



# From quarks and gluons to hadrons: **Research opportunities**

**Gernot Eichmann**

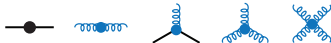
**4th Lisbon Mini-School on Particle and Astroparticle Physics**

**Feb 13, 2019**

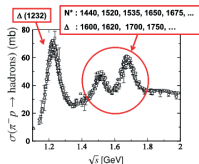
**Costa da Caparica, Portugal**

# Nonperturbative QCD

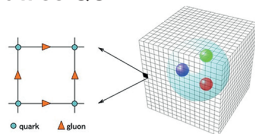
## Functional methods (DSEs & BSEs, FRG, ...)



## Amplitude analyses



## Lattice QCD



## Phenomenological models

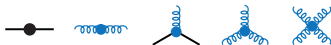


## Effective theories (ChPT, ...)



# Nonperturbative QCD

## Functional methods (DSEs & BSEs, FRG, ...)

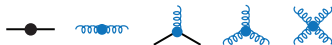


### Math:

- **Integral equations:**  
nonperturbative calculations
- **Linear algebra:**  
dealing with large matrices
- **Complex analysis:**  
accessing the complex plane
- **Group theory:**  
does never hurt ;)

# Nonperturbative QCD

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$$\begin{array}{c} q \\ \diagup \\ \text{---} \circ \text{---} \\ \diagdown \\ \bar{q} \end{array} = \begin{array}{c} \text{---} \\ | \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ | \\ \text{---} \\ | \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ | \\ \text{---} \\ | \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ | \\ \text{---} \\ | \\ \text{---} \end{array} + \begin{array}{c} \text{---} \\ | \\ \text{---} \\ | \\ \text{---} \end{array} + \dots$$

$O(\alpha)$   $O(\alpha^2)$

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**nonperturbative result!**

$$\left( T \right) = \left( K \right) + \left( K \right) \left( G_0 \right) \left( T \right)$$

# Nonperturbative QCD

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## Functional methods (DSEs & BSEs, FRG, ...)



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### Numerics:

- **Symbolic:**  
Mathematica, ...
- **Programming:**  
C++, Fortran, ...
- **Parallel computing:**  
MPI, OpenMP, CUDA, ...

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# Some hot topics in QCD

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- **Resonances**
- **Hadron structure calculations**
- **Exotic hadrons & multiquark states**
- **QCD under extreme conditions**
- **QCD corrections to EW observables**
- **QCD as laboratory for beyond-SM calculations**

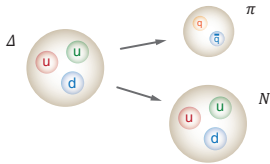
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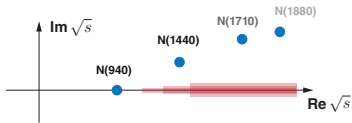
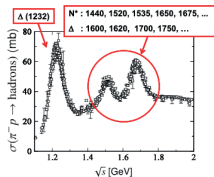
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# Resonances

Most hadrons are short-lived **resonances** and decay into other hadrons



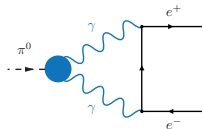
Mathematically: **poles in complex momentum plane**





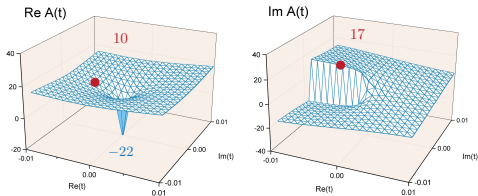
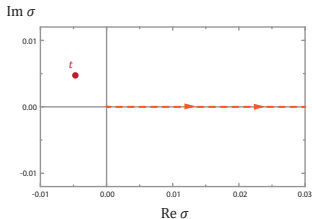
# Resonances

Rare pion decay  $\pi^0 \rightarrow e^+e^-$ :



$$= A(t) = \int_0^\infty d\sigma I(\sigma, t)$$

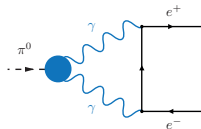
Internal singularities produce branch cuts in integrand:  
**deform integration contour**



Weil, GE, Fischer, Williams, Phys. Rev. D 96 (2017)

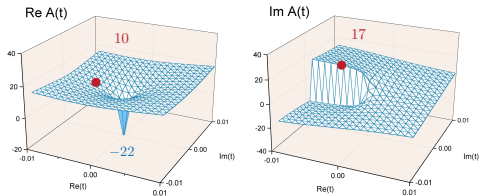
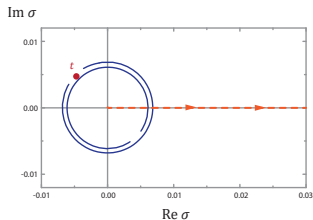
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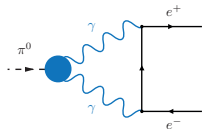
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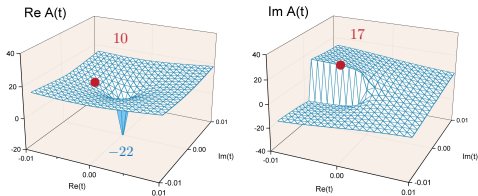
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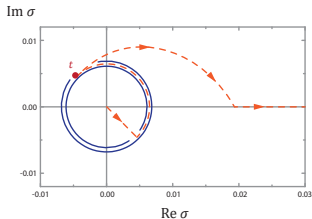


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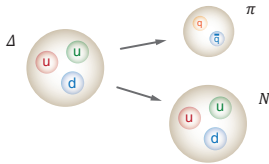
Weil, GE, Fischer, Williams, Phys. Rev. D 96 (2017)

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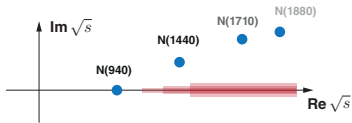
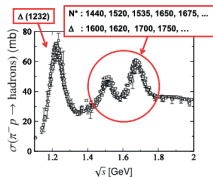


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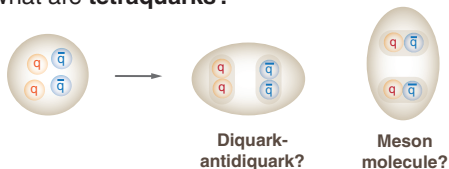


Mathematically: **poles in complex momentum plane**



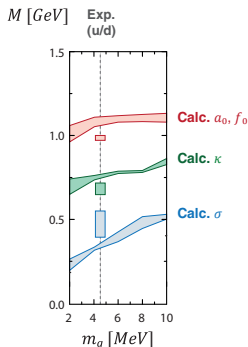
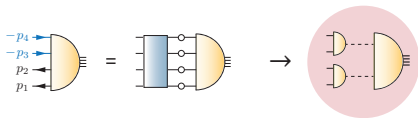
# Exotic hadrons & multiquarks

What are **tetraquarks**?



**Light scalar mesons  $\sigma$ ,  $\kappa$ ,  $a_0$ ,  $f_0$  as tetraquarks:**  
cluster into meson-meson configurations

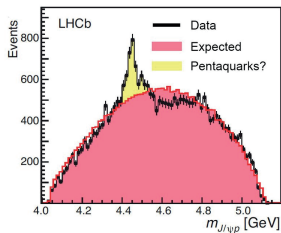
Heupel, GE, Fischer, *Phys. Lett. B* 718 (2012), *Phys. Lett. B* 753 (2016)



$$\begin{aligned}
 f_i(S_0, \nabla, \blacktriangle, \circ) &\rightarrow 1500 \text{ MeV} \\
 f_i(S_0, \nabla, \blacktriangle, \circ) &\rightarrow 1500 \text{ MeV} \\
 f_i(S_0, \nabla, \blacktriangle, \circ) &\rightarrow 1200 \text{ MeV} \\
 f_i(S_0, \nabla, \blacktriangle, \circ) &\rightarrow \mathbf{350 \text{ MeV !!}}
 \end{aligned}$$

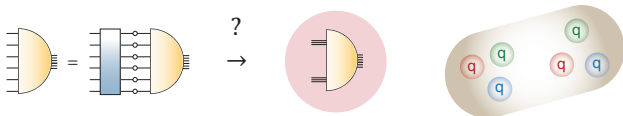
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What are **pentaquarks**?

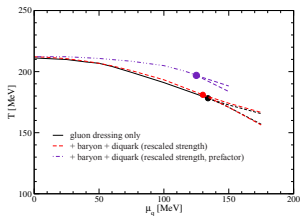
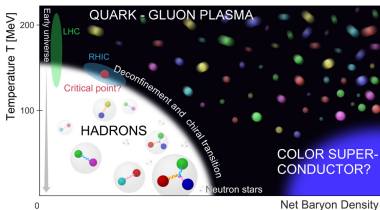


Aaij et al. (LHCb), Phys. Rev. Lett. 115 (2015)

Can we understand the **nuclear force** from first principles?



# QCD under extreme conditions



GE, Fischer, Welzbacher, Phys. Rev. D 93 (2016)

- How do **correlation functions** change with temperature & density?



- Is there **critical endpoint** in QCD phase diagram?

- How important are **baryons** for the phase transition?



- How does **hadronization** work?

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