# Motivations and strategies for detecting $h \to aa$ at hadron colliders

Bob McElrath
University of California, Davis

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# The NMSSM and $\mu$-solvable models

A $\mu$-solvable model is any model which promotes the $\mu$ term to a field, such that the vacuum expectation value of a field dynamically generates $\mu = \lambda \langle S \rangle$.

$$W = \lambda S H_u H_d + \kappa S^3 \tag{1}$$

Such models may involve extra discrete or gauge symmetries to forbid the canonical $\mu$ term.

String-derived models never have a $\mu$ term since masses appearing in the superpotential must be $\mathcal{O}(M_s)$.

The $\kappa$ term may be absent, in favor of Planck-suppressed Kahler operators, and a large discrete symmetry. (a.k.a. MNSSM)

We choose the NMSSM as a prototype of this class of models.

## $U(1)$ symmetries give a small $M_A$

$$W = \lambda S H_u H_d + \kappa S^3 \qquad V_{soft} = \lambda A_\lambda S H_u H_d + \kappa A_\kappa S^3 \tag{2}$$

$$Q_{H_u} = 1 \qquad Q_{H_d} = 1 \qquad Q_S = -2 \tag{3}$$

This is a Peccei-Quinn symmetry. Superpotential $\lambda$ term is symmetric, soft $M_i$ are symmetric, Yukawa's are symmetric. Broken explicitly by $\kappa$ and $A_\kappa$. Symmetry is approximate in $\kappa \ll 1, A_\kappa \ll M_{SUSY}$ limit. [Miller, Moretti, Nevzorov, `hep-ph/0501139` (among others)]

$$Q_{H_u} = 1 \qquad Q_{H_d} = 1 \qquad Q_S = 1 \tag{4}$$

This is an R-symmetry (not respected by supersymmetry). Broken by soft SUSY breaking trilinear terms $A_\lambda$, $A_\kappa$. Symmetry is approximate in $\kappa A_\kappa, \lambda A_\lambda \ll M_{SUSY}$ limit. [Matchev, Cheng, `hep-ph/0008192`]

In *both* cases, $A_1$ is the PNGB of the broken symmetry.

Both also also broken by radiative corrections.

## The gaugino-mediated connection

In gaugino-mediated SUSY breaking, gauginos get soft masses $M_{SUSY}$ first, and transmit SUSY breaking to the rest of the theory at 1-loop.

$H_u$ and $H_d$ are charged under $SU(2)_L$ and $U(1)_Y$, therefore we expect $A_\lambda \simeq M_{SUSY}/4\pi$.

$S$ is *uncharged* under SM gauge symmetries. Therefore we expect $A_\kappa \simeq M_{SUSY}/16\pi^2$.

## Constraints on a light $A$

There are numerous constraints on a very light $A$ (often called the Axion when $\kappa = 0$). Most are for *very* light $A$. For instance microwave cavity searches for the axion that solves the Strong CP problem.

Concentrate on the region $2M_\tau < M_A < M_\Upsilon$

$\Upsilon \rightarrow \gamma + X$ spectrum shows no deviations. (CLEO)

$\rightarrow$ Experimental triggering reqires $E_\gamma >$ 500 MeV. (no constraint on $8.95 GeV < M_A < 9.46 GeV$)

$\Upsilon \rightarrow \gamma + invisible$ shows no deviations. (CLEO)

$\rightarrow$ Measurement requires $E_\gamma > 1$ GeV.

ISR spectrum also makes this measurement insensitive for $M_A$ near $M_\Upsilon$.

## Constraints on a light $A$ (ctd.)

$e^+e^- \rightarrow \gamma + invisible$ shows no deviations. (LEP)

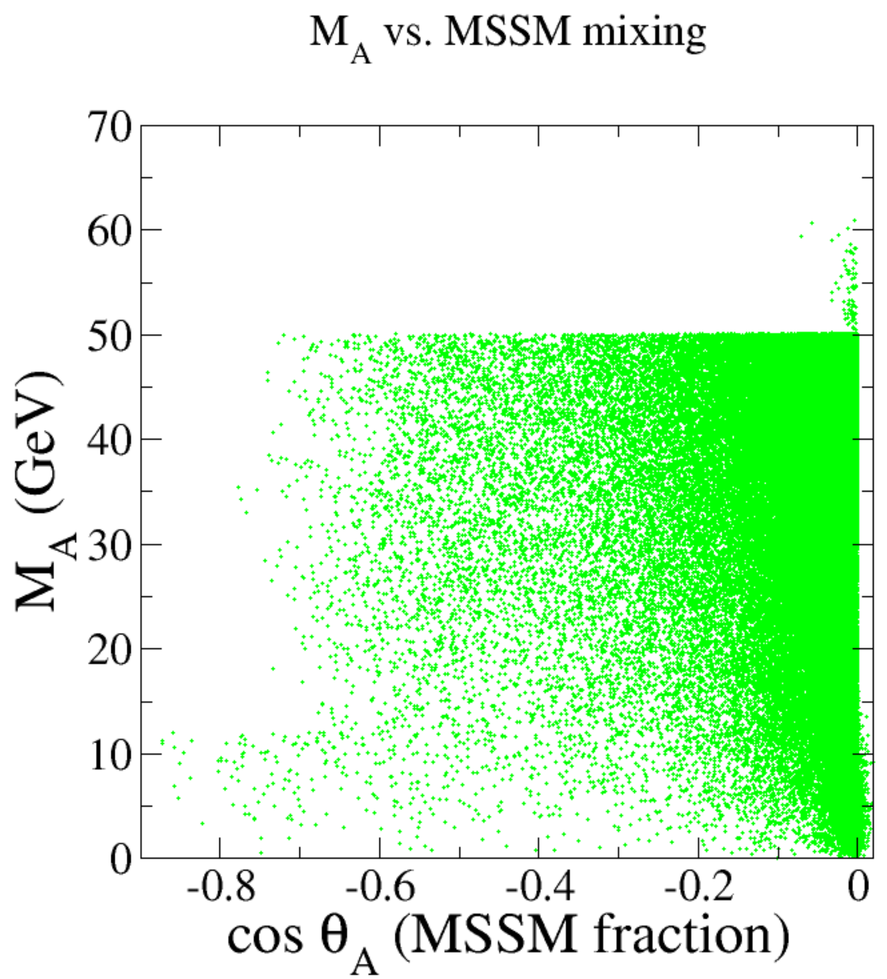
$\rightarrow Aee$ coupling is extremely small.

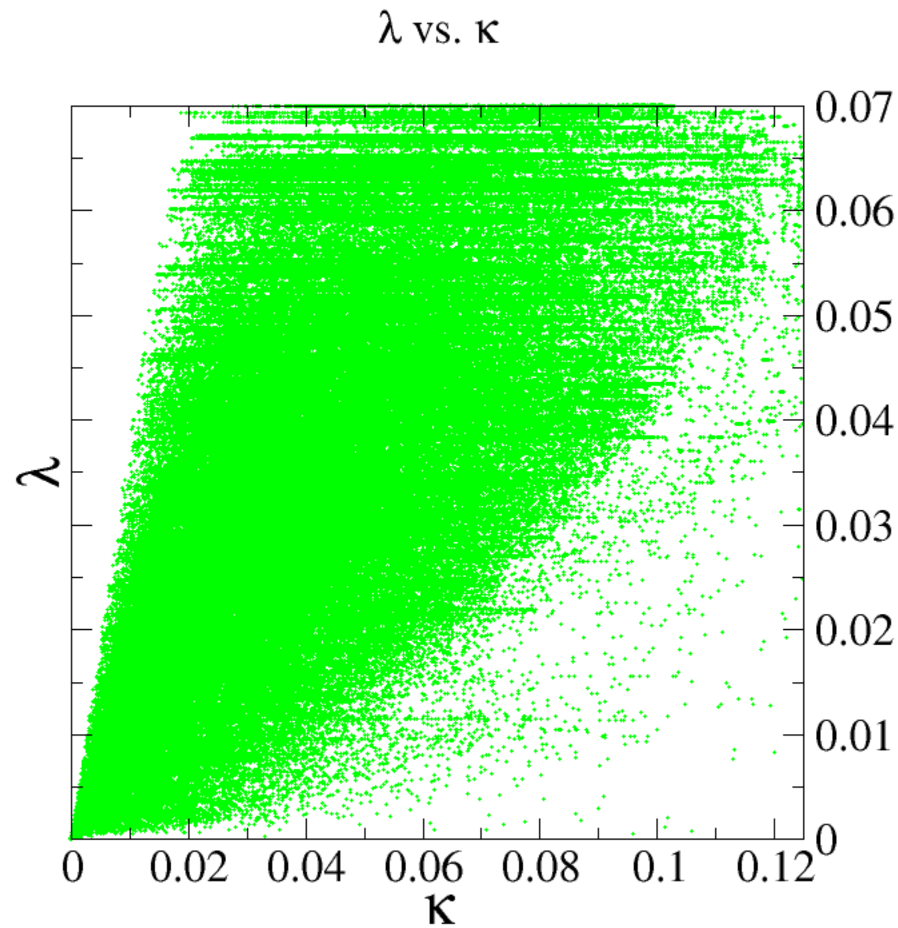
$K \rightarrow \pi A$ is a strong constraint for $M_A \lesssim 400 MeV$.

In all cases, couplings to the SM are suppressed by $\cos\theta_A$. $\cos\theta_A$ can be small at the same time that $h \rightarrow AA$ is large! Unless a neutralino is also light, $A \rightarrow SM$ is also dominant!

$H \rightarrow AA \rightarrow invisible$ is no different phenomenologically than $H \rightarrow invisible$, and can be discovered in the W W fusion channel at the LHC.

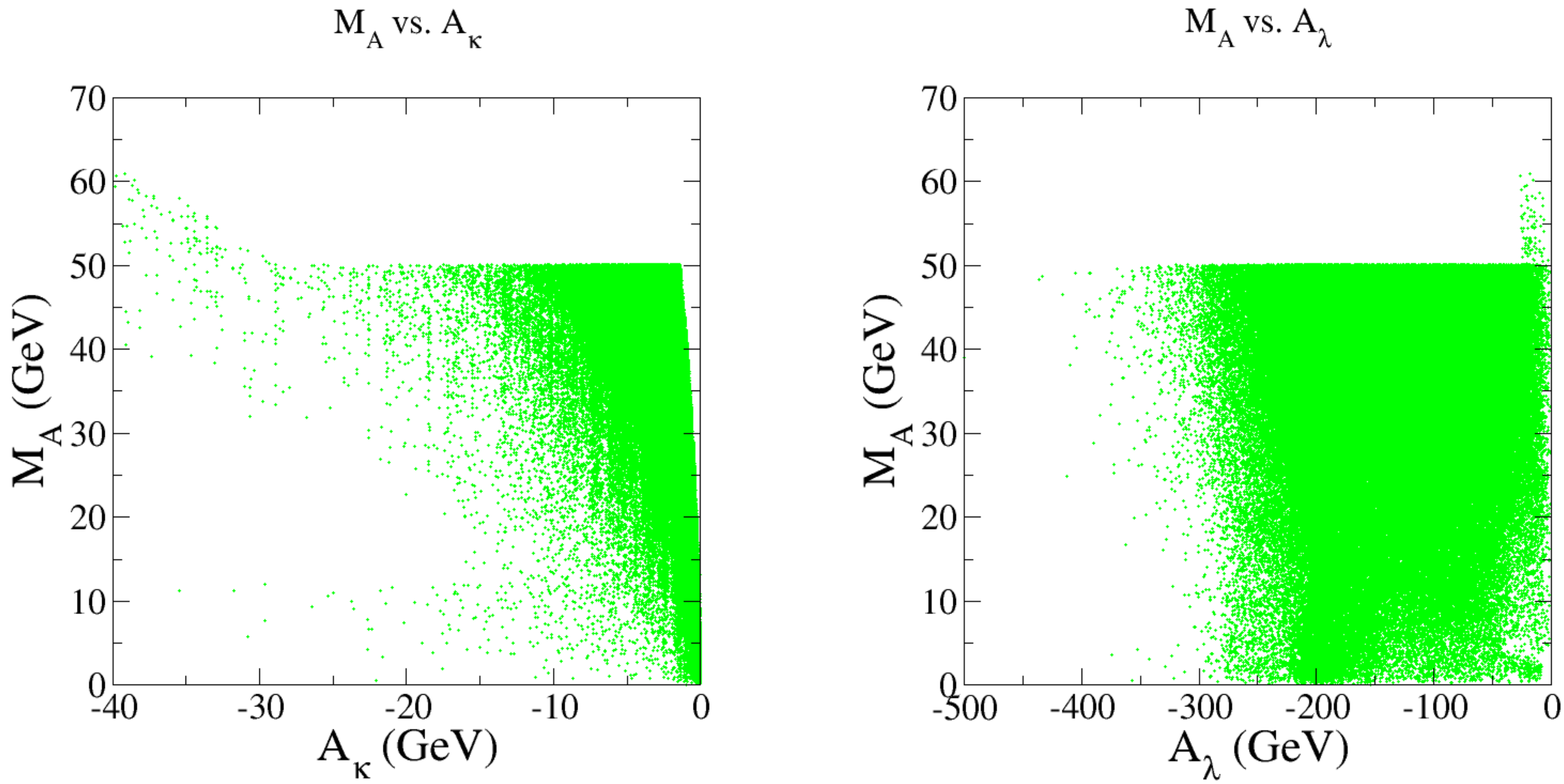
# Does the parameter space exist?



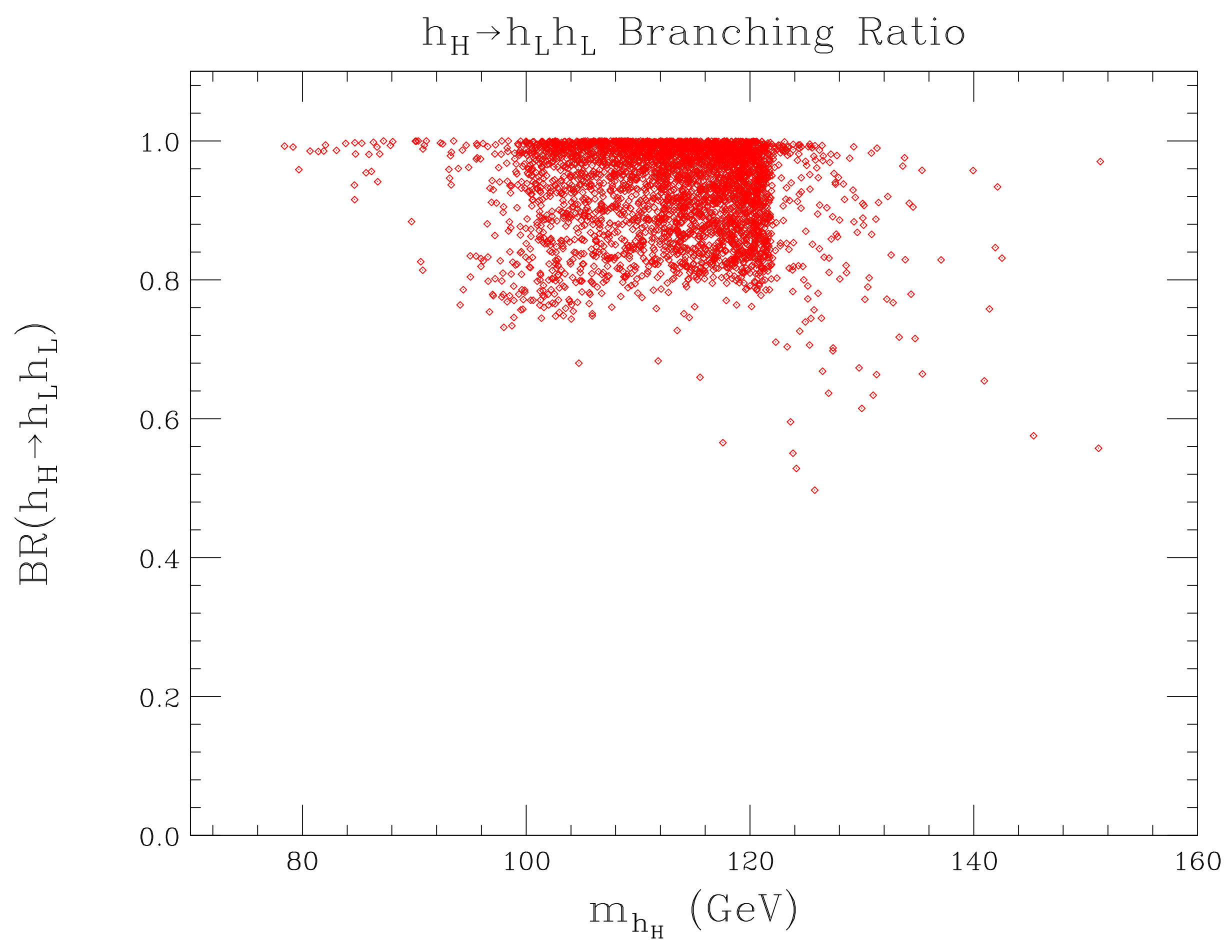

Using modified NMHDECAY [Ellwanger, Gunion, Hugonie, `hep-ph/0406215`]
[Gunion, Hooper, McElrath; to appear]

# Monte Carlo support for $U(1)_R$



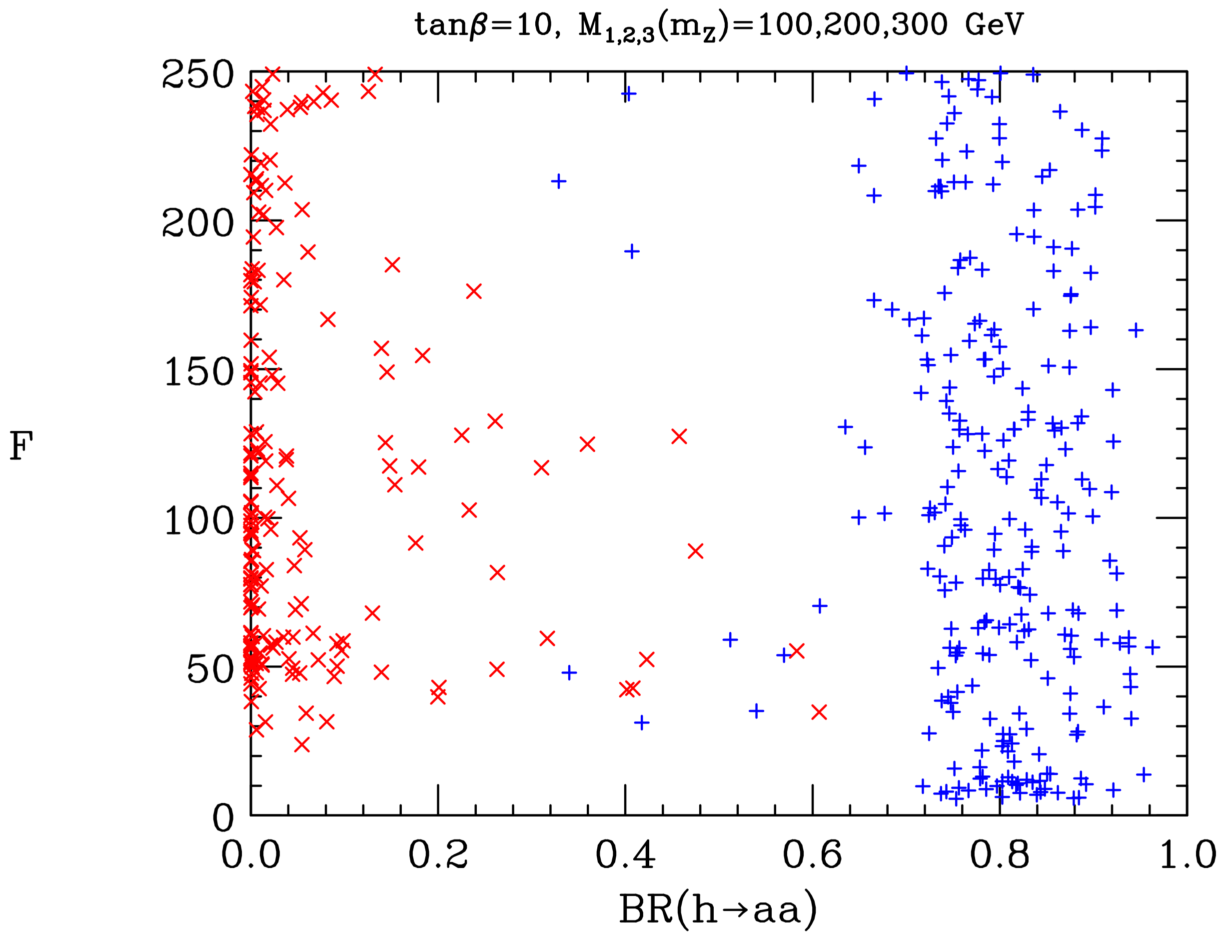

[Gunion, Hooper, McElrath; to appear]

# BR($H \to AA$)



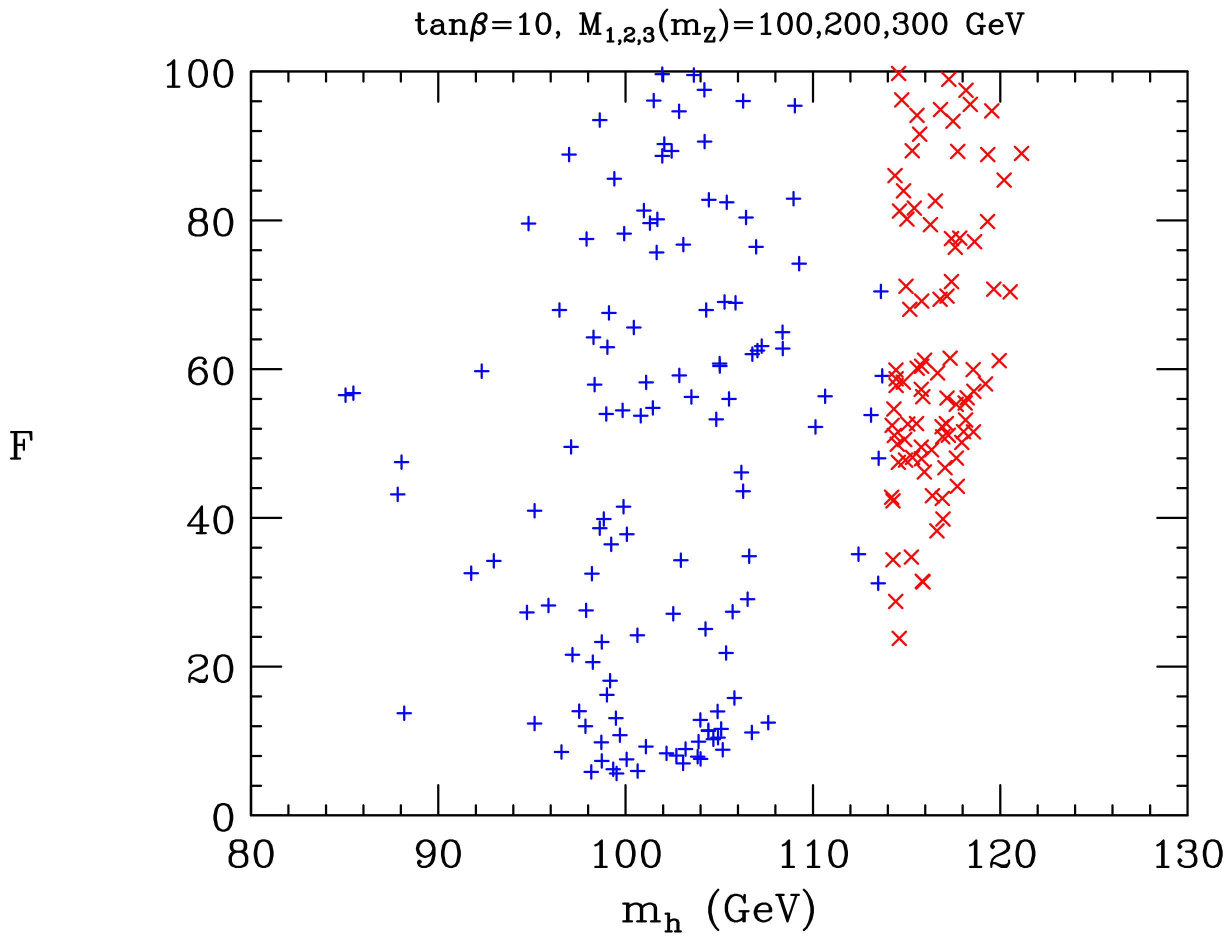

[Ellwanger, Gunion, Hugonie, `hep-ph/0503203`]

# Fine-tuning




[Dermisek, Gunion, hep-ph/0502105]

# Fine-tuning




[Dermisek, Gunion, hep-ph/0502105]

## Electroweak Baryogenesis

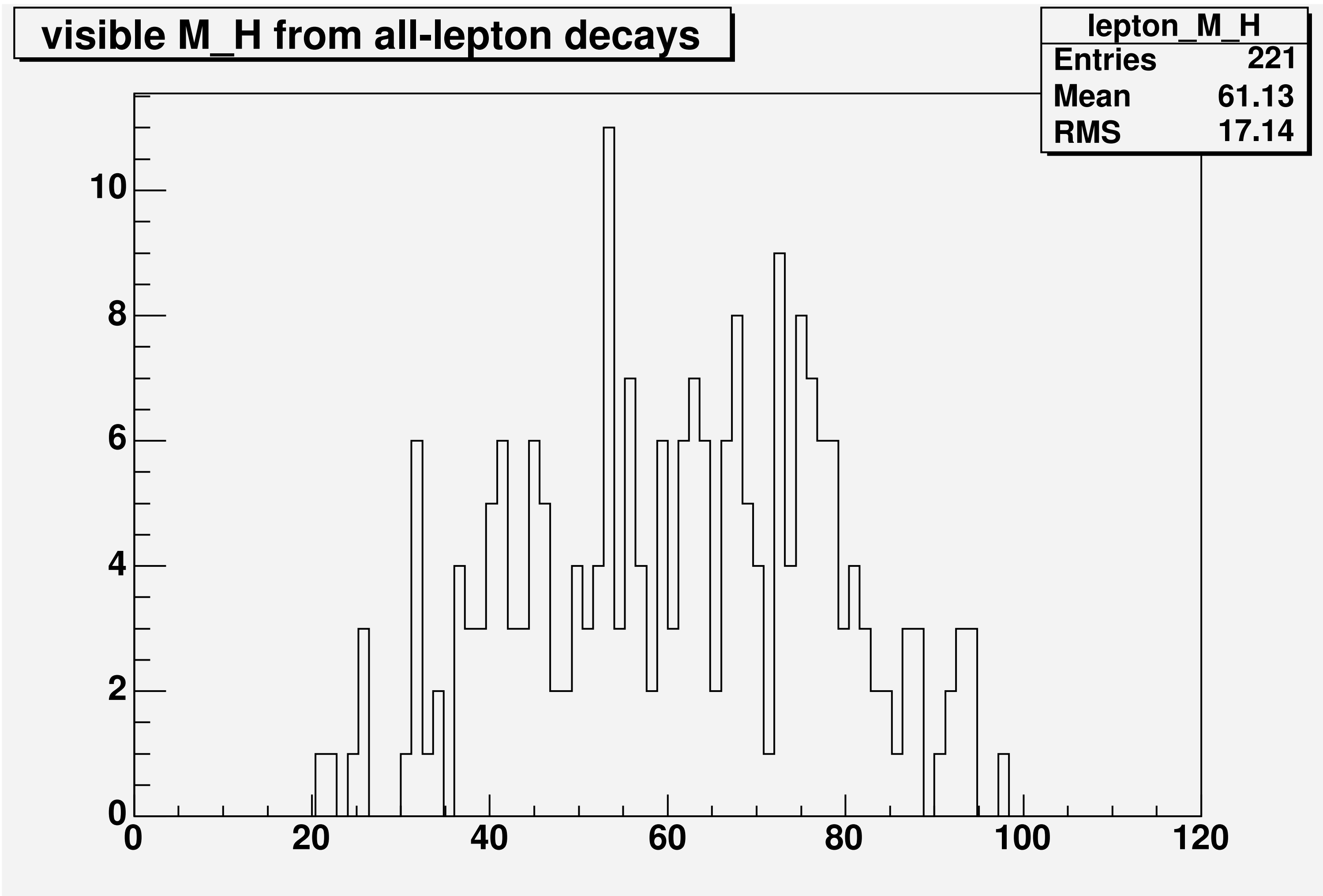
In MSSM:

- Two-loop stop effects required to enhance phase transition.
- Requires $105 < M_{\tilde{t}} < 165$ and $110 < M_h < 115$. [Quiros hep-ph/0101230]

NMSSM can easily get strong first-order phase transition without light stop, due to new trilinear soft SUSY terms.

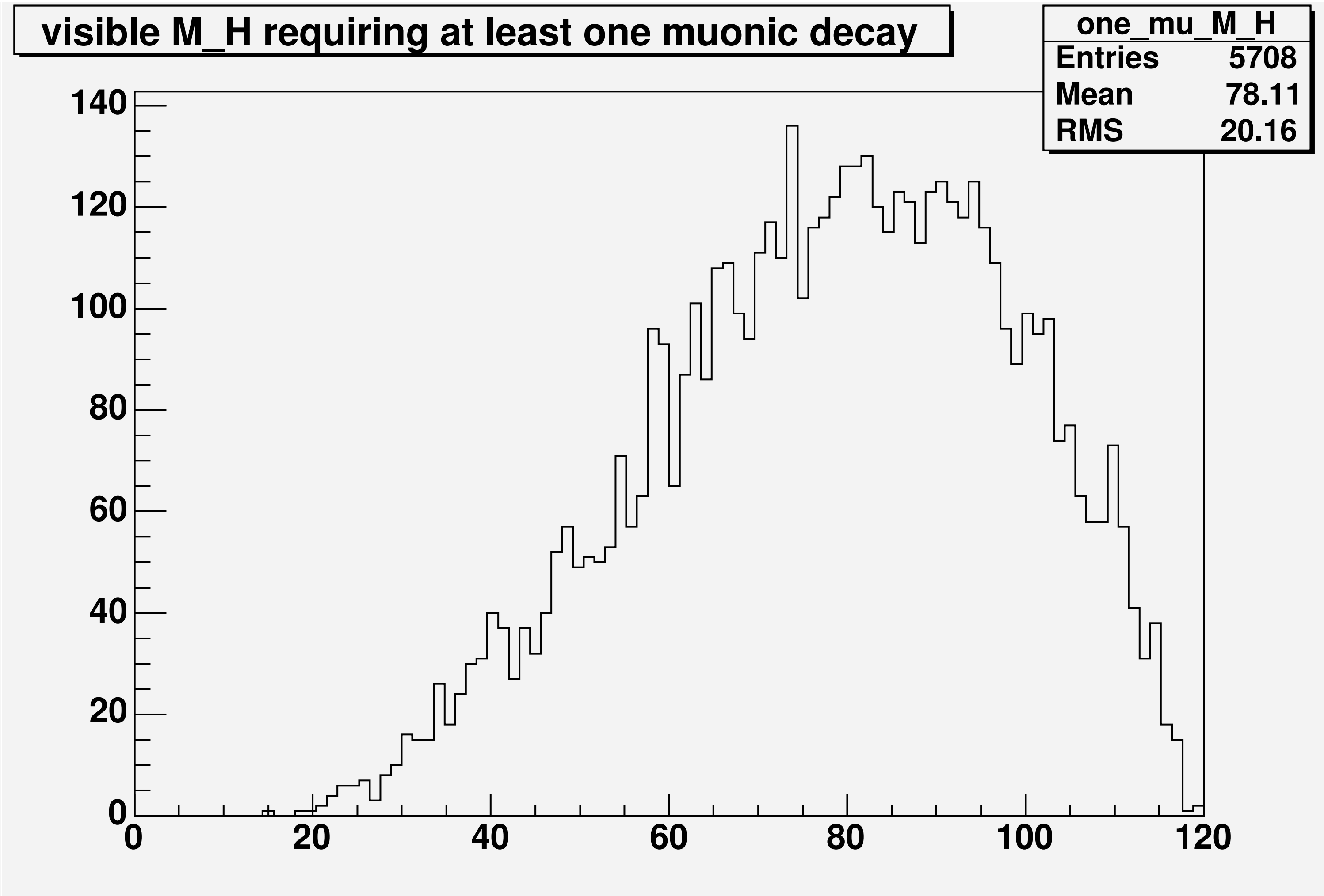
# All-leptonic Tevatron search

All-lepton decays, BR=2.2%, $M_H = 120$, $M_A = 9$.



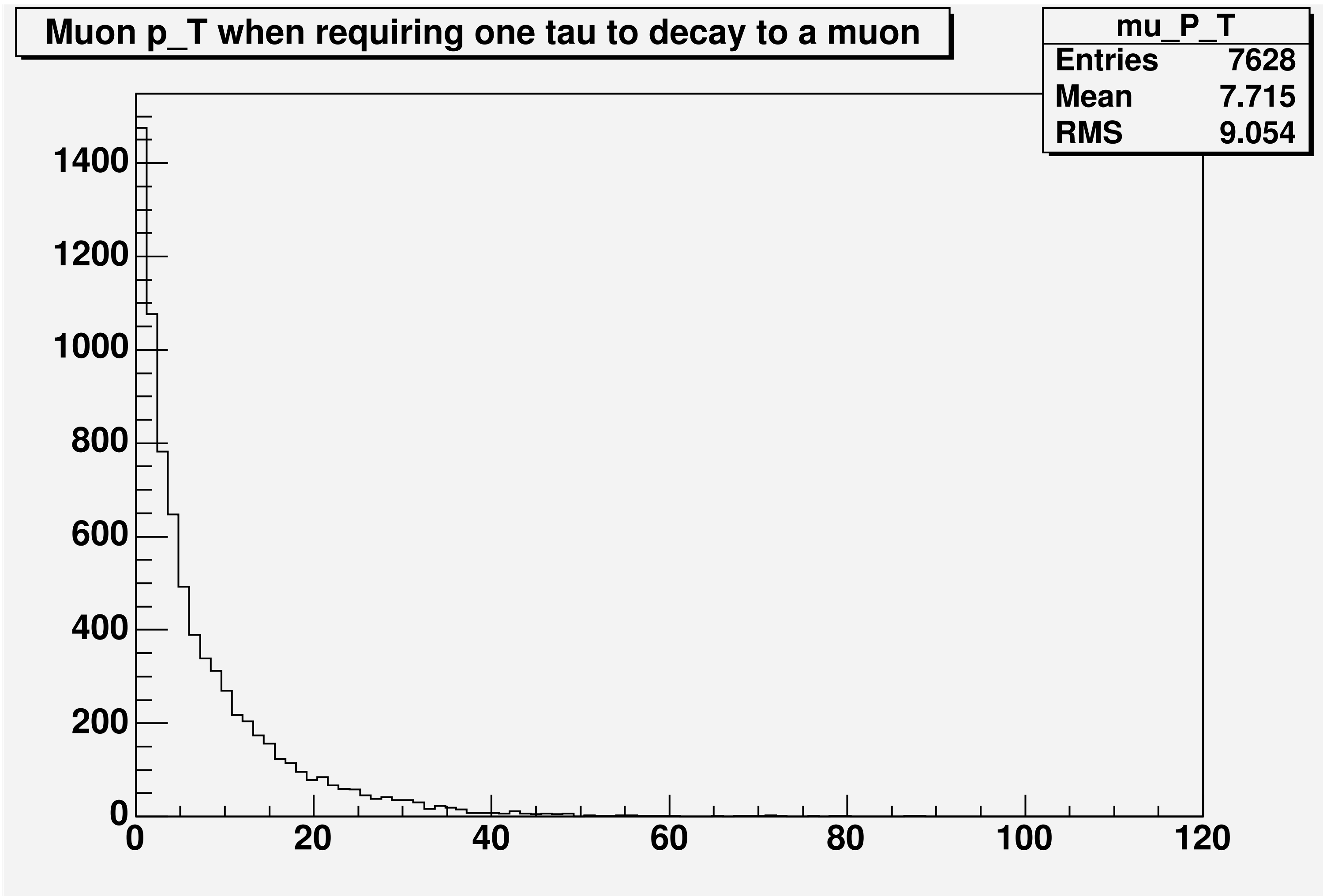
# One-muon Tevatron search

One muon decay, BR=57%, $M_H = 120$, $M_A = 9$.



# $\mu$ $P_T$ in Tevatron search

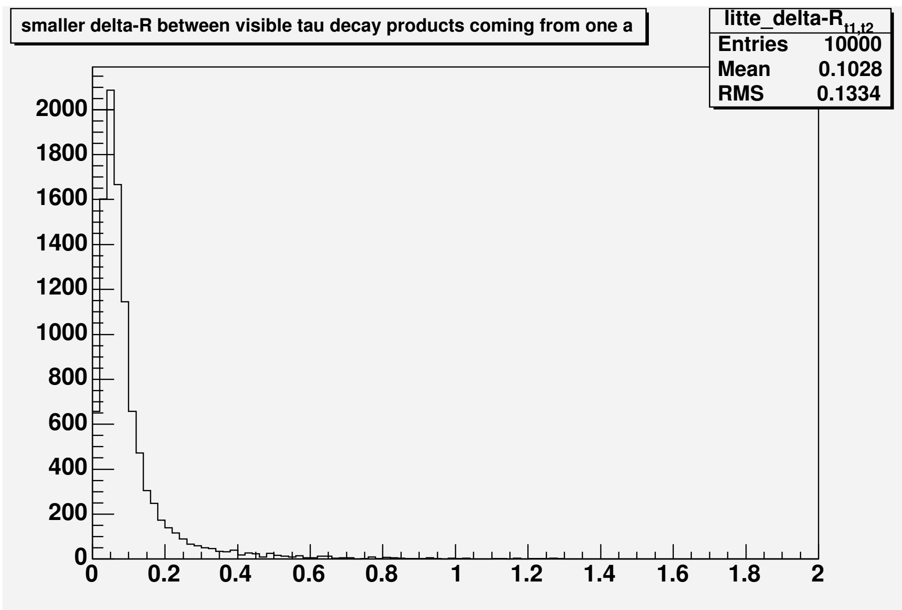
Muon $P_T$, $M_H = 120$, $M_A = 9$.



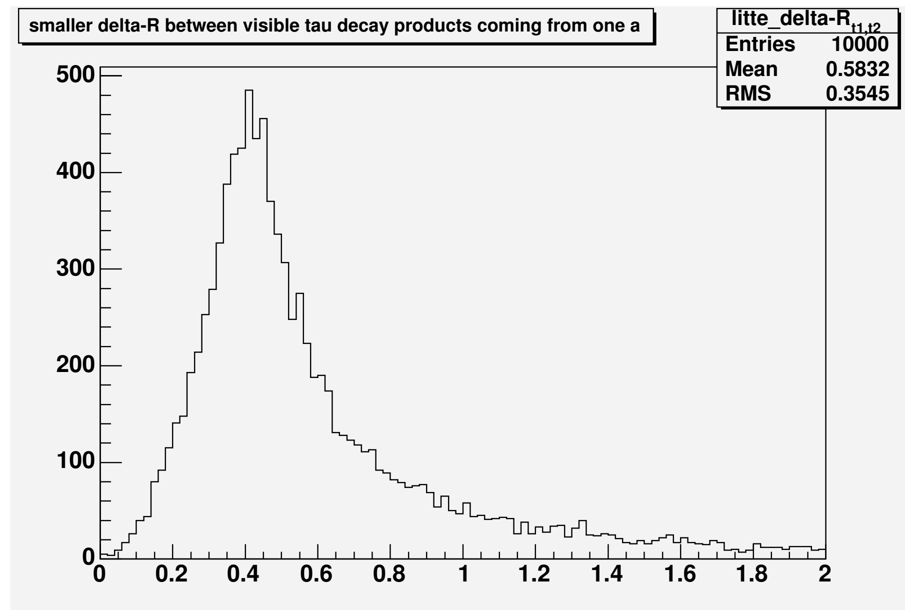
# $\delta R$ in Tevatron search

smaller $\delta - R$ between tau's from the same $A$.

$M_H = 120,\ M_A = 9$




$M_H = 85,\ M_A = 9$



## Suggested Benchmarks

Based on properties of the *experimental* signatures (rather than parameter space), I suggest:

$M_A = 4$: $A$ this light must have significant singlet mixing, cannot be 2HDM or CPX. $M_A = 2M_\tau + \epsilon$ so that tau's merge, and are not isolated.

$M_A = 9$: Escapes direct B-factory searches, $h \to \tau\tau$ still dominant.

$M_H = 85$: Lightest $M_H$ you can reasonably get in the NMSSM with reasonable coupling to the Z.

$M_H = 120$: H can have SM coupling to Z, A evades LEP and B-factory detection, and need not be singlet. (e.g. covers CPX and any other model with a light A that is *not* singlet)

$M_H = 150$: Largest $M_H$ reasonable in a SUSY model,

## Conclusions

$M_{SUSY} \gg M_H \gg M_A$ is a technically natural hierarchy.

A light, singlet $A$ is almost completely unconstrained.

A light, non-singlet $A$ is constrained, but still allowed, especially if $M_A \gtrsim 8$ GeV.

$H \to AA$ can have smaller fine tuning and lower higgs mass than the MSSM.

It is important that $H \to 4\tau$ be carried out at the Tevatron, since LHC may have great difficulty triggering on this.

Clever jet/di-tau separation must be developed.

## The Future: Leave No Stone Unturned

- Develop Monte-Carlos (PYTHIA CARDS file for each point?)

- Develop effective theories which encompass many models (may not be necessary since 2HDM + $Z'/W'$ + SM may cover all bses)

- Choose benchmark points based on:
  - where significant experimental characteristics change
  - where background changes
  - leveraging advantages of different colliders ($\gamma\gamma$, ILC, $\mu\mu$)
  - ability to differentiate individual models
  - Secondary benchmark points (e.g. if found $Z'$, go to "Measure Triple Gauge Coupling", sec. 4.3.7).

Bad Example: $M_H$ max.