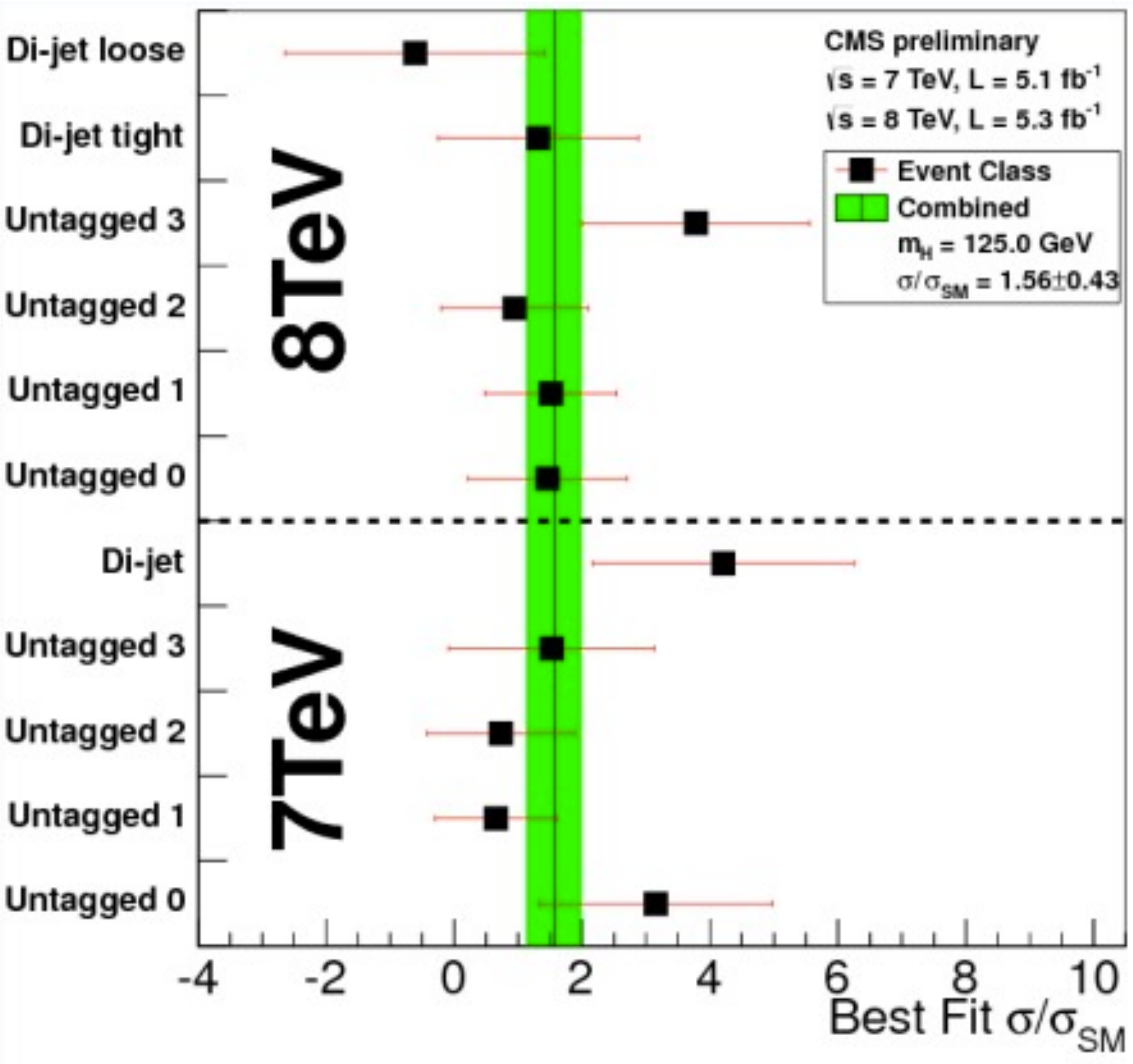
Implications of a Diphoton Excess in Light of Previous Data

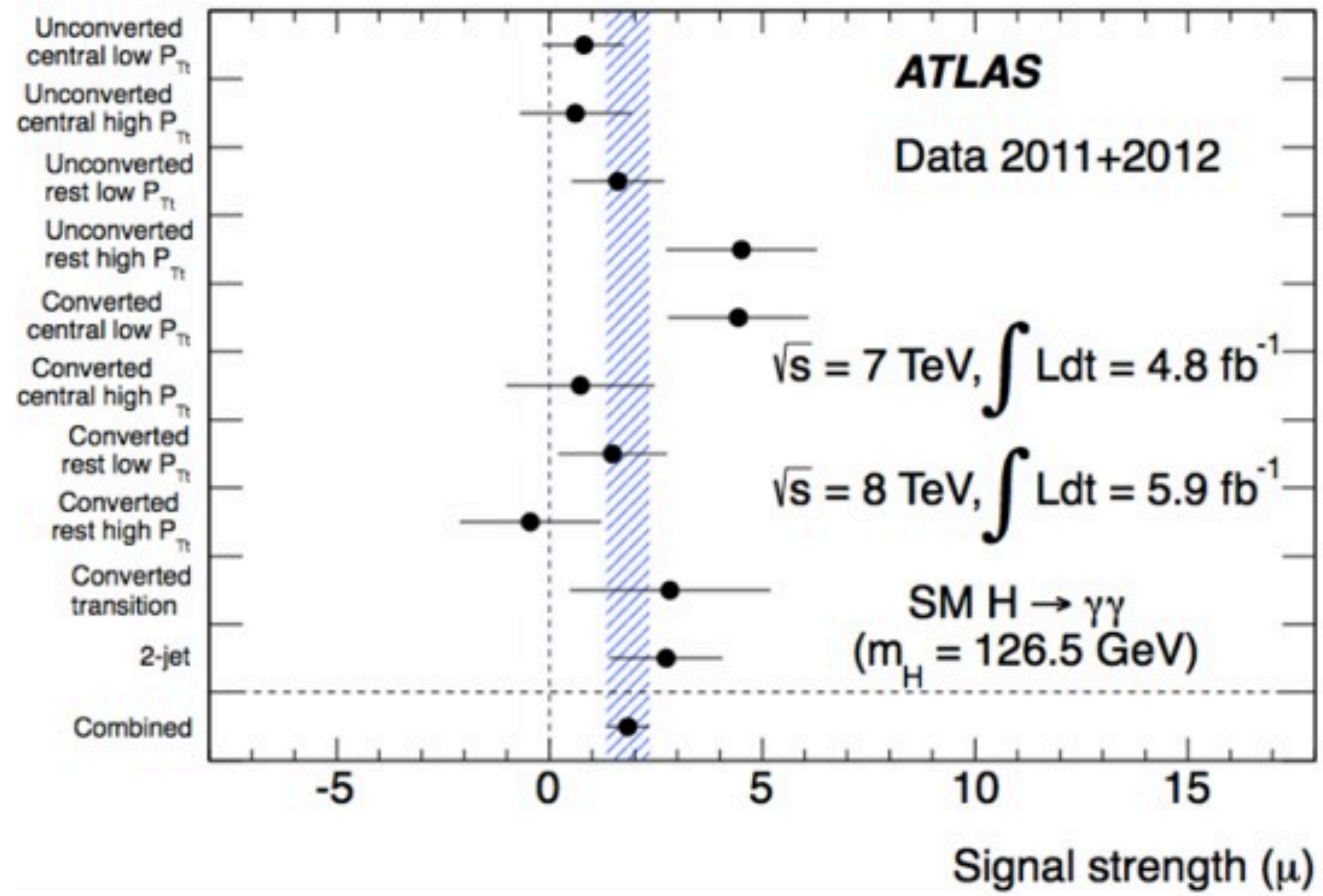
Patrick Draper

University of California, Santa Cruz

Chicago 2012 Workshop on LHC Physics

The Data





CMS $\gamma\gamma$ rate 1.56±0.43 x SM

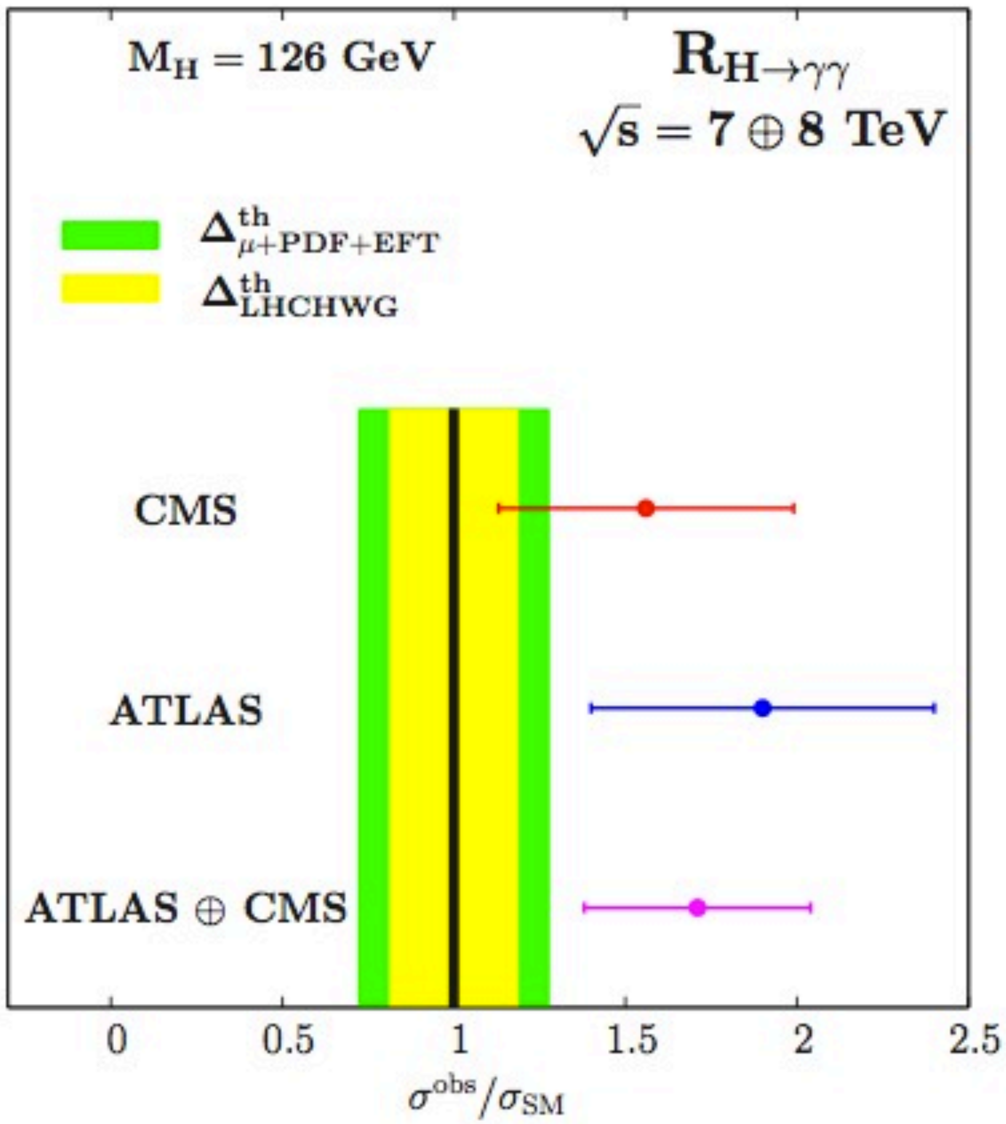
ATLAS $\gamma\gamma$ rate 1.9±0.5 x SM

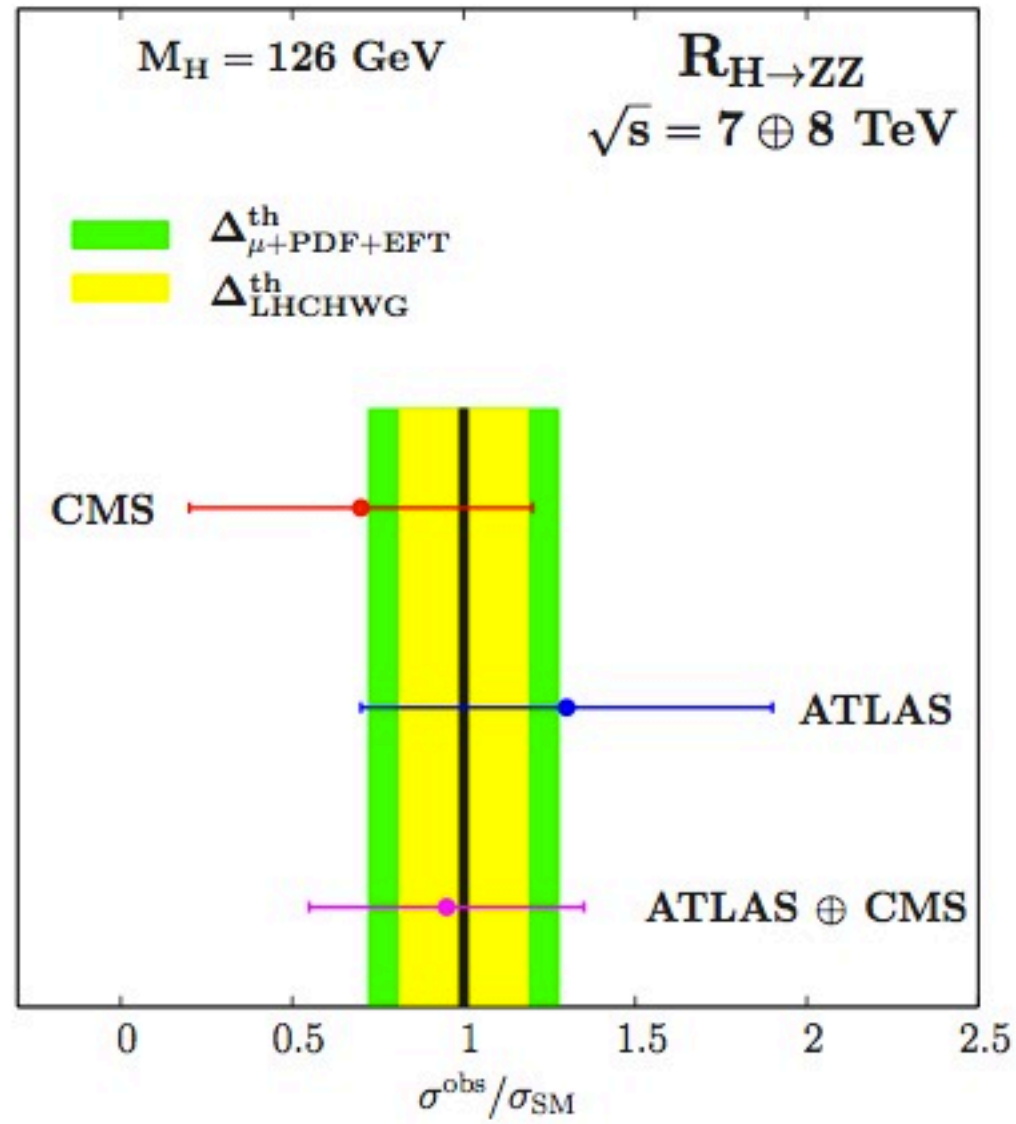
Naive (uncorrelated, Gaussian) combination of $\gamma\gamma$ rates: 1.7±0.3 (Moriond: 2.1±0.5)

What is causing this enormous excess?

Theory Uncertainty?

Baglio, Djouadi, Godbole





Adding theory errors linearly & treating as bias rather than nuisance can bring combined $\gamma\gamma$ fit to within 1.3σ of SM

Broadly speaking, most new-physics proposals for increasing the inclusive $h \to \gamma\gamma$ rate use one/both of these mechanisms:

• New sources of EWSB modify SM couplings that appear in the rate:

-h coupling to W > $2m_W^2/(246\text{ GeV})$ (need doubly charged Higgs. also increases $h \to WW$, $Vh \to bb$)
-h coupling to b < $\text{Sqrt}(2)m_b/(246\text{ GeV})$ (decreases $h \to bb$, increases other rates)

• New states contribute to production and/or decay:

-increase $\sigma \times BR$ with new loops of charged particles (stops with small mixing, staus with large mixing, W', vectorlike charged matter with negative coupling to Higgs portal, vectorlike colored matter with positive coupling to Higgs portal......)

Carena, Gori, Shah, Wagner, Wang; Joglekar, Schwaller, Wagner; Heinemeyer, Stal, Weiglein;
Carena, Low, Wagner; Arkani-Hamed, Blum, D'Agnolo, Fan; etc...

-new final states that look like $\gamma\gamma$ (degenerate Higgs families, $h \to aa \to$ photon jets)

Dobrescu, Landsberg, Matchev; Batell, McKeen, Pospelov; Draper, McKeen; Ellis, Roy, & Scholtz; etc....

The h++ model is an example that uses both mechanisms: direct increase of W coupling through new sources of EWSB, and h++ also appears in the $h \to \gamma\gamma$ decay loop

(Georgi, Machacek 1985; Low, Rattazzi, Vichi 2001; Chang, Newby, Raj, Wanotayaroj 2012)

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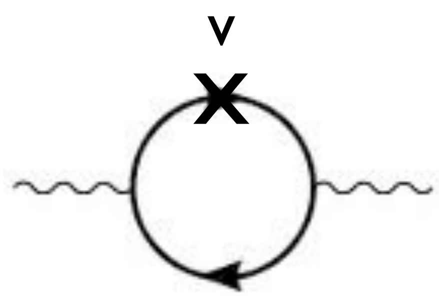
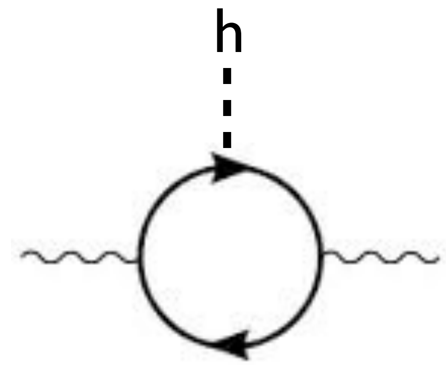
Modifying σ×BR with new particles X in loops

In the limit that $m_h \ll 2m_X$
and h is aligned with v,



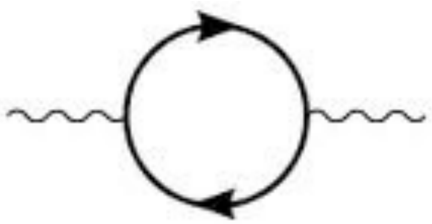
Vacuum Polarization

=

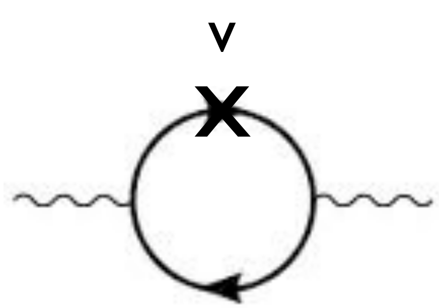


hFF effective coupling

× v



$\sim \Delta\beta \log m_X$, so



$$= \frac{\Delta\beta}{16\pi^2} \frac{\partial \log m_X^2(v)}{\partial \log v}$$

where $\Delta\beta$ is the shift in the EM or QCD beta function generated by X

from multiple X thresholds, get

$$\boxed{\frac{\Delta\beta}{16\pi^2} \frac{\partial \log \det \mathcal{M}_X^2(v)}{\partial \log v}}$$

for the effective hFF, hGG couplings

$$\frac{\Delta\beta}{16\pi^2}\frac{\partial \log \det \mathcal{M}_X^2(v)}{\partial \log v}$$

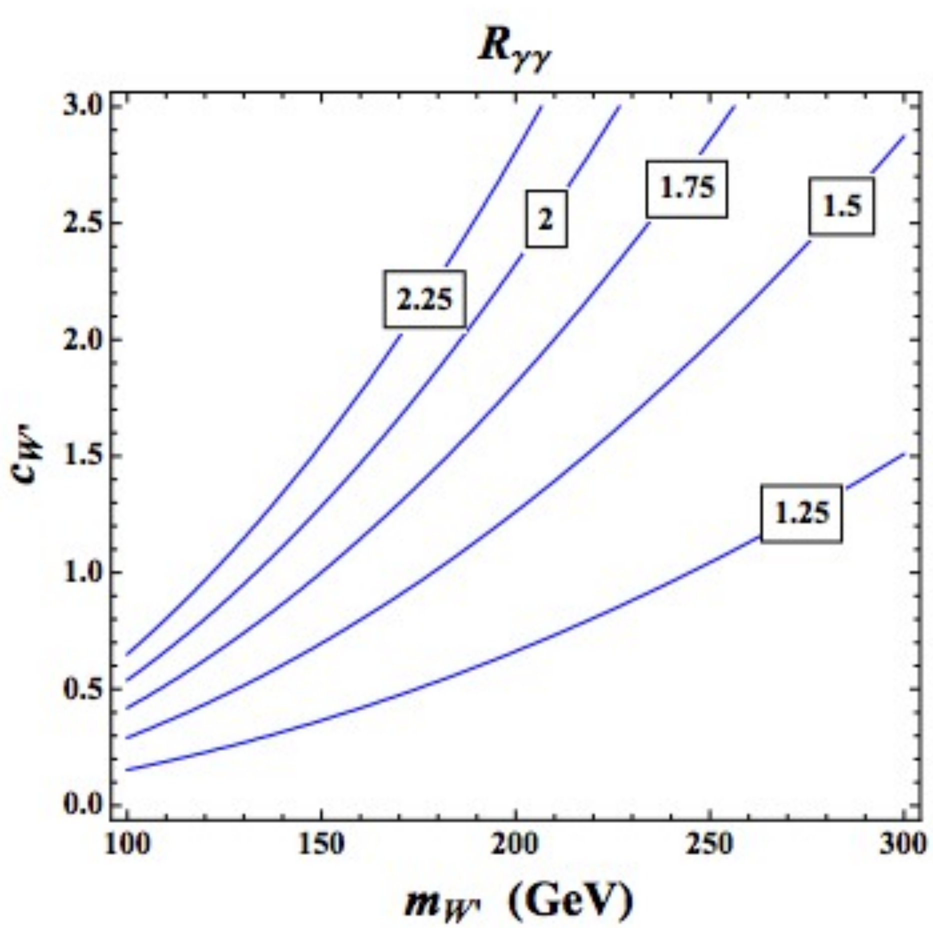
SM: top loop generates hGG coupling and hΓΓ coupling,
W gives ~4x larger contribution to hΓΓ with opposite (negative) sign

To enhance gluon fusion, easiest to have constructive interference with top loop, for example, stops with small mixing

To enhance γγ width, easiest to have constructive interference with W loop ⇒ negative coupling

Negative delta beta,
positive derivative? W'

need light W', suppressed couplings to SM fermions, HHW'W' coupling of order the SU(2) gauge coupling



Carena, Low, Wagner

$$\frac{\Delta\beta}{16\pi^2}\frac{\partial \log \det \mathcal{M}_X^2(v)}{\partial \log v}$$

To enhance γγ width, easiest to have constructive interference with W loop ⇒ negative coupling

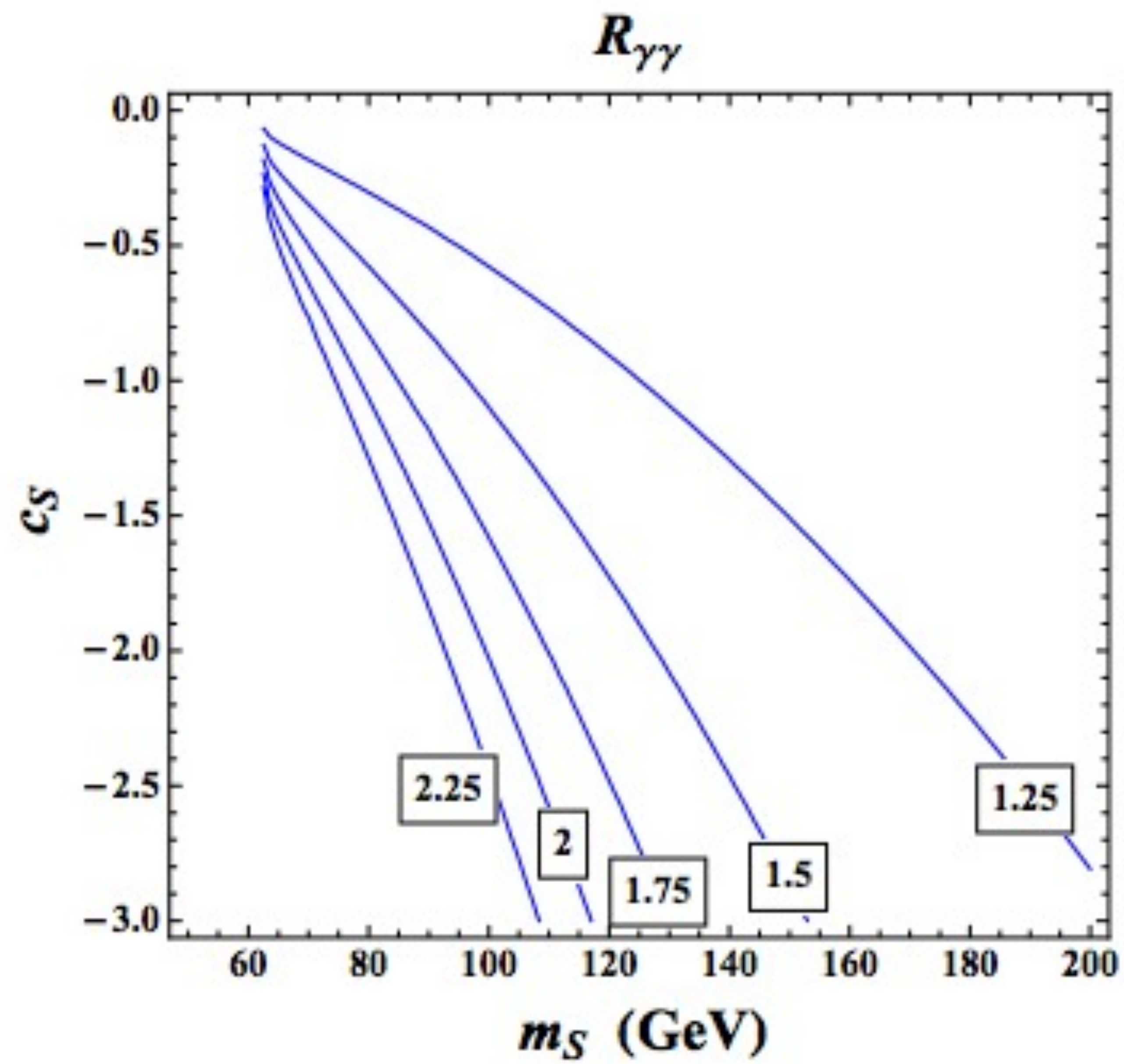
Positive delta beta, negative derivative?
scalar or fermionic matter where $m^2 \sim m_0^2 - |\lambda| v^2 \ll m_0^2$

singlet scalar with negative Higgs portal coupling?

$$\mathcal{O}_S = c_S H^\dagger H\, |S|^2$$

Factor ~10 smaller beta coefficient than W'

Large negative couplings can drive vacuum instabilites unless singlet quartic is also large



Carena, Low, Wagner

$$\frac{\Delta\beta}{16\pi^2}\frac{\partial \log \det \mathcal{M}_X^2(v)}{\partial \log v}$$

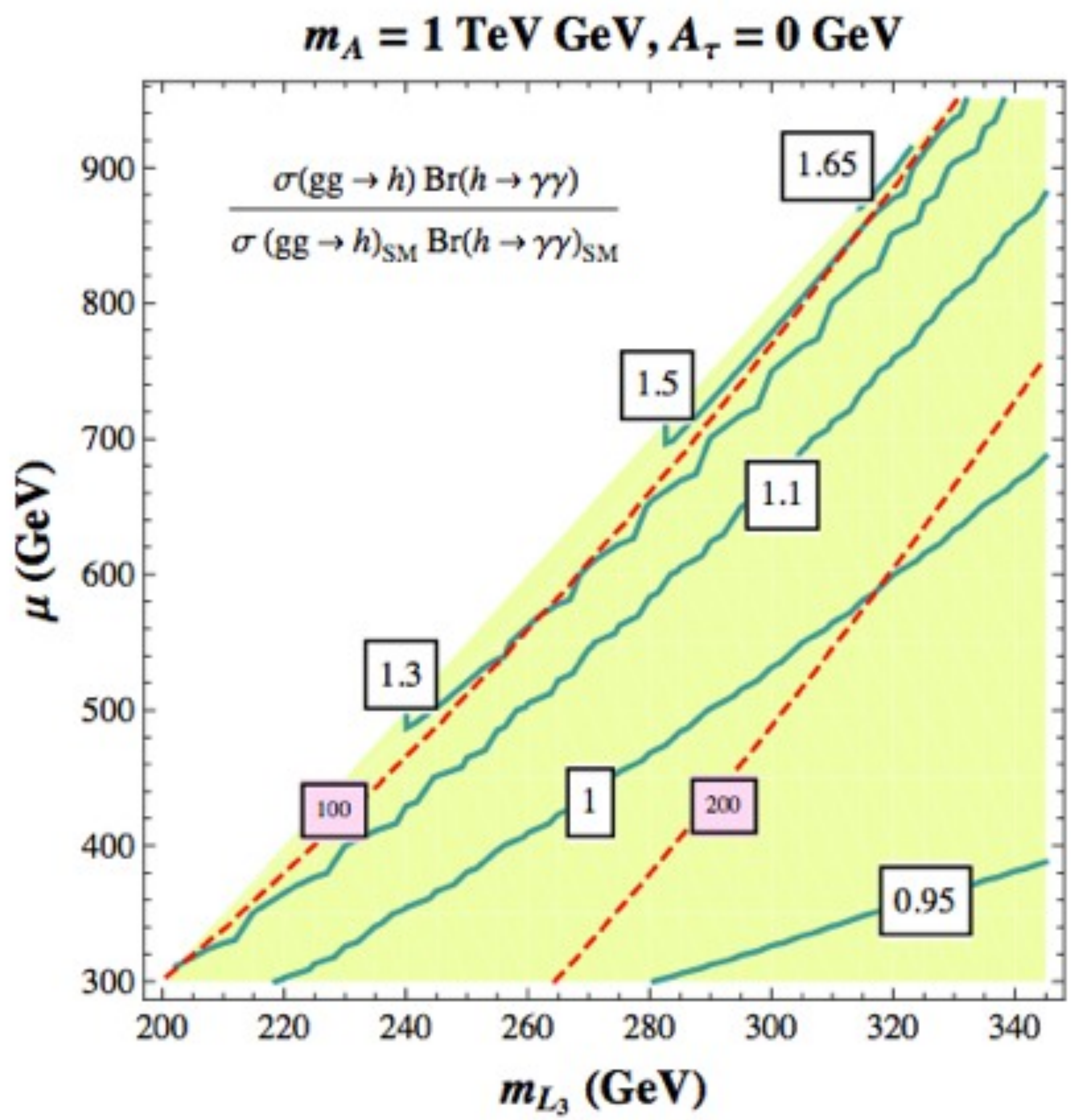
To enhance γγ width, easiest to have constructive interference with W loop ⇒ negative coupling

Positive delta beta, negative derivative?

scalar mixing can also effectively achieve this, eg, staus

Carena, Gori, Shah, Wagner, Wang

$$\mathcal{M}_{\tilde{\tau}}^2 = \begin{pmatrix} m_{L_3}^2 + m_\tau^2 + D_L & m_\tau(A_\tau - \mu\tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & m_{e_3}^2 + m_\tau^2 + D_R \end{pmatrix} \approx \begin{pmatrix} m_{L_3}^2 & -y_\tau^{SM}\tan\beta\, v\mu \\ -y_\tau^{SM}\tan\beta\, v\mu & m_{e_3}^2 \end{pmatrix}$$



Need large mu*tan beta and stau just about ~100 GeV LEP bound

New final states that look like γγ

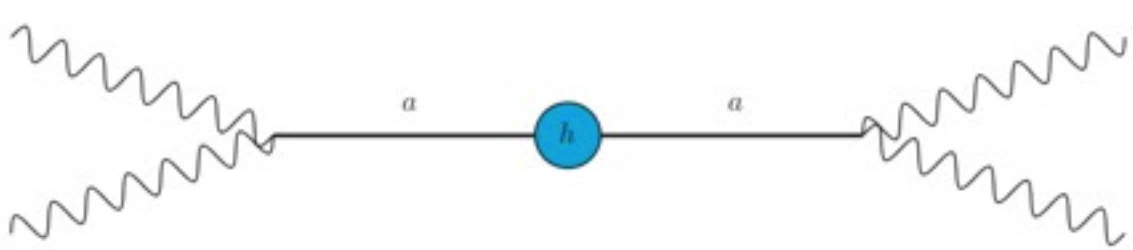
Mechanism proposed by Dobrescu, Landsberg, Matchev (2001):

$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^2} (\partial^\mu a)^2 H^\dagger H - \frac{e^2}{4M} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

given m_h, have 3 basic parameters, which we take to be $m_a, \; Br(h \to aa), \; M$

- $\Gamma(h \to aa) = 1.18 \text{ MeV} \left(\frac{m_h}{125 \text{ GeV}}\right)^3 \left(\frac{\Lambda}{\text{TeV}}\right)^{-4}$ ⇒ Br(h→aa) easily non-negligible;
- Br(a→γγ) can be non-negligible for light enough pseudoscalars;
- m_a/m_h<<1 (PNGB) ⇒ photon pairs are highly boosted and can look like single γ;

⇒ 4γ final state becomes effective γγ contribution



"Photon jets" also studied in
Toro & Yavin (Z' decays and fake violations of Landau-Yang thm)
Ellis, Roy, & Scholtz (distinguishing photons, photon jets, and QCD with jet substructure techniques)

DLM studied @ the Tevatron. Can this be happening now at the LHC?

Basic Requirements:
photon jets need to pass stringent π^0 rejection (controlled by m_a)
satisfy Higgs rate @ LHC (controlled by m_a and $Br(h \to aa)$)
survive LEP search and low-energy constraints (controlled by m_a and M)
decays happen within detector radius (controlled by m_a and M)

-viable parameter space exists
-UV completions are baroque

PD and D. McKeen 2012

Modifications to SM Branching Ratios

$$\mathcal{B}\left(h \to \gamma\gamma\right)_{\text{eff}} = R_{\gamma\gamma} \times \mathcal{B}_{\text{SM}}\left(h \to \gamma\gamma\right),$$
$$\mathcal{B}\left(h \to f\bar{f}, VV\right) = R_{XX} \times \mathcal{B}_{\text{SM}}\left(h \to f\bar{f}, VV\right)$$

$$R_{XX} = 1 - \mathcal{B}(h \to aa)$$ (just from increasing total width)

Assuming 100% $a \to \gamma\gamma$,

$$\mathcal{B}\left(h \to \gamma\gamma\right)_{\text{eff}} = \mathcal{B}\left(h \to \gamma\gamma\right) + \epsilon \times \mathcal{B}\left(h \to aa\right)$$

ϵ is the probability that 4γ is misidentified as 2γ

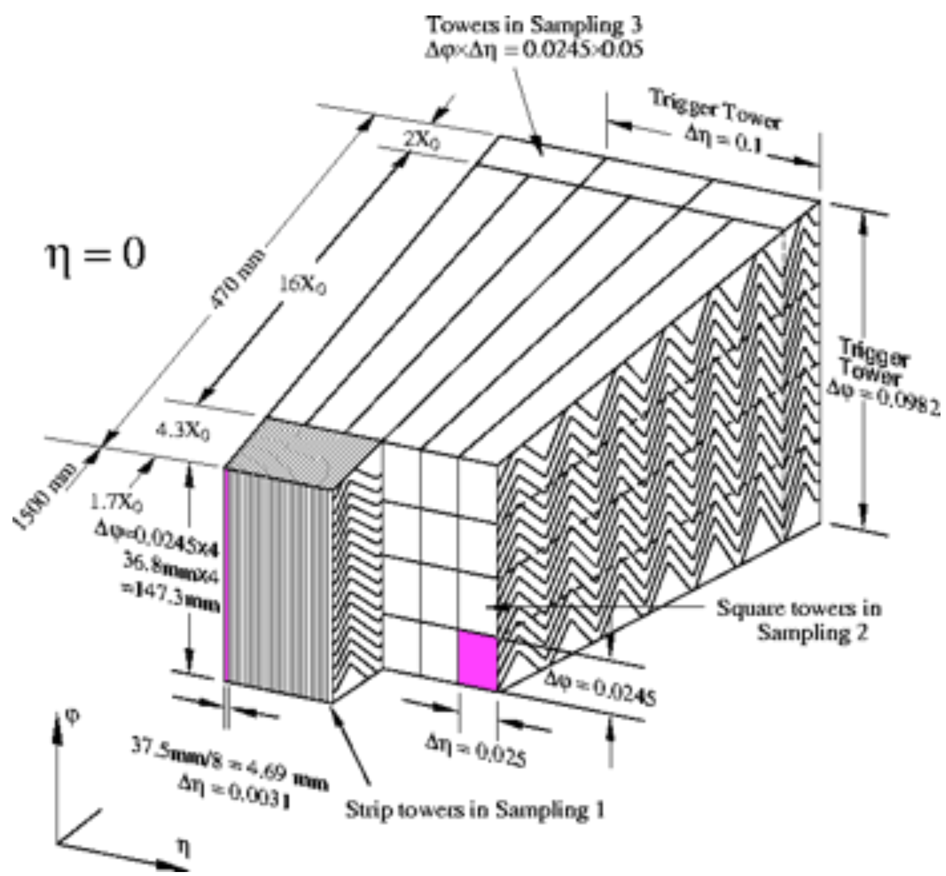
or

$$R_{\gamma\gamma} = 1 + \mathcal{B}(h \to aa)\left(\frac{\epsilon}{\mathcal{B}_{\text{SM}}\left(h \to \gamma\gamma\right)} - 1\right).$$

To get enhancement at m_h=125 GeV, $\epsilon \geq \mathcal{B}_{\text{SM}}\left(h \to \gamma\gamma\right) \simeq 0.0023$

Estimating ϵ for ATLAS

ATLAS efficiently vetoes isolated, boosted $\pi^0 \to \gamma\gamma$ using first ECAL layer, which has finely-segmented strips in rapidity. What about lighter pseudoscalars?



Most sensitive discriminator for our purposes:

$$w_{s3} \equiv \sqrt{\sum_i E_i (i - i_{\max})^2 / \sum_i E_i}$$

Measures energy fraction in two strips directly adjacent to strip with energy maximum. On unconverted photons, ATLAS uses a weakly η-dependent cut on $w_{s3} \sim 0.66$ for the most central strips

We simulate $h \to aa \to 4\gamma$ events and attempt to mock up the more sophisticated cuts on ECAL variables with cuts on $\Delta\eta_{\gamma\gamma},\ \Delta\phi_{\gamma\gamma}$

Opening angles controlled by m_a

We find that requiring $\Delta\eta_{\gamma\gamma} < 1/2 \times \Delta\eta_{\rm strip}$ simulates the cut on w_{s3}. Also use $\Delta\phi < \Delta\phi_{\rm strip}$ although result is insensitive (much coarser in φ)

Estimating ϵ for ATLAS

What about conversion events? Conversions happen with an η- and E_T-dependent probability ranging from about 10% at low η to more than 50% at larger η

Since we have twice as many photons, many more events contain at least one conversion

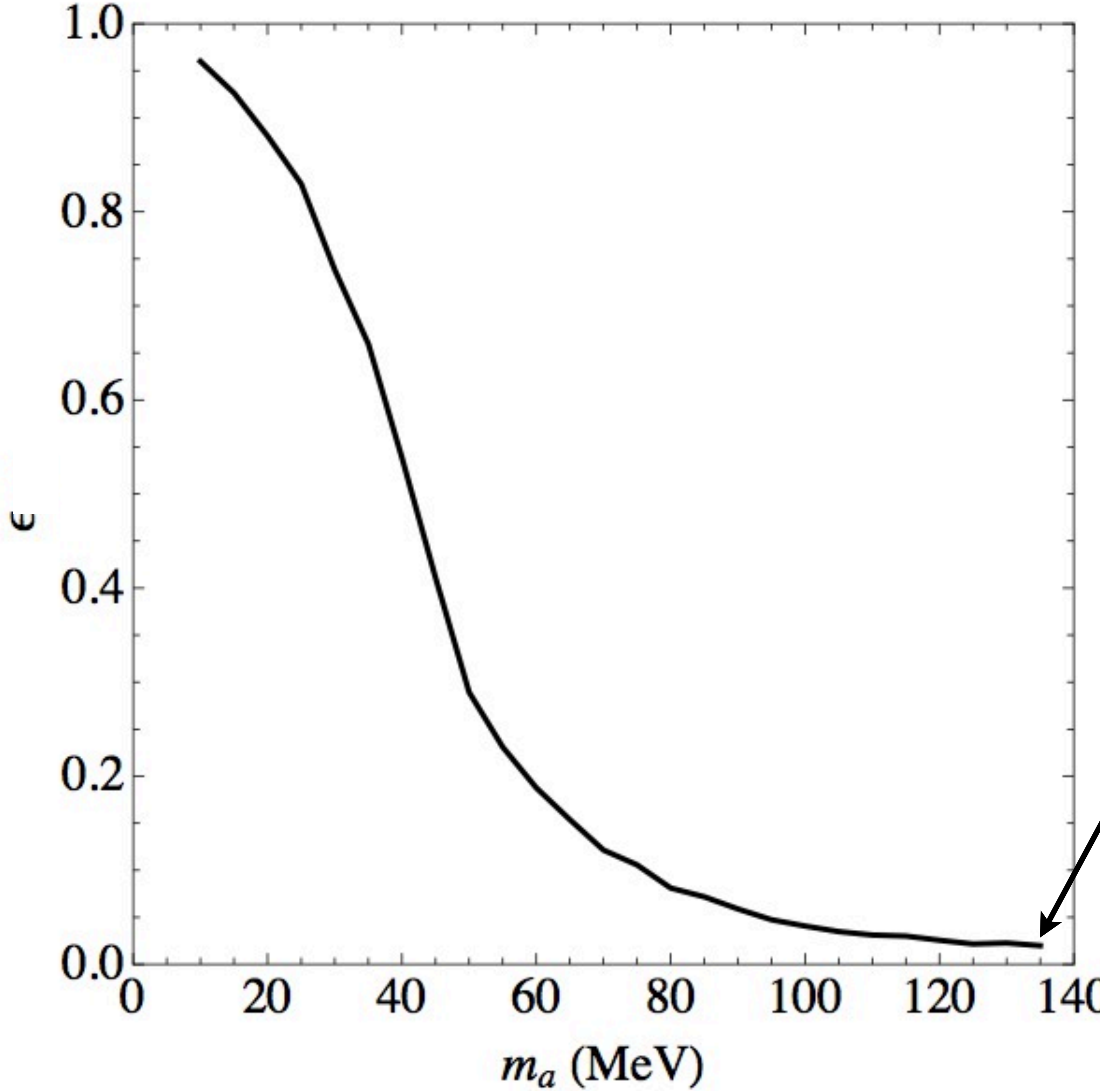
Are these rejected?

- -for case with γe^+e^- in one cluster, mismatch between track p_T and energy in the calorimeter
- -for case with $2e^+e^-$ in one cluster, multiple conversion vertices

ATLAS currently does not veto on either, and relaxes cuts somewhat for conversion events since energy deposit spreads

We will make the approximation that the value of ϵ relevant for 4γ events containing conversions is the same as the value of ϵ for the unconverted sample, and validate for pion

Estimating ϵ for ATLAS



Similar to expectation from known isolated π^0 rejection power on unconverted +converted sample (recall epsilon is probability of two simultaneous fakes)

Substantial contamination requires m_a less than ~100 MeV

CMS

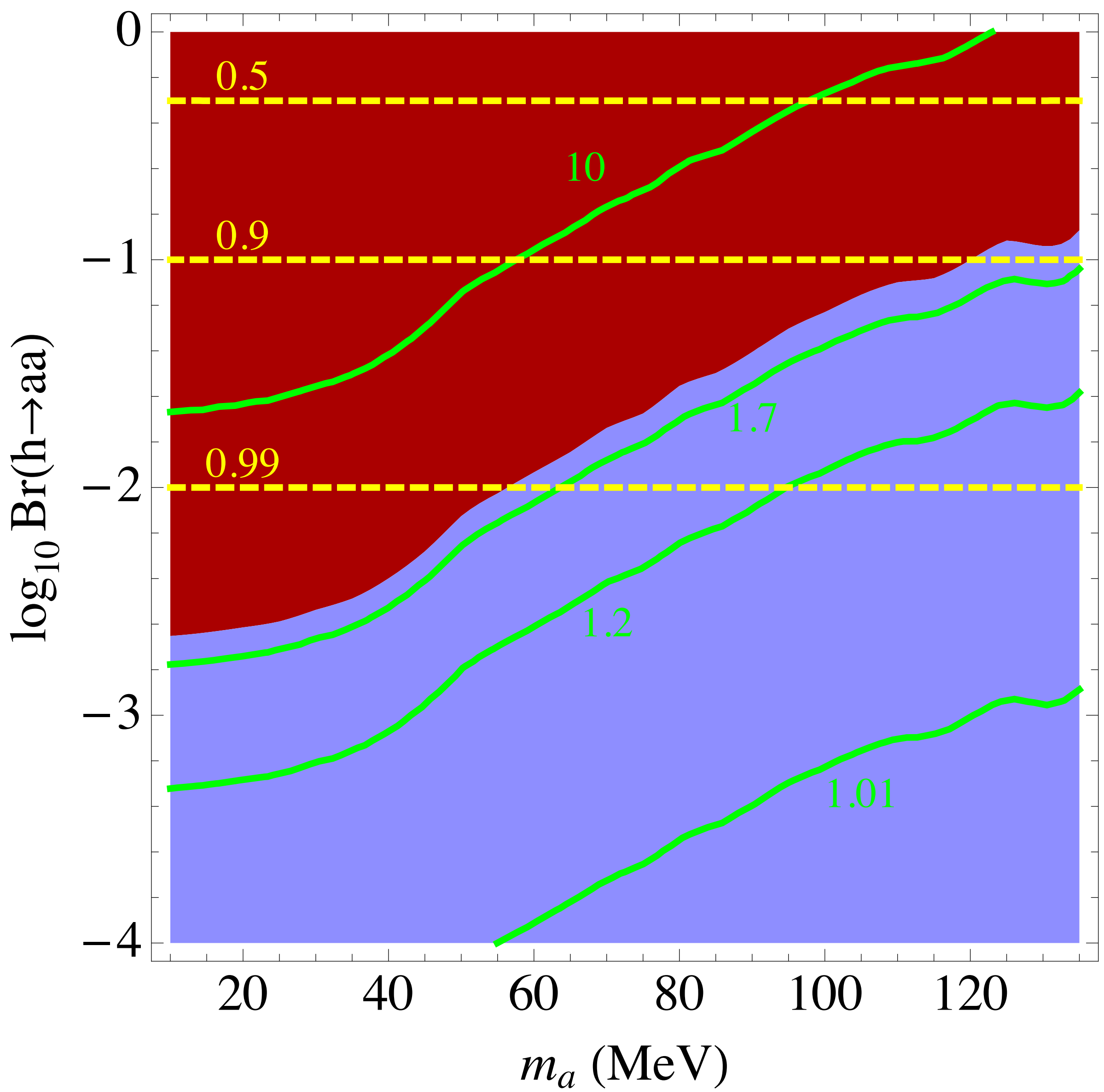
CMS does cut on the ratio of the calorimeter energy to the tracker p_T in order to isolate single photons

Also has 6x barrel strip size!

$\Rightarrow$ Expect a somewhat different ϵ between the two experiments

Predicted Rates at the LHC & Constraints

100% a→γγ



Contours give net diphoton (solid green) and ZZ,WW,bb,ττ rates (dashed yellow) expected at the LHC relative to the SM rates, using previous estimation for ϵ .

Constrain $(m_a, \mathcal{B}(h \to aa))$ parameter space with matched filter

$$\hat{R} = \sigma^2 t_i C^{-1}_{ij} d_j$$
$$\sigma \equiv (t_i C^{-1}_{ij} t_j)^{-1/2}$$

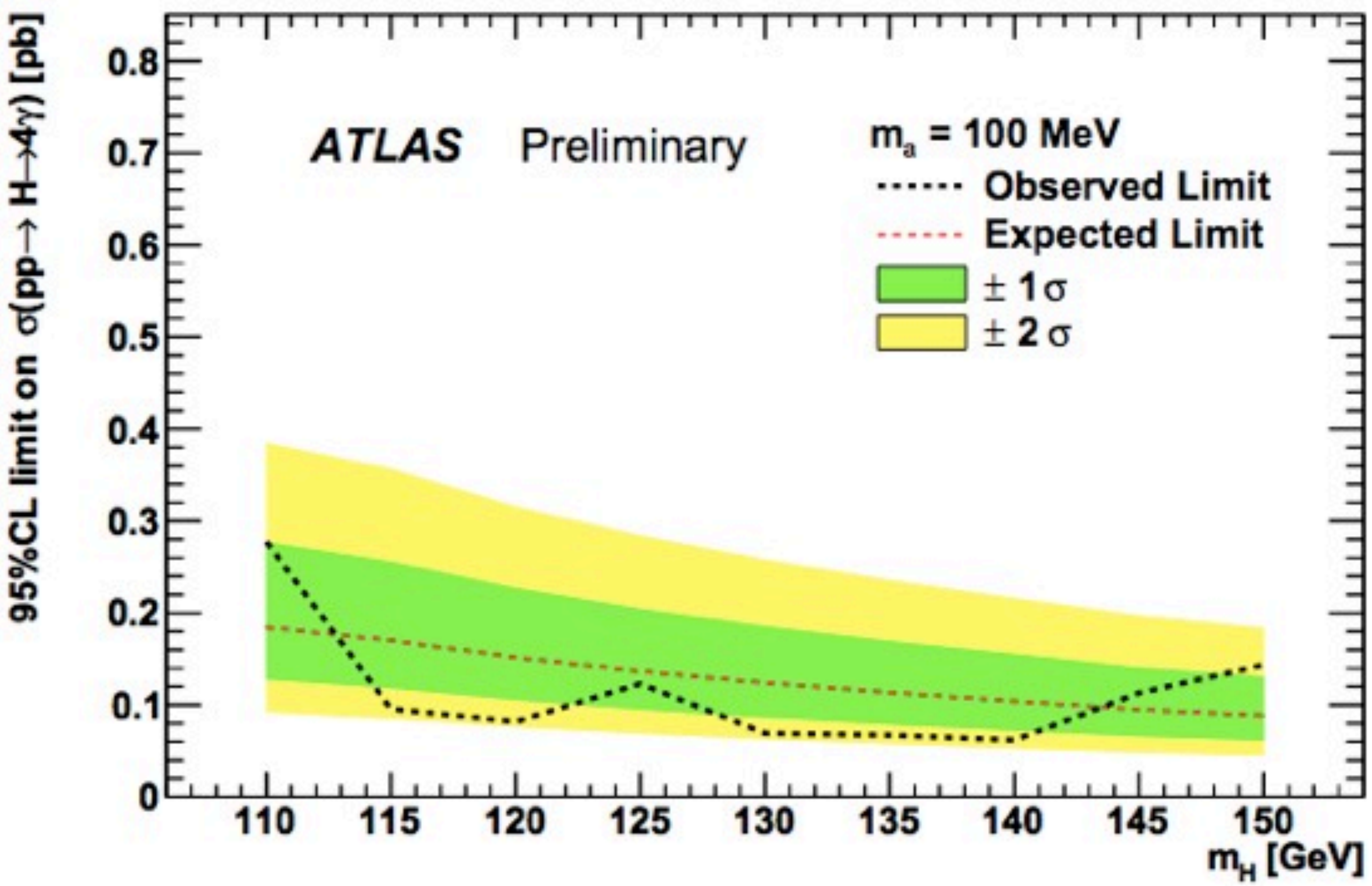
Compute $\hat{R}$ at each point, reject if R=1 is outside 90% CL

Favored points lie along green 1.7 contour; χ^2 shallow along contour, so:

any m_a ok,

Br(h→aa) between 0.1% and a few %.

Predicted Rates at the LHC & Constraints



(a) m_a = 100 MeV

Recent ATLAS search for

$$h \to aa \to 4\gamma$$

(ATLAS-CONF-2012-079)

$$\mathcal{B}\left(h \to aa\right)\left[\mathcal{B}\left(a \to \gamma\gamma\right)\right]^2 < 0.01$$

$$m_a = 100,\ 200,\ 400\ \mathrm{MeV}$$

Relaxed cuts to accept photon jets that would normally fail isolation requirements. Mainly a complementary study at larger m_a, but the m_a =100MeV point overlaps and rules out an $h\to 4\gamma$ explanation of the diphoton excess $(B(h\to aa)B(a\to\gamma\gamma)^2 \sim 0.04)$

Conclusions

In case $h \to \gamma\gamma$ > SM persists, interesting to delineate possible mechanisms

Minimal SUSY ⇒ small-α scenario or light staus in decay loop; many other possibilities in the loop beyond minimal SUSY.

$h \to aa \to 4\gamma$ with γs collected into two photon jets is another possibility

- Favors pseudoscalars between 10 MeV and pion mass and percent-level branching of $h \to aa$
- Low scale of physics generating the $a\, F^{\mu\nu} \tilde{F}_{\mu\nu}$ coupling suggests SM particles; constraints on these couplings make UV model building tricky

Model Building Issues for $a\,F^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling

- Decay length constraints require large $a\,F^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling. For a given decay length,

$$M = 9.3 \text{ GeV} \left(\frac{\gamma c\tau}{1 \text{ cm}}\right)^{1/2} \left(\frac{m_a}{40 \text{ MeV}}\right)^2 \times \left(\frac{m_h}{125 \text{ GeV}}\right)^{-1/2}$$

To get 90% of the decays before the ECAL (~1m), need < 1/2m decay length, so M less than about 200 GeV.
If M generated by integrating out heavy particles, $M \sim 4\pi^2 m/q^2$
So those particles have masses below 10s of GeV: must be SM fermions unless high multiplicity or large q

- NMSSM a possibility. However, light a in NMSSM totally ruled out in this mass range by multiple low-energy measurements Andreas, Lebedev, Ramos-Sanchez, & Ringwald 2010

- Could work if light a couples only to the tau lepton.
  $(g\text{-}2)_\tau$ poorly known, only constrains M>35 GeV.

Backup

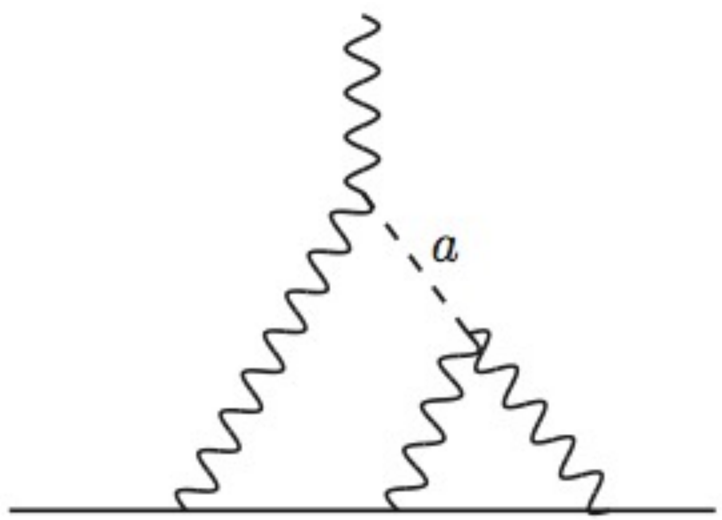


FIG. 3. A representative diagram of the leading contribution of the pseudoscalar, a, to $(g-2)_\mu$.

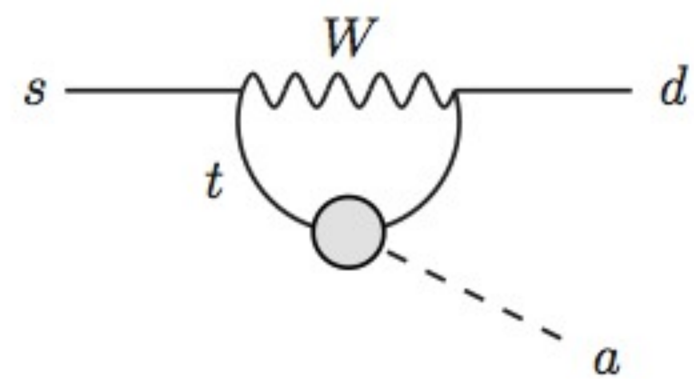


FIG. 4. Diagram that gives the leading contribution to $s \to d + a$ from an effective interaction between a and the top quark.

Direct Constraints

Constrain m_a, and M through $\frac{e^2}{4M} a\, F^{\mu\nu} \tilde{F}_{\mu\nu}$ coupling

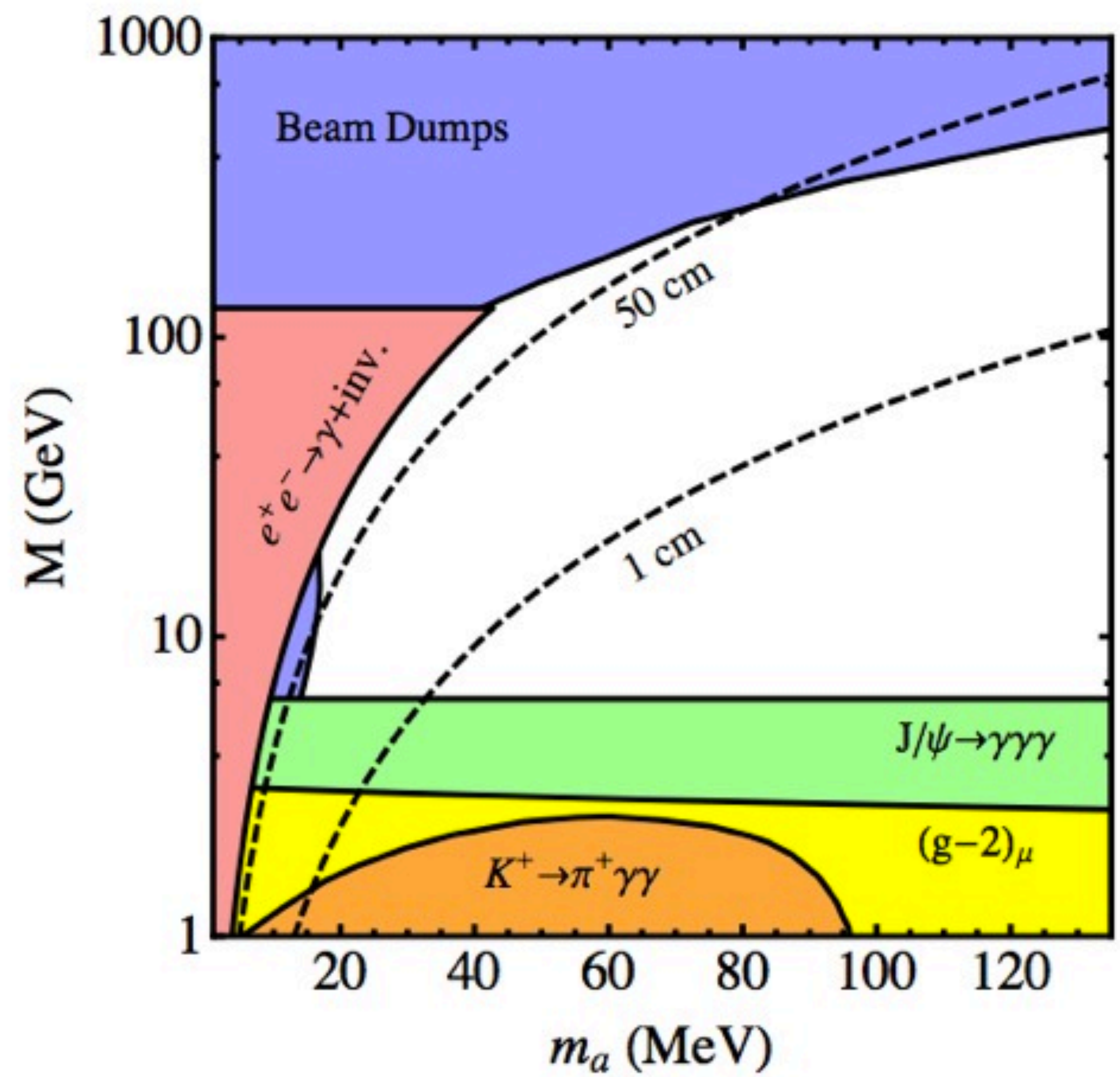
Constraints from Primakoff production in beam dump experiments: ok so long as a's decay length is shorter than the target depth, or past detector

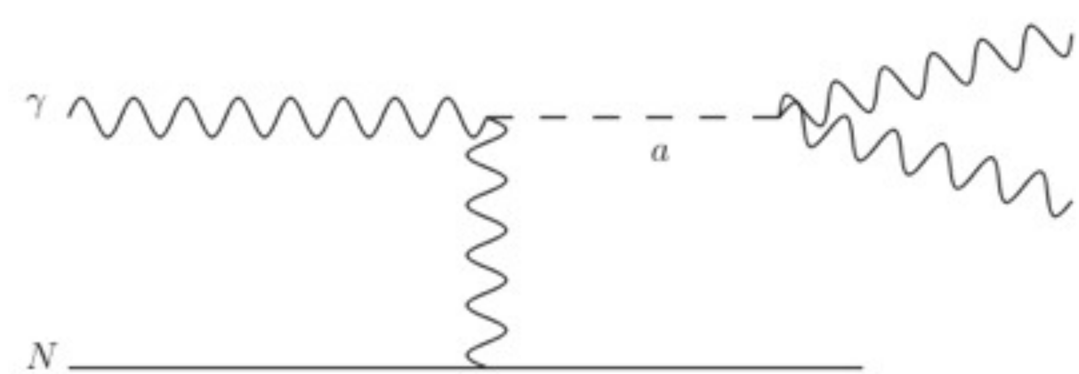
Similarly LEP search for $e^+e^- \to \gamma$+inv ok if a decays before the detector

These bounds coincide roughly with requirement that decay happens before detector at LHC

quarkonia can decay to γa through an s-channel virtual photon ⇒ lower bound on M

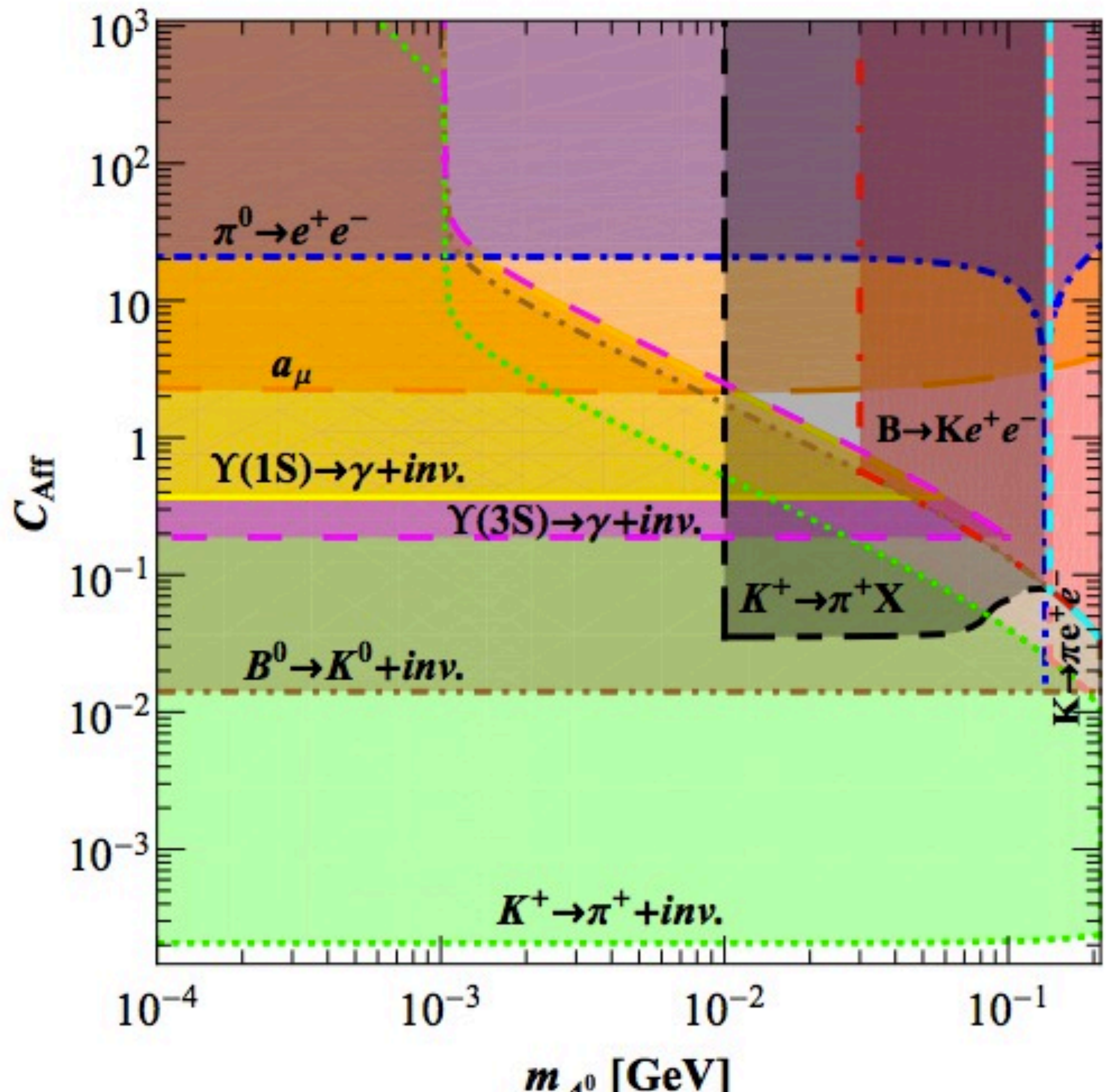
other constraints (g-2, flavor-violating meson decays) more sensitive to additional couplings of pseudoscalar to SM fermions



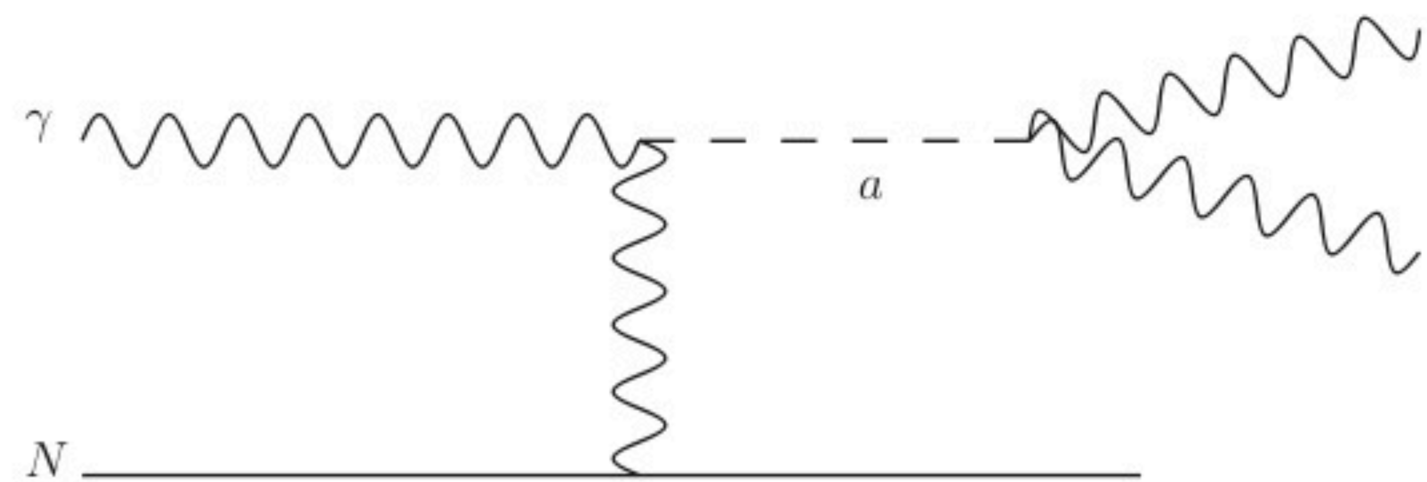


NMSSM

• Andreas, Lebedev, Ramos-Sanchez, & Ringwald 2010



Can produce *a*'s in scattering photons on nuclei:



At upgraded PRIMEX experiment (JLAB):

$$N\left(a\right) \simeq 10^4 \left(\frac{10 \text{ GeV}}{M}\right)^2$$

Potentially within reach...