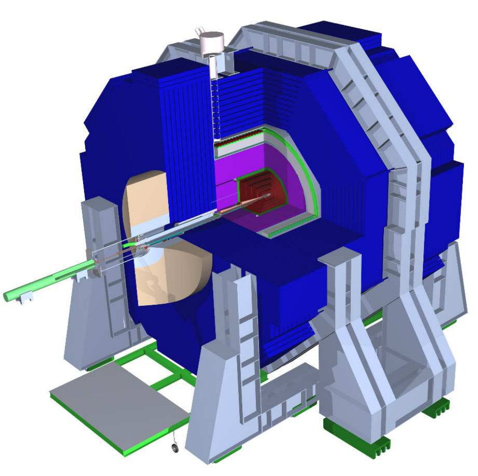
Exotic Higgs Decay $h \rightarrow 2a_1$ at the ILC



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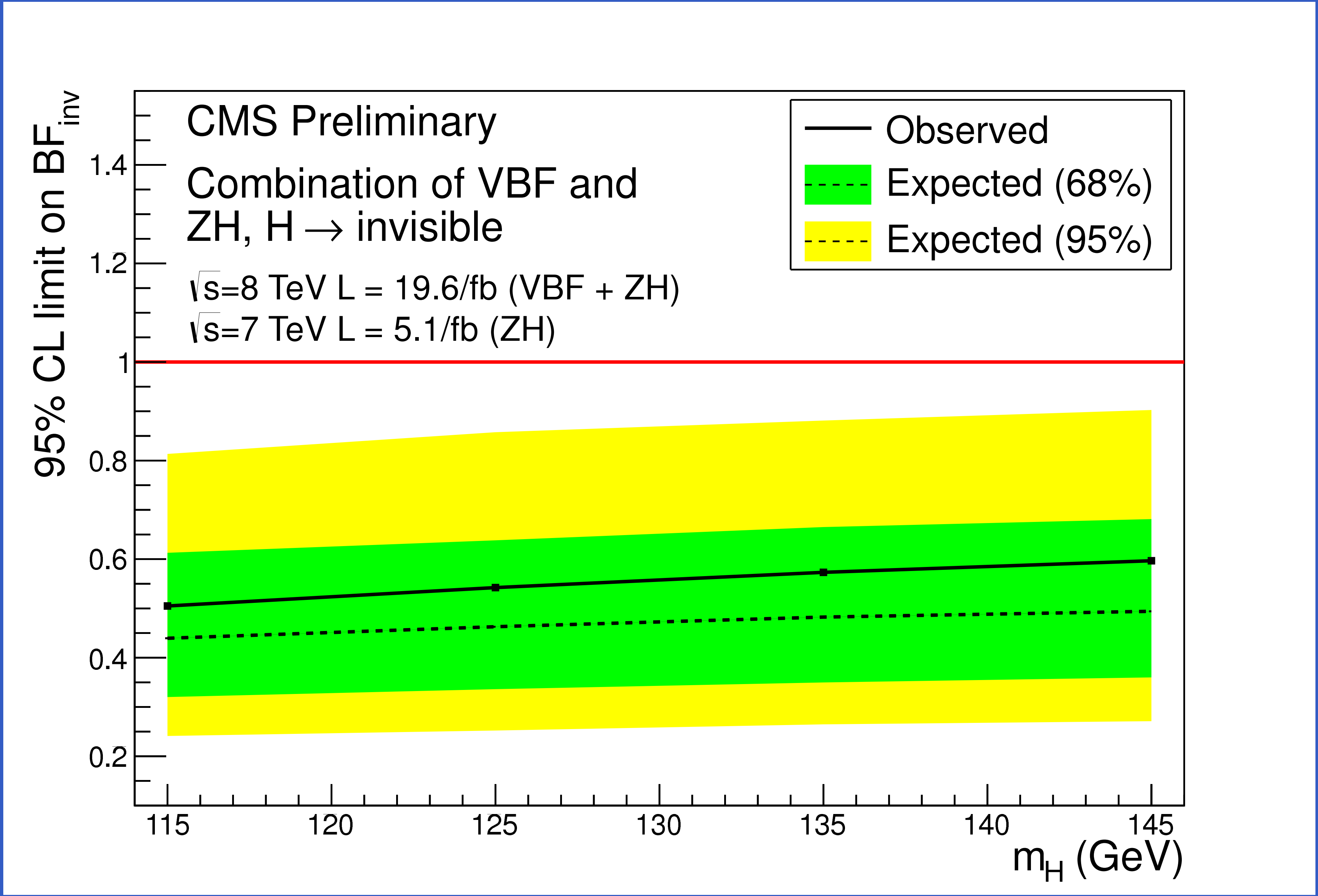
Introduction

- 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 $h_{125} \rightarrow 2a_1$, where a_1 is the lightest CP-odd Higgs boson which might escape detection in the dominant decay $a_1 \rightarrow \tau^+\tau^-$.
- 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.
- Here the h_1 is responsible for the LEPII excess,with $h_1 \rightarrow b\bar{b}$ suppressed to some extent by turning the exotic decay mode $h_1 \rightarrow 2a_1$.
- In this scenario h_{125}, the boson recently observed at the LHC is the NMSSM h_2.
- So $2m_\tau < m_{a_1} < 2m_B$ and $m_{h_1} \approx 98$ GeV are suggested for explaining the LEPII excess.
- While neither ATLAS nor CMS has reported searches for this scenario (CMS has for $m_{a_1} < 2m_\tau$), the $h \rightarrow 2a_1$ LHC sensitivity is studied in 0903.1377, 0805.3505, 1106.4545, 1301.1325.
- The most constraining limits on this scenario are from ALEPH in 1003.0705.
- Full details of this study can be found in the Snowmass White paper SNOW13-00133 (1309.0021).

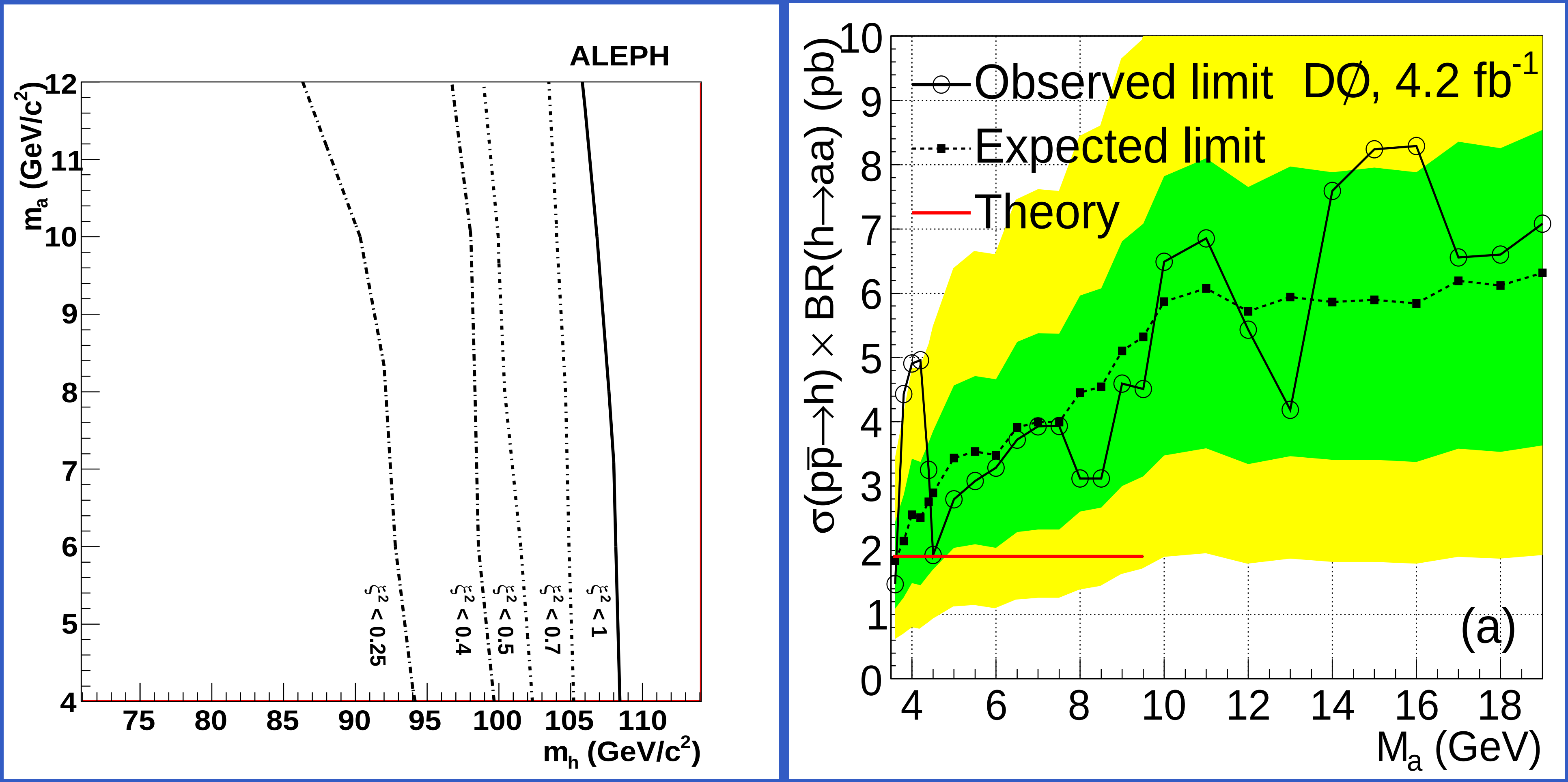
CMS Upper Limits on BR($H \rightarrow$ Invisible/Unobserved)

CMS-PAS-HIG-13-018



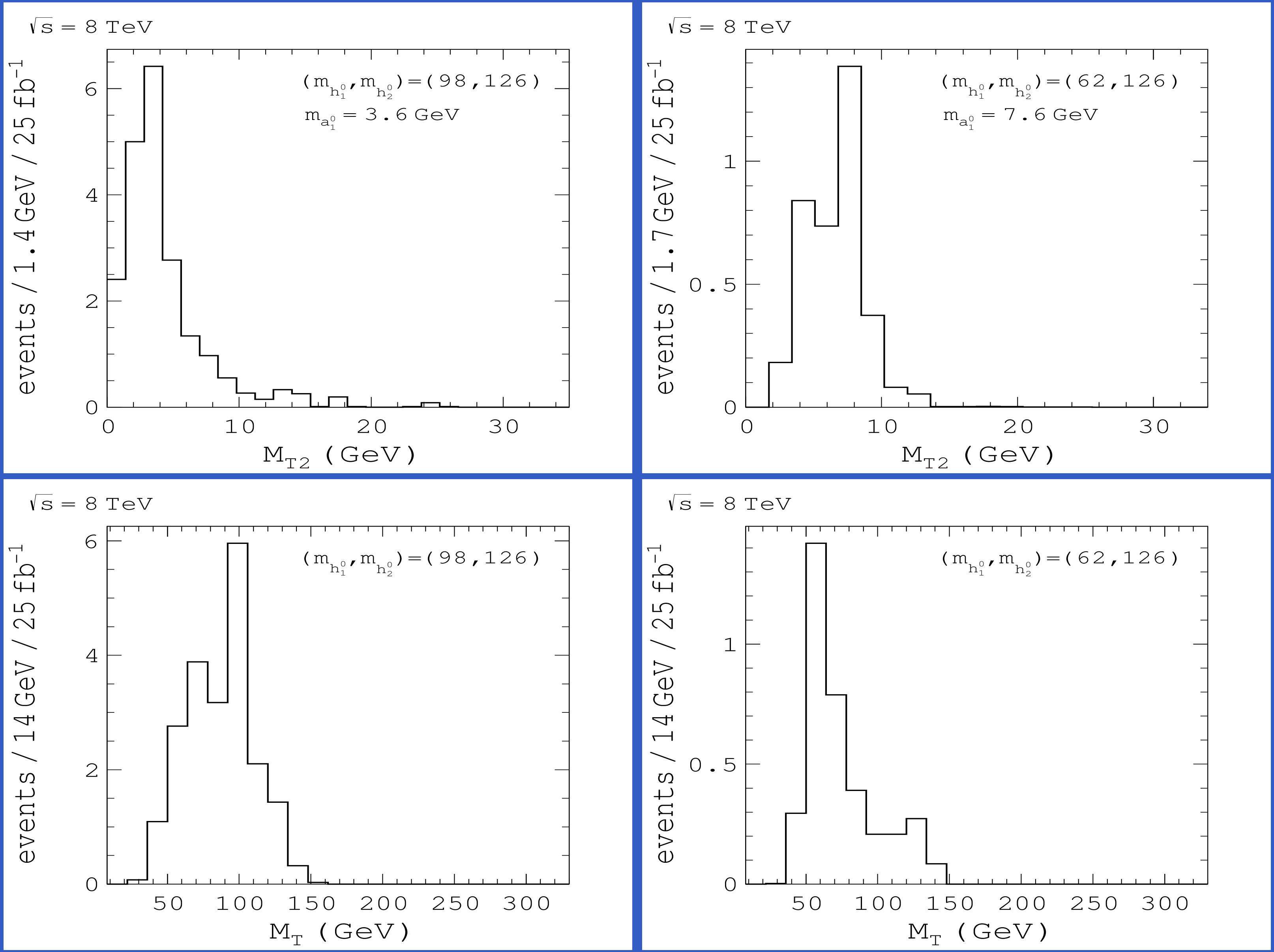
This Scenario at LEPII and the Tevatron

$$\xi^2 = \sigma/\sigma_{SM} \times B(h \to 2a) \times B^2(a \to \tau^+\tau^-)$$



JHEP 1005:049,2010 (left), PRL 103, 061801,2009 (right)

This Scenario at the LHC ($\sqrt{s} = 8$ TeV, 25 fb^{-1})



Cerdeno, Ghosh and Park (arXiv:1301.1325v3)

Next to Minimal Supersymmetric Model (NMSSM)

- The Next-to-Minimal Supersymmetric Model (NMSSM) is motivated to reduce the fine-tuning required for the μ-term in the MSSM superpotential.
- One singlet superfield S is introduced to the MSSM. The NMSSM superpotential is

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

- An effective μ term is generated $\mu_{eff} = \lambda\langle S\rangle$ at a natural scale.
- The soft SUSY breaking terms in the NMSSM Lagrangian are

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

- Six parameters determine the NMSSM Higgs sector at tree level:$\lambda, \kappa, A_\lambda, A_\kappa, \tan\beta$ and μ_{eff}.
- The NMSSM Higgs sector includes neutral CP-odd a_1, a_2, neutral CP-even h_1, h_2, h_3 and charged H^+, H^-.

NMSSM Higgs Parameter Point

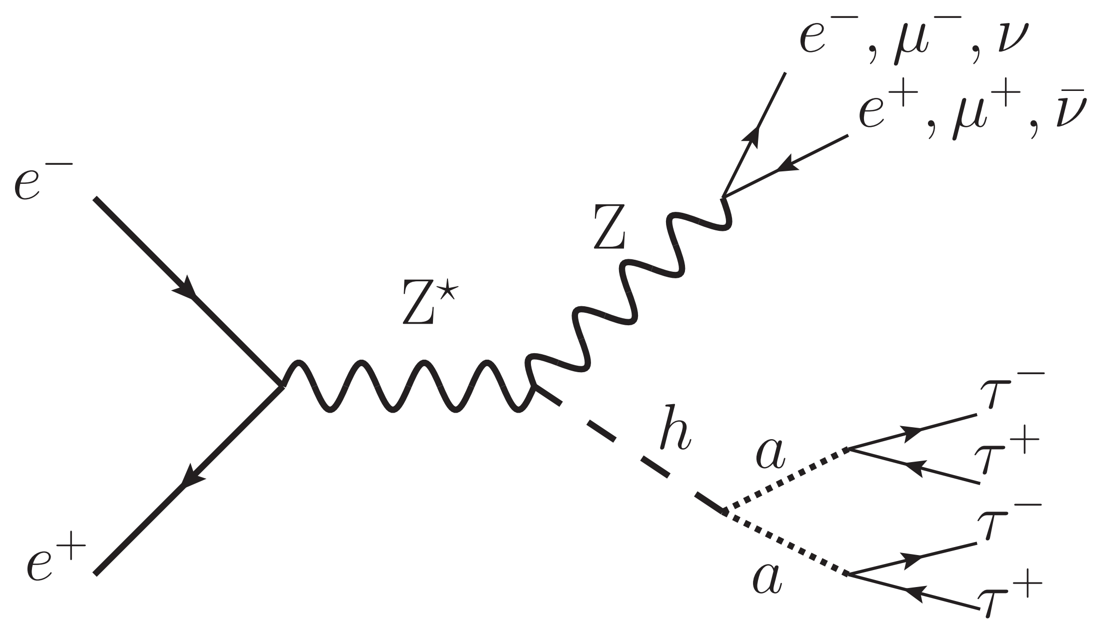
NMSSMTools 3.2.4

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.

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.

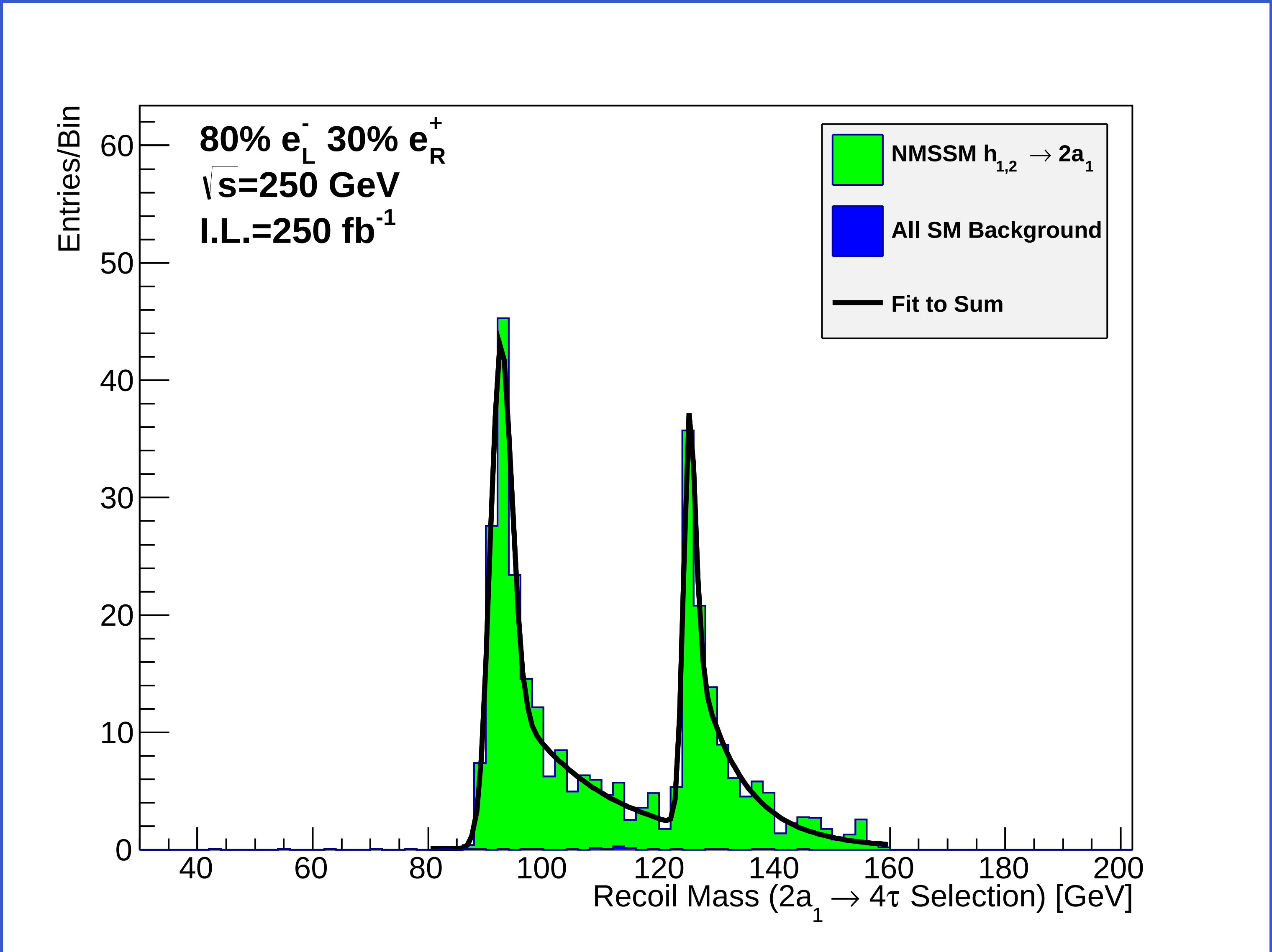
The $h_{1,2} \to 2a_1 \to 4\tau$ Channel

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.

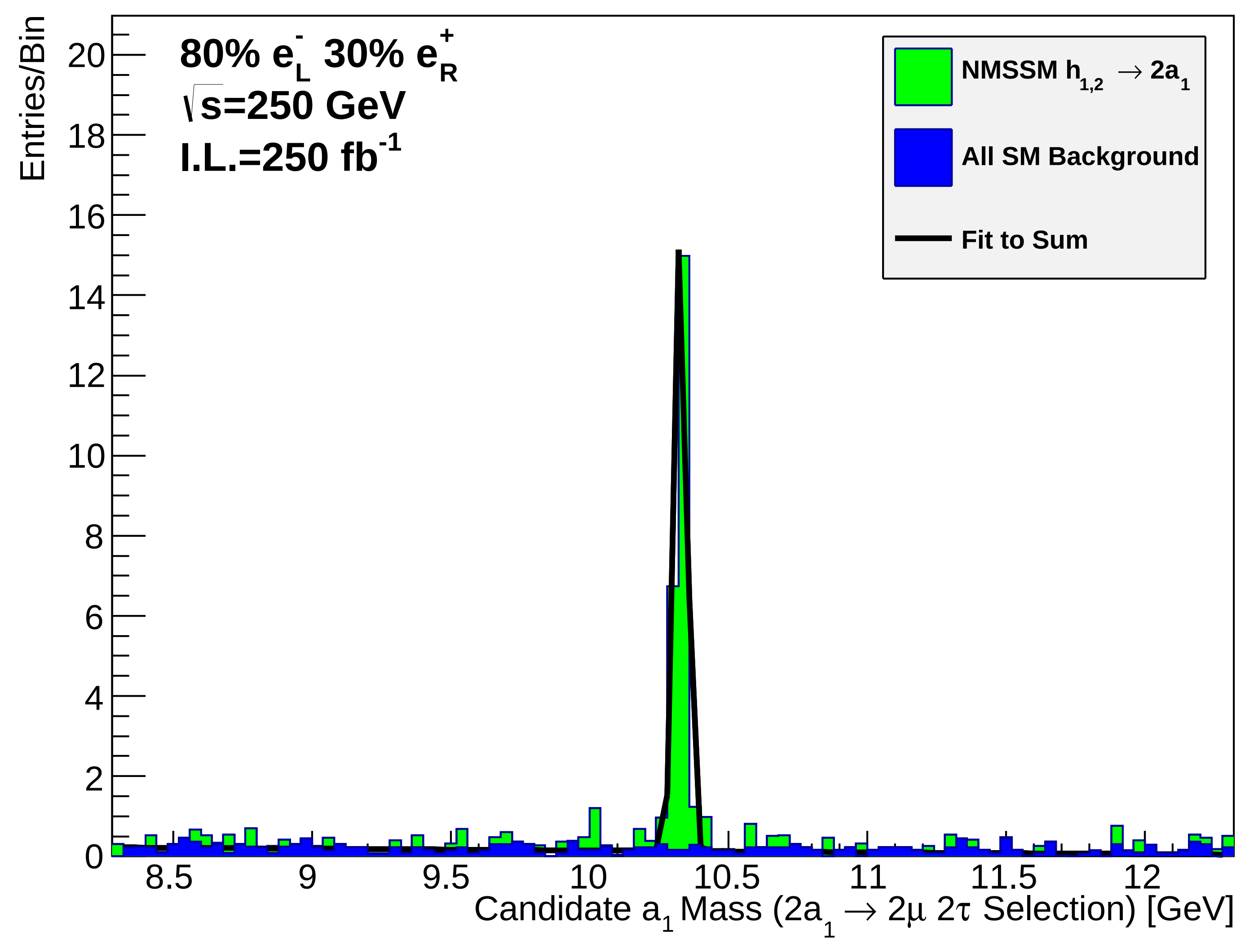
The $h_{1,2} \to 2a_1 \to 2\mu 2\tau$ Channel

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 $a_1 \to \mu^+\mu^-$ After Full Selection



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

Conclusions

- Exotic Higgs decay $h \to 2a_1$ may prove to be the window into new physics.
- At the ILC, the clean interaction environment provides powerful separation between signal and background processes.
- We have performed a study of the exotic Higgs decay $h_{1,2} \to 2a_1$ in the NMSSM with full simulation of the SiD detector at the ILC.
- After initial running with $\int dt\mathcal{L} = 250\text{fb}^{-1}$, we expect discovery for both $h_{125} = h_2$ (SM-like Higgs) and h_1 (non-standard Higgs, $m_{h_1} = 91.6\text{GeV}$).
- With full SM background simulation, we expect nearly negligible background and approximately 1691 signal events after luminosity upgrades.
- We find that the expected precision on the a_1 mass in early running is $m_{a_1} = 10.329 \pm 0.005$ GeV as measured in the $2\mu 2\tau$ channel alone, with significant improvement expected after luminosity upgrades.
- Note that the results here only include the $Z \to \mu^+\mu^-$ tag, and that by including the $Z \to e^+e^-$ and hadronic tags the sensitivity should improve substantially.