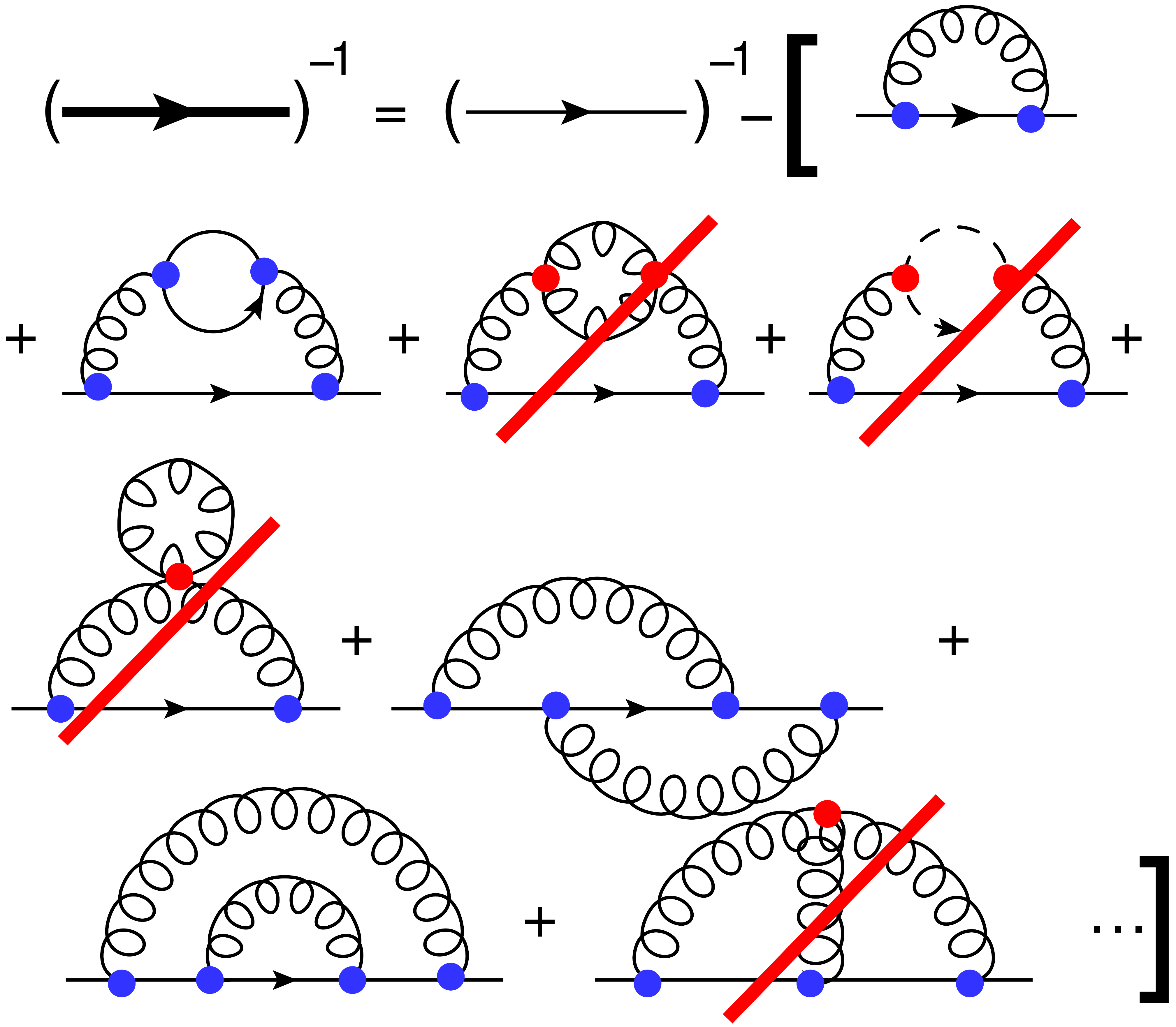
But not really because we can exploit the weakly coupled glue scenario.



Physical quark masses 

How do we decide which diagrams dominate the quark propagator when the coupling is not small?

Neglect diagrams suppressed by λ^{glue}.

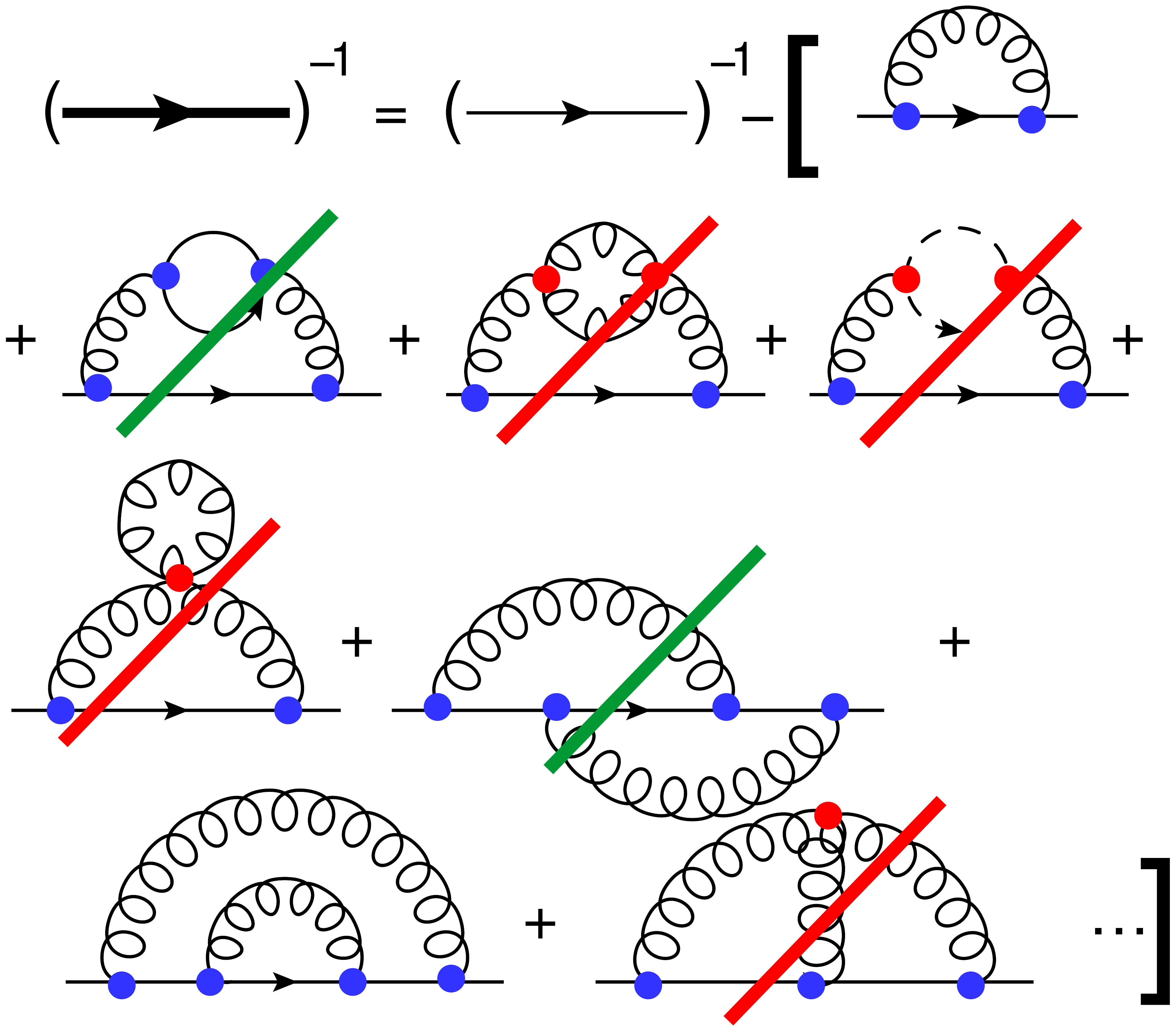


Physical quark masses 

How do we decide which diagrams dominate the quark propagator when the coupling is not small?

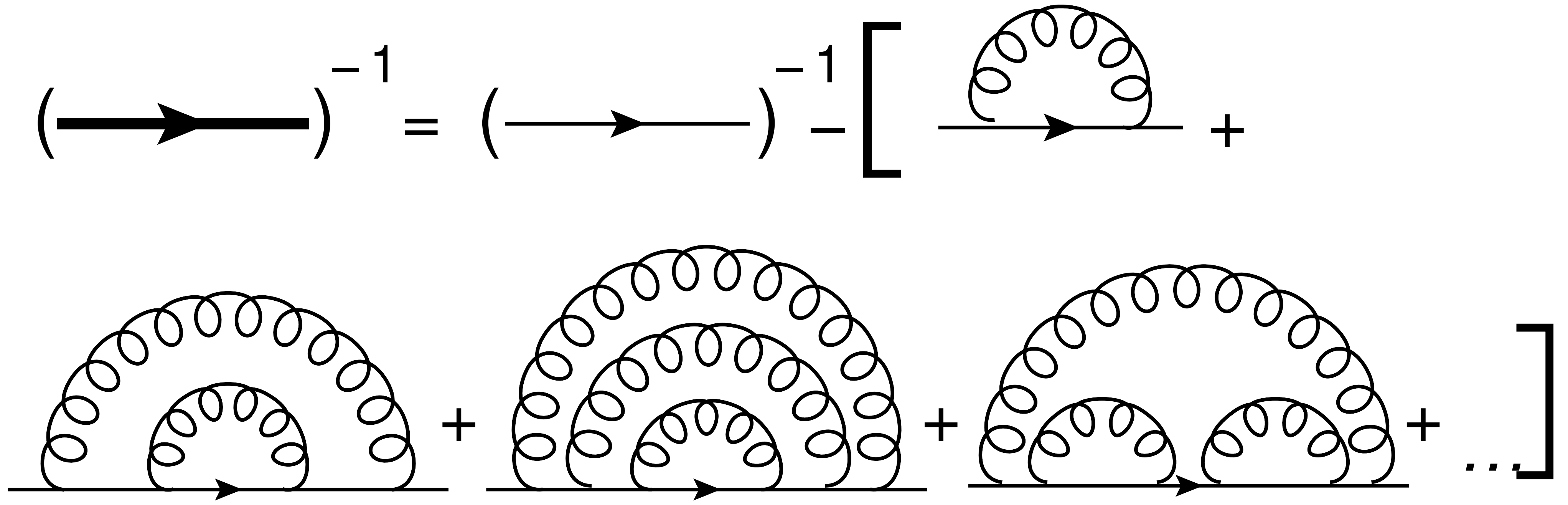
Neglect diagrams suppressed by λ^{glue}.

Treat the rest in a $1/N_c$ expansion.

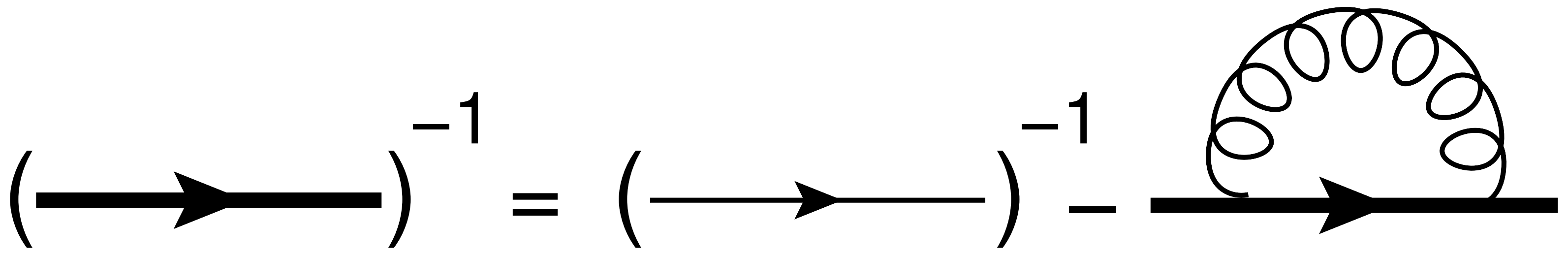


Physical quark masses

At LO, this double expansion in λ^{glue} and $1/N_c$ leads to the subclass of diagrams:



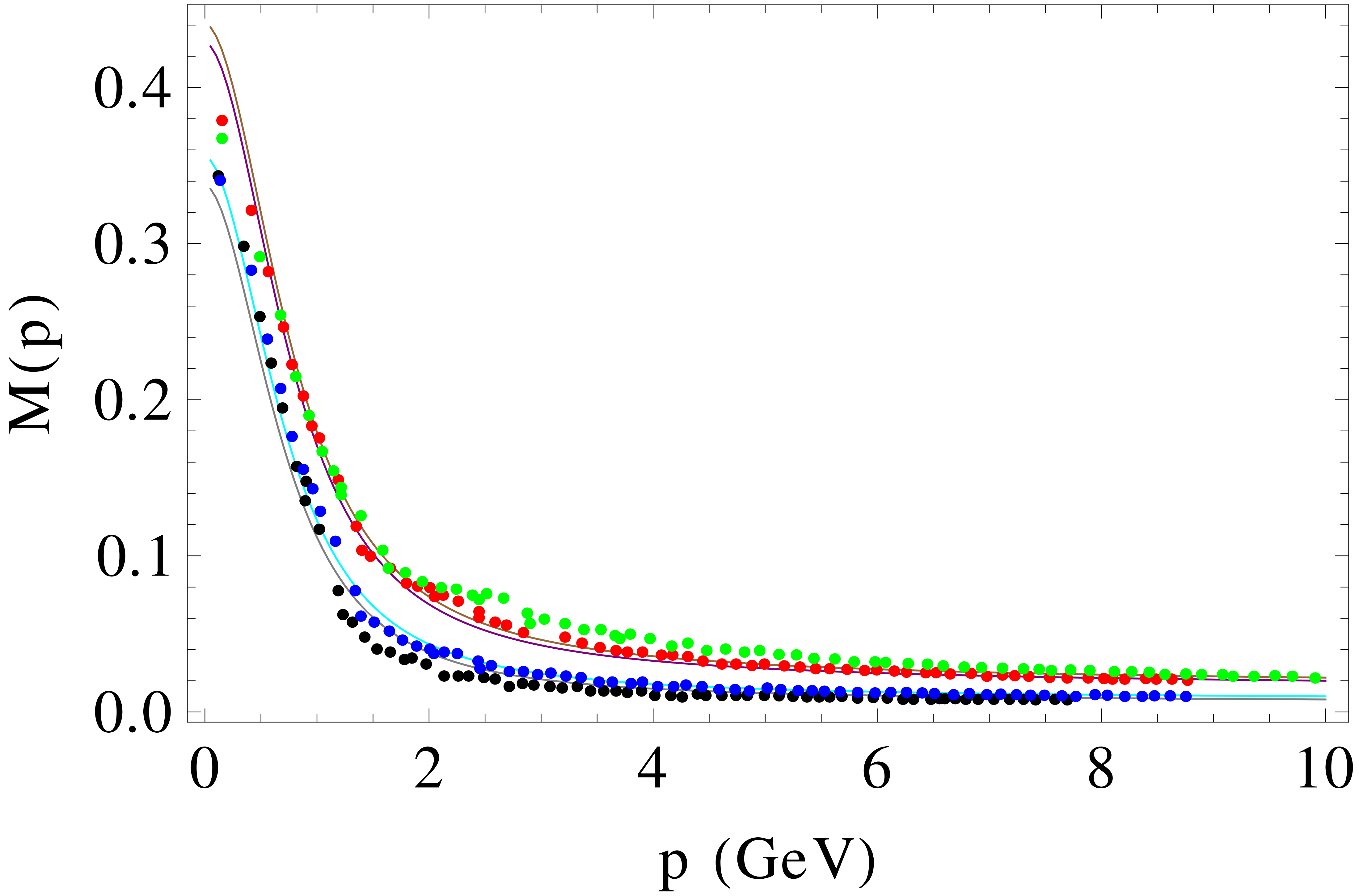
Resummed into an integral equation that can easily be solved:

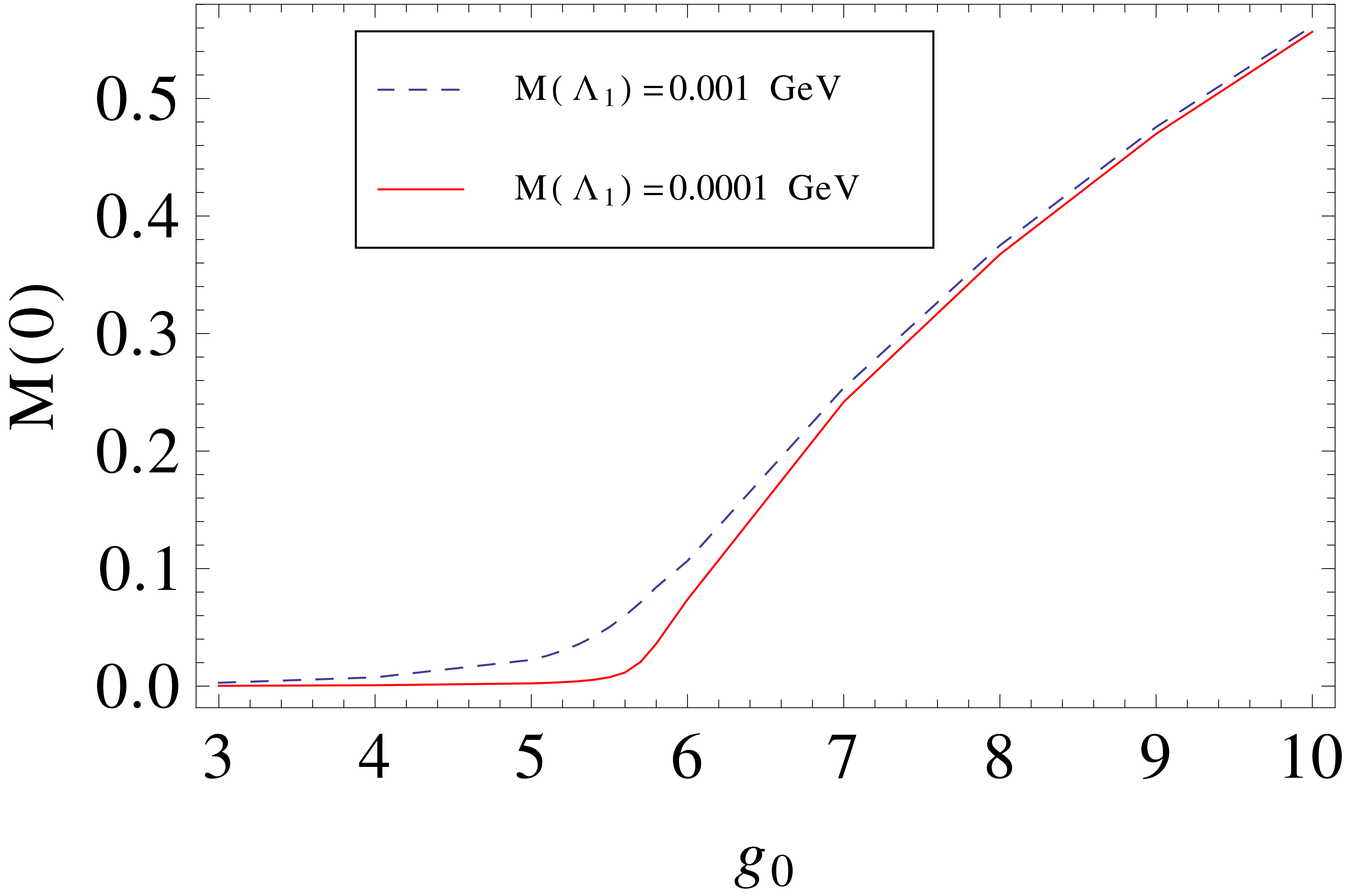


The benefit with respect to other truncations is that the error is controlled by two small parameters λ^{glue} and $1/N_c$.

Physical quark masses 

Good account of chiral symmetry breaking:



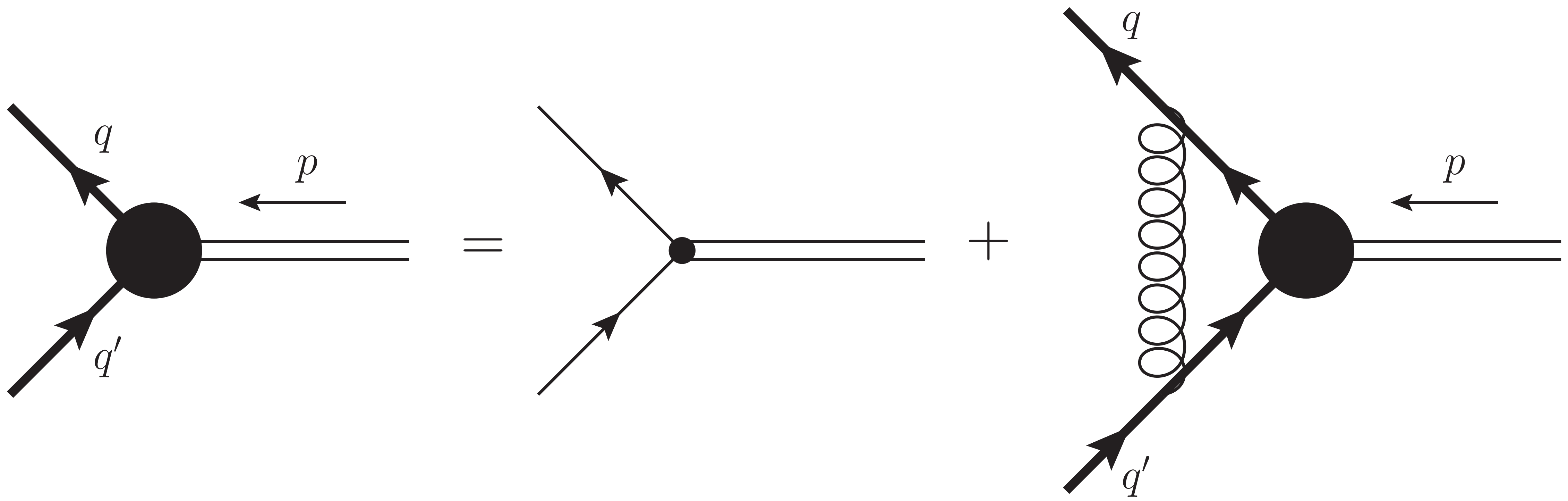


[M. Peláez, U. Reinosa, J. Serreau, M. Tissier, N. Wschebor, Phys. Rev. D96 (2017)]

Physical quark masses 

Entry into the study of hadronic structure.

Using the same expansion, we were able to find a closed integral equation for the pion-quark-antiquark vertex:

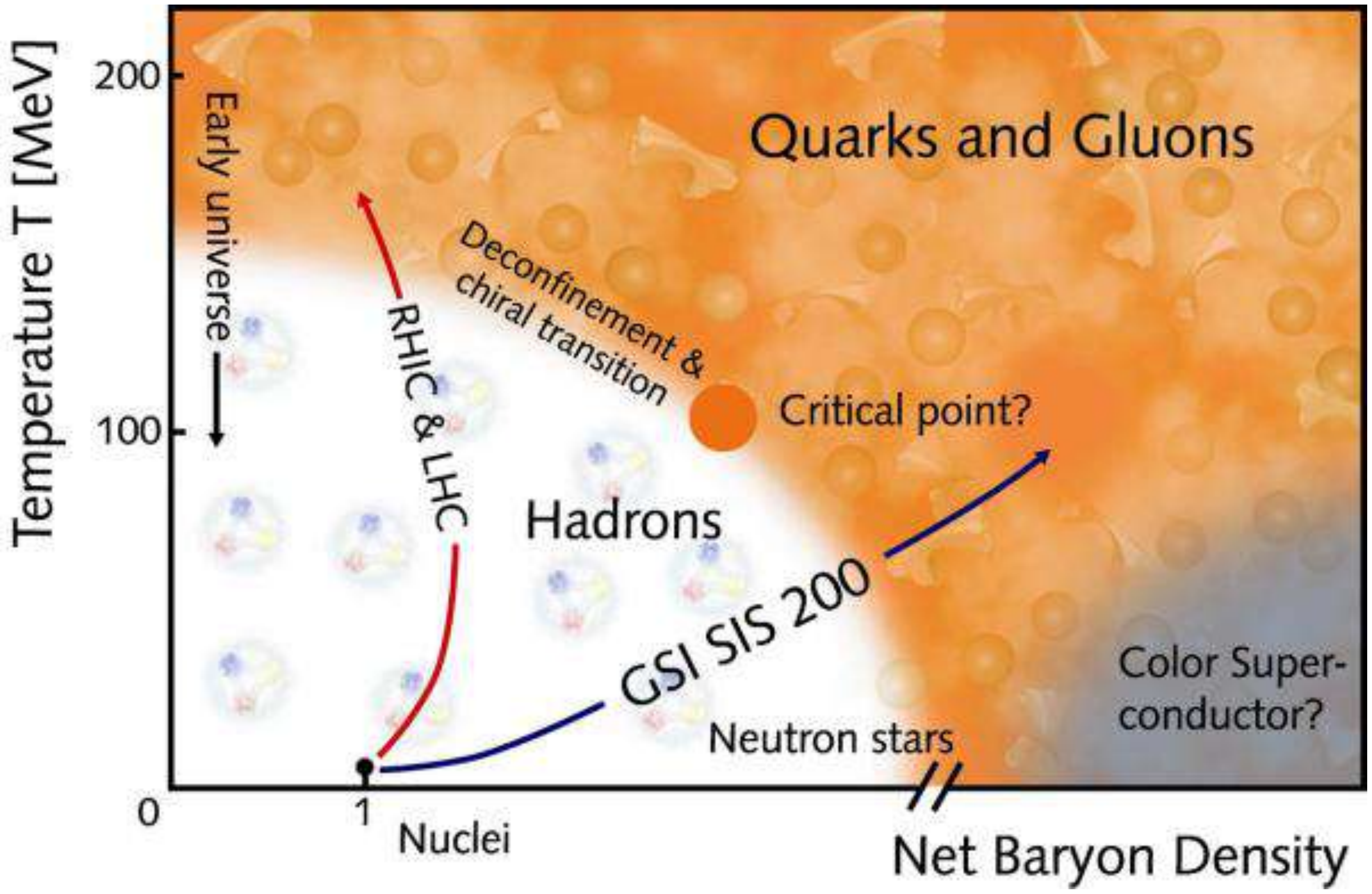


This allowed us to perform an ab-initio calculation of the pion decay constant within the CF model that compares well with other QCD estimates.

[M. Peláez, U. Reinosa, J. Serreau, N. Wschebor, Phys. Rev. D107 (2023)]

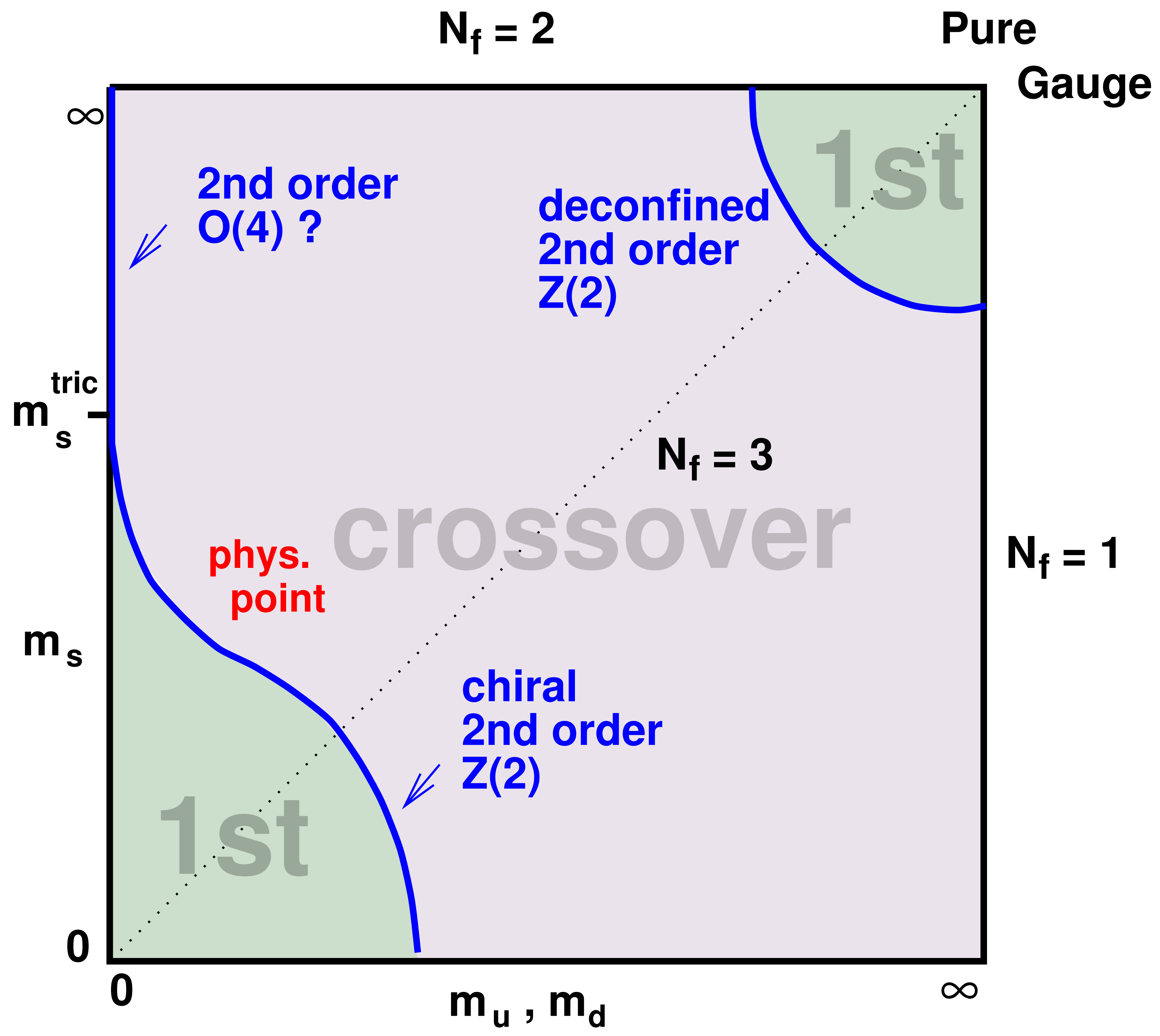
QCD phase structure

What are the predictions of the CF model regarding the QCD phase diagram?



QCD phase structure

Vary the quark masses



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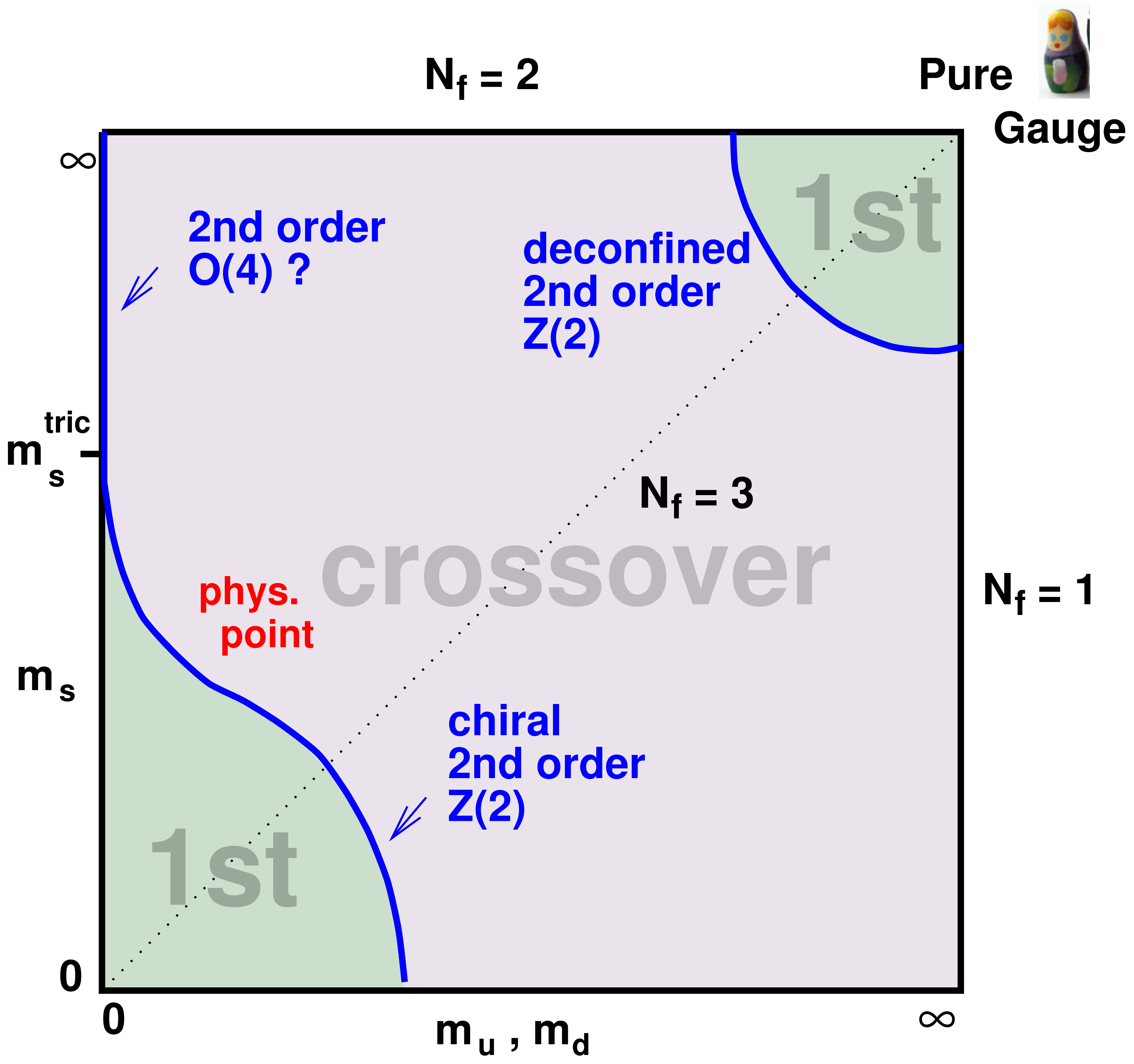

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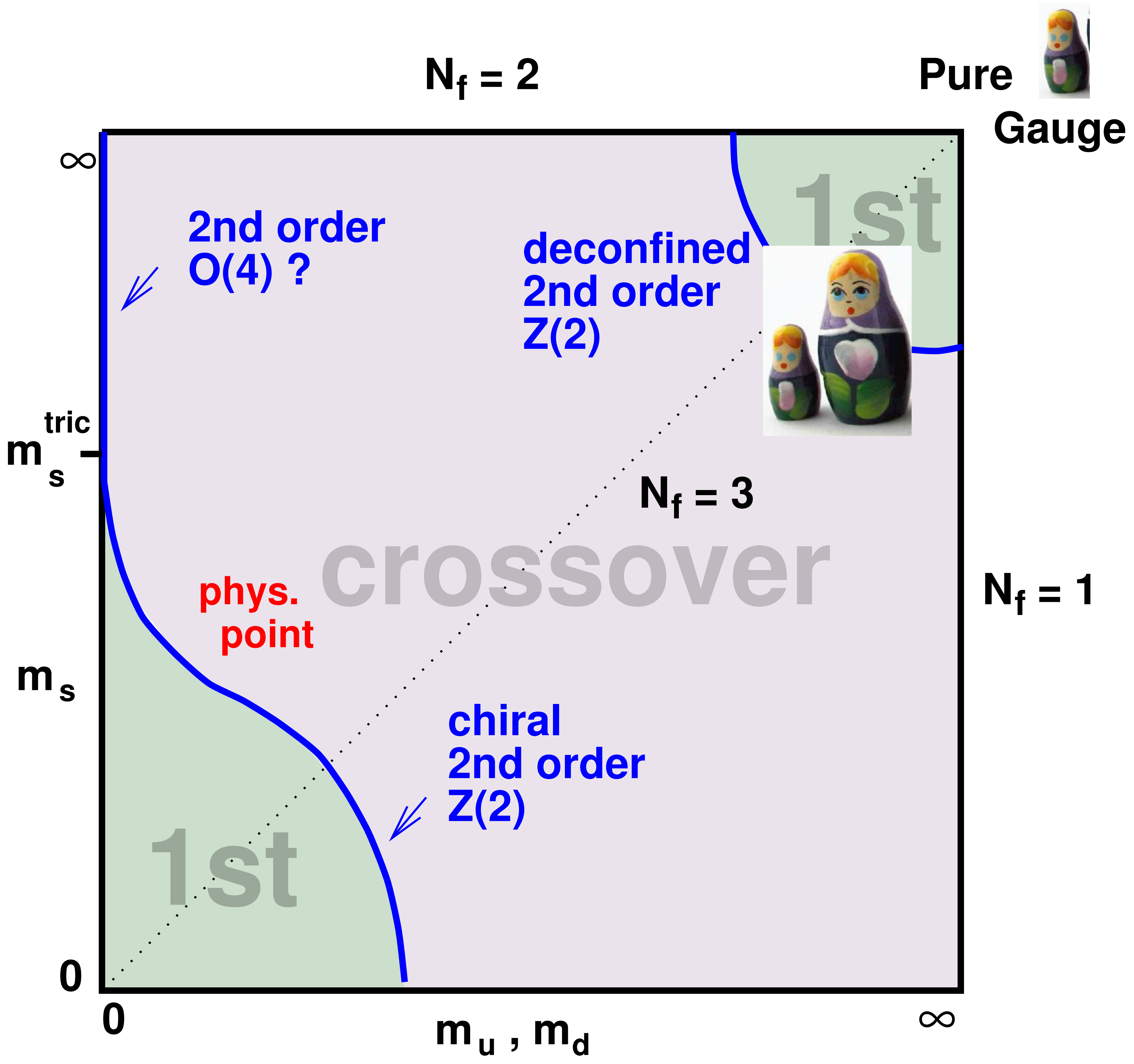

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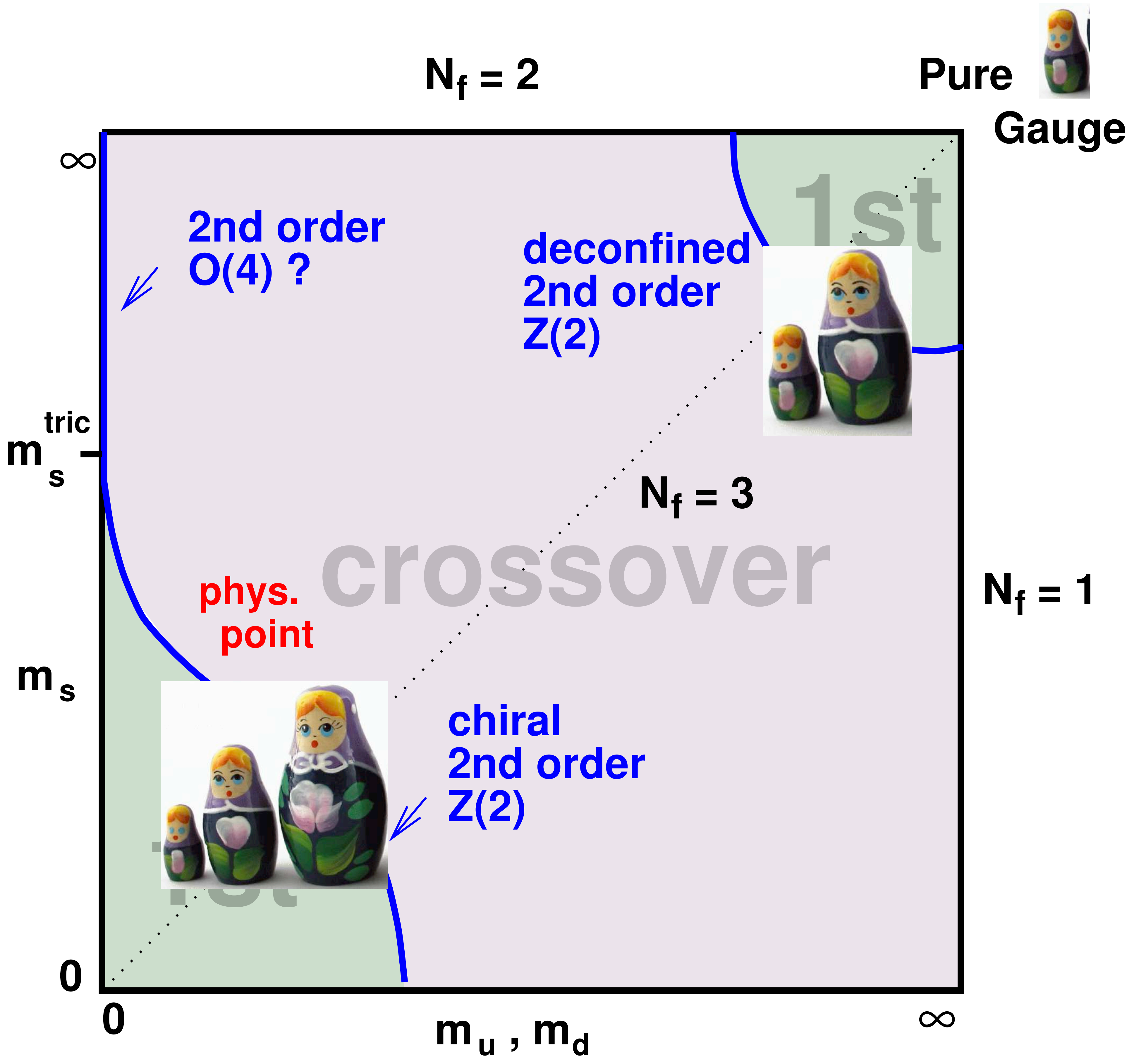

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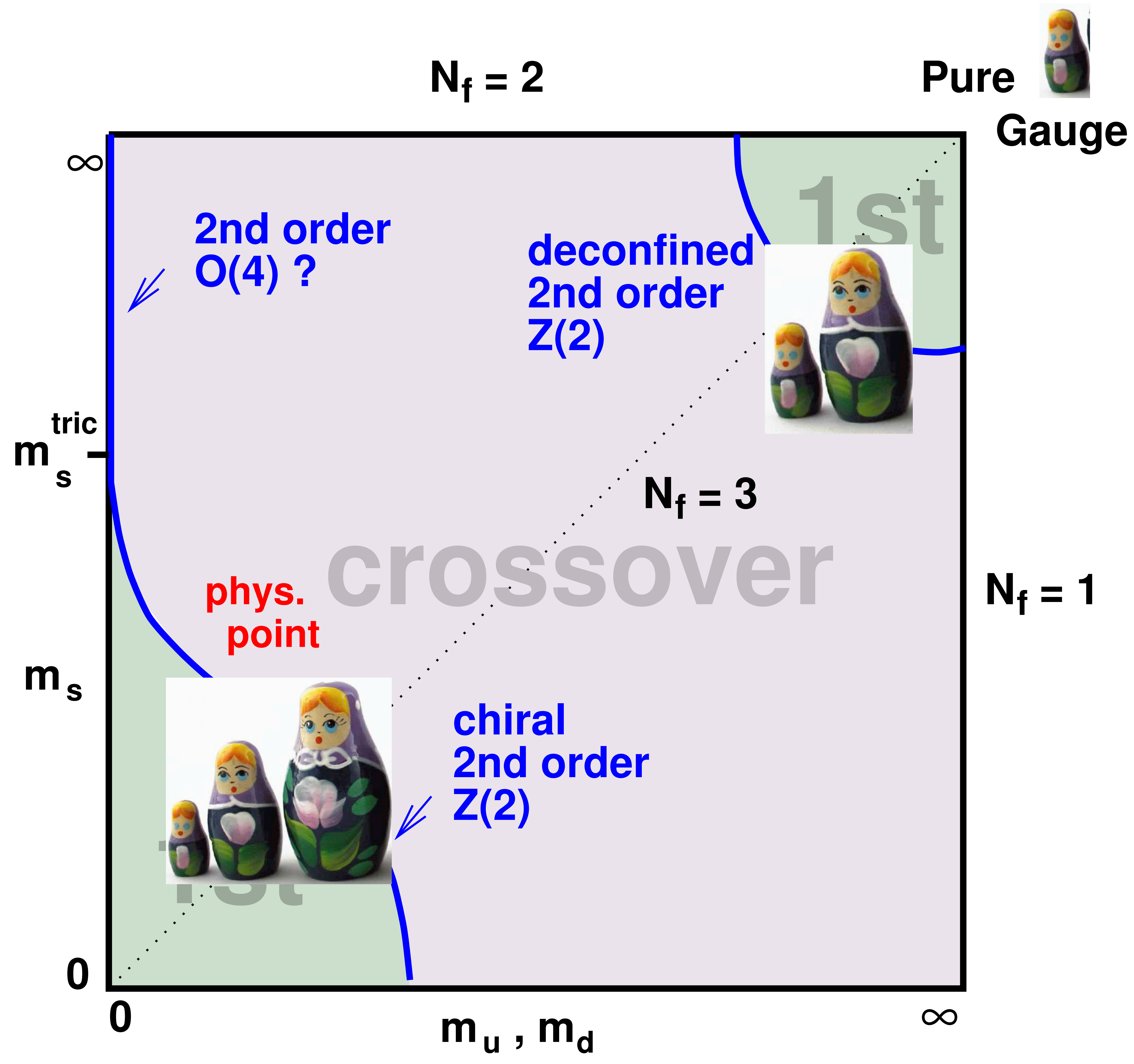
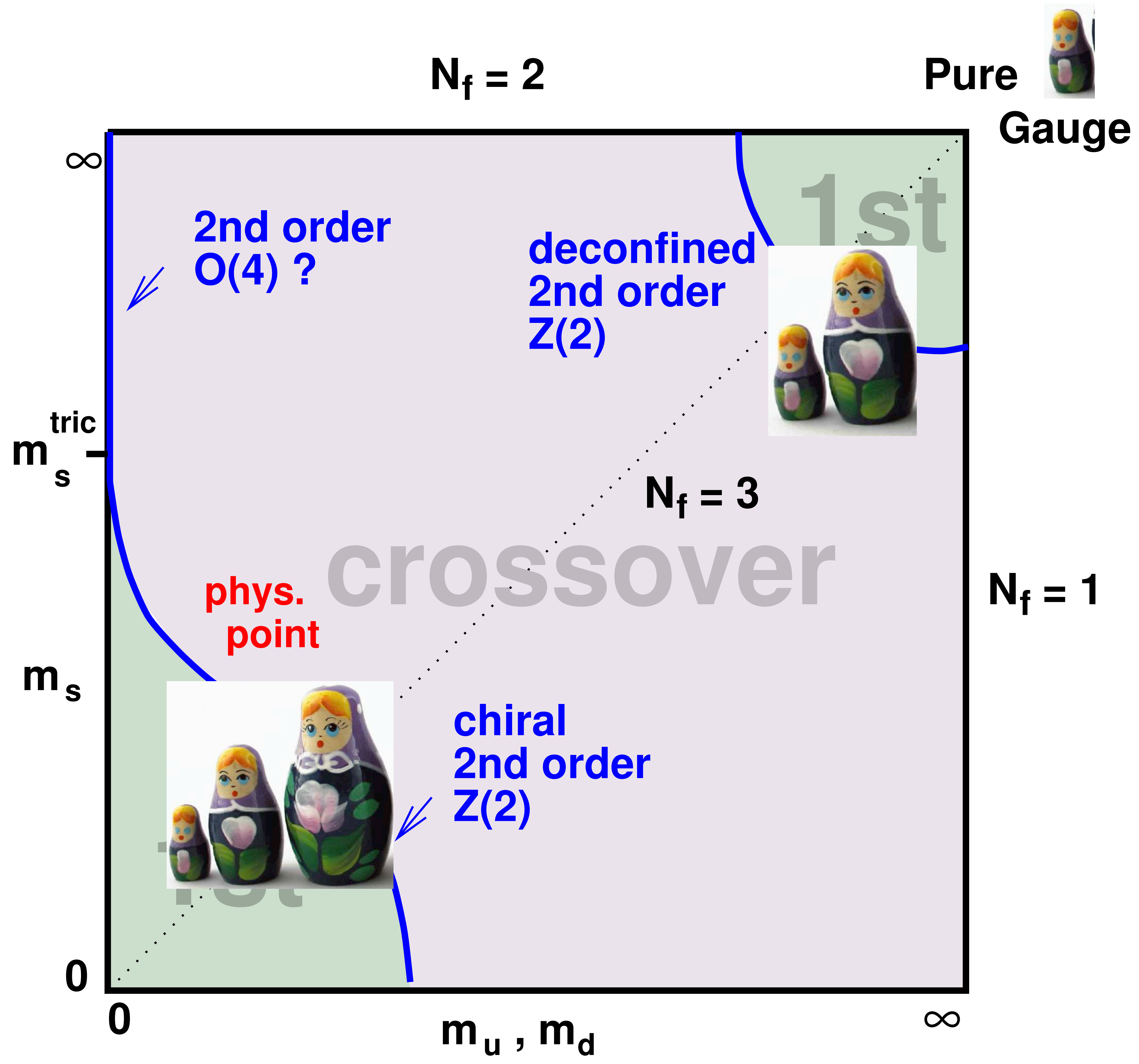


Use order parameters

QCD phase structure

Vary the quark masses

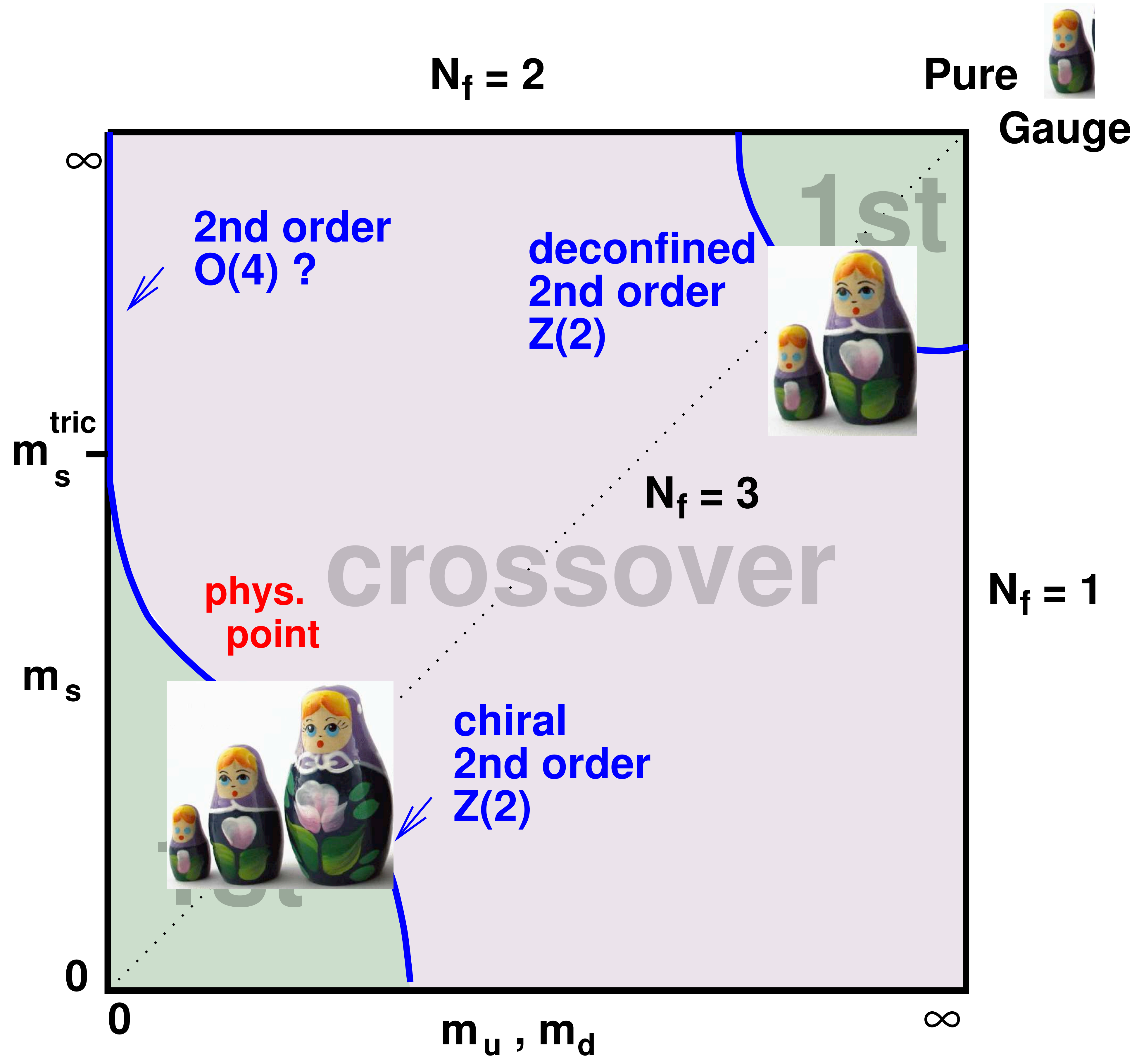


Use order parameters

Polyakov loop :
confinement/deconfinement
breaking of center symmetry

QCD phase structure

Vary the quark masses



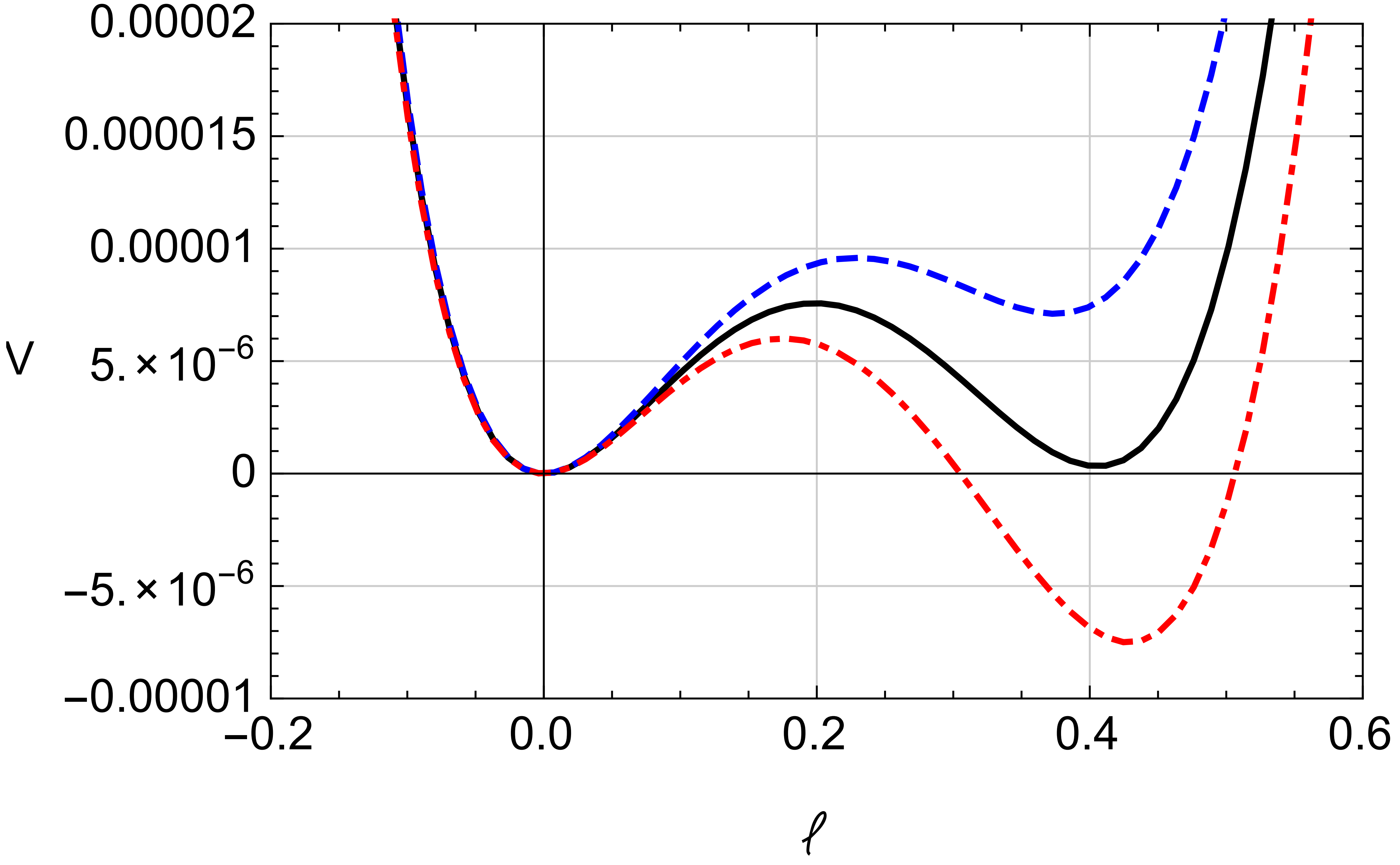
Use order parameters

Polyakov loop :
confinement/deconfinement
breaking of center symmetry

Quark mass function M(p) :
dynamical generation of mass
breaking of chiral symmetry

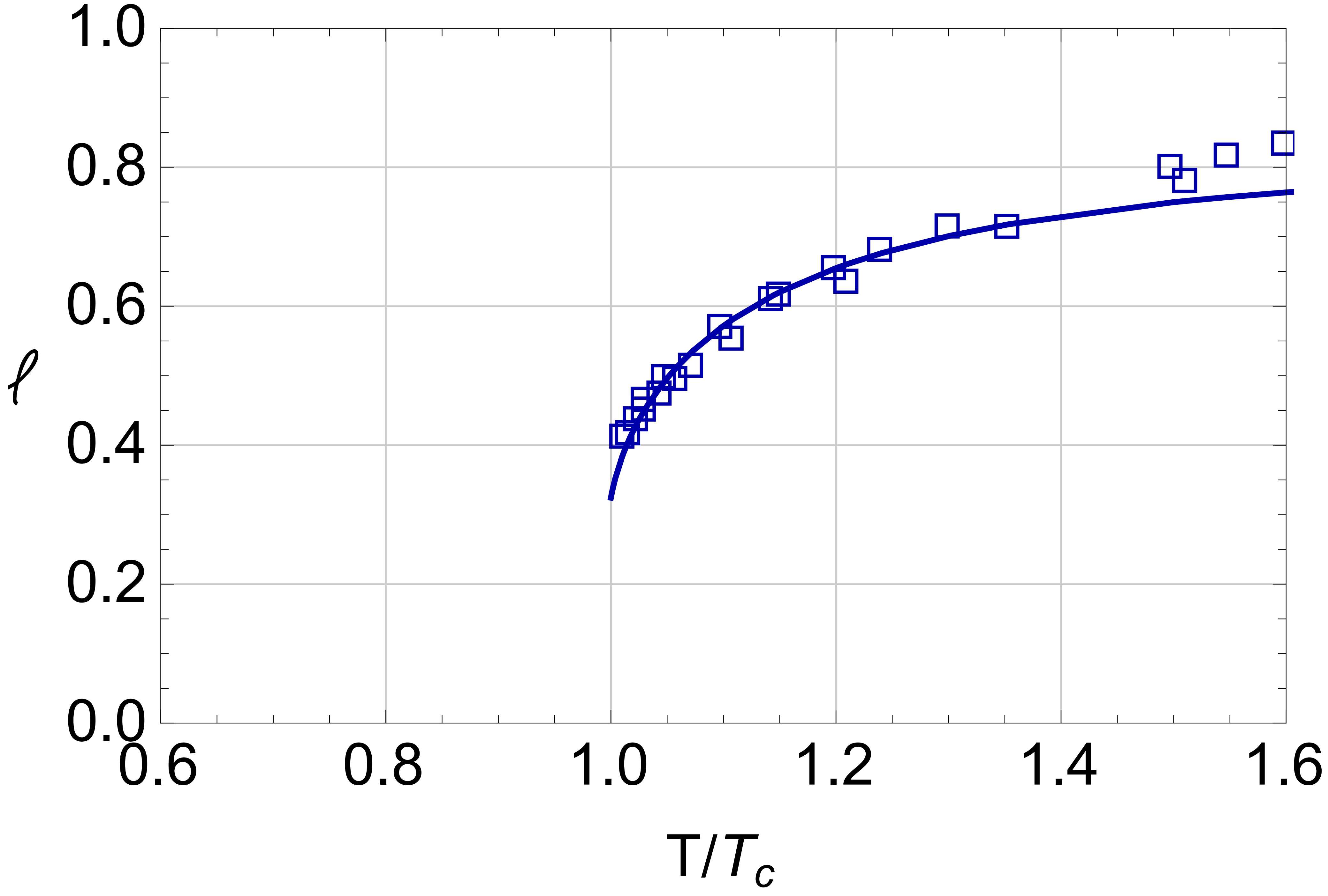
Pure glue 

We have evaluated the thermodynamical potential for the Polyakov loop at one-loop order of the perturbative expansion. It does a pretty good job in reproducing known features of the phase structure:



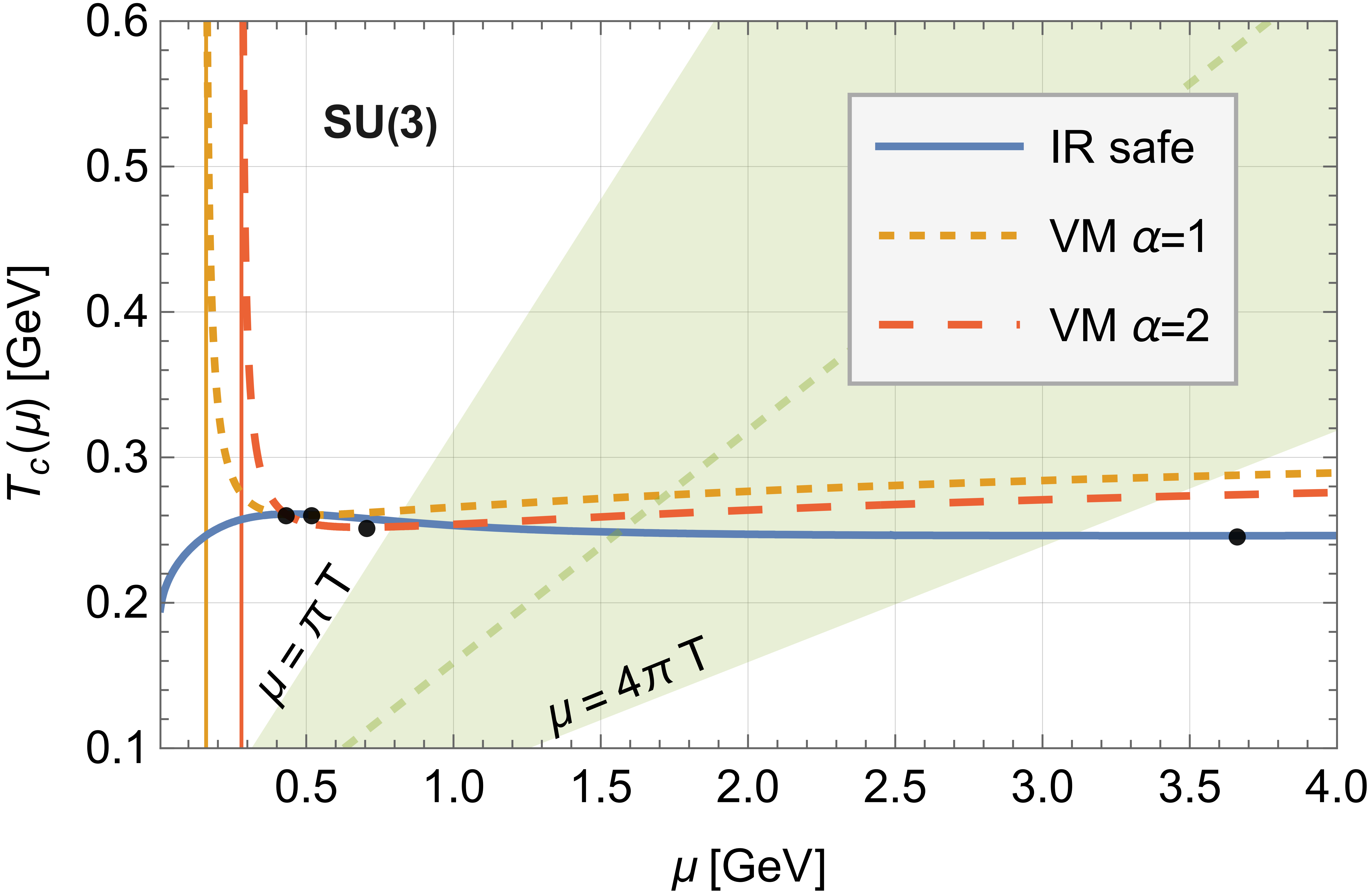
$T_c \simeq 268$ **MeV**

(vs 270 MeV in the simulations)



[D.M. van Egmond, U. Reinosa, J. Serreau, M. Tissier, SciPost Phys. 12 (2022)]

Pure glue 



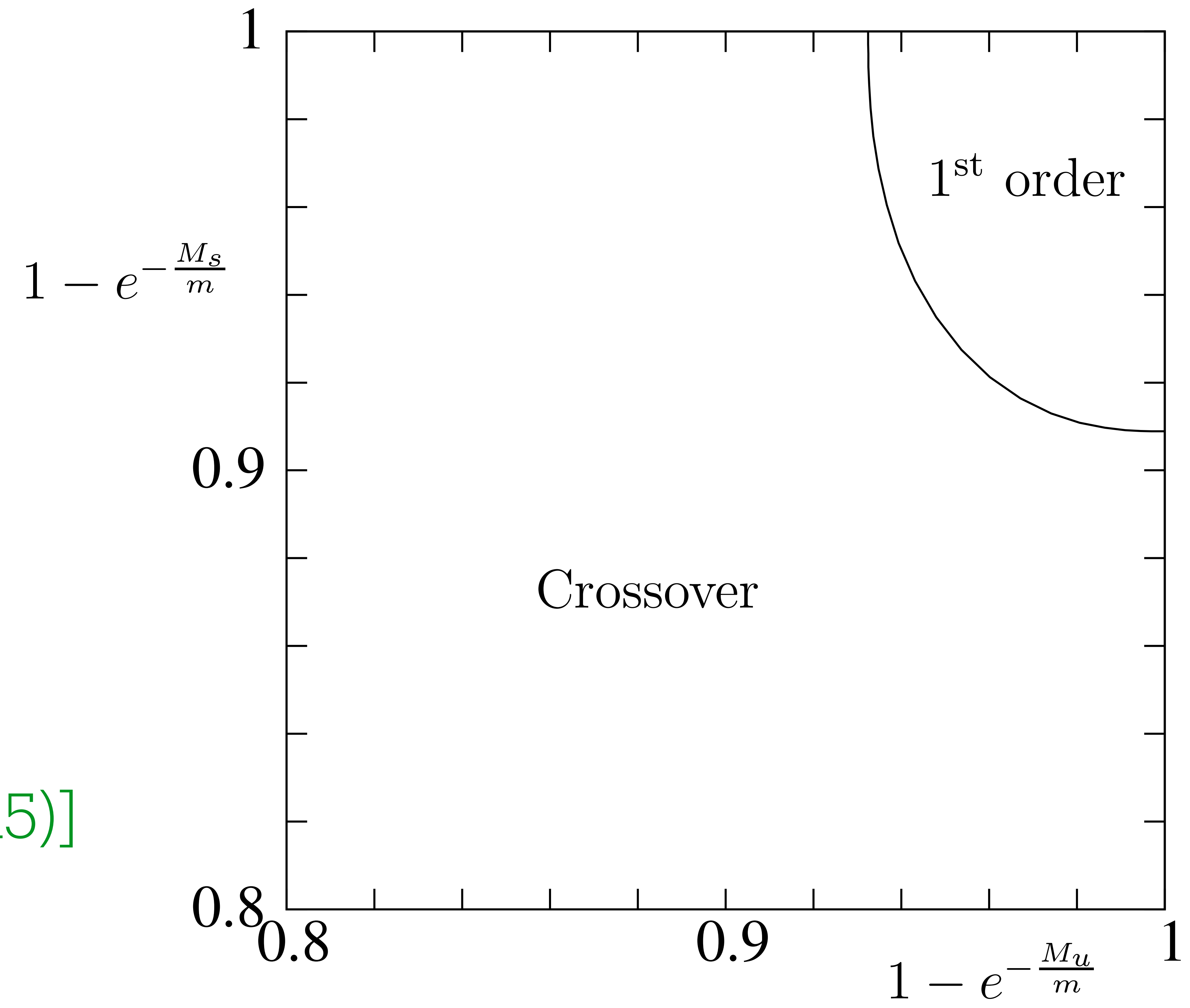
We can test the quality of the one-loop order by comparing different renormalization schemes and studying the spurious renormalization scale dependence of various observables.

[U. Reinosa, V. T. Mari Surkau, Phys. Rev. D109 (2024)]

Heavy-quark QCD 

The CF model does also a good job in retrieving the phase structure in the heavy-quark limit, already at one loop order:

M_c/T_c	$N_f = 1$	$N_f = 2$	$N_f = 3$
Lattice	7.23	7.92	8.33
CF	6.74	7.59	8.07
Matrix	8.04	8.85	9.33
DSE	1.42	1.83	2.04



[U. Reinosa, J. Serreau, M. Tissier, Phys. Rev. D92 (2015)]

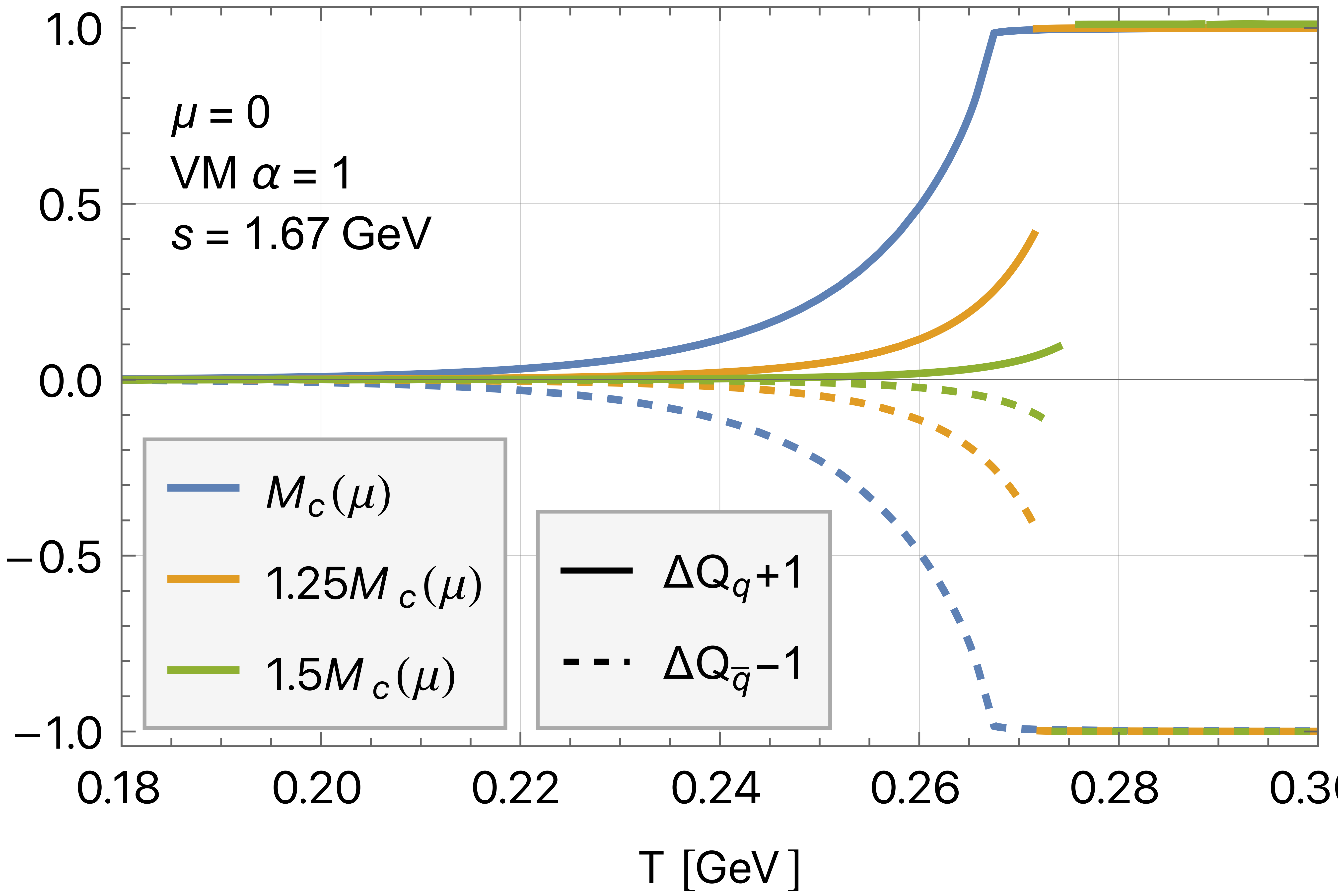
Two-loop results improve the results further.

[J. Maelger, U. Reinosa, J. Serreau, Phys. Rev. D97 (2018)]

Heavy-quark QCD 

Access to interesting observables such as the total quark number of a medium as one tries to bring in an extra quark.

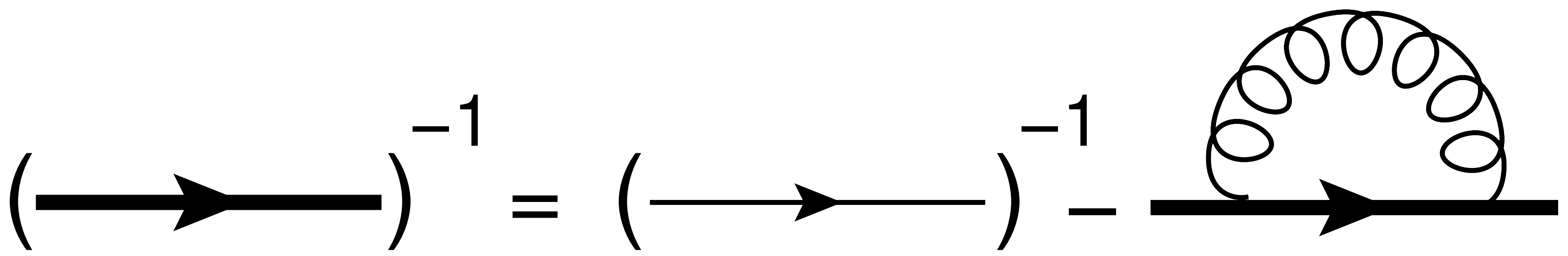
The system reacts rather differently at low and high temperatures, in agreement with the confinement/deconfinement picture.



[U. Reinosa, V. T. Mari Surkau, in preparation]

Physical QCD 

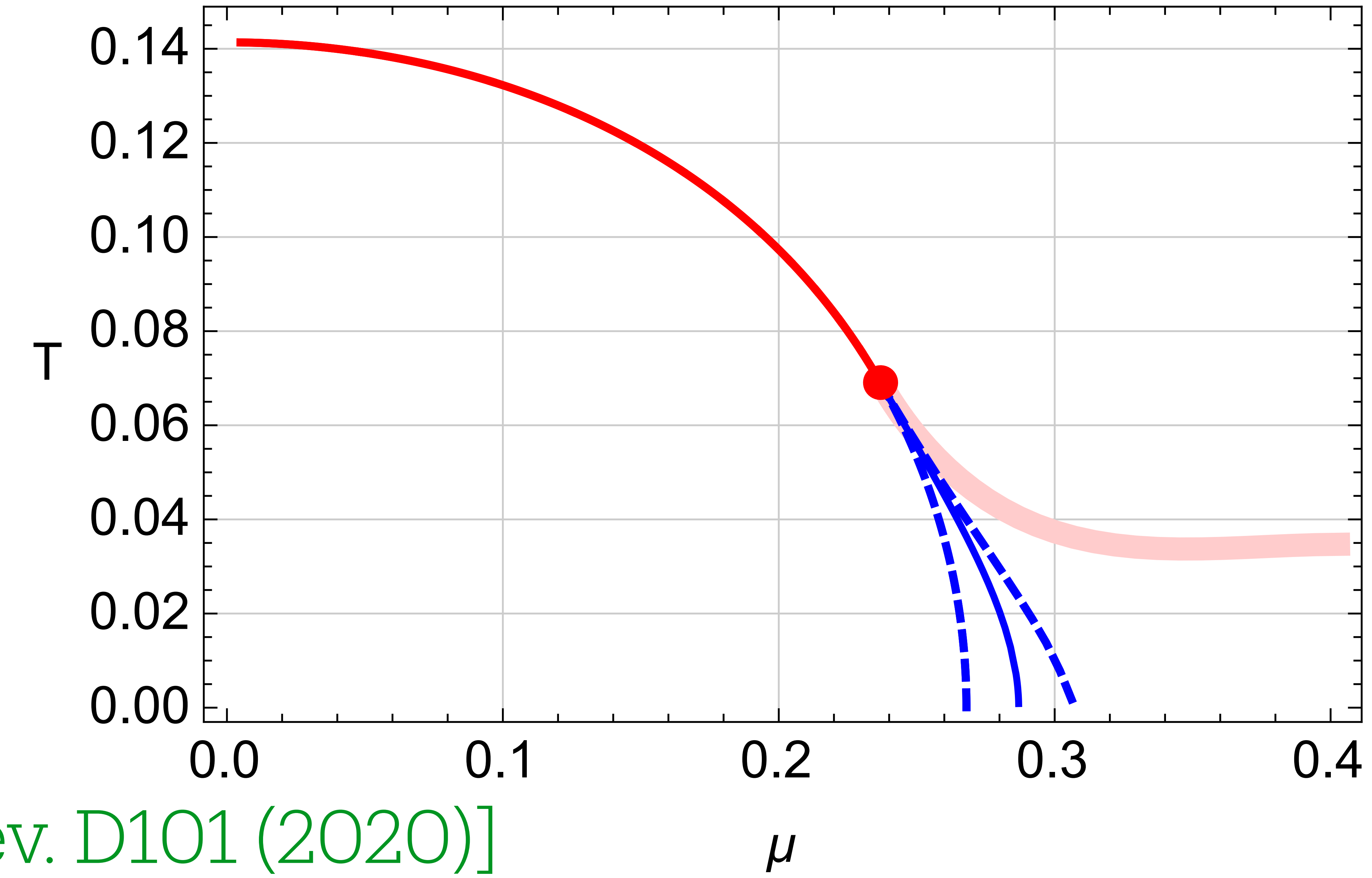
Requires the resolution of the integral equation



at finite temperature and density, possibly coupled to the Polyakov loop.

Full resolution: in progress.

So far: approximate resolution
assuming $M(q) \simeq M(0)$

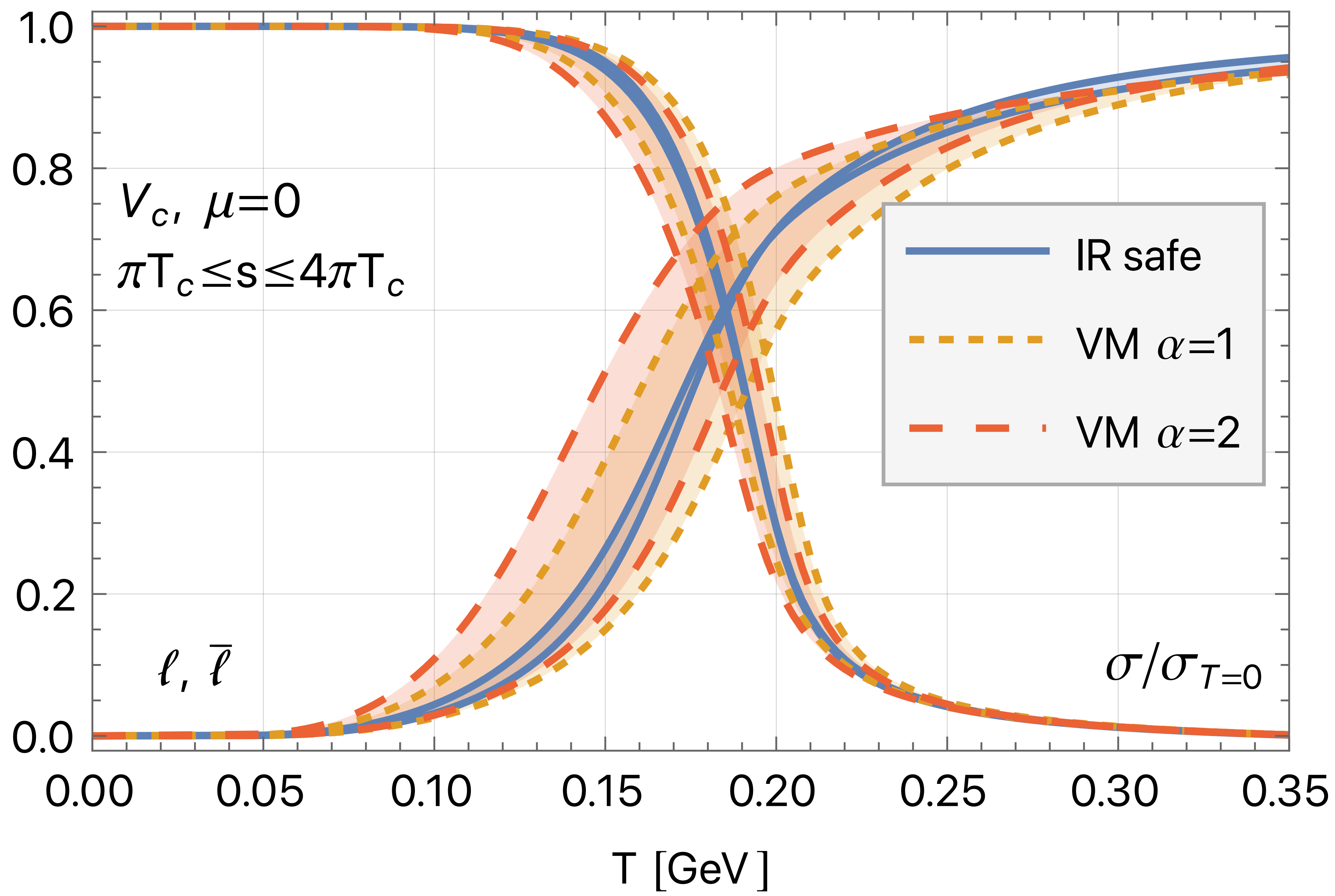


[J. Maelger, U. Reinosa, J. Serreau, Phys. Rev. D101 (2020)]

Physical QCD 

Another option is to couple our accurate Polyakov loop potential to well tested effective models for the matter sector (Nambu-Jona Lasinio model, quark-meson model, ...)

This allows for a low computational cost assessment of the interplay between the deconfinement and chiral transitions.



[U. Reinosa, V. T. Mari Surkau, in preparation]

Conclusions

- Over the past 20 years, lattice simulations of Landau-gauge correlation functions have revealed unexpected aspects of the dynamics of quarks and gluons in the infrared.

- This allows one to contemplate a new path into QCD that treats the pure glue interactions perturbatively, while dealing with the remaining interactions via a well tested $1/N_c$-expansion.

- These ideas cannot be put into practice via the standard perturbative set-up since the latter relies on the FP Landau gauge-fixed action, valid only in the ultraviolet.

Conclusions

- Lattice results for the gluon propagator suggest to model the unknown part of the Landau gauge-fixed action in the infrared via the Curci-Ferrari model.

- Within this model, the new strategy appears to be well under control and allows one to reproduce a number of lattice QCD results (correlators, hadronic properties, phase structure, ...).

- These results point to the idea that a better understanding of the gauge fixing in the infrared could open new pathways into infrared QCD.

THANK YOU!