Scale Hierarchies and Cosmology with an Emergent Particle Physics Standard Model

Steven Bass

- Gauge symmetries determine our interactions: Where do they come from?

- Vacuum stability for the Standard Model
- Scale hierarchies in particle physics
  - Cosmological constant scale $\ll$ Higgs and Planck masses
  - Higgs mass $\ll$ Planck scale

- Hints for new particles or something deeper?
  - Connecting the cosmological constant and (Majorana) neutrino masses
  - IR-UV correspondence and parallels with anomaly theory

Humboldt Kolleg, Kitzbühel June 28th 2022

Emergent Symmetries and Particle Physics

- Are (gauge) symmetries always present ?

  (Gauge symmetries determine our particle interactions)

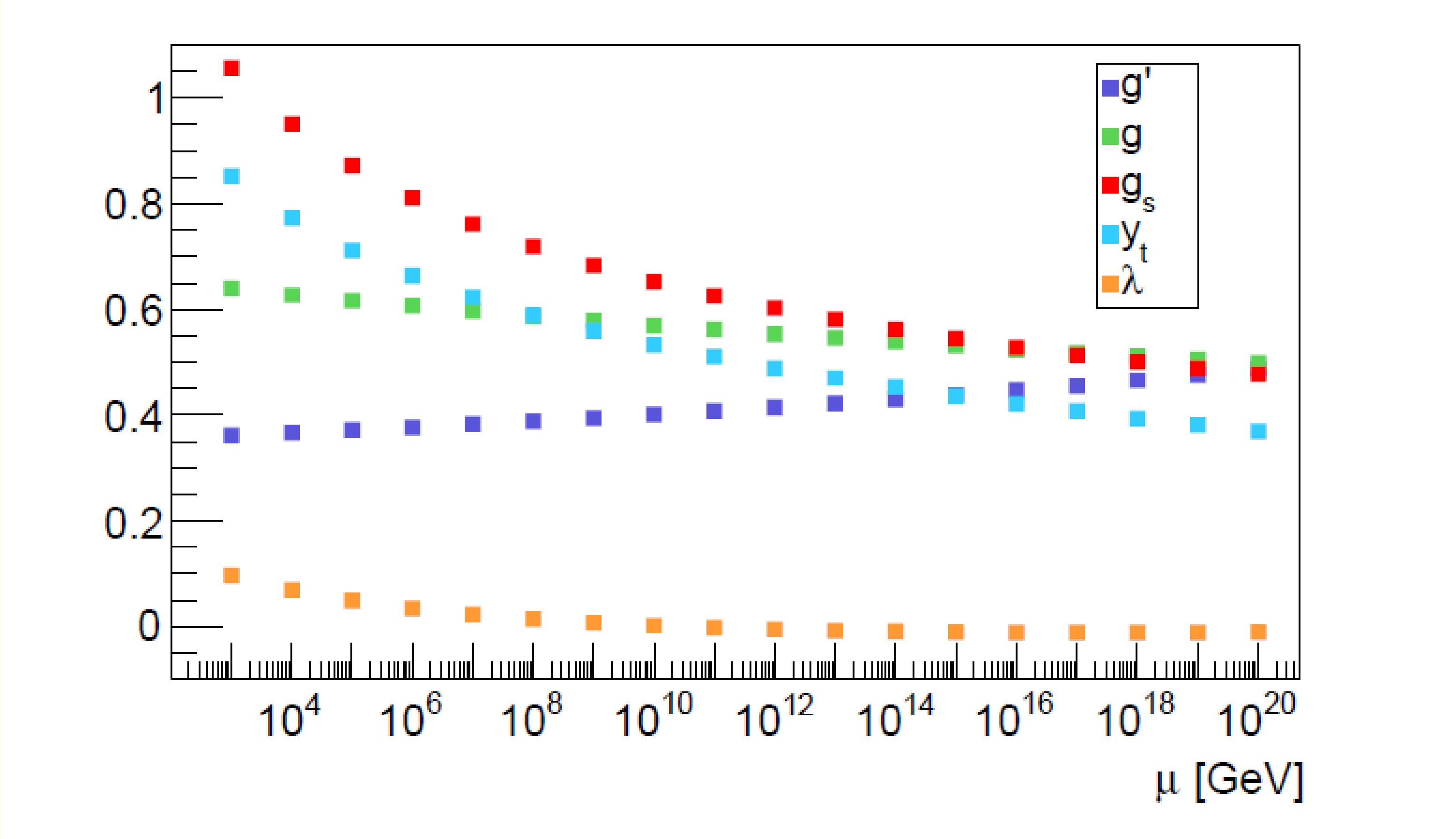
  Making symmetry as well as breaking it

- Emergence: Many body system exhibits collective behaviour in the IR which is qualitatively different from that of its more primordial constituents as probed in the UV.
  - » *Can give extra symmetry in the IR, absent in the UV.*

  - Gauge symmetries dissolving in the UV instead of extra unification
- Standard Model as long range tail of critical system which sits close to Planck scale [Jegerlehner, Bjorken, Nielsen ...].
- Examples in quantum many-body physics: Fermi-Hubbard, Superfluid ^{3}He-A

Running couplings

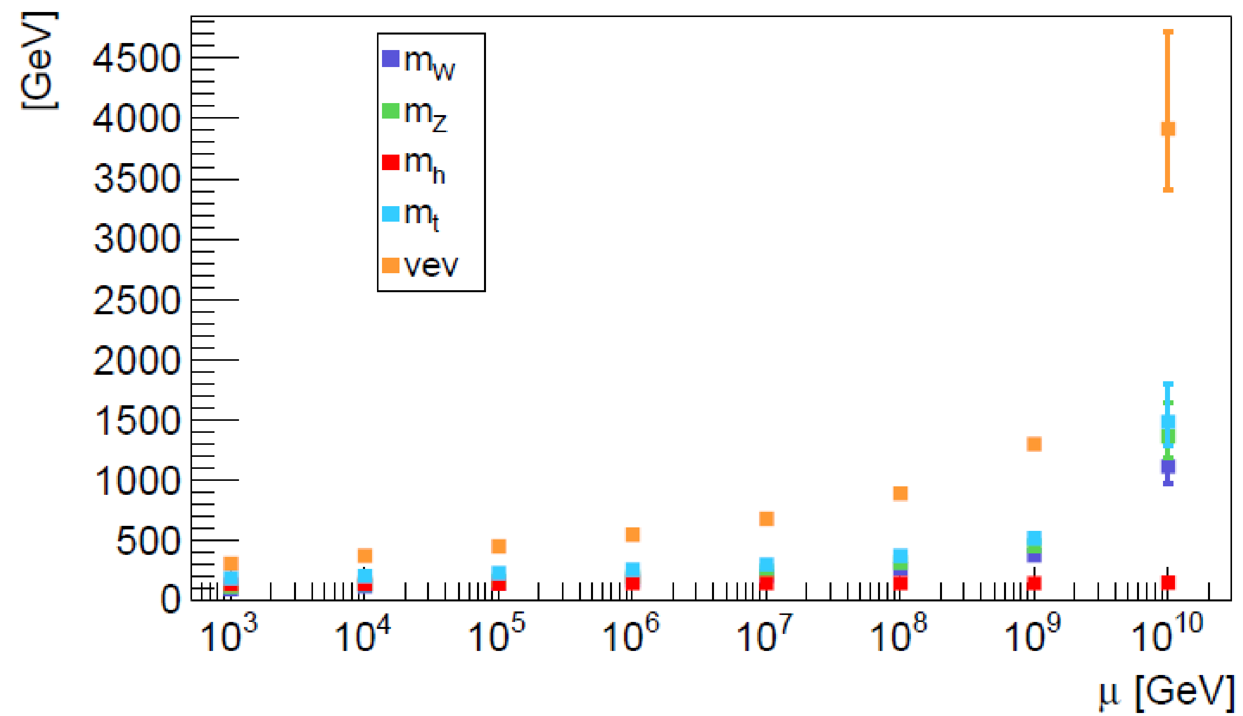
- Running Standard Model parameters [C++ code of Kniehl et al, 2016]



$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

Running masses and Higgs vev

- Running Standard Model parameters [C++ code of Kniehl et al, 2016]
  - Running W, Z, top and Higgs masses and Higgs vev



$$m_h^2 = 2\lambda v^2$$

$$m_W^2 = \frac{1}{4}g^2 v^2, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

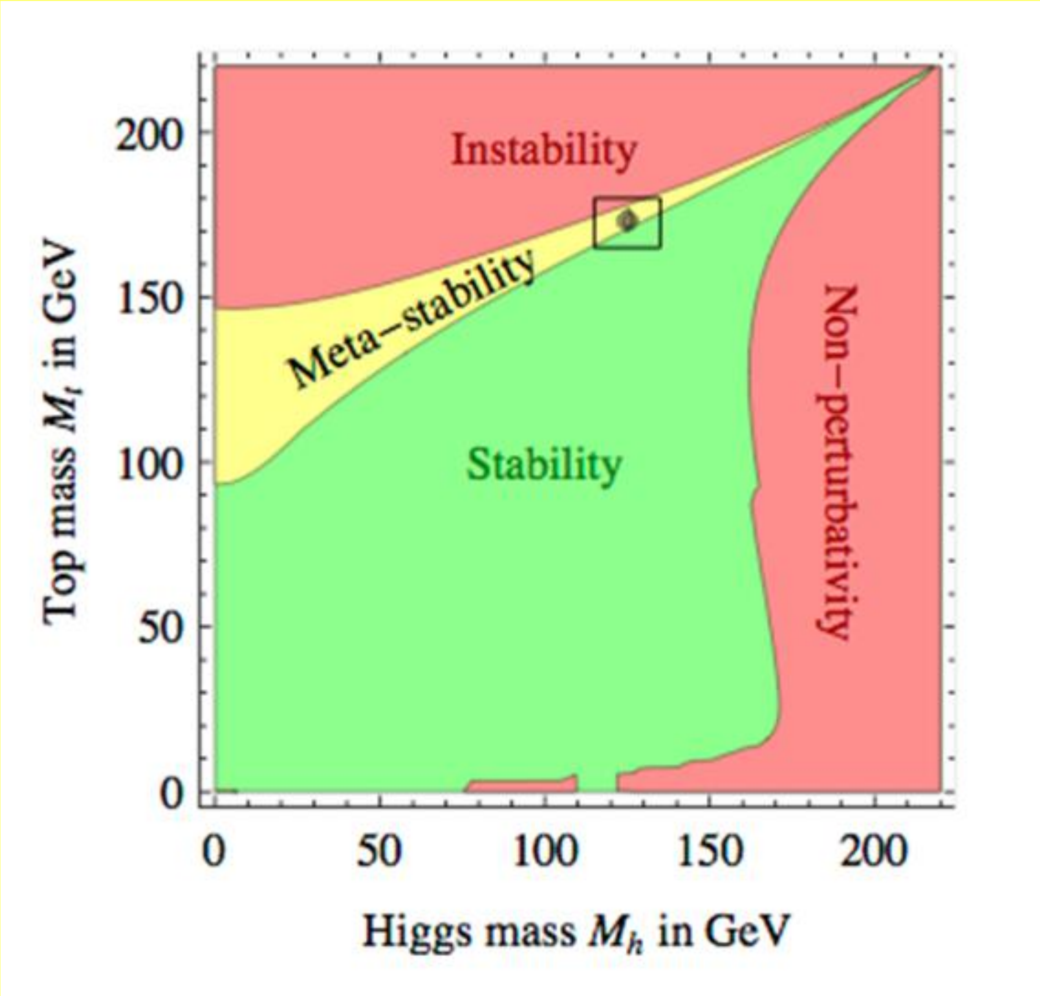
$$m_f = y_f \frac{v}{\sqrt{2}} \qquad (f = \text{quarks and charged leptons})$$

Results from LHC: Critical physics in UV ?

- LHC: So far just Standard Model Higgs and no new particles

- Running masses in loops
- Remarkable: the Higgs and top mass sit in window of possible parameter space where the Standard Model is a consistent theory up to the Planck mass close to the border of a stable and meta-stable vacuum.

- Possible critical phenomena in the extreme ultraviolet.



$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

An emergent particle physics

- (Topological) phase transition ← new dof including gauge symmetries
  - E.g. from Condensed Matter: ^{3}He-A and string-nets, Fermi-Hubbard
  - Or RG decoupling of g.i. (plus Lorentz) violating terms in the IR
  - Critical dimension – might 3+1 dimensions be special?

- Below phase transition
- Renormalised (finite) QFT with massless J=1 excitations → gauge theory!

- Unitarity with massive J=1 bosons → Higgsed and Yang-Mills structure

- Small gauge groups most probably prefered (and issue of chiral fermions)

- Possible hint for emergence scenario
  - vacuum stability and perhaps new critical phenomena in the UV

- Effective theory supplemented by IR-UV correspondence with Higgs mass perhaps connected to vacuum stability.

Emergent Symmetries

- Standard Model as an effective theory with infinite tower of higher dimensional operators, suppressed by powers of the (large) emergence scale M

- Global symmetries tightly constrained by gauge invariance and renormalisability when restricted to dimension 4 operators, e.g. QED

$$\mathcal{L} = \bar{\psi} i \gamma^\mu D_\mu \psi - m\bar{\psi}\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- Can be broken in higher dimensional operators, suppressed by powers of M

- Examples, lepton and baryon number violation, Weinberg, PRL 1979

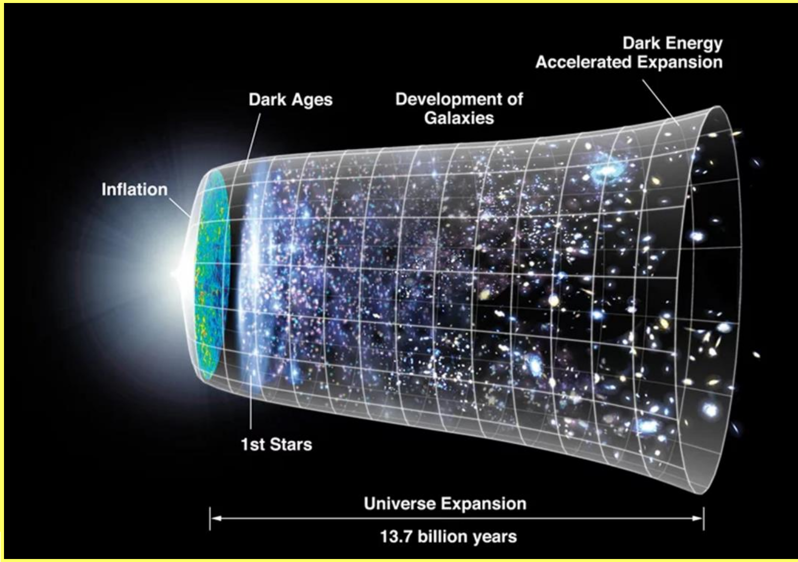
- E.g. Lepton number violation ← Majorana neutrino masses at mass dimension 5 (Weinberg)

$$O_5 = \frac{(\Phi L)_i^T \lambda_{ij} (\Phi L)_j}{M}$$

$$m_\nu \sim \Lambda_{\rm ew}^2 / M$$

The Cosmological Constant

- Vacuum energy is measured just through the Cosmological Constant in General Relativity



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

- Energy density $\rho_{\text{vac}} = \Lambda/(8\pi G)$

receives contributions from ZPEs, vacuum potentials (EWSB, QCD) plus gravitational term

$$\rho_{\text{vac}} = \rho_{\text{zpe}} + \rho_{\text{potential}} + \rho_{\Lambda},$$

- The Cosmological Constant determines accelerating expansion of the Universe ← it is an observable and therefore RG scale invariant
  - Numerically, astrophysics (Planck) tells us $\rho_{vac} \sim (0.002\ \text{eV})^4$

Cosmological Constant

- Is an observable and therefore RG scale invariant

$$\frac{d}{d\mu^2}\rho_{\rm vac} = 0.$$

$$\rho_{\rm vac} = \rho_{\rm zpe} + \rho_{\rm potential} + \rho_\Lambda ,$$

- Scale dependence (explicit μ, in masses and couplings) cancels:
  What is left over?

- Curious: With finite Cosmological Constant there is no solution of Einstein's equations of GR with constant Minkowski metric (Weinberg, RMP)
  - No longer global space-time translational invariant
  - Metric is dynamical with accelerating expansion of the Universe
  - Cf. Success of special relativity and usual particle physics in Lab

Cosmological Constant Scale

- Zero cosmological constant makes sense at dimension 4
  - E.g. Global Minkowski metric works in laboratory experiments

- Cosmological constant scale then suppressed by power of M
  - 4 dimensions of space-time, so to power of 4 in CC

- Then, scale of Cosmological Constant ~ scale of neutrino mass ~ 0.002 eV

$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2/M$$

[SDB+J.Krzysiak, PLB803 (2020) 135351]

Hierarchy Puzzles - Zero Point Energies

- Zero point energies (important through Cosmological Constant)

$$\rho_{\rm zpe} = \frac{1}{2}\sum\{\hbar\omega\} = \frac{1}{2}\hbar \sum_{\rm particles} g_i \int_0^{k_{\rm max}} \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m^2}.$$

- Symmetries – Covariance - and the correct vacuum Equation of State

$$\rho_{\rm zpe} = -p_{\rm zpe} = -\hbar\, g_i\, \frac{m^4}{64\pi^2}\left[\frac{2}{\epsilon} + \frac{3}{2} - \gamma - \ln\left(\frac{m^2}{4\pi\mu^2}\right)\right] + \ldots$$

- For Standard Model particles, ρ_{zpe} comes from coupling to the Higgs
  - Proportional to particle masses, m^4
  - Imaginary part for Higgs with vacuum instability

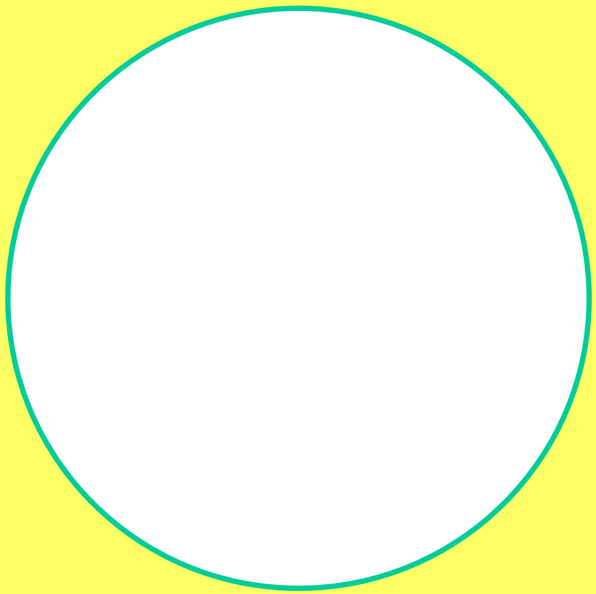
$$m_h^2 = 2\lambda v^2$$

- (Using a brute force cut-off gives radiation EoS, $\rho=3p$, for leading term)
  - Reminds one of Anomalies with symmetries and UV regularisation...

Symmetries and anomalies

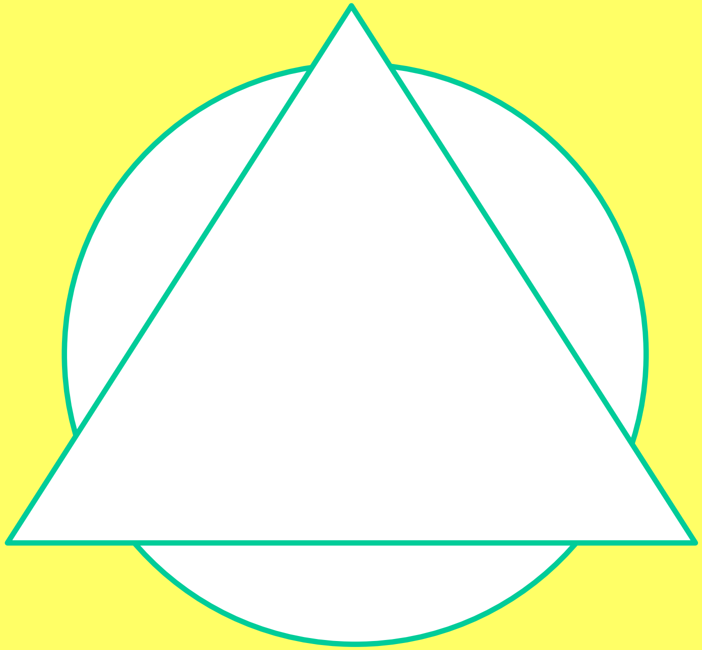
- Symmetries and UV regularization

- Need to define „infinite“ momentum consistent with how nature works



Symmetries and anomalies

- Symmetries and UV regularization
- Need to define „infinite“ momentum consistent with how nature works



- Famous examples: $\pi^0 \to 2\gamma$, η' mass in QCD

Parallels with Anomalies

- Parallels with anomaly theory and fixing the symmetries

$$\partial^\mu J_{\mu 5} = \sum_q 2m_q \bar{\psi}_q i\gamma_5 \psi_q + 3\frac{\alpha_s}{4\pi} G.\tilde{G}$$

$$J_{\mu 5} = J^{\rm con}_{\mu 5} + K_\mu$$

$$K^\mu = \frac{g^2}{32\pi^2} \epsilon^{\mu\alpha\beta\gamma} A^a_\alpha \left(G^a_{\beta\gamma} - \frac{1}{3} g c^{abc} A^b_\beta A^c_\gamma\right)$$

- 1. ZPEs and symmetries with the regularisation ← the ZPE vacuum EoS
- 2. Similarities between ρ_Λ and K_μ in fixing the symmetries, IR-UV correspondence
- Effect through QCD phase transition, e.g., in the early Universe.
  - The observable net ρ_{vac} is conserved, related to the symmetries of the metric to this order, D=4.
- Uniqueness of ρ_{vac} fixed by the symmetries of the metric and emergence

Emergent Gravitation (?)

- Scales of emergence, c.f. Energy penalty terms in quantum simulations

- If particle physics might be emergent, then what about gravitation, ..., „quantum" itself? Might these also be emergent?

- With emergent gravitation, what is the scale of emergence?
  - If below the Planck mass, then conventional „quantum gravity" ideas connected to unphysical extrapolation through the scale of emergence
  - Emergent GR purely classical, with tree-level gravitons or also loops?

- Effect in modified Heisenberg Uncertainty Relations

$$\Delta x \Delta p \geq \frac{1}{2}\hbar\left(1 + \mathcal{B}_0(\Delta p/(M_P c))^2\right)$$

  - Challenge for quantum optics and low energy neutron experiments
  - Possible 10^6 factor, so big enhancement to look for!

Extra reading

- *SDB, e-Print: 2110.00241 [hep-ph], Phil. Trans. Royal Society A*

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Research

Article submitted to journal

Emergent gauge symmetries - making symmetry as well as breaking it

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- *SDB, Prog. Part. Nucl. Phys. 113 (2020) 103756*

- *SDB + J Krzysiak, Phys. Lett. B 803 (2020) 135351*
- *SDB + J Krzysiak, Acta Phys. Polon. B 51 (2020) 1251*

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Vacuum energy with mass generation and Higgs bosons

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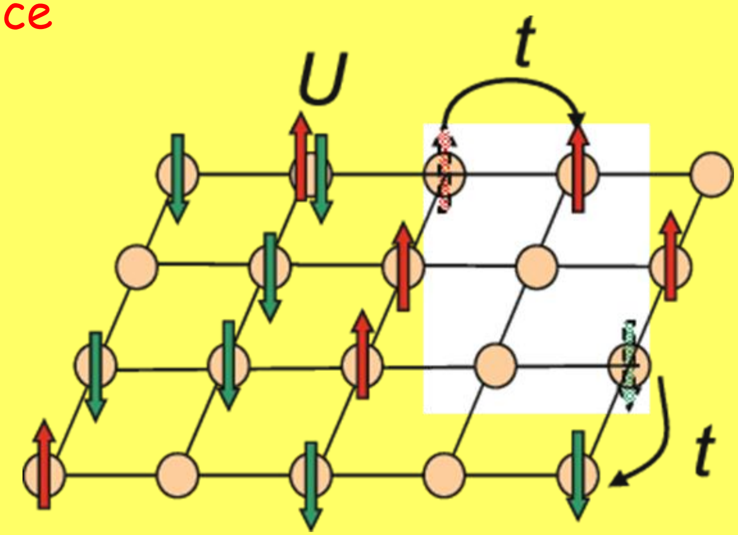
Example: Fermi-Hubbard Model

- Strongly correlated electron system on 2D lattice

$$\mathcal{H} = -t \sum_{(ij)\sigma} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}.$$



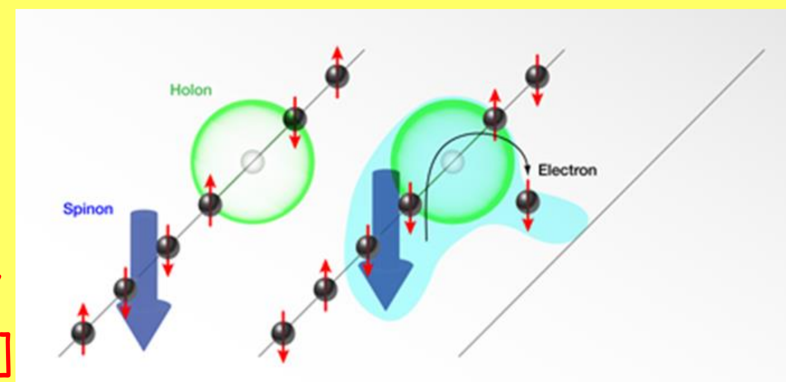
- Low energy limit at half filling, behaves like Heisenberg magnet

$$\mathcal{H}_{\text{eff}} = J \sum_{i,j} (c^\dagger_{i\alpha} \sigma_{\alpha\beta} c_{i\beta}).(c^\dagger_{j\alpha} \sigma_{\alpha\beta} c_{j\beta})$$

$$J = 4t^2/U$$

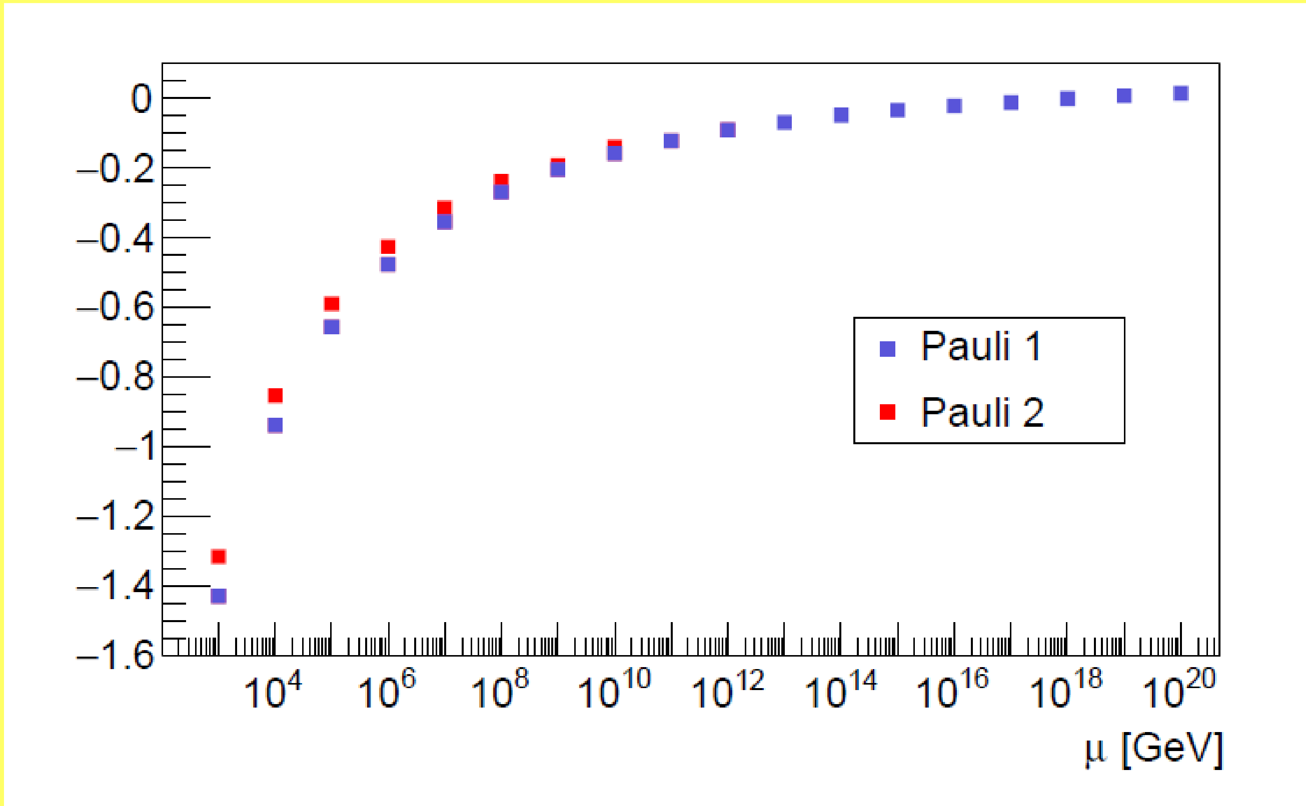
- Quasi-particles with spin-charge separation

- „Spinons" feel new local SU(2) gauge symmetry
  - [PW Anderson and collaborators, PRB 1988]



Running Pauli Conditions

Running Pauli conditions (bosons – fermions)



$$
\begin{aligned}
6m_W^4 + 3m_Z^4 + m_h^4 &= 12m_t^4 \\
6m_W^4 \ln m_W^2 + 3m_Z^4 \ln m_Z^2 + m_h^4 \ln m_h^2 &= 12m_t^4 \ln m_t^2
\end{aligned}
$$

normalised to v^4 (Pauli 1) and $v^4 \ln v^2$ (Pauli 2)