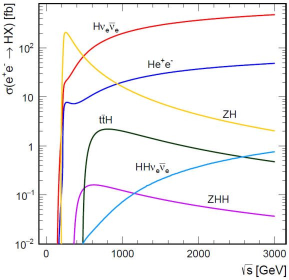
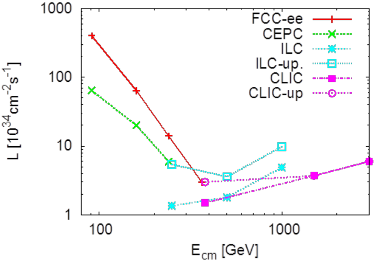
The physics landscape





at a future e^+e^- collider

Stefan Dittmaier

universität freiburg

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The big questions of particle physics in brief:

- Spectrum & properties of fundamental particles?
- Unification of forces?
- Origin of mass / mechanism of electroweak symmetry breaking?
- Limitations of the Standard Model (SM)?
- Nature & properties of neutrinos?
- Nature of Dark Matter?
- Sources of CP violation?
  (to explain matter–antimatter symmetry in the Universe)
- Nature of Dark Energy?

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… require solutions outside the SM!

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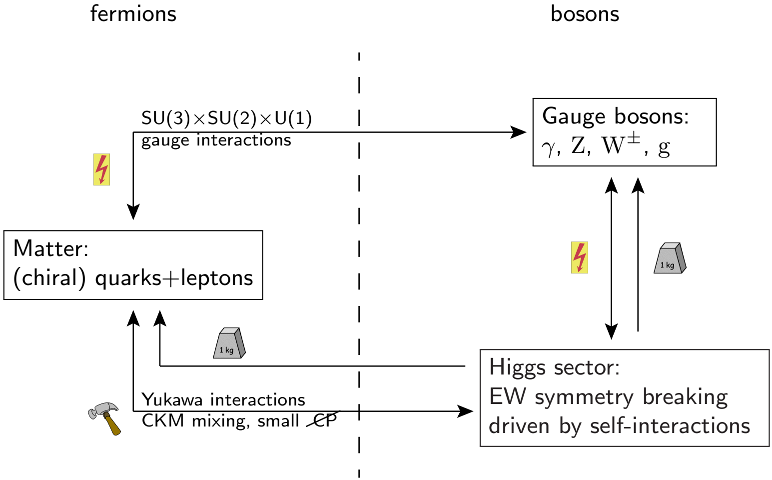
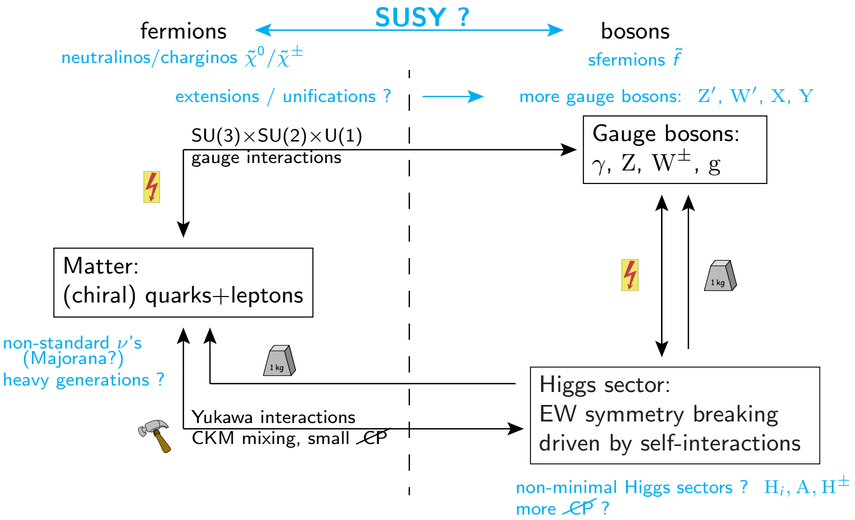
... require solutions outside the SM!

Which windows may be opened by future e^+e^- colliders?

The Standard Model



The Standard Model and ideas for extensions

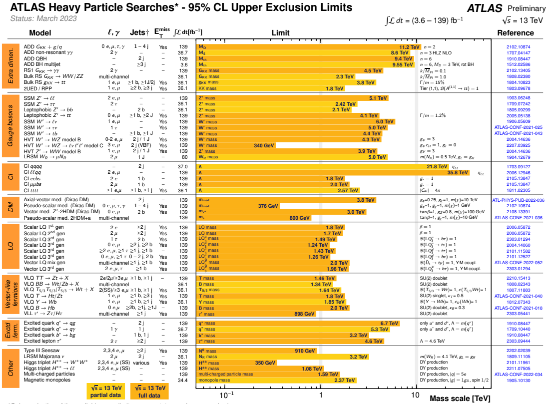


+ more exotic ideas (compositeness, extra dimensions, . . .)

Problem: No indication / evidence for new particles at the LHC !

Searches for heavy particles and their implications

Heavy-particle searches at ATLAS ...

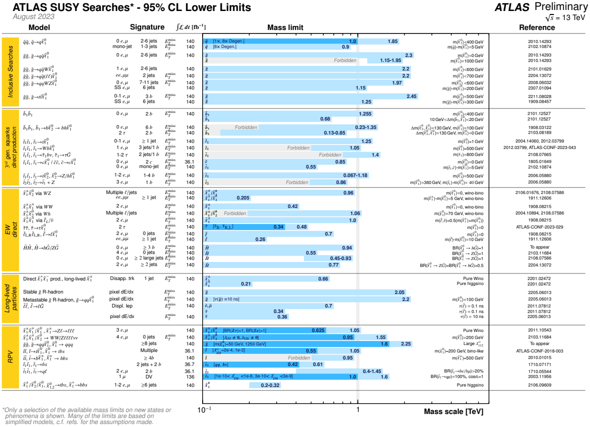


*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Searches for heavy particles and their implications

SUSY-particle searches at ATLAS ...



Searches for heavy particles and their implications

New particle(s) in the TeV mass range ...

- could not be directly investigated with a future e^+e^- collider, but it would be very difficult to directly argue for FCC-hh
- excluded at the LHC only if coupling to SM not suppressed (no small mixings, heavy mediators, or other suppression mechanisms)

  $\hookrightarrow$ weakly / feebly interacting particles of lower mass not ruled out

What to make out of this?

- The naysayer's nightmare:
  no new particle at the LHC, HL-LHC fully confirms SM completely, "everydone done", end of HEP.

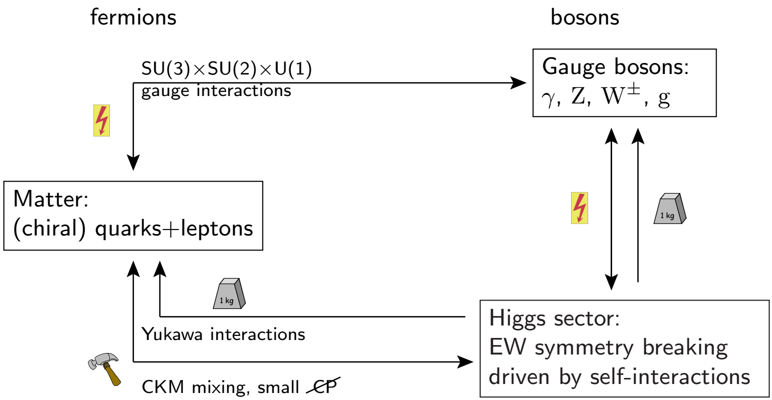
  $\hookrightarrow$ This line of thought is wrong and damaging!

- New Physics $\Rightarrow$ new particles $\Rightarrow$ good physics
  but the converse is not true!

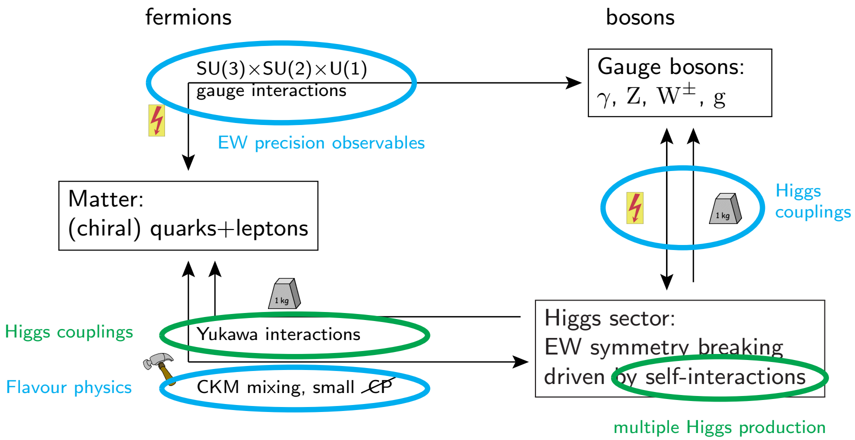
  $\hookrightarrow$ Good physics does not necessarily require new particles!

- HL-LHC will leave (some essential) questions open

The Standard Model



The Standard Model – establishing its dynamics (with precision)



SM challenged via precision → pushed to the extreme by future e^+e^- collider,
sometimes e^+e^- can make a qualitative difference

SM only established after detailed precision studies of all couplings !

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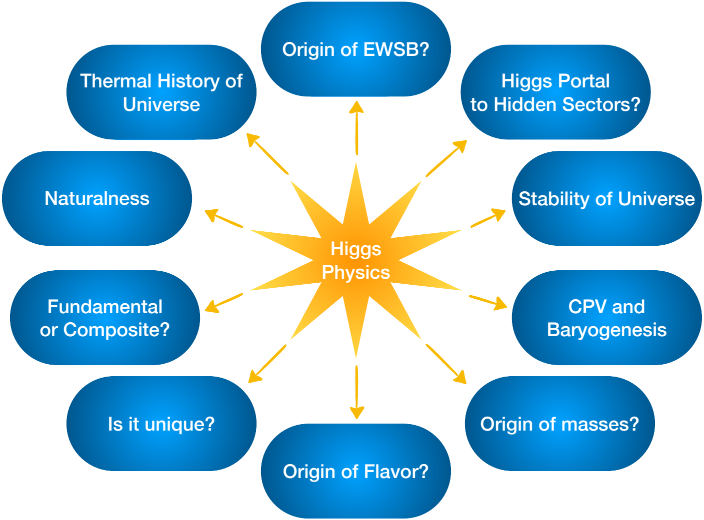
Mystery Higgs sector

Snowmass 2021 US Community Study
on the Future of Particle Physics



The SM Higgs Lagrangian (schematically)

$$\mathcal{L}_{\text{Higgs}} = |D\phi|^2 + (y_{jk}\overline{\psi}_j\psi_k\phi + \text{h.c.}) - V(\phi^\dagger\phi)$$

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$$\mathcal{L}_{\rm Higgs} = \underbrace{|D\phi|^2}_{} + (y_{jk}\overline{\psi}_j\psi_k\phi + \mathrm{h.c.}) - V(\phi^\dagger\phi)$$

gauge interactions,
HWW/HZZ couplings
$\hookrightarrow$ well tested after LHC

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$$\mathcal{L}_{\rm Higgs} = \underbrace{|D\phi|^2}_{\text{gauge interactions}} + \underbrace{(y_{jk}\overline{\psi}_j\psi_k\phi + \text{h.c.})}_{\text{Yukawa interactions}} - V(\phi^\dagger\phi)$$

gauge interactions,
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Yukawa interactions,
$H\bar{f}f$, CKM matrix, $\not{CP}$
$\hookrightarrow$ studied since $\sim$ 2018

"5th force"

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gauge interactions,
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"5th force"

Higgs potential,
HHH/*HHHH* coupl.
↪ not yet tested

"6th force"

The SM Higgs Lagrangian (schematically)

$$\mathcal{L}_{\rm Higgs} = \underbrace{|D\phi|^2}_{} + \underbrace{(y_{jk}\overline{\psi}_j\psi_k\phi + \text{h.c.})}_{} - \underbrace{V(\phi^\dagger\phi)}_{}$$

- $|D\phi|^2$: gauge interactions, HWW/HZZ couplings
  ↪ well tested after LHC
- $(y_{jk}\overline{\psi}_j\psi_k\phi + \text{h.c.})$: Yukawa interactions, $H\bar{f}f$, CKM matrix, $\not{CP}$
  ↪ studied since ∼ 2018
  "5th force"
- $V(\phi^\dagger\phi)$: Higgs potential, $HHH/HHHH$ coupl.
  ↪ not yet tested
  "6th force"

Puzzles of the SM Higgs sector:

The SM Higgs Lagrangian (schematically)

$$\mathcal{L}_{\rm Higgs} = \underbrace{|D\phi|^2}_{\substack{\text{gauge interactions,}\\ HWW/HZZ\text{ couplings}\\ \hookrightarrow \text{ well tested after LHC}}} + \underbrace{(y_{jk}\overline{\psi}_j\psi_k\phi + \text{h.c.})}_{\substack{\text{Yukawa interactions,}\\ H\bar{f}f\text{, CKM matrix, } \not{CP}\\ \hookrightarrow \text{ studied since} \sim 2018}} - \underbrace{V(\phi^\dagger\phi)}_{\substack{\text{Higgs potential,}\\ HHH/HHHH\text{ coupl.}\\ \hookrightarrow \text{ not yet tested}}}$$

"5th force" "6th force"

Puzzles of the SM Higgs sector:

- Yukawa part $y_{jk}\overline{\psi}_j\psi_k H$:

  flavour puzzle, no obvious symmetry, only source of $\not{CP}$

The SM Higgs Lagrangian (schematically)

$$\mathcal{L}_{\rm Higgs} = \underbrace{|D\phi|^2}_{} + \underbrace{(y_{jk}\overline{\psi}_j\psi_k\phi + \text{h.c.})}_{} - \underbrace{V(\phi^\dagger\phi)}_{}$$

- gauge interactions, HWW/HZZ couplings
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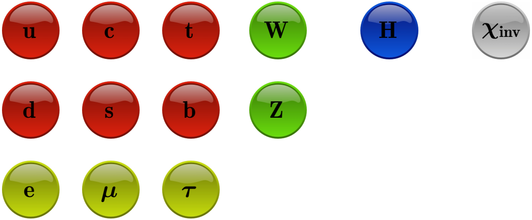
Puzzles of the SM Higgs sector:

- Yukawa part $y_{jk}\overline{\psi}_j\psi_k H$:

  flavour puzzle, no obvious symmetry, only source of $\not{C}\not{P}$

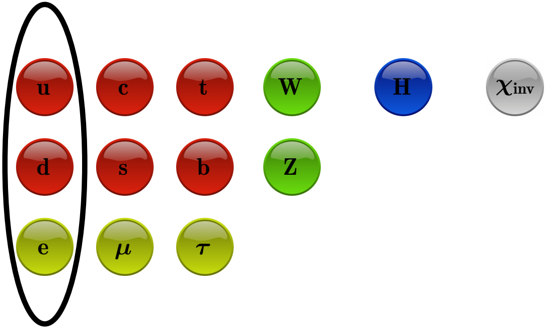
- Higgs potential $V = V_0 - \mu^2(v+H)^2 + \lambda(v+H)^4$:
  - $\mu^2 \propto M_{\rm H}^2 \sim 10^4\,{\rm GeV}^2 \ll M_{\rm Pl}^2 \sim 10^{36}\,{\rm GeV}^2$, — hierarchy problem
  - $\lambda(\mu_0) = 0$ for $\mu_0 \sim 10^{10}\,{\rm GeV}$, $\lambda(M_{\rm Pl}) \sim -0.01$ — metastability of the Universe
  - $V_{\min} = V_0 \underbrace{-\mu^2 v^2 + \lambda v^4}_{\sim -10^{45}\,{\rm J/m^3}} \sim \underbrace{\frac{\Lambda}{8\pi G} \sim 10^{-9}\,{\rm J/m^3}}_{\text{Dark Energy density}}$, — fine-tuning problem of cosmological constant Λ

Elementary Higgs couplings *HXX* to massive or invisible particles *X*



Elementary Higgs couplings HXX to massive or invisible particles X

Higgs couplings to the "real world" yet unkown!



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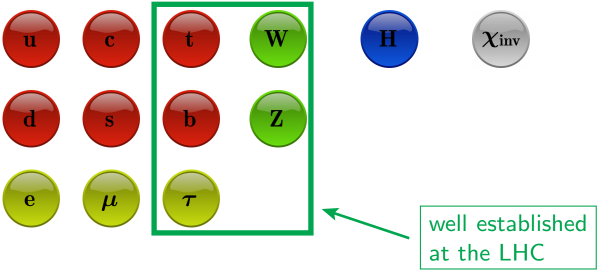

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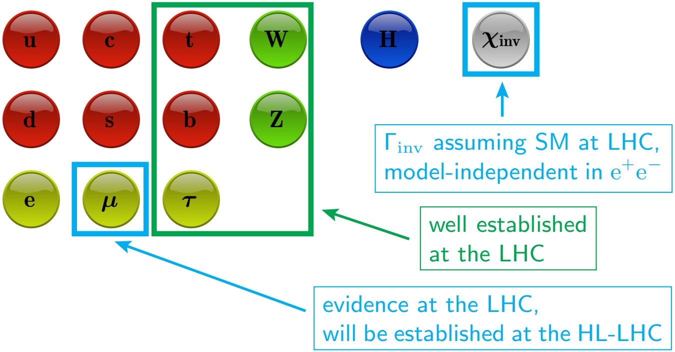

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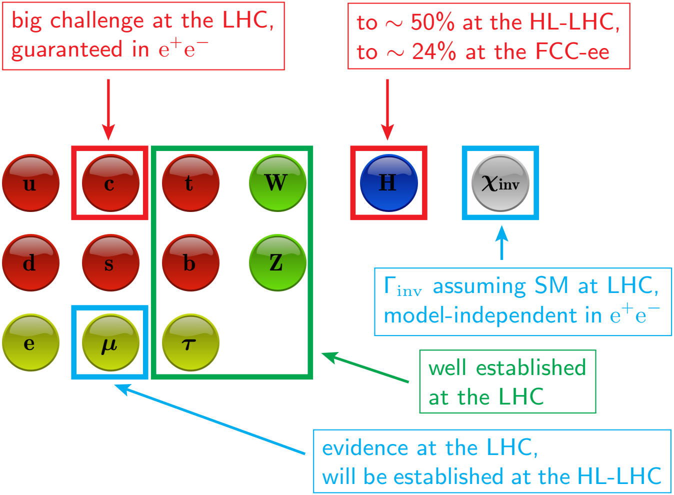

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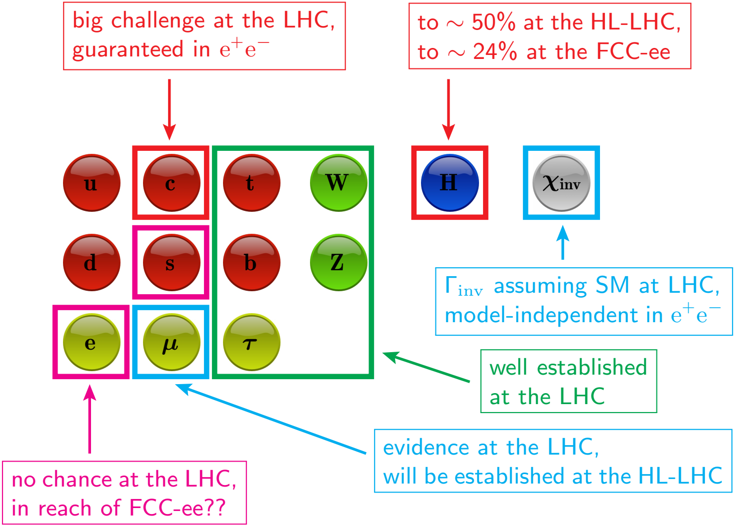

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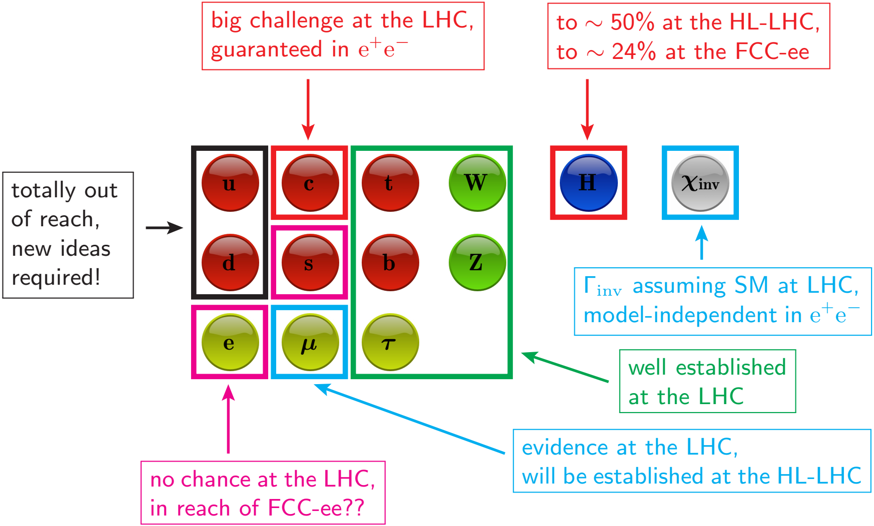
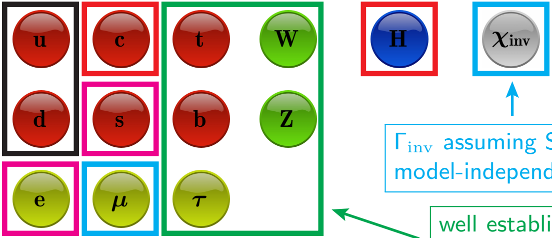


Elementary Higgs couplings *HXX* to massive or invisible particles *X*

big challenge at the LHC,
guaranteed in e^+e^-

to $\sim$ 50% at the HL-LHC,
to $\sim$ 24% at the FCC-ee

totally out of reach, new ideas required!



Γ_{inv} assuming SM at LHC,
model-independent in e^+e^-

well established
at the LHC

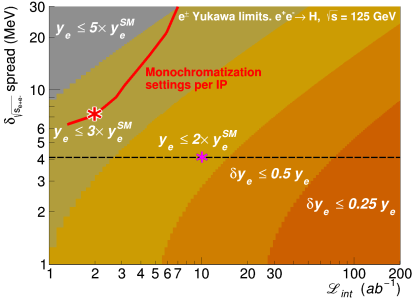
evidence at the LHC,
will be established at the HL-LHC

no chance at the LHC,
in reach of FCC-ee??

$\Rightarrow$ e^+e^- colliders offer great opportunity to complete the Higgs profile!

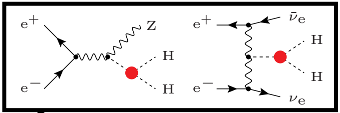
Prospects for measuring the *Hee* coupling

d'Entarria et al., 2107.02686

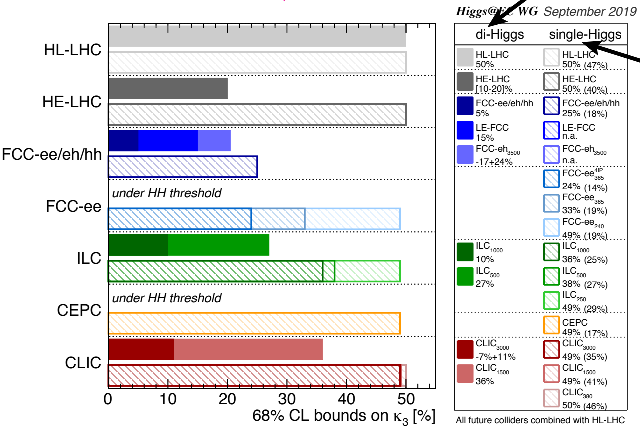


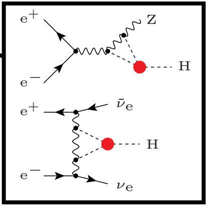
- dedicated run at $\sqrt{s} = M_{\mathrm{H}}$ after $\sqrt{s} = M_{\mathrm{Z}}$ and $\lesssim M_{\mathrm{Z}} + M_{\mathrm{H}}$
- most promising final states:
  $\mathrm{H} \to \mathrm{gg}$: gluon tagging!
  $(\varepsilon_{\mathrm{g}}, \varepsilon^{\mathrm{mistag}}_{q\to\mathrm{g}}) = (70\%, 1\%)$ assumed
  $\mathrm{H} \to \mathrm{WW}^* \to \ell\nu_\ell + 2\mathrm{jets}$:
  spin correlations exploited
- essential: energy monochromatisation
  ($\delta_{\sqrt{s}} = 4.1\,\mathrm{MeV}$ assumed at $10\,\mathrm{ab}^{-1}$)
  $\hookrightarrow$ improvements?! (include polarization?)

Prospects for measuring the *HHH* coupling



de Blas et al., 1905.03764





$$\kappa_3 = \frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}}$$

- HH production not accessible for $\sqrt{s} < 400\,\mathrm{GeV}$ (FCC-ee, CEPC)
  $\hookrightarrow$ ILC / CLIC only $\mathrm{e^+e^-}$ colliders with HH production
- λ_{HHH} via single-H production requires higher-order EFT studies

Side comments on Effective Theories (EFTs) and coupling modifiers

- κ framework (rescaling Higgs couplings)
  - phenomenologically motivated reparametrization of data
  - not a measurement of Higgs couplings
  - resembles Higgs coupling strength only to $\sim 5\%$ level (EW corrs.)
  - projected precisions $< 5\%$ just reflect sensitivity of SM test
- SM Effective Theory (SMEFT) (SM $\oplus$ dim-6 operators $\mathcal{O}_i^{(6)}$)
  - consistent theoretical framework
  - restricted to energies $E \ll \Lambda =$ scale of (decoupling) new physics
  - does not cover SM extensions with feebly interacing particles
  - good diagnostic tool to test SM (even if new physics is beyond SMEFT)
  - constraints on Wilson coefficients $\to$ windows to new physics scale Λ

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \mathcal{O}(\Lambda^{-8})$$

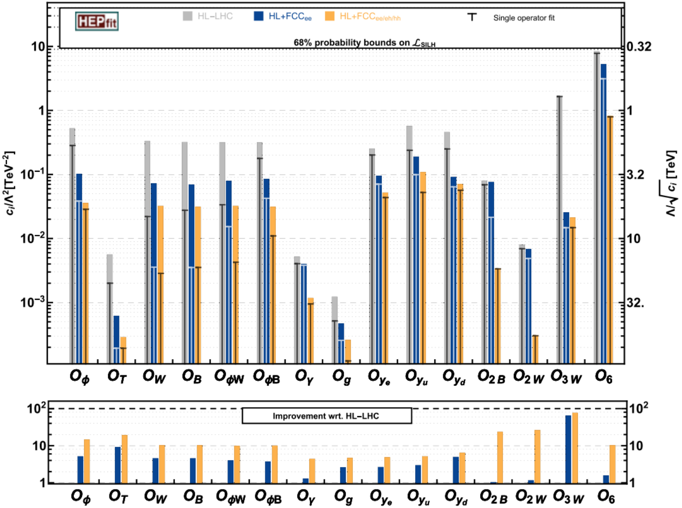
$$\left|\frac{c_i}{\Lambda^2}\right| < C_{\mathrm{exp}} \quad \Rightarrow \Lambda > \frac{|c_i|}{\sqrt{C_{\mathrm{exp}}}}$$

Higher precision (smaller C_{exp})
$\Rightarrow$ larger Λ!

($|c_i|$ depends on expectation for new physics $\to$ $\mathcal{O}(4\pi), \mathcal{O}(1), \mathcal{O}(\alpha_{\mathrm{s}}/\pi)$, ...?)

Gain in Λ from HL-LHC → FCC-ee/hh:

Bernardi et al., 2203.06520



- FCC-ee: Λ already increased by $\sim 2-3$
- FCC-hh: ultimate increase by $\gtrsim 10$

Examples beyond SMEFT: feeble interactions from mixing with SM fields

Higgs mixing:

new Higgs boson (heavy or light), feebly coupled to SM particles → H

Higgs singlet → h_1

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \qquad |\alpha| \ll 1$$

SM-like Higgs boson, coupling to SM particles reduced $\propto \cos\alpha \sim 1 - \frac{1}{2}\alpha^2 + \ldots$ → h

SM-like Higgs doublet → h_2

$\Rightarrow$ Precision measurements of SM-like Higgs couplings constrain α

Examples beyond SMEFT: feeble interactions from mixing with SM fields

Neutral-gauge-boson mixing:

SM-like Z boson,
coupling to SM particles reduced
$\propto \cos\gamma \sim 1 - \frac{1}{2}\gamma^2 + \ldots$

$\mathrm{SU}(2)_I \times \mathrm{U}(1)_Y$ gauge bosons

$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 1 & \cos\gamma & \sin\gamma \\ 0 & -\sin\gamma & \cos\gamma \end{pmatrix} \begin{pmatrix} c_\mathrm{W} & -s_\mathrm{W} & 0 \\ s_\mathrm{W} & c_\mathrm{W} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} B \\ W^0 \\ C \end{pmatrix}, \qquad |\gamma| \ll 1$$

new Z′ boson (heavy or light),
feebly coupled to SM particles

gauge boson of "dark" U(1)

$\Rightarrow$ EW precision observables constrain γ

Examples beyond SMEFT: feeble interactions from mixing with SM fields

Neutral-lepton mixing: (only schematically)

SM-like neutrinos, coupling to SM particles reduced $\propto \cos\theta_k \sim 1 - \frac{1}{2}\theta_k^2 + \ldots$

left-handed neutrino fields (part of $SU(2)_I$ doublets)

unitarity leak!

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ N_1 \\ \vdots \end{pmatrix} = \begin{pmatrix} \boxed{\begin{matrix}\text{PMNS-like} \\ 3\times3 \text{ matrix}\end{matrix}} & \begin{matrix}\theta_1 \\ \vdots\end{matrix} & \cdots \\ -\theta_1^* \quad -\theta_2^* \quad -\theta_3^* & 1 - \frac{1}{2}\theta_1^2 + \ldots & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_e^L \\ \nu_\mu^L \\ \nu_\tau^L \\ N_1^R \\ \vdots \end{pmatrix}, \qquad |\theta_k| \ll 1$$

heavy neutral leptons, feebly coupled to SM particles

sterile right-handed neutrino fields

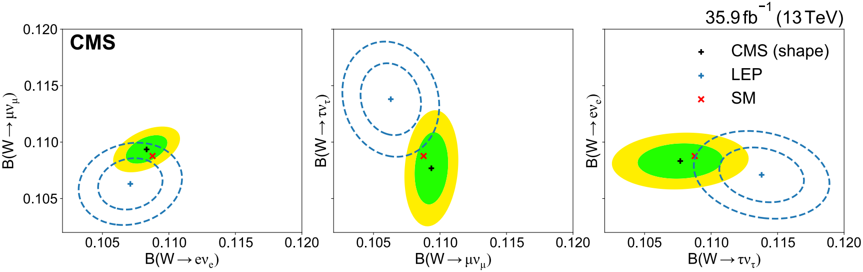
$\Rightarrow$ EW precision observables help to constrain θ_k

Typically in type-1 seesaw:

$$\theta_k \propto \frac{y_{\nu,k} v_{\mathrm{EW}}}{M} \text{ related to mass scale } M \text{ of sterile neutrinos}$$

New ATLAS/CMS analyses helping to constrain neutral-lepton mixing:

W-boson branching ratios (mostly from $t\bar{t}$ events)



↪ tension in LEP results not confirmed

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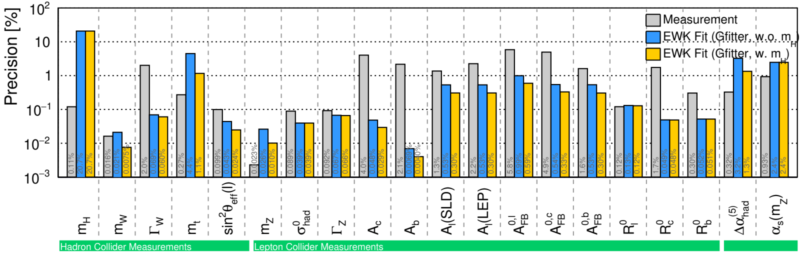
Status of (not only) EW precision physics in the (pre HL-)LHC era

Erler, Schott '19



Current precision: typically $\lesssim 1\%$, even $\sim 0.01{-}0.1\%$ in some cases

Future projections: promise improvements by 1–2 orders of magnitude

$\hookrightarrow$ ultimate challenge of the SM at future $\mathrm{e}^+\mathrm{e}^-$ colliders

But: Can theory provide adequate predictions?

Physics at the Z pole – central EW precision (pseudo-)observables

FCC-ee: Freitas et al., 1906.05379; ILC: Moortgat-Pick et al., 1504.01726

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
$\Delta M_{\mathrm{Z}}[\mathrm{MeV}]$	2.1	–	0.1			
$\Delta\Gamma_{\mathrm{Z}}[\mathrm{MeV}]$	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_{\mathrm{s}}, \alpha\alpha_{\mathrm{s}}^2$	0.15
$\Delta \sin^2\theta_{\mathrm{eff}}^{\ell}[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_{\mathrm{s}}$	1.5
$\Delta R_{\mathrm{b}}[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_{\mathrm{s}}$	5
$\Delta R_{\ell}[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_{\mathrm{s}}$	1.5

Theory requirements for Z-pole pseudo-observables:

- needed:
  - EW and QCD–EW 3-loop calculations
  - $1 \to 2$ decays, fully inclusive
- problems:
  - technical: massive multi-loop integrals, γ_5
  - conceptual: pseudo-obs. on the complex Z-pole

Physics at the Z pole – central EW precision (pseudo-)observables

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	experimental accuracy			intrinsic th. unc.		parametric unc.	
	current	ILC	FCC-ee	current	prospect	prospect	source
$\Delta M_\mathrm{Z}[\mathrm{MeV}]$	2.1	–	0.1				
$\Delta\Gamma_\mathrm{Z}[\mathrm{MeV}]$	2.3	1	0.1	0.4	0.15	0.1	α_s
$\Delta\sin^2\theta^\ell_\mathrm{eff}[10^{-5}]$	23	1.3	0.6	4.5	1.5	2(1)	$\Delta\alpha_\mathrm{had}$
$\Delta R_\mathrm{b}[10^{-5}]$	66	14	6	11	5	1	α_s
$\Delta R_\ell[10^{-3}]$	25	3	1	6	1.5	1.3	α_s

Parametric uncertainties of EW pseudo-observables:

- QCD:
  - most important: $\delta\alpha_\mathrm{s} \sim 0.00015$ @ FCC-ee?
    $\hookrightarrow$ α_s from EW POs competitive $\Rightarrow$ cross-check with other results!
  - quark masses m_t, m_b, m_c
- $\Delta\alpha_\mathrm{had}$: $\delta(\Delta\alpha_\mathrm{had}) \sim 5(3)\times 10^{-5}$ for/from FCC-ee?
  - new exp. results from BES III / Belle II on $\mathrm{e^+e^-} \to \mathrm{hadrons}$
  - $\Delta\alpha_\mathrm{had}$ from fit to radiative return $\mathrm{e^+e^-} \to \gamma + \mathrm{hadrons}$
- other EW parameters: M_Z, M_W, M_H less critical (improved at ILC/FCC-ee)

Homework for theory @ Z pole:

- Full line-shape prediction to NNLO EW + leading effects beyond
  - technical progress in 2- and multi-loop amplitudes/integrals
  - conceptual progress in NNLO EW corrections (unstable particles!)
  - improvements on leading ISR corrections beyond NNLO
  - leading EW corrections beyond NNLO
- Validity of pseudo-observable approach
  - better field-theoretical foundation of Z-pole pseudo-observables (complex pole definition, absorptive parts, continuum subtraction)
  - Improved Born Approximation (IBA) to parametrize line-shape via pseudo-obs. (+ precise concept to treat non-resonant parts)
  - careful validation of IBA against full $\mathrm{e^+e^-} \to \mathrm{Z}/\gamma \to f\bar{f}$ prediction

$\hookrightarrow$ Impact on experimental analysis possible
(continuum subtraction, self-consistency conditions, etc.)

W-boson mass measurements vs. prediction from μ decay

ILC: Baak et al., 1310.6708 FCC-ee: Freitas et al., 1906.05379

	experimental accuracy				theory uncertainty				
		σ_{WW} @ threshold			intrinsic			parametric	
	current	LEP2	ILC	FCC-ee	current	source	prospect	prospect	source
$\Delta M_{\mathrm{W}}[\mathrm{MeV}]$	13	200	3−6	0.5−1	3	$\alpha^3, \alpha^2\alpha_s$	1	1(0.6)	$\Delta\alpha_{\mathrm{had}}$

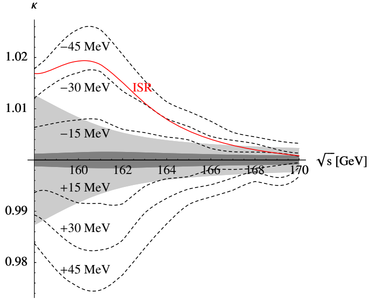
complicated reconstructions (current)
Amoroso et al., 2308.09417

basically counting experiments (σ_{WW} @ threshold)

M_{W} calculated from μ decay (theory uncertainty)

Sensitivity of σ_{WW} to M_{W}:

Beneke et al. '07



$$\kappa = \frac{\sigma_{\mathrm{WW}}(s, M_{\mathrm{W}} + \delta M_{\mathrm{W}})}{\sigma_{\mathrm{WW}}(s, M_{\mathrm{W}})}$$

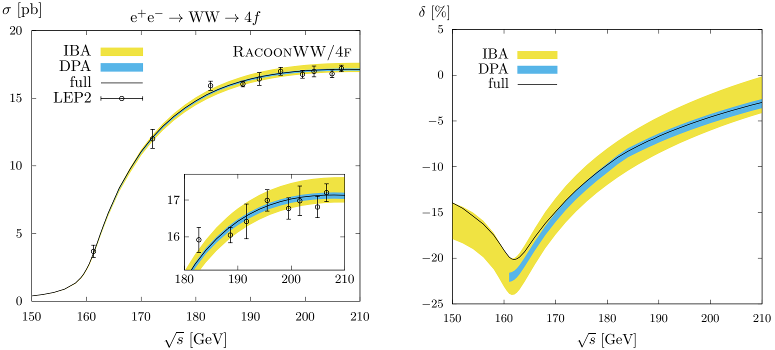
$\Delta\kappa = 0.1\%\,(0.02\%) \leftrightarrow \delta M_{\mathrm{W}} = 1.5\,(0.3)\,\mathrm{MeV}$
for $\sqrt{s} = 161\,\mathrm{GeV}$

$\Rightarrow$ FCC-ee requires
$\Delta_{\mathrm{TH}} \sim 0.01{-}0.04\%$ in σ_{WW}

Shaded areas / ISR curve:
some uncertainties of NLO(EFT) calculation,
improveable via full NLO($\mathrm{ee}\to 4f$) and NNLO(EFT)

State-of-the-art prediction of σ_{WW} in LEP2 energy range

Denner, S.D., 1912.06823

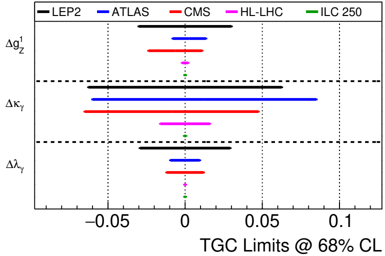


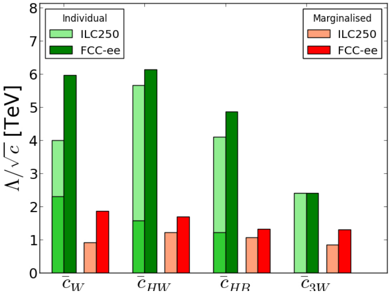
- IBA = based on leading-log ISR and universal EW corrections ($\Delta \sim 2\%$)
  $\hookrightarrow$ shows large ISR impact near threshold (also by GENTLE)
- DPA = "Double-Pole Approximation" (leading term of resonance expansion)
  $\hookrightarrow$ $\Delta \sim 0.5\%$ above threshold, not applicable at threshold RacoonWW, YFSWW
- "full" = full NLO prediction for $\mathrm{e^+e^-} \to 4f$ via charged current Denner et al. '05
  + leading-log improvements for ISR beyond NLO
  $\hookrightarrow$ $\Delta \sim 0.5\%$ everywhere

Triple-gauge couplings (TGC) analyses in $\mathrm{e^+e^-} \to \mathrm{WW}$

- $\mathrm{e^+e^-}$ is ideal framework: no formfactors for damping required!
- SMEFT framework:
  sensitivity to dim-6 operators complementary to Higgs analyses   Ellis, You '15

Bambade et al. '19





- Impact of $\Delta\kappa_\gamma$ on $\mathrm{d}\sigma_{\mathrm{WW}}$:

$\sqrt{s}/\mathrm{GeV}$	200	250	500
$\Delta\kappa_\gamma$	0.05	0.004	0.001
$\mathrm{d}\sigma_{\mathrm{WW}}(\kappa_\gamma)/\mathrm{d}\sigma_{\mathrm{WW}}^{\mathrm{SM}} - 1$	3%	$\sim 0.5\%$	$\sim 0.5\%$

$\hookrightarrow$ SM precision limits reach in TGCs for moderate $\sqrt{s}$!

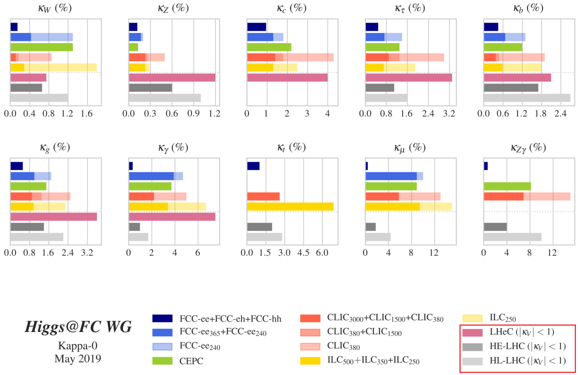
Theory homework for high-precision W-boson physics

- Exclusive analyses & predictions for $e^+e^- \to 4f$:
  - $e^\pm$ final states: proper treatment / separation of single-W channels
  - Hadronic final states: separation of multi-jet events (2j,3j,4j,...)
  - Full NLO $e^+e^- \to 4f$ prediction for each $4f$ type (interferences with ZZ and forward-$e^\pm$ channels)
  - more leading corrections beyond NLO
- σ_{WW} in threshold region:
  - full NNLO EFT calculation (only leading terms available)
  - leading 3-loop Coulomb-enhanced EFT corrections
  - matching of all fixed-order $e^+e^- \to 4f$ and threshold-EFT ingredients

$\hookrightarrow$ Estimate of theory uncertainty:
$\Delta \sim 0.01{-}0.04\%$ for σ_{WW} @ threshold Freitas et al., 1906.05379

- For M_W analysis: Improved M_W prediction from μ decay
  - massive 3-loop computations (vacuum graphs, self-energies)

Higgs couplings analyses at present and future colliders



de Blas et al., 1905.03764

- Many different assumptions in different analyses! Read fine-print!
  Important details: $\Gamma_{\mathrm{H,BSM}} = 0$? $|\kappa_{\mathrm{W}}|, |\kappa_{\mathrm{Z}}| \le 1$? $\kappa_\gamma, \kappa_{\mathrm{g}}$ independent?
- Theory limitations!
  H couplings $\neq$ free parameters, rescaled model $\neq$ consistent field theory
  $\hookrightarrow$ QCD corrections often ok, but EW corrections ($\sim 5\%$) inconsistent!
  $\hookrightarrow$ Coupling rescalings (e.g. κ framework) uncertain to $\sim 5\%$!
  $\Rightarrow$ Use EFT like SMEFT (with corrections)!

Higgs decay widths and Higgs couplings at ILC and FCC-ee

LHC HXS WG; de Blas et al., 1905.03764; HL-LHC: Cepeda et al., 1902.00134; ILC: Bambade et al., 1903.01629 FCC-ee: Freitas et al., 1906.05379

	experimental accuracy			theory uncertainty			param. unc.	
	HL-LHC	ILC250	FCC-ee	current	source	prospect	prospect	source
$\mathrm{H} \to \mathrm{b\bar{b}}$	4.4%	2%	0.8%	0.4%	α_s^5	0.2%	0.6%	m_b
$\mathrm{H} \to \tau\tau$	2.9%	2.4%	1.1%	0.3%	α^2	0.1%	negligible	
$\mathrm{H} \to \mu\mu$	8.2%	8%	12%	0.3%	α^2	0.1%	negligible	
$\mathrm{H} \to \mathrm{gg}$	1.6% (prod.)	3.2%	1.6%	3.2%	α_s^4	1%	0.5%	α_s
$\mathrm{H} \to \gamma\gamma$	2.6%	2.2%	3.0%	1%	α^2	1%	negligible	
$\mathrm{H} \to \gamma\mathrm{Z}$	19%			5%	α	1%	0.1%	M_H
$\mathrm{H} \to \mathrm{WW}$	2.8%	1.1%	0.4%	0.5%	$\alpha_s^2, \alpha_s\alpha, \alpha^2$	0.3%	0.1%	M_H
$\mathrm{H} \to \mathrm{ZZ}$	2.9%	1.1%	0.3%	0.5%	$\alpha_s^2, \alpha_s\alpha, \alpha^2$	0.3%	0.1%	M_H

Note: $\mathrm{e^+e^-}$ colliders from $\sigma_{\mathrm{e^+e^-\to ZH}}$ with *inclusive* Higgs decays!

$\Rightarrow$ Absolute normalization of Higgs BRs

Theory homework for high-precision Higgs physics

- Higgs off-shell effects: $\Gamma_{\mathrm{H}}/M_{\mathrm{H}} \sim 0.00003$ (compare: $\Gamma_{\mathrm{Z}}/M_{\mathrm{Z}} \sim 0.03$)
  - if Higgs fully reconstructable $\to$ isolation of Higgs pole via cuts
    $\hookrightarrow$ factorization of XS into production and decay parts
    (straightforward check at LO and NLO)
  - if Higgs not fully reconstructable (e.g. $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$)
    $\hookrightarrow$ inclusion of off-shell effects required (full off-shell NLO calculations)
- Multi-loop vertex corrections:
  - massive 2-loop vertex corrections (NNLO EW)
  - massless multi-loop corrections (4-/5-loop QCD for $\mathrm{H} \to \mathrm{b\bar{b}/gg}$)
- 2-loop corrections for $\mathrm{e^+e^-} \to \mathrm{ZH}, \nu\bar{\nu}\mathrm{H}$:
  - full NNLO calculation for σ_{ZH}
  - leading NNLO effects for $\sigma_{\nu\bar{\nu}\mathrm{H}}$
- Physics beyond the SM:
  - model independent: EFT approaches with higher-order corrections
  - specific models: full NLO studies (+beyond if relevant)

$\Rightarrow$ Major effort, but feasible!

Enormous challenges for theory!

Can theory provide adequate predictions?

My expectation: Yes.

... anticipating progress + support for young theorists

Table of contents

The case for a future $\mathrm{e}^+\mathrm{e}^-$ collider?

Scenarios for new colliders:

- deeper exploration of a newly discovered phenomenon/particle
  $\hookrightarrow$ Z/W physics at LEP after W/Z discoveries at SPS
- no-lose theorem by theory arguments (new particle/phenomenon ahead)
  $\hookrightarrow$ Higgs boson or new phenomenon at the LHC
- measurements in uncharted territory
  $\hookrightarrow$ deeper reach into microscopic distances
  $\hookrightarrow$ access to rare and yet unobserved phenomena

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high-precision measurements

HHH, *Hcc*, *Hee* couplings + more?

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The problem are the scales in costs + resources + time
+ serious problems of humanity (environmental, political, existential) ...

Physics vision meets reality

- ethical questions: enormous costs, mankind has big essential problems
  $\hookrightarrow$ Use big brains to solve more essential problems?
- technical realizability: unforeseen cost explosions, showstoppers?
- economic problems: energy consumption
- ecological/environmental aspects
  $\hookrightarrow$ cost-effective construction + operation, minimize carbon footprint

$\Rightarrow$ Problems/concerns have to be taken seriously!

- enter open discussions
- work on solutions
- ... and don't sell the physics case under price!

Unique selling points of high-energy physics

- fundamental research → cultural asset

  What are we made of? What rules the microcosm and the universe? ...

  ↪ new collider = only known path to unambiguously identify new particles

- role model for collaborative effort
  - one big effort over many small (redundant) experiments/laboratories
  - masterstroke in management (riddle for managers in economy)
  - sociological success of non-profit driven international collaborations
    ↪ turns down ethnical barriers

- pioneering roles in technology
  - "open-source attitude" (including the www development)
  - technical data analysis, ML/AI (lost against google et al.?)
  - technical spin-offs for industry

- educational aspects
  - fundamental physics research → magnet in academic education
  - ideal educational platform for many academic + non-academic (!) areas
  - eduction = key to a better worldwide society!

⇒ High-energy physics can be more than a "bubble" in the worldwide society?!

… about selling strategies

Maybe we could have done better?!

"If you want to buy a car, would you buy the Standard Model? – No."

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Standard Model 'S' (1913 - 1918)

Standard's first entry into the Light Car Market and introduction to Mass Production

THE 'ALL-BRITISH' STANDARD LIGHT CAR

(http://www.standardregister.co.uk/id16.html)

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Conclusions?

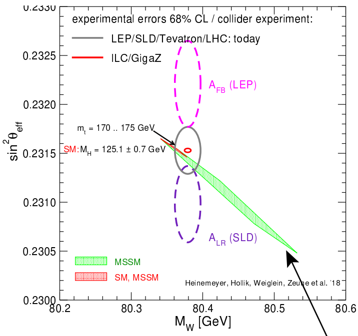
- Standard Model = beautiful?
- Better namings?!

  After all, the Higgs boson WAS "new physics".
- Sell new aspects as NEW!

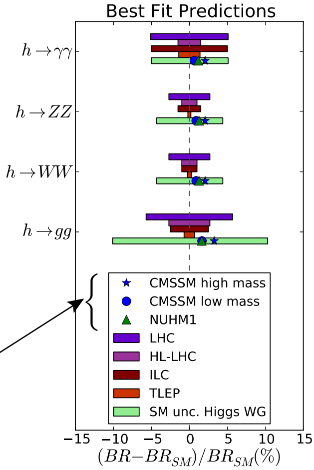
Extra slides

Typical prospects for future high-precision e^+e^- EW physics

EW PO @ ILC 1504.01726 (updated)



Higgs precision @ ILC/TLEP 1308.6176



Fantastic indirect sensitivity
to physics beyond the SM!

Baselines: LHC/HL-LHC: $300\text{fb}^{-1}/3000\text{fb}^{-1}$ @ 14 TeV
ILC: 250fb^{-1} (pol.) @ 250 GeV
TLEP: $4 \times 2.5\text{ab}^{-1}$ @ 240 GeV

Experimental errors and theory uncertainties

Experimental errors:

systematic errors
statistical errors $\Big\}$ $\rightarrow$ LHC status + projections to HL/HE-LHC, ILC, FCC-ee
= input in the following

Theory uncertainties in predictions:

- Intrinsic uncertainties due to missing higher-order corrections, estimated from
  - generic scaling of higher order via coupling factors
  - renormalization and factorization scale variations
  - tower of known corrections, e.g. $\Delta_{\mathrm{NNLO}} \sim \delta^2_{\mathrm{NLO}}$ if δ_{NLO} known
  - different variants to include/resum leading higher-order effects
- Parametric uncertainties due to errors in input parameters, induced by
  - experimental errors in measurements
  - theory uncertainties in analyses

Note:
Estimates of theory uncertainties often (too) optimistic in projections of exp. results...

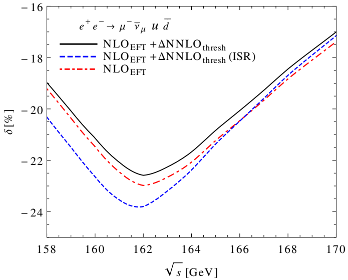
Improvements for σ_{WW} @ threshold via EFT

Beneke et al. '07; Actis et al. '08

EFT provides expansion of σ_{WW} for $\beta = \sqrt{1-4M_{\mathrm{W}}^2/s} \sim \sqrt{\Gamma_{\mathrm{W}}/M_{\mathrm{W}}} \sim \sqrt{\alpha}$:

$$\begin{aligned}\sigma_{\mathrm{WW}} = C\alpha^2\beta\Big[\, & 1 + c^{(0)}\beta && \text{LO} \\ & + \alpha\Big(\frac{c_1^{(1)}}{\beta} + c_2^{(1)}\ln\beta L_{\mathrm{e}} + c_3^{(1)}L_{\mathrm{e}} + c_4^{(1)} + c_5^{(1)}\beta\Big) && \text{NLO} \\ & + \alpha^2\underbrace{\Big(\frac{c_1^{(2)}}{\beta^2} + \frac{c_2^{(2)}}{\beta} + c_3^{(2)}\ln^2\beta L_{\mathrm{e}}^2 + c_4^{(2)}\ln\beta L_{\mathrm{e}}^2 + \dots\Big)}_{\text{leading NNLO parts known}} + \dots\Big] && \text{NNLO}\end{aligned}$$

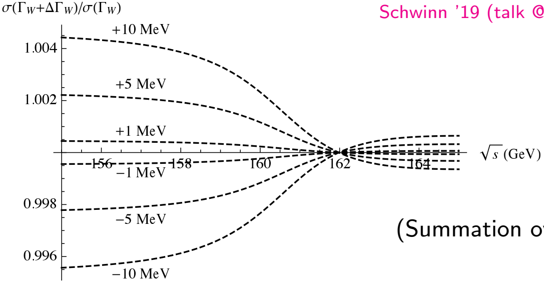
NNLO ↓ required for FCC-ee



ISR enhancement factor $L_{\mathrm{e}} = \ln(m_{\mathrm{e}}/M_{\mathrm{W}})$

Resummation of leading $(\alpha L_{\mathrm{e}})^n$ and subleading $\alpha(\alpha L_{\mathrm{e}})^{n-1}$ ISR necessary!

Γ_W determination from energy scan @ WW threshold:



Schwinn '19 (talk @ FCC-ee Workshop, CERN)

(Summation over all $4f$ states)

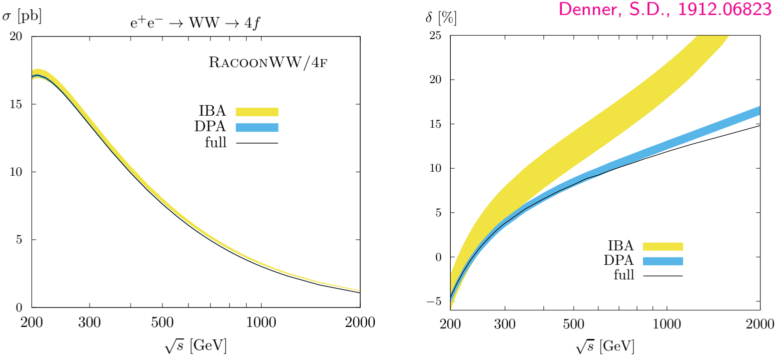
Simultaneous fit of M_W and Γ_W by scan of σ_{WW}:

- FCC-ee study: 1703.01626
  2-point fit ($15\,\mathrm{ab}^{-1}$): $M_W = 0.41\,\mathrm{MeV}, \ \Gamma_W = 1.1\,\mathrm{MeV}$
- CEPC study: 1812.09855
  3-point fit ($2.6\,\mathrm{ab}^{-1}$): $M_W = 1\,\mathrm{MeV}, \ \Gamma_W = 2.8\,\mathrm{MeV}$

WW production beyond LEP2 energy range

Fixed-order NLO + leading-log ISR prediction:

Denner, S.D., 1912.06823



Note: large non-universal weak corrections + sizeable off-shell effects

Achievable precision:

- by full NLO for $\mathrm{e}^+\mathrm{e}^- \to 4f$ + leading NNLO corrections + ISR resummation
- estimate: $\Delta \sim 0.5\%$ in distributions ($\sim 1\%$ in tails) up to $\sqrt{s} \sim 1\,\mathrm{TeV}$