A manifestly gauge-invariant treatment of the Minimal Supersymmetric Standard Model

Philipp Schreiner

Institute of Physics, University of Graz
Supervisor: Axel Maas

September 28, 2022

NAWI Graz
Natural Sciences

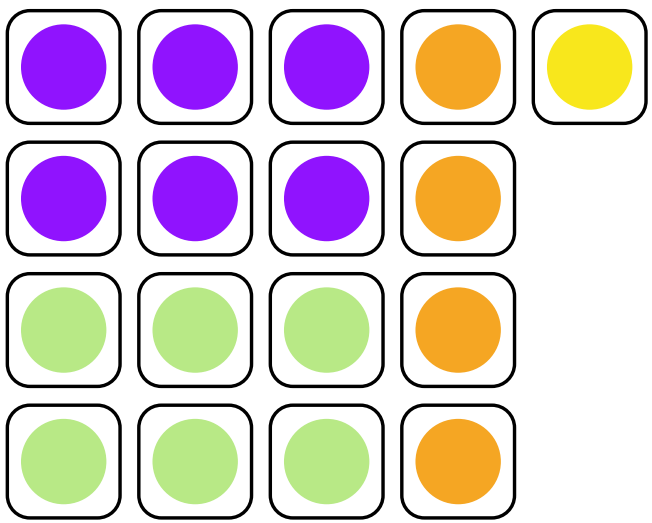
supported by Paul-Urban-Stiftung

Gauge Theories

- Well established construction principle for fundamental theories in particle physics (e.g. Standard Model)
- Elegant mathematical framework
- Introduction of redundant degrees of freedom

Important Question

What are the **physical** degrees of freedom?



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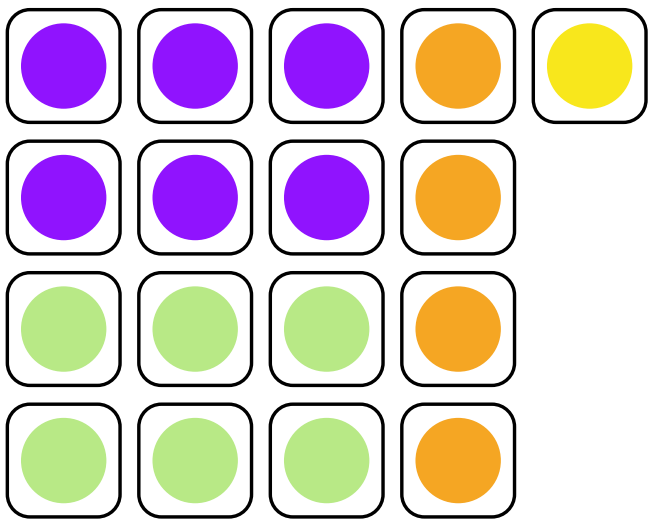


Perturbation Theory (PT)

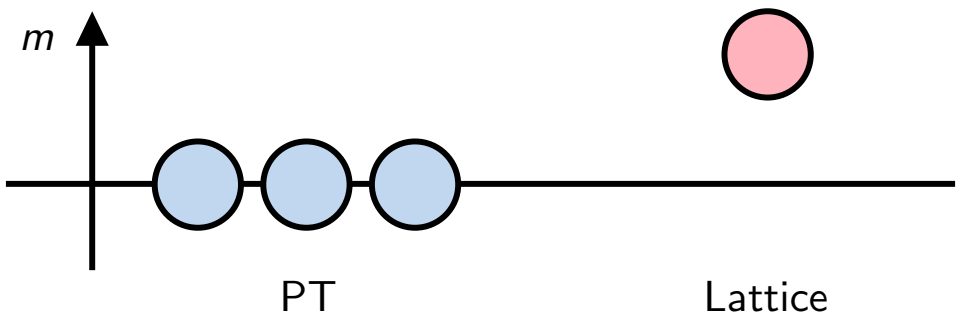
- Gauge-Fixing (c.f. Coulomb Gauge)
- BRST Construction (extract physical states)

Beyond Perturbation Theory

- Non-perturbative methods for large coupling, bound states
- Examples: Lattice Field Theory, Functional Methods

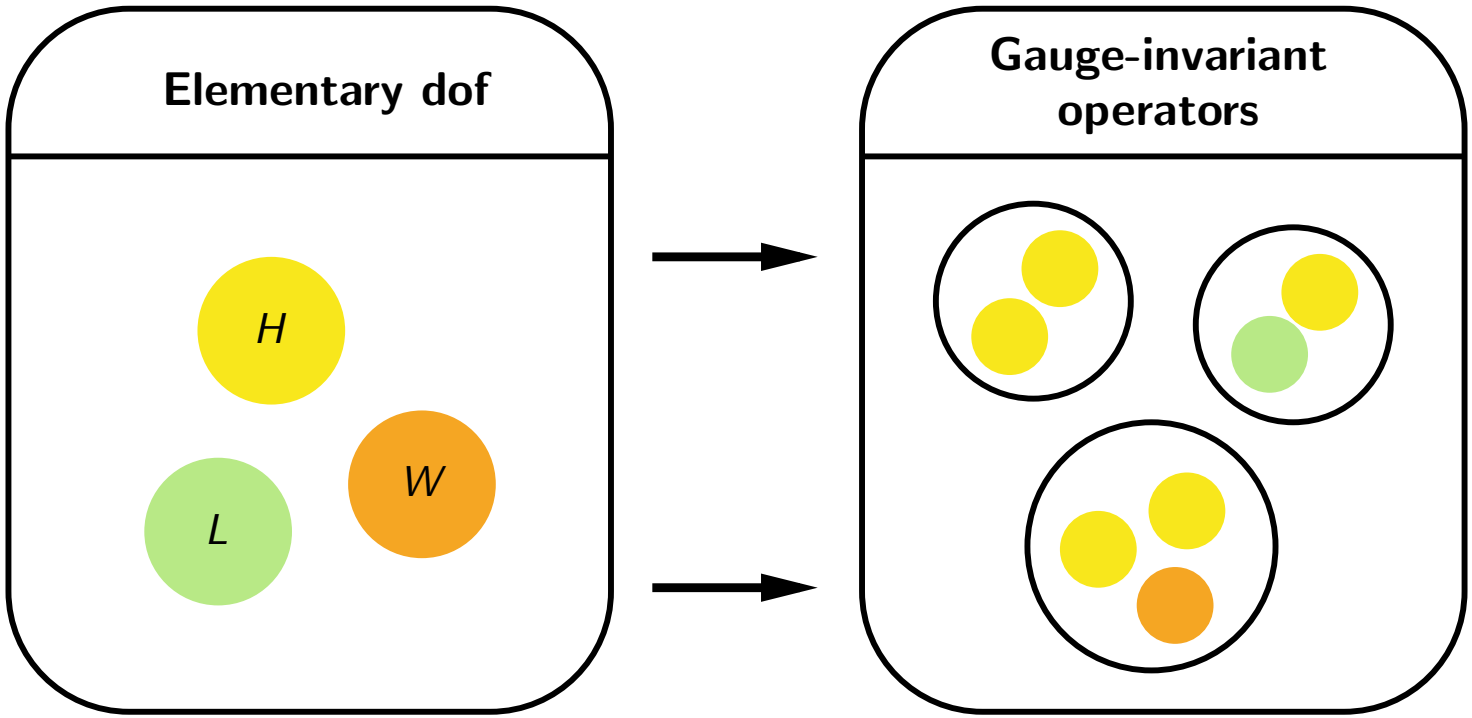
Subtleties and Problems

- Fixing gauge uniquely in general not possible (locally)
  [Gribov, Nucl. Phys. B 139 (1978), Singer, Commun. Math. Phys. 60 (1978)]
- Perturbative BRST construction fails in general
  [Neuberger, Phys. Lett. B 183 (1987)]
- Non-perturbative **physical** states might differ from PT
  [Maas and Török, Phys. Rev. D 95 (2017)]



A shift of view

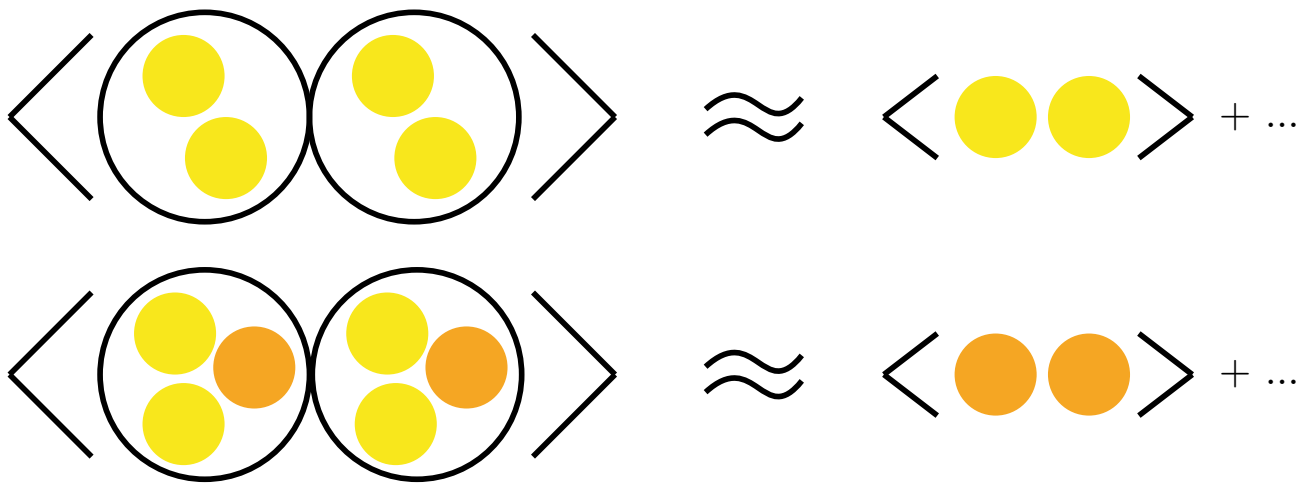
- Introduce **inherently gauge-invariant** (physical) objects
- Spin, Parity, etc. carried by composite operators
- Do PT with those objects (in a special sense)



The FMS Mechanism

[Fröhlich, Morchio, and Strocchi, Phys.Lett.B 97 (1980)]

- In theories with Brout-Englert-Higgs effect
- Expand Higgs field; $H(x) = v + \varphi(x)$

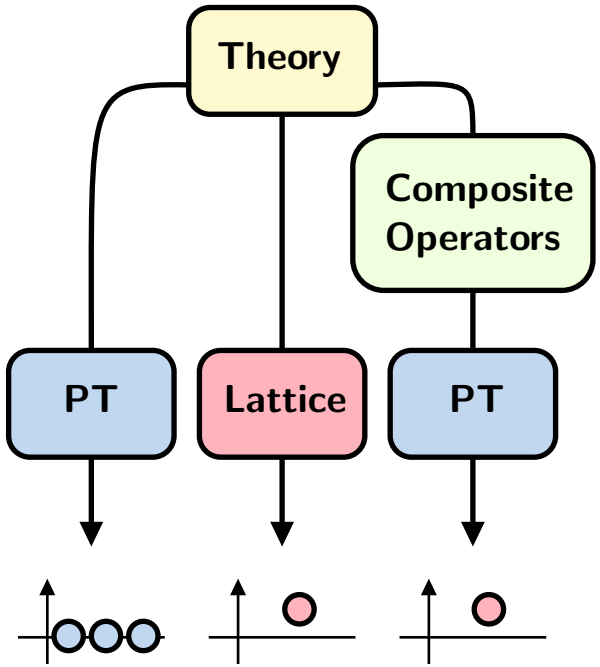


- Propagation of elementary fields $\leftrightarrow$ propagation of gauge-invariant operators with identical quantum numbers (**Augmented Perturbation Theory**)

Augmented Perturbation Theory

Known Results

- ✓ Operator description reduces to PT in SM; Review:
  [Maas, Prog.Part.Nucl.Phys. 106 (2019)]
- ✓ Correct spectrum for BSM toy theory and extensions
  [Maas and Török, Phys. Rev. D 95 (2017), Maas, Sondenheimer, and Török, Annals Phys. 402 (2019)]



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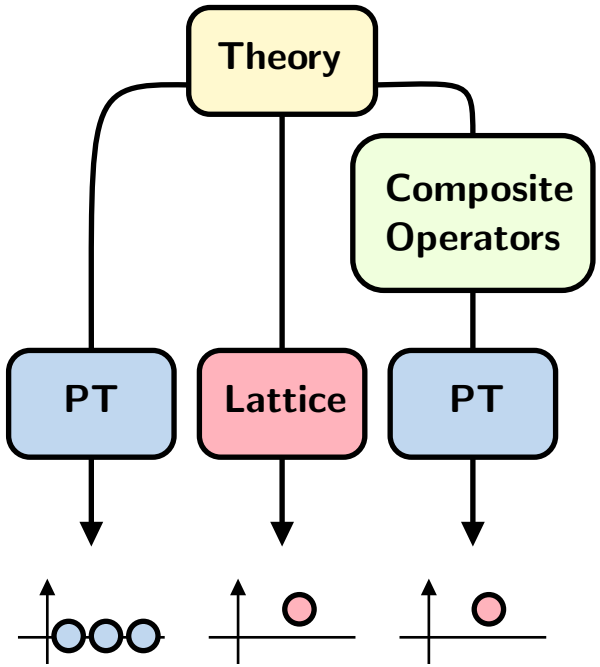


Conclusion

Especially when studying BSM theories one should investigate whether the spectrum predicted by standard PT is even physical!

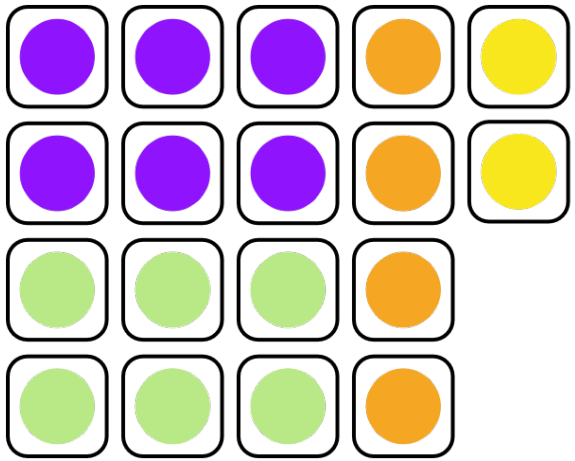
The Minimal Supersymmetric Standard Model (MSSM)

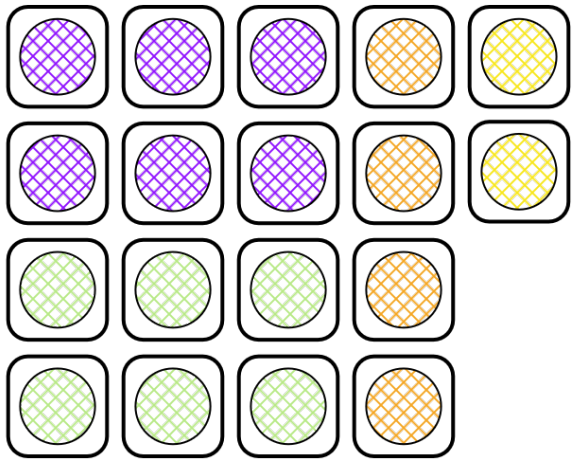
Motivations

- Fine-tuning problem
- Gauge-coupling-unification
- Supergravity
- Rich Phenomenology (Dark Matter)

The MSSM

- Every SM particle gets superpartner
- Additional Higgs (2HDM)
- Soft-breaking necessary
- Keep $SU(2)_{\text{cust}}$





Gauge-invariant description of the MSSM

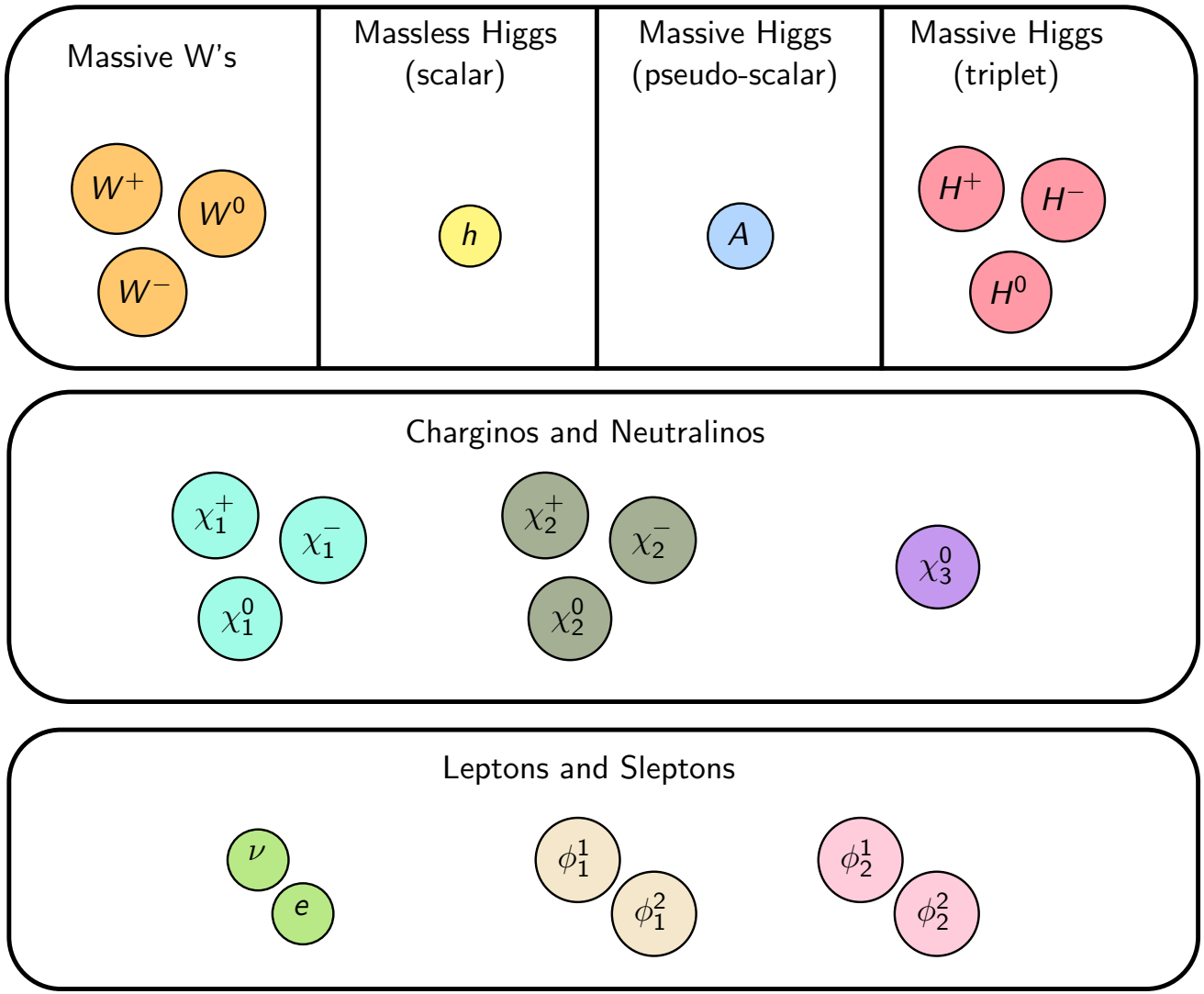
Proceeds in three steps

1. Find perturbative mass eigenstates
2. Build gauge-invariant operators
3. Apply FMS mechanism

For simplicity: Keep custodial symmetry intact for now and consider only weak-Higgs sector as well as one lepton generation.

Gauge-invariant description of the MSSM

1. Mass eigenstates predicted by PT



Gauge-invariant description of the MSSM

2. Inherently gauge-invariant composite operators

Operator	Spin	$SU(2)_{\text{cust}}$
$tr\ H^\dagger H$	0	**1**
$Im\ det\ H$	0	**1**
$tr\ H^\dagger H\sigma^A$	0	**3**
$tr\ H^\dagger D_\mu H\sigma^A$	1	**3**
$tr\ H^\dagger \tilde{H}$	1/2	**1**
$tr\ H^\dagger \tilde{H}\sigma^A$	1/2	**3**
$tr\ H^\dagger\sigma^a H\tilde{W}_a$	1/2	**3**

Gauge-invariant description of the MSSM

3. FMS Mechanism

Operator	Spin	$SU(2)_{\text{cust}}$	Expansion
$tr\ H^\dagger H$	0	**1**	h
$Im\ det\ H$	0	**1**	A
$tr\ H^\dagger H\sigma^A$	0	**3**	H^0 H^+ H^-
$tr\ H^\dagger D_\mu H\sigma^A$	1	**3**	W^0 W^+ W^-
$tr\ H^\dagger \tilde{H}$	1/2	**1**	χ_3^0
$tr\ H^\dagger \tilde{H}\sigma^A$	1/2	**3**	χ_1^0 χ_1^+ χ_1^-
$tr\ H^\dagger \sigma^a H\tilde{W}_a$	1/2	**3**	χ_2^0 χ_2^+ χ_2^-

Remarks and Summary

Further Results

- Broken symmetry: multiplets split, mapping still works
- Can be extended to entire MSSM

Conclusion

- Perturbative mass spectrum of MSSM can be *augmented* by inherently gauge-invariant description
- No qualitative difference expected to usual PT results