Exploring and extending modern particle physics

DocDays 2021 - TU Graz

Bernd Riederer, Fabian Zierler

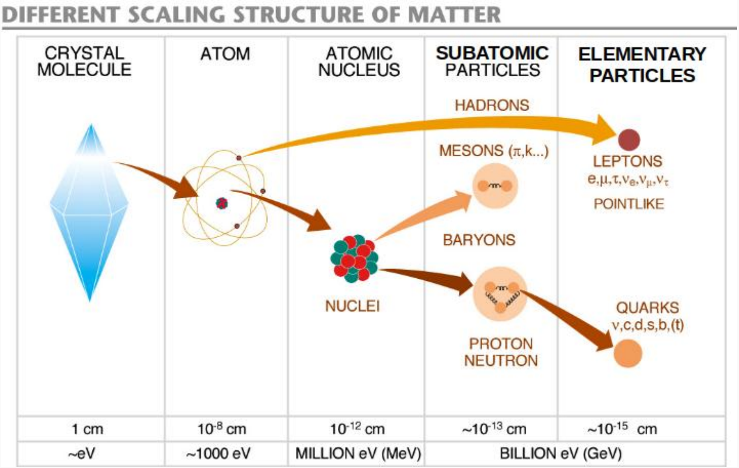
27th September 2021

FWF Der Wissenschaftsfonds.

NAWI Graz Natural Sciences

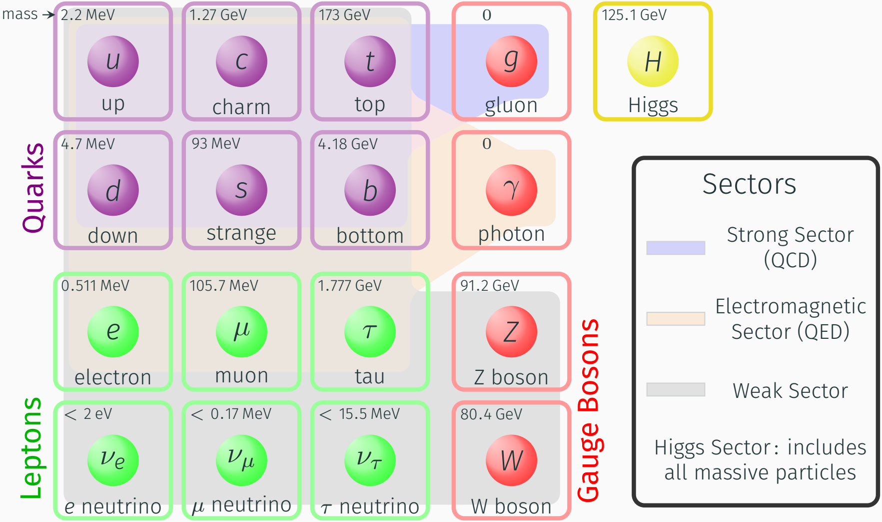
UNI GRAZ

Particle physics



CERN
modified: modern nomenclature

The Standard Model of particle physics



The Standard Model of particle physics

- Most successful theory up to now
- Describes 3 of 4 fundamental interactions and everyday matter as a Quantum Field Theory
    - Electromagnetic interaction
    - Weak nuclear interaction
    - Strong nuclear interaction (QCD)
- Plus the Higgs-sector providing masses to the particles

Need for physics Beyond the Standard Model (BSM)

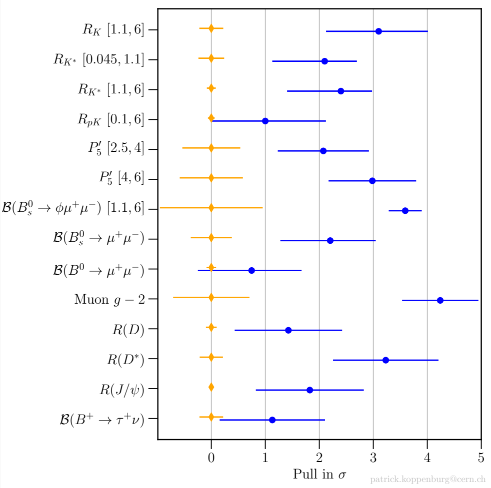
Conceptual Problems

- Dark Matter not part of it
- Matter-Antimatter-Asymmetry not explained
- Quantum Gravity not included
- Breaks down at high energies

Precision tests for the SM

- SM is extremely successful
- Some tension exists
- not (yet?) significant
- theory predictions very non-trivial

Need to understand SM and BSM physics equally well to draw



Current PhD projects @ University of Graz

- Strongly Interacting Dark Matter (S. Mee, FZ)
- Higgs-like theories (E. Dobson, BR)
- Strong Interaction & Sign Problem (M. Anosova, M. Hansen)

Remaining outline

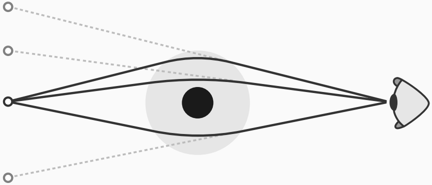
- Dark Matter
- Higgs Physics
- Strong Interactions &
  The Sign Problem
- Wrap up

Dark Matter

DM experimentally well-established!

- Rotation curves
- Gravitional lensing and microlensing
- Early universe structure formation

Particle Dark Matter is a hypothesis!



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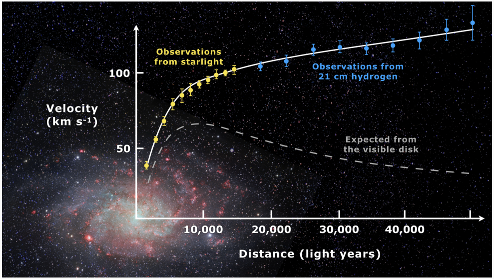

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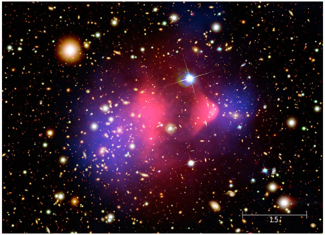
What we know about Dark Matter

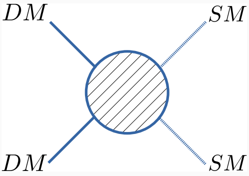


Chandra X-Ray Observatory, NASA/CXC/M. Weiss

- DM density in current universe
  - Mass/number of particles **unknown**!
  - only very loose strict bounds
    - Wavelength of particle smaller than a galaxy (lower mass limit)
    - At least one DM particle per galaxy (upper mass limit)
- Coupling to the SM is small (if it exists)
- Self-interaction among DM is constraint
- A large number of model-dependent constraints exist

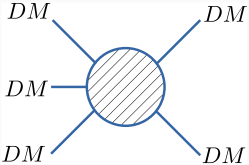
A Class of Dark Matter candidates: Thermal Relics

- Thermal equilibrium in the early, hot universe
- Universe cools: Dark Matter depletes
  - E.g. annihilation: 2 DM $\rightarrow$ 2 SM with heavy DM
  - for low kinetic energy the reverse process is not allowed due to conservation of energy
- Universe expands and cools
  - Eventually DM to spread out for reactions to occur
  - Dark Matter "freeze-out"
- Depends on type of process



A Thermal Relic: Strongly Interacting Massive Particles

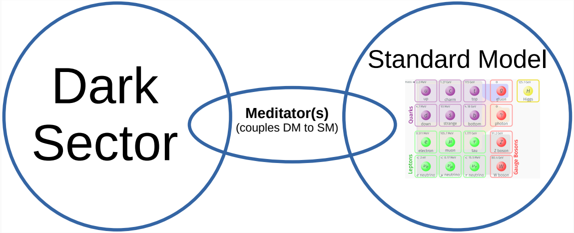
- Another possible process: self-annihilation 3 DM $\rightarrow$ 2 DM
- Occurs naturally in some QCD-like theories
  - Currently studied in Graz!
  - Have many implications but calculations are difficult



  - Connect microscopic underlying theory to an effective theory and to searches at collider, direct detection experiments and astrophysical observations!
  - Connections to experiments at the LHC and CRESST

Adding a Dark Sector to the Standard Model

- 3 DM $\to$ 2 DM: Dark sector would heat up
- Connection to SM needed for equilibrium!
- Different mechanisms available
- Needs to be included ineffective theory!



Goal: Increase discovery potential of such theories!

Higgs Physics

1964

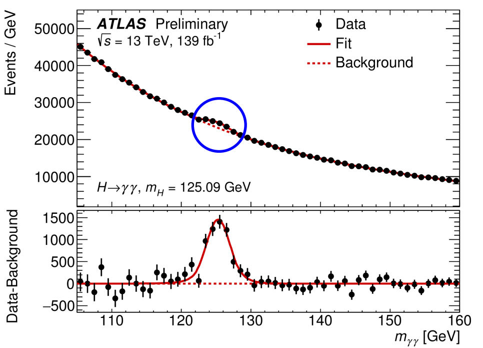
Theoretical prediction of the Higgs boson

July 2012

CERN announces the discovery of a new particle

March 2013

New particle confirmed as Higgs boson



Higgs boson measurement, ATLAS-CONF-2019-029

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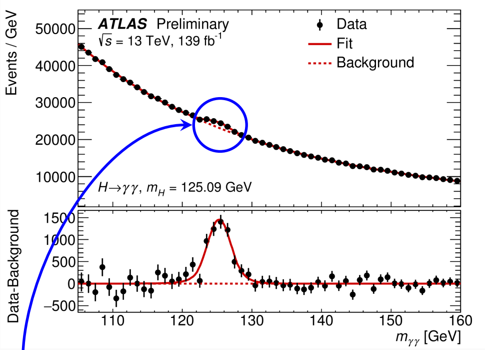
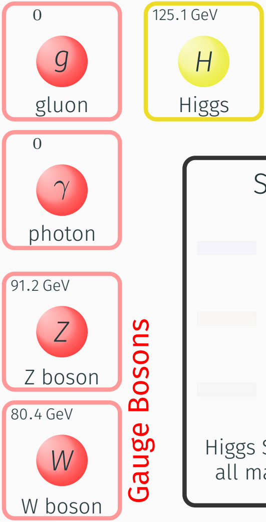


Higgs boson measurement, ATLAS-CONF-2019-029

What did we observe?
What is its purpose?

- Properties of QFTs:
  - Gauge invariance
  - Unitarity
  - Lorentz invariance
- Needs massless gauge bosons



Sectors

Strong Sector (QCD)

Electromagnetic Sector (QED)

Weak Sector

Higgs Sector: includes all massive particles

Why we need the Higgs

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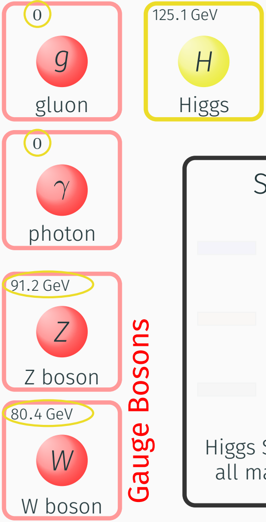

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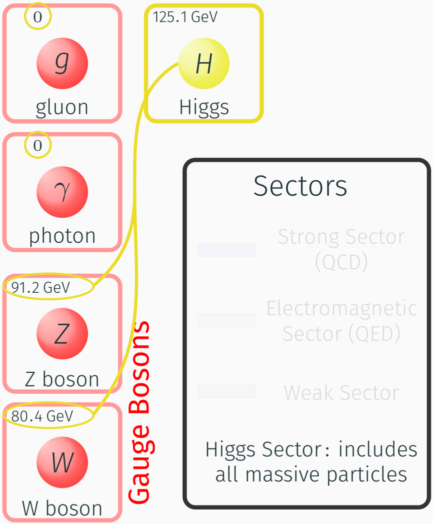
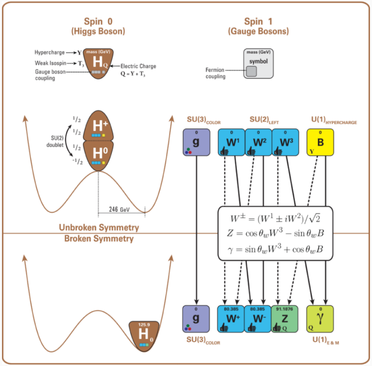
- Needs massless gauge bosons
- Dynamical mass creation



The Brout-Englert-Higgs-mechanism

- Perturbation theory
  $\rightarrow$ expand around minimum of the Higgs-potential
- Mass terms for the gauge fields and the scalar field
- "Gauge symmetry breaking"
- Similar mechanism in Superconductors (Ginsburg-Landau Theory)



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modified: removed fermions

The ambiguity

[Fröhlich et al., PL **B97** (1980) and NP **B190** (1981)]

- In PT elementary fields are used to calculate observables e.g. $\langle W^\dagger(x_1)W(x_2)\rangle$
- Elementary fields are gauge-dependent and thus **unphysical** (human choice)
- Compare to usual quantum mechanics:

$$[\Psi(x_1)^*\Psi(x_2)]^2 \quad ✗ \qquad \{[\Psi(x_1)^*\Psi(x_1)]^*[\Psi(x_2)^*\Psi(x_2)]\}^2 \quad ✓$$

Need to do the same in QFT and use nonperturbative methods

- Usual PT way works really well in the SM. Why?

[Fröhlich et al., PL **B97** (1980) and NP **B190** (1981) / Maas, MPL **A28** (2013) / Maas and Mufti, **JHEP** (2014)]

- Specific (group-) structure of the SM allows a relation
- E.g. the mass spectrum of the Higgs-boson

- Same relation for other fields: $\langle BS \rangle = \langle EF \rangle + \text{small}$
- Lattice spectroscopy $\Rightarrow$ Mass spectrum stays the same

FMS-mechanism in the SM

[Fröhlich et al., PL **B97** (1980) and NP **B190** (1981) / Maas, MPL **A28** (2013) / Maas and Mufti, **JHEP** (2014)]

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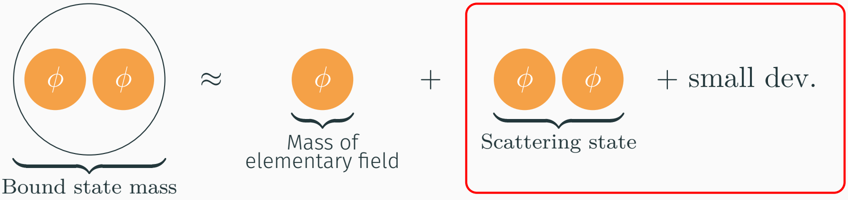

- Same relation for other fields: $\langle BS \rangle = \langle EF \rangle + \text{small}$
- Lattice spectroscopy $\Rightarrow$ Mass spectrum stays the same
- Other observables may change (e.g. cross sections)

BEH and FMS beyond the SM

- Many BSM theories need BEH effect for "gauge symmetry breaking"
- Other setups may alter the previous relations (FMS)
- Systematically study different possibilities
- We can change ...
  a. ...the gauge-gauge interactions (gauge group)
  b. ...the gauge-scalar interactions (scalar representation)

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$\text{SM} = \text{SU}(2) + \text{fun.}$

extensively studied in the past

also master's project of BR

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$\text{SM} = \text{SU}(2) + \text{fun.}$	$\text{SU}(3) + \text{fun.}$
extensively studied in the past	recently studied by former PhDs
also master's project of BR	**currently extended by E. Dobson**

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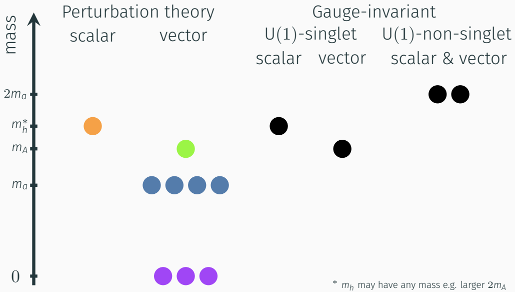
$\mathrm{SM} = \mathrm{SU}(2) + \mathrm{fun.}$	$\mathrm{SU}(3) + \mathrm{fun.}$	$\mathrm{SU}(3) + \mathrm{adj.}$
extensively studied in the past	recently studied by former PhDs	completely unexplored
also master's project of BR	currently extended by E. Dobson	current work of BR

 [Maas, Sondenheimer and Törek **hep-lat**:1710.01941/ Sondenheimer **PRD** 101 (2020)]

- Special structure of SM is not present anymore
- Analytic prediction: spectrum differs for PT and FMS



Changing the gauge group

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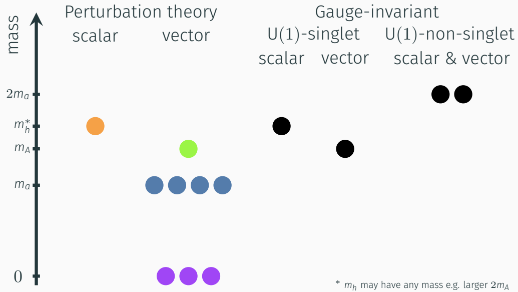
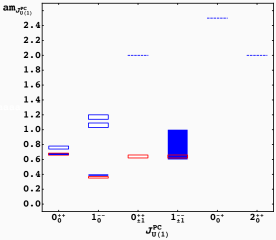


* m_h may have any mass e.g. larger $2m_A$

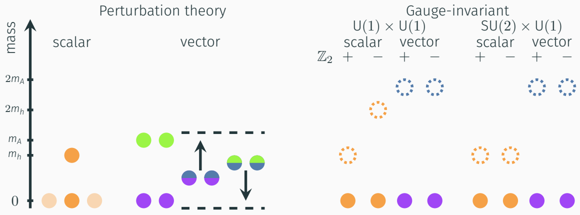


Lattice analysis (blue) with prediction (red)
[Maas and Török **AoP** 397 (2018)]

- Confirmed on the lattice and agrees with FMS-prediction
- **WIP**: E. Dobson is extending our understanding

Changing both

- Allows for variable spectrum in PT (multiple breaking patterns)

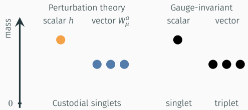


Spectra for SU(3) + adj.

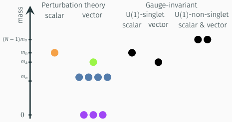
- All channels contain massless state(s) in PT and GI

  Necessary for so-called GUTs to explain the Photon
- Still a huge discrepancy between both spectra
- **WIP**: BR works on confirming GI spectrum

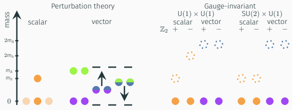
- SM has a very special structure
  - ⇒ PT- & GI-spectrum agree
- Not true in general
  - ⇒ Spectra **do not** agree
- Other observables (e.g. cross sections) may be altered already in the SM
- Nonperturbative methods agree with GI-spectra
  - ⇒ Disagreement with PT-spectra



Spectra for the SM



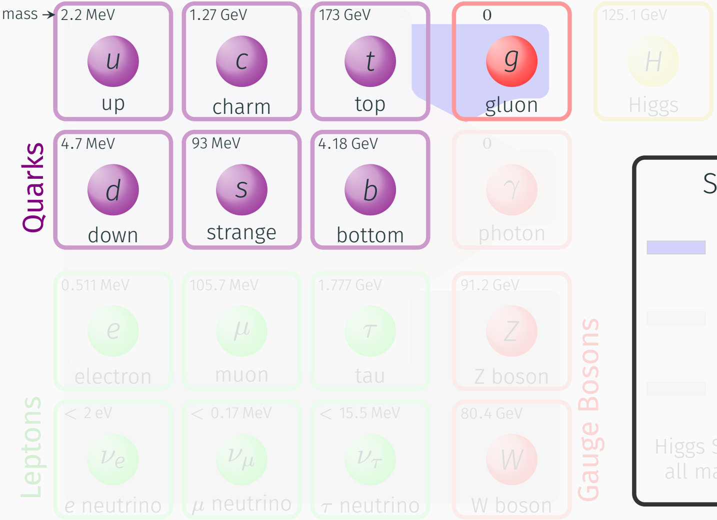
Sample spectra for SU$(N > 2)$ + fun.



Spectra for SU(3) + adj.

Strong Interactions & The Sign Problem

The strong sector



Sectors

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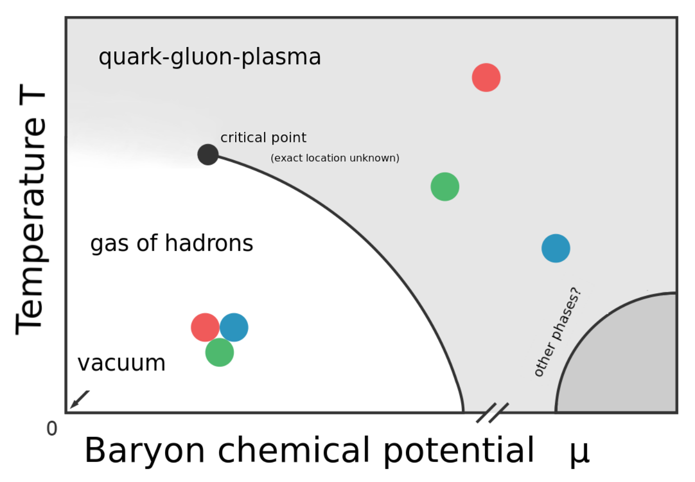
- Electromagnetic Sector (QED)
- Weak Sector
- Higgs Sector: includes all massive particles

A motivating example: QCD Phase Diagram



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modified: translated to English

The Sign Problem: Origins

- Strongly Interactions: Perturbation theory not applicable
- Popular method: Lattice Gauge Theory
  - map problem to a problem in Statistical Mechanics
  - use Monte-Carlo techniques to calculate observables
  - essentially a high-dimensional integral

$$Z = \int \mathcal{D}\phi \exp(-S[\phi])$$

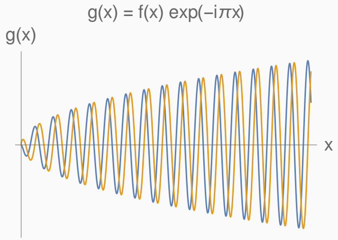
$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}\phi \mathcal{O}[\phi] \exp(-S[\phi])$$

$\exp(-\mathbf{S}[\phi])$ must be positive definite!

- Occurs in many problems outside of particle physics!

Occurrence of Oscillatory Integrals

- Chemical potential μ makes $S[\phi]$ complex
- Poses serious problems
  - No probability distribution $\rightarrow$ Monte-Carlo breaks down
  - Redefining the observables does not help
  - Rapid oscillation occurs $\rightarrow$ Numerical nightmare

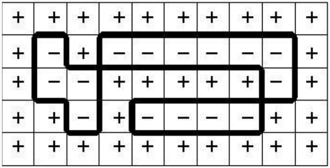


Ways out: Complex Langevin Equations

- Find another way to sample the path integral
- Complex Langevin Equation
  - Stochastic differential equation
  - Evolves to a sample of the path integral
  - Can be extended to complex actions
  - Numerically, still challenging
- **WIP**: M. Hansen studies Complex Langevin for QCD

Ways out: Dual Lattice Formulation

- Rephrase theory in terms of new variables
    - Sign problem: new real action
    - Mapping strong-coupling to weak-coupling
- An example: 2D Ising model



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- **WIP**: M. Anosova studies a self-dual U(1) theory

Wrap up

Strongly Interacting Dark Matter

- **S. Mee**: Connection to SM - Effective theory construction
- **FZ**: Connection to microscopic theory - Lattice methods

Higgs-like theories

- **E. Dobson**: Higgs in BSM context - Lattice methods (latest talk)
- **BR**: Higgs in SM & BSM context - Lattice methods (latest talk)

Strong Interaction & Sign Problem

- **M. Anosova**: Dual Lattice Formulation (latest talk)
- **M. Hansen**: Complex Langevin Equations

Current research