Muon $g-2$ — theory

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Big Questions in . . . Muon $g-2$ — Colloquium
17th September 2021

BSM-Collaborators: Peter Athron, Csaba Balasz, Douglas Jacob, Wojciech Kotlarski, Hyejung Stöckinger-Kim

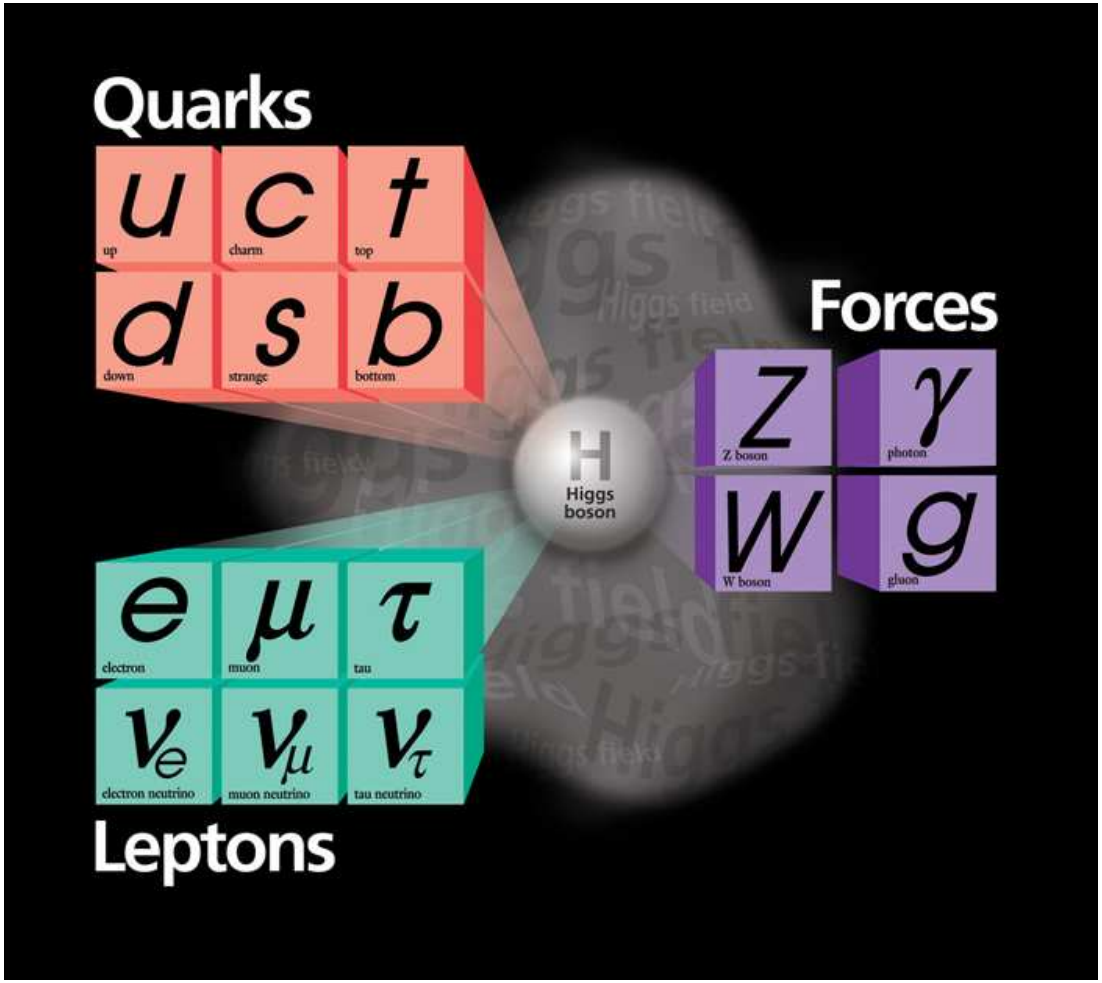
- Brief motivation/definitions
- SM situation
- BSM: general remarks, examples of models, relations to big questions

Frontiers

- High-energy LHC, future e^+e^-, muon colliders ...
- Precision, rare, neutrino $g-2$, flavor physics, dark sectors ...
- Cosmic dark matter searches, dark energy, ...
- ...

Broad programme to investigate open questions — how does $g-2$ fit in?

Standard Model of particle physics (est. 1967...1973))



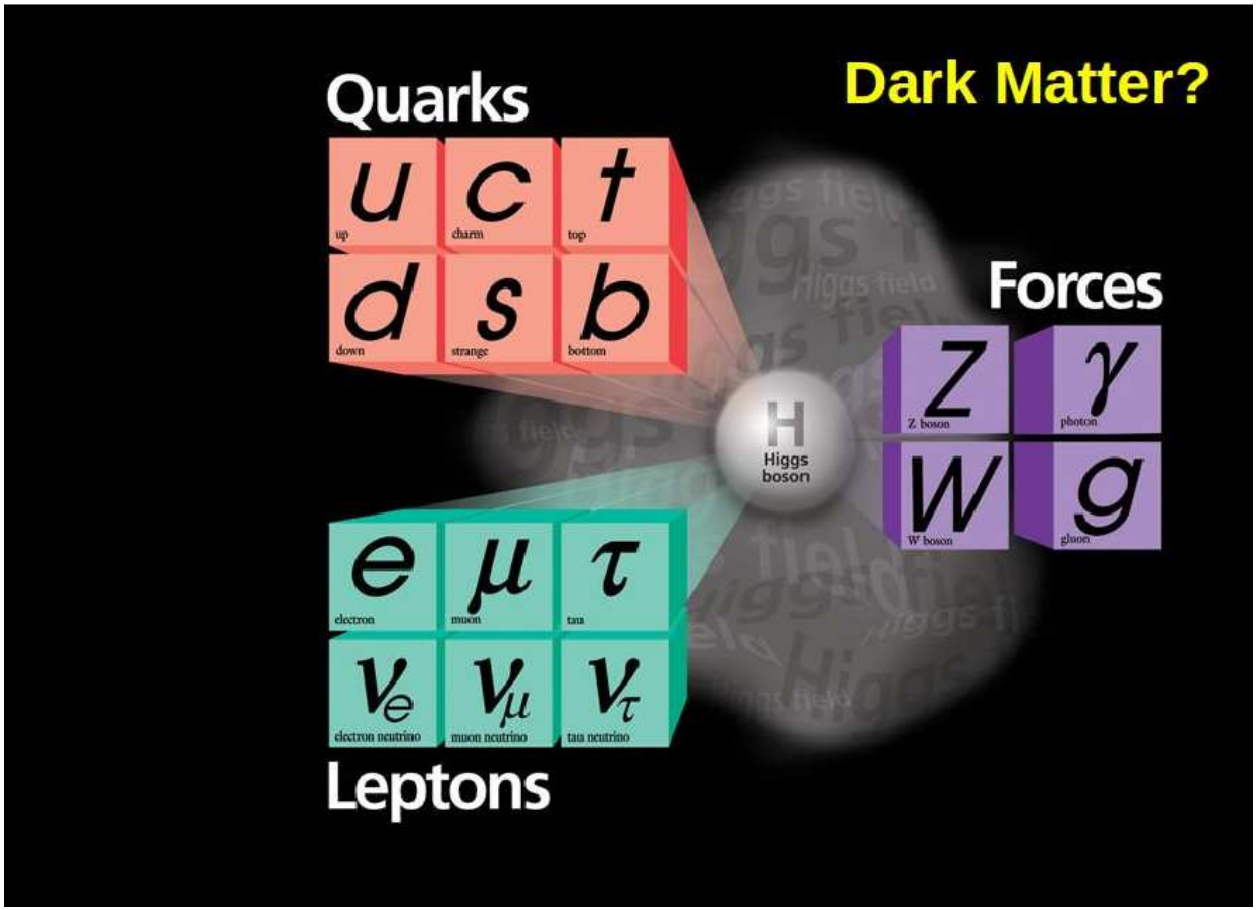
SM very well confirmed!

- All known interactions ($\neq$ gravity)
- relativistic QFT $\rightsquigarrow$ renormalizable
- gauge invariance $\rightsquigarrow$ specific interactions
- spontaneous EWSB $\rightsquigarrow$ Higgs

Open questions!

a_μ sensitive to all particles and forces via quantum fluctuations!

Open questions require Beyond the Standard Model (BSM) physics



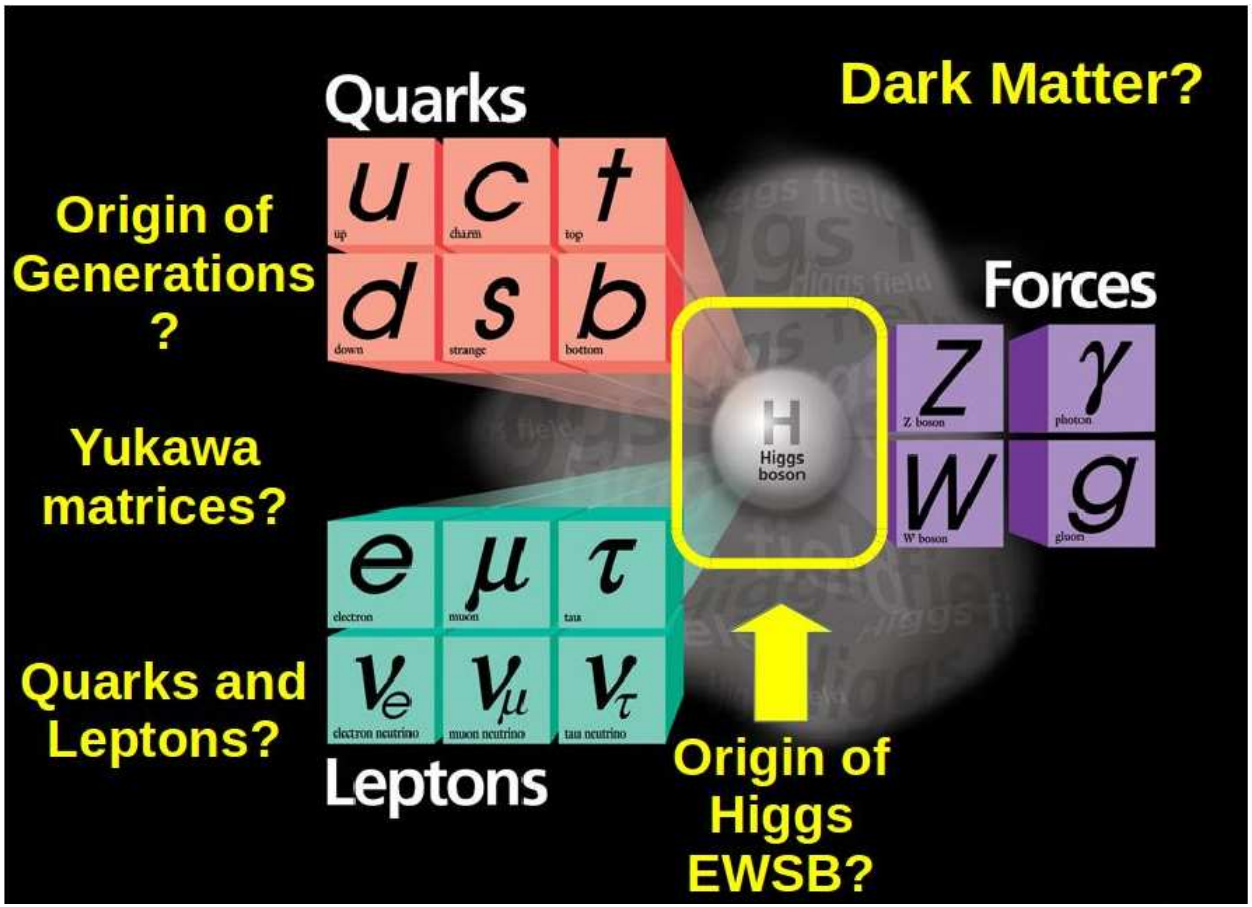
Open questions!

- experimental clues needed! $\rightsquigarrow g-2$!

  not easy to explain!

- relevant and deep questions may be related to $g-2$

Open questions require Beyond the Standard Model (BSM) physics



Open questions!

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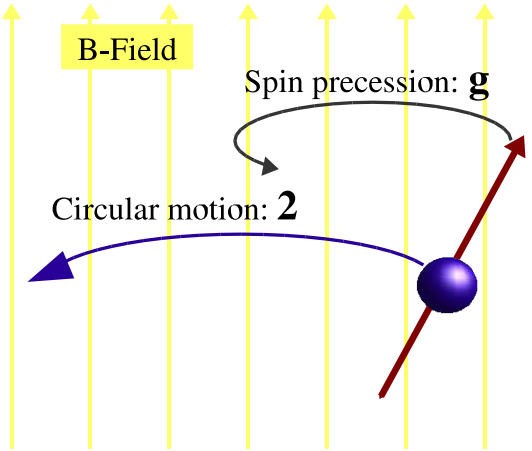
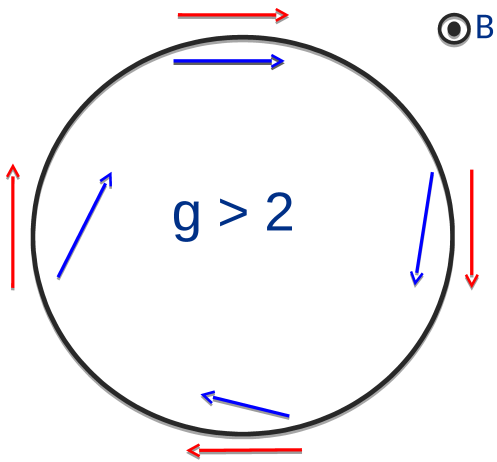
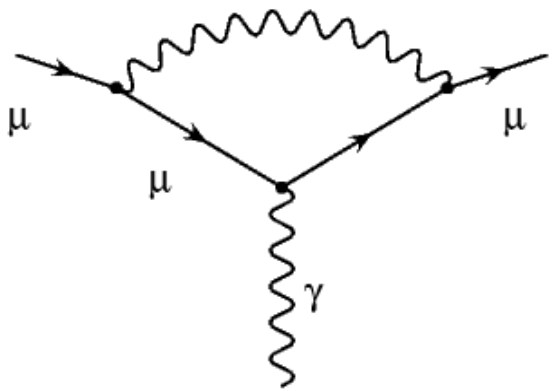
Muon magnetic moment: definition of $g = 2(1 + a_\mu)$





$$\omega_a = \omega_s - \omega_c = -a_\mu \frac{e}{m_\mu} B$$

Quantum field theory:



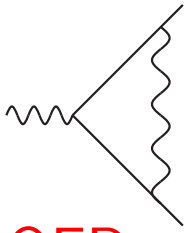
$$\mathcal{L}_{\text{eff}} = \frac{Qe}{2} \left(c \bar{\psi}_R \sigma_{\mu\nu} \psi_L + c^* \bar{\psi}_L \sigma_{\mu\nu} \psi_R \right) F^{\mu\nu}$$

$$a_\mu = -2 m_\mu \text{Re}(c)$$

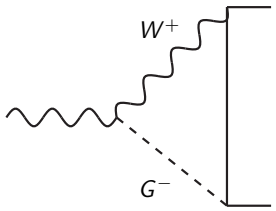
$$d_\mu = Qe \, \text{Im}(c)$$

Theory Initiative prediction $a_\mu^{\rm SM} = (11\,659\,181.0 \quad (4.3) \quad) \; [10^{-10}]$

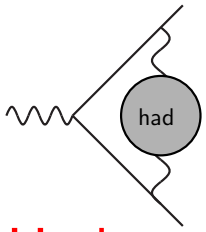
since 2017, 6 workshops, White Paper (2020), 132 authors, ongoing effort



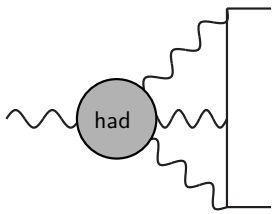
QED: 11 658 471.9 (0.0)



Weak: 15.36 (0.1)



Had vp: 684.5 (4.0)



Had lbl: 9.0 (1.7)

Highlights:

Many QFT methods!

all particles contribute! Even W, Z, Higgs, top

largest uncertainty from Had vp

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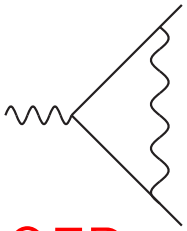

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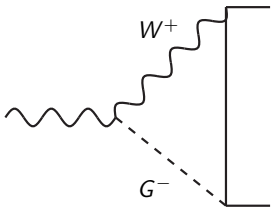

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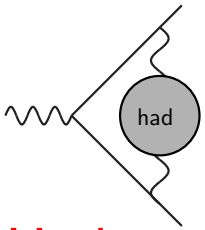

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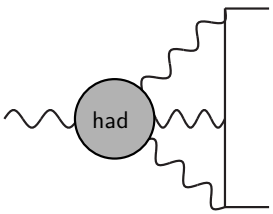

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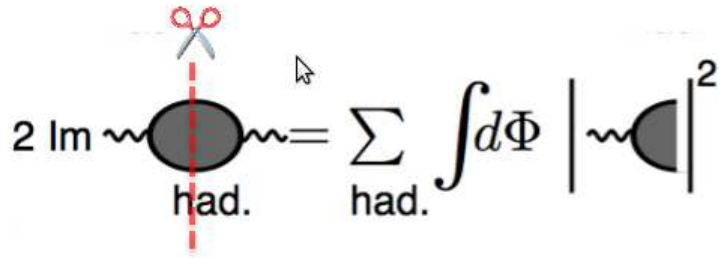
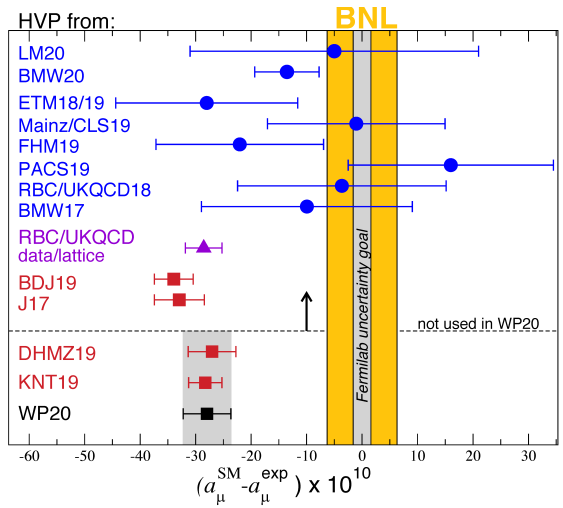
Hadronic vacuum polarization:

- unitarity+causality $\rightsquigarrow$ exact dispersion relation

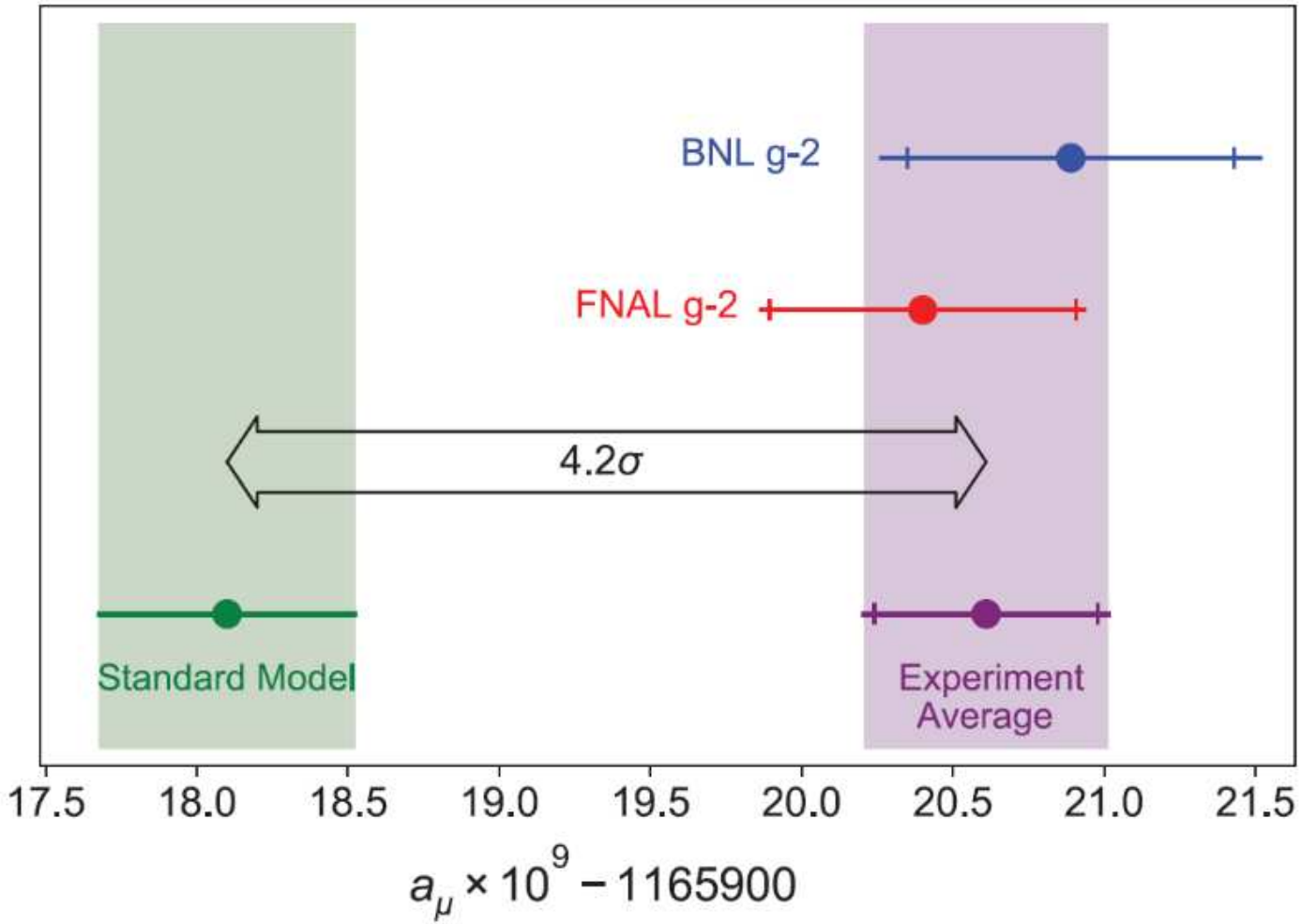




- lattice QCD promising progress

(not yet used in TI value)

Finally: Fermilab Run 1 versus Theory Initiative SM value



Discrepancy — Two important general points

SM prediction too low by $\approx (25 \pm 6) \times 10^{-10}$

Questions: Which models can(not) explain it?

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discrepancy $\approx 2 \times a_\mu^{\mathrm{SM,weak}}$

but: expect $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings

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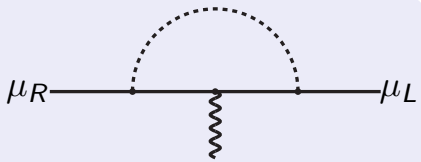
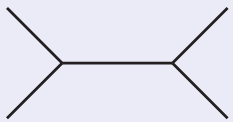
loop-induced, CP- and Flavor-conserving, chirality-flipping

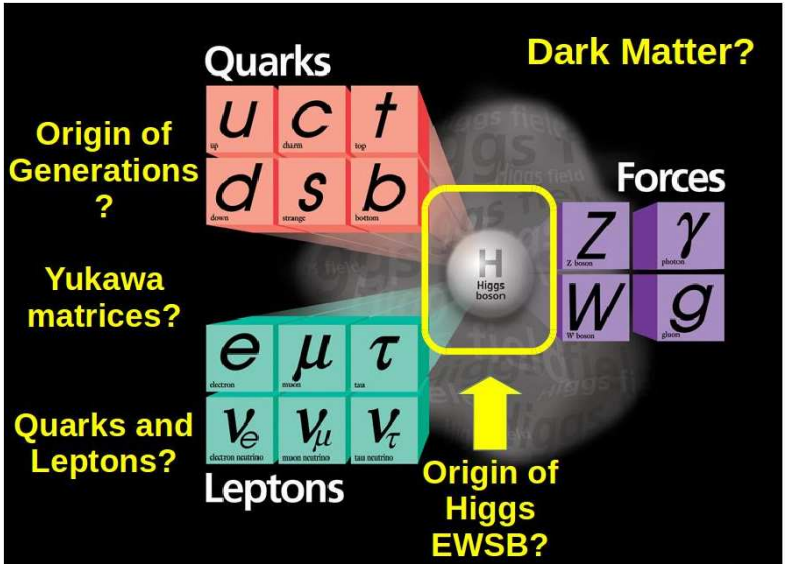


compare:

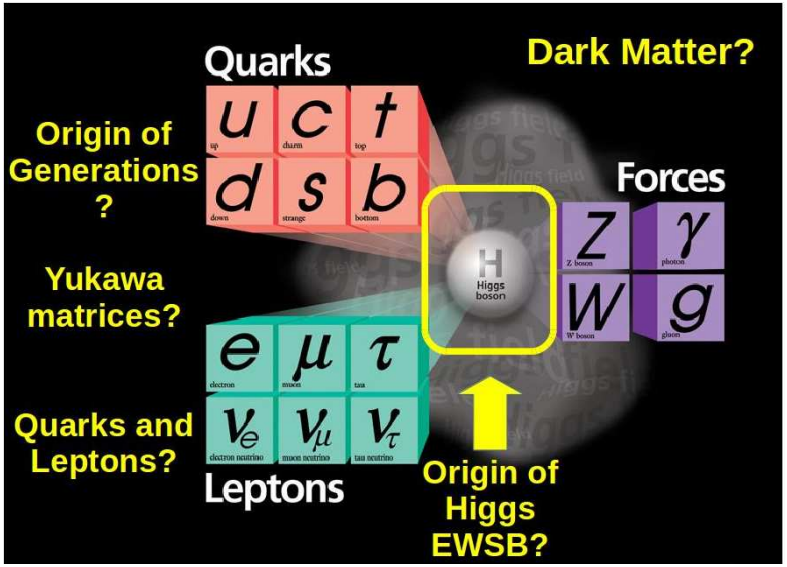


$b \to s\gamma$
EDMs, $B \to \tau\nu$
$\mu \to e\gamma$

EWPO



Two promising connections to big open questions



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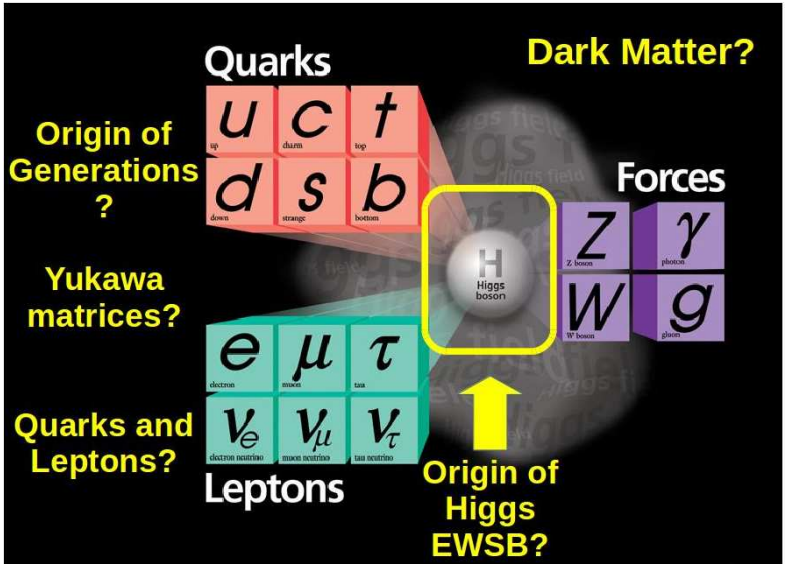
Dark Matter, (light?) dark sectors? Hard to see in detectors but could couple to muon $\rightsquigarrow$ large effects possible!



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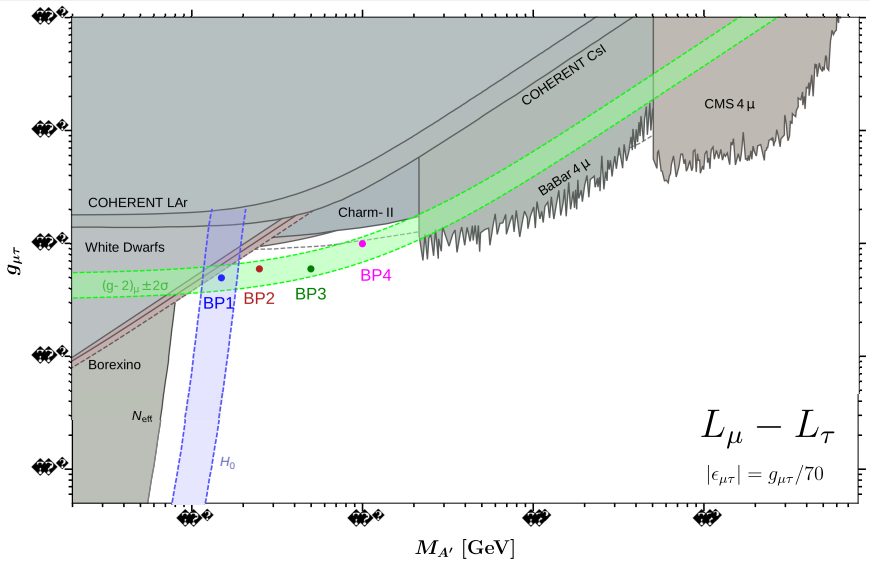
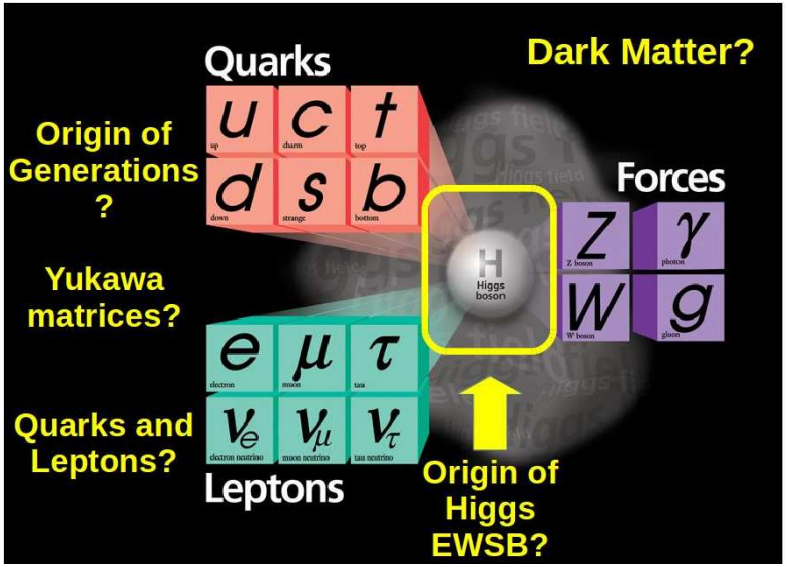
- Dark Photon, Z', $U(1)_{L_\mu - L_\tau}$
- many low-E constraints
- also SUSY, heavy dark matter models . . . (LHC, DMDD!)



Viable: 10 . . . 100 MeV [Amaral,Cerdeno,Cheek,Foldenauer'21]



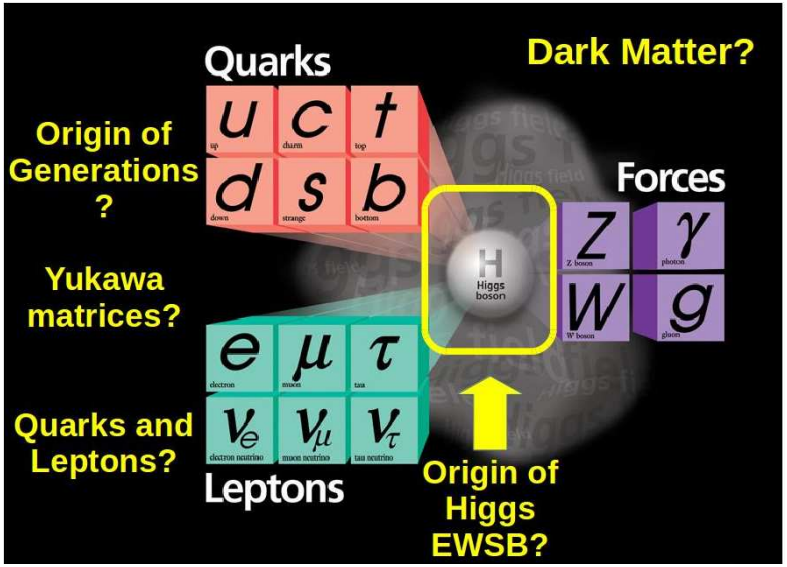
Two promising connections to big open questions

Window to the muon mass generation mechanism (Higgs/Yukawa sectors)

Technically: QFT operators for m_μ and a_μ are chirality flipping and break gauge invariance:

$$m_\mu \bar{\psi}_L \psi_R$$

$$\frac{a_\mu}{m_\mu} \bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu}$$



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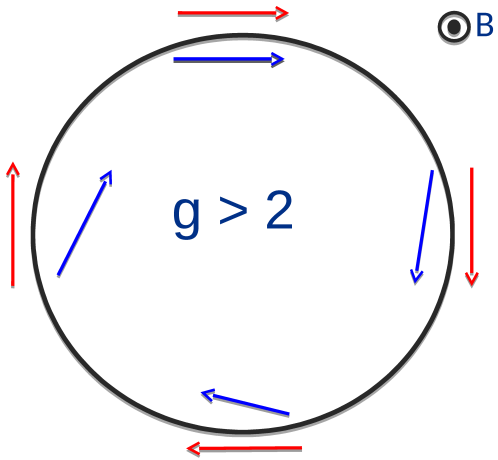
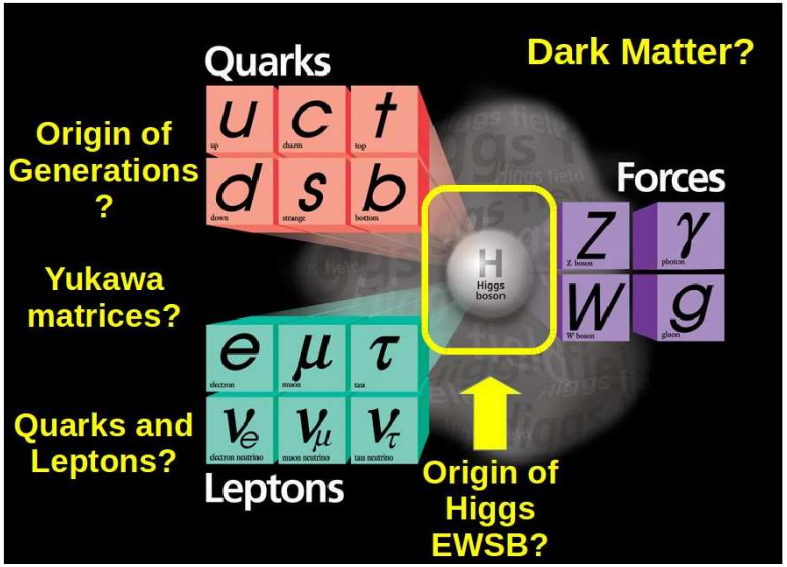
(continuous spin rotation requires rest mass!)





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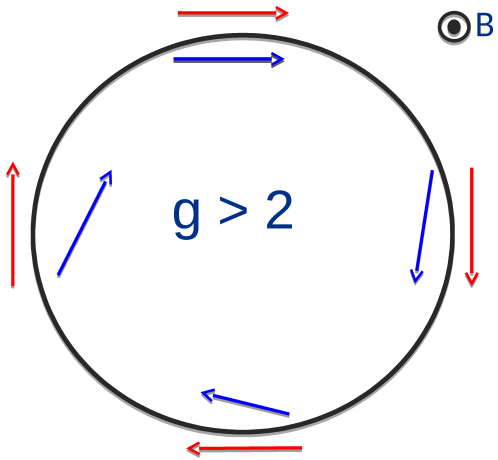
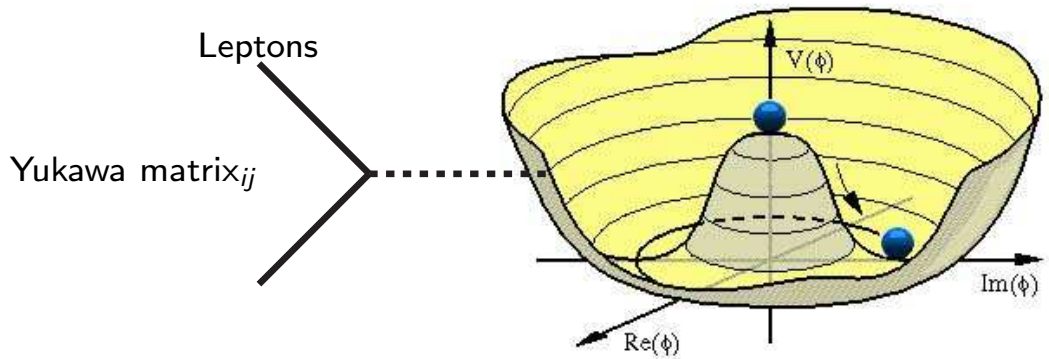


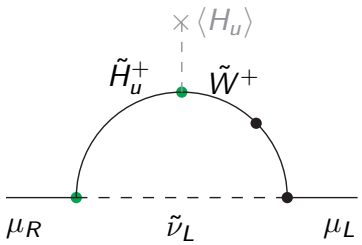


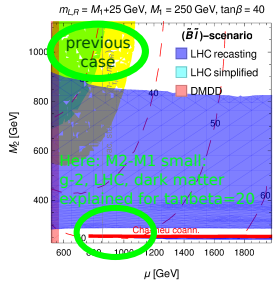
(changed by new physics?)

Examples with enhanced chirality flips...

SUSY: $\neq$ MSugra

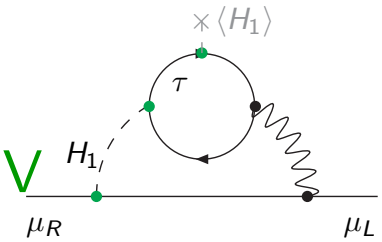
- Higgs, Yukawa, Higgsinos, Smuons...
- Dark Matter
- Constrained by DM, LHC, CLFV...

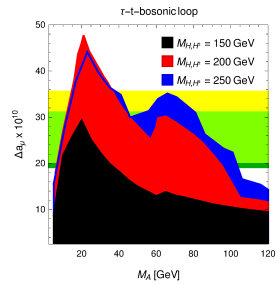




Two-Higgs doublet model: $\neq$Type I, II, Y

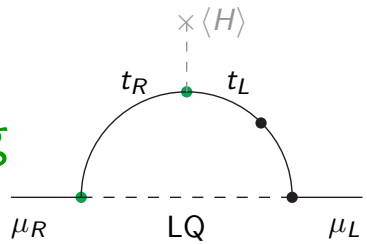
- Higgs, Yukawa
- Constrained by LHC, τ-, B-physics, CLFV

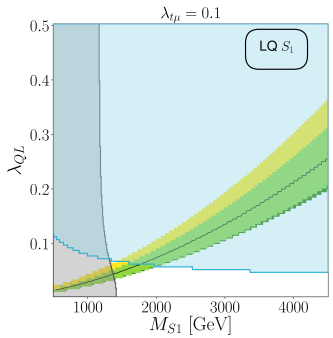




Lepto-quarks S_1, R_2, vector-like leptons

- New Yukawa-like couplings (μ–top–LQ)
- New flavour structures
- Constrained by LHC, flavour, finetuning

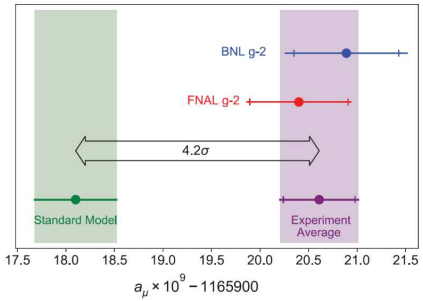




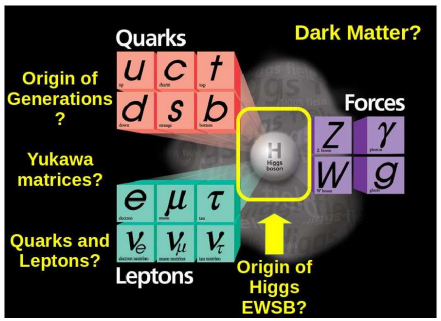
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, 2104.03691]

Conclusions

- SM prediction for $g-2$:
  - All known particles relevant (and all QFT tricks)
  - Theory Initiative: worldwide (ongoing!) effort, agreed & conservative value



- BSM contributions to $g-2$:
  - large effect needed
  - Connections to deep questions
  - many models . . . and constraints
  - often chiral enhancements, new flavor structures
  - Exp. tests:
    Higgs couplings, B-physics, CLFV,
    EDM, light-particle searches, e^+e^-/muon collider
  - not easy to combine with "B-anomalies"



- Many opportunities!