Extracting Higgs “Couplings” from LHC and ILC Data

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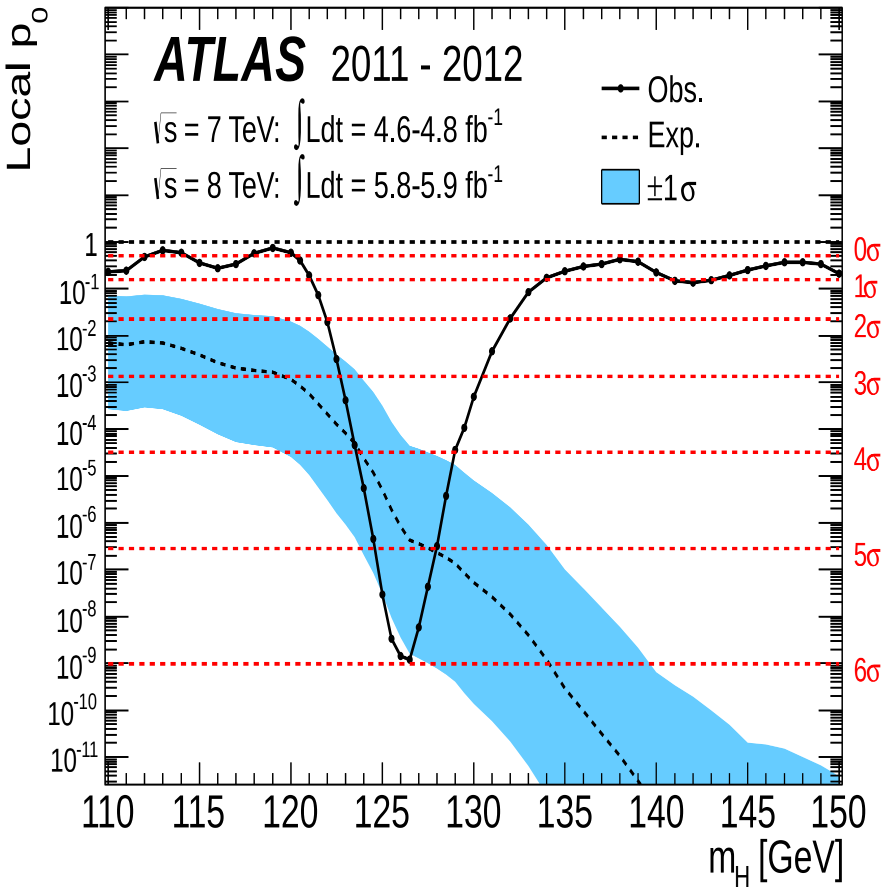
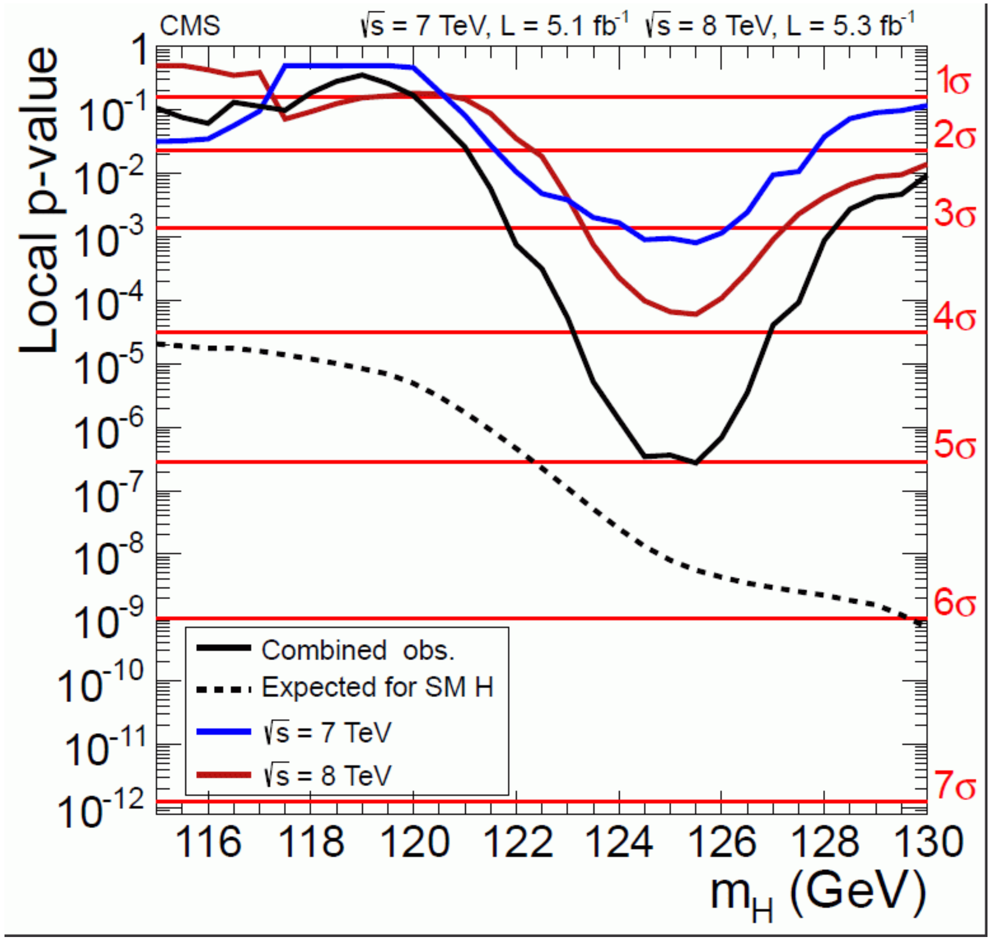
Madrid, 09/2014

1. Introduction
2. Our tool: HiggsSignals
3. Higgs bosons “couplings” from LHC data
4. Higgs boson “couplings” from ILC data
5. Conclusions

1. Introduction

We have a discovery!





1. Introduction

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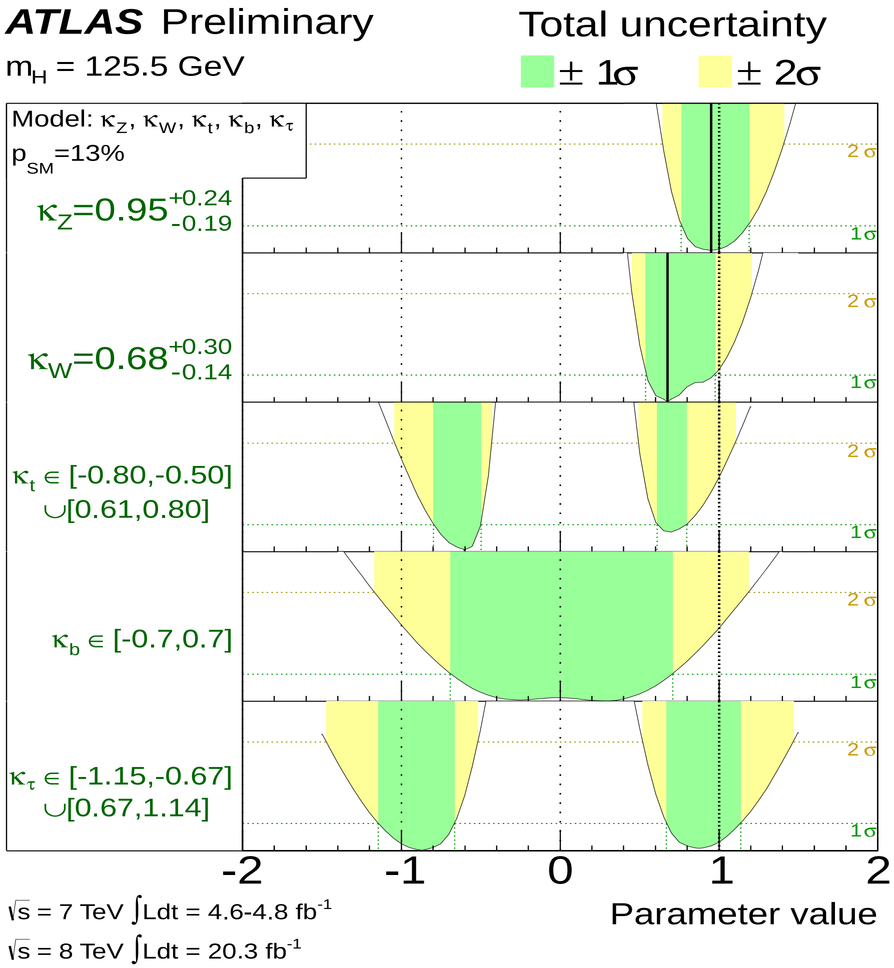

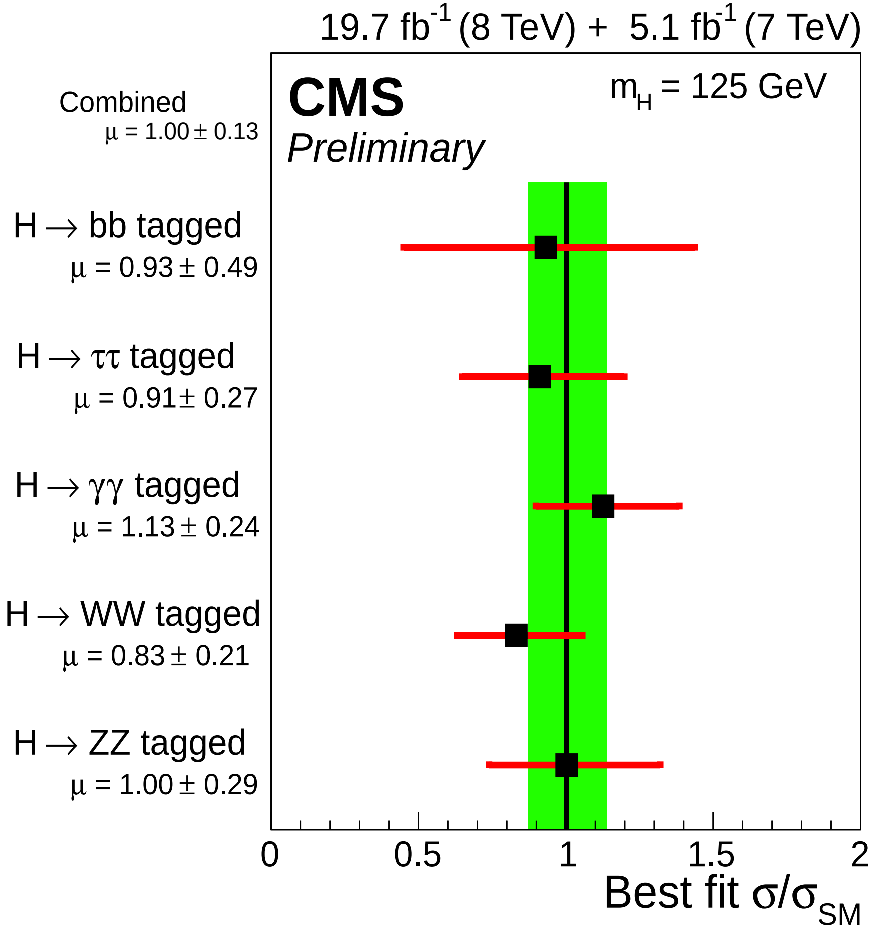

We have a discovery!

But what is it?

Q: Is it a Higgs boson?

Q: Is it the Higgs boson of the SM?

Q: Is it an MSSM Higgs boson?

Q: Is it a Higgs boson of a different model?

Q: Is it an impostor?

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How can we decide?

A: Measure all its characteristics

⇒ cross sections, branching ratios, quantum numbers, . . .

A: Investigate BSM physics:

⇒ compare to predictions of EW singlet, 2HDM, (N)MSSM, . . .

LHC Higgs Cross Section Working Group: Low Mass (LM) subgroup:

Assumptions (for 2012 data):

1. Signal corresponds to only one state, no overlapping signal etc.
2. Zero-width approximation
3. Only modification of coupling strength (absolute values of couplings) but not of tensore structure wrt. to SM

Recommendations (for 2012 data):

1. Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i ($\kappa_i = 1$ corresponds to the SM case)
2. Most general case: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \ldots \oplus$ extra loop contributions to $\sigma(gg \to H)$, $\Gamma(H \to gg)$, $\Gamma(H \to \gamma\gamma)$, $\Gamma_{H,\text{tot}}$
3. benchmarks:
   - one parameter: overall signal strength $\kappa^2 \equiv \mu$
   - two parameters: $\kappa_V := \kappa_W = \kappa_Z$, $\kappa_F := \kappa_t = \kappa_b = \kappa_\tau = \ldots$
   - ...

Recommendations continued:

Total width $\Gamma_{H,\mathrm{tot}}$ cannot be measured without further theory assumptions. (This is not a recommendation, but a fact!)

For each benchmark (except overall coupling strength) two versions are proposed:
with and without taking into account the possibility of additional contributions to the total width

1) additional contributions to $\Gamma_{H,\mathrm{tot}}$ are allowed:

⇒ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

2) additional contributions to $\Gamma_{H,\mathrm{tot}}$ are allowed:

but assume that all additional decays are "invisible" with MET

⇒ Determination of κ_i

3) additional contributions to $\Gamma_{H,\mathrm{tot}}$ are allowed:

but assume that $\kappa_{W,Z} \le 1$ (fulfilled for Higgs-singlets, -doublets)

⇒ Determination of κ_i

4) no additional contributions to $\Gamma_{H,\mathrm{tot}}$ are allowed: ⇒ Determination of κ_i

Precision coupling/spin/parity determination from future data:

Problem:

– κ prescription only accurate up to the 5-10% level

– only valid if data centers around SM values

Solution: Higgs Effective Field Theory [*LHCHXSWG '13*]

– effective Lagrangian: SM + dim 6 operators ($\# \leq 59$)
– linear vs. non-linear parameterization . . .

Existing tools (already):

– MadGraph5
– Hawk
– eHdecay

$\Rightarrow$ NLO calculations? Will take time . . .

$\Rightarrow$ not the topic here

HiggsBounds and *HiggsSignals*

- Programs that use the experimental information on cross section limits (HiggsBounds) and observed signal strengths (HiggsSignals) for testing theory predictions *[P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, K. Williams '08, '12, '13]*

- *HiggsSignals: [P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein '13]*

  - Test of Higgs sector predictions in arbitrary models against measured signal rates and masses

  - Systematic uncertainties and correlations of signal rates, luminosity and Higgs mass predictions taken into account

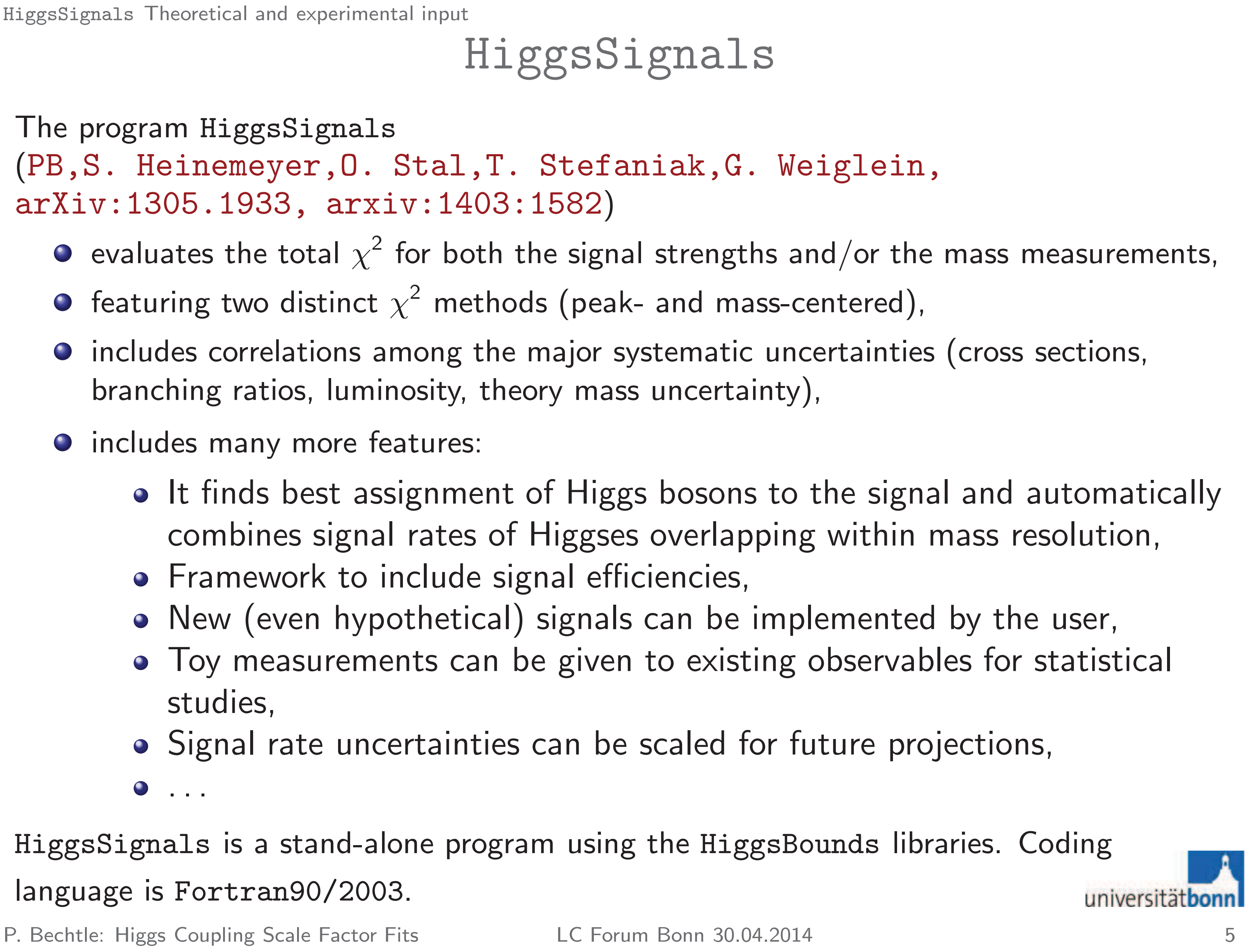
HiggsSignals is much more than a

"Tool for Higgs coupling measurements"

→ determining Higgs coupling strength modifiers is just one "simple" application

Applications:

- Tests of (nearly) any model against existing Higgs data
- including models with multiple/"overlapping" Higgses
- no need for approximation in terms of effective couplings
- capable of dealing with possible "multiple Higgs signals"



HiggsSignals

The program `HiggsSignals`
(PB,S. Heinemeyer,O. Stal,T. Stefaniak,G. Weiglein,
arXiv:1305.1933, arxiv:1403:1582)

- evaluates the total χ^2 for both the signal strengths and/or the mass measurements,
- featuring two distinct χ^2 methods (peak- and mass-centered),
- includes correlations among the major systematic uncertainties (cross sections, branching ratios, luminosity, theory mass uncertainty),
- includes many more features:
  - It finds best assignment of Higgs bosons to the signal and automatically combines signal rates of Higgses overlapping within mass resolution,
  - Framework to include signal efficiencies,
  - New (even hypothetical) signals can be implemented by the user,
  - Toy measurements can be given to existing observables for statistical studies,
  - Signal rate uncertainties can be scaled for future projections,
  - ...

`HiggsSignals` is a stand-alone program using the `HiggsBounds` libraries. Coding language is `Fortran90/2003`.

`HiggsSignals`: The basic idea

1. Take model-predictions of a given (arbitrary) Higgs sector for

$$m_k, \quad \Gamma_k^{\mathrm{tot}}, \quad \sigma_i(pp \to H_k), \quad \mathrm{BR}(H_k \to XX),$$

   with $k = 1, \ldots, N, \quad i \in \{\mathrm{ggH}, \mathrm{VBF}, WH, ZH, t\bar{t}H\}$
   for N neutral Higgs bosons as the program's user input.
   Optional input: Theo. uncertainties for mass, cross sections and BR's.
2. Calculate the predicted signal strength μ for every observable.
3. Perform a χ^2 test of model predictions against all available data from Tevatron and LHC, using signal rate and mass measurements.

The aim is to be as

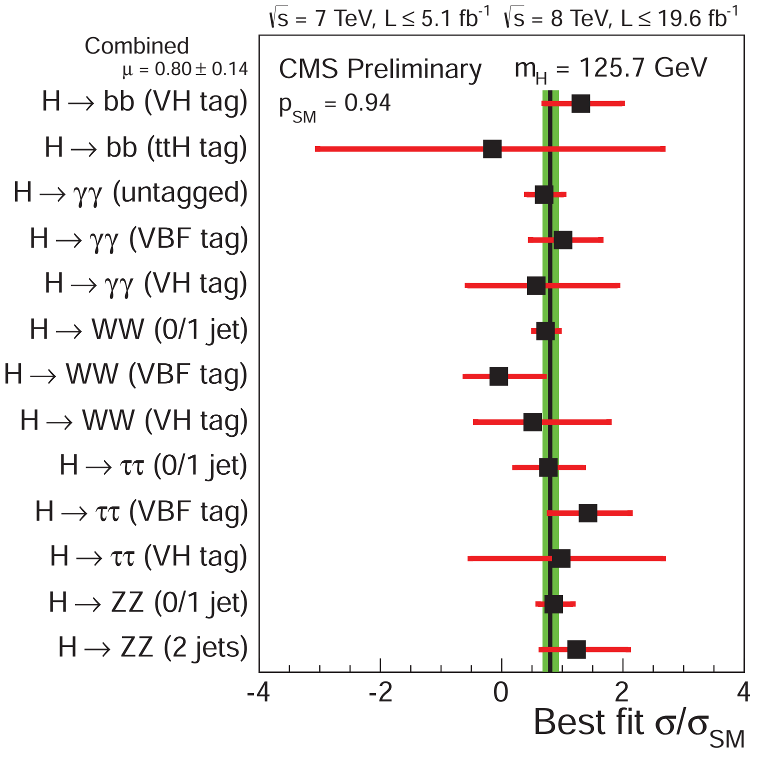
- model-independent as possible,
- precise as possible (given the limited public information available)

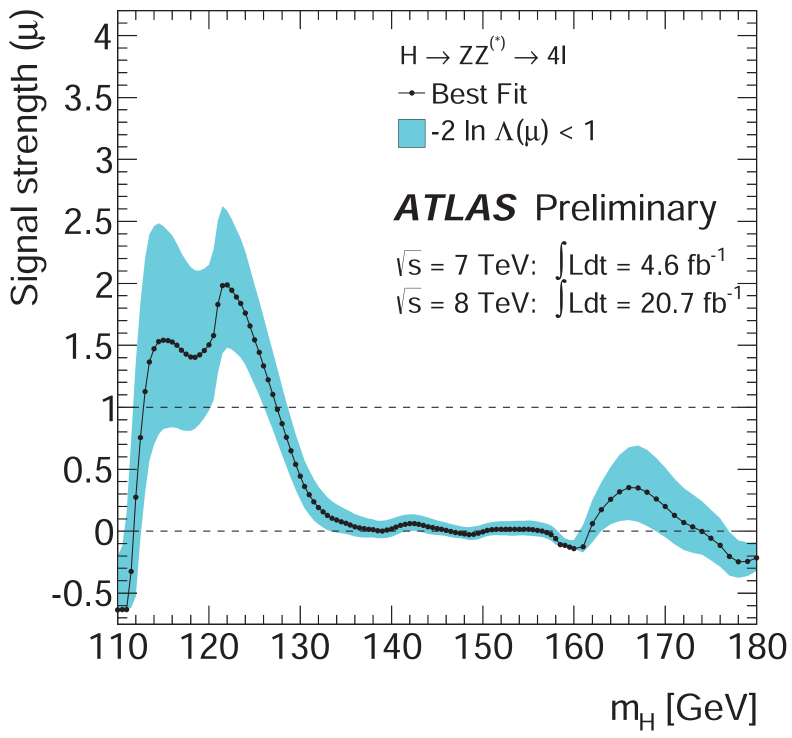
Experimental input

- Signal strength measurements:

$$\mu_{H\to XX} = \frac{\sum_i \epsilon^i_{\text{model}}\,[\sigma_i(pp\to H)\times \text{BR}(H\to XX)]_{\text{model}}}{\sum_i \epsilon^i_{\text{SM}}\,[\sigma_i(pp\to H)\times \text{BR}(H\to XX)]_{\text{SM}}},$$

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





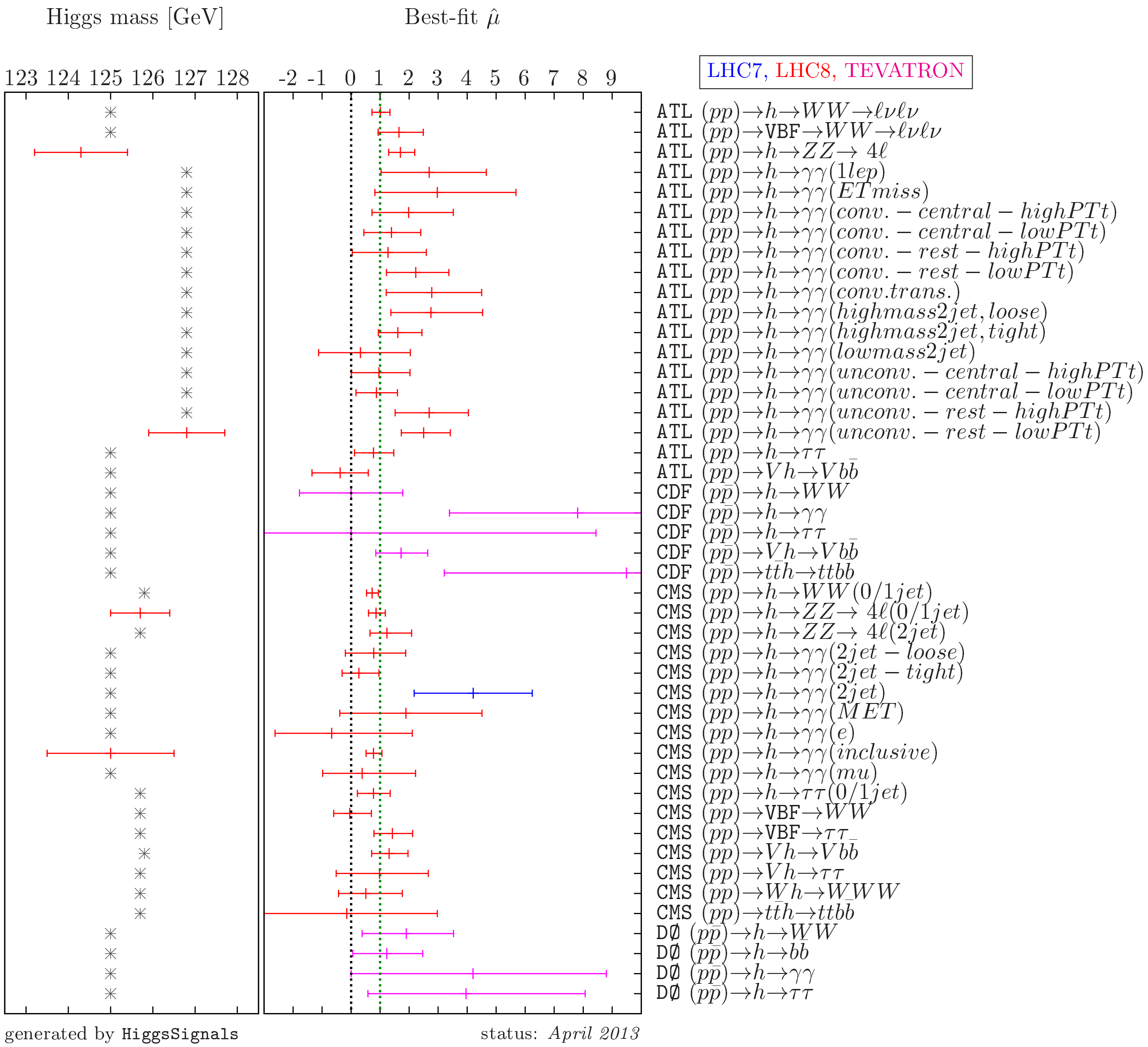
Experimental input

The user can directly add/remove/edit observables via text files:

```
# Published at Moriond 2013.
# Data read in from Fig. 25a.
# No efficiencies are given (for this inclusive result)
# Mass uncertainty contains 0.6 GeV (stat) and 0.5 GeV (syst) error.
#(Gauss: 0.8, linear: 1.1)
2013013101 201301301 1
ATL-CONF-2013-013
LHC, ATL, ATL
(pp)->h->ZZ->4l
8 25.3 0.036
1 1
1.1
124.3 124.3 0.1
4 -1
13 23 33 43

       124.3           1.293           1.697           2.194
```

Default set of observables:



Peak-Centered χ^2 method

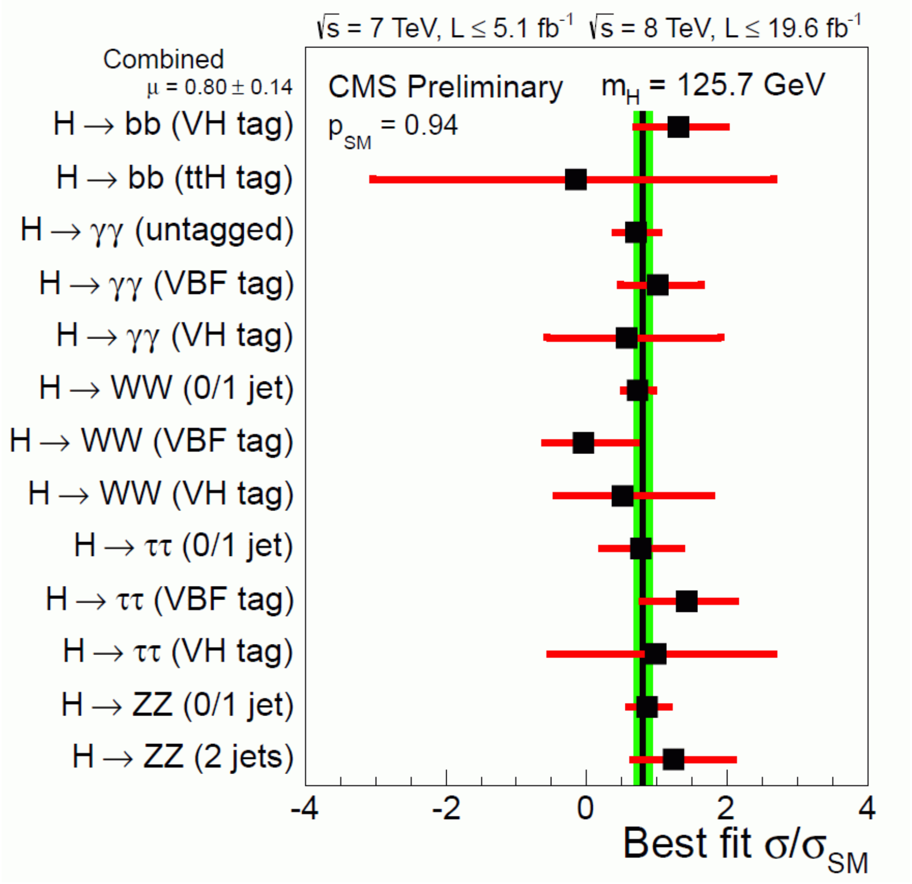
- Tests compatibility of data observed at specified signal mass values, “peaks”, against the model predictions

- This determines whether the model provides one (or more) Higs bosons that can explain the observed signal(s)

- Example: Observed LHC signal around 125 GeV

- Most sane theories would now like to have a reasonably SM-like Higgs boson at this mass

- Complementary to HB exclusion for multi-Higgs models
  HB tests all Higgses individually
  against the exclusion bounds



Details of peak-centered χ^2 method

- Global χ^2 function calculated using Gaussian approximation, correlations of theory + luminosity unc. included

$$\chi^2_\mu = \sum_{\alpha=1}^{N} \chi^2_{\mu,\alpha} = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T \mathbf{C}_\mu^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

- χ^2 for mass observables added: $\chi^2_{\text{tot}} = \chi^2_\mu + \chi^2_m$

- The theoretical prediction □ used for each particular signal is determined by *assigning* one or more Higgs bosons

Required assignment: $|m_i - \hat{m}_\alpha| \leq \Lambda \sqrt{(\Delta m_i)^2 + (\Delta \hat{m}_\alpha)^2}$

Allowed assignment outside this range only for observables with mass measurement if it improves the overall χ^2

The χ^2 evaluation

In the χ^2 evaluation, we try to take into account the correlations of the major systematic uncertainties, that are publicly known. These are

- fully correlated luminosity uncertainty: $\Delta\mathcal{L}$,
- fully correlated theoretical rate uncertainties: $\Delta\sigma_i$, $\Delta\mathrm{BR}_i$.

Other correlations of systematics could be incorporated if they were public.

The global χ^2 for the signal strength measurements is then given by

$$\chi^2_\mu = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T \mathbf{C}_\mu^{-1} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}).$$

A similar calculation is done for the mass observables ⇒ χ^2_m.

Theoretical rate predictions

- Combined signal rate prediction for one Higgs boson and one analysis

$$\mu = \sum_i c_i \omega_i$$

- Individual channel signal rate

$$c_i = \frac{[\sigma \times \mathrm{BR}]_i}{[\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_i}$$

- Channel weights (evaluated in the SM)

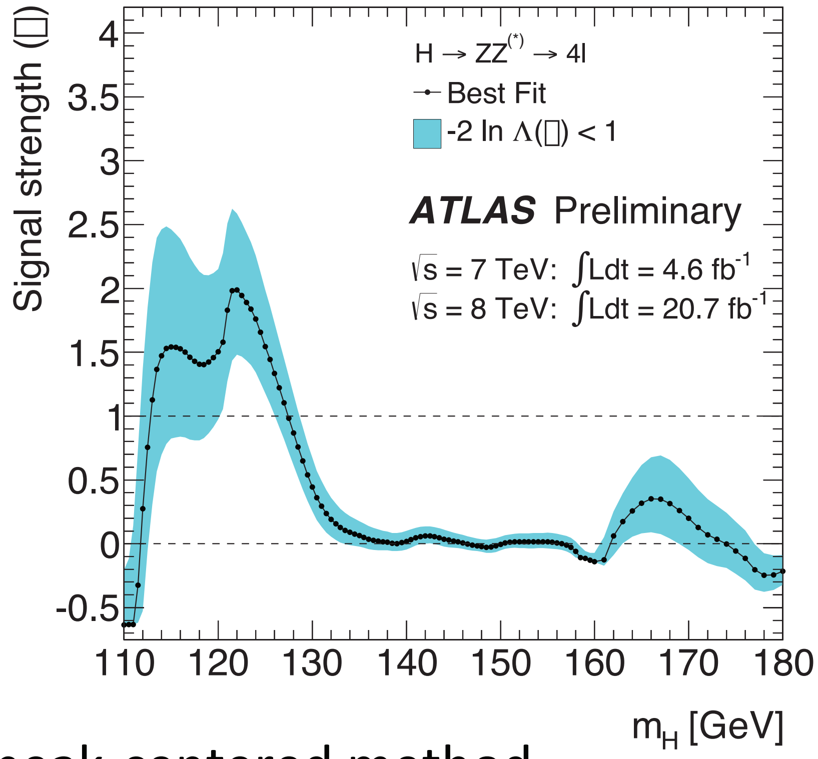
$$\omega_i = \frac{\epsilon_i \, [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_i}{\sum_j \epsilon_j \, [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_j}$$

Mass-Centered χ^2 method

- Compares model prediction to measured data directly at the *predicted* Higgs mass values

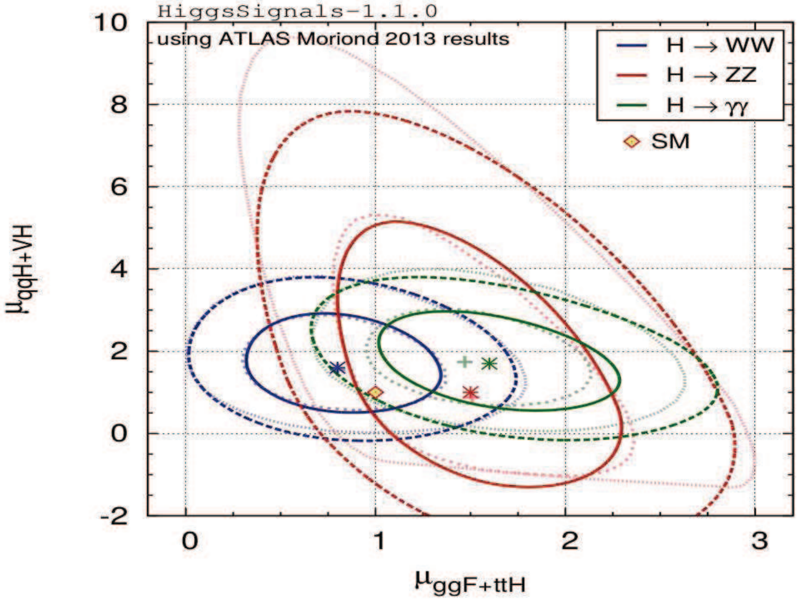
- Combines rate predictions for Higgs bosons that are “nearby” in mass (within exp. resolution)

- Applicability of this method is currently limited by available exp. results, e.g. $M_H < 200$ GeV

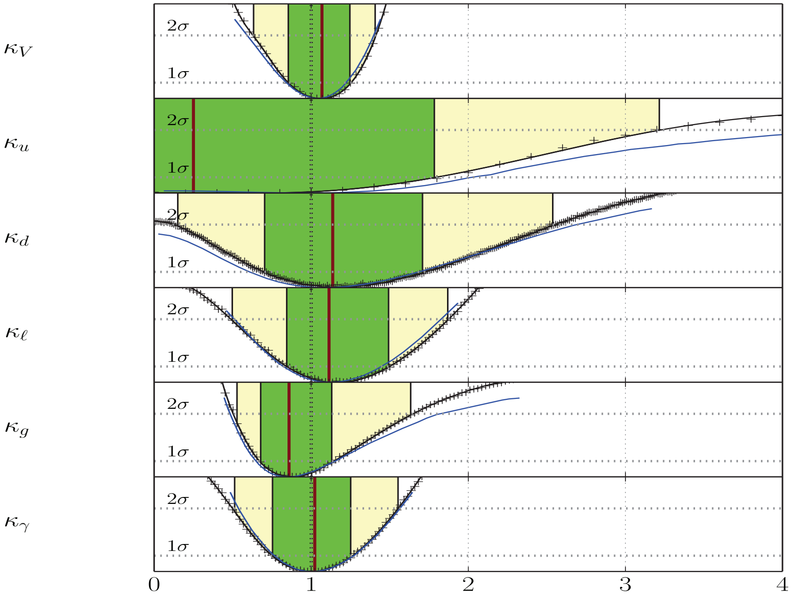


- Can be used simultaneously with peak-centered method for Higgs bosons that have not been assigned to any signal

Validation against ATLAS and CMS (Moriond 2013)



ATL-CONF-2013-034



CMS-PAS-13-005

Generally good agreement Main limiting factors / challenges:

- Missing public information on signal efficiencies,
- Missing public information on correlations of exp. systematics,
- some measurements are performed at different m_H values than validation.

3. Higgs boson "couplings" from LHC data

Results based on [arXiv:1403.1582 [hep-ph]]

⇒ not the very latest data,
but the overall picture does not change too much
⇒ 80 channels from ATLAS, CMS, CDF, DØ

Results for:

(I) $\kappa, \text{BR}(H \to \text{inv.})$

(II) $\kappa_V, \kappa_F, \text{BR}(H \to \text{inv.})$

(III) $\kappa_W, \kappa_Z, \kappa_F, \text{BR}(H \to \text{inv.})$

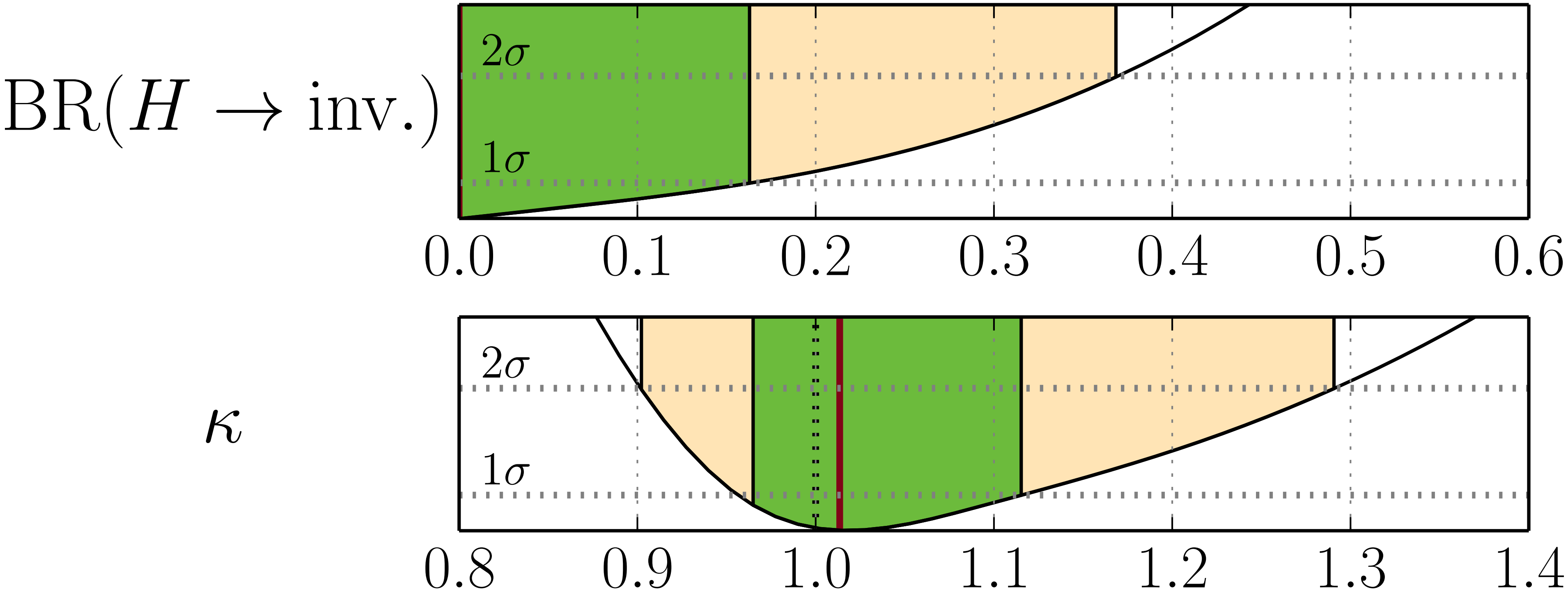
(IV) $\kappa_g, \kappa_\gamma, \text{BR}(H \to \text{inv.})$

(V) $\kappa_V, \kappa_u, \kappa_d, \kappa_l, \kappa_g, \kappa_\gamma, \text{BR}(H \to \text{inv.})$

Coupling scale factor results (I):

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]

Simplest model: $\kappa, \mathrm{BR}(H \to \text{inv.})$



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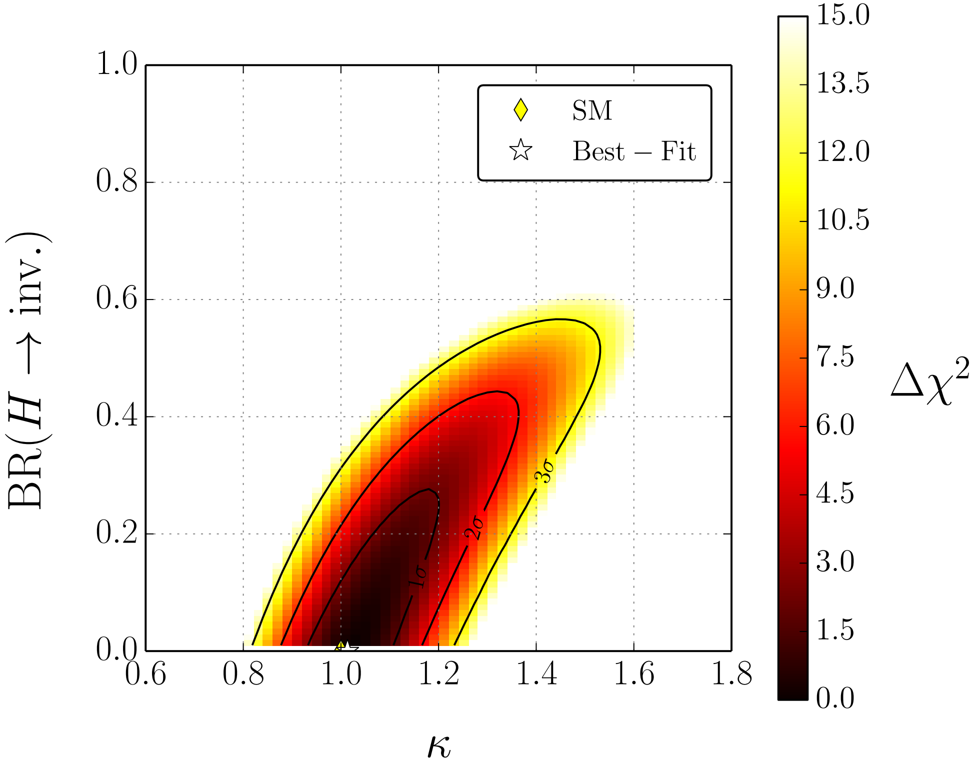
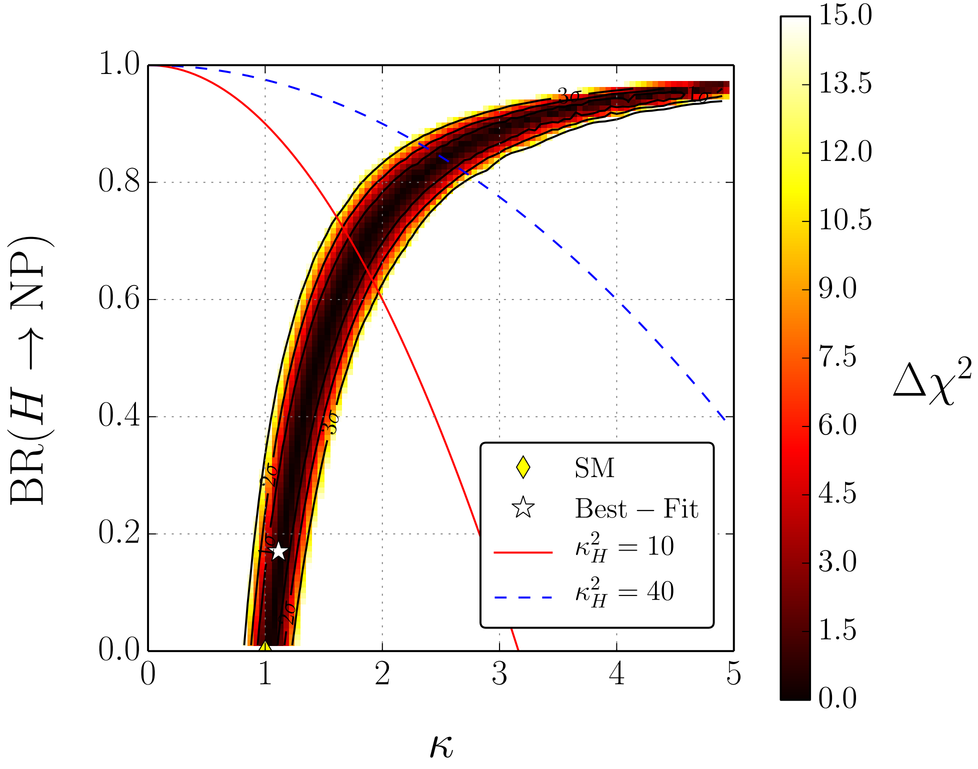
Simplest model: $\kappa, \mathrm{BR}(H \to \text{inv.})$

$\mathrm{BR}(H \to \text{NP}) = \mathrm{BR}(H \to \text{inv.})$



no assumptions

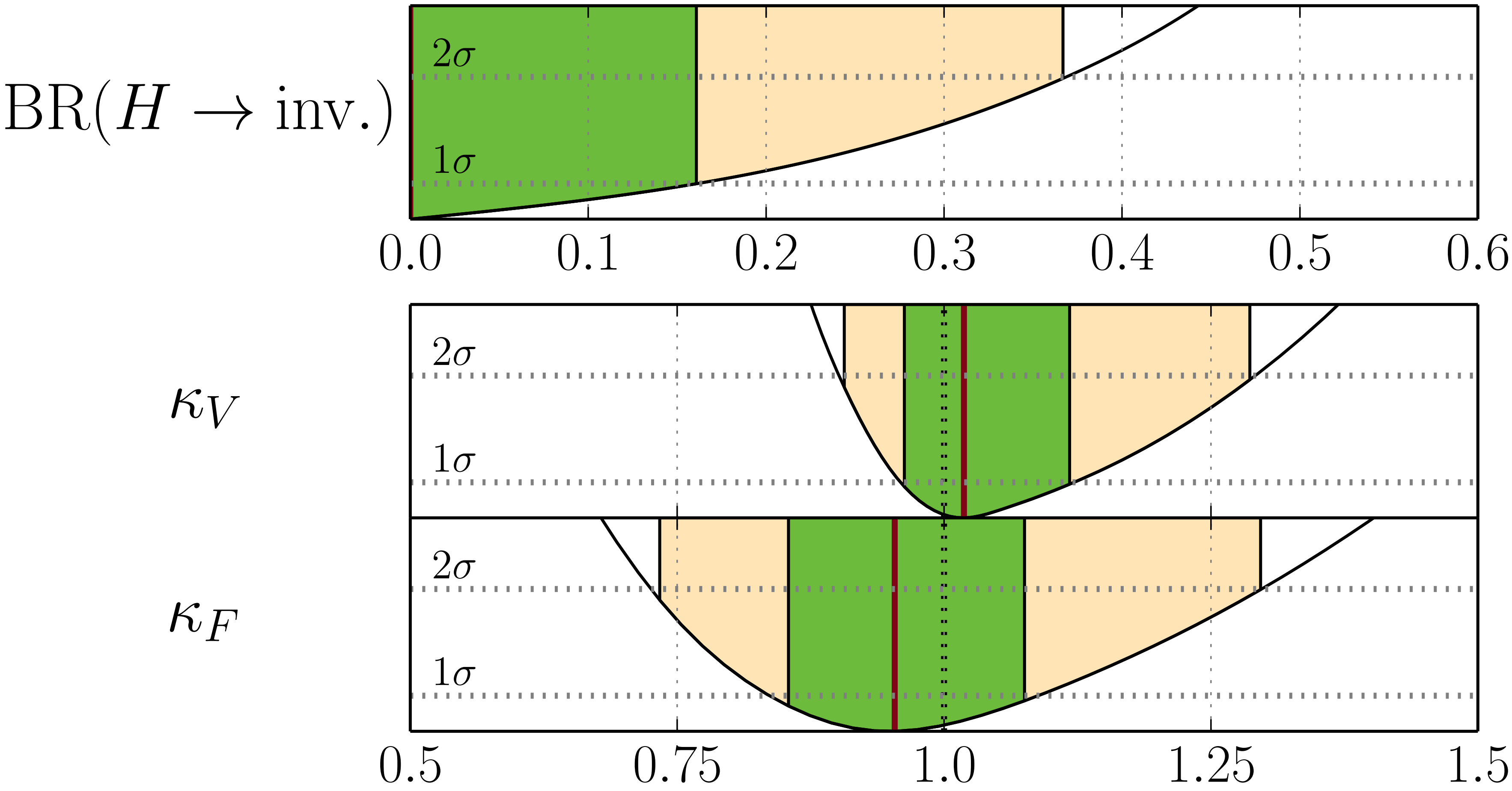


⇒ no theory assumptions on $\Gamma_{H,\text{tot}}$: no limits on κ

Coupling scale factor results (II):

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]

Another simple model: $\kappa_V, \kappa_F, \mathrm{BR}(H \to \mathrm{inv.})$



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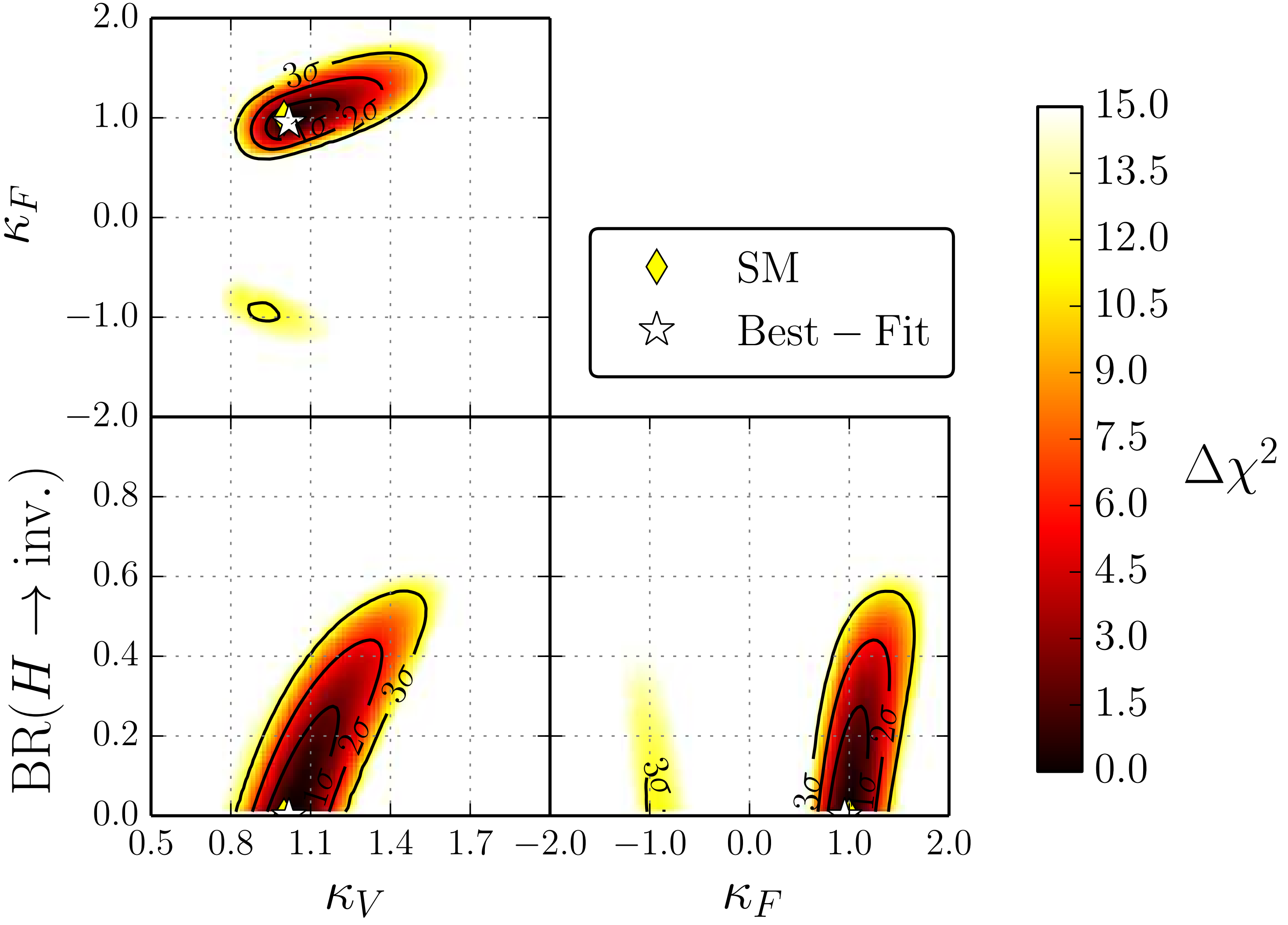

Coupling scale factor results (III):

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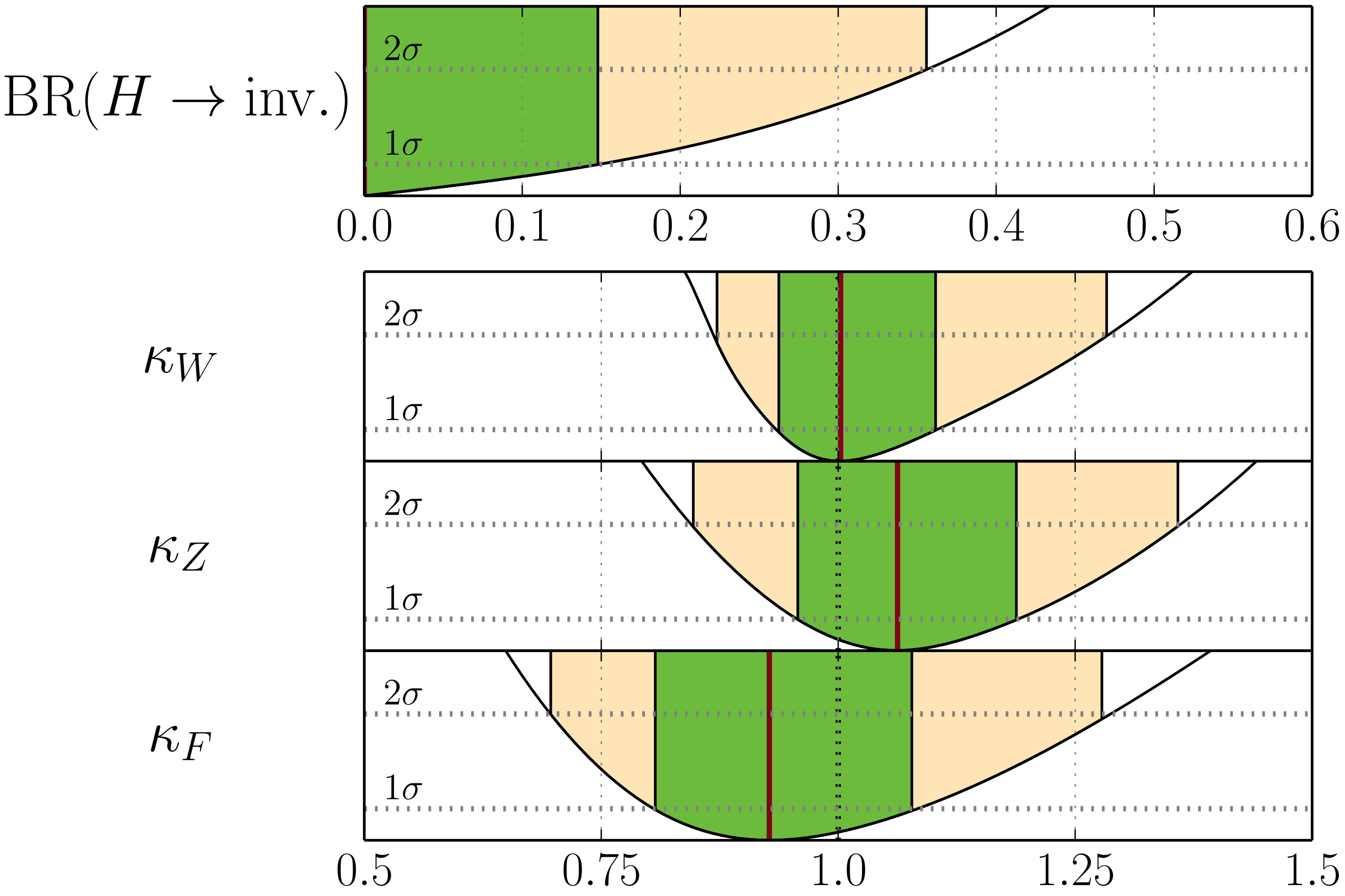
Probing the custodial symmetry: $\kappa_W, \kappa_Z, \kappa_F, \mathrm{BR}(H \to \text{inv.})$



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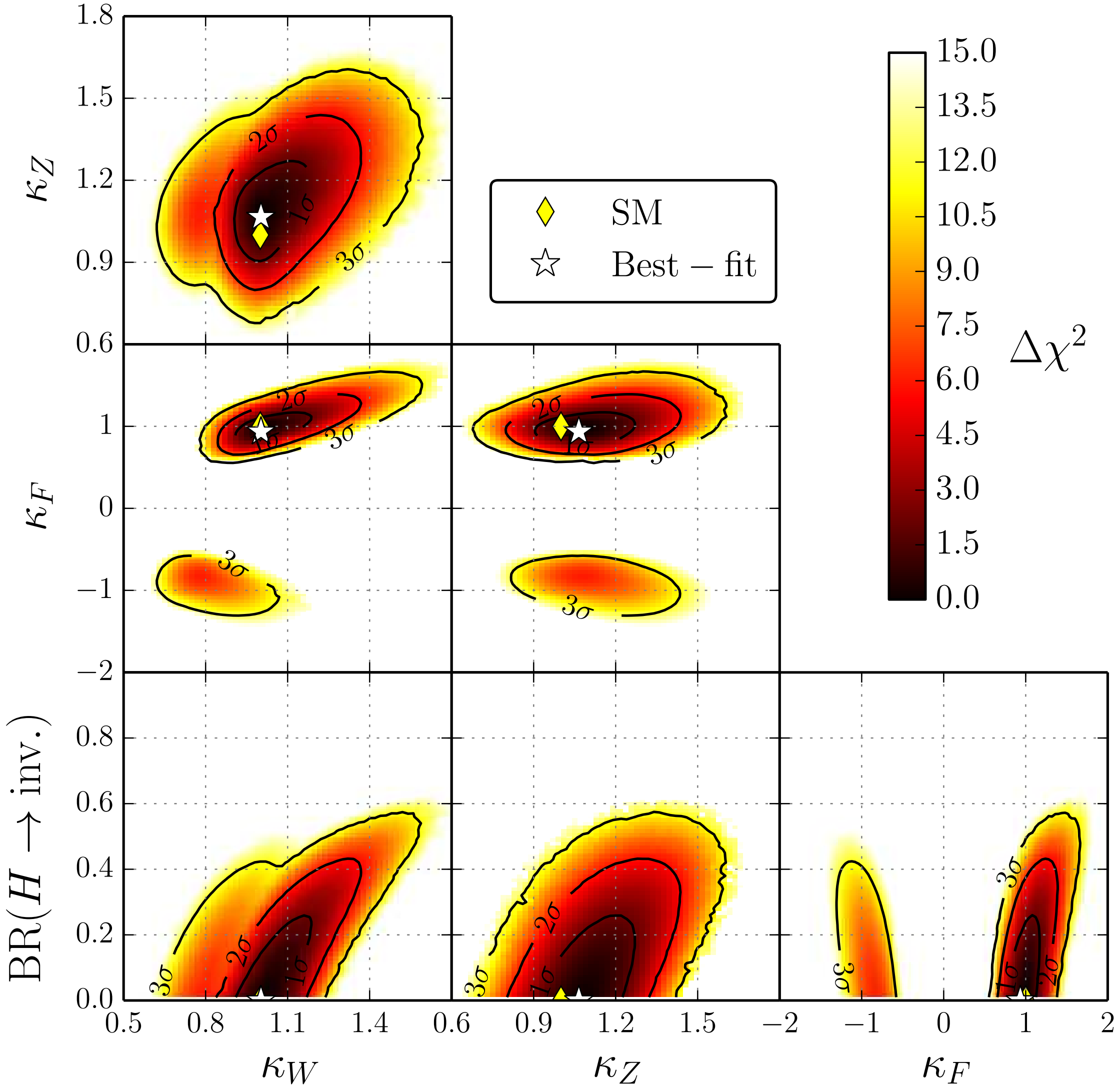

Coupling scale factor results (IV):

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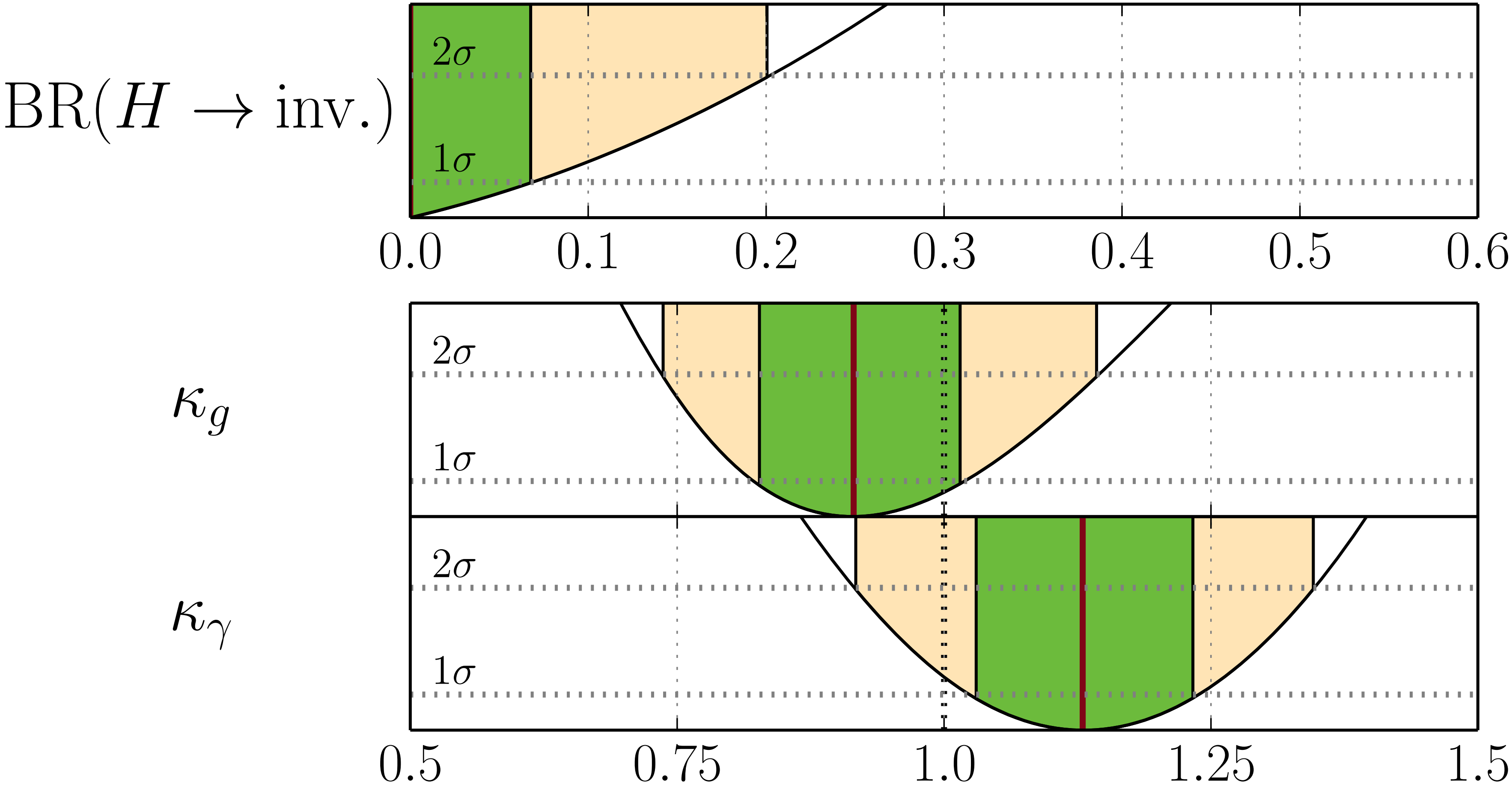
New physics in loop-induced couplings: κ_g, κ_γ, BR($H \to$ inv.)



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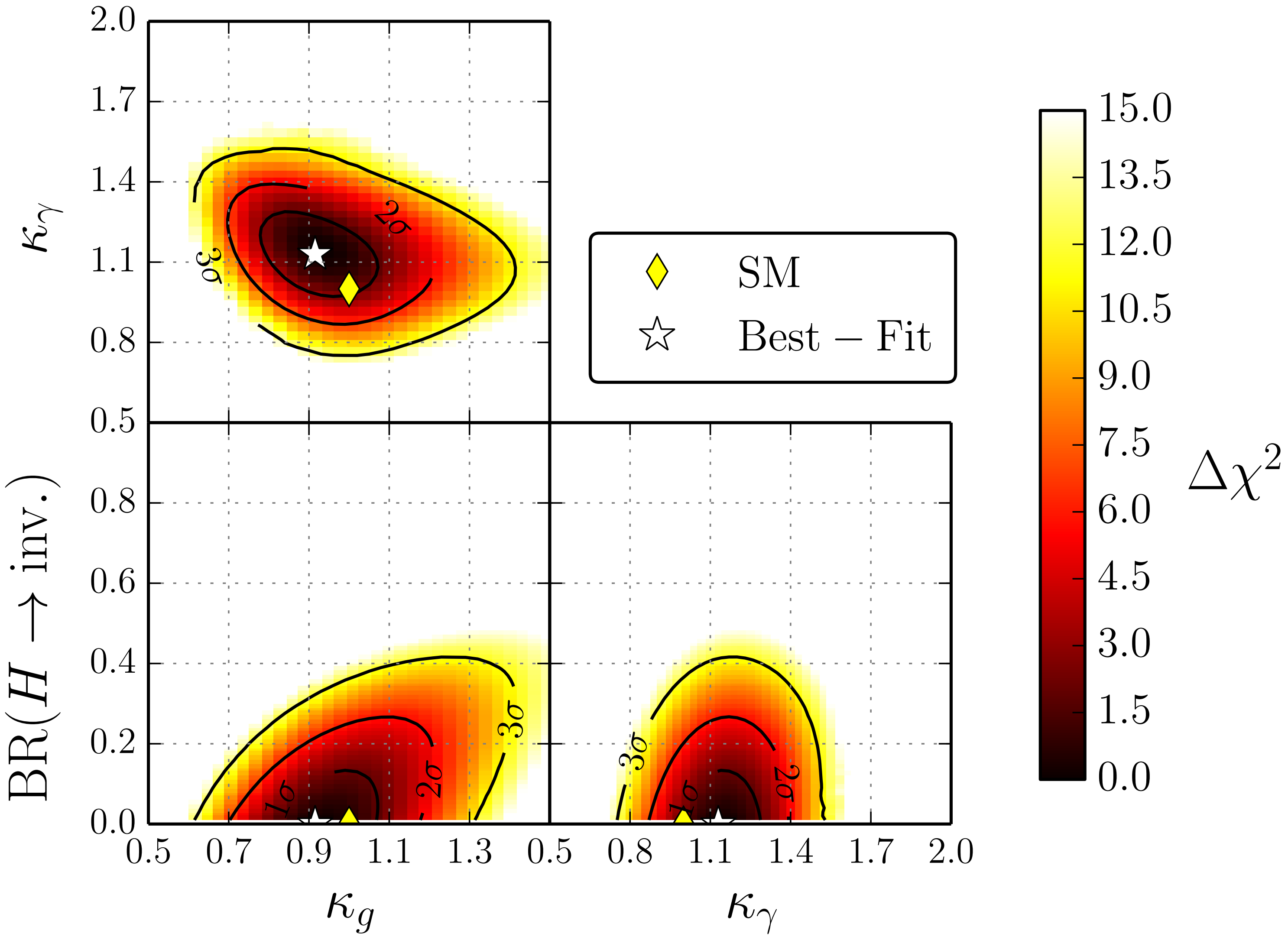
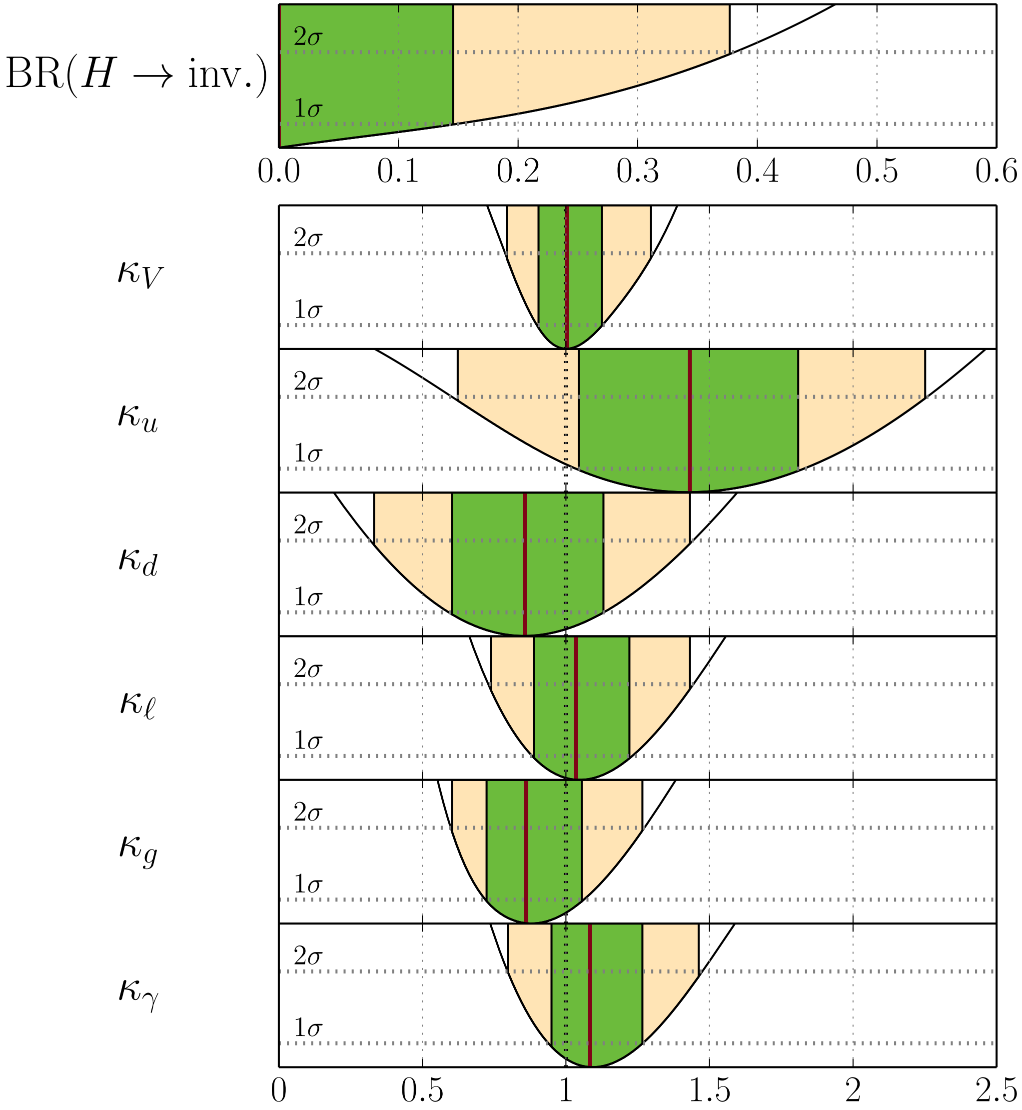


Coupling scale factor results (V):

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]

Very general model: $\kappa_V, \kappa_u, \kappa_d, \kappa_l, \kappa_g, \kappa_\gamma$, BR($H \to$ inv.)



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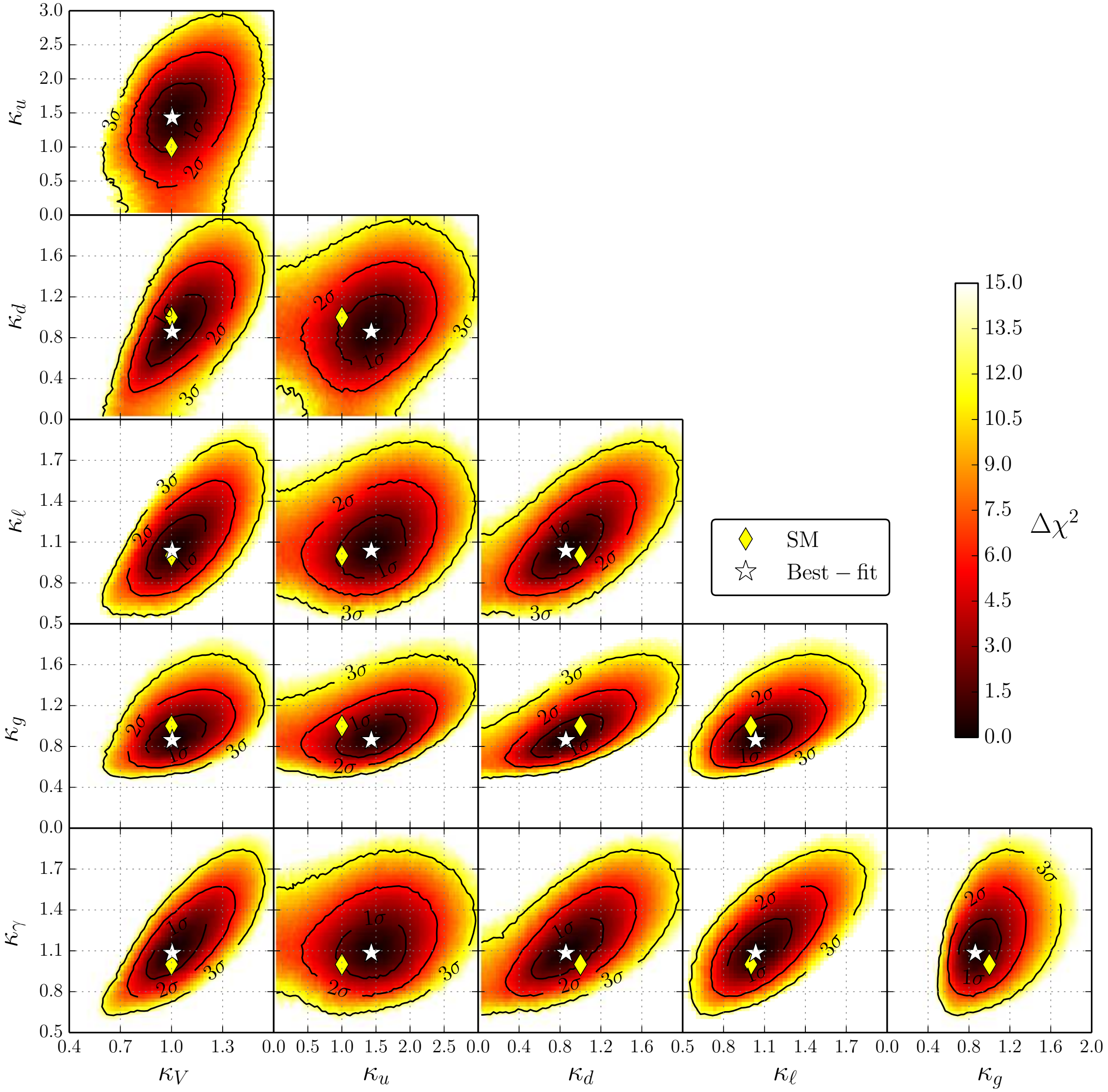

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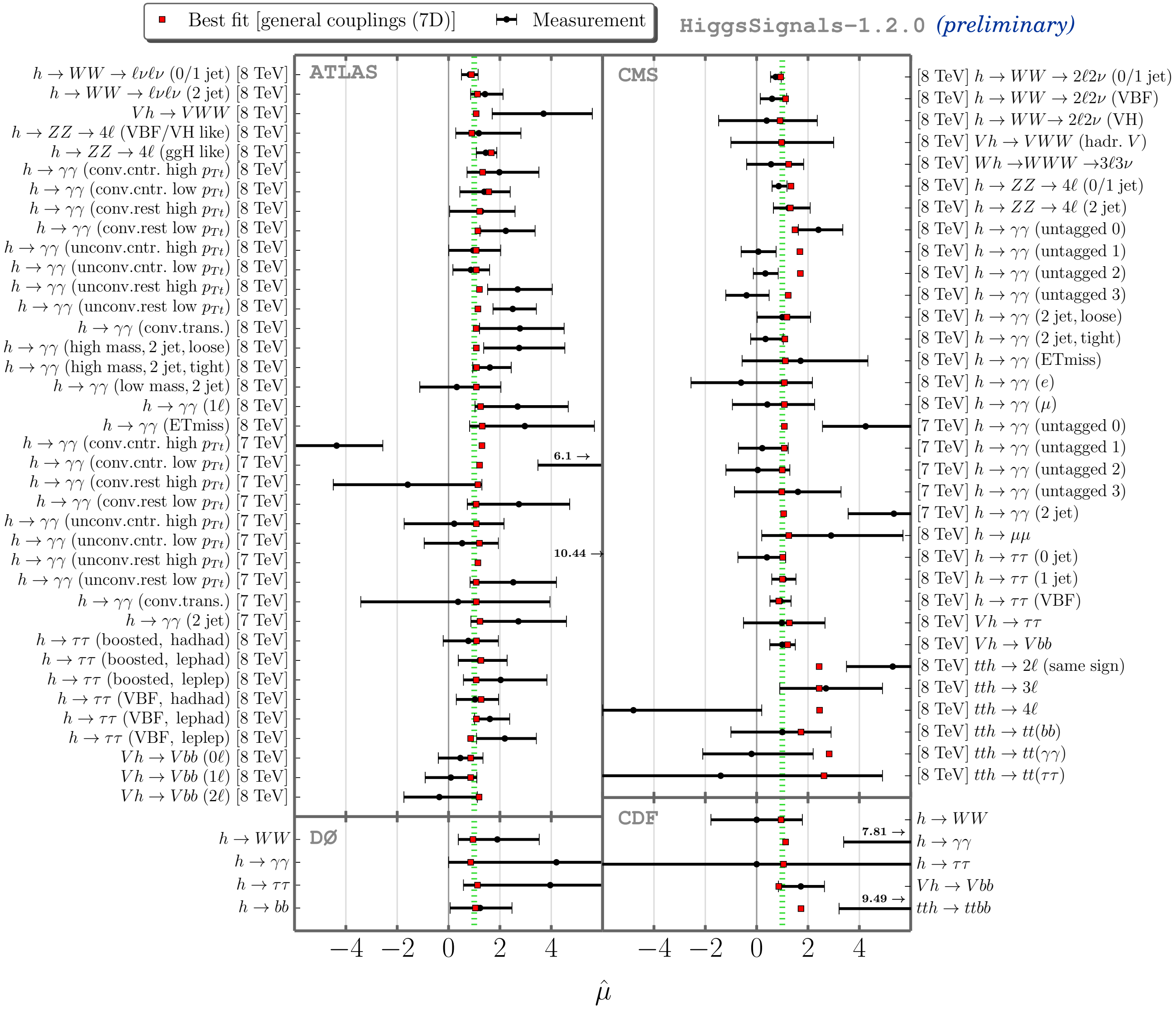
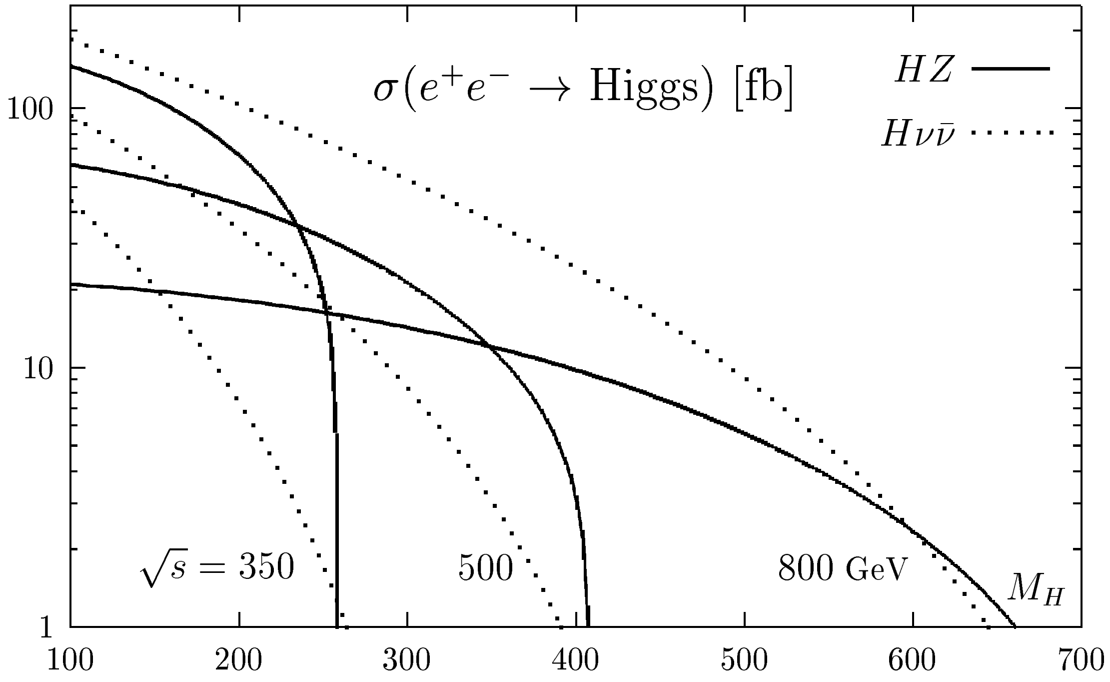


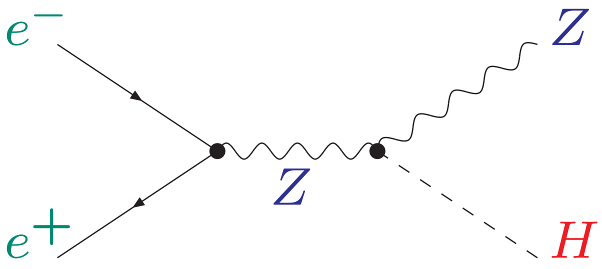
4. Higgs boson “couplings” from the ILC

Higgs production at the ILC:



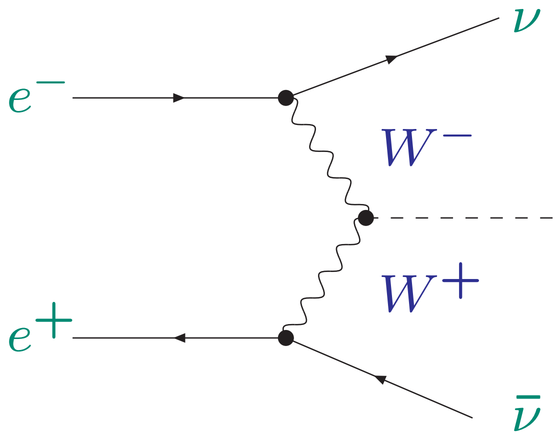
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

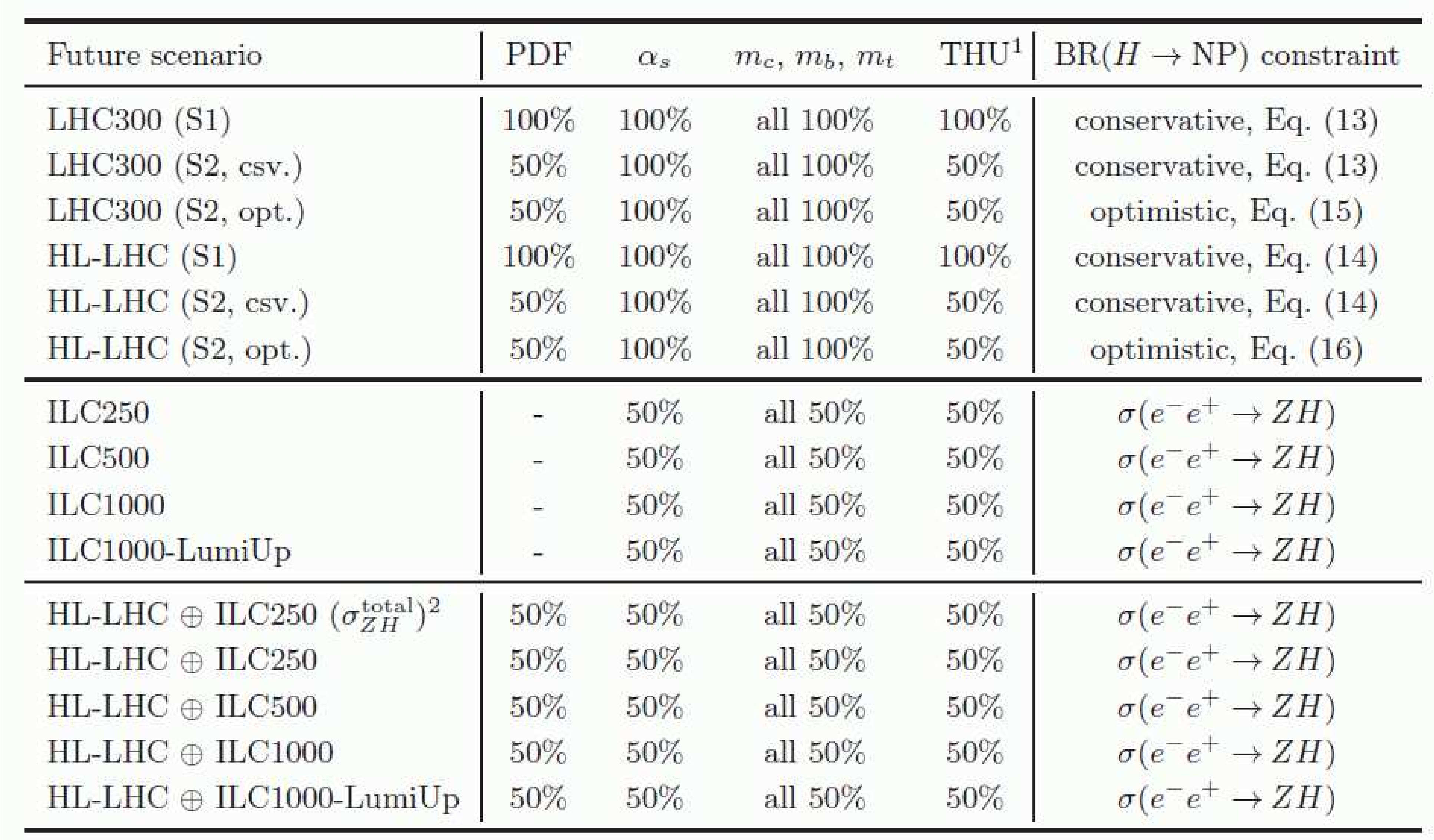
$e+e- \to \nu\bar{\nu}H$



⇒ Measurement of masses, couplings, . . . in per cent/per mille

More complete future options:

LHC300, HL-LHC, ILC250, ILC500, ILC1000, ILC1000-LumiUp

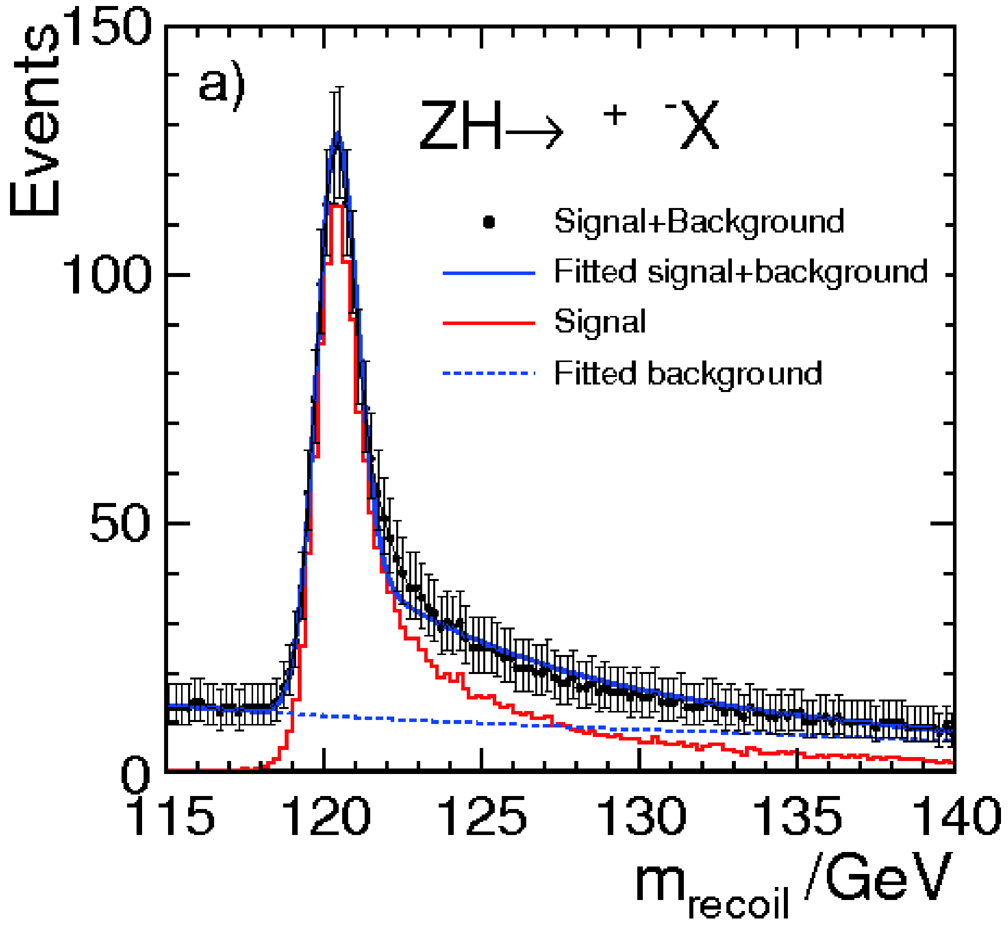


Future scenario	PDF	α_s	m_c, m_b, m_t	THU[1]	BR($H \to$ NP) constraint
LHC300 (S1)	100%	100%	all 100%	100%	conservative, Eq. (13)
LHC300 (S2, csv.)	50%	100%	all 100%	50%	conservative, Eq. (13)
LHC300 (S2, opt.)	50%	100%	all 100%	50%	optimistic, Eq. (15)
HL-LHC (S1)	100%	100%	all 100%	100%	conservative, Eq. (14)
HL-LHC (S2, csv.)	50%	100%	all 100%	50%	conservative, Eq. (14)
HL-LHC (S2, opt.)	50%	100%	all 100%	50%	optimistic, Eq. (16)
ILC250	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
ILC500	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
ILC1000	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
ILC1000-LumiUp	-	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC250 $(\sigma_{ZH}^{\text{total}})^2$	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC250	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC500	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC1000	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$
HL-LHC $\oplus$ ILC1000-LumiUp	50%	50%	all 50%	50%	$\sigma(e^-e^+ \to ZH)$

Model independent cross section measurement

[ILC TDR '13]

Z-recoil method: $e^+e^- \to ZH \to \mu^+\mu^- X$

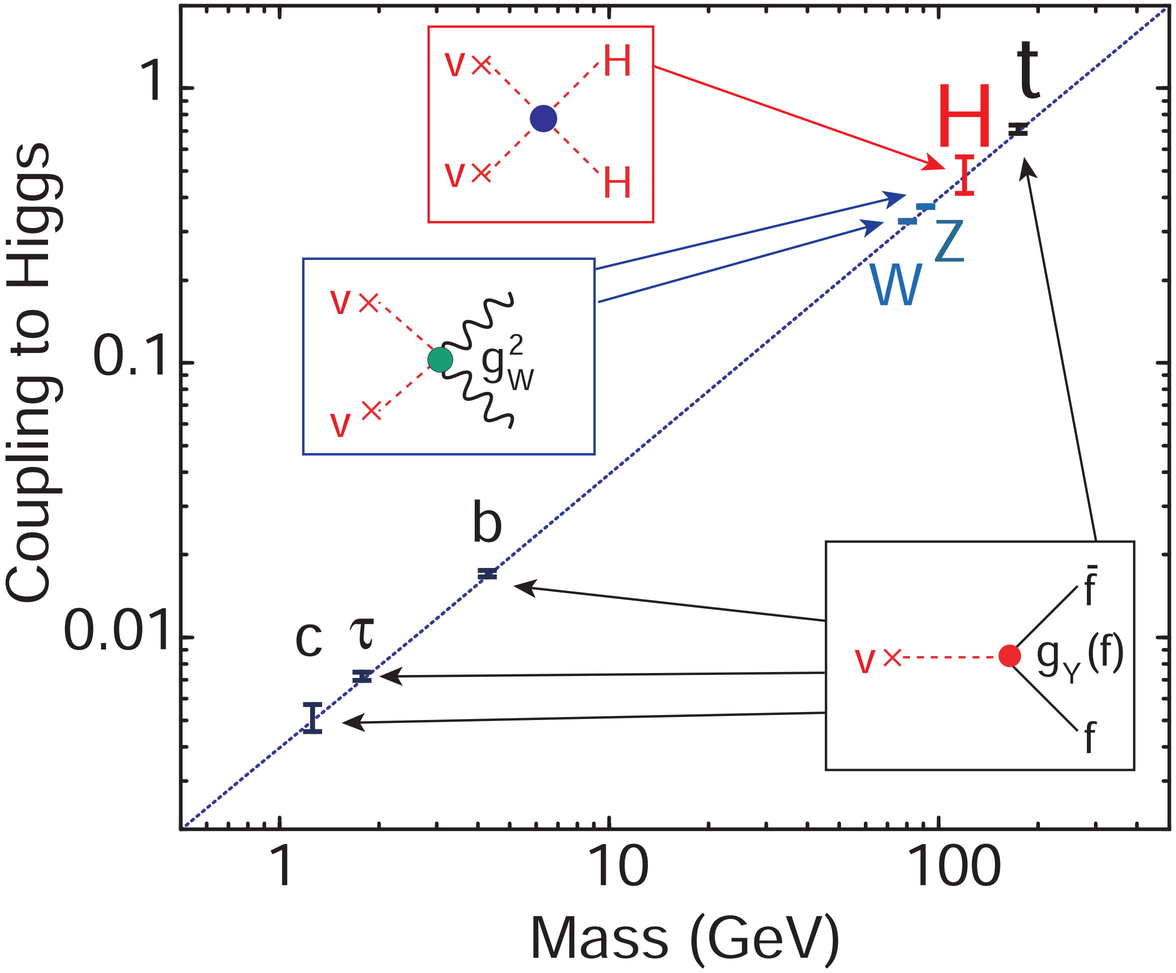


⇒ crucial for a model independent coupling measurement! $\delta M_H^{\text{exp}} \lesssim 0.05$ GeV

Higgs mechanism: mass $\propto$ coupling

[taken from K. Fuji '13]

⇒ clear, testable prediction!



⇒ ILC can test all three types!

ILC: absolute couplings, total width, invisible width, . . .

Expected precision for fermionic and gauge decay modes: [ILC TDR '13]

	$\Delta(\sigma \cdot \mathrm{BR})/(\sigma \cdot \mathrm{BR})$			$\Delta g/g$
mode	ZH @ 250 GeV (250 fb^{-1})	ZH @ 500 GeV (500 fb^{-1})	$\nu\bar{\nu}H$ @ 500 GeV (500 fb^{-1})	combined
$H \to b\bar{b}$	1.0%	1.6%	0.60%	1.3%
$H \to \tau^+\tau^-$	3.6%	4.6%	11%	1.8%
$H \to c\bar{c}$	6.9%	11%	5.2%	2.3%
$H \to gg$	8.5%	13%	5.0%	2.4%
$H \to WW^*$	8.1%	12.5%	3.0%	1.9%
$H \to ZZ^*$	26%	34%	10%	4.7%
$H \to \gamma\gamma$	23-30%	29-38%	19-5%	(13-17%)

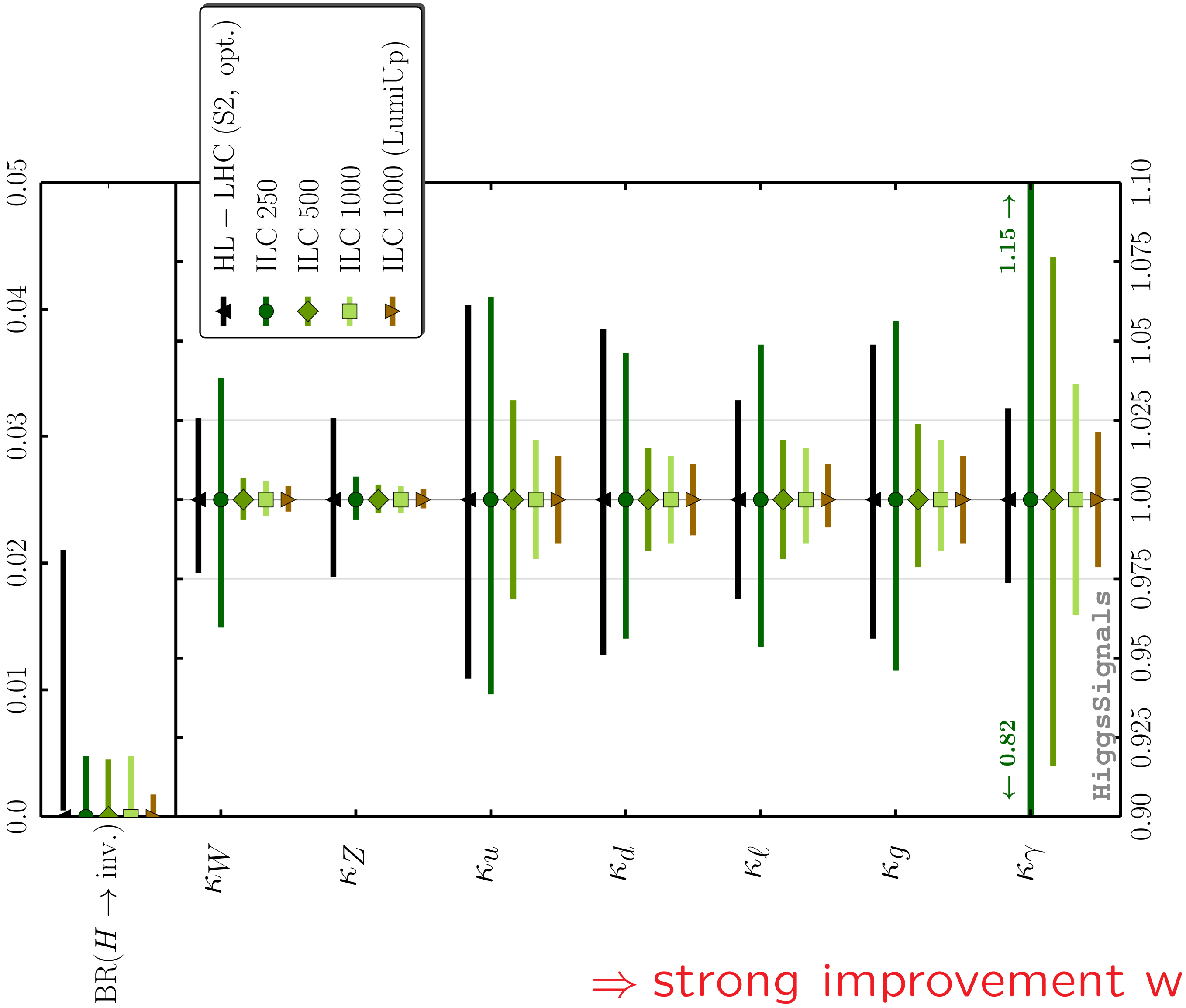
Total width: $\Delta\Gamma_H/\Gamma_H$: 4.8% – 1.2%

Invisible width: $\Delta\Gamma_{\mathrm{inv}}/\Gamma_{\mathrm{inv}}$: 0.44 – 0.26% ($\sqrt{s} = 250 - 1000$ GeV)

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

assumption: $\mathrm{BR}(H \to \mathrm{NP}) = \mathrm{BR}(H \to \mathrm{inv.})$

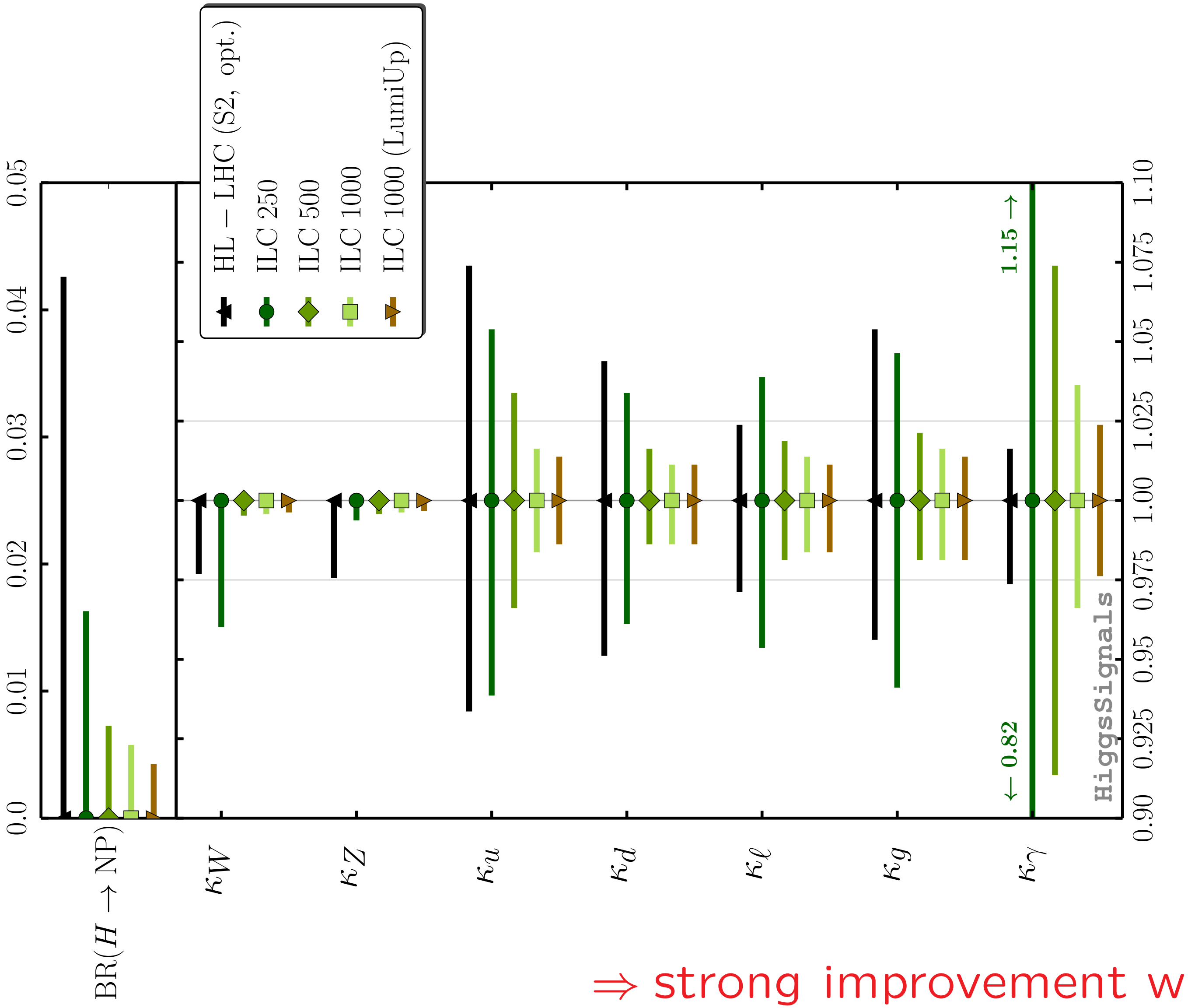


$\Rightarrow$ strong improvement with the ILC

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

assumption: $\kappa_V \leq 1$

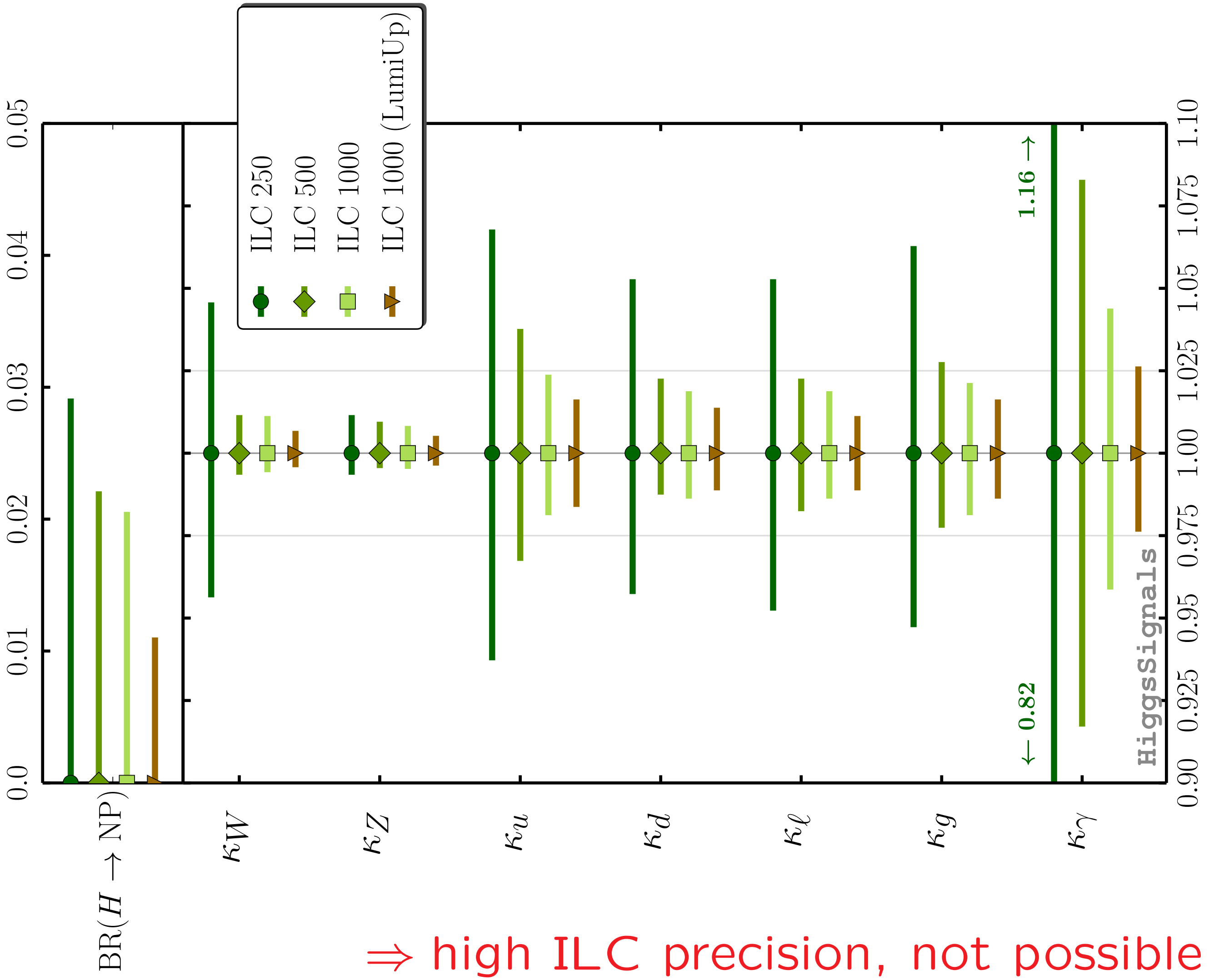


⇒ strong improvement with the ILC

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit

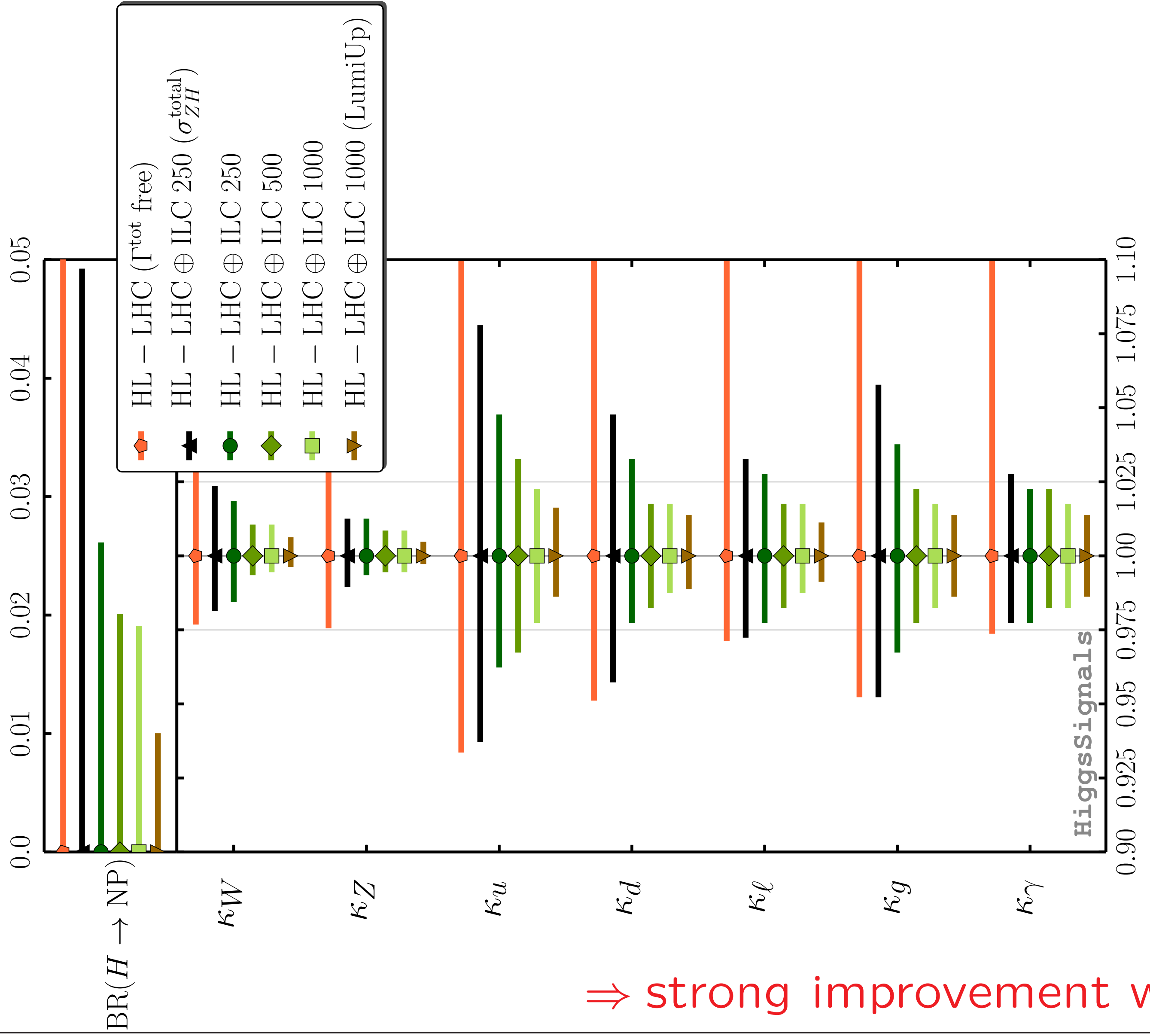


⇒ high ILC precision, not possible at the LHC

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

no theory assumptions, full fit



$\Rightarrow$ strong improvement with the ILC

5. Conclusions

- Our tool: HiggsSignals

  Tool to test theory predictions of – nearly any model
  – assuming SM-like kinematics

  against experimental data – current signal data
  – ready for future "multiple signal" data

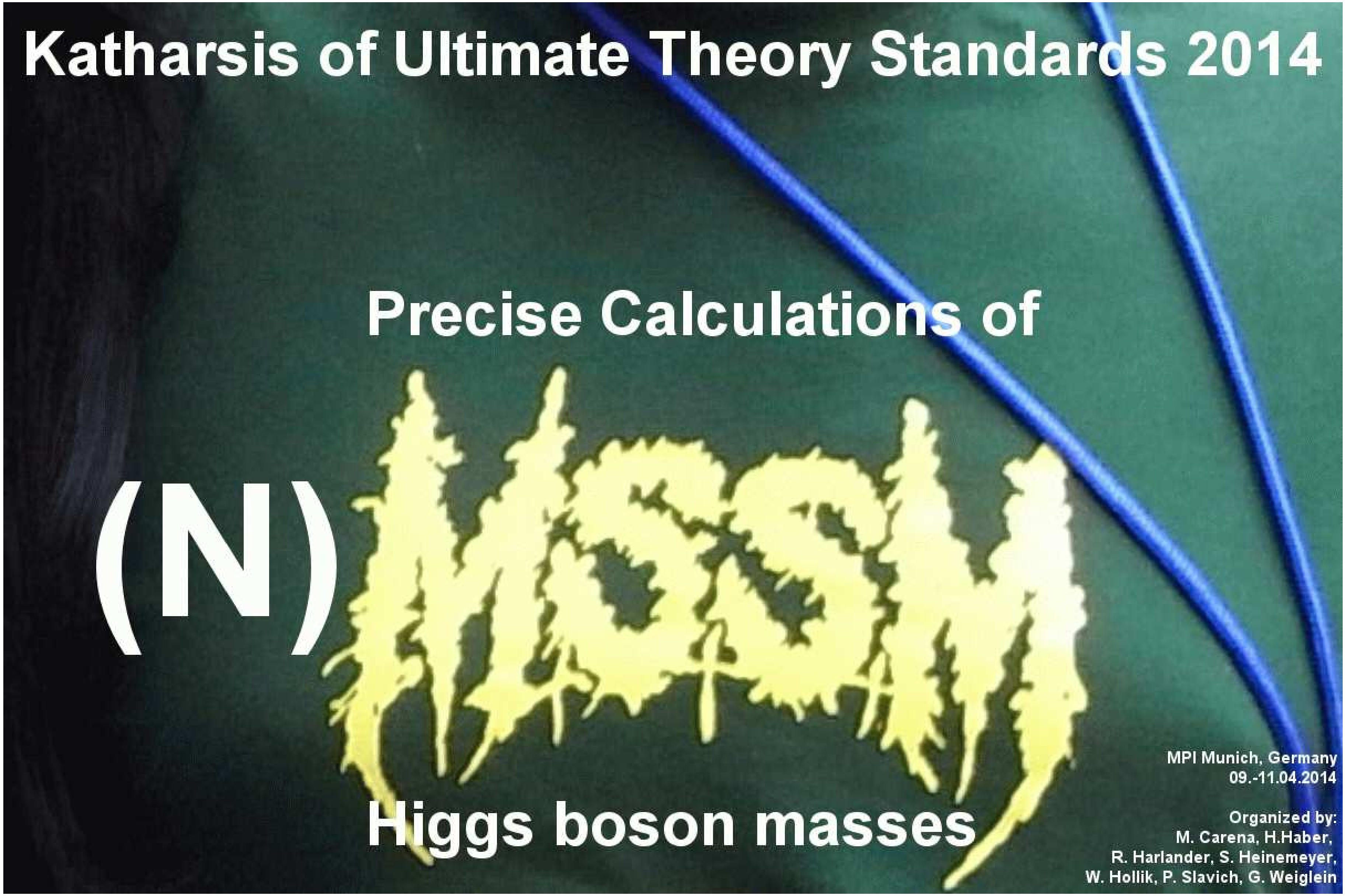
- For 2011/12 Higgs data "coupling" extraction:
  $\Rightarrow \kappa$ framework (recommended by LHCHXSWG)

- LHC data today: width assumption necessary
  κ extraction at the level of 10-20%

- LHC data future: width assumption necessary
  κ extraction (not the way to go . . .) at $\sim 3-5\%$ (most opt. case)

- ILC data: NO width assumption necessary
  κ extraction (not the way to go . . .) at $\lesssim 1\%$

Working group dedicated to SUSY Higgs mass calculations:



Katharsis of Ultimate Theory Standards 2014

Precise Calculations of

(N)MSSM

Higgs boson masses

MPI Munich, Germany
09.-11.04.2014

Organized by:
M. Carena, H.Haber,
R. Harlander, S. Heinemeyer,
W. Hollik, P. Slavich, G. Weiglein

Next meeting: 20.-22.10.2014, DESY, Hamburg, Germany