BSM Higgs Searches at a Muon Collider

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THE MUON COLLIDER AS A *H*/*A* FACTORY

- The couplings of the Higgs-like particle discovered at the LHC are consistent with the SM expectations for the particle associated with electroweak symmetry breaking.
- However, the SM is incomplete. Extensions to SUSY or more generally Two Higgs-Doublet Models (2HDM) require five scalar particles: h^0, H^0, A^0, $H^\pm$. Decay amplitudes depend on two parameters, α and β.
- In the decoupling limit, $m_A >> m_Z$: h^0 is SM-like; and H^0, A^0, $H^\pm$ are nearly mass-degenerate and have suppressed couplings to VV.

H/*A* PRODUCTION

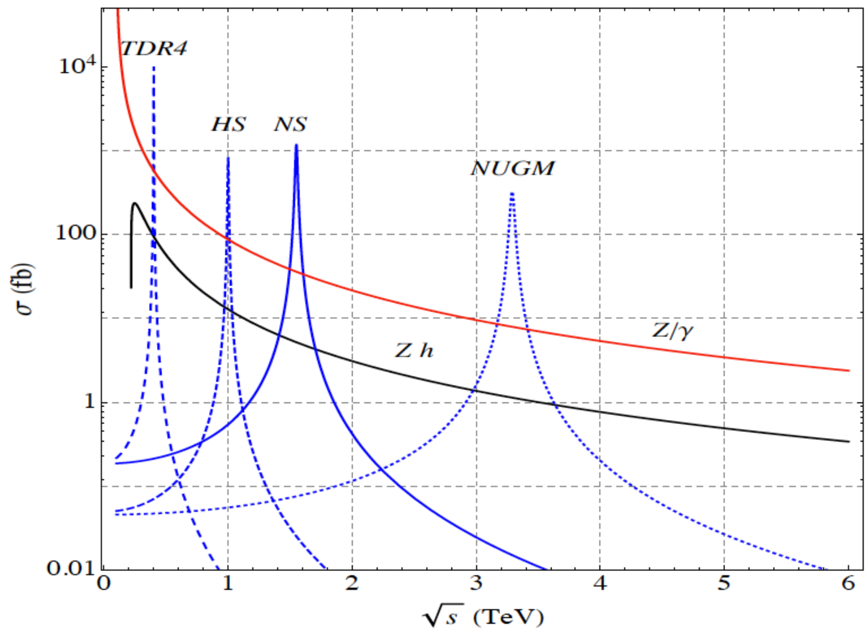
- Since 126 GeV is at the upper end of expectations for m_h in SUSY models, reevaluations of viable models lead to heavy sparticles and heavier *H*/*A* are considered, consistent with current limits.
- *H*/*A* are relatively narrow since couplings to *VV* are suppressed and large tan β suppresses couplings to up-type fermions.
- *H*/*A* are likely to be difficult to find at the LHC, and at $e^+ e^-$ colliders must be produced in association with other particles, such as *Z*, since the electron Yukawa coupling is too small for *s*-channel production.

A MUON COLLIDER AS AN *H*/*A* FACTORY

- The *H* and *A* can be produced as *s*-channel resonances at a muon collider. Recently Eichten and Martin (arXiv:1306.2609) have examined this possibility.

Some ILC Benchmark examples:

Light-slepton NLSP model (TDR4)
Hidden supersymmetry (HS)
Natural supersymmetry (NS)
Non-universal Higgs mass (NUHM)

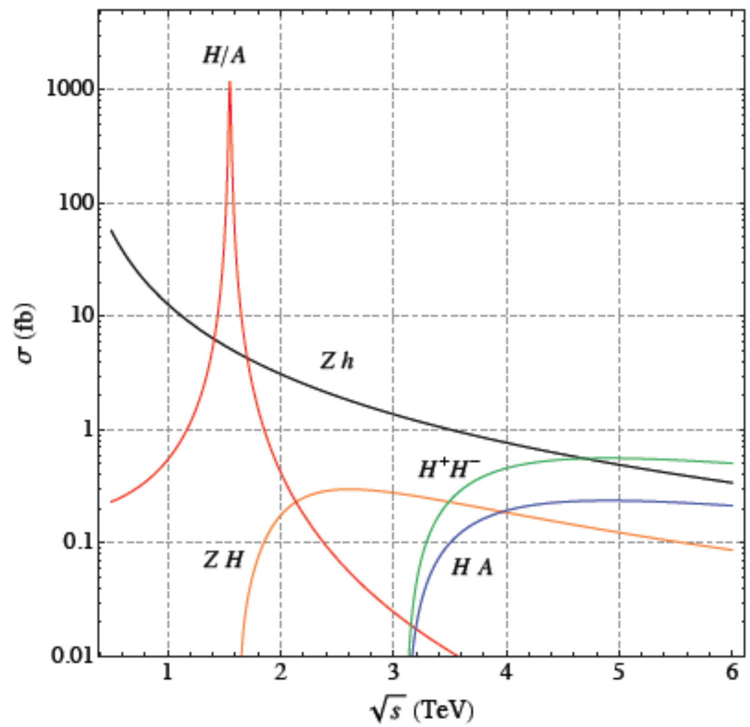


A MUON COLLIDER AS AN *H/A* FACTORY (E. Eichten and A. Martin [arXiv:1306.2609])

- Generic features but look in detail at NS example:

TABLE I. Properties of the H and A states in the Natural Supersymmetry benchmark model [35]. In addition to masses and total widths, the branching ratios for various decay modes are shown.

	H		A	
Mass	1.560 TeV		1.550 TeV	
Width	19.5 GeV		19.2 GeV	
	(Decay)	Br	(Decay)	Br
	$(b\bar{b})$	0.64	$(b\bar{b})$	0.65
	$(\tau^+\tau^-)$	8.3×10^{-2}	$(\tau^+\tau^-)$	8.3×10^{-3}
	$(s\bar{s})$	3.9×10^{-4}	$(s\bar{s})$	4.0×10^{-3}
	$(\mu^+\mu^-)$	2.9×10^{-4}	$(\mu^+\mu^-)$	2.9×10^{-4}
	$(t\bar{t})$	6.6×10^{-3}	$(t\bar{t})$	7.2×10^{-3}
	(gg)	1.4×10^{-5}	(gg)	6.1×10^{-5}
	$(\gamma\gamma)$	1.1×10^{-7}	$(\gamma\gamma)$	3.8×10^{-9}
	(Z^0Z^0)	2.6×10^{-5}	$(Z^0\gamma)$	4.3×10^{-8}
	(h^0h^0)	4.4×10^{-5}		
	(W^+W^-)	5.3×10^{-5}		
	$(\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp)$	9.2×10^{-3}	$(\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp)$	9.5×10^{-3}
	$(\tilde{t}_1\tilde{t}_1^*)$	3.1×10^{-3}	$(\tilde{t}_1\tilde{t}_2^*)$	1.1×10^{-3}
	$(\chi_1^0\chi_1^0)$	2.6×10^{-3}	$(\chi_1^0\chi_1^0)$	3.2×10^{-3}
	$(\chi_2^0\chi_2^0)$	1.3×10^{-3}	$(\chi_2^0\chi_2^0)$	1.1×10^{-3}
	$(\chi_1^0\chi_3^0)$	2.8×10^{-2}	$(\chi_1^0\chi_3^0)$	3.9×10^{-2}
	$(\chi_1^0\chi_4^0)$	1.7×10^{-2}	$(\chi_1^0\chi_4^0)$	4.0×10^{-2}
	$(\chi_2^0\chi_3^0)$	3.8×10^{-2}	$(\chi_2^0\chi_3^0)$	2.7×10^{-2}
	$(\chi_2^0\chi_4^0)$	4.0×10^{-2}	$(\chi_2^0\chi_4^0)$	1.5×10^{-2}
	$(\chi_1^\pm\chi_2^\mp)$	5.7×10^{-2}	$(\chi_1^\pm\chi_2^\mp)$	6.0×10^{-2}



A MUON COLLIDER AS AN *H/A* FACTORY (E. Eichten and A. Martin [arXiv:1306.2609])

- Large production rate: Events/year = 154,000 x $\left(\frac{\mathcal{L}}{10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}}\right)\left(\frac{1\ TeV}{m_{H/A}}\right)^2 \frac{BR(H/A \to \mu^+\mu^-)}{10^{-4}}$
- Use b b decays to extract H and A properties:

TABLE II. Fit of the H/A region to background plus Breit-WIgner resonances. Both a single and two resonance fits are shown. General form of the background fit is $\sigma_B(\sqrt{s}) = c_1(1.555)^2/s($ in TeV$^2)$. The values of the best fit for one or two Breit-Wigner resonances are given.

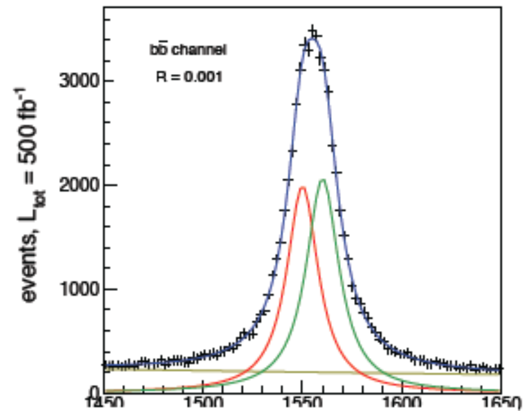
One Resonance

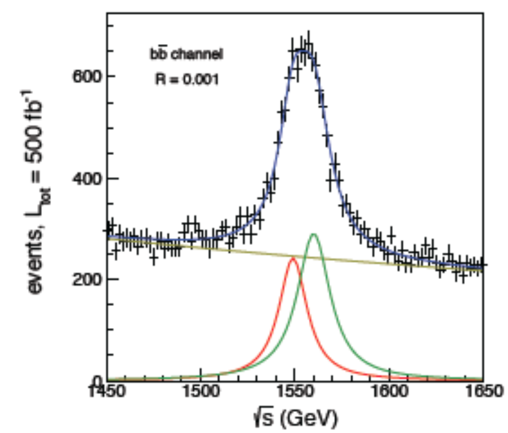
Mass(GeV)	Γ(GeV)	σ_{peak} (pb)
1555 ± 0.1 GeV	24.2 ± 0.2	1.107 ± 0.0076
$\chi^2/\mathrm{ndf} = 363/96$		$c_1 = 0.0354 \pm 0.0006$

Two Resonances

Mass(GeV)	Γ(GeV)	σ_{peak} (pb)
1550 ± 0.5 GeV	19.3 ± 0.7	0.6274 ± 0.0574
1560 ± 0.5 GeV	20.0 ± 0.7	0.6498 ± 0.0568
$\chi^2/\mathrm{ndf} = 90.1/93$		$c_1 = 0.040 \pm 0.0006$

Beam energy resolution R ~ 0.001





- τ+τ-
  - Extract branching ratios
  - Use tau decays to measure CP
- electroweakino's
  - 20% of decays
  - self analysing - unlike the ILC, initial beam polarization not essential.

THE MUON COLLIDER AS A *H*/*A* FACTORY: DETECTOR CHALLENGES

Anna Mazzacane et al.

- In order to fully exploit the opportunity of the Muon Collider as an *H*/*A* factory, the detector must meet very demanding requirements (excellent tracking and calorimetry) pushing the limits of the technologies
- The background is mainly from the interaction of beam muon decay products with beamline componets and the accelerator tunnel
- Shielding structures are needed to reduce this background to acceptable levels: a tungsten nozzle near the IP
- Previous studies have shown that this background is out of time w.r.t. the physics and can be reduced by making timing cuts

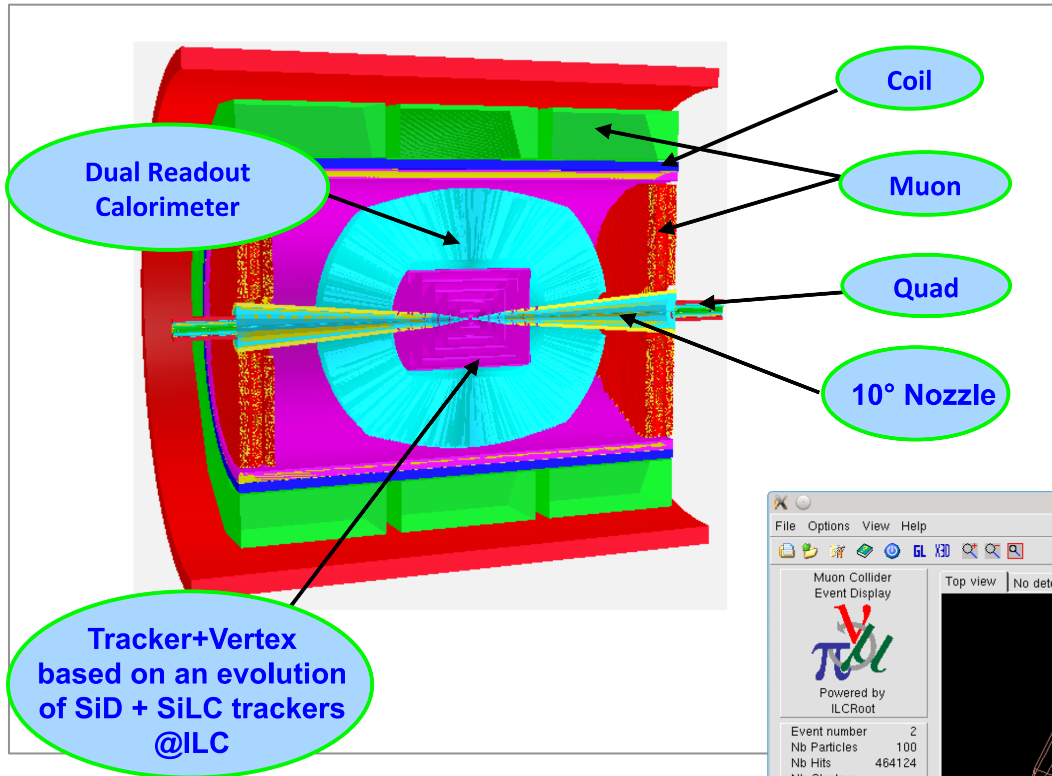
THE MUON COLLIDER AS AN *H/A* FACTORY: DETECTOR CHALLENGES (continued)

References:

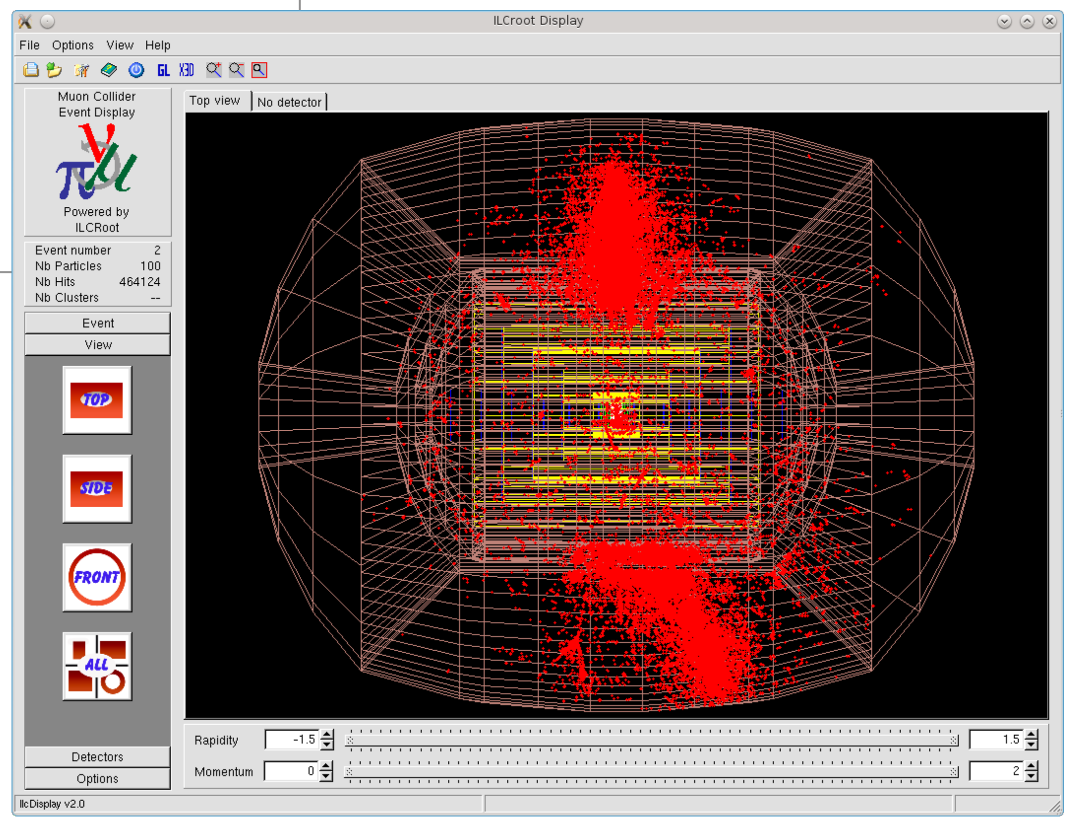
- N. V. Mokhov et al. “Design and simulation of $\mu^+\mu^-$ Higgs Factory machine detector interface,” Higgs Factory Muon Collider Workshop, UCLA, March 2013, and MAP Collaboration Meeting, Fermilab, June 2013.
- N. Terentiev, “Simulation of detector response to backgrounds,” MAP Collaboration Meeting, Fermilab, June 2013; “Simulation of the tracker and vertex silicon detector hits response to machine backgrounds in a muon collider,” Higgs Factory Muon Collider Workshop, UCLA, March 2013
- A. Mazzacane, “Muon Collider tracking studies in ILCroot,”Muon Collider 2011, Telluride, CO; “Muon Collider backgrounds,” Snowmass Lepton Collider Workshop, MIT, April 2013.

DETECTOR AND PHYSICS SIMULATION

- The detector used in these studies has been developed within the ILCroot framework and is an evolution of the detector adopted for the ILC benchmark studies. Shielding structures and dead materials for the supports are included.
- ~ 4000 *H*/*A* events generated with PYTHIA at $\sqrt{s}$ = 1.5 TeV and Gaussian beam energy smearing (R = 0.001) (A. Martin) are fully simulated in the ILCroot framework with track and calorimeter reconstruction.
- In these preliminary studies the $b\bar{b}$ decay (64% B.R.) is considered.
- The analysis process with full beam background is still work in progress and will be presented in Minnesota.



ILCroot Detector Simulation

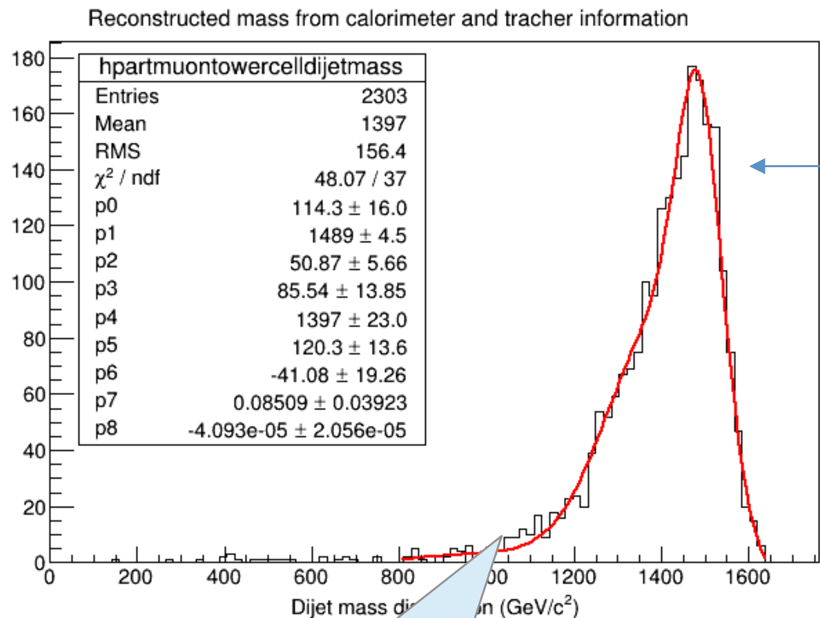


ILCroot Event Display

ANALYSIS STRATEGY

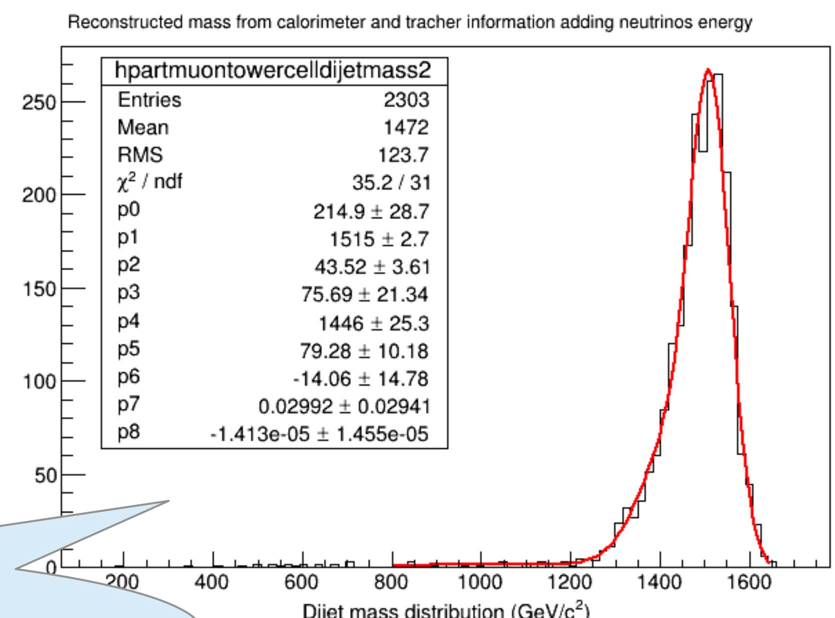
- Perfect b-tagging applied (using information from Monte Carlo truth)
- Assume jet made of 2 non-overlapping regions:
  - Core: region of the calorimeter with overlapping towers
  - Outliers: hit towers separated from the core
- Measure the Jet axis
  - Using information from trackers
- Measure the Core energy
  - Using calorimeter information
- Reconstruct Outliers individually
  - Using tracking and/or calorimetry depending on the charge of the particles
- Add Muons escaping from calorimeter
  - Using muon spectrometer
- No cuts applied to visible energy to compensate for missing energy from neutrinos (preliminary)

ANALYSIS RESULTS



$$\frac{\sigma_M}{M} = 3.4\,\%$$

Significant neutrino component



Dijet mass distribution including neutrino contribution

Preliminary studies: Detector performance not affected by presence of shielding nozzle