Higgs and Precision Observables
at the ILC and TLEP/FCC-ee

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CERN, 06/2015

1. Introduction
2. Electroweak Precision Observables
3. Higgs Observables
4. Conclusions

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LHC/ILC/FCC-ee/TLEP/. . . will provide (high!) accuracy measurements!

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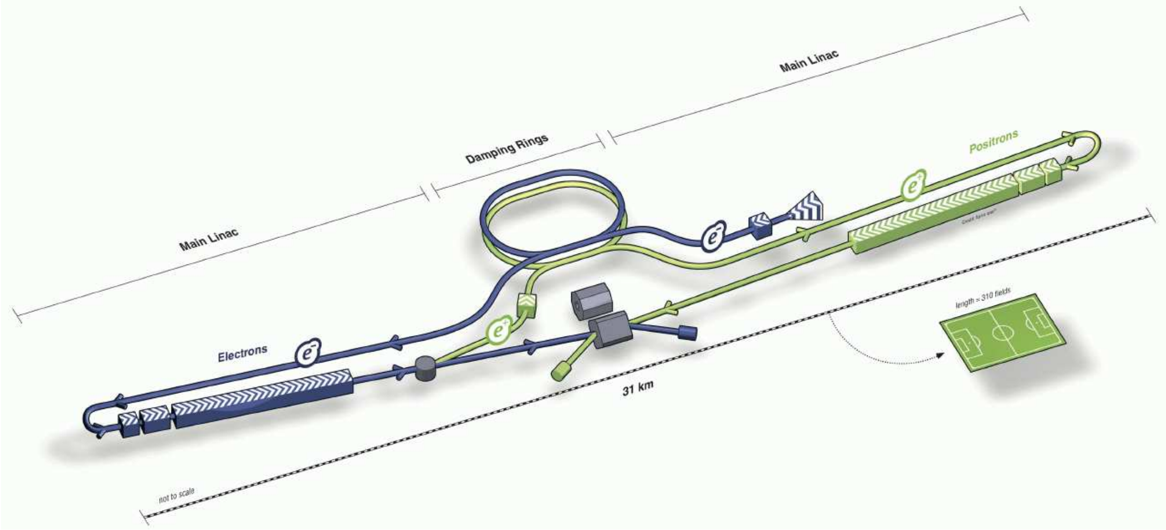
Theoretical calculations should be viewed as
an essential part of all (current and future)
High Energy Physics programs

ILC: 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:

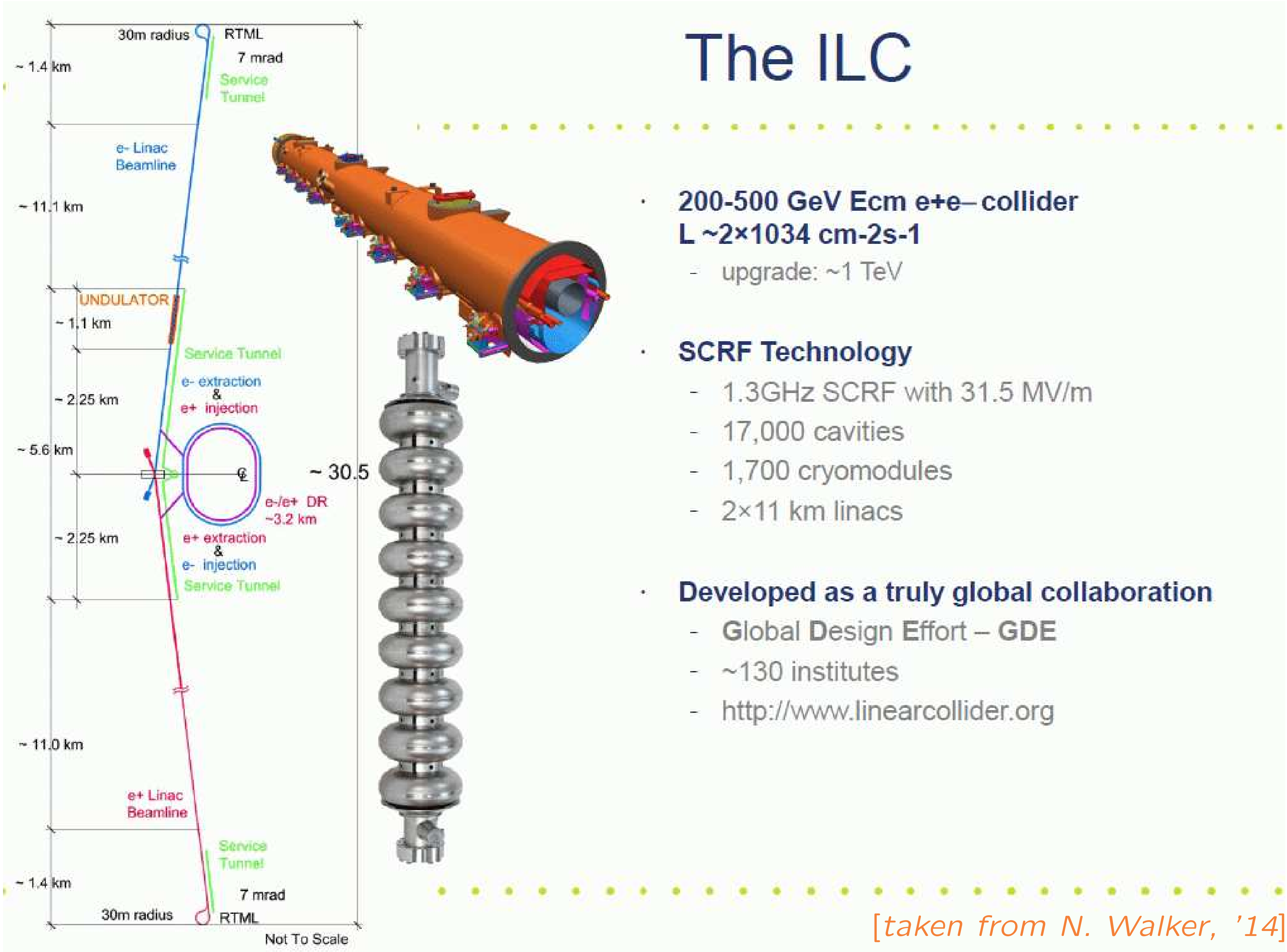
- GigaZ:
  running with high luminosity at low energies (Z pole, WW threshold)

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

- $e^-\gamma$:
  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!

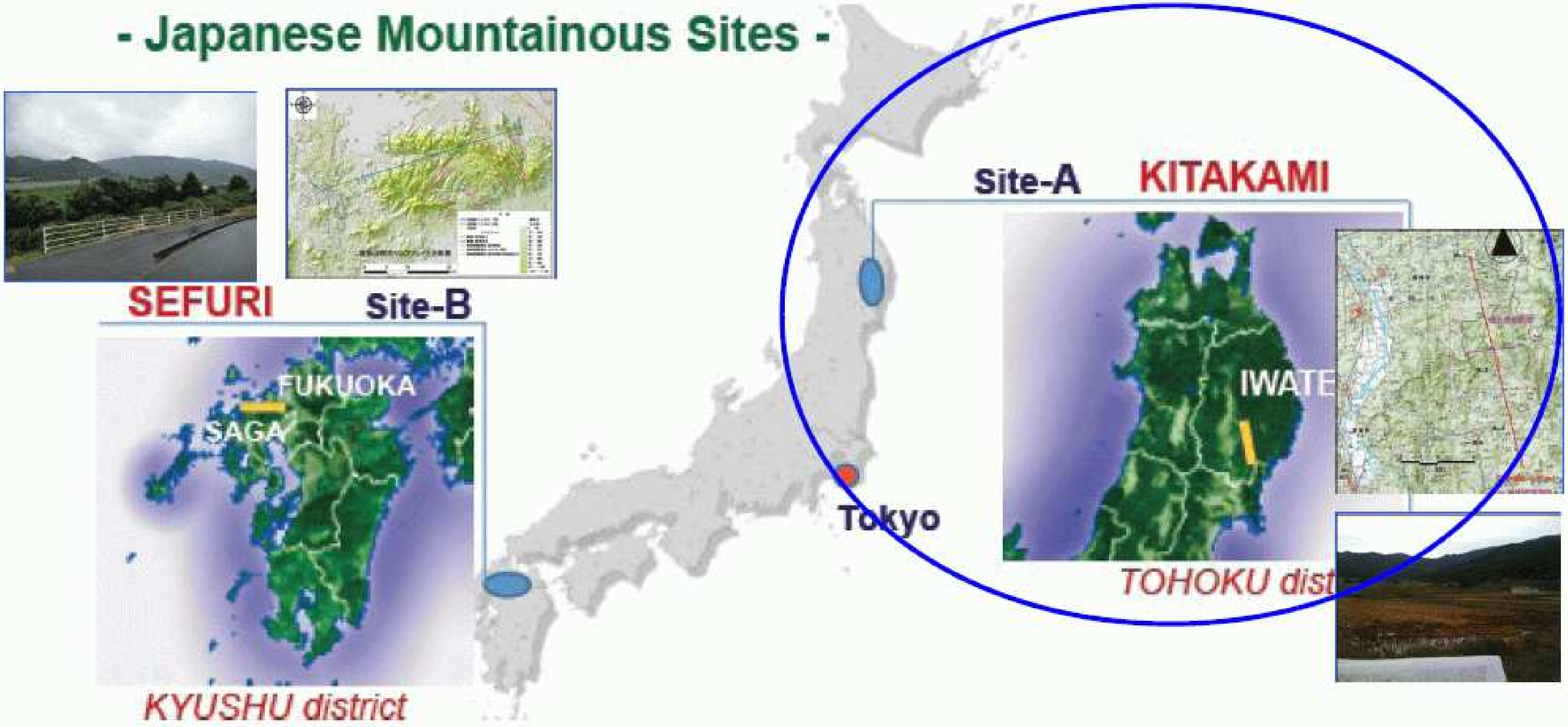


The ILC

- **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.

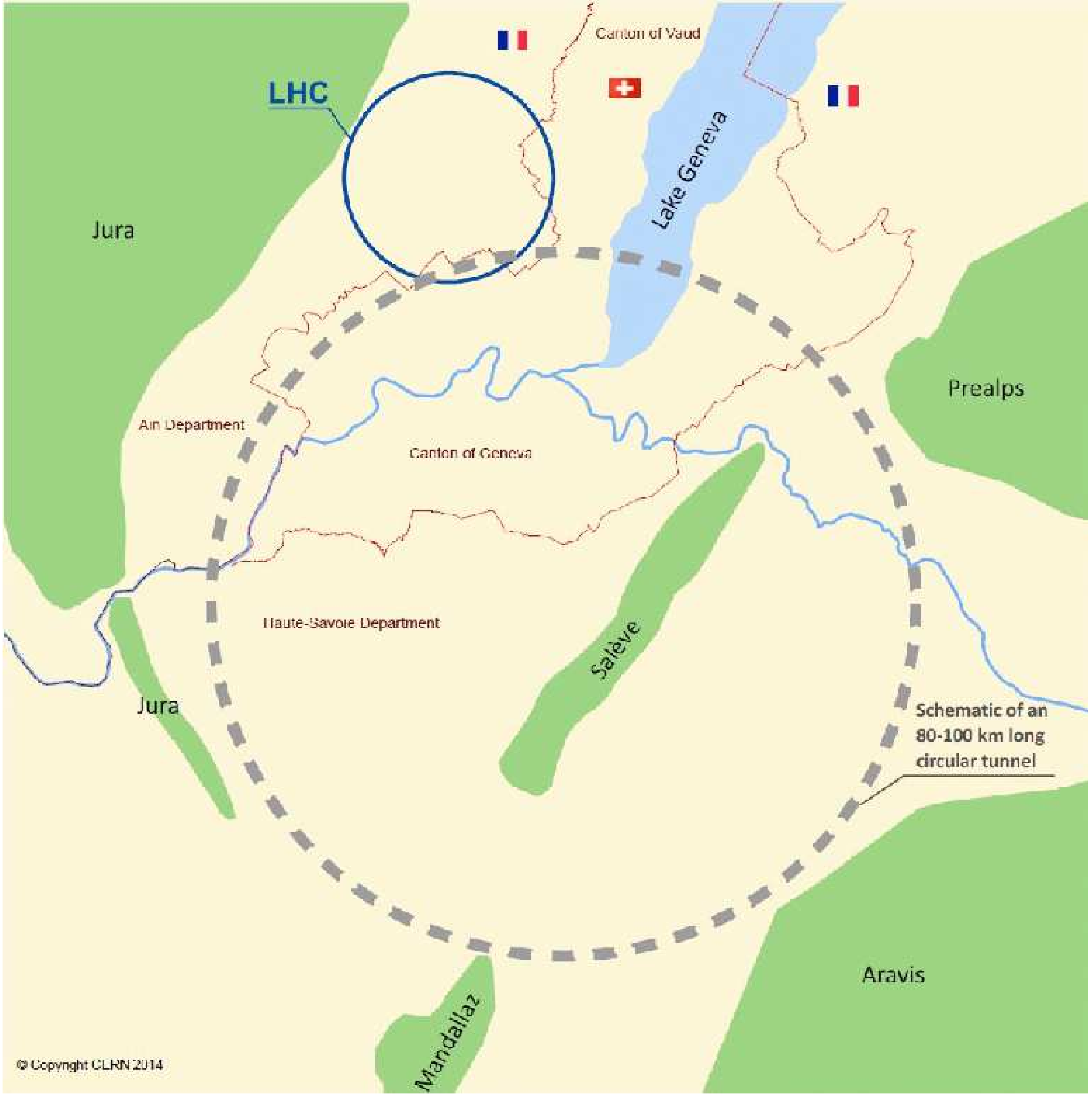
[taken from N. Walker, ’14]

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]

FCC: a 100 km ring . . .



FCC: a 100 km ring . . .

FCC: a 100 km ring for 3 colliders:

FCC-hh: $p\,p$

FCC-ee: e^+e^- ⇐ focus here

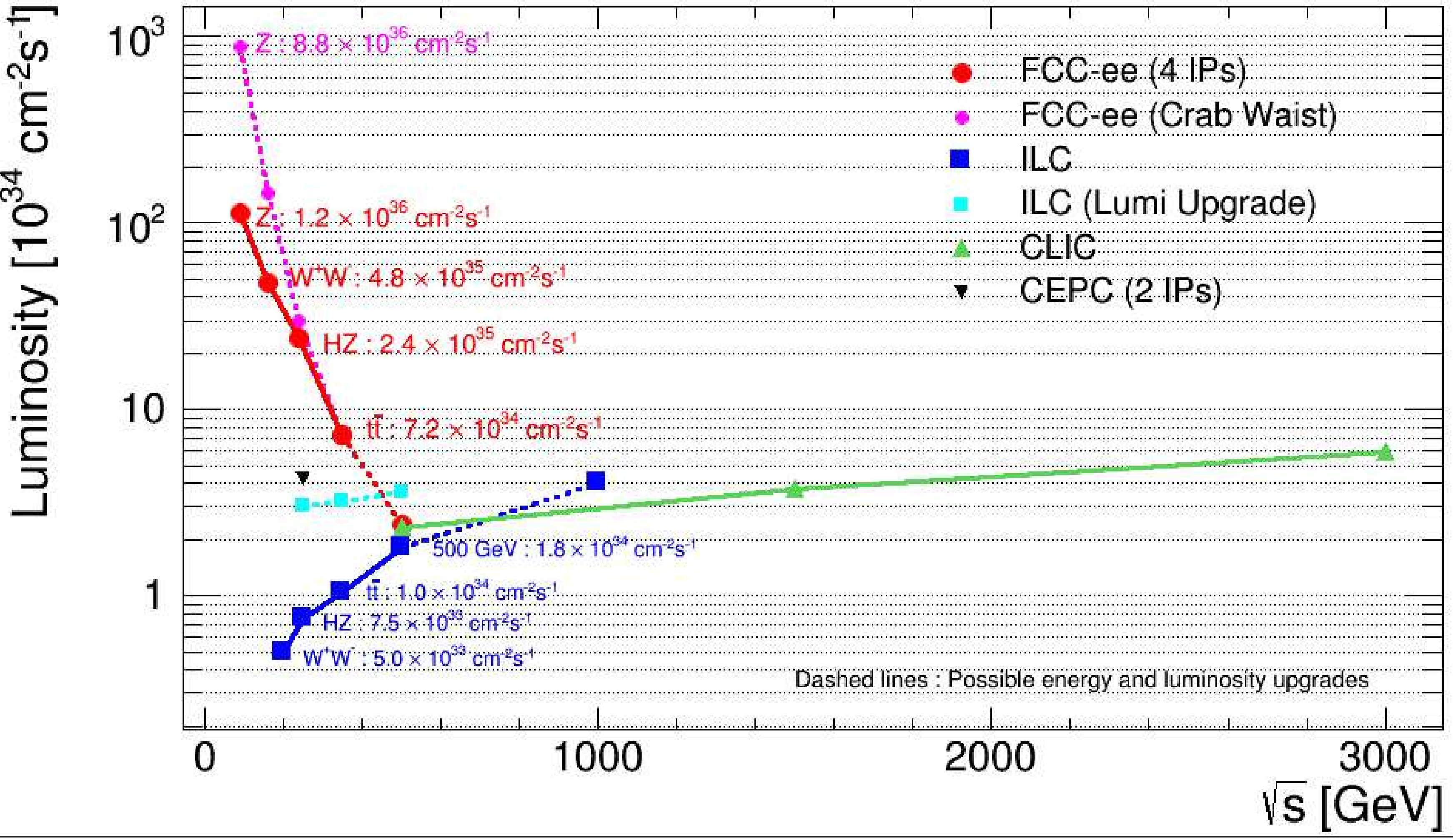
FCC-eh: $p\,e$

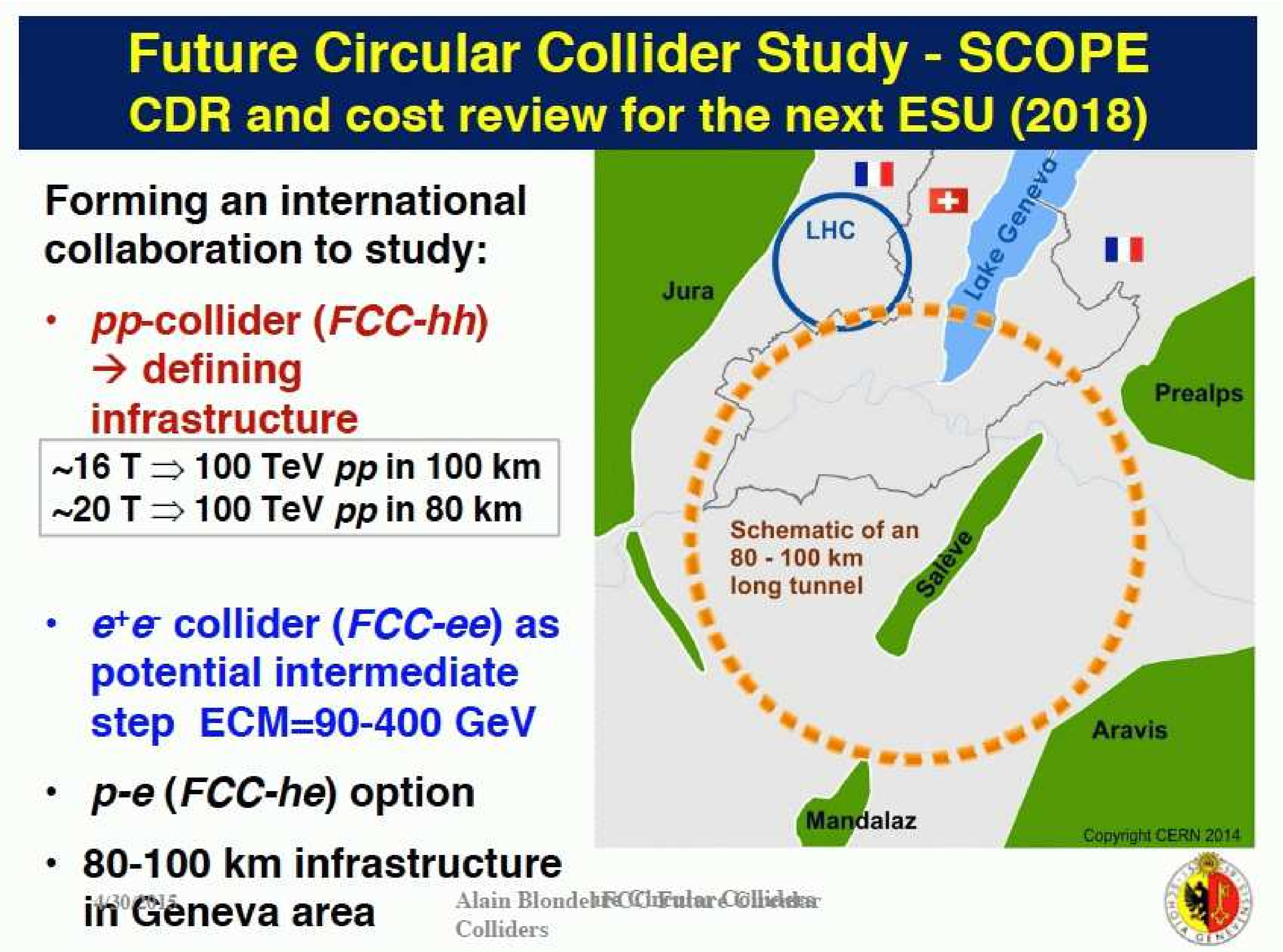
FCC-ee:

e^+e^- collisions in a 100 km tunnel with $\sqrt{s} \lesssim 350$ GeV

$\mathcal{L} \sim 6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (for Higgs physics)

4 interaction regions for maxium luminosity





Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

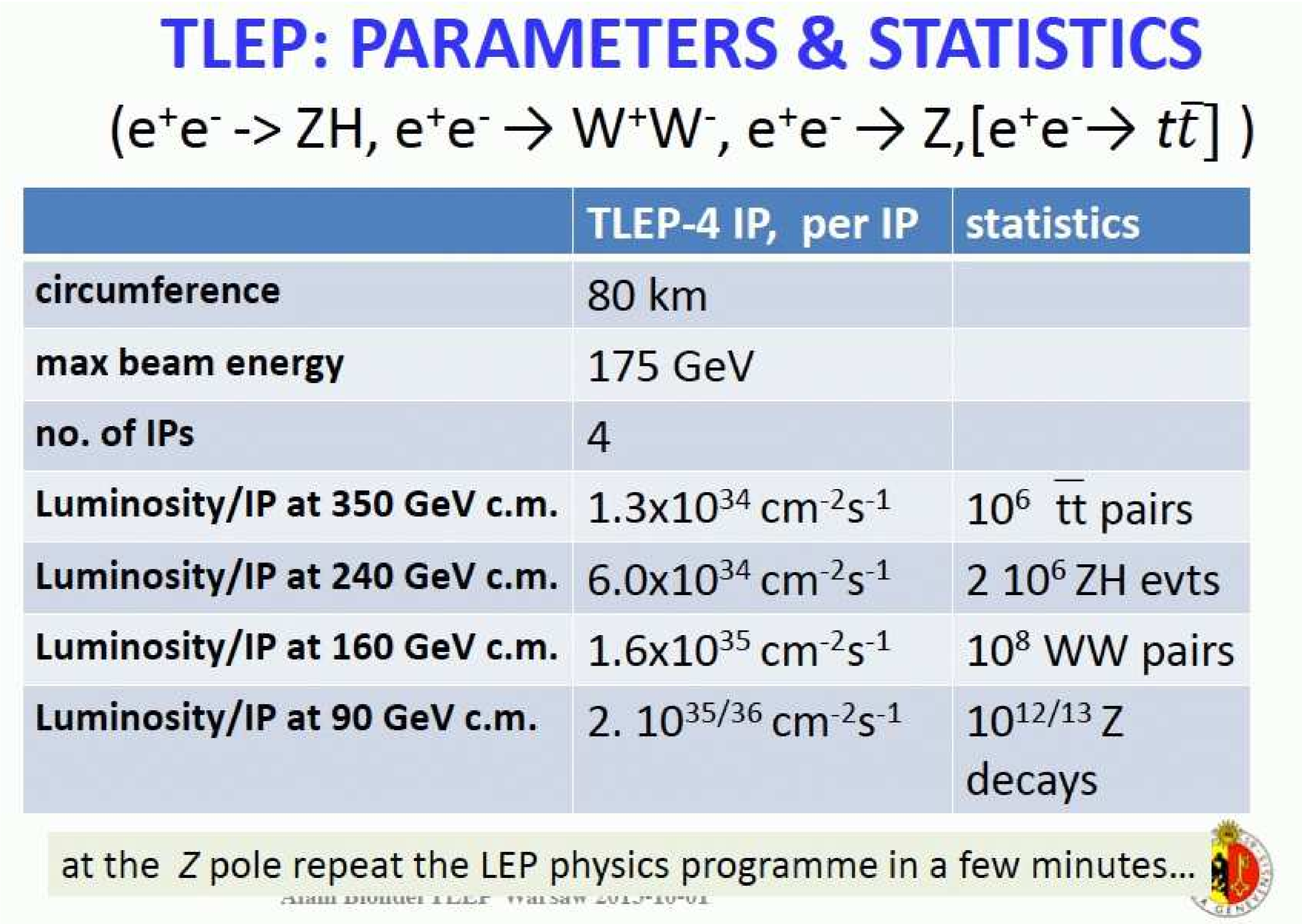
- *pp*-collider (*FCC-hh*) → defining infrastructure

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- e^+e^- collider (*FCC-ee*) as potential intermediate step ECM=90-400 GeV
- *p-e* (*FCC-he*) option
- 80-100 km infrastructure in Geneva area

4/30/2015 Alain Blondel FCC Future Colliders

[*A. Blondel '15*]



TLEP: PARAMETERS & STATISTICS

($e^+e^- \to ZH$, $e^+e^- \to W^+W^-$, $e^+e^- \to Z$,[$e^+e^- \to t\bar{t}$])

	TLEP-4 IP, per IP	statistics
circumference	80 km	
max beam energy	175 GeV	
no. of IPs	4	
Luminosity/IP at 350 GeV c.m.	$1.3\text{x}10^{34}$ cm^{-2}s^{-1}	10^6 $t\bar{t}$ pairs
Luminosity/IP at 240 GeV c.m.	$6.0\text{x}10^{34}$ cm^{-2}s^{-1}	2 10^6 ZH evts
Luminosity/IP at 160 GeV c.m.	$1.6\text{x}10^{35}$ cm^{-2}s^{-1}	10^8 WW pairs
Luminosity/IP at 90 GeV c.m.	2. $10^{35/36}$ cm^{-2}s^{-1}	$10^{12/13}$ Z decays

at the *Z* pole repeat the LEP physics programme in a few minutes…

Alain Blondel TLEP Warsaw 2013-10-01

[A. Blondel '15]

Phenomenology working groups:

Phenomenology studies

The phenomenological studies are coordinated by John Ellis and Chistophe Grojean, and are organized in five working groups:

- Working Group 1: QCD and γγ physics (joint exp/th). Convener: Peter Skands ✉
- Working Group 2: Precision EW calculations. Convener: Sven Heinemeyer ✉
- Working Group 3: Flavour physics (joint exp/th). Convener: Jernej Kamenik ✉
- Working Group 4: Model building and new physics. Convener: Andreas Weiler ✉
- Working Group 5: Global analysis, combination, complementarity. Convener: John Ellis ✉

⇒ here mostly relevant: WG2 :-)

My personal time scale wish/estimate:

1. exploit the LHC

2. construct the ILC as quickly as possible in Japan

3. after LHC construct the FCC at CERN
   depending on physics outcome of LHC/ILC:
   decide whether to start with FCC-ee or FCC-hh

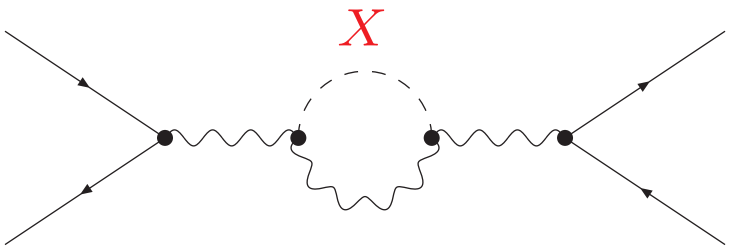
2. Electroweak Precision Observables

Comparison of observables with theory:

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

Precision observables in the SM and the MSSM

M_W, $\sin^2\theta_{\text{eff}}$, 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*]

$$\begin{array}{lcccccc}\Delta r_{1-\text{loop}} = & \Delta\alpha & - & \frac{c_W^2}{s_W^2}\Delta\rho & + & \Delta r_{\text{rem}}(M_H) \\ & \sim \log\frac{M_Z}{m_f} & & \sim m_t^2 & & \log(M_H/M_W) \\ & \sim 6\% & & \sim 3.3\% & & \sim 1\%\end{array}$$

Precision observables in the SM and the MSSM

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

A) Theoretical prediction for M_W in terms

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

$\Updownarrow$

loop corrections

B) Effective mixing angle:

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

Higher order contributions:

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

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

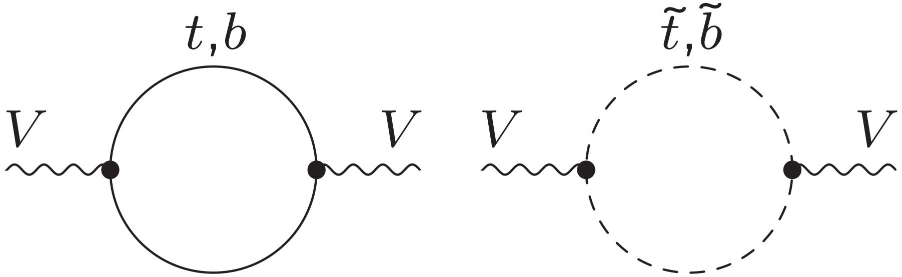
ρ measures the relative strength between
neutral current interaction and charged current interaction

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

(leading, process independent terms)

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

$$\Delta M_W \approx \frac{M_W}{2}\frac{c_{\text{W}}^2}{c_{\text{W}}^2 - s_{\text{W}}^2}\Delta\rho, \qquad \Delta\sin^2\theta_W^{\text{eff}} \approx -\frac{c_{\text{W}}^2 s_{\text{W}}^2}{c_{\text{W}}^2 - s_{\text{W}}^2}\Delta\rho$$



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

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

- 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 $\sin^2\theta_{\text{eff}}$:

- 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!

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)

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

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

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

parametric future: $\delta m_t^{\text{ILC/TLEP}} = 0.1$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$

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

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

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

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

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

parametric future: $\delta m_t^{\text{ILC/TLEP}} = 0.1$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$

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

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?

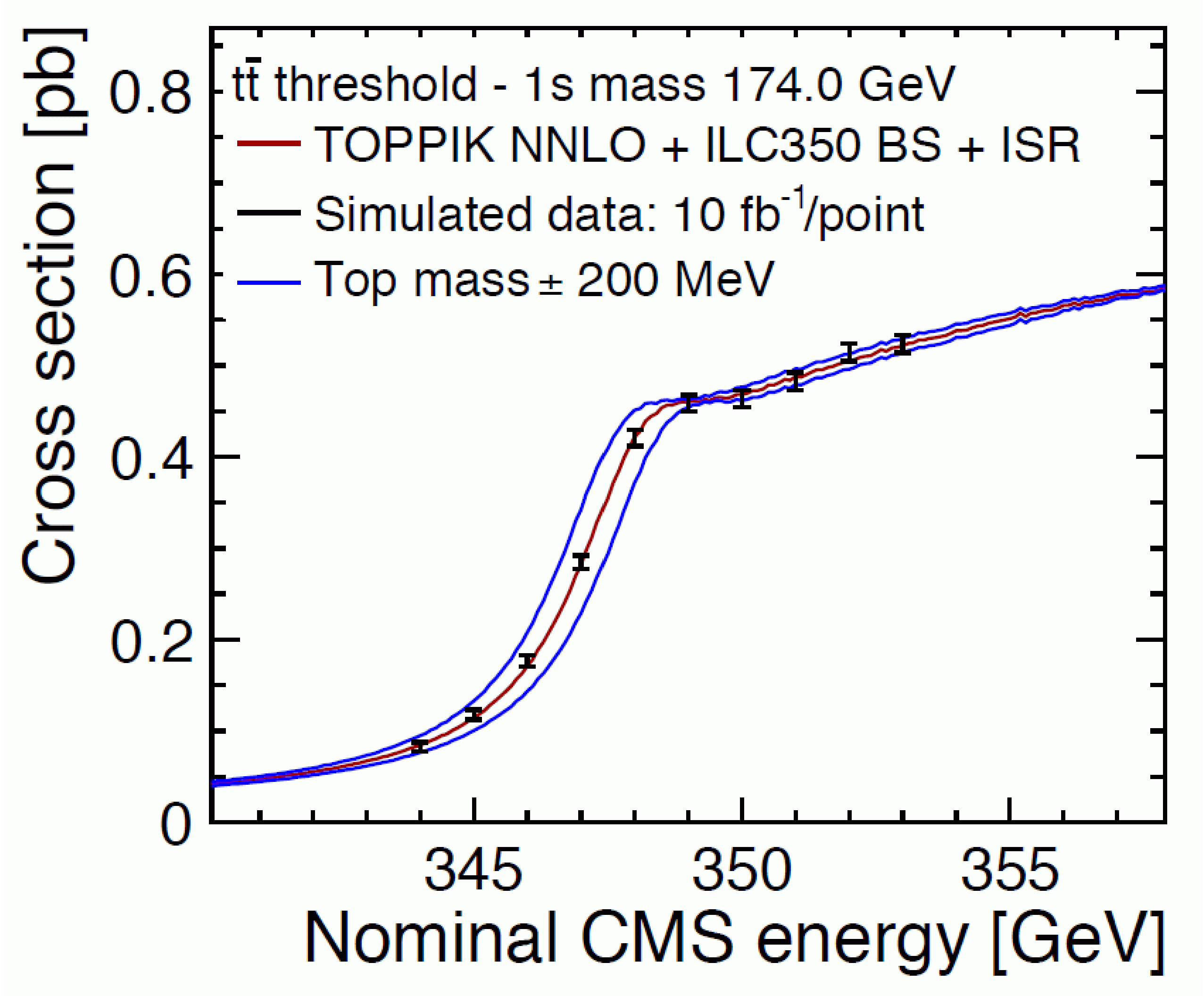
Top pole mass is not IR safe (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\rm QCD})$

Measurement of m_t:

- At Tevatron, LHC:
  kinematic reconstruction, fit to invariant mass distribution
  ⇒ "MC" mass, close to "pole" mass? $\delta m_t^{\rm exp,LHC} \lesssim 1$ GeV
- At e^+e^- colliders: unique possibility
  threshold scan ⇒ threshold mass ⇒ **SAFE!**
  transition to other mass definitions possible, $\delta m_t^{\rm exp,ILC} \lesssim 0.03$ GeV

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

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

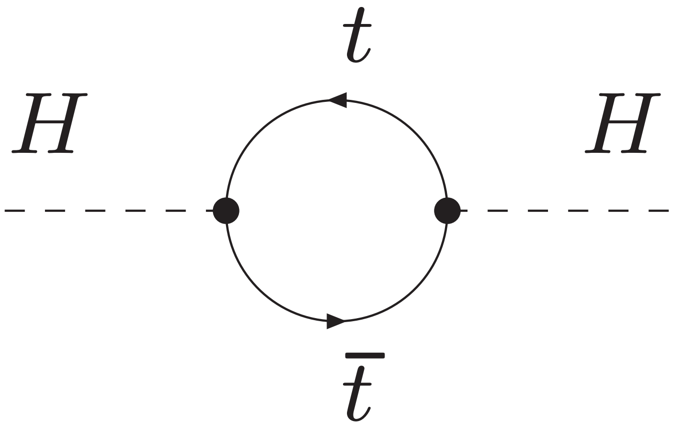


transition to other mass definitions possible ⇒ $\delta m_t^{\text{exp+theo}} \lesssim 0.1$ GeV

⇒ dominated by theory uncertainty! ⇒ ILC and TLEP so far similar!

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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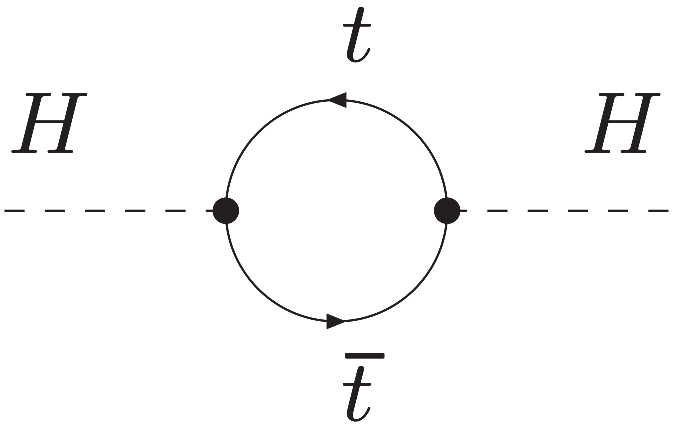

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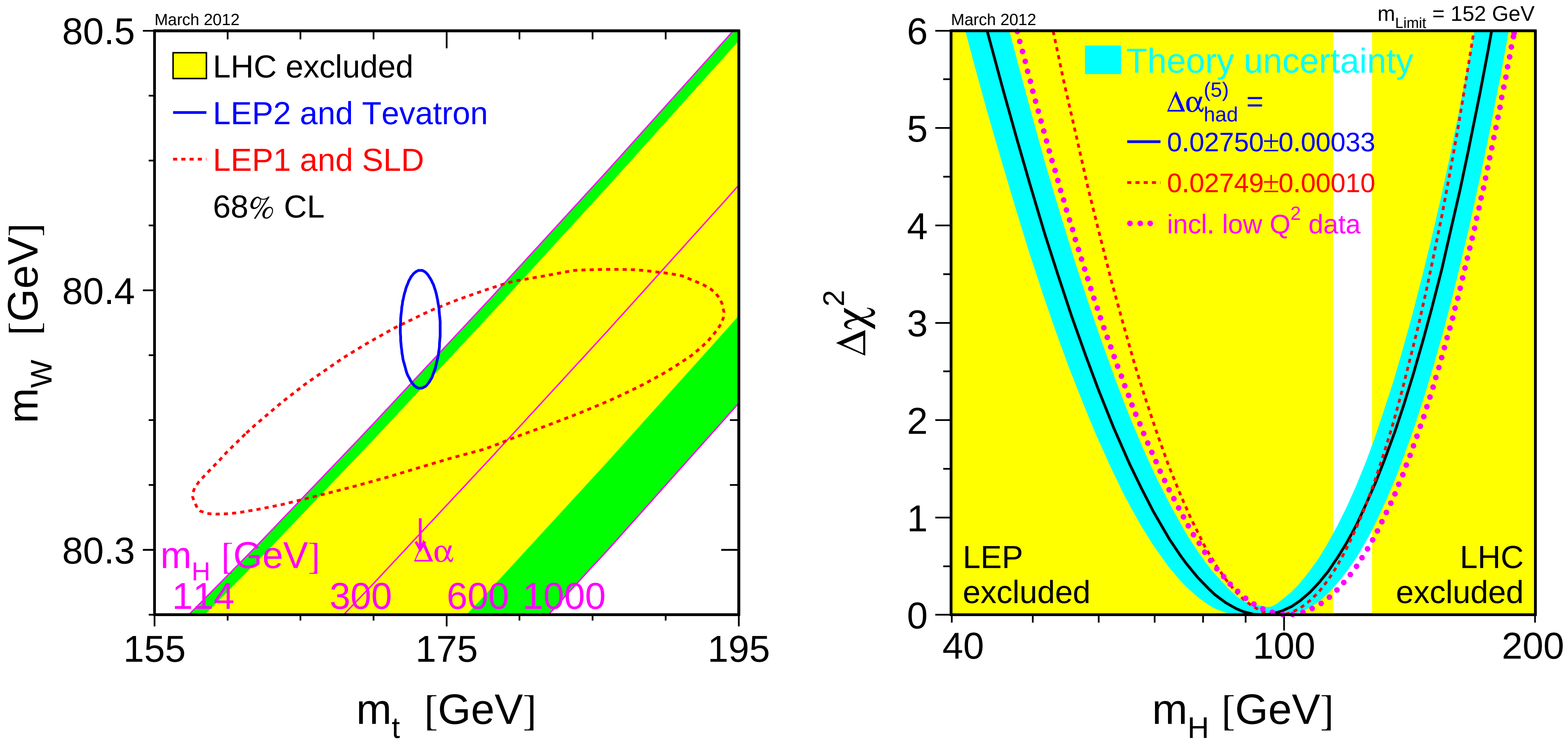
$\Rightarrow$ Precision Higgs physics needs ILC/TLEP precision top physics

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
$\delta\sin^2\theta_{\mathrm{eff}}(\times 10^5)$	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

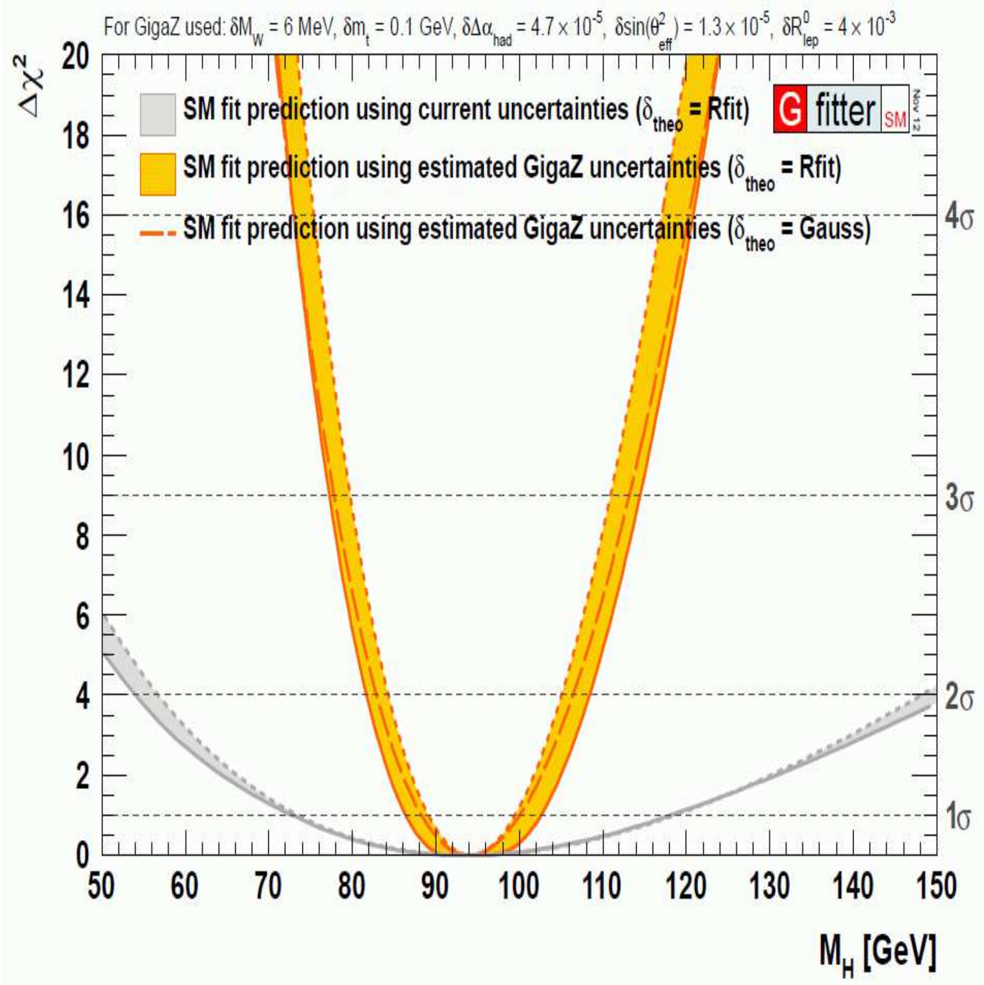
M_W: from direct reconstruction and threshold scan
[*G. Wilson '13*]

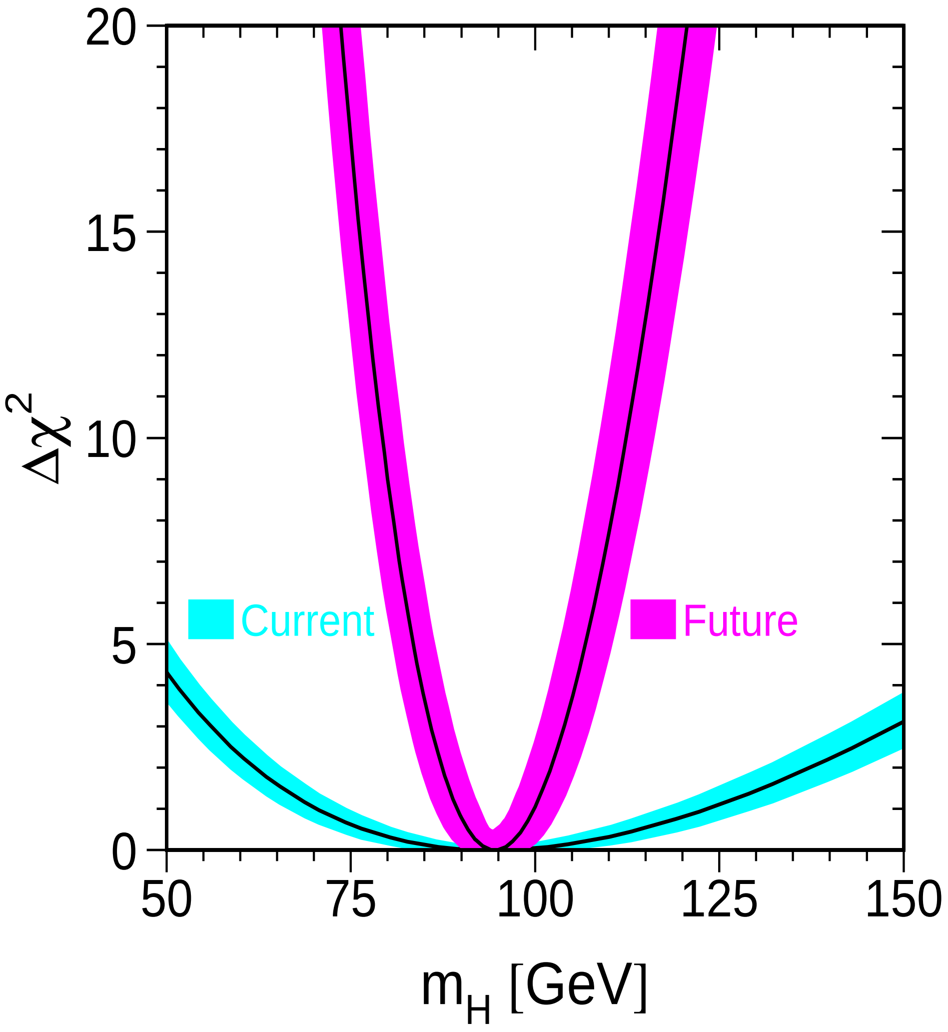
$\sin^2\theta_{\mathrm{eff}}$: 1/2 year GigaZ run, polarization important

α_s : Improvement from GigaZ run

Most precise M_H test with the ILC:

[GFitter '13] [LEPEWWG '13]





⇒ $\delta M_H^{\rm ind} \lesssim 6$ GeV ⇐ no TLEP analysis done so far

⇒ extremely sensitive test of SM (and BSM) possible

3. 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. $\kappa_i\,\kappa_j/\kappa_H$

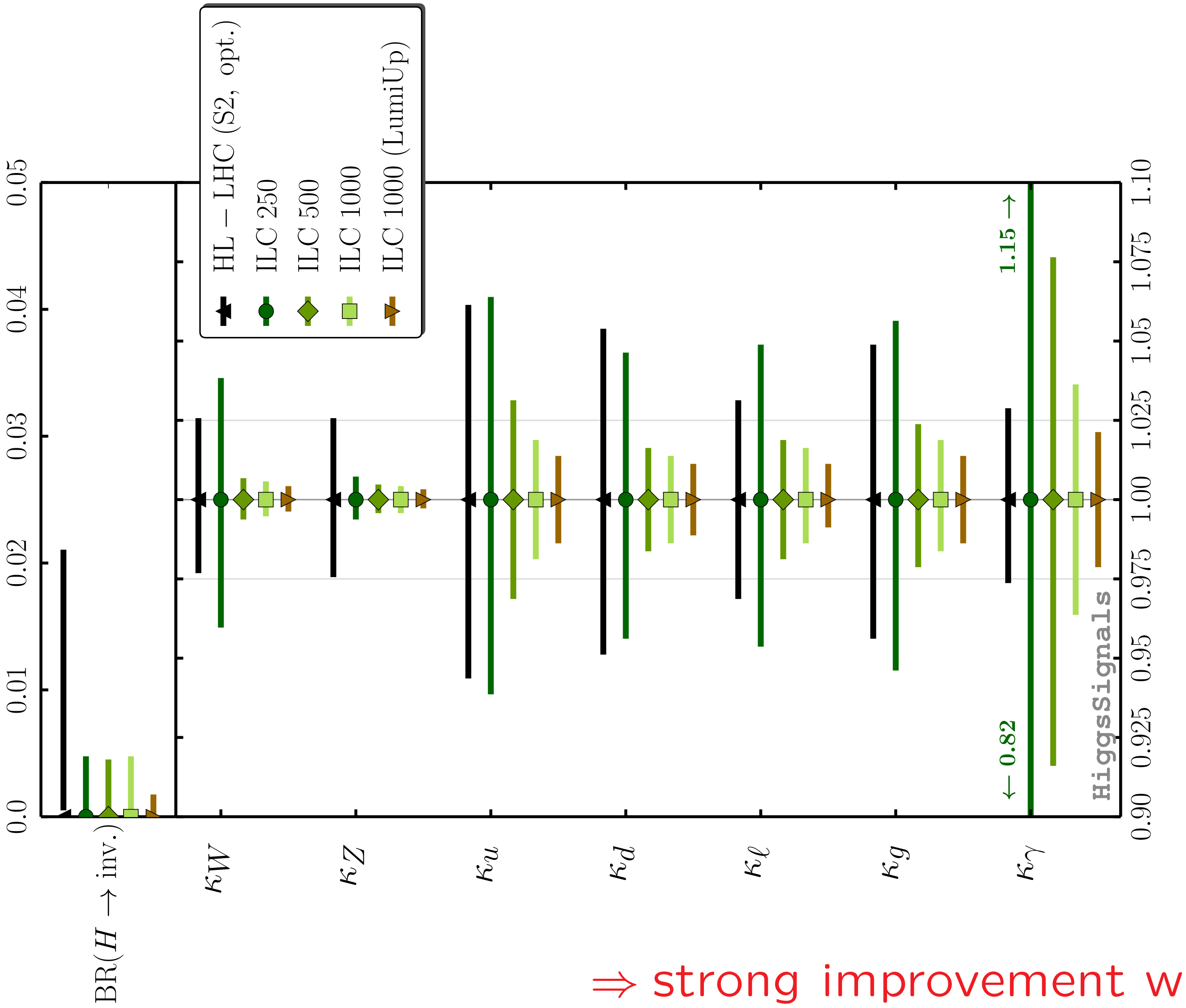
– additional theory assumptions (on $\Gamma_{H,\text{tot}}$ or $\kappa_{W,Z}$ or $H \to$ NP)

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

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

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

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



⇒ strong improvement with the ILC

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

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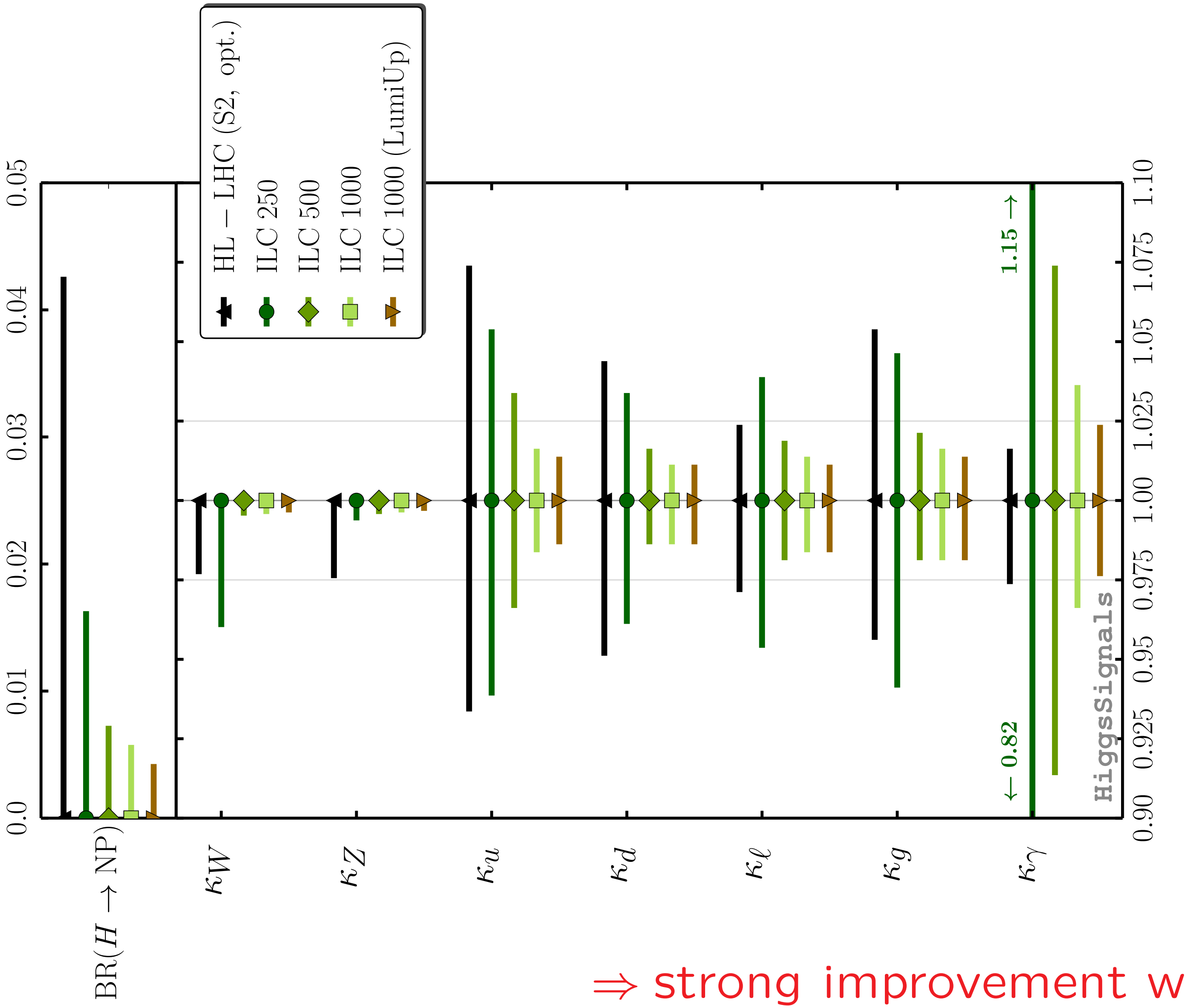
assumption: $\kappa_V \leq 1$



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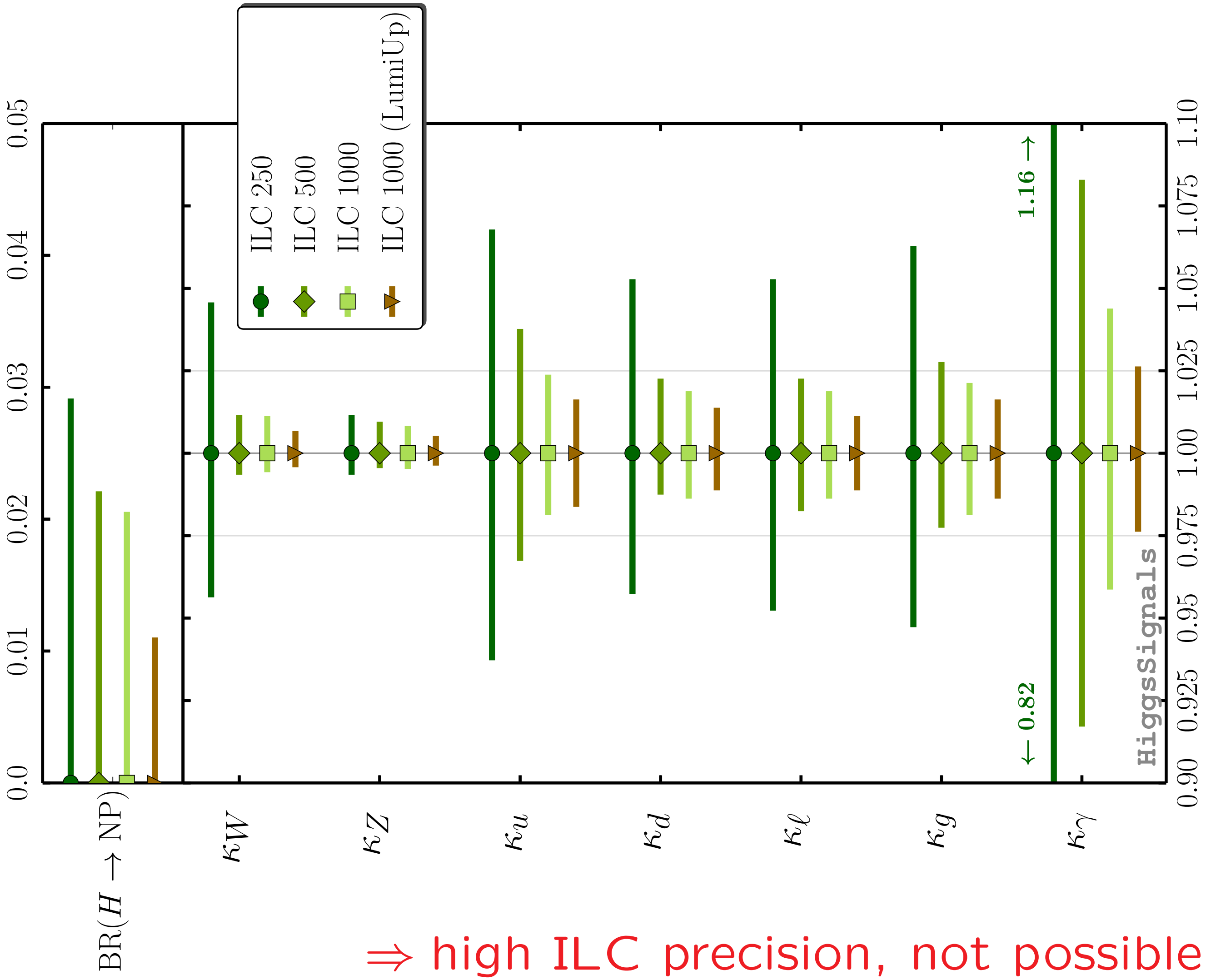
no theory assumptions, full fit



⇒ high ILC precision, not possible at the LHC

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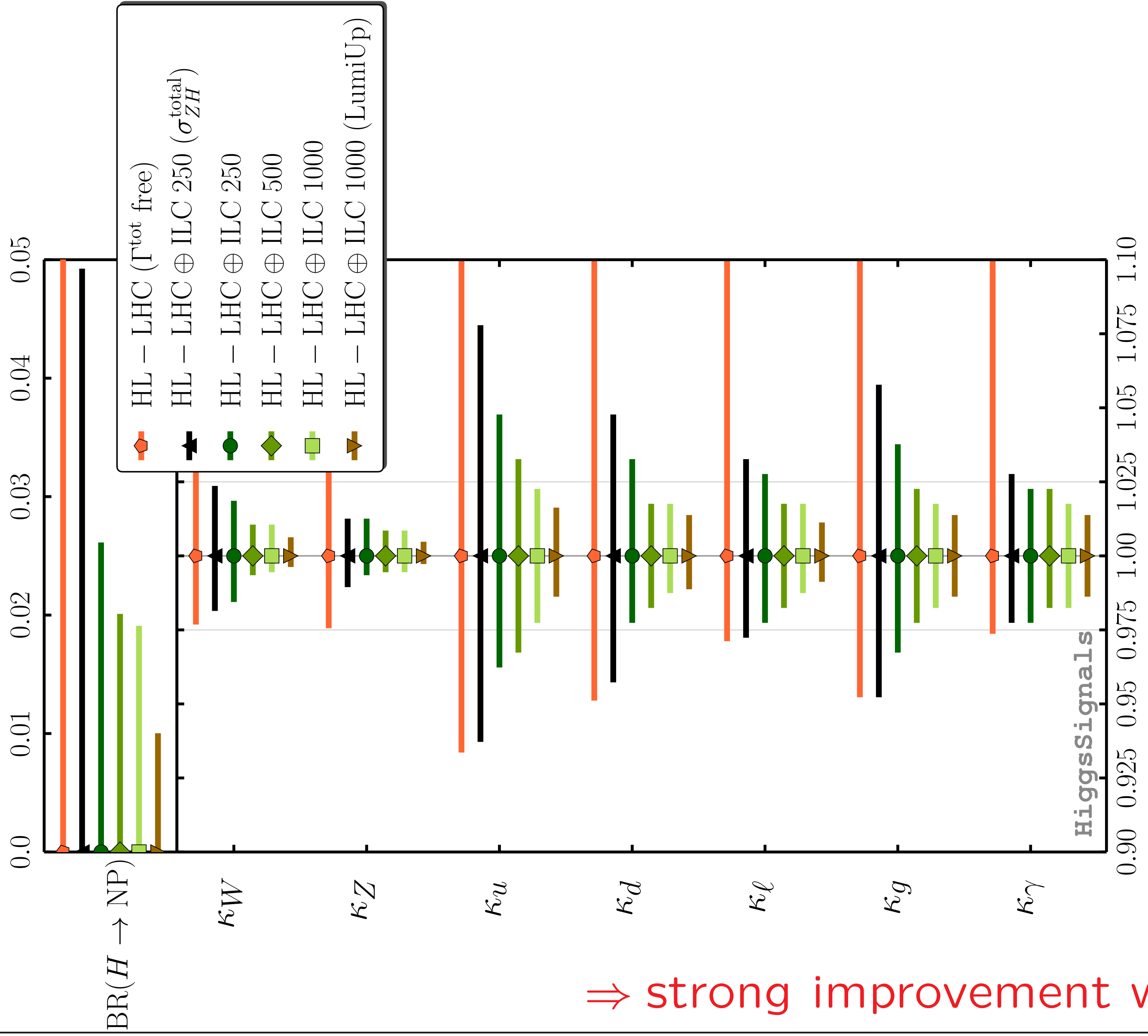

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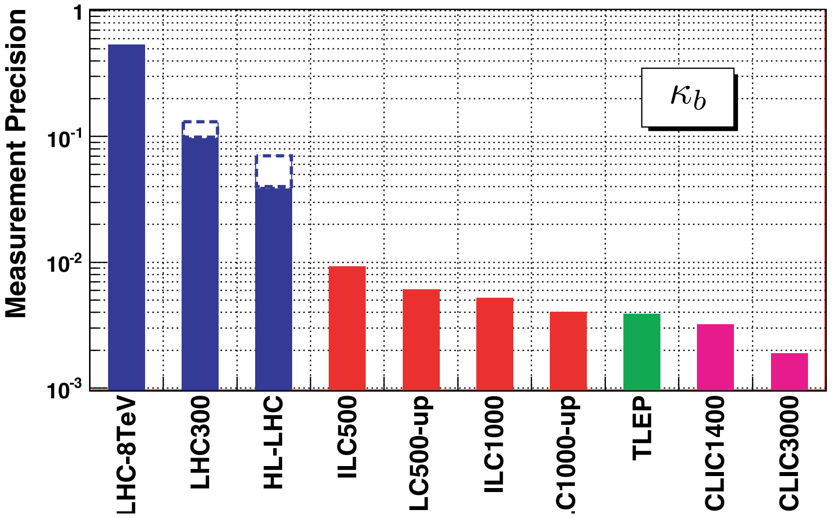
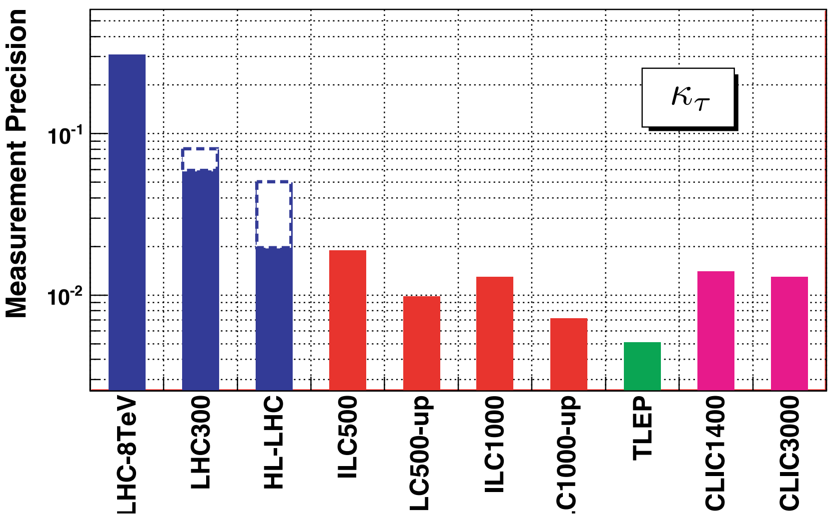
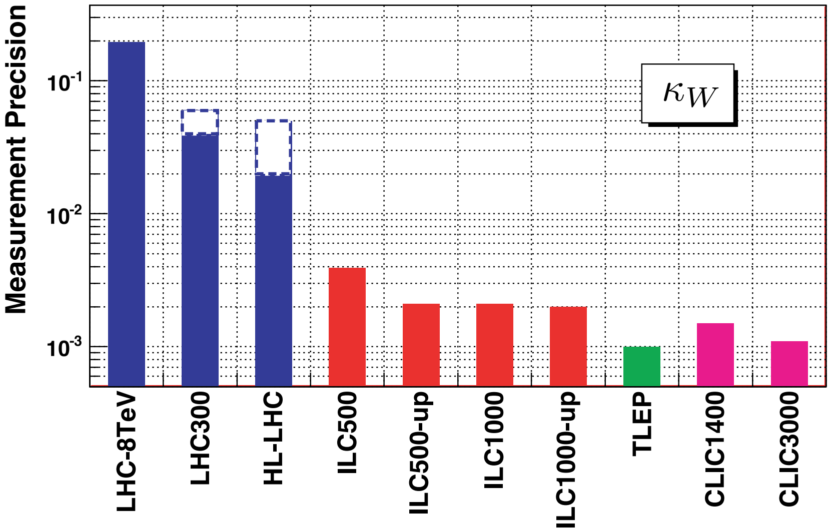
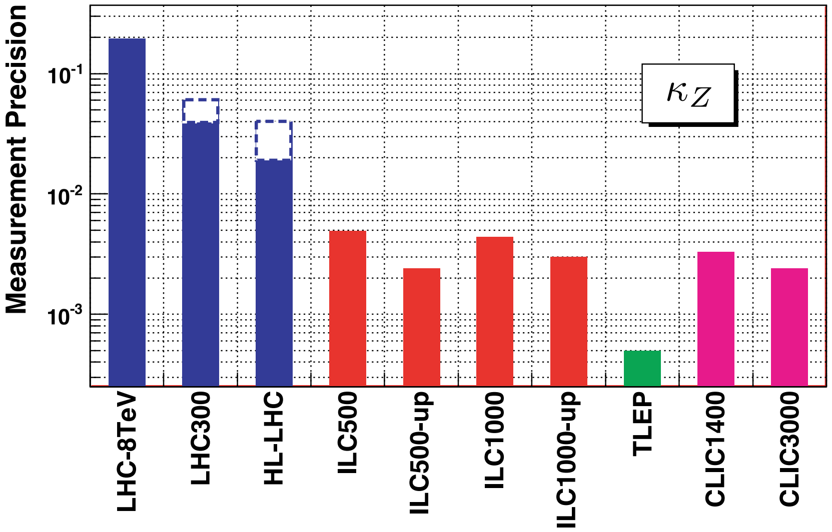
ILC vs. TLEP/FCC-ee:

[*Snowmass Higgs Report '13*]









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

Higgs coupling determination at e^+e^- collider

Some specifics:

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

⇒ total measurement of Higgs production cross section

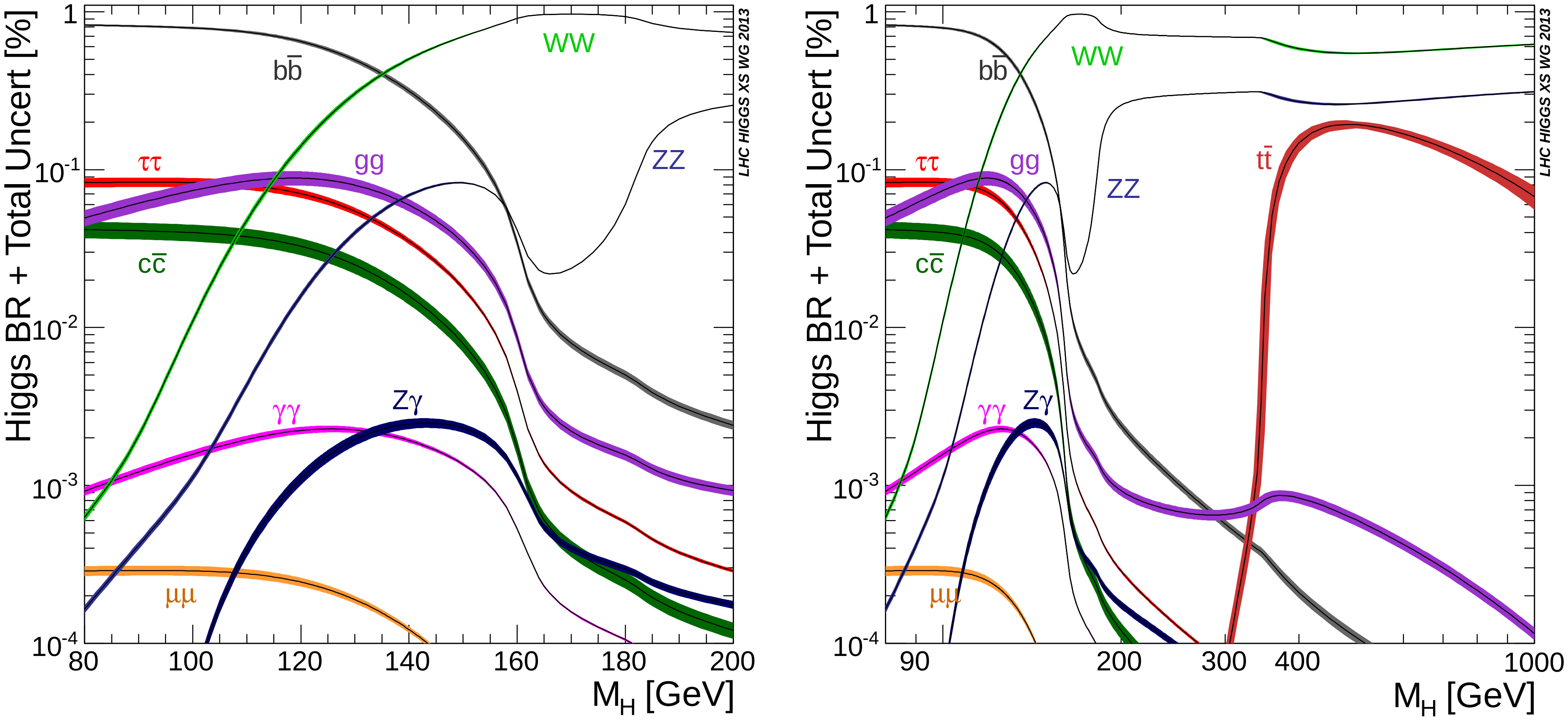
⇒ NO additional theoretical assumptions needed for absolute determination of partial widths

⇒ all observable channels can be measured with high accuracy

⇒ SM cross section predictions at the 1% accuracy level
⇒ improvements necessary . . . full 2-loop calculations and more . . . ?!

⇒ concentrate on theory BR uncertainties from now on

Latest SM Higgs BR predictions:



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 '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

   ⇒ 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 ⇐ now incl. in Hdecay - reevaluation
- Different uncertainties on a given channel added linearly

⇒ Strong improvement in $\sim$ 20 years possible, but . . .

. . . they have to be consistently implemented into codes!

⇒ 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

⇒ substantially larger than κ precision at ILC/TLEP

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:

$H \to b\bar{b}, H \to c\bar{c}$: 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

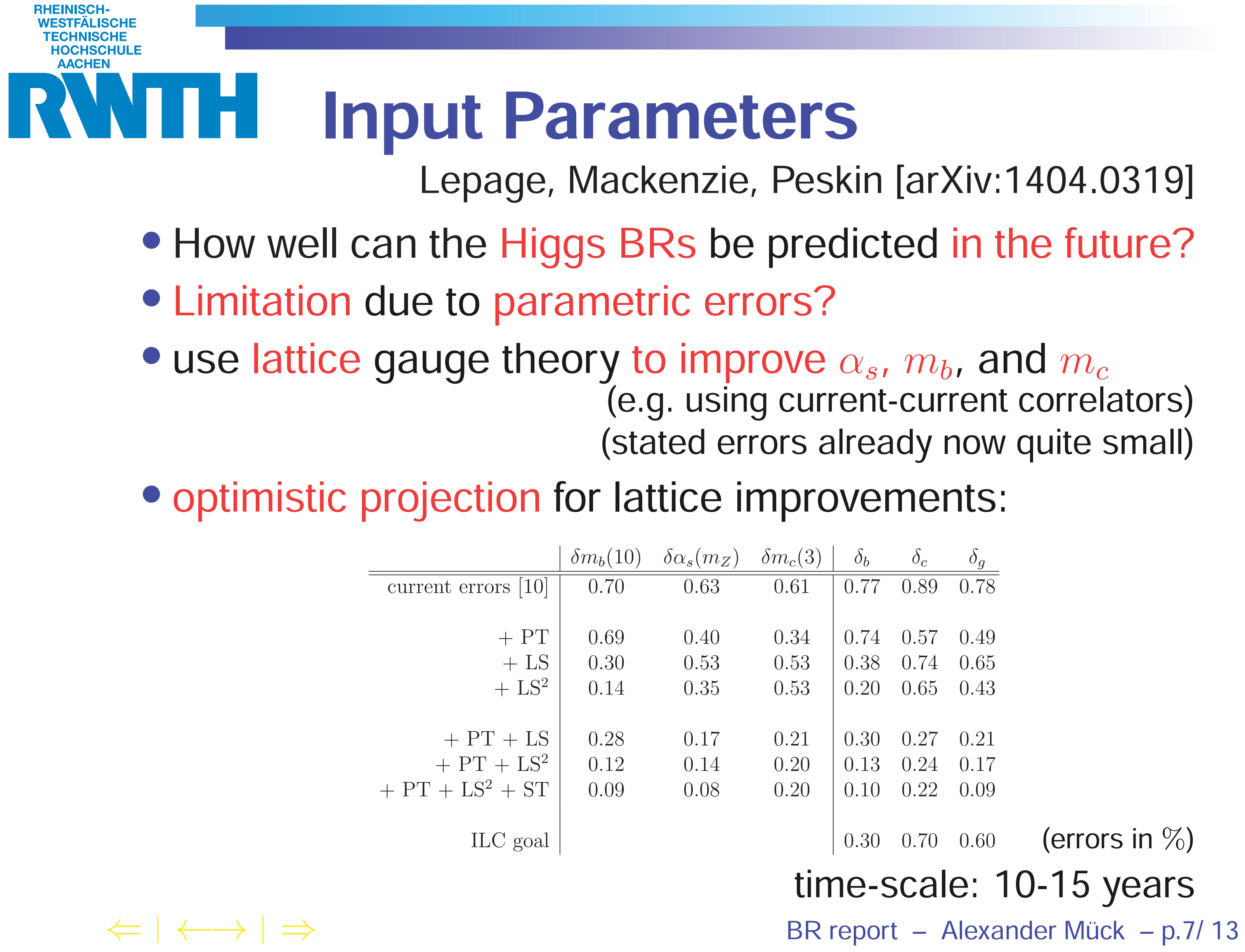
$H \to \gamma\gamma$: already very precise . . .

$H \to Z\gamma$: 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?!

Optimistic(?!) lattice expectations for the future:



RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

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

⇐ | ⟵⟶ | ⇒

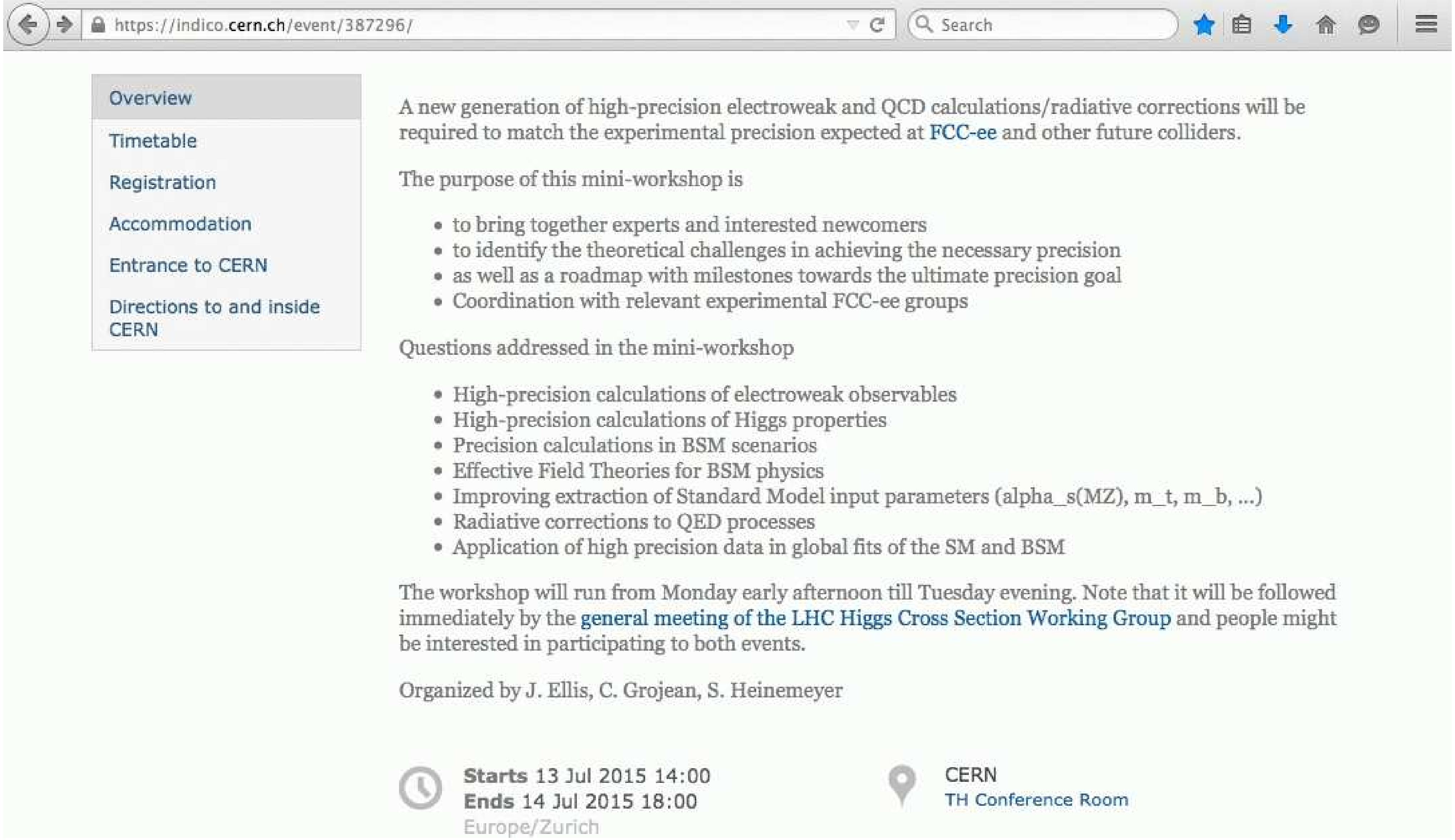
BR report – Alexander Mück – p.7/ 13

Dedicated workshop:

First FCC-ee mini-workshop on Precision Observables and Radiative Corrections

13-14 July 2015
CERN
Europe/Zurich timezone

Dedicated workshop:



A new generation of high-precision electroweak and QCD calculations/radiative corrections will be required to match the experimental precision expected at FCC-ee and other future colliders.

The purpose of this mini-workshop is

- to bring together experts and interested newcomers
- to identify the theoretical challenges in achieving the necessary precision
- as well as a roadmap with milestones towards the ultimate precision goal
- Coordination with relevant experimental FCC-ee groups

Questions addressed in the mini-workshop

- High-precision calculations of electroweak observables
- High-precision calculations of Higgs properties
- Precision calculations in BSM scenarios
- Effective Field Theories for BSM physics
- Improving extraction of Standard Model input parameters (alpha_s(MZ), m_t, m_b, ...)
- Radiative corrections to QED processes
- Application of high precision data in global fits of the SM and BSM

The workshop will run from Monday early afternoon till Tuesday evening. Note that it will be followed immediately by the general meeting of the LHC Higgs Cross Section Working Group and people might be interested in participating to both events.

Organized by J. Ellis, C. Grojean, S. Heinemeyer

Starts 13 Jul 2015 14:00
Ends 14 Jul 2015 18:00
Europe/Zurich

CERN
TH Conference Room

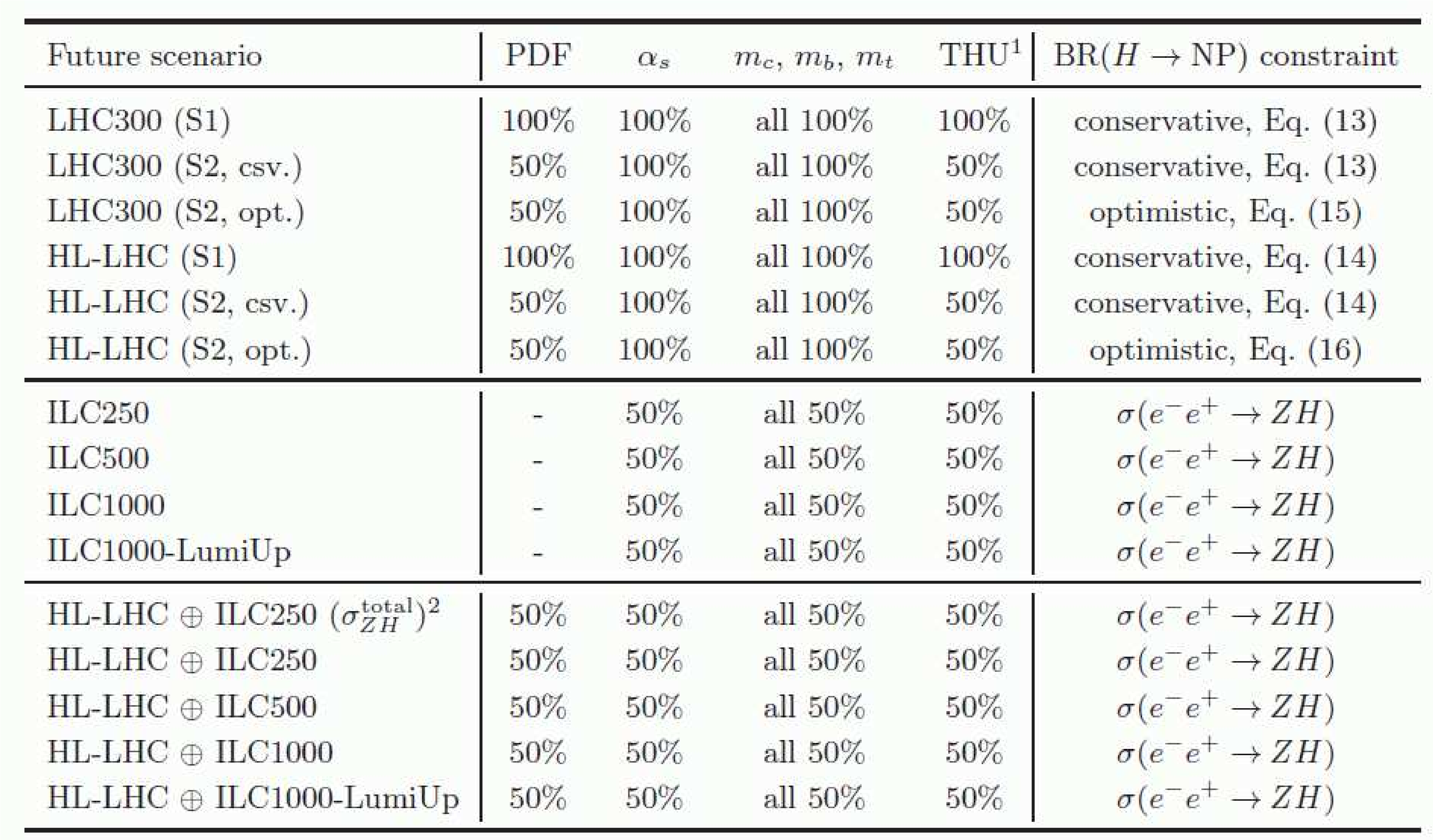
4. Conclusions

- Experimental precision must be matched with theory precision!
- EWPO can give valuable information about SM, BSM
  → only SM, MSSM "ready"
  Most relevant: M_W, $\sin^2\theta_{\text{eff}}$, (m_t), . . .
- Current theory uncertainties of M_W, $\sin^2\theta_{\text{eff}}$ not sufficient
  Future theory uncertainties: M_W in SM: TLEP goals hard to match
  M_W in MSSM: even harder
  $\sin^2\theta_{\text{eff}}$ in SM: more than a $\mathcal{O}(10)$ missing
  $\sin^2\theta_{\text{eff}}$ in MSSM: even worse
- Top quark mass: mainly theory driven. No improvement at TLEP?!
- Higgs couplings: XS and BR have to be under control
  Can sub-percent/permille level be matched?
  - XS: 1% possible, full 2-loop calculations needed?!
  - BR: intrinsic uncertainties could be brought down below 1%
    parametric uncertainties have (to me) unclear perspective

Back-up

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