How Top quark dipole moments affect Higgs decay

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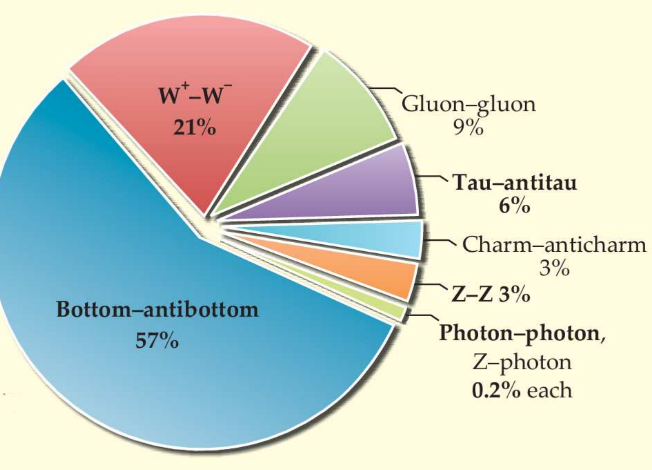
arXiv:1209.1046, arXiv:1210.3150

Higgs 2-photon decay: small fraction but important



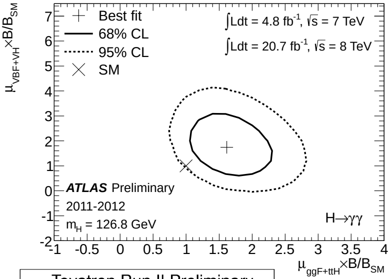
- proves that new particle is boson (spin-0 or spin-2)
- clean signature: helped statistics to achieve discovery

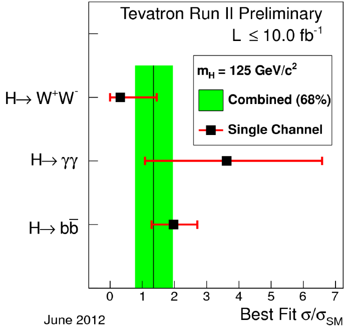
⇒ good place to look for more precise measurements in future runs

Sept 2012, Physics Today

What can we learn from the 2-photon channel?

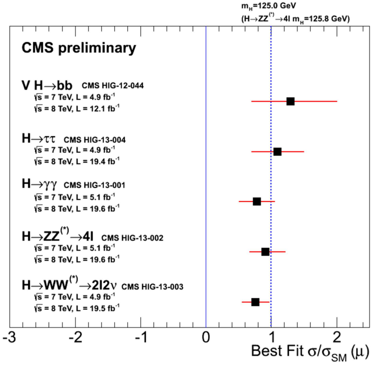
SM-like Higgs, but enhanced 2γ channel





Signal strength:

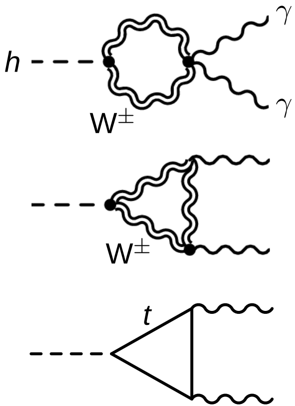
$$\mu = \frac{\sigma_{\rm exp}(h \to 2\gamma)}{\sigma_{\rm th}(h \to 2\gamma)}$$



CMS, TWiki

Higgs 2 photon decay sensitive to top properties

Dominant contributions from W and top loops



$$A_{\text{tot}}(h \to \gamma\gamma) \simeq A_W + A_t$$

- W loop numerically larger and constrained by electroweak precision

- top loop has opposite sign, meaning destructive interference with W loop

small change in A_t can mean big change in $|A_{\text{tot}}|^2$

Combined with constraints on W, **precision measurement of $h \to \gamma\gamma$ yields information on top-higgs system**

Outline

1. Why look at top quark
2. How we can look at top today: Higgs 2γ decay
3. top quark magnetic moment effect on higgs decay
4. Where else to look for top magnetic moment
5. top quark chromomagnetic moment and two gluon decay

Top quark, on the record

Within Standard Model the top quark is ... [PDGLive, 2012]

- Point-like Dirac fermion
- electromagnetic charge $Qe = +(2/3)e$
  known from $t \to bW$ decay
- Mass: $m_t = 173.5\,\mathrm{GeV}$
- Large width $\Gamma_t = 2\,\mathrm{GeV} \to$ considered to decay too quickly to acquire QCD dressing and/or form $t\bar{t}$ bound state
- remarkable minimal top-higgs coupling: $g_{ht} = \dfrac{m_t\sqrt{2}}{v} = 0.99$
  (Higgs vev $v = 246.2\,\mathrm{GeV}$)

Why the interest in top?

★ Highest mass particle measured:

$\Rightarrow$ closest to electroweak symmetry breaking scale $\sim$ 250 GeV–1 TeV

$\Rightarrow$ sensitive to Beyond Standard Model input:

1. quantum corrections (loops with higher mass particles) are least suppressed, depending on mass ratio $\dfrac{m_t}{M_{\mathrm{BSM}}}$

2. smallest Compton wavelength $\frac{1}{m_t}$, most sensitive to compositeness

compositeness = quarks are composed of other “smaller” particles, just as protons and neutrons are composed of quarks

Review of “top” opportunities: W. Bernreuther, J.Phys.G (2008)

Top can be very different from bare dirac fermion

1. Highest mass $\rightarrow$ especially sensitive to Beyond SM

2. large top-higgs coupling $\frac{g_{ht}^2}{4\pi} = \frac{1}{4\pi}\left(\frac{m_t\sqrt{2}}{v}\right)^2 \simeq 0.08$

   $\rightarrow$ possibly non-perturbative higgs-top system

   Harley, Soff, Rafelski, J.Phys.G G16 (1990); Froggatt, Nielsen et al. arXiv:0804.4506, arXiv:0810.0475, arXiv:0811.2089; K. Howe, UofA honors thesis

3. similar QCD coupling strength $\alpha_s(m_t) = 0.108$

(1)+(2)+(3) $\Rightarrow$ Possible large modifications of top properties

Top magnetic dipole moment

Dirac Current: $ie\bar{\psi}\gamma^\alpha\psi = \underbrace{\frac{-ie}{m}\bar{\psi}\overleftrightarrow{\partial}^\alpha\psi}_{} + \underbrace{\frac{ie}{m}\bar{\psi}\sigma^{\alpha\beta}(\overleftarrow{\partial}_\beta + \vec{\partial}_\beta)\psi}_{}$

Gordon decomposition $\rightarrow$ electric charge magnetic dipole

Pointlike dipole arises from spin

$$\sigma^{\alpha\beta} \equiv \frac{i}{2}[\gamma^\alpha, \gamma^\beta]$$

(Dirac spin matrix)

$$\mu_t = \frac{g}{2}\frac{Qe}{2m_t}$$

Gyromagnetic $g \rightarrow 2$ for Dirac fermions at tree-level

g controls spin coupling to field, as seen in "squared" Dirac equation

$$-\left(\gamma^5\left(\gamma_\mu\Pi^\mu - m\right)\right)^2\psi = \left(\Pi^2 - m^2 - \frac{g_D = 2}{2}\frac{e\sigma_{\mu\nu}F^{\mu\nu}}{2}\right)\psi = 0$$

$\Pi = i\partial - eA$ = hermitian momentum operator

More on Dipole Moments

- Electric dipole, $d_t < 10^{-6}\mu_t$ ... Here consider $d_t \to 0$

Kamenik et al. PRD **85** 071501 (2012)

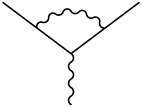
- analogous QCD moments, Chromomagnetic g^c, chromoelectric

Decomposing current $$ie\bar{\psi}\gamma^{\alpha}\psi = \underbrace{\frac{-ie}{m}\bar{\psi}\overleftrightarrow{\partial}^{\alpha}\psi}_{\text{electric}} + \underbrace{\frac{ie}{m}\bar{\psi}\sigma^{\alpha\beta}(\overleftarrow{\partial}_{\beta} + \vec{\partial}_{\beta})\psi}_{\text{magnetic dipole}}$$

... and studying conservation taking ∂_{α}, you find:

Currents are independently conserved
$\Rightarrow$ independent values of charge Qe and dipole moments μ_t, d_t

- Recall quantum corrections generating (effective) lepton $g-2$:



$$\Rightarrow \quad g - 2 = \alpha/\pi + \ldots$$

top $g - 2$ can be large

★ Strongly coupled in two sectors:

a. QCD $\alpha_s(m_t) = 0.108$

b. higgs coupling $\frac{g_{ht}^2}{4\pi} \simeq 0.08$

1-loop estimate

$$g = g_D + \text{q. corrections}$$
$$\simeq 2 + \frac{\alpha}{\pi} + \frac{4}{3}\frac{\alpha_s}{\pi} + \text{E.W.} + \text{higgs}\ldots$$

Example: 2-loop QCD contribution nearly as large as 1-loop

Bernreuther, et al., Nucl. Phys. **B706** 245 (2005), PRL **95** 261802 (2005)

★ Constraints from radiative decay $b \to s\gamma$

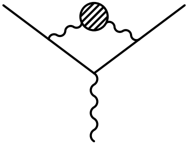
$$-3.49 < g < 3.59$$

Hewett & Rizzo PR **D49** 319 (1994)
Kamenik et al. PRD **85** 071501 (2012)

★ Beyond Standard Model contributions?

Especially with composite structure $g - 2$ can be large

$g-2, g^c-2$ sensitive to BSM input: Examples



1. Beyond Standard Model particles

in loop corrections

2. compositeness $\frac{g-2}{2} \sim \frac{m_t}{M_{\rm comp}}$ Brodsky & Drell PR **D22** 2236 (1980)

Compare proton $\mu_p = 2.79\frac{e}{2m_N} \quad \Rightarrow g = 5.58$

neutron $\mu_n = -1.91\frac{e}{2m_N} \quad \Rightarrow g = -3.82$

Much Theory and experimental study of top dipole moments:

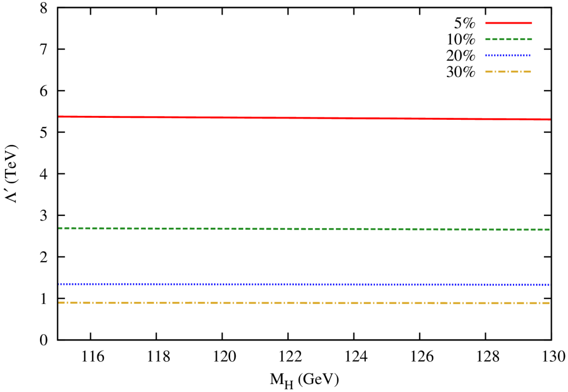
Atwood & Soni PR **D45** 2405 (1992); Atwood et al. PR **D52** 6264 (1995); Haberl et al. PR **D53** 4875 (1996); Hioki & Ohkuma EPJ **C65** 127 (2010); Martinez et al. EPJ **C53** 221 (2008); Larkoski & Peskin PR **D83** 034012 (2011); Kamenik et al. PRD **85** 071501 (2012)

Describing top magnetic moment, 1

Studying g very different from 2 is challenging for theory

One approach:

- Perturbatively evaluate $h \to \gamma\gamma$ with higher dimension ($n > 4$) $g-2$ operator: $\frac{1}{\Lambda}\bar{\psi}e\sigma_{\mu\nu}F^{\mu\nu}\psi$
- Correlate % change in rate with scale Λ



Choudhury & Saha [arXiv:1201.4130]

Describing top magnetic moment, 2

Do better with a theory seeing g-factor as independent parameter

$$\mathcal{L}_{\text{eff}} = \bar{\psi}\left(\Pi^2 - m^2 - \frac{g}{2}\frac{e\sigma_{\mu\nu}F^{\mu\nu}}{2}\right)\psi$$

For Second-order fermion theory the magnetic moment is:

• *renormalizable* interaction – can be resummed nonperturbatively

$\rightarrow$ important in case $g - 2$ is “large”, $\mathcal{O}(1)$

• suitable to study vacuum fluctuations with arbitrary g

• equivalence to first-order theory for $g = 2$ and to scalar electrodynamics for $g = 0$

Long, continuous study: used by Schwinger for effective action, Phys Rev **82**, 664 (1951); studied by Feynman Phys Rev **84**, 108 (1951); Feynman and Gell-Mann Phys Rev **109**, 193 (1958); A. G. Morgan, Phys. Lett. B **351**, 249 (1995); Veltman Acta Phys. Polon. B **29**, 783 (1998); top quark amplitudes, Larkoski & Peskin PRD **83**, 034012 (2011); perturbative QED, Napsuciale et al. Eur. Phys. J. **A 29**, 289 (2006), PRD **83** 073001 (2011), PRD **85** 076004 (2012); effective action of $g = 1$ theory, Labun & Rafelski PRD **86** 041701 (2012)

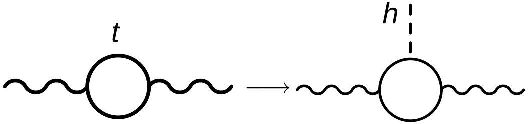
Higgs 2 photon decay: Low energy theorem

Vainshtein, et al. Sov. J. Nucl. Phys. **30**, 711 (1979)

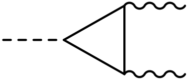
Ellis et al., Nucl. Phys. B **106**, 292 (1976)

1. For $m_t \gg m_h$, dynamical h field approximately constant:
Then effect of $h\bar{\psi}\psi$ interaction is $m_t \to m_t + \frac{h}{v} m_t$

2. Expand QED vacuum polarization $-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \frac{b_t \alpha}{4\pi} \ln \frac{m_t^2}{\Lambda^2}$ to order h



b_t is top contribution to QED β function

$A_t =$  $\simeq b_t \frac{1}{v} \frac{\alpha}{4\pi} (k_1^\kappa \epsilon_1^\lambda - k_1^\lambda \epsilon_1^\kappa)(k_2^\kappa \epsilon_2^\lambda - k_2^\lambda \epsilon_2^\kappa)$

Compare to loop calculation with $m_h \simeq 126\ \mathrm{GeV}$: $\dfrac{A_t(\text{loop calc})}{A_t(\text{low energy})} = 1.03$

Generalizing b_t with arbitrary g

In external field method, compute effective potential and find coefficient of term proportional to $F^{\mu\nu}F_{\mu\nu}$.

$$V_{\text{eff}} = \frac{N_c}{8\pi^2}\int_0^\infty \frac{du}{u^3} e^{-i(m^2-i\epsilon)u} \left(\frac{Qe|\vec{B}|u \cos(\frac{g}{2}Qe|\vec{B}|u)}{\sin(Qe|\vec{B}|u)} - 1 \right) \quad -2 \leq g \leq 2$$

adapting Schwinger's proper time method with $g \neq 2$

Schwinger, PR **82** 664 (1951); Labun & Rafelski, PRD **86** 041701 (2012)

Include factors N_c and $e \to Qe$ for quark colors and top electric charge

$$b_t = -\frac{4}{3}N_c Q^2 \left(\frac{3}{8}g^2 - \frac{1}{2} \right)$$

Extension to $|g| > 2$ is periodic from the base domain $-2 \leq g \leq 2$

preserves unitarity and Lorentz invariant vacuum in external field

Rafelski & Labun arXiv:1205.1835

b_t as function of g

Perturbative[1] and external field[2] methods agree $-2 \leq g \leq 2$

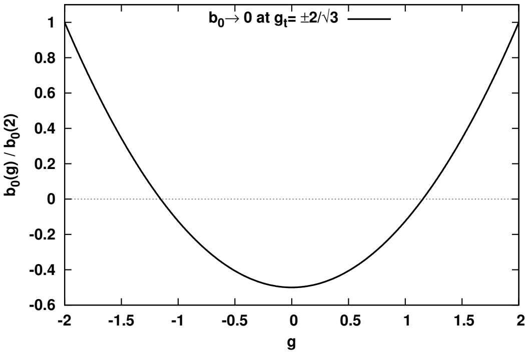
$$b_t(g) = -\frac{4}{3} N_c Q^2 \left(\frac{3}{8} g^2 - \frac{1}{2} \right)$$

$-4/3 =$ Dirac $g \to 2$ value

$N_c = 3 \qquad Q = +2/3$

- sign change at $g = \pm 2/\sqrt{3}$
- $g = 0$ agrees with scalar QED
- periodic[2] for $|g| > 2$

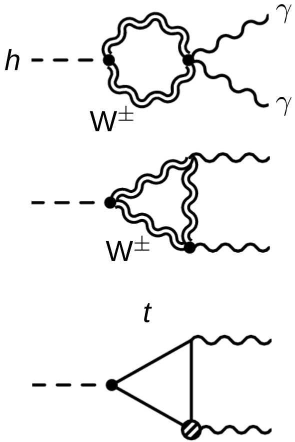
$\Rightarrow b_t$ maximum for $g = \pm 2, \pm 6 \ldots$



[1] Angeles-Martinez & Napsuciale PRD (2012); [2] Rafelski & Labun arXiv:1205.1835

Higgs 2 photon decay via top and W

Dominant contributions from W and top loops



$$A_{\rm tot}(h \to \gamma\gamma) \simeq A_W(h \to \gamma\gamma) + A_t(h \to \gamma\gamma)$$

- W loop numerically larger

$$\frac{A_W}{A_t} \simeq \frac{b_W}{b_t} = \frac{7}{-16/9} = -3.94$$

(ratio of β function coefficients)

- top loop opposite in sign

$\Rightarrow$destructive interference with W

Observed that changing sign of A_t alleviates tension

Giardino, et al. arXiv:1207.1347

$h \to \gamma\gamma$ Amplitude as function of g

Plug $b_t(g)$ into $A_{\rm tot}(h \to \gamma\gamma) \simeq A_t + A_W$

with loop result for A_W: $f_W(x) = 3x(2-x)\left(\arcsin(\frac{1}{\sqrt{x}})\right)^2 + 3x + 2$

$$x = 4m_W^2/m_h^2 = 1.641$$

$$m_W = 80.3\ \mathrm{GeV}$$

$$m_h = 125.5\ \mathrm{GeV}$$

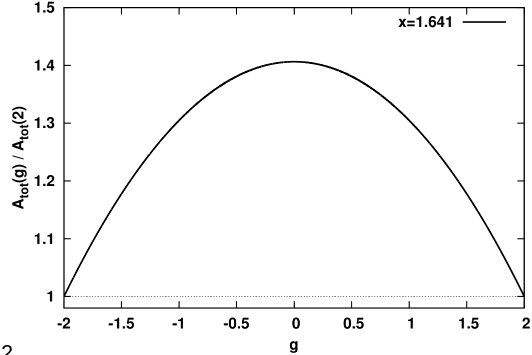
periodic extension to $|g| > 2$

$\Rightarrow$ amplitude *smallest* at $g=2$

(robust qualitative prediction)

Decay rate = (total amplitude)^2

$$\frac{\Gamma(g)}{\Gamma(2)} = \frac{|A_t(g) + A_W|^2}{|A_t(2) + A_W|^2}$$



Labun & Rafelski arXiv:1209.1046

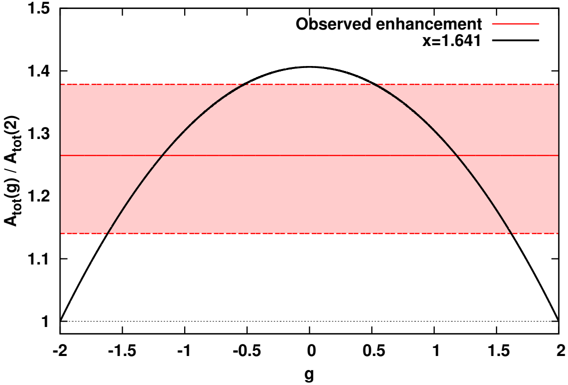
Max @ $g = 0$, $\frac{\Gamma(0)}{\Gamma(2)} = 1.98$

Decay Amplitude as function of g

For $m_h = 125.5\,\mathrm{GeV}$

Compatible with other constraints
$-3.49 < g < 3.59$

Decay rate
$$\frac{\Gamma(g)}{\Gamma(2)} = \frac{|A_{\mathrm{tot}}(g)|^2}{|A_{\mathrm{tot}}(2)|^2}$$



Examples:

meta analysis[†] central value $\sigma/\sigma_{\mathrm{SM}} = 1.6 \Rightarrow g = \pm 1.18, \pm 2.82$

lower end of 1 s.d. range $\sigma/\sigma_{\mathrm{SM}} = 1.3 \Rightarrow g = \pm 1.62, \pm 2.82$

[†] Giardino, et al. arXiv:1207.1347

Where else to look for top $g - 2$

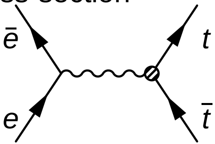
1. Improvements in $b \to s\gamma$ from Super B factories

Kamenik et al PRD (2012), Hewett et al. arXiv:hep-ph/0503261

2. $e\bar{e} \to t\bar{t}$ production, for example at future Linear Collider

see top electromagnetic properties in production cross-section

Atwood & Soni, PRD 45, 2405 (1992)

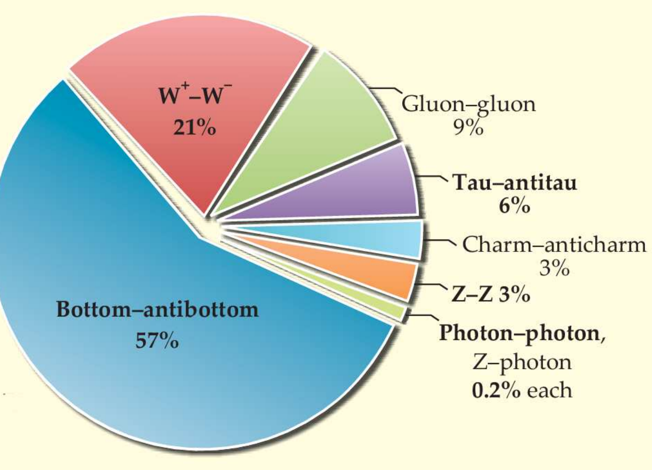


3. Also discussed: $t\bar{t}$ production at $\gamma\gamma$ collider

Grzadkowski et al. Acta Phys. Polon. B 36 (2005)

4. Seek theory relation between electromagnetic g and QCD g^c
(Next: opportunity to measure chromomagnetic moment g^c at LC)

Higgs 2-gluon decay: a larger part of the pie



45 times larger branching ratio than photon-photon

may be harder to measure precisely due to QCD backgrounds

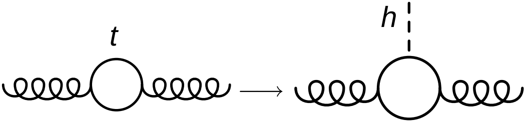
Sept 2012, Physics Today

Higgs 2 gluon decay: Low energy theorem

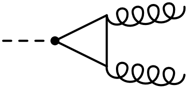
Vainshtein, et al. Sov. J. Nucl. Phys. **30**, 711 (1979); Vainshtein et al. Sov. Phys. Usp. **23**, 429 (1980); Voloshin, Sov. J. Nucl. Phys. **44** 478 (1986); Dawson, Nucl. Phys. B **359**, 283 (1991)

1. For $m_t \gg m_h$, dynamical h field approximately constant:
Then interaction $H\bar{\psi}\psi \to (m_t + \frac{h}{v}m_t)\bar{\psi}\psi$

2. Expand QCD vacuum polarization $\Rightarrow$



amplitude depends on b_t^c = top contribution to QCD β function

$A_t =$  $\xrightarrow{m_t \gg m_h} \quad A_t^{(\mathrm{LE})} = b_t^c \frac{1}{v}\frac{\alpha_s}{4\pi}(k_1^\kappa \epsilon_1^\lambda - k_1^\lambda \epsilon_1^\kappa)(k_2^\kappa \epsilon_2^\lambda - k_2^\lambda \epsilon_2^\kappa)$

For $m_h \simeq 126\ \mathrm{GeV}$, Low Energy very good approximation $\dfrac{A_t}{A_t^{(\mathrm{LE})}} = 1.03$

b_t^c as function of g^c

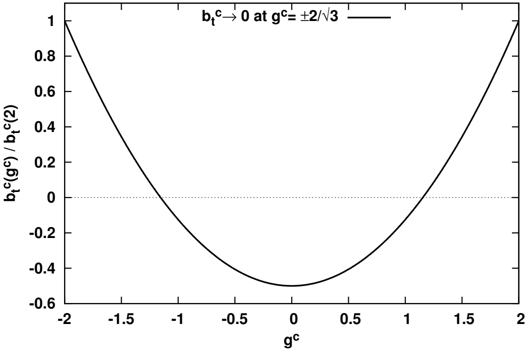
Compute using background field method

Nielsen & Olesen, Nucl. Phys. B **144**, 376 (1978)

$$b_t^c(g^c) = -\frac{2}{3}\left(\frac{3}{8}(g^c)^2 - \frac{1}{2}\right)$$

$-2/3$ is ($g^c \to 2$) value

- sign change at $g^c = \pm 2/\sqrt{3}$

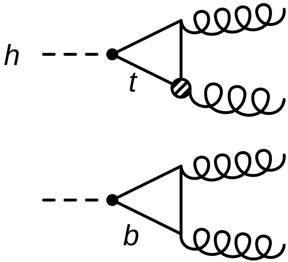


Standard Model perturbative evaluation: $g^c - 2 = -5.6 \times 10^{-2}$

Martinez, Perez, Poveda, Eur. Phys. J. C **53**, 221 (2008)

Higgs 2 gluon decay: interference

Dominant contributions from top and bottom loops



$$A_{\mathrm{tot}}(h \to gg) \simeq A_t^{(\mathrm{LE})} + A_b$$

$$\frac{A_b}{A_t^{(\mathrm{LE})}} = \frac{f(4m_b^2/m_h^2)}{b_t^c} = -0.06$$

- bottom loop opposite in sign

$\Rightarrow$ destructive interference with top

- bottom $g^c - 2$ expected smaller

- $b_t^c(g^c) \ \leq \ b_t^c(2)$: A_t reduced when $g^c < 2$ (SM expectation)

Top supplies most of the amplitude $\Rightarrow$
reducing top suppresses total amplitude

Triangle function: $f(x) = x - \frac{x-x^2}{4}\left(\ln \frac{1+\sqrt{1-x}}{1-\sqrt{1-x}} - i\pi\right)^2$

Dawson, Nucl. Phys. B **359**, 283 (1991)

$h \to gg$ rate as function of g^c

$$A_{\rm tot}(h \to gg) \simeq A_t^{(\rm LE)} + A_b \quad \text{with} \begin{cases} A_t^{(\rm LE)} & \text{low energy theorem with } b_t^c(g^c) \\ A_b \to & \text{loop result} \end{cases}$$

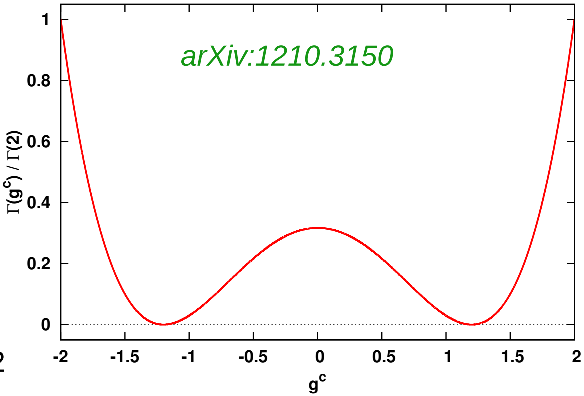
$$m_b = 4.65\ \mathrm{GeV}$$

$$m_h = 125.5\ \mathrm{GeV}$$

Decay rate Γ suppressed

$$\frac{\Gamma(g^c)}{\Gamma(2)} = \frac{|A_t(g^c) + A_b|^2}{|A_t(2) + A_b|^2}$$

amplitude *largest* at $g^c = 2$



SM expected $g^c - 2 = -0.06$ implies 9% suppression

Why look at Higgs 2-gluon decay

★ If there is compositeness, then g and g^c would be different from 2, because constituents must have both QED and QCD charge

★ 2 gluon($\rightarrow$ jet) signature distinguishable from 4 gluon, 6 gluon, etc.

★ much lower QCD background at linear collider

★ 9% branching ratio and Large suppression from $g^c - 2$ possible

★ Measurement challenging at hadron collider: unique opportunity for linear collider to do better at measuring top QCD coupling

Summary

- top quark may be very different from bare Dirac fermion
  due to SM and BSM input $\rightarrow$ large anomalous magnetic moment
  $g-2$

- Higgs 2-photon decay sensitive to top $g-2$
  2-gluon decay sensitive to chromomagnetic moment g^c-2

- Robust theory prediction to be tested: Any $g \neq 2$ implies
  enhancement of higgs decay rate
  (increased as much as factor 2 for $g \rightarrow 0$)

- at Linear Collider, cleaner environment to study 2-gluon decay
  provides unique opportunity to measure top anomalous
  chromomagnetic moment

Summary of experiment

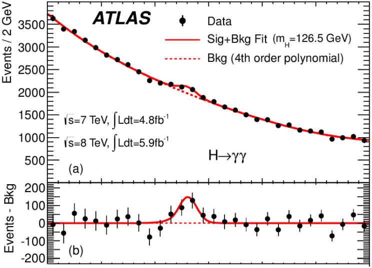
Then a Higgs-like particle drops in...

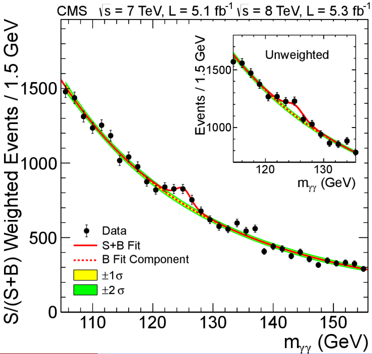
$$m_h = \begin{cases} 126.0 \pm 0.8 \text{ GeV} & \text{ATLAS} \\ 125.3 \pm 0.9 \text{ GeV} & \text{CMS} \end{cases}$$

★ 4-lepton (via ZZ, WW) decays
★ 2-photon decays
(via top and W loops)

⇒ cross-sections at order of magnitude of Standard Model expectation

- ATLAS, arXiv:1207.7214
- CMS, arXiv:1207.7235



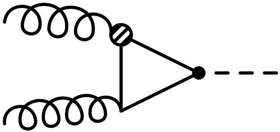


Higgs Production also a function of g^c of top

Hadron colliders, higgs production dominated by gluon fusion:

$\sim$ 80% $gg \to h$ via top loop

$\sim$ 20% other: gluon fusion via bottom loop, vector boson fusion and associated production



In low-energy limit $m_h \ll m_t$:

$$A_{\mathrm{prod}}(gg \to h) \simeq b_t^c \frac{1}{v} \frac{\alpha_s}{4\pi} (k_1^\kappa \epsilon_1^\lambda - k_1^\lambda \epsilon_1^\kappa)(k_2^\kappa \epsilon_2^\lambda - k_2^\lambda \epsilon_2^\kappa)$$

$b_t^c =$ top contribution to QCD β function

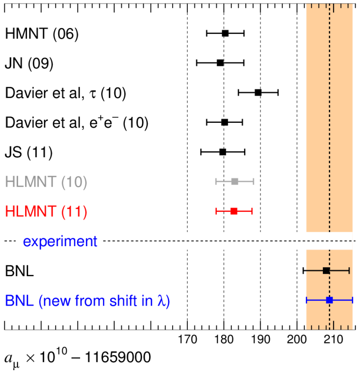
Why $g-2$ needs attention: challenge in the muon

Physical leptons measured $g > 2$:

Hadronic corrections to muon g-factor

$$\left(\frac{g-2}{2}\right)_{\text{had,vac.pol.}} \simeq +17.9\ 10^{-10}$$

$$\left(\frac{g-2}{2}\right)_{\text{had,LbL}} = +(116 \pm 40)\ 10^{-11}$$



Venanzoni, LC 2011, arXiv:1203.1501 [hep-ex]

★ for muon $2.2-3$ std. dev. discrepancy

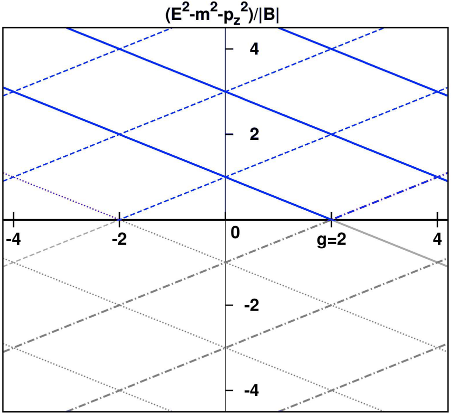
(Muon G-2 Collaboration, PRD 2006; Jegerlehner & Nyffler, Phys Rpt 2009)

Spectrum Periodicity in g

Eigenvalues $E_n = \pm\sqrt{m^2 + p_z^2 + Q|e\vec{B}|(2n+1) \mp \frac{g}{2}|e\vec{B}|}$ $\quad Q = \pm 1$

- Even in g required by C-symmetry
- New states ($Q = -1$) rise into $E_n^2 > 0$ for $|g| > 2$

Want to preserve:
1) unitarity (keep number of states the same)
2) Lorentz invariant vacuum state (no localized states with $E_n^2 < m^2$)



Solution: keep only states with $E_n^2 \geq m^2$
Structure of energy levels periodic in g