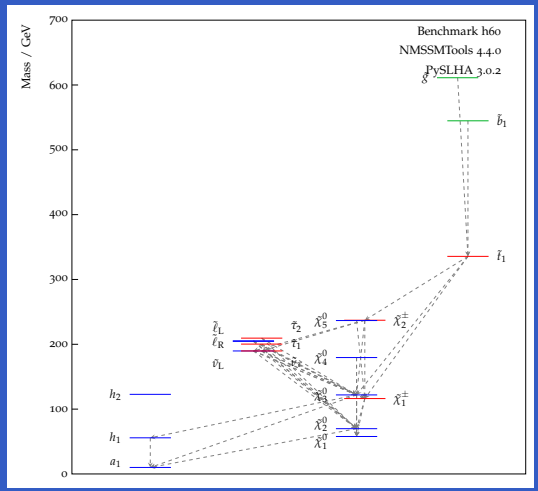
NMSSM at (LEP, LHC and) ILC



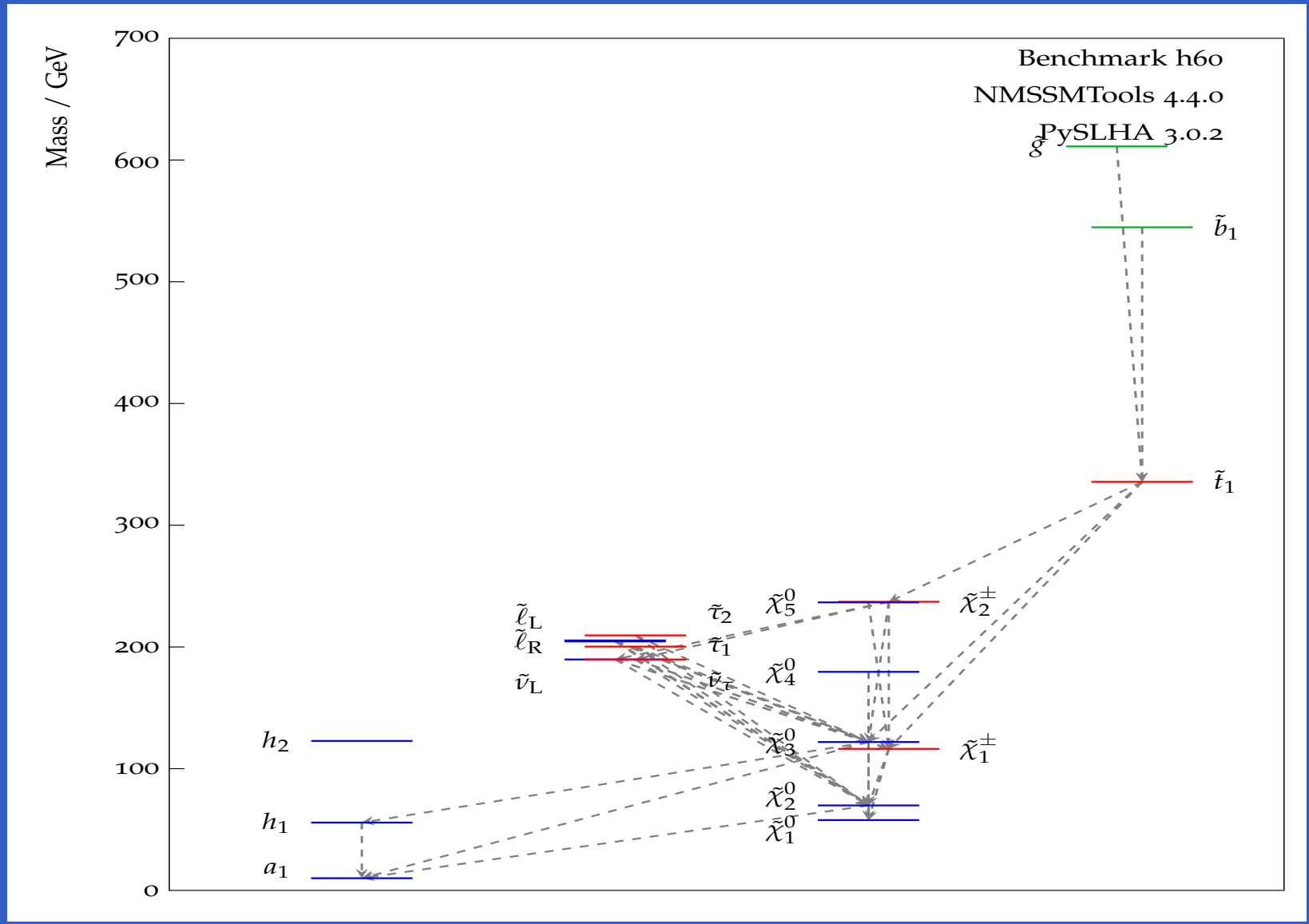
Chris Potter

UO CHEP/Alder IHEP [a]

[a] http://www.alderihep.org/

Synopsis: NMSSM Benchmark Point h_{60}

Natural NMSSM with a Light Singlet Higgs and Singlino LSP (1505.05554v3)



Mass spectrum in benchmark point h_{60} (1505.05554v3, submitted EPJC). Aka BP3 at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGNMSSM

The NMSSM

Theoretical Motivation

Superpotential and Lagrangian

Higgs Sector

Chargino/Neutralino/Stop Sectors

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:

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

- The soft SUSY breaking terms in the NMSSM Lagrangian are

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

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

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

- 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

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

- 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

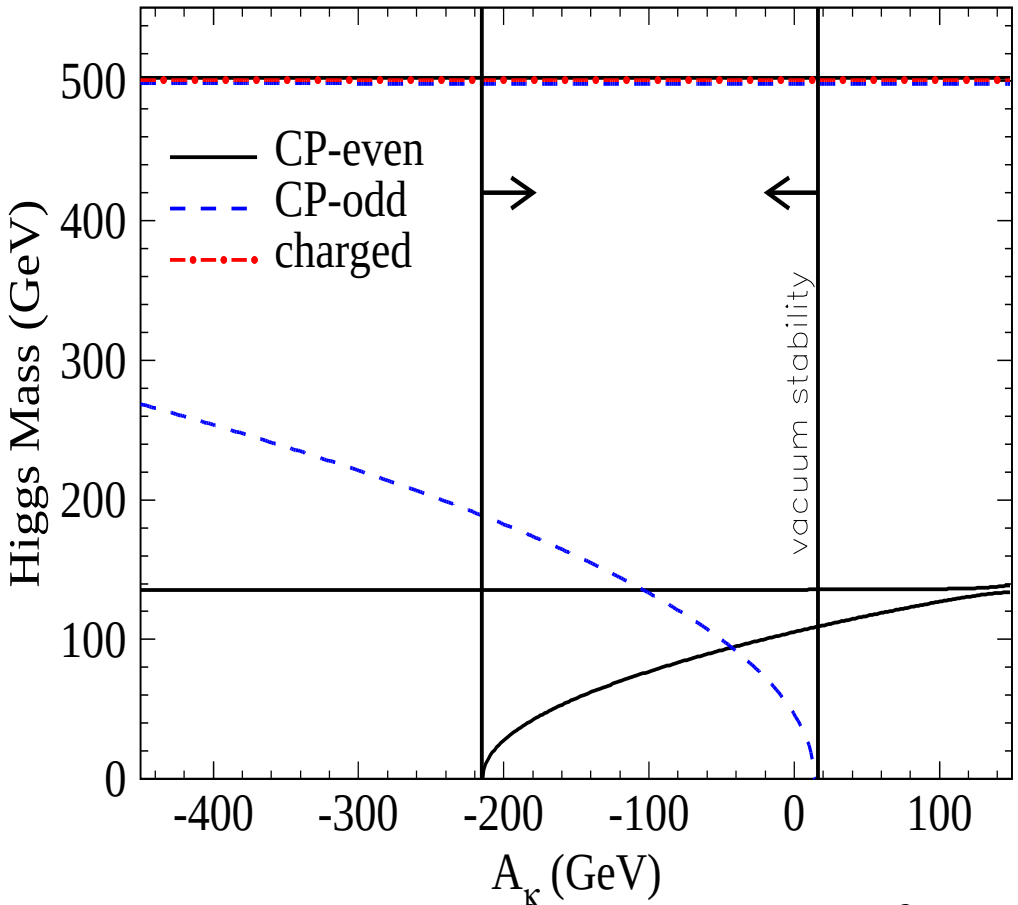
$$\begin{aligned}
m_{a_1}^2 &\approx -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa \\
m_{h_{1,2}}^2 &\approx \frac{1}{2}\left[m_Z^2 + \frac{1}{2}\kappa v_s(4\kappa v_s + \sqrt{2}A_\kappa) \pm f(\kappa, v_s, A_\kappa, \lambda, m_A, \sin\beta)\right] \\
m_{a_2}^2 &\approx m_A^2\left(1 + \frac{1}{4}\cot^2\beta_s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

- 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)

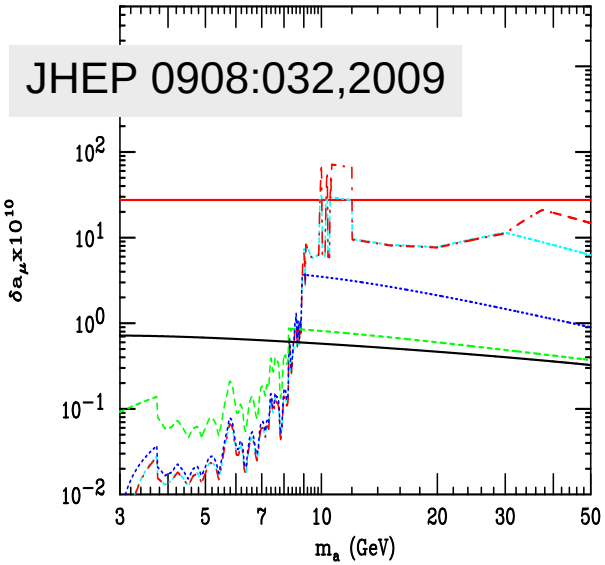
Low mass scalars a_1 and h_1 absent in the MSSM but present in the NMSSM are motivated by the anomalous muon magnetic moment and the LEP excess in the $Zh \to Zb\bar{b}$ channel.

Nucl.Phys.B681:3-30,2004

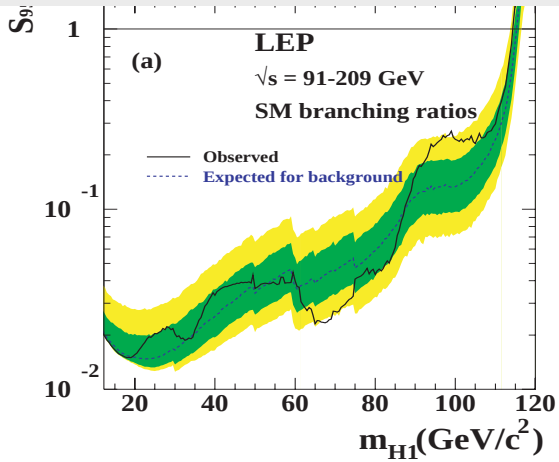


$\lambda = 0.3$, $\kappa = 0.1$, $v_s = 3v$, $\tan\beta = 3$, $m_A = \mu \tan\beta \approx 470$ GeV

JHEP 0908:032,2009



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



NMSSM Parameters and the $h, \chi^+, \chi^0, \tilde{t}$ Sectors

	Symbol	Parameter	Phenomenology
Higgs, χ^+/χ^0	$\tan\beta$	Doublet VEV Ratio	Couplings
	λ	SH_uH_d Yukawa Coupling	Singlet-Doublet
	κ	S^3 Yukawa Coupling	Singlet Mass
	$m_A(A_\lambda)$*	Diagonal Doublet CP-Odd Mass	SM-like h_{125}
	$m_P(A_\kappa)$*	Diagonal Singlet CP-Odd Mass	Singlino Mass
	μ_{eff}	Higgsino Mass	Neutralino Mass
χ^+/χ^0	M_1	Gaugino 1 Mass	Neutralino Mass
	M_2	Gaugino 2 Mass	Neutralino Mass
	M_3	Gaugino 3 Mass	Neutralino Mass
$\tilde{t}$, Higgs	$X_t(A_t)$*	Stop Mixing Parameter	h_{125} Mass
	$m_{\tilde{Q}3_L}$	LH 3rd Gen. Squark	Stop Mass
	$m_{\tilde{U}3_R}$	RH Top Squark	Stop Mass

(*) $m_A^2 \equiv \frac{\lambda v_s}{\sin 2\beta}\left(\sqrt{2}A_\lambda + \kappa v_s\right)$, $m_P^2 \equiv -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa$, $X_t \equiv A_t - \mu/\tan\beta$

Experimental Searches

ALEPH: $h \to 2a$

BaBar: $\Upsilon \to \gamma a$

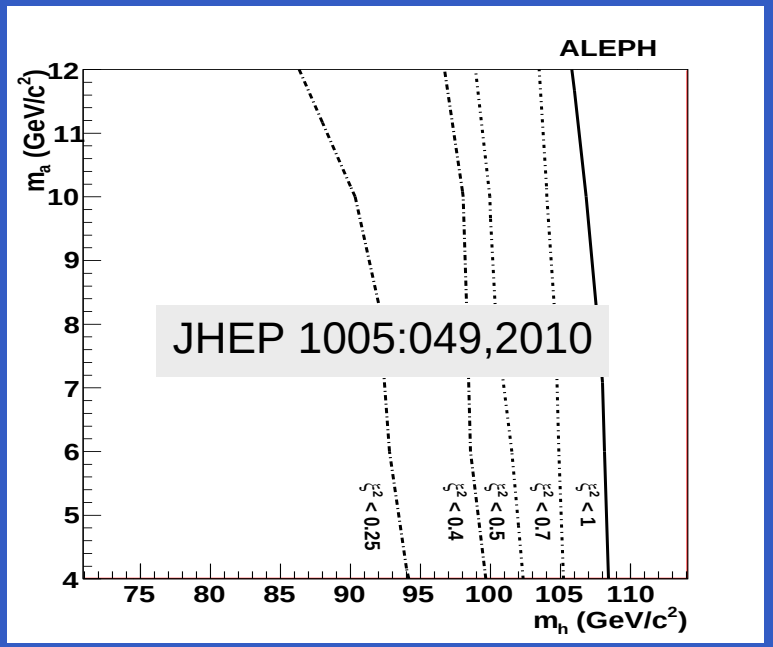
DZero: $h \to 2a$

CDF: $t \to bH^+ \to baW$

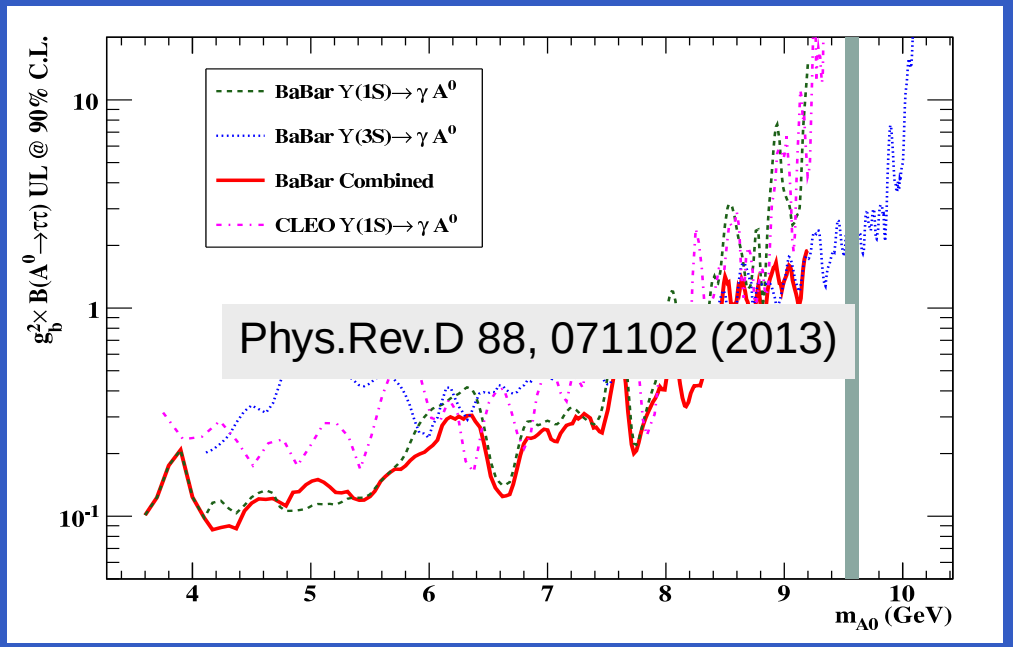
ATLAS/CMS: $gg \to a \to \mu^+\mu^-$

ATLAS/CMS: $gg \to h \to 2a$

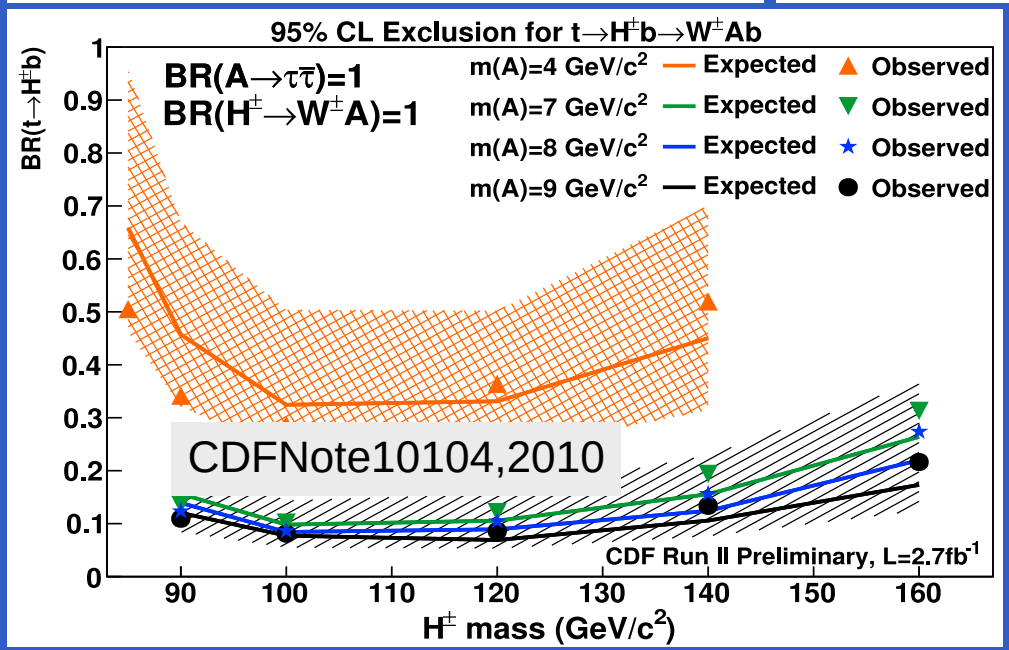
NMSSM Higgs at Aleph,BaBar,DZero,CDF



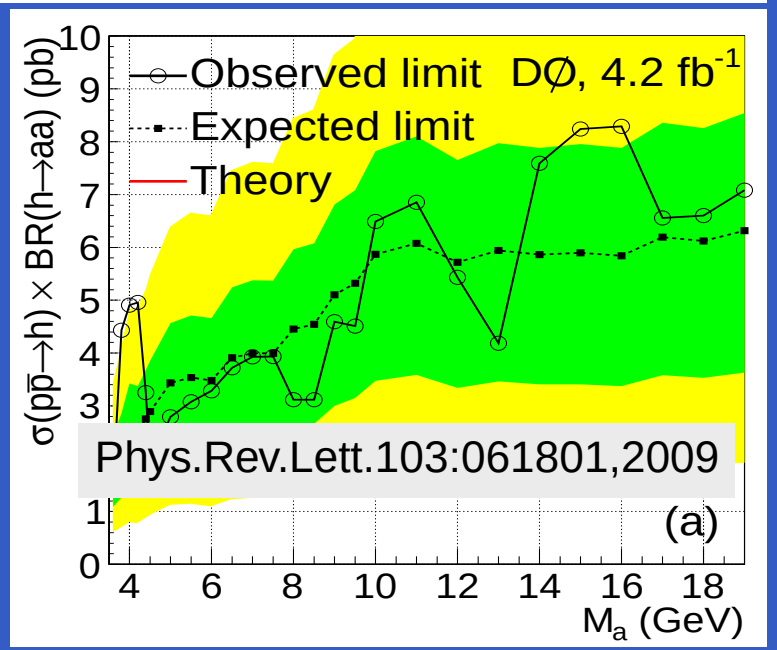
JHEP 1005:049,2010



Phys.Rev.D 88, 071102 (2013)

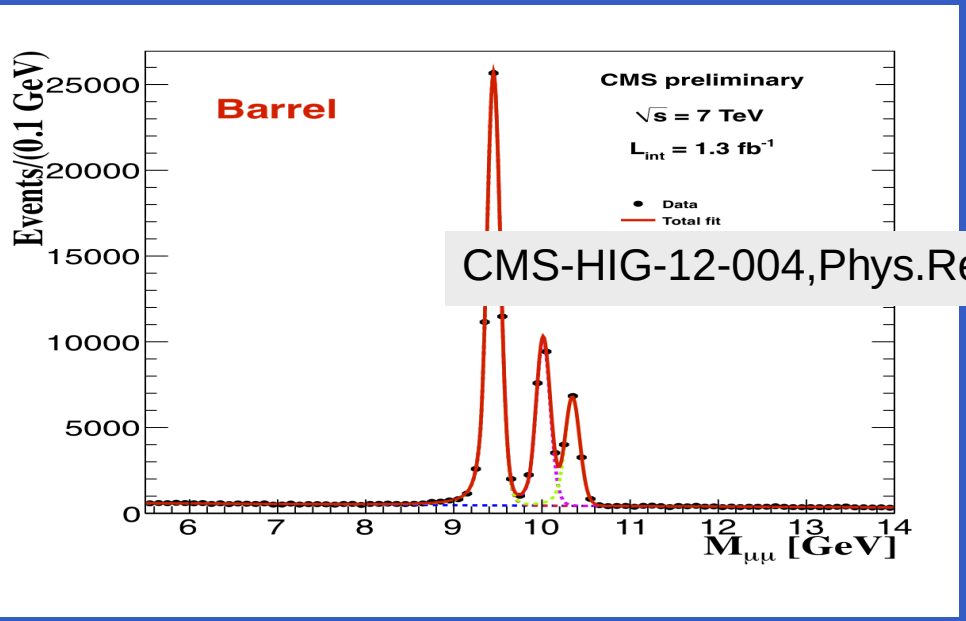


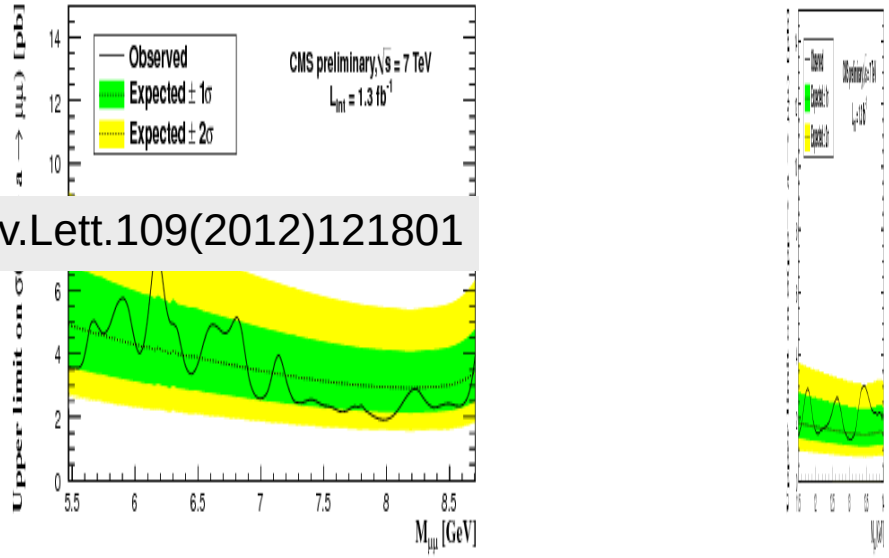
CDFNote10104,2010



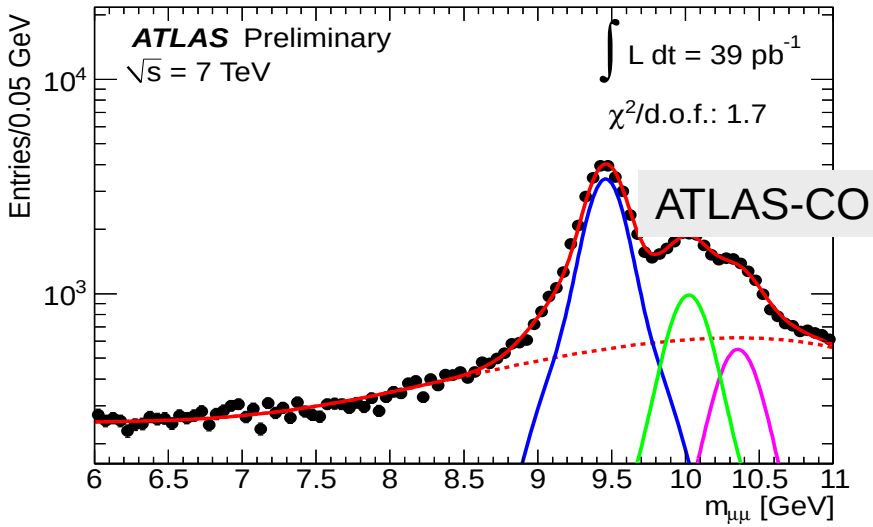
Phys.Rev.Lett.103:061801,2009

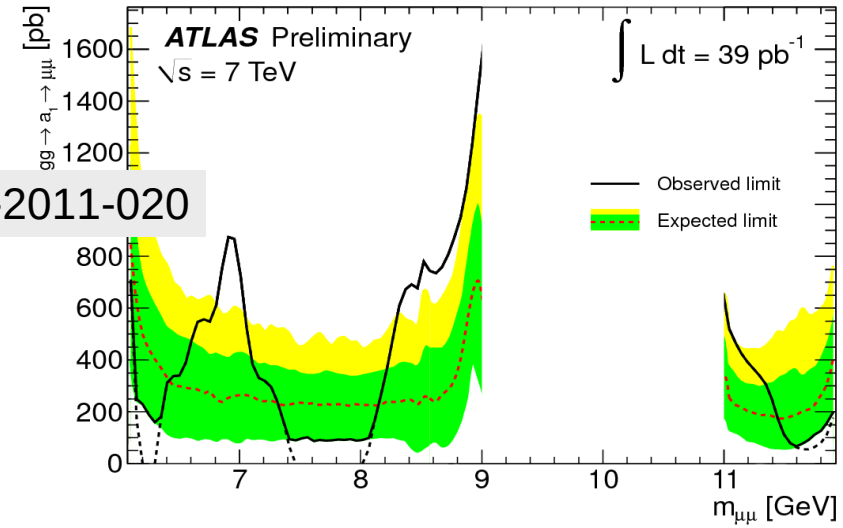
NMSSM $gg \to a_1 \to \mu^+\mu^-$ at CMS,ATLAS





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

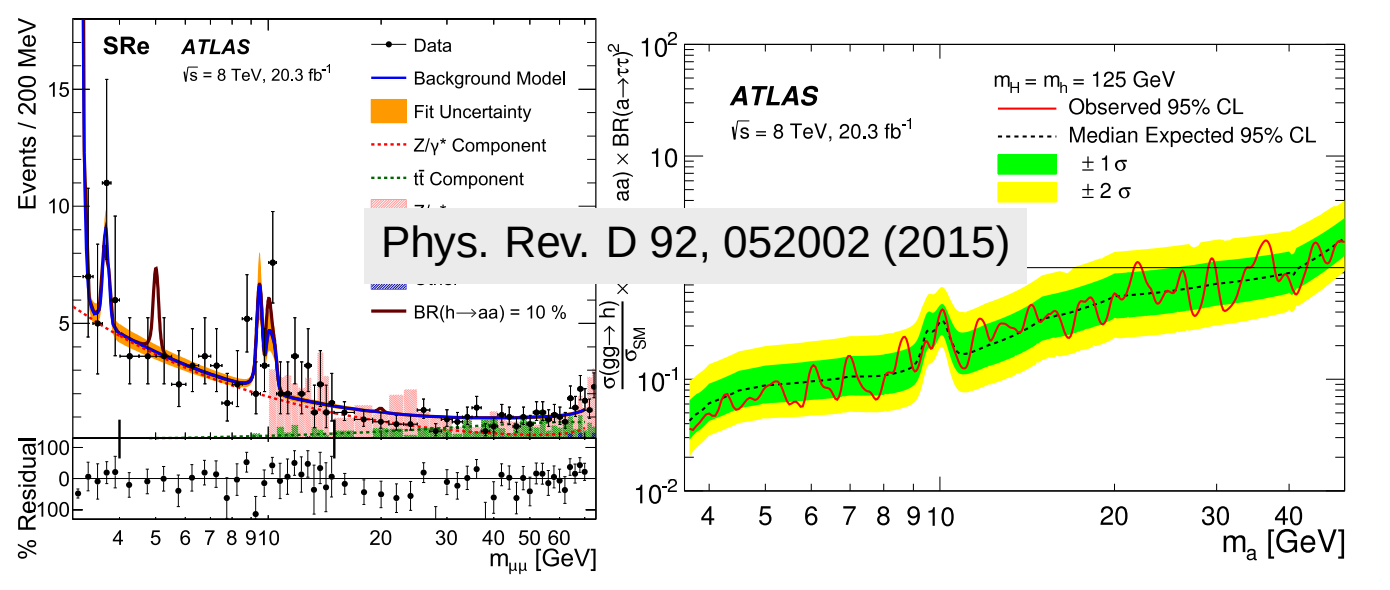




ATLAS-CONF-2011-020

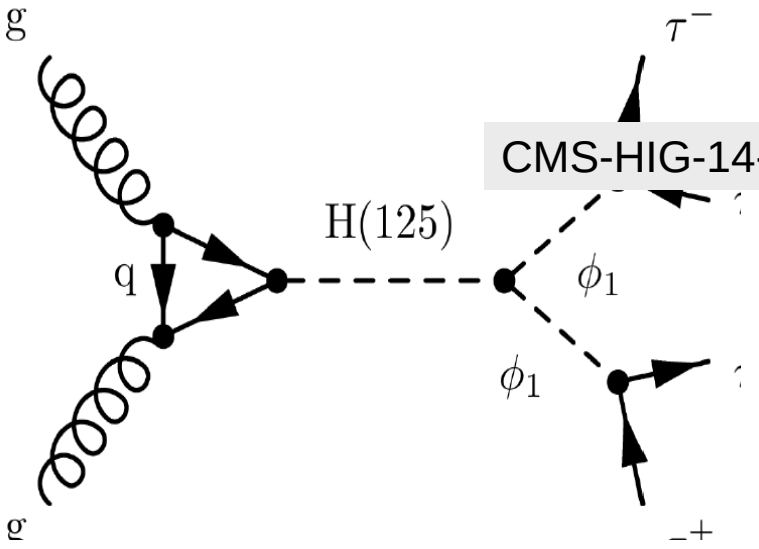
At left, muon pair mass. At right, limits on $\sigma \times BR$ obtained with CLs technique.

NMSSM $gg \to h \to 2a_1$ at ATLAS,CMS

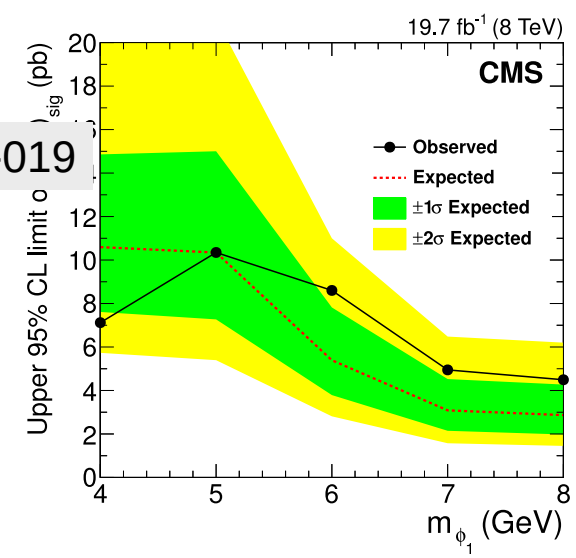


Phys. Rev. D 92, 052002 (2015)

ATLAS limits on $gg \to h \to 2a_1 \to 2\mu 2\tau$ for $m_h > 100$ GeV.



CMS-HIG-14-019



CMS limits on $gg \to h_{125} \to 2a_1 \to 4\tau$ and $h_{125} \to 2h_1 \to 4\tau$ for $m_h = 125$ GeV.

NMSSM Parameter Scan

Parameter Scan Ranges

Fixed Parameters

Experimental Constraints

Provisional Constraints (m_{h_1}, m_{a_1})

Benchmark h_{60}

SM-like h_{125} Recipe for SUSY Higgs

- How can SUSY accommodate the high Higgs mass but also the SM-like Higgs couplings?
- In principle the Higgses from the singlet can mix with the MSSM Higgs sector, but for simplicity consider the MSSM completely decoupled from the singlet.
- 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 the MSSM decoupling limit $m_Z/m_A \propto \cos(\beta - \alpha) \to 0$, the MSSM h couplings approach their Standard Model values. Denote $x \equiv \sin(\beta - \alpha)$. Then this limit is $x \to 1$:

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

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

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

NMSSMTools4.4.0 Random Scan of 10^8 Points

Symbol	Parameter	Range/Value	Motivation	h_{60}
λ	SH_uH_d Yukawa	(0,0.1]	EMSSM	0.03505
κ	S^3 Yukawa	[-0.01,0.01]	EMSSM/PQS	0.006088
$m_A^\star$	Doublet CP-Odd Mass	[500,1500] GeV	SM-like h_{125}	1068. GeV
$m_P^\star$	Singlet CP-Odd Mass	[9.9,10.5] GeV	$g-2$, η_b	10.25 GeV
μ_{eff}	Higgsino Mass	[100,300] GeV	Naturalness	166.7 GeV
$\tan\beta$	Ratio of Doublet VEVs	[1,30]	Constraints	15.49
M_1	Gaugino 1 Mass	$\frac{1}{2}M_2$	Unification	80.73 GeV
M_2	Gaugino 2 Mass	[100,300] GeV	Naturalness	161.5 GeV
M_3	Gaugino 3 Mass	$3M_2$	Unification	484.4 GeV
$X_t^\star$	Stop Mixing	$[0.8X_t^{max}, 1.8X_t^{max}]$	h_{125} Mass	1378. GeV
$m_{\tilde{Q}3_L}$	LH 3rd Gen. Squark	[350,550] GeV	Naturalness	546.9 GeV
$m_{\tilde{U}3_R}$	RH Top Squark	m_{Q3}	Simplicity	546.9 GeV

(*) $m_A^2 \equiv \frac{\lambda v_s}{\sin 2\beta}\left(\sqrt{2}A_\lambda + \kappa v_s\right)$, $m_P^2 \equiv -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa$, $X_t \equiv A_t - \mu/\tan\beta$

- NMSSM parameter scan ranges. κ must satisfy $0.125\lambda < |\kappa| < 0.225\lambda$.
- h_{60} ($\kappa = 0.006088$ and $A_\kappa = -1.087$ GeV) is taken from points surviving the scan.

Fixed NMSSM Scan Parameters

	Symbol	Parameter	Scan Value
Soft	A_b	Soft Trilinear b Coupling	1500
	A_μ	Soft Trilinear μ Coupling	1500
	A_τ	Soft Trilinear τ Coupling	1500
Sleptons	$m_{\tilde{e}_L}$	LH Selectron	200
	$m_{\tilde{\mu}_L}$	LH Smuon	200
	$m_{\tilde{\tau}_L}$	LH Stau	200
	$m_{\tilde{e}_R}$	RH Selectron	200
	$m_{\tilde{\mu}_R}$	RH Smuon	200
	$m_{\tilde{\tau}_R}$	RH Stau	200
Squarks	$m_{\tilde{Q}1_L}$	LH 1st Gen. Squark	1500
	$m_{\tilde{Q}2_L}$	LH 2nd Gen. Squark	1500
	$m_{\tilde{U}1_R}$	RH Up Squark	1500
	$m_{\tilde{U}2_R}$	RH Charm Squark	1500
	$m_{\tilde{D}1_R}$	RH Down Squark	1500
	$m_{\tilde{D}2_R}$	RH Strange Squark	1500
	$m_{\tilde{D}3_R}$	RH Bottom Squark	1000

Constraints Imposed in NMSSM Scan

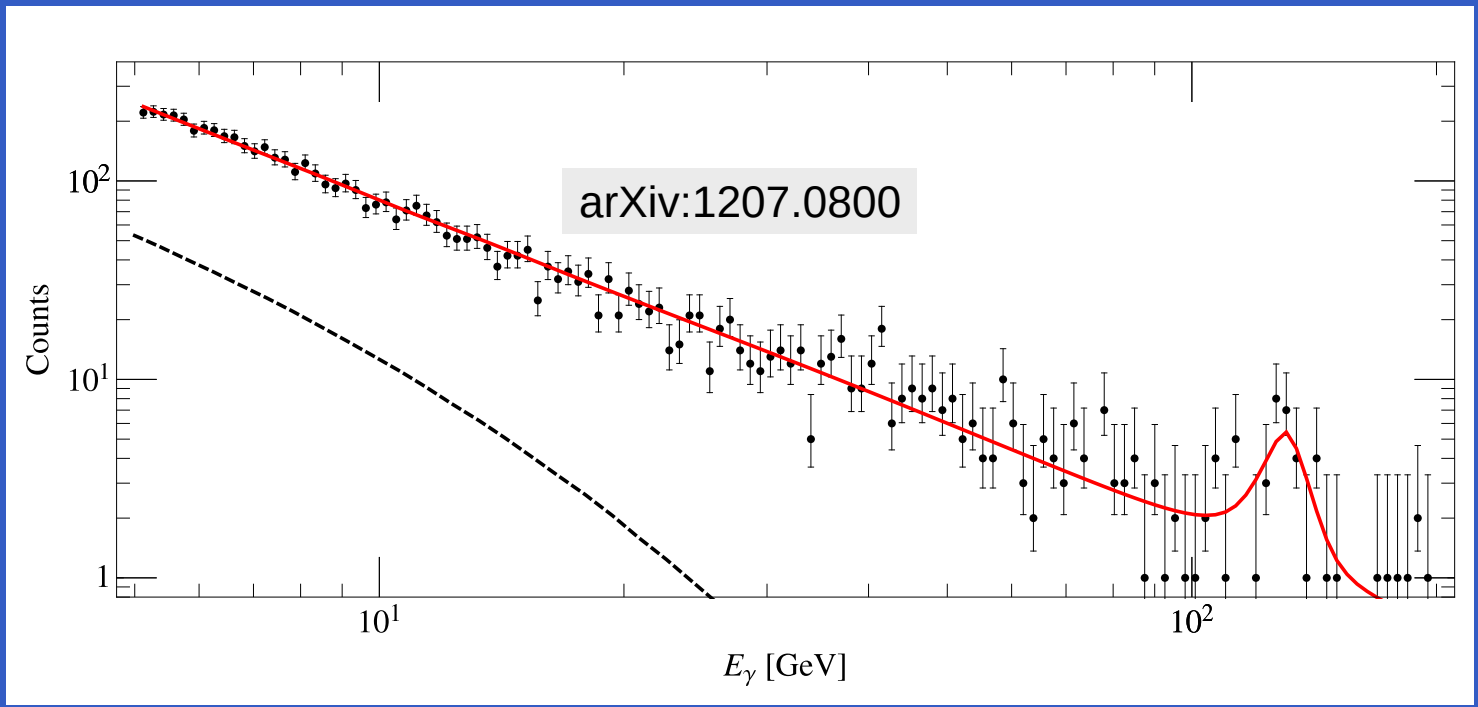
- Muon Magnetic Moment
- Dark Matter
  - Relic density obtained by WMAP
  - Direct Search at LUX
- B Physics
  - $b \to s\gamma$, $B \to X_s \mu^+ \mu^-$, $B^+ \to \tau^+ \nu$ and $B_s \to \mu^+ \mu^-$,
  - $\Upsilon(1s) \to a\gamma$ and $\eta_b(1s)$ mass
- Higgs Searches
  - LHC h_{125} Signal Strengths
  - LEP1/2 Higgs searches in $e^+e^- \to Zh$
  - Tevatron/LHC Charged Higgs searches in $t \to bH^+$
  - LEP2/Tevatron/LHC NMSSM Higgs searches
- SUSY Searches
  - Tevatron/LHC $\chi^+, \tilde{q}, \tilde{g}, \tilde{e}, \tilde{\mu}, \tilde{\tau}$ mass constraints
  - Tevatron/LHC $\tilde{t} \to b\ell\tilde{\nu}, \chi^0 c$ and $\tilde{b} \to \chi^0 b$
- Veto Theoretical Problems

Provisional Constraint: $m_{h_1} \approx 60$ GeV

Require the h_1 mass to satisfy $50 < m_{h_1} < 70$ GeV

Benchmark	m_h	m_H	m_A	$m_{H^\pm}$	$\tan\beta$	$1 - CL_b$	σ
...	...	...	...	...	...	...	...
large-μ	59	108	67	104	3.1	1.0×10^{-2}	2.6
gluophobic	56	124	69	105	4.1	5.5×10^{-3}	2.8
small-α_{eff}	60	121	75	109	5.5	2.4×10^{-3}	3.0

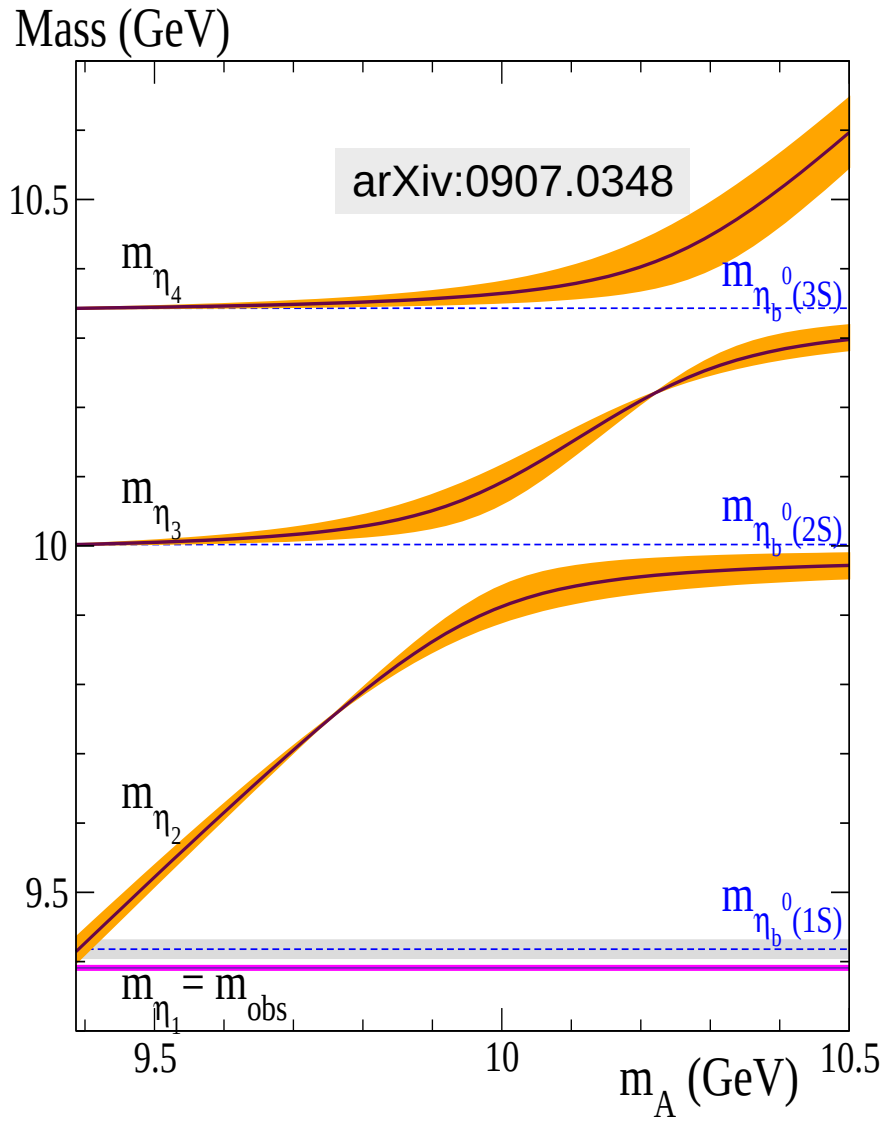
The most significant excesses with respect to the predicted background (JHEP 0908:032,2009).

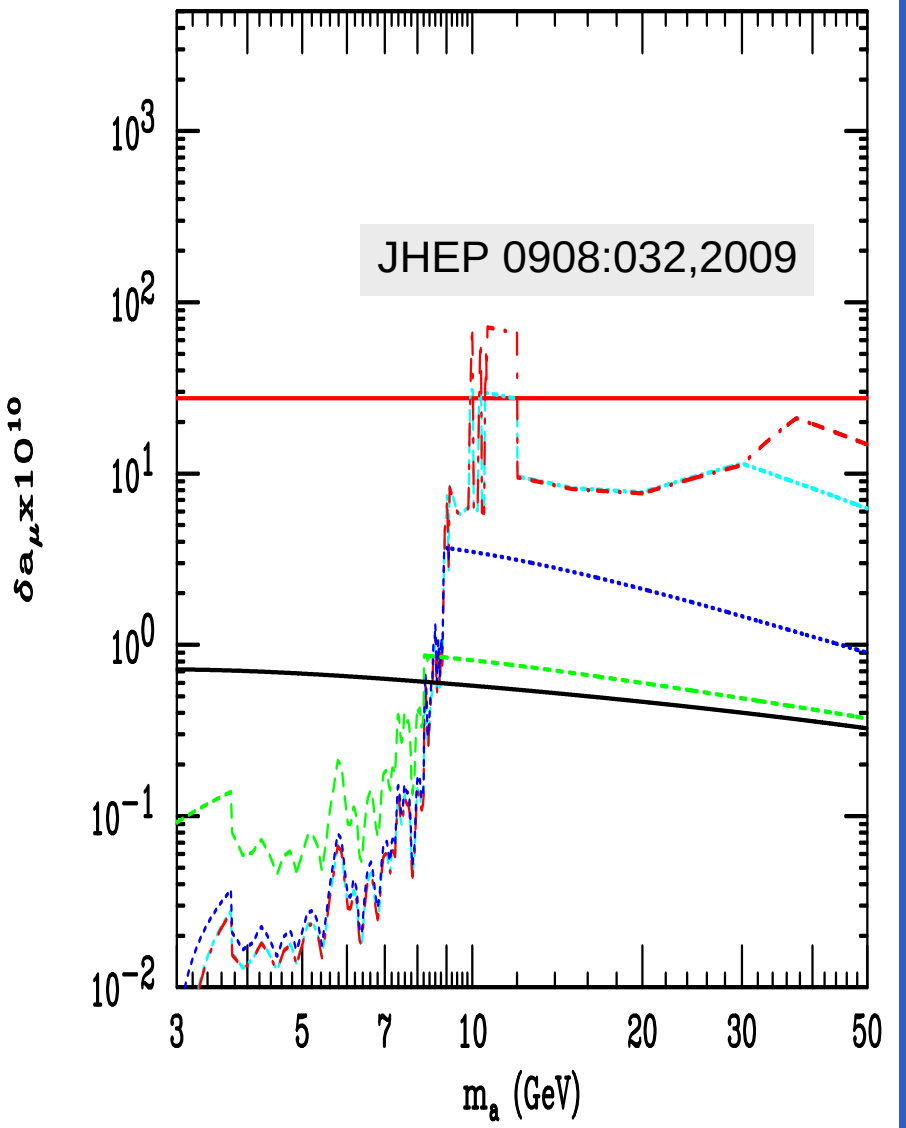


LUX (LAT) has ruled out the feature near 40 (130) GeV, yet feature near 60 GeV remains in Pass8.

Provisional Constraint: $m_{a_1} \approx 10$ GeV

Require the a_1 mass (including off-diagonal terms) to satisfy $9.9 < m_{a_1} < 10.5$ GeV





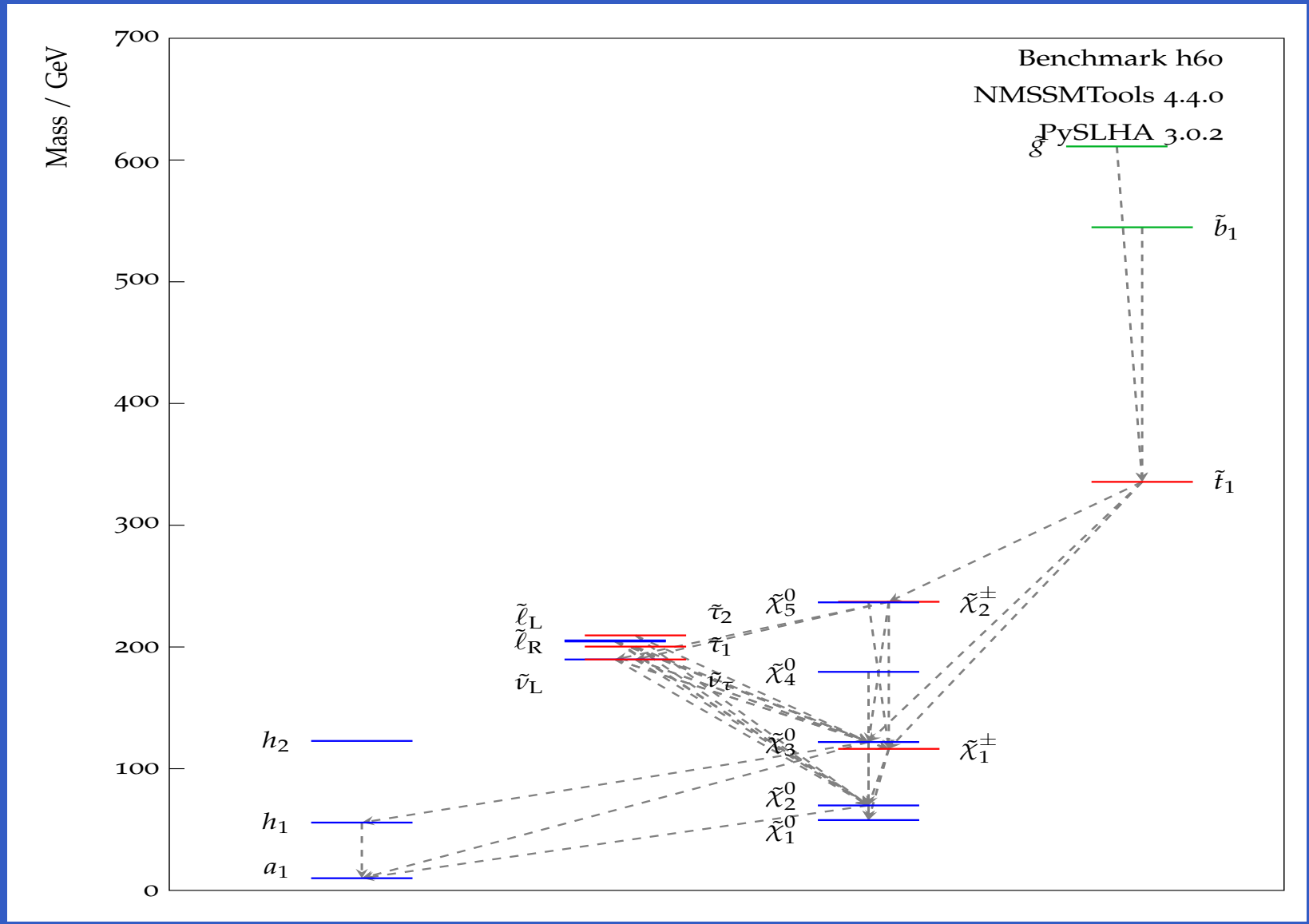
Surviving Points and h_{60}

	Range	Mass	BR1 (%)	BR2 (%)
a_1	[9.9,10.4]	10.0	$\tau^+\tau^-$ (81)	gg (16)
h_1	[53,59]	55.7	$a_1 a_1$ (72)	$b\bar{b}$ (23)
h_2	[122,123]	122.8	$b\bar{b}$ (65)	$WW^\star$ (17)
χ_1	[54,60]	57.8	-	-
χ_2	[57,76]	69.8	$\chi_1 a_1$(75)	$\chi_1 Z^\star$ (25)
χ_3	[107,136]	121.9	$\chi_1 h_1$ (80)	$\chi_2 Z^\star$ (10)
χ_4	[166,209]	179.5	$\chi_2 Z$ (80)	$\chi_1 Z$ (14)
χ_5	[225,254]	236.6	$\chi_1^+ W$ (60)	$\tilde{\nu}\nu, \tilde{\ell}\ell$ (38)
χ_1^+	[104,132]	116.3	$\chi_2 W^\star$ (78)	$\chi_1 W^\star$ (22)
χ_2^+	[225,255]	237.1	$\ell\tilde{\nu}, \tilde{\ell}\nu$ (40)	$\chi_3 W$ (38)
$\tilde{t}_1$	[313,391]	335.6	$\chi_2^+ b$ (75)	$\chi_3 t$ (15)
$\tilde{b}_1$	[486,545]	544.7	$\tilde{t}_1 W$ (41)	$\chi_2^+ t$ (31)
$\tilde{g}$	[505,637]	611.2	$\tilde{t}_1 t$ (94)	$\tilde{b}_1 b$ (6)

Masses and the two dominant decays of the lighter part of the h_{60} benchmark point spectrum obtained by NMSSMTools4. The column titled “Range” is the mass range of the points surviving all scan constraints. Mass units are GeV.

NMSSM Benchmark Point h_{60} (aka BP3)

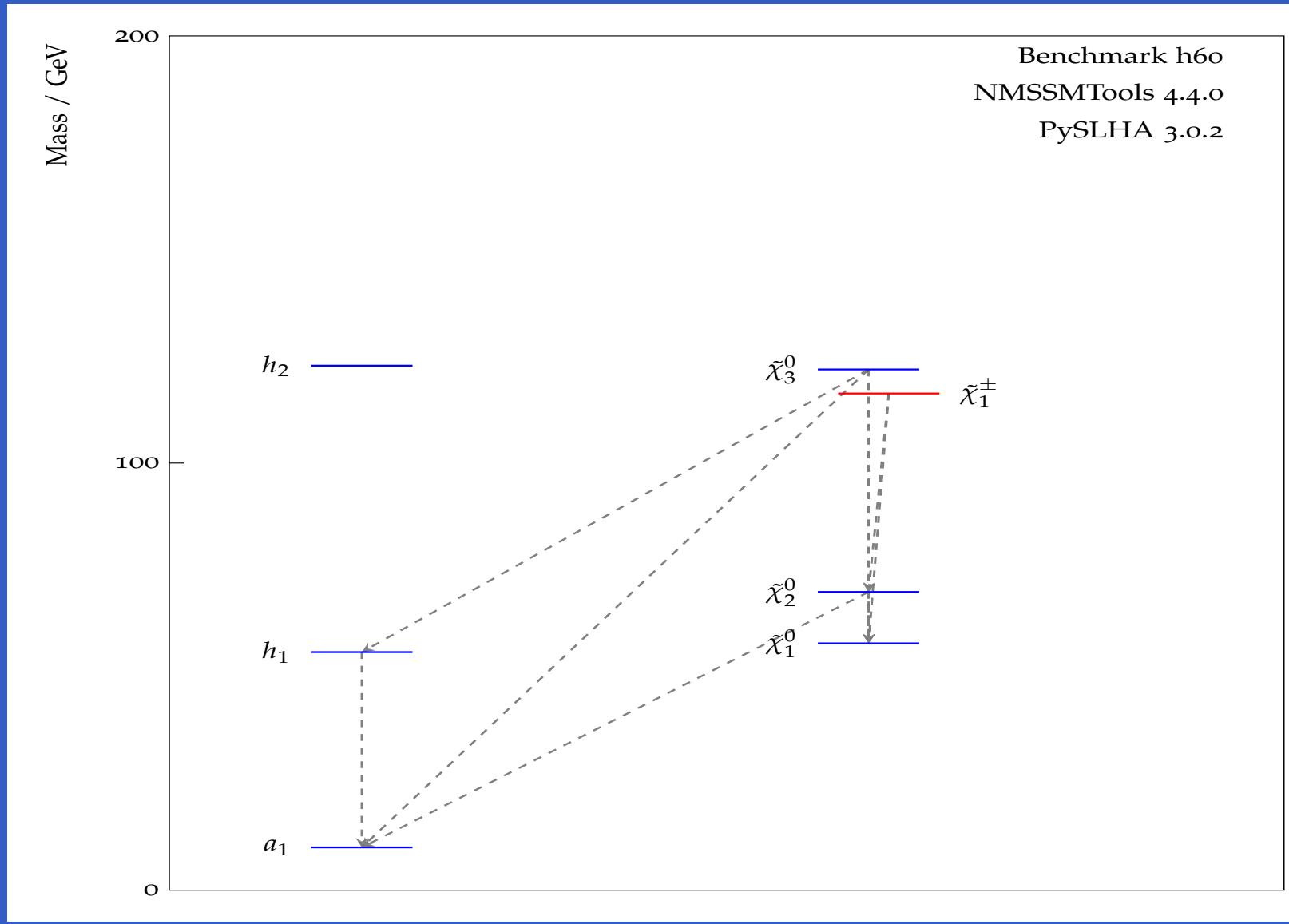
Natural NMSSM with a Light Singlet Higgs and Singlino LSP (1505.05554v3)



Mass spectrum in benchmark point h_{60} (1505.05554v3). Also known as BP3 at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGNMSSM

NMSSM Benchmark Point h_{60} (aka BP3)

Natural NMSSM with a Light Singlet Higgs and Singlino LSP (1505.05554v3)



Zoom of the light mass spectrum in benchmark point h_{60}

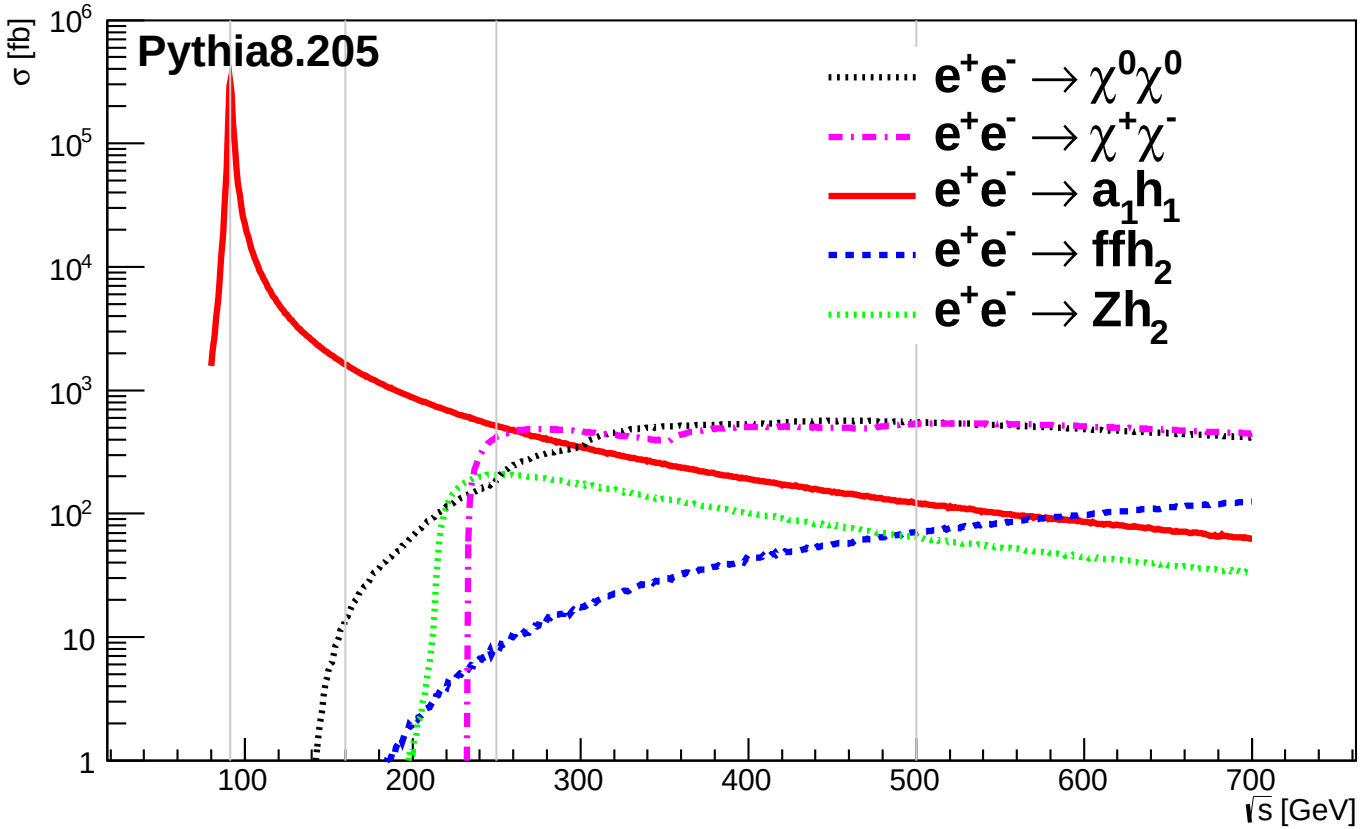
NMSSM h_{60} at Colliders

h_{60} at LEP

h_{60} at LHC

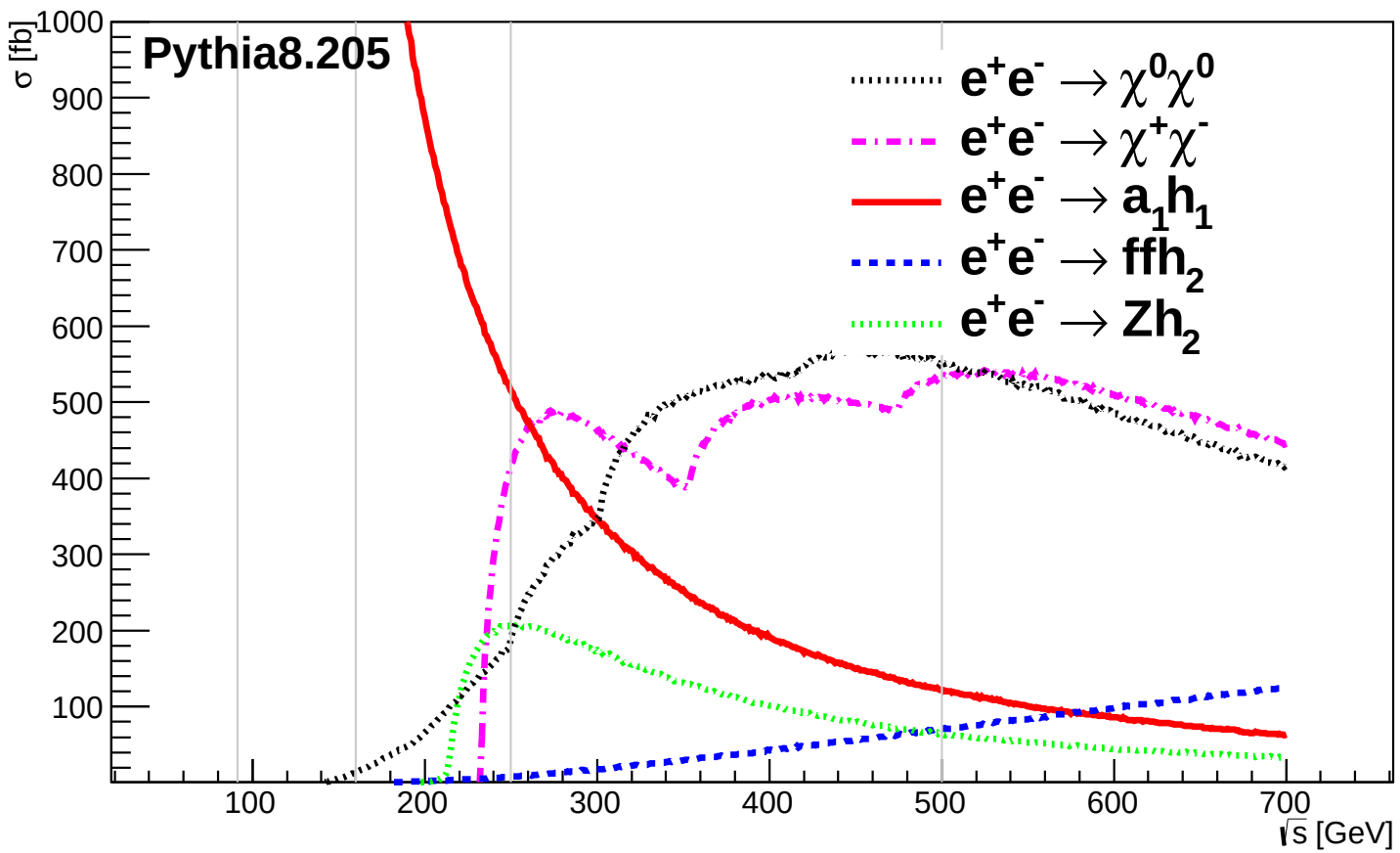
h_{60} at ILC

NMSSM h_{60} at e^+e^- Collider (LEP or ILC)



- Standard Higgstrahlung production channel $e^+e^- \to Zh_1$ is suppressed in the NMSSM due to the NMSSM coupling sum rule $\sum_{1=1}^{3} \xi^2_{ZZh_i} = 1$ and measured $h_{125} \to ZZ^\star$ signal strength.
- In h_{60} we have the possibility of resonant production $e^+e^- \to a_1h_1$, with cross section of several hundred picobarns at $\sqrt{s} = m_Z$.

NMSSM h_{60} at e^+e^- Collider (LEP or ILC)



- For $\sqrt{s} = 500$ GeV, pair production of all neutralinos and all charginos is accessible as well as $a_1 h_1$ and Zh_2 production.

NMSSM h_{60} Signature at LEP or ILC

- NMSSM h_{60} is an example of an Effective MSSM with a slightly broken Peccei-Quinn symmetry.
- λ and κ are small, and the singlet S mixes only weakly with the doublets H_u and H_d
- Denote S^2_{ij} (P^2_{ij}) as the jth component of mass eigenstate h_i (a_i) where $j = 1, 2, 3$ corresponds to the u doublet, the d doublet, and singlet respectively.
- Denote N^2_{ij} as the jth component of χ_i, where $j = 1, 2, 3, 4, 5$ corresponds to bino, wino, u higgsino, d higgsino, and singlino respectively.
- Doublet and singlet components of the a_1, h_1 and gaugino and singlino components of the χ_1, χ_2, χ_3 in h_{60}:

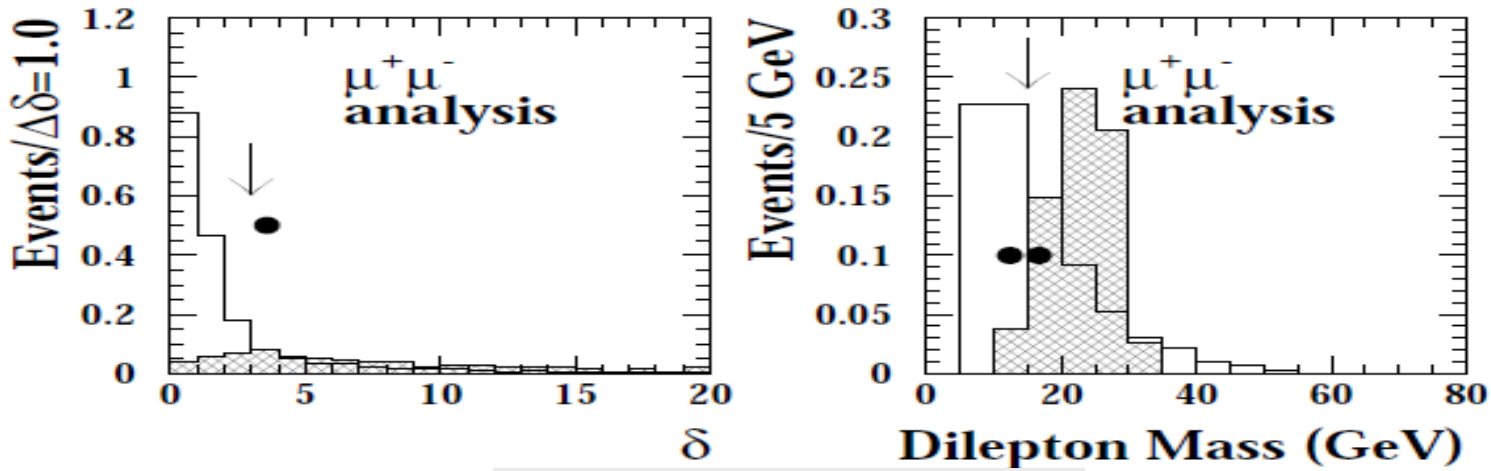
Component	a_1	h_1	χ_1	χ_2	χ_3
$P_{11}/S_{11}/N_{i1}$	-0.002	-0.006	0.151	0.882	0.401
$P_{12}/S_{12}/N_{i2}$	0.000	-0.130	-0.054	-0.153	0.679
$P_{13}/S_{13}/N_{i5}$	1.000	0.992	0.981	-0.189	0.045

- Measuring $BR(Z \to a_1 h_1)$ is measuring the $Z a_1 h_1$ coupling:

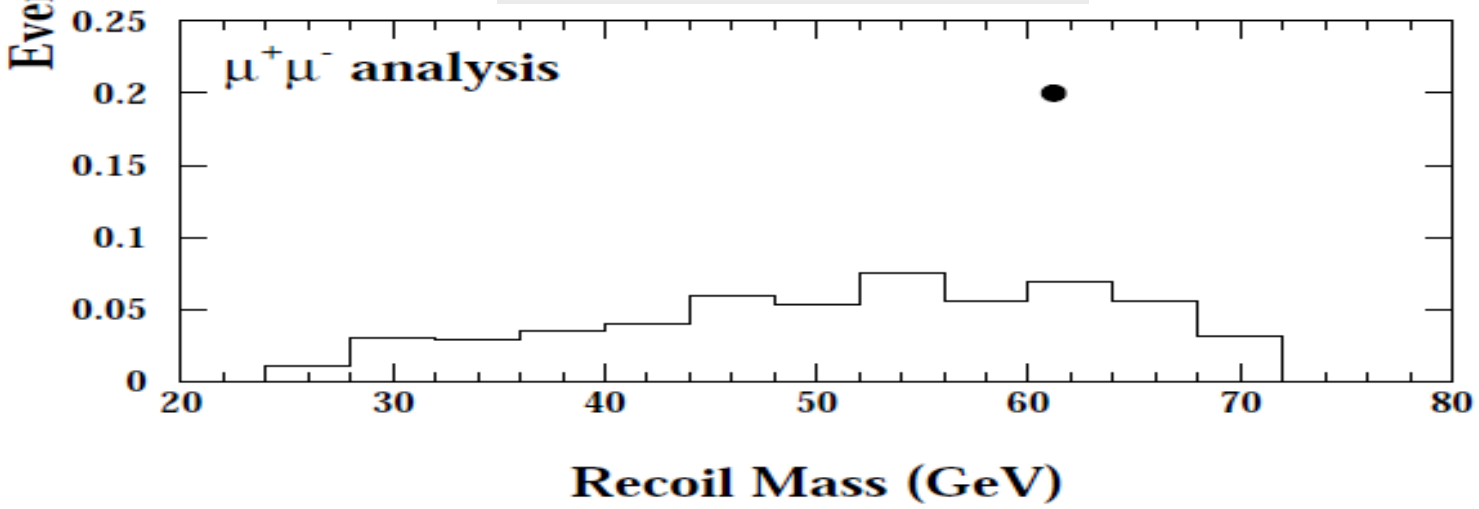
$$\frac{g}{2\cos\theta_W}(S_{11}P_{11} - S_{12}P_{12})$$

- In h_{60}, $S_{11}P_{11} - S_{12}P_{12} = -1.37 \times 10^{-6}$.

LEP1 OPAL Search for $Z \rightarrow h^0 Z^\star$ (160pb^{-1})

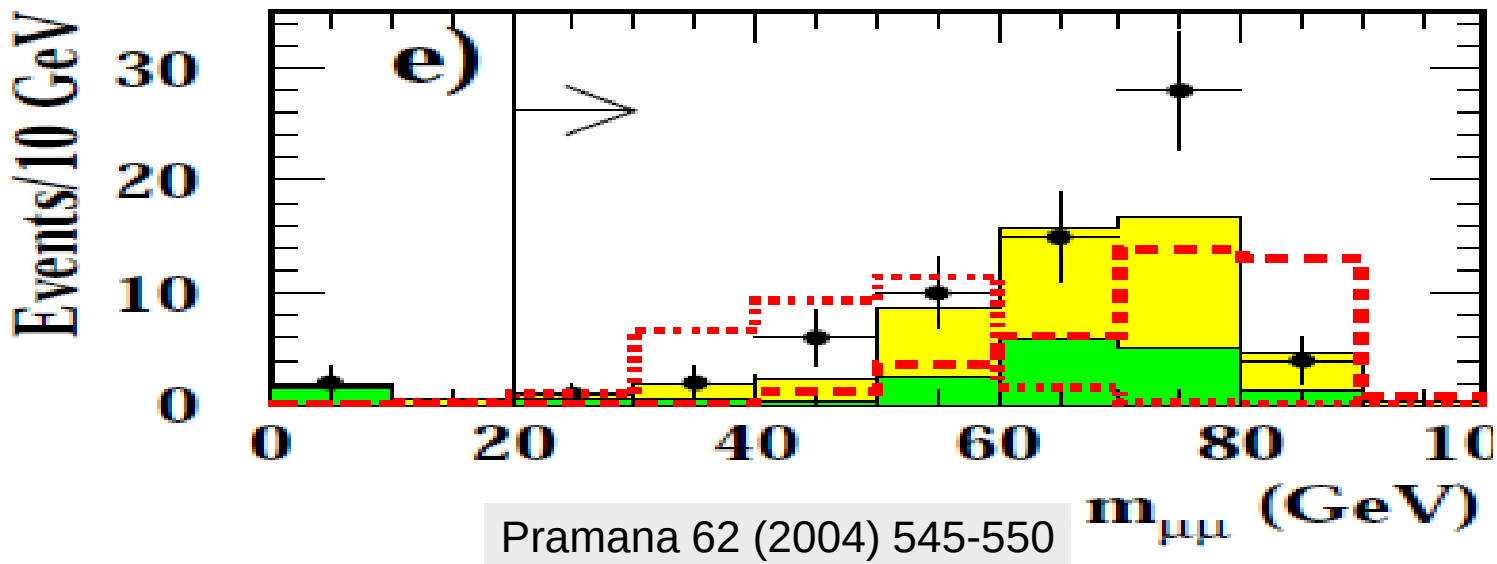


Z.Phys. C73 (1997) 189-199

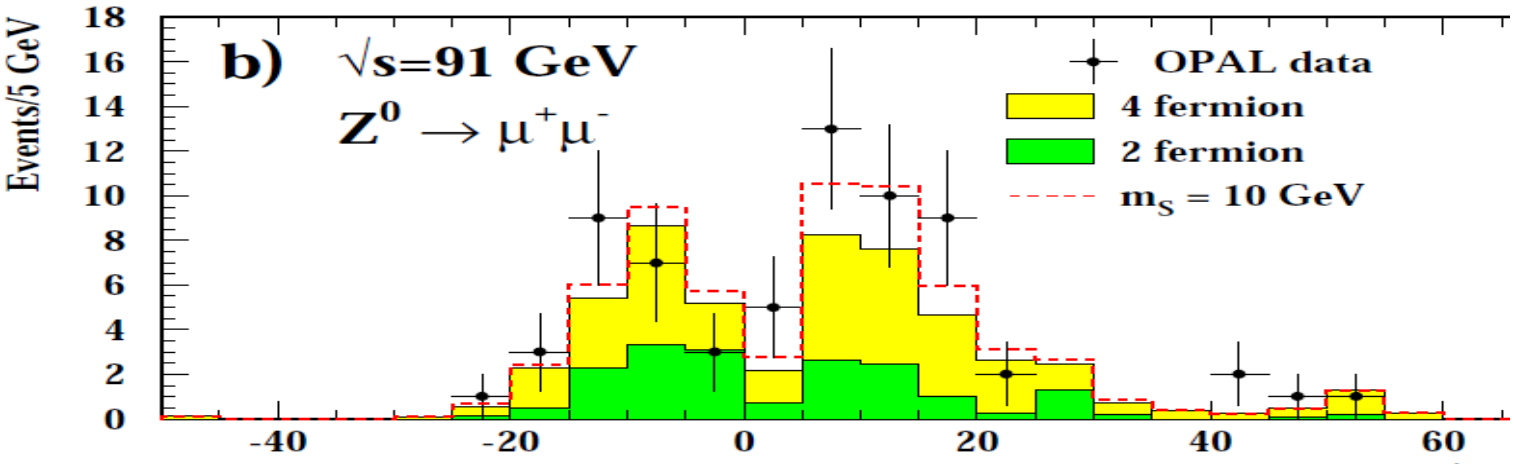


Significance of transverse distance from primary to secondary vertices (top left), dimuon mass (top right) and recoil mass (bottom).

New OPAL Search for $Z \to h^0 Z^\star$ (115pb^{-1})

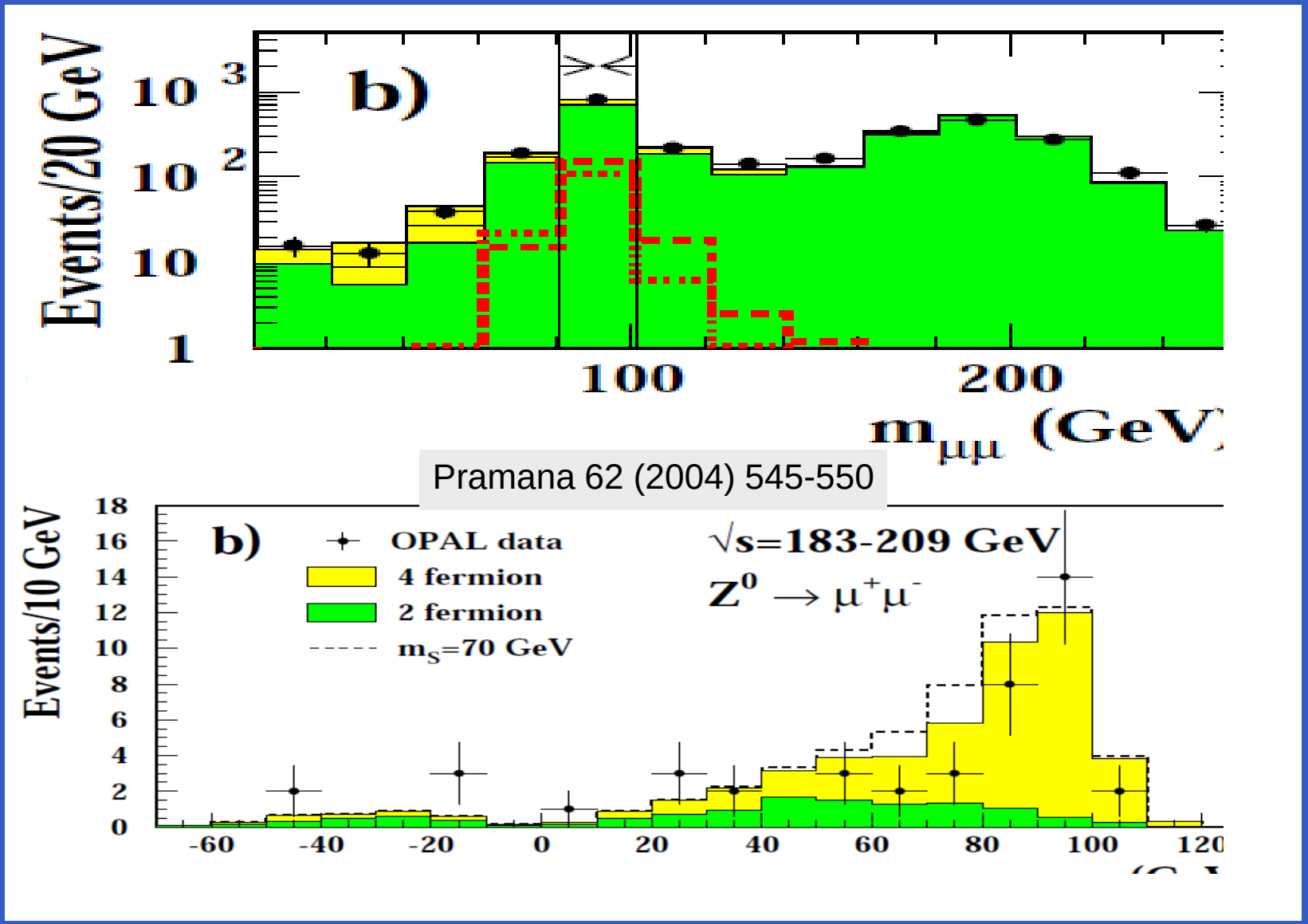


Pramana 62 (2004) 545-550



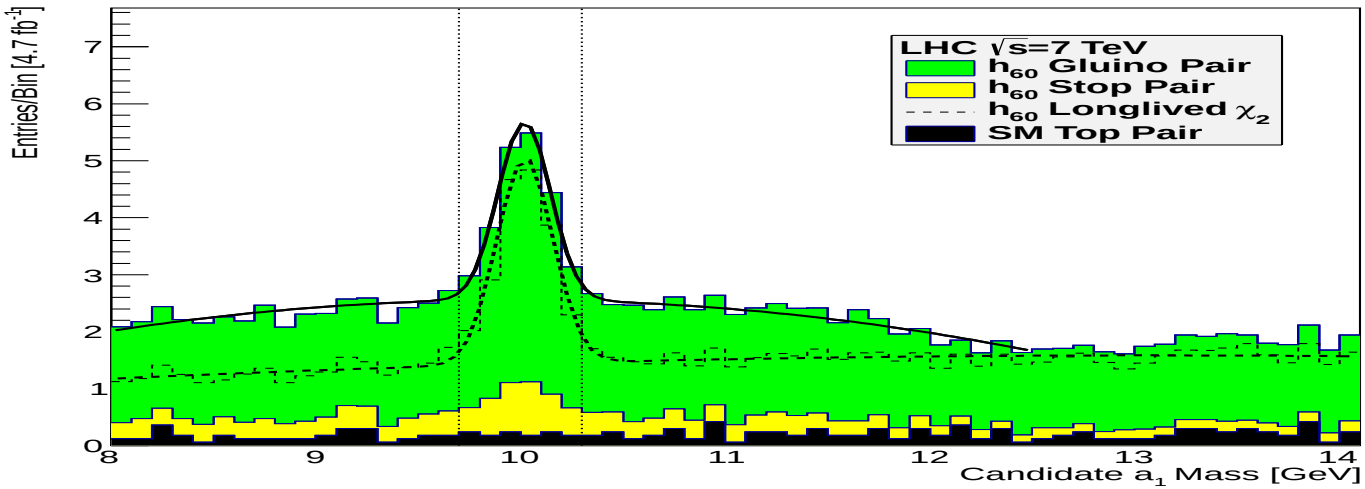
Dimuon (top) and recoil (bottom) masses for a re-analysis of LEP1 data.

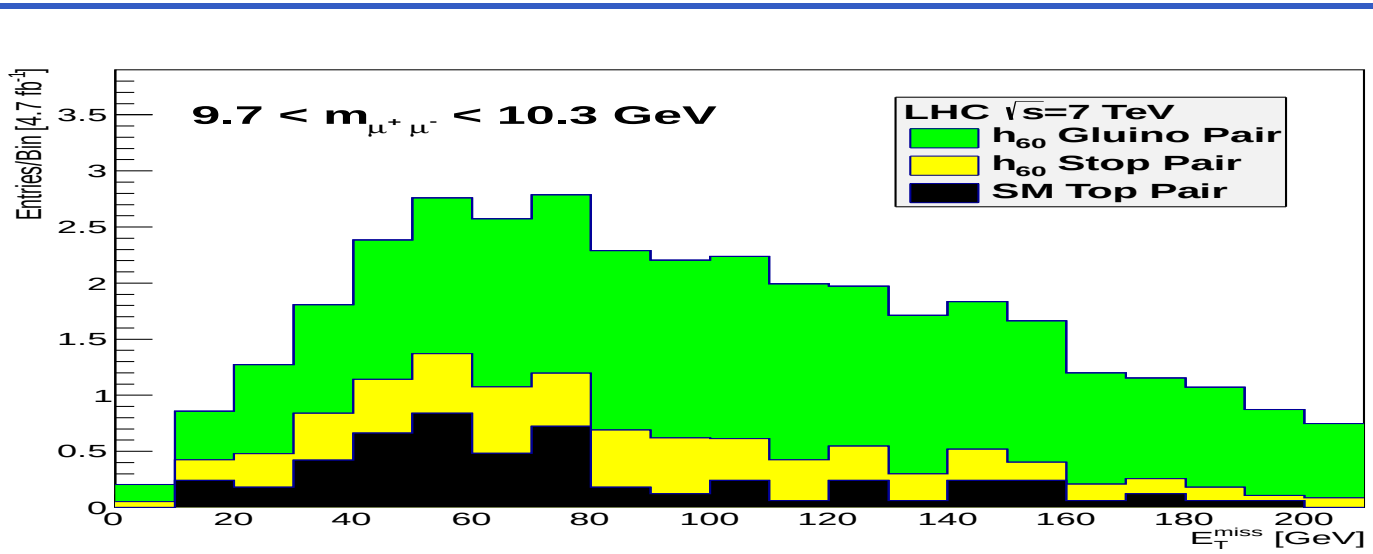
LEP2 OPAL Search for $Z \to h^0 Z^\star$ (662pb^{-1})



Dimuon (top) and recoil (bottom) masses for the LEP2 data.

NMSSM h_{60} at LHC $\sqrt{s} = 7$ TeV





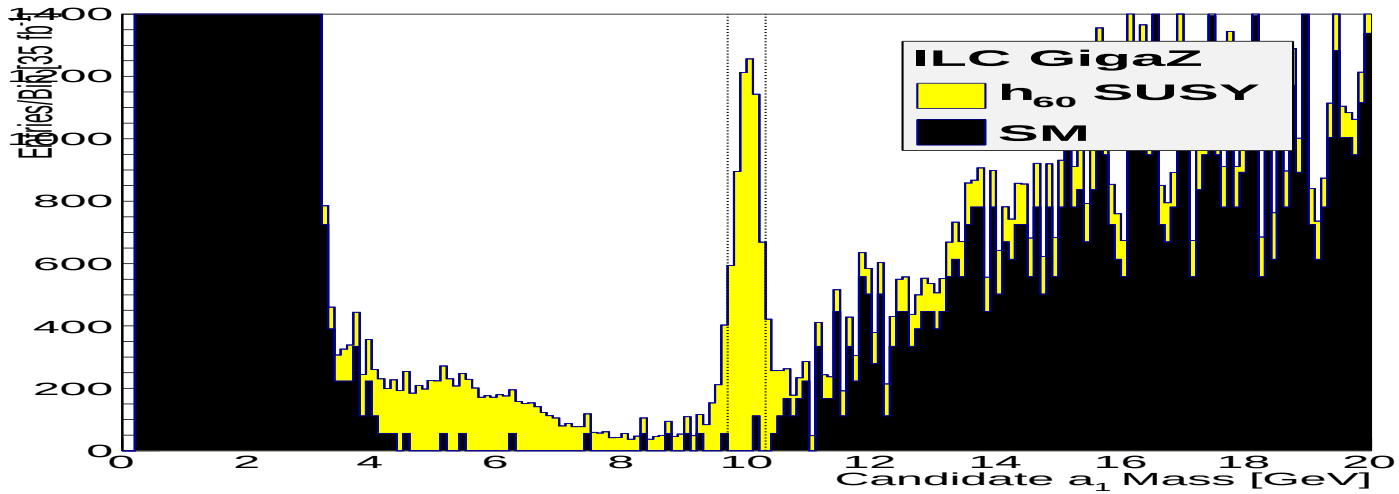
Reconstructed a_1 mass (top) and E_T^{miss} (bottom) after full signal selection with 4.7fb^{-1} at $\sqrt{s} = 7$ TeV. Also shown (dotted) is a variant of h_{60} in which the χ_2 decays outside the effective tracking volume.

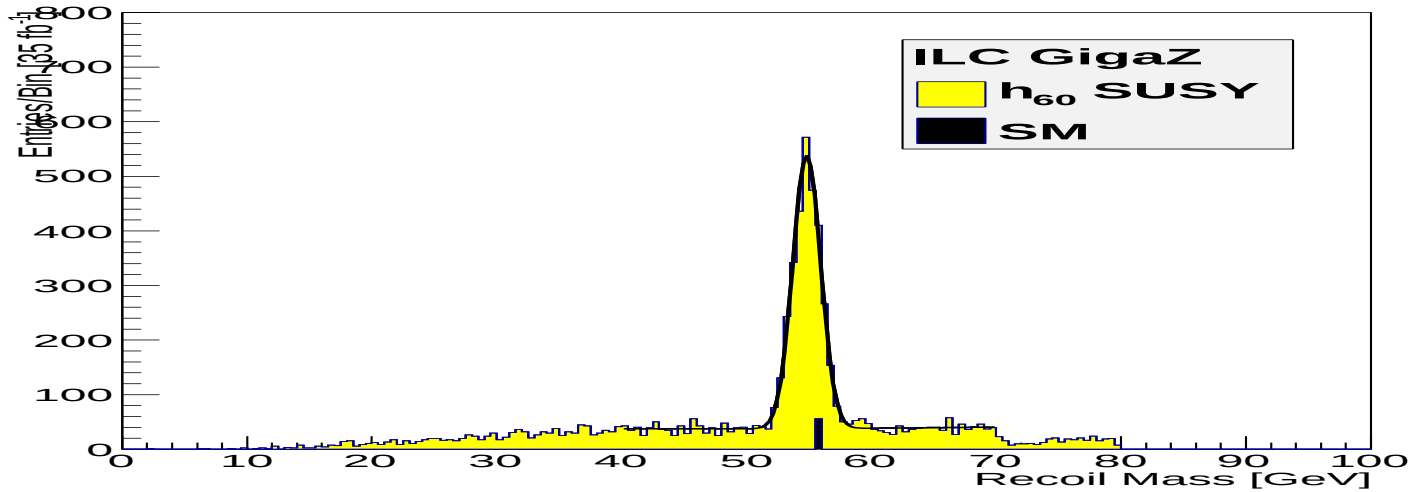
NMSSM h_{60} at LHC $\sqrt{s} = 7, 8$ TeV

Process	$\mathcal{L} = 5$ fb^{-1}			$\mathcal{L} = 20$ fb^{-1}		
	σ_{7T} [pb]	N_n	N_p	σ_{8T} [pb]	N_n	N_p
SM $t\bar{t}$	173.6	1.6	0	247.7	8.5	0
$\tilde{g}\tilde{g}$	0.6	15.4(8.9)	8.6(10.2)	1.2	108.0	65.4
$\tilde{t}_1\bar{\tilde{t}}_1$	0.7	2.6(0.8)	2.2(2.5)	1.1	20.1	19.2
$S/\sqrt{B}$	2.4(3.8)			7.2		

- NLO cross sections for $\tilde{g}\tilde{g}$, $\tilde{t}_1\bar{\tilde{t}}_1$, and $t\bar{t}$ production at the LHC for $\sqrt{s} = 7, 8$ TeV, assuming the h_{60} mass spectrum.
- Also shown are the expected yields for peaking events (N_p), yields for nonpeaking events (N_n) and signal significances after the full signal selection described on the last slide.
- In parentheses are yields and significance for a variation of h_{60} in which the χ_2 decays outside of the effective tracking volume.

NMSSM h_{60} at ILC $\sqrt{s} = m_Z$ in GigaZ Mode





The $a_1 \to \mu^+\mu^-$ and recoil masses requiring two opposite sign muons with $p_T > 5$ GeV.

Summary and Plans

Summary

- The NMSSM is theoretically motivated by the μ-term problem of the MSSM.
- NMSSM Higgs searches have been pursued at BaBar, Aleph, DZero, CDF, ATLAS and CMS.
- A scan has been made in NMSSM parameter space, fixing high mass parameters above 1 TeV and varying the low mass parameters (motivated by Natural SUSY).
- Measurements of dark matter, the muon magnetic moment, B physics, and especially h_{125} mass and signal strengths now constrain the NMSSM.
- Surviving points are characterized by low fine tuning and feature light stops, light higgsinos and a light gluino
- NMSSM points which survive the constraints have important consequences for the ILC.

Plans

- Reproduce LEP searches with fast simulation to establish sensitivity to h_{60}.
- Reproduce LHC searches with fast simulation (and Checkmate) to establish h_{60} sensitivity.
- Investigate sensitivity to $e^+e^- \to a_1 h_1, \chi_i^0 \chi_j^0, \chi_i^+ \chi_j^-$ with fast simulation.
- If sensitive, pursue full simulation studies with SiD.

I invite you to follow developments and provide feedback:

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Supplemental Slides

NMSSM Chargino/Neutralino Mass Spectrum (i)

- Chargino and neutralino masses are determined at tree level by the gaugino mass parameter M_2, the higgsino mass parameter μ, and $\cos\beta, \sin\beta$.
- The chargino masses are given by ($\Delta_C = f(M_2, \mu, \cos\beta, \sin\beta\cos\Phi_\mu)$):

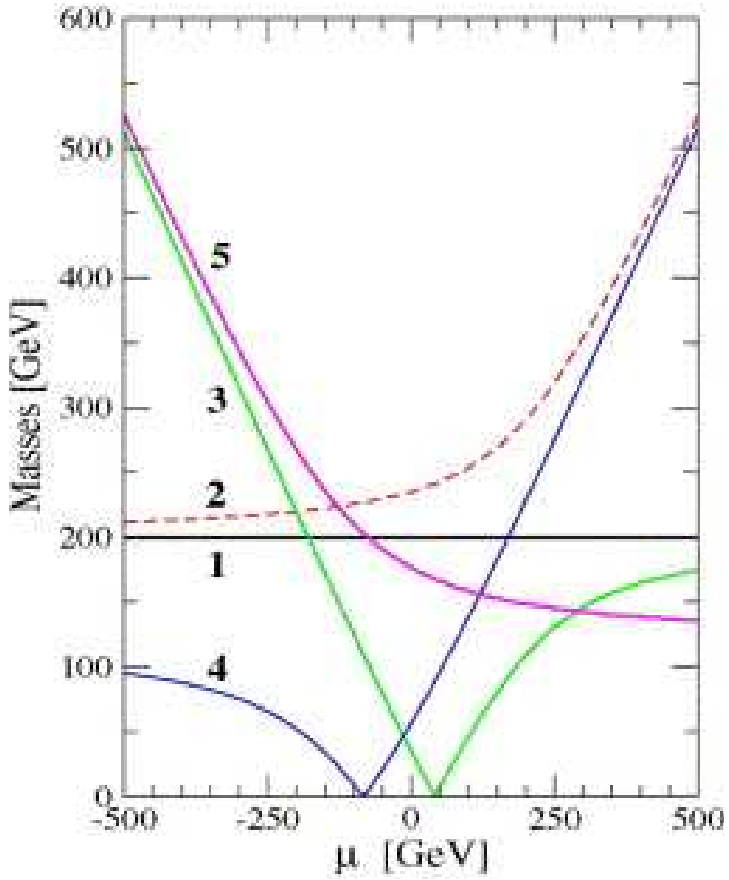
$$m^2_{\chi^+_{1,2}} = \frac{1}{2}\left[M_2^2 + |\mu|^2 + 2m_W^2 \pm \Delta_C\right]$$

- The neutralino masses, for example in the large higgsino mass limit $|\mu| \gg M_{1,2} \gg m_Z$, are:

$$\begin{aligned}
m_{\chi_1} &\approx M_1 + \frac{m_Z^2}{M_1} s_W^2 \\
m_{\chi_2} &\approx M_2 + \frac{m_Z^2}{M_2} c_W^2 \\
m_{\chi_3} &\approx \mu - \frac{M_{12}}{2M_1 M_2} m_Z^2 (1 + s_{2\beta}) + \frac{\mu_\lambda^2}{2\mu}(1 - s_{2\beta}) \\
m_{\chi_4} &\approx -\mu - \frac{M_{12}}{2M_1 M_2} m_Z^2 (1 - s_{2\beta}) - \frac{\mu_\lambda^2}{2\mu}(1 + s_{2\beta}) \\
m_{\chi_5} &\approx \mu_\kappa + \frac{\mu_\lambda^2}{\mu} s_{2\beta}
\end{aligned}$$

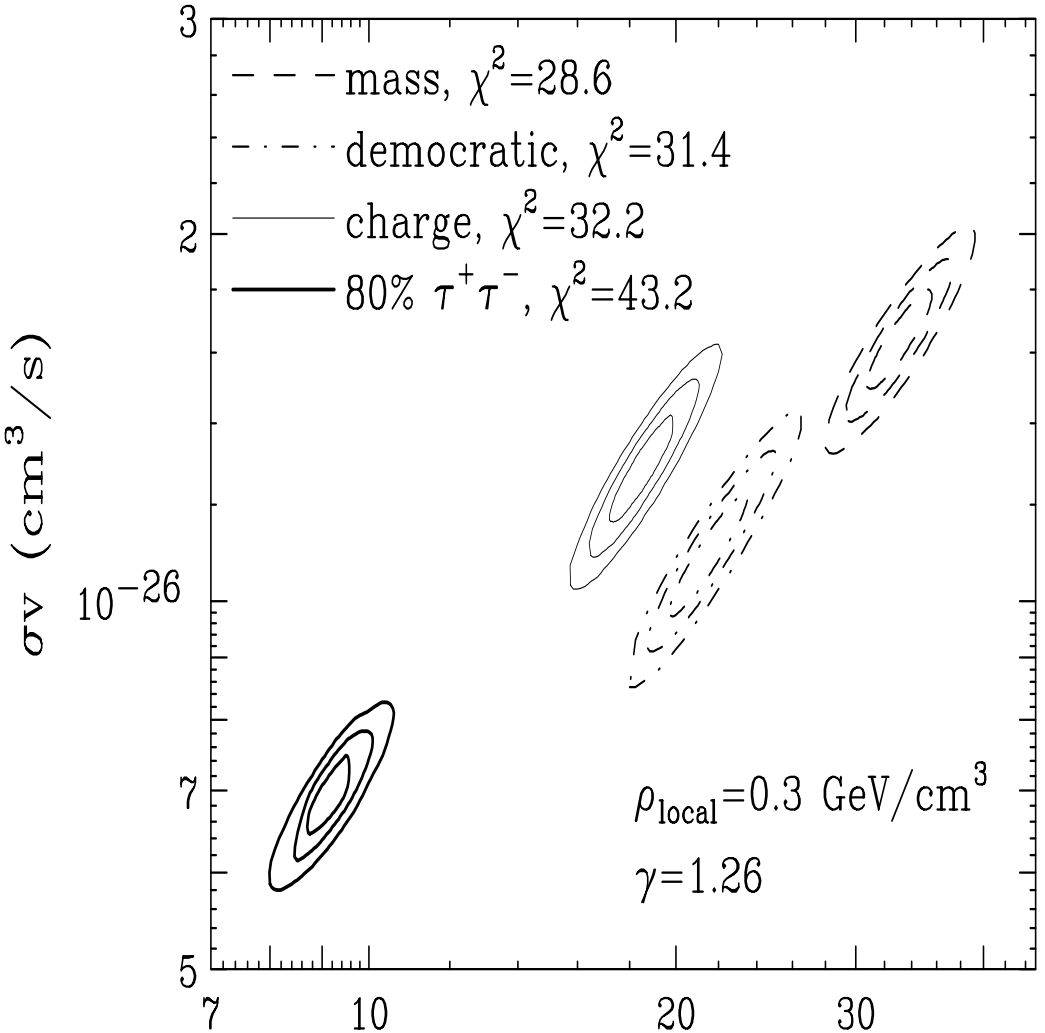
NMSSM Chargino/Neutralino Mass Spectrum (ii)

Low mass neutralinos χ absent in the MSSM are motivated by the gamma ray excess in the galactic core and the dark matter relic density as low mass scalars allow $\chi\chi \to a_1, h_1 \to q\bar{q}, \ell^+\ell^-$.



$m_1 = m_2 = 200$ GeV, $\mu_\kappa = 120$ GeV, $\mu_\lambda = 100$ GeV

Nucl.Phys.B711:83-111,2005



arXiv:1402.6703

NMSSM Stop Mass Spectrum

- The scale of the stop mass sector is set by the parameter m_{Q3}.
- The mass splitting between the $\tilde{t}_1$ and $\tilde{t}_2$ is determined by the stop mixing parameter $X_t \equiv A_t - \mu/\tan\beta$.
- The stop mass sector is therefore connected to the Higgs sector by μ and $\tan\beta$
- The tree level stop masses are given by

$$m^2_{\tilde{t}_{1,2}} = \frac{1}{2}\left(m^2_{Q3} + m^2_{U3} + 2m^2_t \pm \sqrt{(m^2_{Q3} - m^2_{U3})^2 + 4m^2_t X^2_t}\right)$$

- If one assumes $m_{Q3} = m_{U3}$, this simplifies to:

$$m^2_{\tilde{t}_{1,2}} = m^2_{Q3} + m^2_t \pm m_t X_t$$

- Correction to the tree level MSSM h mass from stop mixing ($m^2_{\tilde{t}} \equiv \frac{1}{2}\left(m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}\right)$):

$$\delta m^2_h = \frac{3G_F}{\sqrt{2}\pi^2} m^4_t \left(\log\left(\frac{m^2_{\tilde{t}}}{m^2_t}\right) + \frac{X^2_t}{m^2_{\tilde{t}}}\left(1 - \frac{X^2_t}{12 m^2_{\tilde{t}}}\right)\right)$$

NMSSM h_{60} Signature at the LHC

- Decays $\tilde{t}_1 \to \chi_2^+ b$, $\chi_2^+ \to \chi_3 W$, $\chi_3 \to \chi_1 h_1$, and $h_1 \to 2a_1$ proceed with branching ratios of 75%, 38%, 80%, and 72% respectively, and $\tilde{t}_1 \to \chi_3 t$ proceeds with branching ratio of 15%.
- Stop and gluino pair production with $\tilde{t}_1 \to \chi_2^+ b \to \chi_3 W b$ or $\tilde{t}_1 \to \chi_3 t$ and $\chi_3 \to \chi_1 h_1 \to \chi_1 2a_1$ promising channels for discovery
- Event simulation of the $\tilde{g}\tilde{g}$, $\tilde{t}_1\bar{\tilde{t}}_1$ and $t\bar{t}$ processes is carried out with Pythia8.205
- Fast detector simulation is performed with Delphe3.2.0 with the CMS detector card
- The signal selection employs a standard selection for semileptonic top pair events, together with a selection for $a_1 \to \mu^+\mu^-$, in which one top quark decays via $t \to bW \to b\ell\nu$ and the other via $t \to bW \to bqq'$.
- The requirements for the Run 1 analysis are these:
  - exactly one tight electron with $E_T > 25$ GeV and no isolation requirement
  - missing transverse energy $E_T^{miss} > 85$ GeV
  - four or more jets with $E_T > 20$ GeV, at least two of which are b-tagged
  - two or more tight muons with $p_T > 2$ GeV, no isolation requirement and $d_0/\sigma_{d_0} < 5$
  - zero net charge and $9.7 < m_{\mu^+\mu^-} < 10.3$ GeV in the leading and subleading muons
- The a_1 candidate is then reconstructed from the leading and subleading muons.
- ATLAS members, check the CERN Document Server for ATL-COM-PHYS-2013-001.