New Physics in the Light of the Higgs Discovery

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Nordita Workshop "Beyond the LHC", Stockholm, July 27th, 2013

Outline

1. HiggsSignals
2. Fittino: The CMSSM after the Higgs Discovery
3. Higgs Couplings at the LHC and beyond

HiggsSignals P. Bechtle, S. Heinemeyer, O. Stål, TS, Weiglein, [1305.1933]

→ O. Stål's talk

New public code released on May 9th, 2013 on

http://higgsbounds.hepforge.org.

- Test of extended Higgs sectors in "model-independent" way (*Physical quantities as input*: Higgs masses, total widths, cross sections, BRs, effective couplings, ...)
- Contains Higgs signal strength and mass measurements from Tevatron and LHC. (User can easily implement new observables)

⇒ χ^2 value for compatibility of the parameter point with the data.

Based on HiggsBounds library. Many examples provided.

- Signal strength measurements:

$$\hat{\mu}_{H\to XX} = \frac{\sum_i \epsilon_i \ \sigma_i(pp \to H) \times \mathrm{BR}(H \to XX)}{\sum_i [\epsilon_i \ \sigma_i(pp \to H) \times \mathrm{BR}(H \to XX)]_{\mathrm{SM}}},$$

  with $i \in \{\mathrm{ggH}, \mathrm{VBF}, WH, ZH, t\bar{t}H\}$ and efficiencies ϵ_i.

- Uncertainties for cross sections, branching ratios and Higgs mass prediction as well as luminosity are treated as fully correlated Gaussian errors.

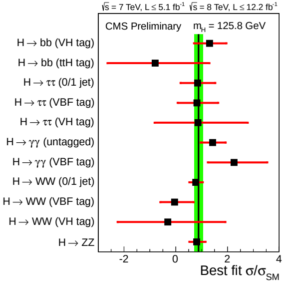
- Potential signal overlap of multiple Higgs bosons is automatically taken into account.

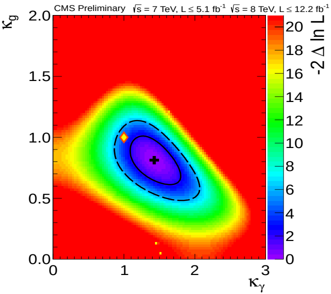
Validation with official Higgs couplings fits

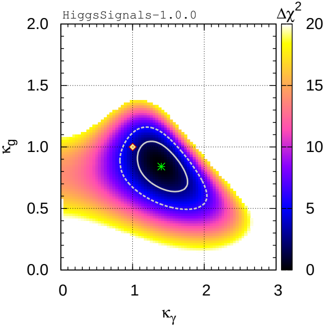
- simple 2D effective coupling benchmark models, proposed in LHC Higgs Cross Section Working Group, Sep.'12, [1209.0040]
- scale loop-induced gluon couplings by κ_g and photon couplings by κ_γ. (keep tree-level couplings at their SM value)

$\rightarrow$ probing new physics contributions to loop-induced couplings.

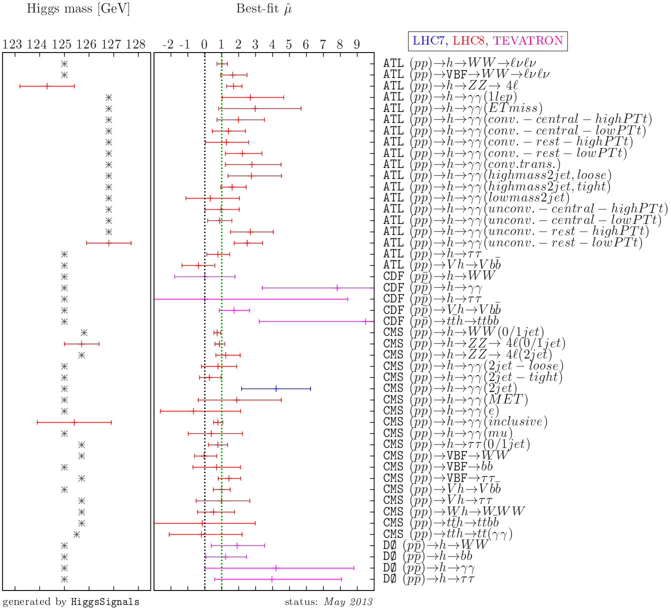
CMS-PAS-HIG-12-045







Default set of observables



The CMSSM after the Higgs Discovery

A global fit with Fittino

PRELIMINARY

in collaboration with

P. Bechtle, K. Desch, H. Dreiner, M. Hamer, M. Krämer, B. O'Leary, W. Porod, X. Prudent, B. Sarrazin, M. Uhlenbrock, P. Wienemann

Global fits of supersymmetry

The SUSY parameter space is strongly constrained by

- indirect effects on SM observables:
  $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu\mu)$, $\mathrm{BR}(b \to \tau\nu)$, Δm_{B_s}, $(g-2)_\mu$, m_W, $\sin^2\theta_{\mathrm{eff}}$
- astrophysical observations:
  Ω_{DM}, direct and indirect DM detection limits
- direct sparticle and Higgs boson search limits from colliders:
  in particular LHC limits from jets+E_T^{miss} searches
- the LHC Higgs signal

Global SUSY fits are addressing the following questions:

- What is the most probable SUSY model parameter space including all available and relevant observables/constraints?
- To what extend are the observations / constraints in mutual agreement?

[see e.g. Mastercode (arXiv:1207.7315), BayesFITS (arXiv:1206.0264), Fittino (arXiv:1204.4199)]

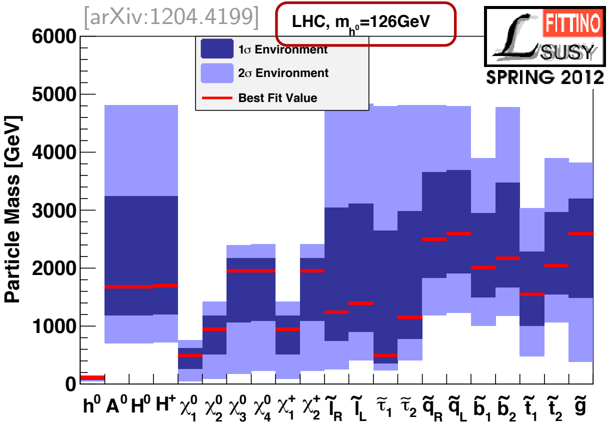
The Fittino SUSY fits

- Consider constrained SUSY models, *here*: CMSSM
- For the evaluation of the model predictions we use
  - the SUSY spectrum generators SPheno and SoftSUSY;
  - FeynHiggs for Higgs masses and couplings, $(g-2)_\mu$;
  - SuperISO for B-physics observables;
  - MicrOMEGAs for dark matter relic density;
  - AstroFit and DarkSUSY for direct and indirect detection limits;
  - HiggsBounds and HiggsSignals for the Higgs limits and signal.
- Calculate and minimize

$$\chi^2 = (\vec{O}_{\rm obs} - \vec{O}_{\rm pred}(\vec{P}))^T \mathrm{cov}^{-1} (\vec{O}_{\rm obs} - \vec{O}_{\rm pred}(\vec{P}))$$

  for each point $\vec{P}$ in the SUSY parameter space.
- Perform sampling with an auto-adaptive Markov Chain Monte Carlo.

- sparticles and H, A, $H^{\pm}$ most likely beyond current LHC reach:



The Fittino CMSSM fit as of spring 2012 predicted

- sparticles and H, A, $H^{\pm}$ most likely beyond current LHC reach. ✓
- branching ratios of the light Higgs h similar as in SM. ✓
- branching ratio $B_s \to \mu\mu$ close to the SM prediction. ✓
- no dark matter signal in current direct or indirect searches. ✓

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- branching ratios of the light Higgs h similar as in SM. ✓
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- no dark matter signal in current direct or indirect searches. ✓

In summary the picture in the CMSSM is:

- The CMSSM looks like the SM with dark matter.
- Grim prospects for LHC phenomenology
  (both for sparticle and heavy/charged Higgs searches).

$\Rightarrow$ Can we test the CMSSM through the properties of h?

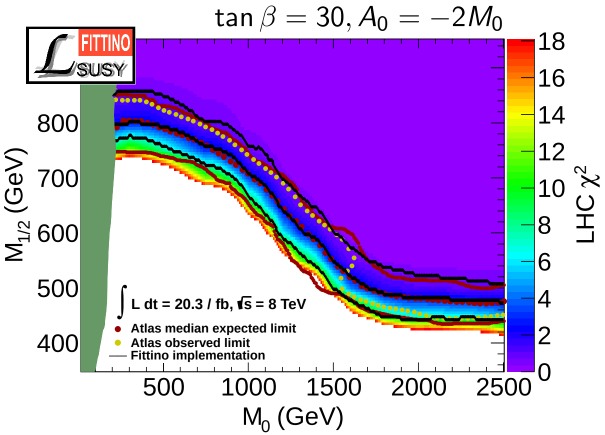
What is new in the Fittino CMSSM fit for summer 2013?

- Include Higgs mass and rate measurements via `HiggsSignals`.
- Updated observables:

$\mathrm{BR}(b \to s\gamma)$	$(3.43 \pm 0.21 \pm 0.07 \pm 0.23) \cdot 10^{-4}$	
$\mathrm{BR}(B_s \to \mu\mu)$	$\mathbf{(3.20 \pm 1.50 \pm 0.76) \cdot 10^{-9}}$	`LHCb '12`
$\mathrm{BR}(B \to \tau\nu)$	$\mathbf{(0.72 \pm 0.27 \pm 0.11 \pm 0.07) \cdot 10^{-4}}$	`Belle '12`
Δm_{B_s}	$(17.719 \pm 0.043 \pm 4.200)\ \mathrm{ps}^{-1}$	
$(a_\mu - a_\mu^{\mathrm{SM}})$	$(28.7 \pm 8.0 \pm 2.0) \cdot 10^{-10}$	
m_W	$(80.385 \pm 0.015 \pm 0.010)\ \mathrm{GeV}$	
$\sin^2\theta_{\mathrm{eff}}$	0.23113 ± 0.00021	
$\Omega_{\mathrm{CDM}} h^2$	$\mathbf{0.1187 \pm 0.0017 \pm 0.0119}$	`Planck '13`
m_{top}	$(173.18 \pm 0.94)\ \ \mathrm{GeV}$	

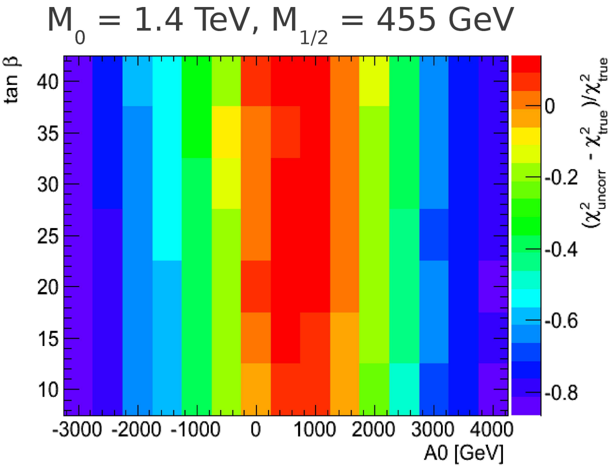
What is new in the Fittino CMSSM fit for summer 2013?

- LHC implementation refined and updated to 20.3 fb^{-1}
  [Herwig++, Delphes, Prospino] [ATLAS-CONF-2013-047]



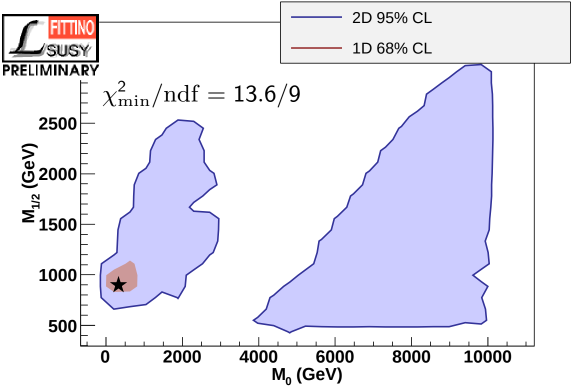
What is new in the Fittino CMSSM fit for summer 2013?

- LHC implementation refined and updated to 20.3 fb^{-1}
  [Herwig++, Delphes, Prospino] [ATLAS-CONF-2013-047]
  $\Rightarrow$ Additional acceptance grid in $A_0 - \tan\beta$ needed due to $\tilde{t}_1\tilde{t}_1$ contribution.



Preferred parameter space

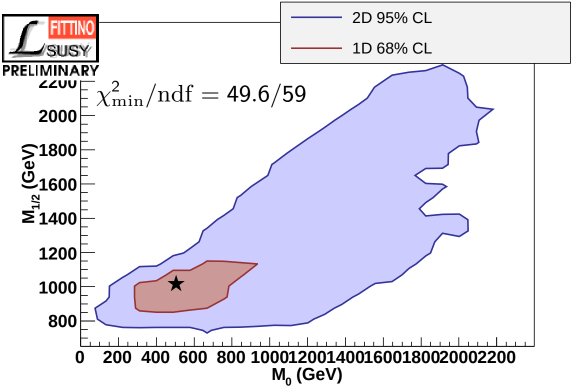
...with $m_H = (125.5 \pm 2 \pm 3)$ GeV but without signal strength:



- focus-point region allowed at 2σ level.
- tension: (LHC limit and m_H) vs. (a_μ and $\mathrm{BR}(b \to s\gamma)$).

Preferred parameter space

...with mass and signal strengths measurements via `HiggsSignals`:

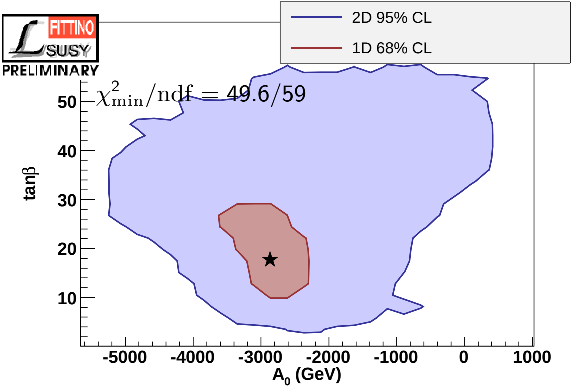


→ focus-point region disfavored.

→ overall fit quality improves.

Preferred parameter space

…with mass and signal strengths measurements via `HiggsSignals`:

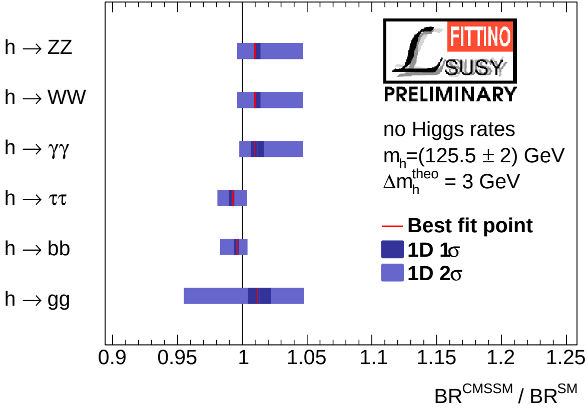


→ focus-point region disfavored.

→ overall fit quality improves.

Preferred Higgs boson branching ratios

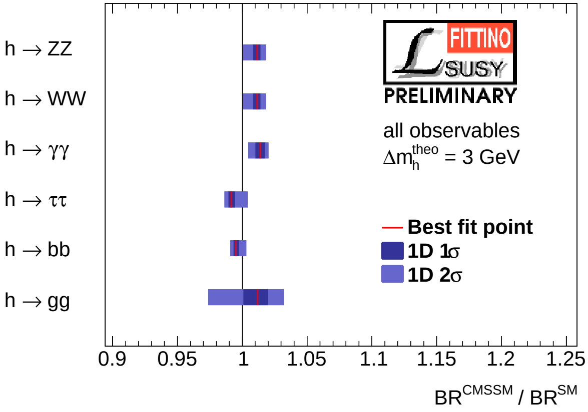
...with $m_H = (125.5 \pm 2 \pm 3)\ \mathrm{GeV}$ but without signal strength:



⇒ SM-like Higgs, small deviations allowed from $\mathrm{BR}_{\mathrm{SM}} \lesssim 5\%$.

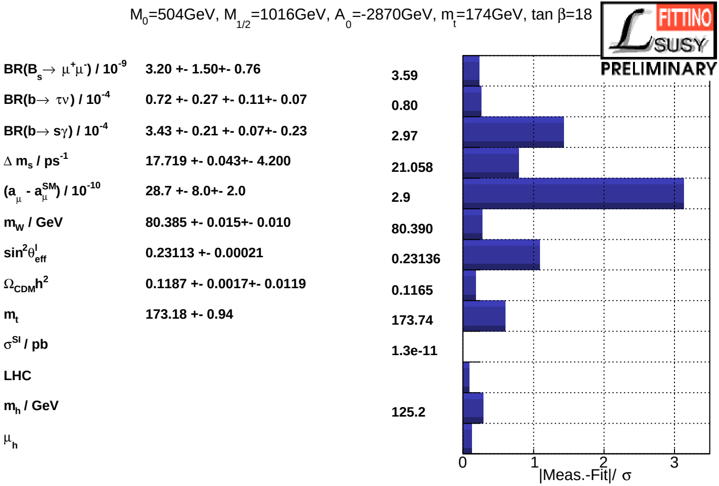
Preferred Higgs boson branching ratios

…with mass and signal strengths measurements via `HiggsSignals`:

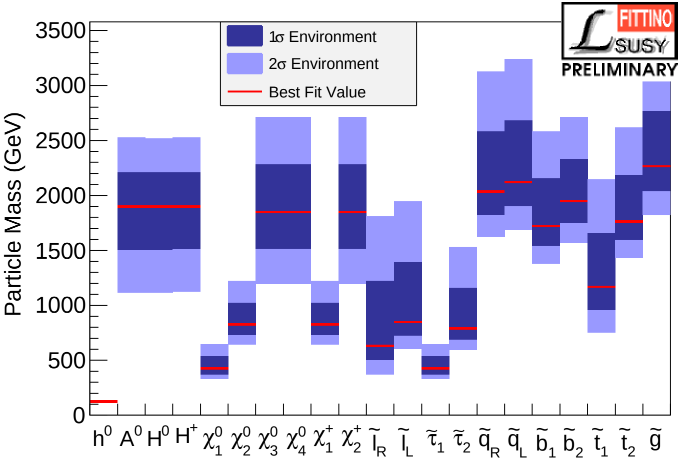


⇒ SM-like Higgs, small deviations allowed from $\mathrm{BR}_{\mathrm{SM}} \lesssim 2 - 3\%$.

Agreement of observations with model predictions



Preferred Higgs and sparticle mass spectrum



Summary of the Fittino results

After including

- updated low energy observables,
- refined and updated LHC limits from full hadronic SUSY search,
- Higgs mass and rate measurements (via `HiggsSignals`),

we find that the CMSSM is not dead, but pretty dull.

- Only small deviations in Higgs rates are allowed.
  $\Rightarrow$ what precision can we reach at LHC / ILC?

What are the next steps?

- Calculate $\mathcal{P}$-values with fits to pseudo-measurements ("Toys").
- Future fits should address more general models, in particular with different connection between colored and uncolored sparticles.
- Then, other LHC sparticle searches become relevant ($\rightarrow$ simplified models).

Higgs Couplings at the LHC and beyond

in collaboration with

P. Bechtle, S. Heinemeyer, O. Stål, G. Weiglein

PRELIMINARY

Motivation

We want to address the following questions:

1. What is the SM compatibility with the current LHC/Tevatron data?
2. How well can we determine the Higgs couplings at the LHC and ILC?

Related work: SFitter, [1301.1322], M. E. Peskin [1207.2516]

What is new / different?

- Statistical treatment in HiggsSignals.
- Slightly different parametrization (next slide).
- Precision estimates on rate measurements from detailed MC.
  - ATLAS and CMS results from European Strategy update (Krakow '12),
  - ILC results from ILC TDR Volume 2: Physics '13, [1306.6352]

Use parametrization recommended by LHC HXSWG for probing *small* deviations from the SM.
[1209.0040]
→ assumes unchanged efficiencies.

At the LHC we can't measure the total width (accurately enough).

→ reasonable assumptions:

1. $\kappa_V \leq 1$
2. $\mathrm{BR}(H \to \mathrm{NP}) \equiv \mathrm{BR}(H \to \mathrm{inv.})$

- Independent scale factors:

$$\kappa_V^2 = \frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \frac{\sigma_{VH}}{\sigma_{VH}^{\mathrm{SM}}} = \frac{\Gamma_{VV^{(*)}}}{\Gamma_{VV^{(*)}}^{\mathrm{SM}}}$$

$$\kappa_u^2 = \frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{\mathrm{SM}}} = \frac{\Gamma_{cc,tt}}{\Gamma_{cc,tt}^{\mathrm{SM}}}$$

$$\kappa_d^2 = \frac{\Gamma_{ss,bb}}{\Gamma_{ss,bb}^{\mathrm{SM}}}$$

$$\kappa_\ell^2 = \frac{\Gamma_{\mu\mu,\tau\tau}}{\Gamma_{\mu\mu,\tau\tau}^{\mathrm{SM}}}$$

$$\kappa_g^2 = \frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \frac{\Gamma_{gg}}{\Gamma_{gg}^{\mathrm{SM}}}$$

$$\kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}}$$

- Additional decay mode:

$$\mathrm{BR}(H \to \mathrm{NP})$$

General 7-dimensional fit to current data

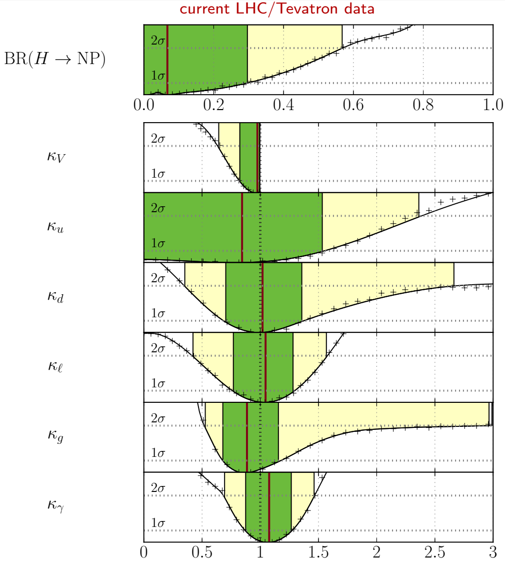
1. $\kappa_V \leq 1$

⇒ Can derive upper limit on undetectable decay mode:

$$\mathrm{BR}(H \to \mathrm{NP}) \lesssim 57\% \text{ (95\% C.L.)}$$

Stronger assumptions typically yield stronger limits.

Belanger et al., [1302.5694]

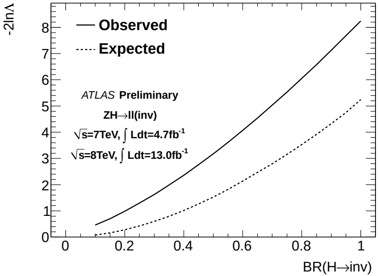


General 7-dimensional fit to current data

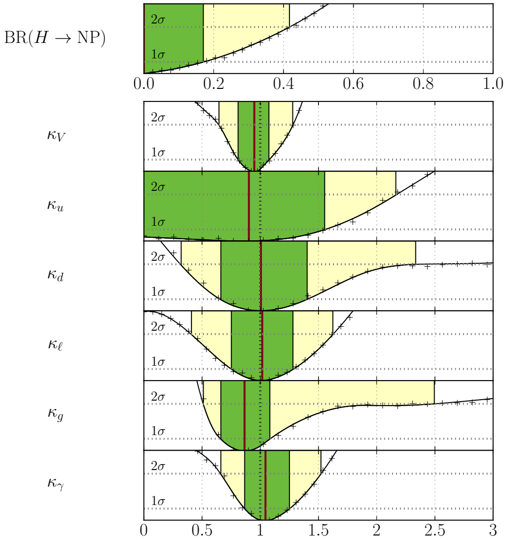
❷ $\mathrm{BR}(H \to \mathrm{NP}) \equiv \mathrm{BR}(H \to \mathrm{inv.})$

$\Rightarrow$ Add constraint from ATLAS search:

$(pp) \to ZH \to Z(\mathrm{inv.})$ [ATLAS-CONF-2013-011]



current LHC/Tevatron data



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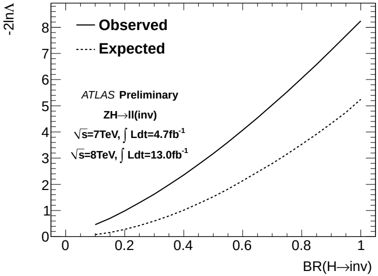

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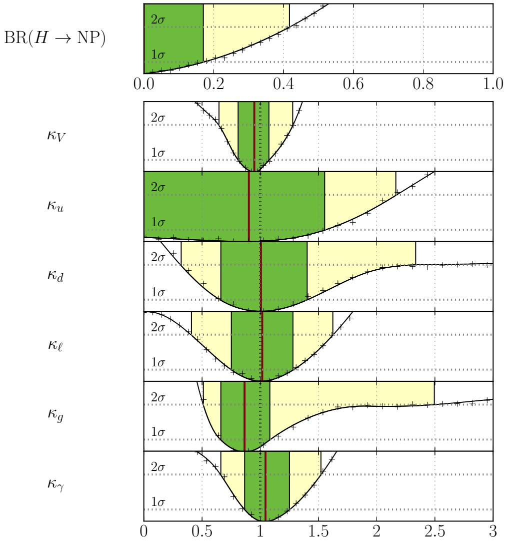
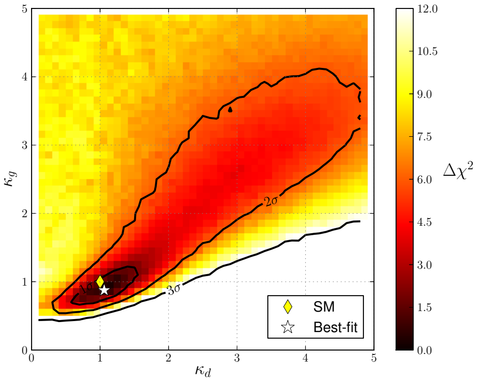


General observations:

⇒ SM is well within 68% C.L..

⇒ Correlation for large κ_g, κ_d.

Correlation of κ_g and κ_d

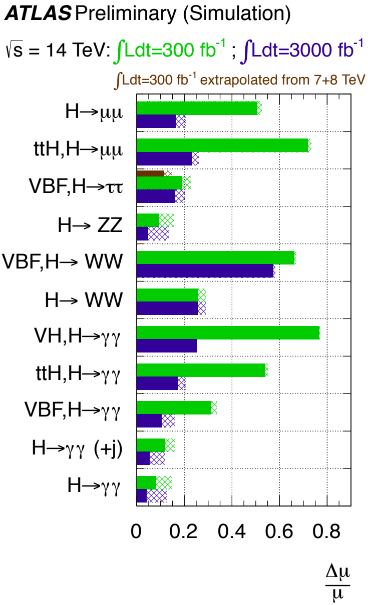


- large $\kappa_g \Rightarrow$ enhanced Higgs production.

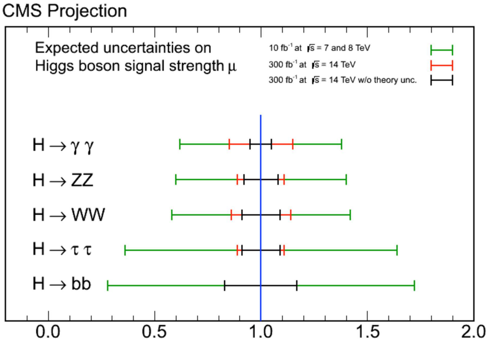
  $\Rightarrow$ theory rate uncertainty dominated by $\Delta\sigma_{\mathrm{ggH}} \sim 14.7\%$.
- large $\kappa_d \Rightarrow$ large $\Gamma_{bb} \Rightarrow$ suppressed BRs (except for $H \to bb$)

$\Rightarrow$ (Sensitive) Higgs rates are still $\approx$ SM-like.

LHC projections



from European Strategy Briefing Book '2013



⇒ implemented in HiggsSignals.

ILC precision for rate measurements

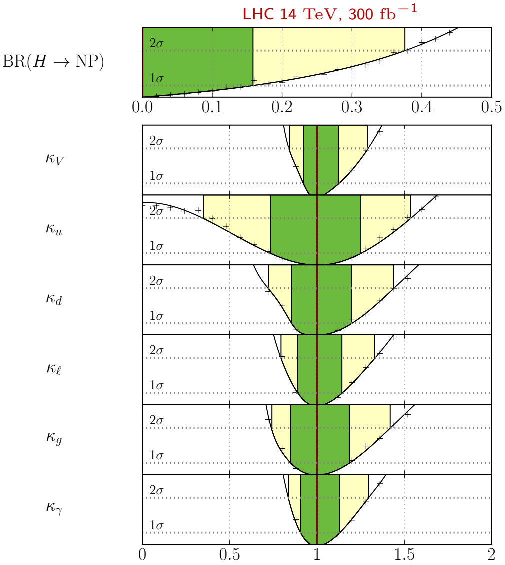
from ILC TDR Volume 2: Physics, [1306.6352]

	$\Delta(\sigma \cdot \mathrm{BR})/(\sigma \cdot \mathrm{BR})$							
$\mathcal{L}$ and $\sqrt{s}$	250 fb^{-1} at 250 GeV		500 fb^{-1} at 500 GeV			1 ab^{-1} at 1 TeV		Theory
mode	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$	$t\bar{t}H$	$\nu\bar{\nu}H$	$t\bar{t}H$	Γ
$H \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	35%	0.47%	8.7%	4.5%
$H \to c\bar{c}$	7.4%	-	12.0%	6.2%	-	7.6%	-	9.6%
$H \to gg$	9.1%	-	14%	4.1%	-	3.1%	-	5.2%
$H \to WW^{(*)}$	6.4%	-	9.2%	2.6%	-	3.3%	-	0.5%
$H \to \tau^+\tau^-$	4.2%	-	5.4%	14%	-	3.5%	-	2.0%
$H \to ZZ^{(*)}$	19%	-	25%	8.2%	-	4.4%	-	0.5%
$H \to \gamma\gamma$	29 − 38%	-	29(−38)%	20(−26)%	-	7(−10)%	-	1.0%
$H \to \mu^+\mu^-$	100%	-	-	-	-	32%	-	2.0%

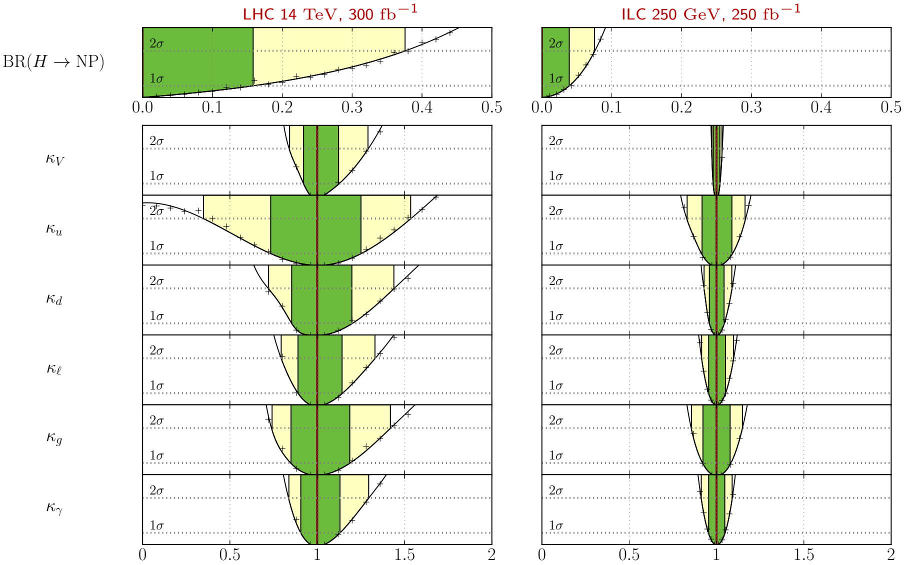
theory errors are taken from LHC HXSWG: YR3 [1307.1347]

+ measurement of $\sigma(e^+e^- \to ZH)$ with precision $\sim 2.5\%$ at ILC 250 GeV, 250 fb^{-1}.

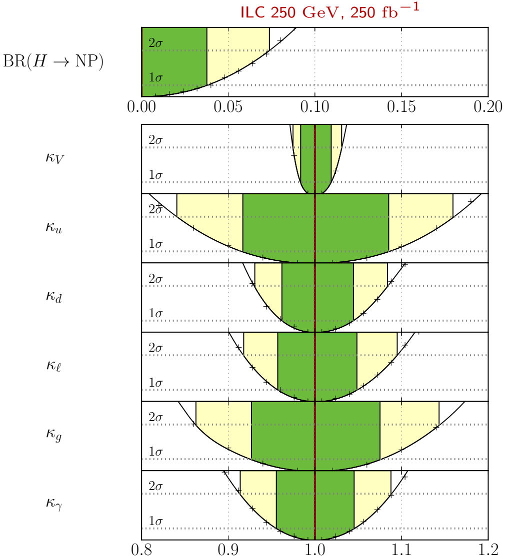
Future Projections



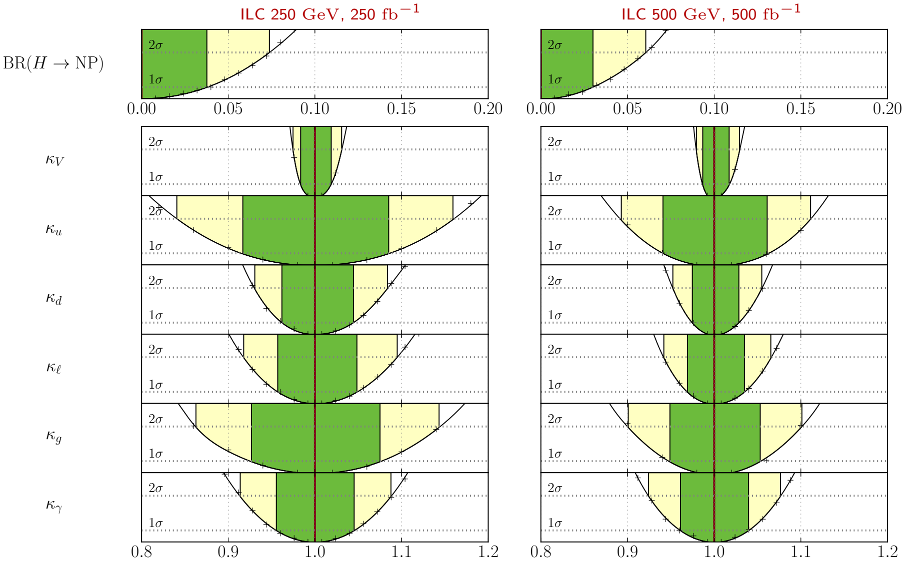
Future Projections



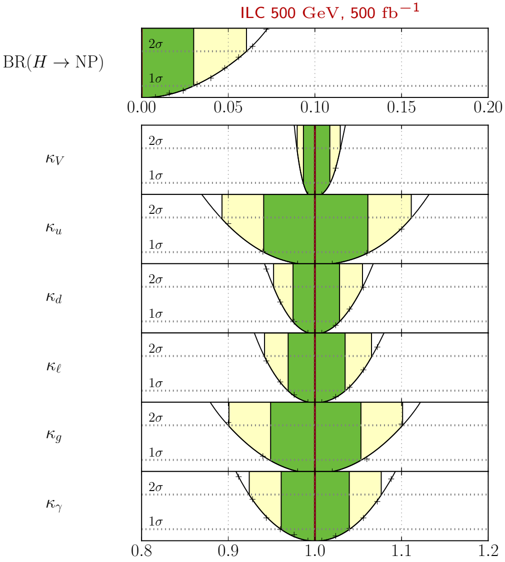
Future Projections



Future Projections



Future Projections



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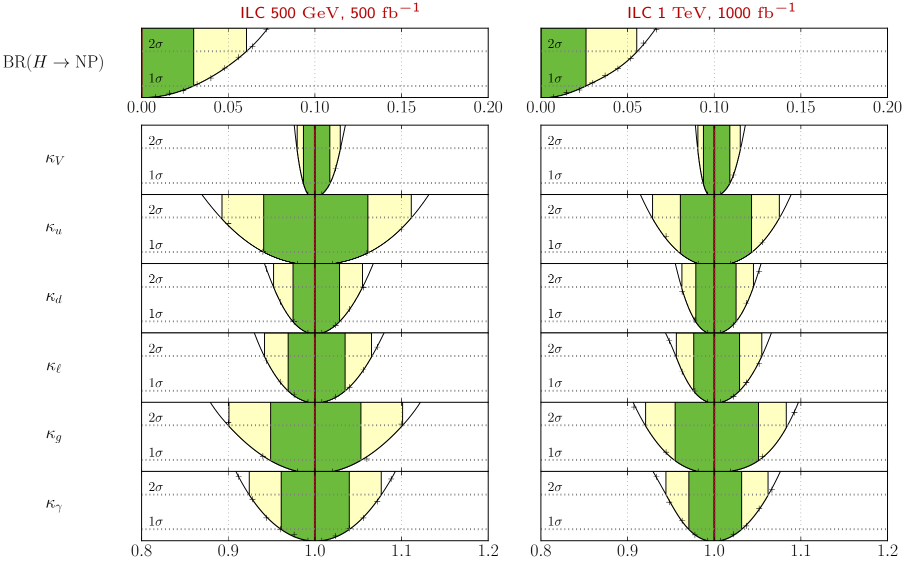
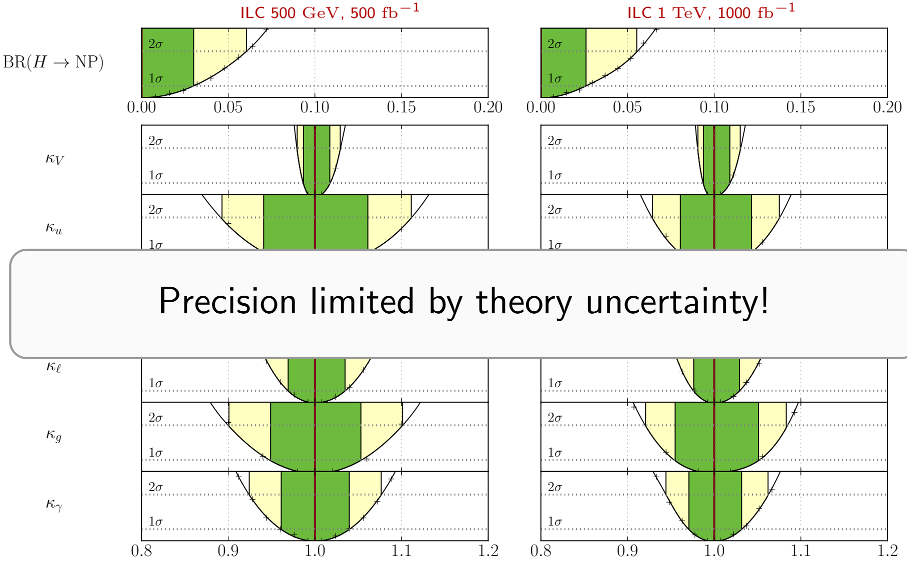


Future Projections



Precision limited by theory uncertainty!

Summary

We are entering the Higgs precision era!

Probing new physics via Higgs rates may require

- precise rate measurements at LHC and ILC,
- precise theory predictions both for SM and BSM,
- accurate statistical tools to confront models with data.
  ($\rightarrow$ `HiggsSignals`)

Present Higgs data agrees remarkably well with the SM predictions.

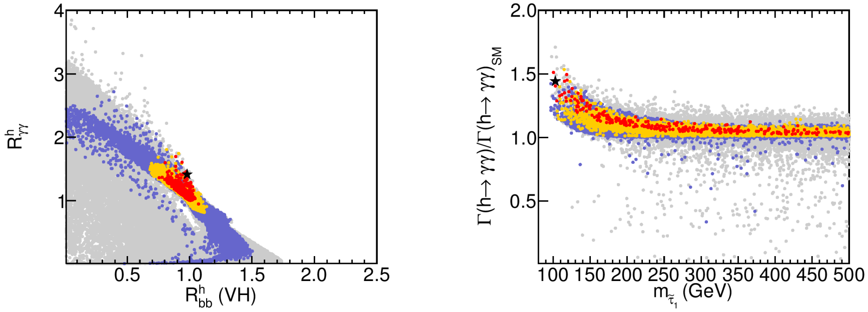
But: Current measurements not very precise

$\rightarrow$ New data may still hold some surprises!

Backup slides

Example: pMSSM-7 fit to Higgs data and low energy observables

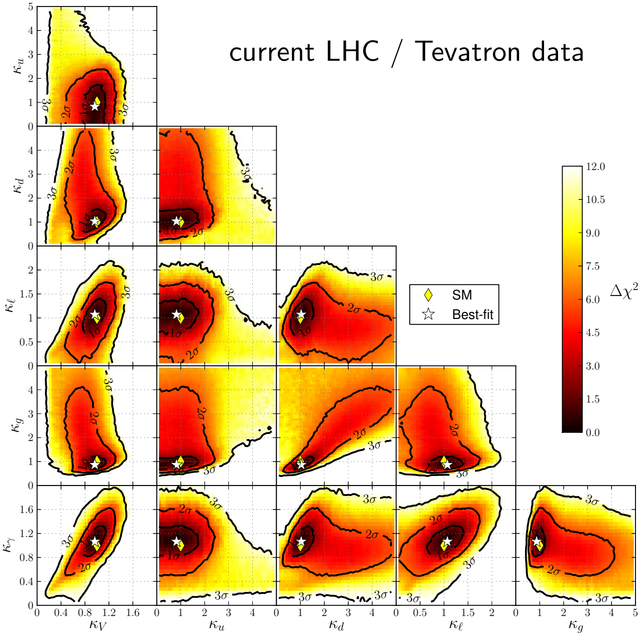
P. Bechtle, S. Heinemeyer, O. Stål, TS, G. Weiglein, L. Zeune, [1211.1955]



⇒ can achieve enhancement of $H \to \gamma\gamma$ rate by $\lesssim$ 50%.

⇒ need precise measurements to constrain / see new physics effects.

current LHC / Tevatron data



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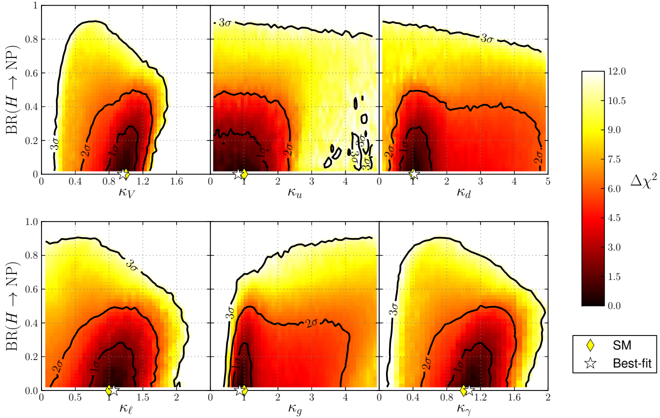
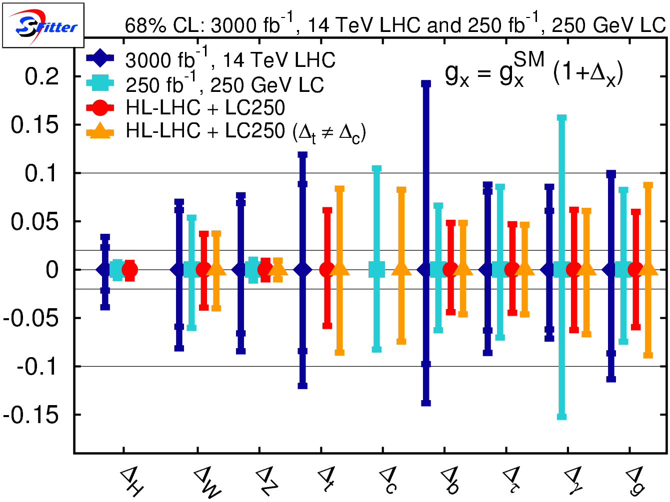
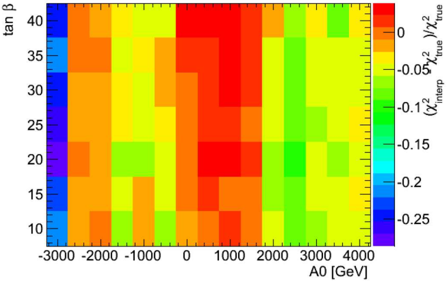
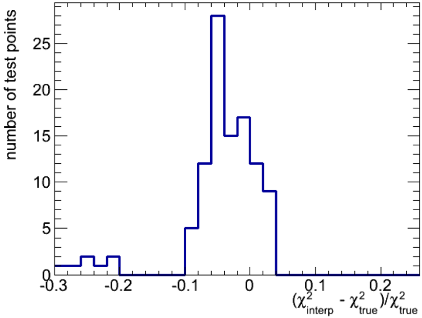




SFitter
68% CL: 3000 fb-1, 14 TeV LHC and 250 fb-1, 250 GeV LC
3000 fb-1, 14 TeV LHC
250 fb-1, 250 GeV LC
HL-LHC + LC250
HL-LHC + LC250 ($\Delta_t \neq \Delta_c$)
$g_x = g_x^{SM} (1+\Delta_x)$
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Δ_H
Δ_W
Δ_Z
Δ_t
Δ_c
Δ_b
Δ_τ
Δ_γ
Δ_g

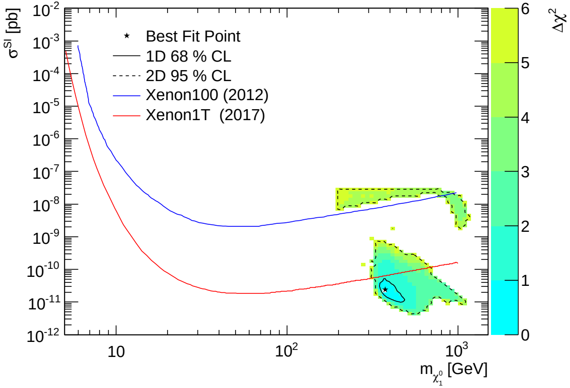
Corrected acceptance grid for LHC implementation





Prospects for Direct DM detection

. . . with $m_H = (125.5 \pm 2 \pm 3)\ \mathrm{GeV}$ but without signal strength:



Prospects for Direct DM detection

. . . with mass and signal strengths measurements via HiggsSignals: