On Gauge Bosons, observable Particles and the Brout-Englert-Higgs mechanism

Bernd Riederer, Axel Maas

PAPAP 2019 Rome/L'Aquila, 05 November 2019

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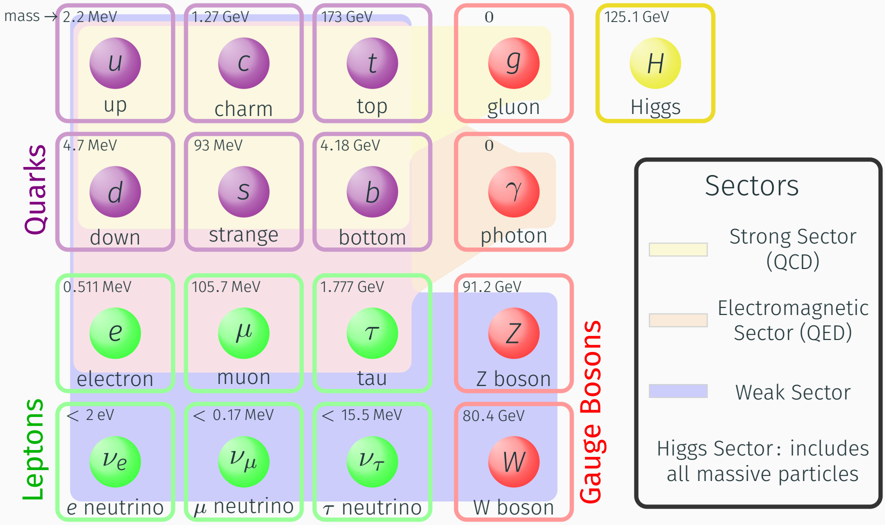
Setting the Scene



Setting the Scene

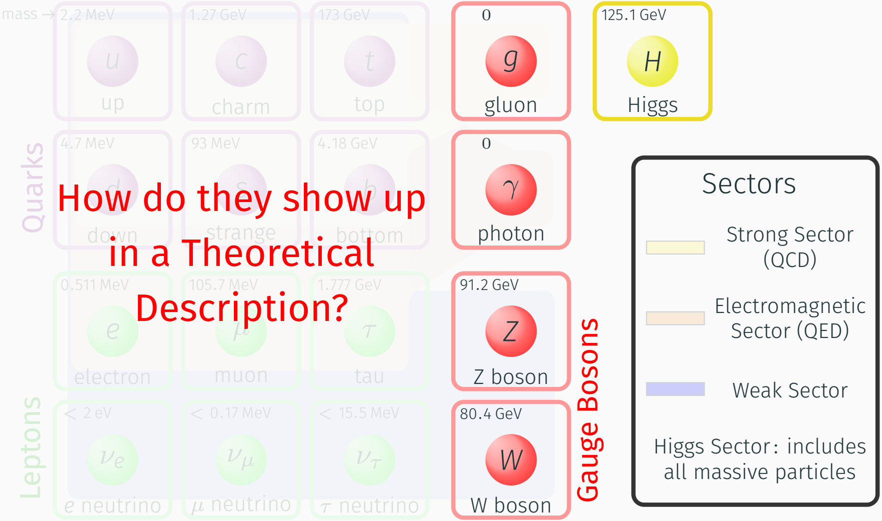
Sectors

- Strong Sector (QCD)
- Electromagnetic Sector (QED)
- Weak Sector

Higgs Sector: includes all massive particles

Setting the Scene

How do they show up in a Theoretical Description?



Electrodynamics

- Formulation using *E*- and *B*-Fields not suitable for a QFT
- Vector Potential $A_\mu = (\varphi, A) \rightarrow$ covariant description

$$B = \nabla \times A \qquad\qquad E = -\nabla\varphi - \partial_t A$$

- Mathematical Tool with redundant degrees of freedom

$$\underbrace{3}_{\#\text{ E-field comps.}} + \underbrace{3}_{\#\text{ B-field comps.}} - \underbrace{4}_{\#\text{ Maxwell eqs.}} = 2 \neq \underbrace{4}_{\#\text{ A-field comps.}}$$

- Invariant under Gauge Transformation ($\Lambda(t, r) = \text{arbitrary}$)

$$A \rightarrow A + \nabla\Lambda \qquad\qquad \varphi \rightarrow \varphi - \partial_t\Lambda$$

- Quantization: Vector Potential A_μ becomes Photon field
- Photons are the excitation quanta of the Photon field

Local Gauge Symmetry

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Local Gauge Symmetry

- Mechanism is invertible:
  Gauge Symmetry $\leftrightarrow$ Equations of Motion
- QCD and Electroweak interaction:
  different details, same principle
- A Gauge Symmetry allows to choose an internal coordinate system for the symmetry at every space-time point
- Observables need to be independent of this **human choice**
- All Gauge Bosons are massless[1]

[1] Naive mass term in the Lagrangian either breaks the local symmetry or violates unitarity

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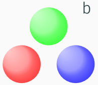

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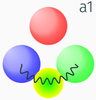

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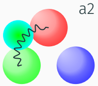

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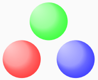

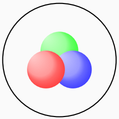

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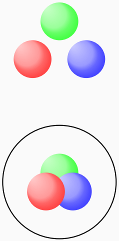

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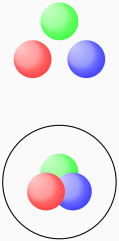

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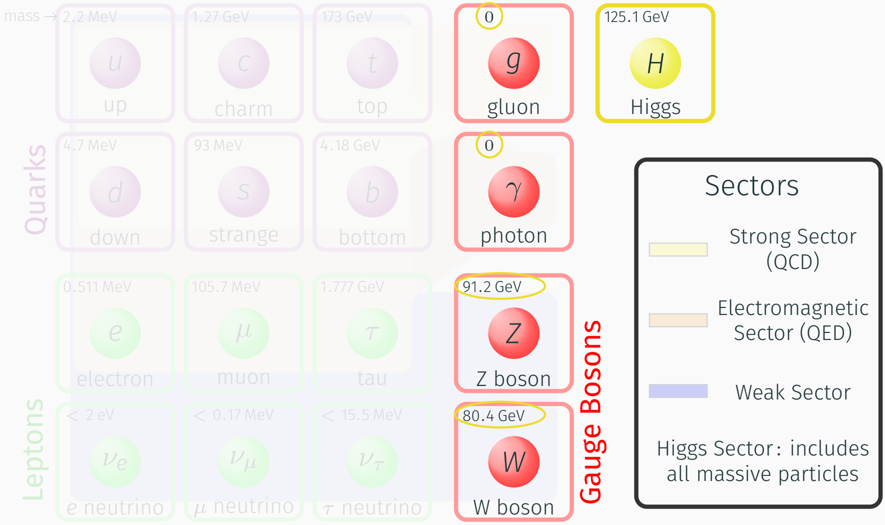

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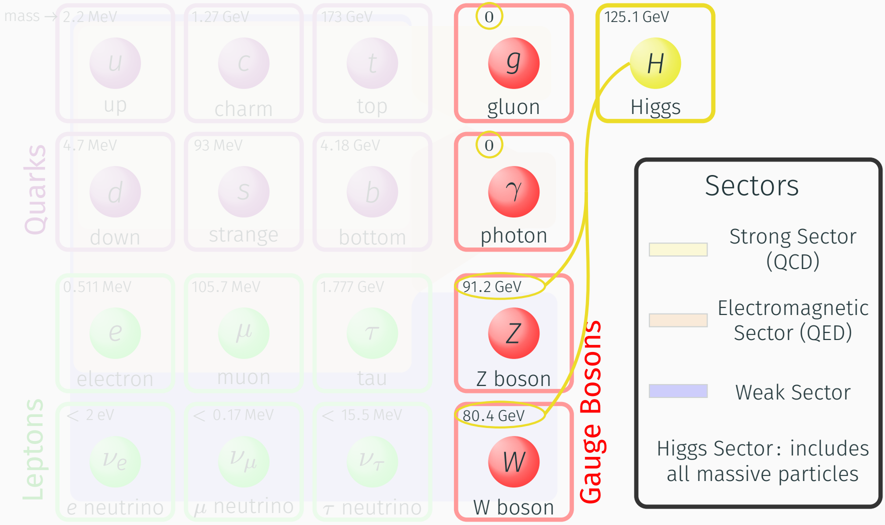

Massive Gauge Bosons

[Englert and Brout, PRL **13** (1964) / Higgs, PRL **13** (1964)]

- Need for Brout-Englert-Higgs-Mechanism
- Heuristic Explanation: Condensed Higgs Field slows down the Gauge Bosons $\rightarrow$ gain mass
- Through Interaction $\Rightarrow m_W \propto v^2$
- Theoretical Approach:
  - Higgs field ϕ is split[1]: $\phi(x) = v + h(x)$
  - Vacuum expectation value v: fixed in a specific gauge
  - Fluctuation Field $h(x)$: such that $\langle h(x) \rangle = 0$

[1] This is the point where the famous 'Spontaneous Gauge Symmetry Breaking' happens

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What's the Problem?

['t Hooft, NATO Sci.Ser. **B59** (1980) / Banks et al., NP **B160** (1979) / Fröhlich et al., PL **B97** (1980))]

- Quite subtle issue known since the 1970's
- v actually carries a 'gauge index'
- Even worse: there exist gauges with $v = 0 \Rightarrow$ Gauge Bosons (and Higgs itself) stay massless
- W/Z-Bosons are also gauge dependent $\rightarrow$ **Cannot be Observable!**

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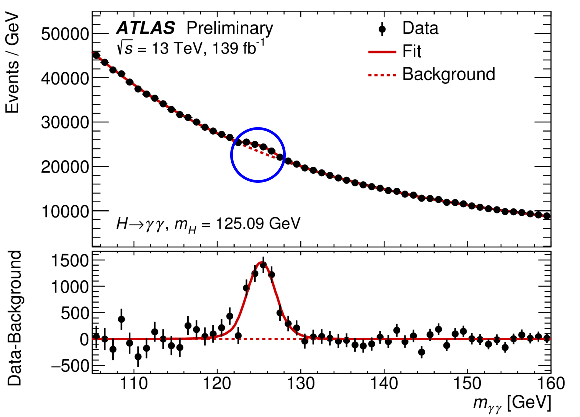
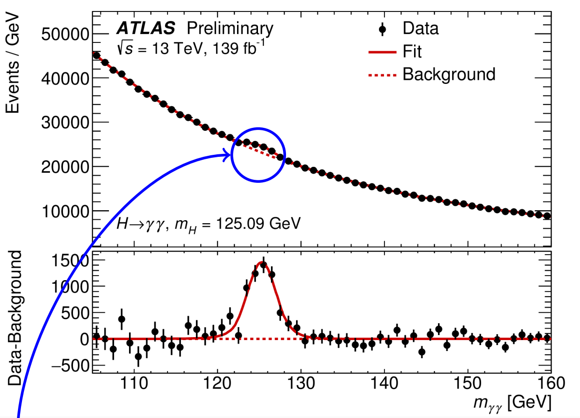
Theory tells us that Gauge Bosons should **not** be observable Particles!


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Data
Fit
Background
H→γγ, mH = 125.09 GeV
Events / GeV
50000
40000
30000
20000
10000
Data-Background
1500
1000
500
0
−500
110
120
130
140
150
160
mγγ [GeV]

[From Report: ATLAS-CONF-2019-029]



What did we actually observe?

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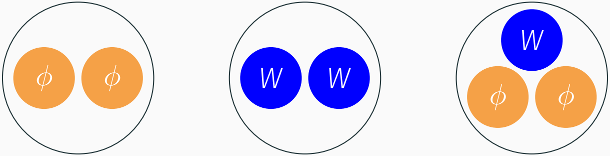
  - Gauge choice needs to be canceled $\rightarrow$ more than one particle
  - Composite Particles ($H, V, \ldots$) ✓
- Observable particles: Higgs-Higgs, W-Ball, Higgs-Higgs-W etc.



The Physical Spectrum

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

- Still compatible with the physical Spectrum?

- e.g.: The Mass spectrum of the Higgs-Boson

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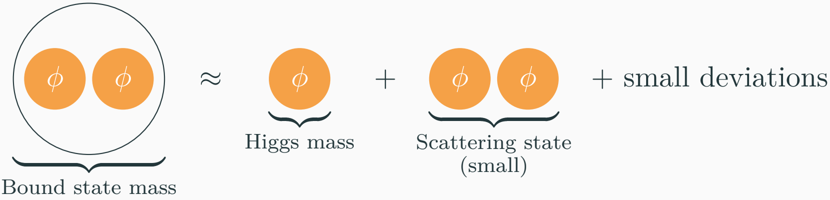

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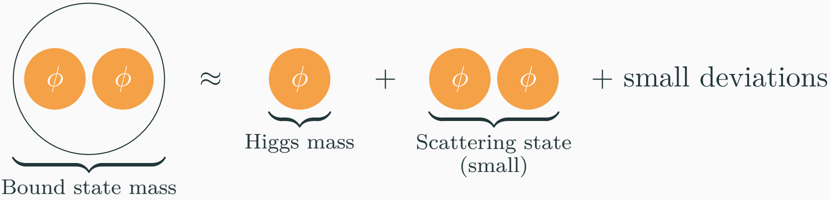

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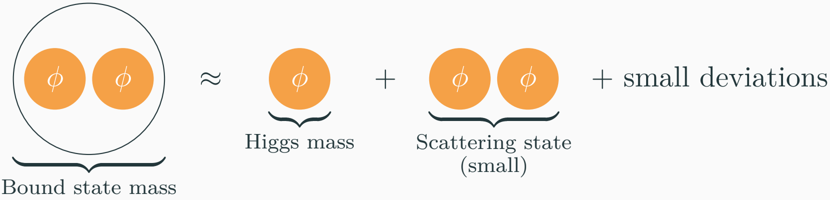

- l.h.s.: gauge invariant / parts of r.h.s.: gauge dependent
- **Confirmed** on the Lattice

Testing the theory

- Investigation of the Electroweak-Higgs Sector of the SM[1] using Gauge-invariant observables
- Lattice Simulations
  - Idea: Take Euclidean-Pathintegral ($t \to i\tau$) $\int \mathcal{D}\Phi e^{-\int d^Dx \mathcal{L}_E[\Phi(x)]}$ and make it discrete: $\int \to \sum$
  - Calculate Observables as a sum over configurations created by MC-Simulation with weight $e^{-\int d^Dx \mathcal{L}_E[\Phi(x)]}$
  - Includes non-perturbative effects $\to$ test for PT
- $H \to WW$-decay
  - Phaseshift can be calculated from PT and will be measurable at HL-LHC $\to$ direct test of PT and FMS
  - Scattering of Bound-States could mimic "new Physics"

[1] Also full SM and BSM theories (including Quantum Gravity [A. Maas, arXiv: 1908.02140]) are investigated by colleagues

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Testing the theory

- Investigation of the Electroweak-Higgs Sector of the SM[1] using Gauge-invariant observables
- Lattice Simulations
  - Idea: Take Euclidean-Pathintegral ($t \to i\tau$) $\int \mathcal{D}\Phi e^{-\int d^D x \mathcal{L}_E[\Phi(x)]}$ and make it discrete: $\int \to \sum$
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[A. Maas, PPNP **106** (2019), arXiv: 1712.04721]

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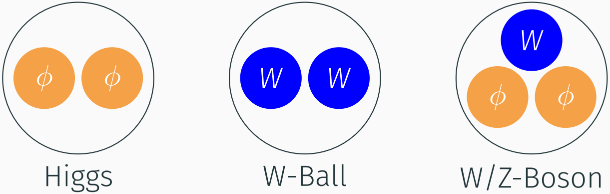

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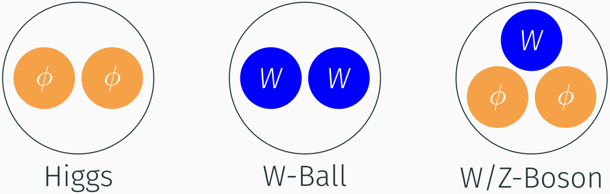

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Questions?

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Gauge-invariant perturbation theory

[Fröhlich et al., PL **B97** (1980) and NP **B190** (1981) / A. Maas, PPNP **106** (2019), arXiv: 1712.04721]

1. Formulate gauge-invariant operator and Correlator e.g.:

$$0^+ \text{ singlet:} \quad H(x) = \left(\phi_i^\dagger \phi_i\right)(x)$$

$$\langle H(x) H(y) \rangle = \left\langle \left(\phi_i^\dagger \phi_i\right)(x) \left(\phi_j^\dagger \phi_j\right)(y) \right\rangle$$

2. Expand Higgs field in fixed Gauge $\phi_i = v n_i + h_i$

$$\left\langle \left(\phi_i^\dagger \phi_i\right)(x) \left(\phi_j^\dagger \phi_j\right)(y) \right\rangle = d v^4 + 4 v^2 \left\langle \Re\left[n_i^\dagger h_i\right]^\dagger (x) \Re\left[n_j^\dagger h_j\right](y) \right\rangle + \\ + 2v \left\{ \left\langle \left(h_i^\dagger h_i\right)(x) \Re\left[n_j^\dagger h_j\right](y) \right\rangle + (x \leftrightarrow y) \right\} + \left\langle \left(h_i^\dagger h_i\right)(x) \left(h_j^\dagger h_j\right)(y) \right\rangle$$

3. Perform standard Perturbation theory

$$\left\langle \left(\phi_i^\dagger \phi_i\right)(x) \left(\phi_j^\dagger \phi_j\right)(y) \right\rangle = d' v^4 + 4 v^2 \left\langle \Re\left[n_i^\dagger h_i\right]^\dagger (x) \Re\left[n_j^\dagger h_j\right](y) \right\rangle_{\mathrm{tl}} + \\ + \left\langle \Re\left[n_i^\dagger h_i\right]^\dagger (x) \Re\left[n_j^\dagger h_j\right](y) \right\rangle_{\mathrm{tl}}^2 + \mathcal{O}(g^2, \lambda)$$

Lattice Formulation

1. Discretize the action on Euclidean N^d-hypercubic

   [I. Montvay and G. Münster, Quantum Fields on a Lattice (1994)]

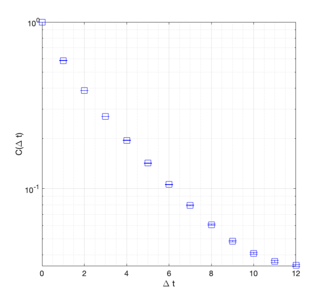
$$S_{cont.} = \int d^4x \left[-\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} + (D_\mu \phi)^\dagger D^\mu \phi - \lambda \left(\phi^\dagger \phi - f^2 \right)^2 \right]$$

$$S_{latt.} = \sum_x \left[\frac{\beta}{d_F} \sum_{\mu<\nu} \mathrm{Re}\left\{ \mathrm{Tr}\left(1 - U_{x,\mu\nu}\right) \right\} - \kappa \sum_{\pm\mu} \phi^\dagger_x U^R_{x,\mu} \phi_{x+\mu} + \phi^\dagger_x \phi_x + \gamma \left(\phi^\dagger_x \phi_x - 1 \right)^2 \right]$$

2. Do Monte Carlo for Gauge-Links (Heatbath) and Higgs-Field (Metropolis)

Spectroscopy

- Calculate Correlators $C(\Delta t) = \langle \mathcal{O}(\Delta t)\mathcal{O}^\dagger(0)\rangle = \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-E_n \Delta t}$
- Correlator contains information about **all** Operators with same quantum numbers
- For large times $\Delta t >> E_{n>0}^{-1}$ $\Rightarrow C(\Delta t) \propto e^{-E_0 \Delta t}$



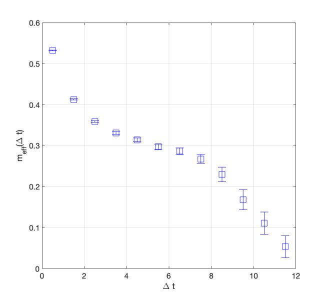
Typical Correlator

Effective Energy Curves

- Calculate an effective Energy from Correlator $C(\Delta t) = \sum_n c_n e^{-E_n \Delta t}$

$$E_{eff}\left(\Delta t + \frac{1}{2}\right) = \ln\left\{\frac{C(\Delta t)}{C(\Delta t + 1)}\right\}$$

- If dominated by E_n: $E_{eff} \approx E_n$
- Better: Take periodicity in Δt and excited states into account $\rightarrow$ fit $C(\Delta t)$ to $\cosh$-behaviour



Effective Mass

Variational Analysis

- Calculate Correlator-Matrix
  $C_{ij}(\Delta t) = \left\langle \mathcal{O}_i(\Delta t)\mathcal{O}_j^\dagger(0) \right\rangle = \sum_n \langle 0|\mathcal{O}_i|n\rangle \, \langle n|\mathcal{O}_j^\dagger|0\rangle \, e^{-E_n \Delta t}$
- Diagonalization disentangles physical states
  $\lambda_n(\Delta t) \propto e^{-E_n \Delta t}\big(1 + \mathcal{O}\big(e^{-\Delta E_n \Delta t}\big)\big)$

  [C. Michael, NP **B259** (1985) / M. Lüscher et al., NP **B339** (1990)]
- Interpolators should have large overlap with Eigenstates $|n\rangle$
- Eigenvectors give overlap of interpolators with the Eigenstates

Lüscher Analysis I

- Infinite Volume Spectrum can be calculated from Spectrum of different finite Volumes

  [M. Lüscher, CMP **105** (1986)]

- Needs to consider Bound-State nature
- Parametrization of Volume dependence (*a* and *b*: fit parameters)

$$m(V) = m_{inf} + ae^{-bV} \tag{1}$$

- Finite momentum states get additional polynomial contributions

Lüscher Analysis II

- Lüscher method: Particles in a box always interact $\rightarrow$ distortion of Energy levels

  [M. Lüscher, NP **B354** (1991) and NP **B364** (1991)]

- Relation between Energy levels E_n and Phaseshift δ_l for spinless particles in elastic region ($2M < E_n < 4M$)

$$\tan\left(\delta_l(q_n)\right) = \frac{\pi^{\frac{3}{2}} q_n}{Z_{00}^{\vec{0}}\left(1, q_n^2\right)} \qquad \text{with } E_n = 2\sqrt{M^2 + \left(q_n \frac{2\pi}{L}\right)^2}$$

$$Z_{lm}^{\vec{d}}(r, q^2) = \sum_{\vec{x} \in P_{\vec{d}}} \frac{\left|\vec{x}\right|^l Y_{lm}(\vec{x})}{\left(\vec{x}^2 - q^2\right)^r} \quad \text{with } P_{\vec{d}} = \left\{ \left(\vec{u} + \frac{\vec{d}}{2}\right) \,\middle|\, \vec{u} \in \mathbb{Z}^3 \right\}$$

- Different Volumes or moving Scattering states needed for reliable data $\rightarrow$ further things need to be considered