Kavli IPMU, Tokyo, Nov. 14, 2019

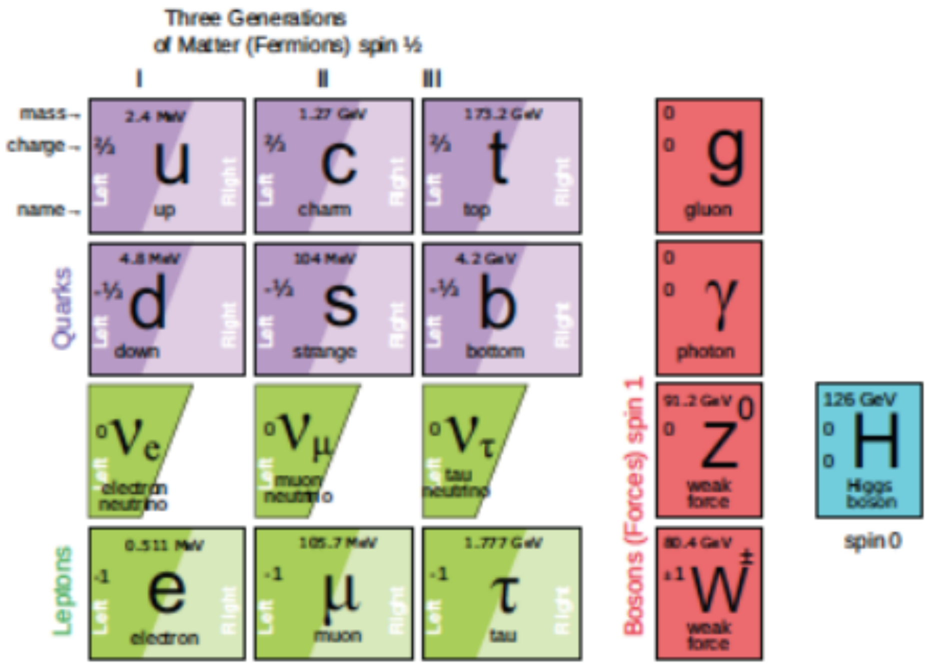
Lepton dipole moments and light (scalar) dark matter as windows to go beyond the Standard Model

Antonio Masiero

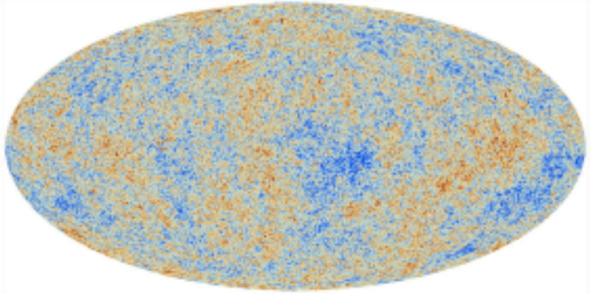
INFN and Univ. of Padova

2013 – 2016 : the triumph of the STANDARD

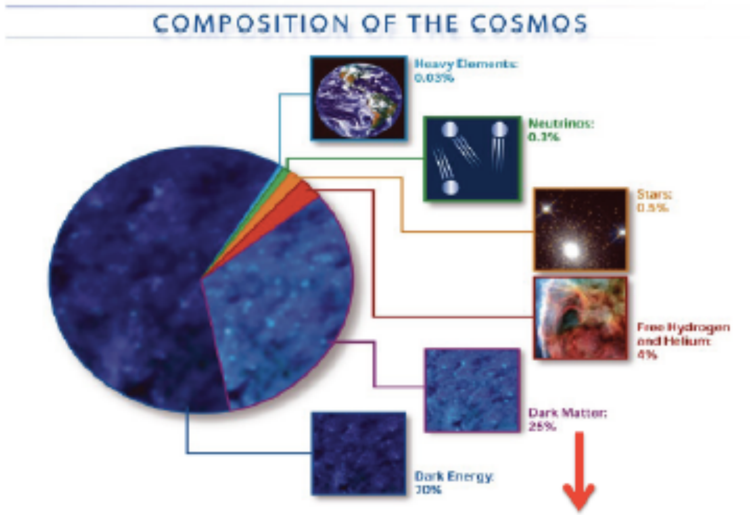
- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



ΛCDM + "SIMPLE" INFLATION



Are the SMs really STANDARD?

G-W-S SM

- **All the experimental results** of both **high-energy particle physics** and **high-intensity flavor physics** are surprisingly (and embarrassingly) in **very good agreement** with the predictions of the GSW SM

- Only (possible) exceptions:

  -- **the anomalous magnetic moment of the muon (3.6 σ discrepancy w.r.t. the SM prediction);**

  -- **hints of violation of the lepton flavor universality in semileptonic B decays**(??)

ΛCDM SM

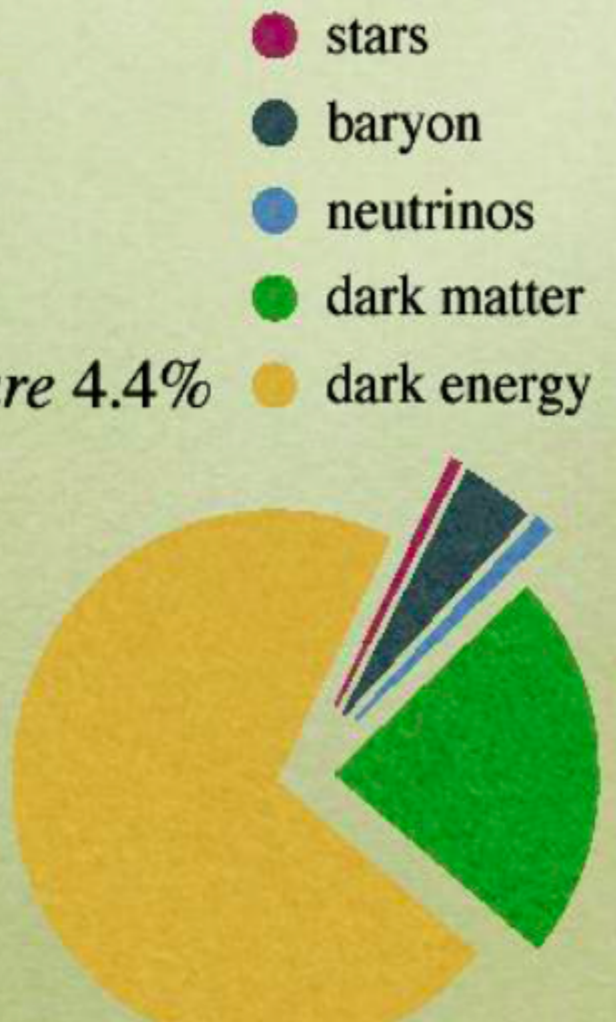
- **All the cosmic observations are in agreement** with the ~25% CDM, ~70% cosmological constant **Λ ,** ~5% ordinary matter of the **ΛCDM SM**

- (Possible) exception: **troubles with pure Cold DM** from absence proto-galaxies, non-existence of spikes in DM density at the centre of the galaxies

- …**Value of the Hubble constant** measured today or inferred from the Planck results on the CMB

***5 numbers, 5 indications of physics beyond the Standard Models of Particle Physics and Cosmology*: NEUTRINO MASSES, DARK MATTER, DARK ENERGY, ANTIMATTER and VACUUM ENERGY**

- *Stars and galaxies are only ~0.5%*
- *Neutrinos are* **> 0.1 %**
- *Rest of ordinary matter (electrons, protons & neutrons) are 4.4%*
- *Dark Matter* **~ 27%**
- *Dark Energy* **~ 68 %**
- *Anti-Matter* **0 %**
- *Higgs Bose-Einstein condensate* ~ **10^{62} %** ??



thanks to H. Murayama

What the SM does not account for…

- neutrino masses
- dark matter
- baryogenesis
- inflation

→ **OBSERVATIONAL REASONS**

- $M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$
- $E_{VACUUM}(DE) / M_{HIGGS} \sim 10^{-14}$
- $\Theta_{\text{CPV in STRONG INTERAC.}} < 10^{-9}$

→ **THEOR. REASONS**

The DM dilemma: to be or not to be related to the electroweak symmetry breaking?

The question can be rephrased into:

Is DM a good honest **weakly** (but not too weakly) **interacting** (with the SM particles) **massive** (typically O(100 GeV)) **particle**, i.e. a "traditional" **WIMP** part of an extension of the SM accounting for a (possibly natural) **explanation of the (incredibly small) electroweak symmetry breaking scale M_W (as compared to the Planck scale M_{Pl}) and constituting an SM UV cut-off at the TeV scale ?**

Or

Is DM unrelated to the existence of a natural solution of the gauge hierarchy problem.
i) In this case DM can be part of an SM extension at E >> M_W (for instance E ~ mutiTeV) and then, presumably, M_{DM} > O(1 TeV) (**heavy DM**) or

ii) DM could be a (very) **light** particle coupling **very weakly** to the SM particles being part of a **new dark sector** of the theory communicating with the SM particles only through a specific "**portal**", i.e. one or more particles **bridging the "dark world" with "our" SM world** (in this case the DM sector is not part of a larger theory extending the SM, but it could be a separate sector of the theory)

Pros and cons to be a WIMP DM (I)

Pros:

- i) the WIMP coincidence or emphatically dubbed "**WIMP miracle**" (namely: take a **weakly interacting O(100 GeV)** particle once in **thermal equilibrium** and compute its number density today – result: typically one ends up with $n_{WIMP} \sim 10^{-8}\ cm^{-3}$ leading to the **correct DM amount** ! ;
- ii) such WIMP DM typically constitutes a form of **COLD DM** (hence correctly accounting for the main bulk of observations on large scale structures distribution)
- iii) remarkably enough, the main SM extensions envisaged to cope with **"natural" explanation** of the gauge hierarchy puzzle $M_W << M_{Pl}$ entail the presence of a **stable particle**, typically the **lightest of the new particles** characterizing such SM extension, which is a potentially good **WIMP DM candidate**.

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	EXTRA DIM.	LITTLE HIGGS.
1) **ENLARGEMENT OF THE SM**	(x^μ, θ)	(x^μ, j^i)	SM part + new part
	Anticomm. Coord.	New bosonic Coord.	to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	***R-PARITY LSP***	***KK-PARITY LKP***	***T-PARITY LTP***
→ **DISCRETE SYMM.**	Neutralino spin 1/2	spin1	spin0
→ **STABLE NEW PART.**	↓	↓	↓
3) FIND REGION (S) PARAM. SPACE WHERE THE “L” NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

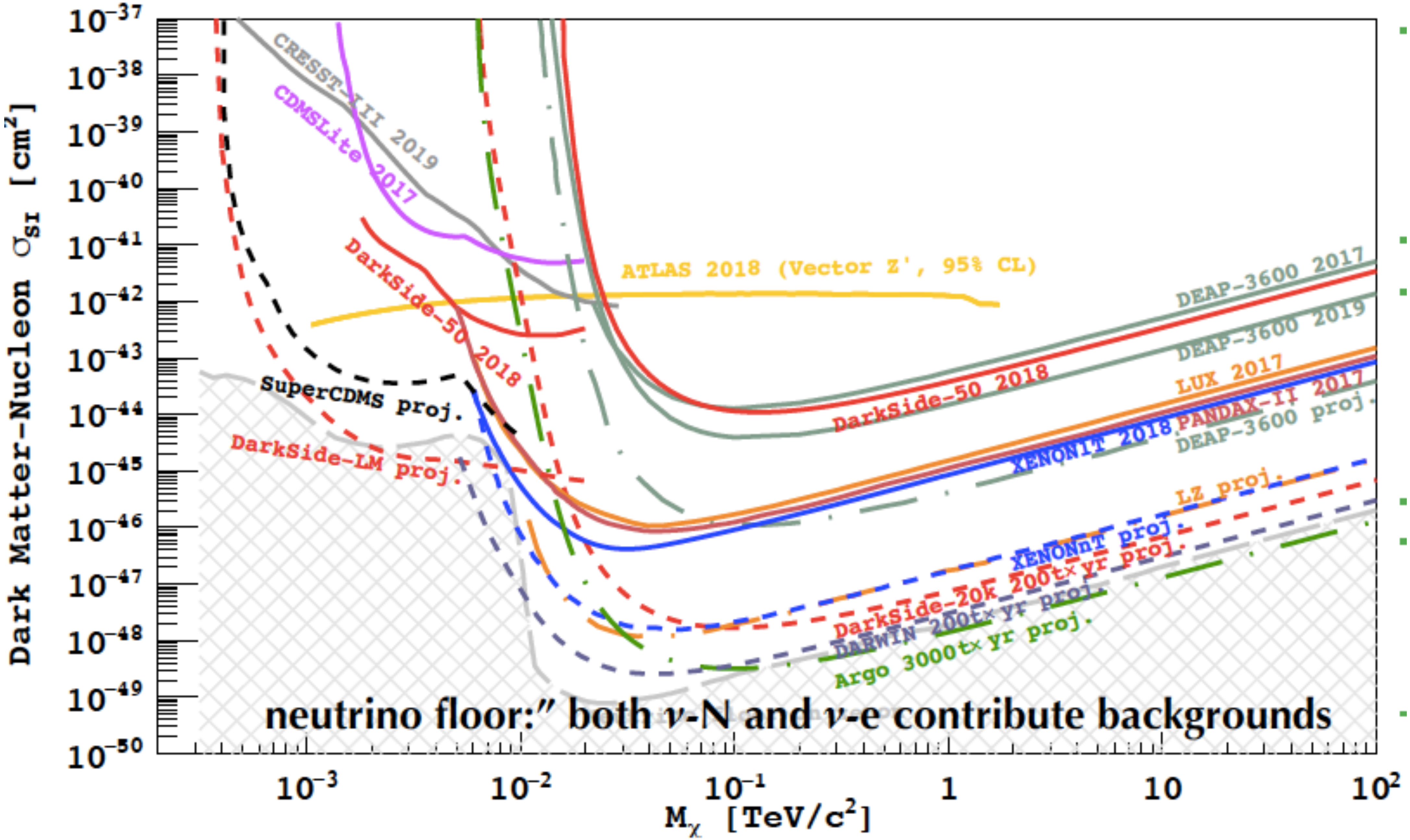
Pros and cons to be a WIMP DM (II)

The **cons**:

i) In spite of constituting the most "wanted" particle candidate for DM, **no WIMP signal** (or at least hint) has ever emerged with searches reaching sensitivities to WIMP-nuclei cross sections down to 10^{-10} pb;

ii) The negative results coming from high-energy and flavour physics (in particular LHC) searches of new physics particles around the corner, i.e. in the O(1TeV) mass range, have (largely) **reduced our enthusiasm for a TeV new physics directly linked to a natural solution of the $M_W << M_{Pl}$ gauge hierarchy problem**. And, as a consequence, **the lightest TeV new physics particle has lost its appeal as "natural" candidate for DM**

iii) The main "victim" of this lost connection DM – TeV new physics is undoubtedly the **Lightest SUSY Particle**, LSP, typically the lightest **neutralino** in SUSY models with R parity



CRESST-III 2019
CDMSLite 2017
DarkSide-50 2018
ATLAS 2018 (Vector Z', 95% CL)
DEAP-3600 2017
DEAP-3600 2019
DarkSide-50 2018
LUX 2017
PANDAX-II 2017
XENON1T 2018
DEAP-3600 proj.
SuperCDMS proj.
DarkSide-LM proj.
LZ proj.
XENONnT proj.
DarkSide-20k 200t× yr proj.
DARWIN 200t× yr proj.
Argo 3000t× yr proj.
neutrino floor:" both ν-N and ν-e contribute backgrounds
Dark Matter-Nucleon σ_SI [cm²]
M_χ [TeV/c²]

- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV
- dark matter definitely exists
  - naturalness problem may be optional?
- need to explain dark matter on its own
- perhaps we should decouple these two
- do we really need big ideas like SUSY?
- perhaps not necessarily heavier but rather lighter and weaker coupling?

Summary talk by Asai and Catena of the DM WG at the EU Strategy Granada Symposium

Dark Sectors

What is meant by a dark sector ?
A Hidden sector, with Dark matter, that talks to us through a Portal

Portal can be the Higgs boson itself or New Messenger/s

Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

Interesting, distinctive phenomenology
Long-Lived Particles
Feebly interacting particles (FIP's)

Summary talk by Asai and Catena of the DM WG at the EU Strategy Granada Symposium

Classes of portal interactions

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda S^2 + A S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu}V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

LHN neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

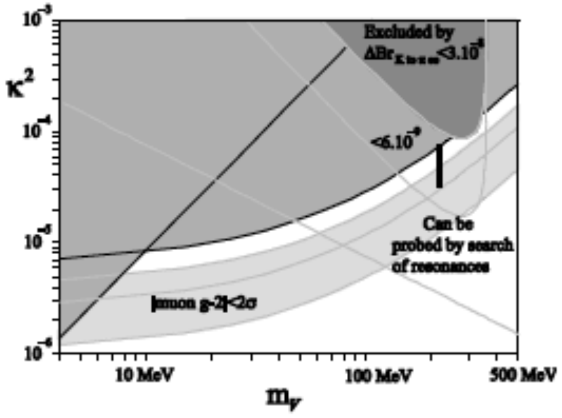
$J_\mu^A\, \partial_\mu a/f$ axionic portal

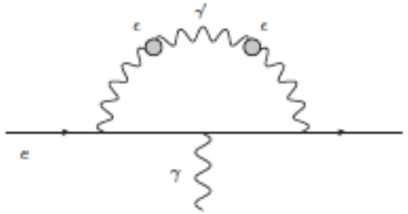
……….

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)}\mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

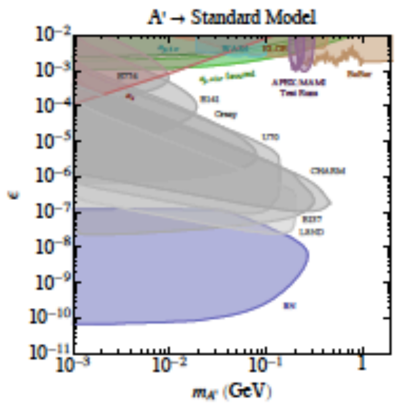
Maxim Pospelov, Physics Beyond Colliders at Cern: Beyond the Standard Model Working Group Report

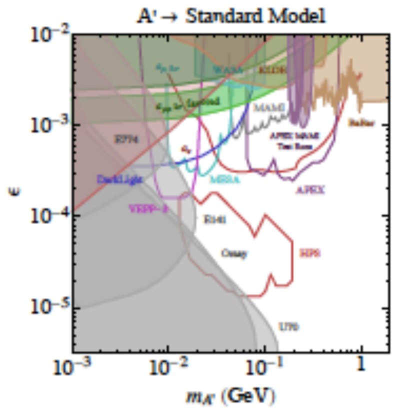
g-2 motivation for dark photons



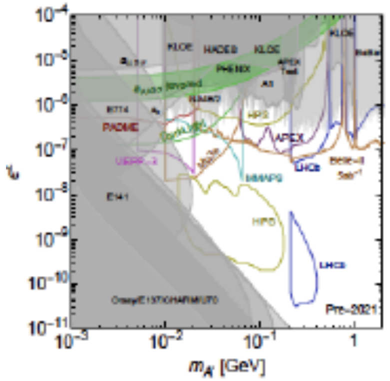


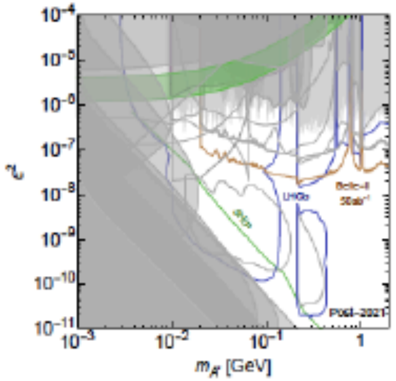
Dark photon with kinetic mixing ~ 10^{-3} is the simplest model that can account for anomalous $\Delta a_\mu \sim 3\ 10^{-9}$, MP, 2008





Search for dark photons ($A' \to e^+e^-$) has become an important part of the intensity frontier program, Snowmass exercise, Minneapolis, 2013

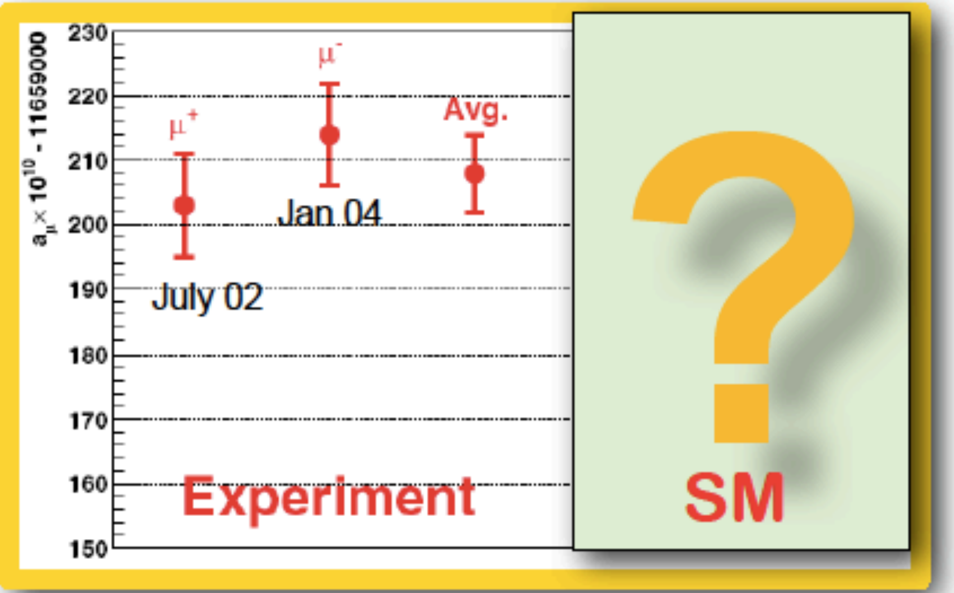




By 2018, there is a large community in place ("Cosmic Vision" summary, 100s of authors, 2017), where the search for dark photon is one of the priorities.

Maxim Pospelov

The muon g-2: experimental status



- BNL 821: $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- New muon g-2 experiments at:
  - Fermilab E989: aims at $\pm 16 \times 10^{-11}$, ie 0.14ppm.
    First two data taking completed. Analysis in progress.
    First result expected very soon with ~ BNL E821 precision.
  - J-PARC proposal: phase-1 start with 0.46ppm (TDR 2017).
- Are theorists ready for this (amazing) precision? Not yet!

g = 2

- Uhlenbeck and Goudsmit in 1925 proposed for electrons

$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$
$$g = \underline{2 \quad \text{(not 1!)}}$$

- Dirac 1928:

$$(i\partial_\mu - eA_\mu)\,\gamma^\mu\psi = m\psi$$

- A Pauli term in Dirac's eq would give a deviation…

$$a\frac{e}{2m}\sigma_{\mu\nu}F^{\mu\nu}\psi \quad \rightarrow \quad g = 2(1+a)$$

…but there was no need for it! g=2 stood for ~20 yrs.

g ≠ 2

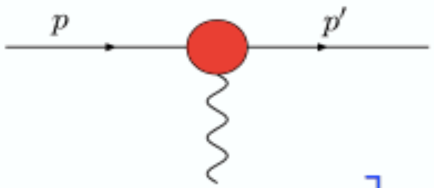
- **Kusch and Foley 1948:**

$$\left(\frac{g_e}{2}\right)^{\rm exp} \equiv 1 + a_e^{\rm exp} = 1.00119 \pm 0.00005$$

- **Schwinger 1948 (triumph of QED!):**

$$\left(\frac{g_e}{2}\right)^{\rm th} \equiv 1 + a_e^{\rm th} = 1.00116\ldots$$

- **We keep studying the lepton–γ vertex:**



$$\bar{u}(p')\Gamma_\mu u(p) = \bar{u}(p')\left[\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m}F_2(q^2) + \ldots\right]u(p)$$

$$F_1(0) = 1 \qquad F_2(0) = a_l$$

A pure "quantum correction" effect!

Comparisons of the SM predictions with the measured g-2 value:

$a_\mu^{EXP} = 116592091\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda=\mu_\mu/\mu_p$ from CODATA'10

$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
116 591 784 (44)	$307\ (77) \times 10^{-11}$	4.0 [1]
116 591 829 (49)	$262\ (80) \times 10^{-11}$	3.3 [2]
116 591 822 (38)	$269\ (74) \times 10^{-11}$	3.6 [3]

with the hadronic light-by-light $a_\mu^{HNLO}(lbl) = 100\ (29) \times 10^{-11}$ of F. Jegerlehner arXiv:1705.00263, and the hadronic leading-order of:

[1] F. Jegerlehner, arXiv:1711.06089.
[2] Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921.
[3] Keshavarzi, Nomura, Teubner, arXiv:1802.02995.

New physics Λ energy scale and $(g\text{-}2)_\mu$

If New Physics (NP) at a scale Λ gives the contribution δm_μ to the muon mass, then such NP leads to a loop contribution to the muon magnetic moment a_μ :

$$a_\mu(\mathrm{N.P.}) = \mathcal{O}(1) \times \left(\frac{m_\mu}{\Lambda}\right)^2 \times \left(\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}\right)$$

Czarnecky and Marciano, 2001; Stockinger 2010

$\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$ ~ O(α/4π) if perturbative contributions to the muon mass

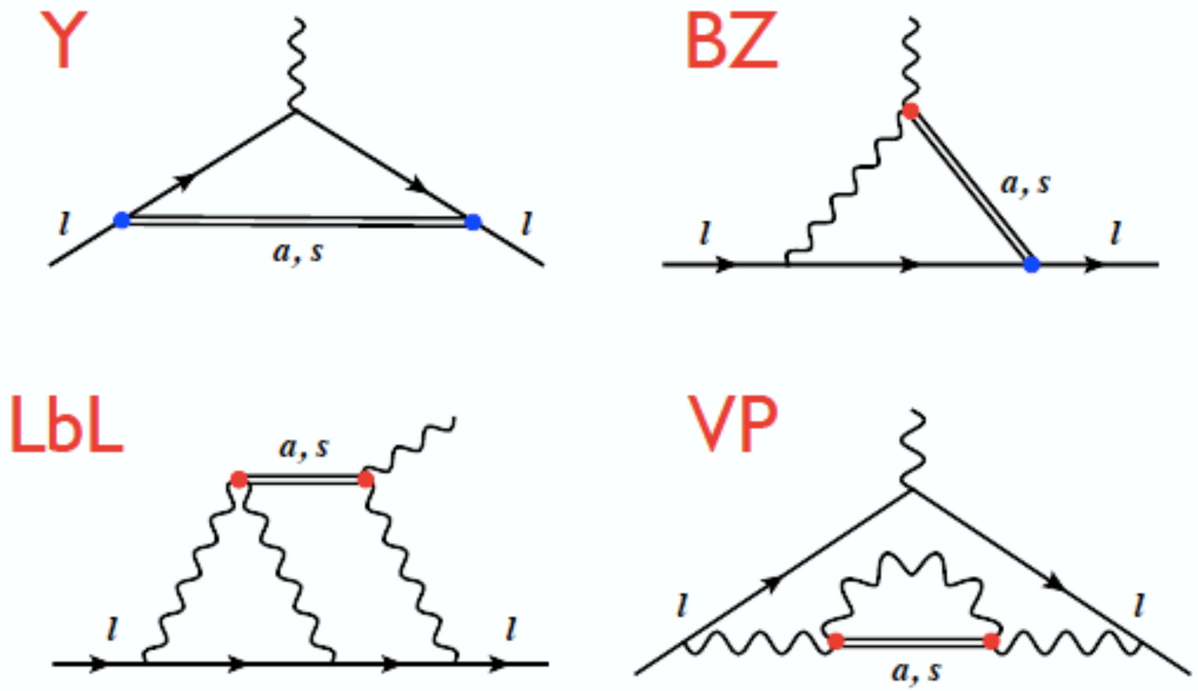
$\frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$ ~ O (1) if the muon mass is radiatively induced

$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 2.87\,(80) \times 10^{-9}$$

If the g-2 discrepancy between exp. and SM expectation is a real fact and if we invoke NP to account for it, then

Λ NP has to be at or below the TeV scale !

ALPs contributions to the muon g-2?



- Both scalar and pseudoscalar ALPs can solve Δa_μ for masses ~ [100MeV-1GeV] and couplings allowed by current experimental constraints.

- They can be tested at present low-energy e^+e^- experiments, via dedicated $e^+e^- \to e^+e^-$+ALP & $e^+e^- \to \gamma$+ALP searches.

The SM prediction of the electron g-2

- **The SM prediction is:**

$$a_e^{SM}(\alpha) = a_e^{QED}(\alpha) + a_e^{EW} + a_e^{HAD}$$

- **The EW (1&2 loop) term is:** Czarnecki, Krause, Marciano '96, Jegerlehner 2017

$$a_e^{EW} = 0.3053\,(23) \times 10^{-13}$$

- **The Hadronic contribution, at LO+NLO+NNLO, is:**

Nomura & Teubner '12, Jegerlehner 2017; Krause'97; Kurz, Liu, Marquard & Steinhauser 2014

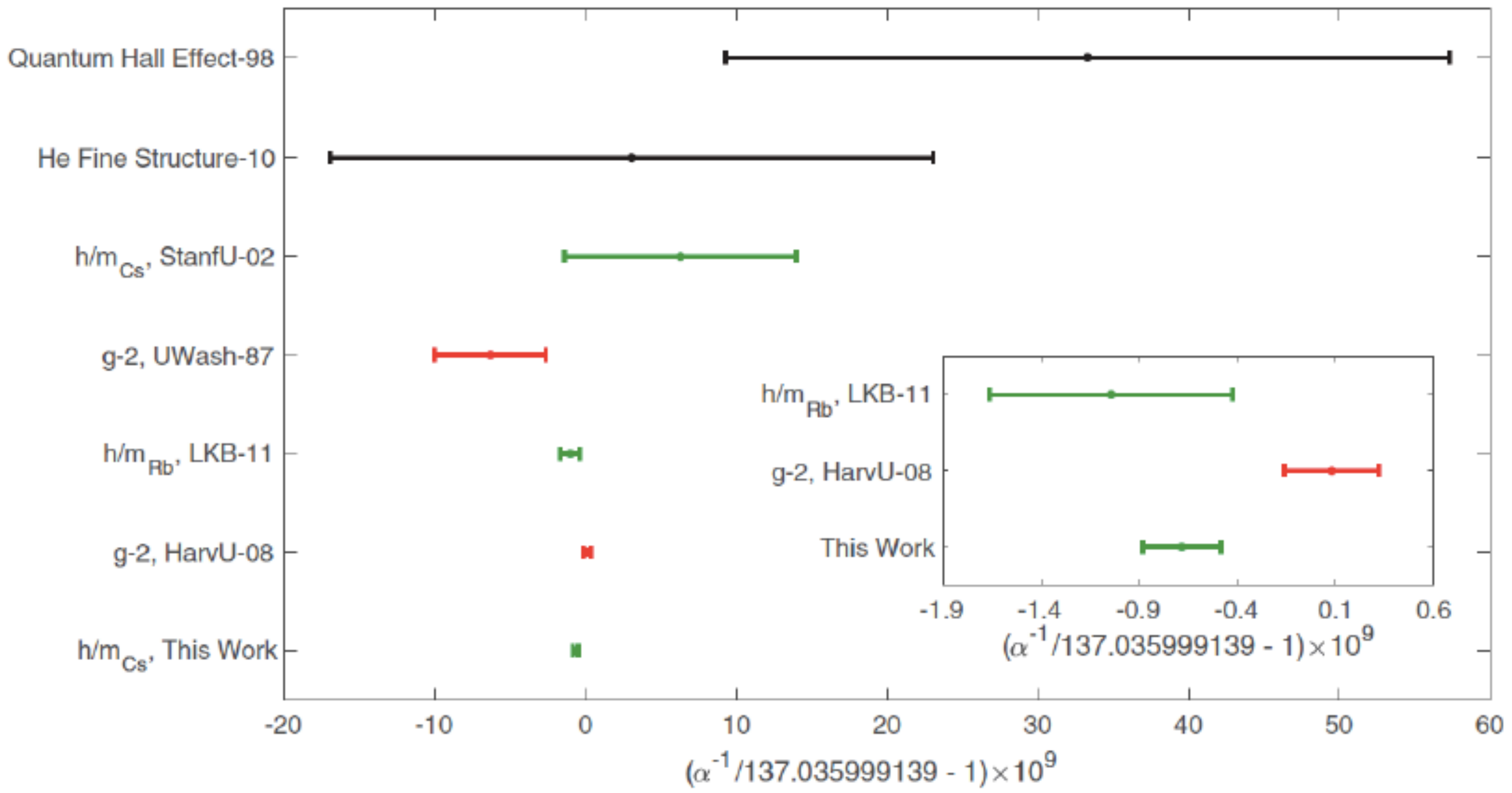
$$a_e^{HAD} = 16.93\,(12) \times 10^{-13}$$

$$a_e^{HLO} = +\,18.490\,(108) \times 10^{-13}$$

$$a_e^{HNLO} = [-2.213(12)_{vac} + 0.37(5)_{lbl}] \times 10^{-13}$$

$$a_e^{HNNLO} = +\,0.28\,(1) \times 10^{-13}$$

- **Which value of α should we use to compute a_e^{SM}?**



Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, Holger Müller
Science 360 (2018) 191

- The 2008 measurement of the electron g-2 is:

  $a_e^{EXP} = 11596521807.3\ (2.8) \times 10^{-13}$ Hanneke et al, PRL100 (2008) 120801

  vs. old (factor of 15 improvement, 1.8σ difference):

  $a_e^{EXP} = 11596521883\ (42) \times 10^{-13}$ Van Dyck et al, PRL59 (1987) 26

- Equate $a_e^{SM}(\alpha) = a_e^{EXP}$ → "g_e-2" determination of alpha:

$$\alpha^{-1} = 137.035\,999\,150\ (33) \quad [0.24\ \text{ppb}]$$

- Compare it with the present best determination of alpha:

$$\alpha^{-1} = 137.035\,999\,046\ (27) \quad [0.20\ \text{ppb}]$$ Science 360 (2018) 191 (Cs)

(was α^{-1} =137.035 998 995 (85) [0.62 ppb] PRL106 (2011) & CODATA 2016)

2.4 sigma discrepancy

The electron g-2: SM vs Experiment

- Using α = 1/137.036 999 046 (27) [Cs 2018], the SM prediction for the electron g-2 is:

$$a_e^{SM} = 115\,965\,218\,16.1\ (0.1)\ (0.1)\ (2.3) \times 10^{-13}$$

δC_5^{qed} δa_e^{had} from $\delta\alpha$

- The (EXP - SM) difference is:

$$\Delta a_e = a_e^{EXP} - a_e^{SM} = -\,8.8\ (3.6) \times 10^{-13}$$

i.e. 2.4 sigma difference. Note the negative sign!
(the 5-loop contrib. to a_e^{QED} is 4.6×10^{-13})

Testing new physics with the electron g-2

e

- The present sensitivity is $\delta\Delta a_e = 3.6 \times 10^{-13}$, ie ($10^{-13}$ units):

$$\underbrace{(0.1)_{\text{QED5}}, \quad (0.1)_{\text{HAD}},}_{(0.2)_{\text{TH}}} \quad (2.3)_{\delta\alpha}, \quad (2.8)_{\delta a_e^{\text{EXP}}}$$

- The $(g\text{-}2)_e$ exp. error may soon drop below 10^{-13} and work is in progress to further reduce the error induced by $\delta\alpha$ →

sensitivity below 10^{-13} may be reached with ongoing exp work

- In a broad class of BSM theories, contributions to a_l scale as

$$\frac{\Delta a_{\ell_i}}{\Delta a_{\ell_j}} = \left(\frac{m_{\ell_i}}{m_{\ell_j}}\right)^2$$

This **Naive Scaling** leads to:

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}; \qquad \Delta a_\tau = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.8 \times 10^{-6}$$

Giudice, Paradisi & MP, JHEP 2012

Testing new physics with the electron g-2 (2)

e

- The sensitivity in Δa_e may soon drop below 10^{-13}! This will bring a_e to play a pivotal role in probing new physics in the leptonic sector.

- NP scenarios exist which violate Naive Scaling. They can lead to larger effects in Δa_e and contributions to EDMs, LFV or lepton universality breaking observables.

Giudice, Paradisi & MP, JHEP 2012
Crivellin, Hoferichter, Schmidt-Wellenburg, PRD 2018

- One real scalar with a mass of ~ 250−1000 MeV could explain the deviations in a_μ and a_e, through one- and two-loop processes, respectively.

Davoudiasl & Marciano, PRD 2018

Minimal extensions of the SM to account for the $(g\text{-}2)_\mu$ anomaly

Addition of a **SINGLE NEW FIELD**:

i) The addition of a **single fermion** cannot explain this anomaly ;

(C. Biggio 2008; Freitas, Lykken, Kell, Westhoff 2014; Biggio, Bordone 2014)

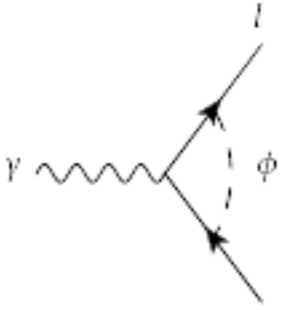
ii) The addition of a **single scalar** can account for the discrepancy if the new scalar is:

a **new Higgs doublet**; (Freitas, Lykken, Kell, Westhoff 2014; Broggio, Chun, Passera, Patel, Vempati 2014; Biggio, Bordone 2014; Cherchiglia, Kneschke, Stockinger, Stockinger-Kim 2017)

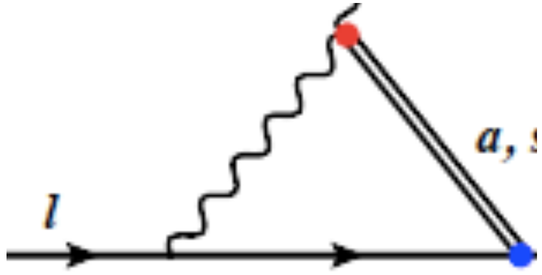
one of the two **leptoquarks**: $S^{1/3}$(3, 1, -1/3; Q= -1/3); $D^{7/6}$(3,2, 7/6; Q = 5/3, 2/3) Chakraverty, D. Choudhuri, Datta 2001; Biggio, Bordone 2014; Queiroz, Shepherd 2014; Coluccio Leskow, D'Ambrosio, Crivellin, Muller 2017

- **iii)** one massive **vector boson**: only possibility → abelian gauge extensions – Z', dark photon (Biggio, Bordone, Di Luzio, Ridolfi 2016; Davoudiasl, H.-S.Lee, Marciano 2014; Altmannshofer, C.-Y. Chen, Dev, Soni 2016;)
- **iv) ALPs (ALP-photon photon + ALP Yukawa interactions with leptons)**

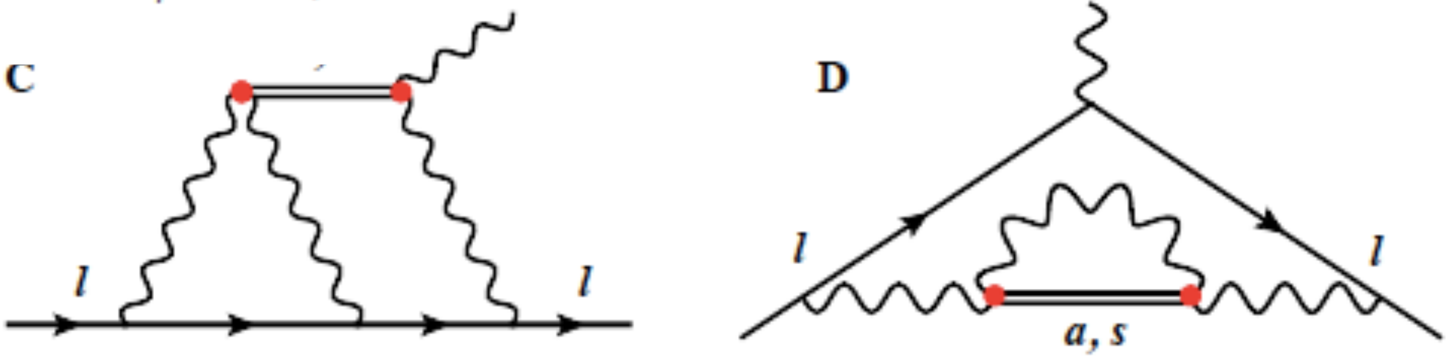
$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} + i\, y_{a\psi}\, a\, \bar{\psi}\gamma_5 \psi$$



Chen, Davoudiasl, Marciano, Zhang 2016



One-loop contribution



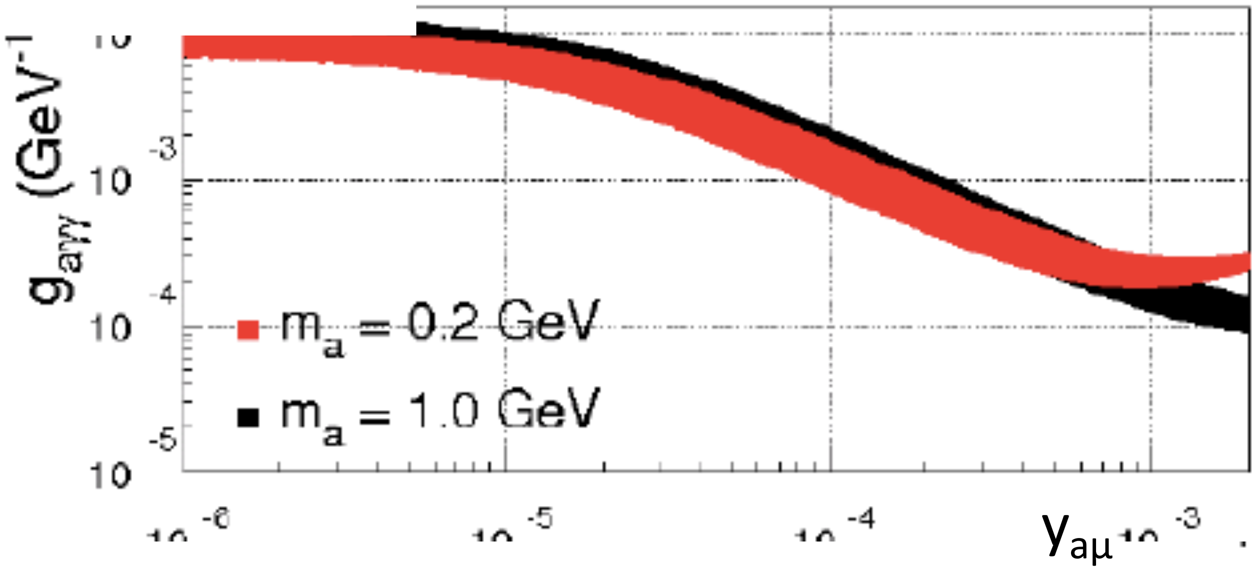
Two-loop contributions

Marciano, Masiero, Paradisi, Passera 2016

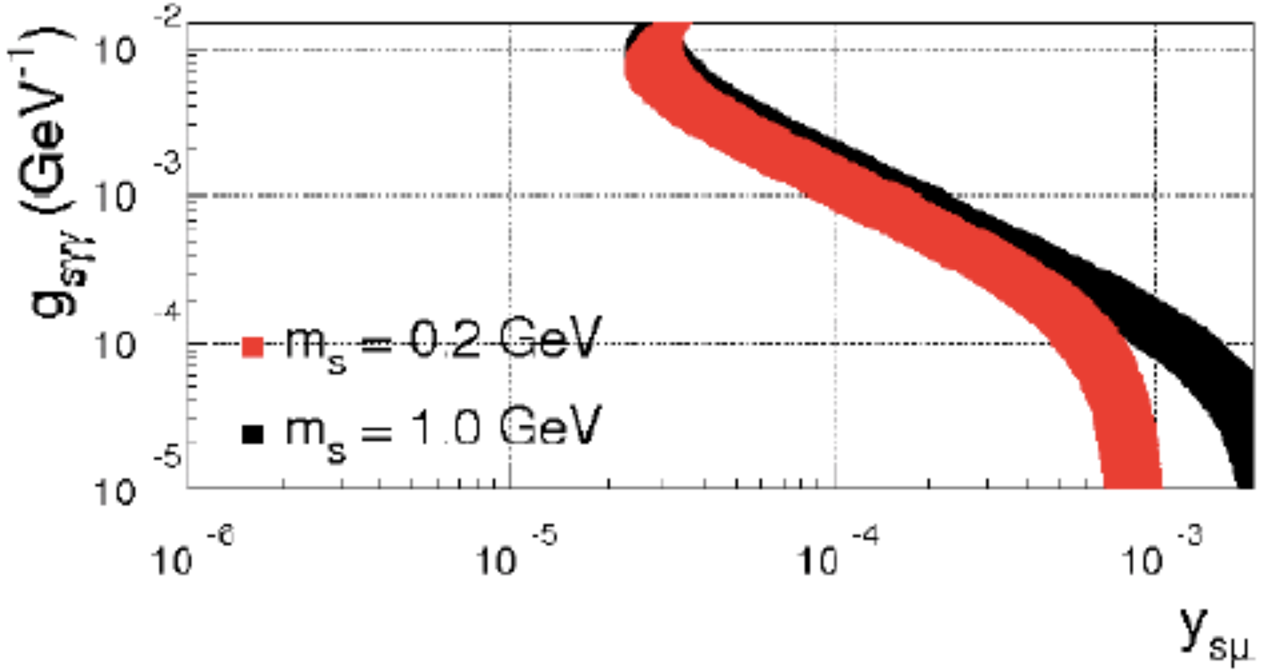
Marciano, Masiero, Paradisi, Passera 2016

$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + i\, y_{a\psi}\, a\, \bar{\psi}\gamma_5\psi$$

$$g_{a\gamma\gamma} \equiv \frac{2\sqrt{2}\,\alpha}{\Lambda}\, c_{a\gamma\gamma}$$



Pseudoscalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV



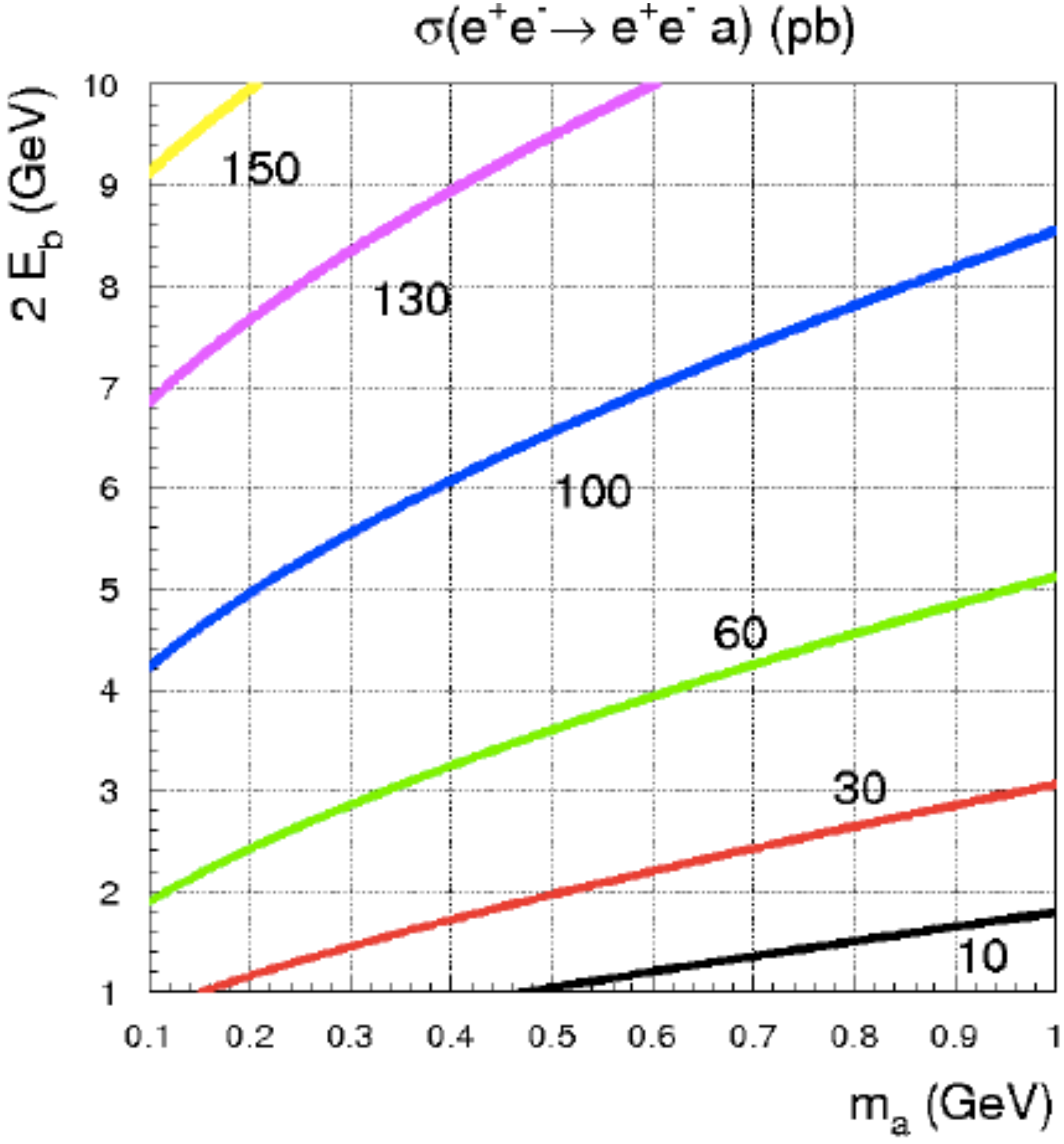
Scalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV

Experimental tests at e^+e^- colliders

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-a\,,$$
$$e^+e^- \rightarrow \gamma^* \rightarrow \gamma a\,,$$

$$\sigma_{eea} \simeq \frac{\alpha^2}{4\pi}\, g^2_{a\gamma\gamma} \left(\ln \frac{E_b}{m_e}\right)^2 f\left(\frac{m_a}{2E_b}\right)$$
$$E_b \equiv \sqrt{s}/2$$

$$\sigma_{eea}(\sqrt{s} = 1\,\mathrm{GeV}) \approx 31\,\mathrm{pb}\,\left(\frac{g_{a\gamma\gamma}}{10^{-2}\,\mathrm{GeV}^{-1}}\right)^2,$$
$$\sigma_{\gamma a}(\sqrt{s} = 1\,\mathrm{GeV}) \approx 9\,\mathrm{pb}\,\left(\frac{g_{a\gamma\gamma}}{10^{-2}\,\mathrm{GeV}^{-1}}\right)^2,$$



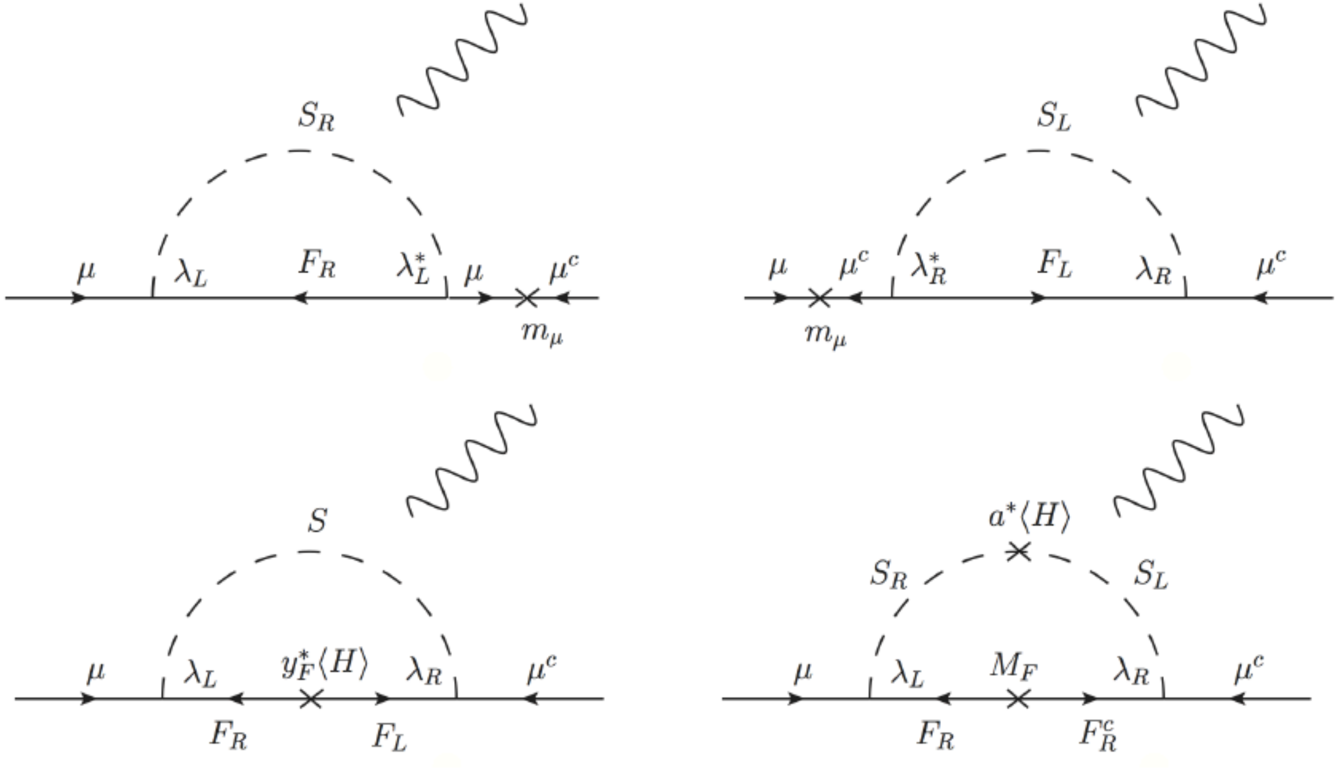
Marciano, Masiero, Paradisi, Passera

DM and g-2 as windows to New Physics

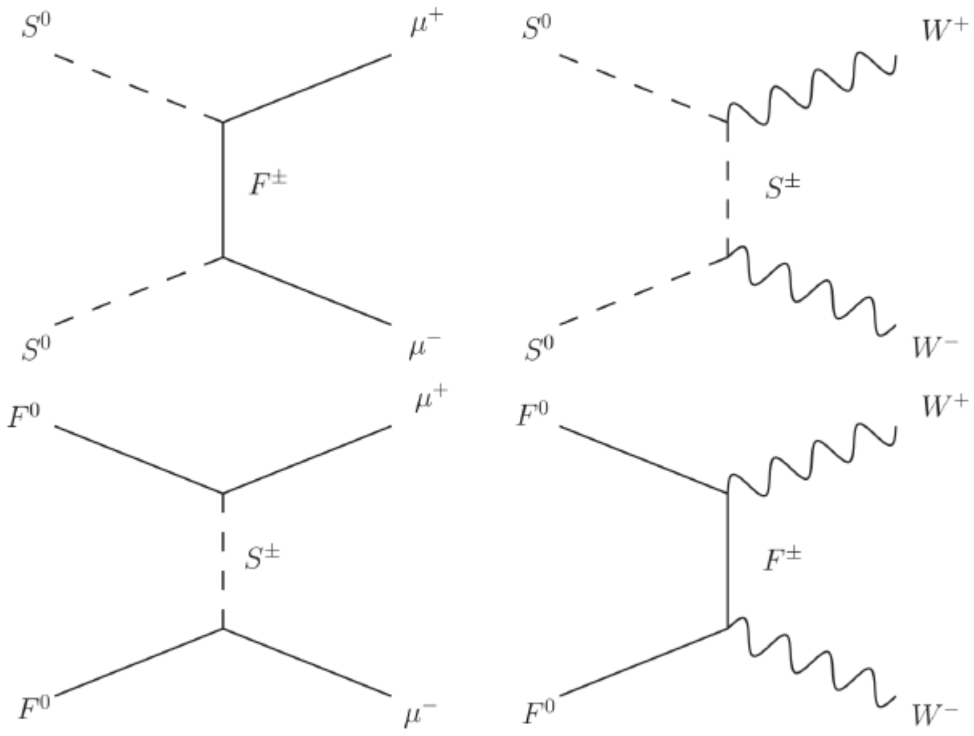
- **Minimal extensions of the SM to account for the DM**: one additional field that being neutral and stable might have been in thermal equilibrium interacting with ordinary matter and today have the correct density to account for the DM
- **Minimal extensions of the SM to account for the g-2 anomaly**: one single additional field (leptoquark or additional Higgs doublet or ALPs) coupling sizeably to leptons and/or photons
- Is it possible to have just one single additional field to account for both the DM **and** the g-2 anomaly? No, the DM fields in these minimal SM extensions decay too quickly to ordinary matter particles. **One needs at least two new fields** (for instance one additional fermion and one additional scalar)

Calibbi, Ziegler, Zupan 2018

Models without and with Higgs insertion

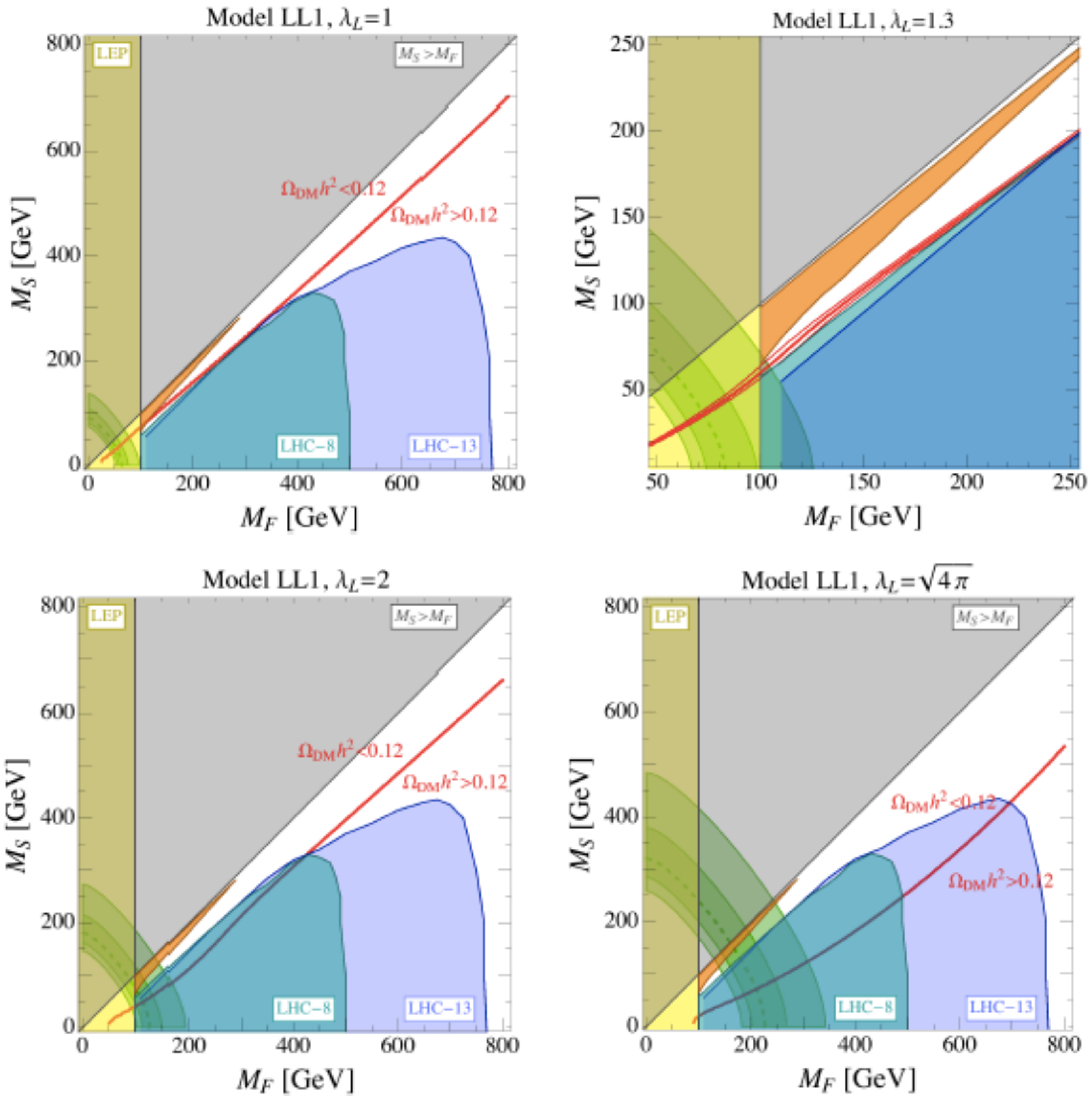


F-S one-loop contribution to g-2



DM annihilations into ordinary matter

Calibbi, Ziegler, Zupan 2018

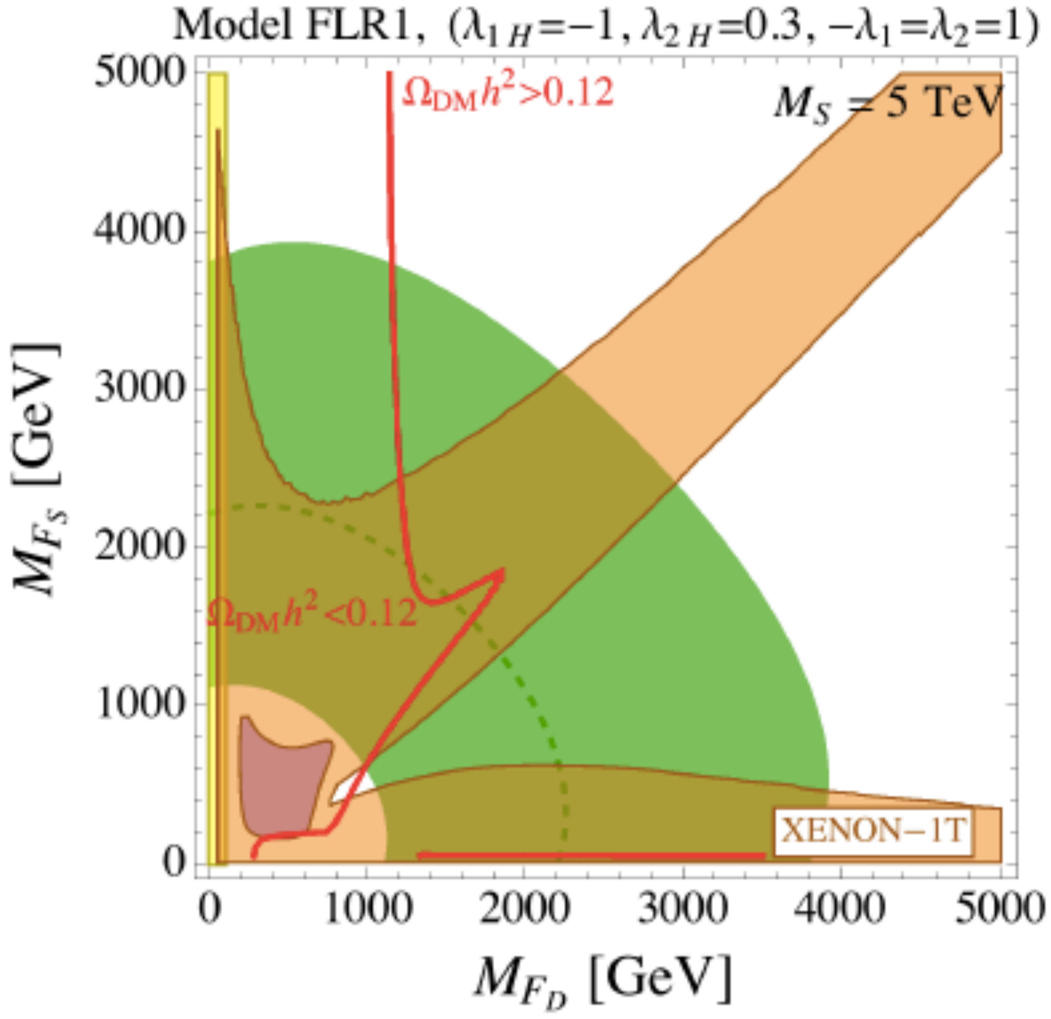


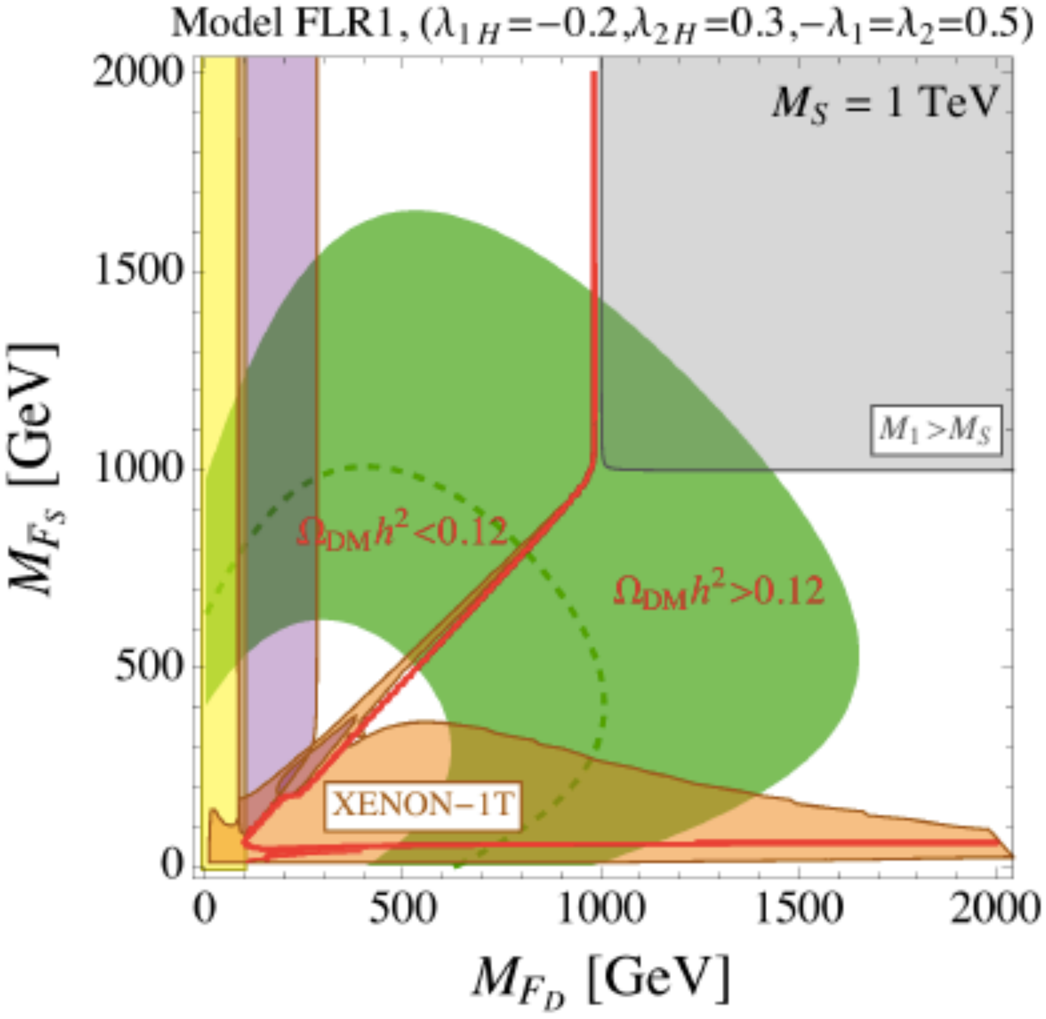
Models without Higgs insertion

Dark (light) green region → total contribution to g-2 compatible at 1 (2) σ with the experimental result

Calibbi, Ziegler, Zupan 2018

Models with Higgs insertion





Calibbi, Ziegler, Zupan 2018

Two leptonic g-2 anomalies ?

Recent (Parker et al. 2018) more precise determination of the fine structure constant $\alpha^{-1}(\mathrm{Cs}) = 137.035999046(27)$

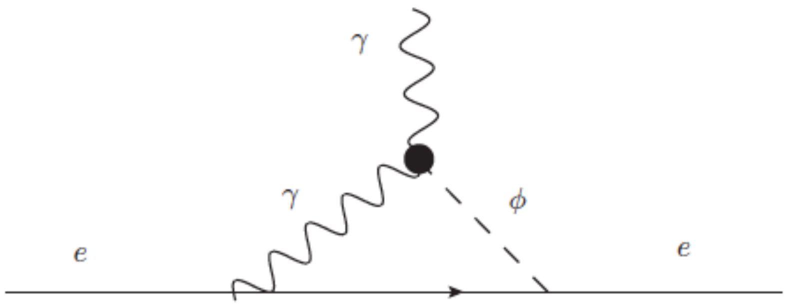
2.4 σ discrepancy (opposite in sign w.r.t. to the muon case)

$$\begin{aligned}\Delta a_e &\equiv a_e^{\exp} - a_e^{\mathrm{SM}} \\ &= [-87 \pm 28\,(\exp) \pm 23\,(\alpha) \pm 2\,(\mathrm{theory})] \\ &\times\ 10^{-14},\end{aligned}$$

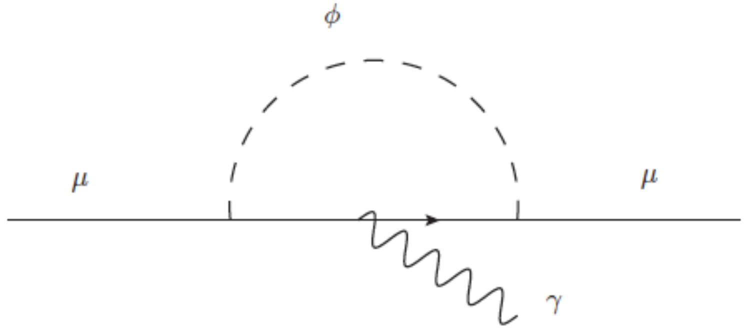
$$\Delta a_e = (-87 \pm 36) \times 10^{-14}$$

A single scalar solution to both anomalies?

Yes, if the **two-loop Barr-Zee diagrams**



dominate over the one loop scalar contributions to the $(g\text{-}2)_e$



with relatively large couplings to the electron and the two photons

Davoudiasl and Marciano 2018

Combined explanation of $(g-2)_e$ AND $(g-2)_\mu$ with a large muon EDM

- EFT analysis (Crivellin and Hoferichter, May 2019)

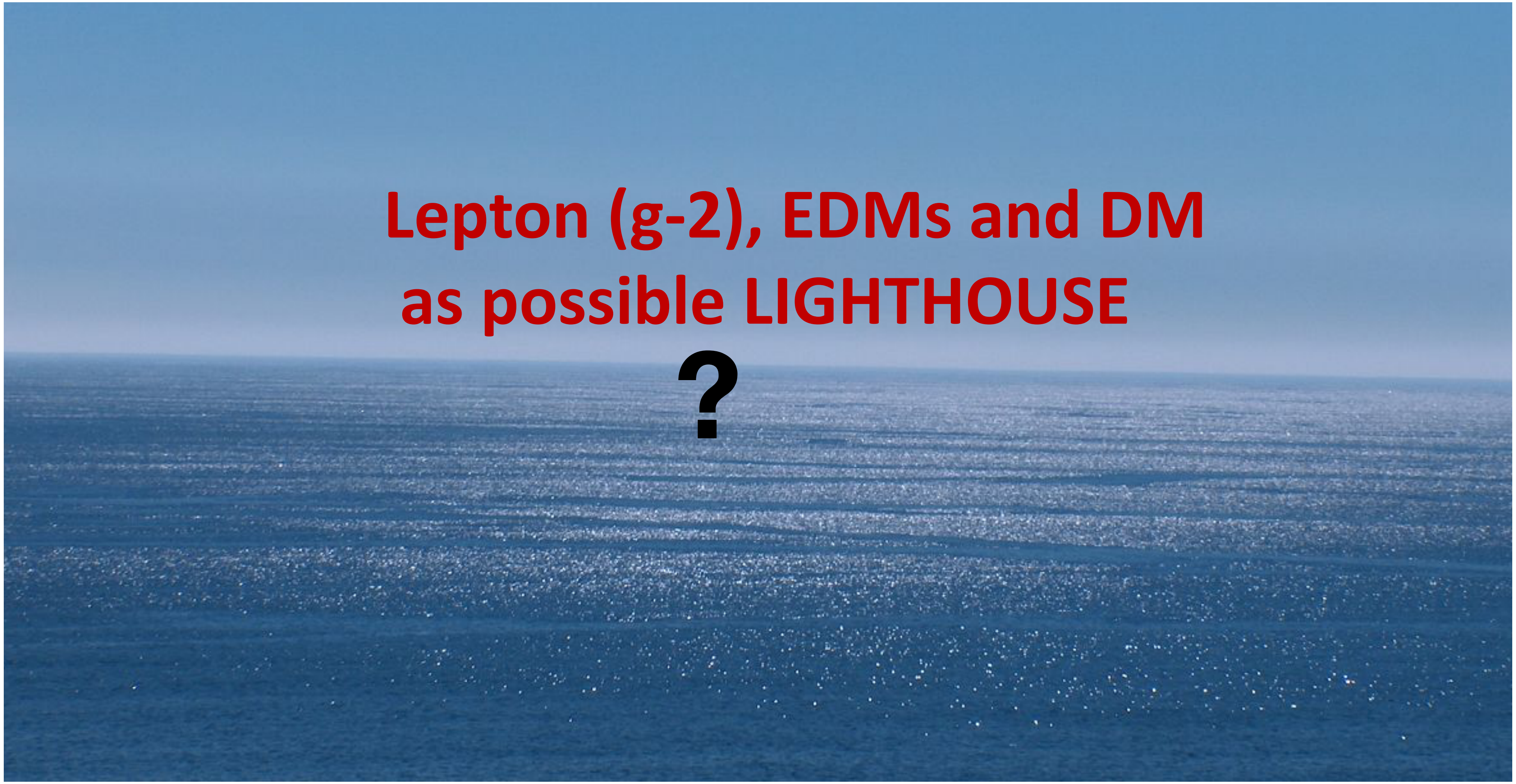
Simultaneous explanation possible in models with chiral enhancement But, very important, one needs a **DECOUPLING** of the electron and muon BSM sectors to avoid the very stringent limit on **BR ($\mu \rightarrow e + \gamma$)**

Such decoupling entails that **there is no correlation between the EDMs of the electron and muon**, i.e. the very stringent bound on d_e does not necessarily imply a very small d_μ

- By the end of the 20^{th} century … **we have a comprehensive, fundamental theory of all observed forces of nature which has been tested and might be valid from the Planck length scale [10^{-33} cm.] to the edge of the universe [10^{+28} cm.]**

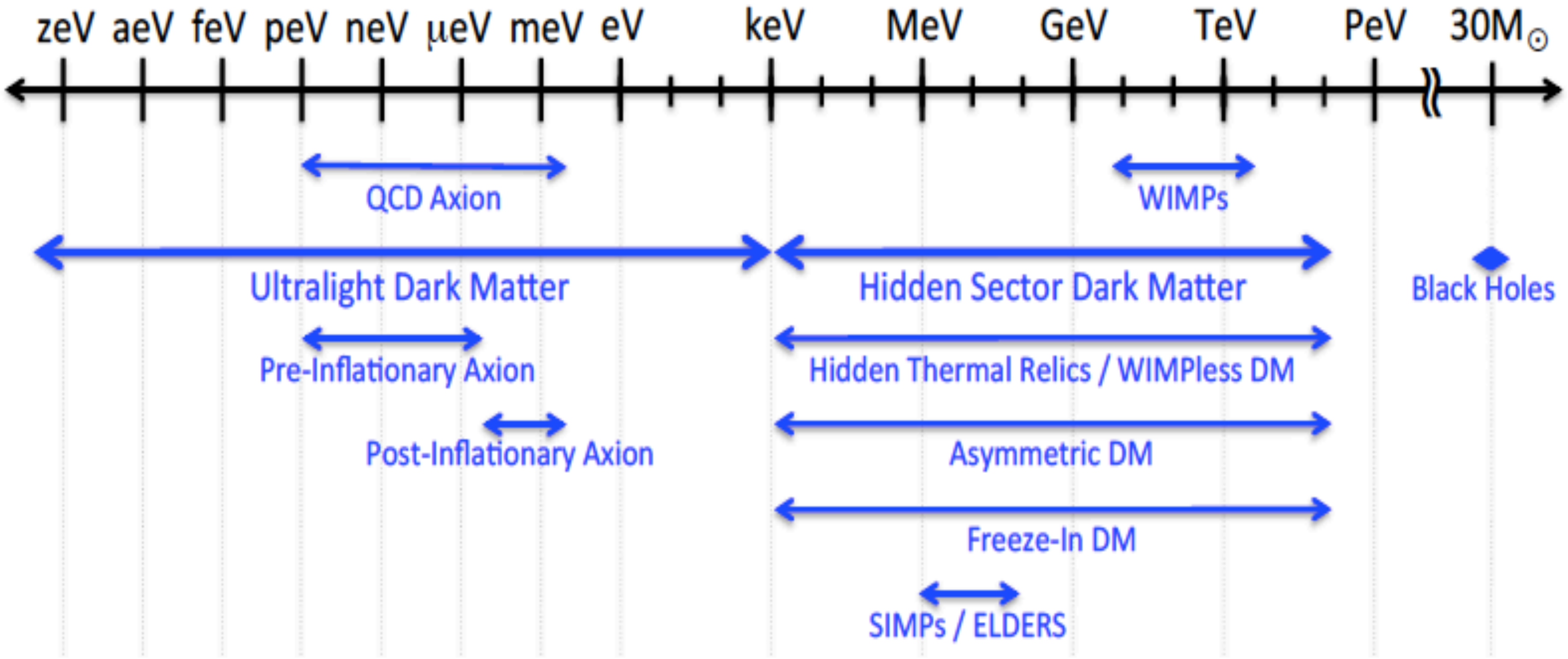
D. Gross 2007

Post – LHC physics

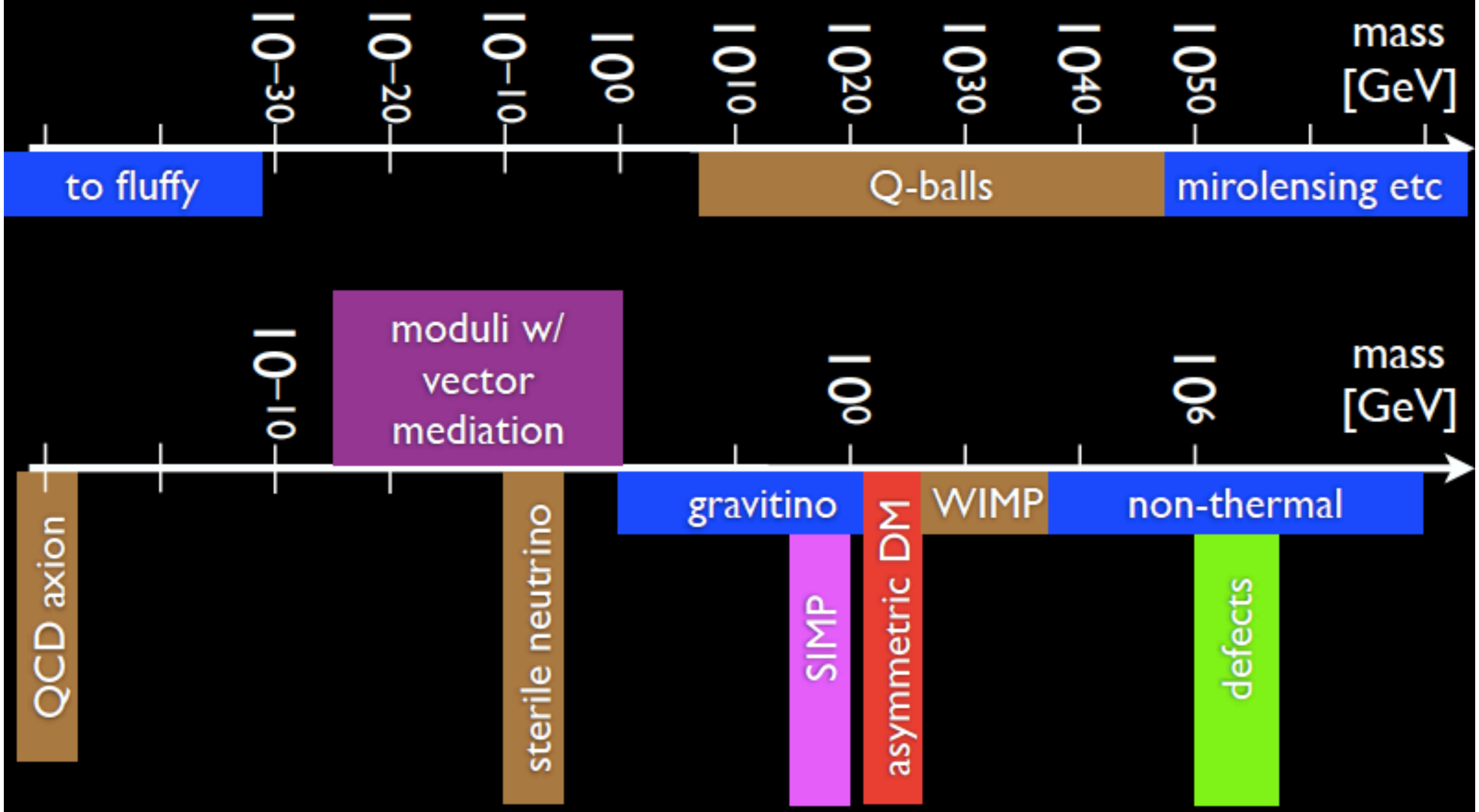


Backup slides

Too small mass
⇒ won't "fit"
in a galaxy!



From MACHOs
searches



10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
mass [GeV]
to fluffy
Q-balls
mirolensing etc
10^{-10}
moduli w/ vector mediation
10^{0}
10^{6}
mass [GeV]
QCD axion
sterile neutrino
gravitino
WIMP
non-thermal
SIMP
asymmetric DM
defects

Muon-electron scattering: The MUonE Project

Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna,
Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

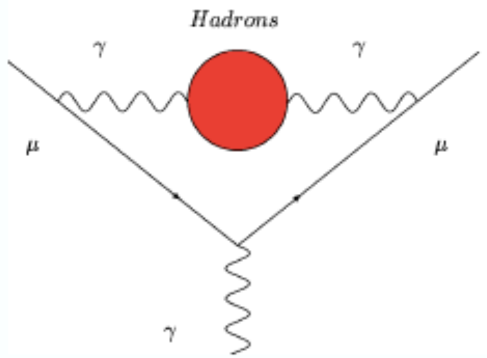
A new approach to a_μ^{HLO}

C. Carloni Calame, MP, L. Trentadue, G. Venanzoni

PLB 2015 - arXiv:1504.02228

Spacelike proposal for a_μ^{HLO}

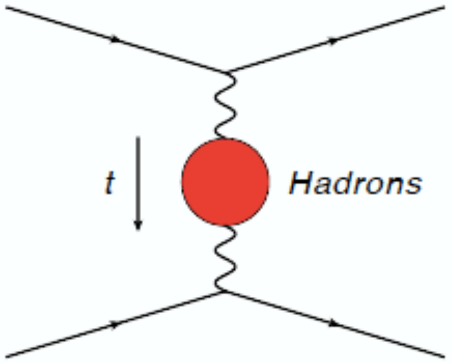
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the timelike formula:



$$a_\mu^{\rm HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{\rm had}(s)$$

$$K(s) = \int_0^1 dx\, \frac{x^2\,(1-x)}{x^2 + (1-x)\,(s/m_\mu^2)}$$

- Alternatively, exchanging the x and s integrations in a_μ^{HLO}



$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

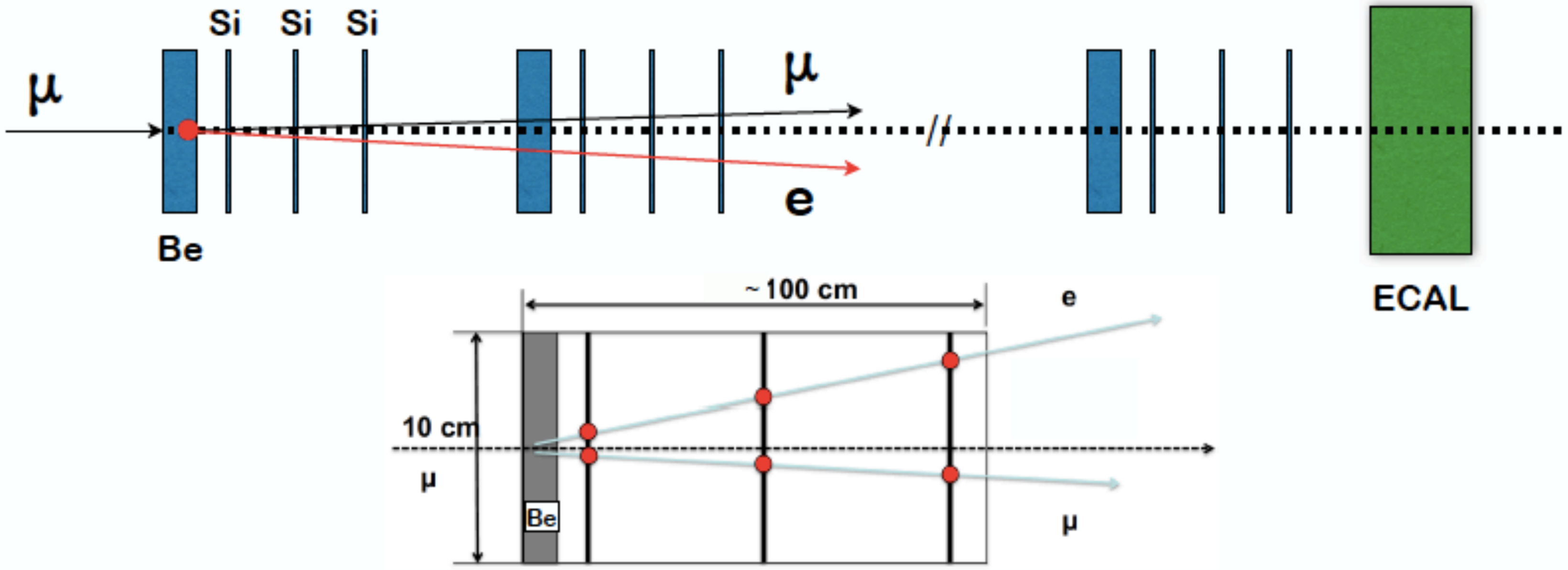
Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the spacelike region: a_μ^{HLO} can be extracted from scattering data!

Carloni Calame, MP, Trentadue, Venanzoni, 2015

Muon-electron scattering @ CERN

- $\Delta\alpha_{had}(t)$ can be measured via the elastic scattering μ e → μ e.
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target (Beryllium). Modular apparatus: each station has one layer of Beryllium (target) followed by several thin Silicon strip detectors.



- State-of-the-art Si detectors: ~20μm hit resolution/1m → ~0.02mrad expected angular resolution. ECAL and μ filter at the end for PID.