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Physics at the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

Abingdon, 11/2014

1. The bigger picture
2. Physics we can do for sure at the ILC
3. Physics we can do likely at the ILC
4. How to go ahead in the next 10 years?

1. The bigger picture

The ILC could start operations in the middle of the next decade

World of High Energy Physics in the year ~ 2025:

LHC detectors (ATLAS/CMS) will have accumulated $\sim 300\,\text{fb}^{-1}$

Initial LHC physics goals are accomplished:

– state compatible with a Higgs found
  corresponding couplings (ratios) measured to 5–30%
– SUSY-like signatures observed (if realized at the EW scale)
  (or not ...???)
– Extra dimensions or ...-like signatures observed
  (or not ...???)

LHC probably awaits luminosity upgrade

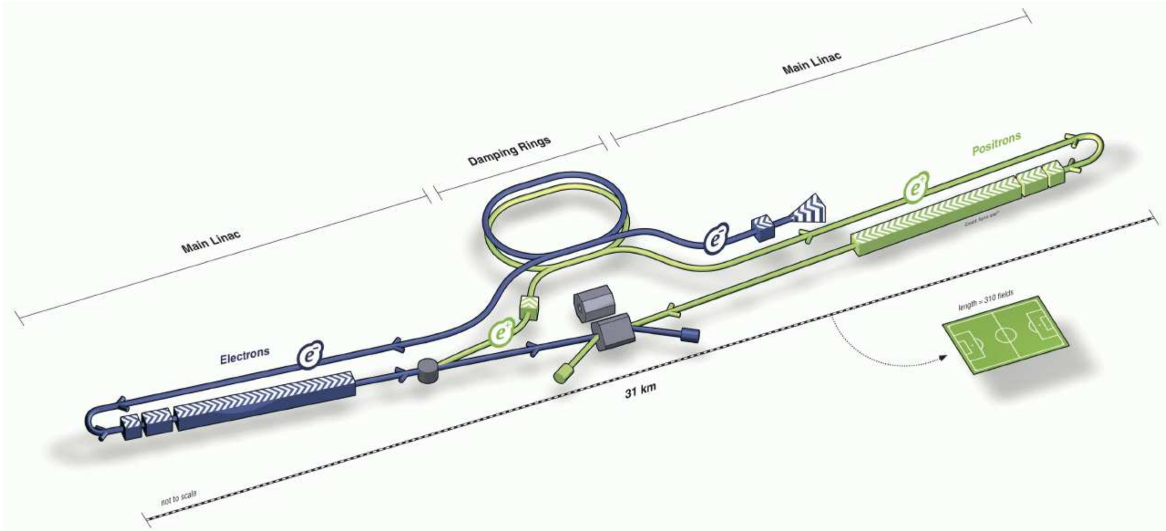
What can the ILC add?

⇒ Implicit in the physics to follow!

Linear e^+e^- collider, $\sqrt{s} = 250 - 1000$ GeV

based on superconducting cavities (cold technology)

Schematic:



Energies: $\sqrt{s} = 250$ GeV, 350 GeV, 500 GeV . . . 1000 GeV

Possible features:

– two detectors in one interaction region (push-pull)
– undulator based e^+ source
– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)
– tunable energy

Other ILC options:

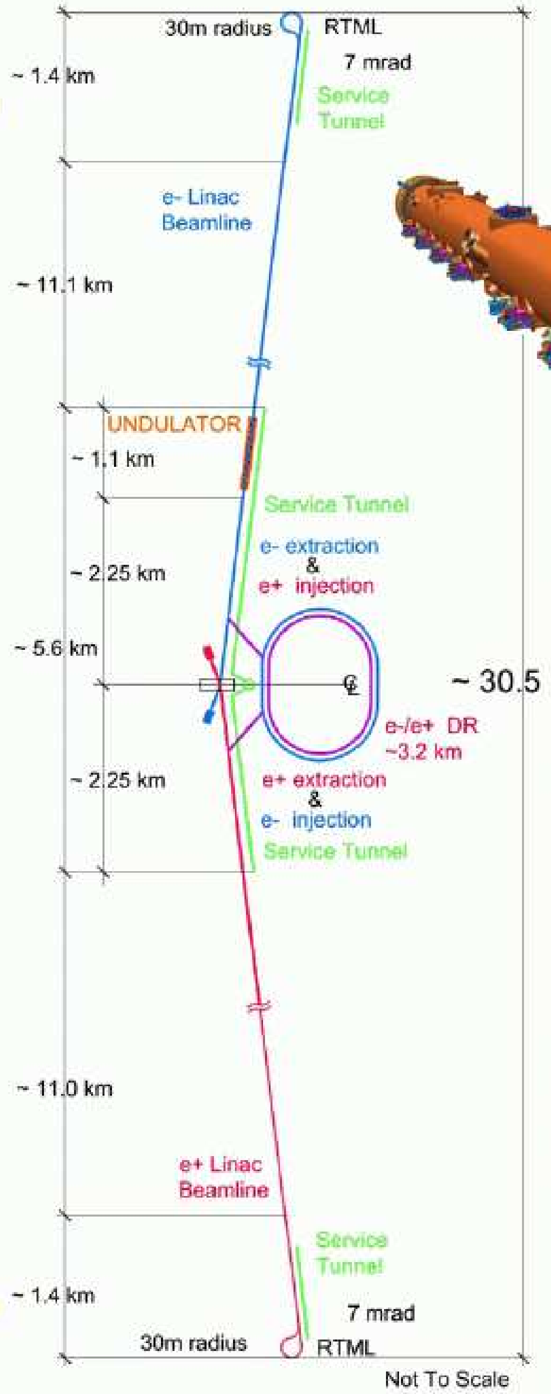
- GigaZ:
  running with high luminosity at low energies (Z pole, WW threshold)

- $\gamma\gamma$:
  use both beams to produce high-energy photons
  (e.g. heavy Higgs production in the s channel, $\Gamma(H \to \gamma\gamma)$, . . .)

- $e^-\gamma$:
  use one e^- beam to produce high-energy photons
  produce charged particles in the s channel

- e^-e^-:
  produce doubly charged particles in the s channel

$\Rightarrow$ to optimize physics potential!

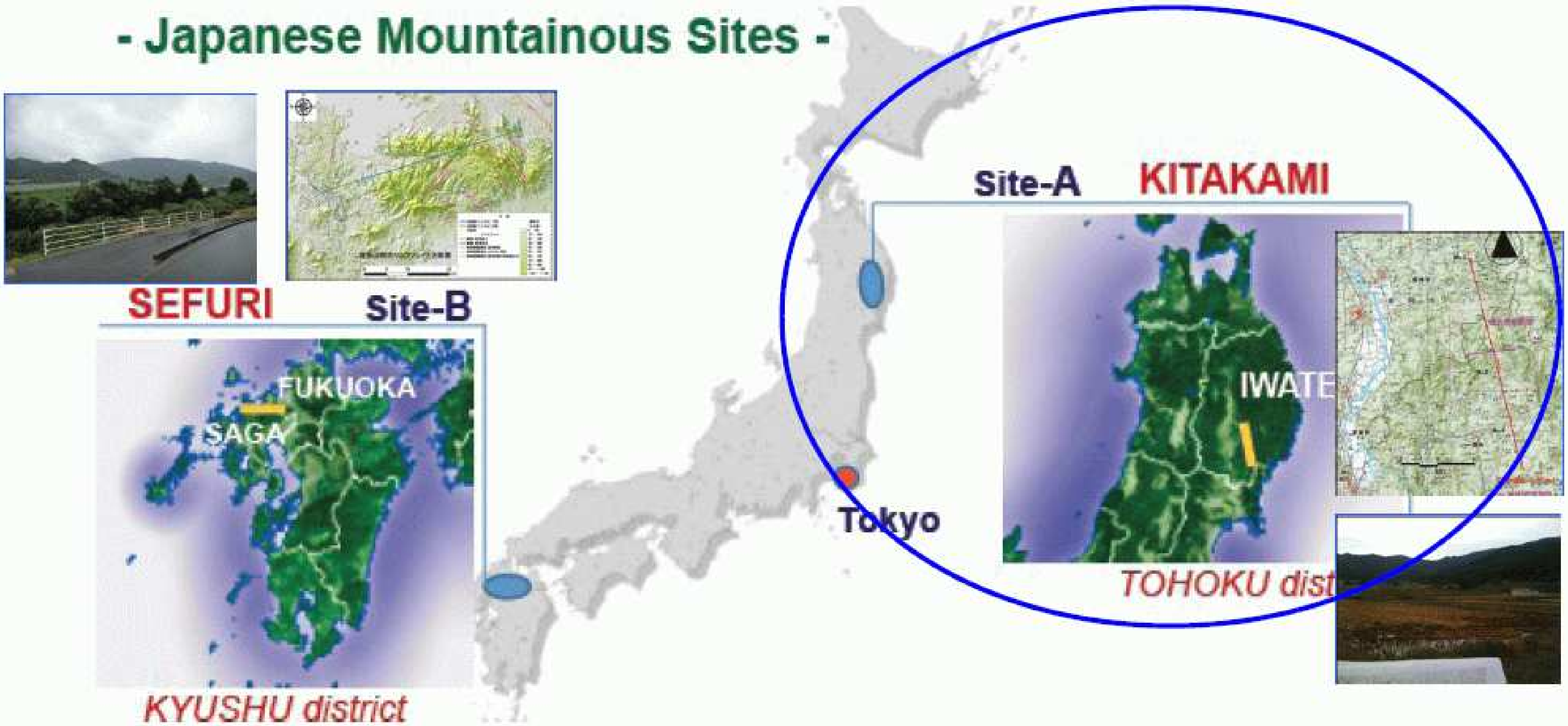


The ILC

- **200-500 GeV Ecm e+e– collider L ~2×1034 cm-2s-1**
  - upgrade: ~1 TeV
- **SCRF Technology**
  - 1.3GHz SCRF with 31.5 MV/m
  - 17,000 cavities
  - 1,700 cryomodules
  - 2×11 km linacs
- **Developed as a truly global collaboration**
  - **G**lobal **D**esign **E**ffort – **GDE**
  - ~130 institutes
  - http://www.linearcollider.org

[*taken from N. Walker, '14*]

Possible candidate sites



LCC technical efforts focused on Kitakami site
(Ratified in independent technical evaluation by KEK and LCC)
No "formal" political decision taken yet.

[*taken from N. Walker, '14*]

Outlook

- **The ILC is a mature project.**
  - Main technologies exist
  - But clearly much engineering" to be done (requiring substantial funding)
- **The primary hurdles now are political**
- **Focus on Japan**
  - MEXT evaluation should be complete by next Spring
  - Further evaluation by SCJ
  - Expecting some statement from Japan in 2016
- **European and US HEP strategies both make positive statements on a "Japanese hosted ILC"**
  - But negotiations with governments has not yet started – waiting for Japan to make "first move"
- **International technical effort (LCC) focused on site-dependent design**
  - But we are totally under resourced!
  - Making progress where we can
  - US funding situation (post-P5) looks better
- **All scenarios put first physics towards the end of 2020's**
  - 10 construction & commissioning schedule
  - Can't possibly start before 2016 (and likely to be later).

[*taken from N. Walker, '14*]

Physics at the ILC $\Rightarrow$ determined by experimental data!

Physics at the ILC ⇒ determined by experimental data!

What we know for sure:

– discovery of a Higgs particle
– top quark
– gauge bosons: $W^{\pm}, Z$
– . . .

⇒ clear physics case

Physics at the ILC ⇒ determined by experimental data!

What we know for sure:

– discovery of a Higgs particle
– top quark
– gauge bosons: $W^{\pm}, Z$
– ...

⇒ clear physics case

Other experimental data:

– dark matter
– the anomalous magnetic moment of the muon, $(g-2)_\mu$
– ...

⇒ "likely" (additional) physics case

The time we have: possible running/luminosity scenarios

[*D. Asner et al., Snowmass study, ’13*]

Name	$\mathcal{L}_{\text{int},1}$ [fb^{-1}]	@	$E_{\text{CM},1}$ GeV	+	$\mathcal{L}_{\text{int},2}$ [fb^{-1}]	@	$E_{\text{CM},2}$ GeV	+	$\mathcal{L}_{\text{int},3}$ [fb^{-1}]	@	$E_{\text{CM},3}$ GeV	AT [$10^7 s$]
ILC (250)	250	@	250									3.3
ILC (500)	250	@	250	+	500	@	500					6.0
ILC (1000)	250	@	250	+	500	@	500	+	1000	@	1000	8.7
ILC (LumUp)	1150	@	250	+	1600	@	500	+	2500	@	1000	17.4

⇒ time includes “ramp up” etc.

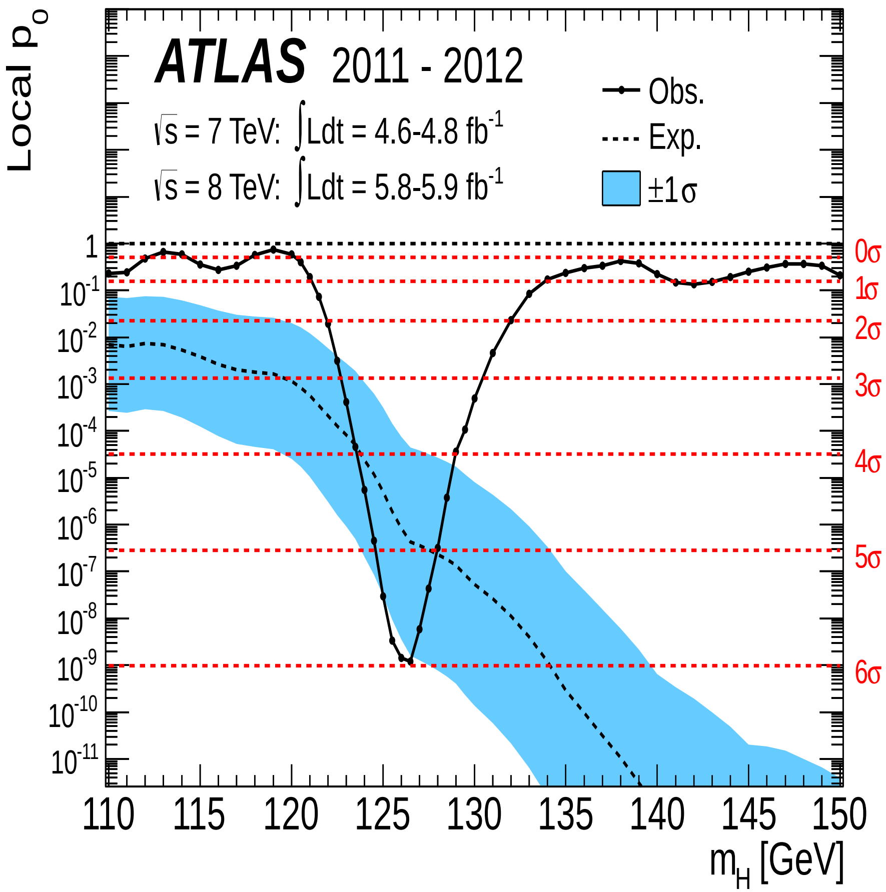
⇒ ILC (1000) : up to nine years

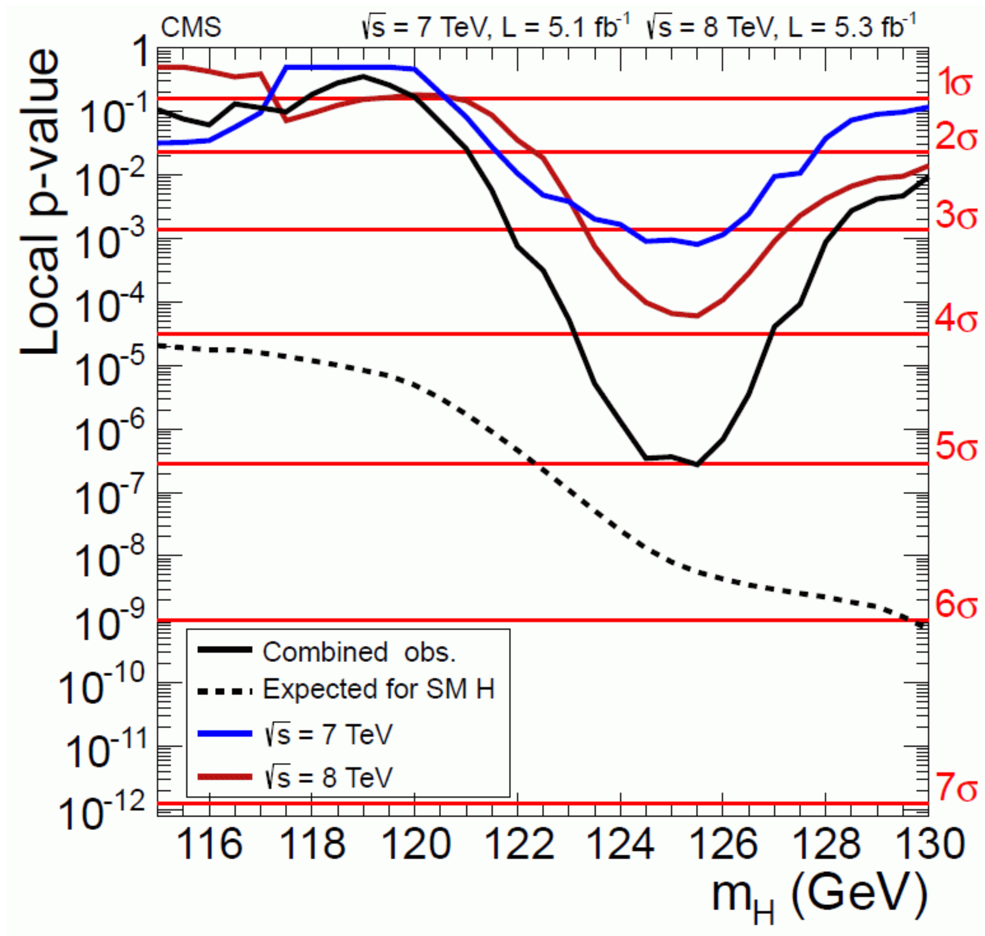
⇒ Luminosity upgrade

⇒ ILC (LumUp) : up to additional nine years

2. Physics we can do for sure at the ILC

We have a discovery!





We have a discovery!

But what is it?

Q: Is it a Higgs boson? ⇒ yes according to CERN!

Q: Is it "the" Higgs boson (i.e. of the SM)?

Q: Is it a supersymmetric Higgs boson?

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

Q: Is it an impostor? ⇒ no according to CERN!

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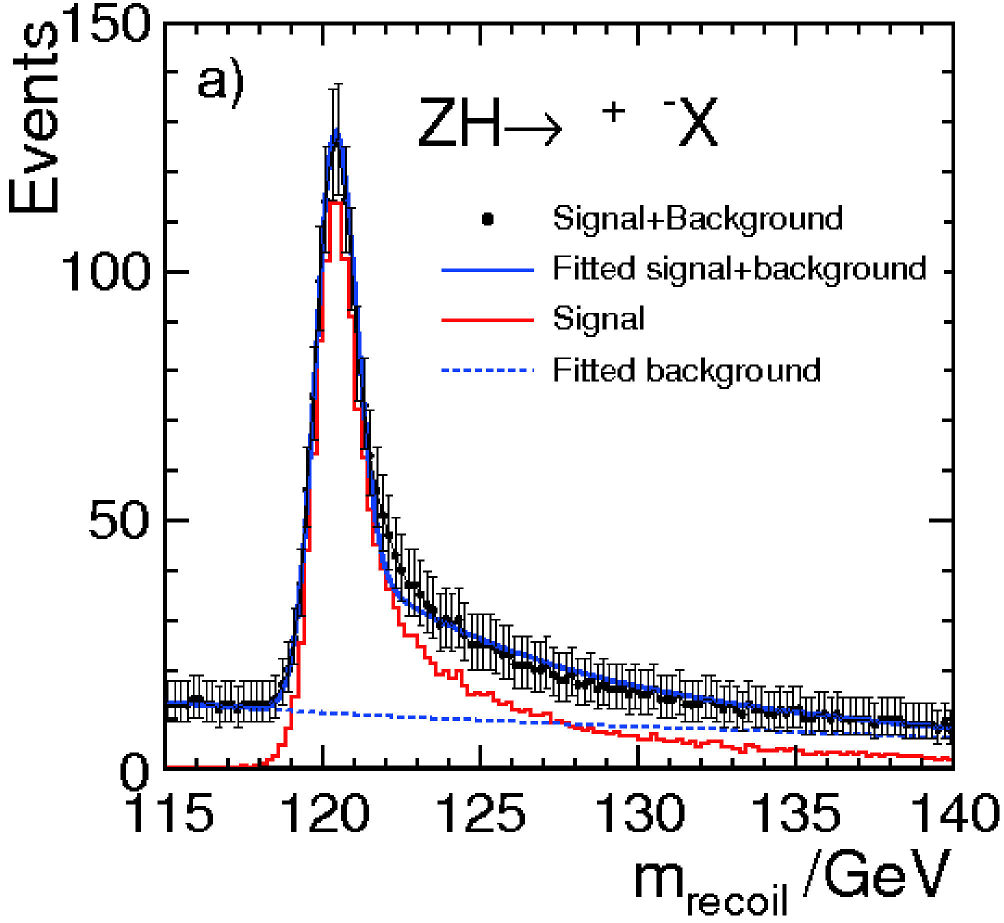
How can we decide?

How can we fully establish the Higgs mechanism?

Model independent cross section measurement

[*ILC TDR '13*]

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

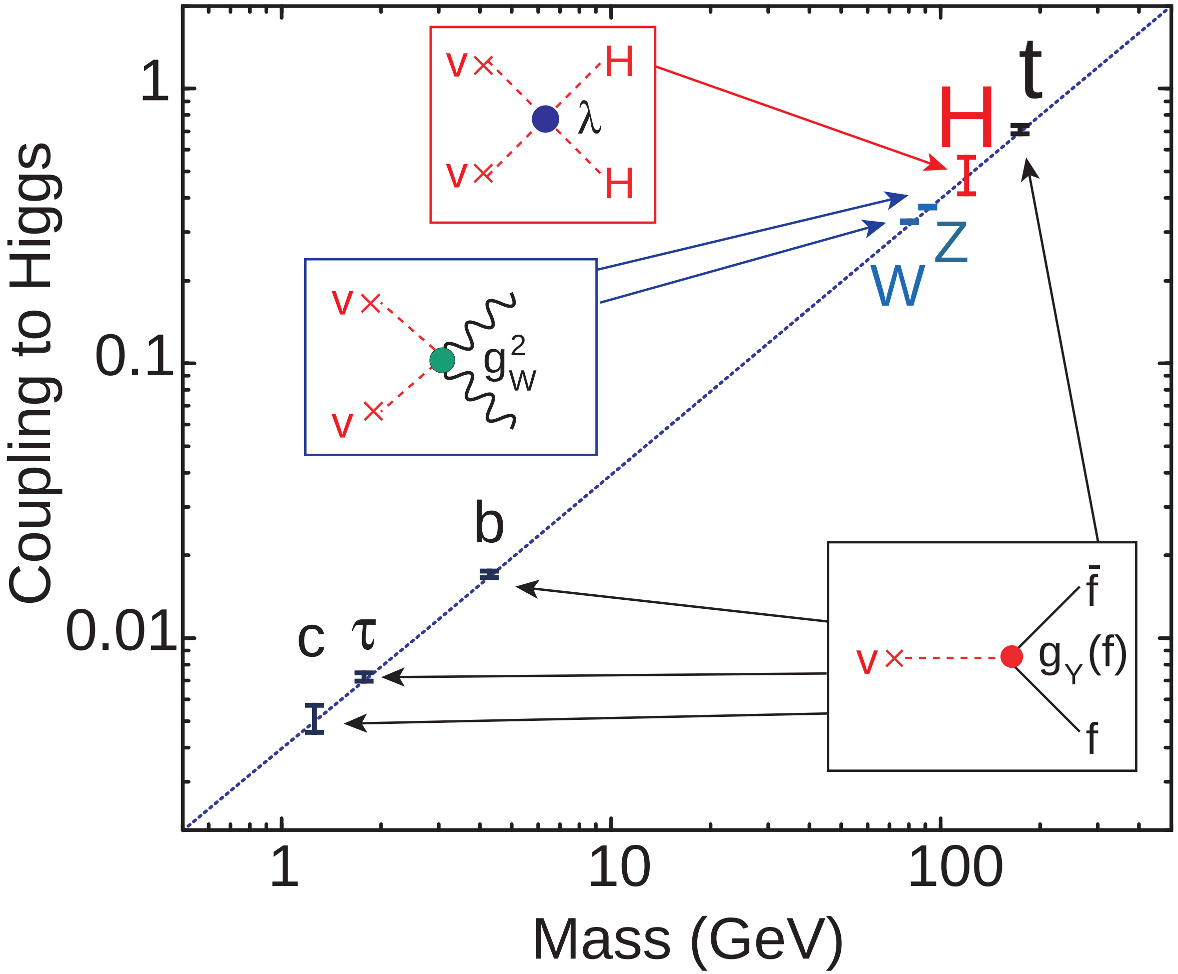


$\Rightarrow$ crucial for a model independent coupling measurement! $\delta M_H^{\rm exp} \lesssim 0.05$ GeV

Higgs mechanism: mass ∝ 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]

	$\Delta(\sigma \cdot \text{BR})/(\sigma \cdot \text{BR})$			$\Delta g/g$
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: $\Delta\Gamma_{\text{inv}}/\Gamma_{\text{inv}}$: 0.44 – 0.26% ($\sqrt{s} = 250 - 1000$ GeV)

More complete future options:

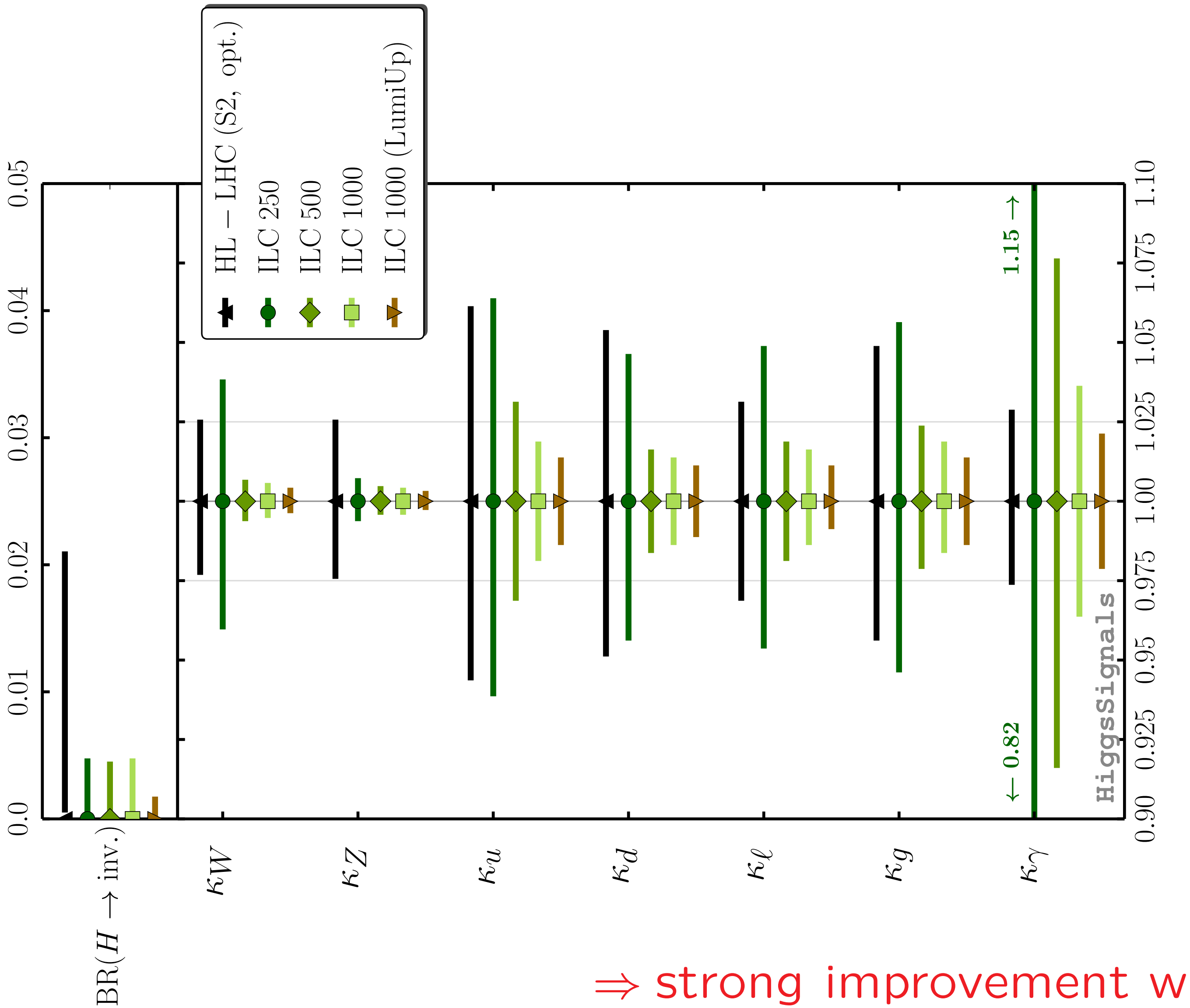
LHC300, HL-LHC, ILC250, ILC500, ILC1000, ILC1000-LumiUp

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%	$\sigma(e^-e^+ \to ZH)$

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

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

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

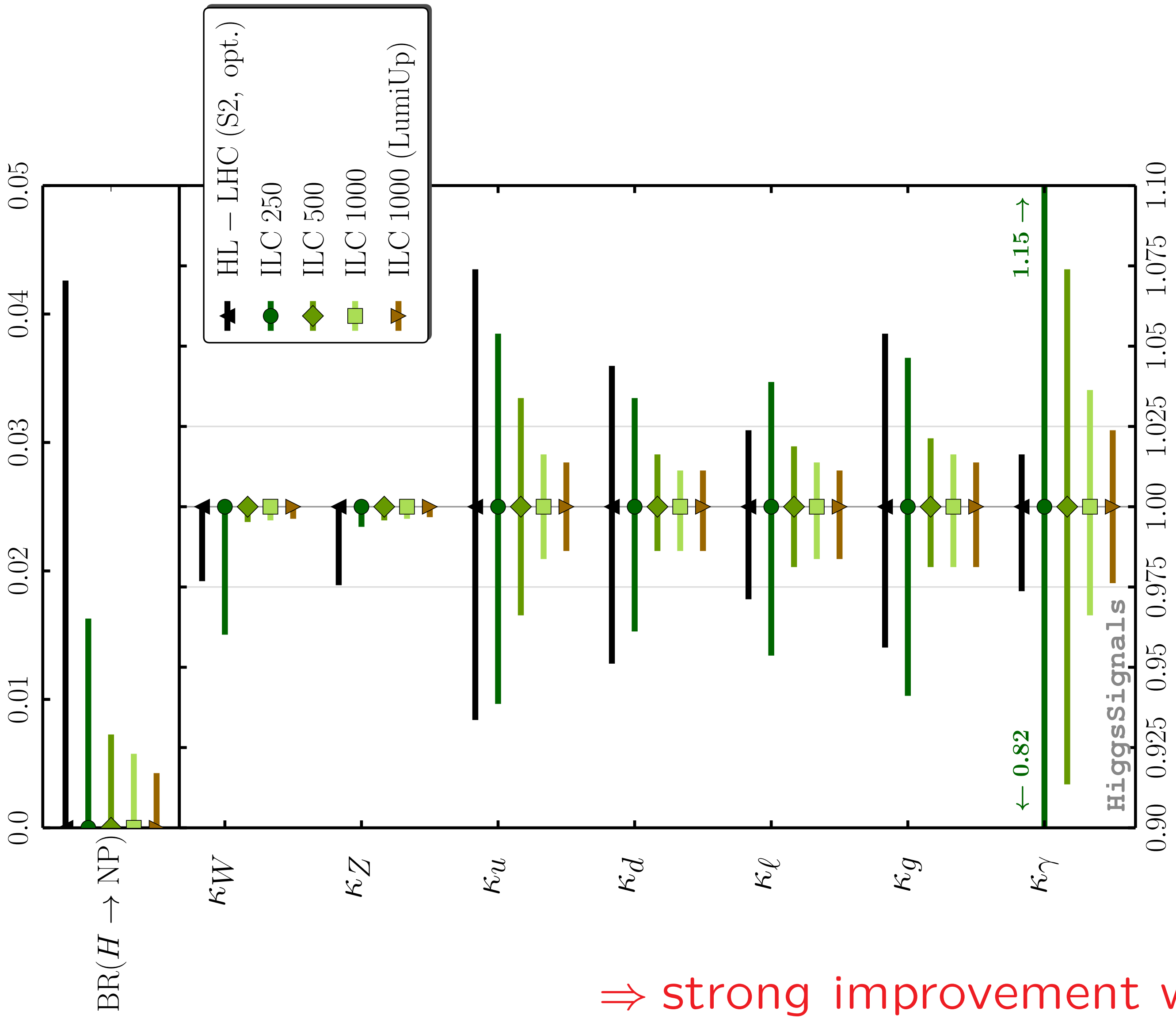


⇒ strong improvement with the ILC

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

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

assumption: $\kappa_V \leq 1$



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

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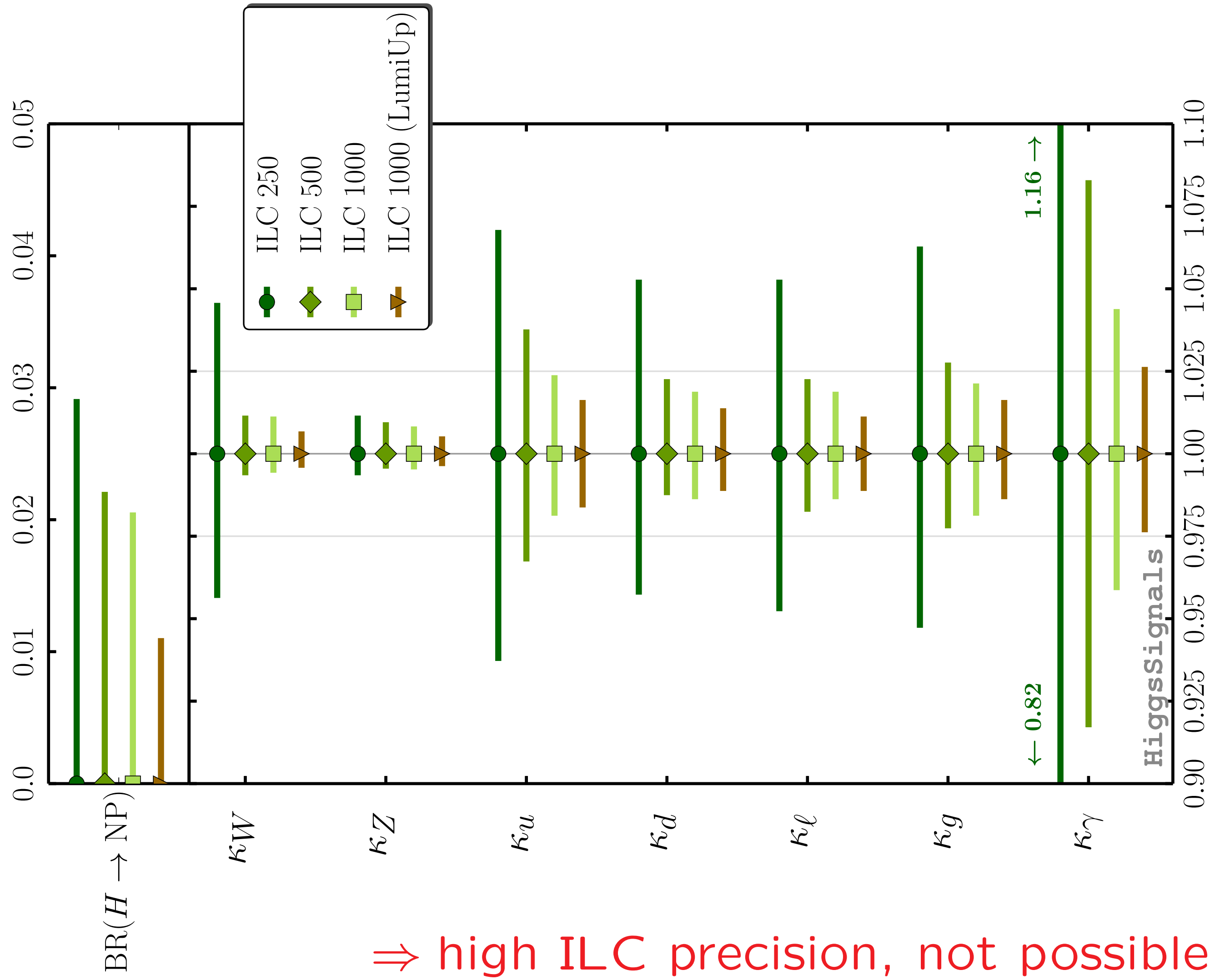
no theory assumptions, full fit

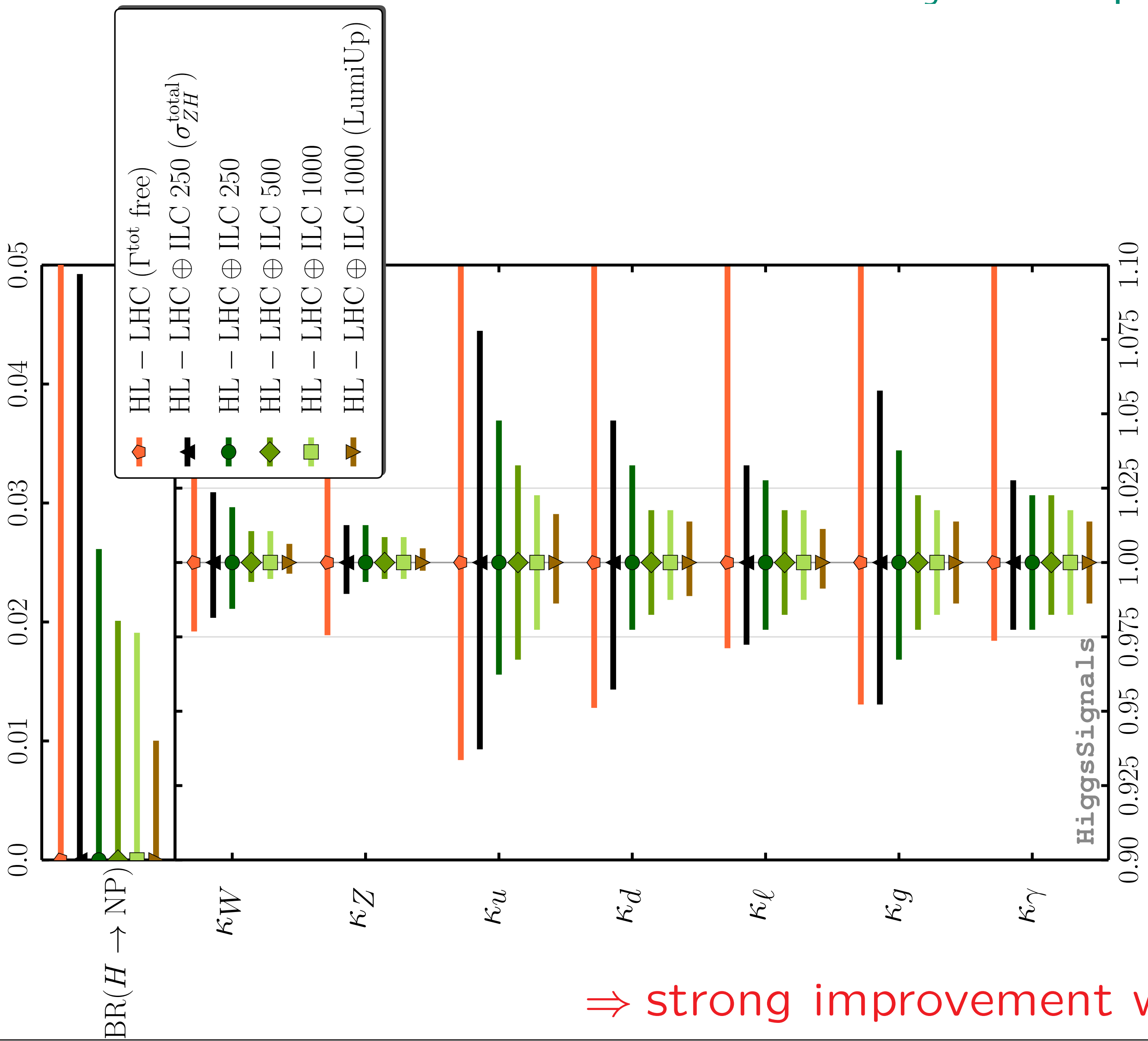


⇒ high ILC precision, not possible at the LHC

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

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

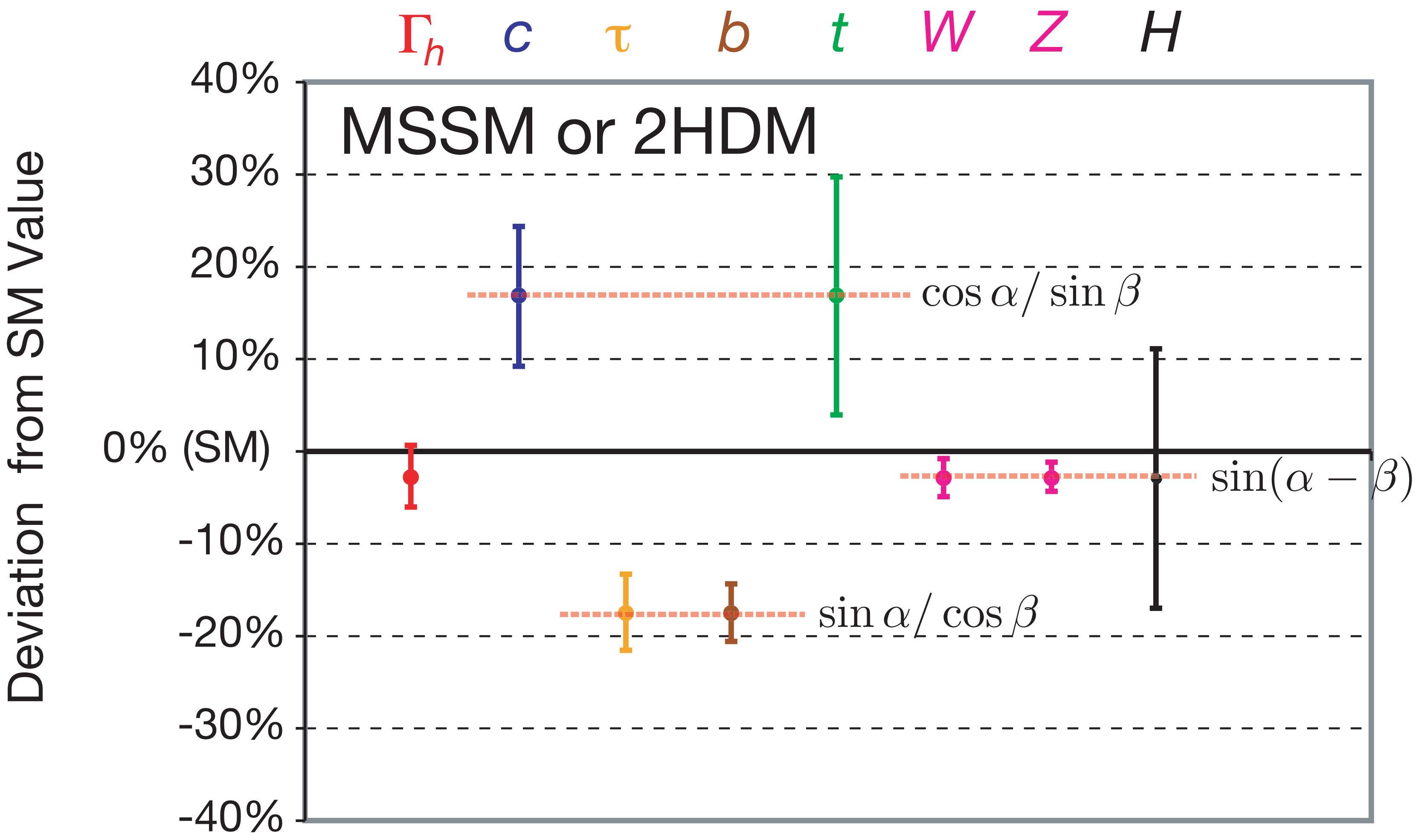
no theory assumptions, full fit



⇒ strong improvement with the ILC

⇒ discrimination between models! ⇒ possible deviations: $\mathcal{O}$ (few%)

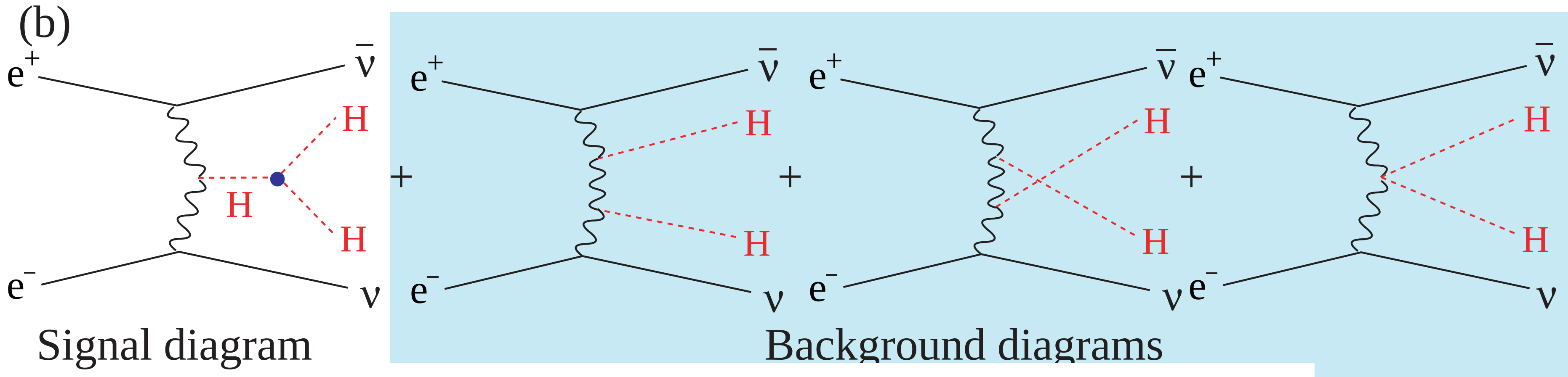
Example: Higgs couplings in the 2HDM:

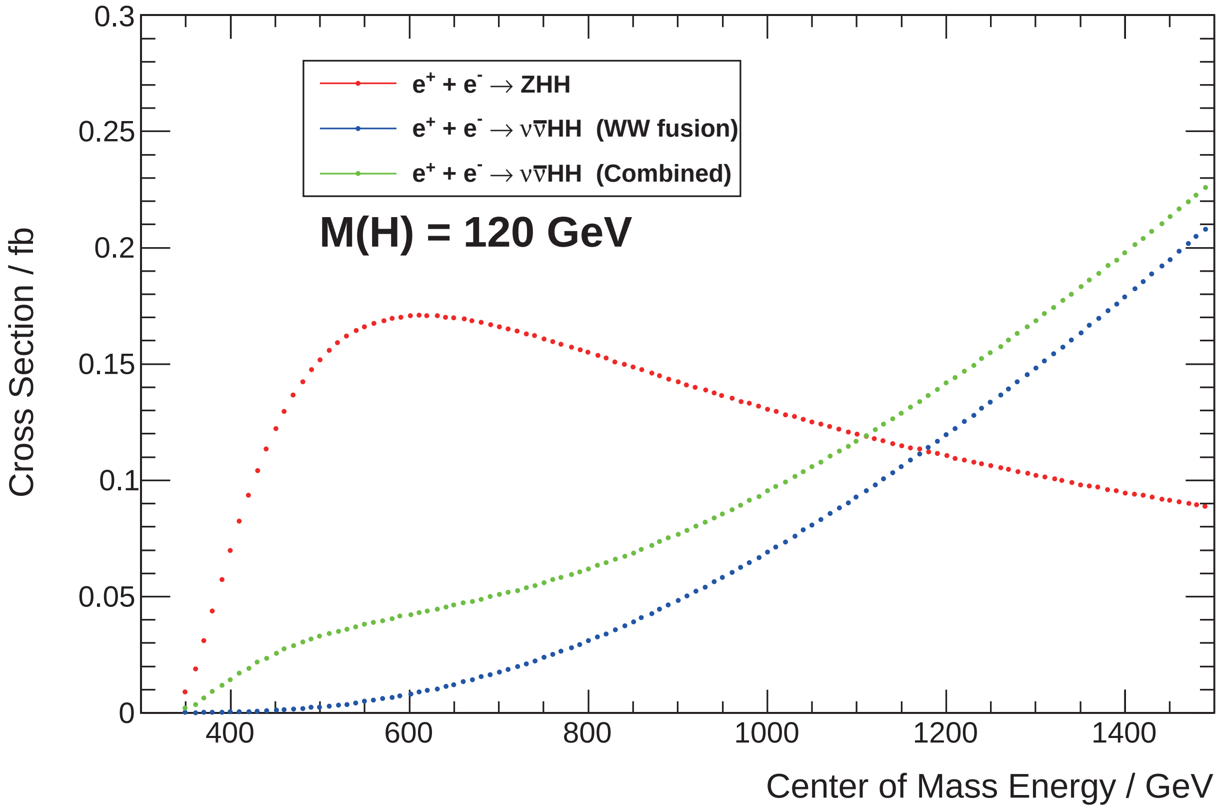


⇒ measurable deviations

Particularly challening: Higgs self-coupling

[ILC TDR '13]

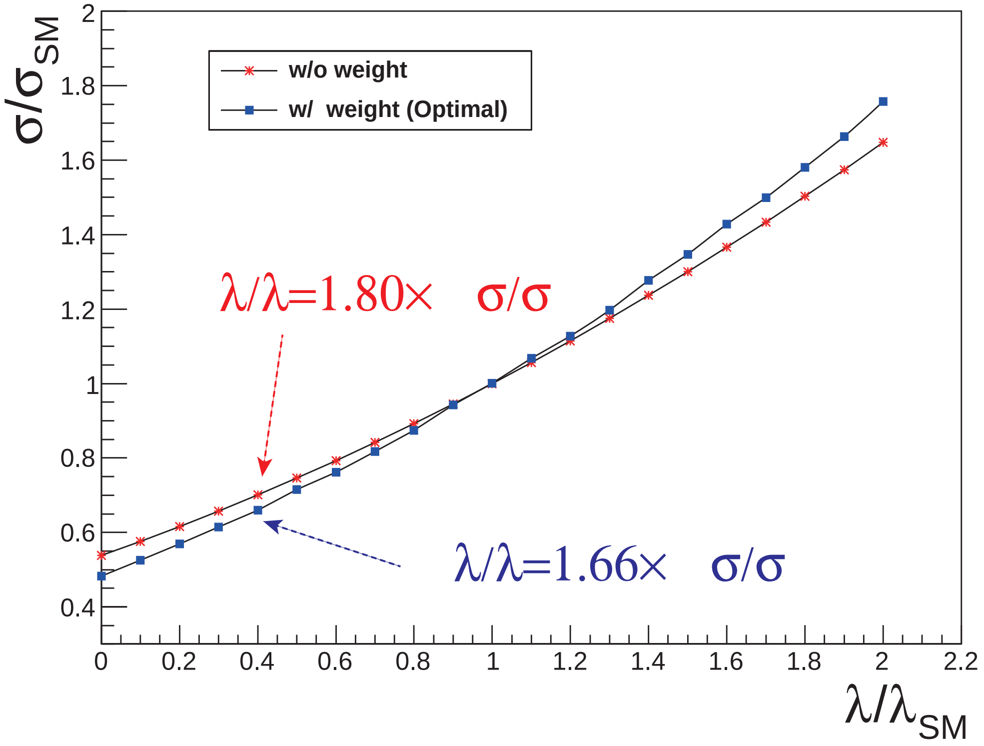




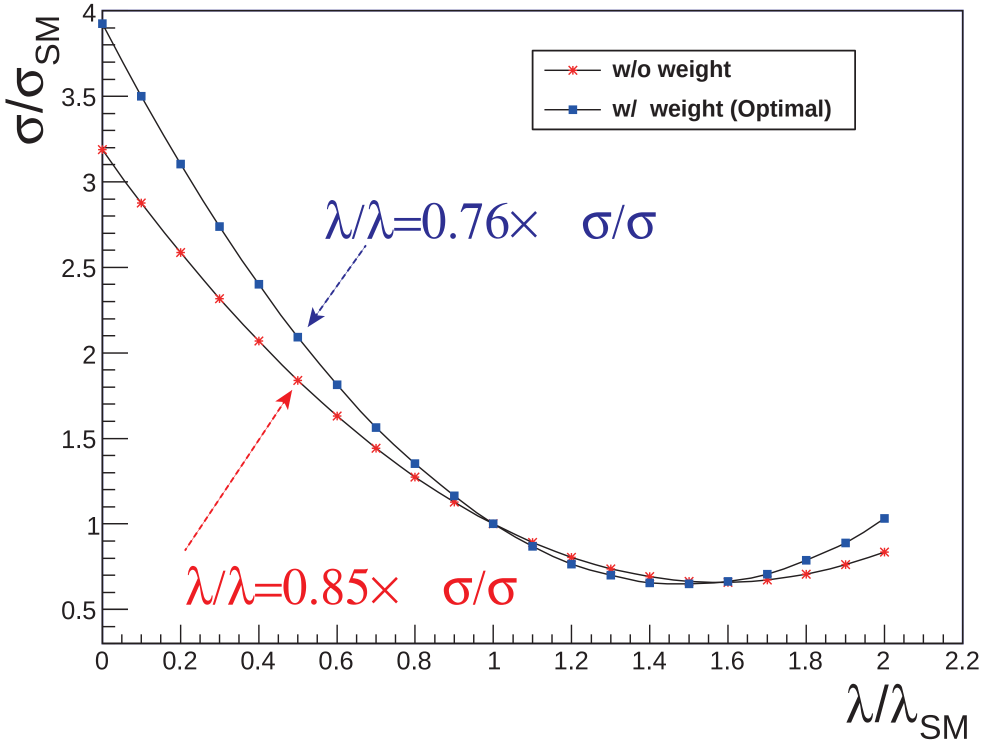
Sensitivity to triple Higgs coupling λ:

[*taken from K. Fuji '13*]

ZHH@500 GeV



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



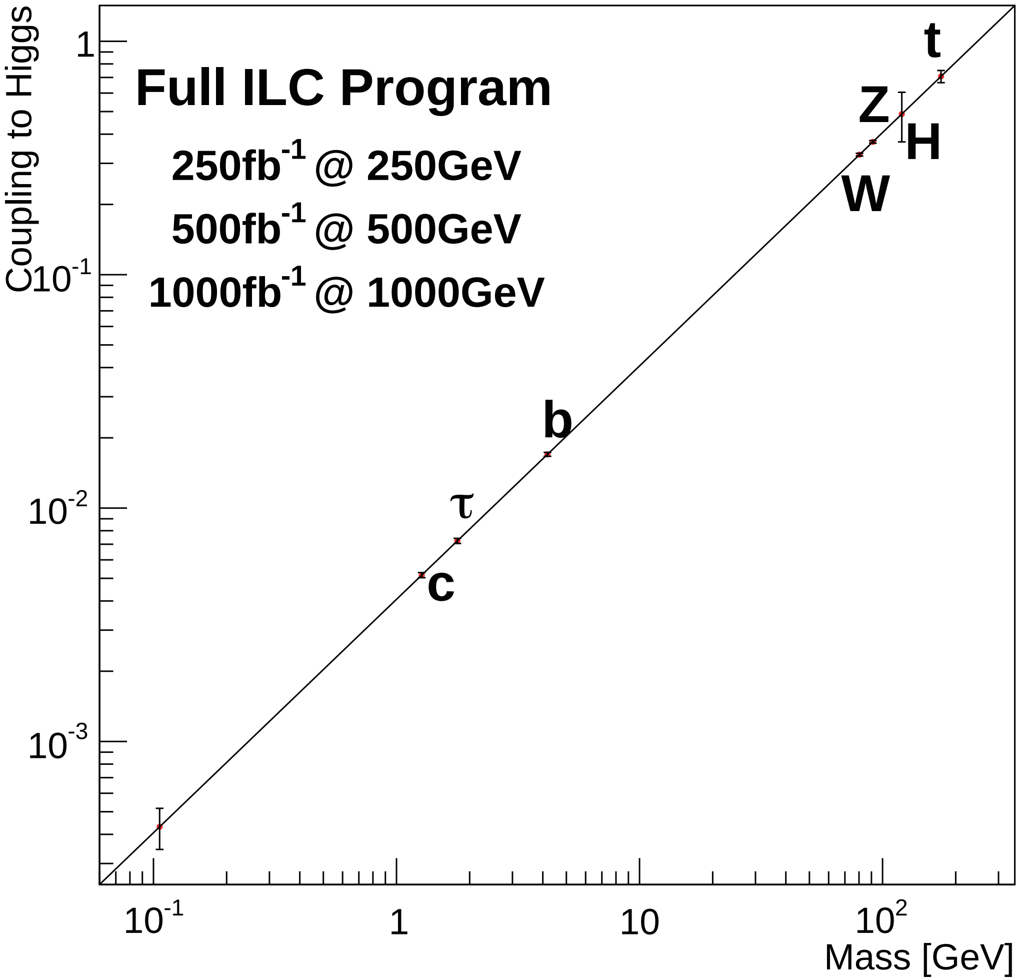
$\Rightarrow$ currently full simulations are performed

Expected sensitivity on λ: $\sim$ 14% ($2\,\text{ab}^{-1}$ @ 1000 GeV) [*ILC TDR '13*]

Higgs mechanism: mass $\propto$ coupling

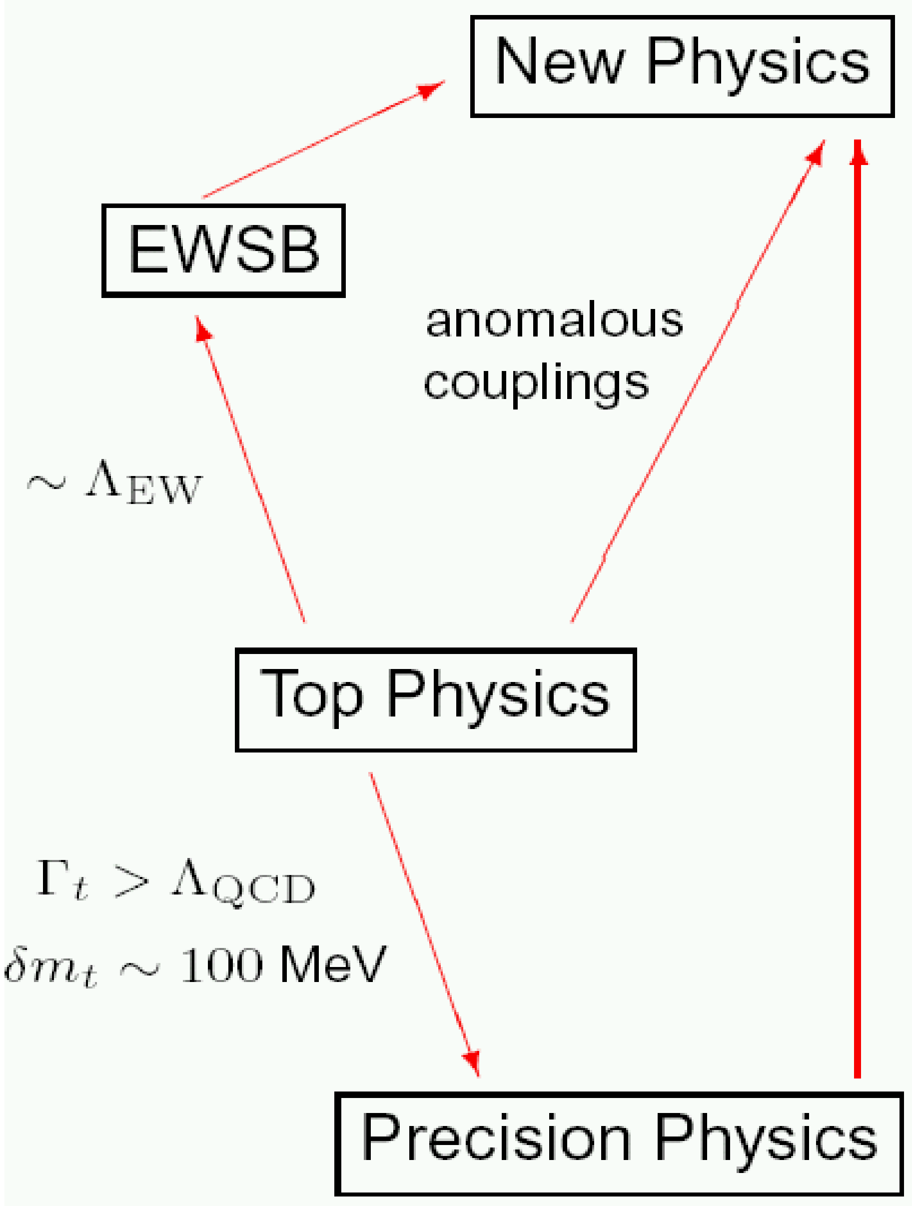
[*ILC TDR '13*]

putting everything together:



$\Rightarrow$ any deviation from straight line indicates BSM physics!

Top physics at the ILC



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

ILC: high precision of everything
incl. couplings

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 $\mathcal{O}(\Lambda_{\rm QCD})$

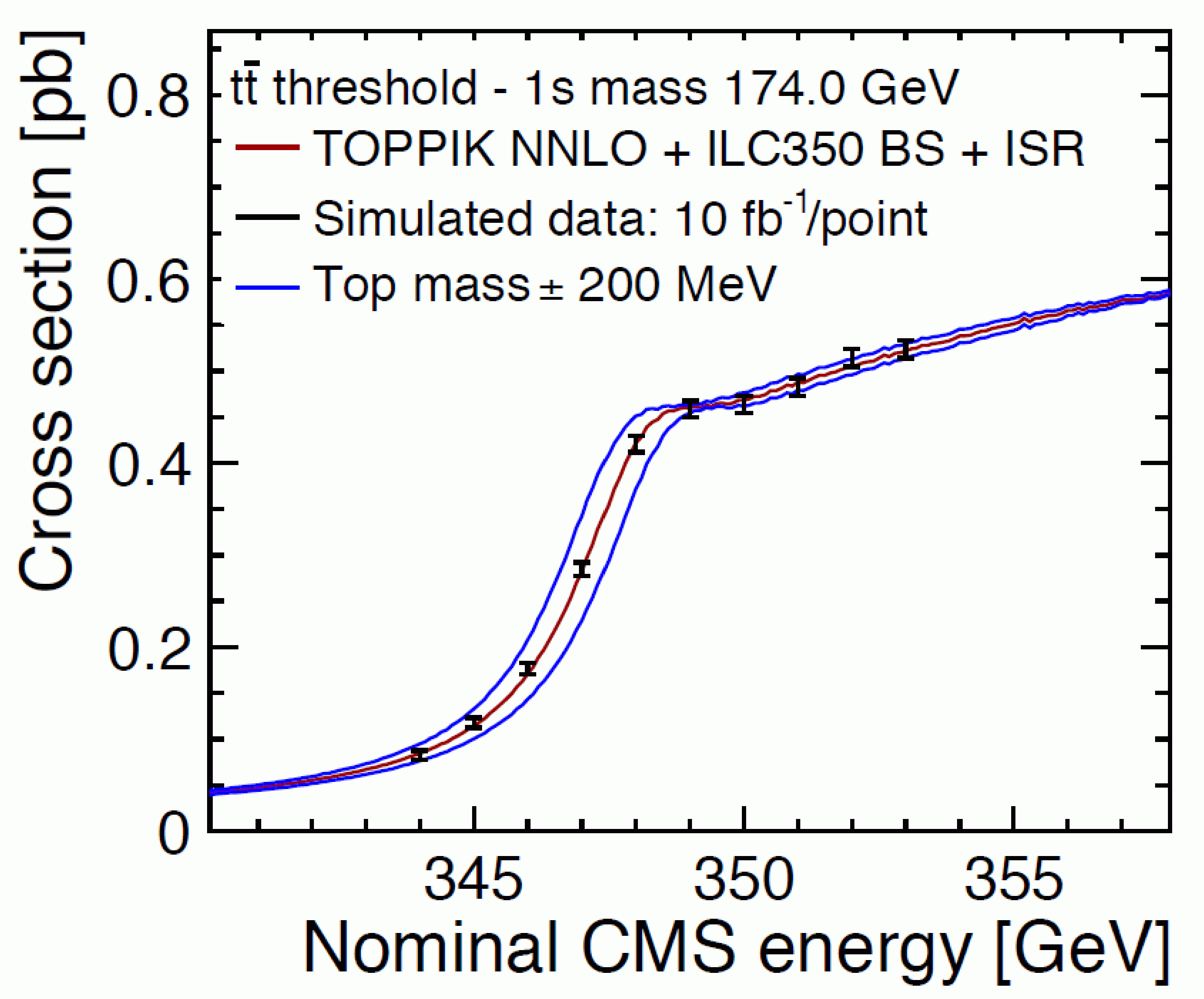
Measurement of m_t:

- At Tevatron, LHC:
  kinematic reconstruction, fit to invariant mass distribution
  $\Rightarrow$ "MC" mass, close to "pole" mass?

- At the ILC: unique possibility
  threshold scan $\Rightarrow$ threshold mass $\Rightarrow$ **SAFE!**
  transition to other mass definitions possible, $\delta m_t \lesssim 100$ GeV

At the ILC: unique possibility [ILC TDR '13]

threshold scan ⇒ threshold mass ⇒ **SAFE!**

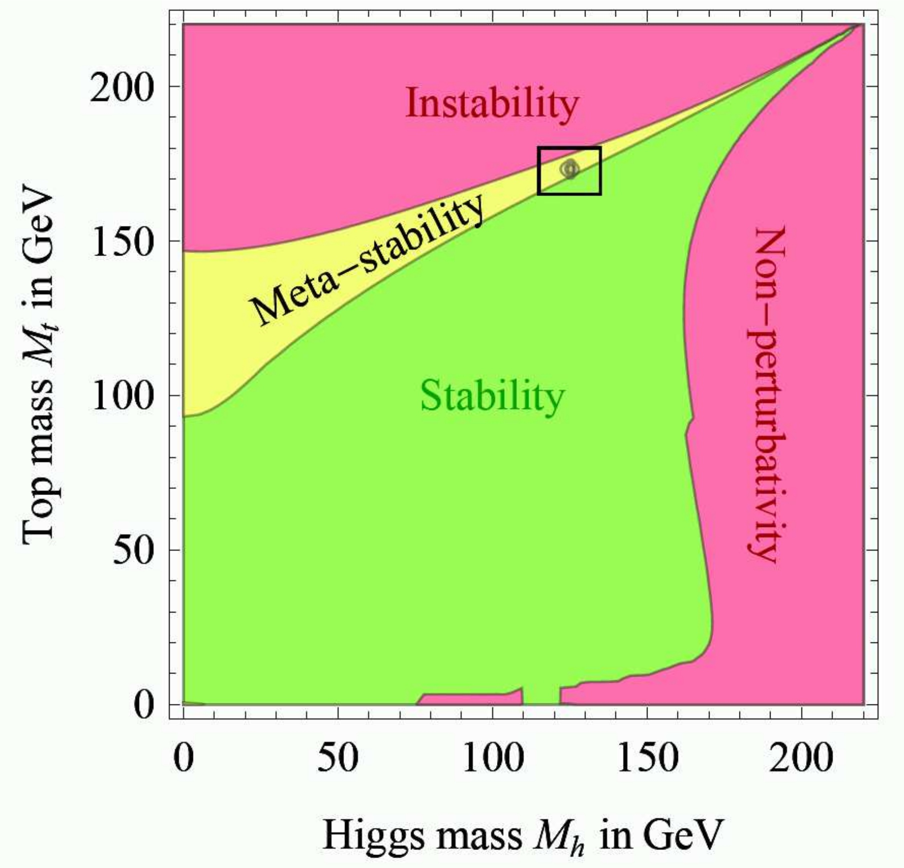


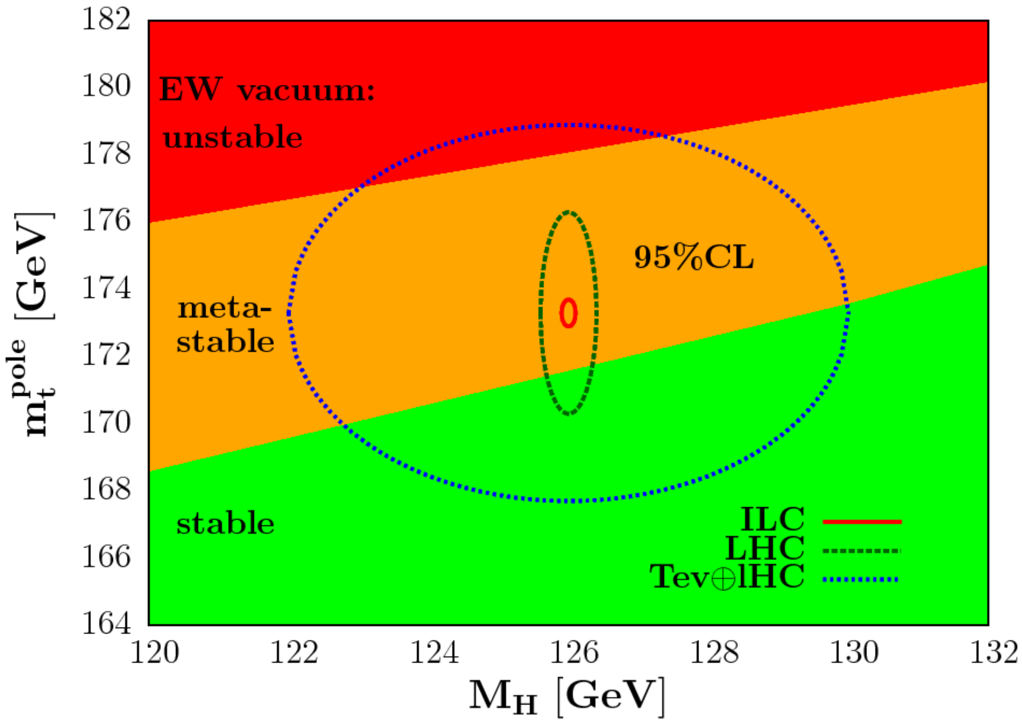
transition to other mass definitions possible ⇒ $\delta m_t^{\text{exp+theo}} \sim 0.1$ GeV

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)

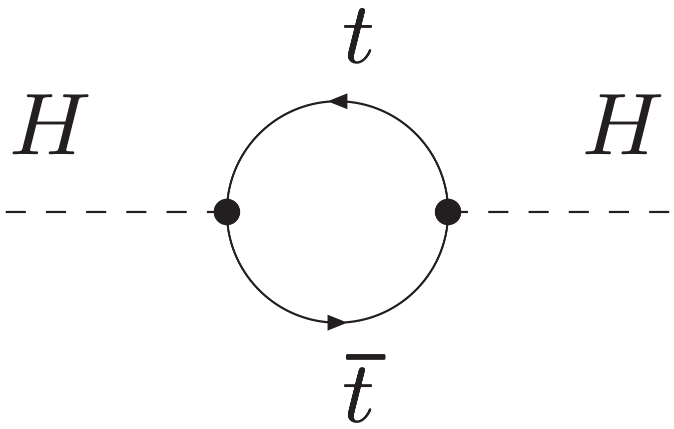




⇒ ILC precision for m_t needed!

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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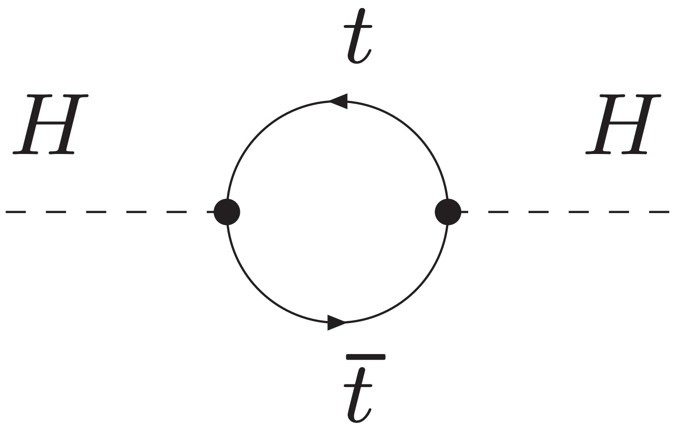

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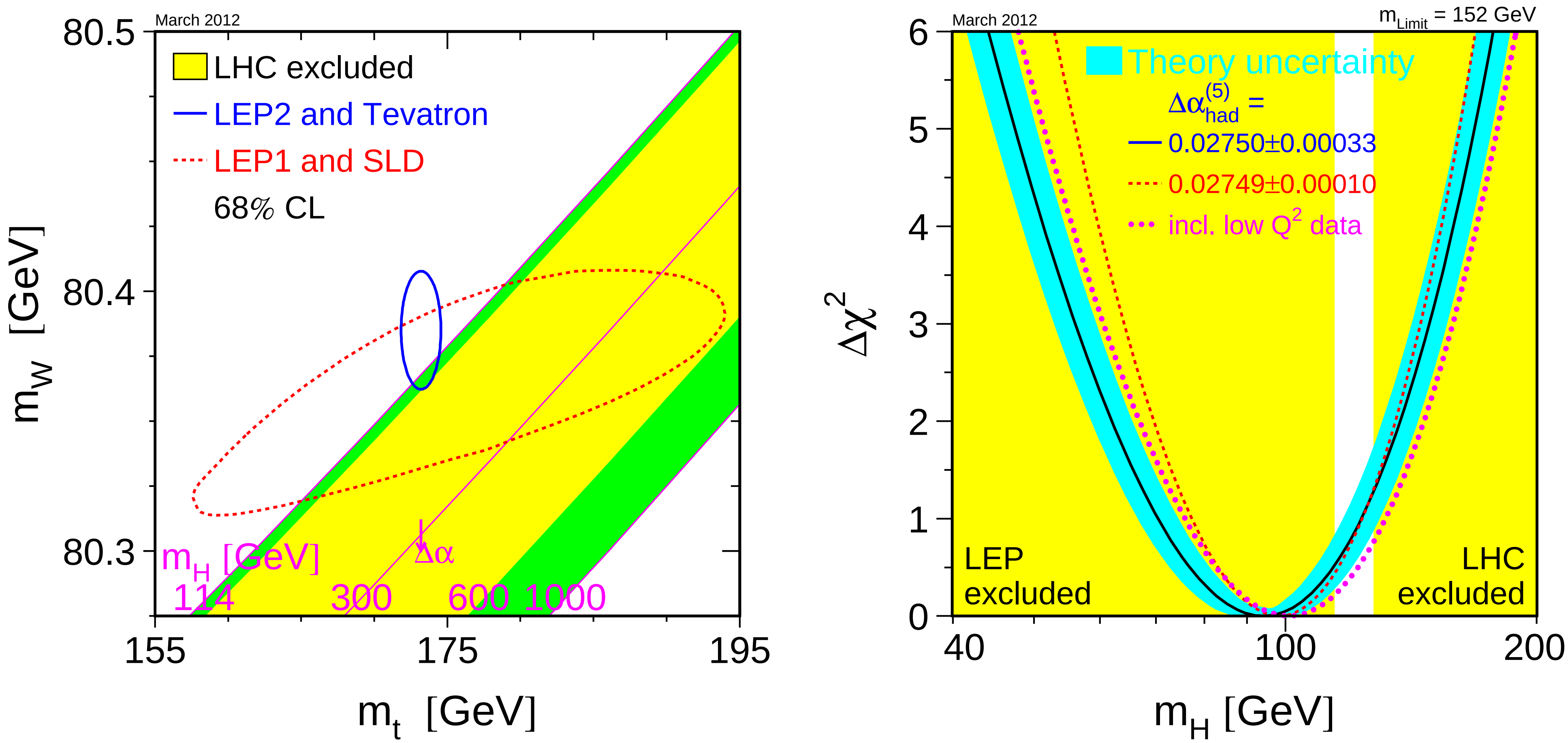
⇒ Precision Higgs physics needs ILC precision top physics

Precision Tests of the SM (and beyond)

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



⇒ fits with today's precision

Improvements with the ILC:

Experimental errors of the precision observables:

	today	Tev./LHC	ILC	GigaZ
$\delta\sin^2\theta_{\rm eff}(\times 10^5)$	16	16	–	1.3
δM_W [MeV]	15	$\lesssim 15$	3-4	3-4
δm_t [GeV]	0.9	$\lesssim 1$	0.1	0.1

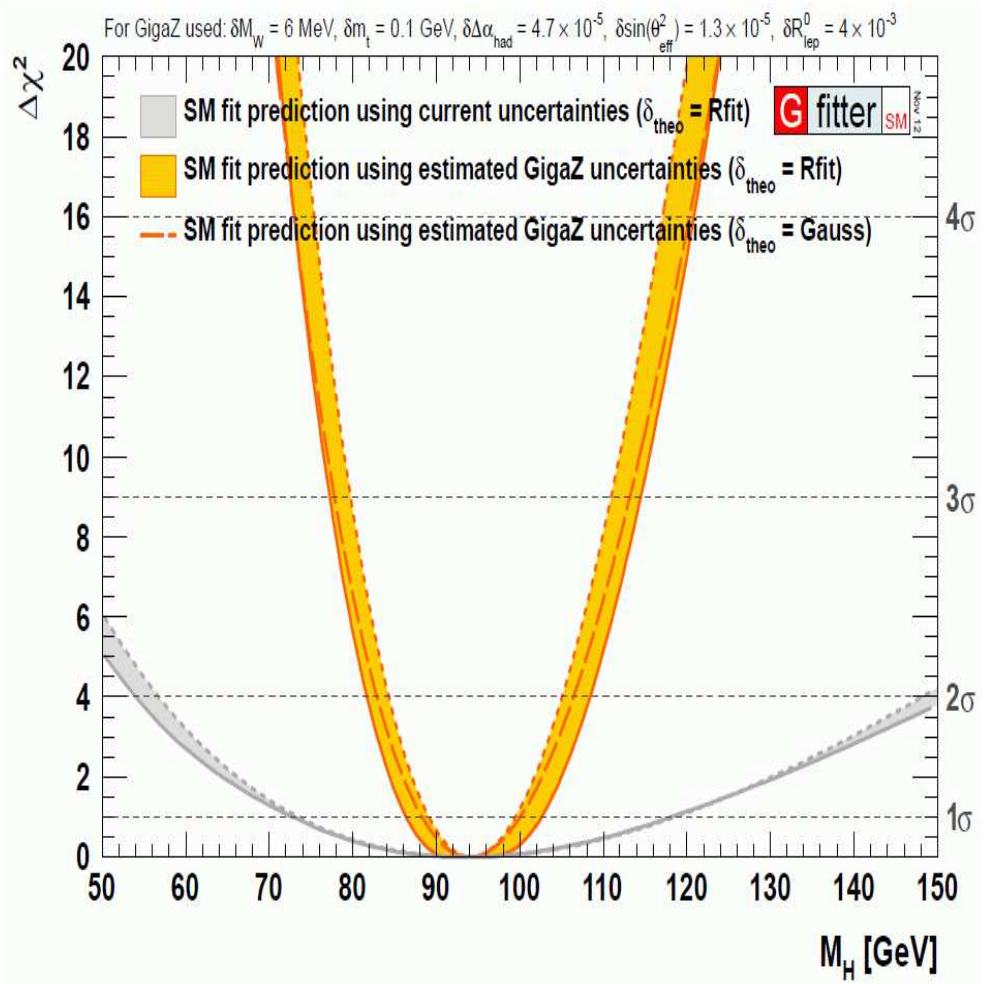
M_W: from direct reconstruction and threshold scan

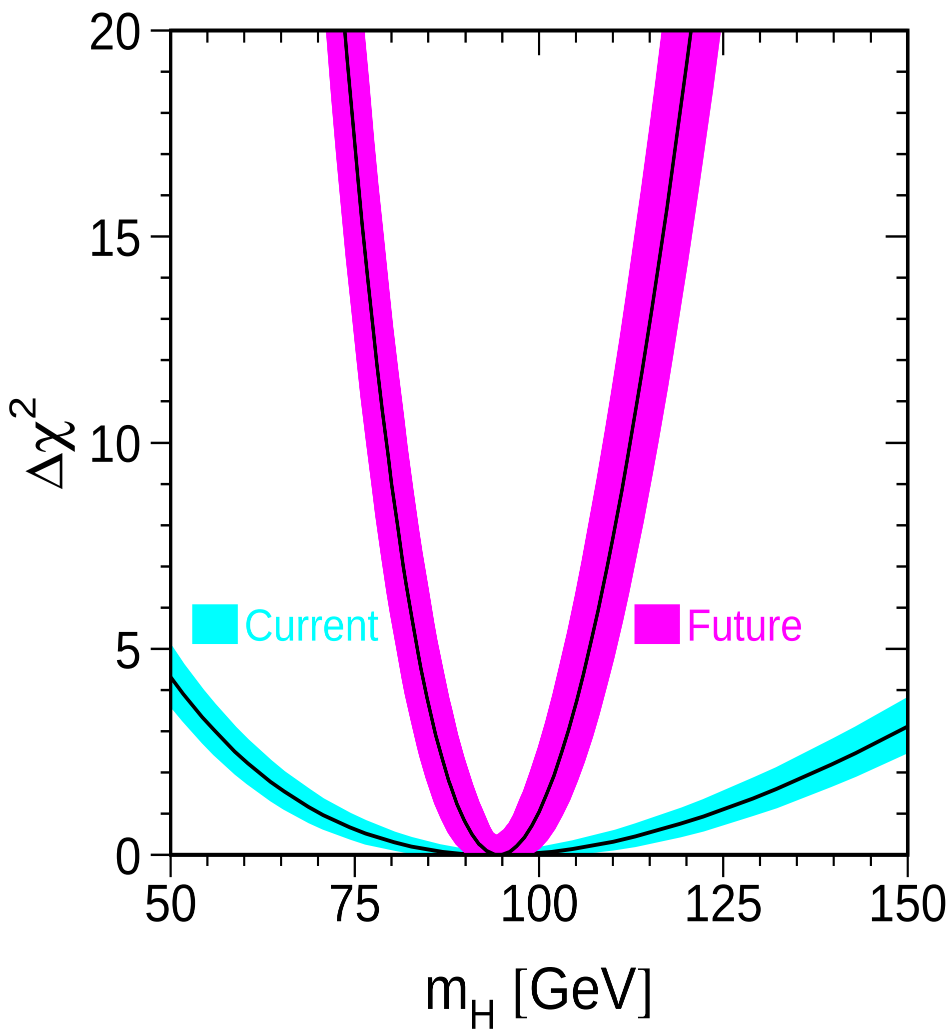
[*G. Wilson '13*]

$\sin^2\theta_{\rm eff}$: 1/2 year GigaZ run, polarization important

α_s : Improvement from GigaZ run

Most precise M_H test with the ILC: [GFitter '13] [LEPEWWG '13]





⇒ $\delta M_H^{\text{ind}} \lesssim 6$ GeV
⇒ extremely sensitive test of SM (and BSM) possible

A word of caution: The W boson mass

Experimental accuracy:

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

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

$\delta M_W^{\text{exp,ILC}} \lesssim 3$ MeV, (from thr. scan) $\Leftarrow$ theory uncertainties 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: $\delta m_t^{\text{ILC/TLEP}} = 0.1$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$

$$\Delta M_W^{\text{para,fut},m_t} = 1 \text{ MeV}, \quad \Delta M_W^{\text{para,fut},\Delta\alpha_{\text{had}}} = 1 \text{ MeV}$$

A word of caution: The effective weak leptonic mixing angle: $\sin^2\theta_{\rm eff}$

Experimental accuracy:

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

GigaZ: both beams polarized, Blondel scheme

$$\delta\sin^2\theta_{\rm eff}^{\rm exp,ILC} = 1.3\times10^{-5} \quad \Leftarrow \text{theory uncertainties neglected}$$

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

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

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

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

$$\delta\sin^2\theta_{\rm eff}^{{\rm para},m_t} = 70, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},\Delta\alpha_{\rm had}} = 36, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},M_Z} = 14$$

parametric future: $\delta m_t^{\rm ILC/TLEP} = 0.1$ GeV, $\delta(\Delta\alpha_{\rm had})^{\rm fut} = 5\times10^{-5}$

$$\Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},m_t} = 4, \quad \Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},\Delta\alpha_{\rm had}} = 18$$

3. Physics we can do likely at the ILC

The SM cannot be the ultimate theory!

Some facts:

1. the hierarchy problem
   gravity is not included

2. Dark Matter is not included

3. neutrino masses are not included

4. anomalous magnetic moment of the muon
   shows a $\sim 4\,\sigma$ discrepancy

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The SM cannot be the ultimate theory!

Some facts:

1. the hierarchy problem $\Leftarrow$ physics for the ILC
   gravity is not included

2. Dark Matter is not included $\Leftarrow$ physics for the ILC

3. neutrino masses are not included $\Leftarrow$ physics for the ILC

4. anomalous magnetic moment of the muon $\Leftarrow$ physics for the ILC
   shows a $\sim 4\,\sigma$ discrepancy

3. Physics we can do likely at the ILC

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Some facts:

1. the hierarchy problem
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2. Dark Matter is not included $\Leftarrow$ more detailed example

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We need physics beyond the Standard Model!

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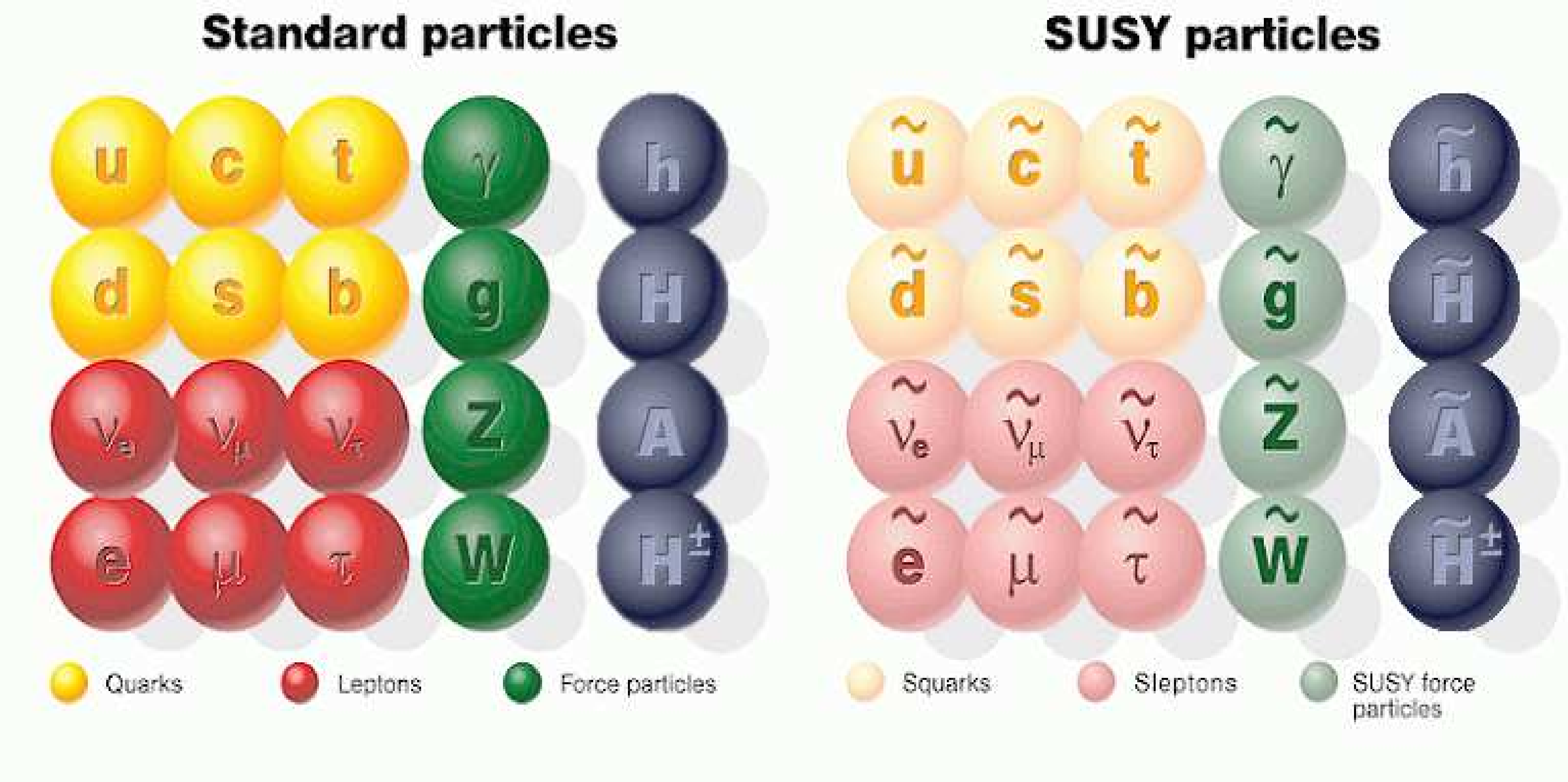
Supersymmetry as a show case:



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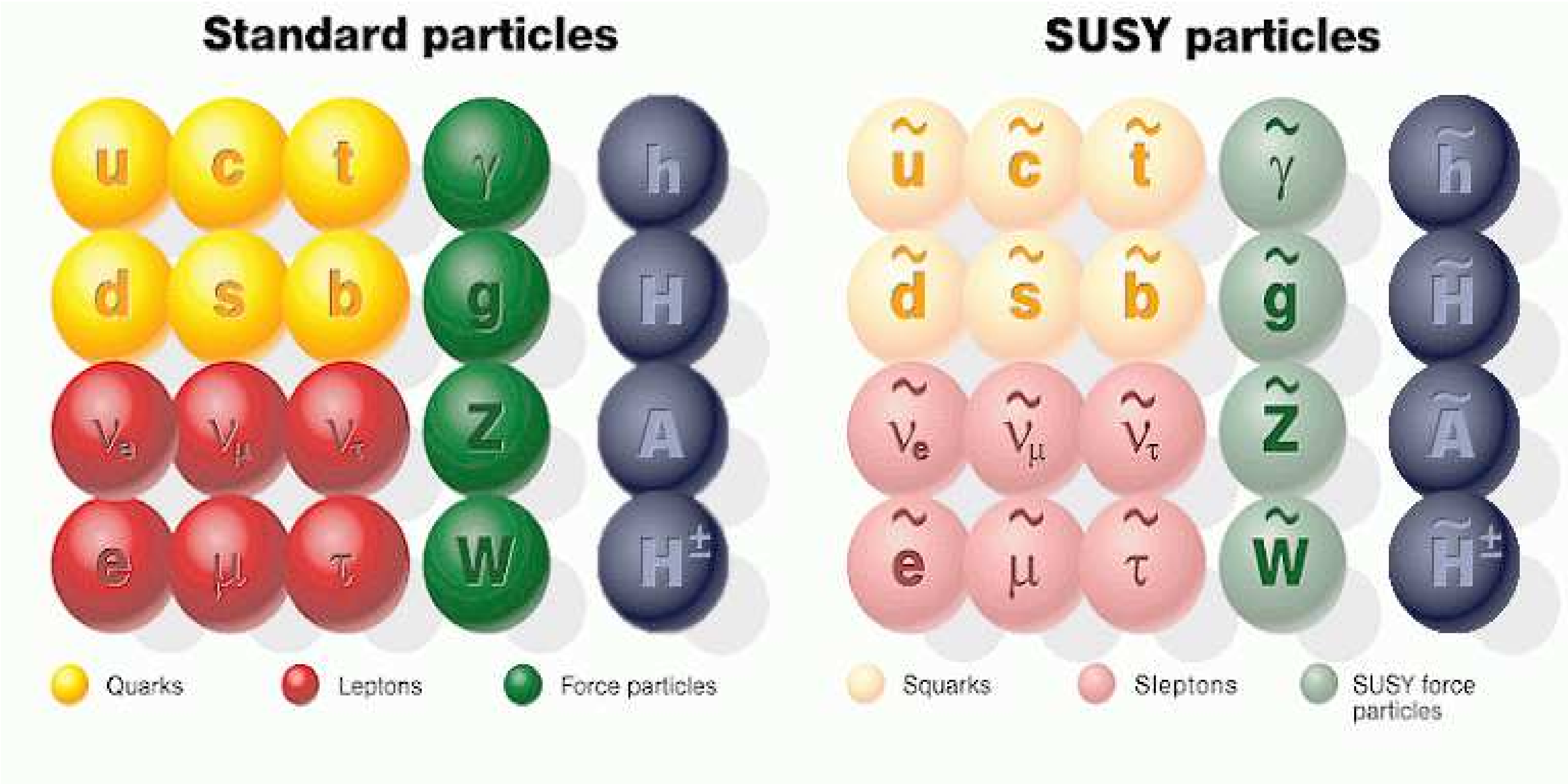


$\Rightarrow$ Hierarchy prob., DM, $(g-2)_\mu$ solved, more Higgses, . . . $\Rightarrow$ Cases I, II, III

Case I: Dark Matter: is it a particle? [*taken from Ellis '13*]

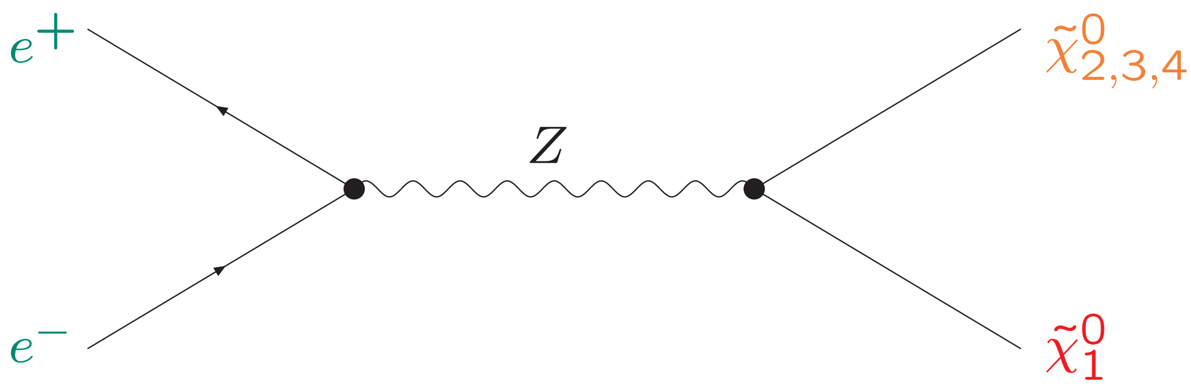
… postulate a new particle:

– QM and Special Relativity:	Antimatter
– Nuclear spectra:	Neutron
– Continuous spectrum in β decay:	Neutrino
– Nucleon-nucleon interactions:	Pion
– Absence of lepton number violation:	Second neutrino
– Flavour SU(3):	Ω^-
– Flavour SU(3):	Quarks
– FCNC:	Charm
– CP violation:	Third generation
– Strong dynamics:	Gluons
– Weak interactions:	$W^\pm$, Z^0
– Renormalizability:	H
– Dark matter:	**WIMP/axion?**

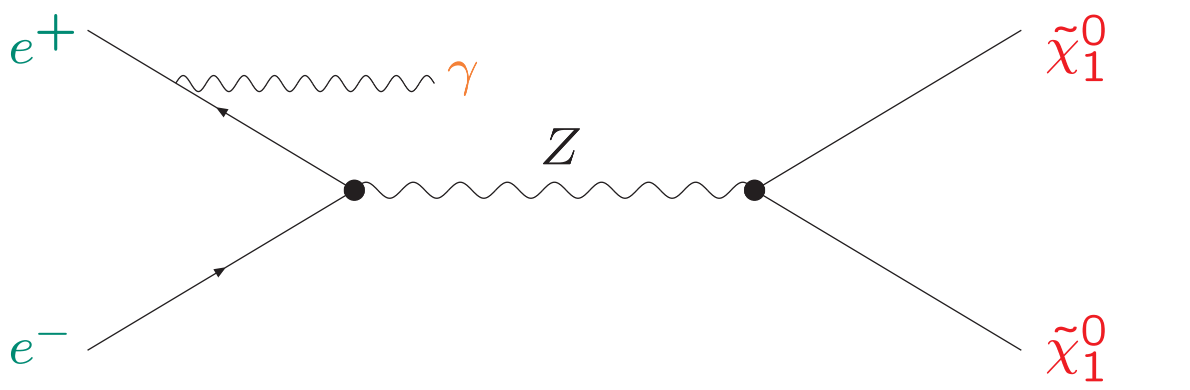
⇒ "particle concept" works!

Supersymmetry: Lightest neutralino as Dark Matter

Production with a heavier particle:

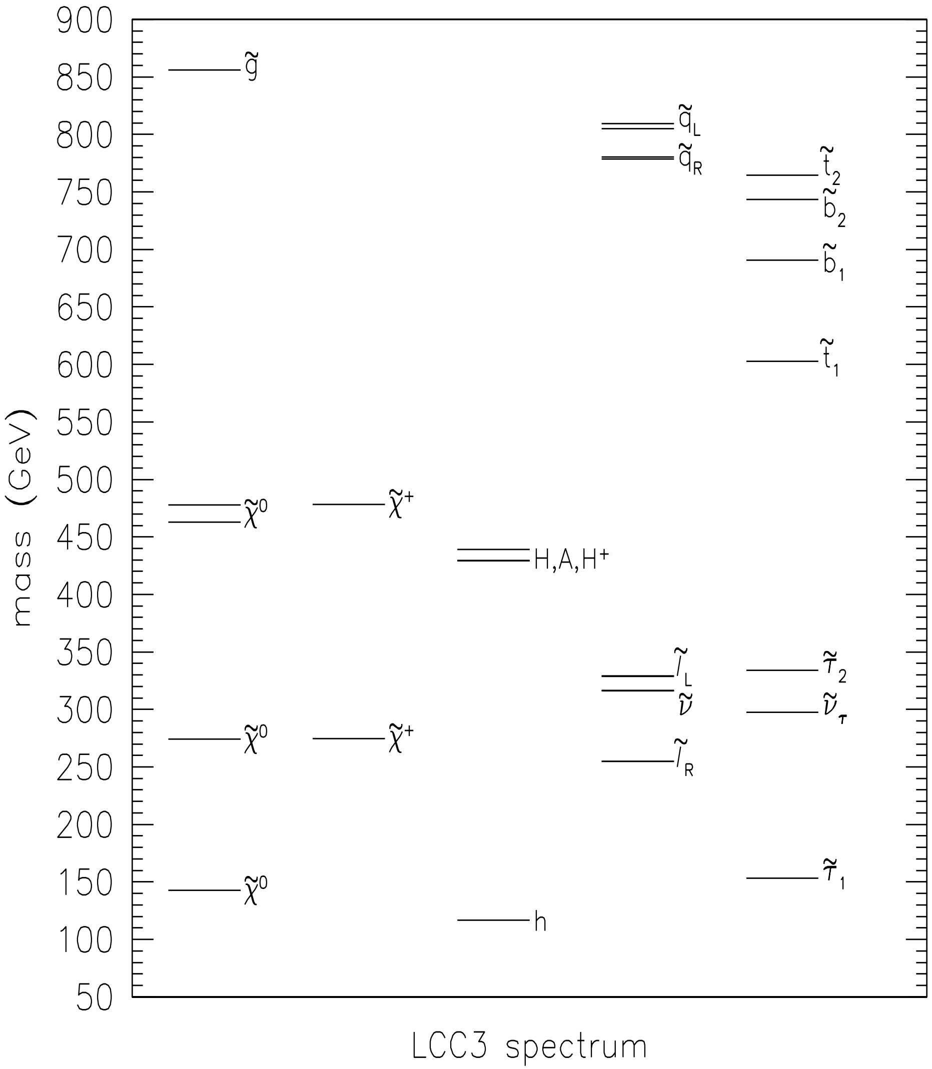


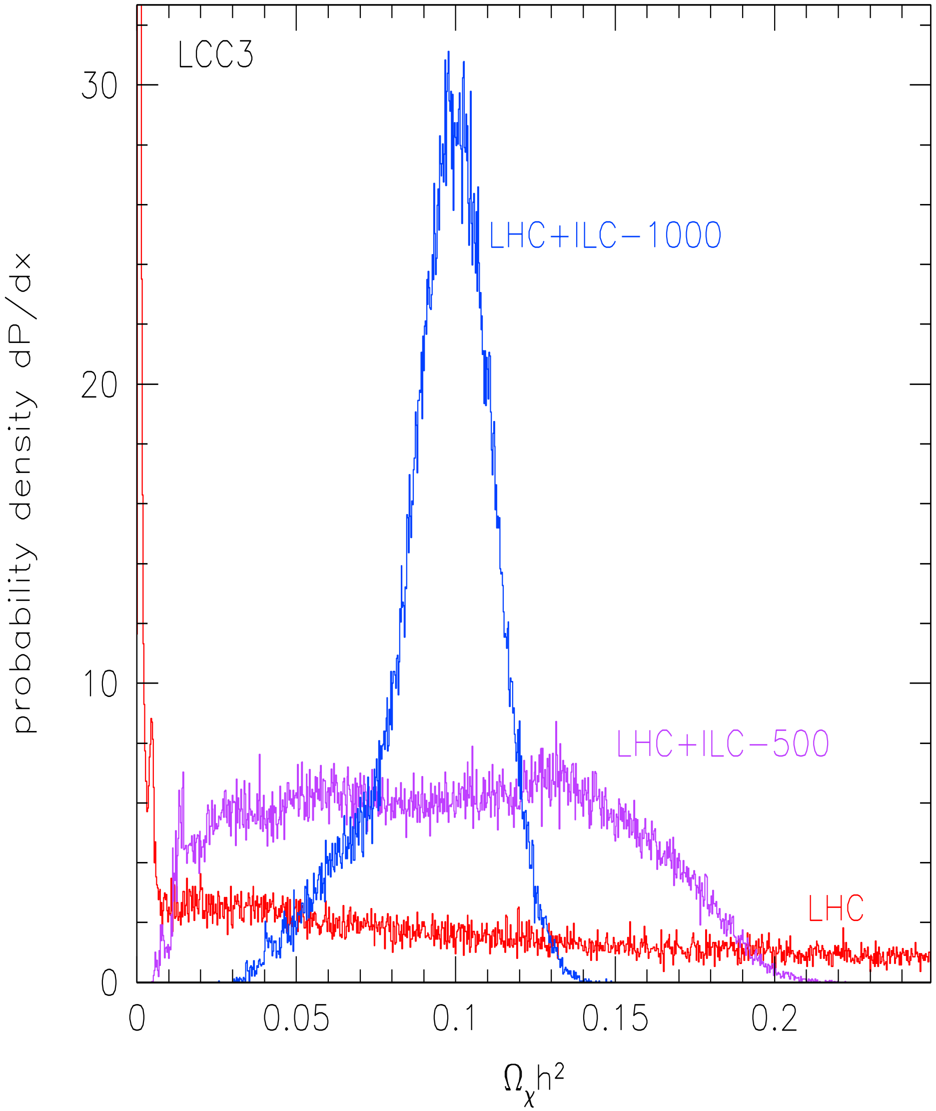
Production with an initial state radiation photon:



Reconstructing DM at the ILC:

[*ILC TDR '13*]

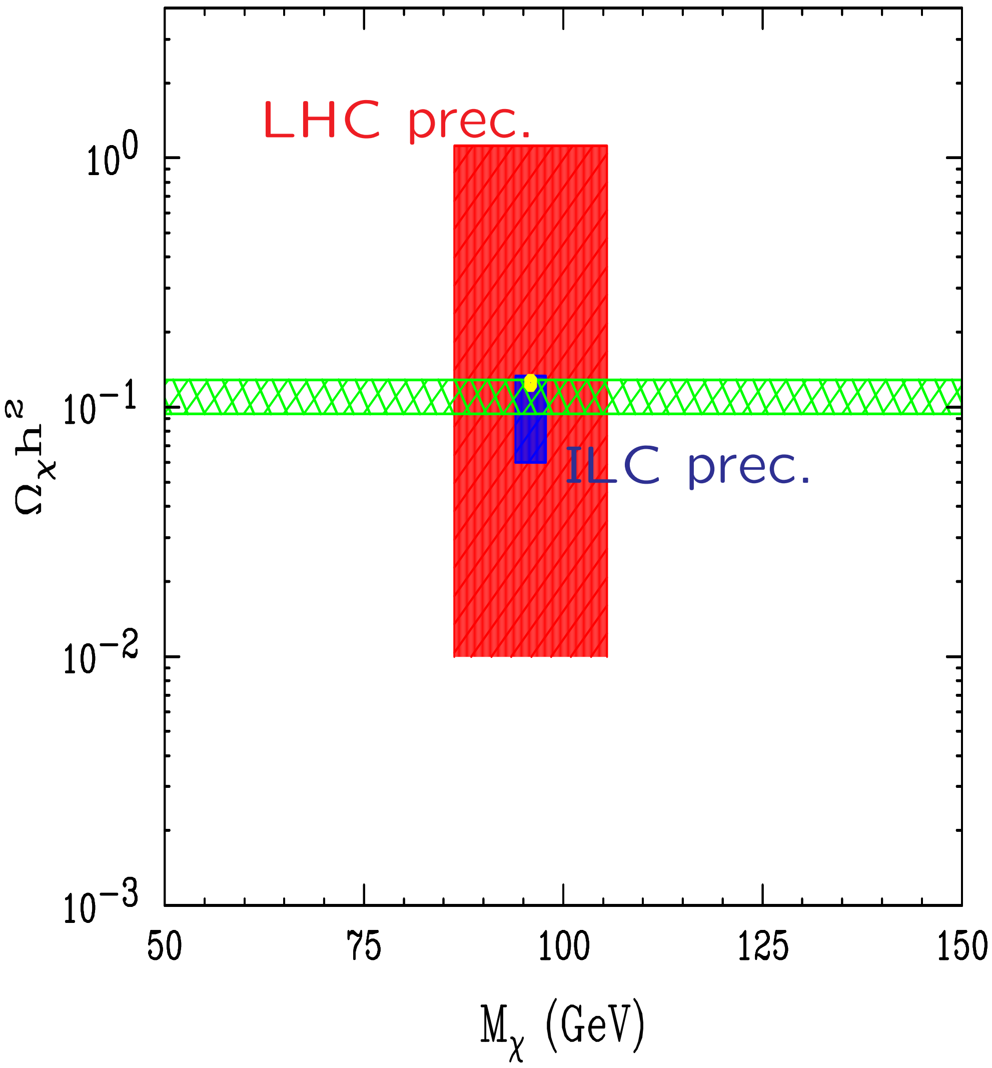


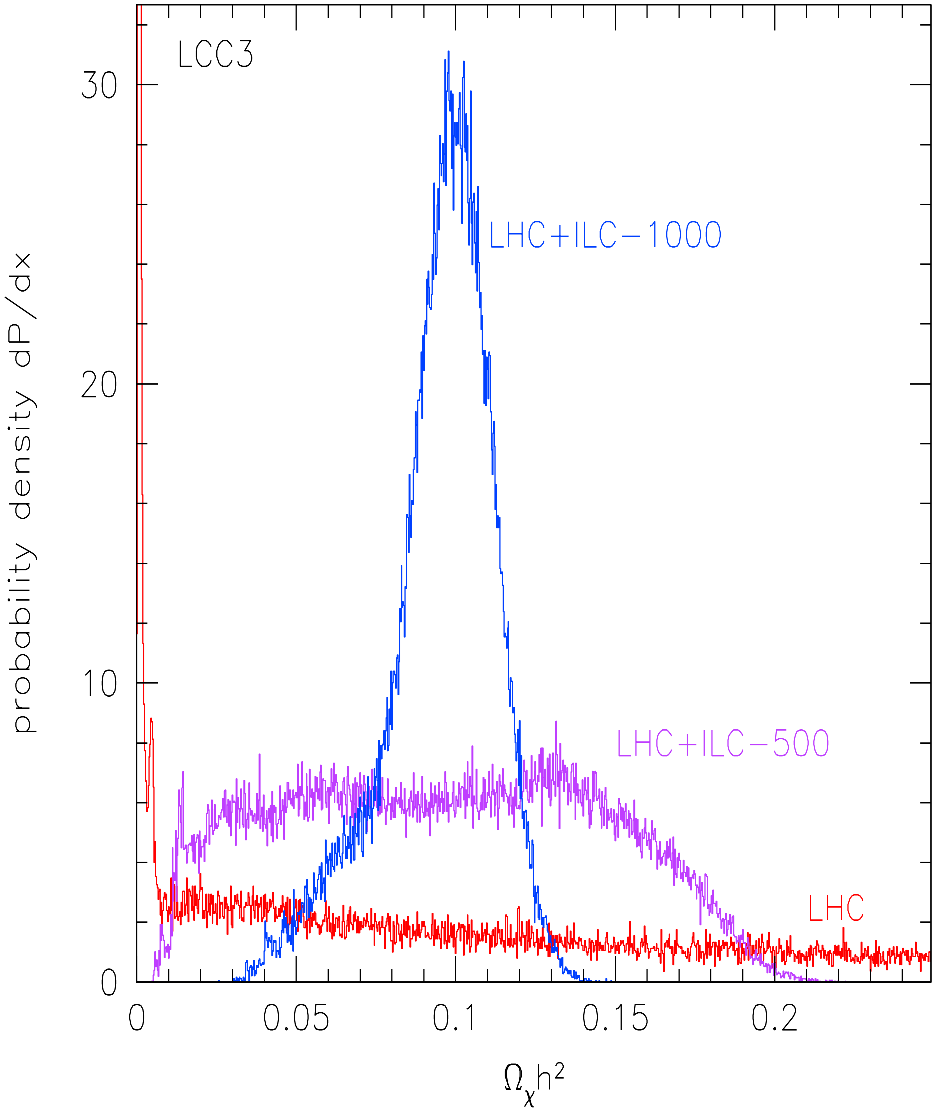


⇒ DM can be reconstructed!

Reconstructing DM at the ILC:

[ILC TDR '13]

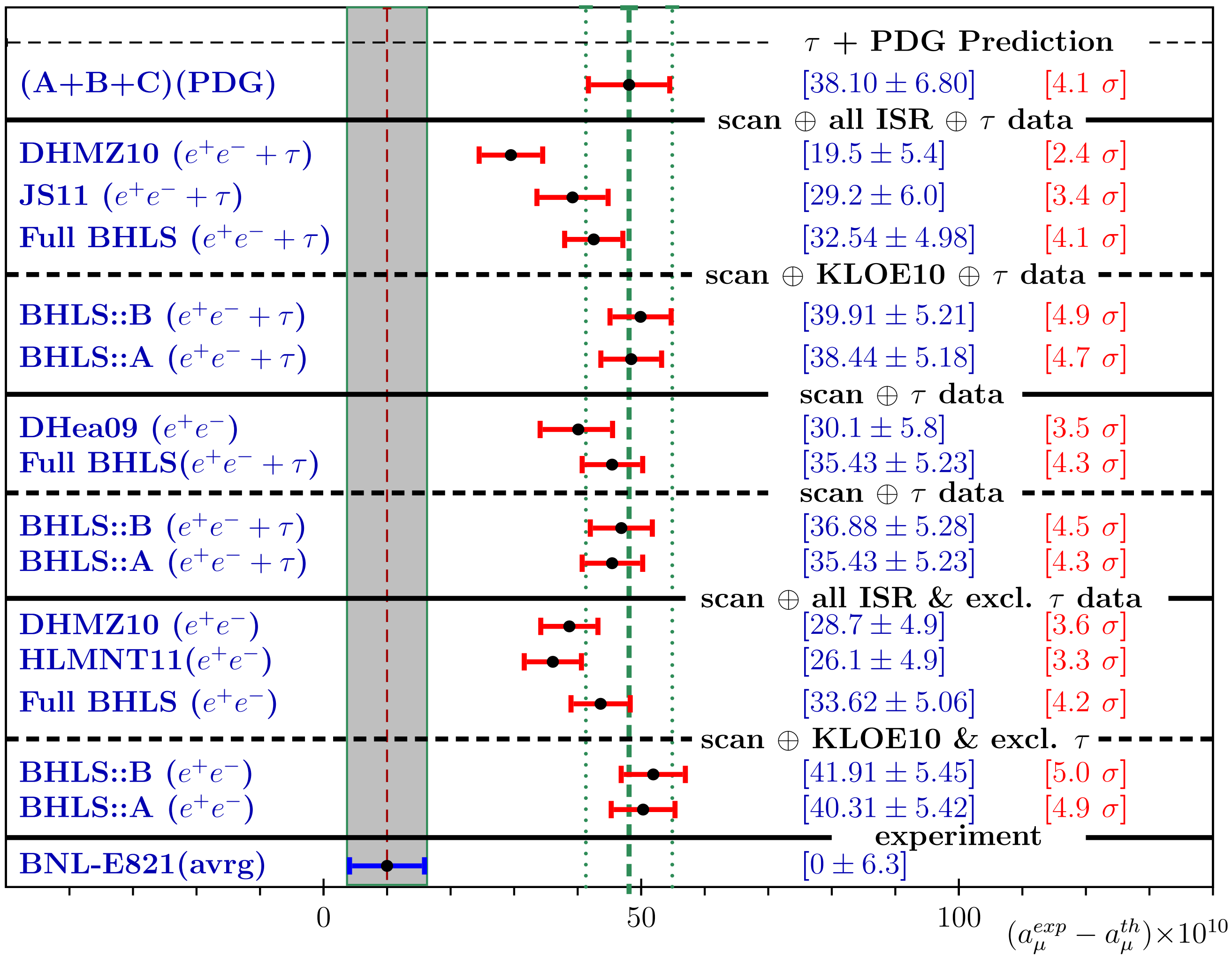




⇒ DM can be reconstructed to match astrophysical data!

Case II: Latest analysis on $(g-2)_\mu$:

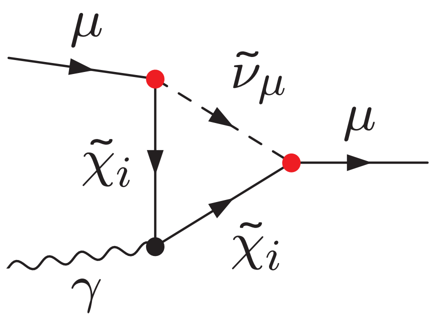
[*M. Benayoun, P. David, L. DelBuono, F. Jegerlehner '12*]

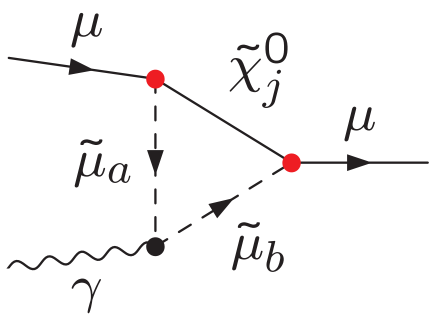


⇒ more than $4\,\sigma$ deviation! ⇒ BSM physics needed?!

BSM example: SUSY easily explains the deviation:

Feynman diagrams for MSSM 1L corrections:





– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Experimental results require:

– not too heavy scalar muons, neutrinos

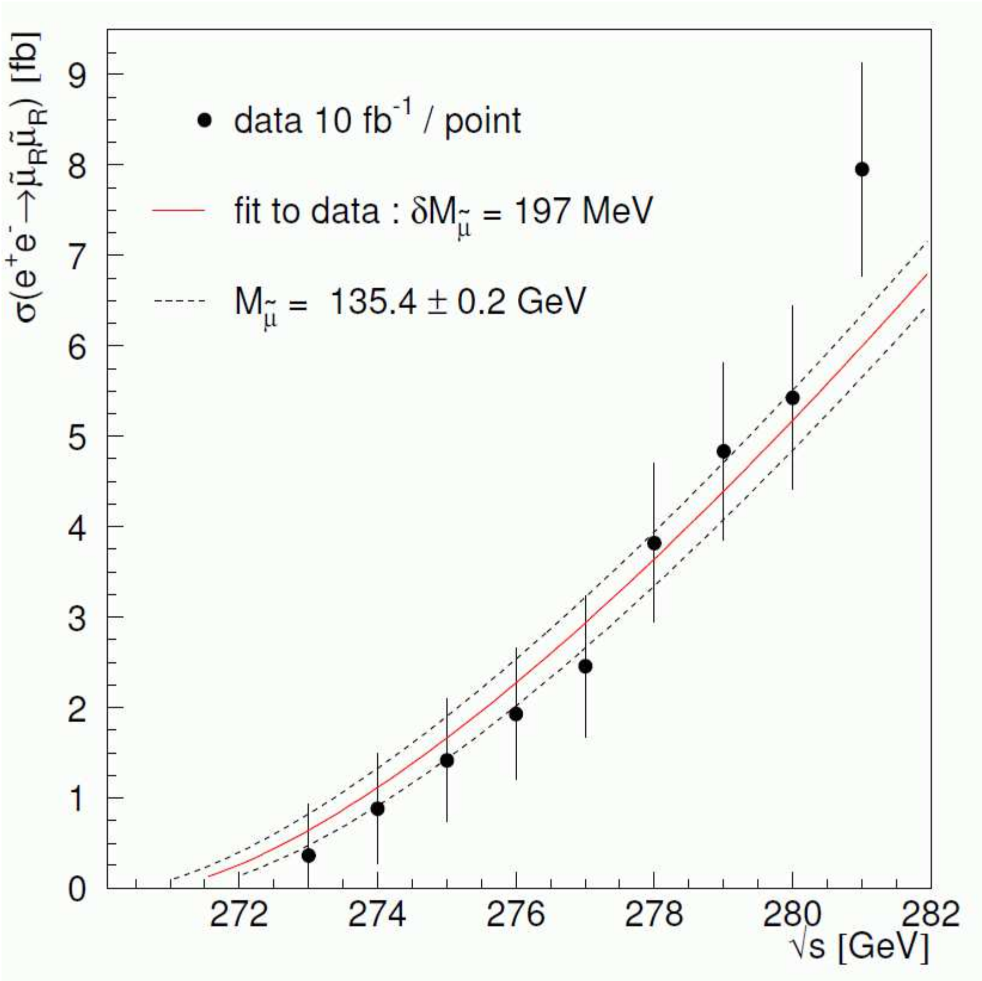
– not too heavy charginos, neutralinos

$\Rightarrow$ precision ILC analyses

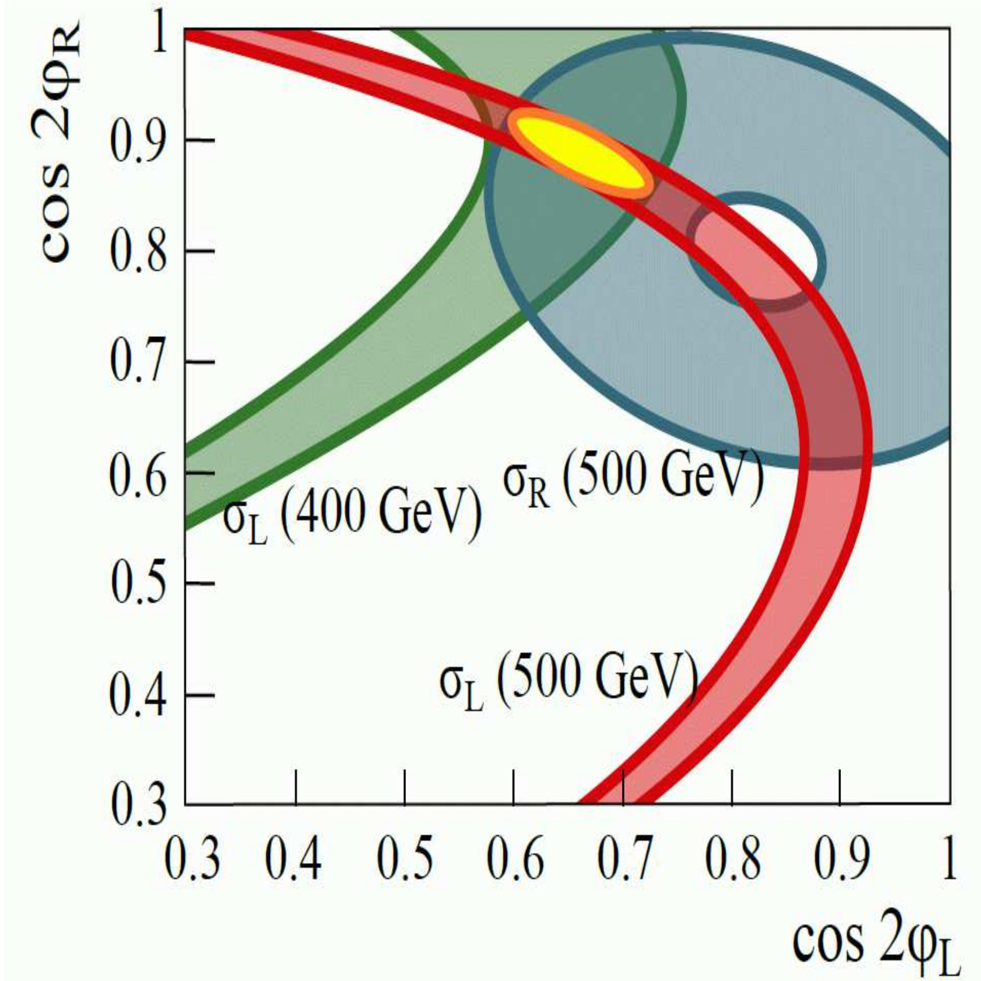
Precision ILC analyses:

[*ILC TDR '13*]

smuon mass



chargino parameter



⇒ (sub)per-cent precision possible at the ILC

Case III: A light Higgs boson below 125 GeV

We have discovered a Higgs at $\sim$ 125 GeV

$\Rightarrow$ this need not be the lightest Higgs in the spectrum!

In principle also possible:

$$M_{h_1} < 125 \text{ GeV}$$
$$M_{h_2} \approx 125 \text{ GeV}$$

Consequences:
– several Higgs bosons very light
– rich(er) Higgs phenomenology

Constraints:
– direct searches for the lightest Higgs
– direct searches for other heavier neutral Higgses
– direct searches for the charged Higgses
– flavor constraints (BR($B_s \to \mu^+\mu^-$) etc.)

Is such a light Higgs detectable at the LHC and/or ILC?

LHC:

– $h_2 \to h_1 h_1$ strongly suppressed for $M_{h_1} \gtrsim 63$ GeV

– so far no LHC searches for a Higgs with $M_{h_1} \lesssim 100$ GeV (difficult . . .)

– Possible: SUSY $\to$ SUSY h_1 , e.g. $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h_1$

ILC:

– good SUSY production mode: $e^+e^- \to hA$

– good general production mode: $e^+e^- \to t\bar{t}h_1$

$\Rightarrow$ could be a unique opportunity for the ILC!

Possible scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC (incl. GigaZ)?

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Q: Do we still need the ILC (incl. GigaZ)?

A: Of course! Or better: even more!

The ILC+GigaZ provides:

– precise Higgs coupling measurements (ILC)

– precision observable measurements (GigaZ)

– precise top mass measurement (ILC/GigaZ)

– additional discovery potential at the ILC

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$\Rightarrow$ Only the ILC+GigaZ can find deviations from the SM predictions via the various precision measurements or new discoveries

$\Rightarrow$ Only the ILC+GigaZ can point towards extensions of the SM

4. How to go ahead in the next 10 years?

(Not only) my personal view:

Discovery of a Higgs particle
together with top, $W^{\pm}$, Z, . . . , DM, $(g-2)_{\mu}$, . . .
is a **perfect physics case** for the ILC

4. How to go ahead in the next 10 years?

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> Discovery of a Higgs particle
>
> together with top, $W^{\pm}$, Z, ..., DM, $(g-2)_{\mu}$, ...
>
> is a **perfect physics case** for the ILC

Staged approach:

- ILC as a Higgs and top factory
  - start at lower energies to produce $\mathcal{O}\left(10^5\right)$ Higgs bosons
  - go to higher energies for top physics
  - go to higher energies for Higgs-top, λ_{HHH}
  - go to higher energies for TeV scale exploration
- go to other options: GigaZ, $\gamma\gamma$, ...

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⇒ unique opportunity for the ILC!

⇒ **Let's go ahead!**

Back-up

Measurement of the Higgs boson spin

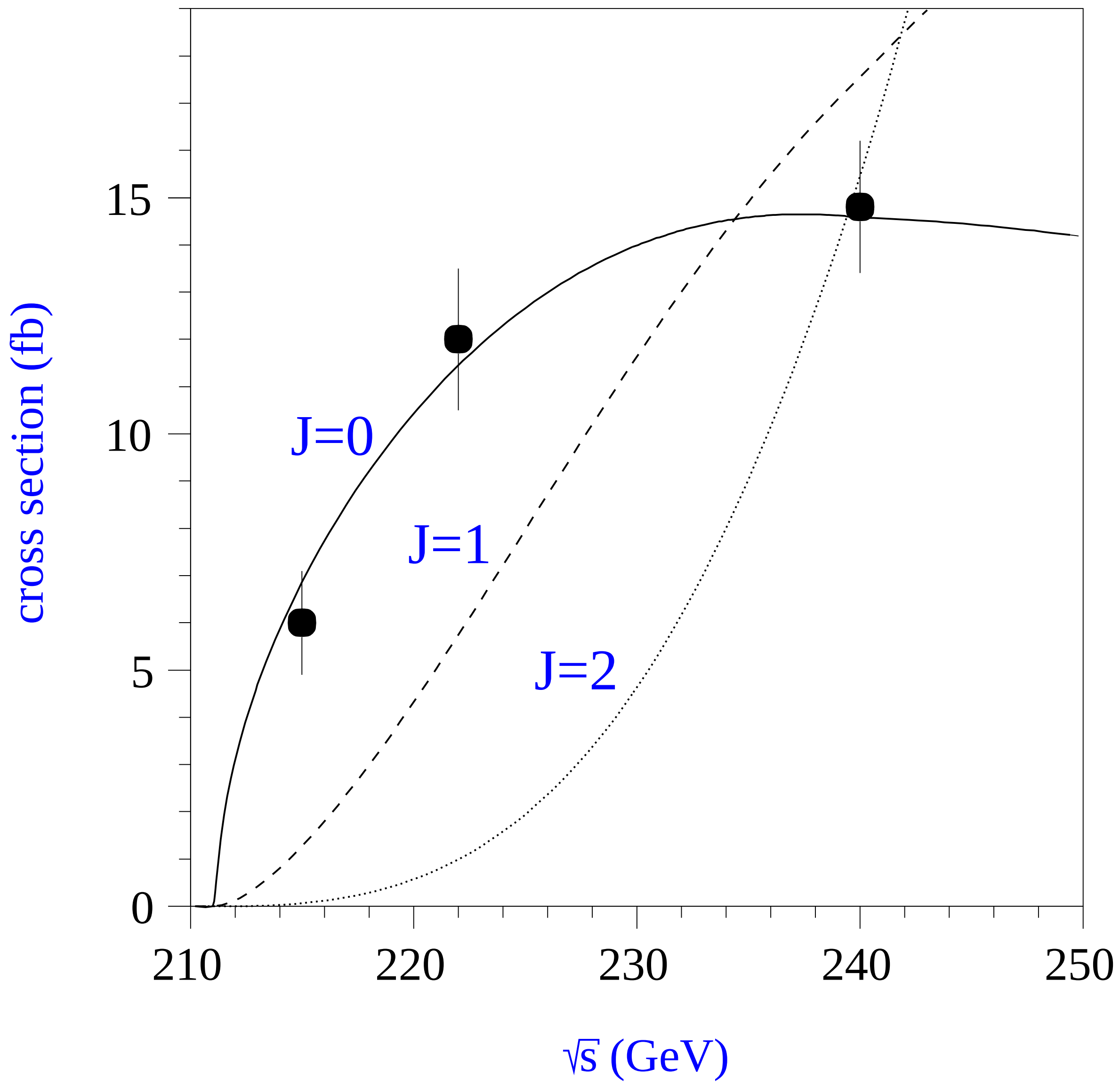
⇒ easy at the ILC

[*M. Schumacher '01*]

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

$X = H \Rightarrow \sigma \sim \beta$
(β from kinematics)

$20\,\text{fb}^{-1}$
⇒ identification easy



Indirect determination of unknown Higgs sector parameters

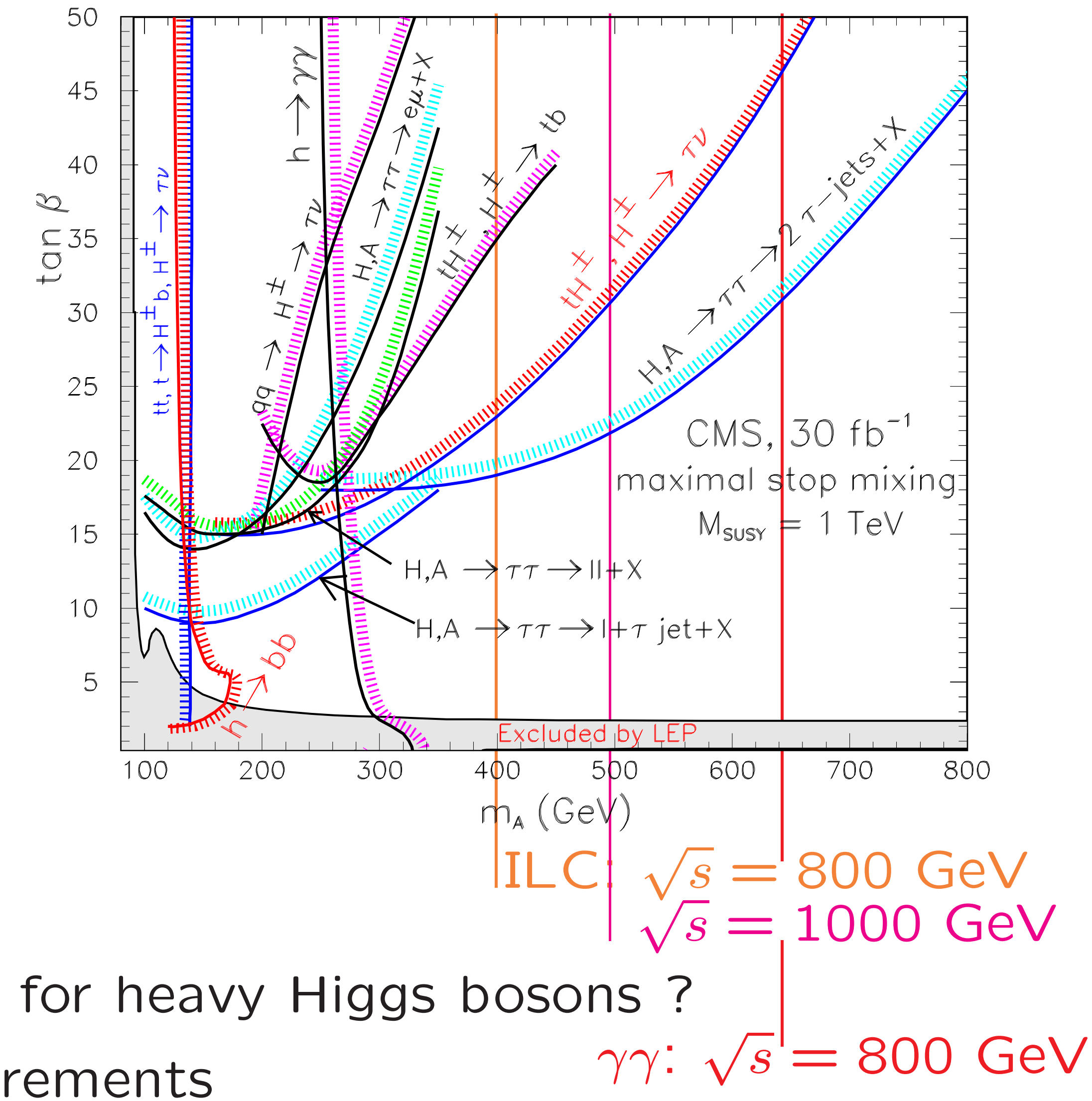
LHC/ILC reach for MSSM Higgs bosons:

LHC:

h : all $M_A - \tan\beta$ plane

H, A : unreachable parts

CMS, 30 fb^{-1}, $m_h^{\max}$ scenario: $\Rightarrow$



ILC:

kinematic limit: $M_A \lesssim \sqrt{s}/2$

$\rightarrow \sqrt{s} = 800$ GeV

$\rightarrow \sqrt{s} = 1000$ GeV

$\gamma\gamma$:

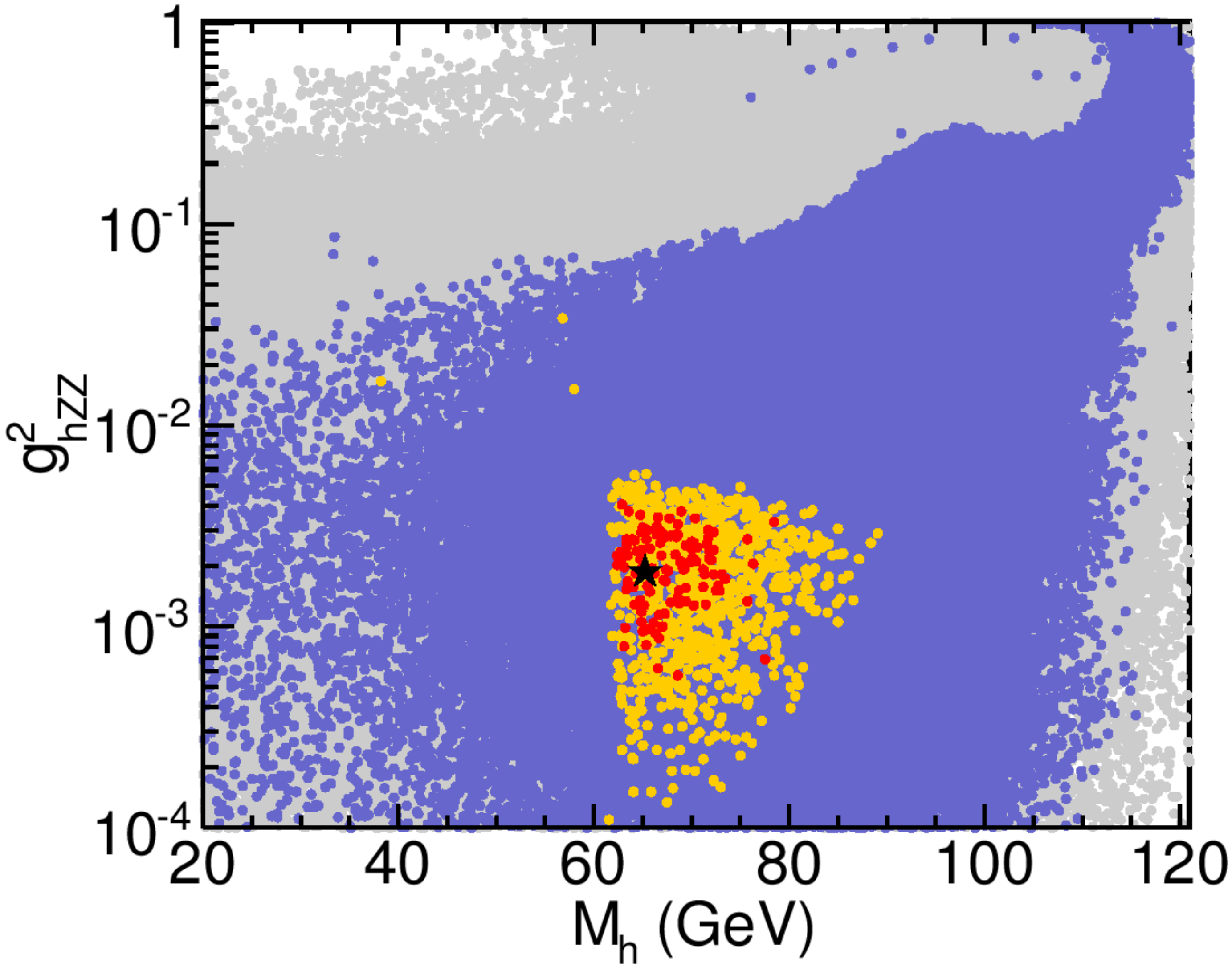
kinematic limit: $M_A \lesssim 0.8\sqrt{s}$

Q: Is it possible to extend the reach for heavy Higgs bosons ?

A: Yes, by direct and indirect measurements

Where is the light Higgs in the "heavy Higgs case"?

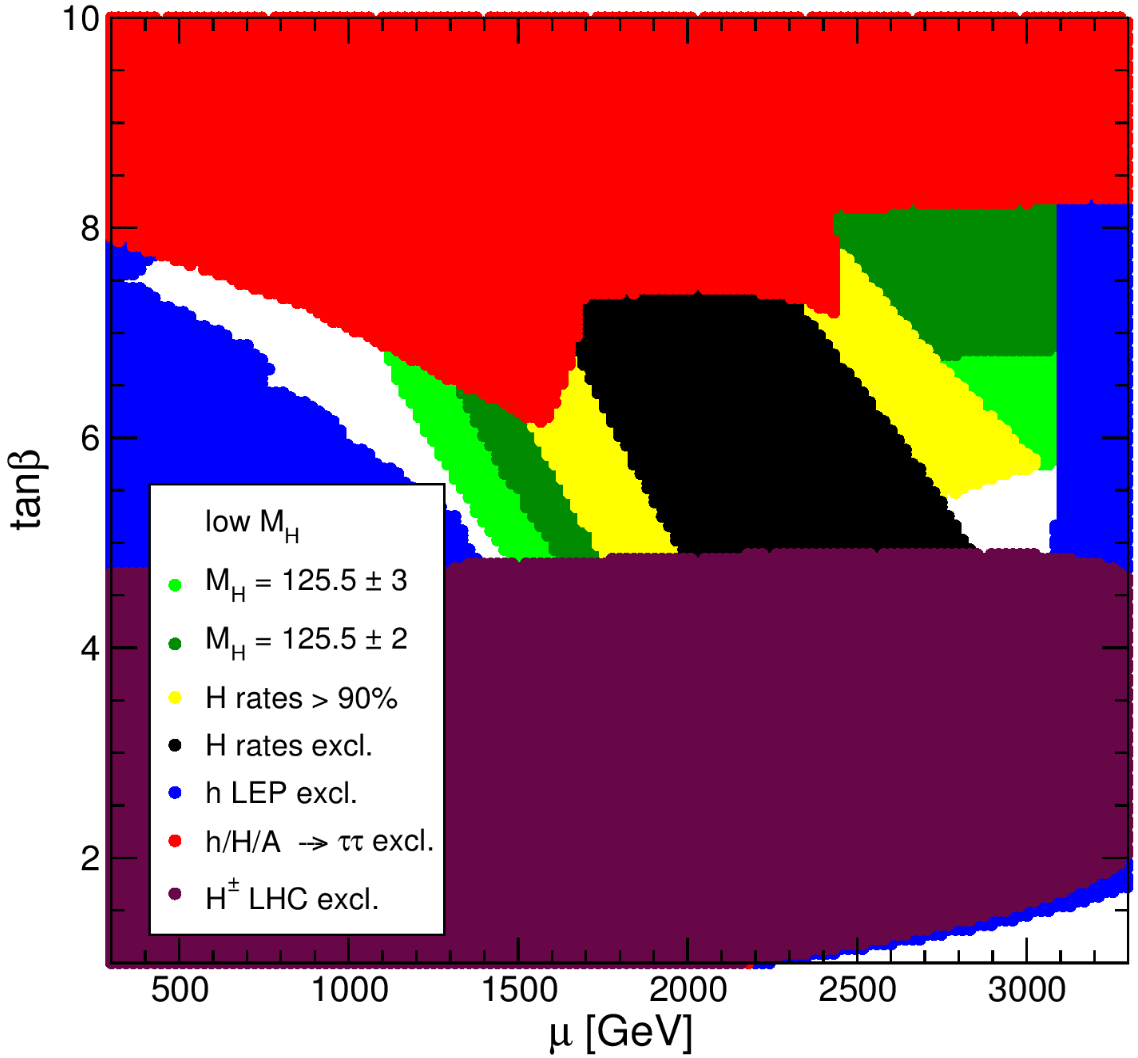
[*P. Bechtle, S.H. O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '12*]



⇒ low M_h values, strongly reduced couplings

low-M_H scenario:

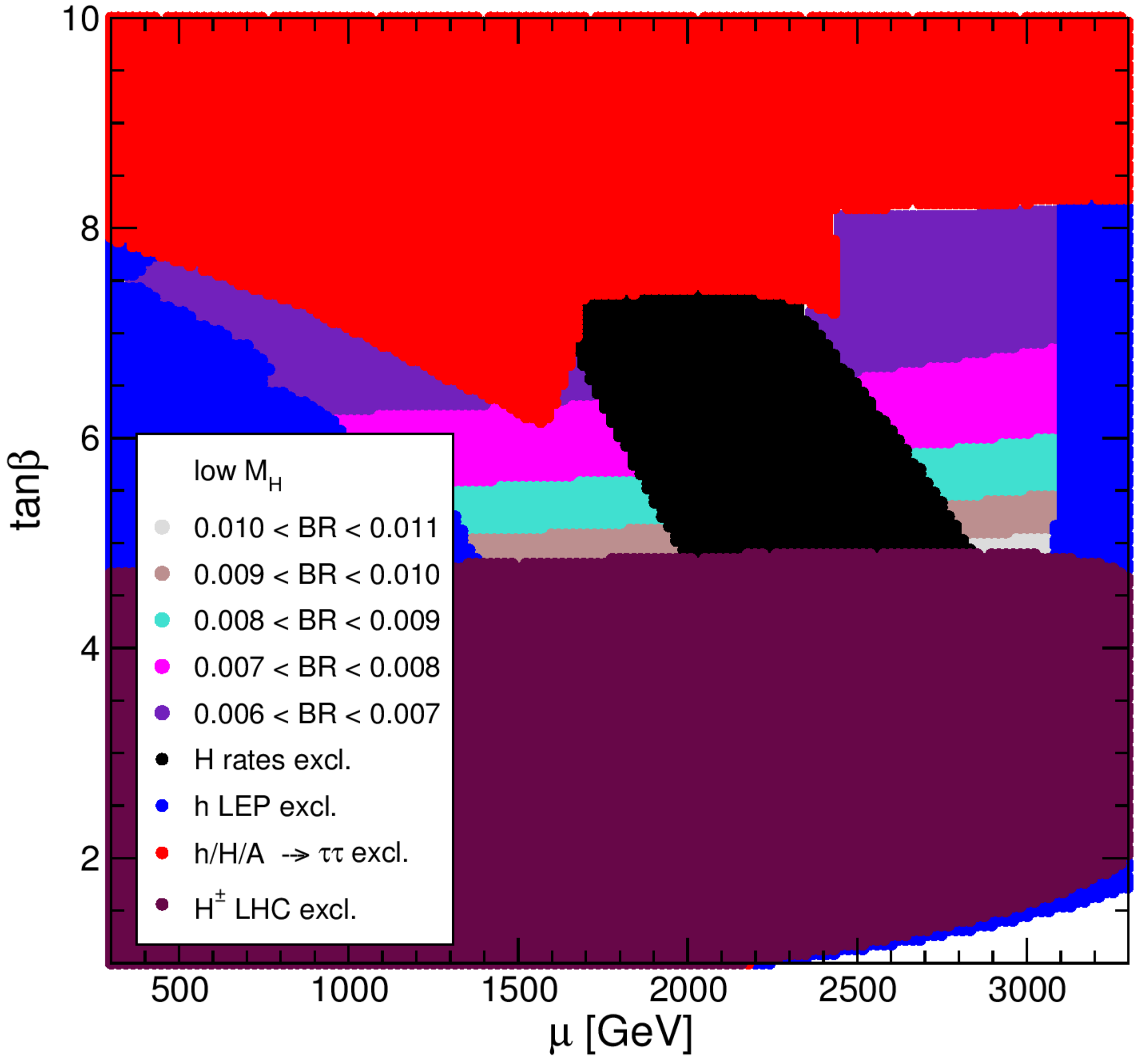
[M. Carena, S.H., O. Stål, C. Wagner, G. Weiglein '13]



$$m_t = 173.2 \text{ GeV},$$
$$M_A = 110 \text{ GeV},$$
$$M_{SUSY} = 1500 \text{ GeV},$$
$$M_2 = 200 \text{ GeV},$$
$$X_t^{OS} 2.45 M_{SUSY}$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde{g}} = 1500 \text{ GeV},$$
$$M_{\tilde{l}_3} = 1000 \text{ GeV} .$$

$\Rightarrow M_H \approx 125.5$ GeV can in principle be realized

low-M_H scenario:



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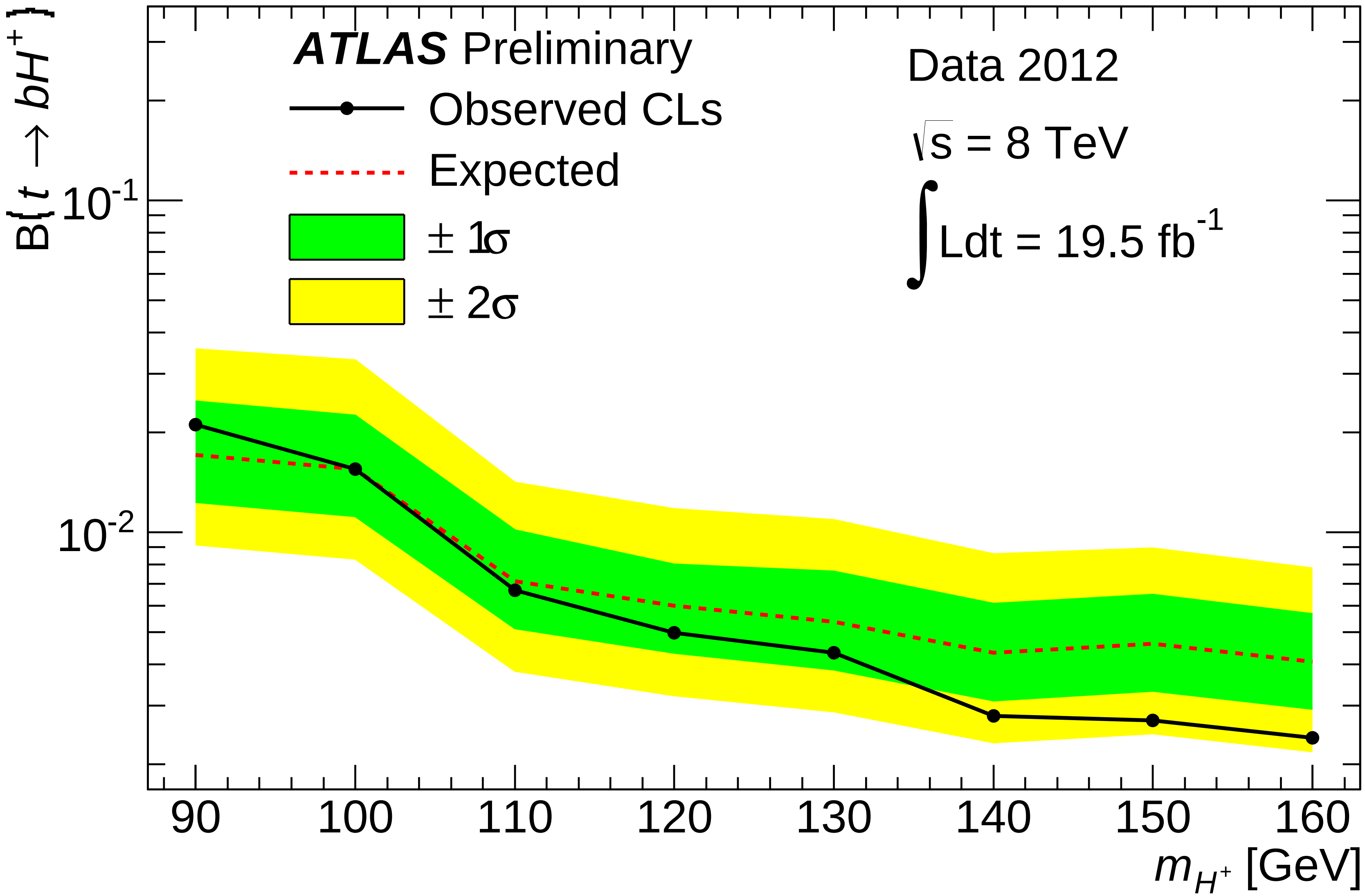
⇒ Interesting prospects also for the charged Higgs searches

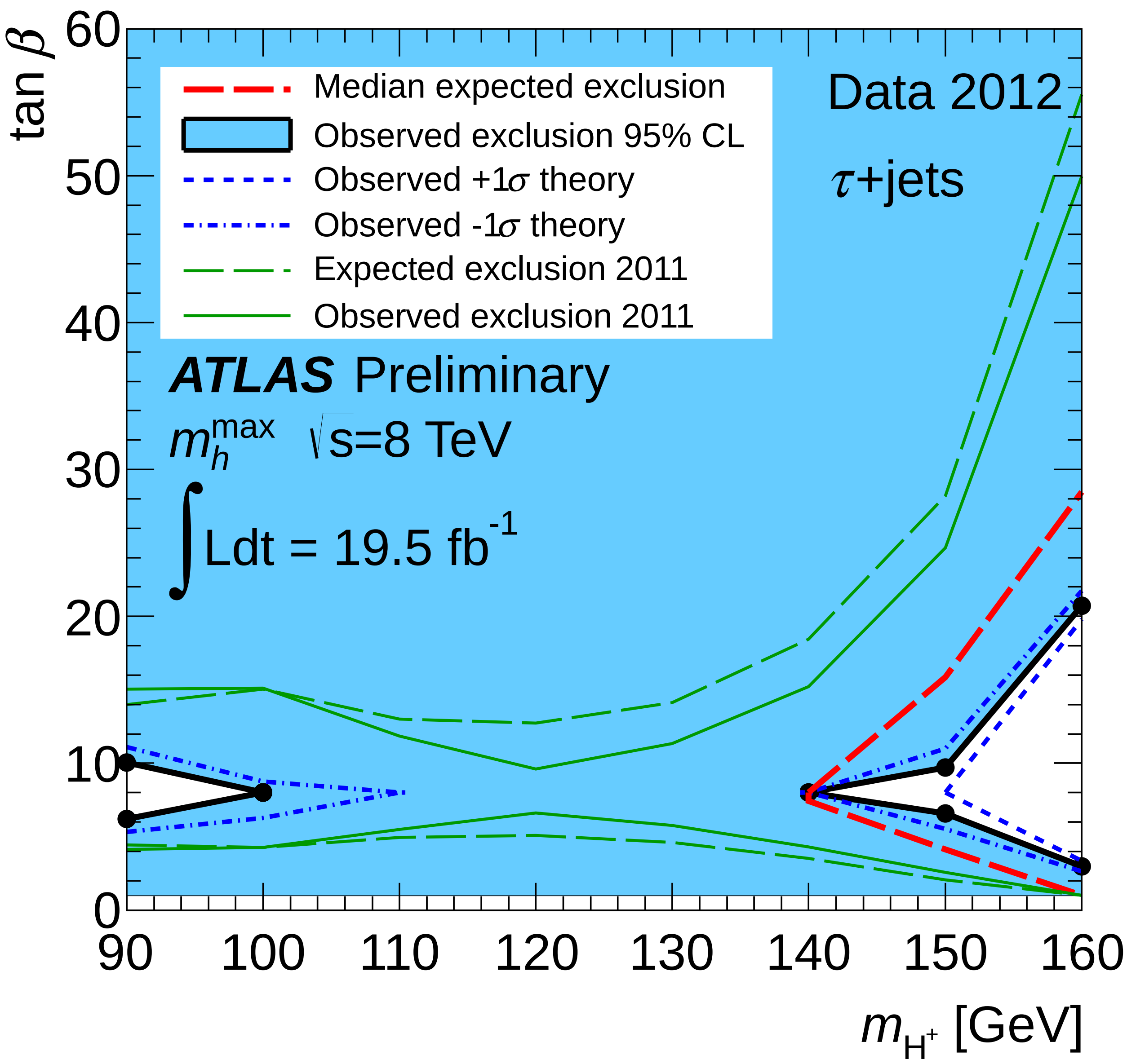
Latest ATLAS results for charged Higgs searches: [ATLAS '13]



⇒ model independent limits!

Latest ATLAS results for charged Higgs searches:

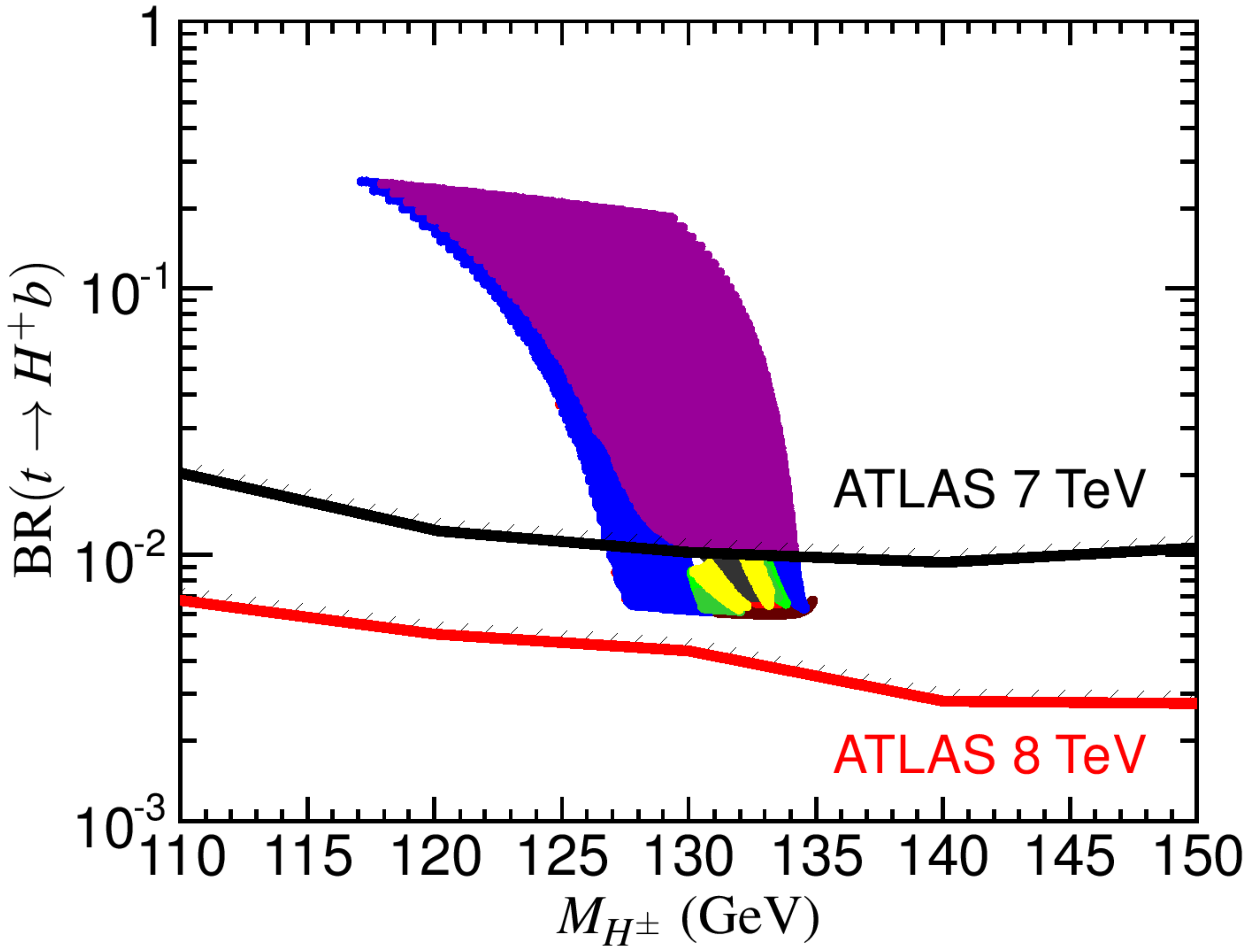
[*ATLAS '13*]



$\Rightarrow$ exclusion of light $M_{H^\pm}$ in the m_h^{max} scenario! . . . low-M_H?

Application of charged Higgs limits on low-M_H scenario:

[*HiggsBounds 4.1*]



⇒ that (particular incarnation of the) low-M_H scenario is excluded?

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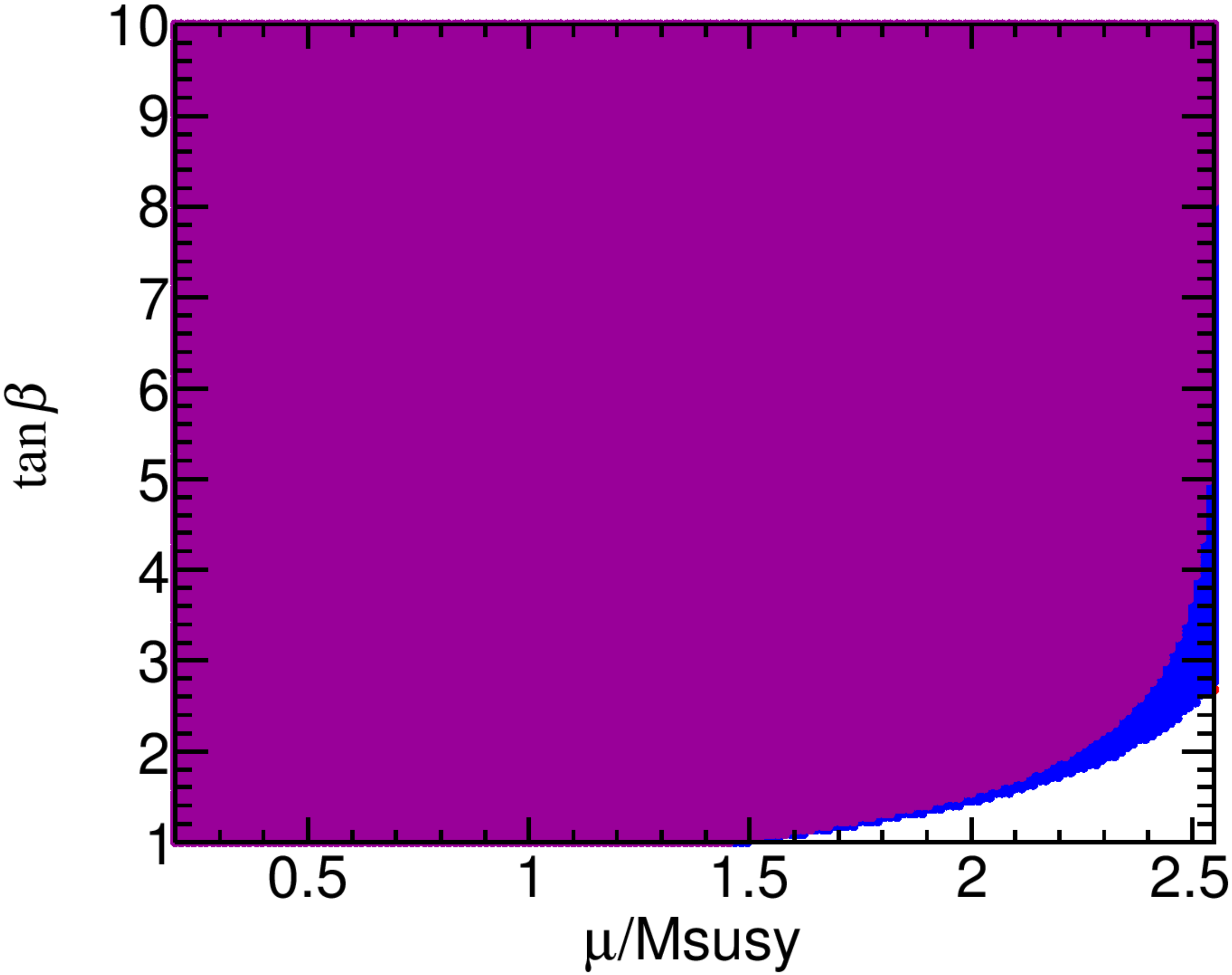
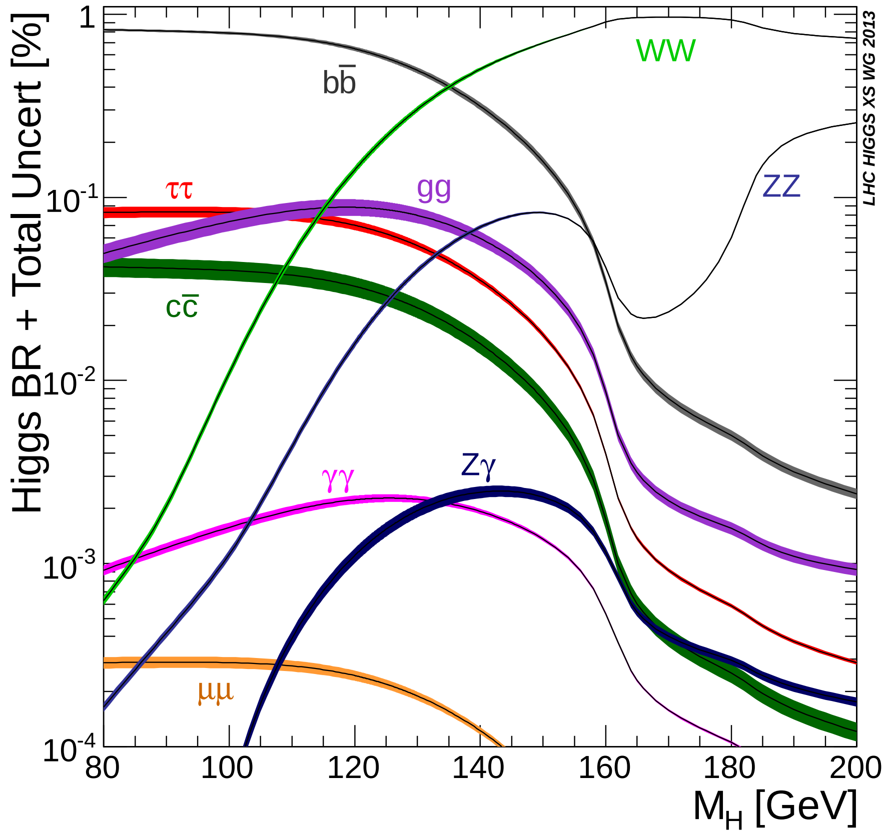
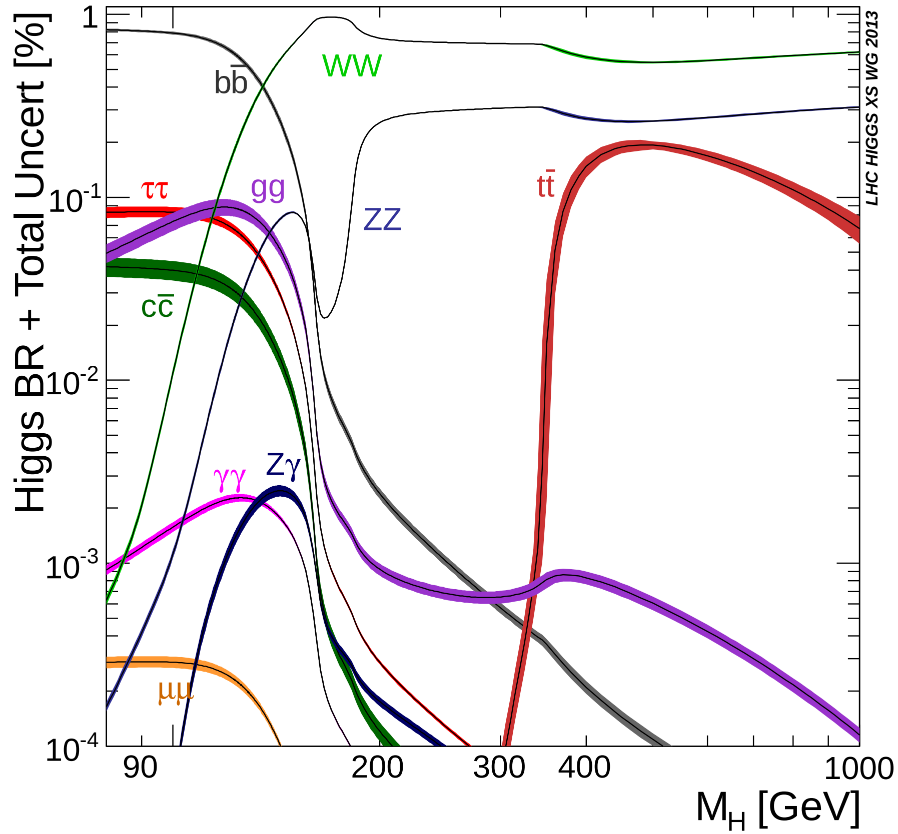
[*HiggsBounds 4.1*]



⇒ that (particular incarnation of the) low-M_H scenario is excluded?

Latest SM Higgs BR predictions:





Based on HDECAY and Prophecy4f:

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

Theoretical uncertainties: General recipe:

[*LHCHXSWG '11*]

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

   $\Rightarrow$ 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	Uncertainty	$m_q(m_q)$
$\alpha_s(M_Z)$	0.119	± 0.002(90% CL)	
m_c	1.42 GeV	± 0.03 GeV($2\,\sigma$)	1.28 GeV
m_b	4.49 GeV	± 0.06 GeV($2\,\sigma$)	4.16 GeV
m_t	172.5 GeV	± 2.5 GeV	165.4 GeV

– m_b, m_c: one-loop pole masses
  those masses accidentally show negligible dependence on α_s, so that their variation can be done independently from α_s

– m_b, m_c uncertainties:
  [K. Chetyrkin, J. Kühn, A. Maier, P. Maierhöfer, P. Marquard, M. Steinhauser, C. Sturm [arXiv:0907.2110]]
  ⇒ Lattice data much more optimistic . . .
  ⇒ but no consensus, not even in the lattice community . . . ?!

Current theoretical uncertainties:

Partial Width	QCD	Electroweak	Total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	$\sim$ 1–2% for $M_H \lesssim$ 135 GeV	$\sim 2\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim$ 1–2% for $M_H \lesssim$ 135 GeV	$\sim 2\%$
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim$ 2–5% for $M_H <$ 500 GeV	$\sim 5\%$
		$\sim 0.1(\frac{M_H}{1\text{ TeV}})^4$ for $M_H >$ 500 GeV	$\sim$ 5–10%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim$ 0.5% for $M_H <$ 500 GeV	$\sim 0.5\%$
		$\sim 0.17(\frac{M_H}{1\text{ TeV}})^4$ for $M_H >$ 500 GeV	$\sim$ 0.5–15%

– 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 $\sim$ 10 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:

[YR3, arXiv:1307.1347]

Channel	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to b\bar{b}$	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
$H \to \tau^+\tau^-$	$2.59 \cdot 10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
$H \to \mu^+\mu^-$	$8.99 \cdot 10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%
$H \to c\bar{c}$	$1.19 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% −0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%
$H \to gg$	$3.57 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% −0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
$H \to \gamma\gamma$	$9.59 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
$H \to Z\gamma$	$6.84 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%
$H \to WW^*$	$9.73 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
$H \to ZZ^*$	$1.22 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%

Data available for $M_H = 122$ GeV, 126 GeV, 130 GeV

$\Rightarrow$ used for ATLAS and CMS evaluations $\Rightarrow$ provided to Snowmass/Higgs

Theory uncertainties at the "ILC times"?

Parametric uncertainties:

- largely driven by $\delta m_b \Rightarrow$ improvement unclear (to me)
  lattice community does not seem to agree
- some improvement in α_s possible

Intrinsic uncertainties:

$H \to b\bar{b}, H \to c\bar{c}$: EW corrections can be included (they are known at 1L)

$H \to \tau^+\tau^-, H \to \mu^+\mu^-$: EW corrections can be included (they are known at 1L)

$H \to gg$: 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