Muon $g-2$ — experiment and theory

Dominik Stöckinger, TU Dresden

Workshop Anomalies and Precision in the Belle-II era,
Vienna, 7th September 2021

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

- Brief motivation, SM situation
- Fermilab $g-2$ experiment
- BSM: general remarks, examples of models, thoughts on questions

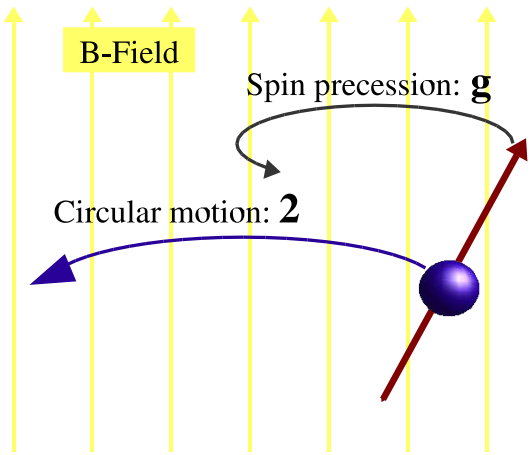
Muon $g-2$ — Overview and SM theory

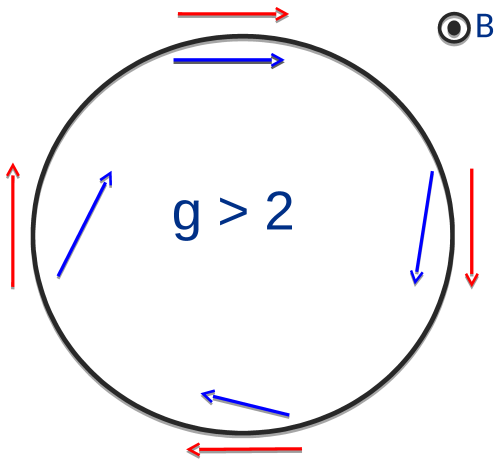
$a_\mu = (g-2)_\mu/2$ is a (magnetic) dipole observable

like many other dipole observables:

- $b \to s\gamma$, $\tau \to \mu\gamma$, $\mu \to e\gamma$
- electric dipole moments
- $\rightsquigarrow$ inclusive probe of all SM properties and of new physics

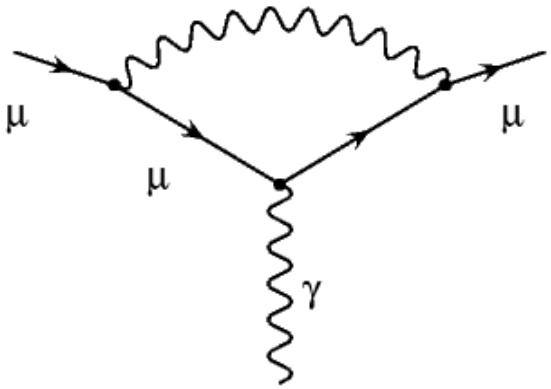
Muon magnetic moment: definition of $g = 2(1 + a_\mu)$





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

Quantum field theory:

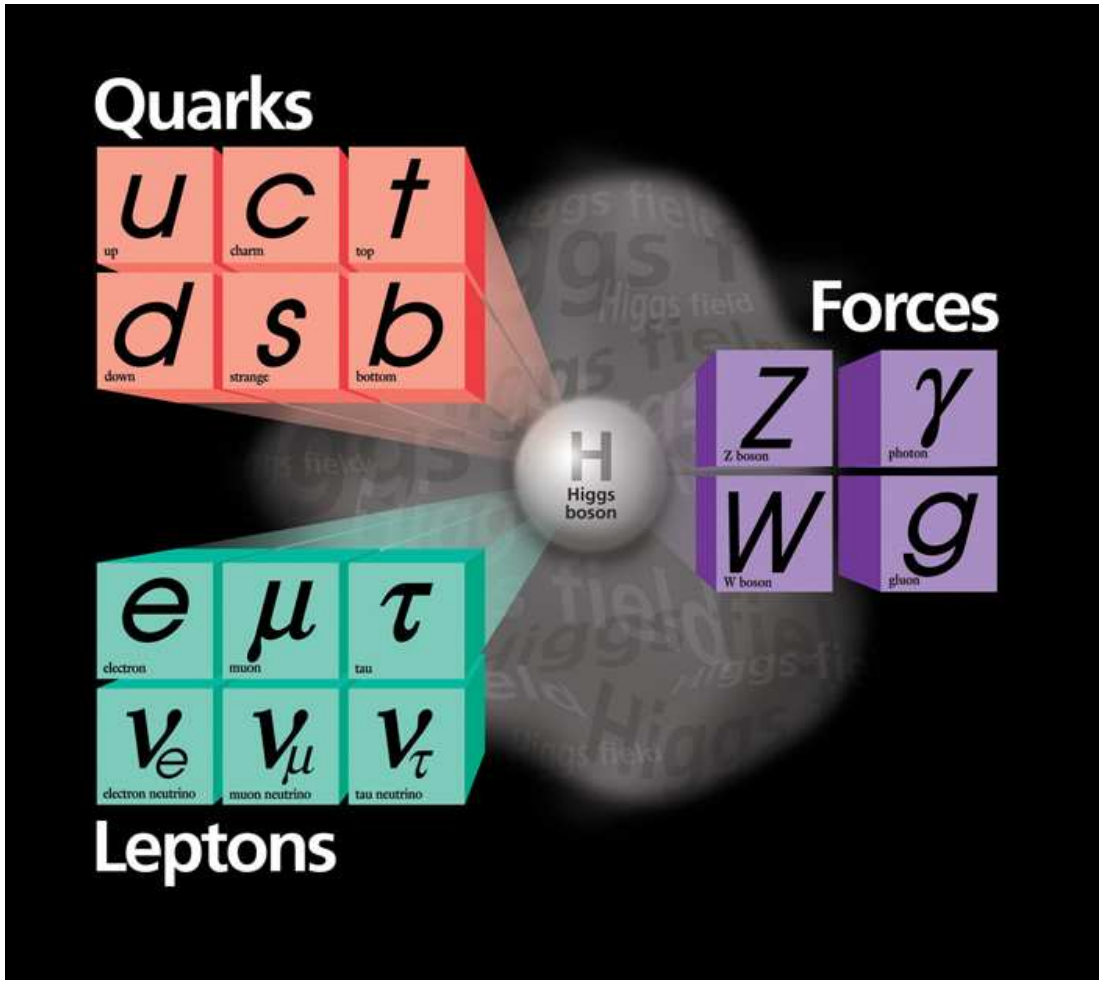


$$\mathcal{L}_{\text{eff}} = \frac{Qe}{2} \left(c \bar{\psi}_R \sigma_{\mu\nu} \psi_L + c^* \bar{\psi}_L \sigma_{\mu\nu} \psi_R \right) F^{\mu\nu}$$

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

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

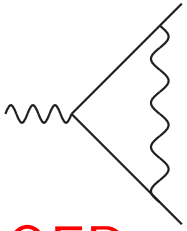
Standard Model of particle physics (est. 1967. . . 1973))



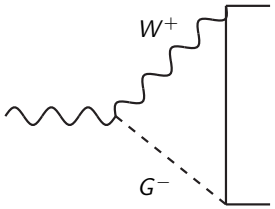
a_μ sensitive to all particles and forces via quantum fluctuations!

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

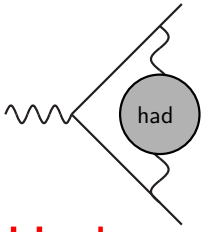
since 2017, 6 workshops, White Paper (2020), 132 authors, ongoing effort



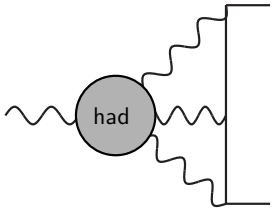
QED: 11 658 471.9 (0.0)



Weak: 15.36 (0.1)



Had vp: 684.5 (4.0)



Had lbl: 9.0 (1.7)

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

largest uncertainty from Had vp

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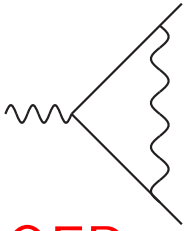

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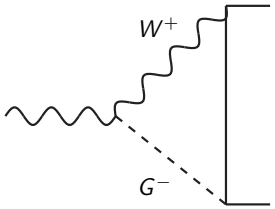

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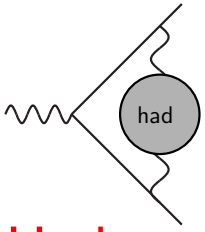

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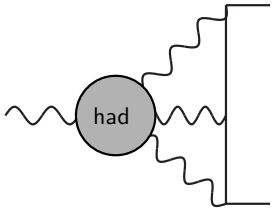

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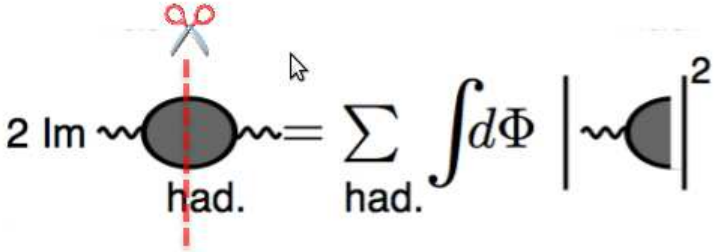
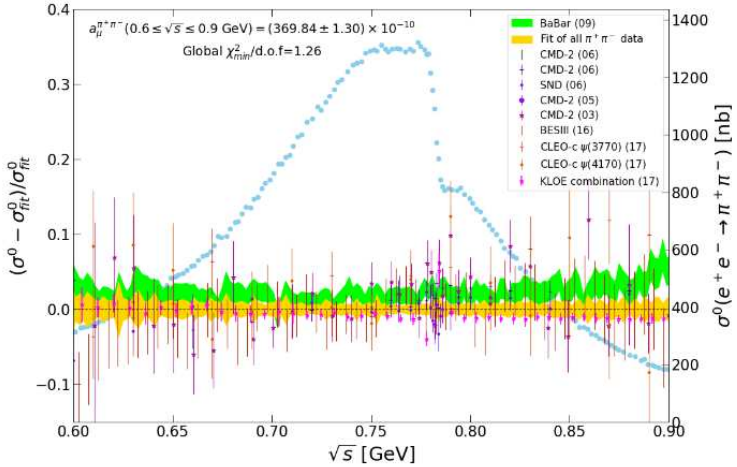
Hadronic vacuum polarization:

- unitarity+causality $\rightsquigarrow$ exact dispersion relation

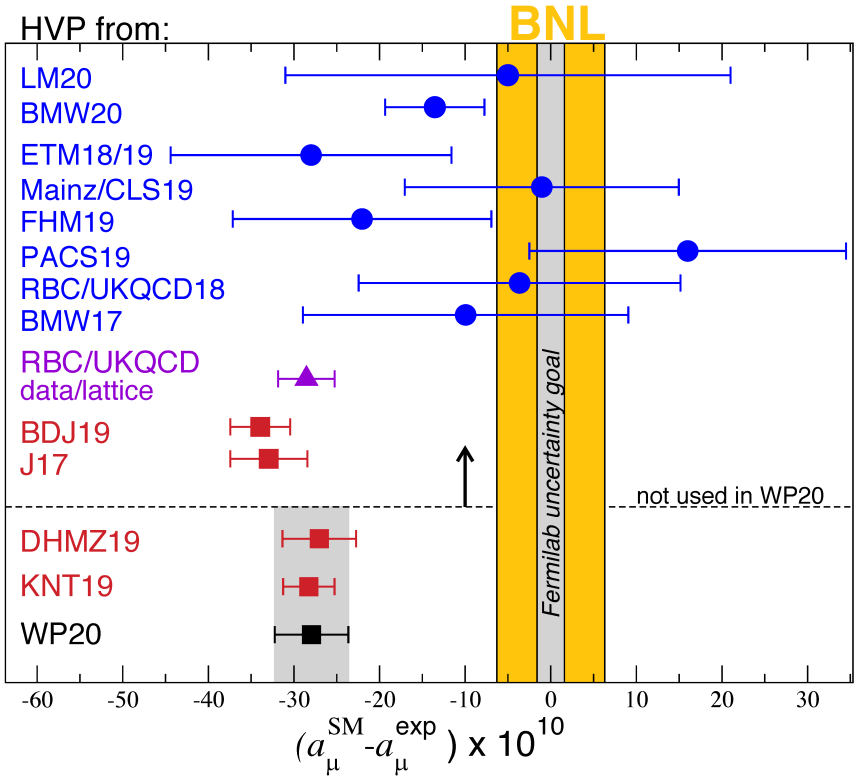




- lattice QCD impressive progress (not yet used in TI value)

Details on hadronic vacuum polarization

a_μ^{HVP} : Status of Hadronic Vacuum Polarisation contributions



Lattice QCD + QED

- impressive progress, but…
- large spread between results
- tensions when looking at `Euclidean time window' comparisons
- large systematic uncertainties (e.g. from non-trivial extrapolation to continuum limit, finite size)

Dispersive/lattice hybrid

(`window' method)

For WP20: Dispersive data-driven from DHMZ and KNT

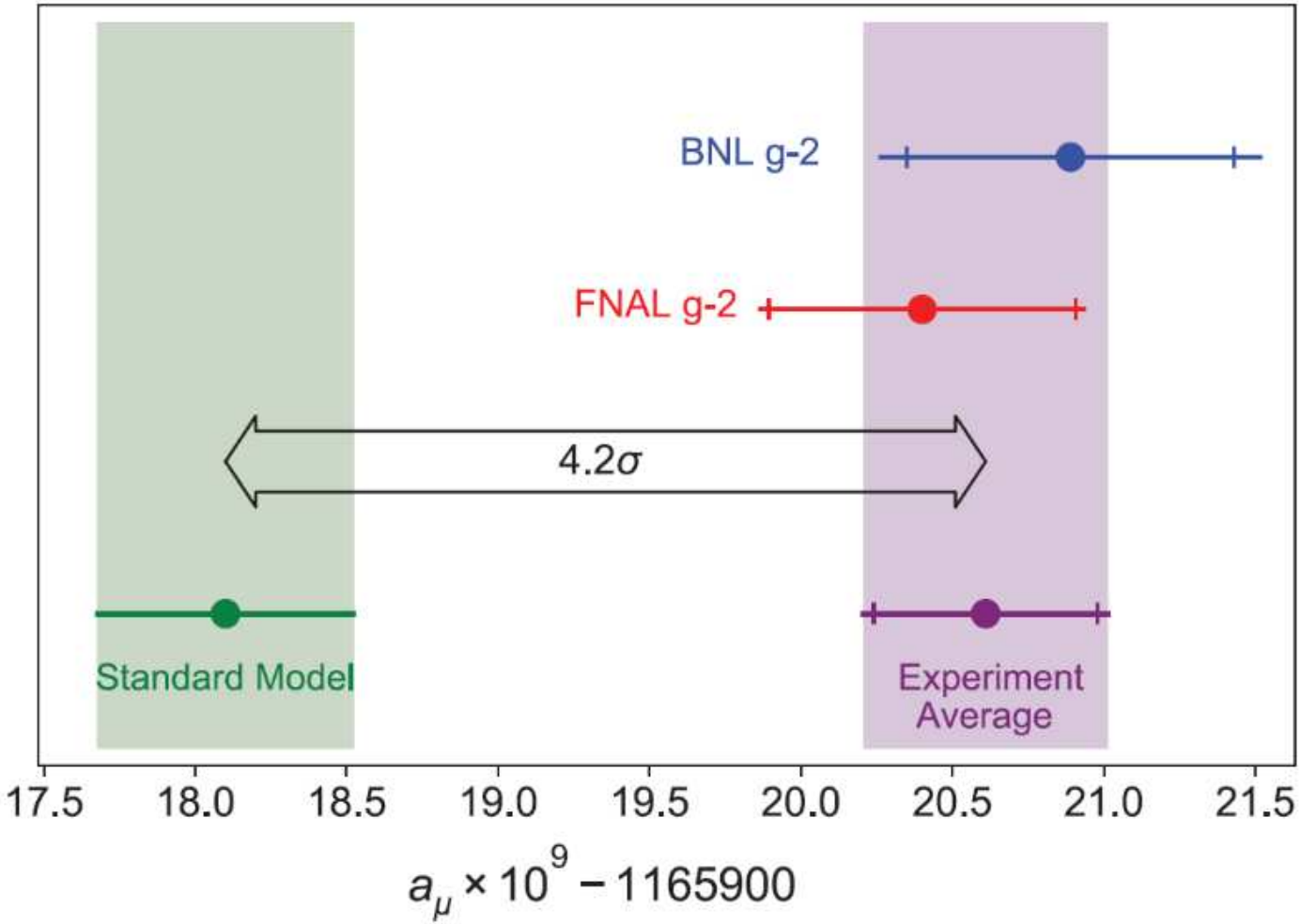
TI White Paper 2020 value:

$a_\mu^{HVP} = 6845\ (40) \times 10^{-11}$

- TI WP2020 prediction uses dispersive data-driven evaluations with **minimal model dependence**
- a_μ^{HVP} **value and error** obtained **by merging** procedure ➠ accounts for tensions in input data and differences in data treatment & combination (going beyond usual χ^2_{min} inflation)

Thomas Teubner 10

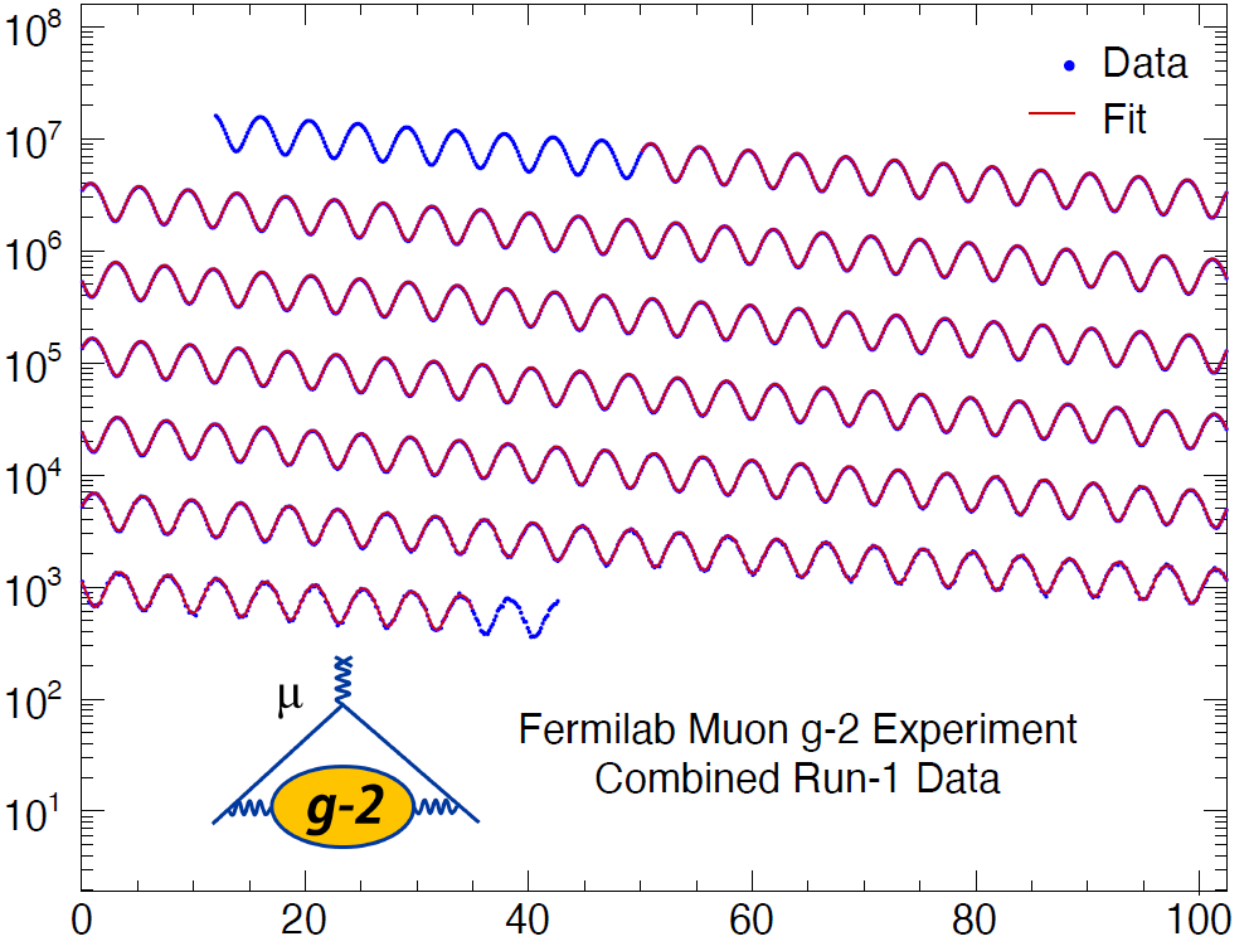
Finally: Fermilab Run 1 versus Theory Initiative SM value



$g-2$ and the Fermilab experiment

How to measure at 10^{-10}-level? Two design advantages

- Direct measurement of $\omega_a = \omega_s - \omega_c$
- Magic γ minimizes E-field influence

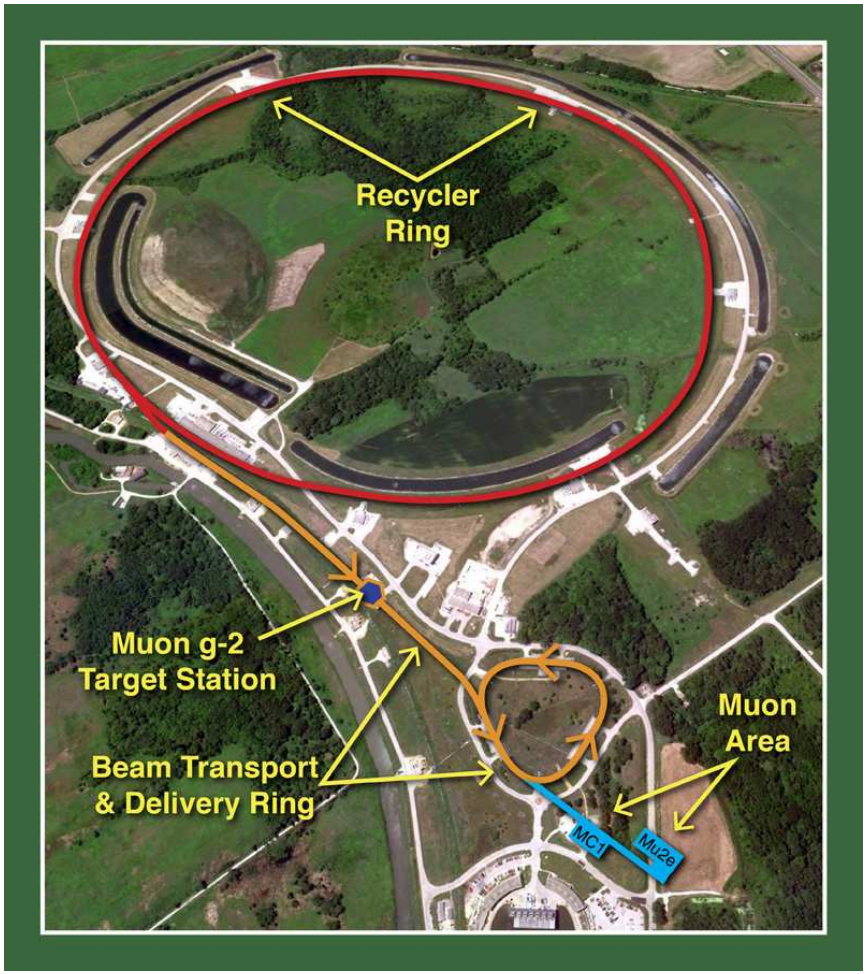


$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{\mathcal{E}}}{c}\right]$$

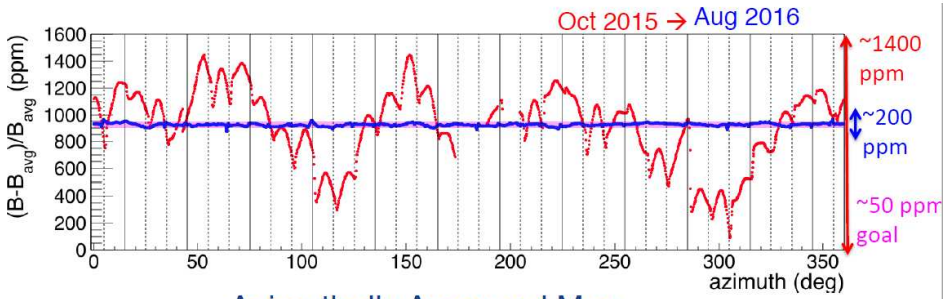
What are advantages of Fermilab experiment

Much longer π decay length

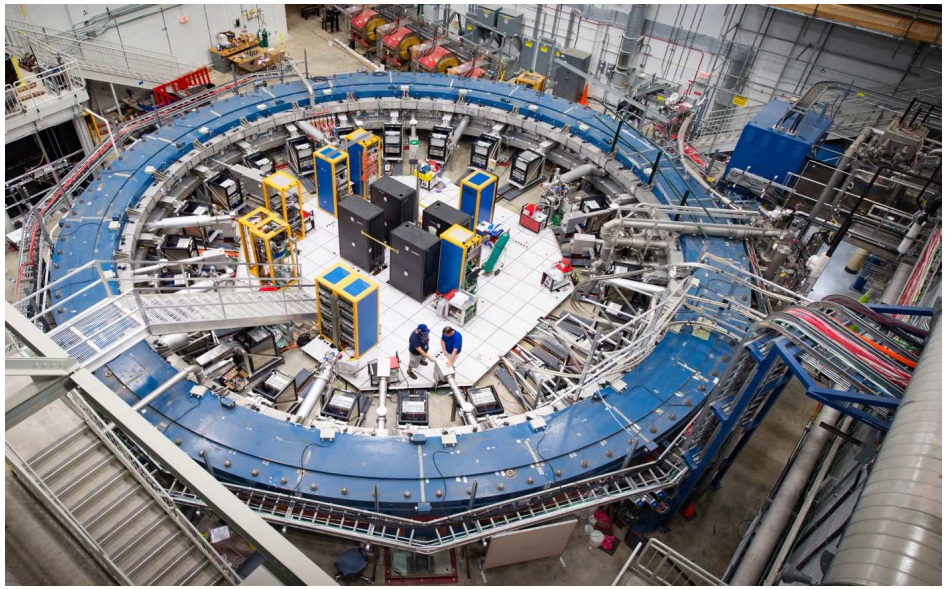
- more muons, cleaner beam



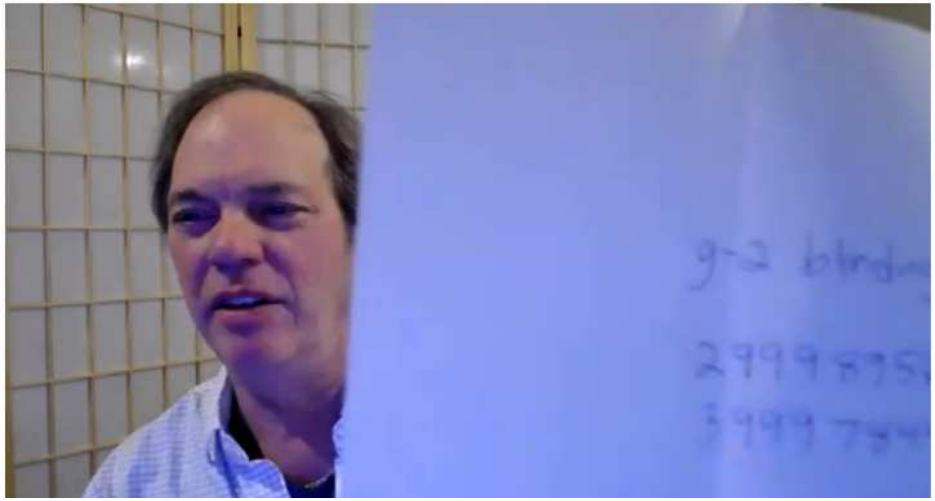
more homogeneous B-field

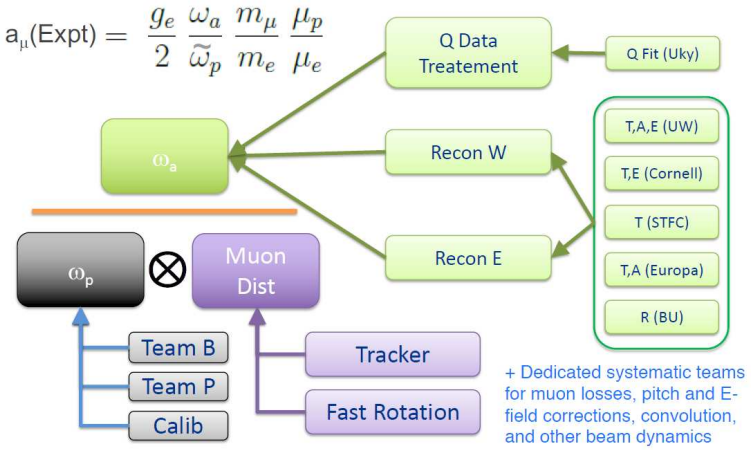


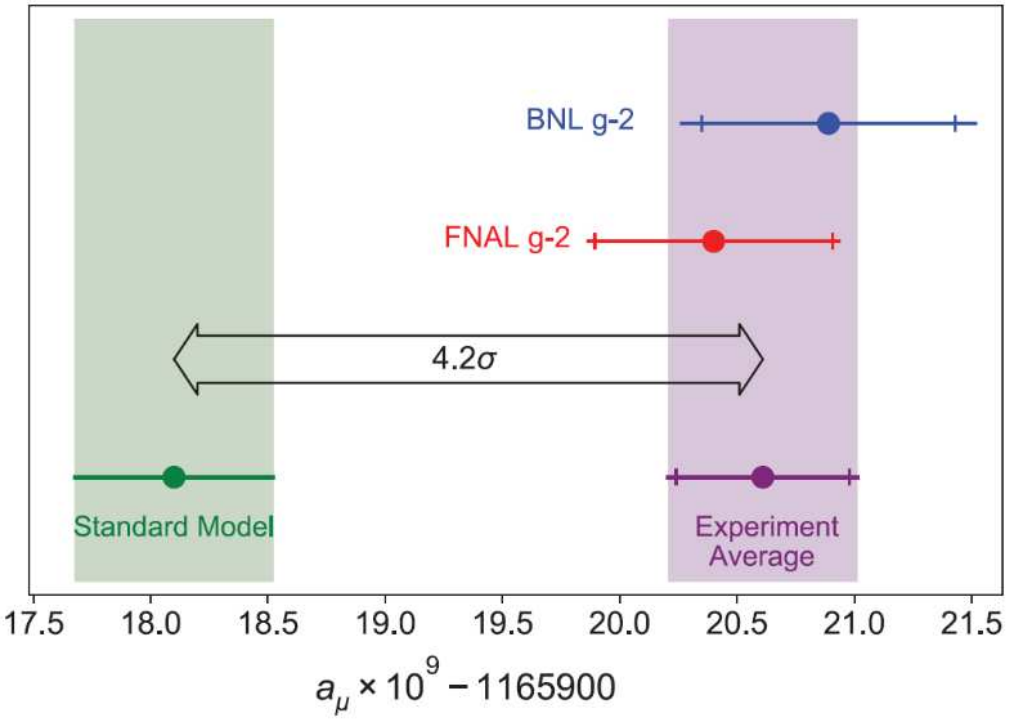
better detectors



Result of Run-1. . . after unblinding

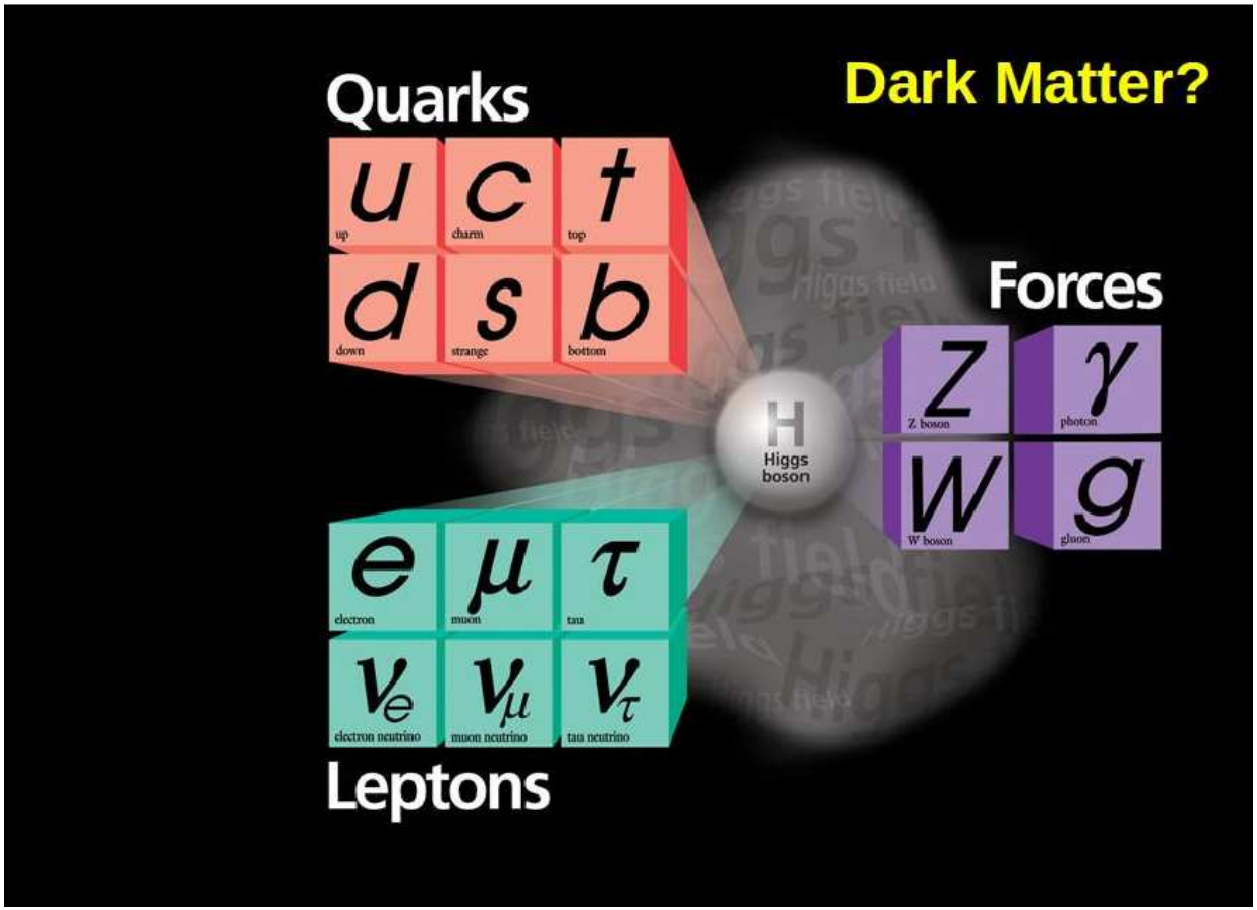






Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	···	434
ω_a^m (systematic)	···	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	···	56
B_k	−27	37
B_q	−17	92
$\mu'_p(34.7°)/\mu_e$	···	10
m_μ/m_e	···	22
$g_e/2$	···	0
Total systematic	···	157
Total fundamental factors	···	25
Totals	544	462

Open questions require Beyond the Standard Model (BSM) physics



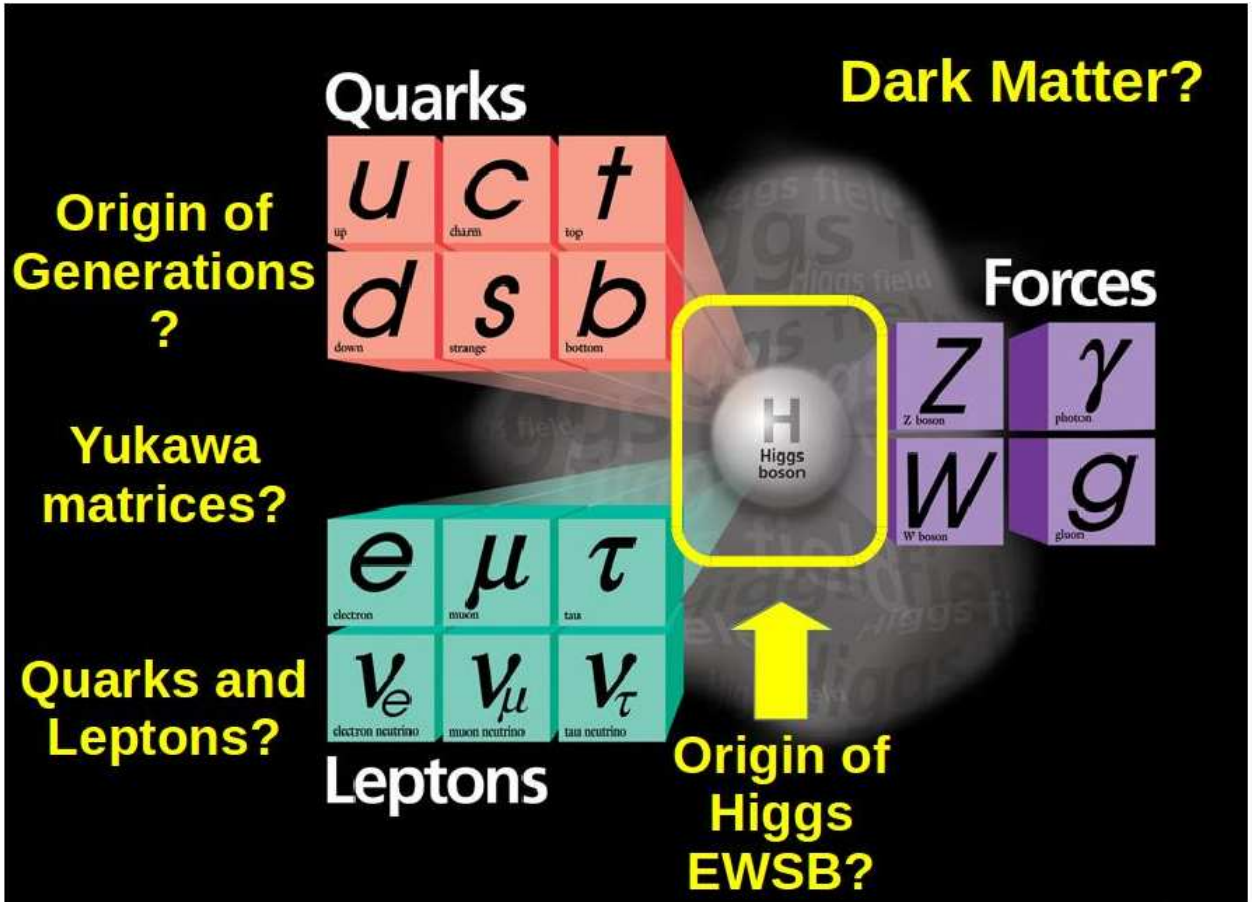
Open questions!

- 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



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Discrepancy — Two important general points

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

Questions: Which models can(not) explain it?

Discrepancy — Two important general points

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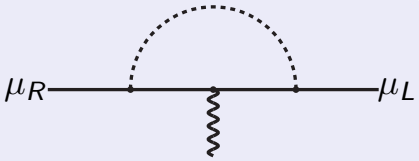
loop-induced, CP- and Flavor-conserving, chirality-flipping

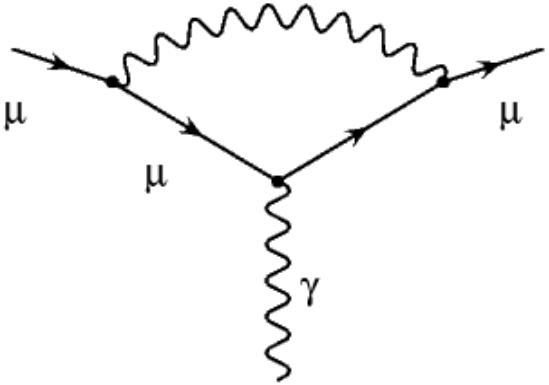


compare: 

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

EWPO

Connection to chirality flip, and structure of BSM



$$\mathcal{L}_{\text{eff}} = -\frac{Qe}{4m_\mu} a_\mu \times \bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu}$$

But:

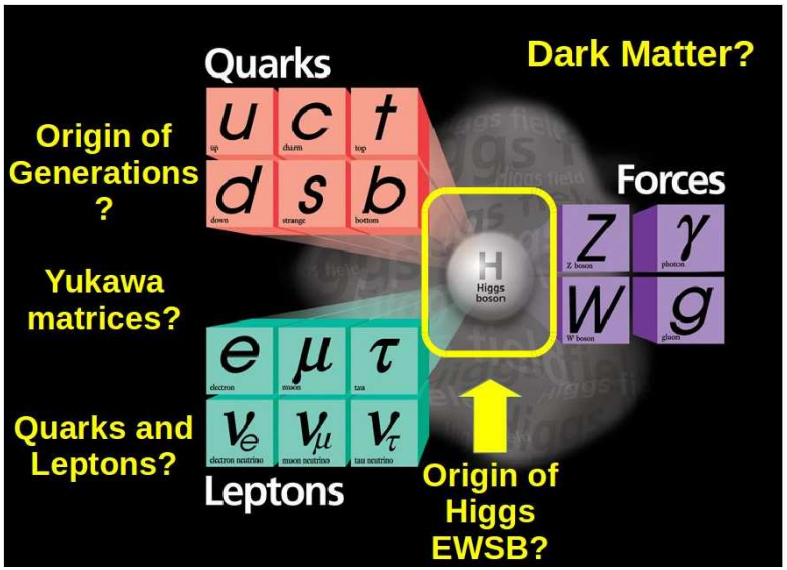
EW gauge invariant a_μ-operator: $\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu}\langle H\rangle$

$$a_\mu \sim m_\mu \times \underbrace{(\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping param.})}_{\text{related to muon mass generation, potential enhancement!}} \times \frac{(\text{other couplings})}{M^2_{\text{typical}}}$$

$m_\mu(\text{SM}) \sim$ (SM Higgs-VEV) $\times$ (muon Yukawa coupling)

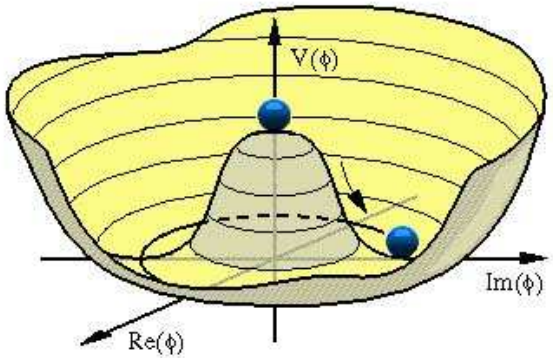
Two promising directions to explain $g-2$

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



Leptons

Yukawa matrix$_{ij}$



(changed by new physics?)

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

Which models can still accommodate large deviation?

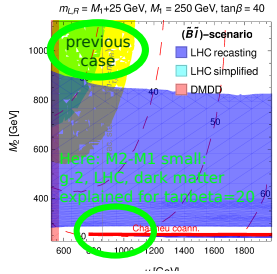
Many (but not all) models!

but always: experimental constraints!

There are many examples. . .

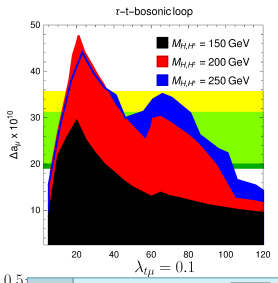
SUSY: (chiral enhancement $\propto \tan\beta$, dark matter)

- MSugra. . . many other generic scenarios
- Bino-dark matter+some coannihil.+mass splittings
- Wino-LSP+specific mass patterns



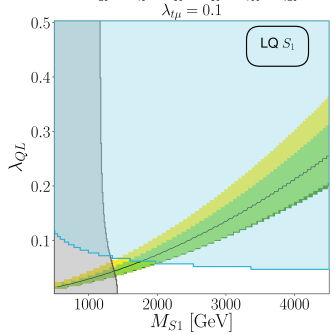
Two-Higgs doublet model: (e.g. $\propto \tan^2\beta$)

- Type I, II, Y, Type X(lepton-specific), flavour-aligned



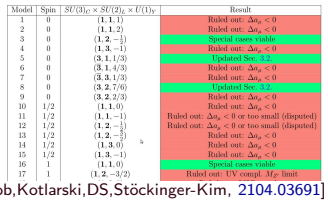
Lepto-quarks S_1, R_2, vector-like leptons (chiral enhancement)

- scenarios with muon-specific couplings to μ_L and μ_R



Simple models (one or two new fields, dark matter possible)

- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)



Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1},\mathbf{1},1)$	Ruled out: $\Delta a_\mu < 0$
2	0	$(\mathbf{1},\mathbf{1},2)$	Ruled out: $\Delta a_\mu < 0$
3	0	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Special cases viable
4	0	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
5	0	$(\mathbf{3},\mathbf{1},1/3)$	Updated Sec. 3.2
6	0	$(\bar{\mathbf{3}},\mathbf{1},4/3)$	Ruled out: $\Delta a_\mu < 0$
7	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	Ruled out: $\Delta a_\mu < 0$
8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 3.2
9	0	$(\bar{\mathbf{3}},\mathbf{2},2/3)$	Ruled out: $\Delta a_\mu < 0$
10	1/2	$(\mathbf{1},\mathbf{1},0)$	Ruled out: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
12	1/2	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
13	1/2	$(\mathbf{1},\mathbf{2},-\frac{3}{2})$	Ruled out: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1},\mathbf{3},0)$	Ruled out: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
17	1	$(\mathbf{1},\mathbf{2},-3/2)$	Ruled out: UV compl. M_F limit

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

Questions for this workshop:

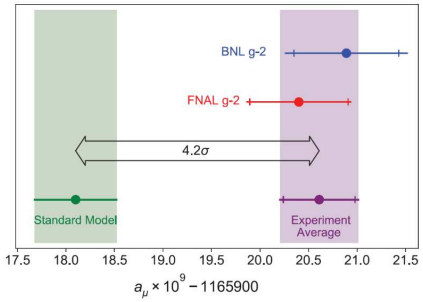
- Is there a common link between anomalies?
- Are we leaving any stone unturned?
- What's the interplay between $g-2$ and B-physics, τ-physics, dark sector physics and high-energy (TeV-scale) physics?

Some thoughts:

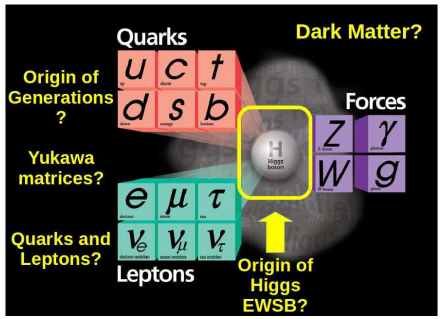
- $g-2$ can be well connected to high-energy physics (with chiral enhancements)
- or to dark sectors
- it can be explained in many models (though in each model we have to go to special parameter regions)
- It is not easy to explain simultaneously with B-anomalies (see e.g. Z'? Leptoquarks?)
- Hence:
  1. explanations of $g-2$ typically contain potential flavour (violating) parameters, which are strongly constrained
  2. if all anomalies are real, then very special models needed $\rightsquigarrow$ progress!

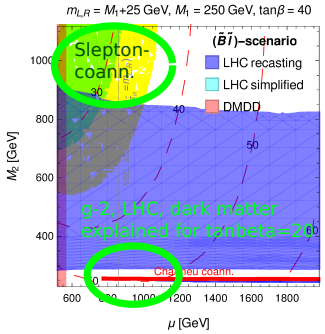
Conclusions

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

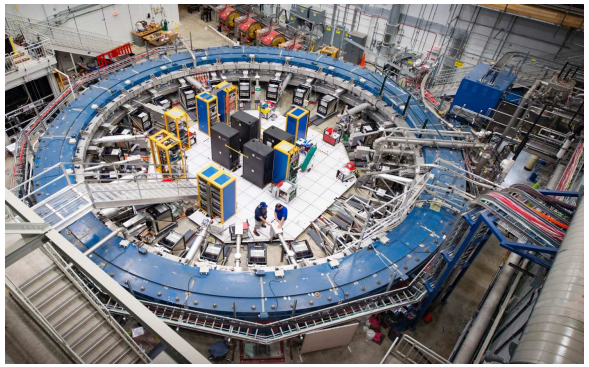


- BSM contributions to $g-2$:
  - large effect needed
  - Connections to deep questions
  - many models ... and constraints
  - Exp. tests:
    Higgs couplings, B-physics, CLFV,
    EDM, light-particle searches, e^+e^-/muon collider





- Fermilab $g-2$ experiment
  - 20 years after BNL... deviation confirmed!
  - stat. dominated! Only 6% data used!
  - Best possible starting point ...
    ... promising future



Typical behaviour: $\sim$ chirality flip ($\rightsquigarrow$ Higgs!) and masses

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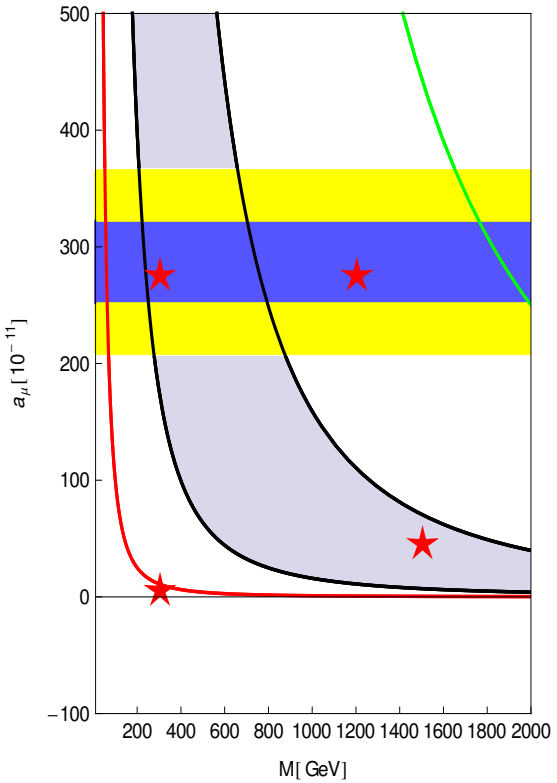

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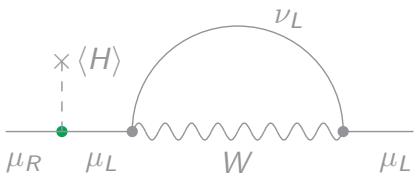
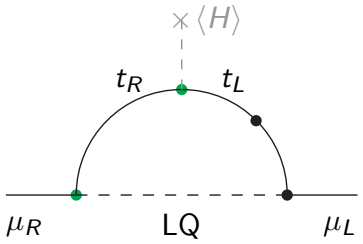
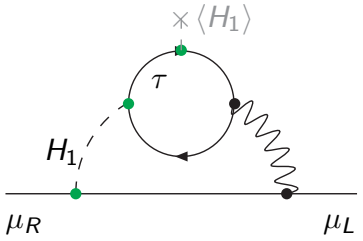
  Similar in Z', Dark Z_d models

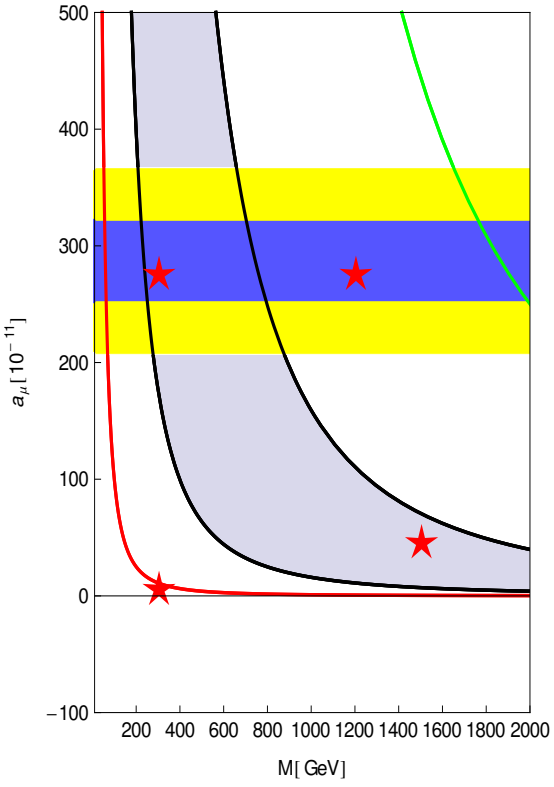


- LQ: $g_L g_R \frac{m_\mu m_t}{M^2_{\text{LQ}}}$



- 2HDM: $\alpha^2 \tan^2\beta \frac{m_\mu^2}{M_H^2}$





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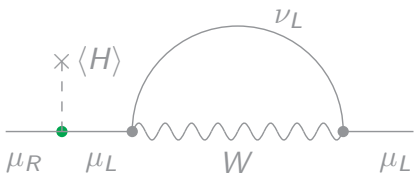

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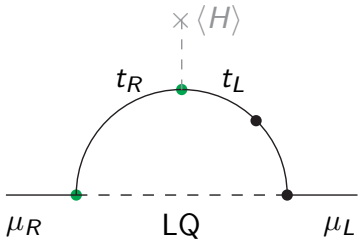
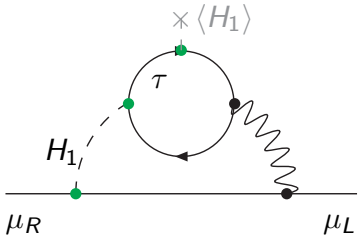


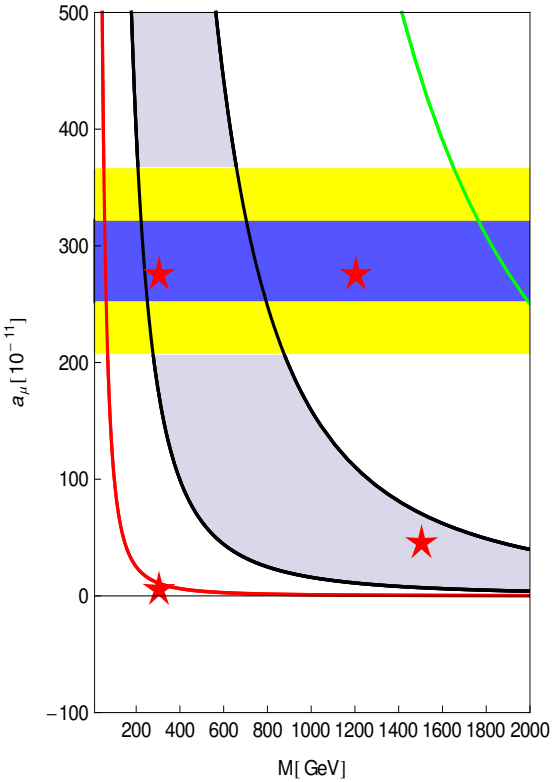
Can also involve Higgs couplings to b, c or new particles.

Beware: $\Delta m_\mu / m_\mu \sim g_L g_R m_t / m_\mu$ restricts couplings

- 2HDM: $\alpha^2 \tan^2 \beta \frac{m_\mu^2}{M_H^2}$



Well motivated; many variants; many constraints



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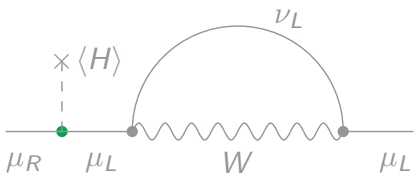
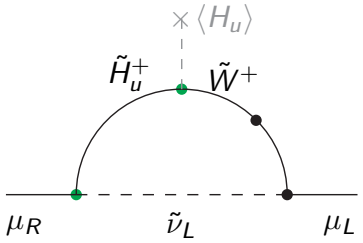
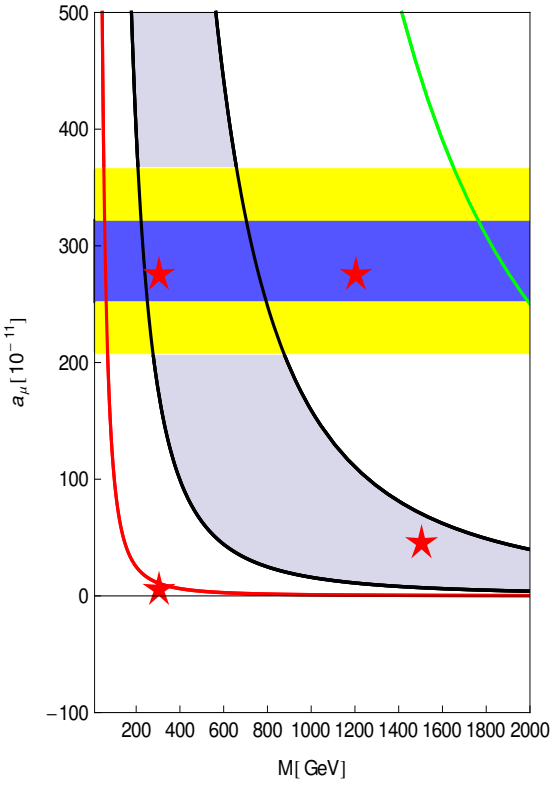


- SUSY: $\alpha \frac{m_\mu^2 \tan\beta}{M^2_{\text{SUSY}}} \frac{\mu}{M_{\text{SUSY}}}$



- rad. m_μ $\sim \frac{m_\mu^2}{M^2_{\text{NP}}}$



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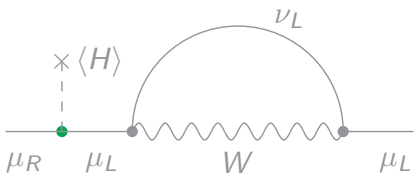

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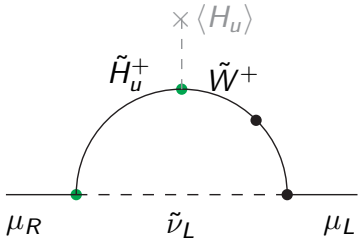
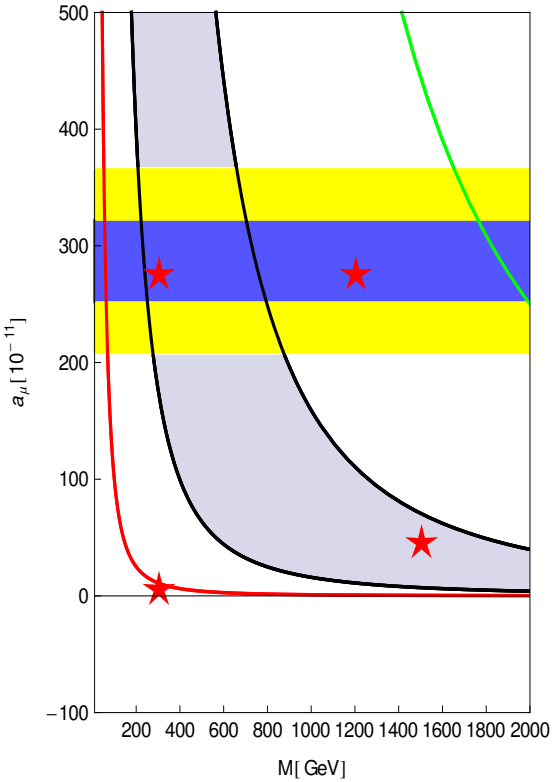


Well-motivated theory. Many other advantages

- rad. $m_\mu \sim \frac{m_\mu^2}{M^2_{\text{NP}}}$

E.g. MSSM for $\tan\beta \to \infty$ [Bach,Park,DS,Stöckinger-Kim'15]



Example BSM idea

- fundamental new QFT symmetry
- predicts Higgs potential/mass
- dark matter candidate
- chirality flip enhancement $\rightsquigarrow g-2$
- viable (LHC)?

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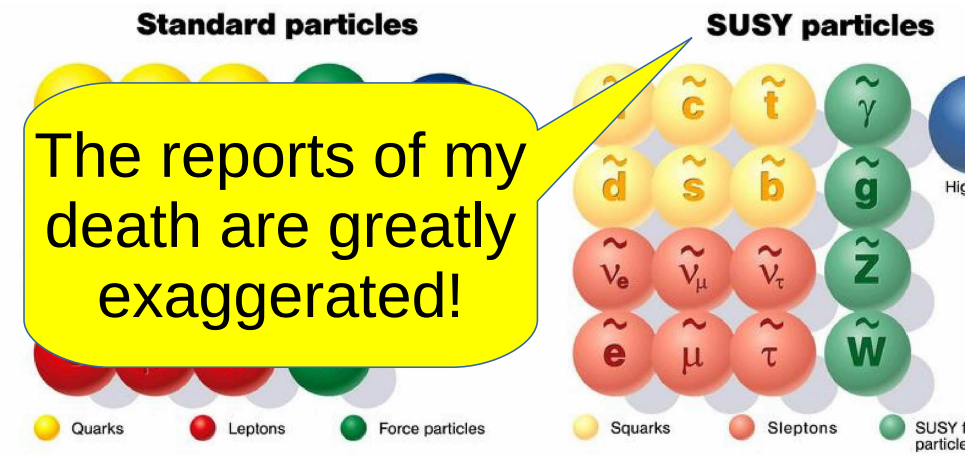

Superpartners and SUSY Higgs sector $\rightsquigarrow \tan\beta = \frac{v_u}{v_d}$, Higgsino mass μ

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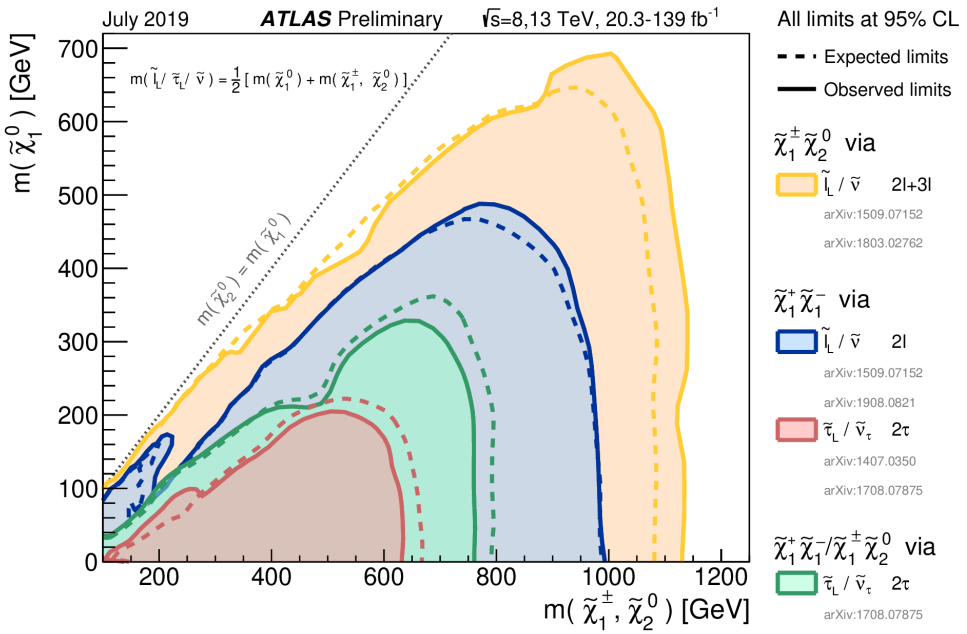

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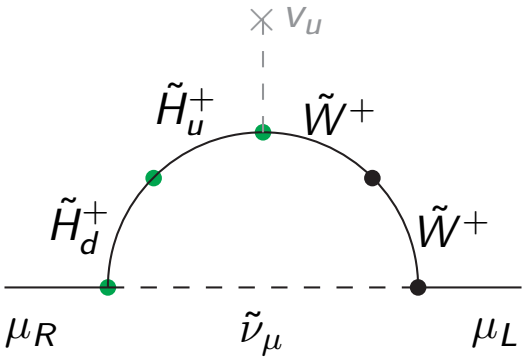
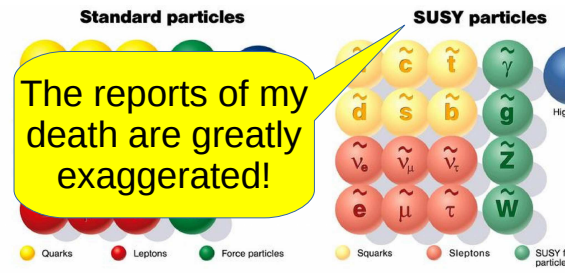
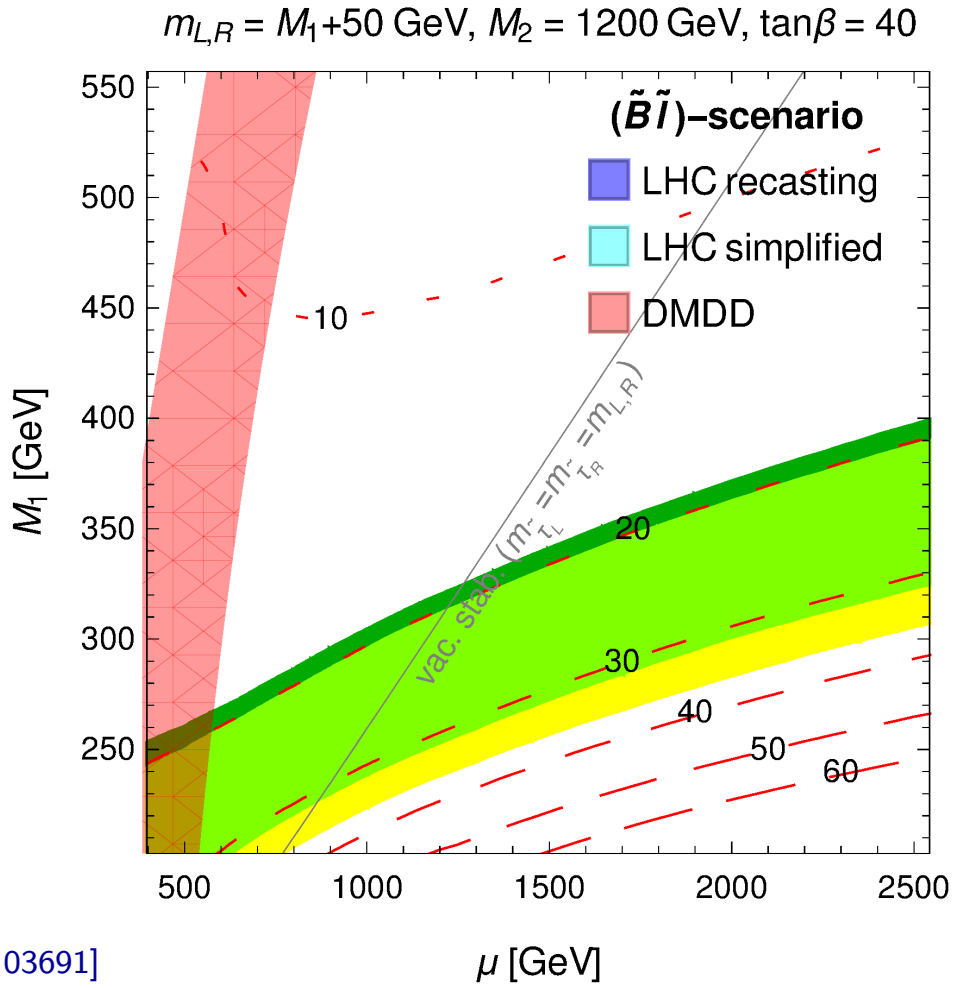
MSSM can explain $g-2$ and dark matter



$$a_\mu^{\rm SUSY} \approx 25\times 10^{-10}\,\frac{\tan\beta}{50}\,\frac{\mu}{M_{\rm SUSY}}\left(\frac{500{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

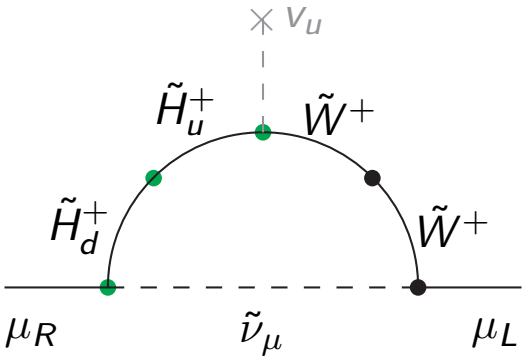
- "Dark matter mass" versus μ
- explains $g-2$ in large region (expands for $\tan\beta \neq 40$)
- DM explained by stau/slepton-coannihilation
- this automatically evades (current) LHC limits





[2104.03691]

MSSM can explain $g-2$ and dark matter



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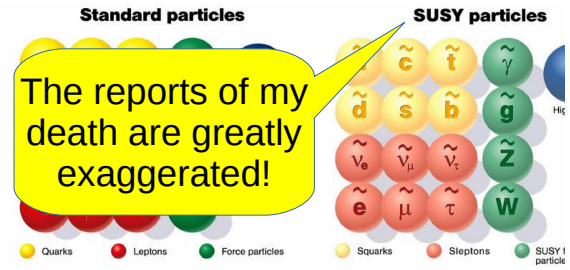
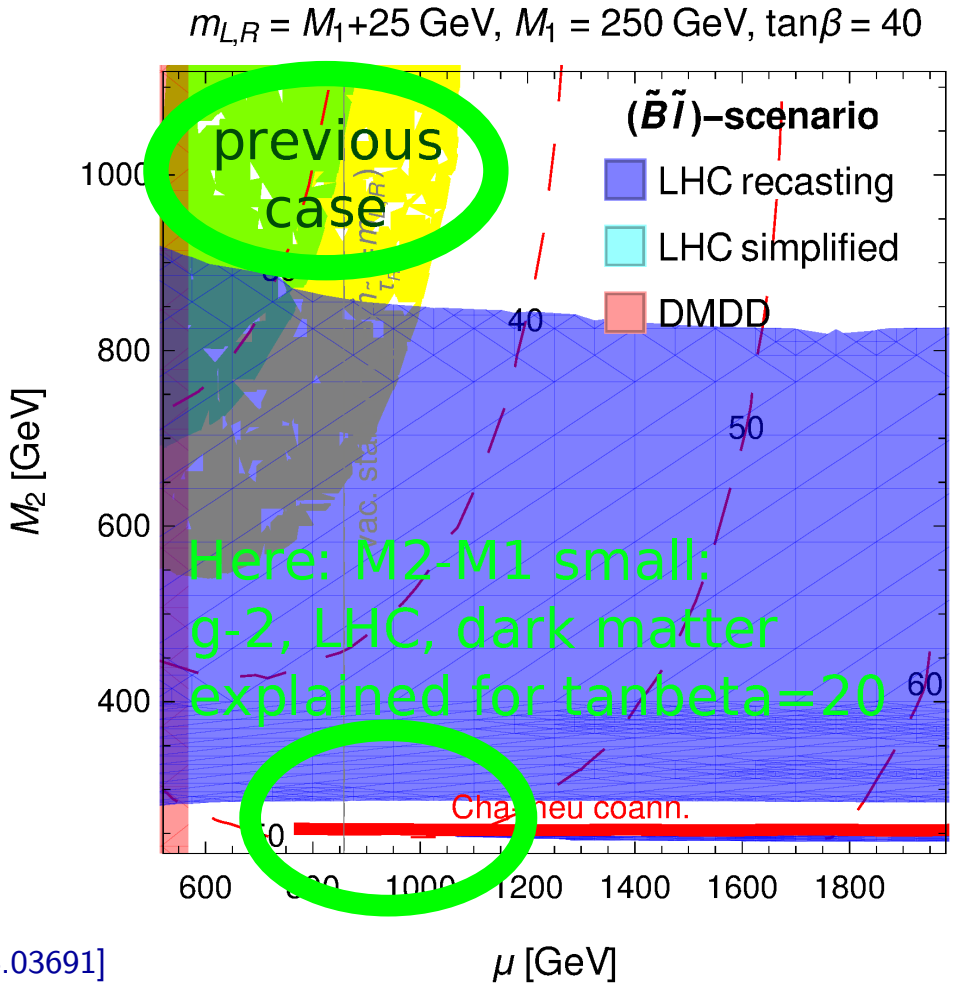
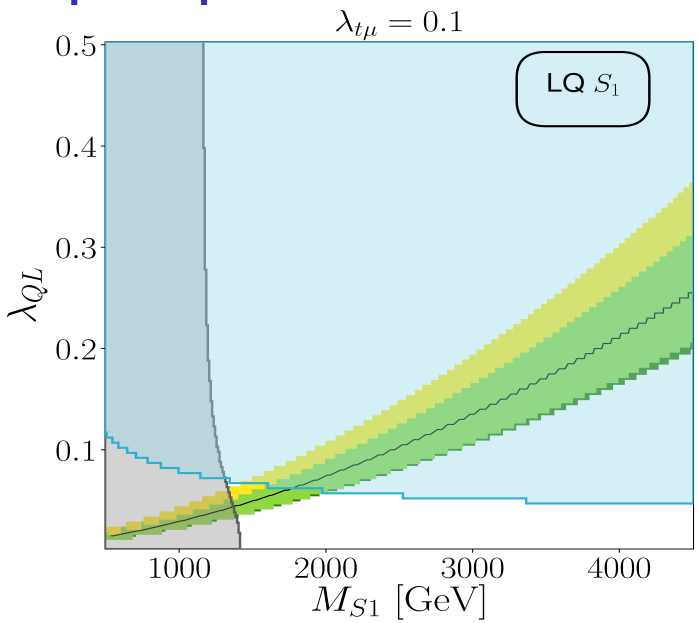
- Strong LHC limits on M_2
- DM also explained by Wino-coannihilation
- again evades (current) LHC limits

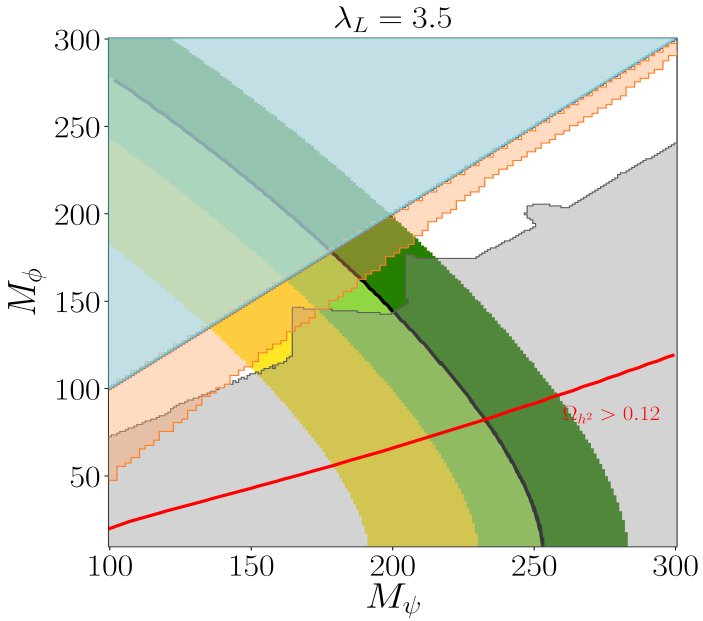




[2104.03691]

Leptoquarks and Model L with 2 fields





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

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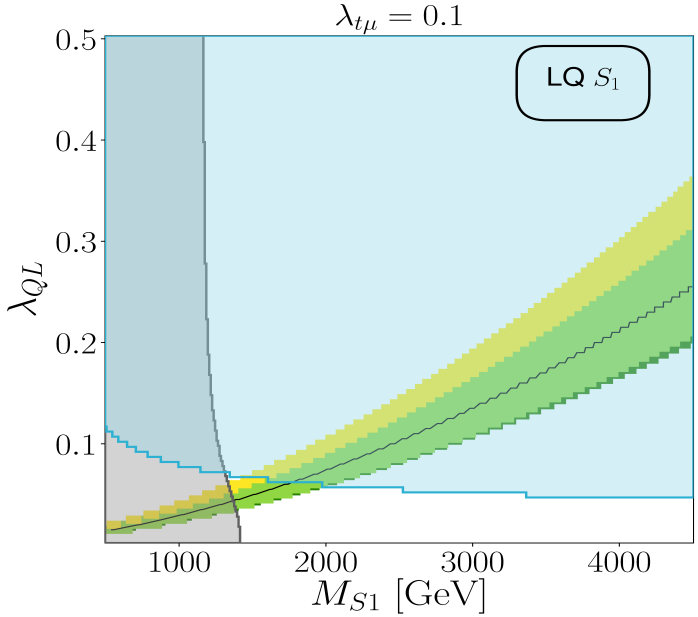
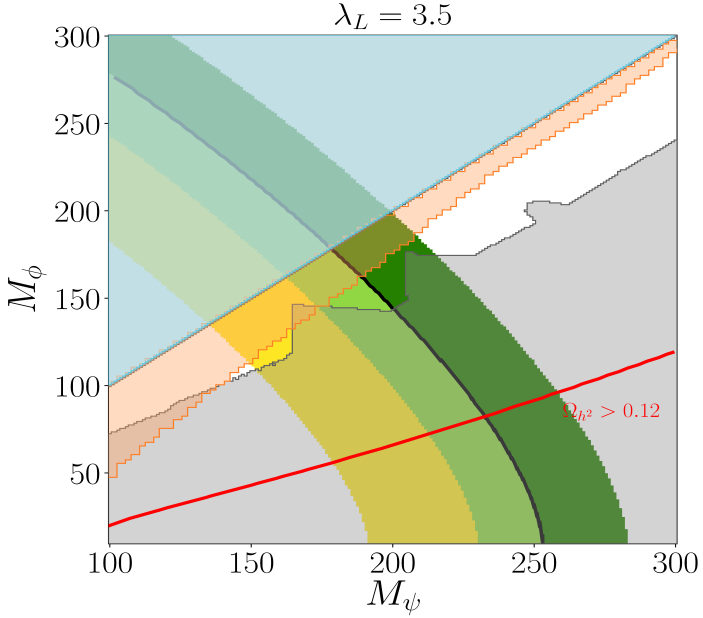
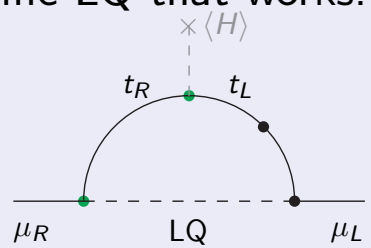




[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, 2104.03691]

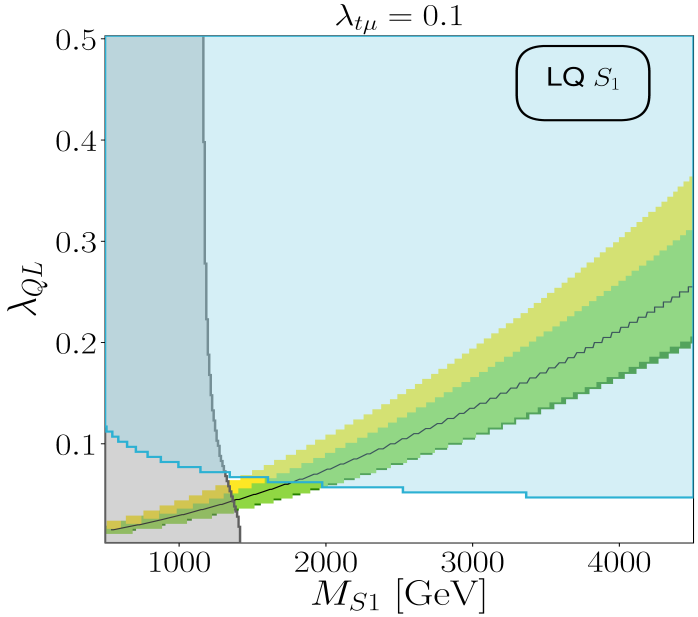
a_μ from LQ (or VLL) $\mathcal{L}_{S_1} = -\left(\lambda_{QL} Q_3 \cdot L_2 S_1 + \lambda_{t\mu} t \mu S_1^*\right)$

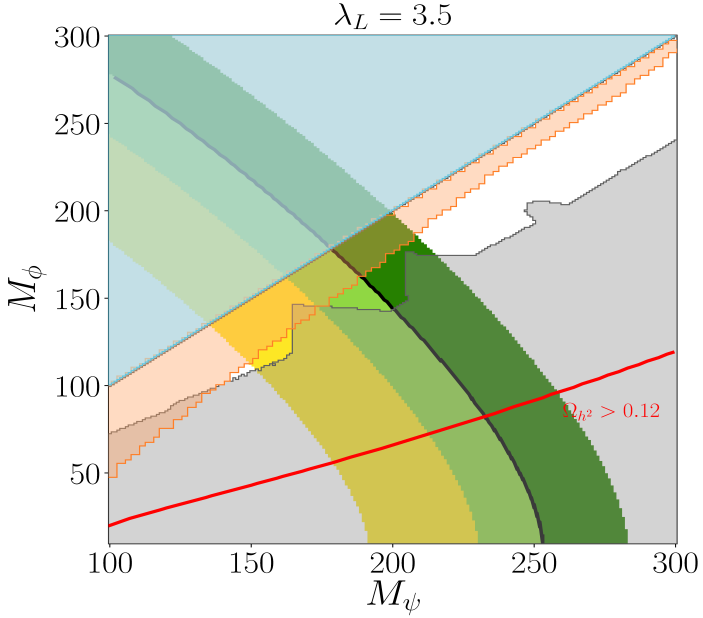
Specific LQ that works:



- Chiral enhancement $\sim y_{\text{top}}, y_{\text{VLL}}$ versus y_μ
- LHC: lower mass limits
- Flavour constraints $\rightsquigarrow$
  assume only couplings to muons
- Viable window above LHC (without m_μ-finetuning)

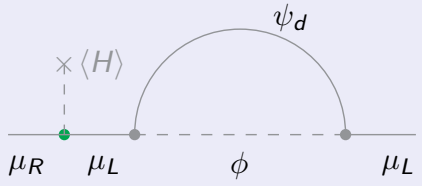
Leptoquarks and Model L with 2 fields





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

a_μ from 2-field model L



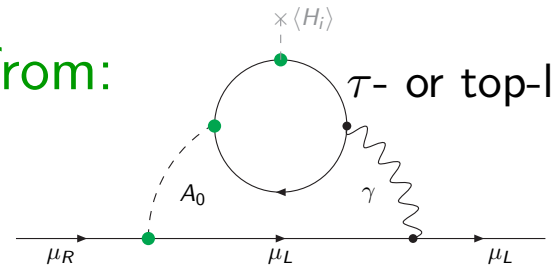
- No chiral enhancement, need very large couplings
- LHC: lower mass limits
- Dark matter candidate, but incompatible with large a_μ

  General result: a_μ and DM require at least three new fields!

BSM with smaller masses, hidden from colliders?

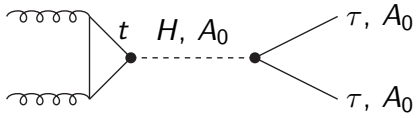
- Aligned 2-Higgs doublet model, rich new Higgs/Yukawa sectors

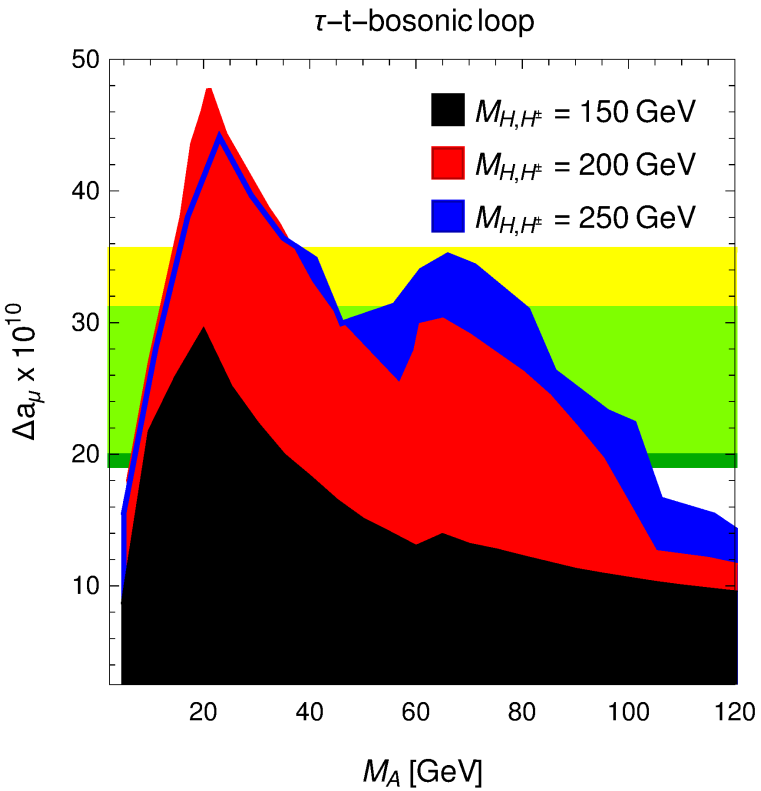
a_μ from:



τ- or top-loop

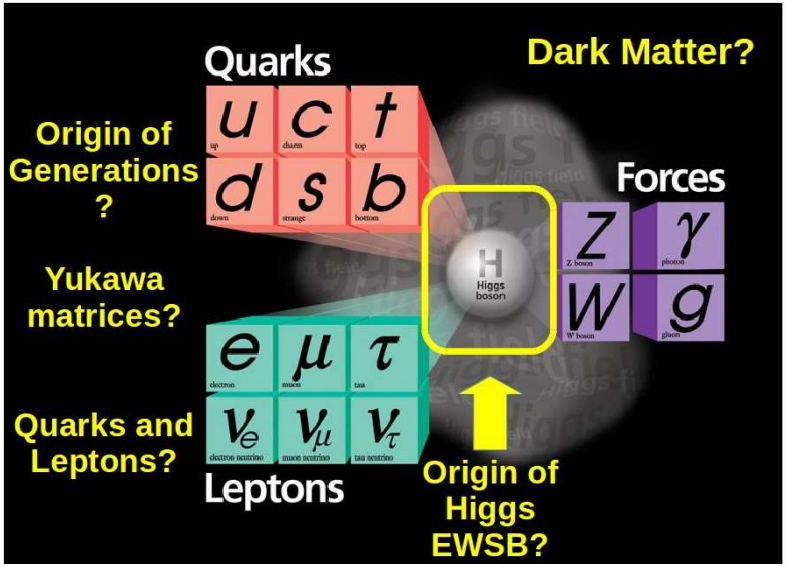
LHC constraints:





[2104.03691]

- can explain $g-2$
- need large new Yukawa couplings
- under pressure, testable at LHC, lepton colliders, B-physics



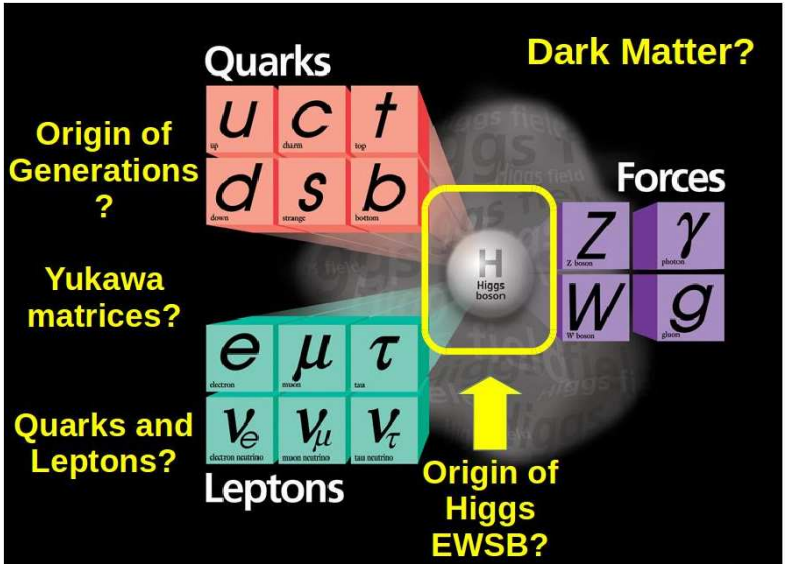
Window to muon mass generation mechanism?

Dark Matter? Hard to see in detectors

but could couple to muon $\rightsquigarrow$ large effects possible!

many examples, but within simple models: need at least three new fields

generally: dark matter direct detection constraints important!



Window to muon mass generation mechanism?
allows significant chiral enhancements,

but such models are constrained by collider, flavour etc

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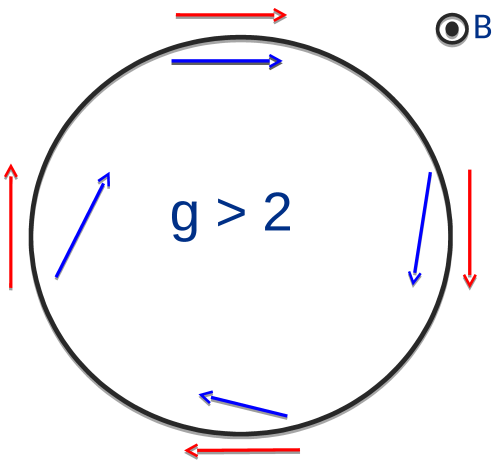
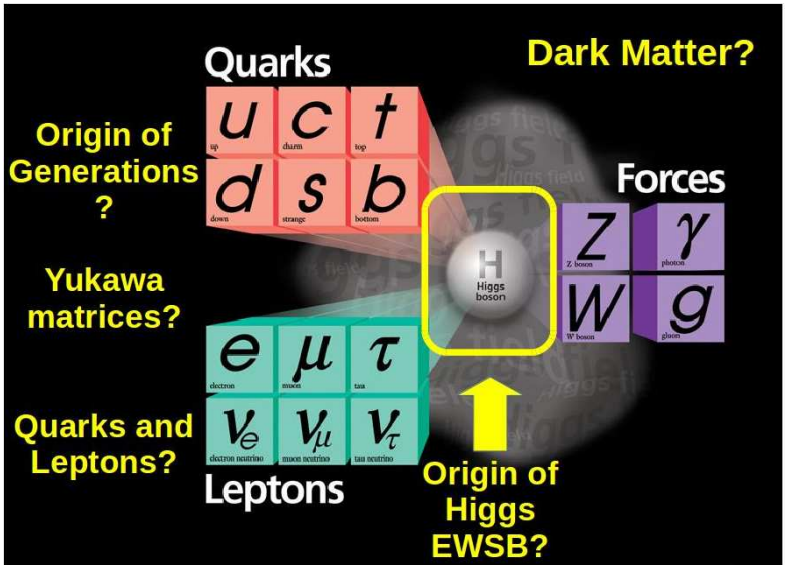
Window to the muon mass generation mechanism (Higgs/Yukawa sectors)

(continuous spin rotation requires rest mass!)





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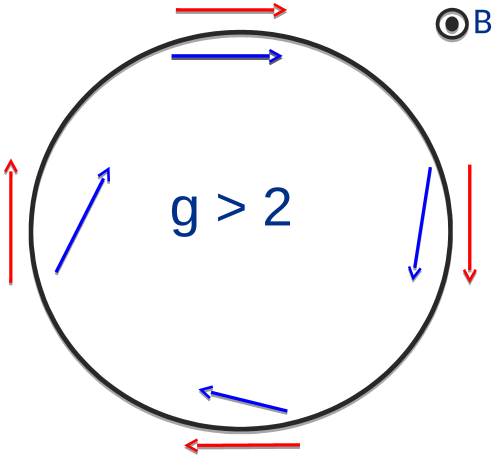
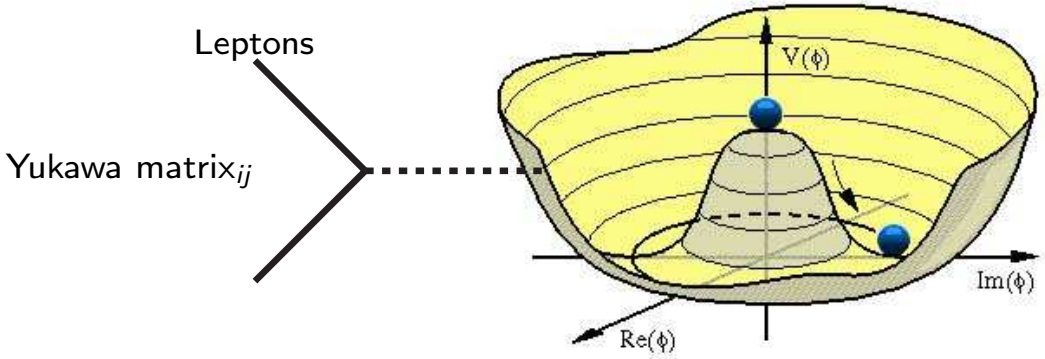




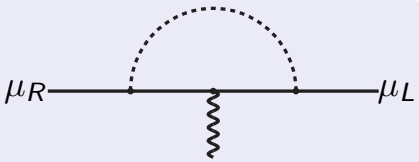
(changed by new physics?)

Two important general points

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

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



compare: 

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

EWPO

Questions: Which models can(not) explain it?

Why is a single number so interesting?

"Why are you happy about a discrepancy?"

$\Rightarrow$ we might make significant progress!

Summary of main points

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

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

a_μ is loop-induced, CP- and flavor-conserving and chirality-flipping

rather light, neutral (?) particles $\rightsquigarrow$ Connection to dark matter?

Chirality flip enhancement $\rightsquigarrow$ Window to muon mass generation? EWSB/generations?

Which models can still accommodate large deviation?

Many (but not all) models!

but always: experimental constraints!

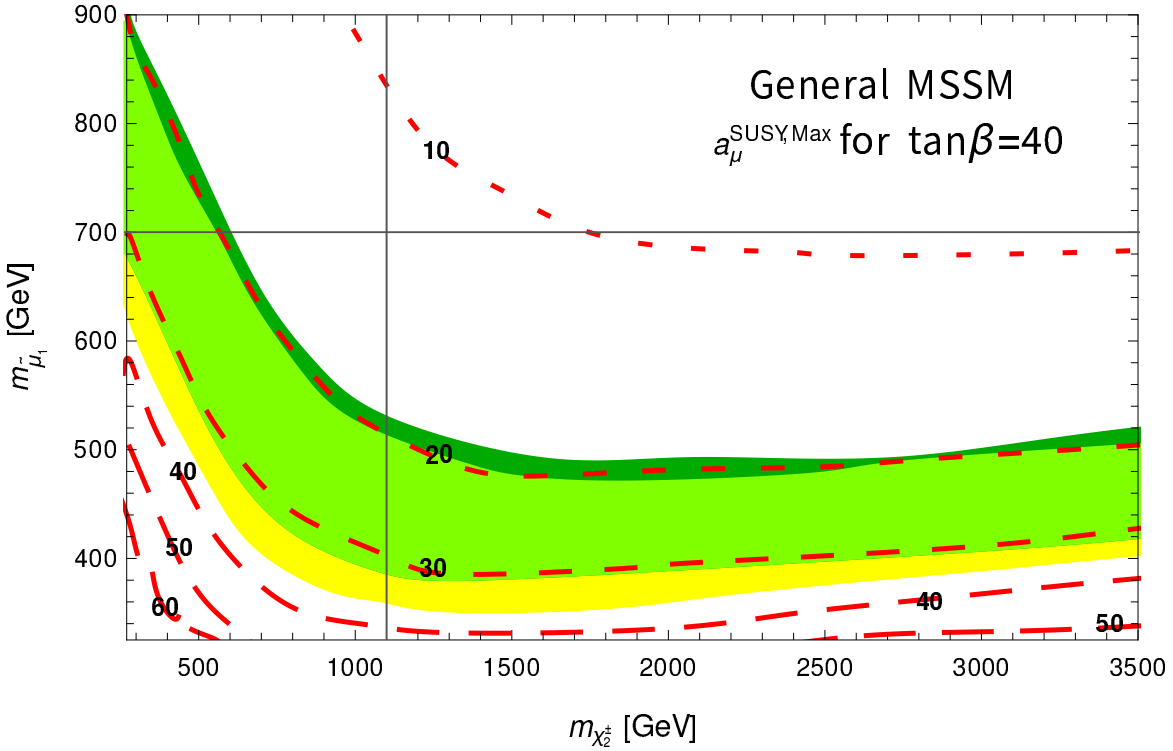
Outlook:

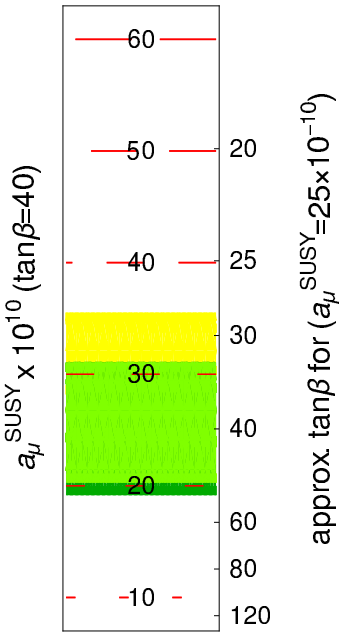
- $g-2$ + LHC, DM $\rightsquigarrow$ constraints on BSM physics, great potential for future
- often chirality flips/new flavor structures/light particles $\rightsquigarrow$ tests: Higgs couplings, B-physics, CLFV, EDM, light-particle searches, e^+e^-/muon collider

20 years after BNL. . . deviation confirmed . . . very promising future!

Full MSSM overview in 7 plots

[Peter Athron, Csaba Balasz, Douglas Jacob, Wojciech Kotlarski, DS, Hyejung Stöckinger-Kim, 2104.03691]





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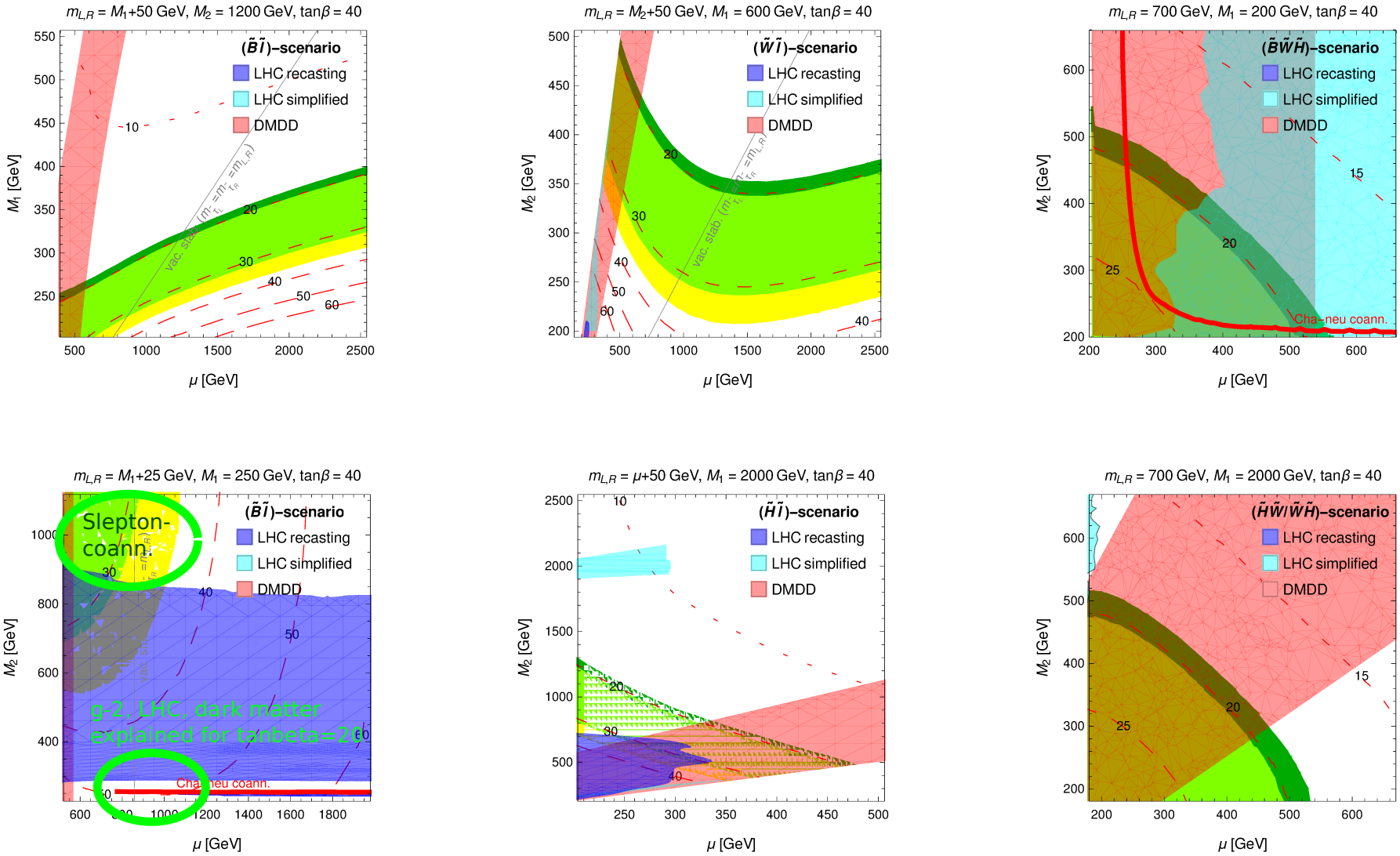
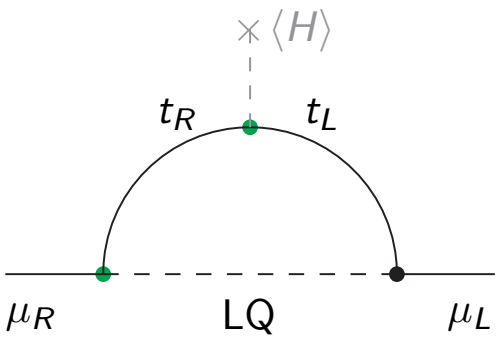
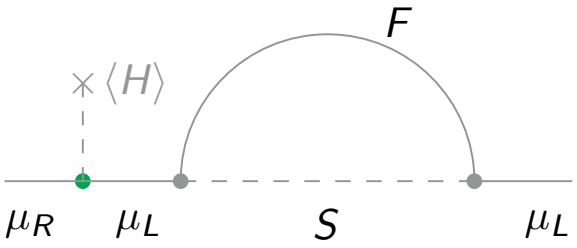


Summary: Bino-LSP: a_μ and DM. Wino-/Higgsino-LSP: a_μ. Both cha<slepton: ≈disfavoured.

DM+LHC⇒mass patterns! Coannihilation regions help! Specific cases excluded, e.g. Constrained MSSM

One-field, two-field models (renormalizable, spin $0, 1/2$)





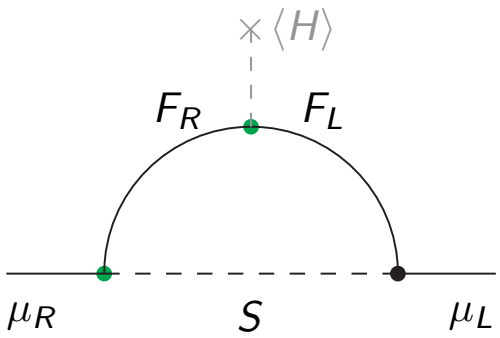
- many models: excluded
- very special models: chiral enhancement
  specific leptoquarks, specific 2HDM versions
- however, no dark matter

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1},\mathbf{1},1)$	Ruled out: $\Delta a_\mu < 0$
2	0	$(\mathbf{1},\mathbf{1},2)$	Ruled out: $\Delta a_\mu < 0$
3	0	$(\mathbf{1},\mathbf{2},-1)$	Special cases viable
4	0	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
5	0	$(\mathbf{3},\mathbf{1},1/3)$	Updated Sec. 4.2
6	0	$(\bar{\mathbf{3}},\mathbf{1},4/3)$	Ruled out: $\Delta a_\mu < 0$
7	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	Ruled out: $\Delta a_\mu < 0$
8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 4.2
9	0	$(\mathbf{3},\mathbf{2},2/3)$	Ruled out: $\Delta a_\mu < 0$
10	1/2	$(\mathbf{1},\mathbf{1},0)$	Ruled out: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
12	1/2	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
13	1/2	$(\mathbf{1},\mathbf{2},-\frac{3}{2})$	Ruled out: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1},\mathbf{3},0)$	Ruled out: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
17	1	$(\mathbf{1},\mathbf{2},-3/2)$	Ruled out: UV compl. M_F limit

- even more models: excluded
- no chirality flip
- few models: either a_μ^{BNL} or dark matter

$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Projected LHC 14 TeV exclusion, not confirmed
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	No	Excluded: LHC searches
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: LEP search
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},0)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0 - (\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},-1)_0 - (\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{3},-1)_0 - (\mathbf{1},\mathbf{3},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},-1)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{1},0)_{1/2} - (\mathbf{1},\mathbf{1},1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},-1)_1$	No	Excluded: LHC searches + LEP contact interactions

Three-field models



- many models: viable, large chirality enhancements
- can explain a_μ^{BNL} and LHC and dark matter