Quark-antiquark potentials in Non-perturbative models

Carlos Mena

Leticia Palhares

3ra Escola do PPGF da UERJ

13 de Fevereiro, 2020. RJ, Br.

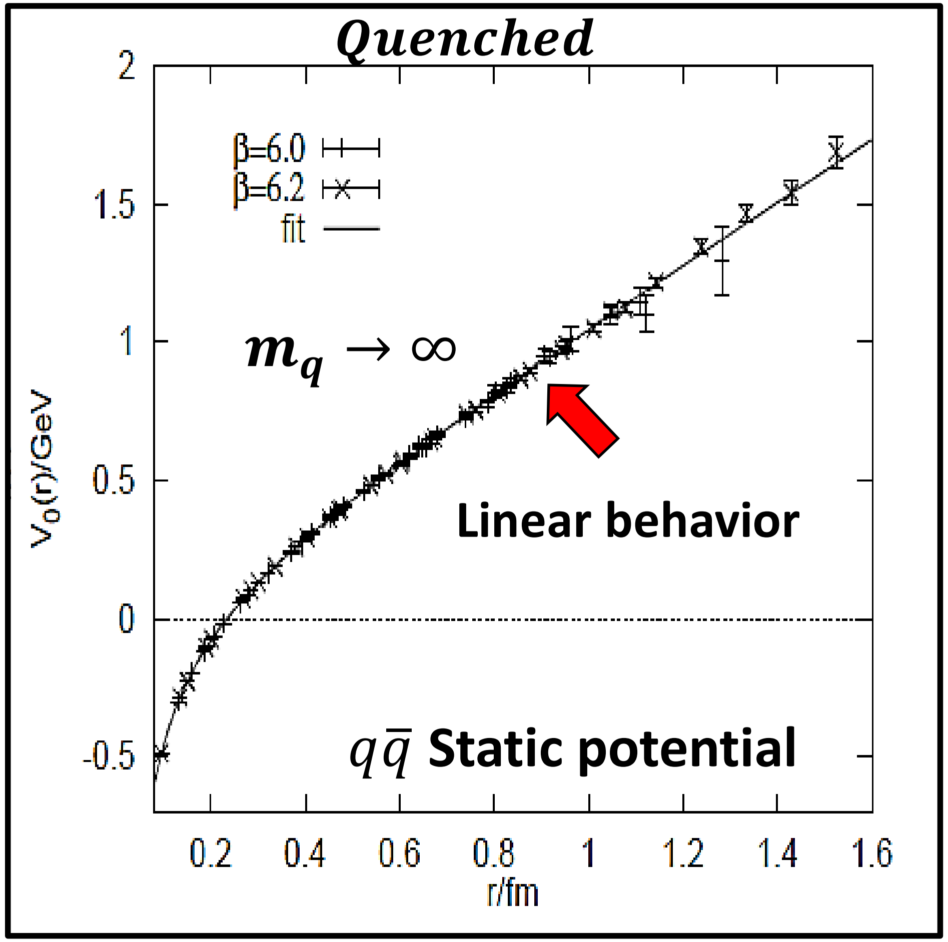
What did we do ?

- We investigated some non-perturbative models for **QCD** and calculated their associated potentials.

- **Why?** Because this function might reveal the appearance of **confinement** properties.

  - **How?** through a linear growth at large and intermediate distances (Lattice results).

Lattice QCD Result*



Numerical Result

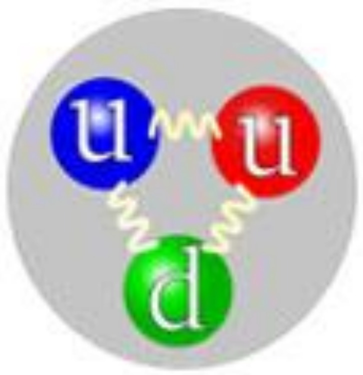
❖ "Linear potential behavior is associated with confinement".

Confinement, quarks?

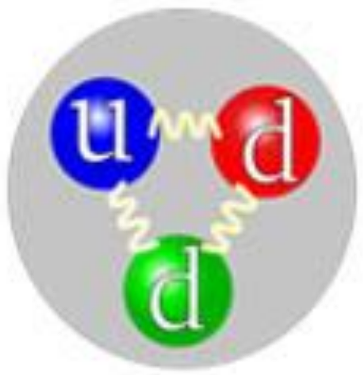
High energy experiments/Data -> Quarks and Gluons (Strong interaction particles).

Hádrons Schematic Representation

Proton



Neutron



Pion

1963

Gell-Mann y Zweig

Quarks Model

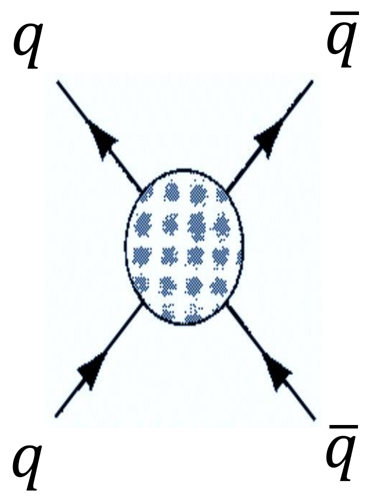
… But they never had been detected into the spectrum like single particle states.

Color confinement try to explain why the color charged particles (quarks and gluons) cannot be found as asymptotic states, but rather forming bound states, like the hadrons.

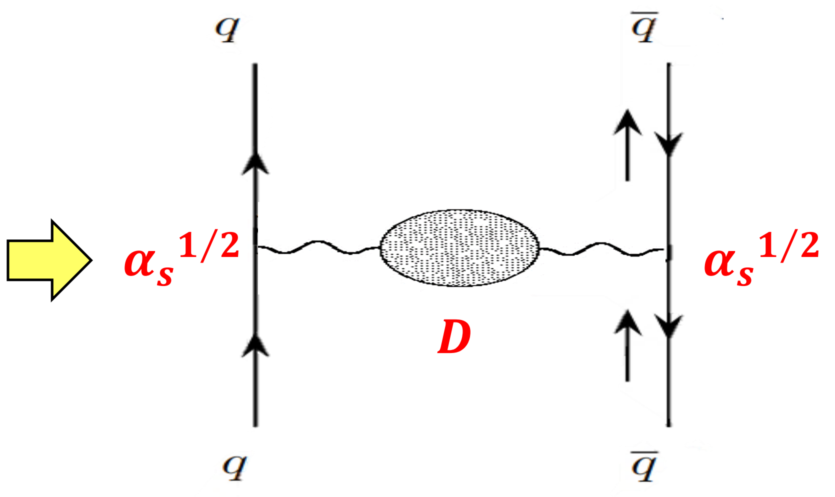
- Even though there is still no analytical demonstration QCD produces confinement, there are numerical results (Lattice QCD) that show confinement properties from QCD.

Calculating the $q\bar{q}$ potential

Quark – antiquark Process



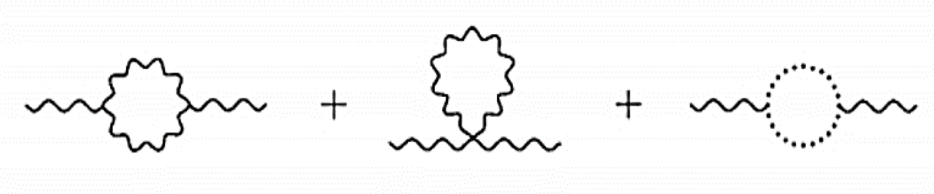
One gluon exchange approximation



➢ **Heavy quarks approximation**

Tree-level approximation

One Loop Correction



$$V(r) = \frac{4i}{3\pi r}\int dp\,[\,p.\alpha_s(p^2).D(p^2).e^{i\,p\,r}\,] \ \& \ p = |\vec{p}|$$

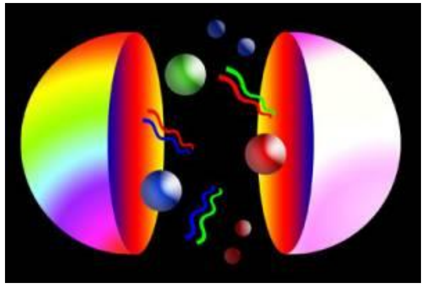
Strong Coupling Constant ***Gluon Propagator***

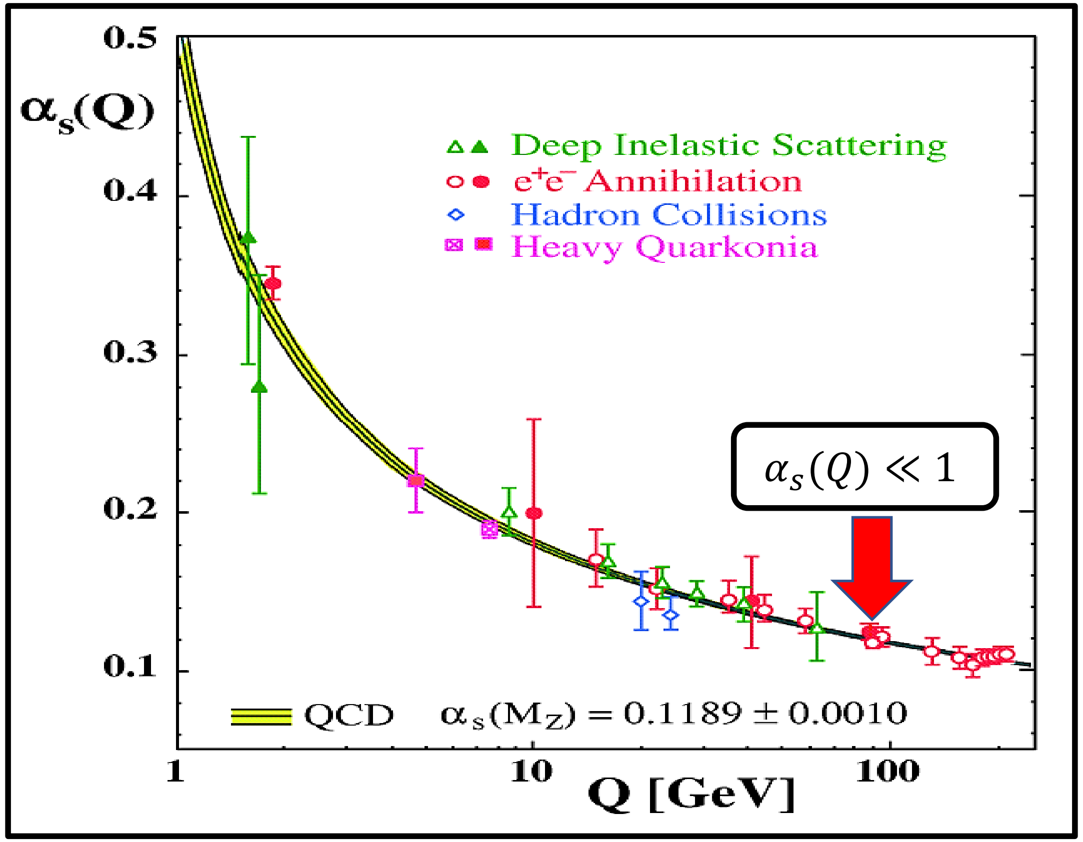
* We know, from perturbative QCD, that the effective strength of the strong coupling depends on the energy scale of the physical process.

Experimental Data – Strong Running Coupling

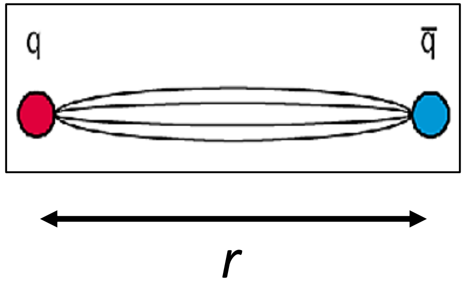
- On the other hand, the intensity of the strong interaction increases for low energy or long distance processes (**Landau Pole**), which is argued to be related to the confinement problem.

COLOR CONFINEMENT ?





Prescription
Q = 1/r



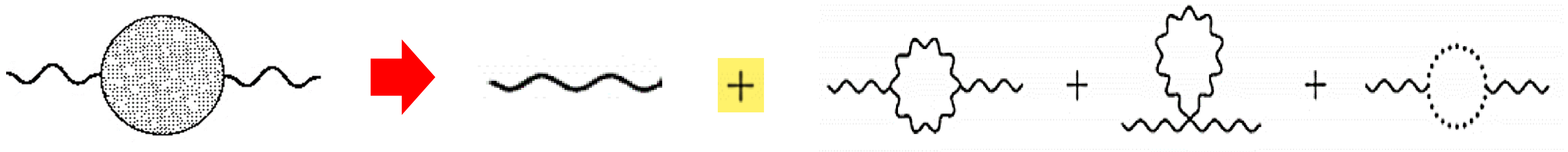
Asymptotic Freedom

- A phenomenon in which the intensity of the strong interaction decrease for processes of high energies or small distances.
  - Quarks behave quasi-free asymptotically.

❖ There is one model/approach that can reproduce the perturbative result of the strong coupling and prevents the appearance of the Landau pole too. This model is in agreement with the Lattice gluon propagator.

Infrared Safe perturbative approach – RGE

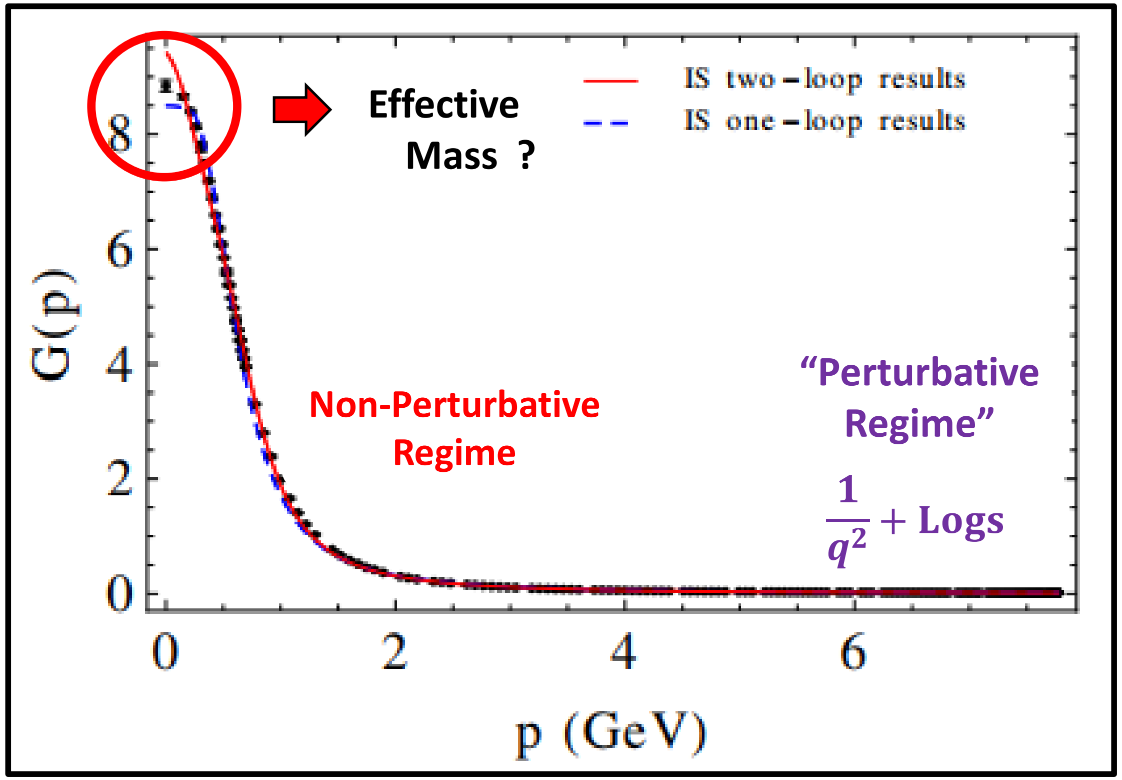
- **Curci-Ferrari Model // Massive Gluon Model.**



M. Tissier, N. Wschebor, Phys. Rev. D 84, 045018 (2011);

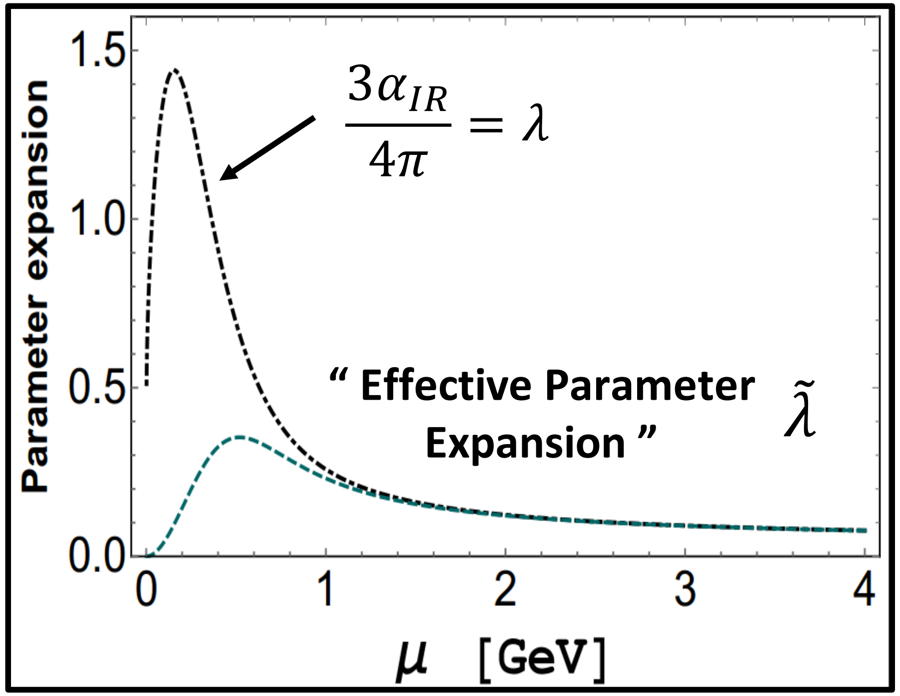
J. A. Gracey, M. Peláez, U. Reinosa, M. Tissier, Phys. Rev. D 100, 034023 (2019);

Some models that try to address confinement are motivated by the behavior of the **Lattice gluon propagator.**



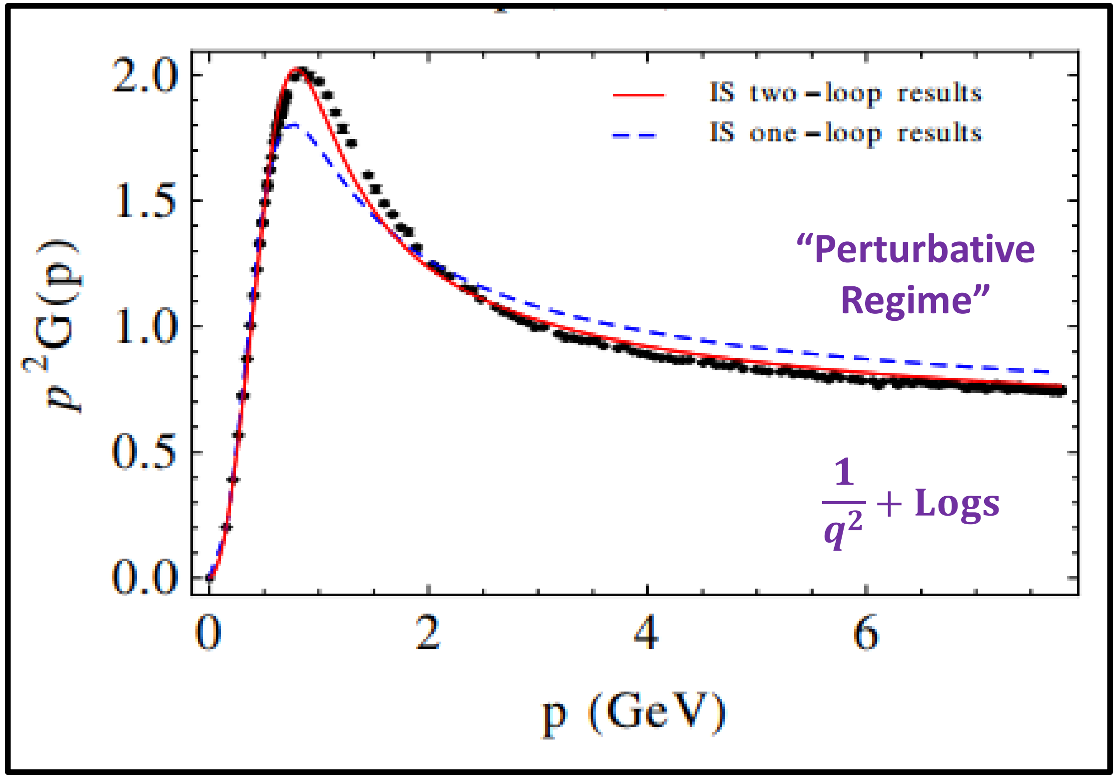
*** Complex poles in the gluon propagator invalidate its interpretation as asymptotic particle.**

❖ Although the Landau pole does not appear in the IS model, the coupling constant runs increasing in the IR.



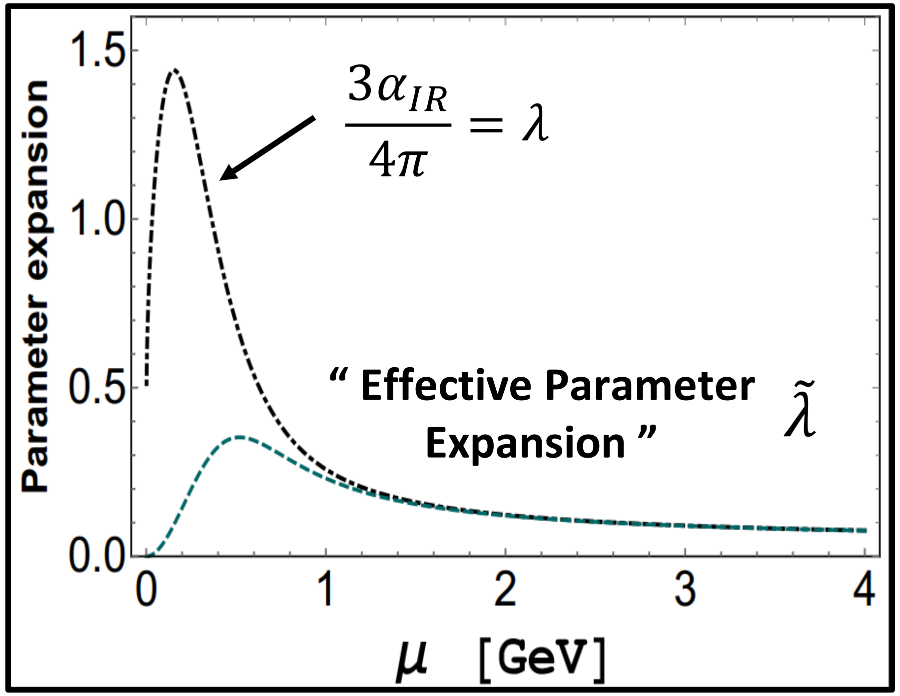
❖ However, the effective expansion parameter is small, allowing for the application of the perturbative approach.

Some models that try to address confinement are motivated by the behavior of the **Lattice gluon propagator.**



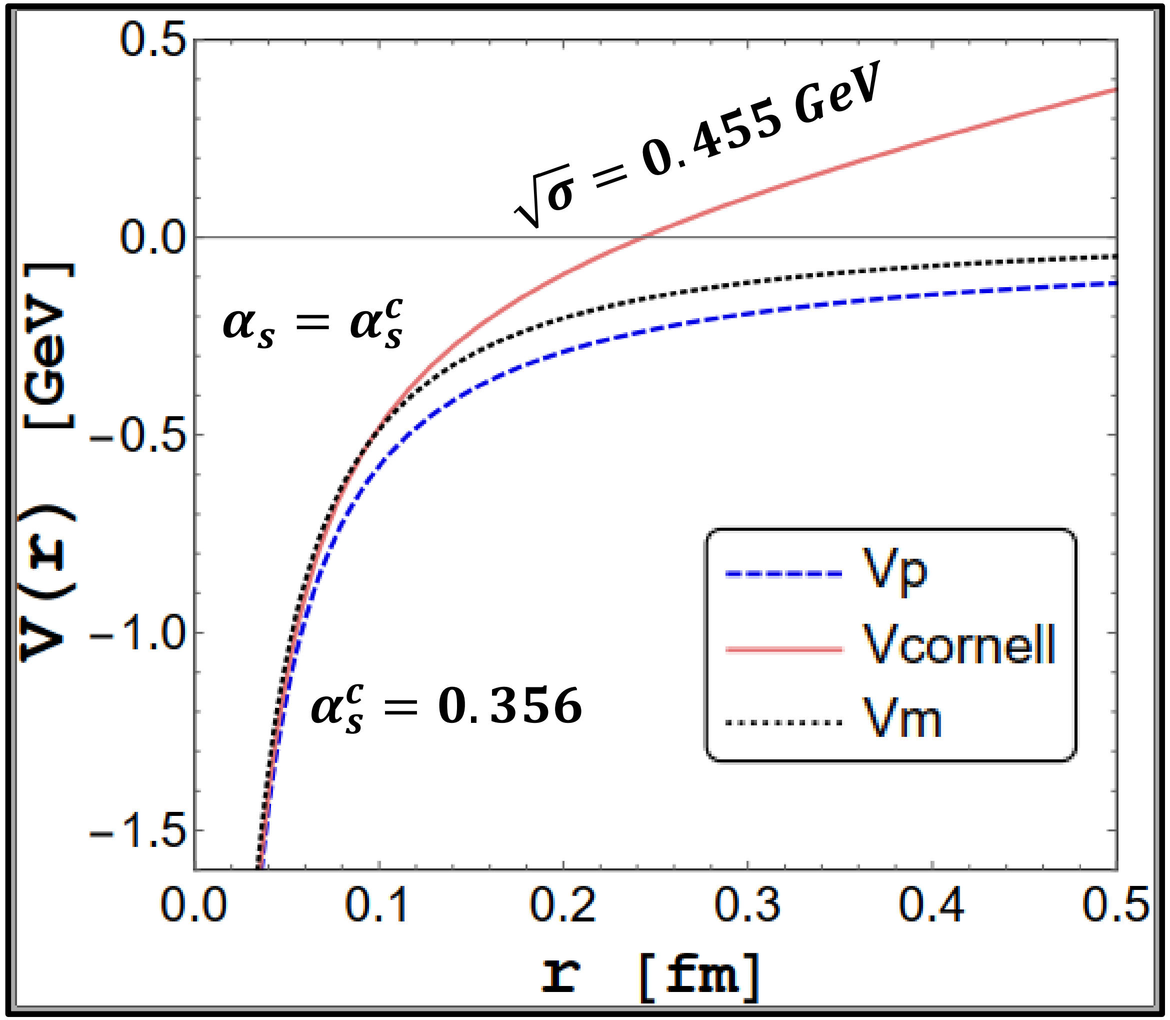
*** Complex poles in the gluon propagator invalidate its interpretation as asymptotic particle.**

❖ Although the Landau pole does not appear in the IS model, the coupling constant runs increasing in the IR.



❖ However, the effective expansion parameter is small, allowing for the application of the perturbative approach.

$q\bar{q}$ potentials

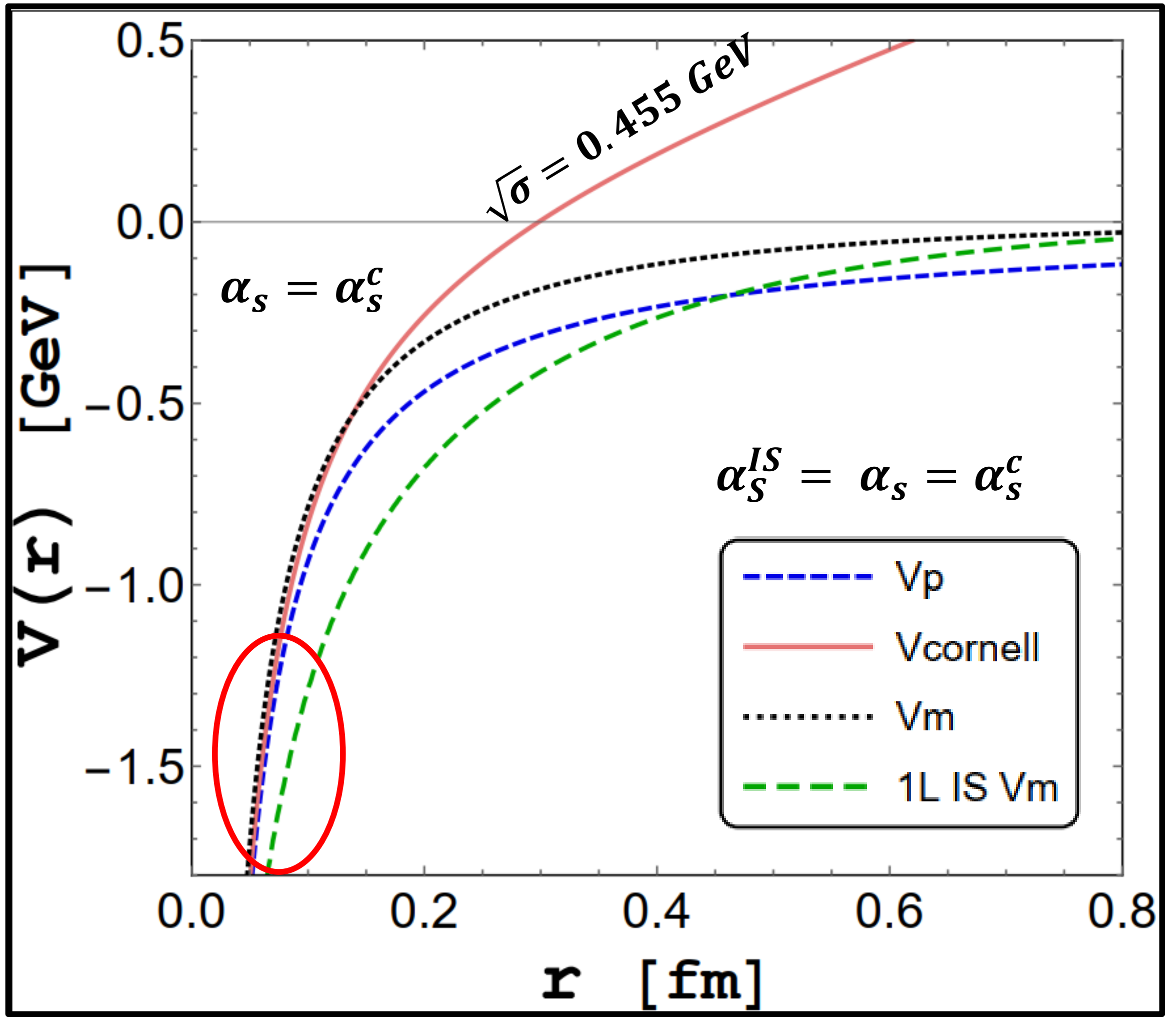


- **Aims:**
  - (i) Test the validity of the models in the perturbative regime and explore their behavior in the infrared region;
  - (ii) Compare (qualitatively) our results with Lattice QCD simulations.

$$V(r) = \frac{4i}{3\pi r}\int dp\,[\,p.\,\boldsymbol{\alpha_s(p^2)}.\,\boldsymbol{D(p^2)}.\,e^{i\,p\,r}\,]$$

- $V_{pert}(r) = -\frac{4\,\alpha_s}{3\,r}$
- $V_{mass}(r) = -\frac{4\,\alpha_s}{3\,r}\,e^{-mr}$
- $V_{cornell}(r) = -\frac{4\,\alpha_s^c}{3\,r} + \sigma\,r.$

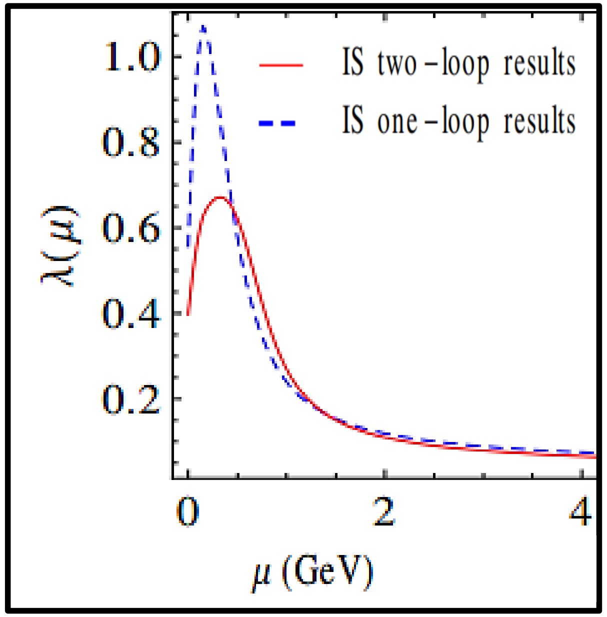
$q\bar{q}$ potentials: Constant Parameters ?

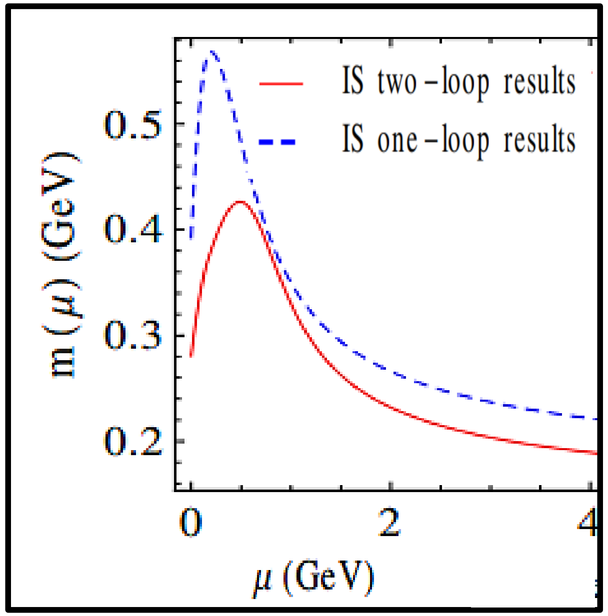


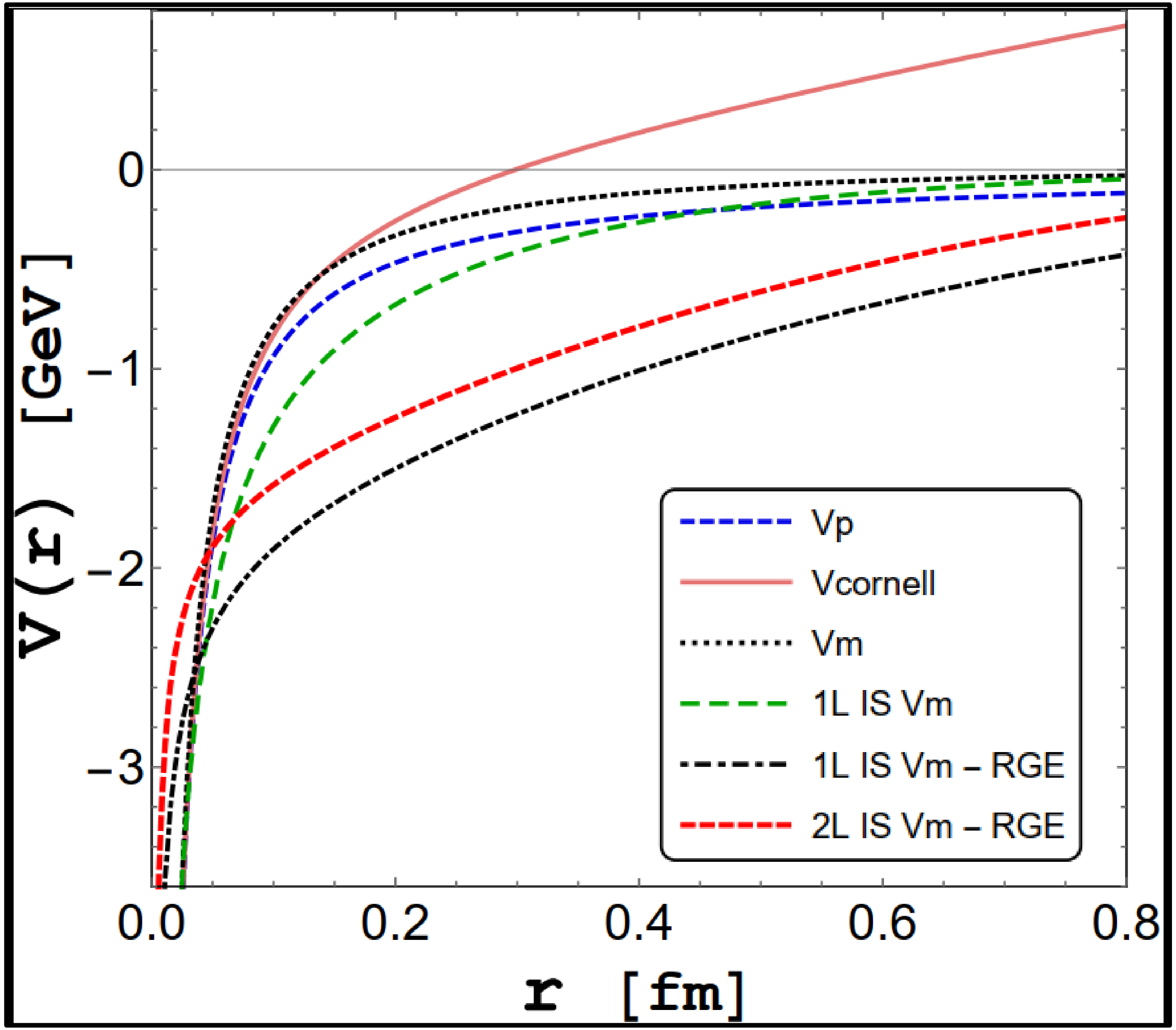
➢ $IS\ V_{m-1L}(r) = -\frac{4\,\alpha_s}{3\,r} + corrections$?

In the framework of the perturbative QFT, the parameters like the mass and the constant coupling of any theory will depend on the scale energy.

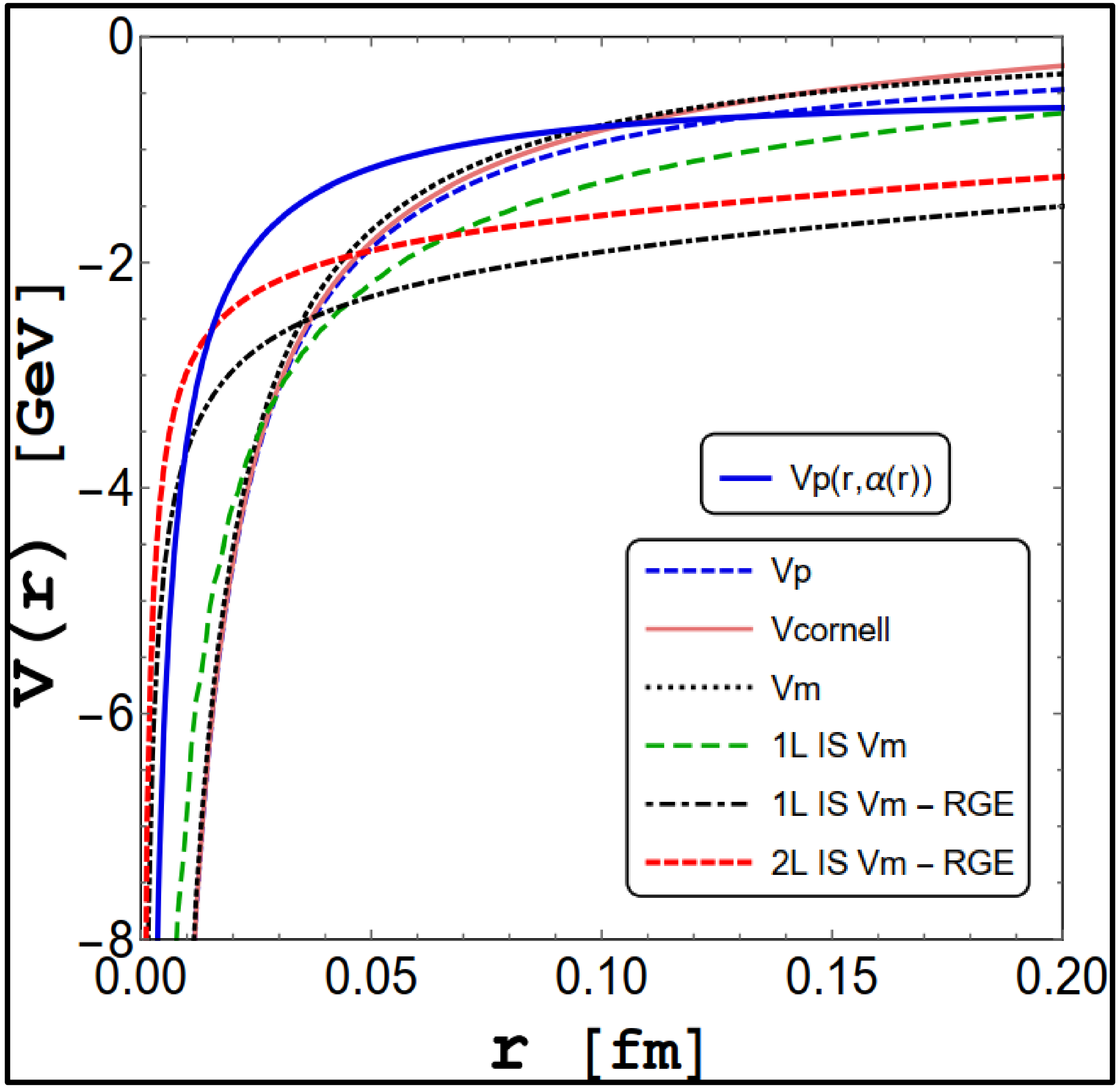
$$D(\mu,\mu_0) = \frac{\lambda(\mu_0)}{m^4(\mu_0)}\frac{m^4(\mu)}{\lambda(\mu)}\frac{1}{\mu^2+m^2(\mu)}$$

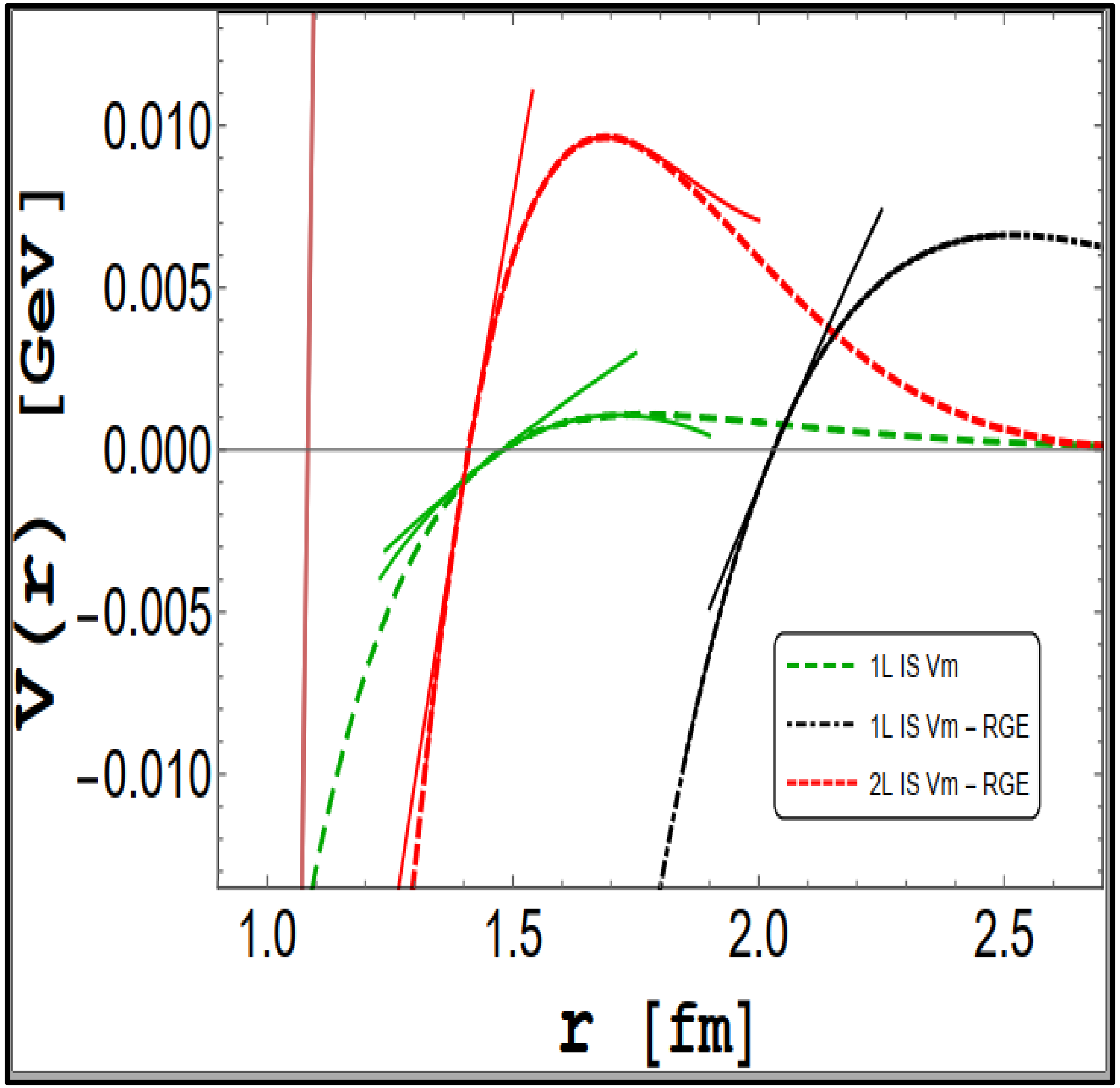






- **Can the models connect with the perturbative result and with the Cornell potential at some range?**





Cornell Parameters (Bottonium)

$\sqrt{\sigma_B} = 455$ MeV

$\alpha_B^C = 0.356$

$\sqrt{\sigma_{IS}} = 60$ MeV

$(\alpha_{IS}^C) = 0.280$ **1L**

$\sqrt{\sigma_{IS}} = 94$ MeV

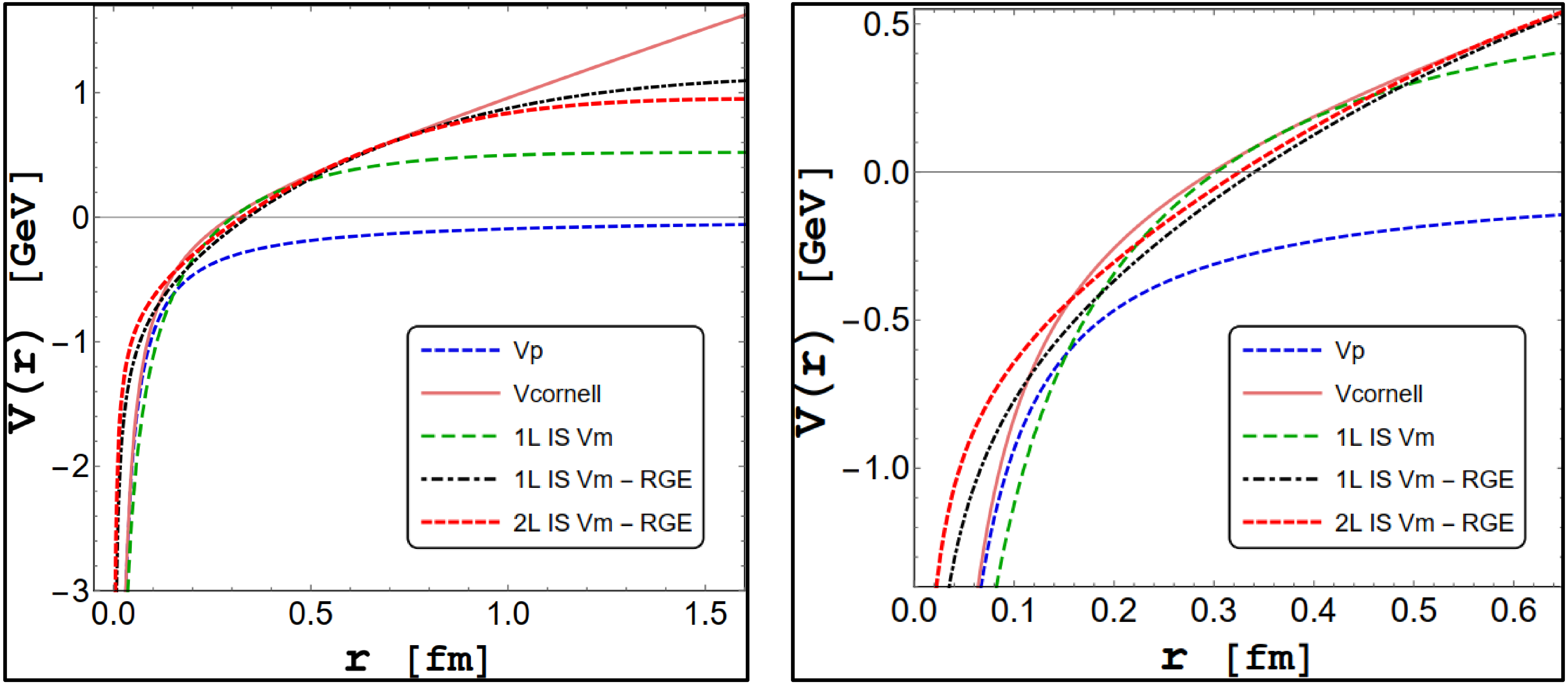
$(\alpha_{IS}^C) = 0.338$ **2L**

Conclusions and Perspectives

- Our results indicate that the potentials we have obtained can reproduce the perturbative result at high energies and some of them bring non-perturbative corrections.
- Complex poles in the gluon propagator invalidate its interpretation as asymptotic particle. Such poles affect the $q\bar{q}$ potential, generating a region in which the potential increases with distance but also generating oscillations.
- Growth regions present in the potentials could be related to the confinement phenomenon.
- For the IS model, loop corrections allow us to verify that the systematic inclusion of more interaction effects leads to better descriptions of the q-$\bar{q}$ potential since the value of the associated string tension increases as more loops are considered.
- Although the IS model (perturbative approach) allows us to describe the Lattice gluon propagator (non-perturbative), it cannot fully reproduce the LATTICE QCD potential. This allows us to make the following questions, how perturbative is the model itself? or, what is missing in the q-$\bar{q}$ potential calculation?

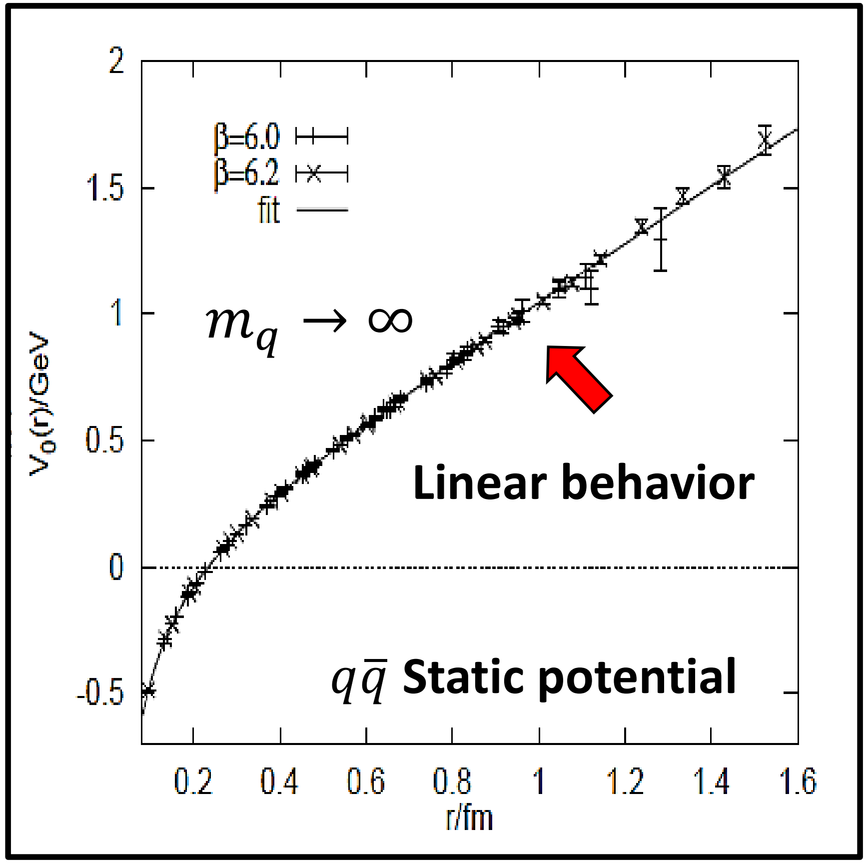
Additional Slides / Information

Other Results: Saturated $q\bar{q}$ potential



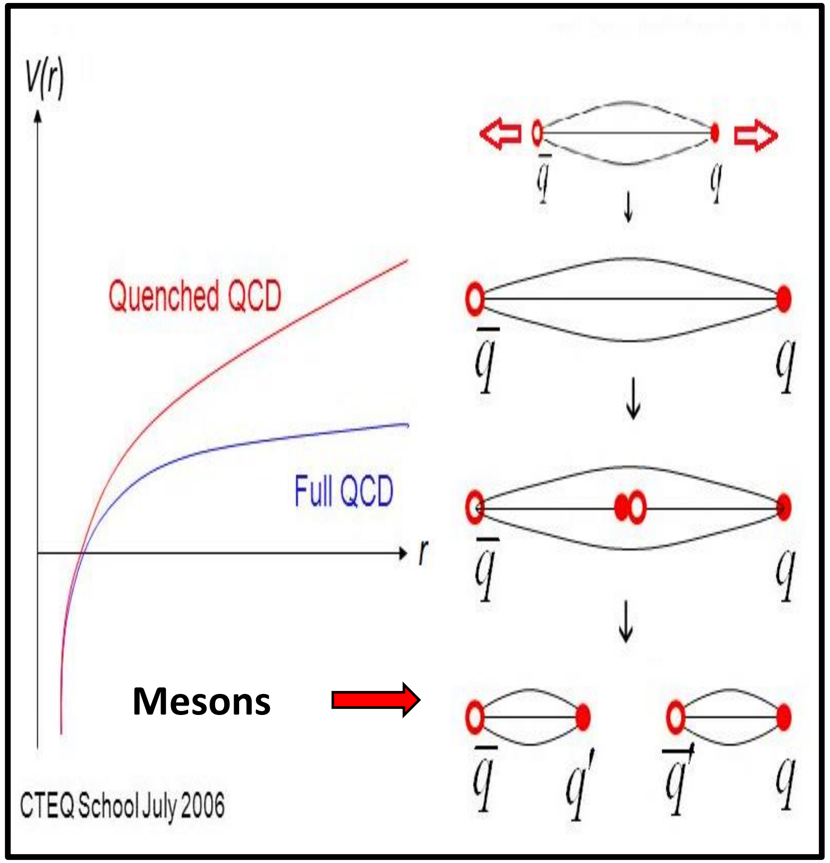
Static potential and the String Breaking Model

Lattice QCD Result



Numerical

String breaking model



Phenomenological

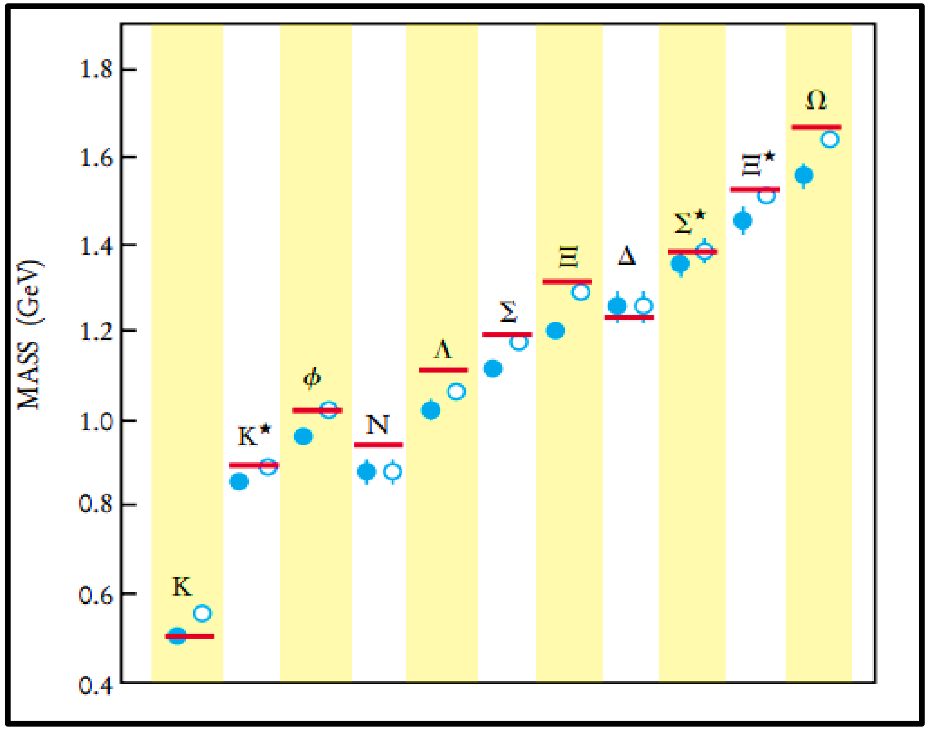
When trying to separate a pair $q\bar{q}$

"Formation" of a color electric flux-tubes between the pair $q\bar{q}$

eventual fragmentation of the flux tube into mesons.

LATTICE QCD RESULTS

Lattice QCD is a technique that uses a discretization of space-time by the functional integration approach in Euclidean space-time, which allows the Non-Perturvative approach to the case of QCD through the use of computational resources.



Mass spectrum of mesons and baryons, predicted by QCD. The agreement with the measured masses (red lines) is at the 10% level.

- Hádrons mass spectrum.
- Decay Constants.
- Form factors.
- Quark antiquark linear potentials.
- Gluon propagator(IR Saturation).

*R, Gupta. Introduction to Lattice QCD. hep-lat/9807028, 1998.

**BRAMBILLA, Nora; VAIRO, Antonio. Quark confinement and the hadron spectrum , 1999. p. 151–220.