

The Cosmological Constant and Majorana Neutrinos with an Emergent 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 $\sim m_\nu \ll$ 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

VCES, Wien November 25th 2022

Emergent Symmetries and Particle Physics

- Are (gauge) symmetries always present ?

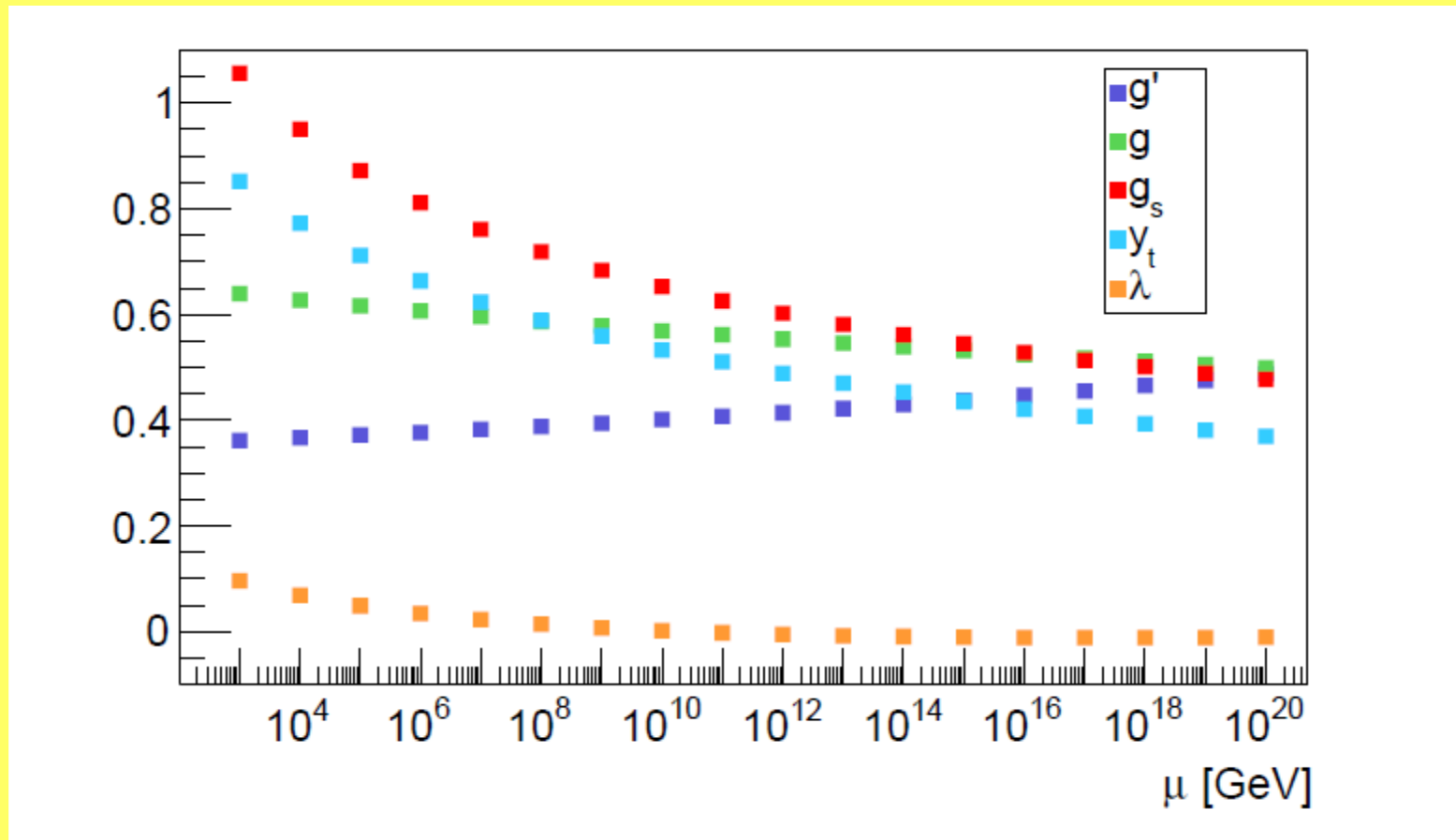
(Gauge symmetries determine our particle interactions)

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 $^3\text{He-A}$

Running couplings

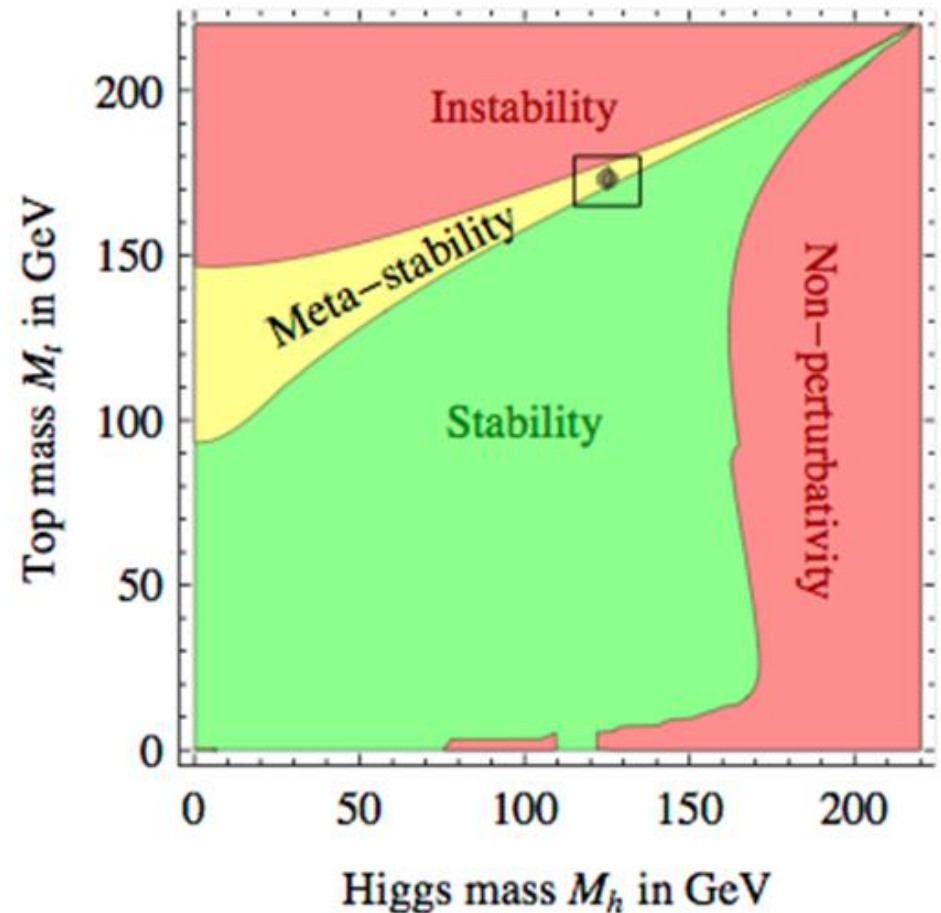
- Running Standard Model parameters [C++ code of Kniehl et al, 2016]



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

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 \leftarrow new dof including gauge symmetries
 - E.g. from Condensed Matter: $^3\text{He-A}$ 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, e.g., statistical system near critical point:
Renormalised (finite) QFT with massless $J=1$ excitations \rightarrow gauge theory!
- Unitarity with massive $J=1$ bosons \rightarrow Higgsed and Yang-Mills structure
- Small gauge groups most probably preferred (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, SM parameters 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 \leftarrow Majorana neutrino masses at mass dimension 5 (Weinberg)

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

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

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

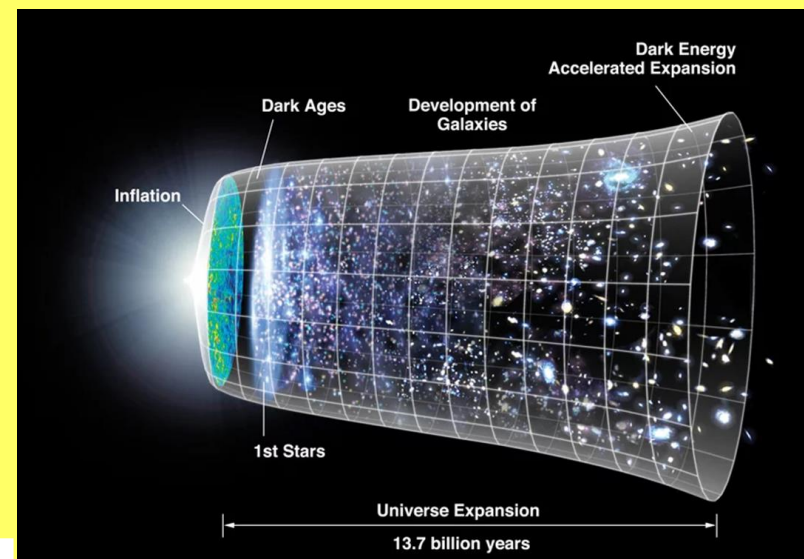
$$\rho_{\text{vac}} = \Lambda / (8\pi G)$$

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 $\rho_{\text{vac}} \sim (0.002 \text{ eV})^4$



Cosmological Constant

- Is an observable and therefore RG scale invariant

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

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

- 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

- With emergence spacetime translation invariance and 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 \sim scale of neutrino mass ~ 0.002 eV

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

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

Hierarchy Puzzles - Zero Point Energies

- Zero point energies (important through Cosmological Constant)

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

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

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

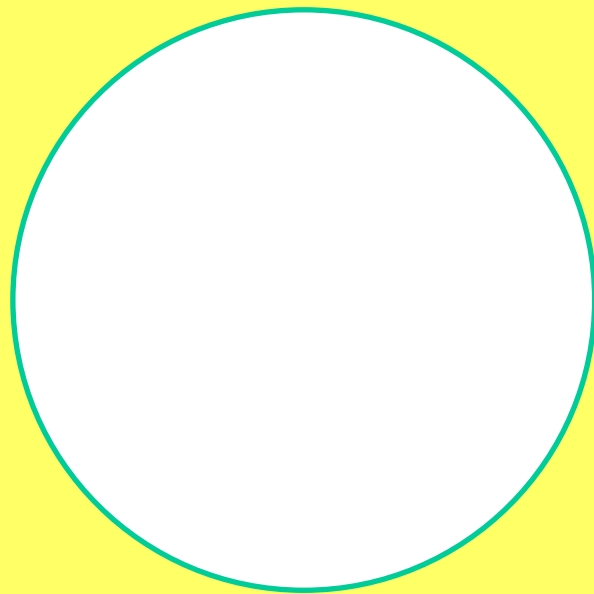
- For Standard Model particles, ρ_{zpe} comes from coupling to the Higgs
 - Proportional to particle masses, m^4
 - Imaginary part for Higgs with vacuum instability

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

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

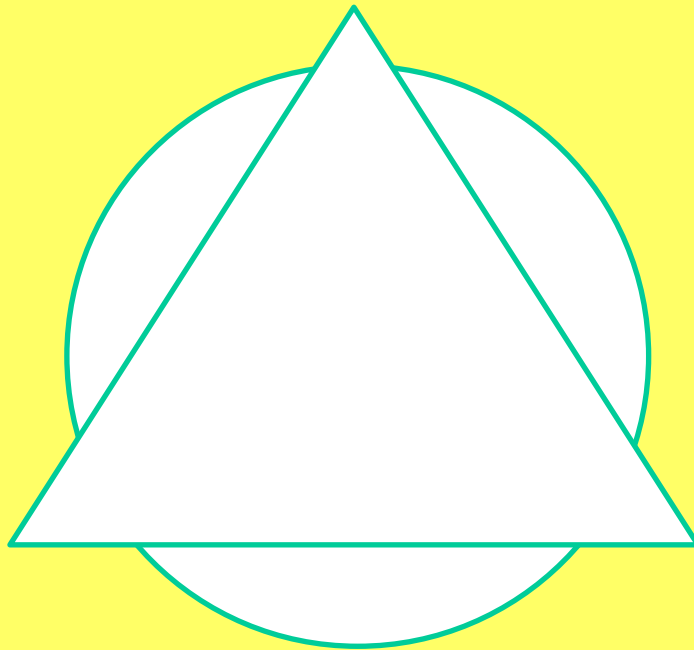
Symmetries and anomalies

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



Symmetries and anomalies

- Symmetries and UV regularization
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- Famous examples: $\pi^0 \rightarrow 2\gamma$, η' mass in QCD

Parallels with Anomalies

- Parallels with anomaly theory and fixing the symmetries

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

$$J_{\mu 5} = J_{\mu 5}^{\text{con}} + K_\mu$$

$$K^\mu = \frac{g^2}{32\pi^2} \epsilon^{\mu\alpha\beta\gamma} A_\alpha^a (G_{\beta\gamma}^a - \frac{1}{3} g c^{abc} A_\beta^b A_\gamma^c)$$

- 1. ZPEs and symmetries with the regularisation \leftarrow 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.
- Uniqueness of ρ_{vac} fixed by the symmetries of the metric and emergence

Emergent Gravitation (?)

- 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*



- *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*





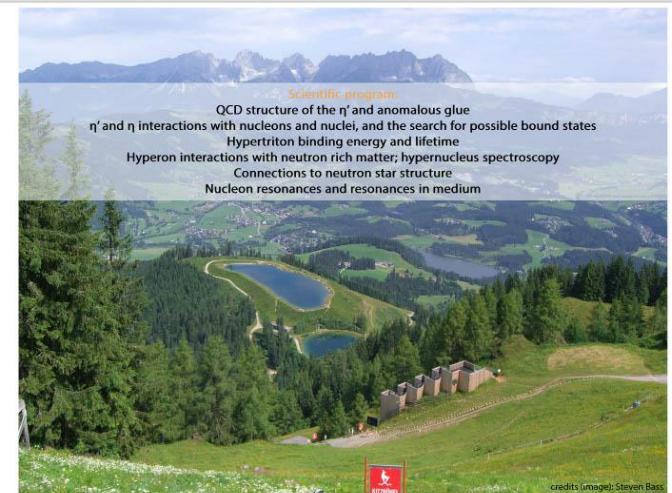
- Humboldt Kollegs 2016, 2019, 2022 on interface of particle, gravity and quantum physics
 - Showcased in CERN Courier, Sept. 2019
- EMMI workshop 2022
 - In total, participants from 15 countries (including 17 Humboldt Prize winners).
- Phil. Trans. Royal Society A
 - Theme issue „Quantum technologies in particle physics“ (eds. SDB and E Zohar)
- Nature Reviews Physics on the Higgs and on Quantum Sensing for HEP
- Outreach program for local schools

ExtreMe Matter Institute EMMI

EMMI Workshop

Meson and Hyperon Interactions with Nuclei

Kitzbuehel, Austria, September 14 - 16, 2022



Organizers:
S.D. Bass, K. Itahashi, V. Metag, K. Saito, C. Scheidenberger, Y. Tanaka

Website:
<https://indico.gsi.de/event/14405/>

Information:
www.gsi.de/emmi/workshops

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Kitzbühel as a Centre for Physics



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MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

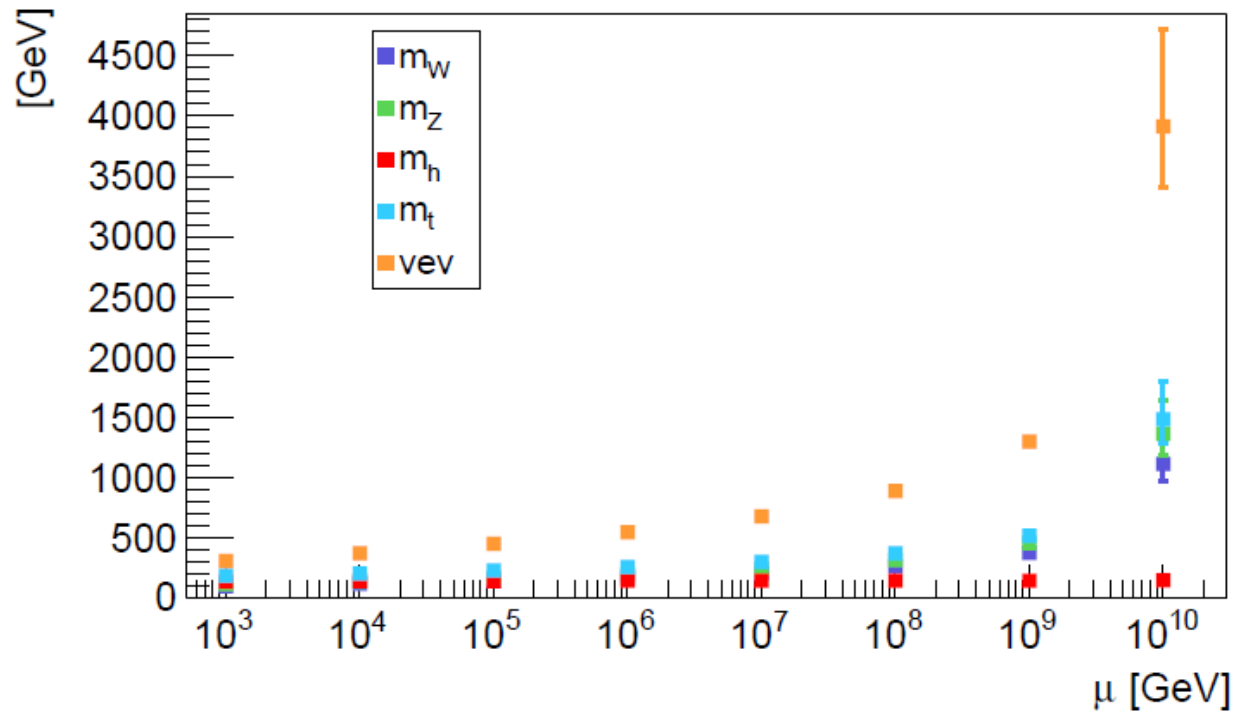
Quantum technologies in particle physics

Theme issue compiled and edited by Steven D. Bass and Erez Zohar



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



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

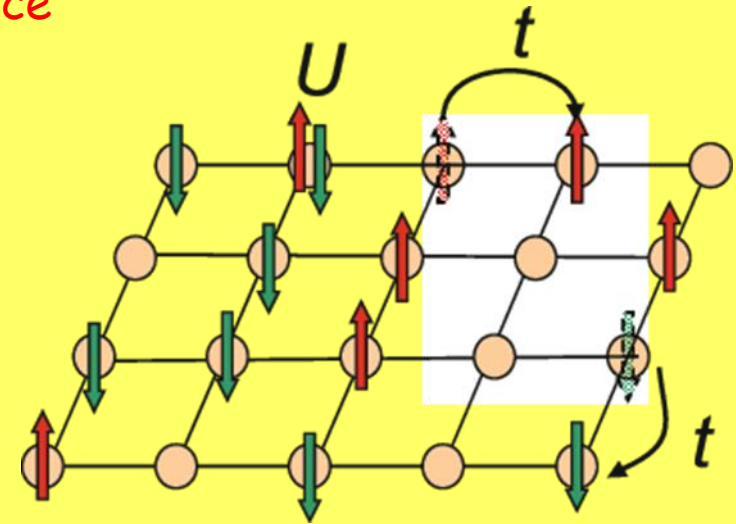
$$m_W^2 = \frac{1}{4}g^2 v^2, \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

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

Example: Fermi-Hubbard Model

- Strongly correlated electron system on 2D lattice

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

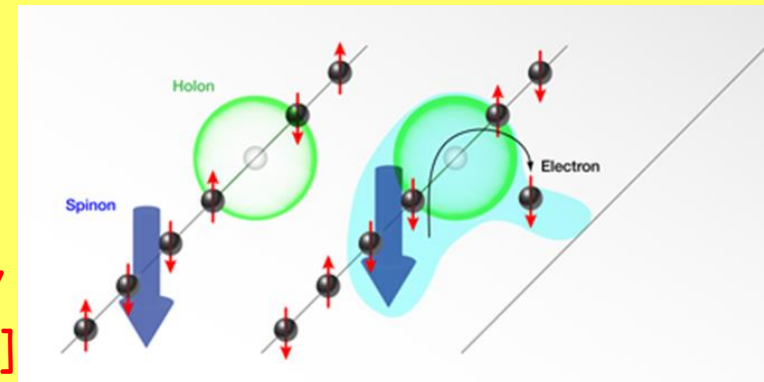


- Low energy limit at half filling, behaves like Heisenberg magnet

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

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

- Quasi-particles with spin-charge separation
- „Spinons“ feel new local SU(2) gauge symmetry
 - [PW Anderson and collaborators, PRB 1988]

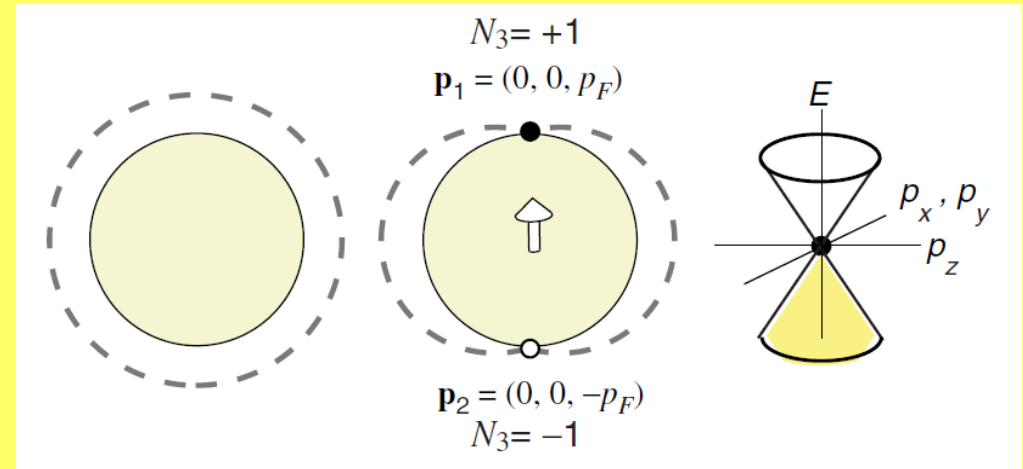


Superfluid $^3\text{He-A}$ with Fermi points

- Emergent gauge symmetries ($SU(2)$ and $U(1)$) plus chiral fermions and limiting velocities. Spin dof becomes dynamical to an internal observer [Volovik].

$$E^2(p) = \left(\frac{p^2}{2m} - \mu \right)^2 + c_\perp^2 (p \times \hat{l})^2,$$

[Anderson+Morel, 1961]



- Green's function

$$\mathcal{G}^{-1}(p_0) = e_i^k \Gamma^i \cdot (p_k - p_k^0) + \text{higher order terms}$$

$$N_3 = \text{tr} \mathcal{N}, \quad \mathcal{N} = \frac{1}{24\pi^2} \epsilon_{\mu\nu\lambda\gamma} \int_\sigma dS^\gamma \mathcal{G} \partial_{p_\mu} \mathcal{G}^{-1} \mathcal{G} \partial_{p_\nu} \mathcal{G}^{-1} \mathcal{G} \partial_{p_\lambda} \mathcal{G}^{-1}$$

$$H = +c\sigma \cdot p \rightarrow e_i^k \Gamma^i \cdot (p_k - p_k^0)$$

$$E^2 \rightarrow g^{\mu\nu} (p_\mu - eA_\mu - e\tau \cdot W_\mu) (p_\nu - eA_\nu - e\tau \cdot W_\nu) = 0$$