The NMSSM lives
(with or without a diphoton excess)

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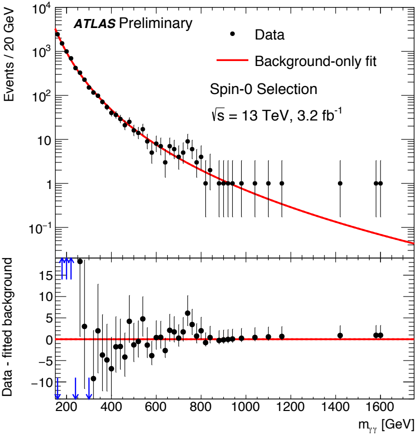
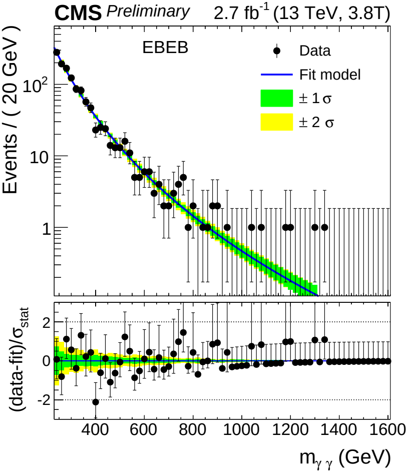
Once upon a time...





SUSY explanations

- a heavy SM-like Higgs cannot explain the excess, since $\sigma \times \mathrm{BR} \simeq 0.0001$ fb but $\mathcal{O}(10)$ fb is required
- large enhancement is required
- in models with extended Higgs sector such as in the MSSM, H and A are mass degenerate and decay mainly into fermions: to top ($\tan\beta$ suppressed) and to bottom ($\tan\beta$ enhanced)
- the tree level decays into fermions will dominate
- loops of SUSY particles cannot sufficiently enhance the signal rate
- exception 1: bounds states of stops in CMSSM (arxiv:1605.00013)
- exception 2: threshold enhancement, i.e. sparticles close to threshold in the loop leads to Coulomb singularity (arxiv:1603.04464,1605.01040)

Outline

Outline

NMSSM lagrangian

- we consider the simplest Z_3 and CP-conserving version of the Next-to-Minimal Supersymmetric Standard Model with a gauge singlet superfield S

$$W \supset \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3$$

where the singlet superfield $\hat{S}$ consists of a scalar Higgs singlet S and the singlino $\tilde{S}$

- the soft breaking lagrangian acquires additional terms

$$\mathcal{L}_{\text{soft}} \supset -\lambda A_\lambda H_u H_d S - \frac{1}{3} A_\kappa S^3$$

- parameters: soft masses $m^2_{H_u},\ m^2_{H_d},\ m^2_S$; couplings $\lambda,\ \kappa$; trilinear couplings $A_\lambda,\ A_\kappa$; 3 vevs

NMSSM

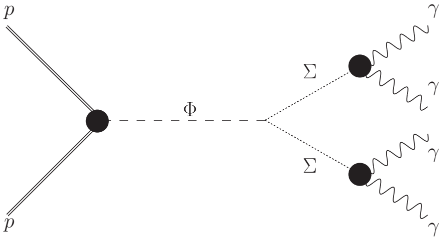
- additional particles on top of the MSSM spectrum: singlino, scalar and pseudoscalar singlet
- singlets mix with the respective MSSM particles: 3x3 CP-even Higgs mass matrix, 5x5 neutralino mass matrix
- the NMSSM Higgs sector consists of two doublet and one singlet CP-even scalars and one doublet as well as one singlet CP-odd scalar and a pair of charged Higgses
- Higgs sector defined using: $(M_A,\ \tan\beta,\ \mu,\ \lambda,\ \kappa,\ A_\kappa)$

$$M_A^2 = \frac{2\lambda s}{\sin 2\beta}(A_\lambda + \kappa s)$$

Prerequisites

- light Σ, preferably $m_\Sigma \lesssim 0.5$ GeV
- short-lived
- significant BR to photons
- $m_\Phi \simeq m_{\gamma\gamma}$
- significant BR for $\Phi \to \Sigma\Sigma$
- $\sigma(pp \to \Phi \to 2(\Sigma \to \gamma\gamma)) \simeq 5$ fb

Domingo ea. arxiv:1602.07691;
Ellwanger, Hugonie arxiv:1602.03344



Other constraints to keep in mind:

- flavor (K and B decays; $(g-2)_\mu$) for Σ
- $H_{\rm SM}$ physics

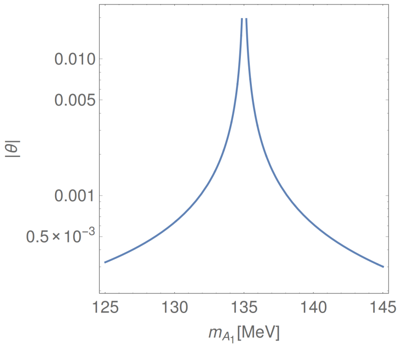
Identifying the light state Σ

- for $A_\kappa, A_\lambda \to 0$, one obtains additional $U(1)$ symmetry of the Higgs sector, with the Higgs charges $Q^R_{H_u,H_d,S}$ satisfying $2Q^R_S - Q^R_{H_u} - Q^R_{H_d} = 0$: this is the R-symmetry limit since the Higgs charges for the specific choice $Q^R_S = -2/3$ coincide with those that these fields would receive under a genuine R-symmetry (also broken by the gaugino masses) of the NMSSM with unbroken supersymmetry.
- in the pseudoscalar base (A_D, A_S), $m^2_{A_S}$ is largely determined by the choice of $A_\kappa \Rightarrow$ should be small to obtain a light singlet pseudoscalar
- the doublet component of the light mass eigenstate is given by $A_1 = \sqrt{1-P_d^2}\, A_S + P_d\, A_D$

$$P_d \simeq \frac{3\kappa\mu v}{M_A^2}\left(1 - \frac{\lambda}{6\kappa}\frac{M_A^2}{\mu^2}\sin 2\beta\right)$$

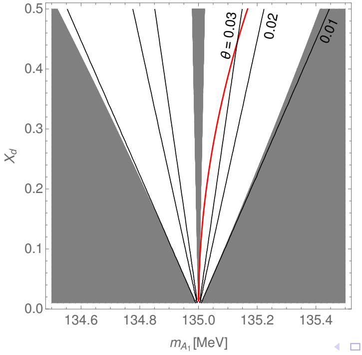
Decays of Σ

- total width: $\Gamma_{A_1} \sim (10^{-13}\ \text{GeV})\, P_d^2 \tan^2\beta \sim 10^{-14}$ GeV for $m_{A_1} \sim 200$ MeV, and narrower at lower masses
  $\Rightarrow$ decay length of about 40 m at the LHC (invisible)
- this can be avoided through mixing with π^0, however the mass difference should be $\lesssim 0.5\ \text{MeV}$



Mixing with pion

- A_1-π^0 mixing might seem catastrophic but in fact it could explain some measurements of pion properties
- reduction of decay width $\Gamma[\pi^0 \to \gamma\gamma]$ as measured directly from the decay length
- the main decay mode of $A_1 \to e^+e^-$, so the mixing could increase this branching ratio for π^0, again in agreement with data



Identifying the heavy state Φ

- consider the doublet-singlet base $(H_{\rm SM} = \cos\beta\, h_d + \sin\beta\, h_u, H_D = -\sin\beta\, h_d + \cos\beta\, h_u, H_S = h_s)$,
- H_D gives a correct cross section: gg fusion $(0.6$ pb$)/\tan^2\beta$ for $\tan\beta \lesssim 15$, and the bbh cross section $(4\cdot 10^{-4}$ pb$)\times\tan^2\beta$
- the decay width into $2A_1$ can be estimated as (still for $m_\Phi \sim m_{\gamma\gamma}$):

$$\Gamma[\Phi \to A_1 A_1] \simeq (10^{-5}\ \text{GeV}^{-1})\, g^2_{\Phi A_1 A_1}$$

- for the doublet $\Gamma[H_D \to A_1 A_1] \ll \mathcal{O}(\text{GeV})$, while fermionic modes have $\Gamma[H_D \to f\bar{f}] \simeq 1\ \text{GeV}$
- on the other hand for the singlet $g_{H_S A_1 A_1} \sim \sqrt{2}\kappa\left(2\frac{\kappa}{\lambda}\mu - A_\kappa\right)$ that could offer a correct partial width of order 1 GeV. Requiring the mass $m_{H_S} \sim m_{\gamma\gamma}$ leads to $2\frac{\kappa}{\lambda}\mu \simeq m_{\gamma\gamma}$

Identifying the heavy state Φ

We need production like H_D and decay like H_S. Two possibilities:

- the excess corresponds to one of the states H_2 or H_3 while the other is gives subdominant effect. Getting the large width $\Gamma[H_S \to A_1 A_1] = \mathcal{O}(45 \text{ GeV})$ would require large, possibly non-perturbative couplings;
- there is a strong mixing and both states contribute at similar level. The mass difference is given by

$$m_{H_3} - m_{H_2}\big|_{\text{min}} \simeq \frac{\kappa v}{2} |\sin 4\beta|$$

which typically gives 10 GeV mass difference and can mimic the large resonance width as preferred by ATLAS

From now on we consider $M_A \simeq m_{\gamma\gamma} \simeq 2\frac{\kappa}{\lambda}\mu$ and $H_{2,3} \sim \frac{1}{\sqrt{2}}[H_D \pm H_S]$

The SM-like state

- the properties of the 125 GeV state are well measured. We have to make sure $H_{\rm SM} \to A_1 A_1$ is suppressed.

$$\Gamma[H_{\rm SM} \to A_1 A_1] \simeq (8 \cdot 10^{-5}\ \text{GeV}^{-1})\, g^2_{H_{\rm SM} A_1 A_1}$$

- the condition
  $\Gamma[H_{\rm SM} \to A_1 A_1] \ll \Gamma_{\rm SM} \cdot {\rm BR}^{\rm SM}[H_{\rm SM} \to \gamma\gamma] \sim 8 \cdot 10^{-6}$ GeV
  translates into $g_{H_{\rm SM} A_1 A_1} < 0.3$ GeV. Taking into account previous considerations this implies

$$\lambda^2 \left[1 - \frac{2\kappa}{\lambda} \sin 2\beta\right] \lesssim 1 \cdot 10^{-3}$$

- small λ would suppress $H_S \to A_1 A_1$, therefore we choose $\frac{\kappa}{\lambda} \sin 2\beta \sim 0.5$

Final refinements

- we've seen before

$$M_A \simeq m_{\gamma\gamma} \simeq 2\frac{\kappa}{\lambda}\mu; \qquad A_\lambda \simeq -\frac{M_A}{2}\left[1 - \frac{2\kappa}{\lambda}\sin 2\beta\right]$$

  so the requirement $\frac{\kappa}{\lambda}\sin 2\beta \sim 0.5$ places us naturally in the R-symmetry limit
- furthermore $\mu \sim M_A \sin 2\beta$ so $\mu \lesssim m_{\gamma\gamma}/2$ as soon as $\tan\beta \gtrsim 3.7$
- finally, perturbativity up to the GUT scale places an upper bound

$$\lambda \lesssim \sin 2\beta \sqrt{\frac{2}{1 + 4\sin^2 2\beta}}$$

- with $\mu \gtrsim 100$ GeV we also find $\tan\beta \lesssim 15$

Preferred parameter space

- $M_A \simeq m_{\gamma\gamma}$ enables a sizable production of the state(s) at $\sim m_{\gamma\gamma}$ via a significant H_D component;
- $\kappa \simeq \frac{\lambda}{2\sin 2\beta}$ ensures a suppressed decay $H_{\rm SM} \to A_1 A_1$; furthermore, $\kappa \gtrsim 0.1$ allows for a competitive $\Gamma[H_S \to A_1 A_1]$ as compared to the fermionic decays of H_D; finally, κ determines the separation in mass for the states at $\sim m_{\gamma\gamma}$;
- $\mu \sim M_A \sin 2\beta$ is fixed both by the requirement $2\frac{\kappa}{\lambda}\mu \simeq m_{\gamma\gamma}$, conditioning the presence of a singlet-like component at $\sim m_{\gamma\gamma}$, with the significant decay to pseudoscalars, and by the condition on $H_{\rm SM} \to A_1 A_1$;

Preferred parameter space

- λ is bounded as $\frac{0.4\tan\beta}{1+\tan^2\beta} \lesssim \lambda \lesssim \frac{2\sqrt{2}\tan\beta}{\sqrt{1+18\tan^2\beta+\tan^4\beta}}$: this results from the conditions of a suppressed decay $H_{\rm SM} \to A_1 A_1$, of perturbativity up to the GUT scale and of a sizable $\Gamma[H_S \to A_1 A_1]$;
- $\tan\beta \lesssim 15$ is constrained by the lower bound on chargino searches $\mu \gtrsim 100$ GeV, as a result of the various correlations; note that $\tan\beta = \mathcal{O}(10)$ satisfies the requirements on the fermionic decays of the states at $\sim m_{\gamma\gamma}$ – which should remain moderate;
- $A_\kappa \lesssim \mathcal{O}(0.1)\ \mathrm{GeV}$ conditions a light CP-odd singlet; note that, together with the requirement $A_\lambda \to 0$, which, in our scenario, follows the assumptions on κ, λ, μ and M_A, $A_\kappa \to 0$ places us in the approximate R-symmetry limit of the NMSSM, and that A_1 thus appears as the pseudo-Goldstone boson of this R-symmetry.

Benchmark points

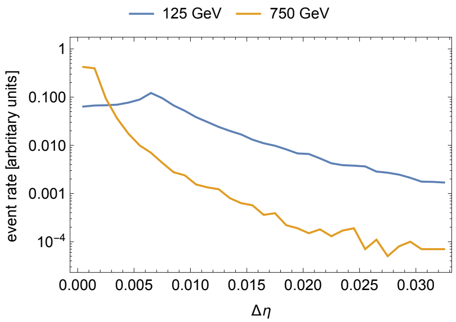
	P2	**P5**	**P7**
Parameters			
λ	0.08	0.15	0.2
κ	0.2	0.19	0.2
$\tan\beta$	10	5	4
μ [GeV]	150	296	375
M_A [GeV]	784	785.5	810
A_κ [GeV]	0.0573065	0.149903	0.4206824
$m_{\tilde{Q}}$ [TeV]	10	10	15
A_t [TeV]	-8.519135	-16	-35
$m_{\tilde{L}}$ [TeV]	0.3	0.305	0.4
M_2 [TeV]	1	1	1
Higgs spectrum			
m_{H_1} [GeV]	125	125	125
m_{H_2} [GeV]	740	734	733
m_{H_3} [GeV]	754	757	763
m_{A_1} [GeV]	0.135	0.135	0.135
m_{A_2} [GeV]	747	744	750
$m_{H^\pm}$ [GeV]	751	747	753
A_1 mixing			
P_d	0.019	0.036	0.047

Outline

We consider the production

$$pp \to H_2\,(H_3) \to 2(A_1 \to \gamma\gamma) + X$$

The small mass of A_1 ensures that the photons are collimated and would be seen as a single photon in the detector



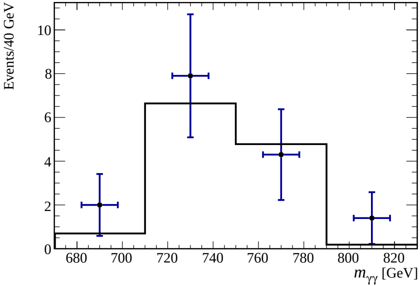
Event numbers in signal regions

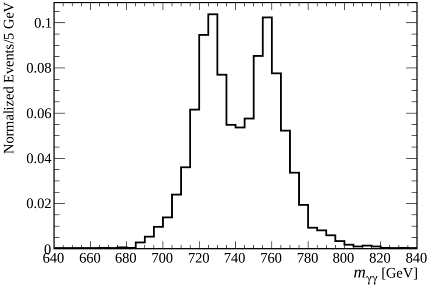
Search	signal	$S95$	**P2**	**P5**	**P7**
$\sqrt{s} = 13$ TeV					
σ^{incl} [fb]			8.5	5.83	7.40
ATLAS13	16.6	27	10.3	7.1	8.9
CMS13 EBEB	4.5	12.8	10.5	7.2	9.2
CMS13 EBEE	0	9.5	4.0	2.7	3.4
$\sqrt{s} = 8$ TeV					
σ^{incl} [fb]			1.6	1.37	1.61
ATLAS8-1407.0653	6	20	11.6	9.7	11.4
ATLAS8-1504.05511	2.6	23	15.7	13.2	15.5
CMS8-EXO-12-045	0	16	6.8	5.7	6.8
CMS8-1506.02301	3	34	11.8	9.9	11.7

- the production through $b\bar{b}$ initial state could somewhat reduce the tension (?) with 8 TeV data

Invariant mass distribution in the signal region

Benchmark point P6





- the broad excess feature is well reproduced
- with higher luminosity the double peak could eventually be observed

Smoking guns

- double peak structure
- the diphotons have different probabilities of conversion into e^+e^- pairs
- events with only one photon converted
- observation of $\tau^+\tau^-$ decay mode of $H_{2,3}$ and A_2
- light higgsinos
- light smuons required to obtain the correct $(g-2)_\mu$
- new effects in pion physics

Outline

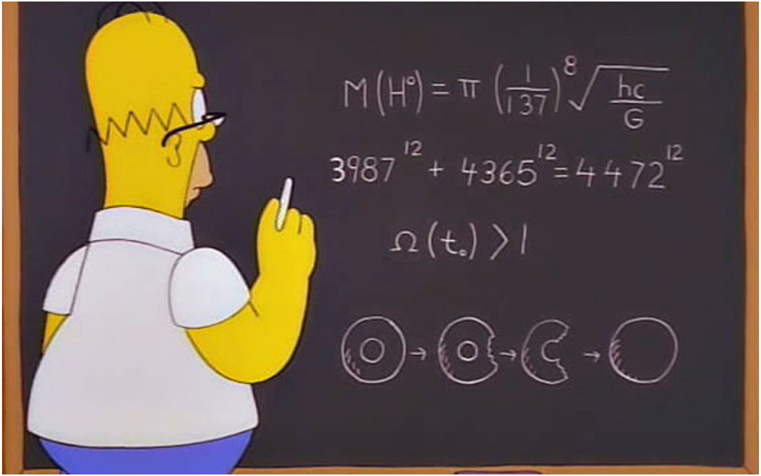
Conclusions

- the NMSSM setup could explain the diphoton excess without invoking new exotic particles:

$$pp \to H_{2,3} \to A_1 A_1 \to (\gamma\gamma)(\gamma\gamma)$$

- apparent broad resonance
- $b\bar{b}$ initial state alleviated tensions with 8 TeV results
- the photons in $A_1 \to \gamma\gamma$ appear as a single photon provided $m_{A_1} \lesssim 500$ MeV
- short lifetime of A_1 achieved by mixing with π^0; $m_{A_1} = 135 \pm 0.5$ MeV
- all low-energy constraints can be satisfied

Who ordered that?



$$m_S = \pi \left(\frac{1}{137}\right)^8 \sqrt{\frac{hc}{G}} = \sqrt{2}\pi^{3/2} M_{\rm Pl}\alpha^8 = 773\ \mathrm{GeV}$$

BACKUP

Benchmark points

	P1	P2	P3	P4	P5	P6	P7	P8	P9
Higgs decays									
BR$[H_1 \to A_1 A_1]$	$7 \cdot 10^{-6}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$9 \cdot 10^{-6}$	$3 \cdot 10^{-6}$	$3 \cdot 10^{-7}$	$8 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$5 \cdot 10^{-6}$
Γ_{H_2} (GeV)	1.60	1.53	2.04	2.71	1.30	1.53	1.29	1.37	1.41
BR$[H_2 \to A_1 A_1]$	0.306	0.174	0.188	0.113	0.190	0.373	0.288	0.363	0.186
BR$[H_2 \to b\bar{b}]$	0.332	0.397	0.439	0.527	0.117	0.087	0.056	0.269	0.599
BR$[H_2 \to t\bar{t}]$	0.094	0.121	0.064	0.032	0.533	0.357	0.551	0.186	0.046
BR$[H_2 \to \tau\bar{\tau}]$	0.048	0.058	0.064	0.077	0.017	0.013	0.008	0.039	0.087
BR$[H_2 \to \tilde{h}\tilde{h}]$	0.012	0.004	0.003	0.003	0.021	0.040	0	0.027	0.002
Γ_{H_3} (GeV)	1.92	1.55	2.00	2.28	1.52	2.09	2.27	1.71	2.05
BR$[H_3 \to A_1 A_1]$	0.231	0.213	0.247	0.185	0.191	0.226	0.099	0.301	0.082
BR$[H_3 \to b\bar{b}]$	0.279	0.292	0.327	0.427	0.073	0.062	0.043	0.182	0.608
BR$[H_3 \to t\bar{t}]$	0.096	0.104	0.055	0.029	0.452	0.395	0.655	0.162	0.052
BR$[H_3 \to \tau\bar{\tau}]$	0.041	0.043	0.048	0.062	0.011	0.009	0.006	0.027	0.089
BR$[H_3 \to \tilde{h}\tilde{h}]$	0.165	0.154	0.135	0.090	0.112	0.123	0.002	0.222	0.087
Γ_{A_2} (GeV)	2.40	2.37	3.02	4.19	2.18	2.30	2.83	1.80	2.99
BR$[A_2 \to \tau\tau]$	0.065	0.065	0.075	0.084	0.018	0.016	0.009	0.055	0.102

π^0–A_1 mixing

$$-\mathcal{L}_{\text{eff}} \ni \delta m^2_{A_1\pi^0}\, A_1\pi^0 + \delta m^2_{A_1\eta}\, A_1\eta + \ldots$$

$$\begin{aligned}
\mathcal{L} \ni & -\frac{\imath P_d}{\sqrt{2}v}\left\{m_u \tan^{-1}\beta\, \bar{u}\gamma_5 u + m_d \tan\beta\, \bar{d}\gamma_5 d + m_s \tan\beta\, \bar{s}\gamma_5 s\right\} A_1 \\
= & -\frac{P_d}{2\sqrt{2}v}\partial_\mu \left\{\tan^{-1}\beta\, \bar{u}\gamma^\mu\gamma_5 u + \tan\beta\, \bar{d}\gamma^\mu\gamma_5 d + \tan\beta\, \bar{s}\gamma^\mu\gamma_5 s\right\} A_1 \\
= & -\frac{P_d}{4v}\left\{\sqrt{\frac{2}{3}}(\tan^{-1}\beta + 2\tan\beta)\,\partial_\mu J^\mu_{A\,1} + (\tan^{-1}\beta - \tan\beta)\,\partial_\mu J^\mu_{A\,3} + \frac{1}{\sqrt{3}}(\tan^{-1}\beta - \tan\beta)\partial_\mu J^\mu_{A\,8}\right\} A_1 \\
= & -\frac{P_d}{4v}\left\{\sqrt{\frac{2}{3}}(\tan^{-1}\beta + 2\tan\beta) f_{\eta_1} m^2_{\eta_1}\,\eta_1 + (\tan^{-1}\beta - \tan\beta) f_\pi \left[m^2_\pi\,\pi_3 + \frac{m^2_\eta}{\sqrt{3}}\,\pi_8\right]\right\} A_1
\end{aligned}$$

where $J^\mu_{A\,1} = \frac{1}{\sqrt{3}}(\bar{u}\gamma^\mu\gamma_5 u + \bar{d}\gamma^\mu\gamma_5 d + \bar{s}\gamma^\mu\gamma_5 s)$, $J^\mu_{A\,3} = \frac{1}{\sqrt{2}}(\bar{u}\gamma^\mu\gamma_5 u - \bar{d}\gamma^\mu\gamma_5 d)$, $J^\mu_{A\,8} = \frac{1}{\sqrt{6}}(\bar{u}\gamma^\mu\gamma_5 u + \bar{d}\gamma^\mu\gamma_5 d - 2\bar{s}\gamma^\mu\gamma_5 s)$ and the divergences of these currents in the pion model are determined by the equations of motion: $\partial_\mu J^\mu_{A\,1} = f_{\eta_1} m^2_{\eta_1}\,\eta_1$, $\partial_\mu J^\mu_{A\,3} = f_\pi m^2_\pi\,\pi_3$ and $\partial_\mu J^\mu_{A\,8} = f_\pi m^2_\eta\,\pi_8$

$$\delta m^2_{A_1\pi^0} = \frac{f_\pi}{4v} P_d(\tan^{-1}\beta - \tan\beta) m^2_\pi\,, \qquad \delta m^2_{A_1\eta} = \frac{f_\pi}{4\sqrt{3}v} P_d(\tan^{-1}\beta - \tan\beta) m^2_\eta$$