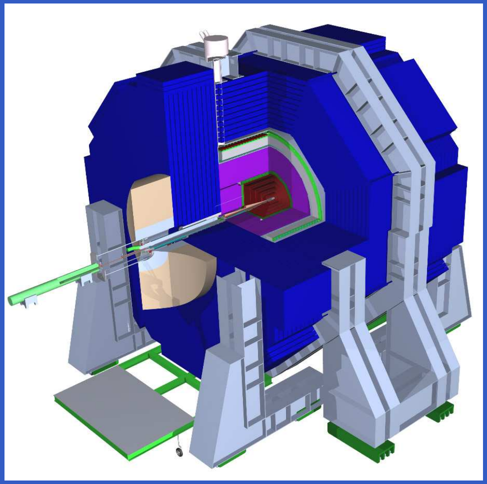
NMSSM Higgs Decay $h \rightarrow 2a_1$ at SiD

Recasting the Snowmass Study



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Introduction

- We know that the Standard Model (SM) is not complete. Supersymmetry is an exciting extension which has a much richer Higgs sector. In this talk I discuss the Next-to-Minimal Supersymmetric Model (NMSSM)
- While h_{125} decay channel signal strengths from CMS and ATLAS are consistent with the Standard Model prediction, they are also consistent with a large branching ratio to invisible/unobserved final states.
- One possibly unobserved channel is $h_{125} \to 2a_1$, where a_1 is the lightest CP-odd Higgs boson which might escape detection in the dominant decay $a_1 \to \tau^+\tau^-$.
- Another interesting possibility is that the there is a lighter CP-even Higgs h_1 which has so far escaped detection but may account for the LEPII 2.3σ excess in the $Zb\bar{b}$ channel.
- This scenario has been studied at ALEPH, BaBar, CDF, DZero, ATLAS and CMS. The most constraining limits are from ALEPH in 1003.0705.
- Full details of the original SiD study can be found in the Snowmass White paper SNOW13-00133 (1309.0021).
- In this talk I also discuss recasting the results of the original study into regions of NMSSM parameter space which are still viable after all constraints, including h_{125}, are applied.

Next-to-Minimal Supersymmetric Model

- One singlet superfield S is introduced to the MSSM. An effective μ term is generated $\mu_{eff} = \lambda \langle S \rangle$ at a natural scale.
- The NMSSM superpotential is given by:

$$\mathbf{W} = \lambda \mathbf{S} \mathbf{H_u} \mathbf{H_d} + \frac{\kappa}{3} \mathbf{S}^3$$

- The soft SUSY breaking terms in the NMSSM Lagrangian are

$$V_{soft} = m^2_{H_d} |H_d|^2 + m^2_{H_u} |H_u|^2 + m^2_S |S|^2 + (-\lambda A_\lambda H_u H_d S + \frac{1}{3} A_\kappa \kappa S^3 + h.c.).$$

- Six parameters determine the NMSSM Higgs sector at tree level:

$\lambda, \kappa, A_\lambda, A_\kappa, \tan\beta$ and μ_{eff}

- The NMSSM Higgs sector has 2 neutral CP-odd, 3 neutral CP-even and 2 charged scalars:

$$a_1, a_2, h_1, h_2, h_3, H^+, H^-$$

NMSSM Higgs Mass Spectrum (i)

- Define a parameter $m_A^2 = \frac{\lambda v_s}{\sin 2\beta}\left(\sqrt{2}A_\lambda + \kappa v_s\right)$ where $v_s = \sqrt{2}\langle S\rangle$. The NMSSM charged Higgs mass at tree level is given by ($v = 246$ GeV):

Nucl.Phys.B681:3-30,2004

$$m_{H^\pm}^2 = m_A^2 + m_W^2 - \frac{1}{2}\left(\lambda v^2\right)$$

- Consider the large $\tan\beta$, large $m_A \gg m_Z$ limit ($\tan\beta_s \equiv v_s/v$):

Nucl.Phys.B681:3-30,2004

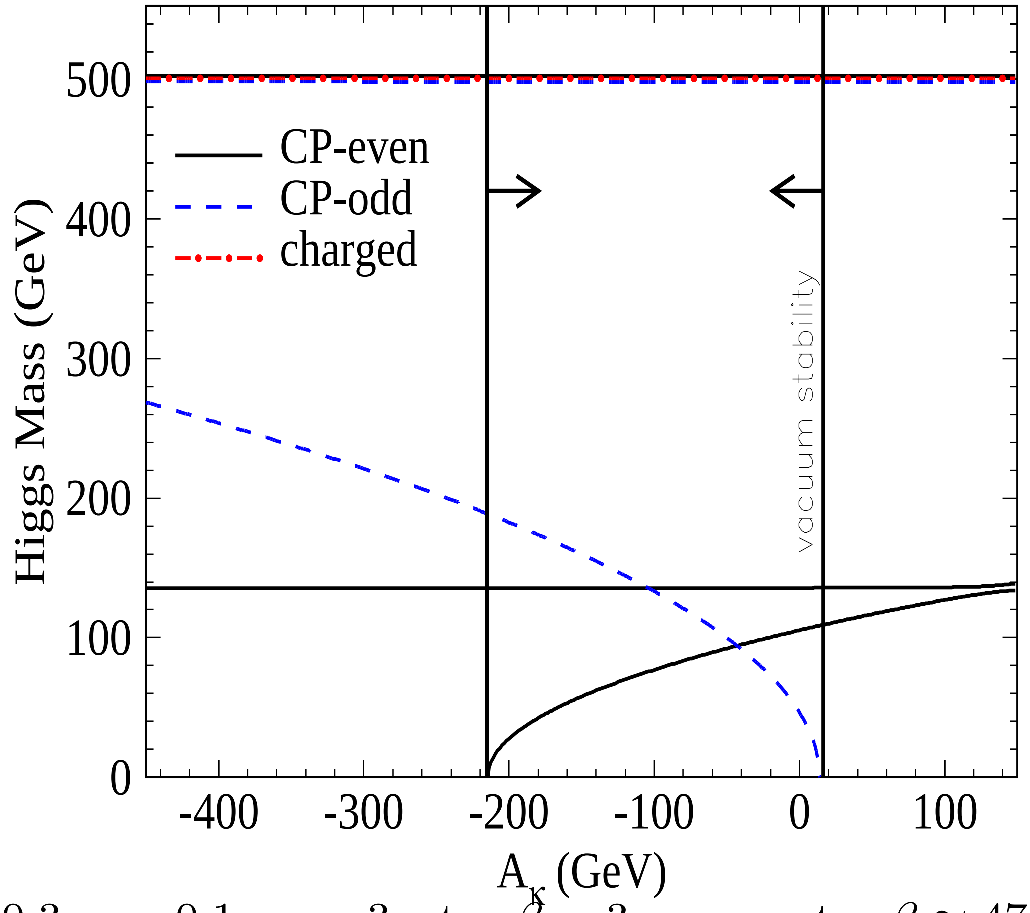
$$\begin{aligned}
m_{a_1}^2 &\approx -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa \\
m_{h_{1,2}}^2 &\approx \frac{1}{2}\left[m_Z^2 + \frac{1}{2}\kappa v_s(4\kappa v_s + \sqrt{2}A_\kappa) \pm f(\kappa, v_s, A_\kappa, \lambda, m_A, \sin\beta)\right] \\
m_{a_2}^2 &\approx m_A^2\left(1 + \frac{1}{4}\cot^2\beta_s \sin^2 2\beta\right) \\
m_{h_3}^2 &\approx m_A^2\left(1 + \frac{1}{4}\cot^2\beta_s \sin^2 2\beta\right)
\end{aligned}$$

- Note that in the $m_A \gg m_Z$ *decoupling* limit, the lighter Higgses m_{a_1,h_1,h_2} are decoupled from the heavier Higgses $m_{a_2,h_3,H^\pm} \approx m_A$.

NMSSM Higgs Mass Spectrum (ii)

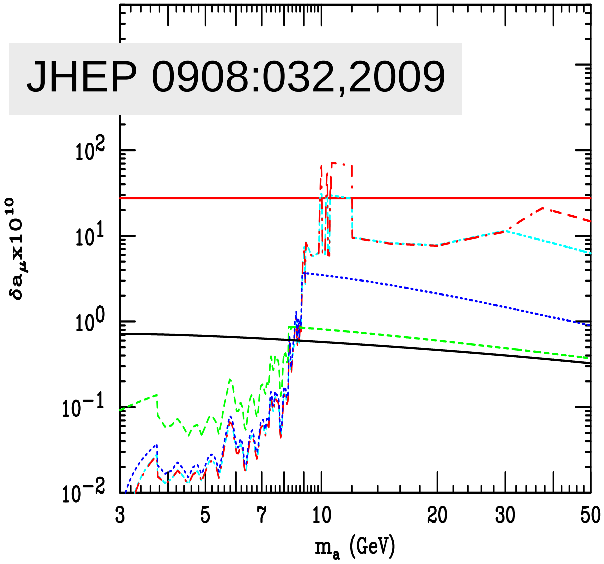
Low mass scalars a_1 and h_1 absent in the MSSM but present in the NMSSM are motivated by the anomalous muon magnetic moment and the LEP excess in the $Zh \to Zb\bar{b}$ channel.

Nucl.Phys.B681:3-30,2004

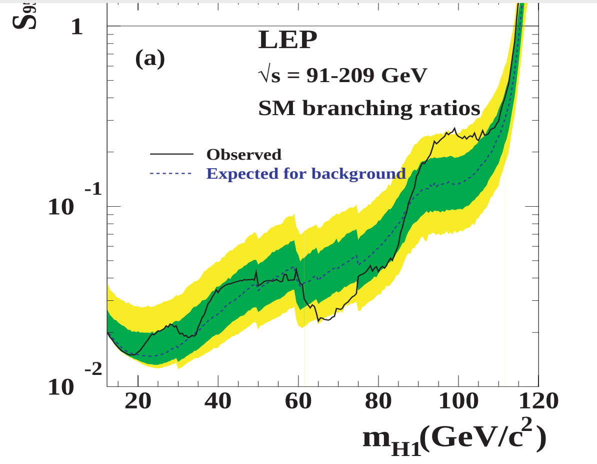


$\lambda = 0.3,\ \kappa = 0.1,\ v_s = 3v,\ \tan\beta = 3, m_A = \mu\tan\beta \approx 470$ GeV

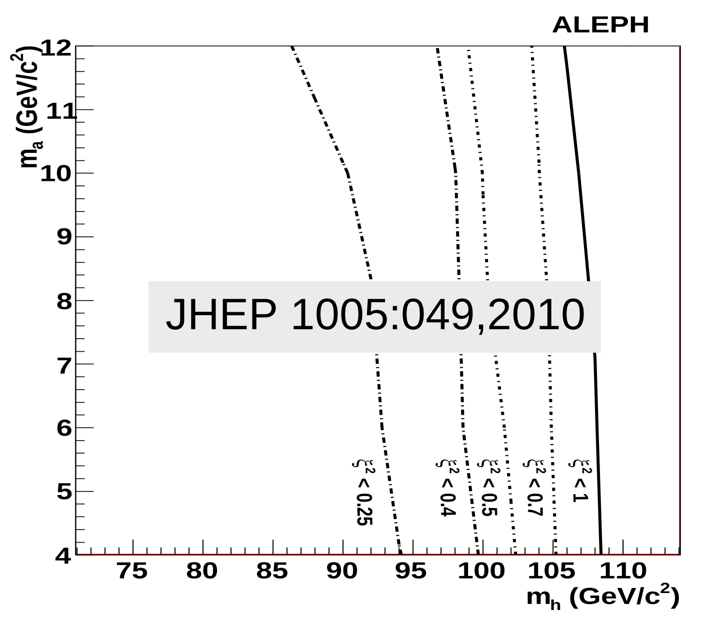
JHEP 0908:032,2009



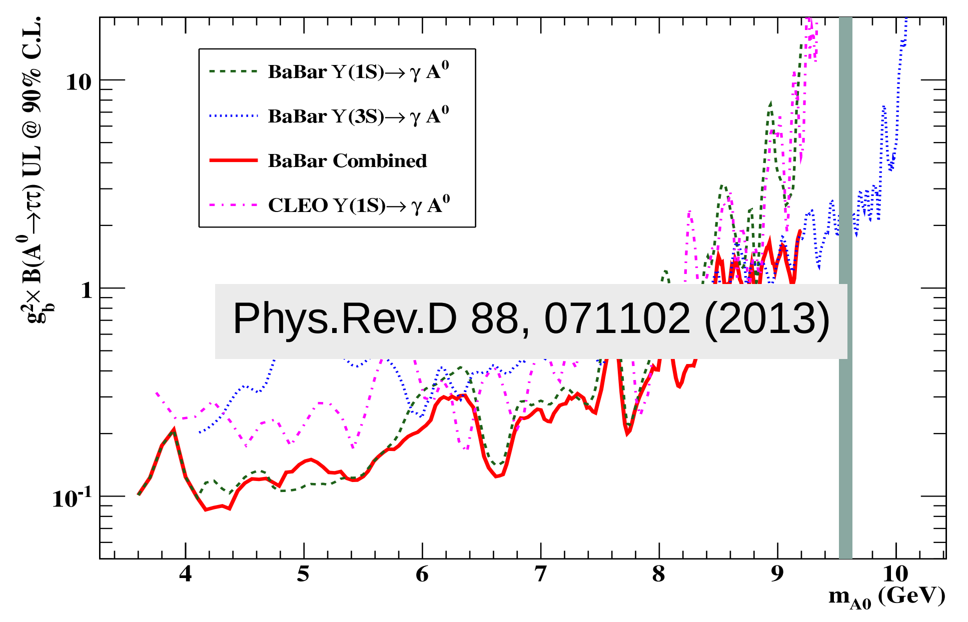
Eur.Phys.J.C47:547-587,2006



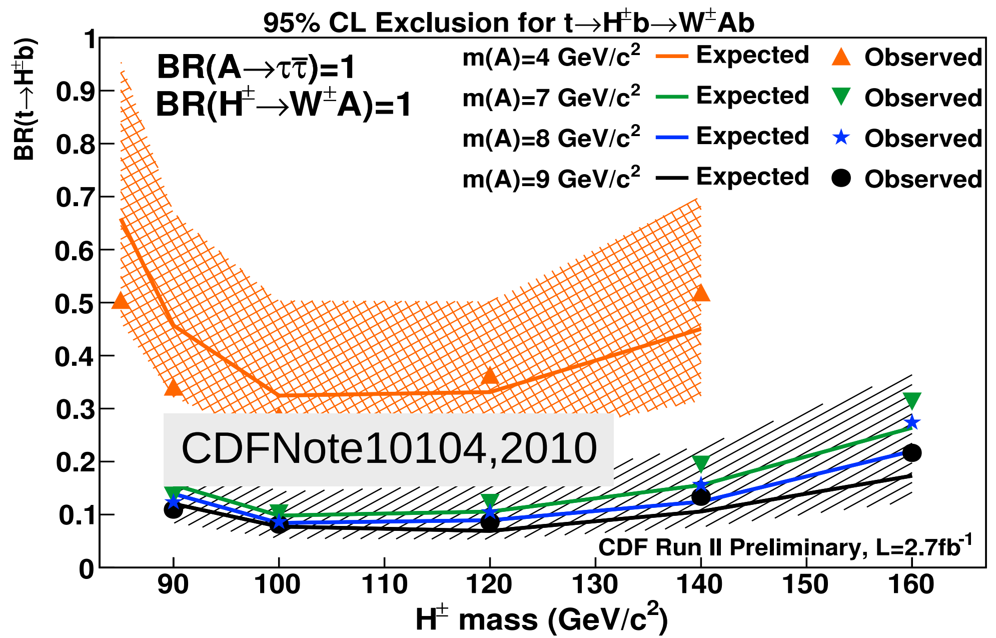
NMSSM Ideal Higgs at Aleph,BaBar,DZero,CDF



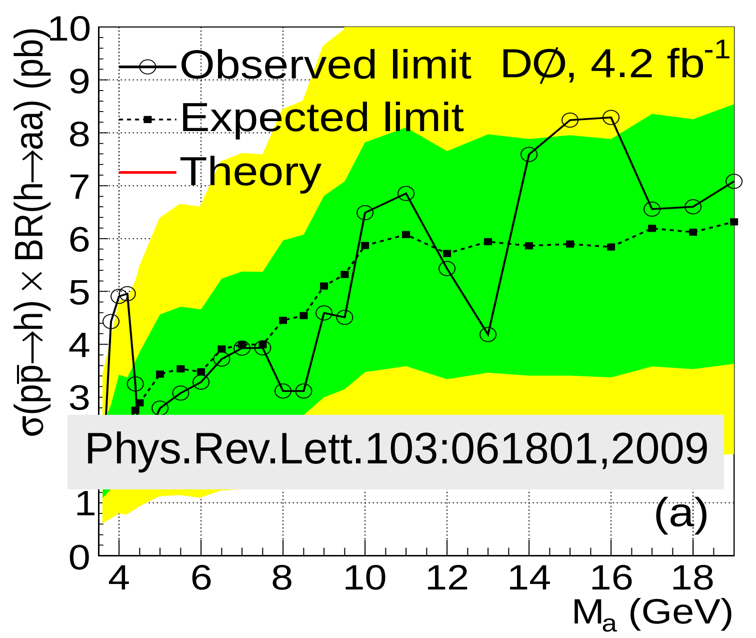
JHEP 1005:049,2010



Phys.Rev.D 88, 071102 (2013)

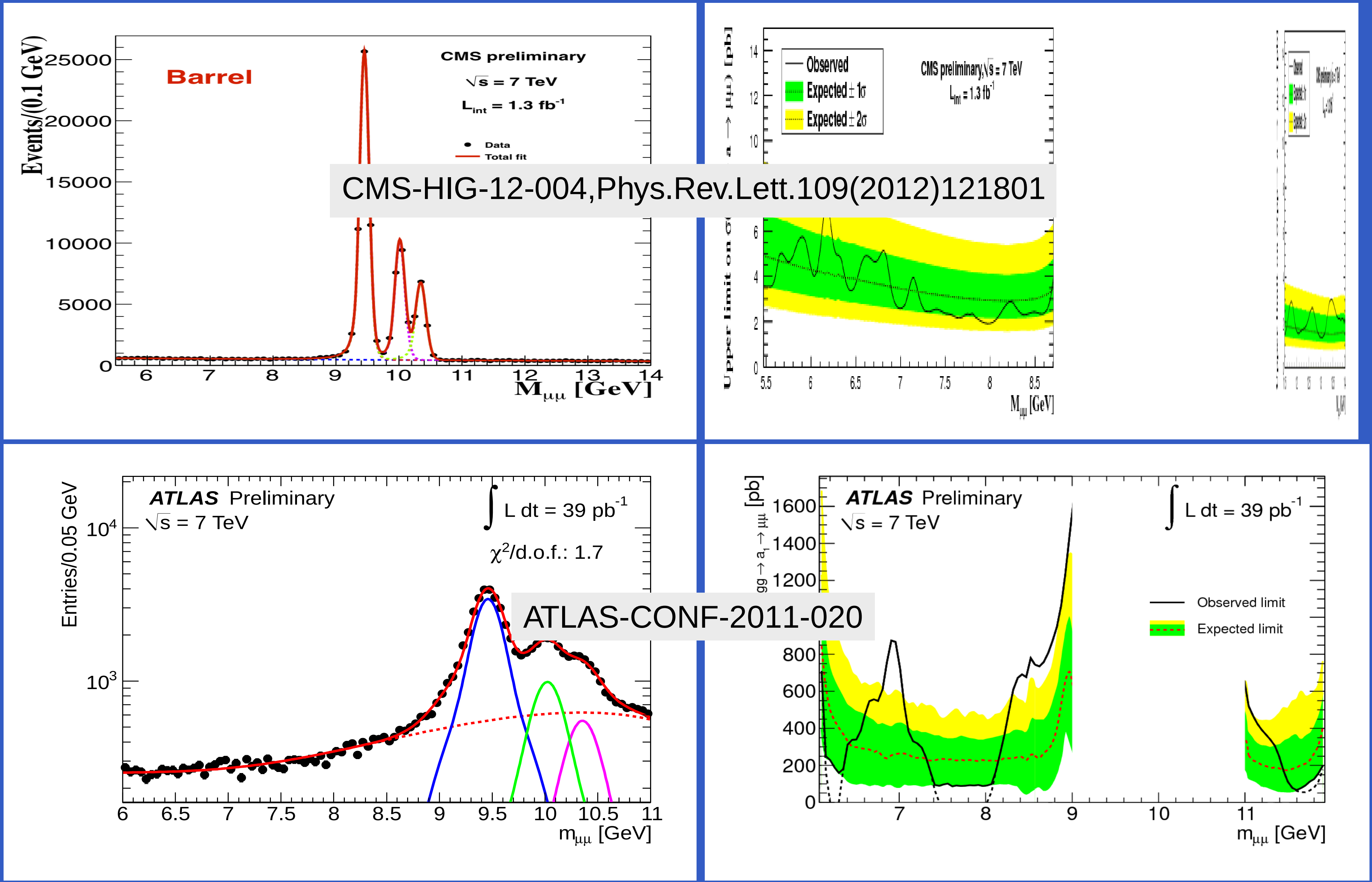


CDFNote10104,2010



Phys.Rev.Lett.103:061801,2009

NMSSM Ideal $gg \to a_1 \to \mu^+\mu^-$ at CMS,ATLAS

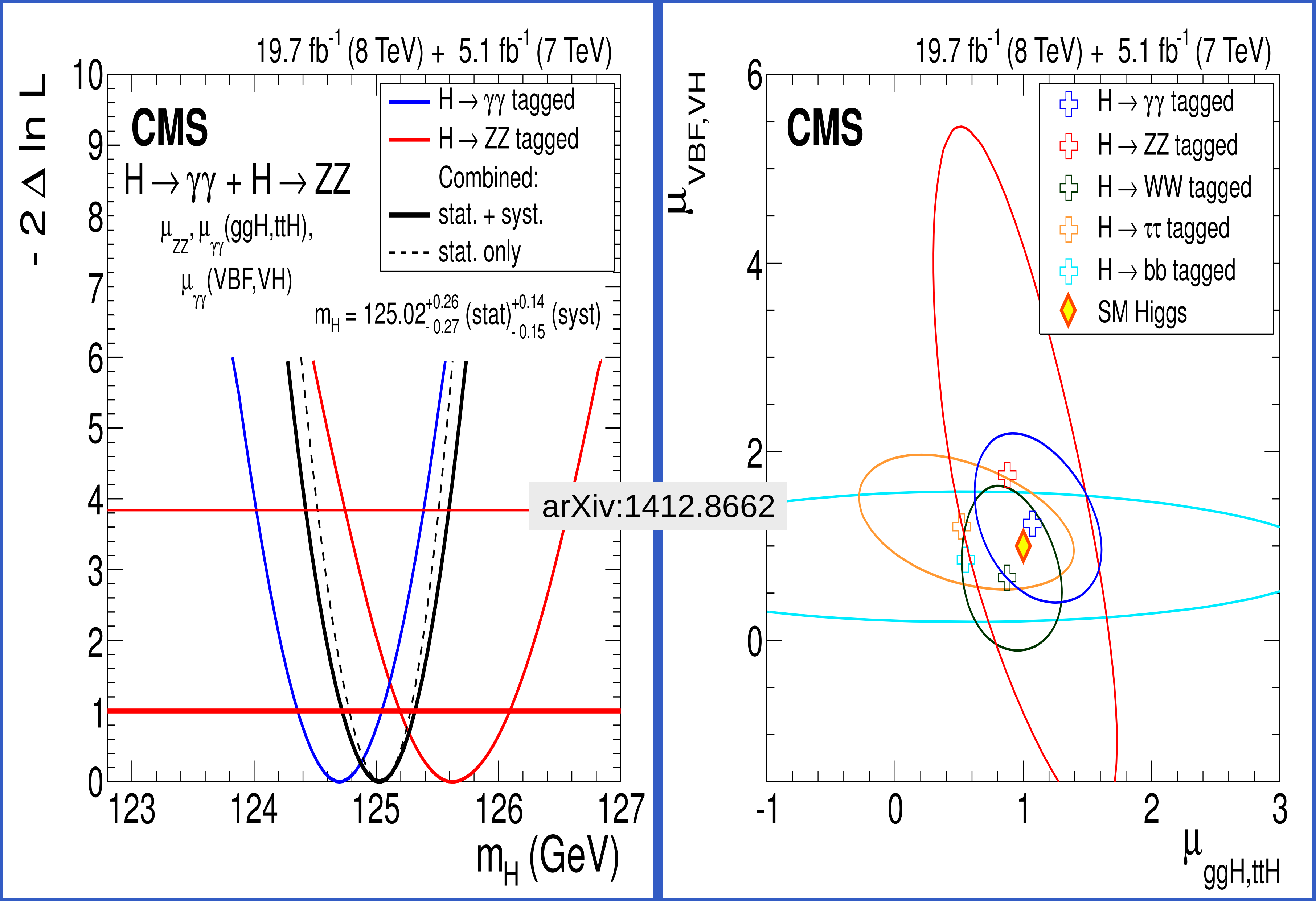


CMS-HIG-12-004,Phys.Rev.Lett.109(2012)121801

ATLAS-CONF-2011-020

At left, muon pair mass. At right, limits on $\sigma \times BR$ obtained with CLs technique.

The h_{125} Mass and Signal Strengths



arXiv:1412.8662

Snowmass Study: NMSSM Higgs BP0 (Excluded)

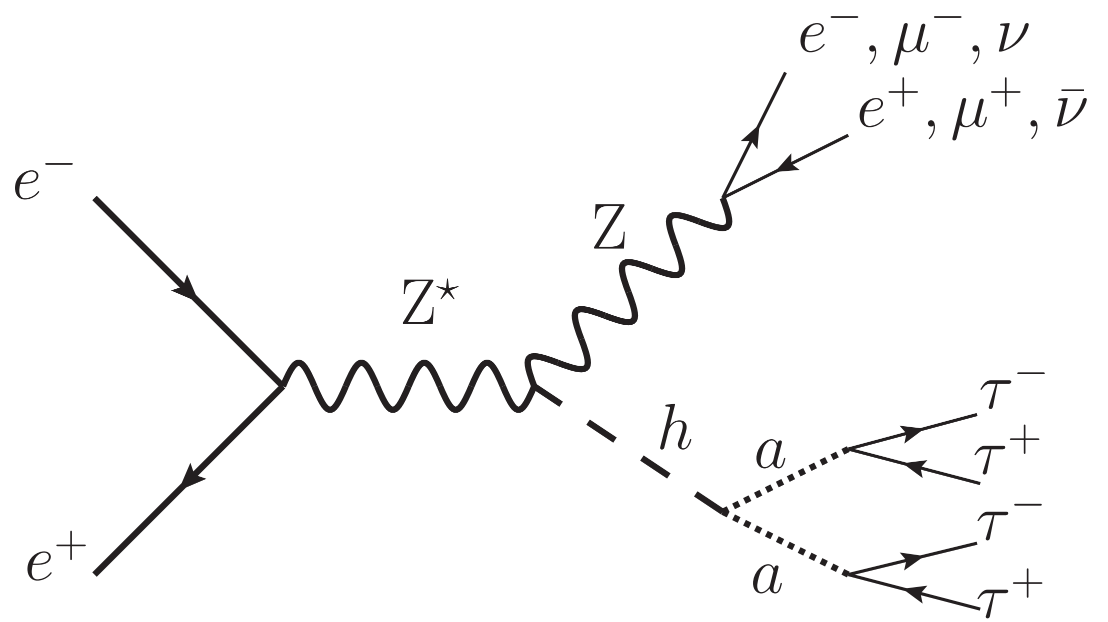
NMSSMTools 3.2.4

Target: $2m_\tau < m_{a_1} < 2m_B$, $90 < m_{h_1} < 100$ GeV, $m_{h_2} \approx 125$ GeV

Parameter	Value	Scalar	Mass [GeV]	Decay	Br [%]
λ	0.3	a_1	10.3	$h_1 \longrightarrow 2a_1$	85.4
κ	0.1	h_1	91.6	$h_2 \longrightarrow 2a_1$	87.4
A_κ	11.6	h_2	124.5	$a_1 \longrightarrow \tau^+\tau^-$	73.2
m_A	465 GeV	a_2	465.2	$a_1 \longrightarrow 2g$	22.3
$\tan\beta$	3.1	h_3	469.2	$a_1 \longrightarrow c\bar{c}$	3.1
μ_{eff}	165 GeV	$H^\pm$	465.7	$a_1 \longrightarrow \mu^+\mu^-$	0.3

The generated particle spectrum and decay tables are saved in SLHA files and passed to Whizard. See SNOW13-00133 (1309.0021) for full details. *This point has been excluded by the h_{125} signal strength constraints. Other points with similar phenomenology survive.*

Signal/Background Simulation



- Simulation of the signal process $e^+e^- \rightarrow Zh_{1,2} \rightarrow f\bar{f}a_1a_1$ was performed with the Whizard event generator, which has a full implementation of the NMSSM.
- Whizard interfaces the NMSSM model with the SLHA file generated by NMSSMTools.
- Signal events are weighted by $Zh_{1,2}$ production cross section multiplied by the branching ratio for $Z \rightarrow f\bar{f}$.
- Background is $e^+e^- \rightarrow ZZ \rightarrow Z\tau_{-pr}\tau_{3-pr}$, a dedicated high statistics sample generated.
- Thanks to Tim Barklow for generating the Whizard events and Norman Graf for SiD detector simulation and event reconstruction.

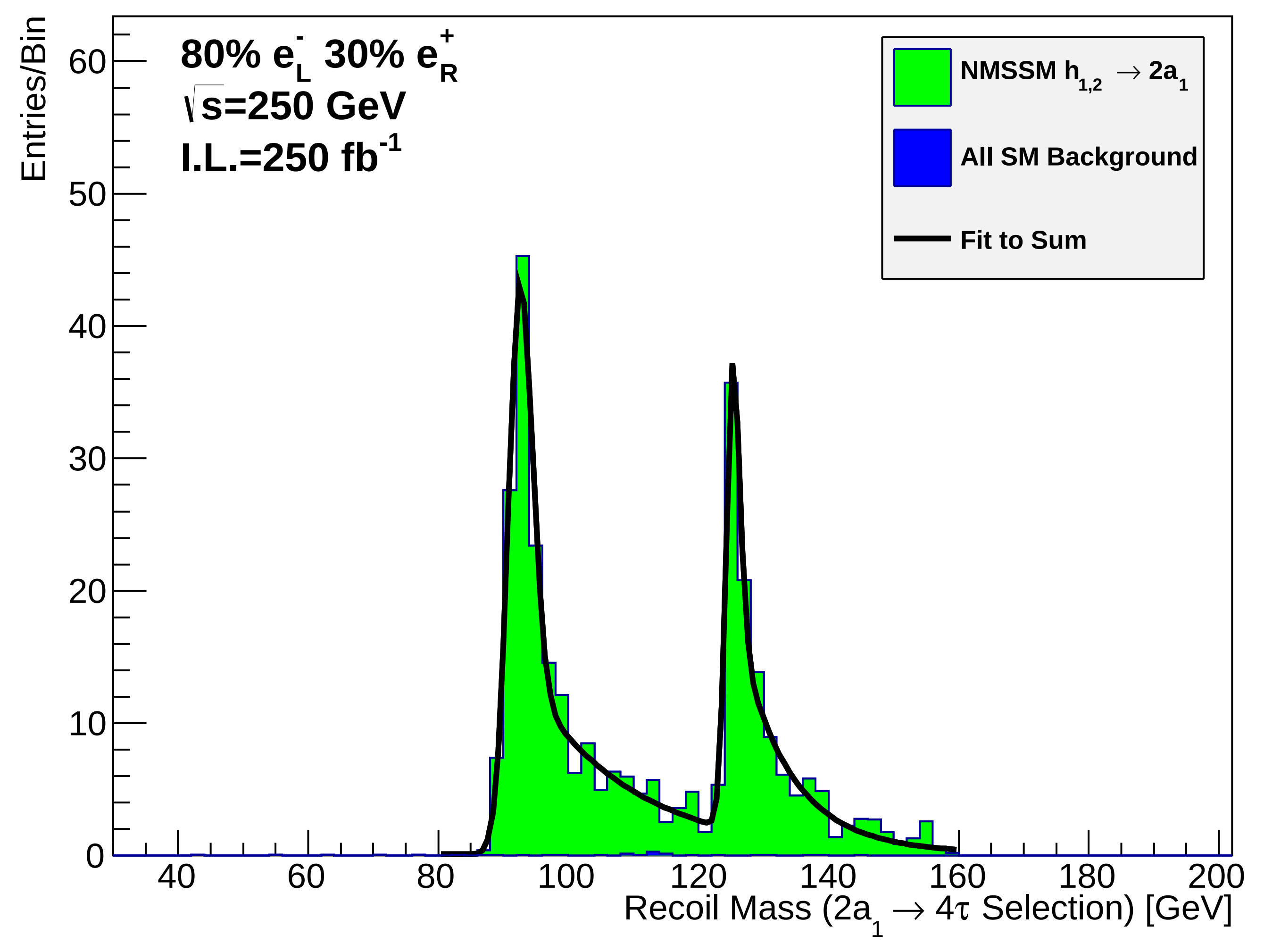
The $h_{1,2} \to 2a_1 \to 4\tau$ Channel

The $h_{1,2} \to 2a_1 \to 4\tau$ Selection Requirements

- Require at least two muons with $p_T > 5$ GeV ($N_{\mu 5} \geq 2$)
- Require the muon pair closest to the Z mass within 3σ of the nominal Z mass ($|m_Z - m_{\mu^+\mu^-}| < 3\sigma$)
- Require exactly six tracks with $p_T > 0.2$ GeV ($N_{trk} = 6$)
- Require zero net charge in the recoil tracks ($Q_{4trk} = 0$)
- Veto $\tau \to a_1(1260)\nu$ by requiring candidate $a_1(1260)$ mass $m_{3trk} > 2$ GeV
- Case I: require $123 < m_{recoil} < 160$ GeV;
- Case II: or require $80 < m_{recoil} < 123$ GeV;
- Case III: or require none.
- Yields assume $\sqrt{s} = 250$ GeV, 250fb^{-1} luminosity, and 80% e^-_L, 30% e^+_R beam polarization:

	Case I	Case II	Case III
Signal	121	182	302
Background	0.4	1.3	1.7

$h_{1,2}$ Recoil Masses after Full Selection



The fits yield $m_{h_1} = 90.8 \pm 0.2$ GeV and $m_{h_2} = 124.7 \pm 0.2$ GeV.

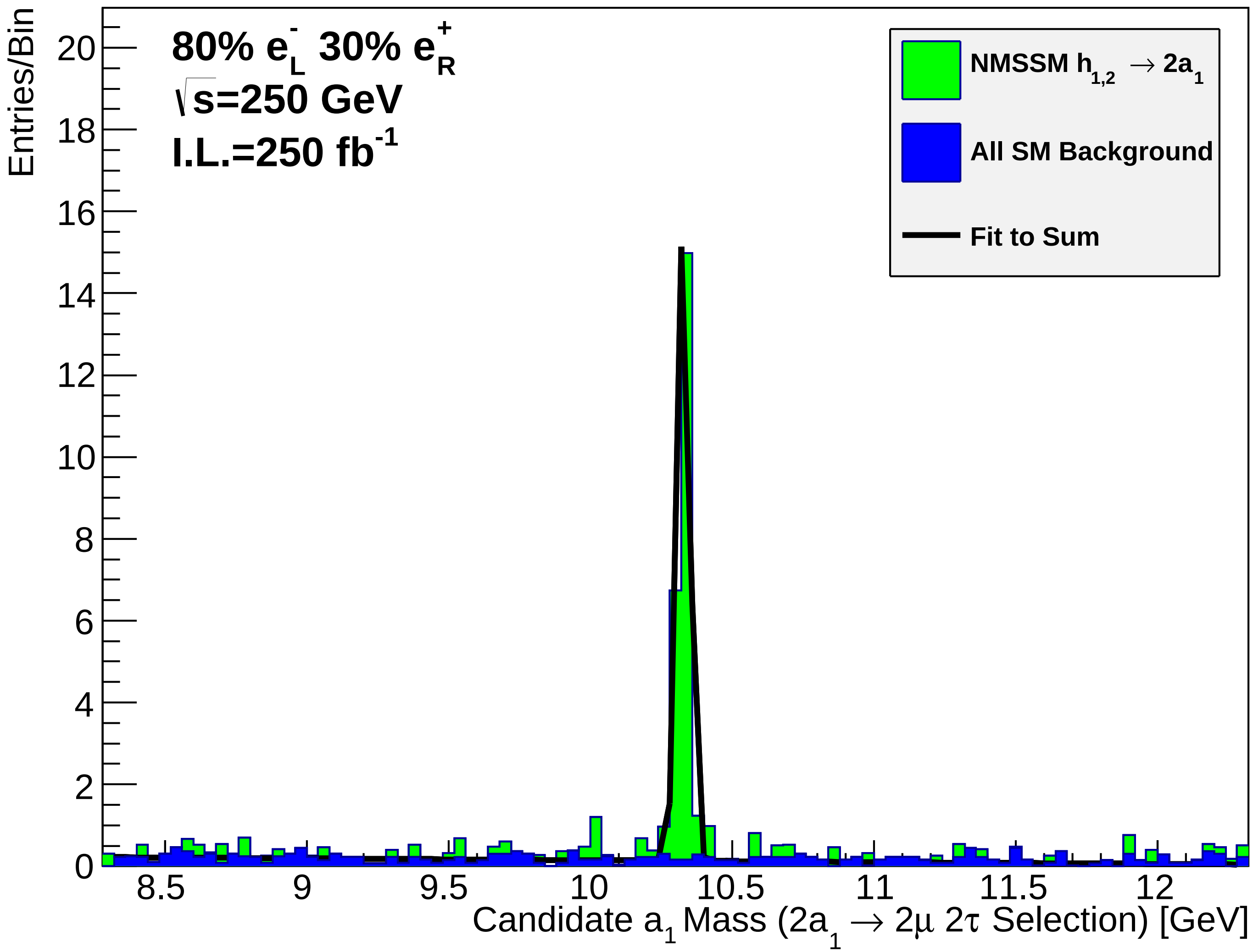
The $h_{1,2} \to 2a_1 \to 2\mu 2\tau$ Channel

The $h_{1,2} \to 2a_1 \to 2\mu 2\tau$ Selection Requirements

- require at least two muons with $p_T > 5$ GeV ($N_{\mu 5} \geq 2$)
- require exactly six or eight tracks with $p_T > 0.2$ GeV ($N_{trk} = 6, 8$)
- require zero net charge in the tracks ($Q_{trks} = 0$)
- require the muon pair mass closest to the a_1 mass within 3σ of the fitted a_1 mass ($|m_{a_1} - m_{\mu^+\mu^-}| < 3\sigma$)
- The expected SM background is 0.7 events and the expected signal yield is 23 events for Case III.
- After luminosity upgrades (1150 fb^{-1}), the expected number of signal events is 106 for Case III.

Here we seek to identify $a_1 \to \mu^+\mu^-$ events without requiring the $Z \to \mu^+\mu^-$ decay channel, greatly enlarging the signal yield. On the Z side we require no-track or two-track decays $Z \to \nu\bar{\nu}, e^+e^-, \mu^+\mu^+, \tau_{1-pr}, \tau_{1-pr}$ and on the $h_{1,2}$ side require one $a_1 \to \mu^+\mu^-$ and one $a_1 \to \tau^+\tau^-$ where the taus decays as either 1- or 3-prongs.

Reconstructed $a_1 \rightarrow \mu^+\mu^-$ After Full Selection



The fit yields $m_{a_1} = 10.329 \pm 0.005$ GeV.

SM-like h_{125} Recipe for Parameter Scan

- How can SUSY accommodate the high Higgs mass and the SM-like Higgs couplings?
- Correction to the tree level MSSM h mass from stop mixing ($m_{\tilde{t}}^2 \equiv \frac{1}{2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2\right)$):

arXiv:1110.6926

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right)$$

- Here $X_t \equiv A_t - \mu/\tan\beta$ is the *stop mixing parameter*. Maximal mixing, and therefore the maximum contribution to the Higgs mass, occurs for $X_t = X_t^{max} = \sqrt{6} m_{\tilde{t}}$.
- In principle the NMSSM Higgses from the singlet can mix with the MSSM Higgs sector, but for simplicity consider the MSSM completely decoupled from the singlet.
- In the MSSM decoupling limit $m_Z/m_A \propto \cos(\beta - \alpha) \rightarrow 0$, the MSSM h couplings approach their Standard Model values. Denote $x \equiv \sin(\beta - \alpha)$. Then this limit is $x \rightarrow 1$:

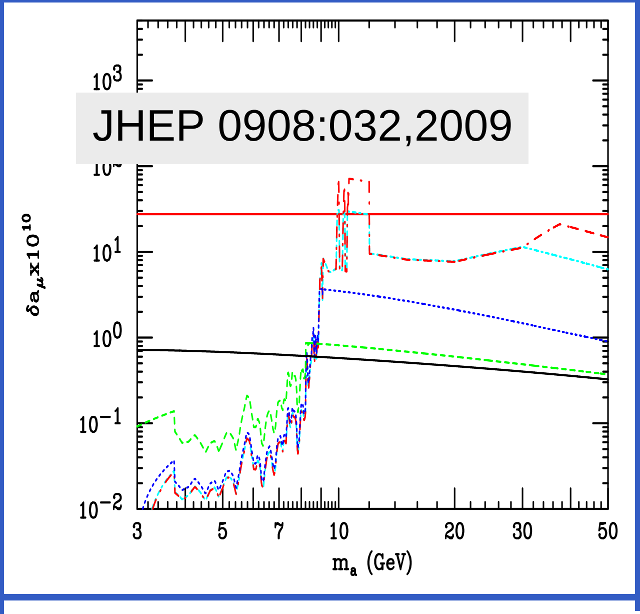
Prog.Part.Nucl.Phys.50:63-152,2003

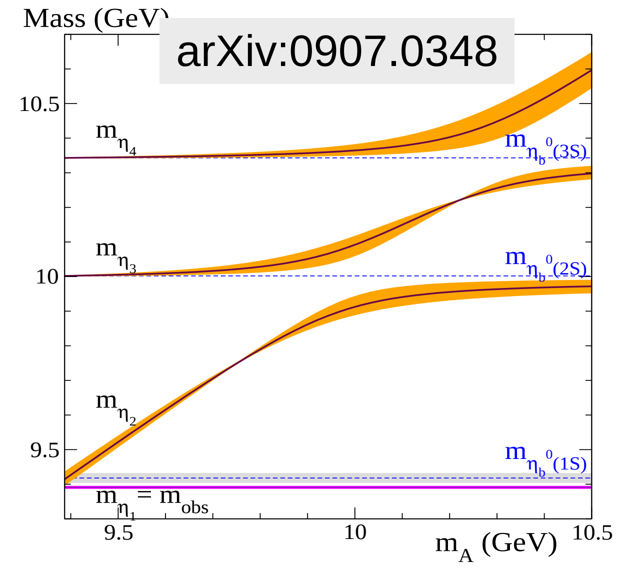
$$\begin{aligned} g_{hVV} &= x \times g_{hVV}^{SM} \\ g_{hff} &= g_{hff}^{SM} \times \left(x - \sqrt{1 - x^2}\tan^n\beta\right) \end{aligned}$$

- Easy. Allow large stop mixing and put m_A in the decoupling limit.

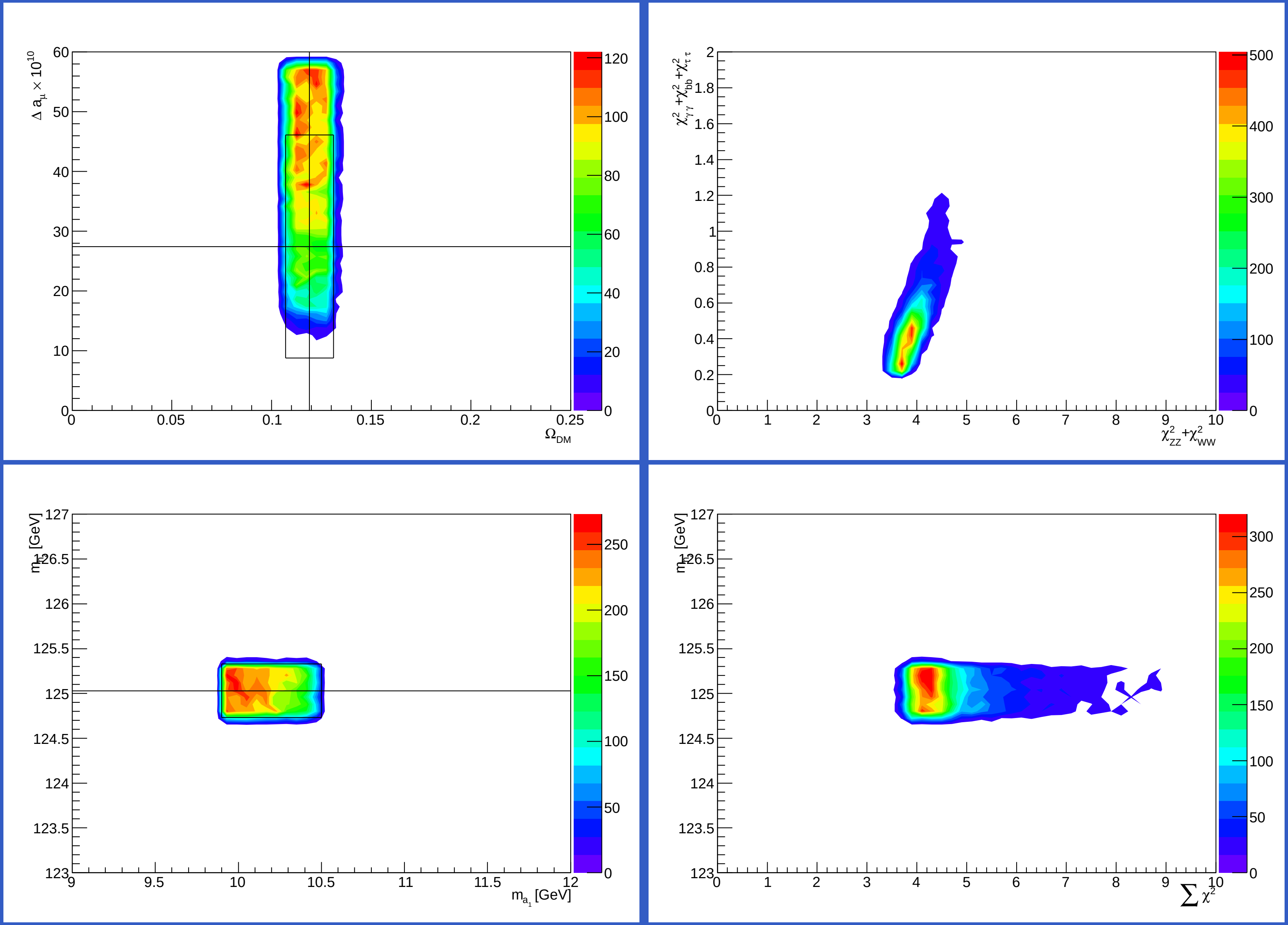
NMSSMTools4.4.0 Random Scan of 10^9 Points

- Scan Parameter Ranges
  - $300 < m_A < 3000$ GeV and $9.9 < m_P < 10.5$ GeV
  - $1 < \tan\beta < 30$ and $100 < \mu < 200$ GeV
  - $0 < |\kappa| < 0.01$ and $0 < \lambda < 0.02$
  - $0.8 < X_t/X_0^{max} < 1.8$, X_0^{max} is tree-level max. mix.
  - $250 < M_{Q3}, M_{U3} < 1500$ GeV, $A_t = X_t + \mu/\tan\beta$
  - $100 < M_2 < 400$ GeV, unif. constraints M_1, M_3
- Constraints Imposed During Scan (10.9M points survive)
  - DM Relic Density Ω_{DM}, (+In)direct DM searches
  - Anomalous Muon Magnetic Moment Δa_μ
  - All Collider and B Physics Constraints
  - $123 < m_{h_1} < 127$ GeV or $123 < m_{h_2} < 127$ GeV
  - Higgs signal strength μ $\chi^2_{ZZWW}, \chi^2_{bb\tau\tau}, \chi^2_{\gamma\gamma} < 6$
- Constraints Imposed After Scan (13K points survive)
  - $124.73 < m_{h_2} < 125.33$ GeV (CMS-PAS-HIG-14-009)
  - Signal strength $\chi^2_{ZZWW} + \chi^2_{bb\tau\tau} + \chi^2_{\gamma\gamma} < 7$


JHEP 0908:032,2009

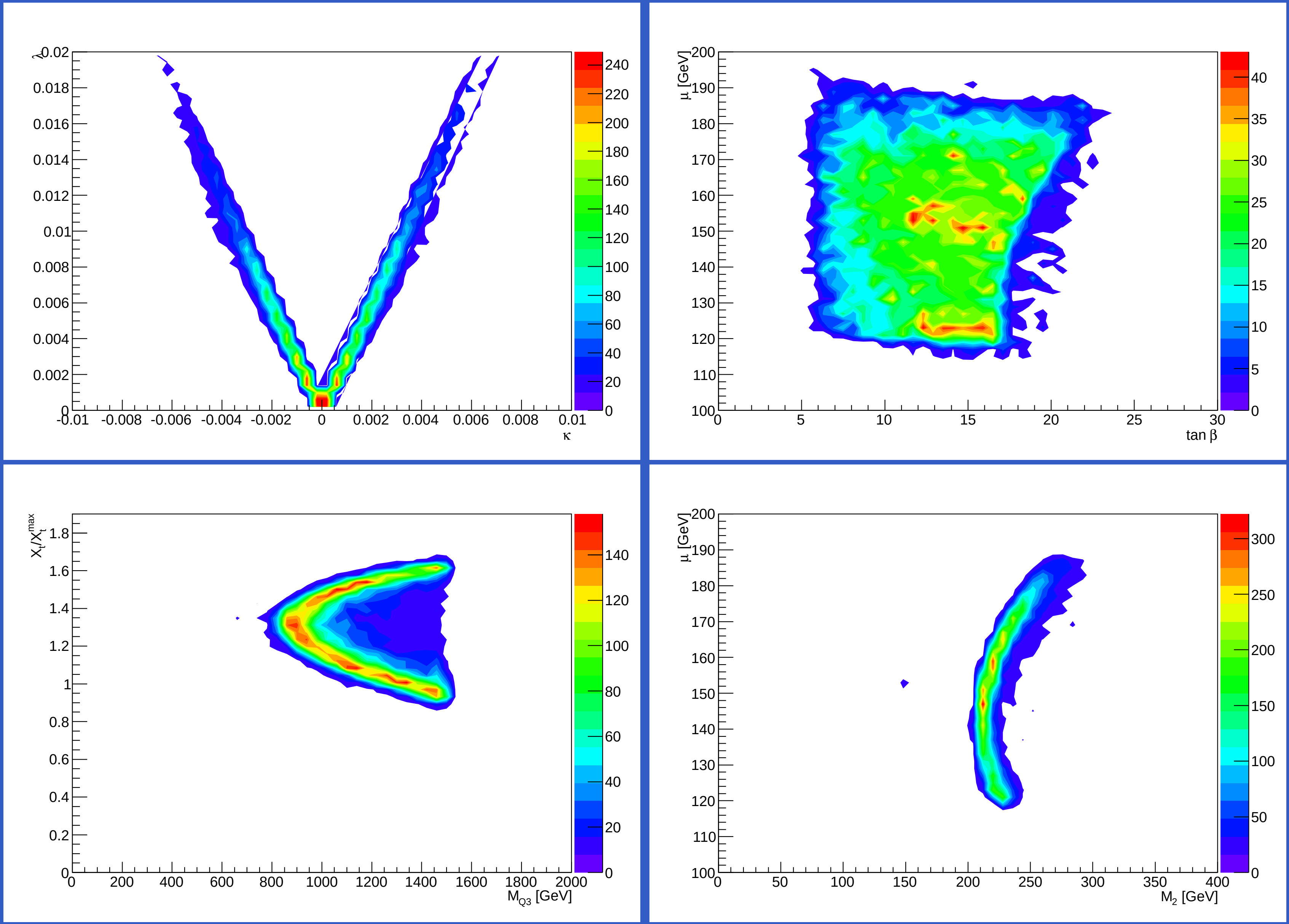

arXiv:0907.0348

Constraints: Δa_μ, Ω_{DM}, h_{125}



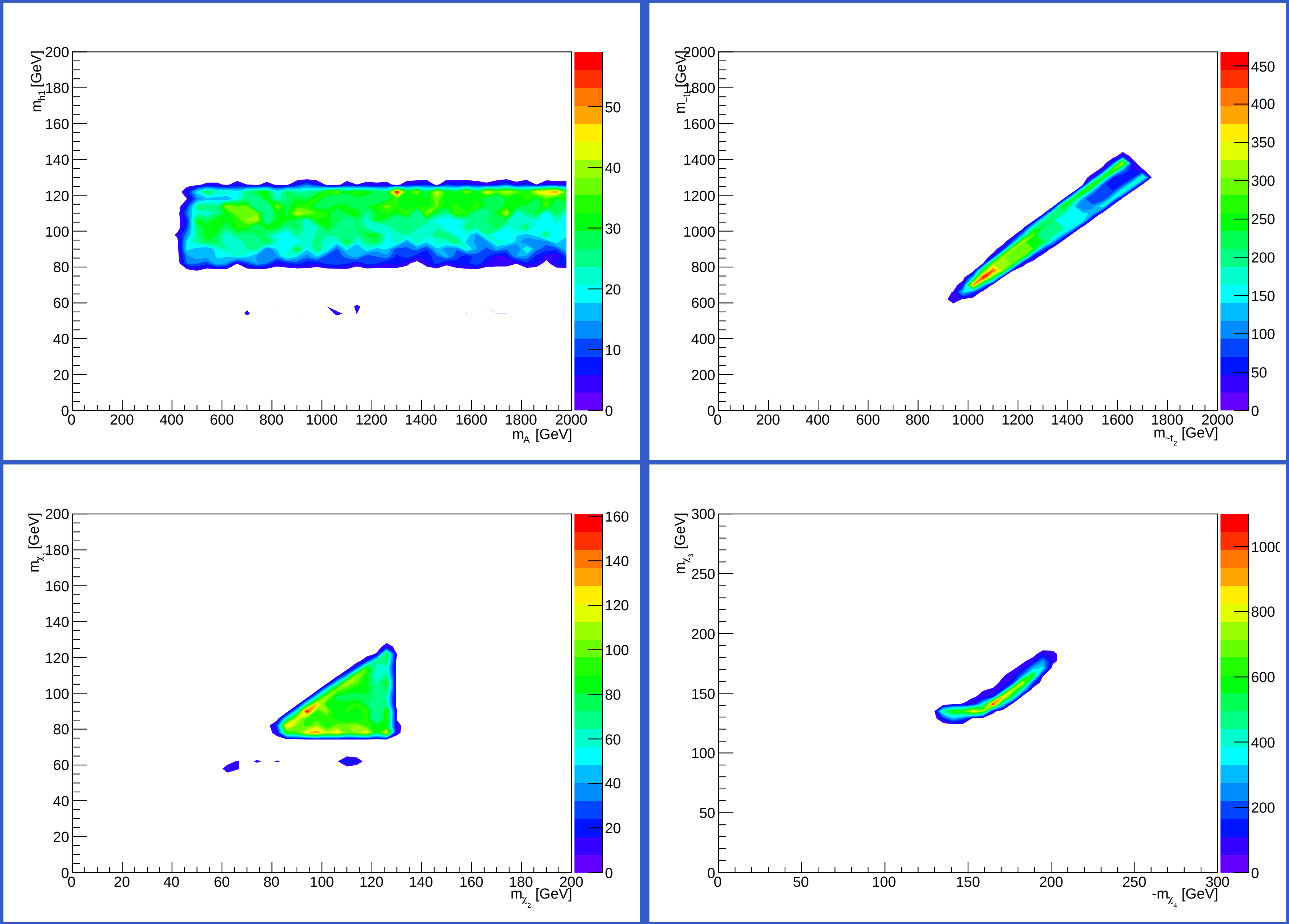
Clockwise from top left, Δa_μ vs Ω_{DM}, $\sum\chi^2_{ff}$ vs $\sum\chi^2_{VV}$, m_{h_2} vs $\sum\chi^2$, m_{h_2} vs m_{a_1}.

Scanned Parameters After Constraints



Clockwise from top left, λ vs κ, μ vs $\tan\beta$, μ vs M_2, X_t/X_0^{max} vs M_{Q3}.

Mass Spectra After Constraints



Clockwise from top left, m_{h_1} vs m_A, $m_{\chi 1}$ vs $m_{\chi 2}$, $m_{\chi 3}$ vs $m_{\chi 4}$, $m_{\chi 1}$ vs $m_{\chi 5}$.

Two Viable Points with $m_{h_1} \approx 60, 100$ GeV (BP1,BP2)

NMSSMTools4.4.0

BP1 Target: $9.9 < m_{a_1} < 10.5$ GeV, $m_{h_1} \approx 60$ GeV, $m_{h_2} \approx 125$ GeV

Parameter	Value	Scalar	Mass [GeV]	Decay	Br [%]
λ	0.0018	a_1	10.1	$h_1 \to 2a_1$	0.987
κ	0.00036	h_1	59.3	$h_2 \to 2a_1$	6.0×10^{-5}
m_P	10.3 GeV	h_2	121.7	$a_1 \to \tau^+\tau^-$	0.790
m_A	914 GeV	a_2	914	$a_1 \to 2g$	0.176
$\tan\beta$	7.5	h_3	914	$a_1 \to c\bar{c}$	0.020
μ_{eff}	150 GeV	$H^\pm$	917	$a_1 \to \mu^+\mu^-$	0.0030

BP2 Target: $9.9 < m_{a_1} < 10.5$ GeV, $m_{h_1} \approx 100$ GeV, $m_{h_2} \approx 125$ GeV

Parameter	Value	Scalar	Mass [GeV]	Decay	Br [%]
λ	0.0021	a_1	10.3	$h_1 \to 2a_1$	0.0399
κ	0.00076	h_1	96.9	$h_2 \to 2a_1$	5.9×10^{-6}
m_P	10.4 GeV	h_2	121	$a_1 \to \tau^+\tau^-$	0.792
m_A	2667	a_2	2662	$a_1 \to 2g$	0.174
$\tan\beta$	7.7	h_3	2663	$a_1 \to c\bar{c}$	0.020
μ_{eff}	138	$H^\pm$	2667	$a_1 \to \mu^+\mu^-$	0.0030

Recast BP0 to BP1,BP2

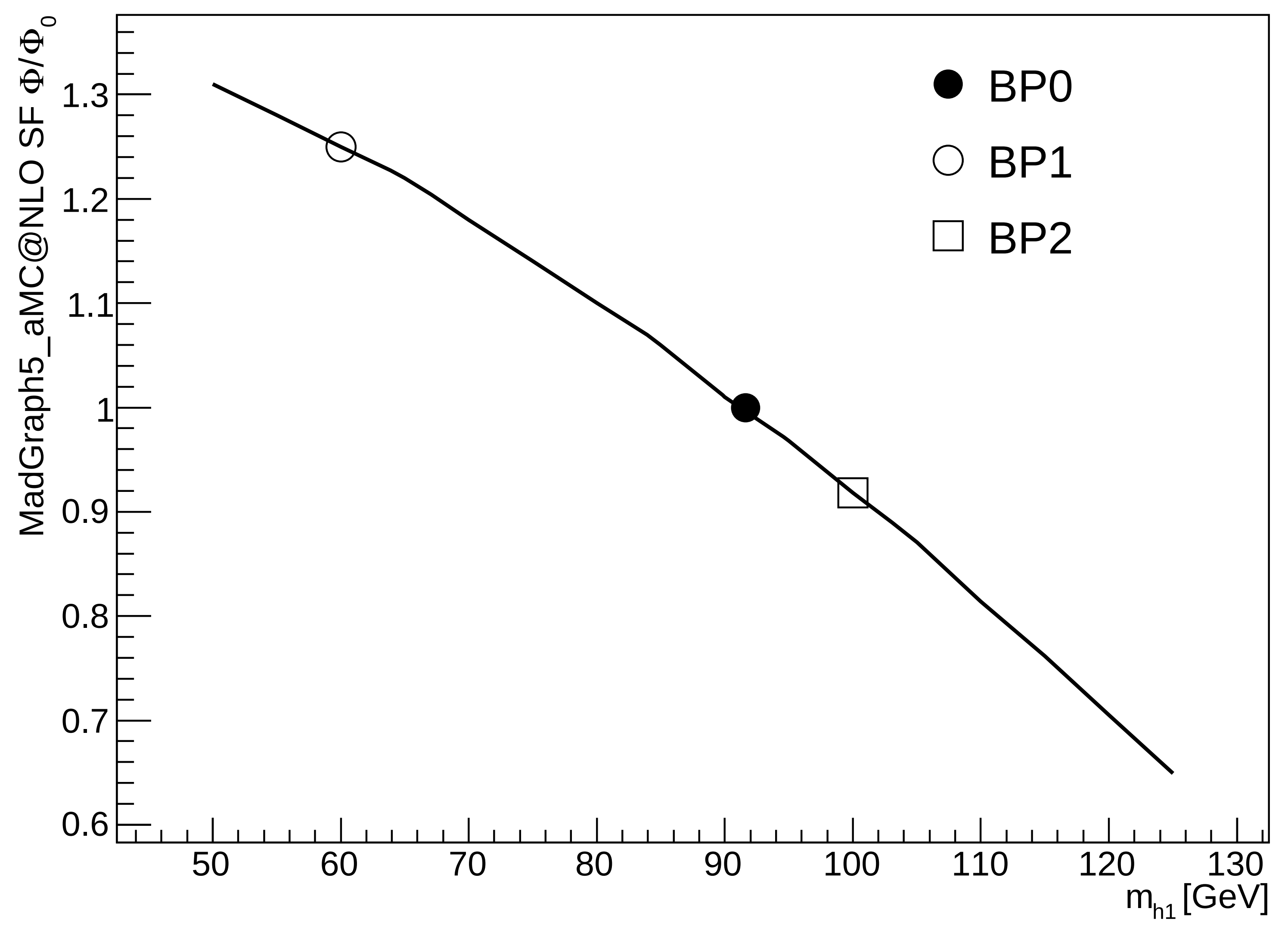
- Denote the reduced couplings $\xi_i \equiv g_{ZZh_i}/g_{ZZh_{SM}}$. Scale factors from the signal yield expression $N = \epsilon\sigma B \int dt\mathcal{L}$:

$$\begin{aligned} \frac{N_{xy}}{N_0}(m_{h_1}) &= \frac{\epsilon}{\epsilon_0}(m_{h_1})\frac{\Phi}{\Phi_0}(m_{h_1})\left(\frac{\xi_1}{\xi_1^0}\right)^2 \frac{B(h_1 \to 2a_1)B(a_1 \to x)B(a_1 \to y)}{B_0} \\ \frac{N_{xy}}{N_0}(m_{h_2}) &= \left(\frac{\xi_2}{\xi_2^0}\right)^2 \frac{B(h_2 \to 2a_1)B(a_1 \to x)B(a_1 \to y)}{B_0} \end{aligned}$$

- MG5_aMC@NLO2.2.0 is used to determine ϵ and Φ. Initial studies indicate $\epsilon/\epsilon_0 \approx 1$.
- NMSSMTools4.4.4 provides the reduced couplings $\xi_{1,2}$ and branching ratios B.

Point	ξ_1	ξ_2	$h_1 \to 2a_1$	$h_2 \to 2a_1$	$a_1 \to \tau^+\tau^-$	$a_1 \to \mu^+\mu^-$
BP0	0.792	0.610	0.854	0.875	0.732	0.00276
BP1	0.0284	0.999	0.987	6.0×10^{-5}	0.790	0.00299
BP2	0.101	0.995	0.0399	5.9×10^{-6}	0.792	0.00298

Scale Factor Φ/Φ_0



Phase space scale factor as a function of m_{h_1} determined with MG5_aMC@NLO.

Status and Plans

- The NMSSM
  - The NMSSM is highly motivated both theoretically and experimentally.
  - The h_{125} mass and signal strength measurements provide very strong constraints on NMSSM Higgs phenomenology.
  - If a low mass pseudoscalar $9.9 < m_{a_1} < 10.5$ GeV is assumed, as motivated by the anomalous muon magnetic moment and η_b spectroscopy, the model becomes highly predictive.
- Snowmass Study
  - The Snowmass SiD study SNOW13-00133 (1309.0021) assumed signal strengths which are now excluded, so the study will be recast for scenarios which survive all h_{125} constraints.
  - The $e^+e^- \to Zh_i$ cross section depends on the reduced ZZh_i couplings, which in turn depend on the mixing of h_1, h_2, h_3.
  - Challenging NMSSM points will provide excellent benchmarks for detector development with more sophisticated reconstruction techniques than were used for this study.
  - A systematic study of remaining viable NMSSM points is underway.