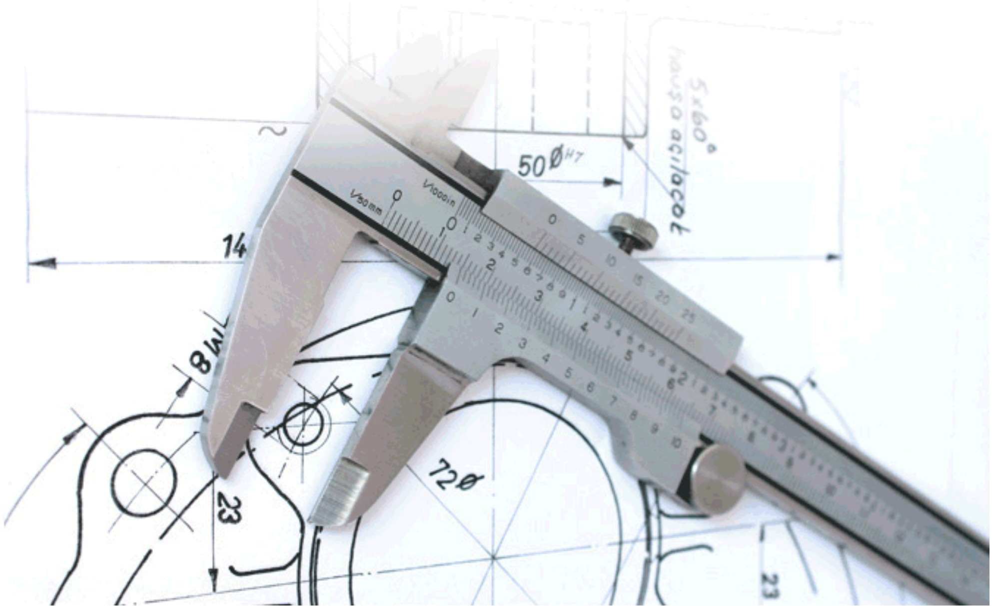


saabgroup.com

Higgs Boson Physics: Future Machines Potential

James Wells (Ann Arbor)

Higgs Hunting 2014, Paris

Higgs Boson Observables

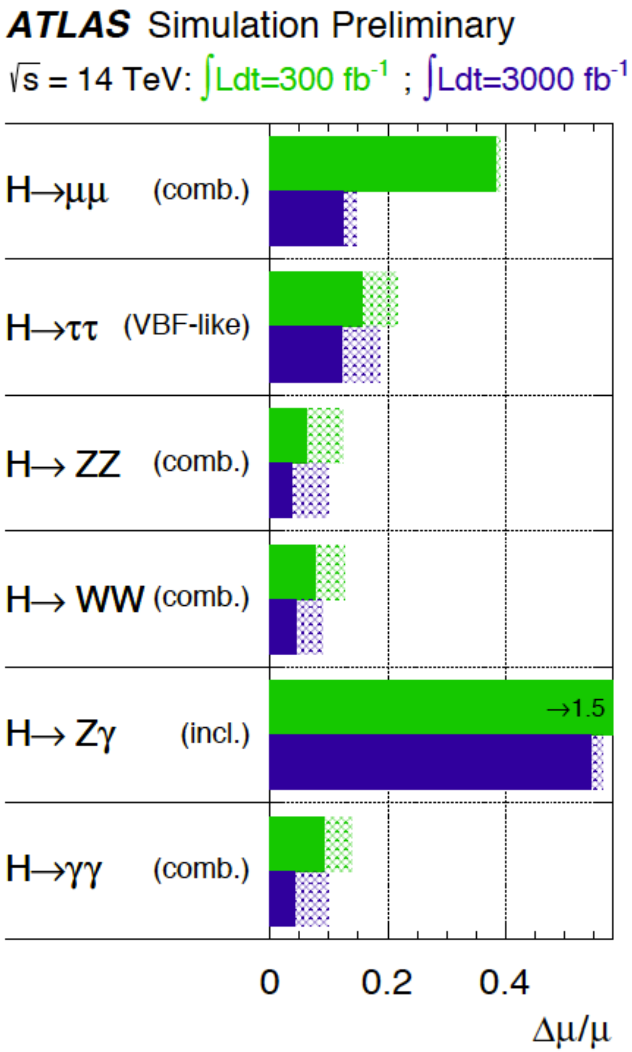
Our consideration is Higgs boson observables:

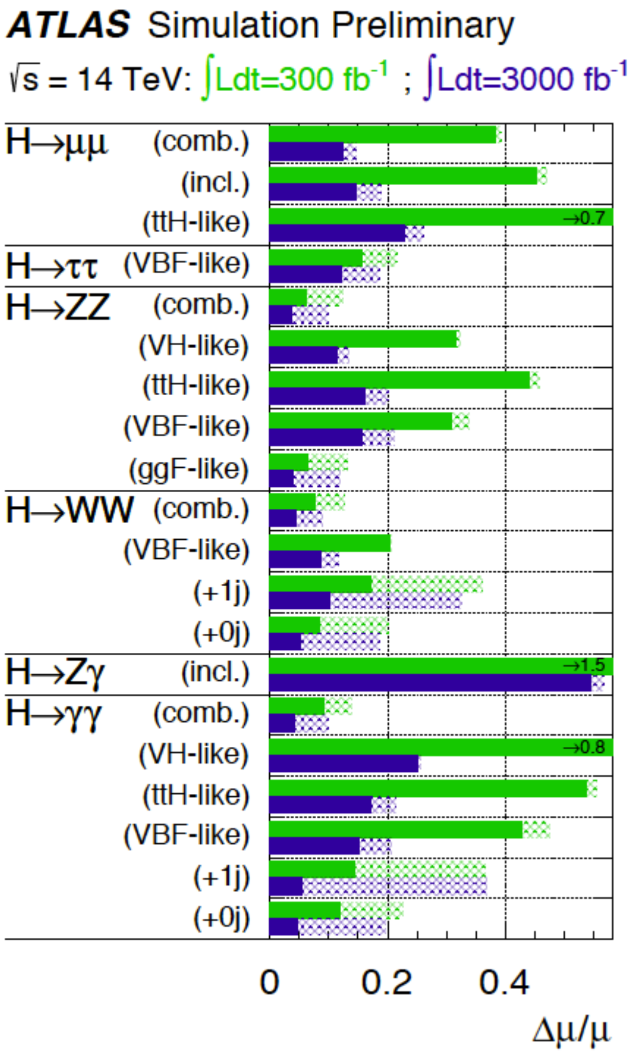
$\sigma(pp \rightarrow hX \rightarrow AB+X)$ subject to experimental cuts, which are unfolded to yield measurements.

Precise theory predictions include knowing precisely the theory predictions for

$\sigma(pp \rightarrow hX)$ and $BR(h \rightarrow AB)$

LHC-HL measurements of σ x BR





LHC-HL σ x BR determinations typically in the ten percent range. Near term LHC running expects about twice the values.

ILC σ x BR determinations

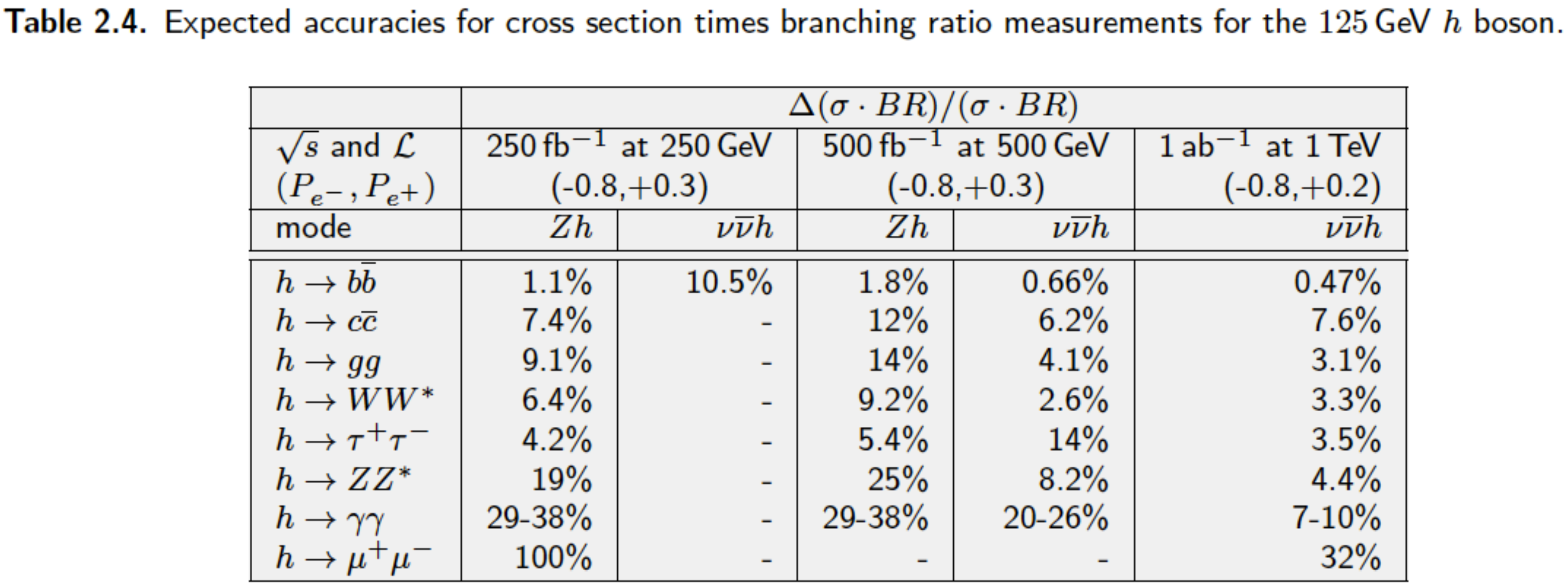


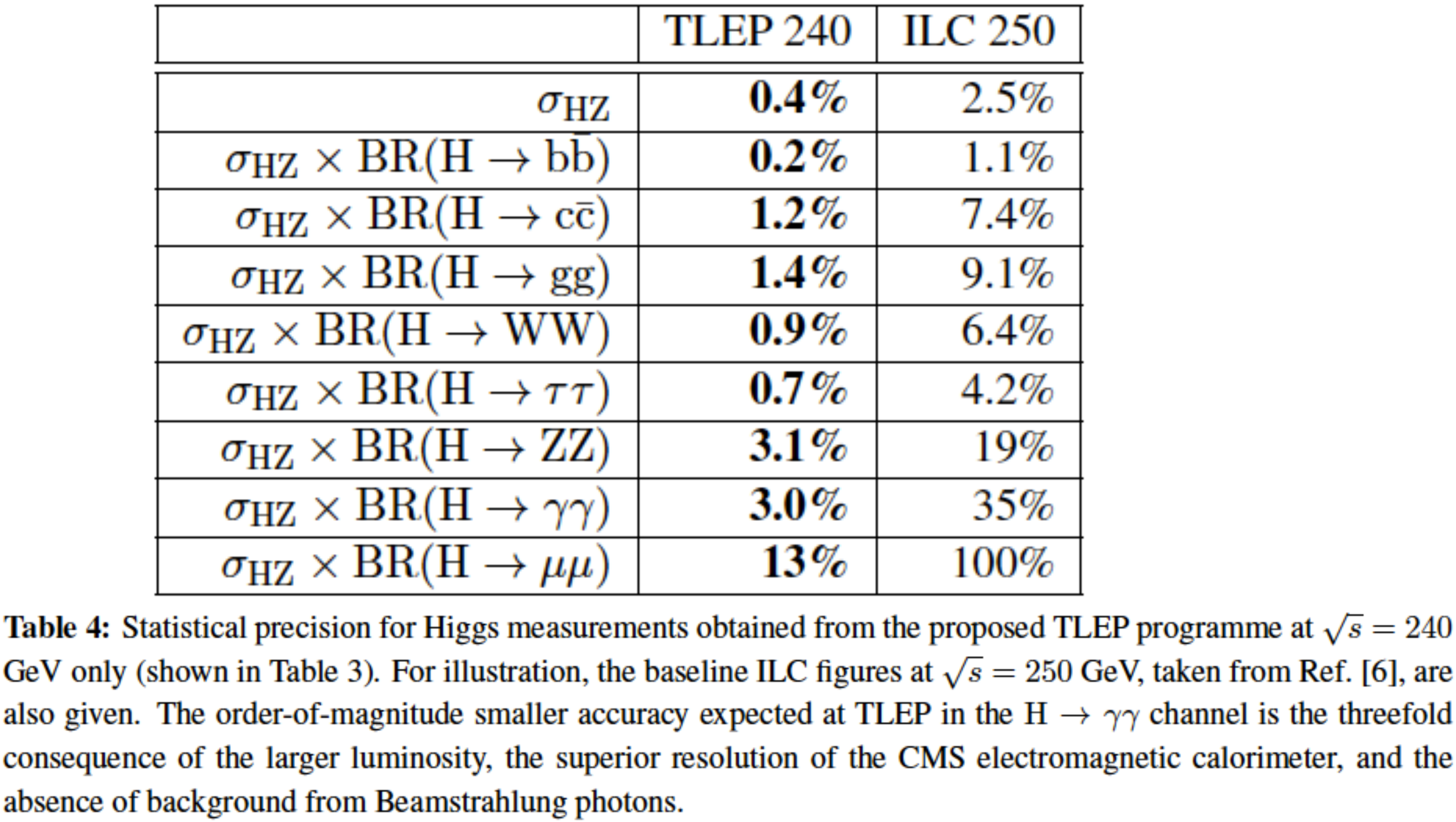
Table 2.4. Expected accuracies for cross section times branching ratio measurements for the 125 GeV h boson.

	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)		500 fb^{-1} at 500 GeV (-0.8,+0.3)		1 ab^{-1} at 1 TeV (-0.8,+0.2)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h \to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h \to gg$	9.1%	-	14%	4.1%	3.1%
$h \to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h \to \tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h \to ZZ^*$	19%	-	25%	8.2%	4.4%
$h \to \gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h \to \mu^+\mu^-$	100%	-	-	-	32%

ILC TDR 2013

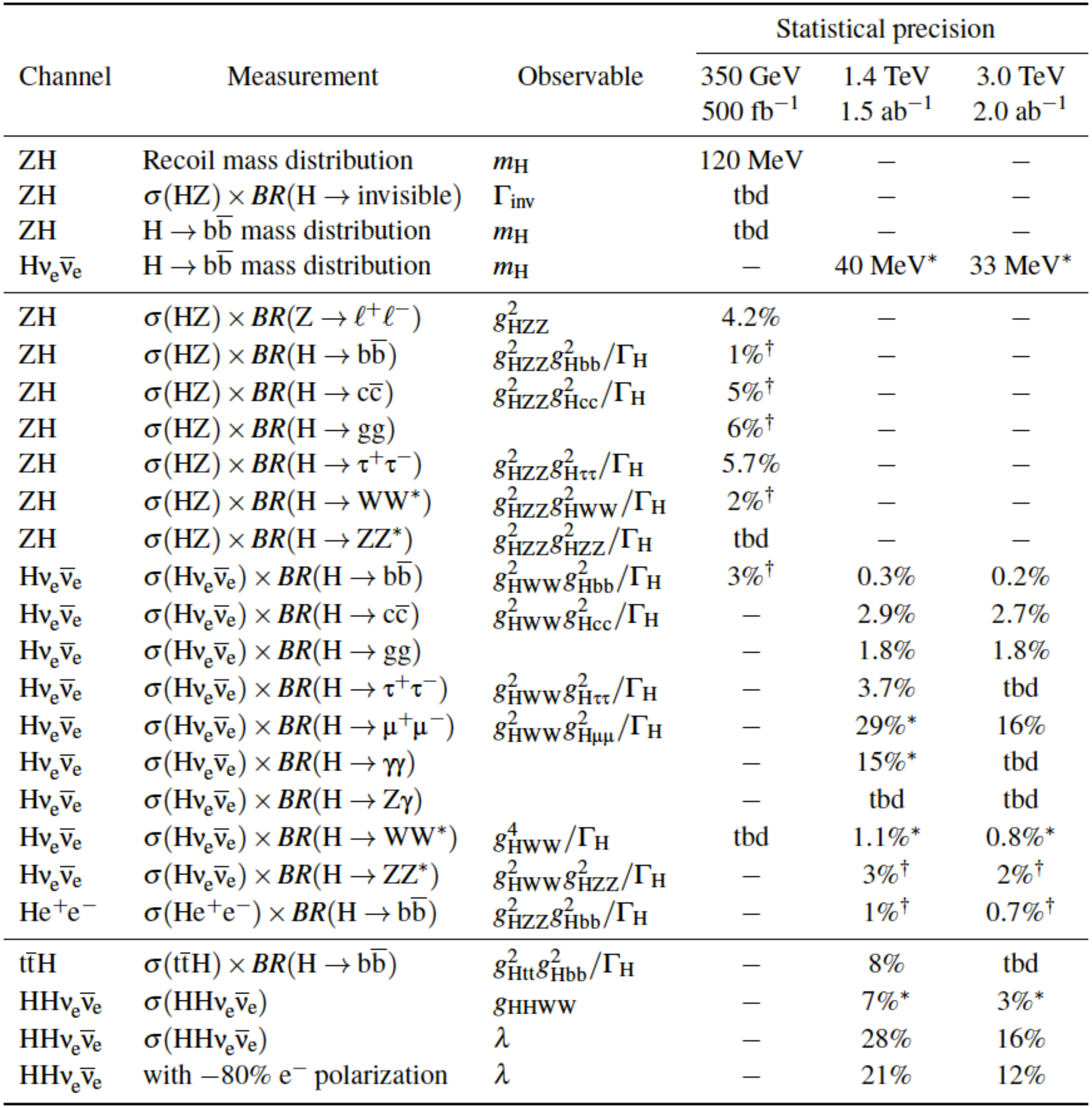
Typically in the neighborhood of a few percent.

TLEP Estimates



	$10\ ab^{-1}$	$0.25\ ab^{-1}$
	TLEP 240	ILC 250
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**	4.2%
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**	19%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**	35%
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**	100%

Table 4: Statistical precision for Higgs measurements obtained from the proposed TLEP programme at $\sqrt{s} = 240$ GeV only (shown in Table 3). For illustration, the baseline ILC figures at $\sqrt{s} = 250$ GeV, taken from Ref. [6], are also given. The order-of-magnitude smaller accuracy expected at TLEP in the H → $\gamma\gamma$ channel is the threefold consequence of the larger luminosity, the superior resolution of the CMS electromagnetic calorimeter, and the absence of background from Beamstrahlung photons.



Channel	Measurement	Observable	Statistical precision		
			350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow \text{invisible})$	Γ_{inv}	tbd	–	–
ZH	$H \rightarrow b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \rightarrow b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \rightarrow \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	5.7%	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \rightarrow ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	3%†	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	3.7%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	29%*	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \gamma\gamma)$		–	15%*	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow Z\gamma)$		–	tbd	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow WW^*)$	g^4_{HWW}/Γ_H	tbd	1.1%*	0.8%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \rightarrow b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \rightarrow b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	28%	16%
$HH\nu_e\bar{\nu}_e$	with −80% e^- polarization	λ	–	21%	12%

CLIC Sensitivity

Snowmass
2013 Report

Theory Issues

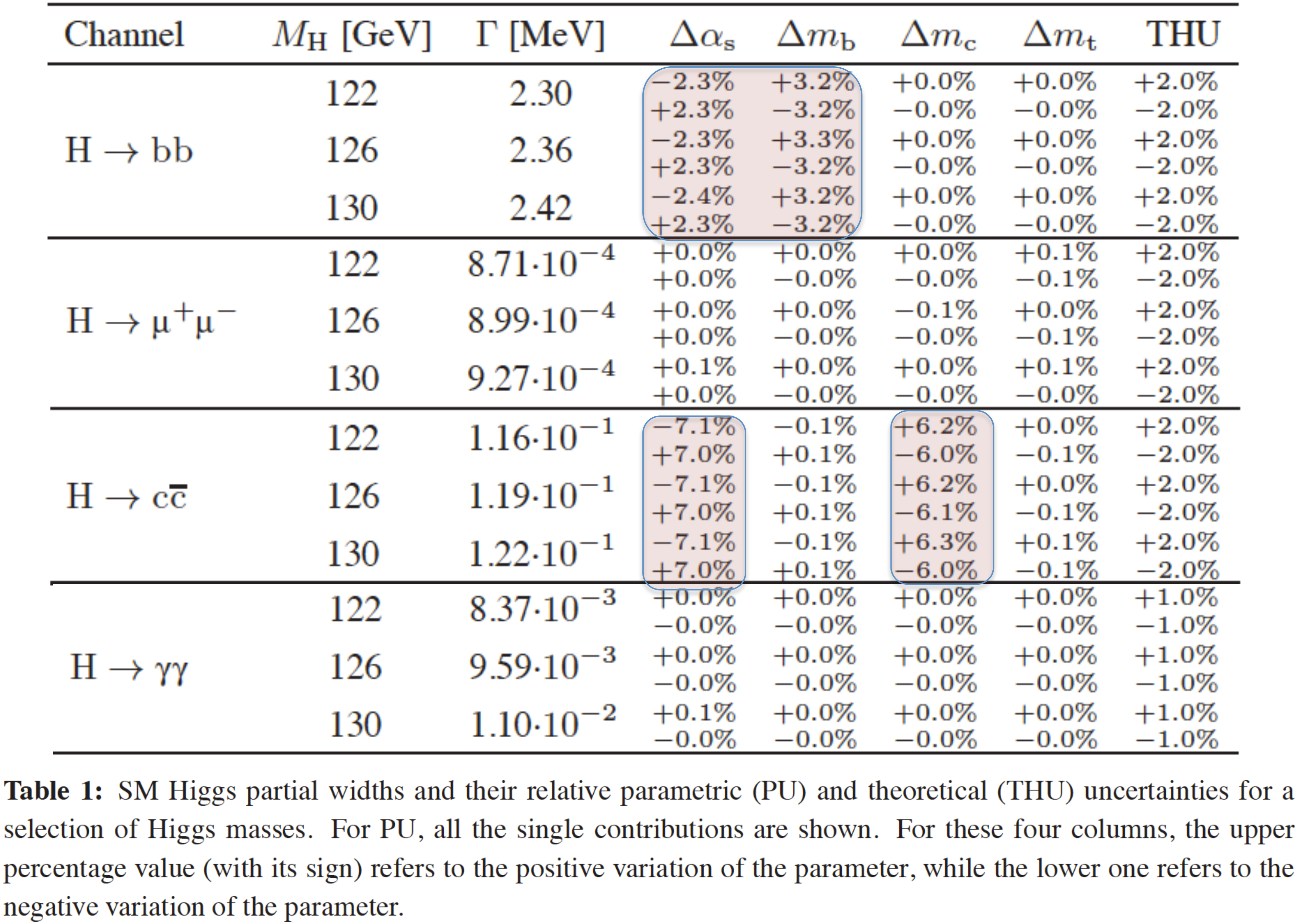
We shall come to new physics soon.

However, SM theory errors threaten the usefulness of percent-level Higgs measurements.

For example, measurements of σ x Br(bb) is at percent level or lower at ILC, TLEP and CLIC.

Errors at few percent level, relevant to LHC-HL, also need attention.

Tremendous work going into this.



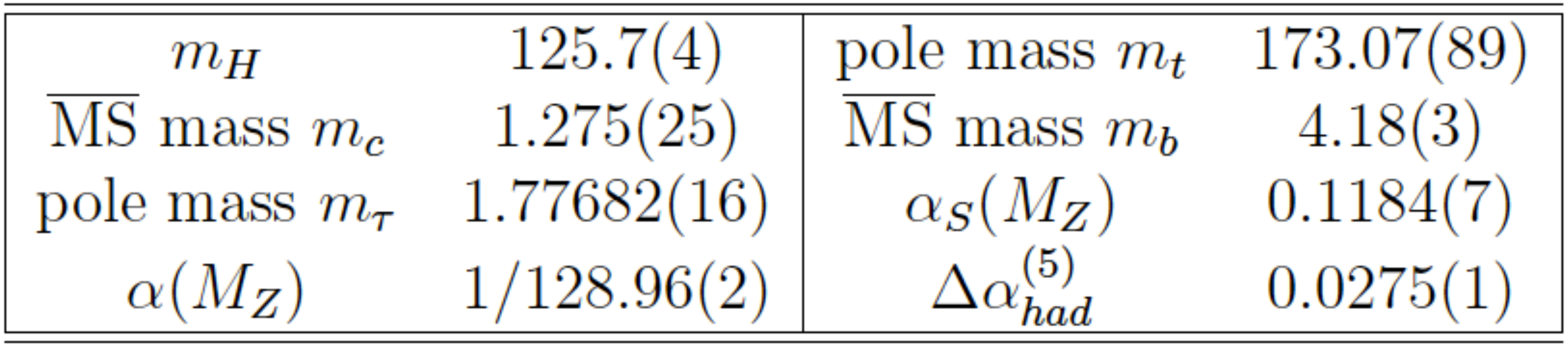
Channel	M_H [GeV]	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
H → bb	122	2.30	−2.3% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
	126	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
	130	2.42	−2.4% +2.3%	+3.2% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
H → $\mu^+\mu^-$	122	$8.71{\cdot}10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
	126	$8.99{\cdot}10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%
	130	$9.27{\cdot}10^{-4}$	+0.1% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.0%	+2.0% −2.0%
H → $c\bar{c}$	122	$1.16{\cdot}10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.2% −6.0%	+0.0% −0.1%	+2.0% −2.0%
	126	$1.19{\cdot}10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%
	130	$1.22{\cdot}10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.3% −6.0%	+0.1% −0.1%	+2.0% −2.0%
H → γγ	122	$8.37{\cdot}10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
	126	$9.59{\cdot}10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
	130	$1.10{\cdot}10^{-2}$	+0.1% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%

Table 1: SM Higgs partial widths and their relative parametric (PU) and theoretical (THU) uncertainties for a selection of Higgs masses. For PU, all the single contributions are shown. For these four columns, the upper percentage value (with its sign) refers to the positive variation of the parameter, while the lower one refers to the negative variation of the parameter.

Handbook of LHC Higgs Cross Sections. 3. Higgs Properties (2013)

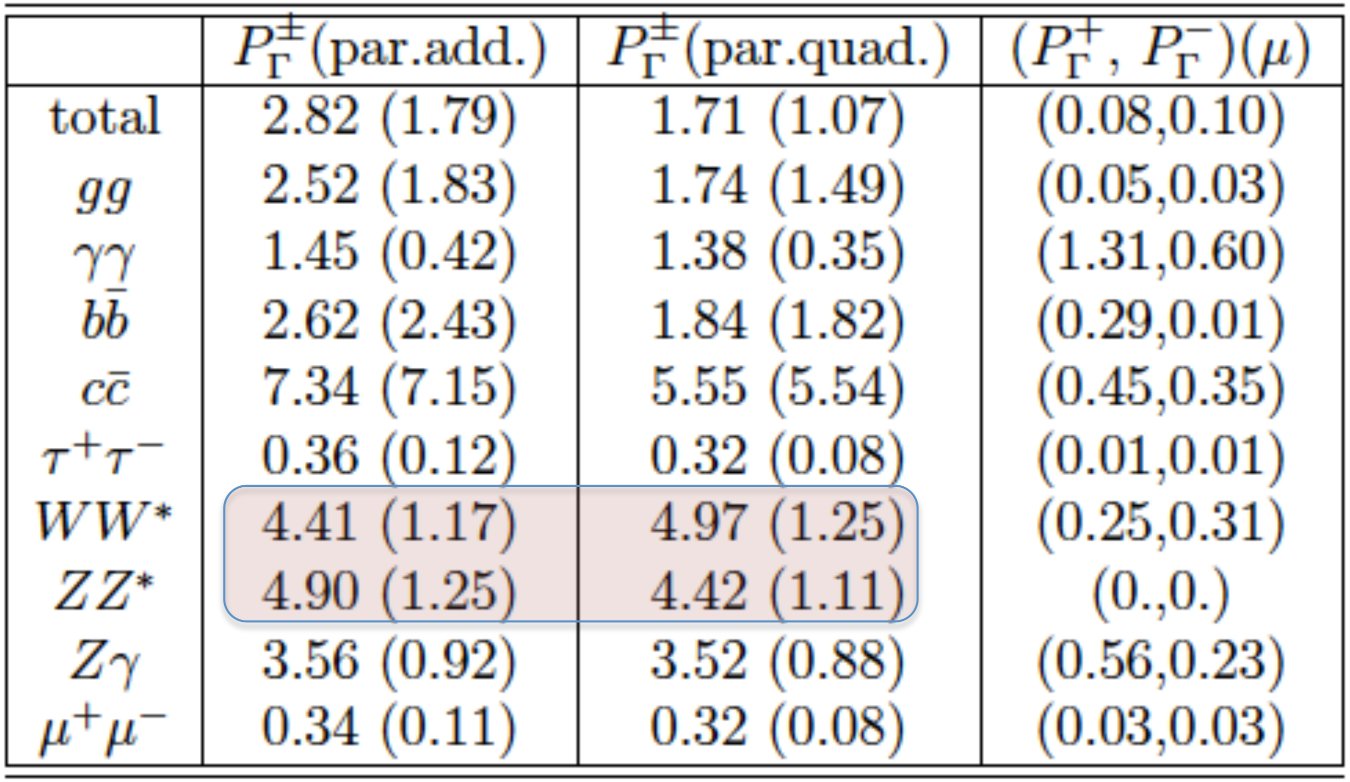
Calculating Higgs boson partial widths and branching fractions is an exercise in precision SM analysis.

Specifying the input observables and their uncertainties translates into central values and errors on Higgs partial widths and BRs.



m_H	125.7(4)	pole mass m_t	173.07(89)
$\overline{\mathrm{MS}}$ mass m_c	1.275(25)	$\overline{\mathrm{MS}}$ mass m_b	4.18(3)
pole mass m_τ	1.77682(16)	$\alpha_S(M_Z)$	0.1184(7)
$\alpha(M_Z)$	1/128.96(2)	$\Delta\alpha_{had}^{(5)}$	0.0275(1)

Almeida, Lee, Pokorski, JW 2013



	$P_\Gamma^\pm$(par.add.)	$P_\Gamma^\pm$(par.quad.)	$(P_\Gamma^+, P_\Gamma^-)(\mu)$
total	2.82 (1.79)	1.71 (1.07)	(0.08,0.10)
gg	2.52 (1.83)	1.74 (1.49)	(0.05,0.03)
$\gamma\gamma$	1.45 (0.42)	1.38 (0.35)	(1.31,0.60)
$b\bar{b}$	2.62 (2.43)	1.84 (1.82)	(0.29,0.01)
$c\bar{c}$	7.34 (7.15)	5.55 (5.54)	(0.45,0.35)
$\tau^+\tau^-$	0.36 (0.12)	0.32 (0.08)	(0.01,0.01)
WW^*	4.41 (1.17)	4.97 (1.25)	(0.25,0.31)
ZZ^*	4.90 (1.25)	4.42 (1.11)	(0.,0.)
$Z\gamma$	3.56 (0.92)	3.52 (0.88)	(0.56,0.23)
$\mu^+\mu^-$	0.34 (0.11)	0.32 (0.08)	(0.03,0.03)

Percent relative uncertainty on the partial widths from parametric and scale-dependence uncertainties. WW, ZZ uncertainties mainly due to Δm_H.

Almeida, Lee, Pokorski, JW 2013

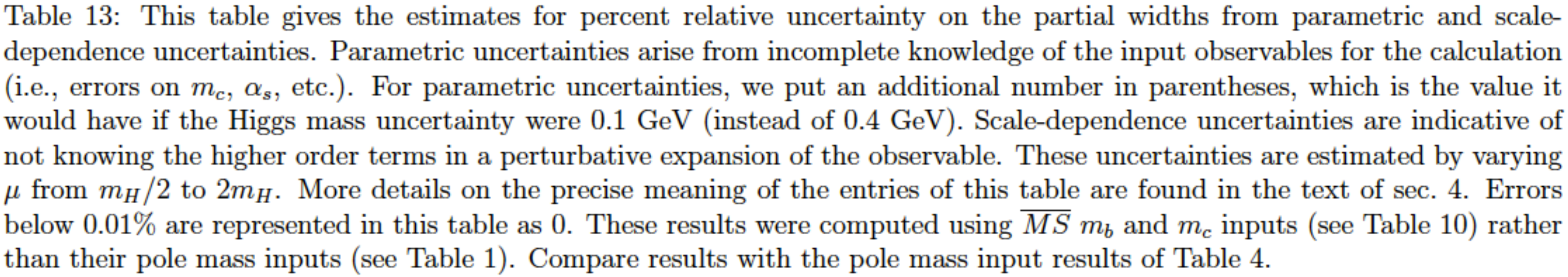
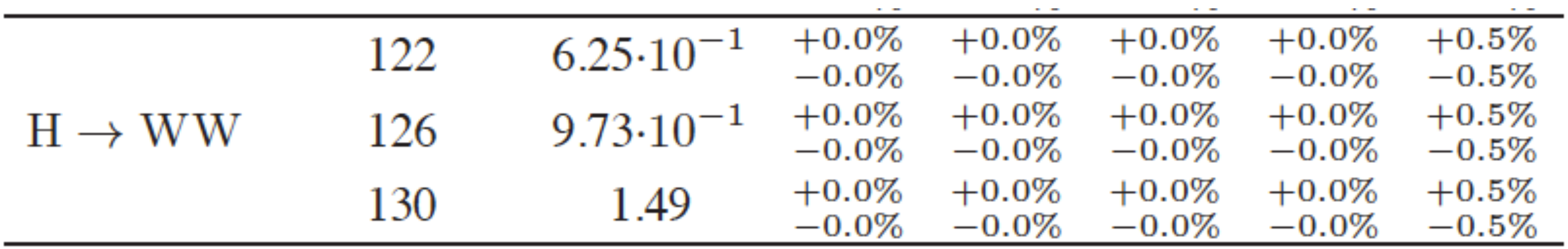


Table 13: This table gives the estimates for percent relative uncertainty on the partial widths from parametric and scale-dependence uncertainties. Parametric uncertainties arise from incomplete knowledge of the input observables for the calculation (i.e., errors on m_c, α_s, etc.). For parametric uncertainties, we put an additional number in parentheses, which is the value it would have if the Higgs mass uncertainty were 0.1 GeV (instead of 0.4 GeV). Scale-dependence uncertainties are indicative of not knowing the higher order terms in a perturbative expansion of the observable. These uncertainties are estimated by varying μ from $m_H/2$ to $2m_H$. More details on the precise meaning of the entries of this table are found in the text of sec. 4. Errors below 0.01% are represented in this table as 0. These results were computed using $\overline{MS}$ m_b and m_c inputs (see Table 10) rather than their pole mass inputs (see Table 1). Compare results with the pole mass input results of Table 4.

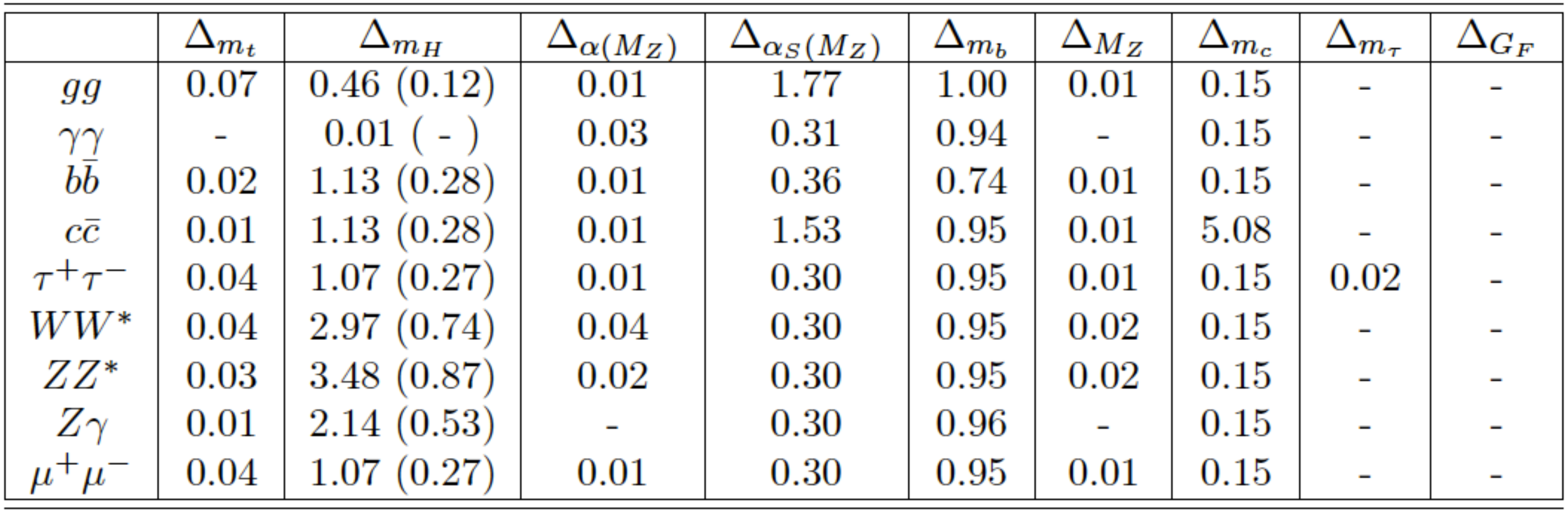
Compare this with LHC Cross Sections Handbook, which upon first look appears to have little uncertainty on H→WW.

BR



$H \to WW$	122	$6.25 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$
	126	$9.73 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$
	130	1.49	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.0\%}_{-0.0\%}$	$^{+0.5\%}_{-0.5\%}$

There is no mistake in table. Each row is for fixed m_H. But notice how strongly the BR changes from 122 to 126 to 130 GeV.



	Δ_{m_t}	Δ_{m_H}	$\Delta_{\alpha(M_Z)}$	$\Delta_{\alpha_S(M_Z)}$	Δ_{m_b}	Δ_{M_Z}	Δ_{m_c}	Δ_{m_τ}	Δ_{G_F}
gg	0.07	0.46 (0.12)	0.01	1.77	1.00	0.01	0.15	-	-
$\gamma\gamma$	-	0.01 (-)	0.03	0.31	0.94	-	0.15	-	-
$b\bar{b}$	0.02	1.13 (0.28)	0.01	0.36	0.74	0.01	0.15	-	-
$c\bar{c}$	0.01	1.13 (0.28)	0.01	1.53	0.95	0.01	5.08	-	-
$\tau^+\tau^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	0.02	-
WW^*	0.04	2.97 (0.74)	0.04	0.30	0.95	0.02	0.15	-	-
ZZ^*	0.03	3.48 (0.87)	0.02	0.30	0.95	0.02	0.15	-	-
$Z\gamma$	0.01	2.14 (0.53)	-	0.30	0.96	-	0.15	-	-
$\mu^+\mu^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	-	-

Almeida, Lee, Pokorski, JW 2013

Uncertainties on the branching fractions due to uncertainties in the input observables.

Note, due to Γ(bb) in the denominator of all BRs, the uncertainties due to m_b and α_s propagate to all others.

In Higgs column, uncertainty is due to Δm_H=400 MeV (100 MeV)

Reducing Uncertainties in Γs and BRs

Reducing the uncertainties in extracted m_b and m_c MSbar masses (or the equivalent) are needed to reduce uncertainties in theory calculations.

Likewise for α_s and m_H.

The precision Higgs program is just as well stated as a precision m_b , m_c , α_s and m_H program.

α_s and m_H seem easier to improve than m_b and m_c. However, Lepage et al (2014) have pointed out that lattice results can help. For example: estimates are that Δm_b, Δm_c and $\Delta\alpha_s$ could be reduced by more than a factor of 7, 3 and 6 respectively.

Measurement of Higgs Couplings

The proper way to test the SM is to compute SM observables and compare with data in a χ^2 type of analysis.

In this approach, you are primarily limited to listing experimental measurements and their errors, and compare with SM calculations – using tables, plots, χ^2 analysis, etc.

For example, with the SM you cannot talk about measuring the Higgs coupling to bottom quarks. All you can talk about is extracting the Yukawa coupling y_b, and its uncertainties, through observables via a global fit of observables.

"Measurement of hbb coupling"

You can, however, "measure hbb coupling" by deleting m_b observable and seeing how well y_b can be extracted by $h \rightarrow bb$ plus all the rest: y_b(higgs) and compare that to y_b extracted from m_b plus all the rest.

Global fit of $\sigma(h \rightarrow bb)$ + all other obs but without m_b

$\Rightarrow$ $y_{b,\text{higgs}}$ extracted

Global fit of all obs including m_b but without $\sigma(h \rightarrow bb)$

$\Rightarrow$ $y_{b,mb}$ extracted

Compare by renormalizing to common scale, say m_Z.

This ratio $y_{b,\text{higgs}}(m_Z) / y_{b,mb}(m_Z)$ should be 1.

New Physics: HκSM

Harder to do the analogy with hVV couplings (V=γ, g, W, Z).

Instead a *new theory of physics beyond the SM* is considered:

I will call this the "Higgs kappa Standard Model" (HκSM).

It is parametrized by κ's, which are defined by replacing

$g(hAA)_{SM}$ ➔ $\kappa_A\, g(hAA)_{SM}$; other interactions remain SM.

Attention must be given to clear definitions of κ_γ and κ_g.

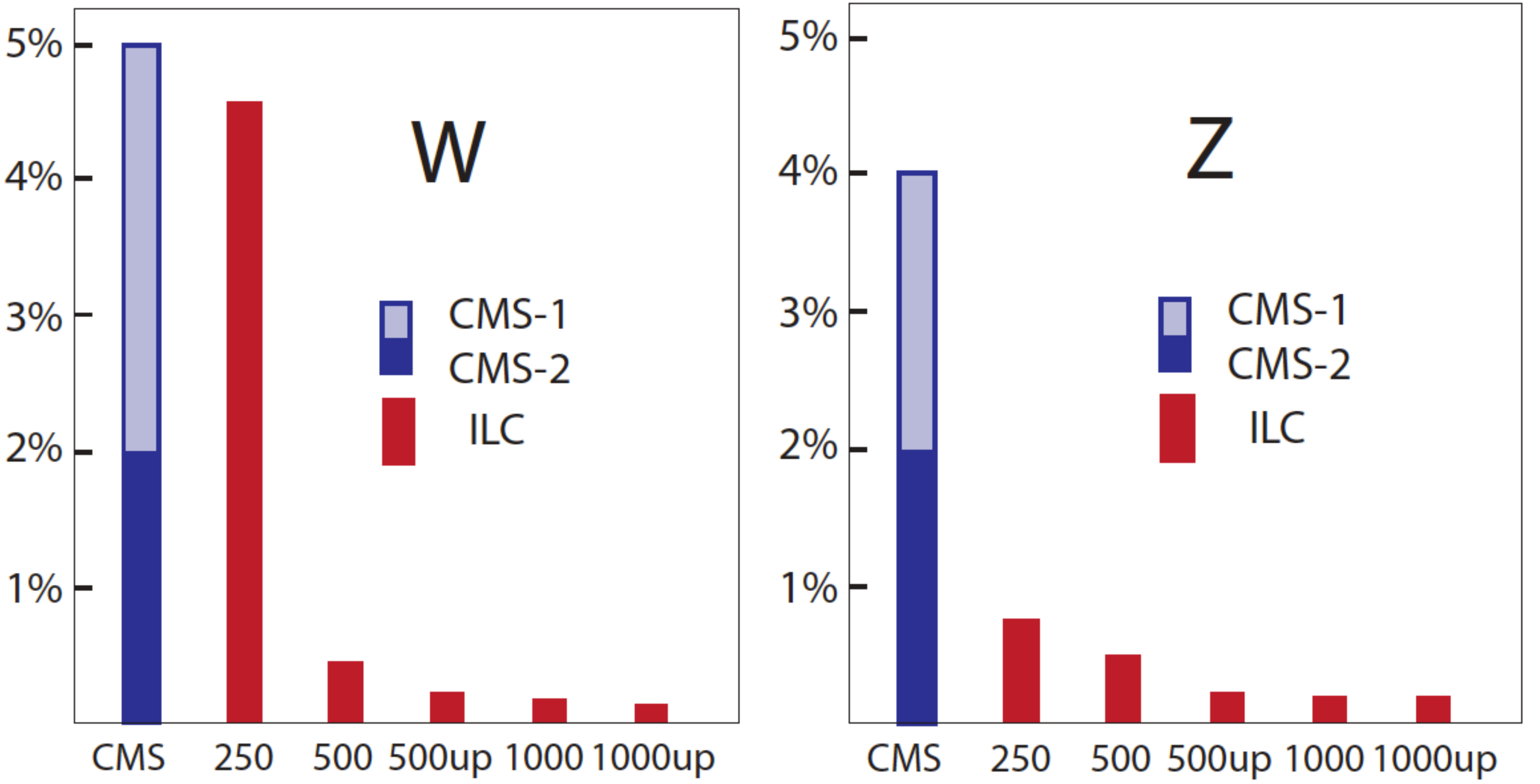
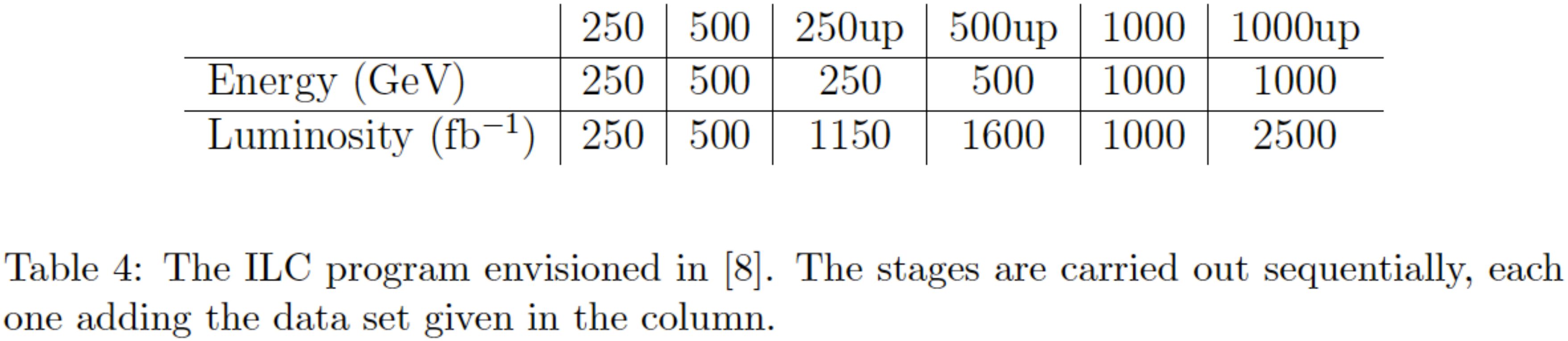


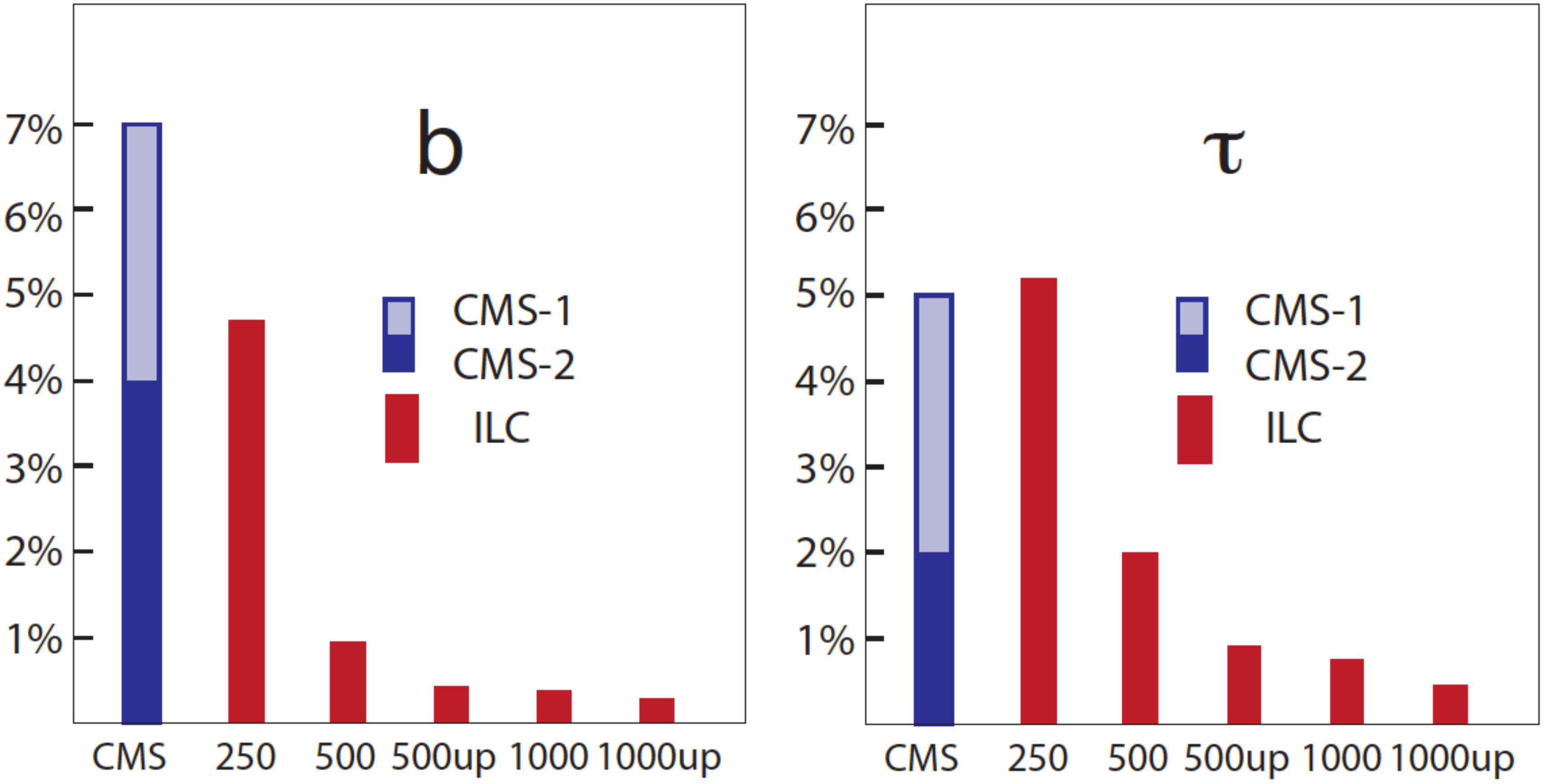
Figure 1: Estimates of the ILC measurement accuracies for the Higgs boson couplings to WW and ZZ. These estimates are based on the 10-parameter fit described in the text. The successive entries correspond to the stages of the ILC program shown in Table 4. The CMS Scenario 1 and Scenario 2 estimates for 3000 fb^{-1}, from [7], are shown on the left.

Peskin summary, 2013



	250	500	250up	500up	1000	1000up
Energy (GeV)	250	500	250	500	1000	1000
Luminosity (fb^{-1})	250	500	1150	1600	1000	2500

Table 4: The ILC program envisioned in [8]. The stages are carried out sequentially, each one adding the data set given in the column.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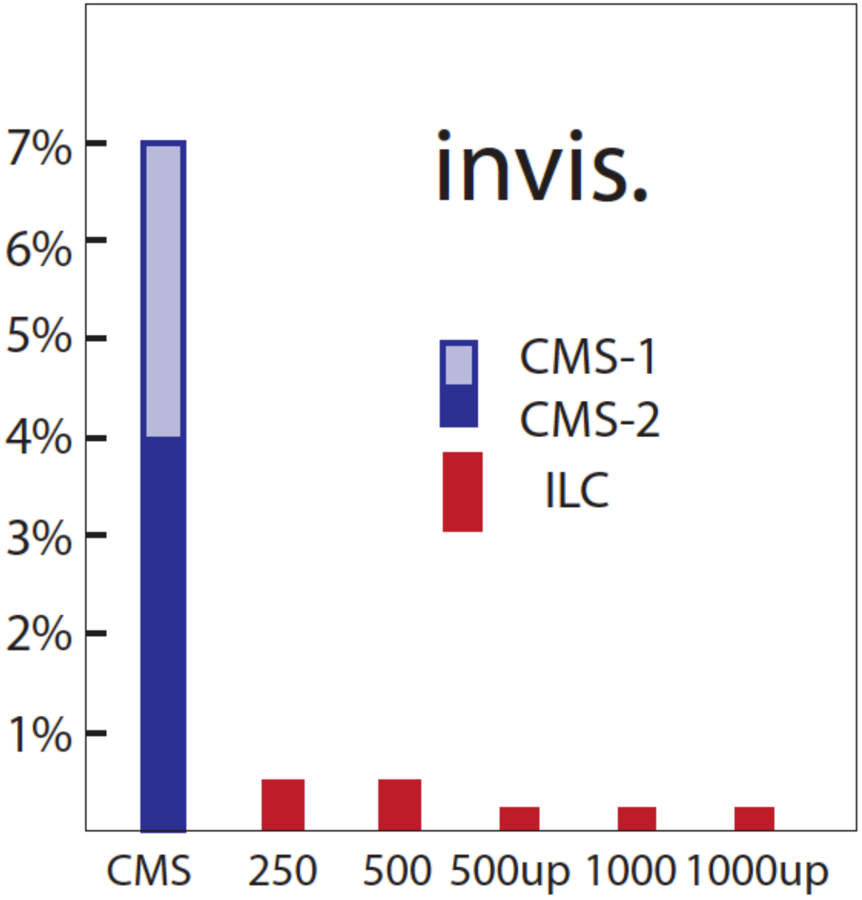
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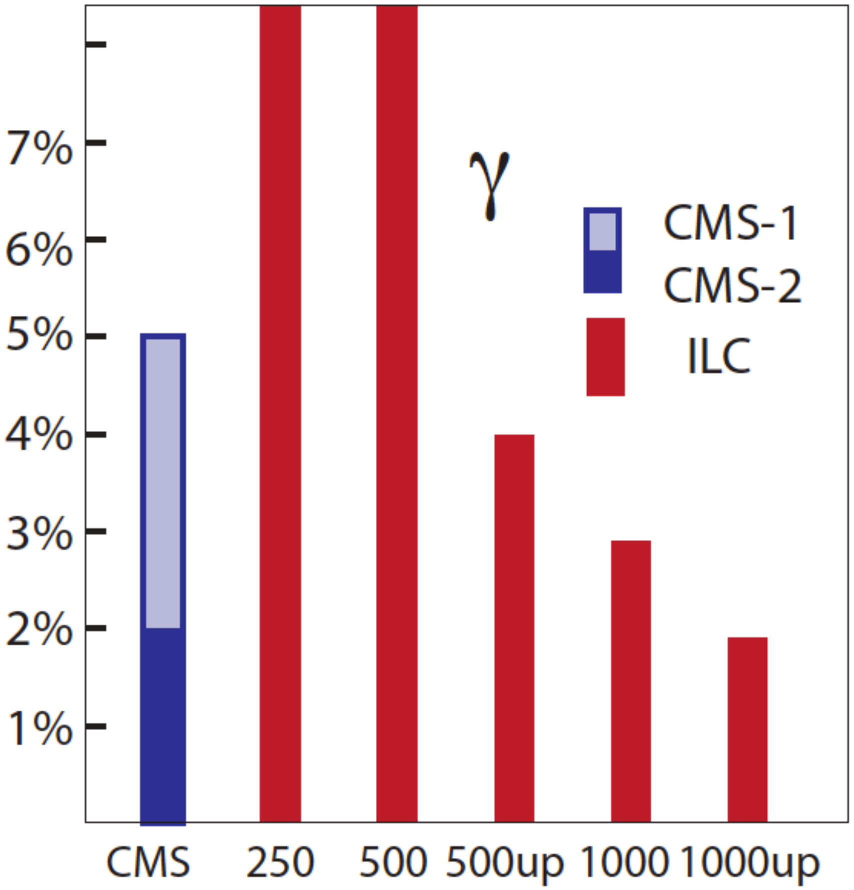
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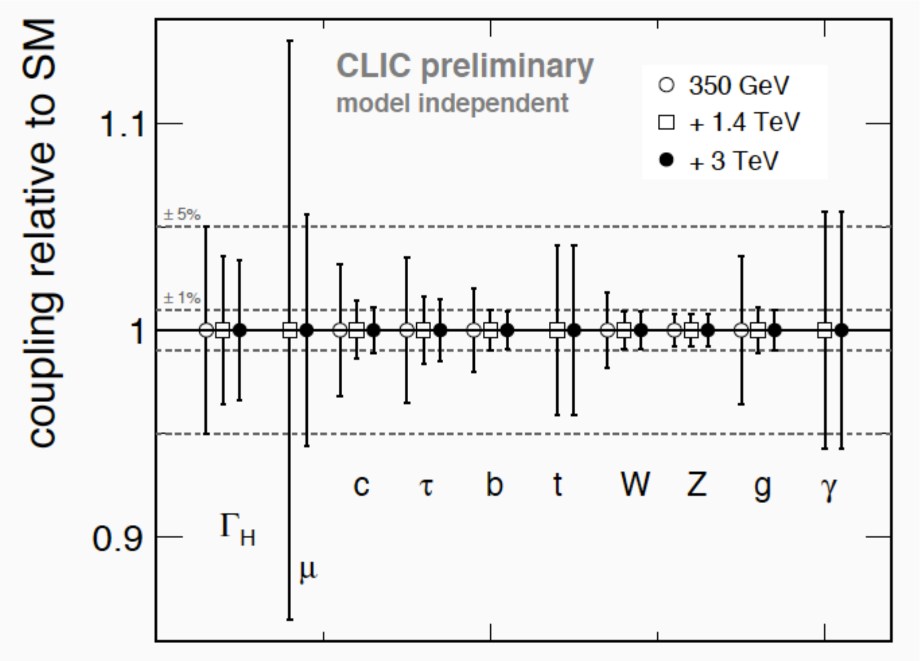
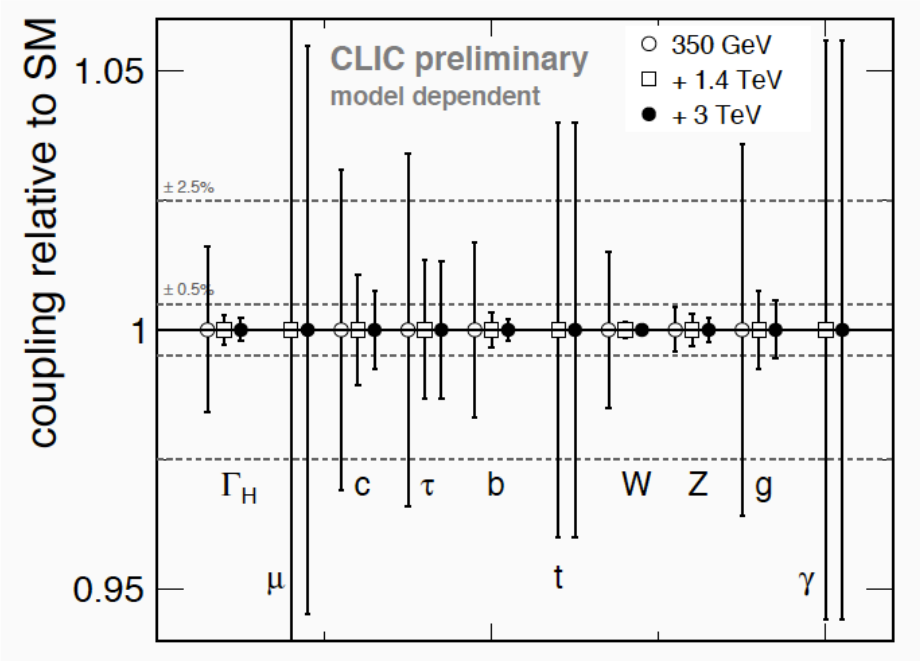
Global fits

CLIC

Eva Sicking, ICHEP 2014

- Fit of presented statistical precisions → extract couplings and Higgs width
- Fit results at higher energy include measurements from lower energies





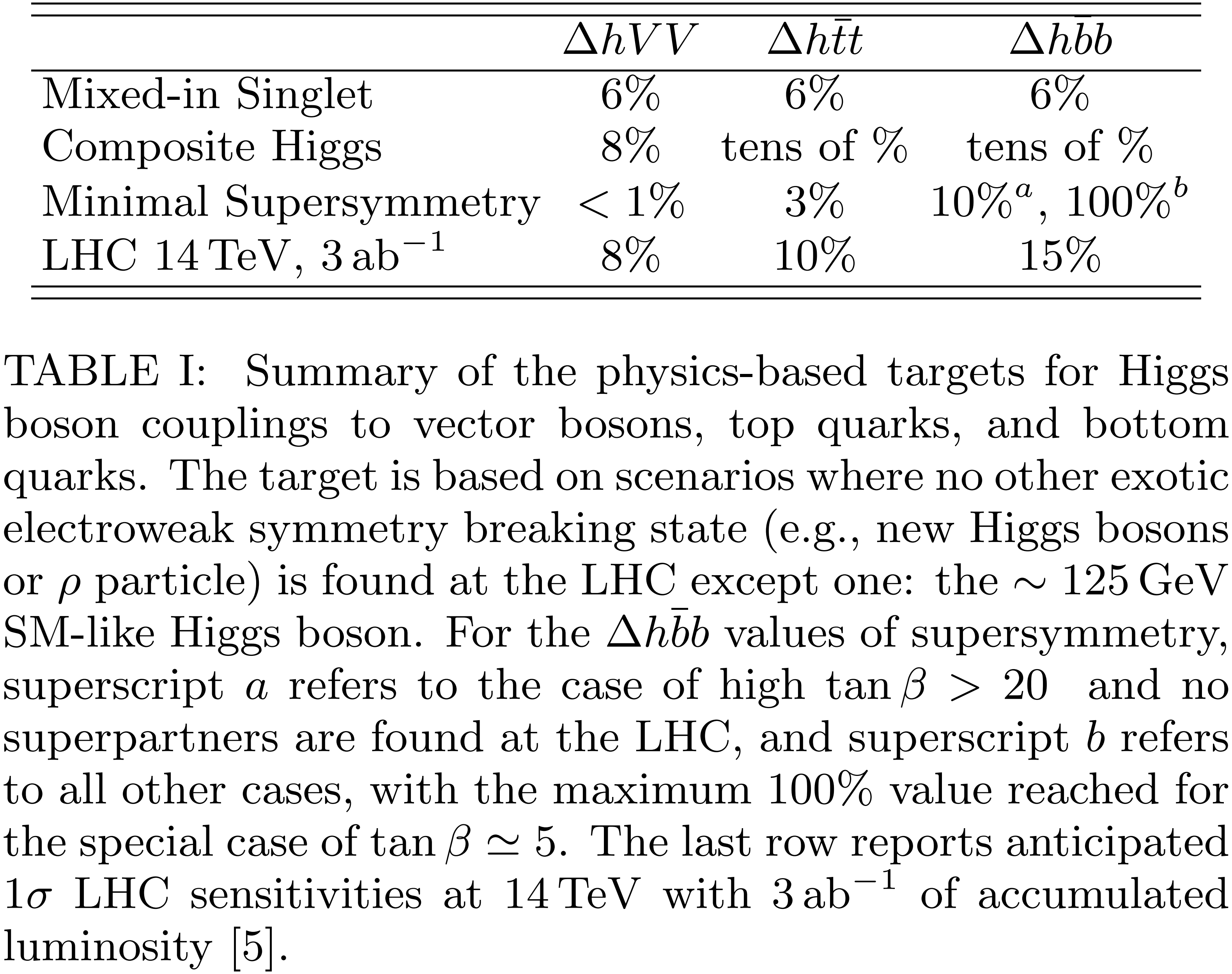
- Fully model independent approach, unique for lepton colliders
- All results are limited by 0.9 % from $\sigma(HZ)$ measurement
- Higgs width extraction with 5-4 % precision

- LHC-like constraints: no invisible decays, fixed total width
- Sub-percent precision at high energies
- Higgs width extraction with 1.7-0.2 % precision

Fine to ask how well colliders can do, but important to ask:

How well do we need to measure the Higgs boson coupling?

Criterion: What are the largest coupling deviations away from the SM Higgs couplings that are possible if no other state directly related to EWSB (another Higgs, or “rho meson”) is directly accessible at the LHC.



	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$
LHC 14 TeV, $3\,\mathrm{ab}^{-1}$	8%	10%	15%

TABLE I: Summary of the physics-based targets for Higgs boson couplings to vector bosons, top quarks, and bottom quarks. The target is based on scenarios where no other exotic electroweak symmetry breaking state (e.g., new Higgs bosons or ρ particle) is found at the LHC except one: the $\sim 125\,\mathrm{GeV}$ SM-like Higgs boson. For the $\Delta h\bar{b}b$ values of supersymmetry, superscript a refers to the case of high $\tan\beta > 20$ and no superpartners are found at the LHC, and superscript b refers to all other cases, with the maximum 100% value reached for the special case of $\tan\beta \simeq 5$. The last row reports anticipated 1σ LHC sensitivities at $14\,\mathrm{TeV}$ with $3\,\mathrm{ab}^{-1}$ of accumulated luminosity [5].

Details in Gupta, Rzehak, JW, arXiv:1206.3560.

Conclusions

Higgs boson physics is at present not yet quite a "precision field", with the exception of Higgs mass determination.

Nevertheless, many ideas have been ruled out by the ~20% measurements taken of couplings.

Much better results will be coming at LHC in the new run, HL phase and HE options.

Future machines (ILC, CLIC, TLEP/FCC-ee, etc.) promise high precision Higgs boson coupling measurements – valuable!

Of course, much more to say about "new Higgs" phenomenology (SUSY Higgs, Higgs portal, singlet higgs, invisible decays, exotic production of Higgs, etc.