The Higgs Sector and the Linear Collider

Marco Battaglia
UCSC and CERN

INFN ILC Workshop
Cernobbio, 16 Maggio 2013

A Tryptic

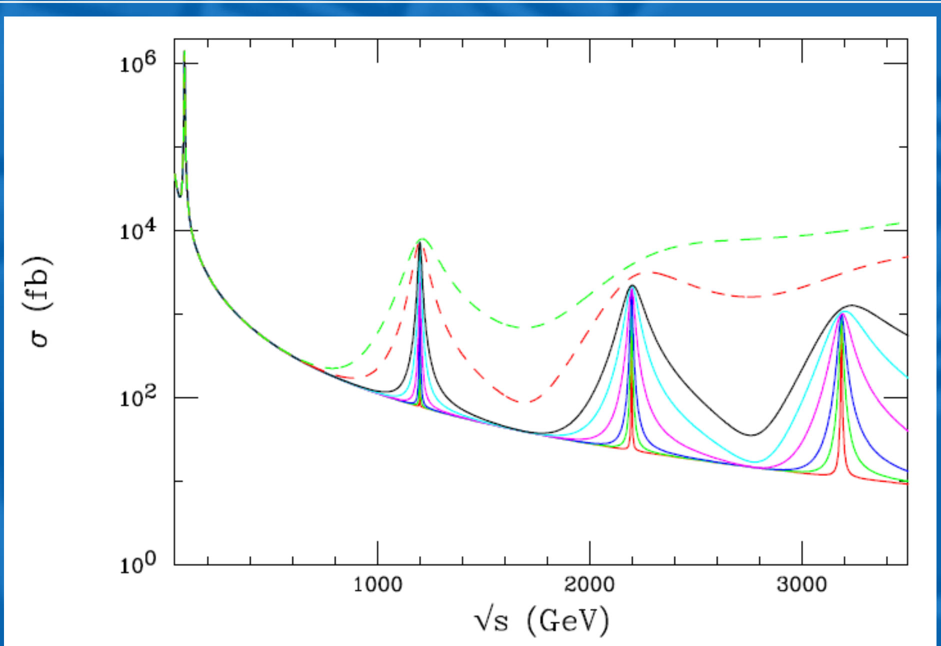
Phenomenological motivations for the Higgs profile reconstruction
(this talk)

Experimental Opportunities at the ILC in relation to the LHC projected capability
(K Desch)

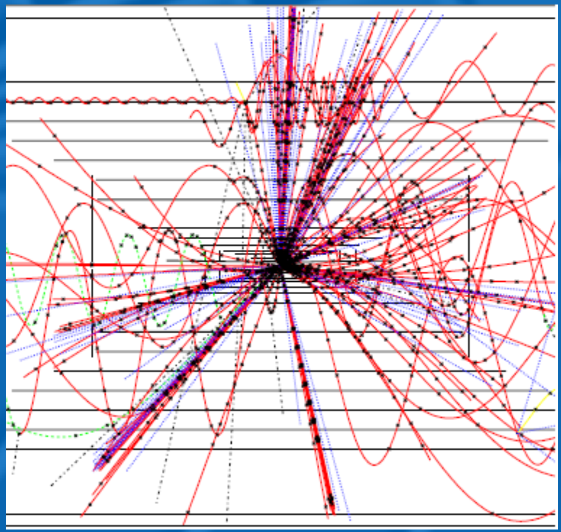
Experimental Opportunities at a Muon Collider
(E Eichten)

LHC results have provided a focal point for the future HEP collider program at the energy frontier

Community has been discussing for long different Higgs scenarios, strong symmetry breaking, new resonances, extra dimensions, SM completions



Rizzo, hep-ph/0108235



Barklow, De Roeck, hep-ph/0112313

Each of these scenarios had specific, and often contrasting, requirements in terms of beam energy, luminosity and detection capabilities

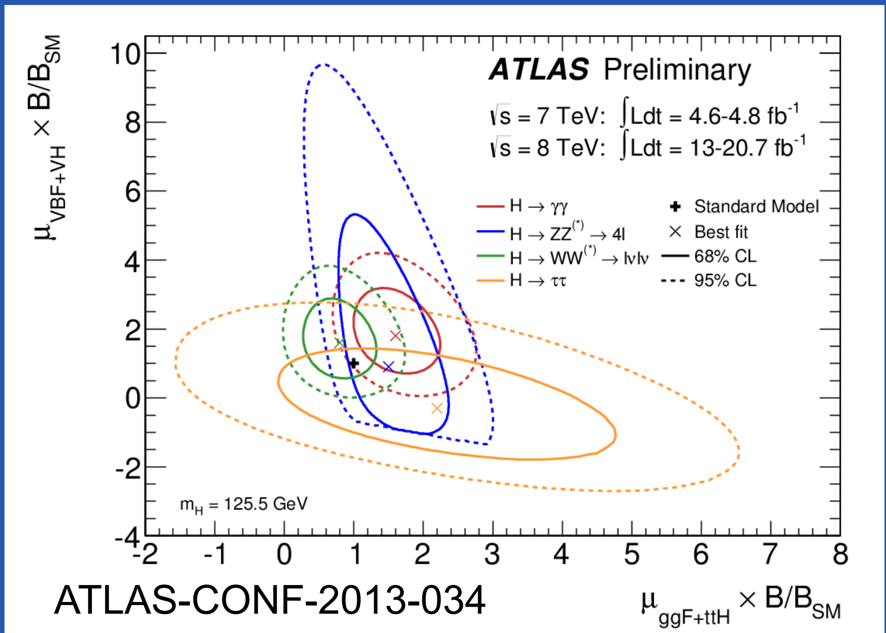
Now we have a well defined program with a Higgs-like scalar to be tested for its implications in the SM (couplings to gauge bosons and fermions, loop-induced couplings, self couplings, Spin-parity, regularization of $W_L W_L \rightarrow W_L W_L$) and in models of New Physics (model-independent NP, SUSY, DM WIMP scenarios, ...)

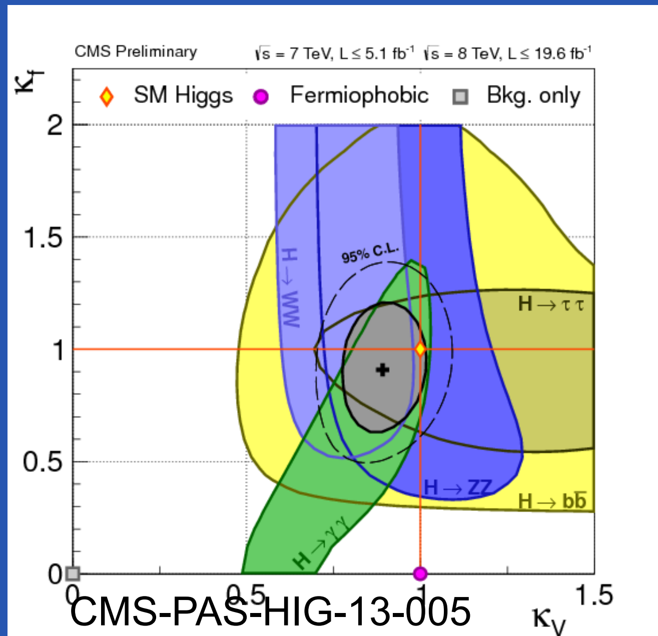
New particle provides us with main themes of investigation in HEP collider program for the next decades and represents an unavoidable test for new models and scenarios

It also provides us with clear specifications for the next large scale collider facility to carry out this program in a way complementary to the LHC

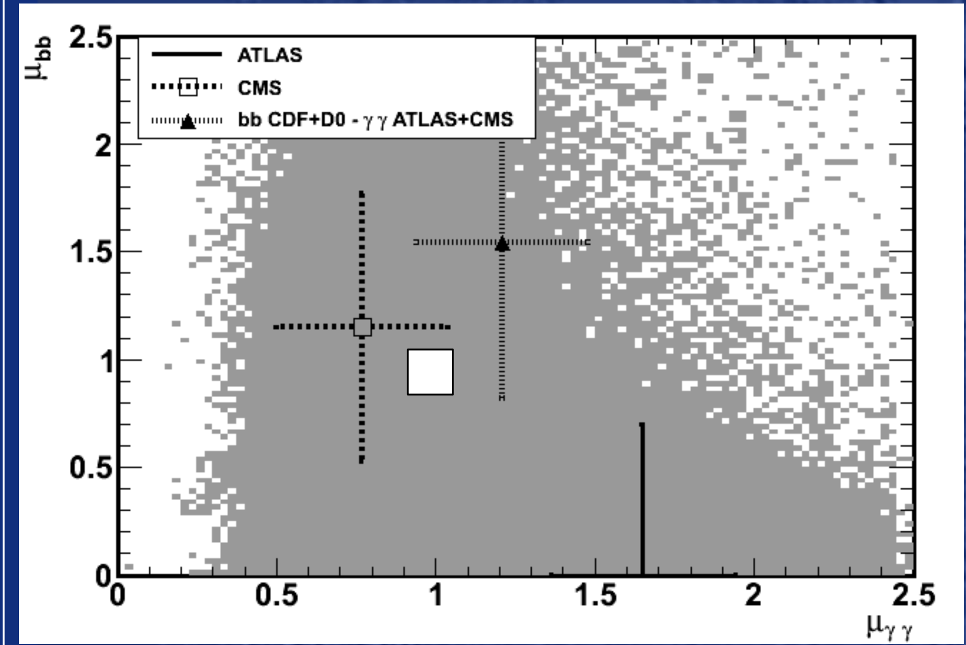
Future studies require model independent analyses (sensitivity to couplings to non-SM particles), access to all production channels and decay modes to over-constrain couplings and decay widths, accuracy (stat + bkg control + theory syst. control)

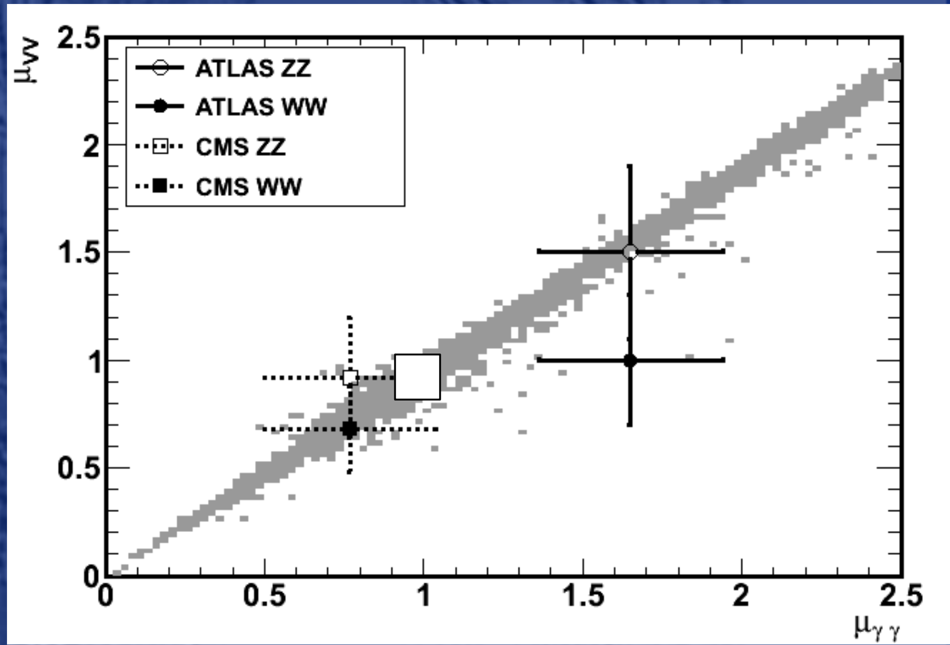
Higgs Signal Strengths and couplings at LHC





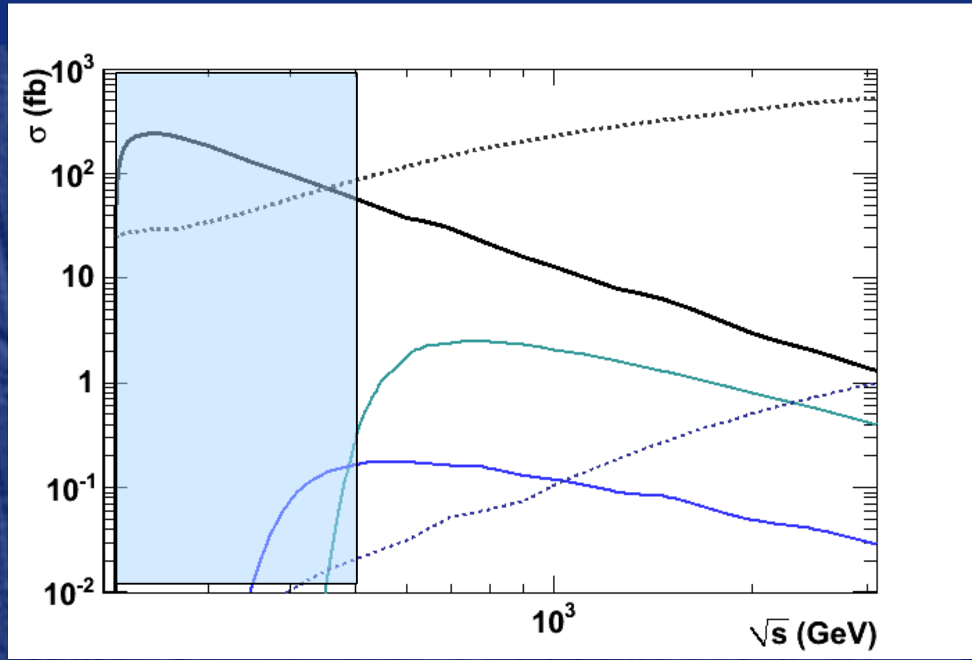
Higgs Signal Strengths, SM and SUSY Scenarios

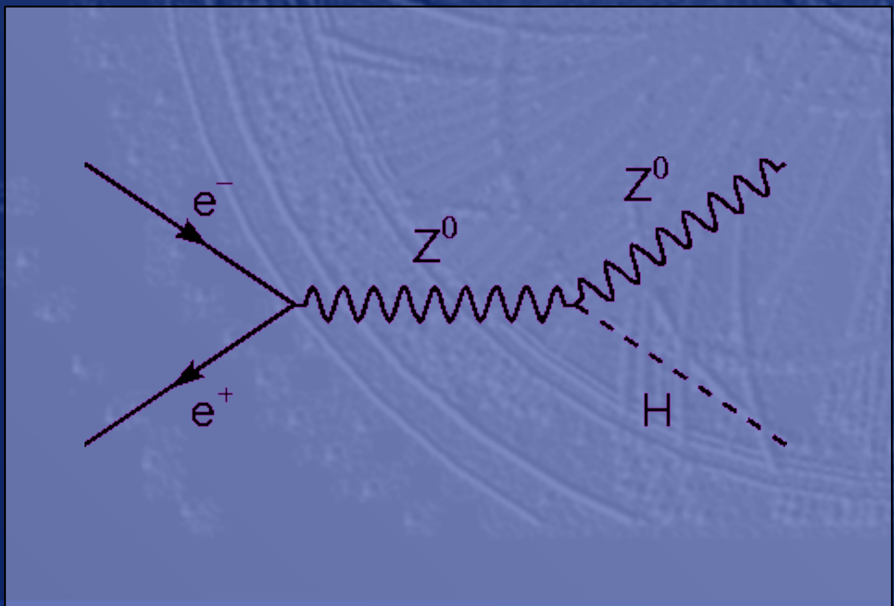


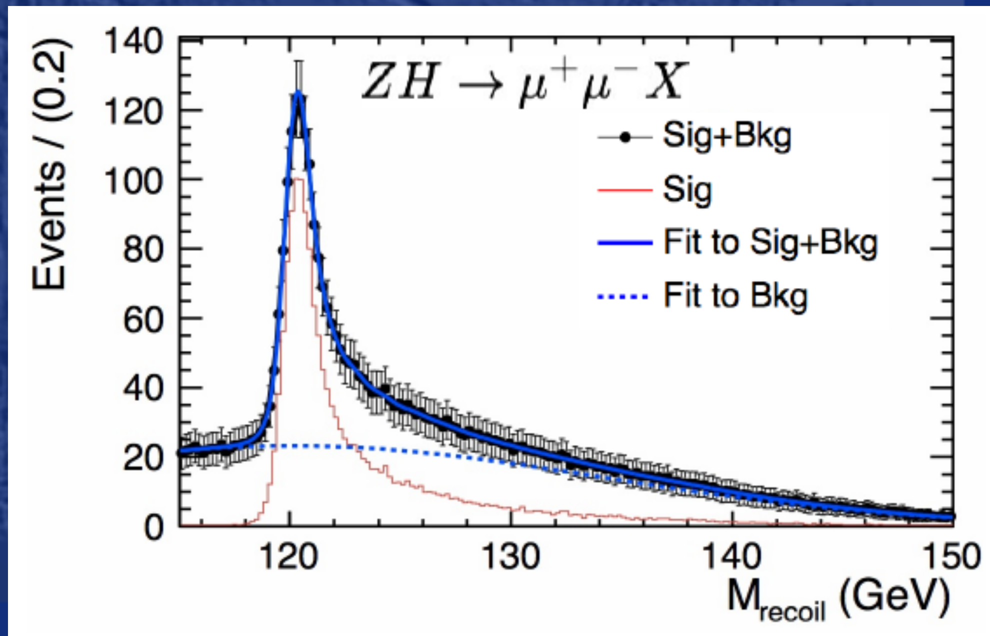


Beyond existence of ~126 GeV particle LHC data still needs to settle: signal strengths providing access to particle couplings still compatible with several hypotheses and spread of results is still of same order as range of viable scenarios within MSSM.

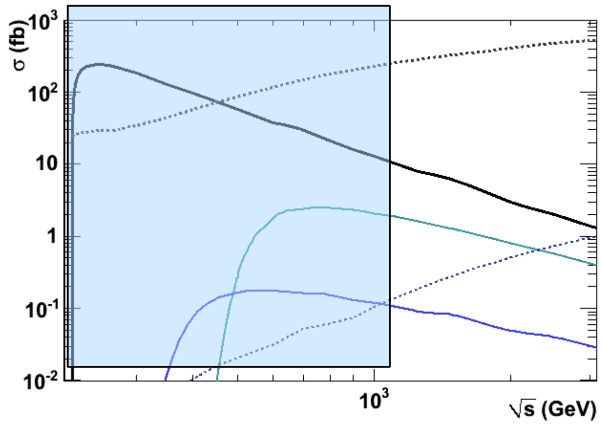
Higgs and e^+e^- Collisions

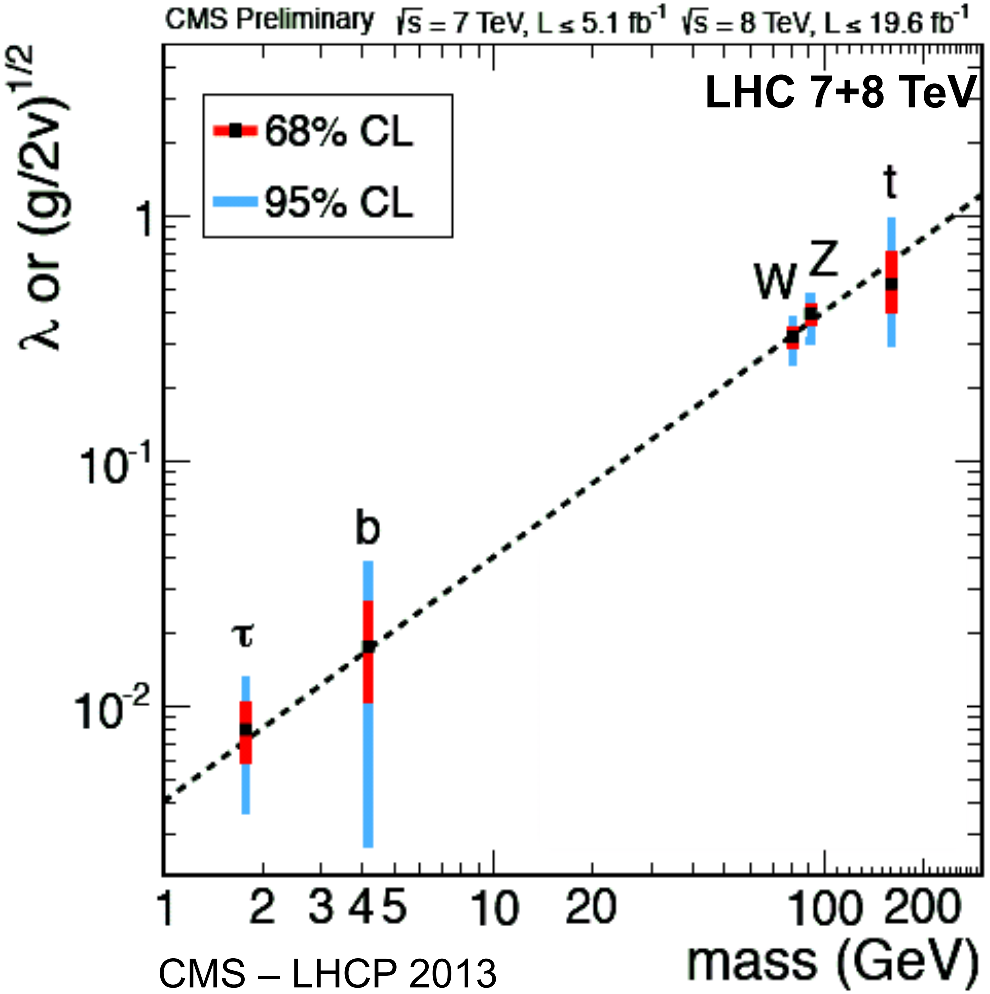




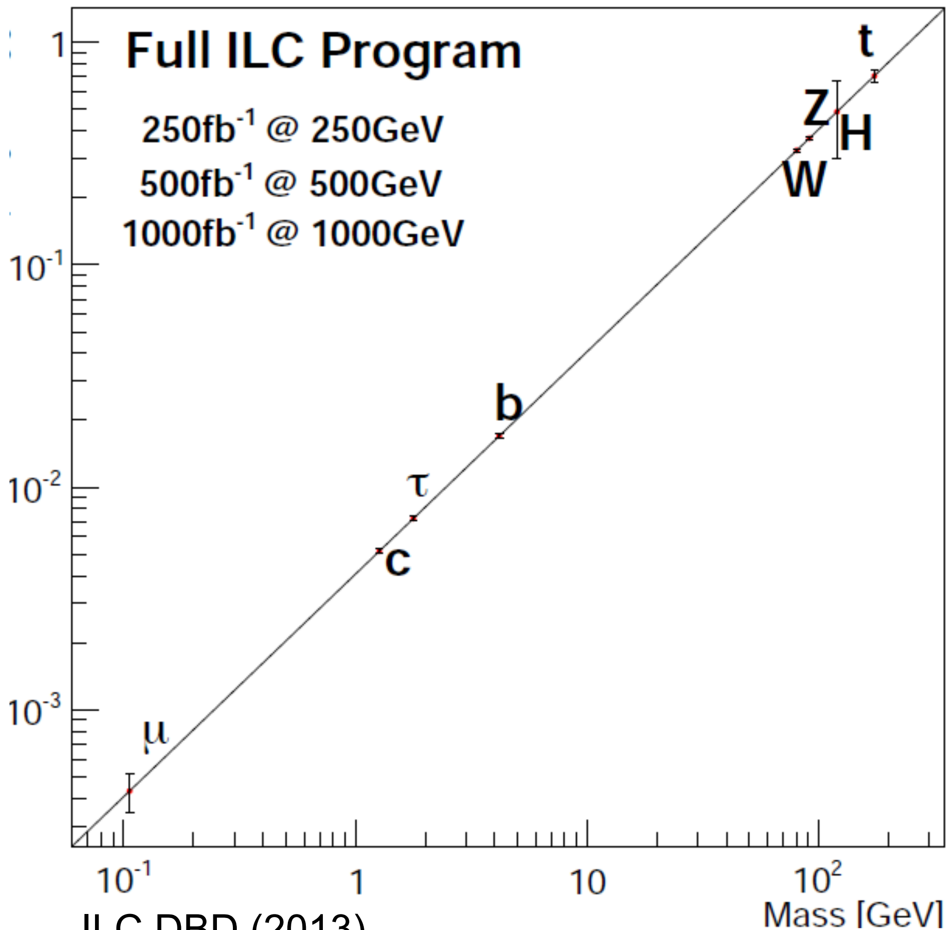


The essence of the Higgs mechanism: Coupling vs Mass





CMS – LHCP 2013

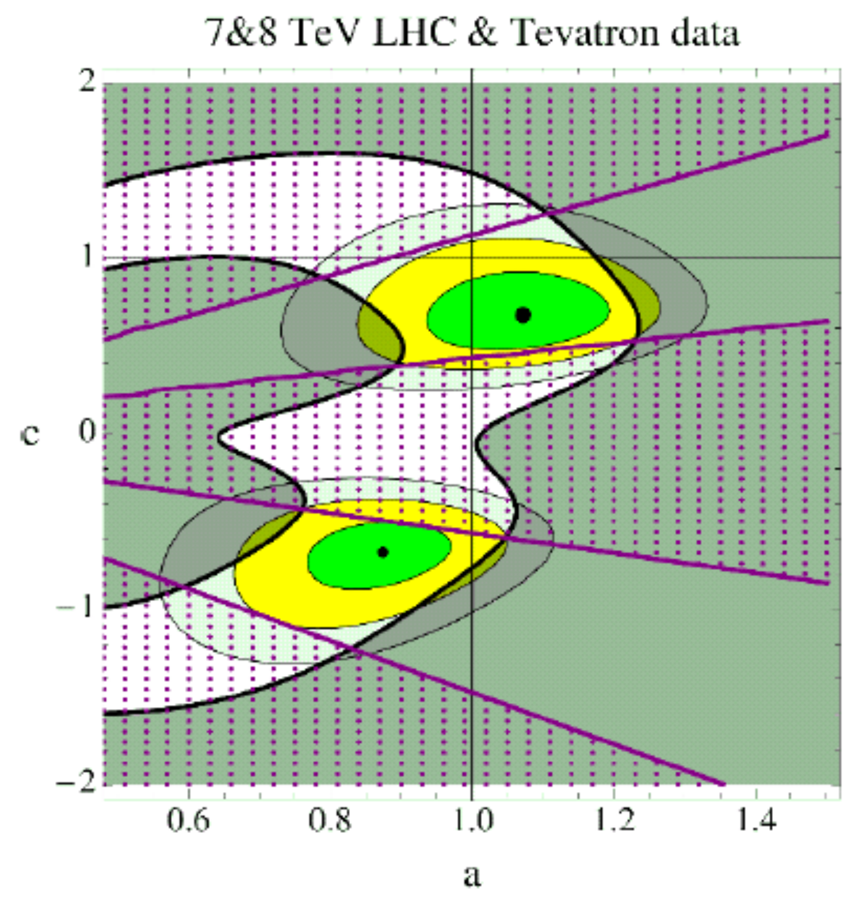


ILC DBD (2013)

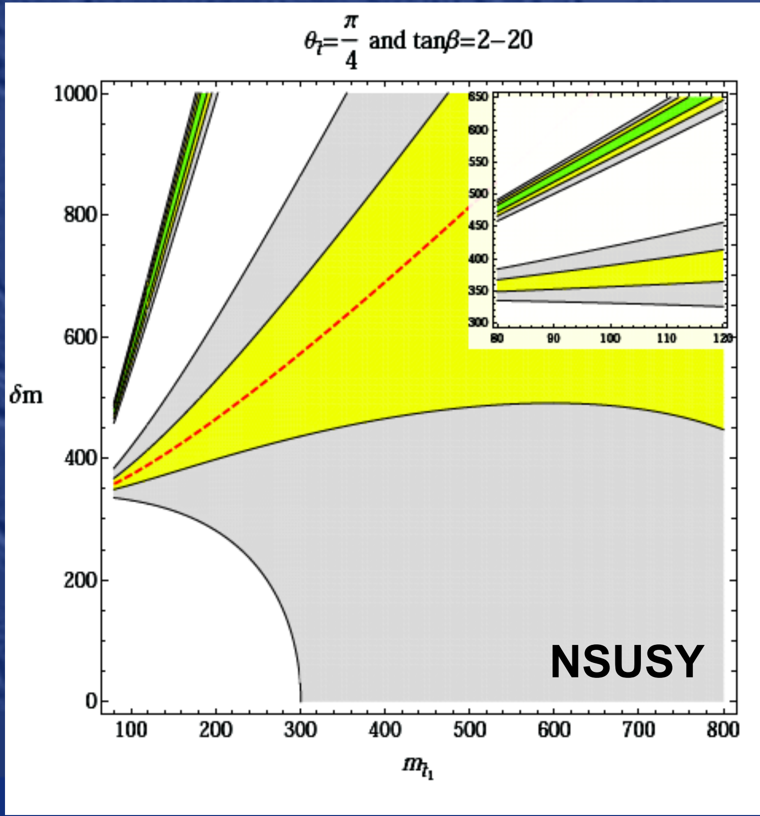
Model Independent Higgs Implications on New Physics

$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma)\left[1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots\right]$$

$$-\frac{v}{\sqrt{2}}\,(\bar{u}_L^i\bar{d}_L^i)\,\Sigma\,\left[1 + c_j\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u\,u_R^j \\ y_{ij}^d\,d_R^j\end{pmatrix} + h.c.\cdots,$$



Espinosa et al., JHEP12 (2012) 045, 077
Contino et al, arXiv:1303.3876



Extended Higgs Sector: Indirect Sensitivity and Direct Searches

In non-minimal Higgs models modified couplings to gauge bosons, up, down quarks

2HDM (as SUSY) couplings depend on 2 additional parameters: M_A and tan β

$$g_{hVV} \xrightarrow{M_A \gg M_Z} 1 - \frac{M_Z^4}{8M_A^4} \sin^2 4\beta \xrightarrow{\tan\beta \gg 1} 1 - \frac{2M_Z^4}{M_A^4 \tan^2\beta}$$

$$g_{huu} \xrightarrow{M_A \gg M_Z} 1 + \frac{M_Z^2}{2M_A^2} \frac{\sin 4\beta}{\tan\beta} \xrightarrow{\tan\beta \gg 1} 1 - \frac{2M_Z^2}{M_A^2 \tan^2\beta}$$

$$g_{hdd} \xrightarrow{M_A \gg M_Z} 1 - \frac{M_Z^2}{2M_A^2} \sin 4\beta \tan\beta \xrightarrow{\tan\beta \gg 1} 1 + \frac{2M_Z^2}{M_A^2}$$

Away from the decoupling limit sensitivity to scale of heavy Higgs states and tan β from measurement of couplings of lightest Higgs state, provided these are measured with sufficient accuracy.

Indirect Sensitivity to Extended Higgs Sector

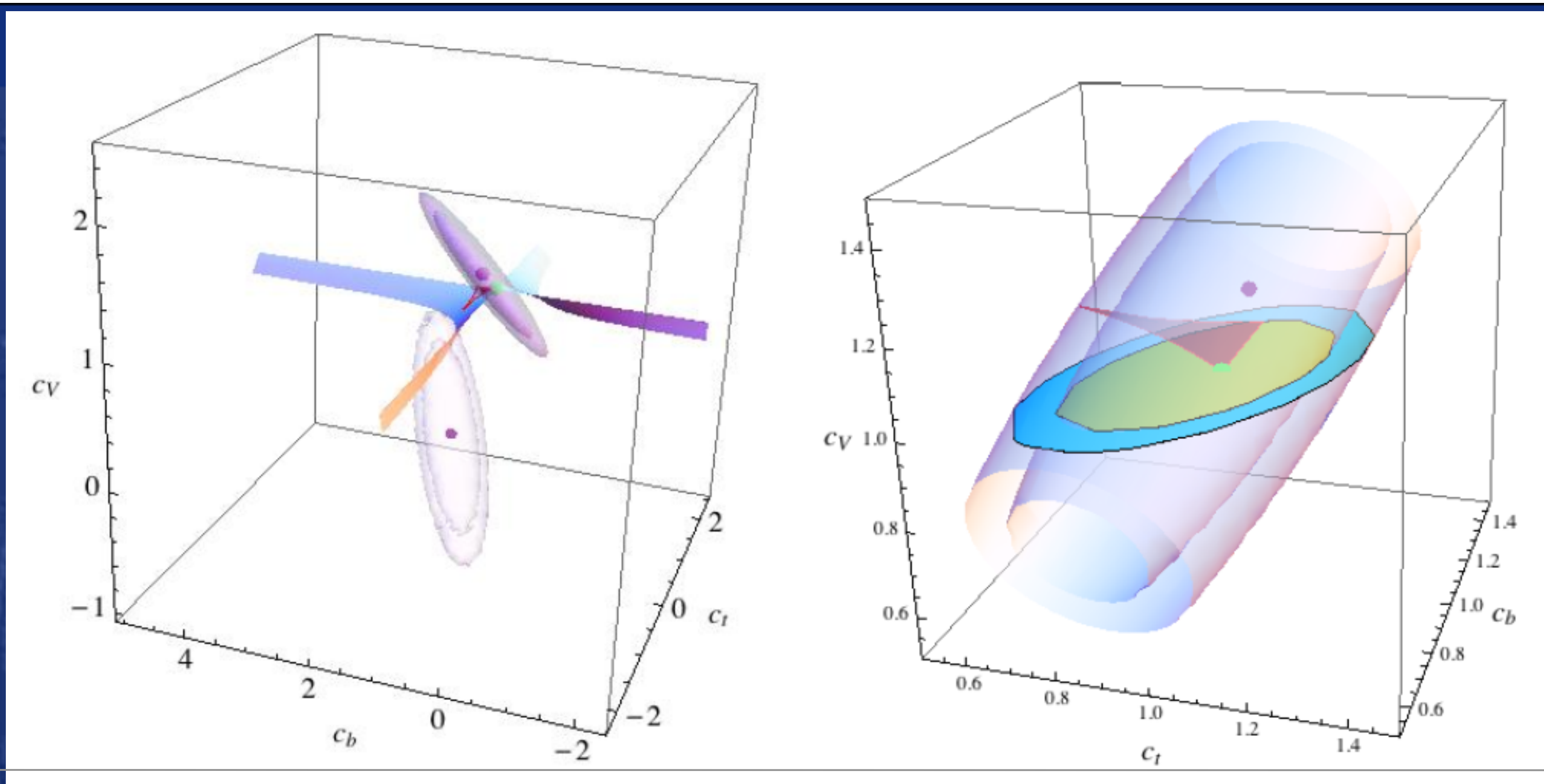
$$\mathcal{M}_S^2 = (M_Z^2 + \delta_1) \begin{pmatrix} \cos^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \sin^2\beta \end{pmatrix} + M_A^2 \begin{pmatrix} \sin^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \cos^2\beta \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2\beta} \end{pmatrix}$$

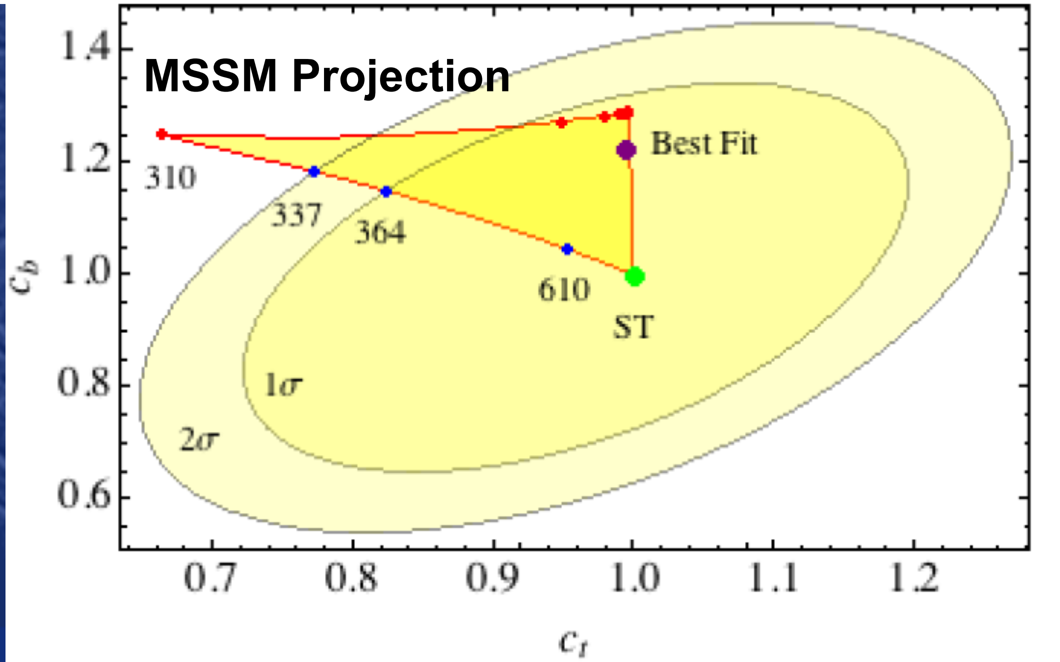
Setting M_H = 125 GeV provides value for δ correction term;
Replace (C_V, C_f) couplings by (c_t, c_b, c_V) triplet to accomodate MSSM shifts to up- and down-like quarks:

$$\begin{aligned} c_t(\tan\beta, m_H) &= \frac{\sqrt{1+\tan^2\beta}}{\tan\beta} S_{hu}(\tan\beta, m_H) \\ c_b(\tan\beta, m_H) &= \sqrt{1+\tan^2\beta}\, S_{hd}(\tan\beta, m_H) \\ c_V(\tan\beta, m_H) &= \frac{1}{\sqrt{1+\tan^2\beta}} S_{hd}(\tan\beta, m_H) + \frac{\tan\beta}{\sqrt{1+\tan^2\beta}} S_{hu}(\tan\beta, m_H) \end{aligned}$$

in MSSM with decoupled sparticle masses, c_t, c_b couplings depend on two parameters (M_A, tanβ), $c_V \sim 1$ → MSSM is a surface in 3D space.

Maiani et al,
PLB718 (2012) 465
arXiv:1305.2172

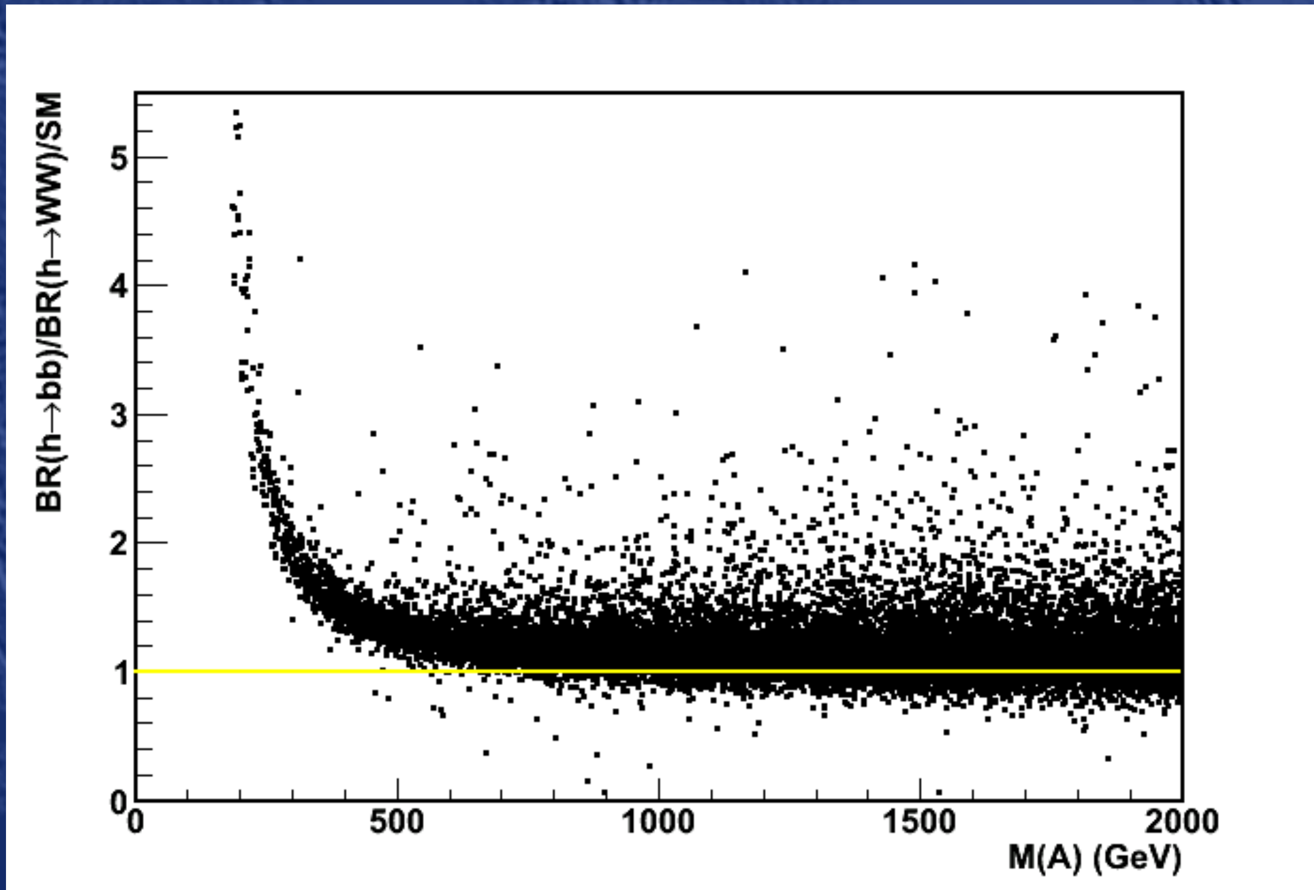




Maiani et al, arXiv:1305.2172

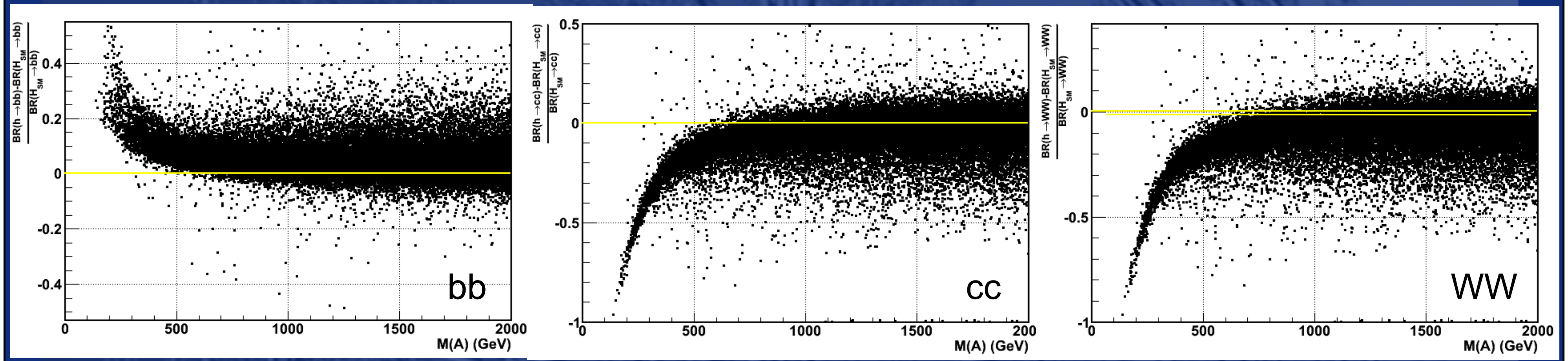
Indirect M_A Sensitivity in the pMSSM

More general scenario with 19 free parameters accounting also for SUSY loops effects to Higgs fermionic couplings;



Some Requirements on Accuracy

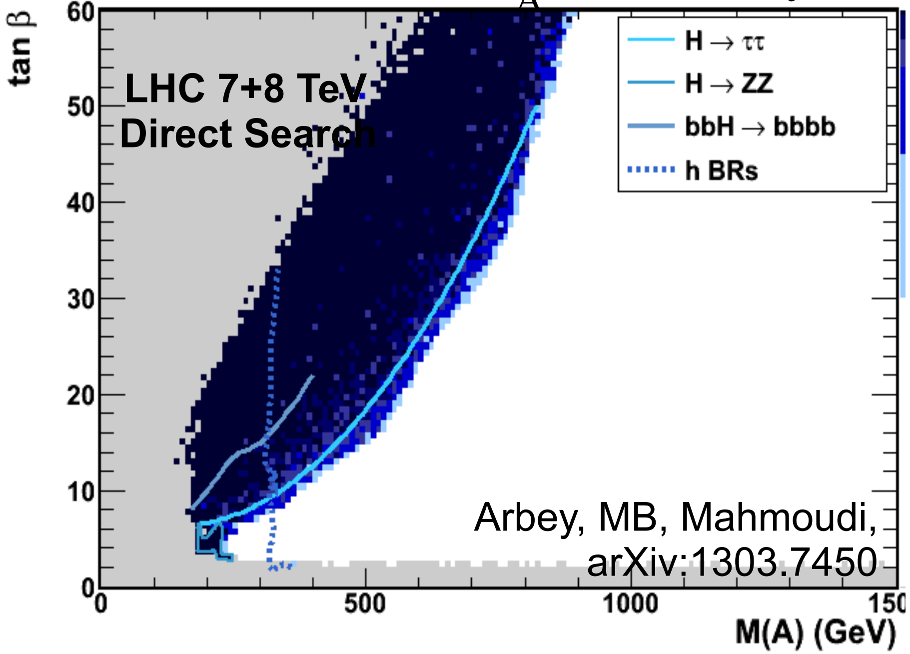
Sensitivity to Extended Models: ΔBR/BR vs M_A

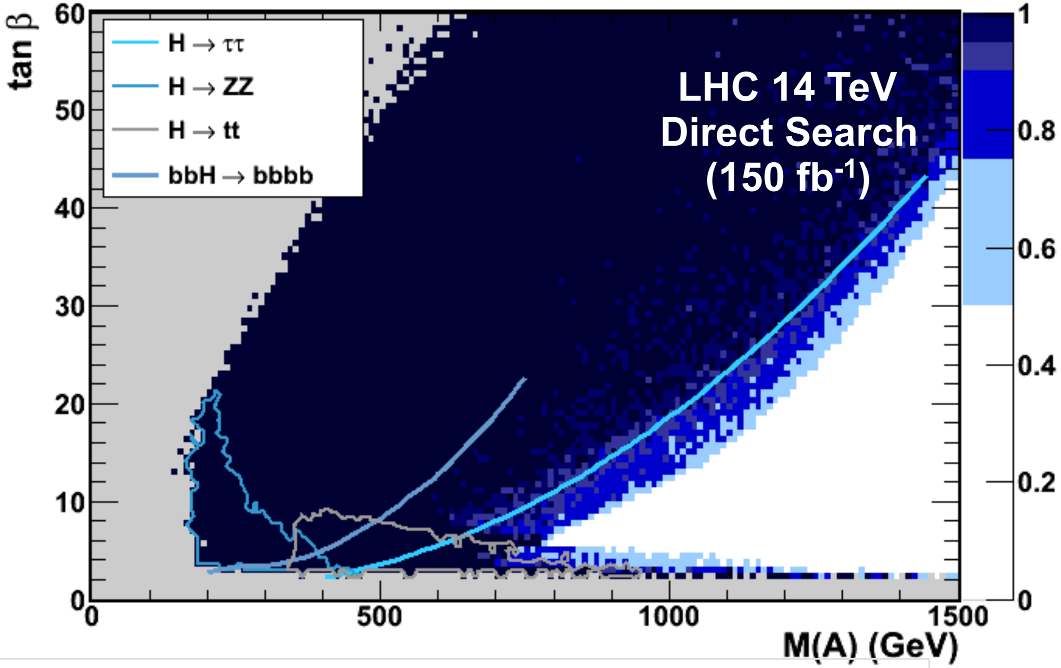


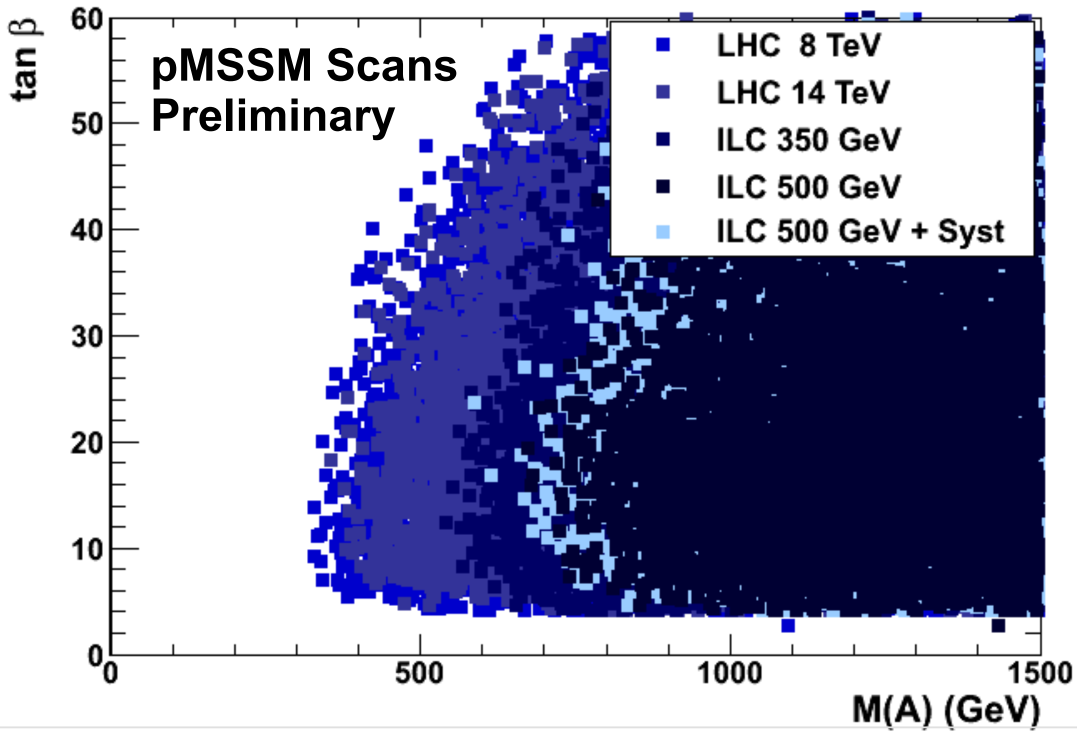
Parametric Uncertainties on SM Higgs BRs

Parameter	Value	BR(H → bb)	BR(H → cc)	BR(H → ττ)
m_b (pole)	4.78 ± 0.06	0.012	0.019	0.018
$\alpha_s(M_Z)$	0.1184 ± 0.0007	0.004	0.020	0.004
mt_{op}	173 ± 1.0	0.0001	0.0001	0.0001
Total		**0.013**	**0.030**	**0.020**

LHC and ILC M_A Sensitivity in the pMSSM







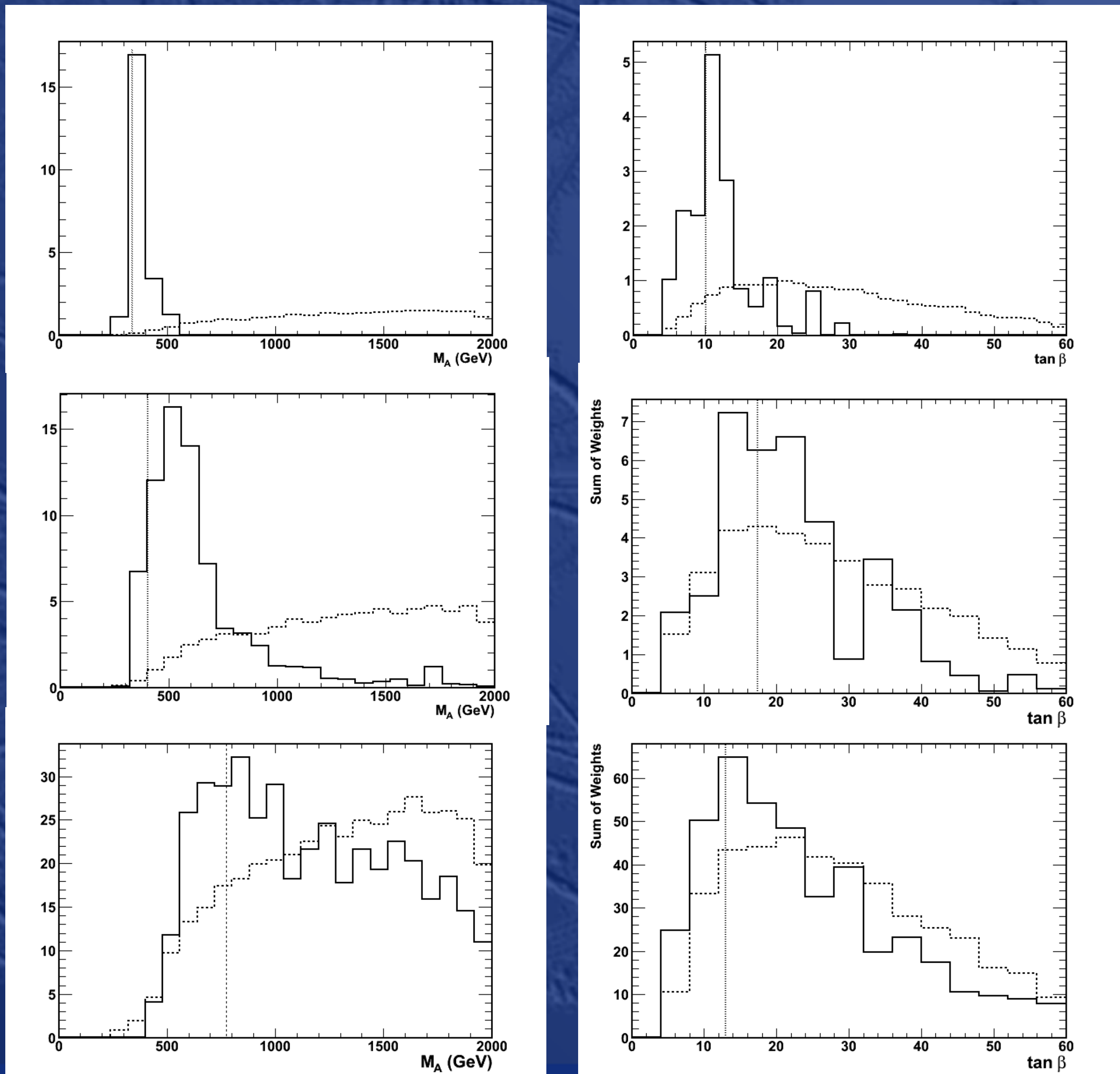
ILC indirect M_A sensitivity extends up to ~700 GeV corresponding to LHC direct detection reach at 14 TeV (150 fb^{-1})

Estimate of M_A and tanβ in pMSSM from Higgs decay BRs at ILC

M_A = 340 GeV

M_A = 440 GeV

M_A = 775 GeV



Arbey, MB, Mahmoudi,
LPCC, 03 2012

New Particles, Loop Effects and Higgs Couplings

Sensitivity to new particles in loops may arise from modification of total decay width Γ_h

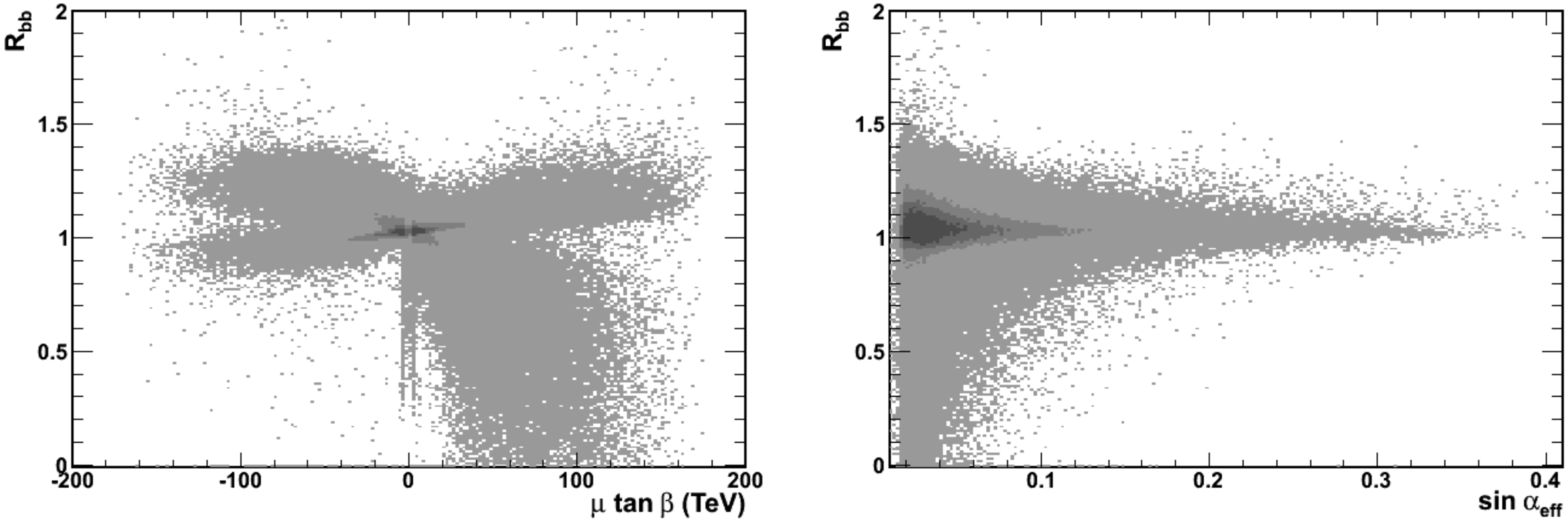
bb is dominant contribution to Γ_h , its suppression/enhancement induces enhancement/ suppression of all other BRs, even if their couplings are SM-like.

$$\Delta_b \approx \frac{2\alpha_s}{3\pi} \frac{m_{\tilde{g}} \mu \tan\beta}{\max(m_{\tilde{g}}^2, m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2)} + \frac{m_t^2}{8\pi^2 v^2 \sin^2\beta} \frac{A_t \mu \tan\beta}{\max(\mu^2, m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2)}$$

… but also from corrections of individual vertices (gg, γγ)

$$g_{hbb} \approx g_{Abb} \approx \tan\beta(1 - \Delta_b)$$

$$g_{hb\bar{b}} = -\sin\alpha_{\rm eff} / \cos\beta \approx 1 - \Delta_b/(\tan\alpha_{\rm eff} \tan\beta)$$

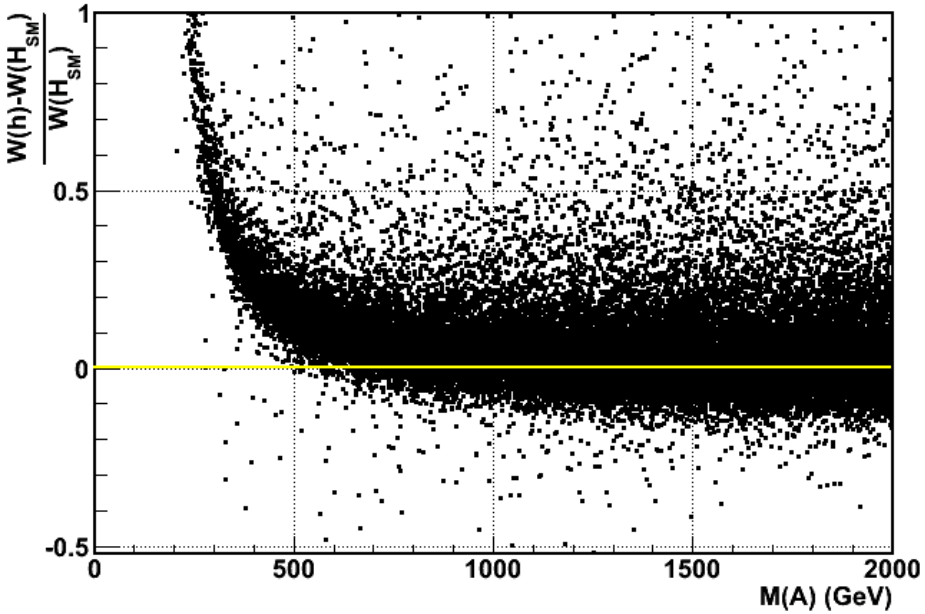


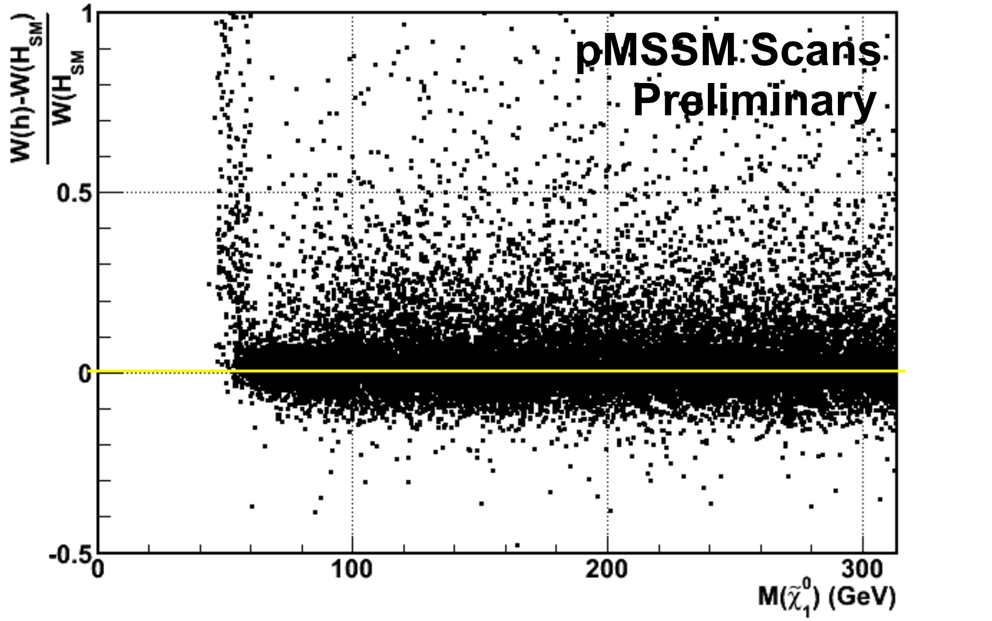
Arbey, MB, Djouadi, Mahmoudi, PLB720 (2012) 153

Higgs Total Width

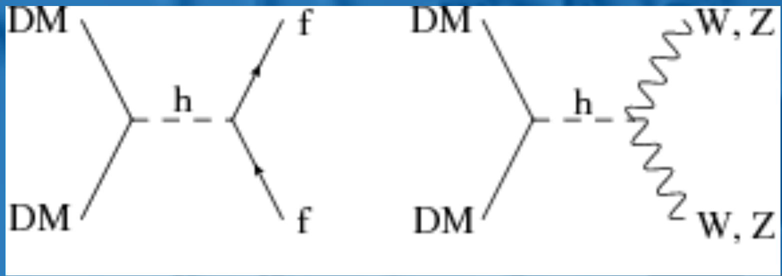
Strategy to reduce LHC systs by studying ratios of BRs (Djouadi arXiv:1208.3436) ($\gamma\gamma$/VV) insensitive to corrections affecting total width (changes in g_{bb}, h → SUSY, etc), important to obtain model independent determination of total decay width;

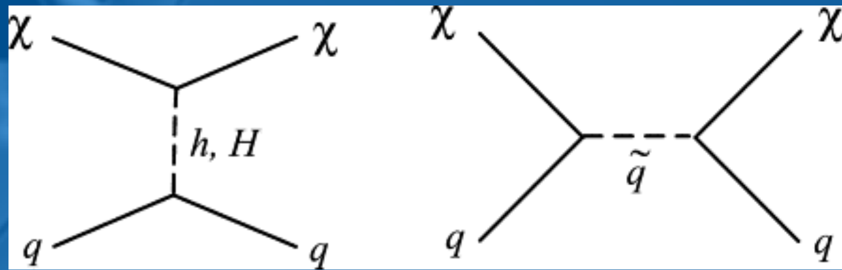
ILC by combining BR(H → VV) with VV → H;
MuC by $\mu\mu$ → H scan.





Higgs and WIMP Dark Matter

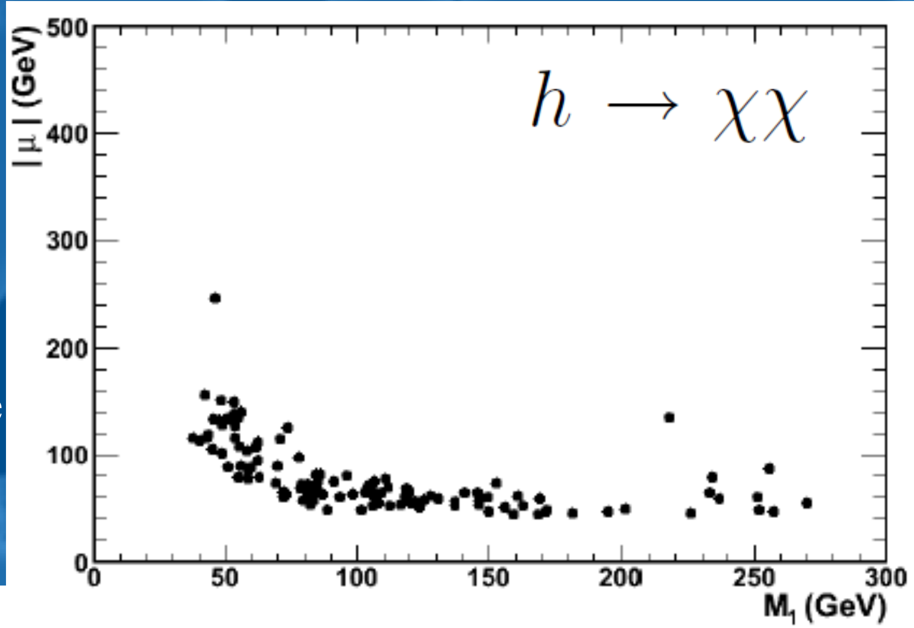


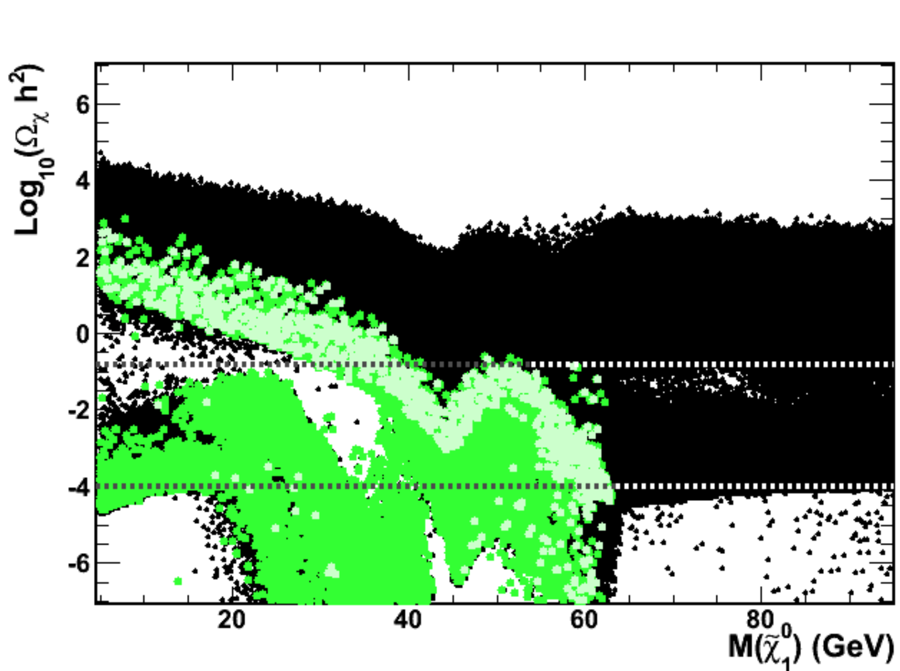


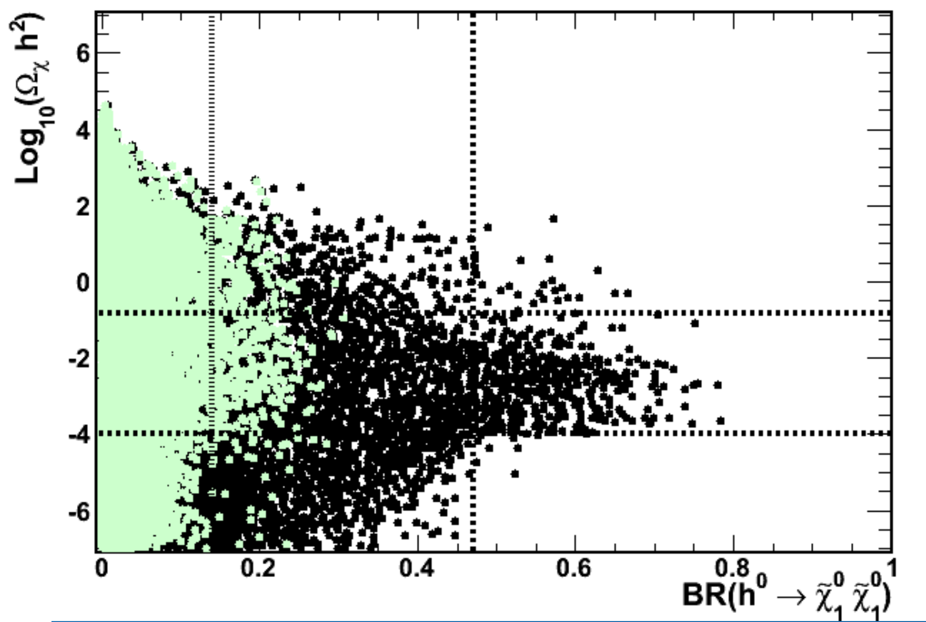
$h \to \chi\chi$ and DM Relic Density

$$g_{h\chi_1^0\chi_1 0} \propto (Z_{12} - \tan\theta_W Z_{11})\,(\sin\beta Z_{13} + \cos\beta Z_{14})$$

Neutralino coupling to Higgs requires mixed LSP and low |μ|, for invisible decay width $M(\chi^0{}_1)<M_h/2$
LEP Z width constraint imposes LSP bino like and large |μ| values: viable solutions with h → invisible still occur for $45 < M(\chi^0{}_1) < M_h/2$ but BR is small if WMAP / PLANCK CMB $\Omega_\chi h^2$ result is imposed.





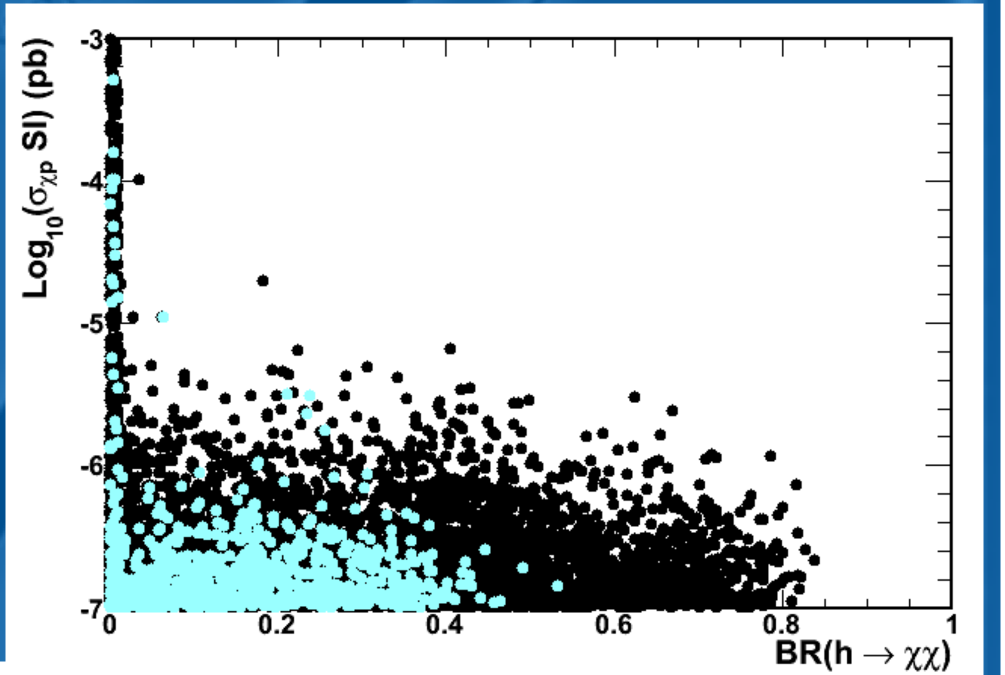


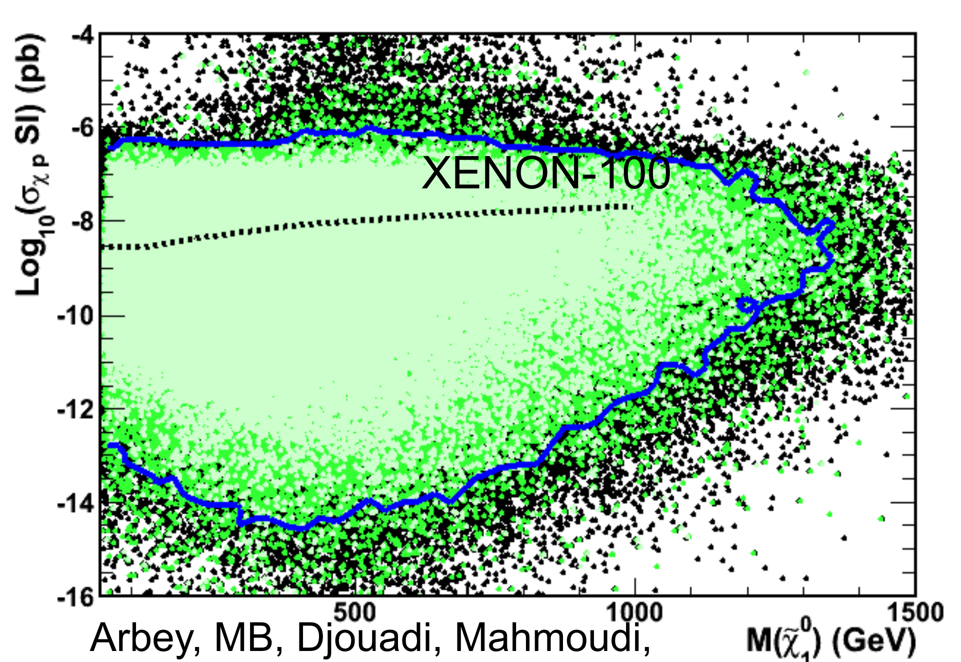
Arbey, MB, Djouadi, Mahmoudi, PLB720 (2012) 153

$h \rightarrow \chi\chi$ and DM Direct Detection

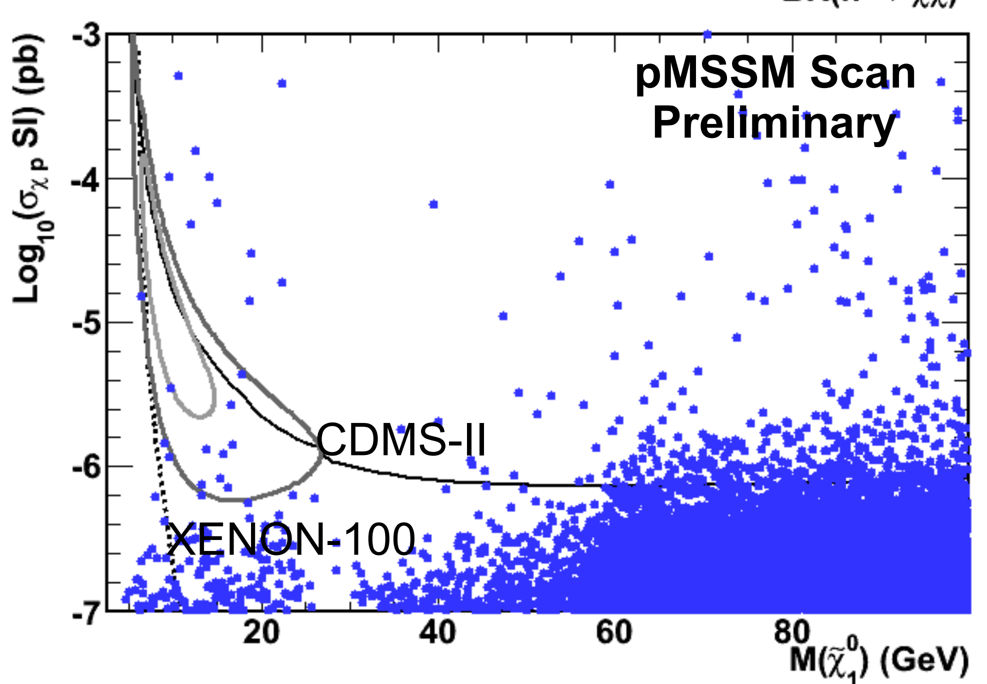
Combined study of Higgs sector and DM stimulated by results of DM direct detection experiments (in particular CDMS, Xenon, CoGENT, CRESST, Dama)

Model independent sensitivity to χ at LC through $e^+e^- \rightarrow \chi\chi\gamma$

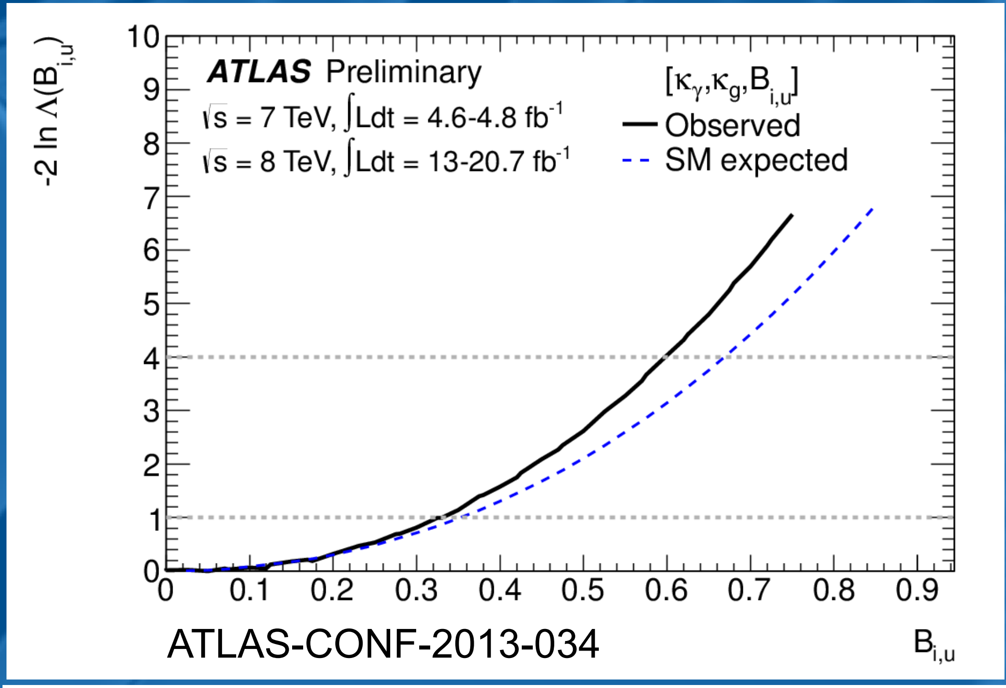


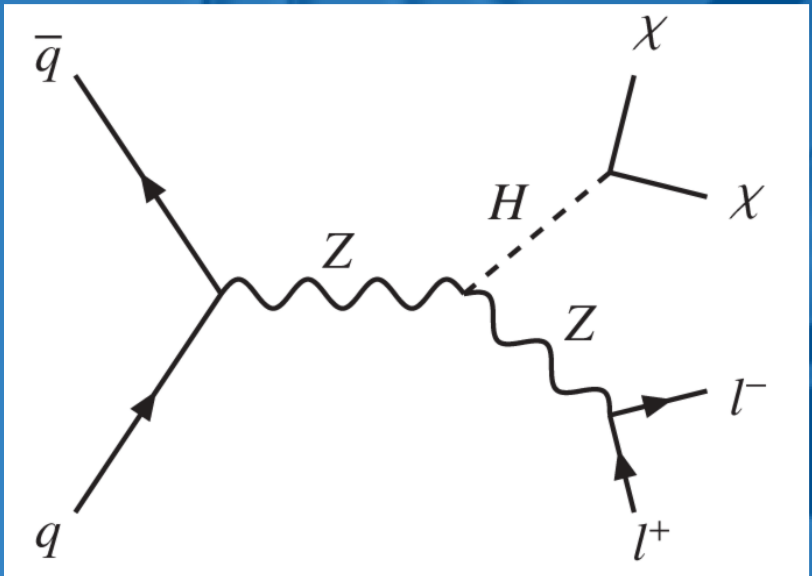


Arbey, MB, Djouadi, Mahmoudi, PLB720 (2012) 153

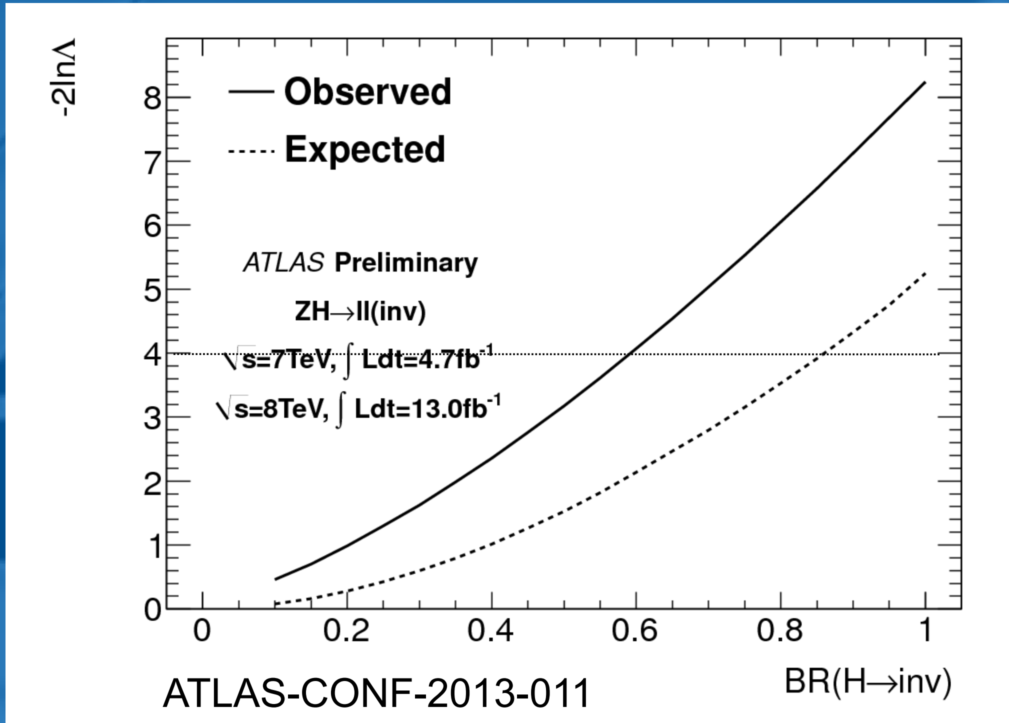


Invisible Higgs Decays



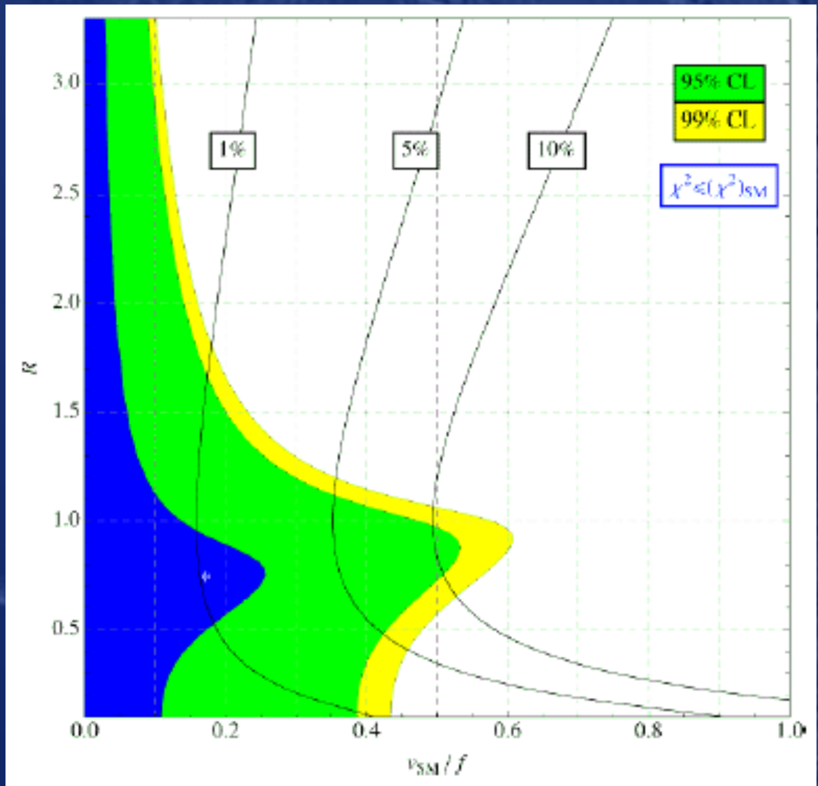


LC sensitivity down to BR(h → inv)~ 2%

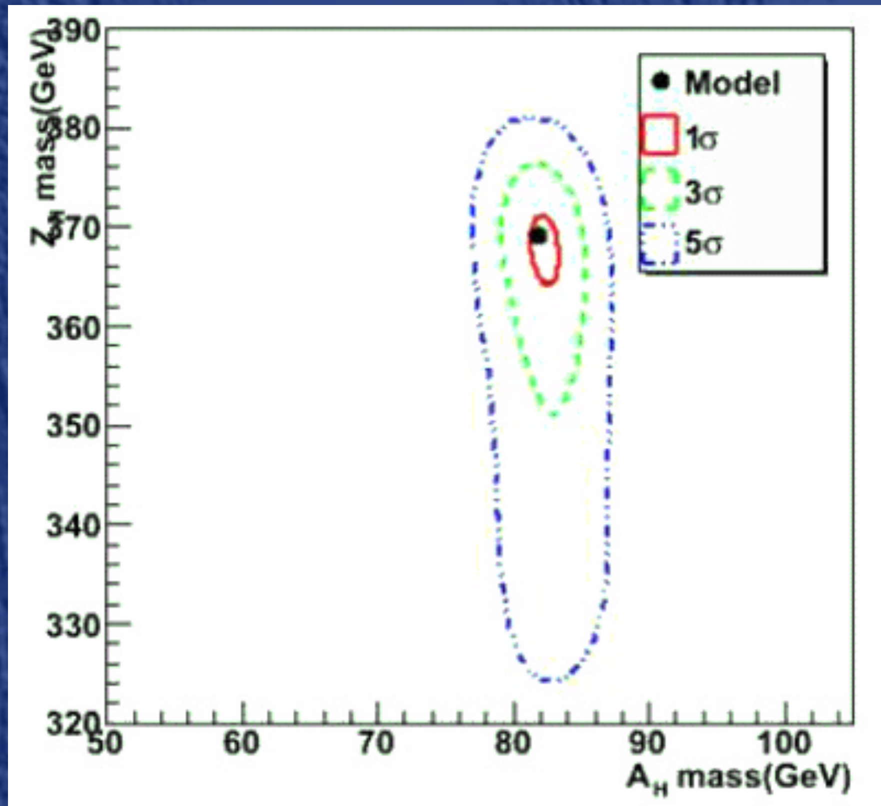


Little Higgs Models

LHC Constraints

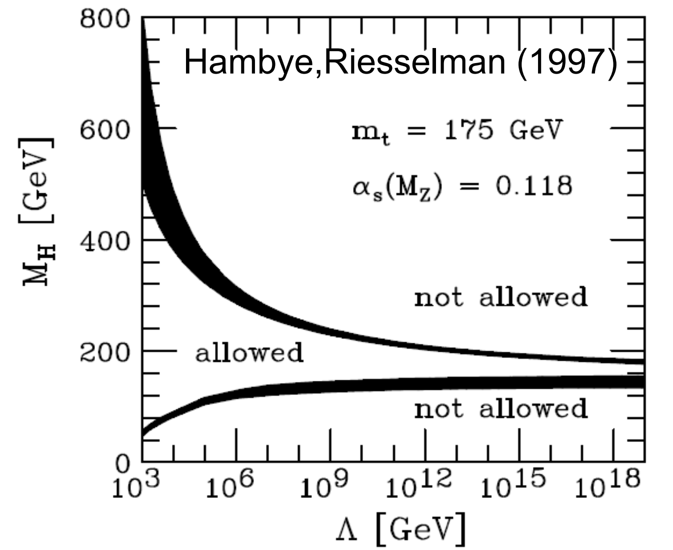


ILC Parameter Measurements



Reuter, Tonini, JHEP02 (2013) 077

Kato et al, arXiv:1203.0762

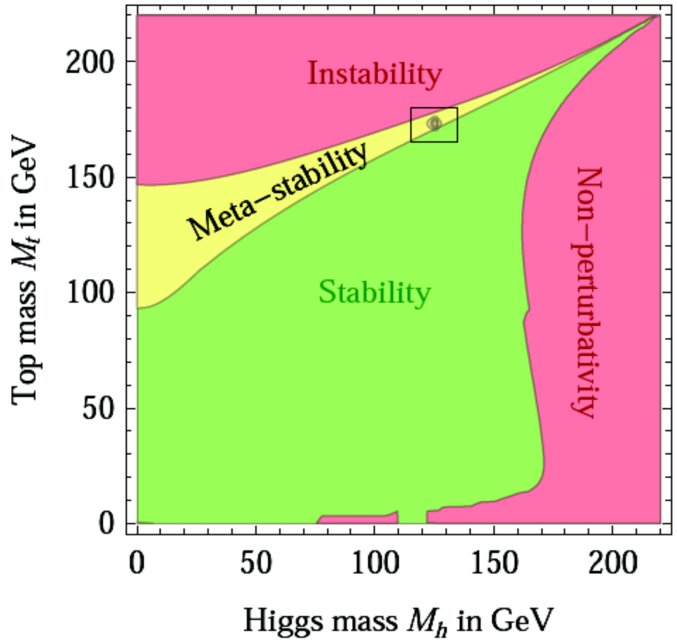


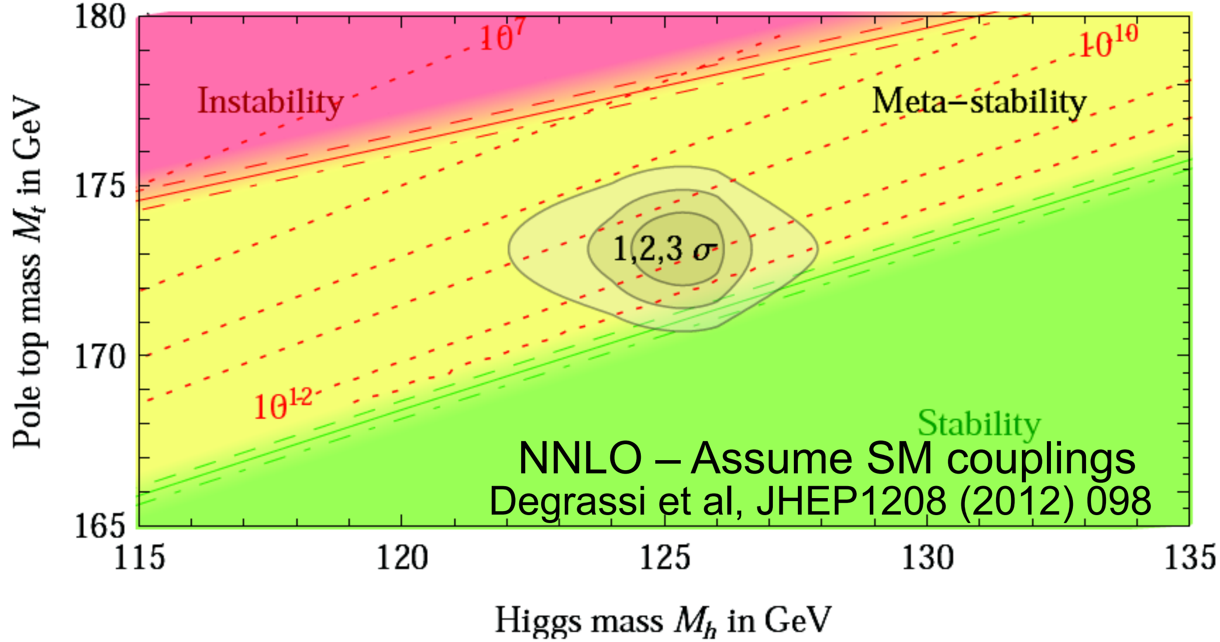
M_H and M_{top} define up to which scale the SM can be extended w/o invoking NP to stabilise the Higgs potential:

Stability of Higgs potential has cosmological implications for relation between Higgs and Inflaton

Fundamental for understanding connection between EW & Planck scales and between particle physics & cosmology via scalar potentials

Answers come through accurate mass & coupling meas.

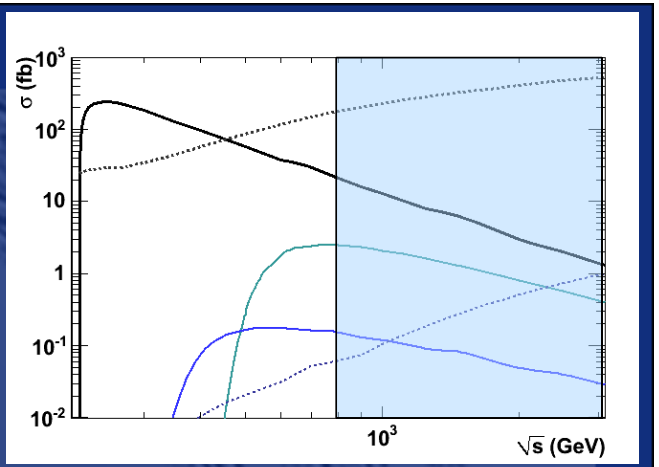




Today : M_{top} ± 0.7 GeV → δ M_H(stability) = 1.4 GeV ⟷ δ M_H(exp) ~ 1.0 GeV

ILC : M_{top} ± 0.1 GeV → δ M_H(stability) = 0.2 GeV ⟷ δ M_H(exp) = 0.05 GeV

Higgs and high energy collisions



log s increase of fusion cross sections (Hνν, HHνν) make high energies important for low σ x BR processes (H→μμ), if fwd production can be accurately reconstructed, ttH reaches the maximum of its cross section at ~800 GeV.

e^+e^- collisions at (and beyond) 1 TeV offer important opportunity to perform accurate study of double Higgs production in HHνν channel and extract triple Higgs coupling (while quartic coupling remains elusive even at a multi-TeV colliders).

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{d_3}{6}\left(\frac{3\, m_h^2}{v}\right) h^3 + \frac{d_4}{24}\left(\frac{3 m_h^2}{v^2}\right) h^4 + \cdots$$

Measuring triple Higgs coupling, beyond observing double Higgs production, is a genuine experimental "tour-de-force" testing (but also highlighting) experimental advantages of Higgs studies in e+e- collisions.

Test WW scattering at high energy to verify Higgs cancellation or new effects.