LHC Findings and The Intensity Frontier

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Early LHC "Lessons"

- ***SM Higgs Scalar Discovered!***: m_H=125-126GeV

  After 45 years Weinberg was right.

  Great Discovery but reopens old Issues.

$\lambda\Phi^4$ theory: Trivial, Quadratic Divergences, Vacuum stability…

Higgs Properties become a primary goal

Branching Ratios (Couplings), - Precision! Anomalies!

ATLAS

BR(H➔γγ) ≈ 1.5 BR(H➔γγ) $_{SM}$ Anomalous? Maybe?

New CP Violation Source?

1) Implications for edms! d_e, d_n, d_p

No Sign of Supersymmetry (yet)
LHC, MEG, g-2, Theory Tension

Early LHC tension $m_{susy} \geq 1, 3, 10\ldots$TeV Naturalness?

Recent BR($\mu \rightarrow e\gamma$)$\leq 5.7\text{x}10^{-13}$ MEG (Motivated by SUSY)

Muon Anomalous Magnetic Moment **(3.6 sigma deviation)**

What about SUSY GUT Unification?

What if $m_{susy} \geq 10$TeV?

2) Muon g-2, (Dark Photon Alternative Solution?)

Electron Scattering, Rare K, π, μ, B… Decays

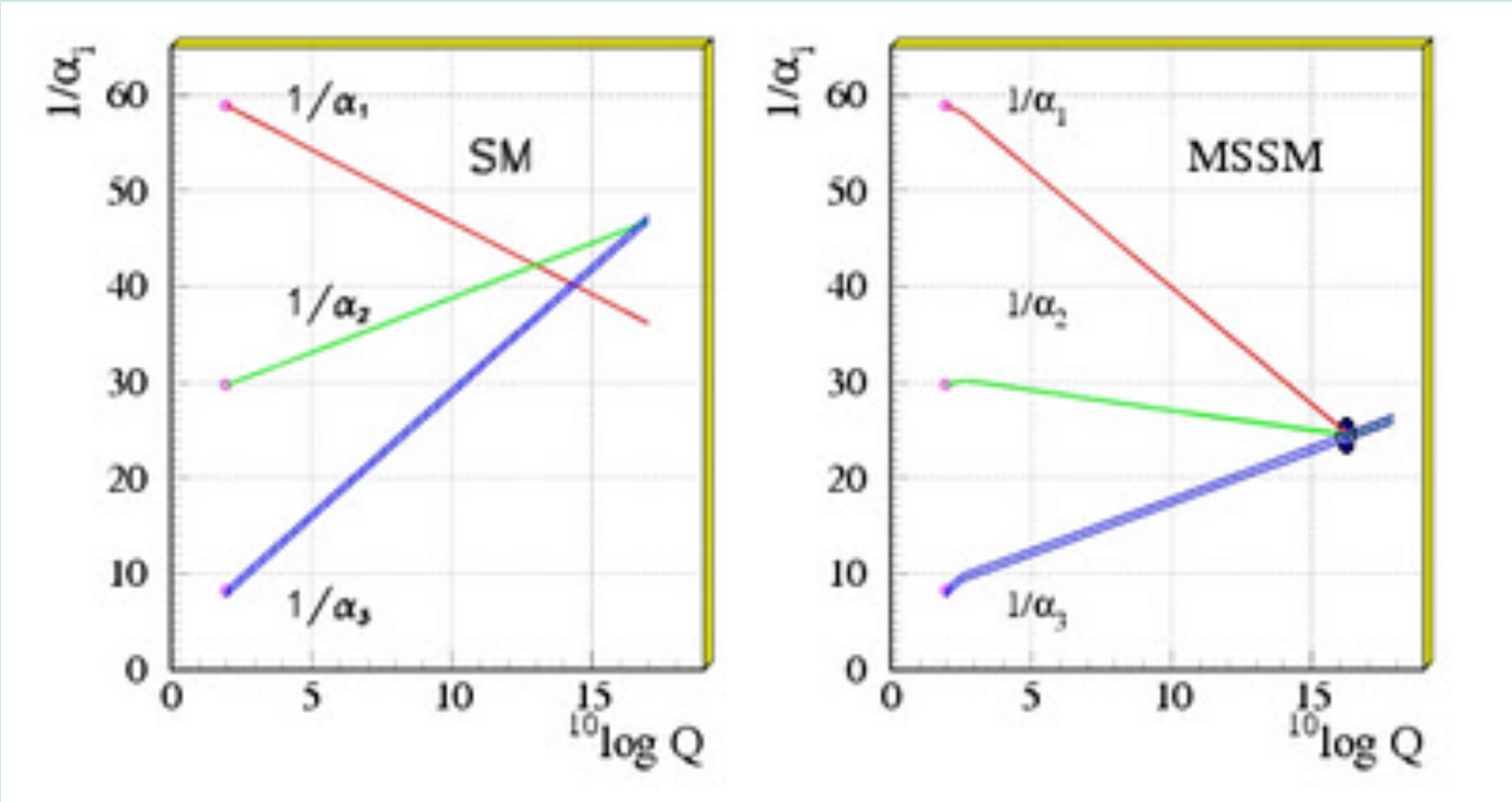
3) Proton Decay ($p \rightarrow e + \pi^0$ easier discovery?)

Major Goal of LBNE! Window to Unification!

$\sin^2\theta_W(m_Z)^{exp}=0.23125$ better agreement with GUTS!

SUSY GUT Unification

S. Raby PDG (2010)



Properties of the Higgs Boson?

The Higgs Boson

Now the Center of Attention

Where will it lead us?

Higgs (125-126GeV) Discovery & Properties

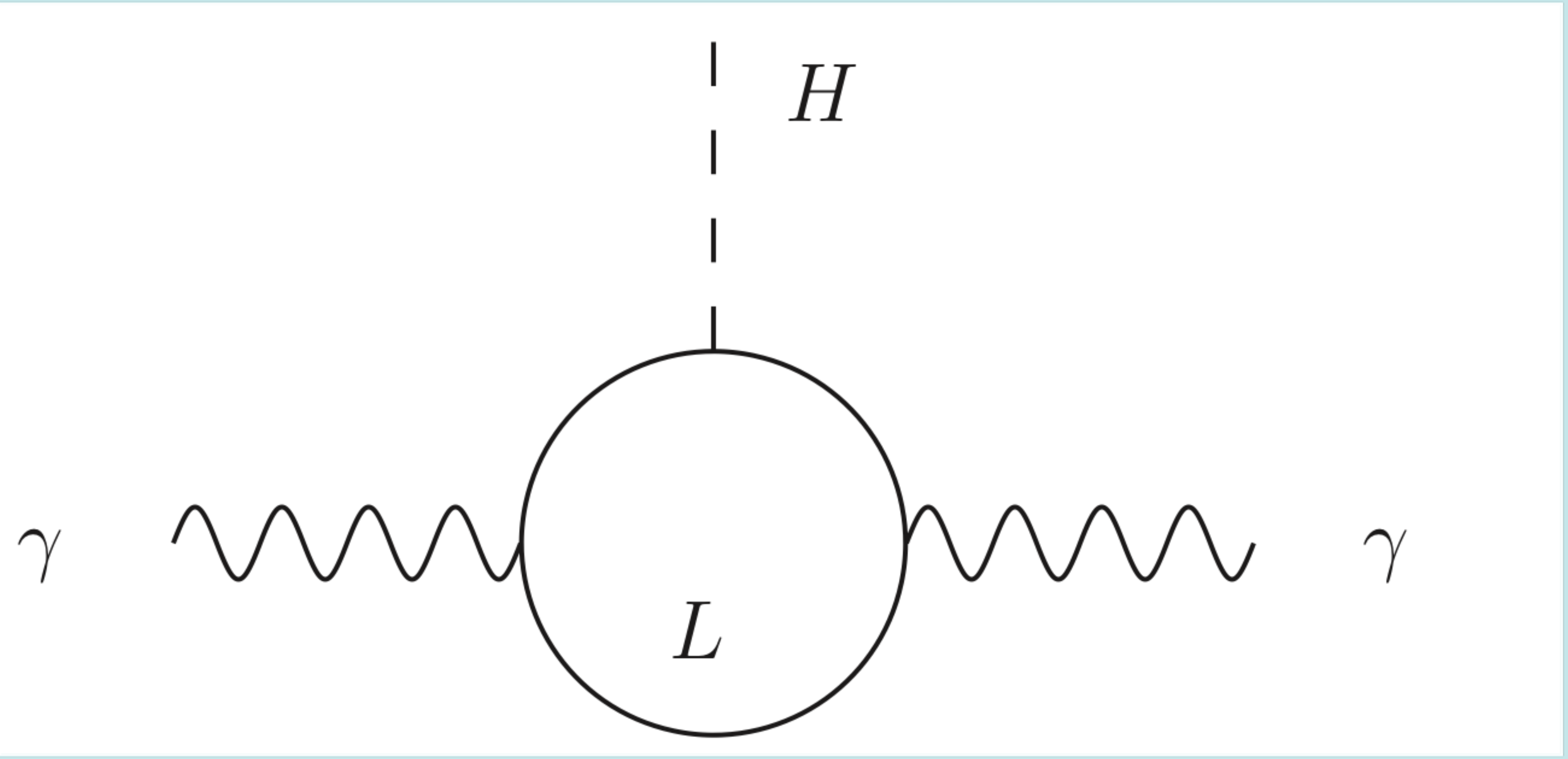
- ATLAS and CMS Experiments have strong evidence for a
- Higgs like (spin 0) new particle with mass 125-126GeV

Expected Higgs SM Properties

H Decay Channel	Branching Ratio
$b\bar{b}$	0.578
WW^*	0.215
gg	0.086
$\tau^+\tau^-$	0.063
$c\bar{c}$	0.029
ZZ^*	0.026
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$	1.5×10^{-3}
$H \to ZZ^* \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$	1.2×10^{-4}
$H \to ZZ^* \to \ell^+\ell^-\nu\bar{\nu}$	3.6×10^{-4}

New Physics Loops or Pseuoscalar Mixing etc.
New CP Violation Source (eg. Voloshin)

$aHF^{\mu\nu}F_{\mu\nu} + b\tfrac{1}{2}\varepsilon^{\mu\nu\alpha\beta}HF_{\mu\nu}F_{\alpha\beta}$ **(CP odd)**



Higgs 2 Loop Effects Important

1977 **Bjorken and Weinberg**: hμe coupling more important for μ➔eγ at 2 loops than 1 loop!

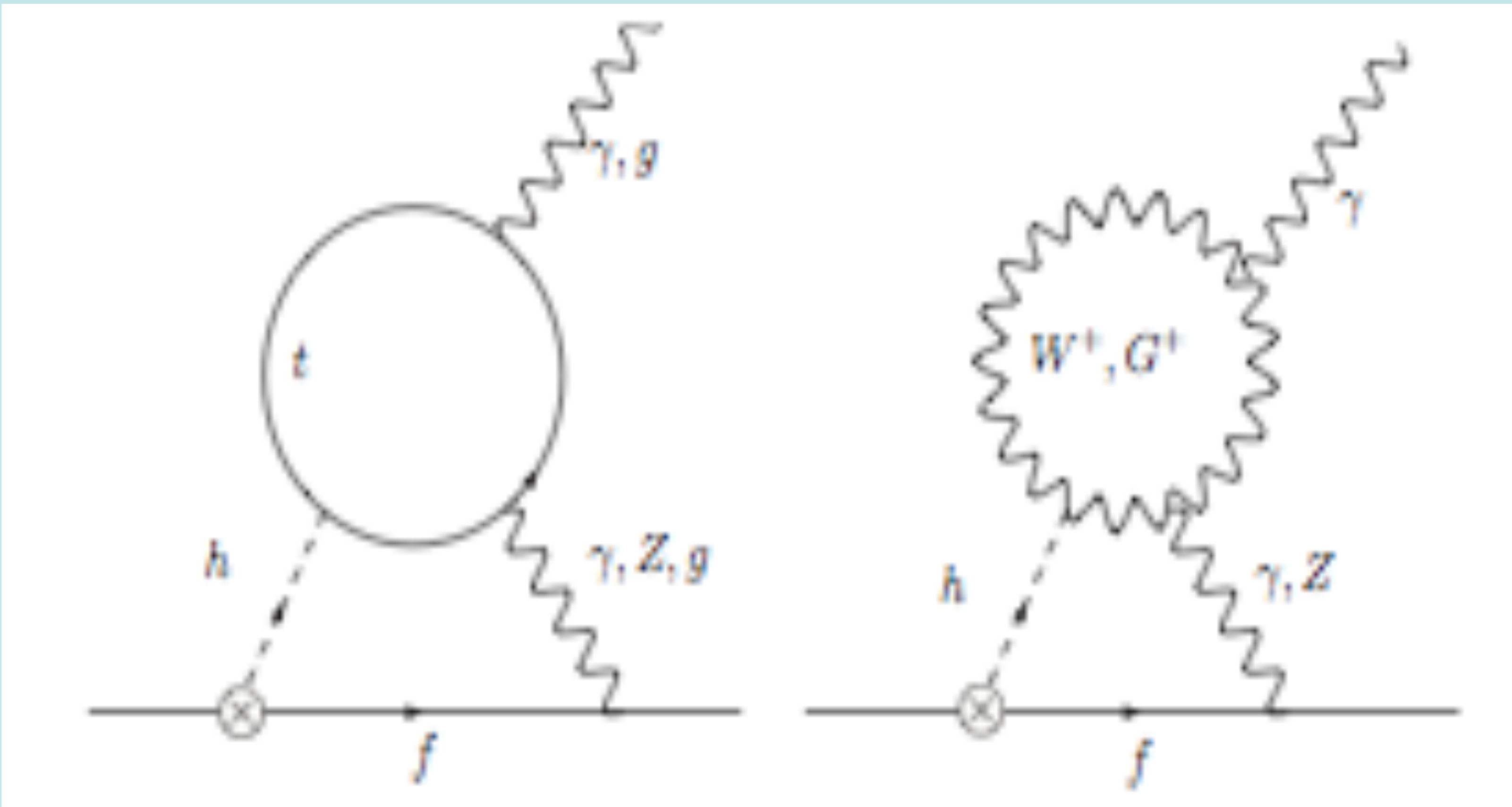
1990 **Barr and Zee**: 2 loop hee coupling can lead to larger d_e (edm) than 1 loop contribution!

1995 **Czarnecki, Krause & WJM:** show 2 loop Higgs contribution ($\sim 4\times 10^{-11}$) to the $g_\mu - 2$ is ~1000 times larger than 1 loop!

2 loop dipole moment examples:

McKeen, Pospelov, Ritz

Huber, Pospelov, Ritz



Some Current edm Bounds

fermion	$\|d_f^{exp}\|$ e-cm
e	$<1\times10^{-27}$ (from TFI)
p	$<8\times10^{-25}$ (from d_{Hg})
n	$<3\times10^{-26}$

electron & neutron bounds roughly comparable
(Very Powerful SUSY Constraints)

Scale as $1/m^2_{susy}$ (1 loop)

m_{susy}~ 0.1PeV Probed!

McKeen, Pospelov, Ritz *(EDM Champions)*

a_f vs d_f (very roughly)

- 2 loop Higgs contribution: $a_\mu(H) \approx \text{few} \times 10^{-11}$ (exp~ 6×10^{-10})
  $a_e(H) \approx 5\times10^{-16}$ (exp~10^{-12})

Unobservably Small Effect!

2 Loop Higgs edm contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e−cm

roughly $|d_n(H)| \approx |d_p(H)| \approx 5\times10^{-26} \sin\phi$ e−cm

Already d_e bound roughly implies **$\sin\phi \leq 0.1$**

CP conttribution to *H➔γγ* $\sin^2\phi \leq 0.01$

Unlikely to be directly observable, but edm experiments can explore down to $\sin\phi \approx O(10^{-3})$! ***Unique!***

Great Future Expectations

- ***Several orders of magnitude improvement expected***

$d_n \rightarrow 10^{-27}$-10^{-28} e-cm Neutron Spallation/Reactor Sources
$d_e \rightarrow 10^{-29}$ e-cm or better!
d_p & $d_D \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring Proposal (BNL/COSY)

If Hγγ coupling violates CP: d_e:d_n:d_p :: 1:-5:5 roughly

d_e atomic, d_n nuclear, d_p hep all must do exps.
Potentially only accesss to hee, huu & hdd couplings

What if g_μ-2 discrepency not due to SUSY?

- **$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(80) \times 10^{-11}$ (*3.6σ!*)**

***This is a very large deviation*!**

Interpretations

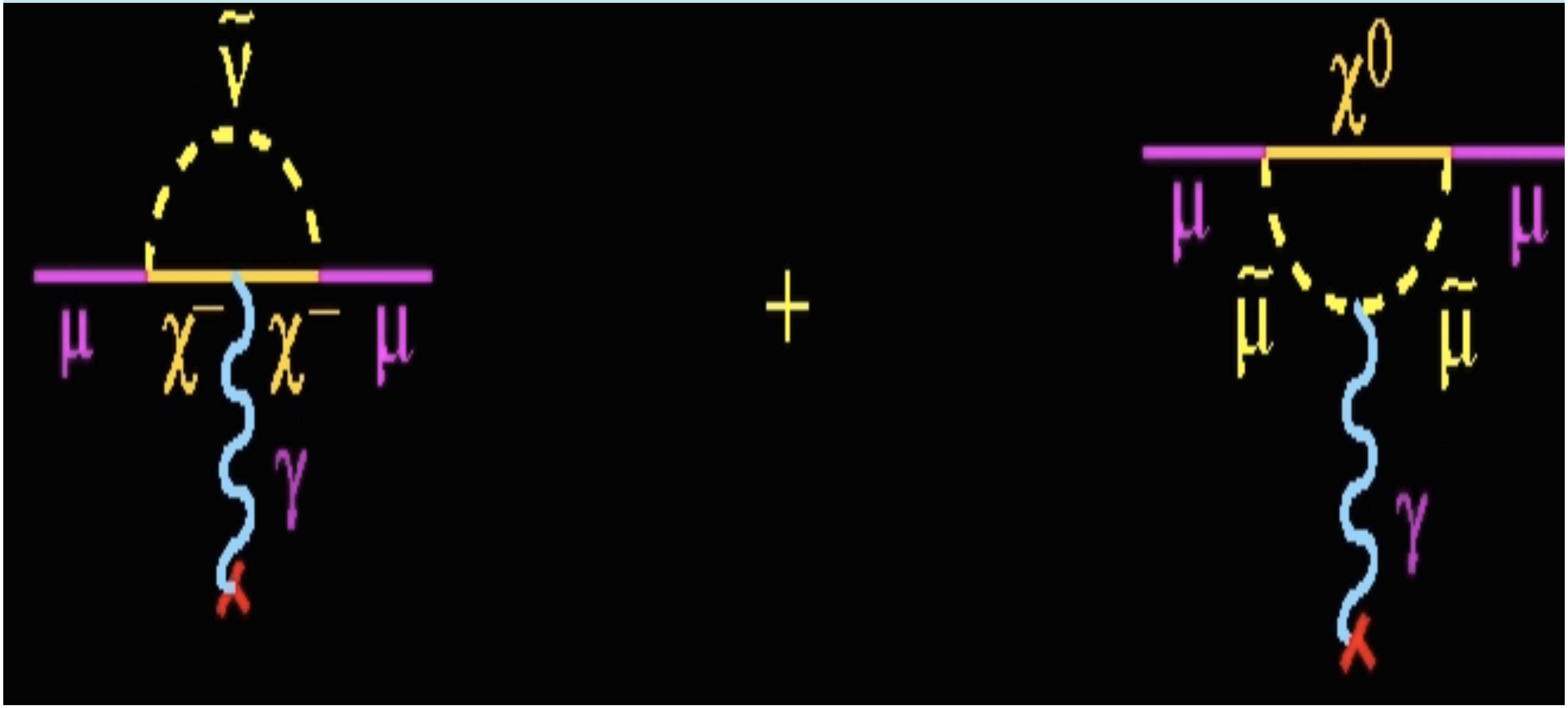
***Generic 1 loop SUSY Contribution*:**

$a_\mu^{SUSY} = (\mathrm{sgn}\mu) 130 \times 10^{-11} (100\mathrm{GeV}/m_{susy})^2 \tan\beta$

$\tan\beta \approx 3\text{-}40$, $m_{susy} \approx 100\text{-}500\mathrm{GeV}$ ***Some LHC Tension***

SUSY 1 loop a_μ Corrections

(Still Most Likely Scenario)



Other Explanations: ***Hadronic e^+e^- Data? HLBL (3loop)?***

Multi-Higgs Models *(2 loop effects)*

Extra Dimensions<2TeV, Heavy Z', Dynamics…

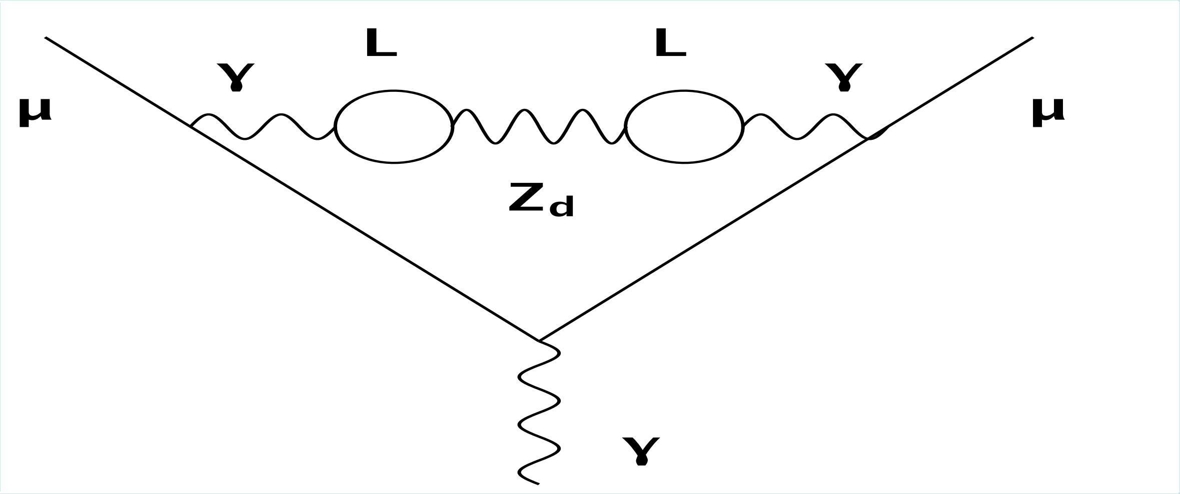
Light Higgs Like Scalar <10MeV?

* ***Dark Photons (Fayet, Pospelov…)***

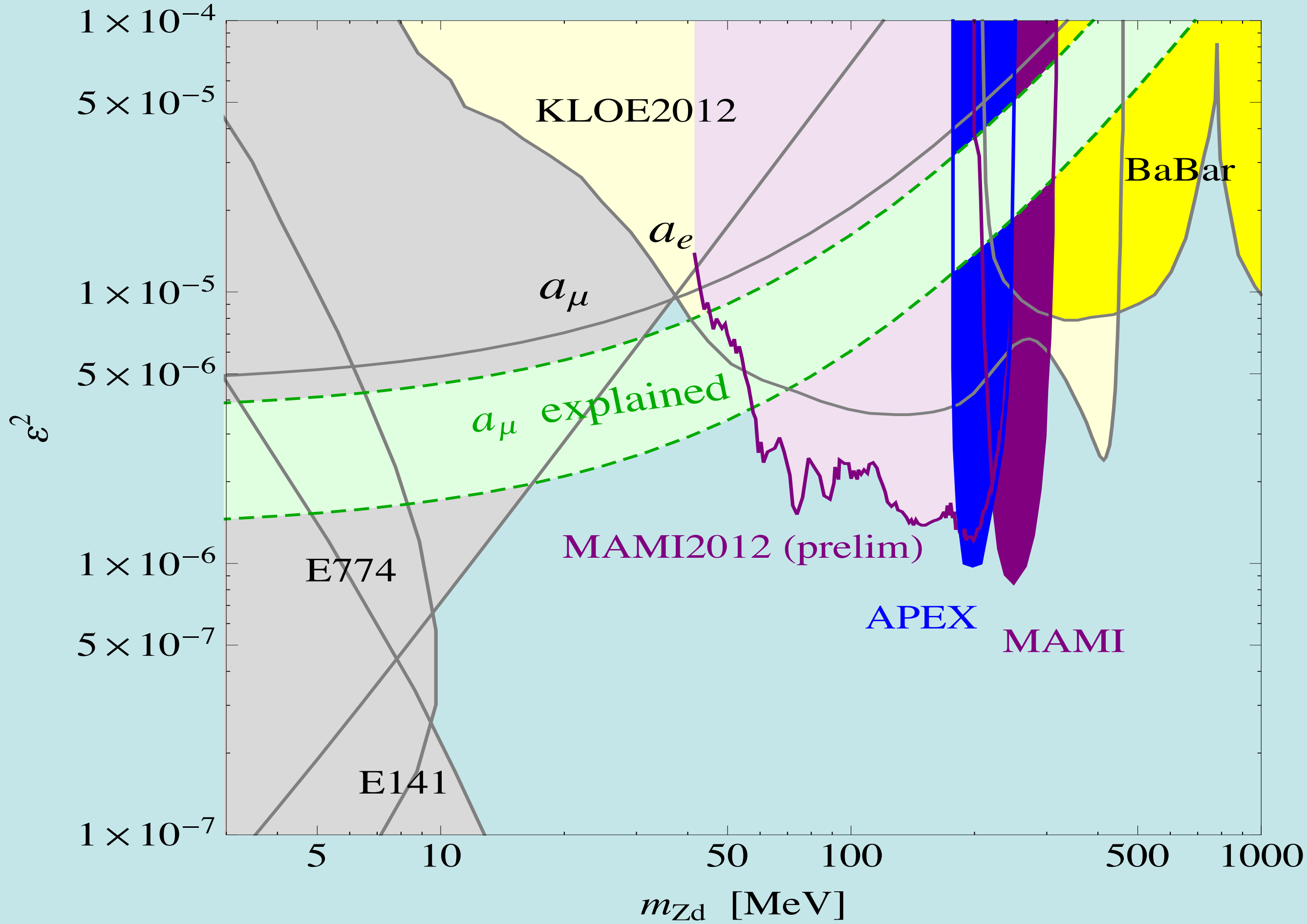
Kinetic Mixing $U(1)_Y x U(1)_d$ $\varepsilon e Z_d^\mu J_\mu^{em}$ $\varepsilon \approx \alpha/\pi \approx 2x10^{-3}$

$a_\mu^{Zd} = \alpha/2\pi \varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ solves g_μ-2 discrepancy

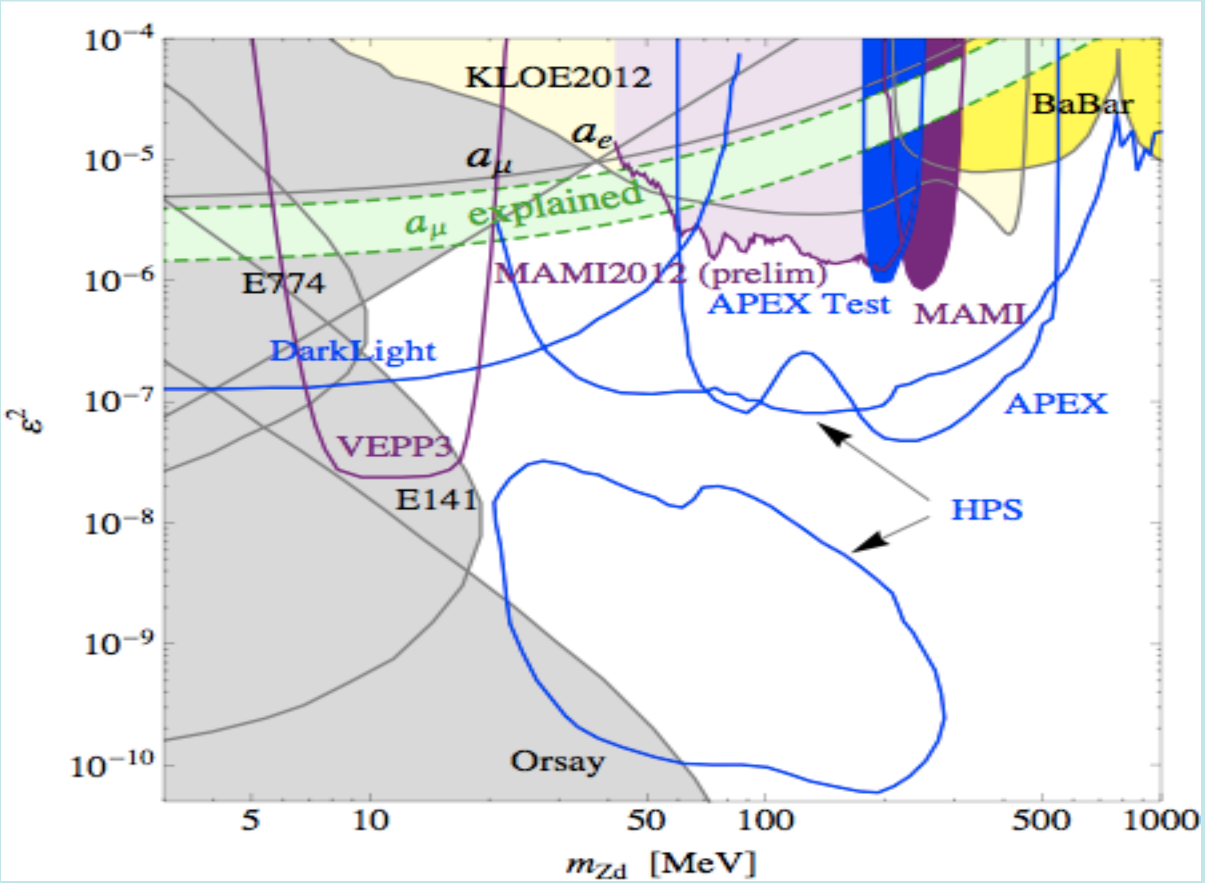
for $\varepsilon^2 \approx 3\text{-}5x10^{-6}$ & $m_{Zd} \approx 20\text{-}50$MeV (see figure)



Recent Updates➔20MeV-50MeV Left



Current Bounds & Future Dark Photon Sensitivity Generally Assume Br($Z_d \rightarrow e^+e^-$)=1



GUT Coupling Unification

Current Values: $\alpha_3(m_Z)=0.117(1)$
$\alpha_2(m_Z)=0.0338(1)$
$\alpha_1(m_Z)=0.0170(1)$

Come together but do *not* unify without an intermediate mass scale: m_{susy}, m_R SO(10), m_{scalar}…

Generic SUSY GUT ➔ $m_X \approx (1\text{TeV}/m_{susy})^{2/15} \times \underline{10^{16}\text{GeV}}$

Also depends on other mass splittings (eg. Scalars)

Proton Partial Lifetime:

$\boldsymbol{\tau(p \rightarrow e^+\pi^0)} \approx (1\text{TeV}/m_{susy})^{8/15} \times 10^{35\pm1}\text{yr}$

Uncertainties: Matrix Elements (Lattice), $\alpha_3(m_Z)$, mass splittings, particle content…

SUSY GUT Unification

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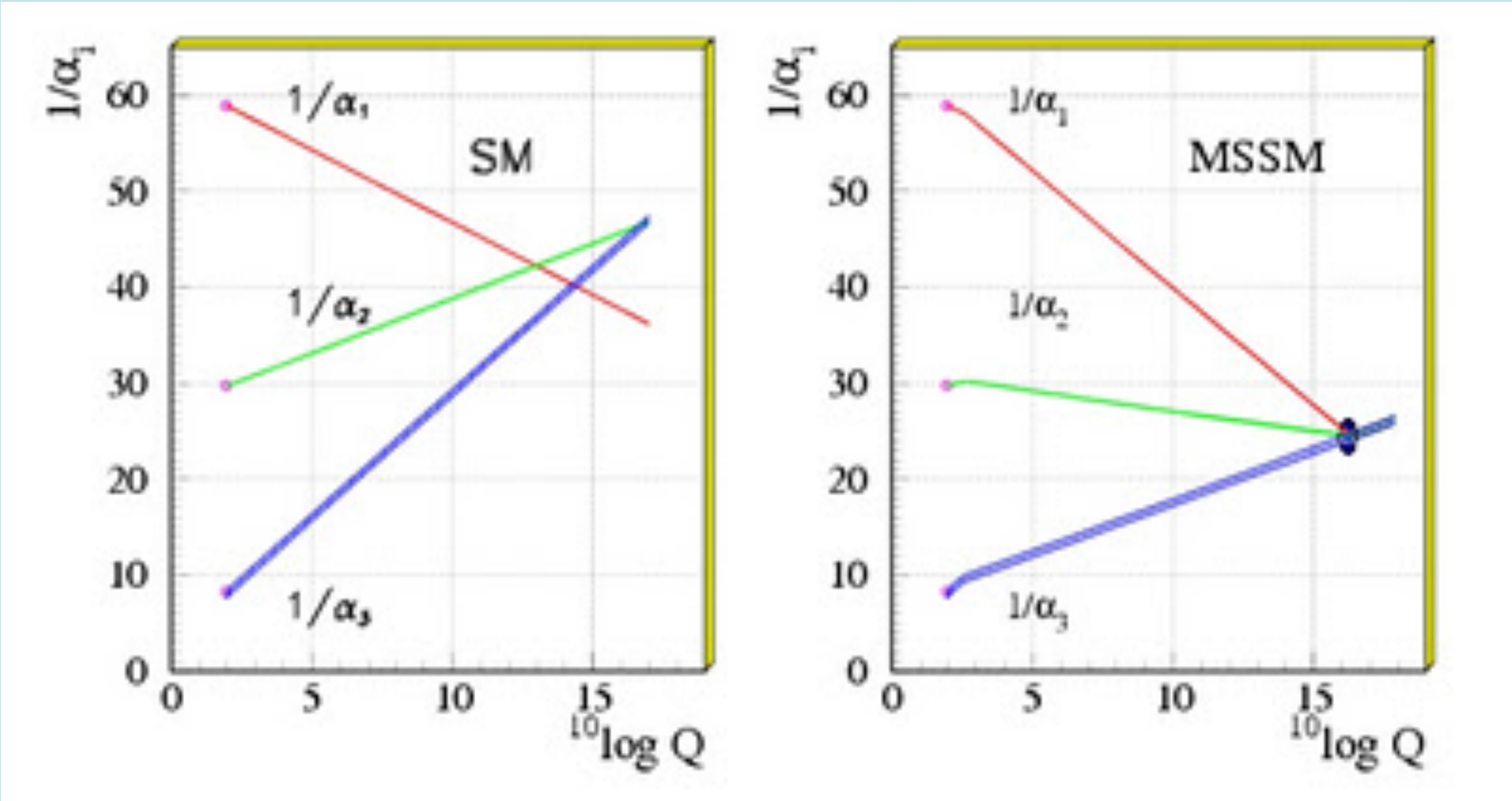

Predictions of SUSY GUTS
Senjanovic & WJM PRD1982

$m_X \approx (1\text{TeV}/m_{susy})^{2/15} \times \underline{10^{16}\text{GeV}}$

$\boldsymbol{\tau(p \rightarrow e^+\pi^0) \approx} (1\text{TeV}/m_{susy})^{8/15} \times 10^{35\pm1}\text{yr}$

$\boldsymbol{\tau(p \rightarrow e^+\pi^0) \approx 3} \times 10^{34\pm1}\text{yr}$ for $m_{susy} \approx 10\text{TeV}$

$\boldsymbol{\tau(p \rightarrow e^+\pi^0) \geq 1.3} \times 10^{34}\text{yr}$ (suoer-K) not far away?

$\sin^2\theta_W(m_Z) = 0.233 - 0.0007\ln(m_{susy}/1\text{TeV})$

$\sin^2\theta_W(m_Z)^{exp} = 0.23125$ (favors $m_{susy} \sim 10\text{TeV}$)

take with a grain of salt!

LHC/ Proton Decay Complementarity

LHC tension with m_{susy} ~ 1 TeV (squarks & gluinos)

SUSY GUTS prefer heavier $m_{susy} \approx 3\text{-}10\,TeV$

Heavier m_{susy} → shorter $\tau(p \rightarrow e^+\pi^0) \approx (1TeV/m_{susy})^{8/15} x 10^{35\pm1} yr$

Heavier m_{susy} makes $p \rightarrow e^+\pi^0$ easier to observe!

but it makes direct SUSY at the LHC less likely

Together They Squeeze SUSY

Almost a No Lose Theorem

LBNE vs SuperK

- SuperK 22.5Kton Fiducial Vol. H_2O Cerenkov
  will have run 20 yrs before LBNE starts ~ 400Kton-yr
  LAr advantage factor ***3-5*** (use $\mathbf{p \rightarrow e^+\pi^0 + n \rightarrow e^+\pi^-}$)
  lower backgrounds? Etc.

  LBNE 34Kton LAr x10yr ~ m_{GUT} =10^{16}GeV sensitivity!
  Roughly equivalent to 100-200Kton water

Summary

EDMs extremely well motivated by possible CP violation in Hγγ and possible heavy m_{susy} should be pushed as far as possible

a_μ 3.6 sigma discrepancy SUSY or something else (dark photon)?

Primary LBNE Goal: CP violation in ν oscillations

Proton Decay has Similar Detector Requirements (Fortuitous)

Heavier m_{SUSY} makes proton decay discovery more likely!

Start as soon as possible

"***He who hesitates is lost***"