Low energy

Complementary (to LHC and flavour) probes of BSM physics, tests of fundamental symmetries

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Bad Honnef, November 2014

Outline

Electric Dipole Moments (EDMs)	0σ
Electroweak Precision Observables (EWPO)	$\sim 1\sigma$
Muon g-2 a_μ	3–4σ
Proton Charge Radius	7–8σ

Outline

Electric Dipole Moments (EDMs)	$\gg$ 1 TeV
Electroweak Precision Observables (EWPO)	$\sim$ 1 TeV
Muon g-2 a_μ	$\sim$ 1 TeV
Proton Charge Radius	$<$ 1 GeV

Outline

- Electric Dipole Moments (EDMs) CP symmetry
- Electroweak Precision Observables (EWPO) Custodial symmetry
- Muon g-2 a_μ Chiral symmetry
- Proton Charge Radius Universality?

Outline

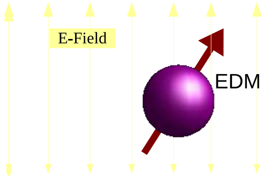
1. Electric Dipole Moments (EDMs)

2. Electroweak Precision Observables

3. Muon Magnetic Moment a_μ

4. Proton Charge Radius

Electric Dipole Moment

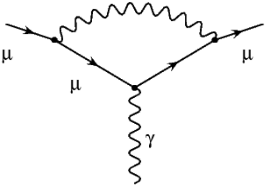


$$H_{\mathrm{EDM}} = -\vec{E}\cdot\vec{d} \propto -\vec{E}\cdot\vec{S}$$

$$T:(\vec{E},\vec{d}) \rightarrow (+\vec{E},-\vec{d})$$

T, *P*, *CP*-violating!

Quantum field theory:



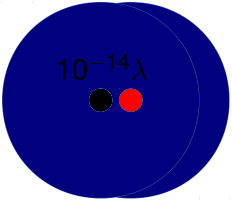
$$\overset{\sim}{=} \bar{u}(p')\left[\gamma_\mu F_1 + \frac{i}{2m}\sigma_{\mu\nu}q^\nu\left(F_2 + \gamma_5 F_3\right)\right]u(p)$$

Units and Expectations

$$a_\mu = F_2(0), \quad d_\mu = eF_3(0)/2m_\mu$$

Electron:

- suppose $F_2(0) \sim 10^{-14}$, and also $F_3(0) \sim 10^{-14}$
- expect



$$d_e \sim 10^{-14}\frac{e}{m_e} \sim 10^{-24} e\,cm$$

Compton wavelength λ

CP violation in the Standard Model from Yukawas

CP transformation in general:

$$\phi_i \to e^{i\alpha_i}\phi_i^\dagger$$

CP violation if: $\mathcal{L}$ contains complex phases which cannot be absorbed!
Standard Model: only possible in quark Yukawas

$$y^u_{ij}\bar{u}^i_L\phi^c u^j_R + y^d_{ij}\bar{d}^i_L\phi d^j_R$$

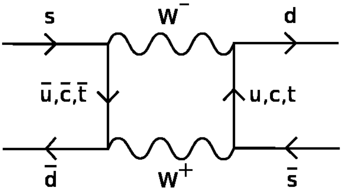
$$\begin{array}{lll} N^2+1 \text{ physical param.} = & +2\times 2N^2 & \text{(real } y\text{-entries)} \\ & -3\times N^2 & \text{(unitary redef. } q_L, u_R, d_R\text{)} \\ & +1 & \text{(overcounting one phase)} \end{array}$$

- 1 Gen.: 2 = 2 masses
- 2 Gen.: 5 = 4 masses + Cabibbo angle
- 3 Gen.: 10 = 6 masses + 3 CKM angles + 1 CKM phase

CP violation in SM ↔ flavour ⇒ tiny!

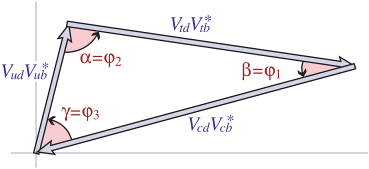
[ignore θ_{QCD}!]

- requires three generations — also in Feynman diagrams!



$K^0 \leftrightarrow \bar{K}^0$ oscillation

- Jarlskog invariant J = area of all unitarity triangles
  $\mathrm{Im}(V_{ij}V_{kl}V_{il}^*V_{kj}^*) = J\sum_{m,n}\epsilon_{ikm}\epsilon_{jln}$

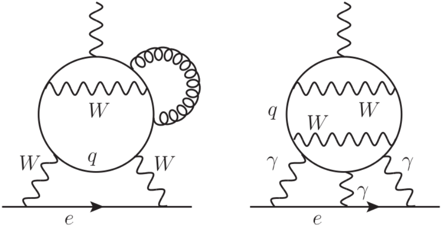


[PDG]

$J \approx 3 \times 10^{-5}$
CPV suppressed by product of all physical CKM angles!

EDMs in SM are suppressed by flavour

- Electron EDM in SM needs quarks of all generations!



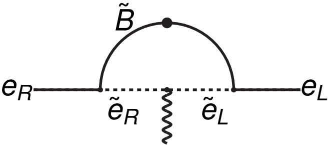
[Pospelov, Ritz '13]

4-, 5-loop diagrams
$d_e \sim 10^{-44} e\,cm$
$(10^{-34} \times$ Compton!)

- slightly larger effects to quark EDMs and other CPV operators
- "EDM experiments could become sensitive to SM predictions in 2075 (neutron), 2115 (electron) [Timmermans, Cape Cod '14]"

EDMs in SUSY from Flavour-Independent Phases

- e.g. gaugino/Higgsino masses μ, M_3, M_2, M_1 (e.g. M_2 can be chosen real)
- SUSY:
  e.g. electron-EDM
  from bino



$$\propto \alpha \sin \phi_{M_1} \frac{m_e^2}{M_{\text{SUSY}}^2}$$

- can be as large as $\sim 10^{-14} \times$ Compton for electron-EDM
- EDMs could be larger by factor 10^{20}, motivates searches for EDMs

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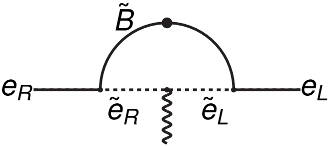

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- Generally: CPV beyond the SM motivated (Baryogenesis)
- Then: CPV without flavour is possible and typical!
- e.g. CPV in $H \to \gamma\gamma$ induces EDM

Elementary vs. Composite EDMs — The Dirty Details

- How to observe EDMs? Use neutral nuclei, atoms, molecules!
- EDMs of composite systems $\Leftrightarrow$ $d_{e,u,d}$ and other CPV!

$$\mathcal{L}_{\text{fund.}}(1\text{TeV}) = \text{fundamental CPV phases}$$

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$$\Downarrow$$

$$\mathcal{L}_{\text{EFT}}(1\text{GeV}) = d_{e,u,d} + d_{u,d}^{\text{Chromo}} + G^{\mu\nu}\tilde{G}_{\nu\rho}G^{\rho}{}_{\mu} + \text{4-fermion op.}$$

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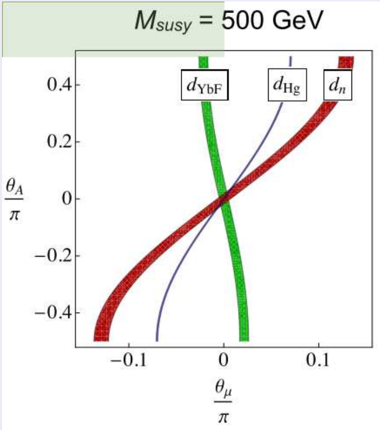
$$

- then compute atomic/molecular EDM using appropriate methods

Overview of 3 important cases

- paramagnetic atom/molecule (unpaired electron) ⇒ dominated by d_e
- diamagnetic atom ⇒ dominated by nuclear effects
- neutron ⇒ dominated by quark-(chromo-)EDMs



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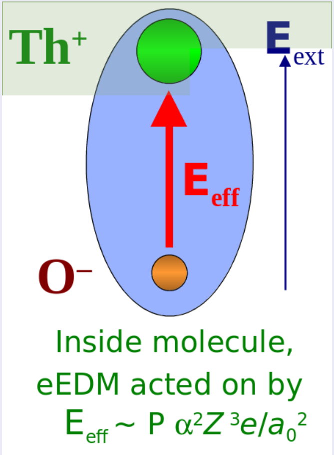
Paramagnetic (Tl, ThO, YbF)



Inside molecule, eEDM acted on by $E_{eff} \sim P\,\alpha^2 Z^3 e/a_0^2$

ACME (Harvard/Yale) measurement of ThO

slides: [D. DeMille]

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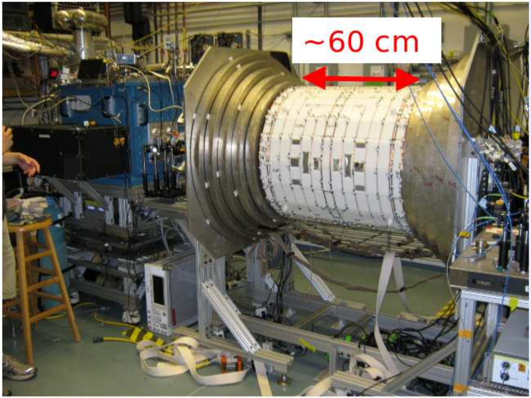

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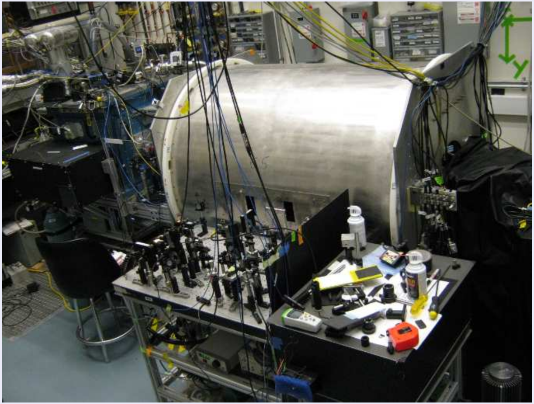

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Diamagnetic (Hg)

- Exp: [U Washington, Griffith et al]

$$d_{\mathrm{Hg}} < 2.6 \times 10^{-16} e\, fm$$

- atomic part:

$$d_{\mathrm{Hg}} = 2.8(6) \times 10^{-4} S_{\mathrm{Hg}}\; fm^{-2}$$

- nuclear Schiff moment in terms of $NN\pi$ interaction parameters:

$$S_{\mathrm{Hg}} = (0.4(3)\bar{g}_0 + 0.4(8)\bar{g}_1) e\; fm^3$$

[Flambaum et al, Engel et al, review: Dekens et al ’14]

- large uncertainty

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Neutron

- Exp: [RAL/Sussex/ILL '06]

$$d_n < 5 \times 10^{-27} e\,cm$$

- Estimate (constituent quark model)

$$d_n \approx \frac{4}{3} d_d - \frac{1}{3} d_u + \dots$$

Overview of 3 important cases

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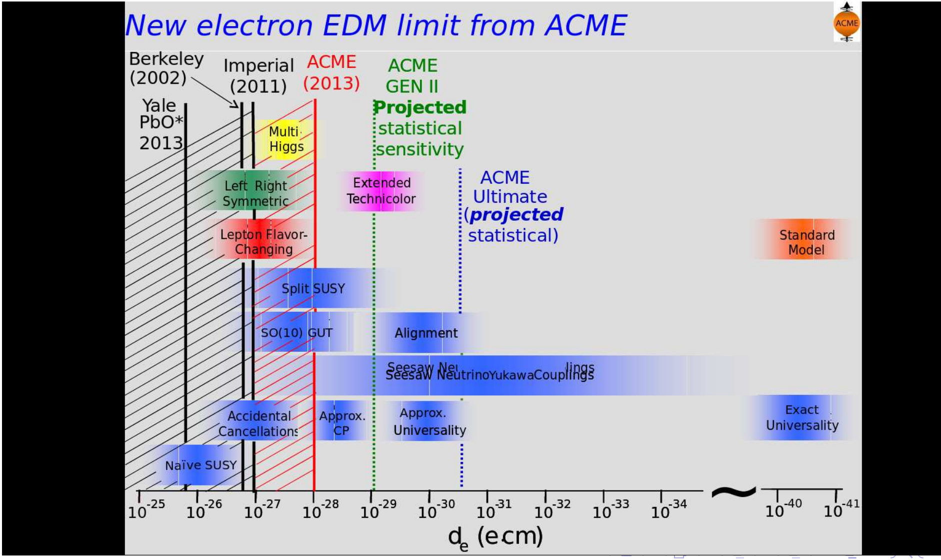
Overall:

- very active exp. progress on all fronts
- ThO will improve
- further diamagnetic atoms (Ra, Rn, Xe)
- many n-EDM searches (PSI, Triumf, ILL, Munich, SNS)
- however, so far: no EDM found!

Impact on new physics

[from DeMille]

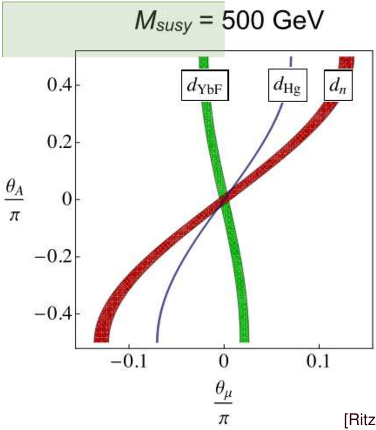


New electron EDM limit from ACME

Impact on new physics

Example: SUSY — many flavour-independent sources of CPV

- CPV at low energy $\propto \frac{\sin(\text{phases})}{M^2_{\text{SUSY}}}$
- constraints from different EDM searches are complementary
- "naive": phases = $\mathcal{O}(1)$, $M_{\text{SUSY}} \sim 500$ GeV $\Rightarrow$ excluded!
- need: either very small phases, or very large M_{SUSY}



[Ritz]

General conclusion: strong constraints on new physics at TeV scale $\Rightarrow$ need organizing principle/non-generic CPV phases! When EDMs are found $\Rightarrow$ improvements in nuclear theory needed for precise results on fundamental CPV

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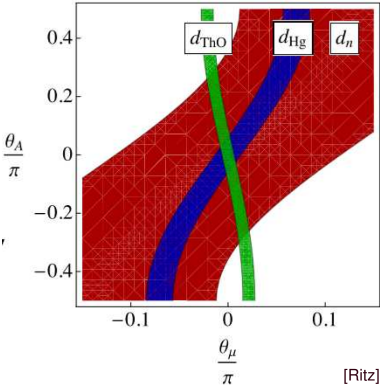
M_{susy} = 2 TeV



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Outline

1. Electric Dipole Moments (EDMs)
2. Electroweak Precision Observables
3. Muon Magnetic Moment a_μ
4. Proton Charge Radius

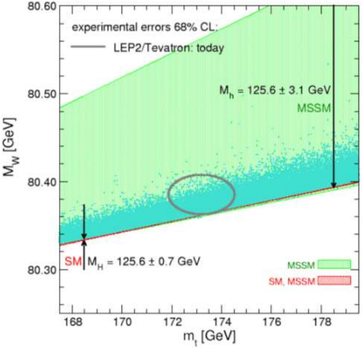
Some Numbers

$M_W^{\mathrm{exp}} = 80.385(15)$ GeV 0.02%

SM	1L top-effects	$> 30\sigma$
	$\mathrm{1LHiggs}, \geq \mathrm{2L}$	10σ
SUSY	loop effects	$\mathcal{O}(0\ldots 10\sigma)$

Need very precise calculations

- SM full two-loop [Awramik,Czakon,Hollik,Freitas,Walter,Weiglein,. . .] + leading higher orders [v.d.Bij,Boughezal,Czakon,Chetyrkin,Kühn,Sturm,. . .]
- MSSM leading two-loop [Haestier,Heinemeyer,Hollik,DS,Weber,Weiglein,Zeune,. . .]



- Result: SM agrees with Exp., room for new physics of $\mathcal{O}(.02\%)$

Relevant Symmetry

- M_W, further EWPO provide strong constraints on new physics
- SM has a further, approximate symmetry which protects behaviour of EWPO
  - "Custodial Symmetry" ⇒

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 + \dots \text{ where } \cos^2\theta_W \equiv \frac{g_2^2}{g_1^2 + g_2^2}$$

- ⇒ new physics should have this approximate symmetry, too!

Custodial Symmetry in General

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_{Q=T^3+Y}$$

- breaking pattern implies in general tree-level mass matrix with $\mathrm{U}(1)_Q$ invariance $\leftrightarrow$ O(2) invariance:

$$\mathcal{M}^2_{ab} = \langle\phi\rangle^\dagger\{T^a, T^b\}\langle\phi\rangle = \begin{pmatrix} g_2^2 v^2 & & & \\ & g_2^2 v^2 & & \\ & & g_2^2 u^2 & -g_1 g_2 u^2 \\ & & -g_1 g_2 u^2 & g_1^2 u^2 \end{pmatrix}$$

- and therefore

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{v^2}{u^2}$$

- Hence $\rho = 1$ means $u = v$ — an additional O(3) or SU(2) custodial symmetry!

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- For $g_{1,2} = 0$ this is an SU(2) symmetry under which the Goldstone fields transform as a triplet

Custodial Symmetry in SM

- rewrite SM Higgs doublet and Higgs potential using

$$\phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} \longrightarrow \Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{-} & \phi^{0} \end{pmatrix}$$

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$$V(\Phi) = \mu^{2}\mathrm{Tr}(\Phi^{\dagger}\Phi) + \lambda\mathrm{Tr}(\Phi^{\dagger}\Phi)^{2}$$

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$$V(\Phi) = \mu^2 \mathrm{Tr}(\Phi^\dagger \Phi) + \lambda \mathrm{Tr}(\Phi^\dagger \Phi)^2$$

- symmetric under $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$, $\Phi \to L \Phi R^\dagger$
- vacuum $\langle \Phi \rangle_{\mathrm{vac}} = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix}$ invariant under $\mathrm{SU}(2)_{L=R}$
- ($\mathrm{U}(1)_Y$ and $\mathrm{U}(1)_Q$ are subgroups)

Violation of Custodial Symmetry by Higgs Triplet

- Triplet Φ, Y=0, SU(2)⇔O(3)-rotations
- but in vacuum: $\langle\Phi\rangle = \begin{pmatrix} 0 \\ 0 \\ v \end{pmatrix}$, no remnant SU(2) or O(3)
- mass term

$$\mathcal{M}^2_{ab} = \langle\phi\rangle^\dagger\{T^a, T^b\}\langle\phi\rangle = \begin{pmatrix} g_2^2 v^2 & & & \\ & g_2^2 v^2 & & \\ & & 0 & 0 \\ & & 0 & 0 \end{pmatrix}$$

- $M_W^2 = g_2^2 v^2$, $M_Z^2 = 0$

...but it can be well motivated to consider such models

Example: Constraints on SUSY with R-Symmetry

SUSY well motivated, but maximal possible symmetry =
SUSY + R-Symmetry

- particle and SUSY partner have different R-charges
- gauginos always R-charged
- Dirac gaugino masses required → $N = 2$ sector → adjoint scalars
- minimal model (MRSSM) [Fayet. . . Kribs,Poppitz,Weiner]

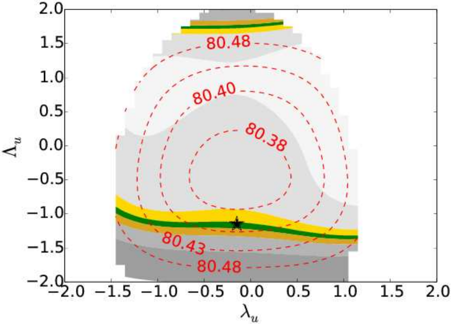
R-Symmetry has phenomenological advantages

- solves SUSY flavour problem with small M_{sfermion} [Kribs, Poppitz, Weiner]
- sub-TeV squarks compatible with LHC (suppressed cross section)

[Kribs, Martin]

Question: MRSSM compatible with Higgs, W mass measurements?

- Dirac gauginos $\rightarrow$ additional scalar partners $\rightarrow$ SU(2) scalar (Higgs) triplet!
- breaks custodial symmetry
- additional Yukawa-like couplings λ, Λ
- can increase M_h and M_W



[Diessner,Kalinowski,Kotlarski,DS]

- SUSY masses $\chi^{0,\pm} \sim 500$ GeV . . . $m_T \sim 3$ TeV
- very promising!

Lower Energy

- Weak mixing angle $\sin^2\theta_W$ key SM parameter (related to M_W)

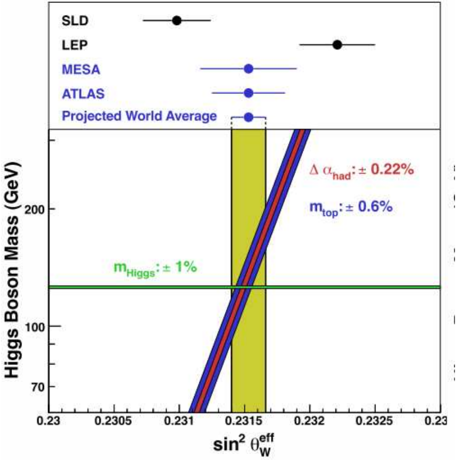
$$\sin^2\theta_W = \frac{g_1^2}{g_1^2+g_2^2} = 1 - \frac{M_W^2}{M_Z^2}$$

tree-level, SM

$\rightarrow$ SU(2) × U(1), Custodial Symmetry in Higgs sector

- important higher order effects from top, Higgs, new physics
- Many definitions, measurements in different observables/energies
- Legacy of LEP/SLD: 3σ disagreement

Lower Energy



planned:

- JLab/MOLLER: e^-e^-(11GeV)
- JLab/Qweak: e^-p(1GeV)
- Mainz/MESA: e^-p(0.1GeV)

Low-energy measurements help to clarify the situation and/or could find new light physics!

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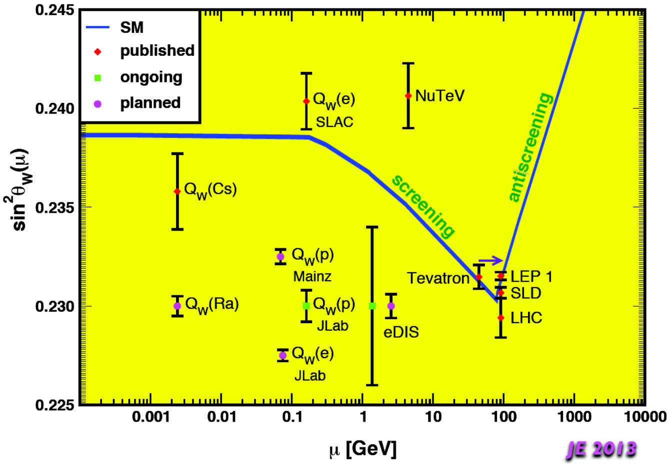

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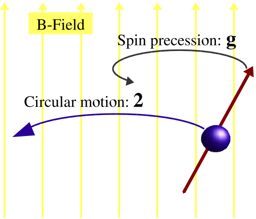
Some Numbers

$a_\mu^{\mathrm{exp}} = 11\,659\,208.9(6.3) \times 10^{-10}$ 0.5ppm

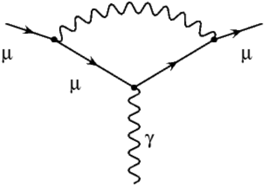
SM	QED $\geq$ 2L	7000σ
	had	100σ
	weak	2.5σ
SUSY	loop effects	$\mathcal{O}(0 \ldots \pm 10\sigma)$

Muon magnetic moment



$$H_{\text{magnetic}} = -2(1+a_\mu)\frac{e}{2m_\mu}\vec{B}\cdot\vec{S}$$

Quantum field theory:



$$\hat{=}\bar{u}(p')\left[\gamma_\mu F_1 + \frac{i}{2m}\sigma_{\mu\nu}q^\nu(F_2+\gamma_5 F_3)\right]u(p)$$

Discrepancy

SM prediction too low by $(26.1 \pm 8.0) \times 10^{-10}$

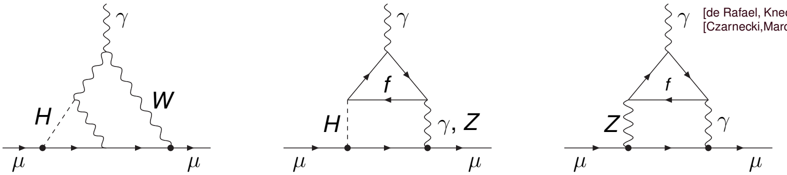
[Hagiwara et al; similar: Davier et al, Jegerlehner et al]

Note: discrepancy twice as large as $a_\mu^{\mathrm{SM,weak}}$

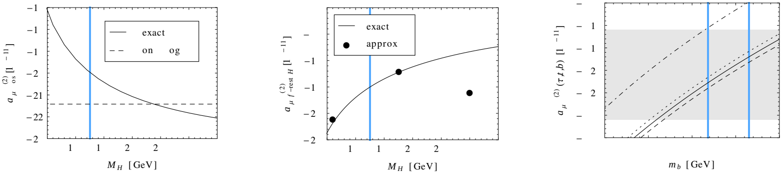
but we expect: $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings

Two complementary new experiments at Fermilab and JParc!

Higgs impact: final a_μ(2L,weak) [Gnendiger, DS, Stöckinger-Kim '13]

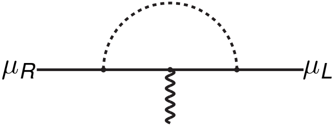


[de Rafael, Knecht, et al '95–'02]
[Czarnecki,Marciano,Vainshtein '03]



- exact evaluation of M_H-dependent parts
- consistent parametrization of 1-, 2-, 3-loop $\propto G_F\alpha^{n-1}$
- final result: $(15.36 \pm 0.10) \times 10^{-10}$

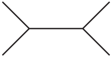
Relevant Symmetry: Chiral Symmetry



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

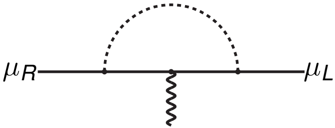
compare: EDMs, $b \to s\gamma$, $B \to \tau\nu$, $\mu \to e\gamma$

EWPO



Chiral Symmetry relates a_μ and m_μ

$a_\mu \bar{\mu}_L \sigma^{\mu\nu} \mu_R$



$m_\mu \bar{\mu}_L \mu_R$

a_μ, m_μ related to common source of chirality flips

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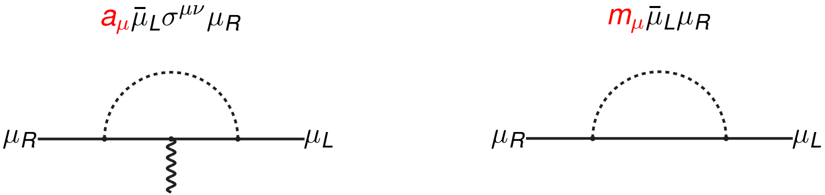


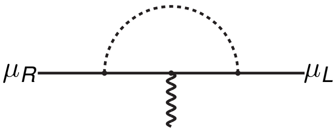
a_μ, m_μ related to common source of chirality flips

SM: only Yukawa coupling $y_\mu H \bar{\mu}_L \mu_R$

New physics: y_μ very different? E.g. $y_\mu^{\text{SUSY}} \approx \tan\beta\, y_\mu^{\text{SM}}$

Very different contributions to a_μ: classify $\propto C$

$$\mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2$$



$$C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$

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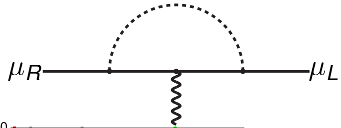

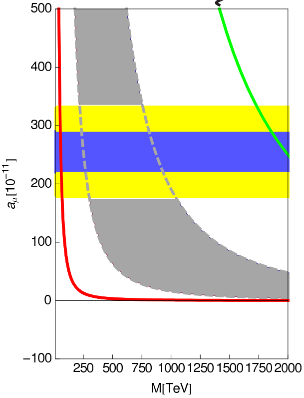

$\mathcal{O}(1)$	
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)...

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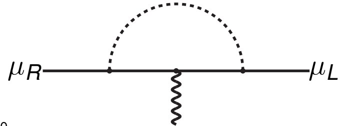

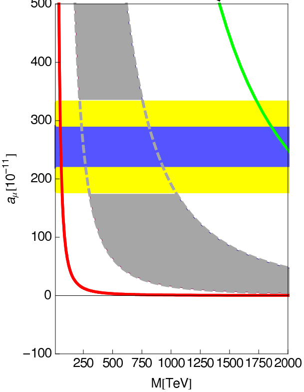

$\mathcal{O}(1)$	
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry ($\tan\beta$), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c)... [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
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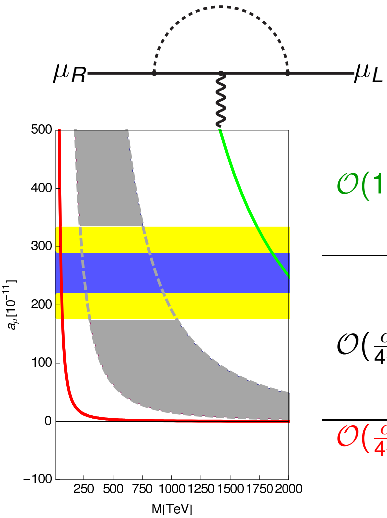

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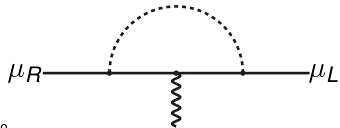

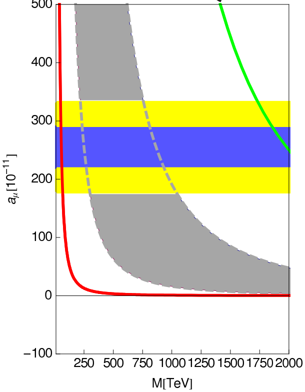

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$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)...

LHC-data! The tension is increasing . . .

LHC:

$m_{\tilde{q},\tilde{g}} >\sim$ 1TeV

a_μ

$m_{\tilde{\mu},\chi} <\sim$ 700GeV

$m_h = 126$ GeV

$m_{\tilde{t}} >\sim$ 1TeV

finetuning

$m_{\tilde{t}}, \mu$ small

(Conclusions apply to specific scenarios!)

Tension motivates non-traditional models with mass hierarchies

SUSY, some examples

Typically (all relevant masses equal)

$$a_\mu^{\mathrm{SUSY}} \approx 12 \times 10^{-10} \tan\beta \,\mathrm{sign}(\mu) \left(\frac{100\mathrm{GeV}}{M_{\mathrm{smuons,charginos}}}\right)^2$$

SUSY could be the origin of the observed $(30 \pm 8) \times 10^{-10}$ deviation!

Some SUSY masses can be much larger

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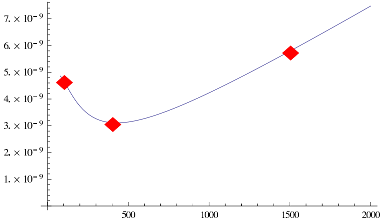
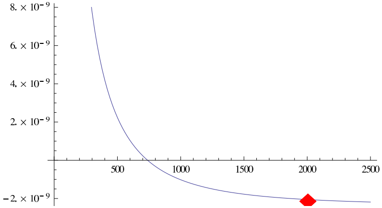
[Fargnoli,Gnendiger,Passehr,DS,Stöckinger-Kim '13]

small/large μ



small/large $M_{\tilde{\mu}_L}$



Alternative: radiative muon mass in SUSY

$$m_\mu^{\text{tree}} = y_\mu v_d$$

1. $y_\mu = 0$
   generate m_μ via $A'_\mu \tilde{\mu}_L \tilde{\mu}_R H_u$ [Borzumati et al '99][Crivellin et al '11]
2. $v_d \to 0$, $\tan\beta \to \infty$
   generate m_μ via coupling to v_u [Dobrescu, Fox '10][Altmannshofer, Straub '10]

Radiative muon mass: MSSM for $\tan\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, soon]

“standard case” (equal masses, 1-loop)

$$a_\mu^{\rm SUSY} \approx 12 \times 10^{-10} \tan\beta \; {\rm sign}(\mu) \left(\frac{100{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

Radiative muon mass: MSSM for $\tan\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, soon]

actually, including higher order effects $y_\mu \approx \frac{m_\mu}{v_d + v_u(\text{1-loop})} = \frac{y_\mu^{\text{tree}}}{(1+\sim\mu\tan\beta)}$
[Marchetti,Mertens,Nierste,DS '08]

$$a_\mu^{\mathrm{SUSY}} \approx \frac{12\times10^{-10}\tan\beta\,\mathrm{sign}(\mu)}{1-0.0018\tan\beta\,\mathrm{sign}(\mu)}\left(\frac{100\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

Radiative muon mass: MSSM for tan $\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, soon]

limit tan $\beta \to \infty$

$$a_\mu^{\mathrm{SUSY}} \approx -70 \times 10^{-10} \left(\frac{1000\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

tan β and sign(μ) drop out, large contributions for $M_{\mathrm{SUSY}} \sim$ TeV!

Radiative muon mass: MSSM for tan $\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, soon]

limit tan $\beta \to \infty$

$$a_\mu^{\mathrm{SUSY}} \approx -70 \times 10^{-10} \left(\frac{1000\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

“standard” case: sign wrong!

Radiative muon mass: MSSM for tan $\beta \to \infty$

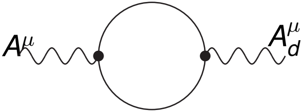
[Bach,Park,DS,Stöckinger-Kim, soon]

limit tan $\beta \to \infty$

$$a_\mu^{\rm SUSY} \approx +37 \times 10^{-10} \left(\frac{1000{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

sign positive e.g. if $|\mu| \gg M_{\rm SUSY}$ (then only $\tilde{B}\tilde{\mu}_L\tilde{\mu}_R$ important)

What if the LHC does not find new physics?



- Dark sector

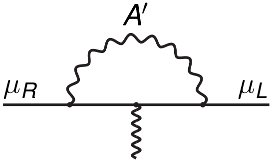
  still possible and appealing:

$$\mathcal{L} = \ldots \frac{\epsilon}{2} F_d^{\mu\nu} F_{\mu\nu} \quad \overset{\text{diag.}}{\Rightarrow} \mathcal{L}_{\text{int}} = \ldots (A_\mu + \epsilon A'_\mu) J^\mu_{\text{e.m.}}$$

two parameters: coupling ϵ, mass $m_{A'}$

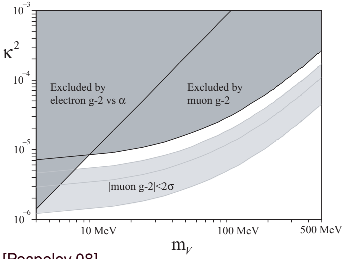
- is generic if there is new U(1) gauge boson (GUT, strings,...)
- window to possibly many new, SM-neutral particles
- Motivation: dark matter, $(g-2)_\mu$
  (assume specific coupling/mass range)

Dark photon and a_μ

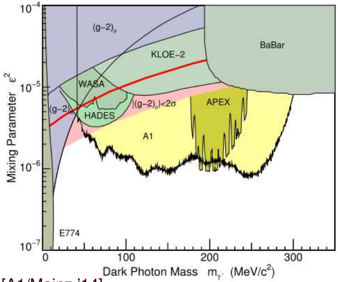


$$= \epsilon^2 \frac{\alpha}{4\pi} F\left(\frac{m_\mu}{m_{A'}}\right)$$

explain a_μ without messing up a_e: $M_{A'} \gg 1\text{MeV}$



[Pospelov 08]



[A1/Mainz '14]

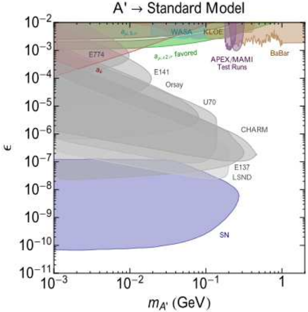
- a_μ-explanation almost completely excluded!

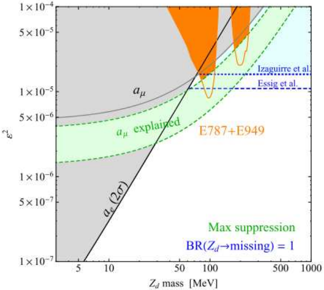
More on bounds on dark photons

Beyond the a_μ parameter region!

- beam dump: dark bremsstrahlung (works for specific coupling range)
- electron fixed target (APEX,A1)
- Babar, KLOE, WASA: meson decays
- often assumed: $A' \to e^+e^-$ dominant
- if not: $K \to \pi A'$, $A' \to$invisible and $e^+e^- \to \gamma+$invisible lead to bounds

  [Davoudiasl,Lee,Marciano'14][Izaguirre et al '13]
- generalization: also mass mixing "dark Z" with more general couplings, also strongly constrained





Outline

1. Electric Dipole Moments (EDMs)
2. Electroweak Precision Observables
3. Muon Magnetic Moment a_μ
4. Proton Charge Radius

Proton radius

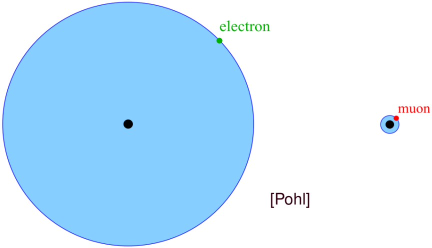
$$\langle r^2 \rangle = -\frac{6}{G(0)} \frac{dG(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

The second muon puzzle! $r_p = 0.88\text{fm}$ or $r_p = 0.84\text{fm}$?

- a_μ: 3–4 σ
- r_p: 7.9σ

How is r_p, electric charge form factor $G(Q^2)$ measured?

- by atom in S- or P-state, lamb shift $\propto r^2$
- or by *ep* scattering at energies $\ll$1 GeV
- or, much better: lamb shift in muonic hydrogen



[Pohl]

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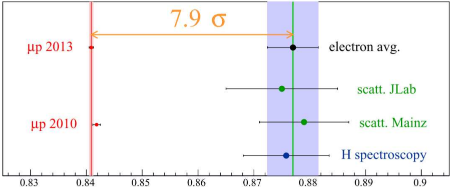

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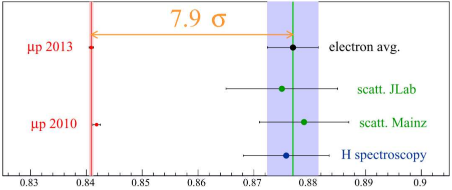

- hydrogen Exp or Theory?
- muon-specific (dark?) forces?

  [McKeen, Pospelov, Yavin, Jaeckel . . .]
- NB: don't mess up a_μ, neutrino physics!

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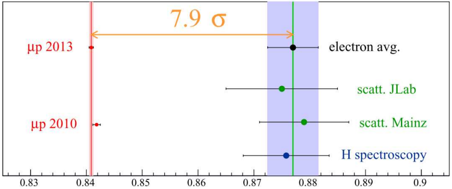

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- NB: don't mess up a_μ, neutrino physics!

Future: new *ep* scattering [Mainz,JLab], maybe μp scattering [MUSE PSI], repeat everything for deuterium etc

Conclusions

Four examples for low-energy (precision) observables, related to fundamental (approximate) symmetries, sensitive to different aspects of new physics

- Electric Dipole Moments (EDMs)
  Non-standard CPV expected, EDMs sensitive to many models
- Electroweak Precision Observables (EWPO)
  BSM strongly restricted; low-energy checks of $\sin^2\theta_W$
- Muon g-2 a_μ
  New experiments soon — will they confirm deviation?
  Could only be explained by BSM$<\sim$ 2TeV
- Proton Charge Radius
  if signal survives further cross-checks $\Rightarrow$ proof of BSM!