Using deep learning to investigate QCD phase transitions or The unexpected virtue of ignorance

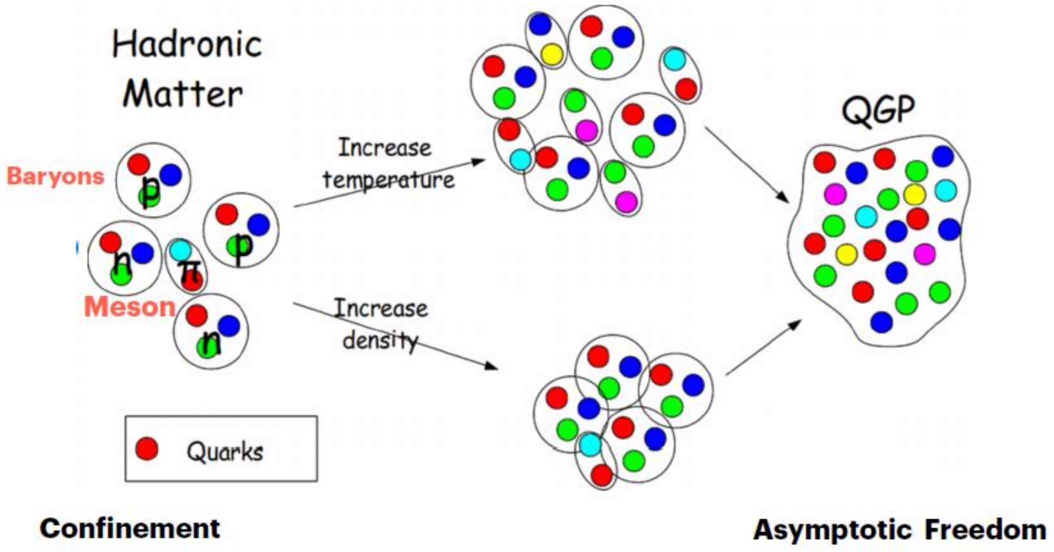
Ahmed Abuali

Advisor : Prof. Claudia Ratti

Collaborators: Dr. David Clarke, Prof. Ricardo Vilalta, Prof. Morten Hjorth-Jensen

What is QCD?

The theory of strong interactions



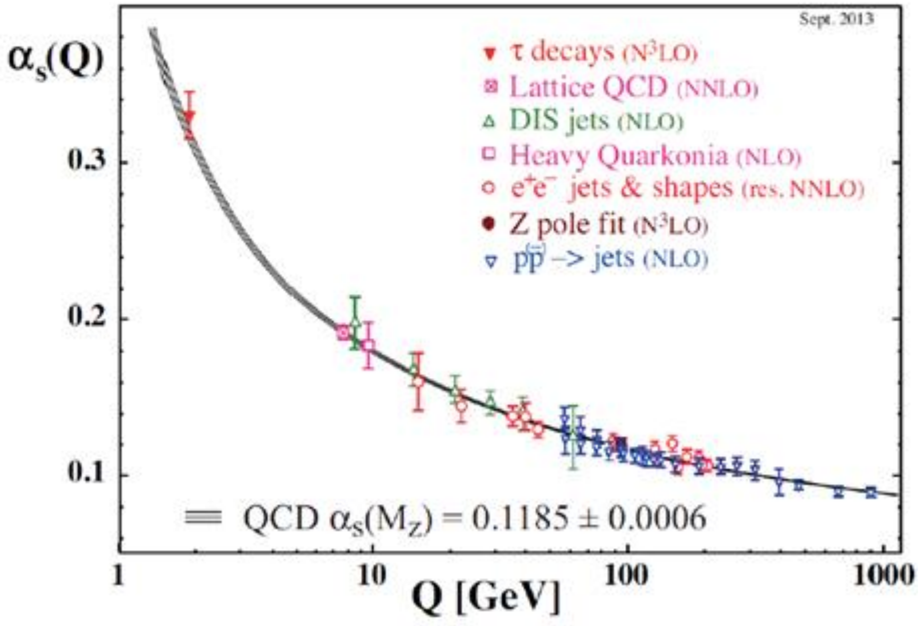
$$\alpha_s(|q^2|) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}[11n - 2f]\log\left(\frac{|q^2|}{\mu^2}\right)}$$

$|q^2| >> \mu^2$ *Perturbative*

$|q^2| << \mu^2$ *Non − Perturbative*

n - number of colors = 3

F -number of flavor = 6



QCD Lagrangian & gauge group

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i i\gamma^\mu (D_\mu)_{ij}\psi_j - \bar{\psi}_i m\,\delta_{ij}\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

The gauge group for QCD is SU(3)

Introducing Lattice QCD

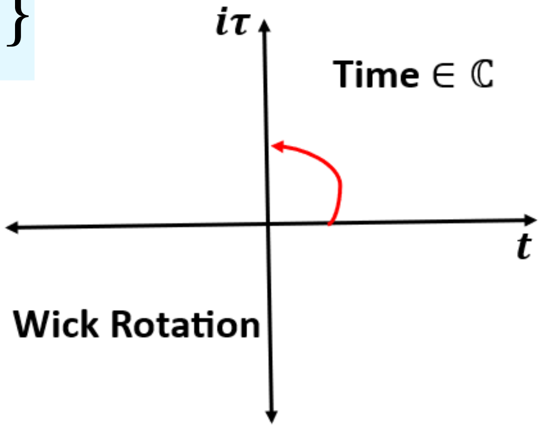
We go from **4D Minkowski spacetime** to **4D Euclidean spacetime**

- Introduce complex time
- Do Wick rotation $t \to i\tau$
- Interpreting the denominator of the propagator as a partition function
- Space-time discretization
- Monte-Carlo Simulation

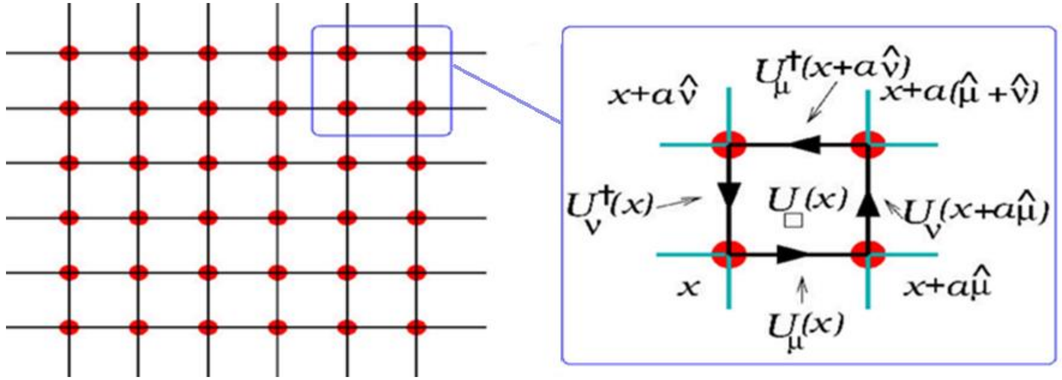
$$Z = \int D\varphi \exp\{i S[\varphi]\} \Rightarrow Z = \int D\varphi \exp\{-S[\varphi]\}$$

This can be interpreted as partition function $\mathcal{Z}$

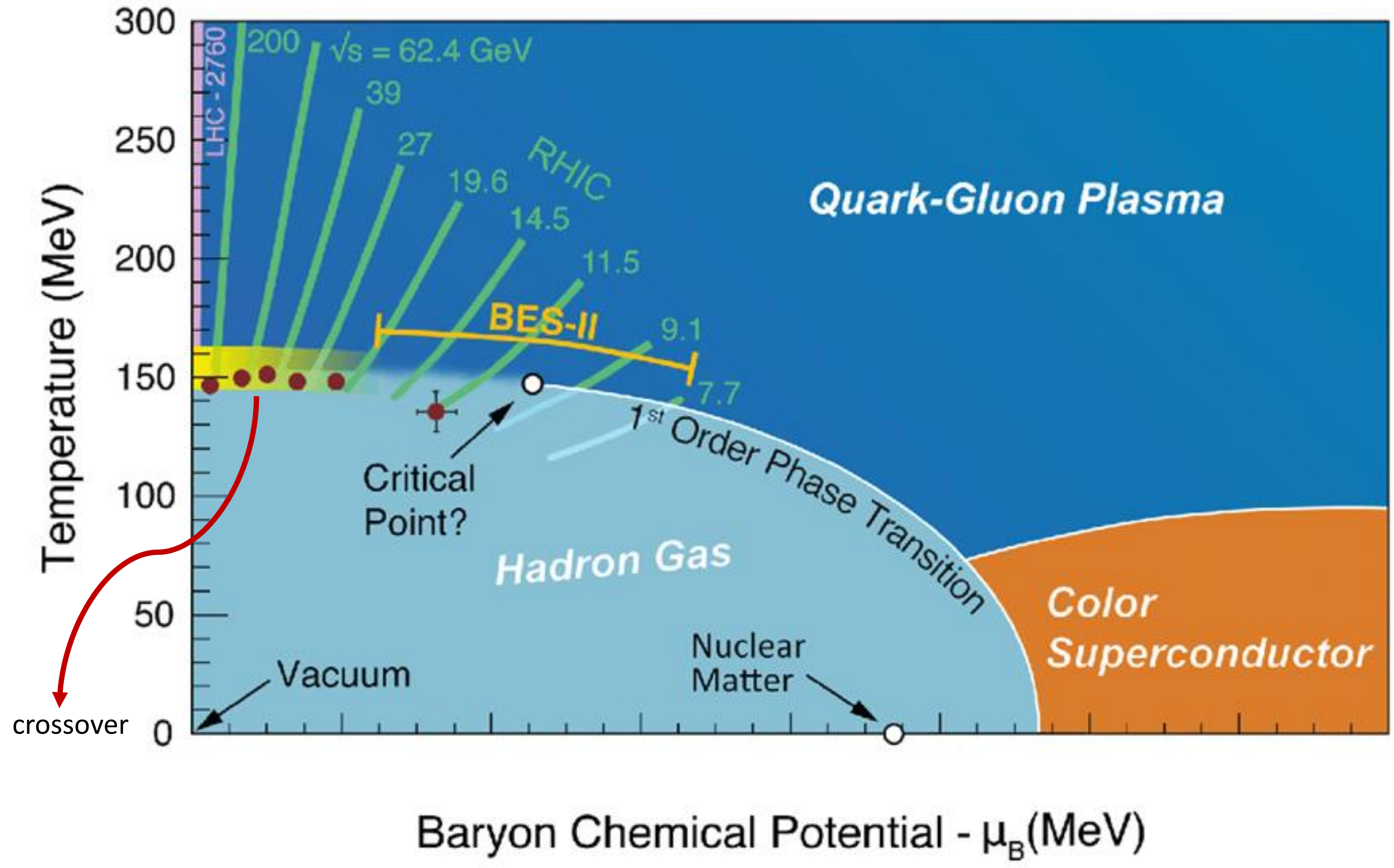
$$t \to i\tau$$



$$D\varphi(x) \Rightarrow \prod_x d\varphi_x \Rightarrow Z = \int \prod_x d\varphi_x \exp\{-S[\varphi]\}$$



QCD Phase Diagram



What do we know?

- We know from the experiment and lattice calculations that the transition is a crossover at $\mu_B = 0$

Open questions

- How broad is the crossover?
- We do not have a real order parameter

Problem Statement

Q: Is Deep Learning able to tell us how broad the crossover is? Can it do that using only the lattice configurations and with complete ignorance of the physics behind, doing it without imposing our preconceived notion of a pseudo-order parameter?

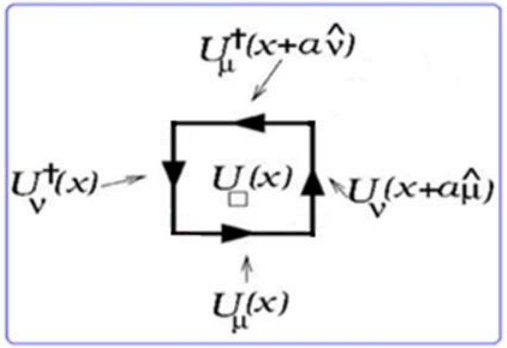
A: Probably yes.

Q: How will we use Deep Learning to solve the problem?

A: learn from simple, well-known statistical models, then move to complex models:

- 2D/3D Ising and Heisenberg models
- Transfer our knowledge to pure gauge lattice QCD configurations
- Build a deep learning model to study system with quarks

Understand pure-gauge critical behavior

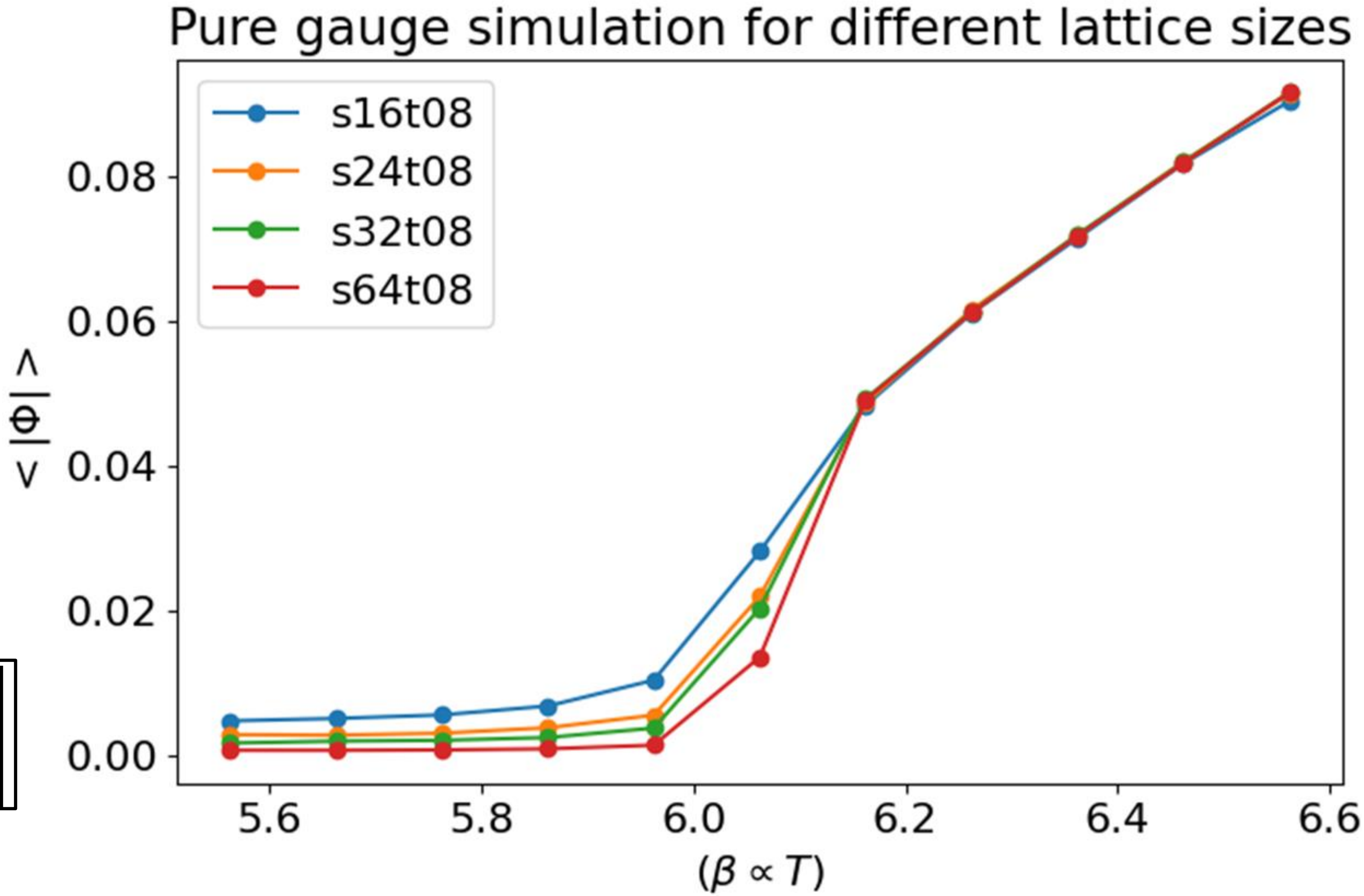


Z(3) Symmetry

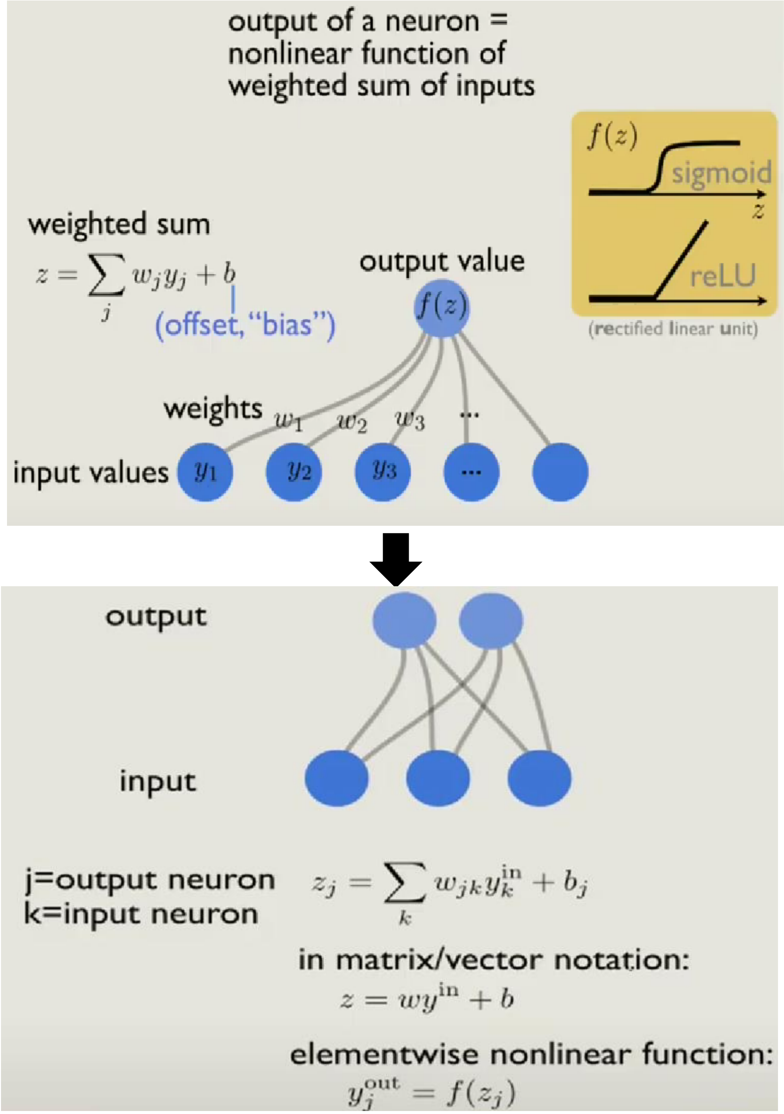
$$z = exp\left(\frac{2\pi i n}{3}\right), \text{n} = 1,2,3$$

The Polyakov Loop (order parameter)

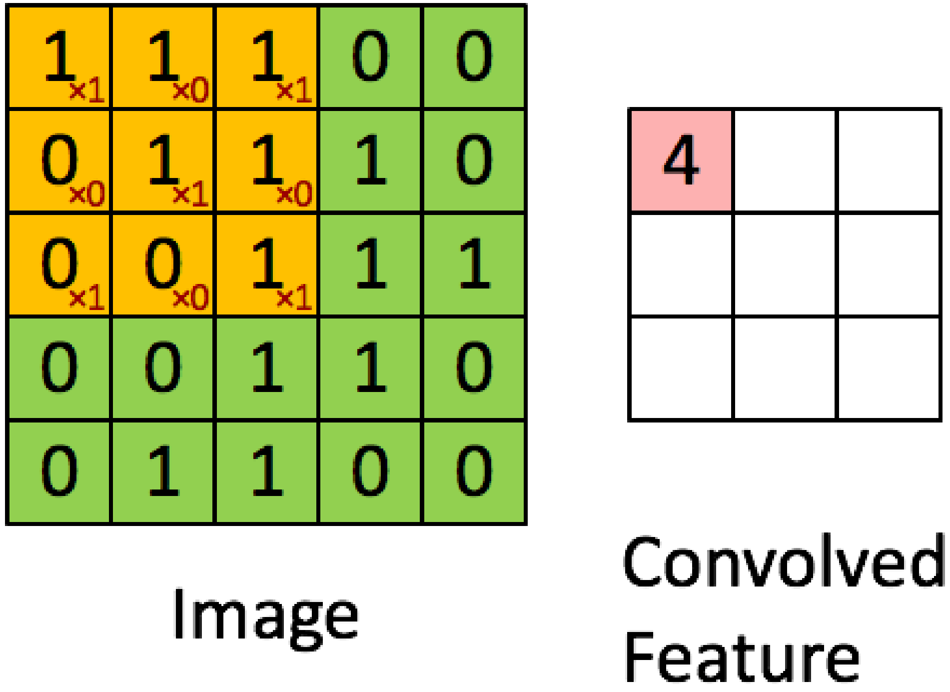
$$\Phi(\vec{x}) = \frac{1}{3} Tr\left[P\ exp\left[i\int_o^\beta dx_4\, G_4(\vec{x}, x_4)\right]\right]$$



What is Deep Learning ?



How does the CNN work?



Implementation for 2D/3D Ising and Heisenberg Models

Generating configuration files: Monte Carlo simulation for different statistical models

Build DL model → Feed conf files to the model → Train the model (**Supervised training**) → Test the model

Use the trained model to predict the phase of a **different set** of configurations, for example one thousand configuration files per temperature

Model prediction per configuration : $0 \leq P \leq 1$

$$P = \begin{cases} 0 & 0.0\%\ Ferromagnetic \\ & \vdots \\ 1 & 100\%\ Ferromagnetic \end{cases}$$

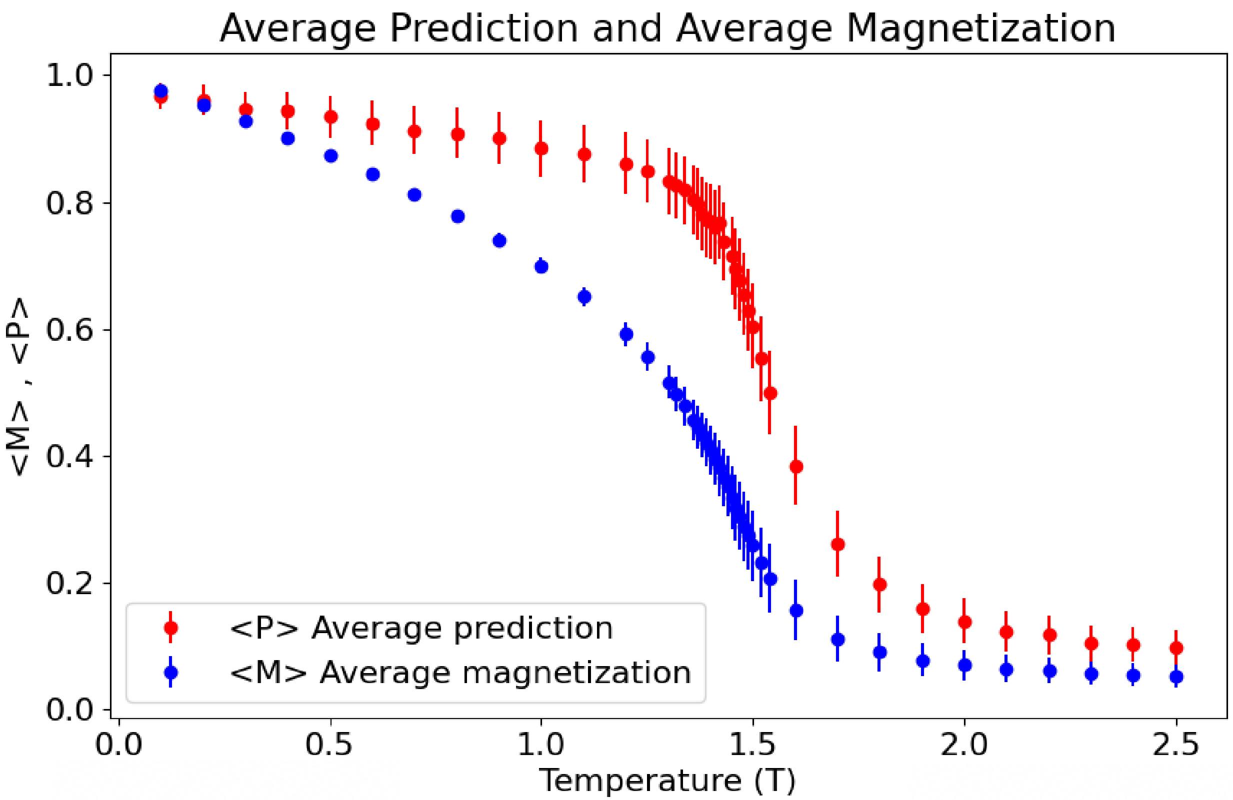
Doing statistics on the 1000 predictions

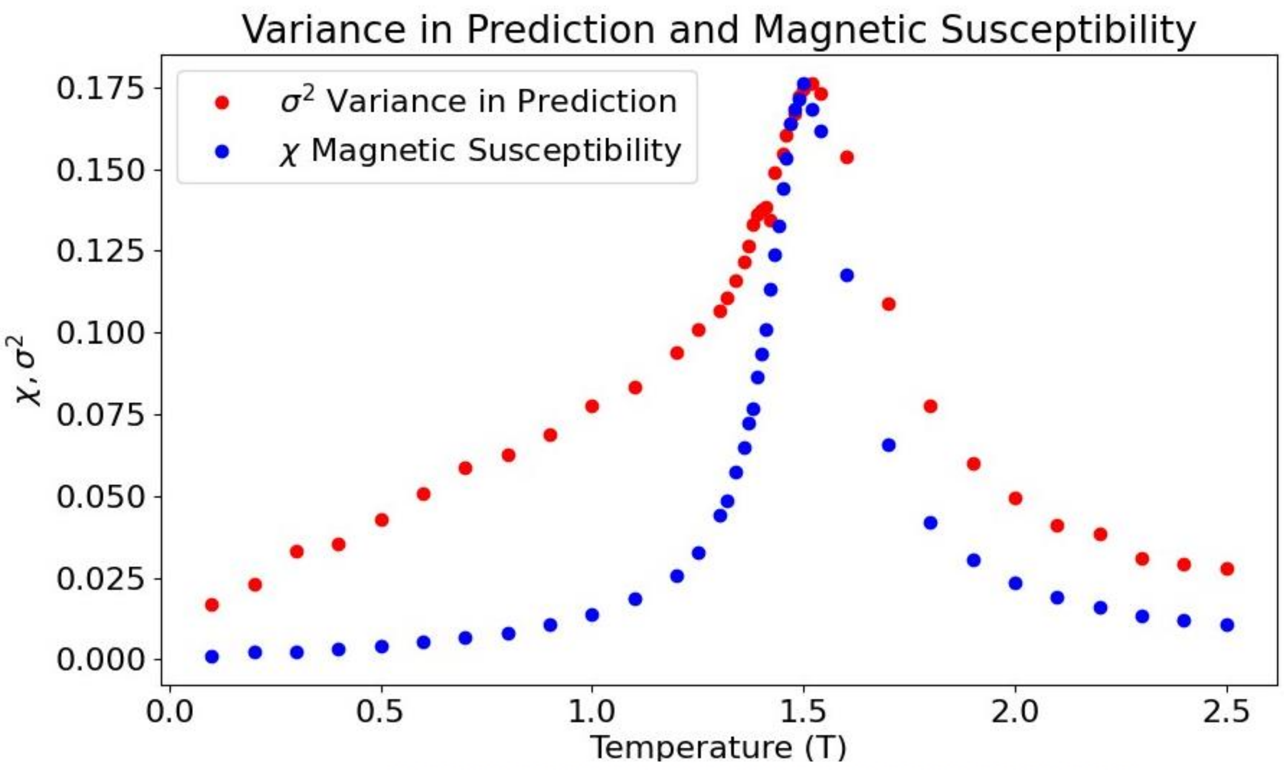
- **Average prediction per configuration <P>**
- **Standard deviation prediction (error bars)**
- **Variance in prediction σ^2**

Classical 3D-Heisenberg Model Results X-Component Only

We got very good results for:

- ❑ 2D/3D Ising Model ✓
- ❑ 3D Heisenberg Model ✓





Conclusions and future work

Conclusions:

- The classification tasks for complex statistical models needs building CNN networks
- The average prediction mimics the behavior of an order parameter
  - we can use it to get insight in systems for which we don't have a real order parameters
- The variance in prediction is a very good indicator for the location of the phase transition
  - we can use it in systems for which we do not know the value of the transition temperature

Future work:

- Build a model to do classification tasks the in the pure gauge sector
- Build a model to do the classification task in a QCD system that includes fermions

Thank You