

# EDMs and precision $g-2$ as a window into New Physics

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# Plan

1. Intro: similar looking operators, different physics.
2. Why EDMs? EDMs and New Physics. BAU and EDMs.
3. Pre-LHC expectations: lots of super-partners near weak scale – EDM constraints on their properties. *Hard realities for New Physics in 2016*. EDM constraints on *CP properties of the new Higgs-like resonance*. EDMs from 100 TeV SUSY.
4. Muon  $g-2$  at a glance. What is the origin of current discrepancy? Interpreting the discrepancy as New Physics: either un-colored NP around the EW scale, or a very light new vectors and/or scalars around the muon mass. Implications for intensity frontier physics.
5. Conclusions: importance of multitude of probes, and of new experimental initiatives.

# Anomalous magnetic moment and EDM of an elementary fermion

Anomalous magnetic moment:

$$\frac{1}{2} \bar{\psi} F_{\mu\nu} \sigma^{\mu\nu} \psi$$

- Induced by “any” interactions.
- The leading effect is large ( $\sim O(1)$  for hadrons,  $O(10^{-3})$  for leptons)
- Can be made into a precision tool *if* the accuracy of measurements is matched by accuracy of calculations

Electric dipole moment:

$$\frac{1}{2} \bar{\psi} \tilde{F}_{\mu\nu} \sigma^{\mu\nu} \psi$$

- Tilde flips E and B.
- Only CP-violating interactions induce it; very special, *not* common.
- Is a precision tool “*automatically*” as SM (apart from strong CP caveat) does not induce large EDMs

Purcell and Ramsey (1949) (“How do we know that strong interactions conserve parity?”  $\longrightarrow |d_n| < 3 \times 10^{-18} \text{ ecm.}$ )

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d \mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$d \neq 0$  means that both P and T are broken. If CPT holds then CP is broken as well.

CPT is based on locality, Lorentz invariance and spin-statistics = very safe assumption.

*search for EDM = search for CP violation, if CPT holds*

Relativistic generalization

$$H_{\text{T,P-odd}} = -d \mathbf{E} \cdot \frac{\mathbf{S}}{S} \rightarrow \mathcal{L}_{\text{CP-odd}} = -d \frac{i}{2} \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi F_{\mu\nu},$$

corresponds to dimension five effective operator and naively suggests  $1/M_{\text{new physics}}$  scaling. Due to  $SU(2) \times U(1)$  invariance, however, it scales as  $m_f/M^2$ .

## Current Experimental Limits

”paramagnetic EDM”, Berkeley experiment

$$|d_{\text{Tl}}| < 9 \times 10^{-25} e \text{ cm}$$

”diamagnetic EDM”, U of Washington experiment

$$|d_{\text{Hg}}| < 2 \times 10^{-28} e \text{ cm} \quad 7.4 \times 10^{-30}$$

factor of 7 improvement in 2009!

$$|d_{\text{Hg}}| < 3 \times 10^{-29} e \text{ cm}$$

neutron EDM, ILL experiment

$$|d_n| < 3 \times 10^{-26} e \text{ cm}$$

Notice that Thallium EDM is usually quoted as  $d_e < 1.6 \times 10^{-27} e \text{ cm}$  bound, and in 2011 it was improved to  $1.0 \times 10^{-27} e \text{ cm}$ .

**2013 ThO result by Harvard-Yale collaboration:  $|d_e| < 8.7 \times 10^{-29} e \text{ cm}$**

# Dedicated experiments to measure EDMs at CERN?

- Nuclear EDMs (apart from from neutrons) are screened inside the atoms (**Schiff theorem**) resulting in a huge penalty in sensitivity. Mercury EDM at  $10^{-25}$  cm results in  $\sim 10^{-25}$  cm bound on  $d_{p,n}$ . Not so for charged particles in the [future dedicated] storage rings.
- Opportunity for CERN to pursue the EDM projects (proton, deuteron, and in the future possibly more complicated nuclei). The method has been developed by **Y. Semerdzidis and collaborators**. A breakthrough down to  $10^{-29}$  e cm sensitivity level has been claimed possible. See **T. Bowcock** talk tomorrow.
- Muon EDMs are poorly constrained [we know constraints on WIMP EDMs better than muon EDMs!]. Room for improvement.

## Why bother with EDMs?

Is the accuracy sufficient to probe TeV scale and beyond?

Typical energy resolution in modern EDM experiments

$$\Delta\text{Energy} \sim 10^{-6}\text{Hz} \sim 10^{-21}\text{eV}$$

translates to limits on EDMs

$$|d| < \frac{\Delta\text{Energy}}{\text{Electric field}} \sim 10^{-25}\text{e} \times \text{cm}$$

Comparing with theoretically inferred scaling,

$$d \sim 10^{-2} \times \frac{1 \text{ MeV}}{\Lambda_{CP}^2},$$

we get **sensitivity to**

$$\Lambda_{CP} \sim 1 \text{ TeV}$$

**Comparable with the LHC reach! EDMs are one of the very few low-energy measurements sensitive to the fundamental particle physics.**

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**An improvement from  $10^{-25}$  to  $10^{-29}$  would scale up the sensitivity to  $\Lambda_{CP}$  to 100 TeV !**

**Comparable with the LHC reach! EDMs are one of the very few low-energy measurements sensitive to the fundamental particle physics.**

# CKM model

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} (\bar{U}_L W^+ V D_L + \text{H.c.}).$$

CP violation is closely related to flavour changing interactions.

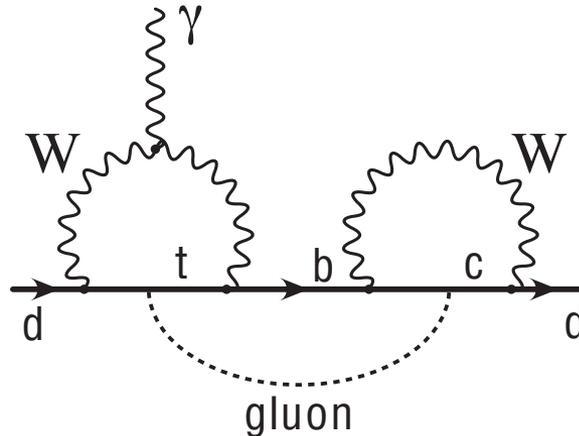
$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

CKM model of  $CP$  violation is independently checked using neutral  $K$  and  $B$  systems. *No other sources of  $CP$  are needed to describe observables!*

$CP$  violation disappear if any pair of the same charge quarks is degenerate or some mixing angles vanish.

$$J_{CP} = \text{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*) \times \\ (y_t^2 - y_c^2)(y_t^2 - y_u^2)(y_c^2 - y_u^2)(y_b^2 - y_s^2)(y_b^2 - y_d^2)(y_s^2 - y_d^2) \\ < 10^{-15}$$

# EDMs from CKM



CKM phase generates tiny EDMs:

$$d_d \sim \text{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*)\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$

$$< 10^{-33} \text{ ecm}$$

Direct quark EDMs identically vanish at 1 and 2 loop levels (**Shabalin**, 1981). 3-loop EDMs are calculated by **Khriplovich**.

$d_e$  first appears at 4 loops (**Khriplovich, MP**, 1991)  $< 10^{-37} \text{ cm}$

$d_n$  is dominated by long distance effects but does not exceed  $10^{-31}$ . 10

# CP violation from the Theta term

- If CKM gave too small an EDM, there is a much bigger source of CP violation in the flavor conserving channel - theta term

Energy of QCD vacuum depends on  $\theta$ -angle:

$$E(\bar{\theta}) = -\frac{1}{2}\bar{\theta}^2 m_* \langle \bar{q}q \rangle + \mathcal{O}(\bar{\theta}^4, m_*^2)$$

where  $\langle \bar{q}q \rangle$  is the quark vacuum condensate and  $m_*$  is the reduced quark mass,  $m_* = \frac{m_u m_d}{m_u + m_d}$ . In CP-odd channel,

$$d_n \sim e \frac{\bar{\theta} m_*}{\Lambda_{\text{had}}^2} \sim \bar{\theta} \cdot (6 \times 10^{-17}) e \text{ cm}$$

**Strong CP problem** = naturalness problem = Why  $|\bar{\theta}| < 10^{-9}$  when it could have been  $\bar{\theta} \sim O(1)$ ?  $\bar{\theta}$  can keep "memory" of CP violation at Planck scale and beyond. Suggested solutions

**Axions or clever symmetry for keeping theta=0;  $m_u=0$ ...**

# Cosmological reasoning for extra CP violation: Baryogenesis

Basic facts that are known about observable Universe:

1.  $n_B \gg n_{\bar{B}}$
2.  $\eta_B \equiv n_B/n_\gamma = 6.1 \pm 0.1 \times 10^{-10}$  (Any baryogenesis scenario would have mostly *theoretical* uncertainties. )
3. Fluctuations in the CMB spectrum give a strong support to an inflationary paradigm. The *initial* state of the Universe according to inflation was vacuum-like, and therefore  $B$ - $\bar{B}$  symmetric. **Baryogenesis is needed!**

**Baryogenesis**  $\equiv$  a process that transfers initial baryo-symmetric state of the universe to a state with  $n_B - n_{\bar{B}} > 0$ .

Baryons can be generated dynamically ! (Sakharov, 1967)

Three **Sakharov's conditions** for baryogenesis

1. **Baryon number violation**
2. **C and CP violation**
3. **Departure from thermal equilibrium**

First three conditions are *in principle* satisfied within Standard Model at  $T \sim 100$  GeV.

# SM by itself doesn't seem to work for BAU

**Objection 1.** There is not enough  $CP$  violation.  $\eta_B(\delta_{CKM})$  is suppressed by  $J_{CP} < 10^{-15}$ .  $\eta_B(\theta_{QCD})$  is suppressed by  $m_u m_d m_s m_c m_b m_t / T^6$ .

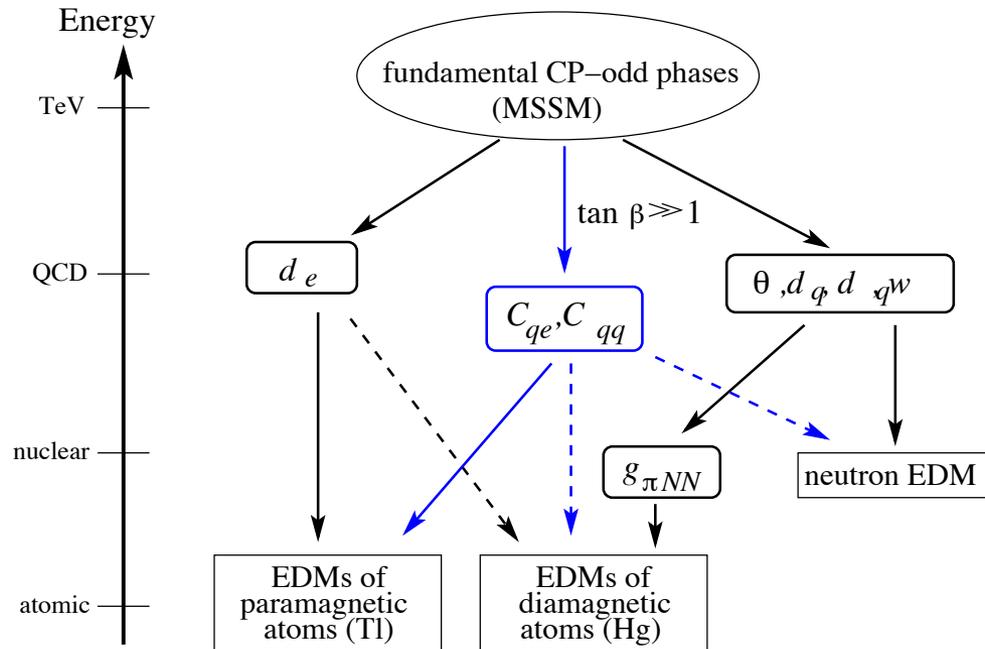
**Objection 2.** The departure from equilibrium is *very small* because the constraint from LEP II,  $m_h > 114$  GeV necessarily implies the *absence* of the first order electroweak phase transition. **Now, we know that  $m_h = 125$  GeV**

**New Physics is required**

50+ scenarios have been put forward

EDMs, hand-in-hand with the LHC, could soon close out the **electroweak baryogenesis scenario**, where new resonances and new sources of CP violation are required close to electroweak scale.

# From SUSY to an atomic/nuclear EDM



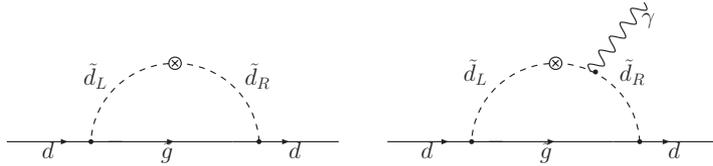
There are many potential sources of CP breaking: leptonic, semi-leptonic, hadronic – many probes are required

Hadronic scale, 1 GeV, is the normalization point where perturbative calculations stop.

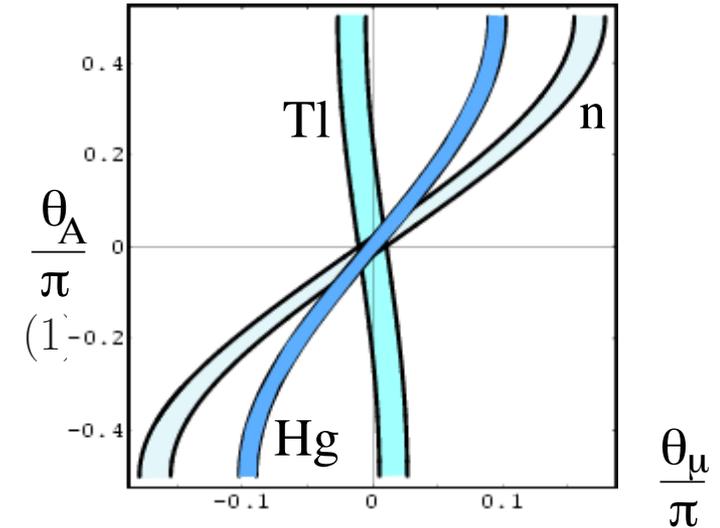
My old slide from the pre-LHC time, in line with “common” expectations of super-partners below a TeV.

# Anatomy of SUSY EDMs

All one-loop and most important ( $\tan \beta$ -enhanced) two-loop diagrams have been computed.



$M_{\text{SUSY}} = 500 \text{ GeV}$ , and  $\tan \beta = 3$ .



$$\frac{d_e}{e\kappa_e} = \frac{g_1^2}{12} \sin \theta_A + \left( \frac{5g_2^2}{24} + \frac{g_1^2}{24} \right) \sin \theta_\mu \tan \beta,$$

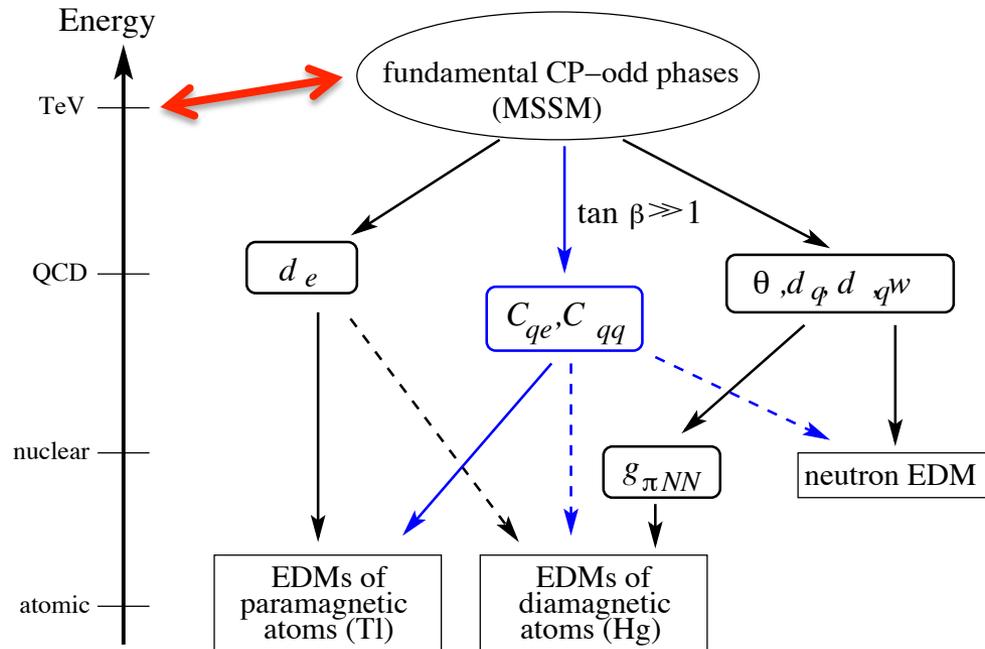
$$\frac{d_q}{e_q \kappa_q} = \frac{2g_3^2}{9} (\sin \theta_\mu [\tan \beta]^{\pm 1} - \sin \theta_A) + O(g_2^2, g_1^2),$$

$$\frac{\tilde{d}_q}{\kappa_q} = \frac{5g_3^2}{18} (\sin \theta_\mu [\tan \beta]^{\pm 1} - \sin \theta_A) + O(g_2^2, g_1^2).$$

$$\kappa_i = \frac{m_i}{16\pi^2 M_{\text{SUSY}}^2} = 1.3 \times 10^{-25} \text{ cm} \times \frac{m_i}{1 \text{ MeV}} \left( \frac{1 \text{ TeV}}{M_{\text{SUSY}}} \right)^2.$$

# From SUSY to an atomic/nuclear EDM

In light of the LHC results, is this connection still here?



Hadronic scale, 1 GeV, is the normalization point where perturbative calculations stop.

# EDMs and New Physics

- EDM observable  $\sim$   
 $\sim$  [some QCD/atomic/nuclear matrix elements]  $\times$

$$\text{SM mass scale } (m_e, m_q) \times (\text{CP phase})_{\text{NP}} / \Lambda_{\text{NP}}^2$$

With some amount of work all matrix elements can be fixed. For the flavor blind NP,  $d_i \sim m_i$ . **Unfortunately, we have no idea where actually  $\Lambda_{\text{NP}}$  is !!!**

100 GeV, 1 TeV, 10 TeV, 100 TeV, 1000 TeV ... GUT scale ...  $M_{\text{p}}$

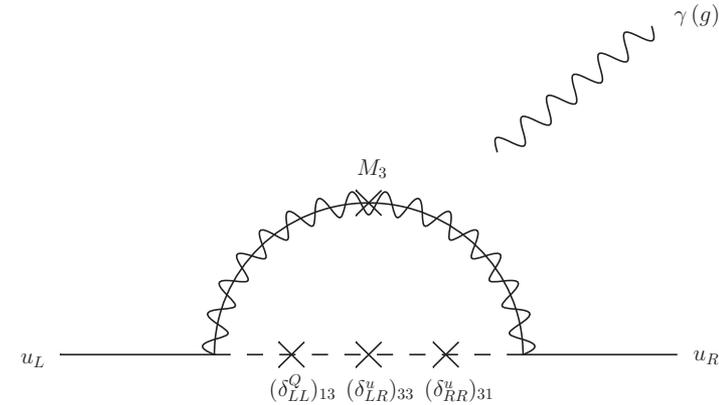
After the LHC did not find the abundance of new states immediately above EW scale, “guessing EDMs” became even more difficult. *What shall we put in the denominator? E.g. (TeV)<sup>2</sup> or (PeV)<sup>2</sup>?*

# EDMs from 100 TeV SUSY

- Measured Higgs mass value,  $\sim 126$  GeV, may be pointing toward very heavy squark mass scale. The Higgs potential must be “tuned” to a considerable level.
- Such mass scale, 50 TeV-PeV allows [almost] not to worry about SUSY flavor issues [and about producing sfermions at the LHC]. Wells, 2003; .... Most recently Arvanitaki et al., Arkani-Hamed et al, other groups, 2012-2013. “Mini-split” scenario.
- Gaugino could be around EW scale, giving dark matter and allowing many models of SUSY breaking to easily explain such a scenario.
- Such a huge mass scale suppresses all EDMs, of course, but the absence of flavor-diagonal squark mass matrix can lead to a considerable enhancement via  $d_i \sim m_{\text{top}}$ , McKeen, MP, Ritz, 2013. See also Altmannshofer et al., 2013.

# Naturalness of masses and EDMs

$$\begin{aligned}
 \tilde{d}_u &\simeq \frac{\alpha_s}{4\pi} M_3 (\delta_{LL}^u)_{13} (\delta_{LR}^u)_{33} (\delta_{RR}^u)_{31} \times \frac{3}{M_{\text{sc}}^2} \log \left( \frac{M_{\text{sc}}^2}{M_3^2} \right) \sin \phi_{\tilde{u}\mu} \\
 &\sim 3 \frac{\delta m_u}{\Lambda_{\text{SUSY}}^2} \log \left( \frac{\Lambda_{\text{SUSY}}^2}{M_3^2} \right) \sin \phi_{\tilde{u}\mu} \\
 &\sim 1 \times 10^{-26} \text{ cm} \left( \frac{3}{\tan \beta} \right) \left( \frac{\theta_u^2}{1/3} \right) \left( \frac{M_3}{1 \text{ TeV}} \right) \left( \frac{100 \text{ TeV}}{\Lambda_{\text{SUSY}}} \right)^3 \\
 &\quad \times \left[ \log \left( \frac{\Lambda_{\text{SUSY}}^2}{M_3^2} \right) / 10 \right] \left( \frac{\sin \phi_{\tilde{u}\mu}}{0.1} \right)
 \end{aligned}$$



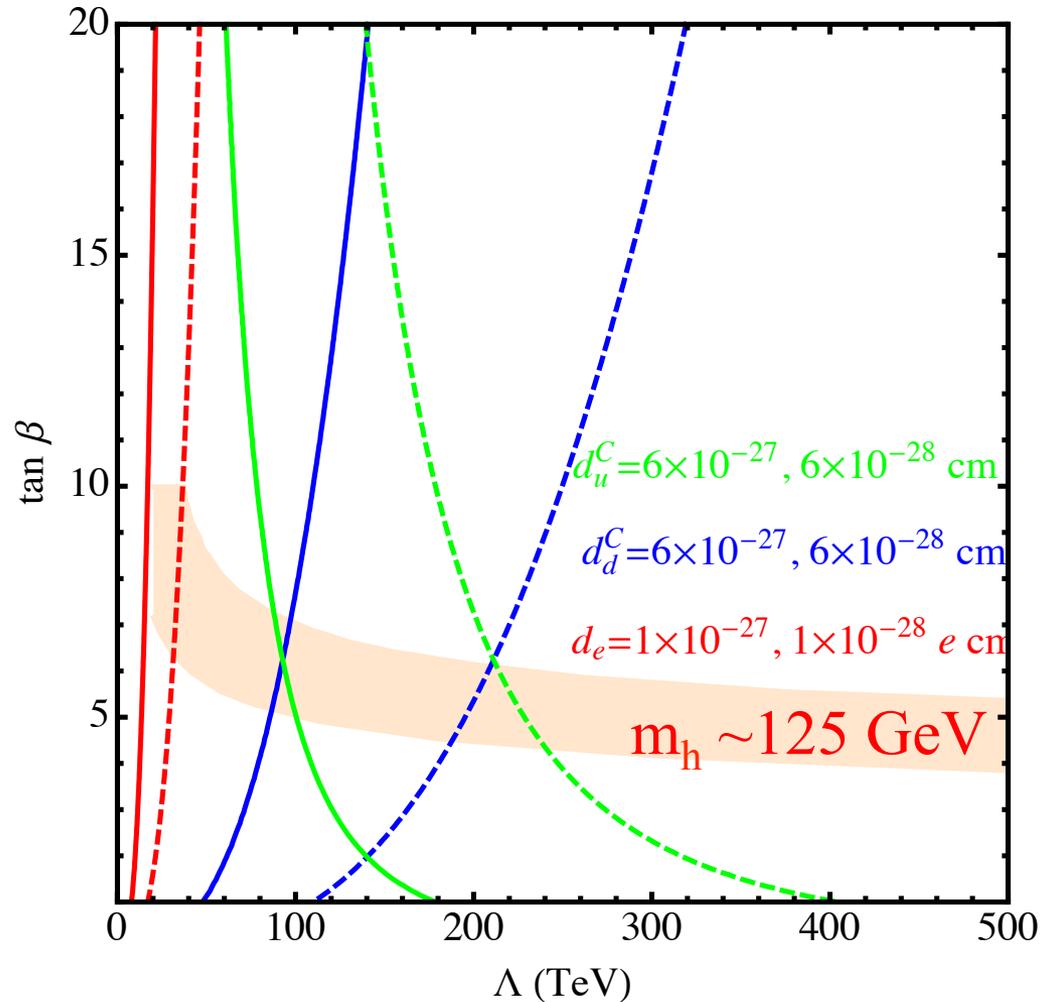
Common squark, Higgsino mass scale is assumed. Quark mass itself is also corrected and we require the tuning in  $m_u$  not be very large,

$$\begin{aligned}
 \delta m_u &\sim \frac{\alpha_s}{4\pi} \theta_u^2 \frac{m_t M_3}{\Lambda_{\text{SUSY}} \tan \beta} \\
 &\sim 2 \text{ MeV} \left( \frac{3}{\tan \beta} \right) \left( \frac{\theta_u^2}{1/3} \right) \left( \frac{M_3}{1 \text{ TeV}} \right) \left( \frac{100 \text{ TeV}}{\Lambda_{\text{SUSY}}} \right)
 \end{aligned}$$

Saturating naturalness in  $m_u$  allows fixing many free parameter in  $d_u$ .

Current bounds on  $d_{Hg}$  limit CEDM of up quark at  $\sim 5 \times 10^{-27} \text{ cm}$

# Naturalness estimates for EDMs

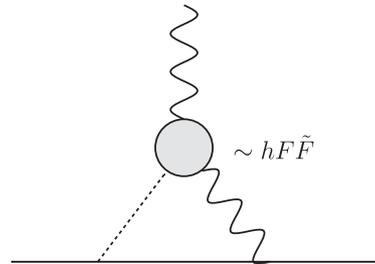


Currently  $d_{\text{Hg}}$  probes  $\sim 100$  TeV scale in this scenario. So, sub-PeV SUSY is not hopeless for EDMs. But we may never learn that it is SUSY...

# Constraining properties of 125 GeV Higgs-like particle with EDMs

- New resonance discovered 4 years ago at the LHC may be exactly the SM Higgs, or it may be a SM-Higgs-like with some deviations of its couplings from what's expected in the SM.
- Its CP-properties are not arbitrary – are being tested at the LHC, and are constrained by the absence of large EDMs. (E.g. large, O(10%) modifications of branching ratios due to additional CP-violating amplitudes are generically not allowed.)

$$\frac{c_h v}{\Lambda^2} h F_{\mu\nu} F^{\mu\nu} + \frac{\tilde{c}_h v}{\tilde{\Lambda}^2} h F_{\mu\nu} \tilde{F}^{\mu\nu}$$



$$\Delta R_{\gamma\gamma}^{CP\text{-odd}} < 1.1 \times 10^{-6}$$

McKeen, MP, Ritz, 2012

- CP-violating couplings to light quarks and electrons are constrained through EDM better than CP-conserving ones directly!

# Main principles of g-2 measurement

(I am talking about muon – apologies to electron g-2 people)

- Precession of spin relative to the momentum in the storage ring is due to  $g-2 \neq 0$ .

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

- The measurement is performed at “magic”  $\gamma = 29.3$  that minimizes the influence of electric field.
- Well-measured ratios of muon and proton magnetic moments is used as an additional input

$$a_\mu = \frac{\omega_a}{\omega_L - \omega_a} = \frac{\omega_a / \tilde{\omega}_p}{\omega_L / \tilde{\omega}_p - \omega_a / \tilde{\omega}_p} = \frac{\mathcal{R}}{\lambda - \mathcal{R}}, \quad \lambda = \omega_L / \omega_p = 3.18334539(10)$$

# BNL E821 experiment

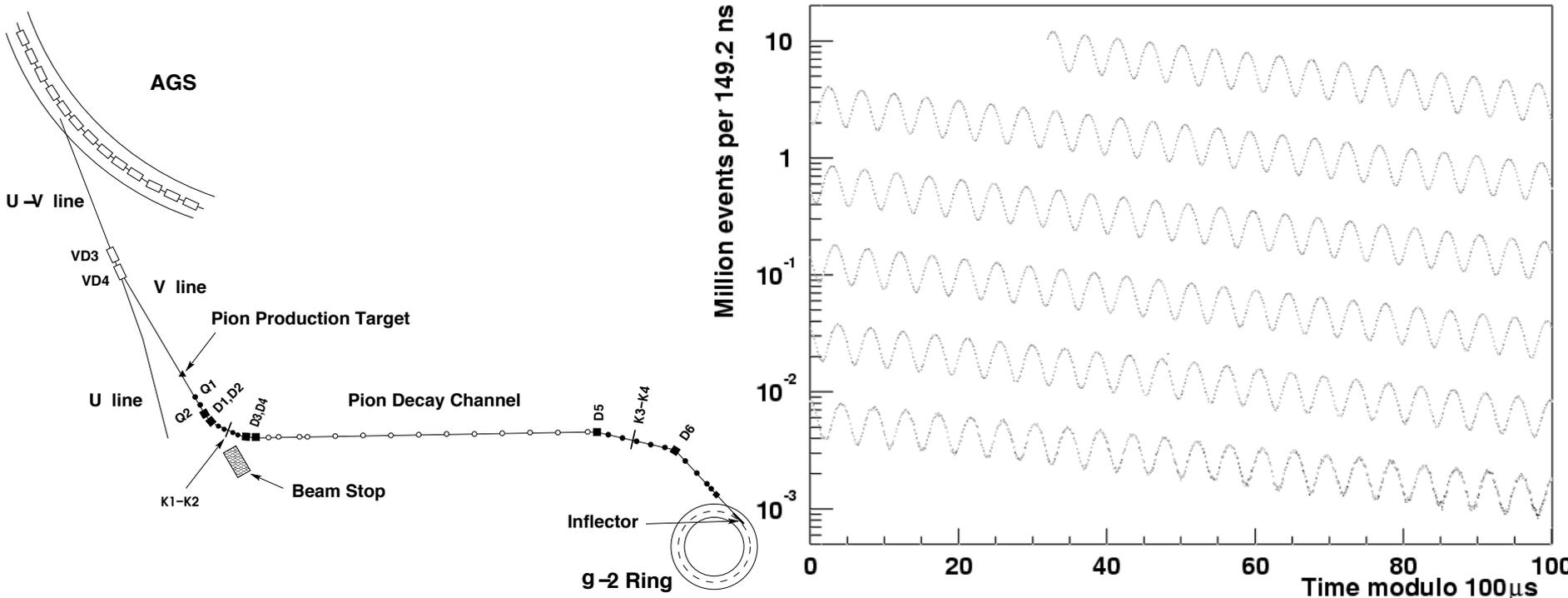


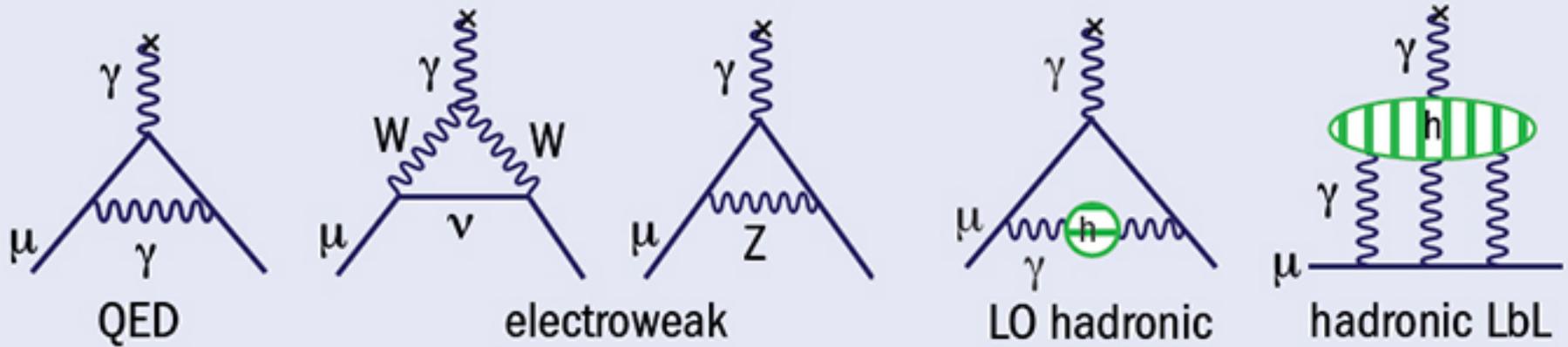
FIG. 2: Distribution of electron counts versus time for the 3.6 billion muon decays in the data-taking period. The data is wrapped around modulo 100  $\mu\text{s}$ .

$$a_{\mu}^{\text{experiment}} = 116592089(63) \times 10^{-11},$$

Consistent for positively and negatively charged muons

Run Period	Polarity	Electrons [millions]	Systematic $\omega_p$ [ppm]	Systematic $\omega_a$ [ppm]	Final Relative Precision [ppm]
R97	$\mu^+$	0.8	1.4	2.5	13
R98	$\mu^+$	84	0.5	0.8	5
R99	$\mu^+$	950	0.4	0.3	1.3
R00	$\mu^+$	4000	0.24	0.31	0.73
R01	$\mu^-$	3600	0.17	0.21	0.72

# Theoretical status of muon g-2, SM



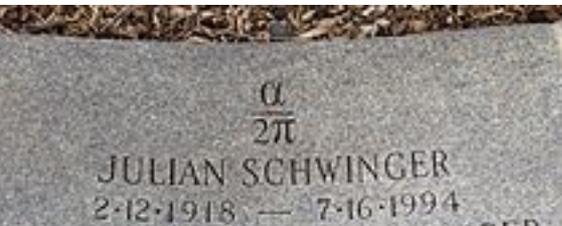
The history of theoretical calculations goes very far in the past. Back to Schwinger's result,  $a_\mu^{1\text{-loop QED}} = \alpha / (2\pi)$

Currently, the QED calculations are carried out to four-loop order,

$$a_\mu^{\text{QED}} = 116584718.08(15) \cdot 10^{-11}$$

Electroweak calculations are also under control,

$$a_\mu^{\text{EW}} = (154 \pm 2) \cdot 10^{-11}$$

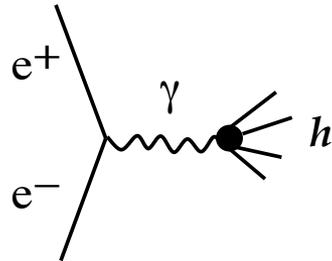
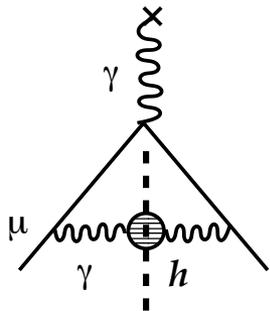


[the errors are well below the discrepancy] 24

# Theoretical status of muon g-2

Hadronic contributions: A. vacuum polarization B. “light-by-light”

For A. unitarity + analyticity comes to rescue:



$$a_{\mu}^{\text{had, LO VP}} = \frac{1}{4\pi^3} \int_{m_{\pi}^2}^{\infty} ds \sigma_{\text{had}}^0(s) K(s)$$

$$a_{\mu}^{\text{had, LO VP}} = (694.91 \pm 3.72_{\text{exp}} \pm 2.10_{\text{rad}}) \cdot 10^{-10}.$$

For B. some hadronic model calculations are necessary at this points  
(loops of heavy quarks + loops of light mesons, e.g. pions)

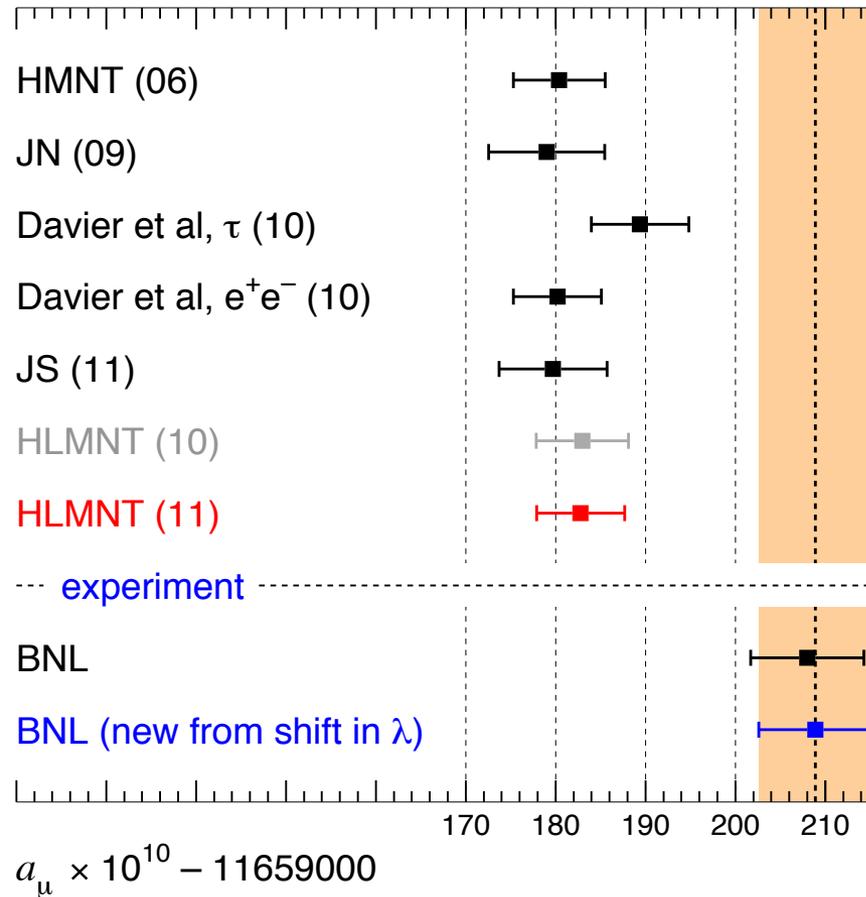
Recent evaluations give

$$a_{\mu}^{\text{had, l-by-l}} = (10.5 \pm 2.6) \cdot 10^{-10}$$

$$a_{\mu}^{\text{had, l-by-l}} = (11.6 \pm 4.0) \cdot 10^{-10}$$

# Summary of the current discrepancy

From Hagiwara et al. (2011)



There is a theoretical “deficit” of  $3 \times 10^{-9}$ , and the tension is  $\sim 3.5 \sigma$  26

# What are the logical possibilities behind the discrepancy?

1. *Statistical fluctuation.* [happens]. Only one experimental group got the result [could be an error].
2. *SM calculators could be overly optimistic about their error bars.* After all, HVP is needed to  $O(1\%)$  accuracy, and HLbL is calculated within models, not ab-initio QCD (although lattice is making steady progress).
3. *Yet undiscovered “New Physics” supplies  $+3 \times 10^{-9}$ .* What kind of new physics could it be? (converting it to “dipole” units, it is  $3 \times 10^{-22}$  e cm)
4. Any combination of the above.

# Future: new experiment at Fermilab



Repeat of the BNL experiment with the same storage ring, but much enhanced intensities, and improved monitoring of the magnetic field.

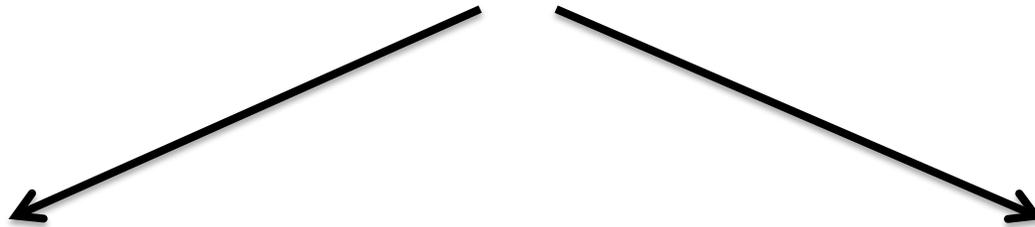
Goal: *shrink the size of the experimental errors by a factor of  $\sim 4$ .*

**+ New efforts for the lattice QCD calculations of hadronic contributions.**

# What if it is New Physics?

The New Physics contribution could be  $\sim a_{\mu}^{\text{NP}} = (26.1 \pm 8) \times 10^{-10}$ .

This is  $\sim$  twice the size of the SM electroweak contribution, and in these units *not small*.



## Weak scale solutions.

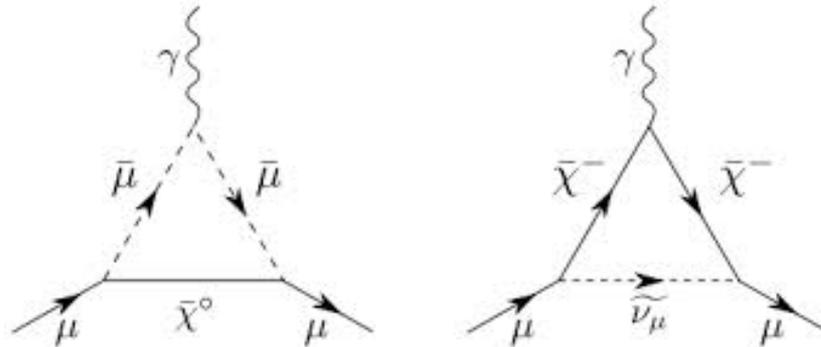
Main challenges are to create such a large shift of  $a_{\mu}$  and stay undetected at LEP, Tevatron and LHC experiments

## Sub-GeV scale solutions.

These must be additional electrically *neutral* states, with small couplings to normal matter that somehow escape detection

*Similar dichotomy exists for neutrino physics where NP effects are real*

# Supersymmetric models to fix g-2



1. Historically, in the last  $\sim 15$  years, the muon g-2 has been an important “motivator” for SUSY. *However, most of the 2002 Snowmass “benchmark points” are now excluded!*
2. The sign of  $a_\mu^{\text{NP}}$  (SUSY) is not fixed – so it is not guaranteed that SUSY “helps”. To achieve a large contribution comparable to SM EW contribution, a large Yukawa coupling is needed (aka large  $\tan \beta$  solutions). See works by **D. Stockinger** et al.
3. No superpartners at the LHC + Higgs mass of 125 GeV may be pointing towards heavy scale  $m_{\text{SUSY}} \sim \text{O}(10 \text{ TeV})$ . Solutions to g-2 are still possible if SUSY is “crafty”:  $m_{\text{sleptons, EWK-ino}} \ll m_{\text{squarks}}$
4. *LHC is not finished – stay tuned. ILC or CLIC could do better?* 30

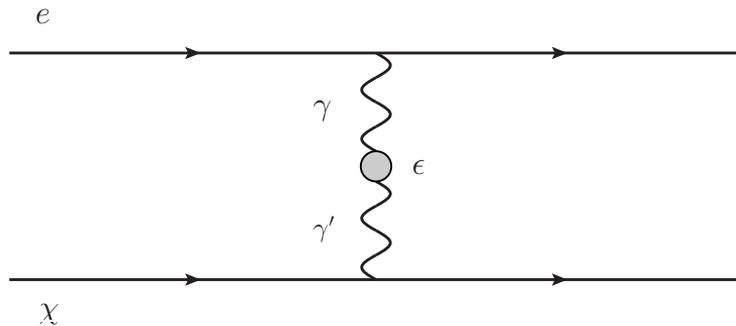
# “Simplified model” of light dark sector

(Okun', Holdom,...)

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi} [\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi] \psi$$

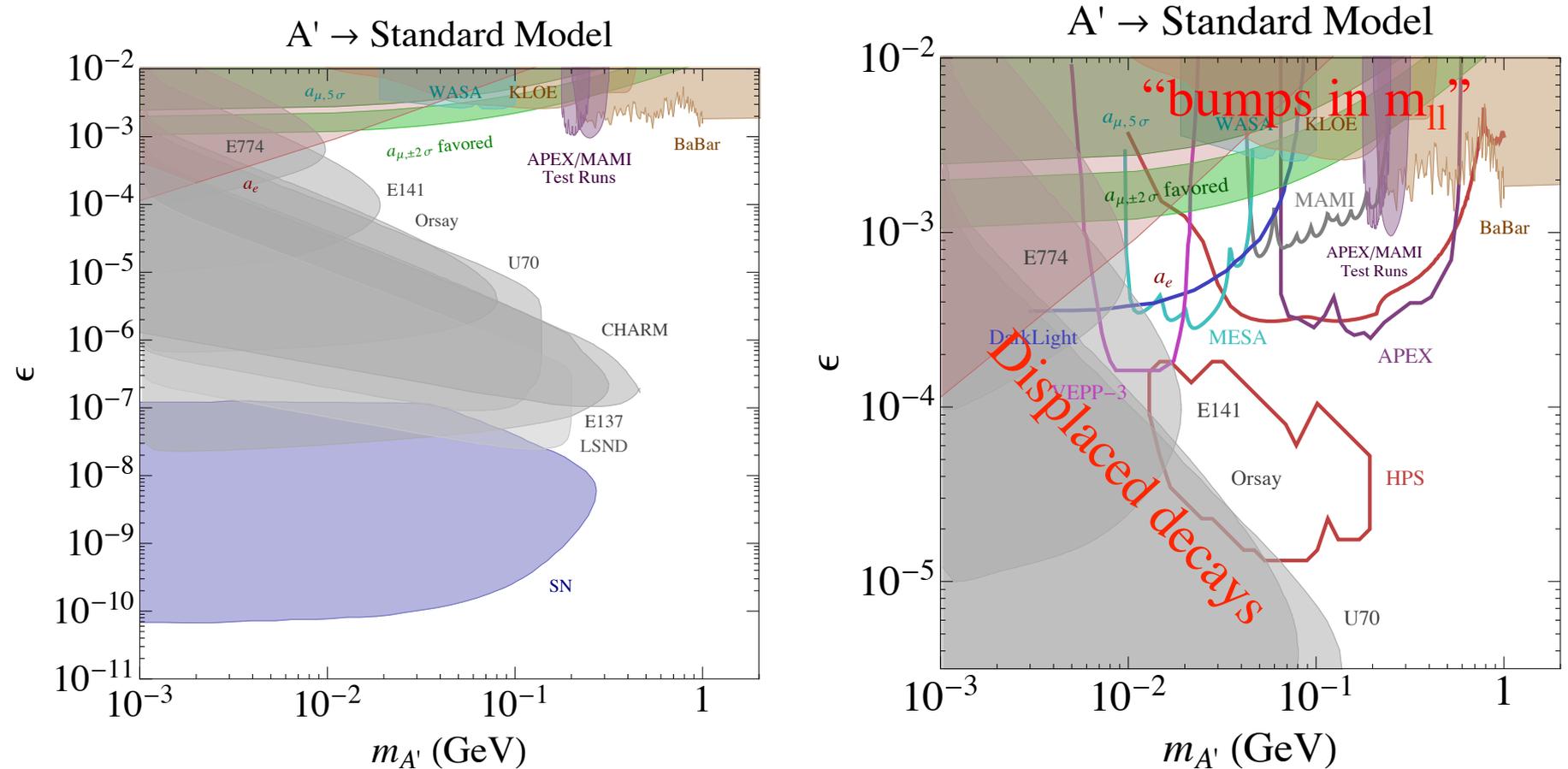
$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi} [\gamma_\mu (i\partial_\mu - g'A'_\mu) - m_\chi] \chi,$$



$A$  – photon,  $A'$  – “dark photon”,  
 $\psi$  – an electron,  $\chi$  – a DM state,  
 $g'$  – a “dark” charge

- “Effective” charge of the “dark sector” particle  $\chi$  is  $Q = e \times \epsilon$  (if momentum scale  $q > m_V$ ). At  $q < m_V$  one can say that particle  $\chi$  has a non-vanishing EM charge radius,  $r_\chi^2 \simeq 6\epsilon m_V^{-2}$ .
- Dark photon can “communicate” interaction between SM and dark matter. *It represents a simple example of BSM physics.*

# Search for dark photons, Snowmass study, 2013



Dark photon models with mass under 1 GeV, and mixing angles  $\sim 10^{-3}$  represent a “window of opportunity” for the high-intensity experiments, not least because of the tantalizing positive  $\sim (\alpha/\pi)\epsilon^2$  correction to the muon  $g - 2$ .

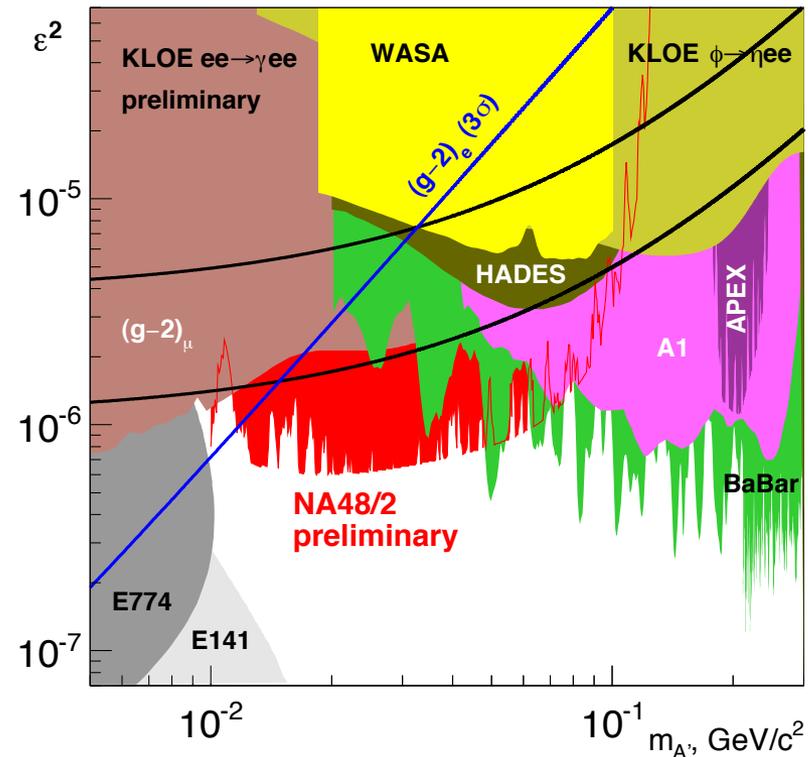
# Latest results: A1, Babar, NA48

Signature: “bump” at invariant mass of  $e^+e^-$  pairs =  $m_A$ ,

**Babar:**  $e^+e^- \rightarrow \gamma V \rightarrow \gamma l^+l^-$

**A1(+ APEX):**  $Z e^- \rightarrow Z e^- V$   
 $\rightarrow Z e^- e^+e^-$

**NA48:**  $\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+e^-$



Latest results by NA48 exclude the remainder of parameter space relevant for  $g-2$  discrepancy.

Only more contrived options for muon  $g-2$  explanation remain, e.g.  $L_\mu - L_\tau$ , or dark photons *decaying to light dark matter*.

# Signatures of $Z'$ of $L_\mu - L_\tau$

## Experimental results on “trident”

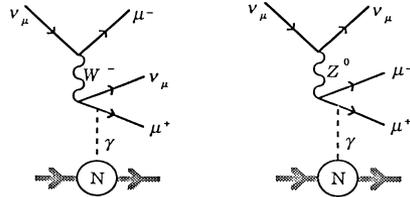


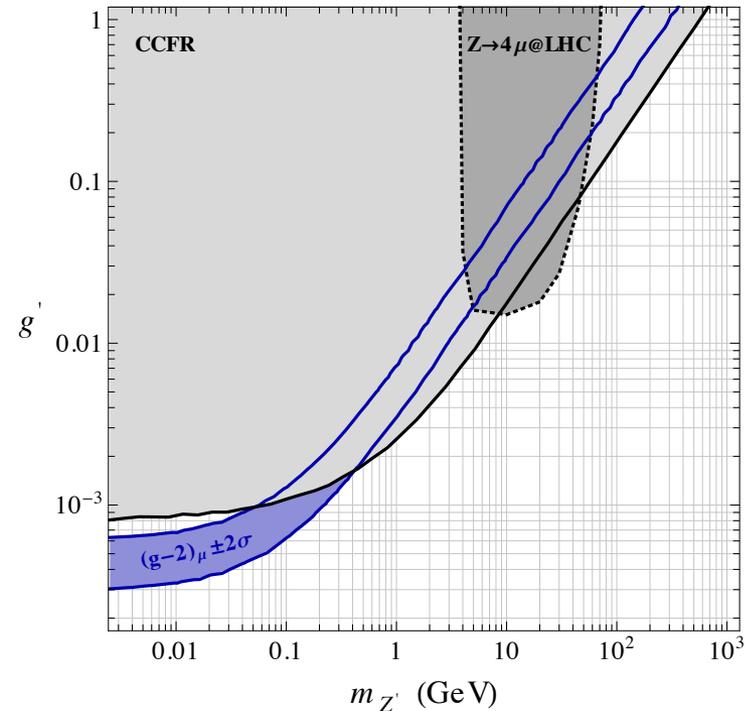
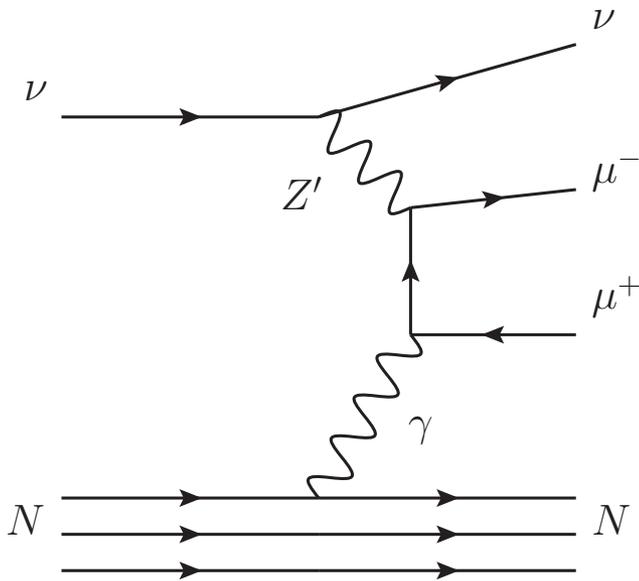
FIG. 1. Feynman diagram showing the neutrino trident production in  $\nu_\mu$ - $A$  scattering via the  $W$  and the  $Z$  channels.

$$\sigma_{\text{CHARM-II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57 ,$$

$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28 ,$$

$$\sigma_{\text{NuTeV}}/\sigma_{\text{SM}} = 0.67 \pm 0.27 .$$

Hypothetical  $Z'$  (any  $Z'$  coupled to  $L_\mu$ ) contributes constructively to cross section. (Almannshofer et al., 2014)



New BaBar (+B. Shuve) analysis also limits  $Z'$  mass range.

# Ample opportunities to look for light New Physics at CERN

- LHC experiments, including LHCb.
- NA62, via rare radiative kaon decays. Sensitive to light scalar solutions to muon  $g-2$  puzzle.
- Missing momentum signal in NA64: search for light mediators decaying to dark matter and/or neutrinos ( $L_\mu - L_\tau$  model). Very relevant for the remaining viable solutions to  $g-2$  with use of light particles.
- *Most importantly, a possibility to discover light new states at SHiP:*
  - Heavy neutral leptons
  - Dark photons
  - Produced light dark matter scattering in the  $\nu$ -detector

# Conclusions I

1. CKM phase gives too small an EDM, and before experimentally we cross  $10^{-30}$  cm, we can be sure that we are probing new physics.
2. EDMs generated by theta term is too large – one needs to remove theta from the theory by some adjustment mechanism. Neither  $\theta_{\text{QCD}}$  nor  $\delta_{\text{CKM}}$  look as viable sources for BAU. Likely, there are more sources of CP breaking but its scale is unknown.
3. EDMs are capable of probing scales as high as several 100 TeV. (Example = “minimally unnatural SUSY, or mini-split”.) EDM bounds become competitive with Kaons ( $\Delta m$ ,  $\epsilon_K$ ), and EDM sensitivity can be further improved.
4. If EDMs were to be discovered close to today's bounds, it would most generically point to the existence of new SM-charged states at scales up to 100 TeV. Light dark sectors cannot generate EDMs.

# Conclusions II

1.  $g-2$  of the muon is a difficult measurement and calculations. A long-standing discrepancy by over 3 sigma could be a hint on new physics. Unlike the EDMs, this can be a result of new heavy or light states (such as dark photon model and its variants).
2. CERN is making major contribution to the understanding of the muon  $g-2$  discrepancy, via LHC, NA62, NA64, and hopefully SHiP.

## If dark matter particles have EDM...

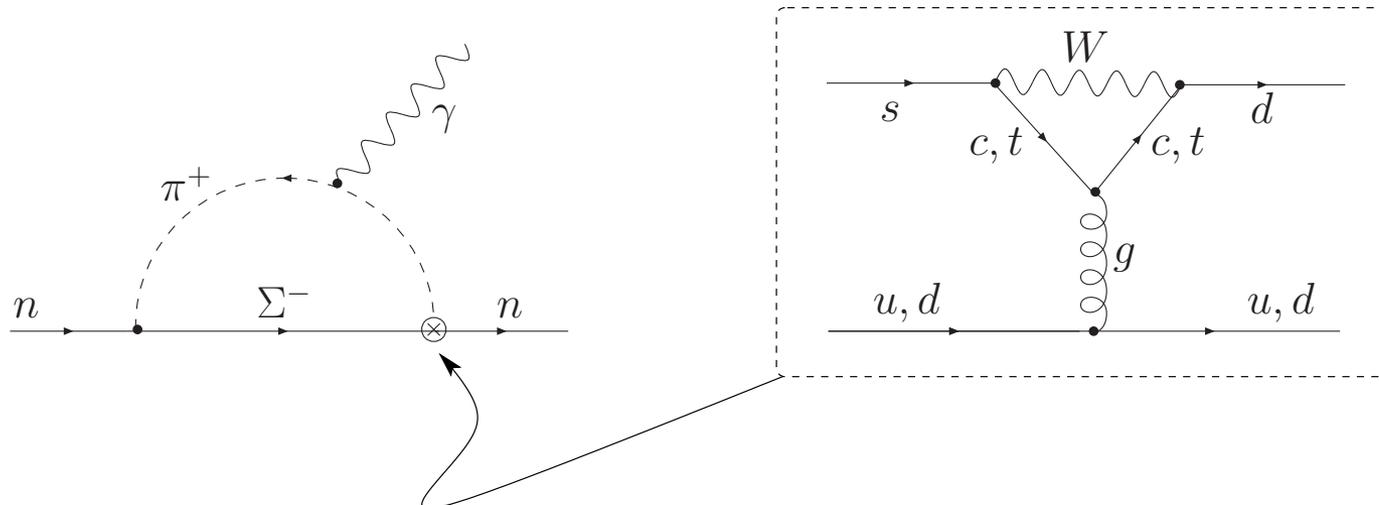
it also must be small. They will contribute to the elastic scattering on normal nuclei (Pospelov, ter Veldhuis, 2000),

$$\sigma = 8\pi Z^2 \left(\frac{d}{e}\right)^2 \left(\frac{\alpha}{v}\right)^2 \frac{S+1}{3S} \ln \frac{q_{min}}{q_{max}}.$$

Recent constraints from Xenon 100 experiments would limit an EDM of a hypothetical WIMP to better than  $10^{-22}$  e cm.

# Long(er) distance contribution dominate

- Combination of  $\Delta S = +1$  and  $\Delta S = -1$  (and  $\Delta \text{charm} = \pm 1$ ) gives a larger estimate to  $d_n$  than just  $d_q$ . Can be as large as  $10^{-31}$  e cm (**Khriplovich, Zhitnitskiy; Gavela et al**). Charm contribution was recently looked at by **Mannel, Uraltsev**.
- EDMs of diamagnetic atomic species (closed e shells, nuclear spin) are generated by the CKM contribution to the nuclear Schiff moment. (Novosibirsk group; **Donoghue, Holstein, Musolf**)
- Direct contribution of  $d_e(\text{CKM})$  to  $d_{\text{Atom}}$  is negligible compared to the semi-leptonic contribution (Schiff moment, nuclear CP-odd polarizability).



Bottom line: EDMs(CKM) are  $\sim 5$  orders and more below current limits

# Effective CP-odd Lagrangian at 1 GeV

in the spirit of Wolfenstein's superweak interaction,

Khriplovich et al., Weinberg,... Applying EFT, one can classify all CP-odd operators of dimension 4,5,6,... at  $\mu = 1$  GeV.

$$\begin{aligned} \mathcal{L}_{eff}^{1\text{GeV}} = & \frac{g_s^2}{32\pi^2} \theta_{QCD} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} \\ & - \frac{i}{2} \sum_{i=e,u,d,s} d_i \bar{\psi}_i (F\sigma) \gamma_5 \psi_i - \frac{i}{2} \sum_{i=u,d,s} \tilde{d}_i \bar{\psi}_i g_s (G\sigma) \gamma_5 \psi_i \\ & + \frac{1}{3} w f^{abc} G_{\mu\nu}^a \tilde{G}^{\nu\beta,b} G_{\beta}^{\mu,c} + \sum_{i,j=e,d,s,b} C_{ij} (\bar{\psi}_i \psi_i) (\bar{\psi}_j i \gamma_5 \psi_j) + \dots \end{aligned}$$

If the model of new physics is specified, for example, a specific parameter space point in the SUSY model, Wilson coefficients  $d_i, \tilde{d}_i$ , etc. can be calculated.

To get beyond simple estimates, one needs  $d_{n, atom}$  as functions of  $\theta, d_i, \tilde{d}_i, w, C_{ij}$ , which requires non-perturbative calculations. which I review in the next few transparencies.

# Synopsis of EDM formulae

## Thallium EDM:

The Schiff (EDM screening) theorem is violated by relativistic (magnetic) effects. Atomic physics to 10 – 20% accuracy gives

$$d_{\text{Tl}} = -585d_e - e 43 \text{ GeV} C_S^{(0)}$$

where  $C_S$  is the coefficient in front of  $\bar{N}Ni\bar{e}\gamma_5e$ . Parametric growth of atomic EDM is  $d_e \times \alpha^2 Z^3 \log Z$ .

## neutron EDM:

~50-100% level accuracy QCD sum rule evaluation of  $d_n$  is available. Ioffe-like approach gives

$$d_n = -\frac{em_*\bar{\theta}}{2\pi^2 f_\pi^2}; \quad d_n = \frac{4}{3}d_d - \frac{1}{3}d_u - e \left( \frac{m_n}{2\pi f_\pi} \right)^2 \left( \frac{2}{3}\tilde{d}_d + \frac{1}{3}\tilde{d}_u \right)$$

(Reproduces naive quark model and comes close to chiral-log estimates)

**Mercury EDM:** Screening theorem is avoided by the finite size of the nucleus

$$d_{\text{Hg}} = d_{\text{Hg}} \left( S(\bar{g}_{\pi NN}[\tilde{d}_i, C_{q1q2}], C_S[C_{qe}], C_P[C_{eq}], d_e) \right).$$

For most models  $\bar{g}_{\pi NN}$  is the most important source. The result is dominated by  $\tilde{d}_u - \tilde{d}_d$  but the uncertainty is large:

$$d_{\text{Hg}} = 7 \times 10^{-3} e (\tilde{d}_u - \tilde{d}_d) + \dots$$