
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD

Precision Studies of SM-like signatures:
EW, QCD, Higgs, top

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1. Introduction

2. Electroweak Precision Observables

3. Top and QCD

4. Higgs Observables

5. Conclusions

1. Introduction

Experimental situation:

ILC/CLIC/FCC-ee/CEPC will provide (high!) accuracy measurements!

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Theoretical calculations should be viewed as an essential part of all (current and future) High Energy Physics programs

To be covered:

- Interesting (SM-like) observables
- Relevant/required precision
- Corresponding theoretical uncertainties (show stoppers?)
- Machine related issues (as far as possible)

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: M_W
   $\to$ at the same level or better as the experimental precision

2. Prediction of the measured process to extract the quantity
   Example: $e^+e^- \to W^+W^-$
   $\to$ better than then "pure" experimental precision

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Two types of theory uncertainties:

1. intrinsic: missing higher orders

2. parametric: uncertainty due to exp. uncertainty in SM input parameters
   Example: m_t, m_b, α_s, $\Delta\alpha_{\text{had}}$, . . .

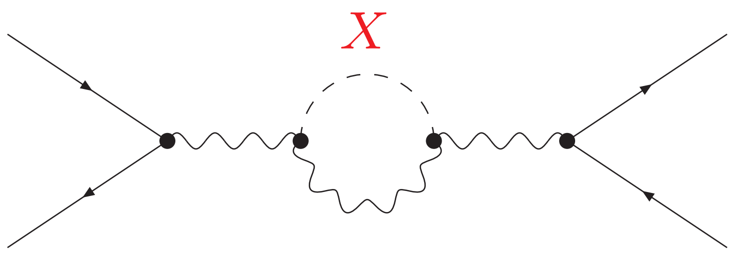
2. Electroweak Precision Observables

Comparison of observables with theory:

Precision data: $M_W, \sin^2\theta_{\text{eff}}, a_\mu,\ M_h$	$\leftrightarrow$	Theory: SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. X



$\Downarrow$

SM: limits on M_H, BSM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed
$\Rightarrow$ only models "ready" so far: SM, MSSM $\Leftarrow$ more TH input needed!

Precision observables in the SM and the MSSM

M_W, $\sin^2\theta_{\rm eff}$, M_h, $(g-2)_\mu$, b physics, . . .

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{\text{1-loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$\sim \log\frac{M_Z}{m_f}$	$\sim m_t^2$	$\log(M_H/M_W)$
$\sim 6\%$	$\sim 3.3\%$	$\sim 1\%$

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$\Updownarrow$

loop corrections

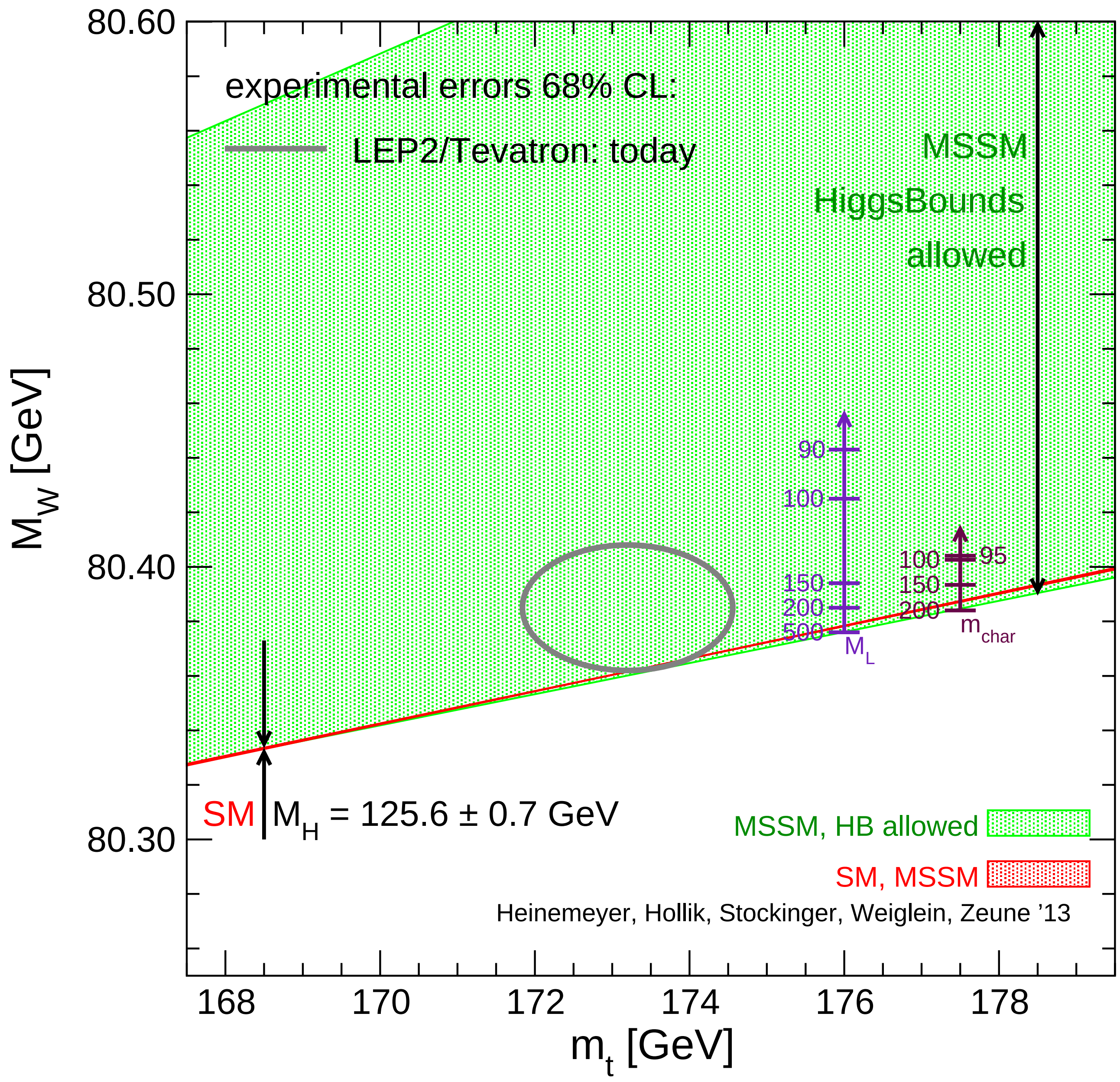
B) Effective mixing angle:

$$\sin^2\theta_{\rm eff}=\frac{1}{4\,|Q_f|}\left(1-\frac{\mathrm{Re}\,g_V^f}{\mathrm{Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f\to g_V^f+\Delta g_V^f,\qquad g_A^f\to g_A^f+\Delta g_A^f$$

What M_W precision do we want? SUSY as a show case:



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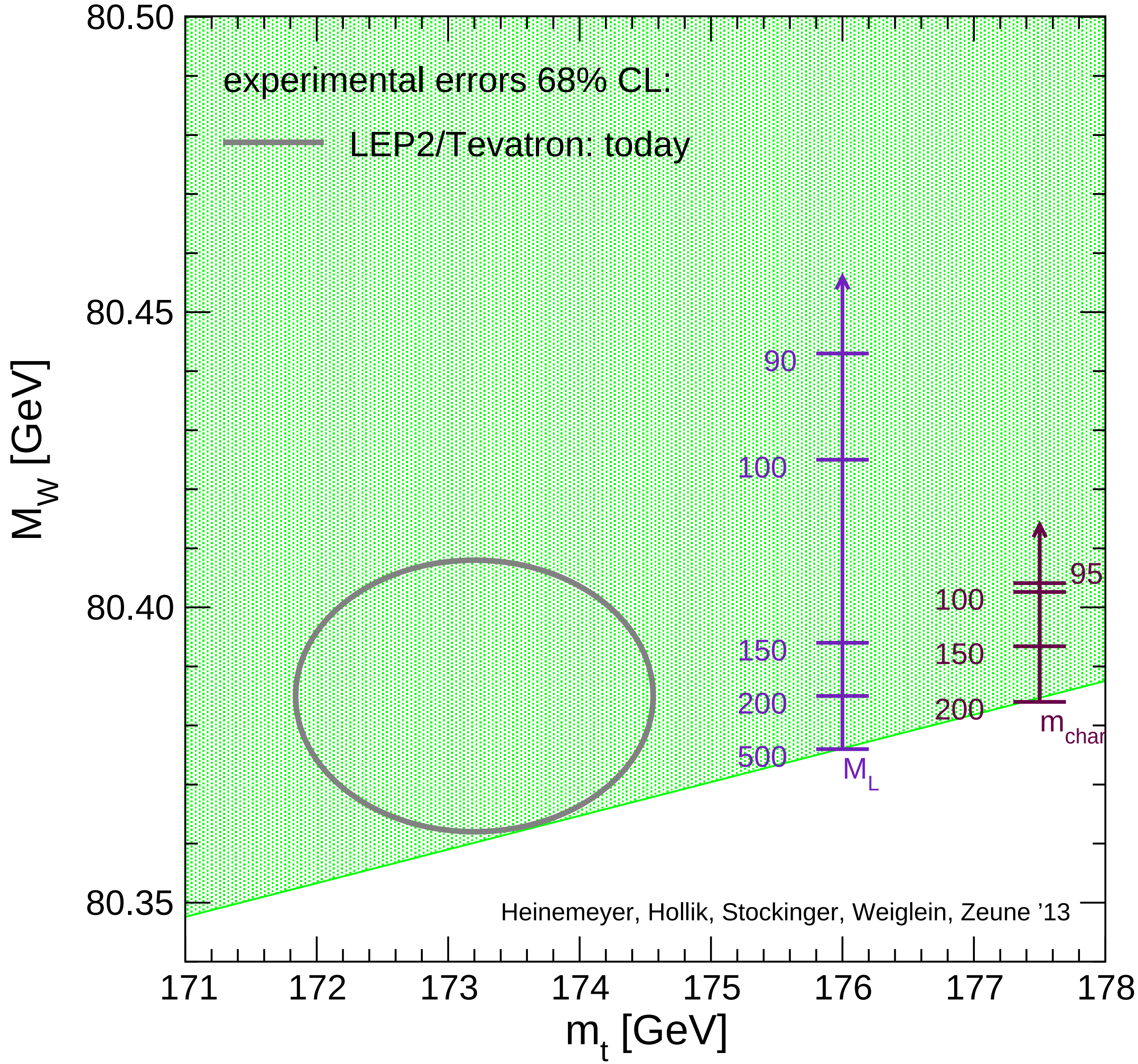
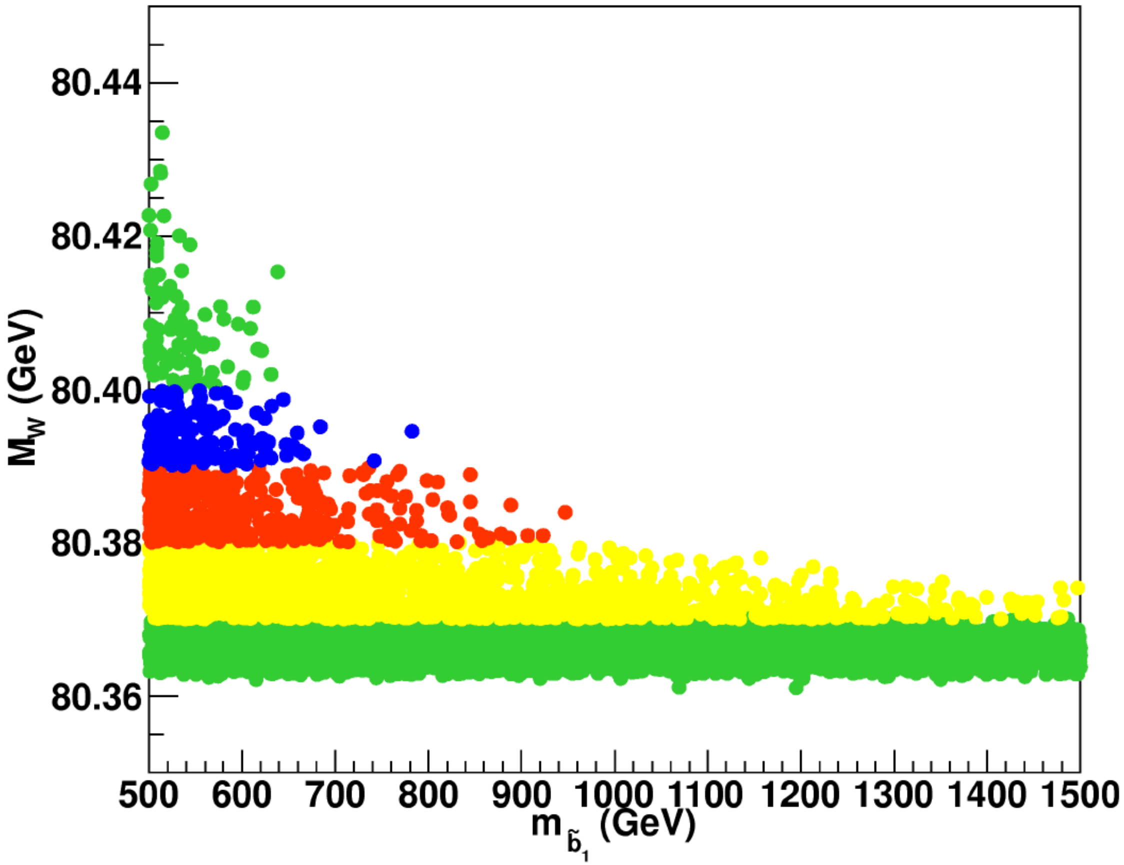


Example MSSM scenario:

$m_{\tilde{t}_1} = 400 \pm 40$ GeV, Other masses $\gtrsim 500$ GeV

$M_W^{\rm exp} = 80.375 \pm 0.005$ GeV, 80.385 ± 0.005 GeV, 80.395 ± 0.005 GeV



⇒ precision below 5 MeV required, the better the better!

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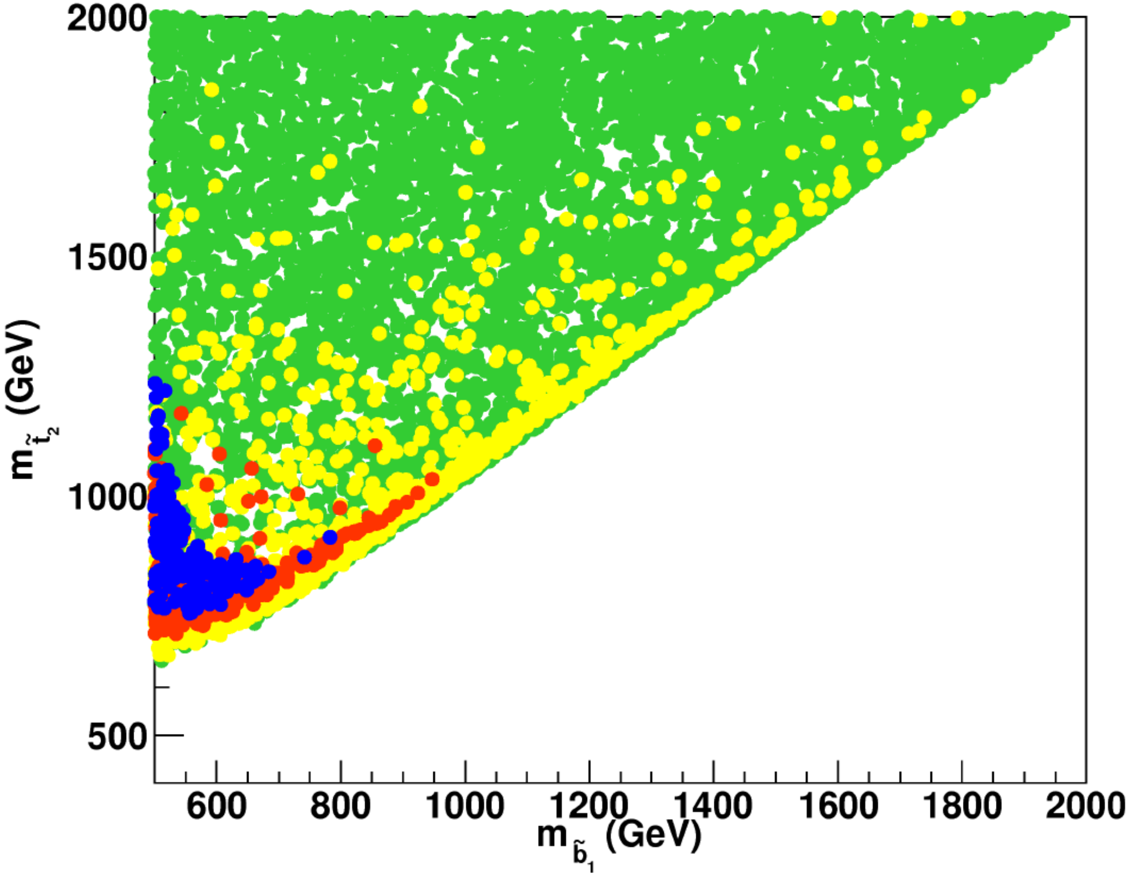

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The W boson mass

Experimental accuracy:

Today: LEP2, Tevatron: $M_W^{\text{exp}} = 80.385 \pm 0.015$ GeV

ILC/FCC-ee: – polarized threshold scan
– kinematic reconstruction of W^+W^- [G. Wilson '13]
– hadronic mass (single W)

$\delta M_W^{\text{exp,ILC(FCC-ee)}} \lesssim 3\,(1)$ MeV (from thr. scan) $\Leftarrow$ TU neglected

Theoretical accuracies:

intrinsic today: $\delta M_W^{\text{SM,theo}} = 4$ MeV, $\delta M_W^{\text{MSSM,today}} = 5 - 10$ MeV

intrinsic future: $\delta M_W^{\text{SM,theo,fut}} = 1$ MeV, $\delta M_W^{\text{MSSM,fut}} = 2 - 4$ MeV

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$\delta M_W^{\text{para},m_t} = 5.5$ MeV, $\delta M_W^{\text{para},\Delta\alpha_{\text{had}}} = 2$ MeV, $\delta M_W^{\text{para},M_Z} = 2.5$ MeV

parametric future: $\delta m_t^{\text{fut}} = 0.05$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$, $\delta M_Z^{\text{ILC/FCC-ee}} = 1/0.1$ MeV

$\Delta M_W^{\text{para,fut},m_t} = 0.5$ MeV, $\Delta M_W^{\text{para,fut},\Delta\alpha_{\text{had}}} = 1$ MeV, $\Delta M_W^{\text{para,fut},M_Z} = 0.2/0.02$ MeV

M_W from threshold scan:

Not only $e^+e^- \to W^{(*)}W^{(*)}$, but $e^+e^- \to WW \to$ 4f needed

Current status:

full one-loop for $2 \to 4$ process

[*A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99-'02*]

$\Rightarrow$ extraction of M_W at the level of ~ 6 MeV

Most recent improvement:

leading 2L corrections from EFT

[*Actis, Beneke, Falgari, Schwinn '08*]

$\Rightarrow$ impact on M_W at the level of ~ 3 MeV

$\Rightarrow$ full 2L for $2 \to 4$ process not foreseeable

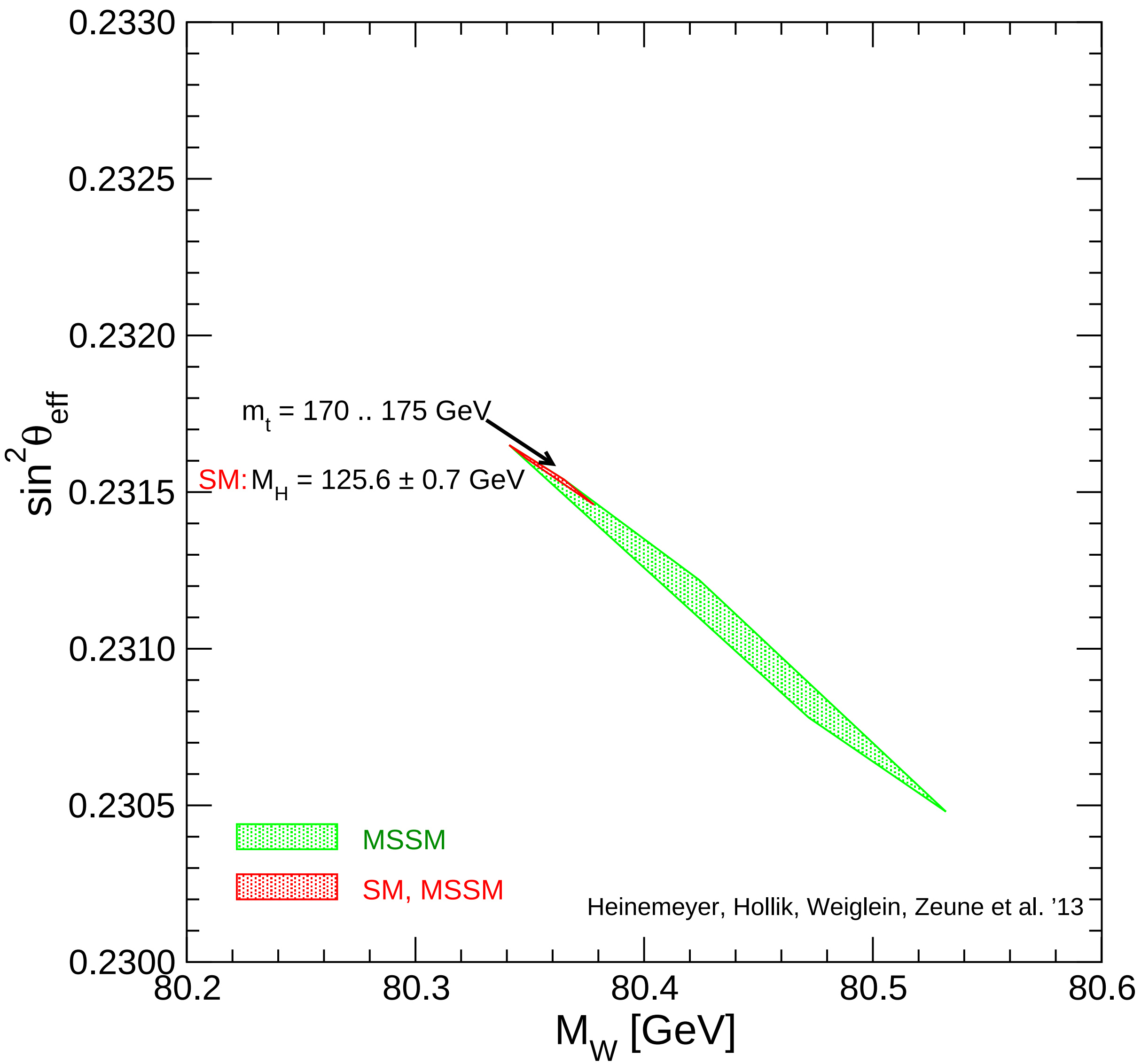
Potentially possible:

2L resummed higher-order terms for $e^+e^- \to WW$ and $W \to ff'$

$\Rightarrow$ extraction of M_W at ~ 1 MeV??

What $\sin^2\theta_{\rm eff}$ precision do we want? SUSY as a show case:

[*S.H., W. Hollik, G. Weiglein, L. Zeune et al. '13*]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

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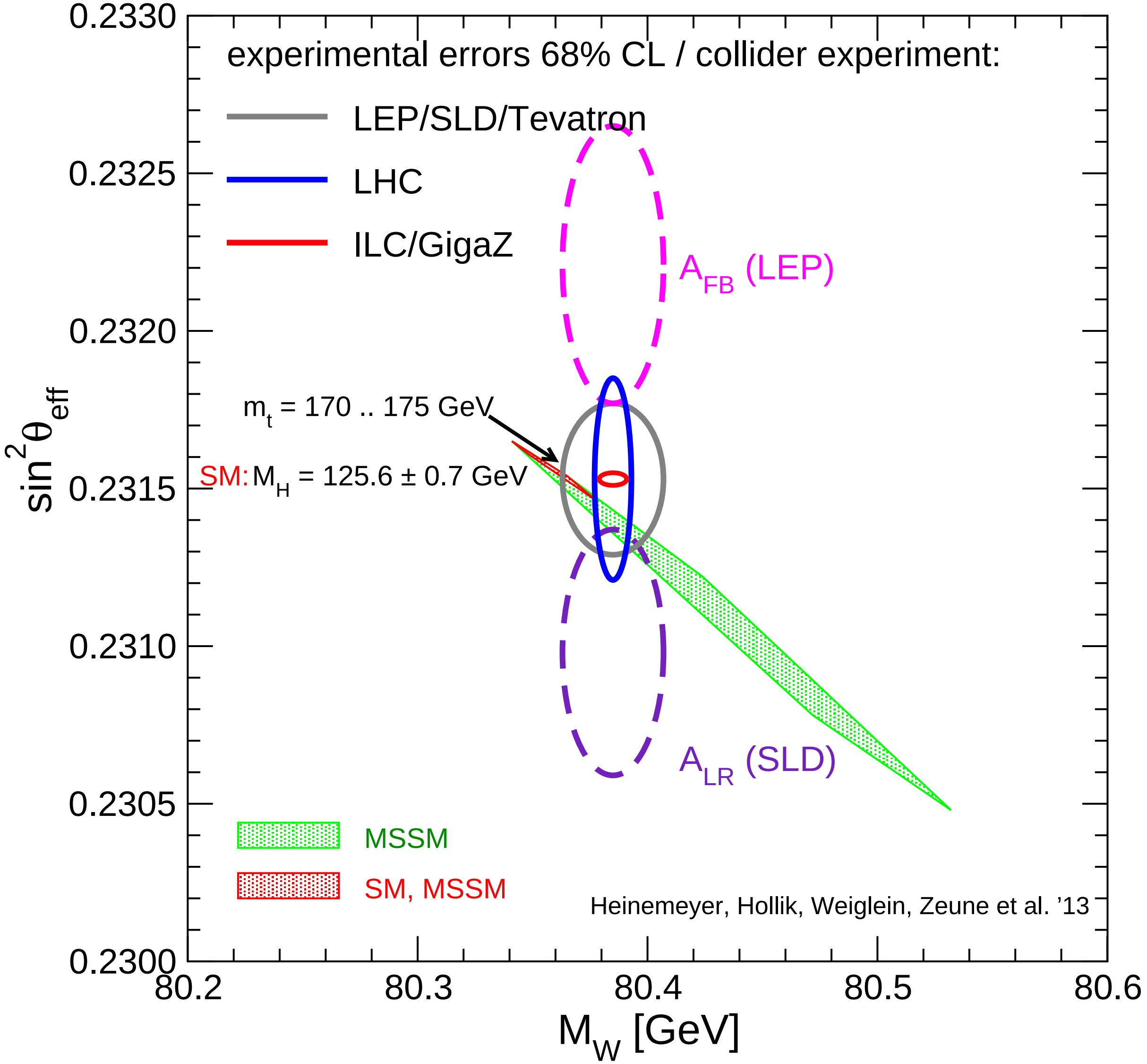

MSSM band:
scan over
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overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

The effective weak leptonic mixing angle: $\sin^2\theta_{\text{eff}}$

Experimental accuracy:

Today: LEP, SLD: $\sin^2\theta_{\text{eff}}^{\text{exp}} = 0.23153 \pm 0.00016$

GigaZ/TeraZ: both beams polarized, Blondel scheme

$$\delta\sin^2\theta_{\text{eff}}^{\text{exp,ILC(FCC-ee)}} = 13\,(3) \times 10^{-6} \quad \Leftarrow \text{TU neglected}$$

Theoretical accuracies: $[10^{-6}]$

intrinsic today: $\delta\sin^2\theta_{\text{eff}}^{\text{SM,theo}} = 47 \quad \delta\sin^2\theta_{\text{eff}}^{\text{MSSM,today}} = 50 - 70$

intrinsic future: $\delta\sin^2\theta_{\text{eff}}^{\text{SM,theo,fut}} = 15 \quad \delta\sin^2\theta_{\text{eff}}^{\text{MSSM,fut}} = 25 - 35$

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$$\delta\sin^2\theta_{\text{eff}}^{\text{para},m_t} = 30, \quad \delta\sin^2\theta_{\text{eff}}^{\text{para},\Delta\alpha_{\text{had}}} = 36, \quad \delta\sin^2\theta_{\text{eff}}^{\text{para},M_Z} = 14$$

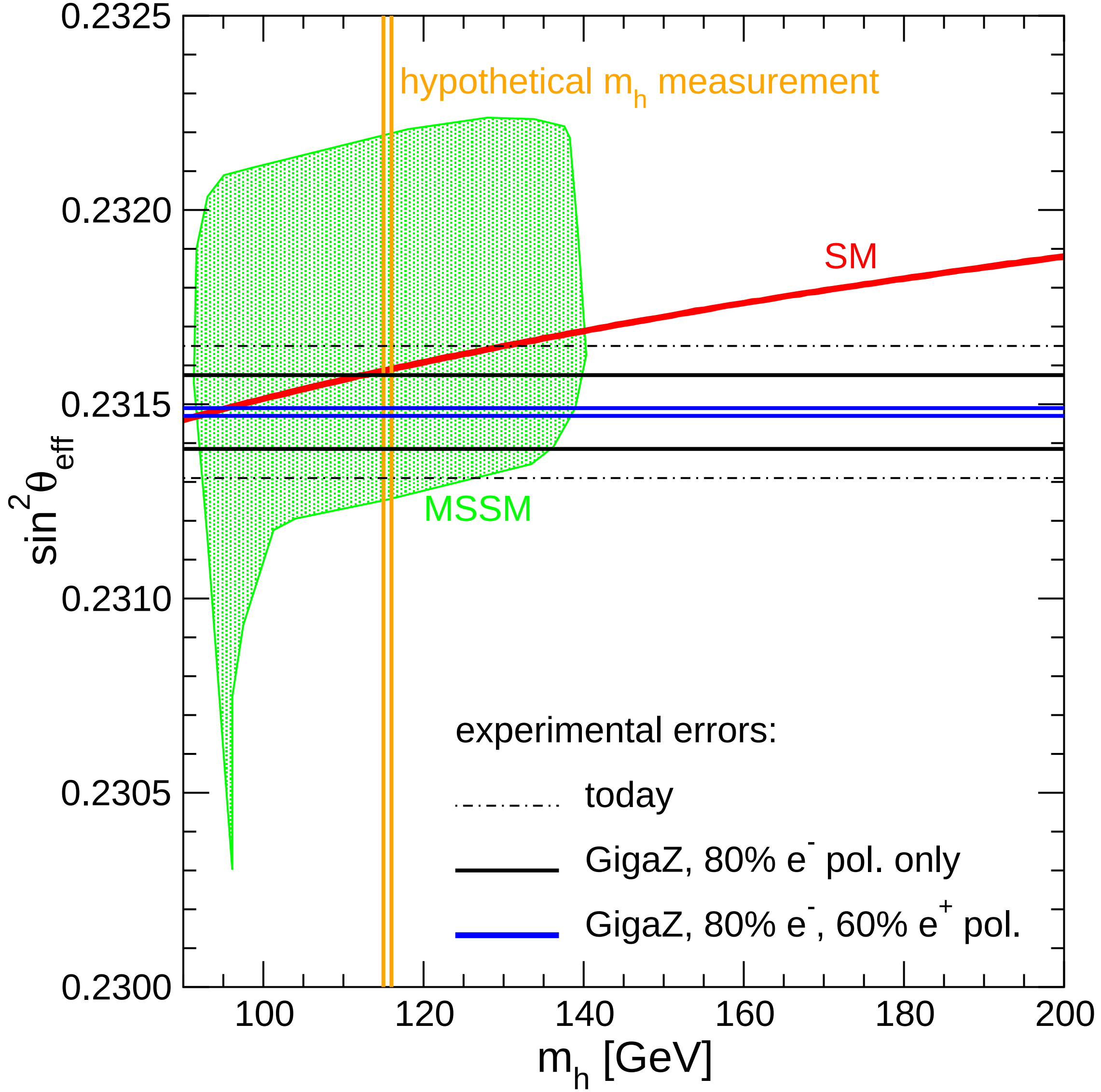
parametric future: $\delta m_t^{\text{fut}} = 0.05$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$, $\delta M_Z^{\text{ILC/FCC-ee}} = 1/0.1$ MeV

$$\Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},m_t} = 2, \ \Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},\Delta\alpha_{\text{had}}} = 18, \ \Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},M_Z} = 6.5/0.7$$

Relevance of both beams polarized:

[S.H., G. Weiglein '05]

⇒ precision of $\sin^2\theta_{\rm eff}$ relies heavily on both beams polarized:



⇒ crucial to reach sensitivity!

SM input: $\Delta\alpha_{\rm had}$ $\Rightarrow$ could be limiting factor!

From $e^+e^- \to$ had. using dispersion relation

today: $\delta(\Delta\alpha_{\rm had}) \sim 10^{-4}$
possible improvement in the future: $\delta(\Delta\alpha_{\rm had}) \sim 5 \times 10^{-5}$

Direct determination at FCC-ee from $e^+e^- \to f\bar{f}$ off the Z peak

[P. Janot '15]
possible improvement in the future: $\delta(\Delta\alpha_{\rm had}) \sim 2 \times 10^{-5}$ $\Rightarrow$ TU neglected

Calculation of $e^+e^- \to f\bar{f}$ needed at 3-loop and beyond: *[A. Freitas '16]*
current techniques (2L/3L): corrections of $\sim 10^{-3}$
new calculation methods (2L/3L): corrections of $\sim 10^{-4}$
unknown methods 3L: $\lesssim 10^{-5}$
unknown methods 4L: $\sim 10^{-5}$
(+ higher-orders in real photon emission)
$\Rightarrow$ improvement unclear

Current uncertainties for EWPOs

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	Experiment	Theory error	Main source
M_W	80.385 ± 0.015 MeV	4 MeV	α^3, $\alpha^2\alpha_s$
Γ_Z	2495.2 ± 2.3 MeV	0.5 MeV	α^2_{bos}, α^3, $\alpha^2\alpha_s$, $\alpha\alpha_s^2$
σ^0_{had}	41540 ± 37 pb	6 pb	α^2_{bos}, α^3, $\alpha^2\alpha_s$
$R_b \equiv \Gamma^b_Z/\Gamma^{had}_Z$	0.21629 ± 0.00066	0.00015	α^2_{bos}, α^3, $\alpha^2\alpha_s$
$\sin^2\theta^\ell_{eff}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_s$

Methods for theory error estimates:

- Parametric factors, *i. e.* factors of α, N_c, N_f, ...
- Geometric progression, *e. g.* $\frac{\mathcal{O}(\alpha^3)}{\mathcal{O}(\alpha^2)} \sim \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}$
- Renormalization scale dependence (often underestimates error)
- Renormalization scheme dependence (may underestimate error)

 [*talk by A. Freitas '16*]

Theory and parametric uncertainties

	ILC	FCC-ee	perturb. error with 3-loop†	Param. error ILC*	Param. error FCC-ee**
M_W [MeV]	3–5	~ 1	1	2.6	1
Γ_Z [MeV]	~ 1	~ 0.1	$\lesssim 0.2$	0.5	0.06
R_b [10^{-5}]	15	$\lesssim 5$	5–10	< 1	< 1
$\sin^2 \theta^\ell_{\rm eff}$ [10^{-5}]	1.3	0.6	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$

(N_f^n = at least n closed fermion loops)

Parametric inputs:

* **ILC:** $\delta m_t = 100$ MeV, $\delta\alpha_s = 0.001$, $\delta M_Z = 2.1$ MeV

****FCC-ee:** $\delta m_t = 50$ MeV, $\delta\alpha_s = 0.0001$, $\delta M_Z = 0.1$ MeV

also: $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$

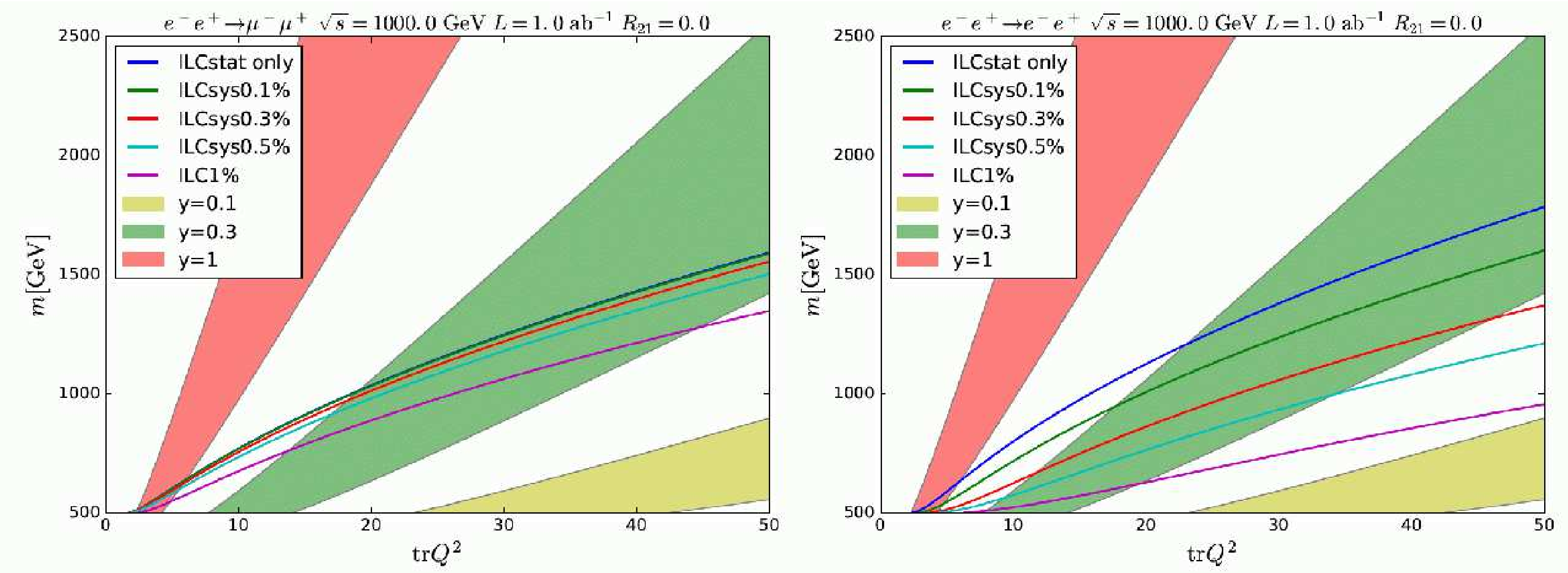
Note: ILC parametric somewhat pessimistic

What about the 750 GeV thingy?

⇒ too much "freedom" to make clear prediction

Just one example for $e^+e^- \to \mu^+\mu^-$: [arXiv:1604.08307]

$$\mathcal{L}_\psi = \sum_i \bar{\psi}_i (i\not{D} - m)\psi_i \; - \; i \sum_i y S \bar{\psi}_i \gamma_5 \psi_i$$

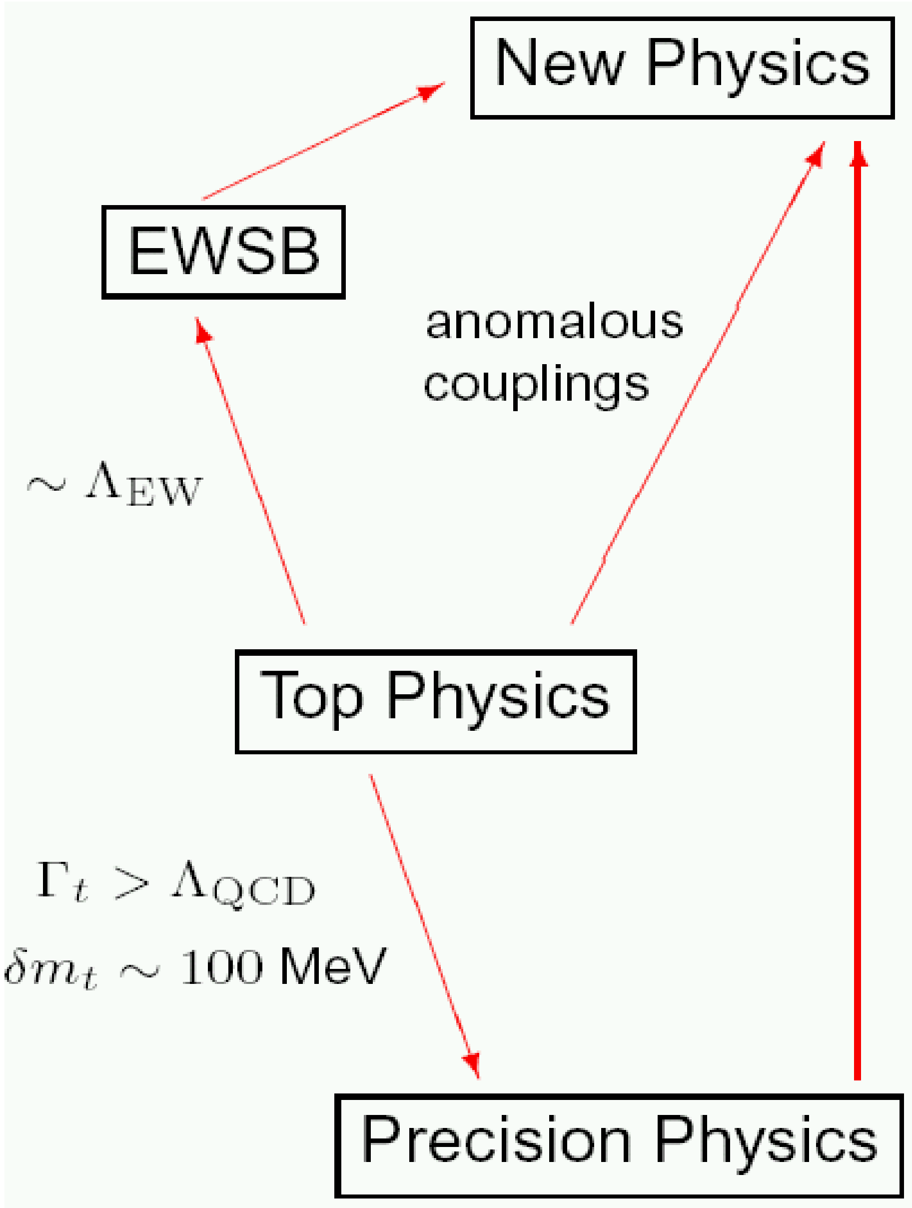


trQ^2: trace of electric charge
R_{21}: ratio of $SU(2)$ to $U(1)$ contributions to trQ^2

⇒ "some" parameter space can be tested

Note: just one example out of many possible realizations!

3. Top/QCD



EWSB: just a heavy quark?
special role for t in EWSB?
strong constraint on any model

Precision physics:
$\delta m_t^{\rm exp}$ leading parametric uncertainty
$\rightarrow$ could obscure new physics

SUSY: m_t crucial input parameter
drives SSB/unification

Many BSM models: heavier top partners

LHC: measurements of
mass, BRs, asymmetries

Needed: high precision of everything
incl. couplings

Important top measurements:

Top quark mass

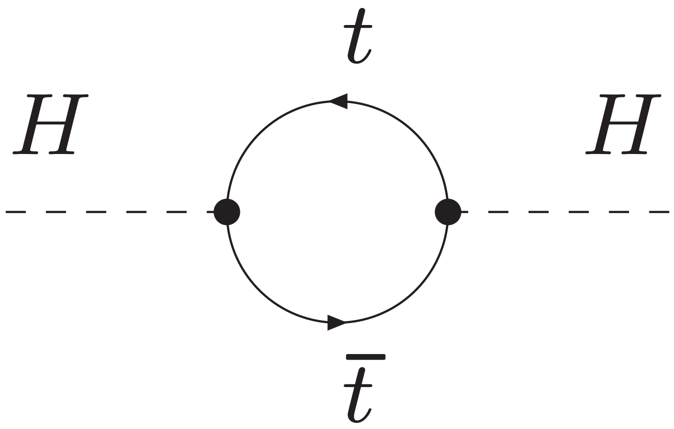
- M_H fit in the SM ⇒ example!
- M_h calculation in BSM models ⇒ example!
- leading parametric uncertainty in EWPO ⇒ see above!
- ...

Top quark couplings

- senstivity to BSM physics ⇒ example!
- rare top decays ⇒ precision better than $\mathcal{O}\left(10^{-5}\right)$ needed
- ...

Top/Higgs physics in BSM:

Nearly any model: large coupling of the Higgs to the top quark:



$\Rightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$

$\Rightarrow$ M_H depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

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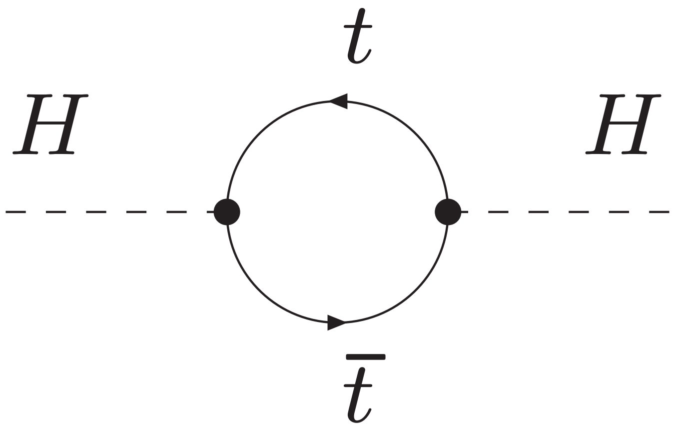

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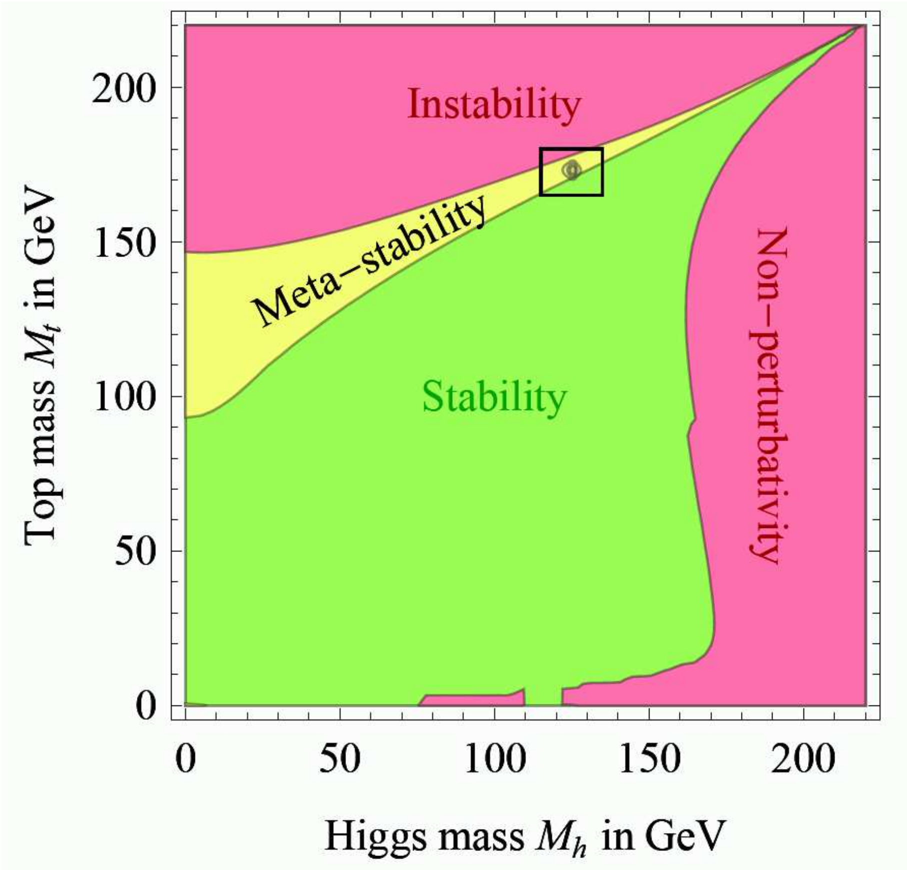
SUSY as an example: $\Delta m_t \approx \pm 1$ GeV $\Rightarrow$ $\Delta M_h \approx \pm 1$ GeV

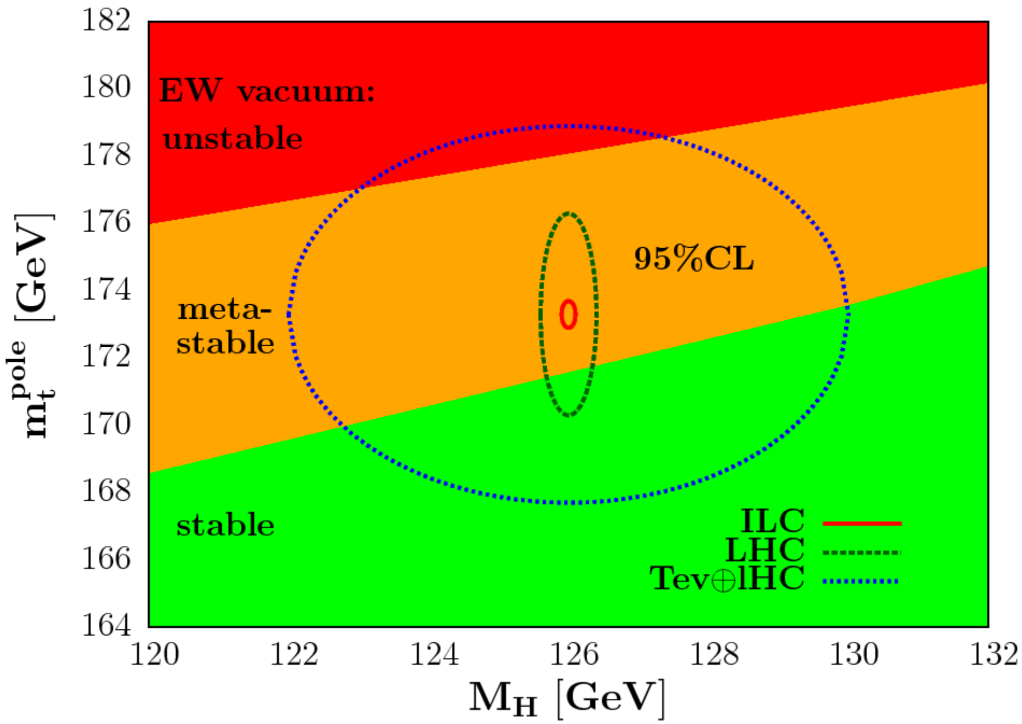
$\Rightarrow$ Precision Higgs physics needs $\mathcal{O}$(50 MeV) in m_t!

Top mass in the SM: crucial for the **Fate of the universe**

[*Degrassi et al. '12*] [*Alehkin et al. '12*]

Is the Higgs potential (and thus our universe) stable?
(neglecting gravity/Planck scale)

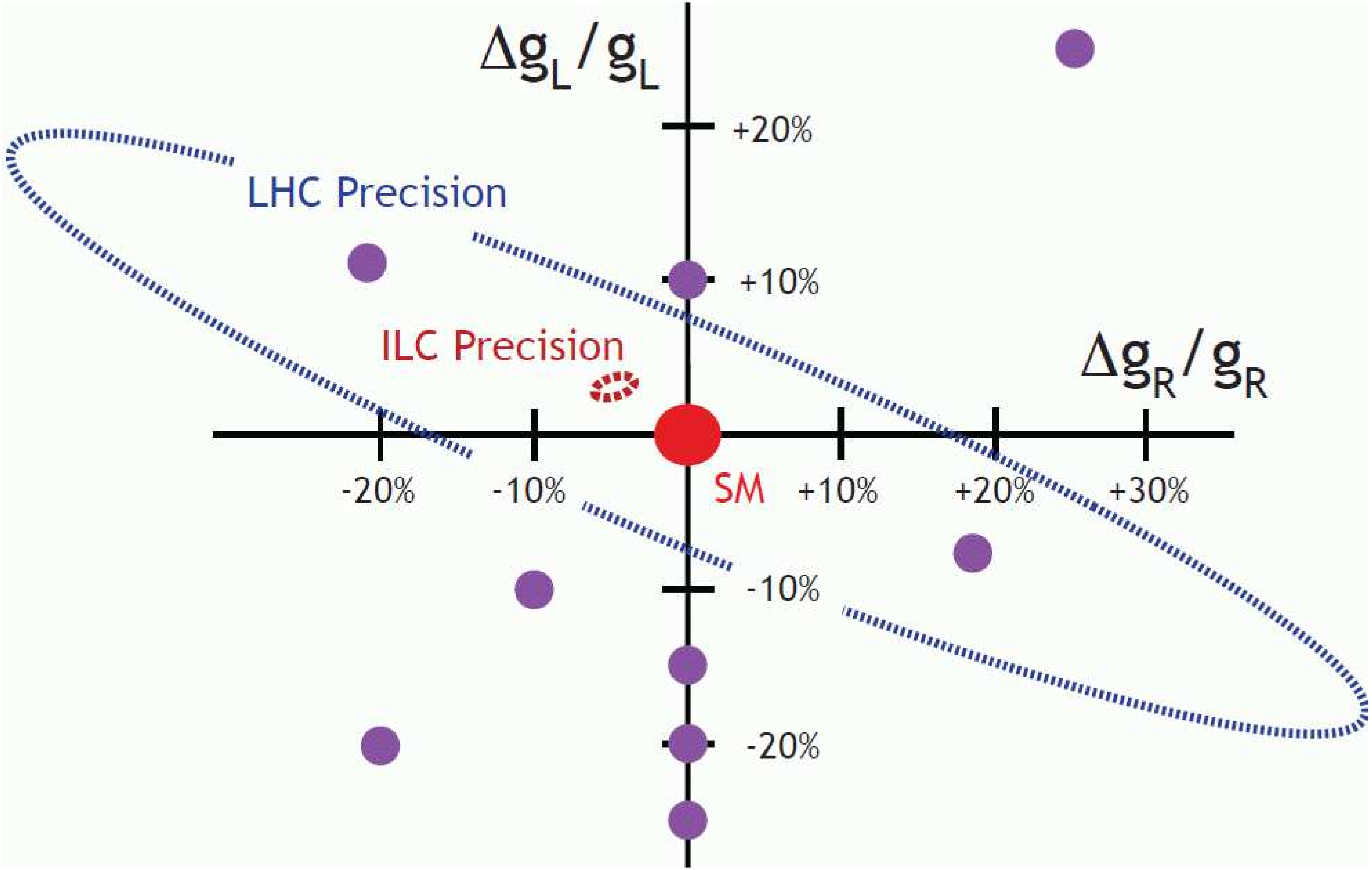




⇒ high precision for m_t needed!

Sensitivity of top couplings to BSM physics: [*F. Richard '15*]

$g_{L,R}$: $t\bar{t}Z$ couplings



⇒ per cent precision needed!

The top quark mass: m_t

What is the top mass?

Particle masses are not direct physical observables
one can only measure cross sections, decay rates, . . .

Additional problem for the top mass:

what is the mass of a colored object?

Top pole mass is not IR safe (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\rm QCD})$

Measurement of m_t:

- At Tevatron, LHC: kinematic reconstruction, fit to invariant

  mass distribution $\Rightarrow$ "MC" mass, close to "pole" mass? $\delta m_t^{\rm exp,LHC} \lesssim 1$ GeV

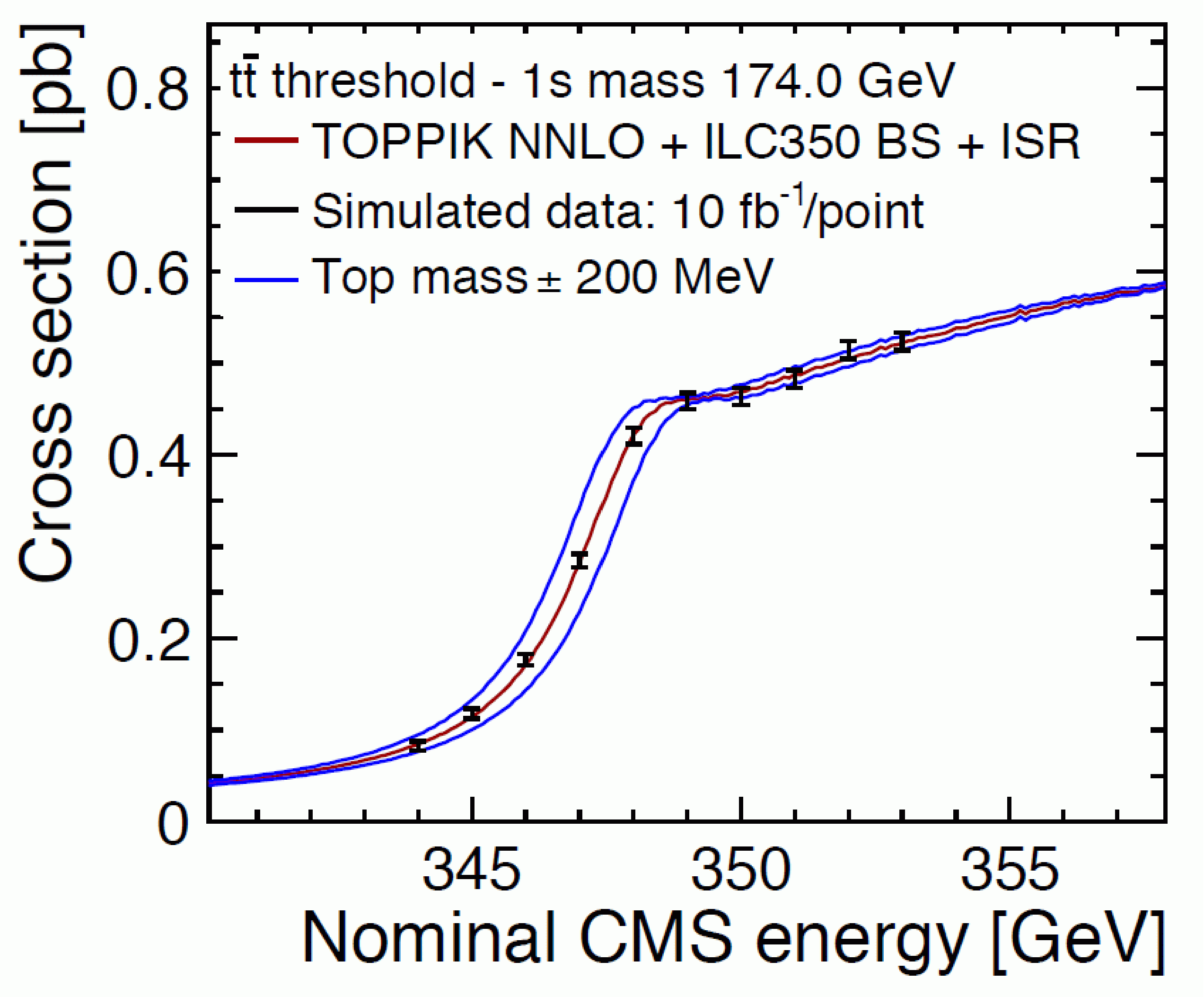
- At e^+e^- colliders: unique possibility (crucial: reach $t\bar{t}$ threshold!)
  threshold scan $\Rightarrow$ threshold mass $\Rightarrow$ **SAFE!**

  transition to other mass definitions possible, $\delta m_t^{{\rm exp},e^+e^-} \lesssim 0.03$ GeV

  Impact of polarization (on systematics) ? $\Rightarrow$ not studied yet

At e^+e^- colliders: unique possibility [ILC TDR '13]

threshold scan $\Rightarrow$ threshold mass $\Rightarrow$ **SAFE!**



transition to other mass definitions possible $\Rightarrow \delta m_t^{\text{theo-trans}} \sim 0.025$ GeV

$\Rightarrow \delta m_t^{\text{theo-thresh}} \lesssim 0.035$ GeV $\Rightarrow \delta m_t \lesssim 50$ MeV, TH dominated!

Uncertainty budget for m_t: [*talk by A. Hoang '15*]

$\delta\alpha_s(M_z) = 0.001$

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\rm SD-low})^{\rm exp}$	$(\delta M_t^{\rm SD-low})^{\rm theo}$	$(\delta\overline{m}_t(\overline{m}_t))^{\rm conversion}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

$\Rightarrow$ improvement in α_s crucial

e^+e^- collider: precision measurement:

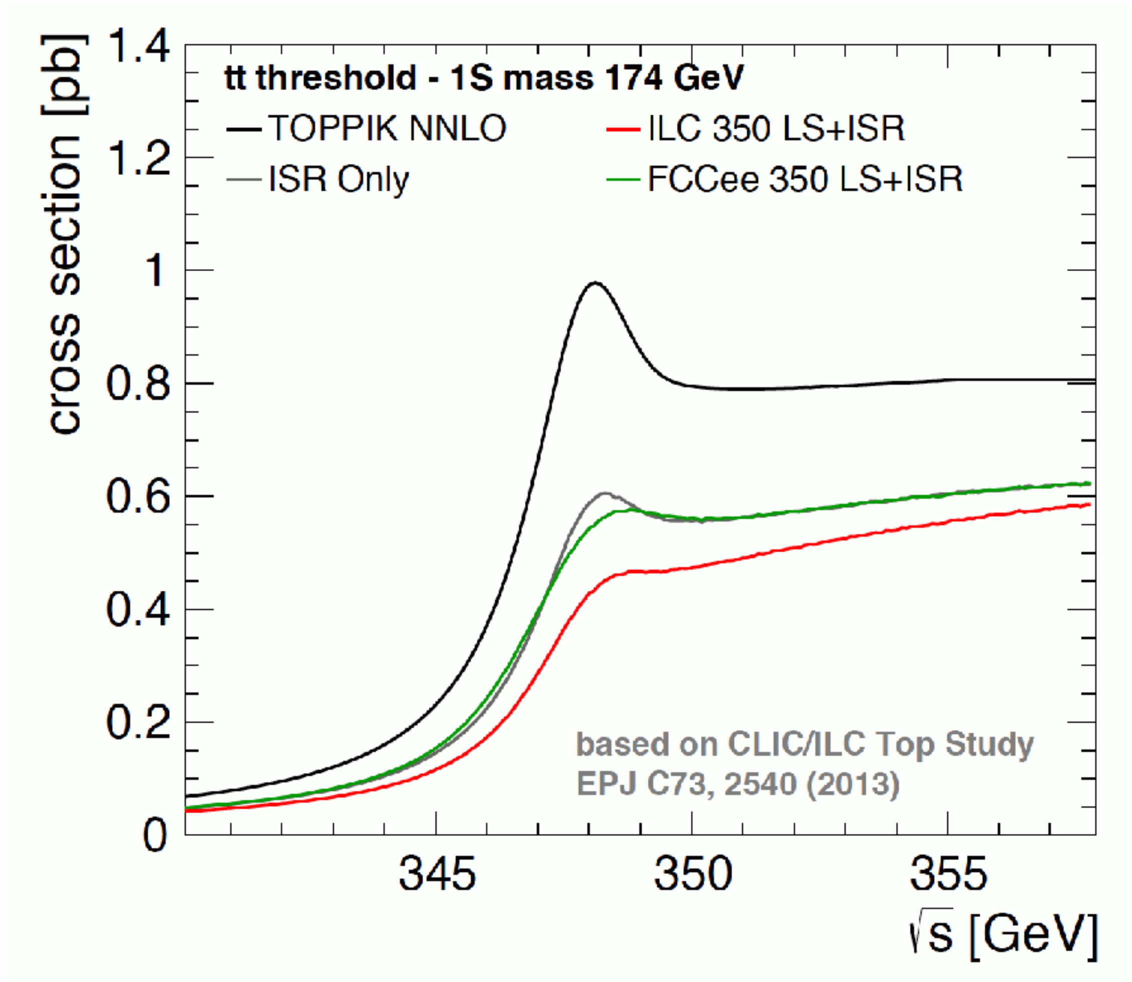
$$R_l := \frac{\Gamma(Z \to \text{ hadrons})}{\Gamma(Z \to l^+l^-)}$$

Improvement down to $\delta^{\rm exp}\alpha_s \sim 0.001 - 0.0001$ possible?!

Note: TH uncertainty (assuming fermionic 3-loop corrections):

$\delta^{\rm theo}R_l \sim 0.0015 \Rightarrow \delta^{\rm theo}\alpha_s \sim 0.0002$ $\Rightarrow$ hard to beat . . .

Threshold measurement: circular vs. linear (beamstrahlung)? [*F. Simon '15*]



⇒ Circular collider has higher cross section, but broader threshold

⇒ overall small, $\mathcal{O}\,(10\%)$, differences . . .

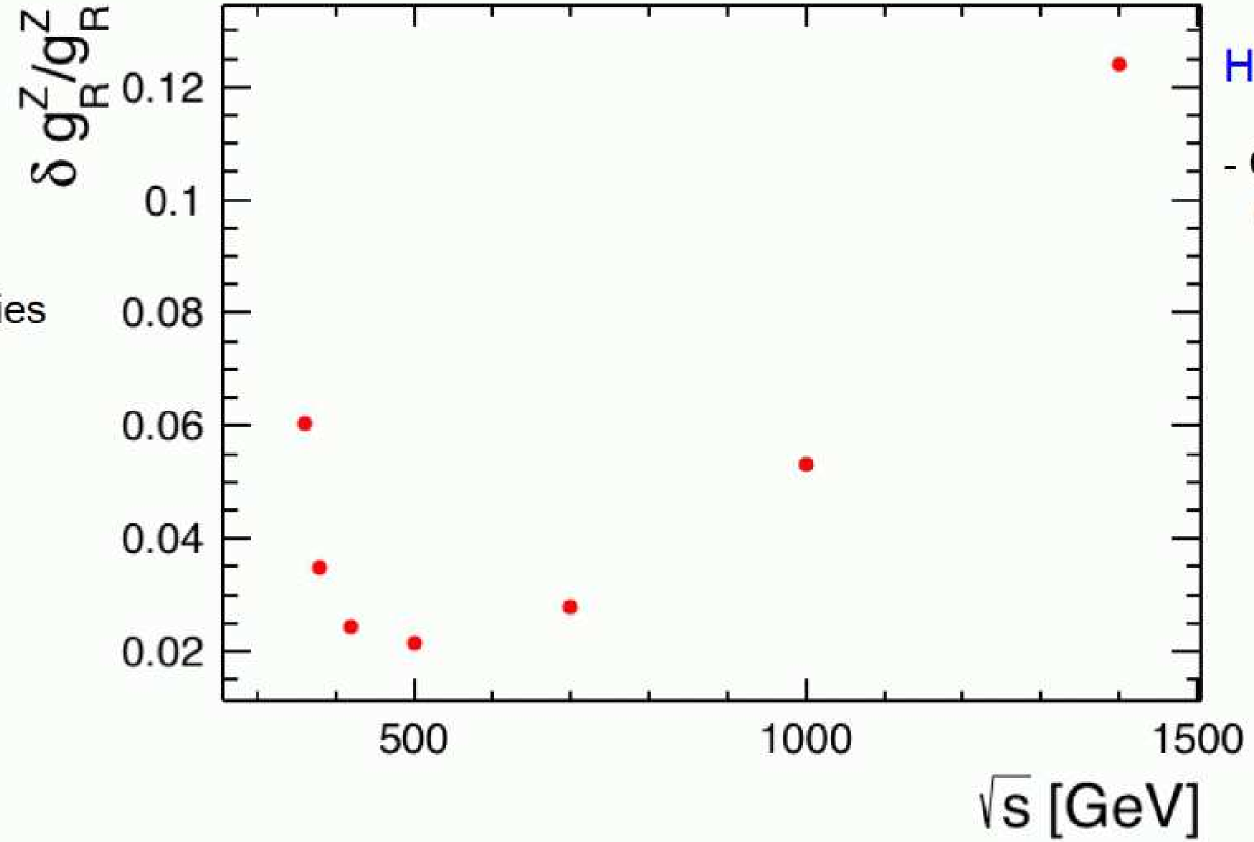
$\sqrt{s}$ dependence for top couplings?

[*R. Poeschl '15*]

... simplified discussion for gRZ

Small cms energies:

- Vanishing axial vector coupling
- On top (not shown) large QCD uncertainties (Juergen's talk)



High cms energies:

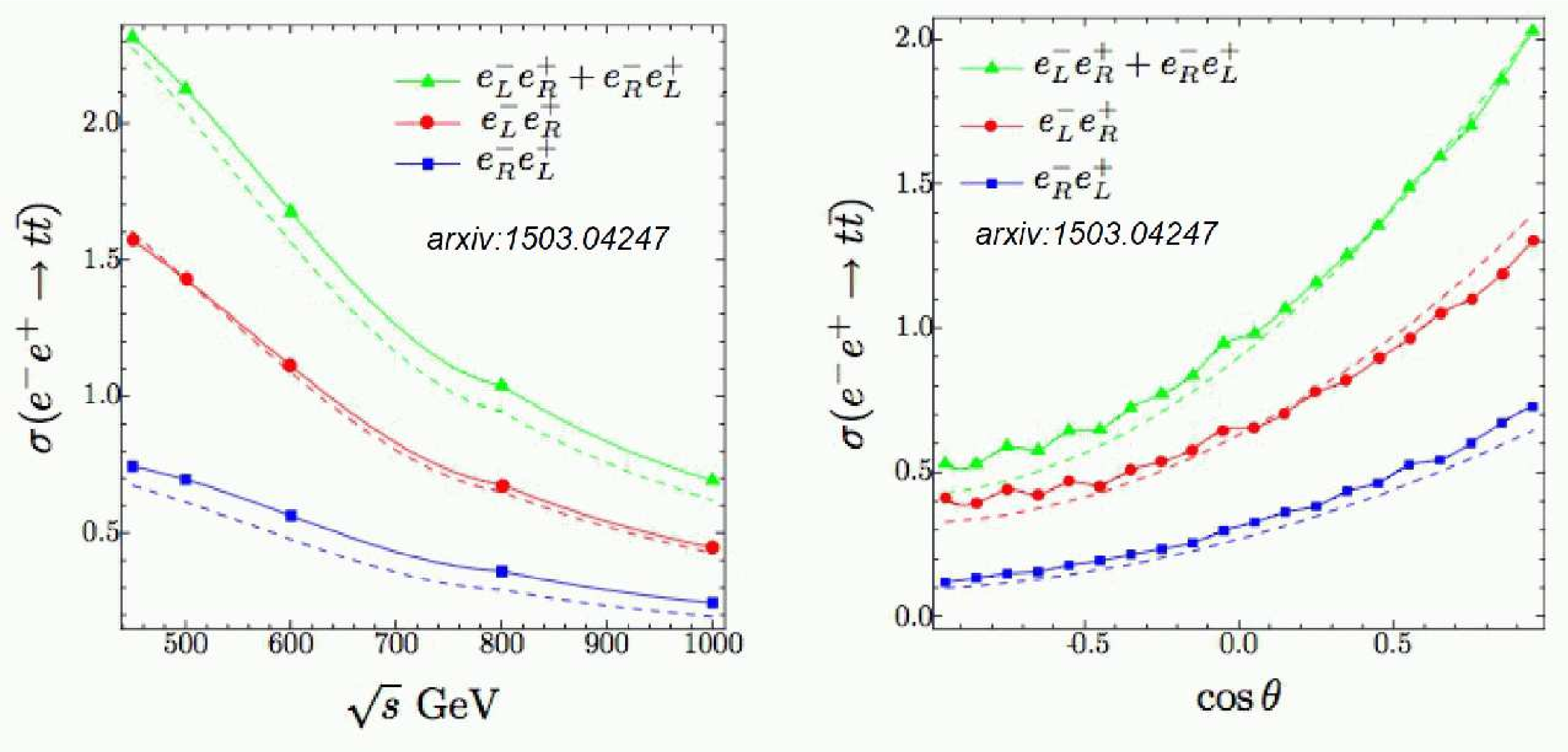
- Quickly decreasing cross section

Broad minimum between 400 and 700 GeV

$\Rightarrow$ broad minimum

$\Rightarrow$ $\sqrt{s} \sim 500$ GeV best for top coupling measurement

Polarization vs. EW higher-order corrections? [GRACE '15]

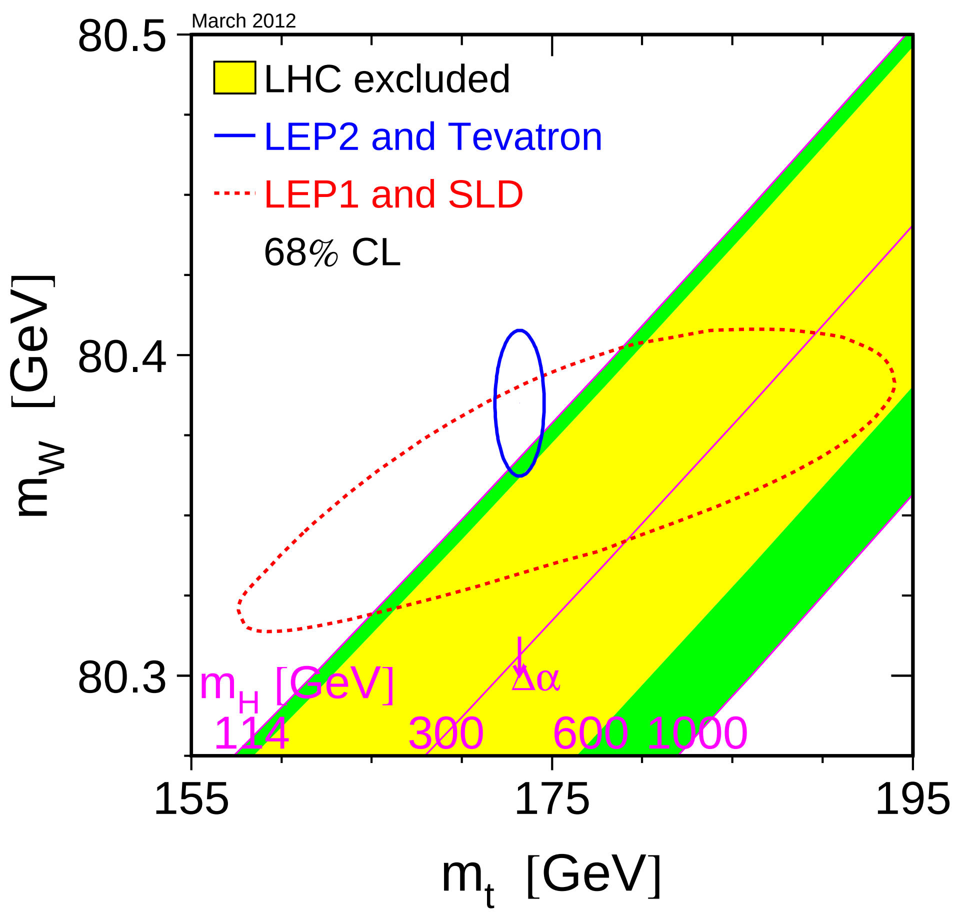


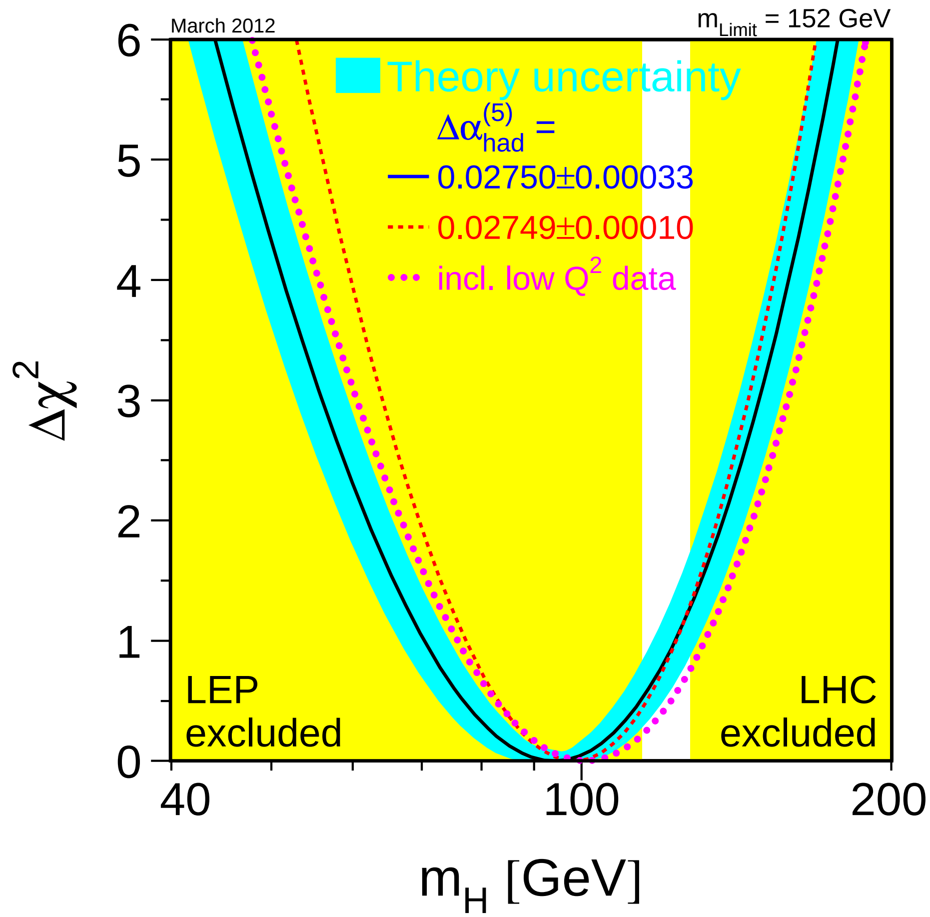
⇒ EW corrections different for different polarizations!

⇒ polarization needed to disentangle SM from new physics effects!

Precision Tests of the SM (and beyond)

⇒ indirect prediction of the Higgs mass in the SM *[LEPEWWG '12]*

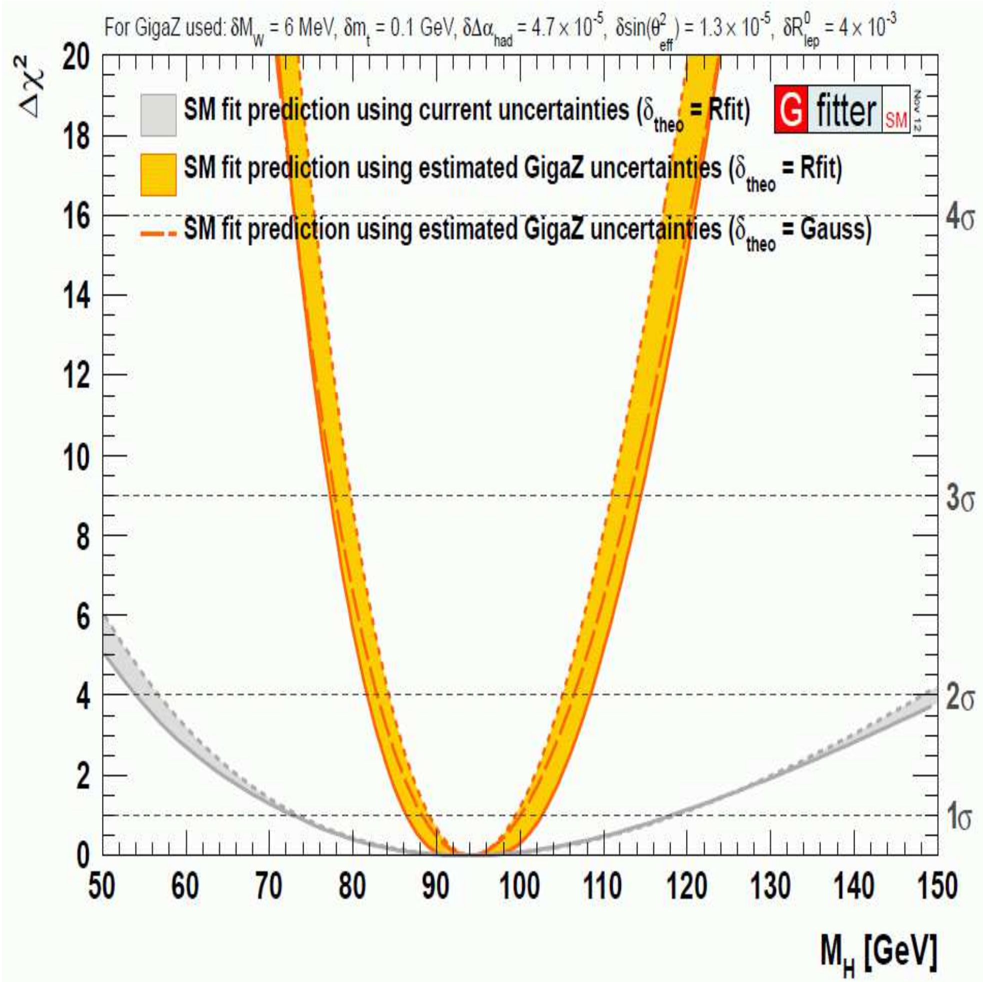


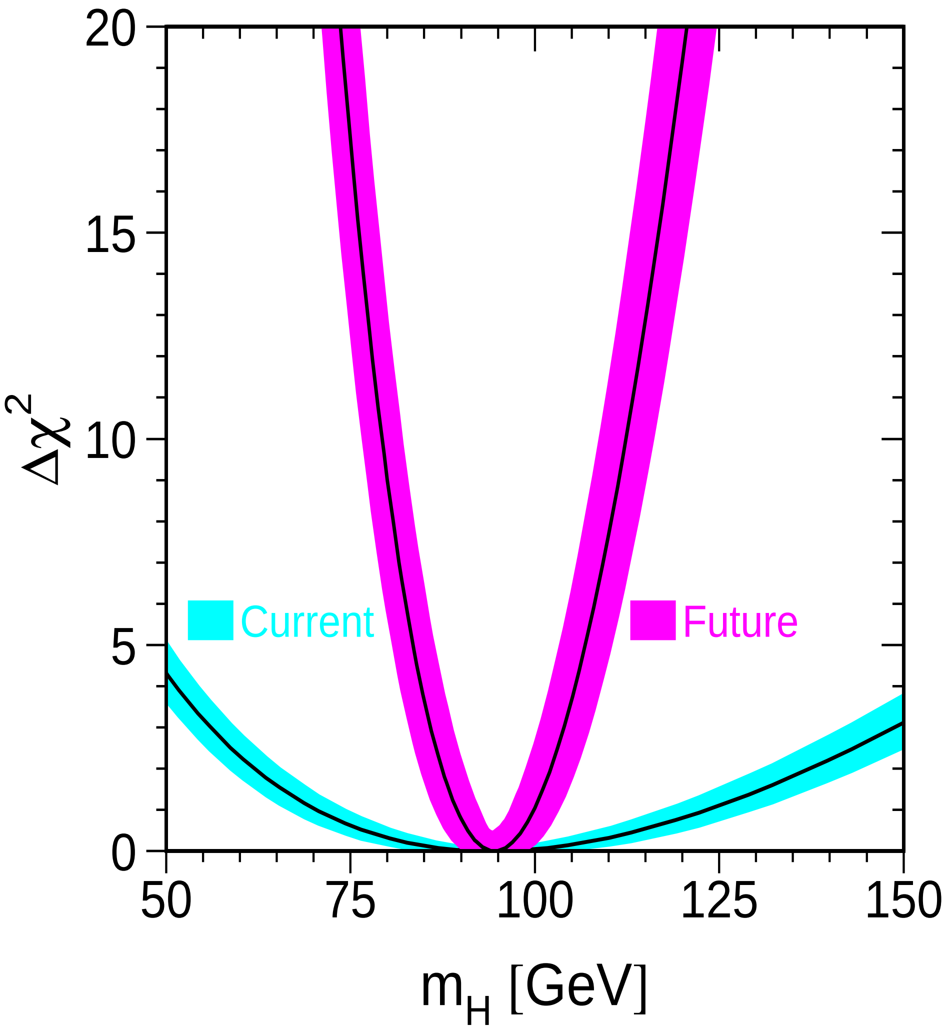


⇒ fits with today's precision

Most precise M_H test with the ILC:

[*GFitter '13*] [*LEPEWWG '13*]

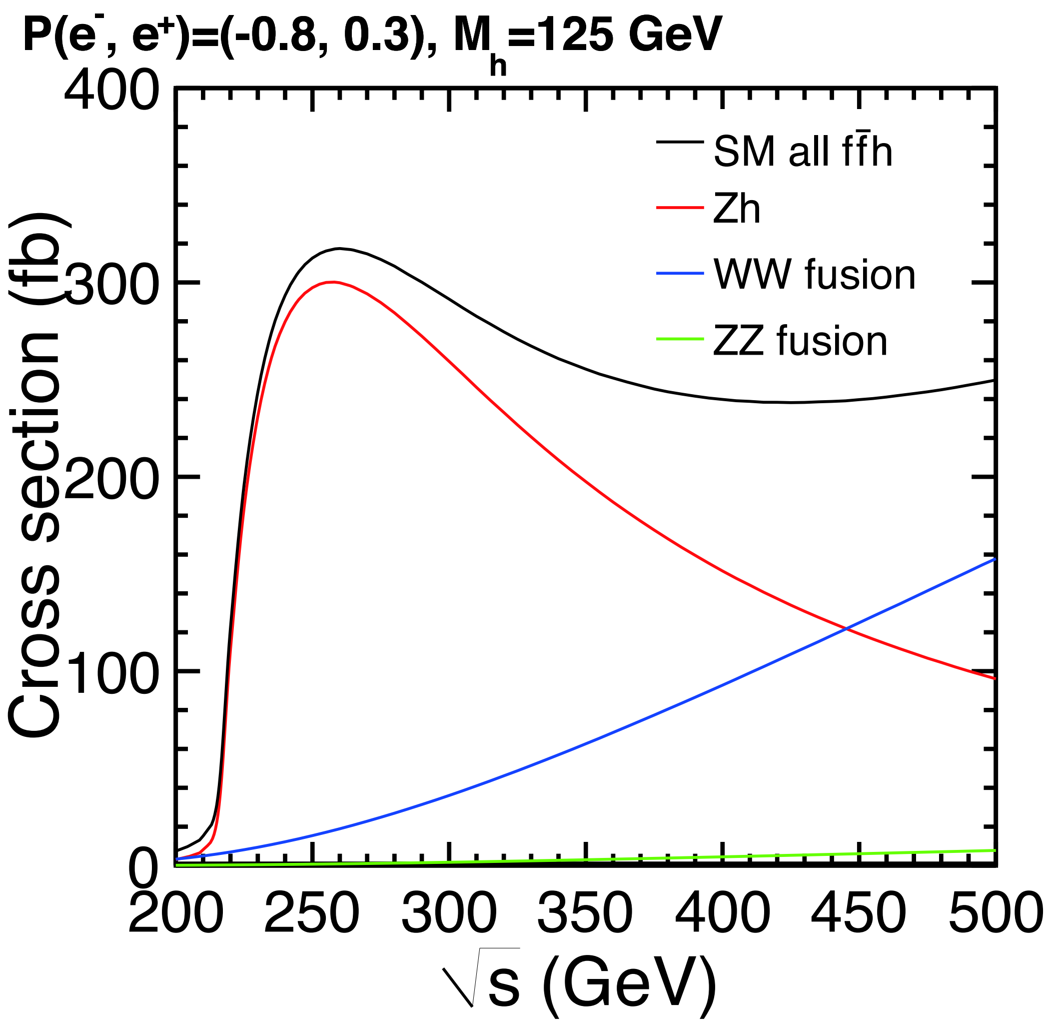




$\Rightarrow \delta M_H^{\text{ind}} \lesssim 6$ GeV $\Leftarrow$ only ILC analysis available so far

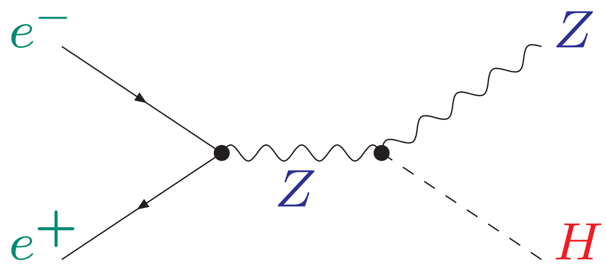
$\Rightarrow$ extremely sensitive test of SM (and BSM) possible

4. Higgs observables



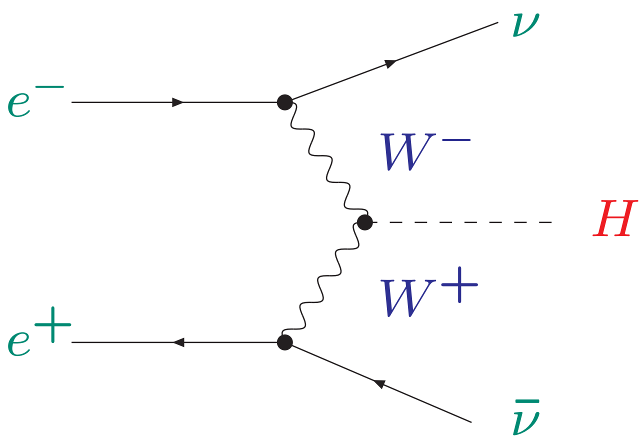
Higgs-strahlung:

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



weak boson fusion (WBF):

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



The main questions:

- What are the couplings of this particle to other known elementary particles? Is its coupling to each particle proportional to that particles mass, as required by the BEH mechanism?
- What are the mass, total width, spin and $\mathcal{CP}$ properties of this particle? Are there additional sources of $\mathcal{CP}$ violation in the Higgs sector?
- What is the value of the particles self-coupling? Is this consistent with the expectation from the symmetry-breaking potential?
- Is this particle a single, fundamental scalar as in the SM, or is it part of a larger structure? Is it part of a model with additional scalar singlets/doublets/ldots? Or, could it be a composite state, bound by new interactions?
- Does this particle couple to new particles with no other couplings to the SM ("Higgs portal")? Is the particle mixed with new scalars of exotic origin, for example, the radion of extra-dimensional models?

Required precision for M_H?

– M_H is fundamental parameter
  $\Rightarrow$ high precision measurement on its own right

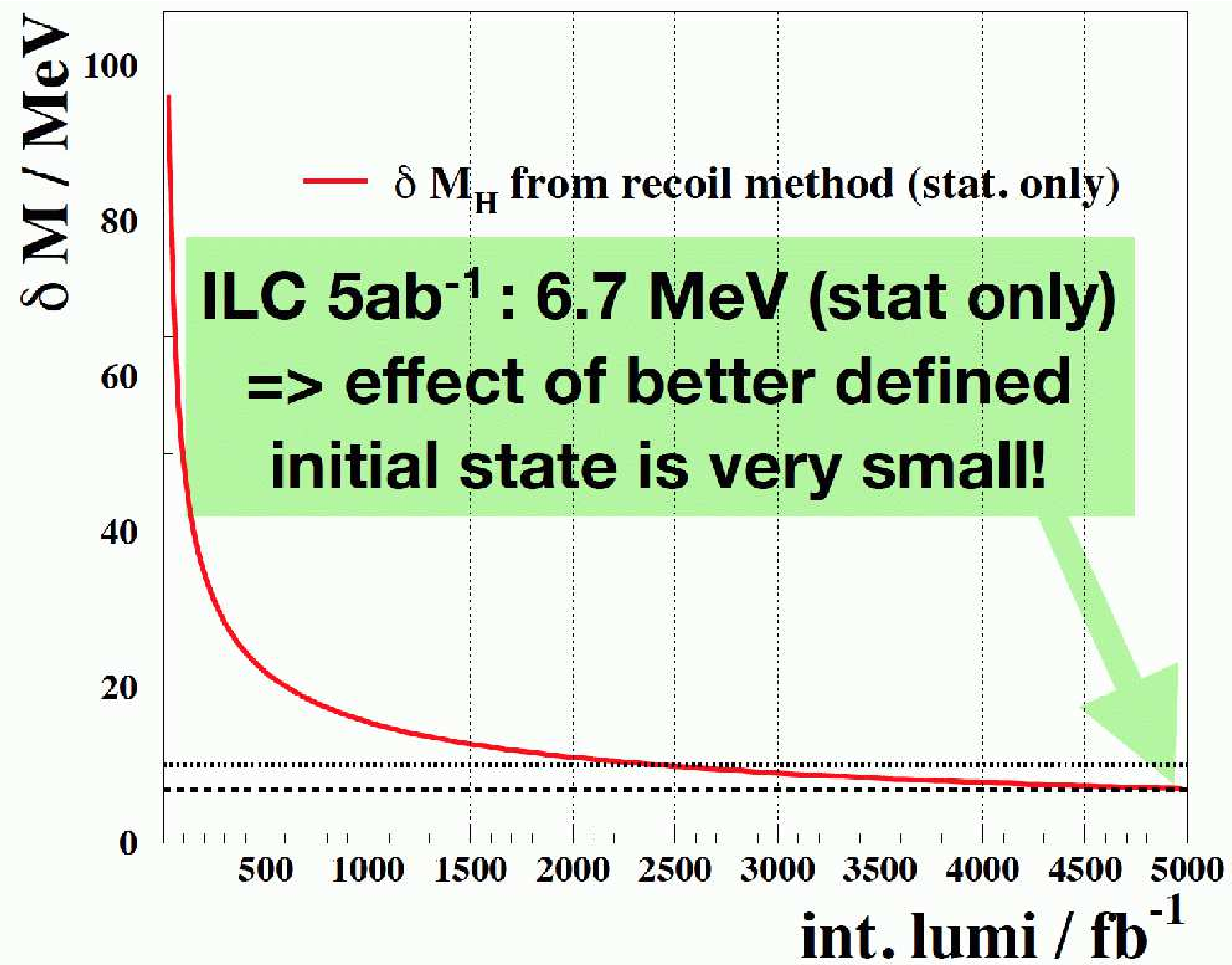
– M_H is input parameter for Higgs physics:

$$\delta M_H = 0.2 \text{ GeV} \quad \Rightarrow \quad \frac{\delta \text{BR}(H \to ZZ^*)}{\text{BR}(H \to ZZ^*)} \sim 2.5\%$$

$$\frac{\delta \text{BR}(H \to WW^*)}{\text{BR}(H \to WW^*)} \sim 2.2\%$$

$\Rightarrow \delta M_H \lesssim 0.02$ GeV desirable

M_H: circular vs. linear (beamstrahlung)?



ILC precision scaled up to CEPC luminosity: same precision

Required precision for Higgs couplings?

MSSM example:

$$\kappa_V \approx 1 - 0.5\% \left(\frac{400\ \text{GeV}}{M_A}\right)^4$$

$$\kappa_t = \kappa_c \approx 1 - \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \approx 1 + \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2$$

Composite Higgs example:

$$\kappa_V \approx 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

$$\kappa_F \approx 1 - (3-9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

⇒ couplings to bosons in the per mille range

⇒ couplings to fermions in the per cent range

⇒ the more precise the better

⇒ theory match?

Required precision for $\mathcal{CP}$-admixture?

$$\boxed{H = \cos\alpha\ \mathcal{CP}\text{-even} + \sin\alpha\ \mathcal{CP}\text{-odd}}$$

$$\mathcal{A}(X \to VV) = \frac{1}{v}\left(a_1 m_V^2 \varepsilon_1^* \varepsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$\mathcal{A}(X \to f\bar{f}) = \frac{m_f}{v} \bar{u}_2 \left(b_1 + i b_2 \gamma_5\right) u_1$$

$$f_{\mathcal{CP}} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$$

Desired precision:

gauge bosons: $f_{\mathcal{CP}} \lesssim 10^{-5}$ (loop suppressed)

fermions: $f_{\mathcal{CP}} \lesssim 10^{-2}$

Higgs coupling determination at e^+e^- collider

Some specifics: $\rightarrow$ T

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

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

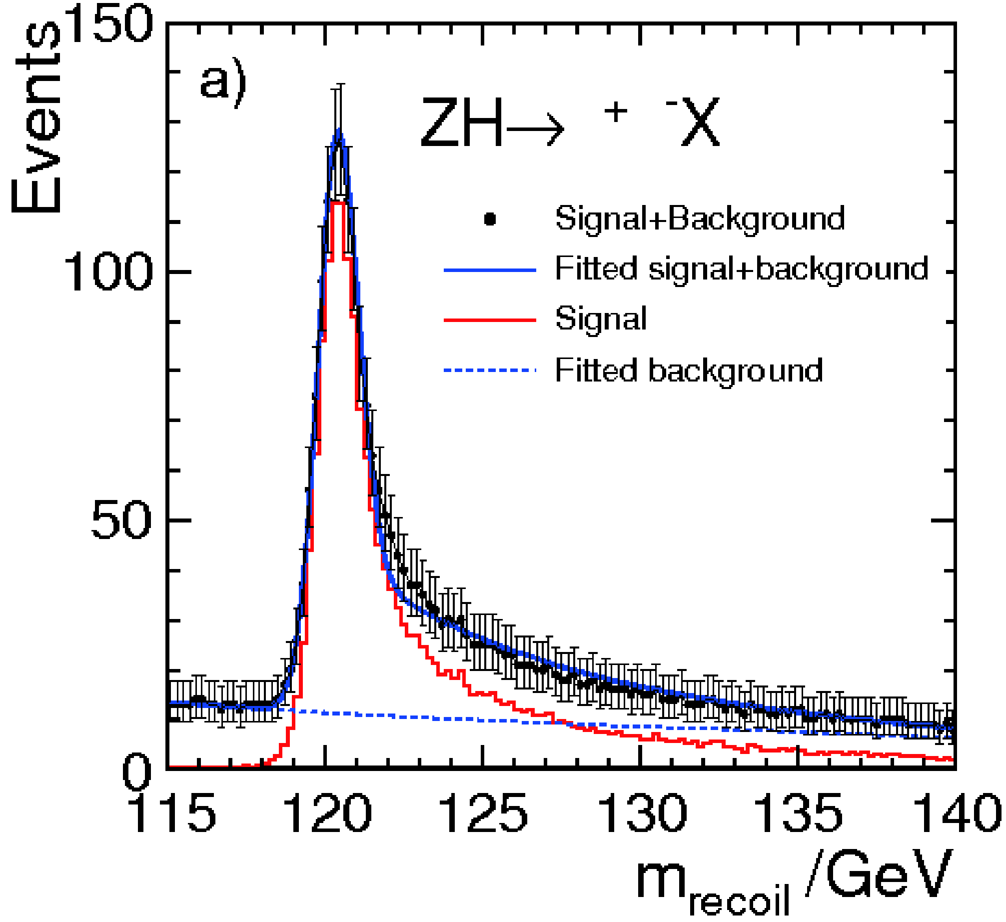
$\Rightarrow$ all observable channels can be measured with high accuracy

$\Rightarrow$ SM cross section predictions at the 1% accuracy level

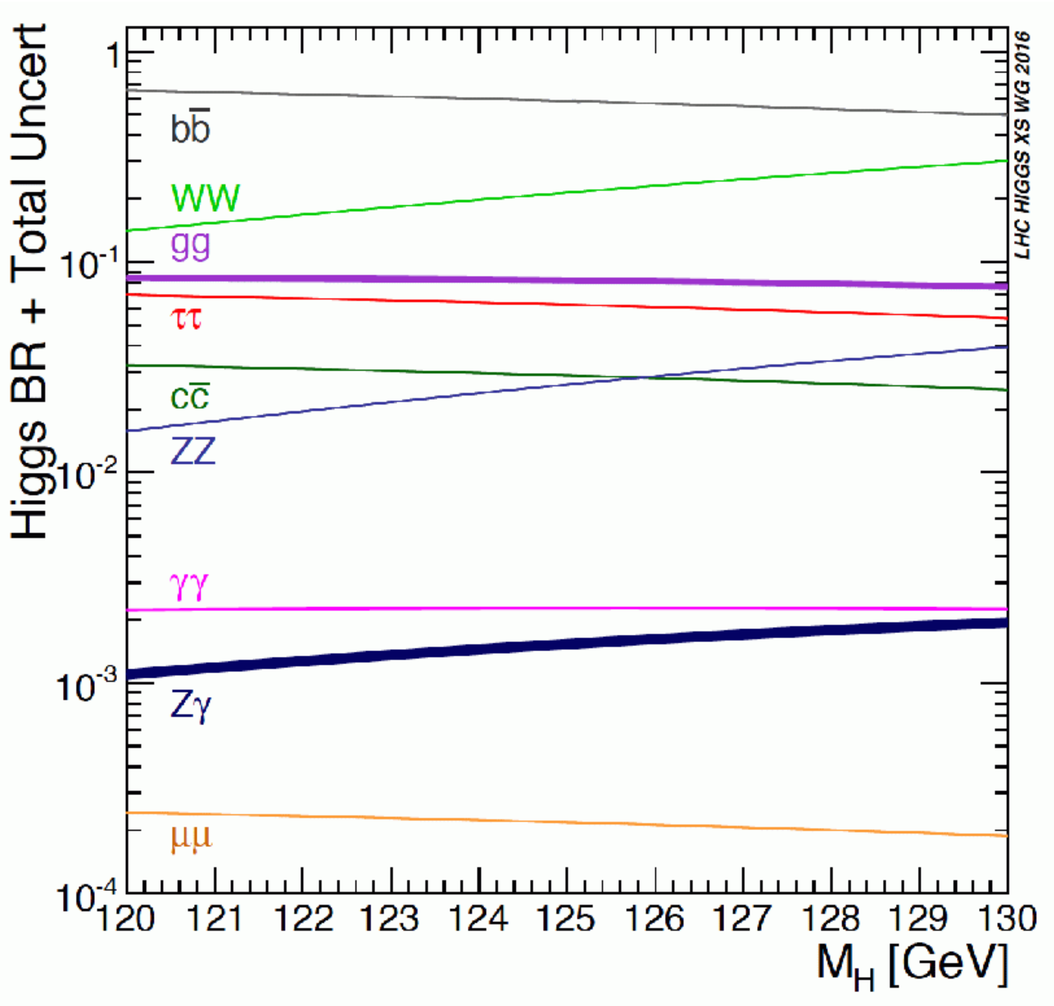
$\Rightarrow$ improvements necessary . . . full 2-loop calculations and more . . . ?!

$\Rightarrow$ concentrate on theory BR uncertainties from now on

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



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



Based on HDECAY and Prophecy4f:

$$\Gamma_H = \Gamma^{\text{HD}} - \Gamma^{\text{HD}}_{ZZ} - \Gamma^{\text{HD}}_{WW} + \Gamma^{\text{P4f}}_{4f}$$

Theoretical uncertainties: General recipe: [LHCHXSWG BR group '15]

1. Parametric Uncertainties: $p \pm \Delta p$
   - Evaluate partial widths and BRs with p, $p + \Delta p$, $p - \Delta p$ and take the differences w.r.t. central values
   - Upper ($p + \Delta p$) and lower ($p - \Delta p$) uncertainties summed in quadrature to obtain the Combined Parametric Uncertainty

2. Theoretical Uncertainties:
   - Calculate uncertainty for partial widths and corresponding BRs for each theoretical uncertainty
   - Combine the individual theoretical uncertainties linearly to obtain the Total Theoretical Uncertainty

   ⇒ estimate based on "what is included in the codes"!

3. Total Uncertainty:

   Linear sum of the Combined Parametric Uncertainty and the Total Theoretical Uncertainties

Current parametric uncertainties:

Parameter	Central value	$\overline{\text{MS}}$ masses	Uncertainty
$\alpha_s(M_Z)$	0.118		± 0.0015
m_c	1.403 GeV	$m_c(3\text{ GeV}) = 0.986$ GeV	± 0.026 GeV
m_b	4.505 GeV	$m_b(m_b) = 4.18$ GeV	± 0.03 GeV
m_t	172.5 GeV	$m_t(m_t) = 162.7$ GeV	± 0.8 GeV

Uncertainties: "consensus" of LHCHXSWG

$\Rightarrow$ strong improvement with e^+e^- data!

But: m_b uncertainty remains crucial

$\Rightarrow$ anticipated lattice data much more optimistic ...

$\Rightarrow$ but no consensus, not even in the lattice community ...?!

Current theoretical uncertainties:

[LHCHXSWG BR group '15]

Partial Width	QCD	Electroweak	Total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$ for $M_H \lesssim 500$ GeV	$\sim 0.5\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$ for $M_H \lesssim 500$ GeV	$\sim 0.5\%$
$H \to t\bar{t}$	$\lesssim 5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 5\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$

– QCD corrections: scale change by factor 2 and 1/2
– EW corrections: missing HO estimation based on the known structure and size of the NLO corrections
– Different uncertainties on a given channel added linearly

$\Rightarrow$ Strong improvement in $\sim$ 20 years possible, but . . .
. . . they have to be consistently implemented into codes!
$\Rightarrow$ intrinsic uncertainty can/will be sufficiently under control?!

Current uncertainties on decay widths:

[LHCHXSWG YR4]

Channel	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to b\bar{b}$	2.38	−1.4% +1.4%	+1.7% −1.7%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
$H \to \tau^+\tau^-$	$2.56{\cdot}10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+0.5% −0.5%
$H \to \mu^+\mu^-$	$8.90{\cdot}10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+0.5% −0.5%
$H \to c\bar{c}$	$1.18{\cdot}10^{-1}$	−1.9% +1.9%	−0.0% −0.0%	+5.3% −5.2%	+0.0% −0.0%	+0.5% −0.5%
$H \to gg$	$3.35{\cdot}10^{-1}$	+3.0% −3.0%	−0.1% +0.1%	+0.0% −0.0%	−0.1% +0.1%	+3.2% −3.2%
$H \to \gamma\gamma$	$9.28{\cdot}10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
$H \to Z\gamma$	$6.27{\cdot}10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%
$H \to WW^*$	$8.74{\cdot}10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
$H \to ZZ^*$	$1.07{\cdot}10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%

Data available for $M_H = 124$ GeV, 125 GeV, 126 GeV

⇒ substantially larger than κ precision at ILC/FCC-ee

Full BR uncertainty overview: [LHCHXSWG YR3]

Still YR3 data, no update

$M_H = 126$ GeV			
Decay	TU [%]	PU [%]	Total [%]
$H \to \gamma\gamma$	±2.7	±2.2	±4.9
$H \to b\bar{b}$	±1.5	± 1.9	±3.3
$H \to \tau\tau$	±3.5	±2.1	±5.6
$H \to WW$	±2.0	±2.2	±4.1
$H \to ZZ$	±2.0	±2.2	±4.2

Parametric uncertainties: largely driven by m_b ("in the denominator")

$\Rightarrow$ not sufficient to meet κ goals

Future theory uncertainties?

Parametric uncertainties:

– largely driven by δm_b $\Rightarrow$ improvement unclear (to me)
  lattice community does not seem to agree

– some improvement in α_s possible

Intrinsic uncertainties:

$H \to b\bar{b}, H \to c\bar{c}$: higher-order EW corrections ??

$H \to \tau^+\tau^-, H \to \mu^+\mu^-$: higher-order EW corrections ?

$H \to gg$: improvement difficult

$H \to \gamma\gamma$: already very precise ...

$H \to Z\gamma$: EW corrections could help ...

$H \to WW^*, H \to ZZ^*$: already very precise, two-loop corrections unclear

$\Rightarrow$ intrinsic uncertainty can/will be sufficiently under control?!

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN RWTH

Input Parameters

Lepage, Mackenzie, Peskin [arXiv:1404.0319]

- How well can the Higgs BRs be predicted in the future?
- Limitation due to parametric errors?
- use lattice gauge theory to improve α_s, m_b, and m_c

(e.g. using current-current correlators)

(stated errors already now quite small)

- optimistic projection for lattice improvements:

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

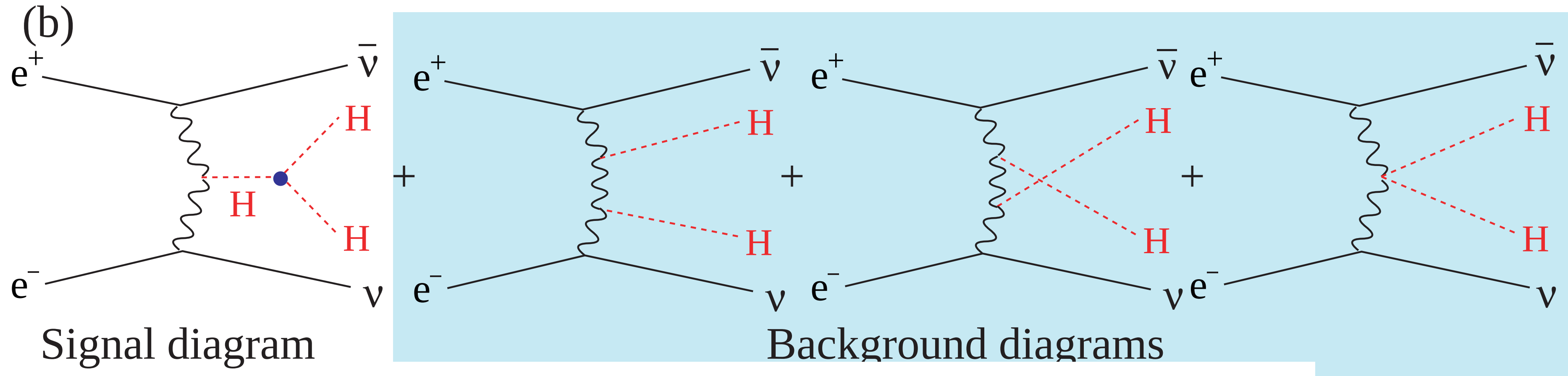
(errors in %)

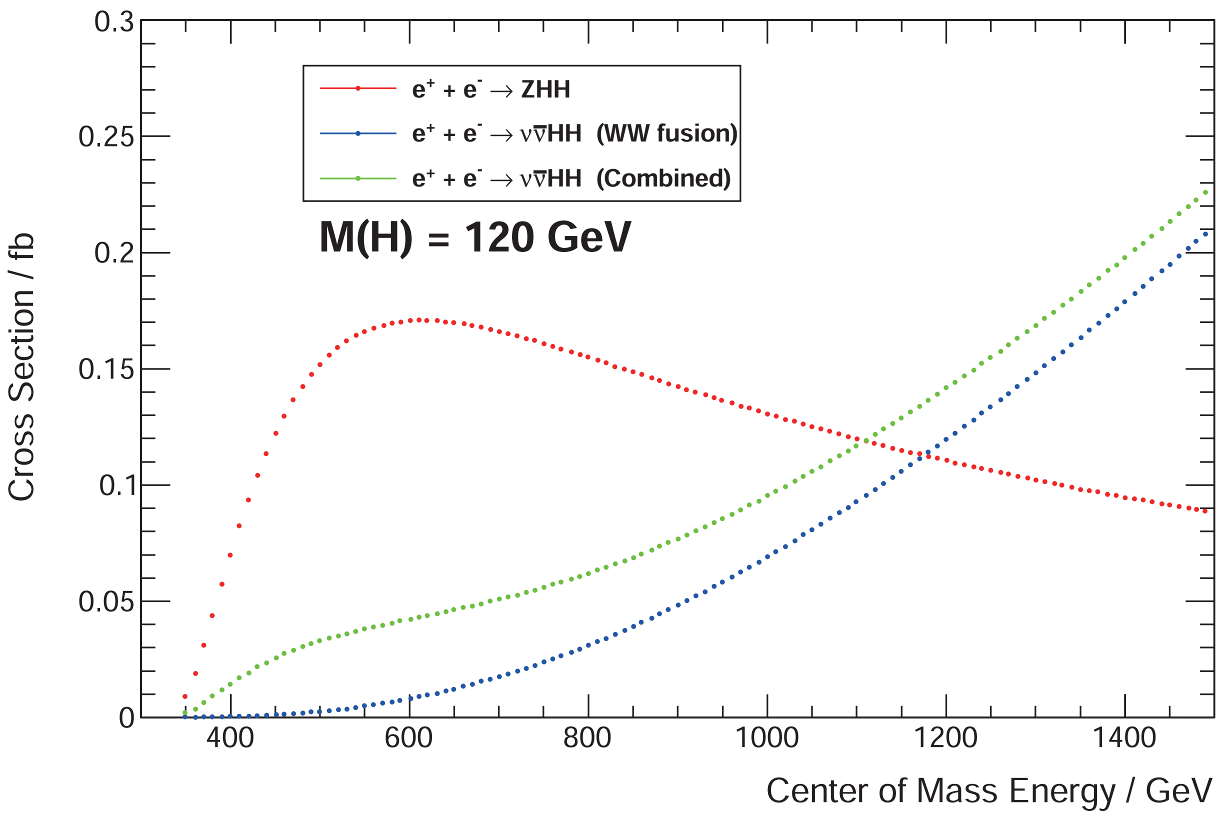
time-scale: 10-15 years

⇐ | ←→ | ⇒ BR report – Alexander Mück – p.7/ 13

Particularly challening: Higgs self-coupling

[ILC TDR '13]





Desired precision in λ?

$\Rightarrow$ highly model dependent

Examples: [*R. Gupta, H. Rzehak, J. Wells '13*]

- Higgs singlet extension: $(\Delta\lambda/\lambda)^{\mathrm{max}} \sim -18\%$
- Composite Higgs models: $(\Delta\lambda/\lambda)^{\mathrm{max}} \sim +20\%$
- MSSM: $(\Delta\lambda/\lambda)^{\mathrm{max}} \lesssim -15\%$
- NMSSM: $(\Delta\lambda/\lambda)^{\mathrm{max}} \lesssim -25\%$

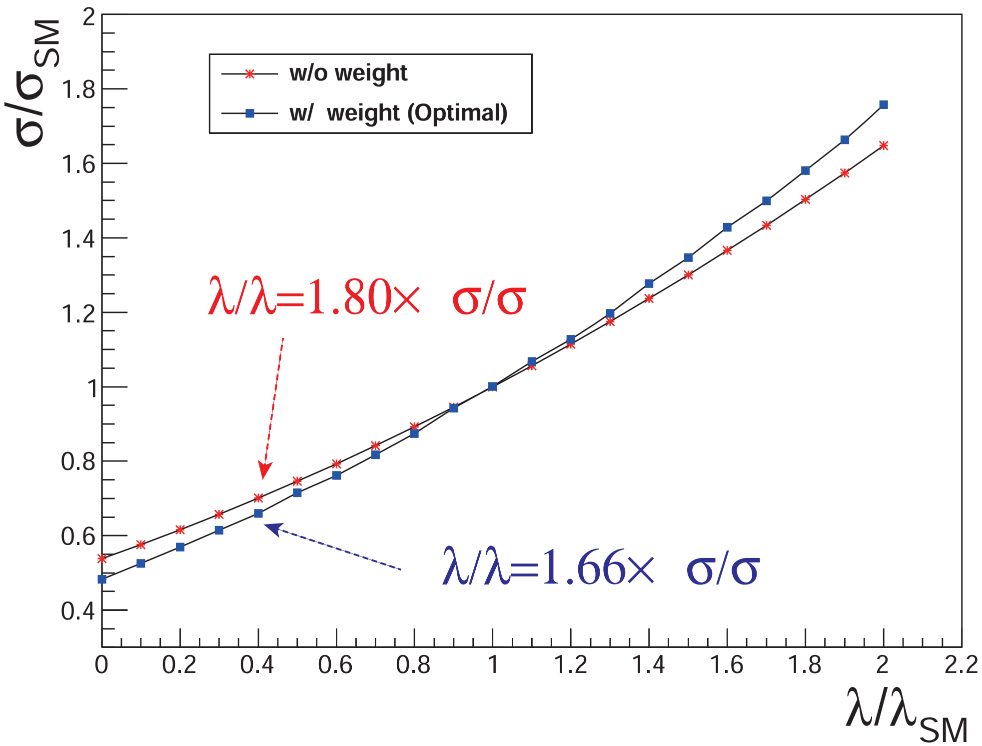
Decoupling leads to non-vanishing effects!

But we want to test "confirm" the SM value in the first place!

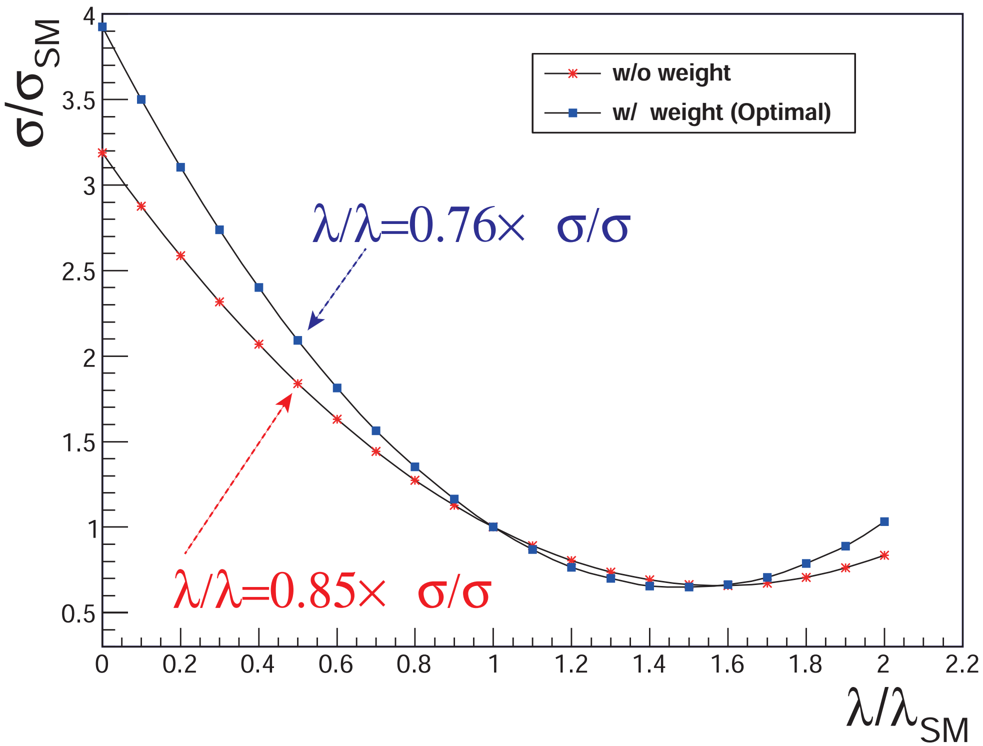
Sensitivity to triple Higgs coupling λ:

[taken from K. Fuji '13]

ZHH@500 GeV

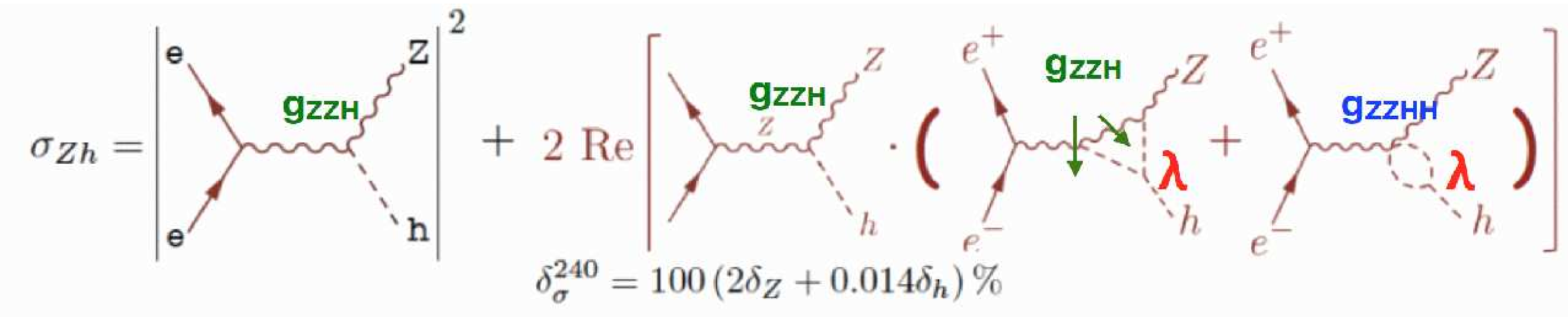


$\nu\bar{\nu}HH$@1000 GeV



$\Rightarrow$ desirable: at least $\sqrt{s} \sim 500$ GeV
high luminosity

Higgs self-coupling from loop corrections? [arXiv:1312.3322]



⇒ sensitivity to λ_{HHH} goes down for higher $\sqrt{s}$

⇒ percent precision possible on σ_{ZH}, λ_{HHH}

⇒ indirect and model dependent measurement
(to be included in a global coupling fit - within a model)

⇒ $\mathcal{O}\,(10\%)$ measurement of λ_{HHH} needed
to measure σ_{HZ} at the percent level!

5. Conclusions

- Experimental precision must be matched with theory precision!
- EWPO can give valuable information about SM, BSM
  $\rightarrow$ only SM, MSSM "ready", more needed $\Rightarrow$ TH input/effort needed!
  Most relevant: M_W, $\sin^2\theta_{\rm eff}$, m_t, $\Delta\alpha_{\rm had}$, ...
  Extraction from experiment? $\Rightarrow$ TH input/effort needed!
- Current theory uncertainties of M_W, $\sin^2\theta_{\rm eff}$ not sufficient
  Future theory uncertainties: not sufficient! $\Rightarrow$ TH input/effort needed!
  $\Delta\alpha_{\rm had}$: could be the limiting factor
- Top quark mass: mainly theory driven, α_s crucial!
  $\Rightarrow$ TH input/effort needed!
- Higgs couplings: XS and BR have to be under control
  Can sub-percent/permille level be reached?
  - XS: 1% possible, full 2-loop calculations needed?!
  - BR: intrinsic uncertainties could be brought down below 1%
    parametric uncertainties (m_b) have (to me) unclear perspective

  $\Rightarrow$ TH input/effort needed!


Further Questions?

Options for the evaluation of intrinsic uncertainties:

1. Take the known contribution at n-loop and $(n-1)$-loop and thus estimate the $n+1$-loop contribution:

$$\frac{(n+1)^{(\text{estimated})}}{n^{(\text{known})}} \approx \frac{n^{(\text{known})}}{(n-1)^{(\text{known})}}$$

   $\Rightarrow$ simplified example! Has to be done
   "coupling constant by coupling constant"

2. Variation of $\mu^{\overline{\text{DR}}}$ (QCD, EW!)

3. Compare different renormalizations

4. ???

Corrections to M_W, $\sin^2\theta_{\text{eff}}$ → approximation via the ρ-parameter:

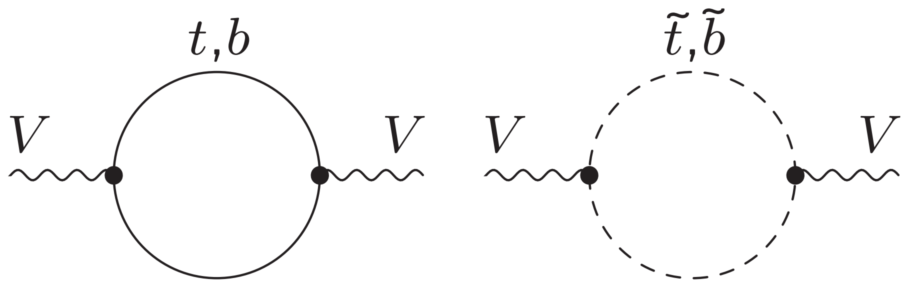
ρ measures the relative strength between
neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta\rho} \qquad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

(leading, process independent terms)

$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2} \frac{c_W^2}{c_W^2 - s_W^2} \Delta\rho, \qquad \Delta \sin^2\theta_W^{\text{eff}} \approx -\frac{c_W^2 s_W^2}{c_W^2 - s_W^2} \Delta\rho$$



$\Delta\rho^{\text{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\Rightarrow M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$, $\sin^2\theta_{\text{eff}}^{\text{SUSY}} \lesssim \sin^2\theta_{\text{eff}}^{\text{SM}}$

$\Delta\rho^{\rm SUSY}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\Rightarrow M_W^{\rm SUSY} \gtrsim M_W^{\rm SM}$, $\sin^2\theta_{\rm eff}^{\rm SUSY} \lesssim \sin^2\theta_{\rm eff}^{\rm SM}$

SM result for M_W and $\sin^2\theta_{\rm eff}$:

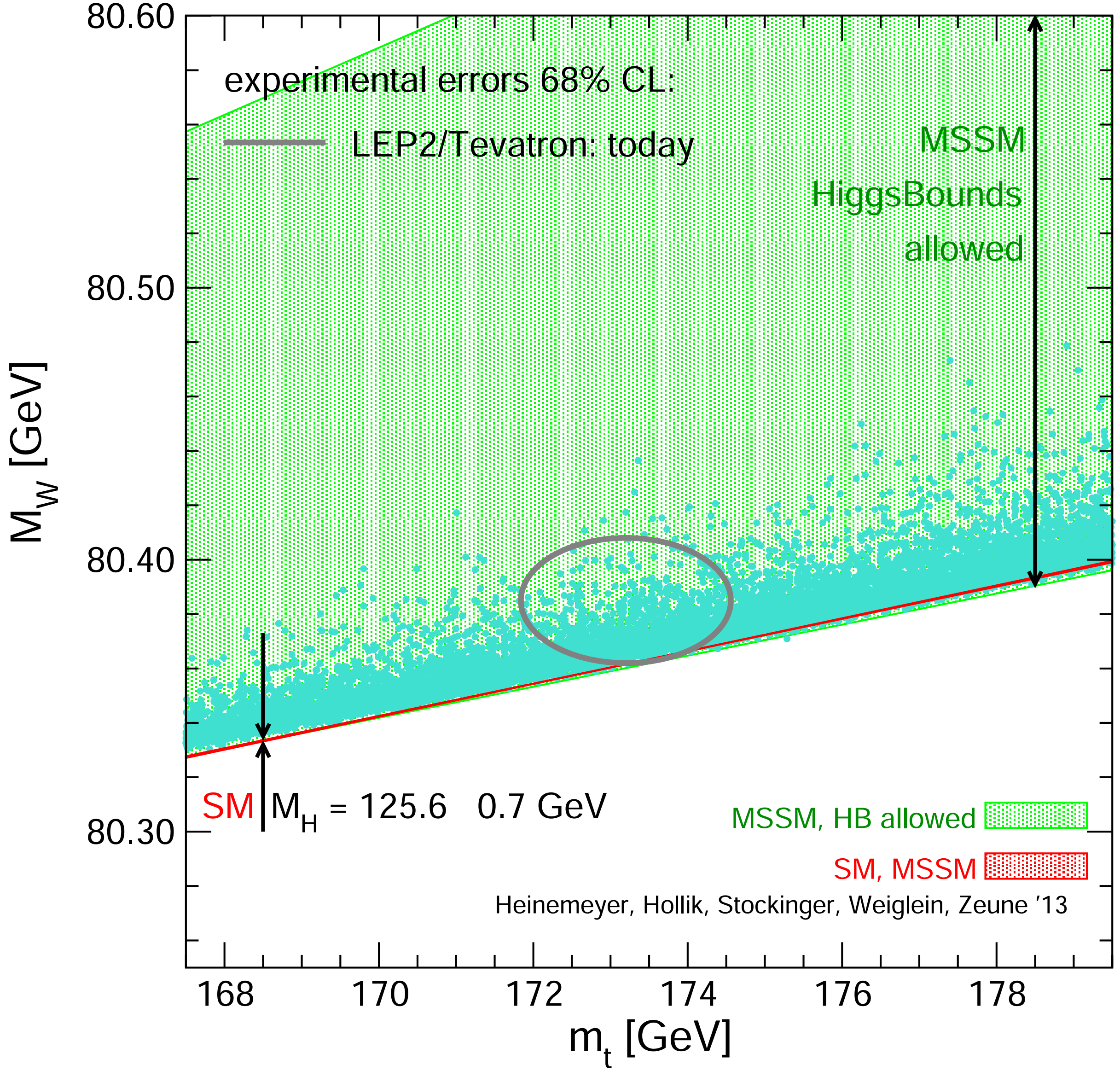
- full one-loop
- full two-loop
- leading 3-loop via $\Delta\rho$
- leading 4-loop via $\Delta\rho$

Our MSSM result for M_W and $\sin^2\theta_{\rm eff}$:

- full SM result (via fit formel)
- full MSSM one-loop (incl. complex phases)
- all existing two-loop $\Delta\rho$ contributions

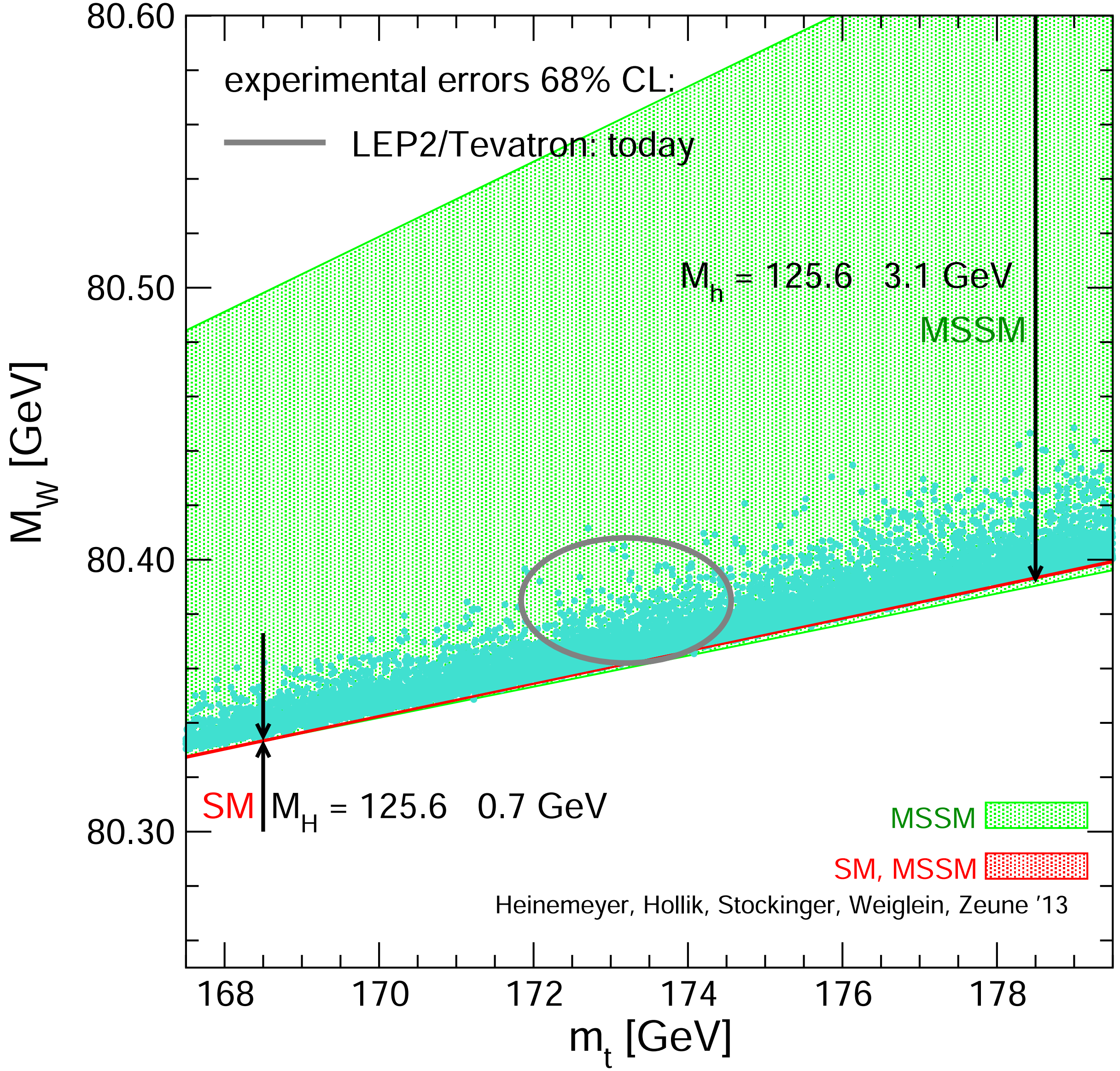
$\Rightarrow$ non-$\Delta\rho$ one-loop and $\Delta\rho$ two-loop contributions sometimes non-negligible!

Scenario 1: Effects of stops, sbottoms, M_h:



light blue: $m_{\tilde{t}_i}, m_{\tilde{b}_j} > 500$ GeV, $m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

Scenario 1: Effects of stops, sbottoms, M_h:



light blue: $m_{\tilde{t}_i}, m_{\tilde{b}_j} > 500$ GeV, $m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

Higgs observables: Higgs couplings

LHC always measures $\sigma \times$ BR

$\Rightarrow$ Total width $\Gamma_{H,\text{tot}}$ cannot be measured without further theory assumptions.

Recommendation of the LHCHXSWG:

$\Rightarrow$ Higgs coupling strength scale factors: κ_i
For each benchmark (except overall coupling strength) various versions are proposed:
with and without additinal theory assumptions

– no additional theory assumptions:

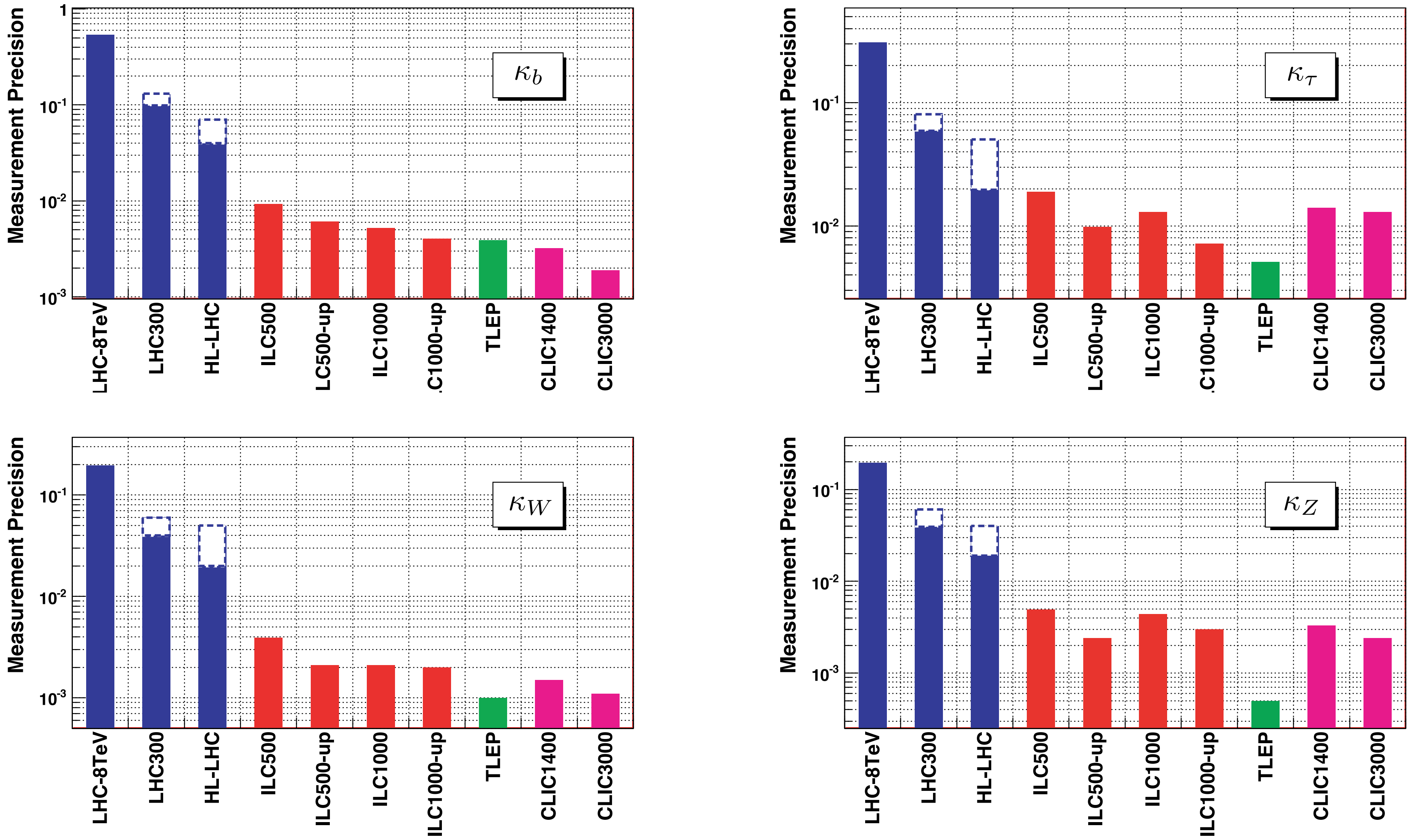
$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

– additional theory assumptions (on $\Gamma_{H,\text{tot}}$ or $\kappa_{W,Z}$ or $H \to$ NP)

$\Rightarrow$ Determination of κ_i (evaluated to NLO QCD accuracy)

ILC vs. FCC-ee/FCC-ee:

[*Snowmass Higgs Report '13*]

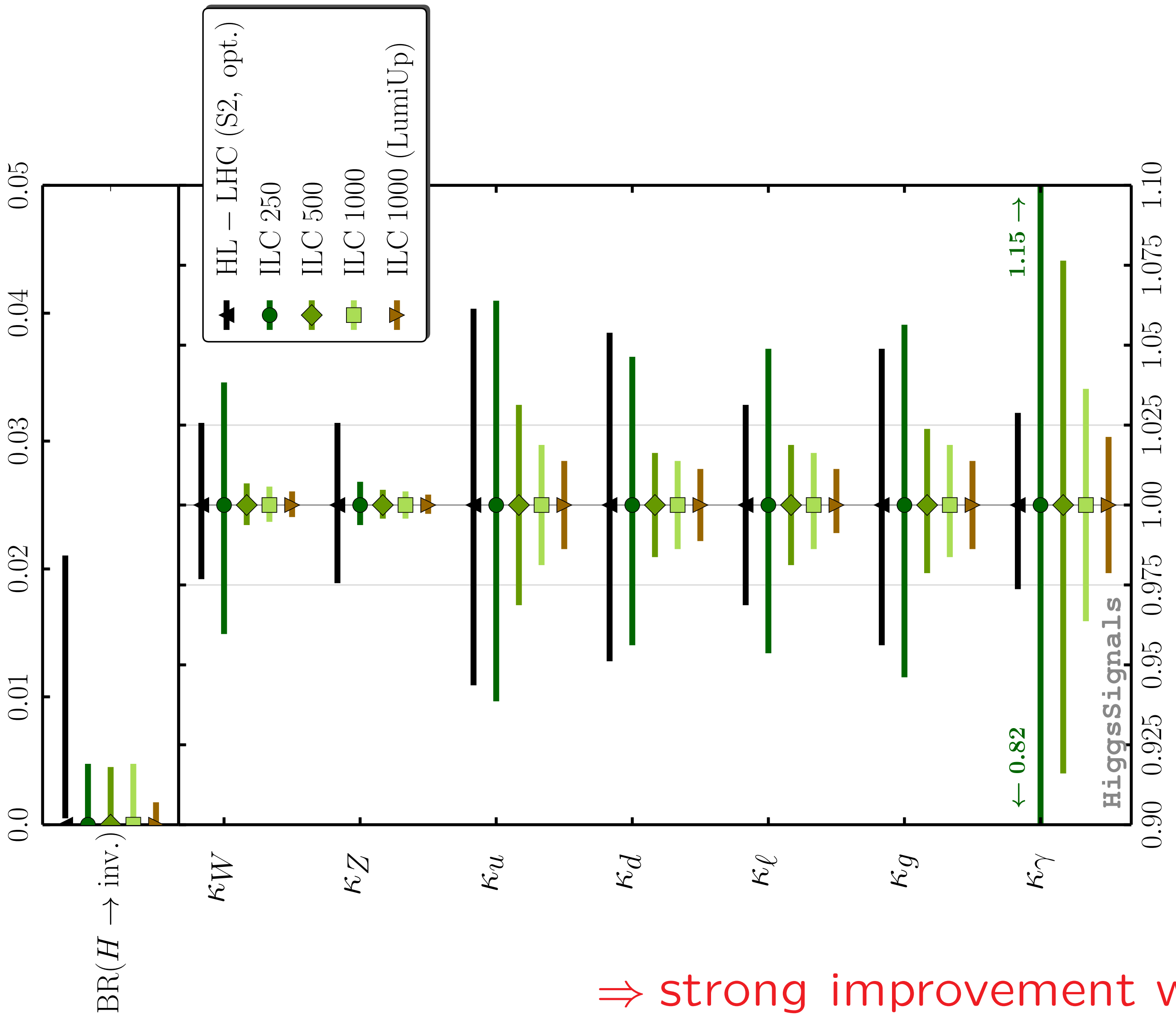


⇒ can the sub-percent/permille level be matched by theory?

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

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

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

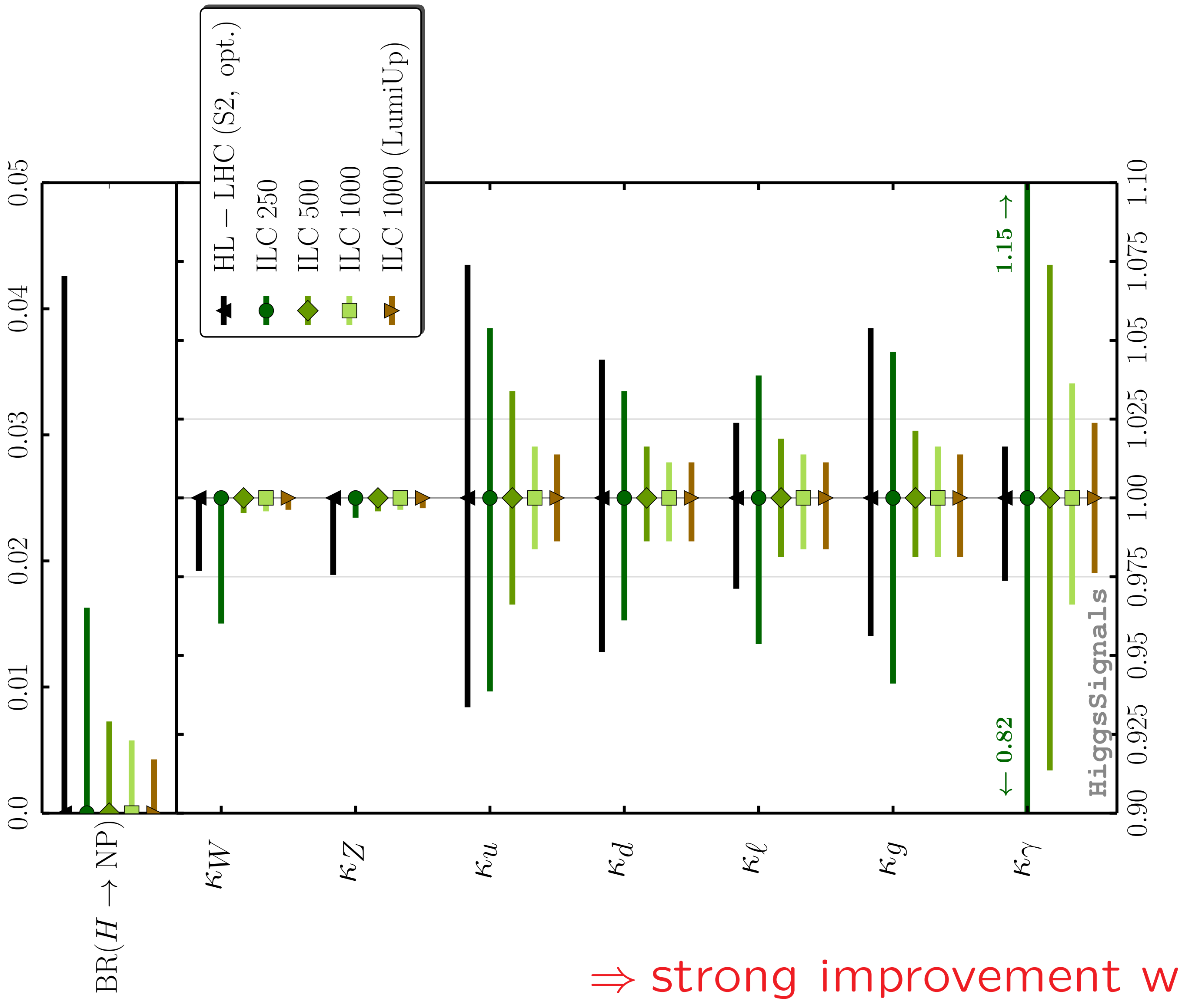


⇒ strong improvement with the ILC

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

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

assumption: $\kappa_V \leq 1$

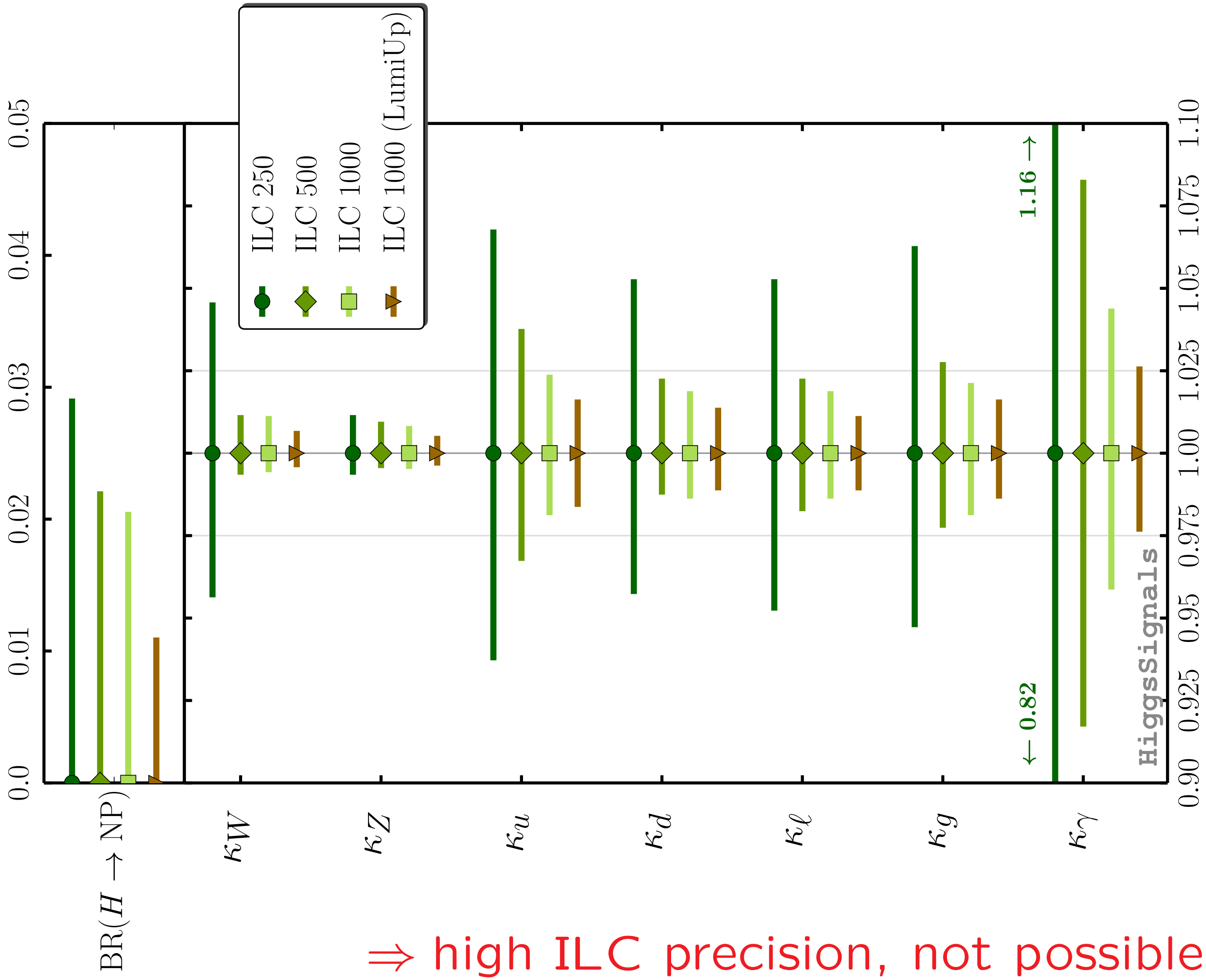


$\Rightarrow$ strong improvement with the ILC

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

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

no theory assumptions, full fit

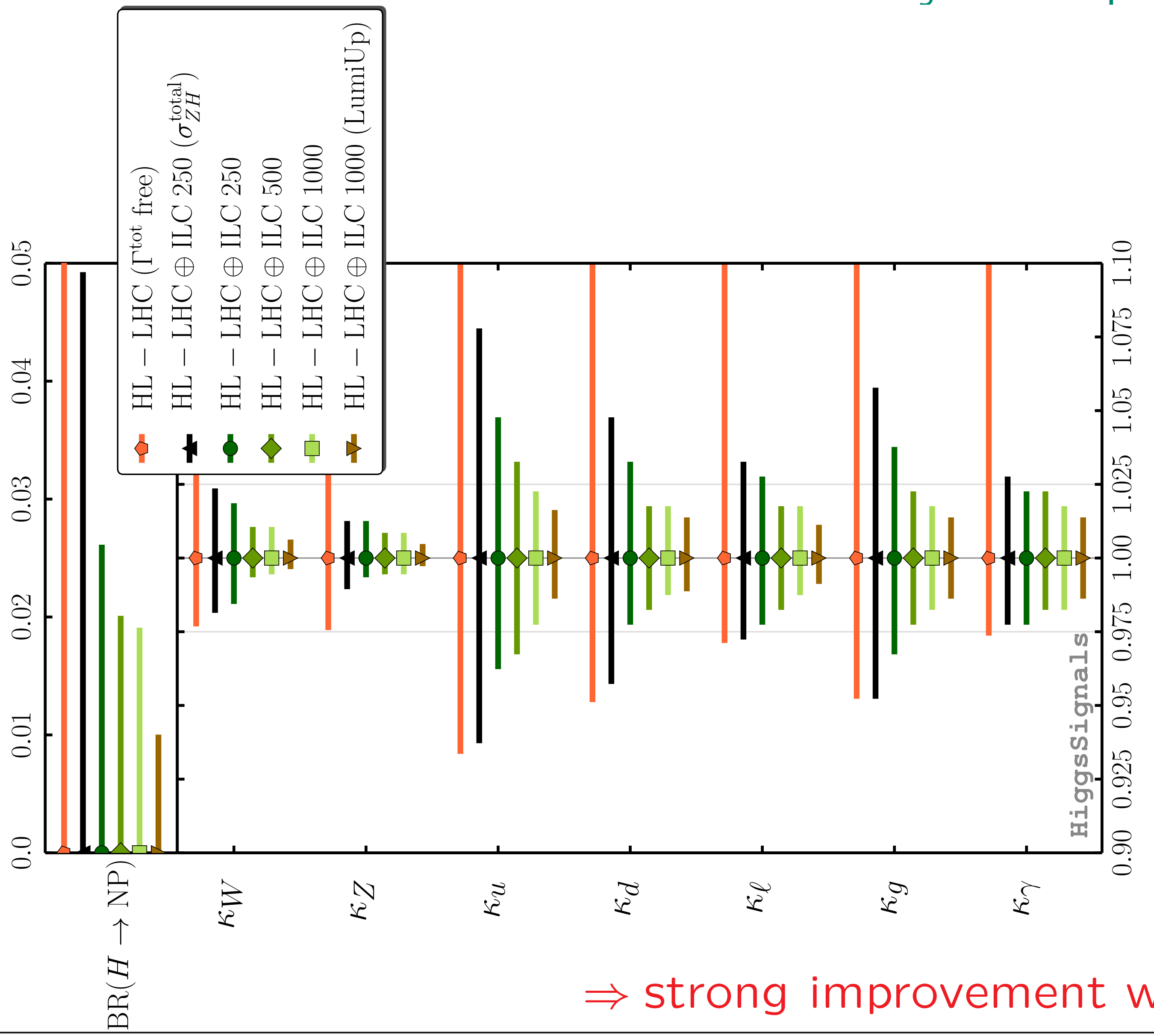


$\Rightarrow$ high ILC precision, not possible at the LHC

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



⇒ strong improvement with the ILC