Unraveling New Physics at Future High Energy Colliders

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PARTICLEFACE 2021: Unraveling New Physics Workshop Management Committee Meeting

Zagreb, 16 July 2021 (hybrid)

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

NATIONAL SCIENCE CENTRE POLAND

WG3: Assessing the discovery potential of future high energy colliders

Objectives:

Assessment of the discovery potential of future high energy colliders based on the experimental results from the high-energy run of the LHC combined with progress in theoretical research.

Tasks:

- T3.1 Prospects for the physics of the Higgs boson, EW bosons, top quarks, and high-energy jets at future colliders with ultra-high multiplicities (M. Raidal, B. Fuks)
- T3.2 Combined EW and QCD predictions at the highest energies (D. Wackeroth, B. Jäger)
- T3.3 Resummation techniques for multi-scale processes at the highest energies (A.Hoang, E. Laenen)
- T3.4 Smoking-gun new physics signals at high energies (M. Nemevsek)

+ Radja Boughezal

Now: Over 140 regular publications (scopus).

BSM: DM & RHN, ..., in principle no target scale

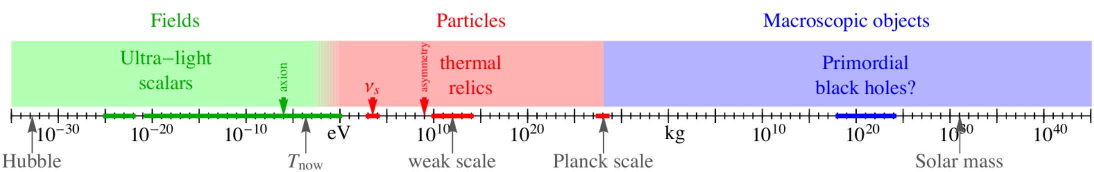
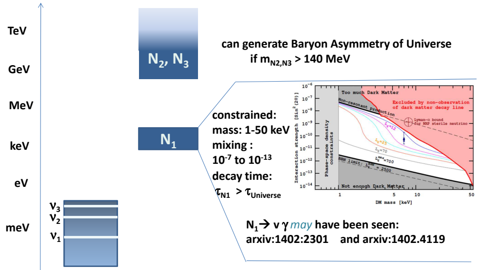
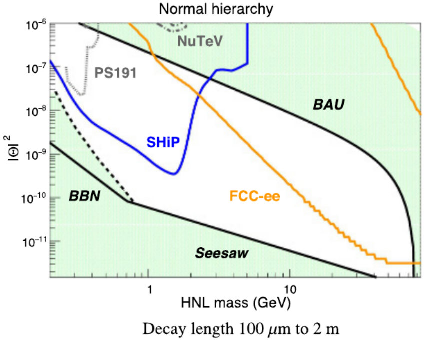


Fig.: Marco Cirelli



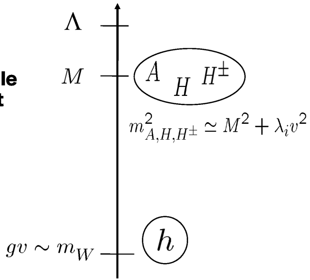
A. Blondel et al. 1411.5230



FCC-ee CDR vol.1

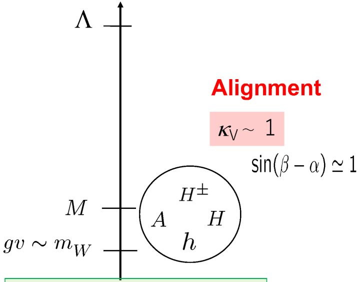
Two Possibilities satisfying current data

Λ **: Cutoff**
M **: Mass scale irrelevant to VEV**



$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM
Decoupling



$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm nonSM} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

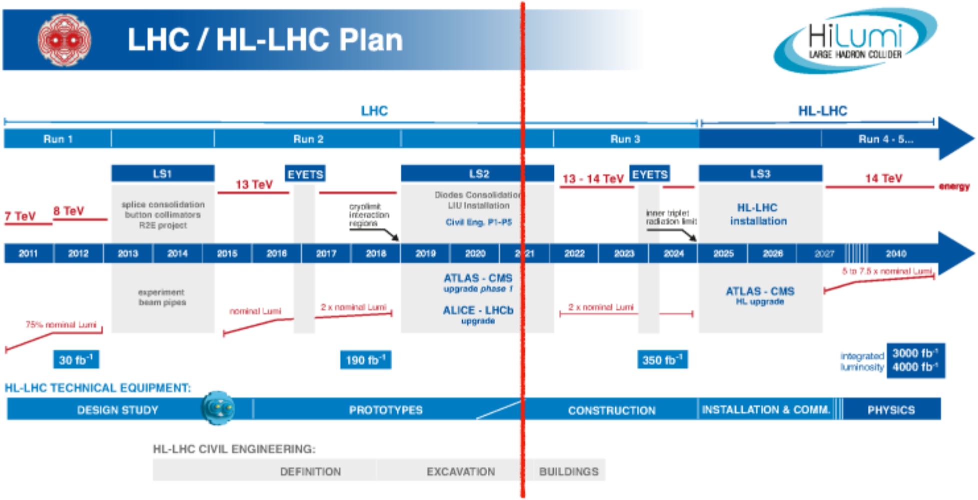
Effective Theory is an extended Higgs sector
Alignment without decoupling

... **terra incognita**, but many details established thanks to the activity of the ParticleFace groups, both concerning precise SM predictions and BSM directions.

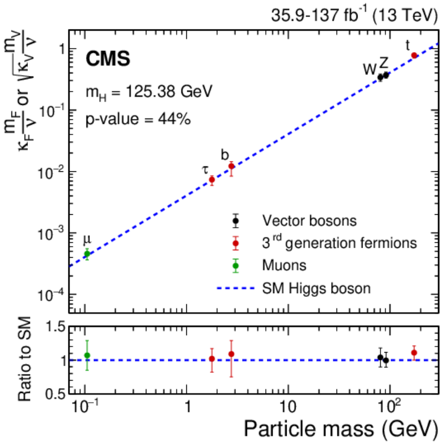
For BSM, ParticleFace contributors and efforts should be acknowledged, the broad spectrum of topics (if not complete, let me know):
Higgs potentials and masses: MSSM, 2HDM, MLRSM, HTM, IDM;
false vacuum studies;
unified theories with reduced couplings;
neutrino mixing and mass models;
long-lived particles;
gauge left-right-colour-family grand unification;
gravitation vs massive neutrinos and LFV; LFV;
compositeness.

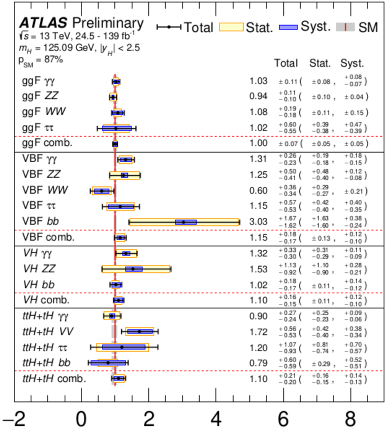
Where we are in HEP now

today



Since 2012: Increasing precision, wide physics processes spectrum



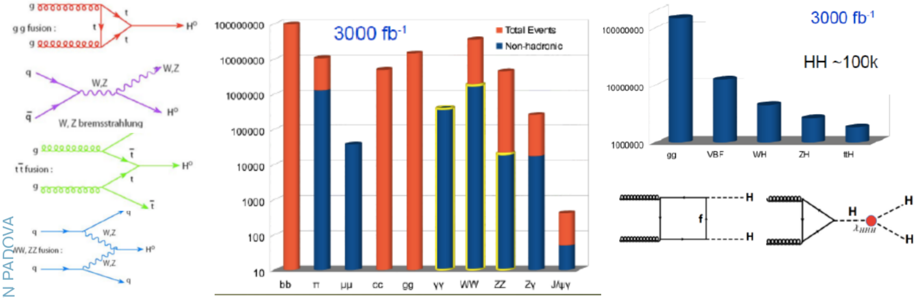


ATLAS 2020: https://cds.cern.ch/record/2725733

CMS 2020: http://cds.cern.ch/record/2730058

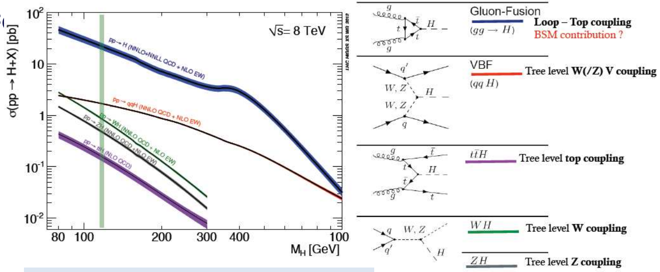
HL-LHC IS A HIGGS FACTORY

- At HL-LHC, we expect to produce ~170M Higgs Bosons, including ~120k of pair produced events
- Over 1Million for each of the main production mechanisms, spread over many decay modes



- Enables a broad program:
  - Precision O(few%) measurements of couplings across broad kinematics
  - Exploration of Higgs potential (hh production)
  - Sensitivity to rare decays involving new physics
  - extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)

PATRIZIA AZZI - INFN PADOVA



THE LHC is a Higgs Factory…BUT

~100 Million Higgs already produced… more than most "Higgs factory" projects.

$$\sigma_{i\to f}^{\text{observed}} \propto \sigma_{\text{prod}} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

relative error scales with
1/purity and 1/√efficiency of signal

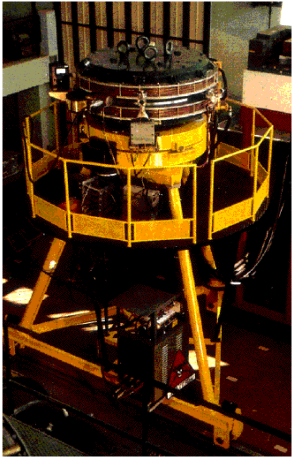
We don't know this until measured directly

difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown
(invisible+ unmeasured channels) → must do physics with ratios.

Two examples why we have to try to reach as much/far as possible and why we need new:

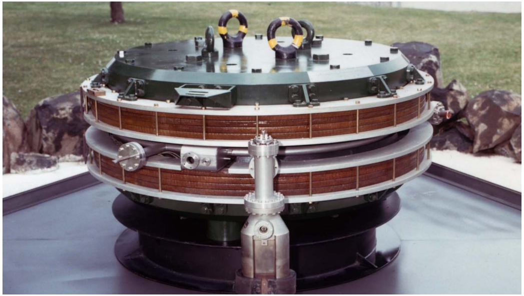
PRECISION and ENERGY frontiers

‘The first accelarator dates back to prehistoric-historic times, when men built bows and arrows for hunting.’, S.Y. Lee, "Accelarator Physics"



ADA/ADONE: The first [circular] e^+e^- collider

1969-1993, Frascati, $\sqrt{s} \leq 3$ GeV



To be lucky is an important life/research factor, 2 PRLs in 1974 for J/Ψ discovery

SPEAR at SLAC

"J"

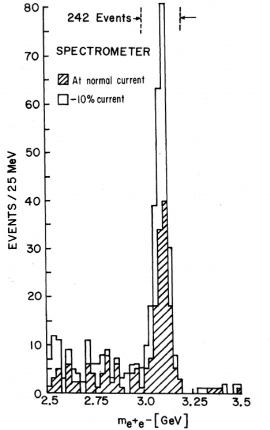


FIG. 2. Mass spectrum showing the existence of J.

"Psi"

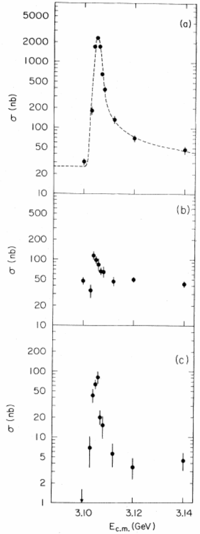


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the ex-

Z.Ligeti

Aside: factor-of-2 improvements can matter!

Search for $K_L \to \pi\pi$

ANNALS OF PHYSICS: 5, 156–181 (1958)

Long-lived Neutral K Mesons*

M. Bardon, K. Lande, and L. M. Lederman

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

and

William Chinowsky

Brookhaven National Laboratories, Upton, New York

set an upper limit <0.6% on the reactions

< 0.6%

$$K_2^0 \to \begin{cases} \mu^\pm + e^\mp \\ e^+ + e^- \\ \mu^+ + \mu^- \end{cases}$$

and on $K_2^0 \to \pi^+ + \pi^-$.

VOLUME 6, NUMBER 10 — PHYSICAL REVIEW LETTERS — MAY 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3% for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our

< 0.3%

"At that stage the search was terminated by administration of the Lab."

[Okun, hep-ph/0112031]

VOLUME 13, NUMBER 4 — PHYSICAL REVIEW LETTERS — 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

= 0.2 ± 0.04 %

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

Talking about precision at LHC and the ParticleFace WG3 second part of activity

Progress in precision studies for LHC/HL-LHC ($\sim$20 times larger statistics)

1. Fixed order (NLO up, QCD-EW) $\rightarrow$ N3LO revolution
2. Resummations (LL, NLL, parton showers)
3. PDFs, fits

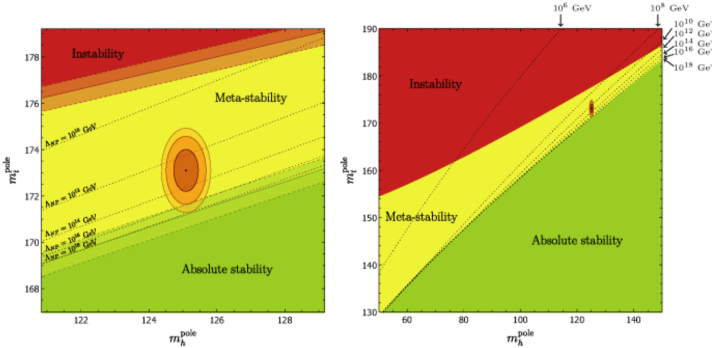
ParticleFace contributors: Bonciani, R., Buccioni, F., Rana, N., Vicini, A., Holguin, J., Forshaw, J.R., Plätzer, S., De Angelis, Greif, M., Greiner, C., Schenke, B., Schlichting, S., Pich, A., Laenen, E., Sinninghe Damste, J., Vernazza, L., Waalewijn, W., Zoppi, L., Andersen, J.R., Gütschow, C., Maier, A., Prestel, S., Olsson, J., Sjödahl, M., Grozin, A.G., Marquard, P., Smirnov, A.V., Smirnov, V.A., Steinhauser, M., Das, G., Moch, S., Vogt, Alekhin, S., Jäger, B., Karlberg, A., Scheller, J., Zaro, M., Boito, D., Mateu, V., Ablinger, J., Blümlein, J., Marquard, P., Rana, N., Schneider, C., De Freitas, A., Raab, C.G., Schönwald, K., Heinrich, G., Jones, S., Kerner, M., Luisoni, G., Scyboz, L., Goedicke, A., Saragnese, M., A., von Manteuffel, Pires, J. , Andersen, J.R., Hapola, T., Heil, M., Maier, A., Smillie, J., Cormier, K., Reuschle, C., Richardson, P., Webster, S., , Van Hameren, A., Jung, H., Kusina, A., Kutak, K., Andersen, J.R., Cockburn, J.D., Heil, A., Smillie, J.M., Maas, A., Fernbach, S., Lechner, L., Schöfbeck, R., Törek, P., Gieseke, S., Kirchgaeser, P., Siódmok, A., Gutierrez-Reyes, D., Scimemi, I., Waalewijn, W.J., Zoppi, L., Hoang, A.H., Samitz, D., Procura, M., Zeune, L., Buchalla, G., Capozi, M., Celis, A., Scyboz, L., Renteria-Estrada, D.F., Hernandez-Pinto, ...

In quest of new effects: Basic questions for SM and BSM

We are facing fundamental problems:

1. Actual Higgs potential, more scalars? What kind of?
2. Which BSM model in case of spotted anomalies? (which is more than the "Higgs inverse problem")
3. CP asymmetry (quarks, neutrinos, scalars);
4. Flavour mixings, quarks and lepton mass hierarchies;
5. Astroparticle and cosmological puzzles.

The ‘universe’ stability fate phase diagram, https://arxiv.org/abs/1707.08124



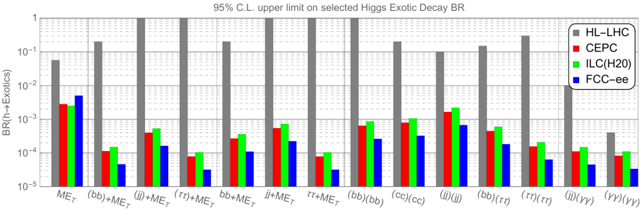
Dotted lines indicating the scale at which the addition of higher-dimension could stabilize the SM (one of possible BSM scenarios). Is BSM needed there?

‘The Standard Model of Particle Physics as a Conspiracy Theory and the Possible Role of the Higgs Boson in the Evolution of the Early Universe’, F. Jegerlehner, 2106.00862

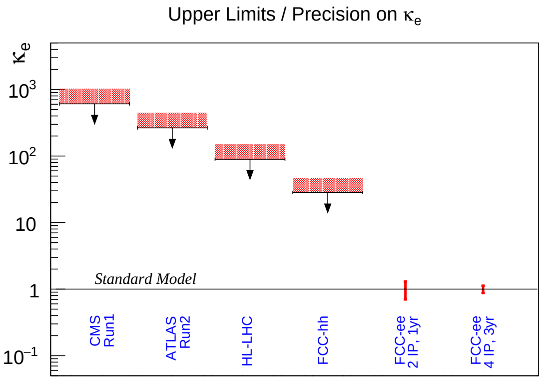
The LHC/HL-LHC will (certainly) not be sufficient to clarify the situation, in many points

The answers to the SM/BSM issues will lie in the exploration of TeV-scale physics at high energy colliders. To which scale? In which colliders?
It depends on how well we will be prepared for undertaking the challenge, in theory and experiment, and will be decided in next years ($\sim$2025, next ESPPU).

The example from 1612.09284 'Exotic decays of the 125 GeV Higgs boson at future e^+e^- lepton colliders' by Liu, Wang, Zhang.



Sensitivity of FCC-ee, comparisons, Blondel & Janot inspires



Current upper limits on the Higgs boson coupling modifier to electrons, κ_e; projected κ_e upper limits at HL-LHC and FCC-hh; and projected κ_e precisions at FCC-ee in two different running configurations (one year with 2 IPs, or three years with 4 IPs).

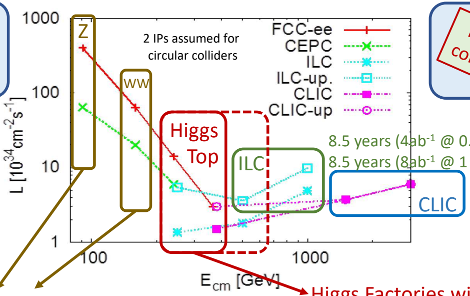
e^+e^- Higgs Factories (incl. B/c/τ/EW/top factories)

precision frontier — circular colliders

synchrotron radiation

for the same power, less luminosity at higher E_{cm}

(Energy Recovery Linac technology might mitigate this & allow to go to higher E_{cm})



linear colliders — energy frontier

8.5 years ($4ab^{-1}$ @ 0.5 TeV)
8.5 years ($8ab^{-1}$ @ 1 TeV)
7 years ($2.5ab^{-1}$ @ 1.5 TeV)
8 years ($5ab^{-1}$ @ 3 TeV)

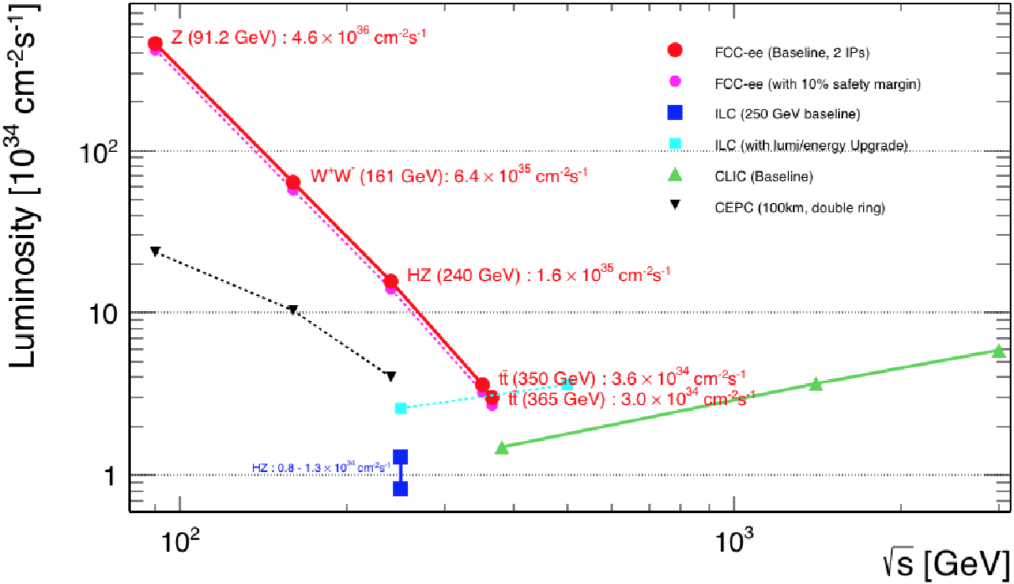
B/c/τ/EW Factories

per detector in e^+e^-	# Z	# B	# τ	# charm	# WW
LEP	4 x 10^6	1 x 10^6	3 x 10^5	1 x 10^6	2 x 10^4
SuperKEKB	-	10^{11}	10^{11}	10^{11}	-
FCC-ee	2.5 x 10^{12}	7.5 x 10^{11}	2 x 10^{11}	6 x 10^{11}	1.5 x 10^8

Higgs Factories with complementarity

- g_{HZZ} (250GeV) versus g_{HWW} (380GeV)
- top quark physics
- beam polarization for EW precision tests

(transverse polarization in circular e^+e^- colliders only at lower E_{cm} while longitudinal polarization at linear colliders)



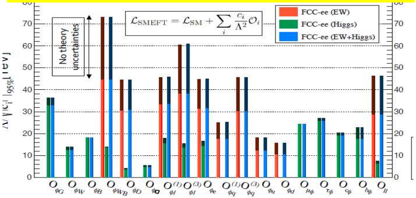
Luminosity [10^{34} cm^{-2}s^{-1}]
$\sqrt{s}$ [GeV]
Z (91.2 GeV) : 4.6 × 10^{36} cm^{-2}s^{-1}
W^+W^- (161 GeV): 6.4 × 10^{35} cm^{-2}s^{-1}
HZ (240 GeV) : 1.6 × 10^{35} cm^{-2}s^{-1}
$t\bar{t}$ (350 GeV) : 3.6 × 10^{34} cm^{-2}s^{-1}
$t\bar{t}$ (365 GeV) : 3.0 × 10^{34} cm^{-2}s^{-1}
HZ : 0.8 - 1.3 × 10^{34} cm^{-2}s^{-1}
FCC-ee (Baseline, 2 IPs)
FCC-ee (with 10% safety margin)
ILC (250 GeV baseline)
ILC (with lumi/energy Upgrade)
CLIC (Baseline)
CEPC (100km, double ring)

Alain Blondel, Epiphany 2021 https://indico.cern.ch/event/934666

The opportunities **The challenges**

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

Precision EW measurements:
is the SM complete?



-^- EFT D6 operators (some assumptions)

-^- Higgs and EWPOs are complementary

-^- top quark mass and couplings essential!

(the 100km circumference is optimal for this)

<-- systematics are preliminary

(aim at reducing to systematics)

<-- tau, b, and c observables still to be added

<-- complemented by high energy FCC-hh

Theory work is critical and initiated *1809.01830*

"Personal Remarks on SMEFT for Snowmass",
M. E. Peskin, EF1-EF4 meeting, Sept. 2020, pdf

1. "... the interpretation depends on the connection to explicit models of BSM physics".
   How $\frac{C_i}{\Lambda^2}$, O_H, O_{WW}, ..., are releated to the BSM parameters?
2. Linear dependence on SMEFT parameters?
3. SMEFT at high Q^2 vs specific models?
4. h.o. SMEFT corrections and cancellations with SMEFT tree level
5. SMEFT contribution to SM background.

Multiple ways to new physics

Tools:

1. low-energy physics (g-2, LFV, ...) Example:
2. high-energy physics - our basic interest

Methods:

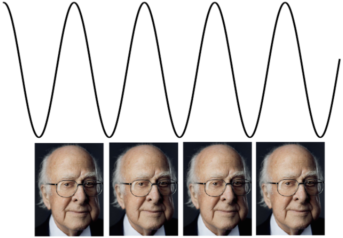
1. precision
2. direct discoveries

"Precise measurements of known particles and interactions are just as important as finding new particles", F. Gianotti

$\rightarrow$ e.g. compositeness

Higgs Factories

- The Higgs boson has a size/wavelength. What's inside?



Precision measurements are different ways of probing the "compositeness of the Higgs".

$\lambda_h \approx 10^{-17}$ m

$\lambda_{10\ \mathrm{TeV}} \approx 10^{-19}$ m

Matthew Philip Mccullough, Oxford 2019,
https://indico.cern.ch/event/783429/contributions/3305140/attachments/1829729/2996092/CEPC.pdf

Many parameters must be improved in collider studies:

(i) to show incompleteness of SM

(ii) uncover fully the nature of NP

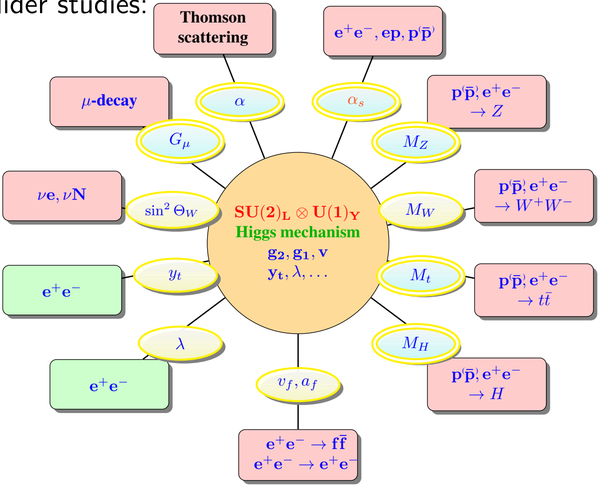


Fig. from a report on α_{QED}, F. Jegerlehner in "Theory for the FCC-ee : Report on the 11th FCC-ee Workshop Theory and Experiments", https://e-publishing.cern.ch/index.php/CYRM/issue/view/110

A list of challenges ahead of us

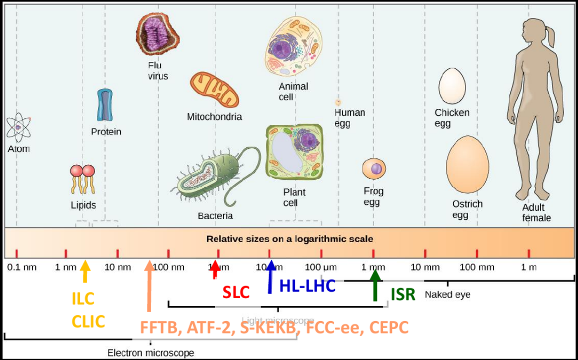
1. Challenges at Z-pole:
   1. 3-loop EW and mixed EW-QCD, leading 4-loop corrections for $Z \to 2f$ vertices
   2. QED interference effects, non-factorizable corrections
   3. Adjusting MC generators at NNLO and beyond (Bhabha (!), exclusive NNLO $e^+e^- \to f\bar{f}$).
2. Challenge to improve input parameters (α, α_s, physics at ZH, WW, tt)
3. Challenge to optimize/understand paths towards BSM discovery (RHNs, DM, CP effects,...)
4. Challenge: SM(BSM)EFT, precision physics for concrete BSM models
5. Challenge: Tools (MC generators, multiloop numerical, analytical programs)

With LHC (HL-LHC) and next colliders choices, there are great challenges and opportunities for theory, and a lot of work to be done. (Good for us).

$\to$ The real challenge for the young generation!

From F. Zimmermann talk at the 11th FCC-ee workshop: Theory and Experiments, https://indico.cern.ch/event/7668598-11 January 2019, CERN

vertical spot size challenge



FCC-ee in the regime of FFTB, ATF-2, and especially SuperKEKB

FUTURE COLLIDERS

HL-LHC,
HE-LHC,
FCC-hh,
Ion, Ion-e,
LHeC/FCC-eh,
b/c/tau,
muon,
CEPC,
SppC,
FCC-ee,
ILC,
CLIC,
...

Fabiola Gianotti, 'CERN's vision and plans for 2021-2025', at FCC Week 2021

Scientific recommendations of the ESPP

Full exploitation of the physics potential of LHC and high-luminosity LHC — CERN's implementation (2020 and 2021 Medium-Term Plans)
→ LHC and HL-LHC are CERN's highest priority in the short/medium term

Highest-priority next collider: e^+e^- Higgs factory
→ FCC-ee, continued development of CLIC key technologies (includes limited support to ILC)

Increased R&D on accelerator technologies: high-field superconducting magnets, high-gradient accelerating structures, plasma wakefield, muon colliders, ERL, etc.
→ high-field magnet efforts enhanced, SCRF and NCRF, AWAKE, muon colliders, etc.

Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider at CERN, with e^+e^- Higgs and electroweak factory as a possible first stage.
→ see next slides

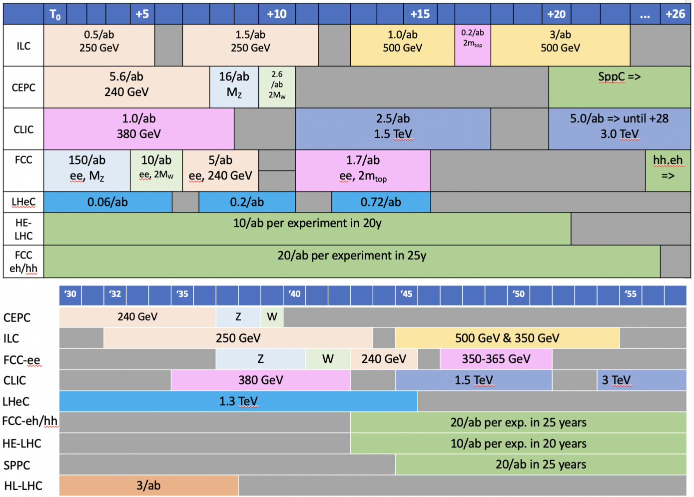
Support to long-baseline neutrino projects in US and Japan, in particular successful implementation of DUNE at LBNF
→ continued/expanded support to Neutrino Platform

Support to high-impact scientific diversity programme complementary to high-E colliders
→ increased support to Physics Beyond Colliders

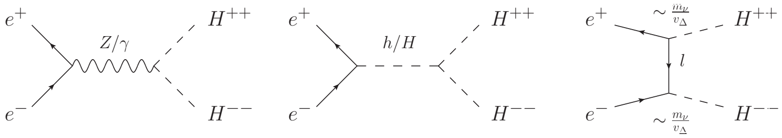
Support to R&D on detector, SW and computing, as crucial tools for the field
→ R&D for future detectors initiative; new Quantum Technology Initiative at CERN

Support to theory as an essential driver for particle physics
→ increased synergies with neighbouring fields

Timelines: would-be starting year and absolute timescale



Case study: comparing signals from different models, Chinese Physics C, JG, M.Kordiaczynska, T.Srivastava, https://iopscience.iop.org/article/10.1088/1674-1137/abfe51

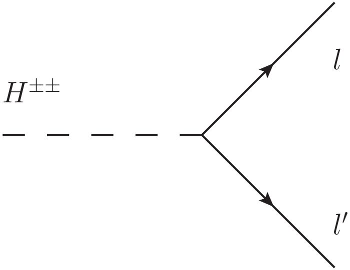


HTM	$\mu = 1.7 \times 10^{-7}, \quad \lambda = 0.519, \quad \lambda_1 = 0.519, \quad \lambda_2 = 0, \quad \lambda_3 = -1, \quad \lambda_4 = 0.$ M_h = 125.3 GeV, M_H = 700 GeV, $M_{H^\pm}$ = 700 GeV, $M_{H^{\pm\pm}}$ **= 700 GeV**.
MLRSM	$\lambda_1 = 0.129,\ \rho_1 = 0.0037,\ \rho_2 = 0.0037,\ \rho_3 - 2\rho_1 = 0.015,\ \alpha_3 = 4.0816,\ 2\lambda_2 - \lambda_3 = 0.$ $M_{H_0^0}$ = 125.3 GeV, $M_{H_1^0}$ = 10 TeV, $M_{H_2^0}$ = 600 GeV, $M_{H_3^0}$ = 605.4 GeV, $M_{H_1^{\pm\pm}}$ **= 700 GeV**, $M_{H_2^{\pm\pm}}$ **= 700 GeV**, $M_{H_1^\pm}$ = 654.4 GeV, $M_{H_2^\pm}$ = 10 003.1 GeV.

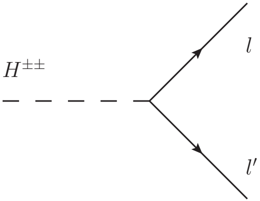
$H^{\pm\pm} - l - l'$ coupling

$$\mathcal{L}_Y = \frac{1}{2} f_{\ell\ell'} L_\ell^T C^{-1} i\sigma_2 \Delta L_{\ell'} + \text{h.c.}$$

$$\mathcal{L}_\nu = \frac{1}{2}\, \bar{\nu}_\ell\, \frac{v_\Delta}{\sqrt{2}}\, f_{\ell\ell'}\, \nu_{\ell'}$$



HTM - $H^{\pm\pm} - l - l'$ coupling



$$f = \frac{1}{\sqrt{2}v_\Delta} V^*_{PMNS} D_\nu V^\dagger_{PMNS} \qquad D_\nu = \frac{1}{2}\,\mathrm{diag}\{m_1, m_2, m_3\}$$

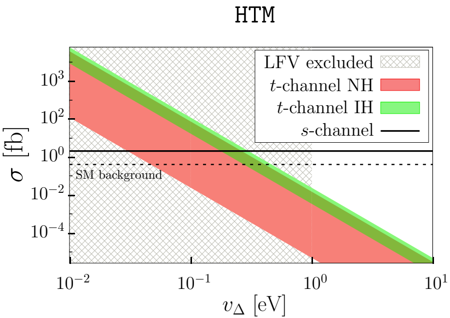
$$v_\Delta \Longleftrightarrow f_{ll'} \Longleftrightarrow$$

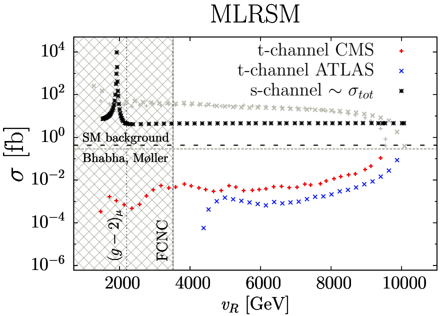
Neutrino parameters

$\theta_{12},\ \theta_{23},\ \theta_{13},\ \delta_{\mathrm{CP}}$

$m_1,\ m_2,\ m_3$

Low energy and LHC constraints



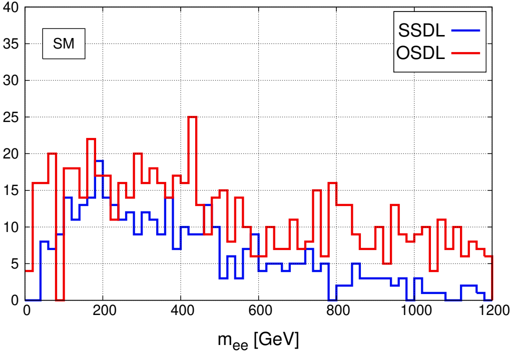


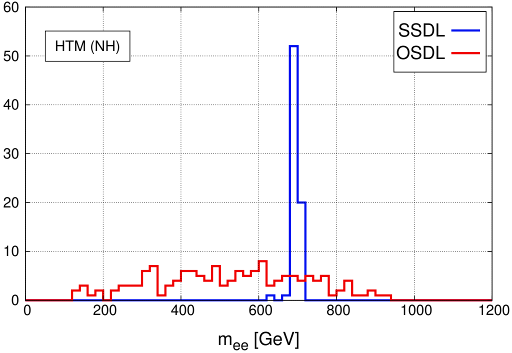
$pp \to 4l$

SM background: $pp \to 4l$	
$4e$	No cuts: $\sigma = 9.1$ [102.6] fb After cuts: $\sigma = 0.0071$ [0.153] fb, N = **28 [3825]**
4μ	No cuts: $\sigma = 9.1$ [100.6] fb After cuts: $\sigma = 0.022$ [0.62] fb, N = **88 [15 167]**

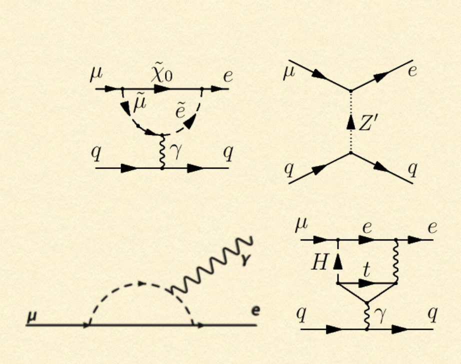
BSM signal: $pp \to H^{++}H^{--} \to 4l$		HTM		LRSM	
		NH	IH	v_R = 6 TeV	v_R = 15 TeV
$4e$	No cuts:	0.0038 fb [0.39 fb]	0.0109 fb [1.11 fb]	0.0029 fb [0.87 fb]	0.136 fb [19.6 fb]
	After cuts:	0.00032 fb N=**1.3** [0.020 fb] [N=**484**]	0.00092 fb N=**3.7** [0.059 fb] [N=**1459**]	0.00026 fb N=**1.1** [0.0407 fb] [N=**1032**]	0.0116 fb N=**45** [0.98 fb] N=**[24 492]**
4μ	No cuts:	0.0092 [1.086 fb]	0.0039 fb [0.48 fb]	0.0029 fb [0.87 fb]	0.136 fb [19.6 fb]
	After cuts:	0.0031 N=**11.5** [0.202 fb] [N=**5057**]	0.00132 fb N=**5.3** [0.090 fb] [N=**2262**]	0.001 fb N=**4** [0.181 fb] [N=**4509**]	0.048 fb N=**180** [3.9 fb] N=**[97 199]**

Luckily, faint signals over background can be extracted

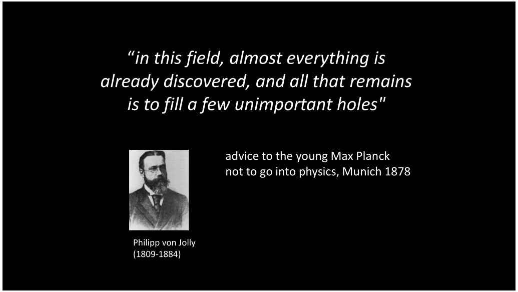




Competition (and complementarity): low energy intensity frontiers, LFV: $\mu \to e\gamma$, $\mu \to e$ conversion



$m_\mu \sim 200\ m_e$
$R^{\mu \to e} < 7 \cdot 10^{-13}$, expected 4 orders of magnitude improvement,
Sensitivity to NP $\sim$ 10 000 TeV!
Such data such (and are) taken in our studies



Setting definitive statements is dangerous.

Albert Michelson (1894):

"It seems probable that most of the grand underlying principles have been firmly established (...) the future truths of physical science are to be looked for in the sixth place of decimals"

Q: Dear Albert: What about special and general relativity, and quantum mechanics?

I am looking for the MTTD2021 talk by German and his thoughts on the future of our field

Matter To The Deepest 2021

Matter To The Deepest

15-17 September 2021
Europe/Warsaw timezone

- Overview
- Committees
- Registration
  - Modify my Registration
- Participant List
- Previous Conferences
- Poster

Support

matter.to.the.deepest...

Matter To The Deepest Recent Developments In Physics Of Fundamental Interactions XLIV International Conference of Theoretical Physics

Matter To The Deepest is one of the oldest conferences in Poland organized every two years by theoretical particle and astrophysics physicists from the University of Silesia in Katowice, Poland. It started in 1975.

Due to the ongoing pandemic, and in order to mitigate difficulties with global travel restrictions, the conference will take a fully virtual format. A special outreach talk is planned entitled "The future of particle physics" by professor German Rodrigo (CSIC-Valencia U., IFIC).

Main Topics:

1. Precision tests of the Standard Model,
2. Low energy physics,
3. Methods in multi-loop calculations,
4. Extensions of the Standard Model,
5. Neutrinos, astrophysics and cosmology.

To optimize as much as possible the time schedule for colleagues from different sites of the world we plan to start daily at about 1 or 2 pm (Warsaw time zone). Sessions with about 8 talks per day will last for about 5 hours.

Contact: matter.to.the.deepest@us.edu.pl

Supported by the Institute of Physics in Katowice, COST Action CA16201 PARTICLEFACE and Physics of Fundamental Interactions Section of the Polish Physical Society.

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Backup slides

what not gathered here, in my earlier related talks:

‘Assessing the discovery potential of future high energy colliders: summary for WG3’, ParticleFace meeting in Combra, 2019: talk

"FCC-ee: the challenge for theory", 4th FCC Physics and Experiments Workshop in 2020, talk at link.

Z,W,H,t electroweak factories

Table: Run plan for FCC-ee in its baseline configuration with two experiments. The WW event numbers are given for the entirety of the FCC-ee r unning at and above the WW threshold.

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3.10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ even ts

Table from arXiv:1809.01830

EWPOs 2020

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ^0_{had} $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365\,\text{GeV}$ run

Future: W, t, H

- $e^+e^- \to HZ$ at 240 GeV: Kinematic constraint fits with $Z \to ll$ and $H \to bb$, ...,
  $\delta m_H^{exp} =$ 10 MeV;
  Theory errors subdominant.

- $e^+e^- \to W^+W^-$ at 161 GeV: $\delta m_W^{exp} = 0.5 \div 1$ MeV.
  Challenge to get the same TH error:
  NNLO $e^+e^- \to 4f$.

- $e^+e^- \to t\bar{t}$ at 350 GeV: $\delta m_t{}^{exp} =$ 17 MeV
  Big challenge for theory, today > 100 MeV, future projection $\leq$ 50 MeV:
  $\sim$ 10 MeV unc. from mass def.;
  $\sim$ 15 MeV from α_s unc. to threshold mass def.;
  ~ 30 MeV - h. orders resummation

Estimated theoretical uncertainties from missing higher orders and the perturbative orders (QCD/elw.) of the results included in the analysis.

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$	$\sim 0.5\%$	N^{4}LO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$	—	$\sim 0.5\%$	$\sim 0.5\%$	— / NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	N^{3}LO / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	NLO/NLO

Higgs boson decays: theoretical status, https://arxiv.org/abs/1906.05379

Projected intrinsic and parametric uncertainties for the partial and total Higgs-boson decay width predictions. The last column: the target of FCC-ee precisions.

decay	intrinsic	para. m_q	para. α_{s}	para. M_{H}	FCC-ee prec. on g^2_{HXX}
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–	$\sim 0.8\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	$\sim 1.4\%$
$H \to \tau^+\tau^-$	$< 0.1\%$	–	–	–	$\sim 1.1\%$
$H \to \mu^+\mu^-$	$< 0.1\%$	–	–	–	$\sim 12\%$
$H \to gg$	$\sim 1\%$		0.5% (0.3%)	–	$\sim 1.6\%$
$H \to \gamma\gamma$	$< 1\%$	–	–	–	$\sim 3.0\%$
$H \to Z\gamma$	$\sim 1\%$	–	–	$\sim 0.1\%$	
$H \to WW$	$\lesssim 0.3\%$	–	–	$\sim 0.1\%$	$\sim 0.4\%$
$H \to ZZ$	$\lesssim 0.3\%^{\dagger}$	–	–	$\sim 0.1\%$	$\sim 0.3\%$
Γ_{tot}	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	$\sim 1\%$

† From $e^+e^- \to HZ$ production