Introduction to theory parallel sessions

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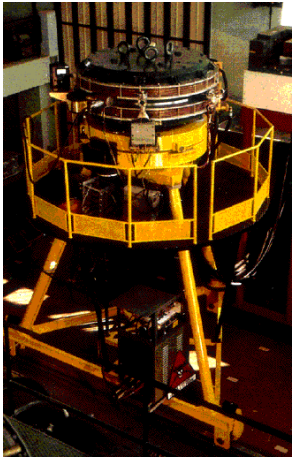
11th FCC-ee workshop: Theory and Experiments

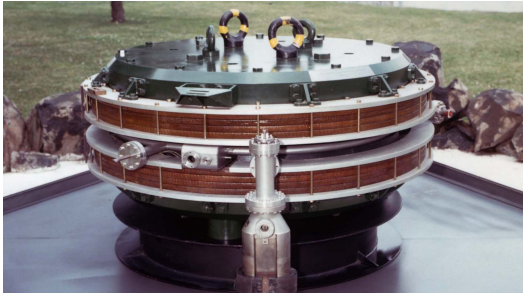
CERN, 8 January 2019

"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



FCC-ee: **High Energy Intensity Frontier**

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 running 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	$\mathbf{3 \cdot 10^{12}}$ 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 $t\bar{t}$ events

Table from arXiv:1809.01830, also in FCC CDR

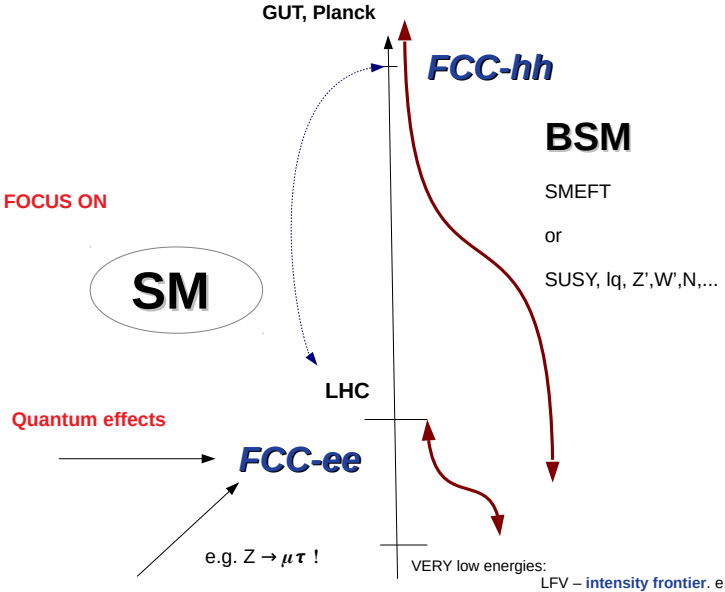
E.g. flavour physics - many, many directions for SM theory and beyond

Table 7.1: Expected production yields of heavy-flavoured particles at Belle II (50 ab^{-1}) and FCC-ee.

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B_s^0 / $\overline{B}_s^0$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	1000	1000	250	250	550	170

Table 7.2: Comparison of orders of magnitude for expected reconstructed yields of a selection of electroweak penguin and pure dileptonic decay modes in Belle II, LHCb upgrade and FCC-ee experiments. Standard model branching fractions are assumed. The yields for the electroweak penguin decay $\bar{B}^0 \to K^{*0}(892)e^+e^-$ are given in the low q^2 region.

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)


GUT, Planck
FCC-hh
BSM
SMEFT
or
SUSY, lq, Z',W',N,...
FOCUS ON
SM
LHC
Quantum effects
FCC-ee
e.g. Z → μτ !
VERY low energies:
LFV – intensity frontier. e.g. $(\beta\beta)_{0\nu}$
Precise SM predictions, e.g. $(g-2)_{\mu}$
Neutrinos

Theory contribution to European Strategy Particle Physics

	$\delta\Gamma_Z$ [MeV]	δR_l [10^{-4}]	δR_b [10^{-5}]	$\delta \sin^{2,l}_{eff}\theta$ [10^{-6}]
Present EWPO uncertainties				
EXP-2018	2.3	250	66	160
TH-2018	0.4	60	10	45
EWPO uncertainties when FCC-ee will start				
EXP-FCC-ee	0.1	10	$2 \div 6$	6
TH-FCC-ee	?	?	?	?

$\delta\Gamma_Z \sim 0.1$ MeV $\ll \Gamma_Z$ **Incredible!** $\delta\Gamma_Z/\Gamma_Z \sim 10^{-4}$

Typically, at the FCC-ee, measurements better by factors $\mathcal{O}(20)$ from present situation.

A big question:

Can theory in about two decades ($\simeq$ start of data taking) comply with the level of anticipated experimental accuracy?

Present theoretical accuracy is not enough, we need to calculate higher order quantum corrections.

We estimated amount of missed quantum effects for basic EWPOs at the first FCC-ee, Tera-Z stage.

The answer to a big question is POSITIVE.

Yes, we can keep pace with experimental demands.
Conditions to be fulfilled are known.

Details in: arXiv:1809.01830, submitted to CERN Yellow Report

Standard Model Theory for the FCC-ee: The Tera-Z

A. Blondel (Geneva U.), J. Gluza (Silesia U.), S. Jadach (Cracow, INP), P. Janot (CERN), T. Riemann (Silesia U. & DESY, Zeuthen), A. Akhundov (Valencia U. & Baku, Inst. Phys.), A. Arbuzov (Dubna, JINR), R. Boels (Hamburg U., Inst. Theor. Phys. II), S. Bondarenko (Dubna, JINR), S. Borowka (CERN) *et al.* Show all 38 authors

Sep 6, 2018 - 243 pages

Conference: C18-01-12
BU-HEPP-18-04, CERN-TH-2018-145, IFJ-PAN-IV-2018-09, KW 18-003, MITP/18-052, MPP-2018-143, SI-HEP-2018-21
e-Print: arXiv:1809.01830 [hep-ph] | PDF

Abstract (arXiv)
The future 100-km circular collider FCC at CERN is planned to operate in one of its modes as an electron-positron FCC-ee machine. We give an overview of the theoretical status compared to the experimental demands of one of four foreseen FCC-ee operating stages, which is Z-boson resonance energy physics, FCC-ee Tera-Z stage for short. The FCC-ee Tera-Z will deliver the highest integrated luminosities as well as very small systematic errors for a study the Standard Model (SM) with unprecedented precision. In fact, the FCC-ee Tera-Z will allow to study at least one more quantum field theoretical perturbative order compared to the LEP/SLC precision. The real problem is that the present precision of theoretical calculations of the various observables within the SM does not match that of the anticipated experimental measurements. The bottle-neck problems are specified. In particular, the issues of precise QED unfolding and of the correct calculation of SM pseudo-observables are critically reviewed. In an Executive Summary we specify which basic theoretical calculations are needed to meet the strong experimental expectations at the FCC-ee Tera-Z. Several methods, techniques and tools needed for higher order multi-loop calculations are presented. By inspection of the Z-boson partial and total decay widths analysis, arguments are given that at the beginning of operation of the FCC-ee Tera-Z, the theory predictions may be tuned to be precise enough not to limit the physics interpretation of the measurements. This statement is based on the anticipated progress in analytical and numerical calculations of multi-loop and multi-scale Feynman integrals and on the completion of two-loop electroweak radiative corrections to the SM pseudo-observables this year. However, the above statement is conditional as the theoretical issues demand a very dedicated and focused investment by the community.

Note: 243 pages, Report on the 1st Mini workshop: Precision EW and QCD calculations for the FCC studies:

Here we are with Tera-Z physics:

	$\delta\Gamma_Z$ [MeV]	δR_l [10^{-4}]	δR_b [10^{-5}]	$\delta \sin^{2,l}_{eff}\theta$ [10^{-6}]
Present EWPO uncertainties				
EXP-2018	2.3	250	66	160
TH-2018	0.4	60	10	45
EWPO uncertainties when FCC-ee will start				
EXP-FCC-ee	0.1	10	$2 \div 6$	6
TH-FCC-ee	0.07	7	3	7

Electroweak 3-loop and the dominant 4-loop EW-QCD corrections will be needed at the start of FCC-ee: $\mathcal{O}(\alpha\alpha_s^2), \mathcal{O}(N_f\alpha^2\alpha_s), \mathcal{O}(N_f^2\alpha^3)$

For more details, see Executive Summary and Chapter 2 in arXiv:1809.01830

Now, we go also to issues beyond FCC-ee Tera-Z

At this workshop we will focus on:

1. FCC-ee-W. Experimental direct values, present $\rightarrow$ FCC-ee (CDR):

$$M_W = 80358 \pm 15(12)[\mathrm{MeV}]\ (\mathrm{LEP2, Tevatron, global})$$

$$\boxed{\text{FCC-ee: } \delta M_W \sim 0.5[\mathrm{MeV}]}$$

Theoretical, present (CDR):

$$M_W = 80358 \pm 8\ [\mathrm{MeV}] \quad (4_{\mathrm{theory}}, \text{plus } 4_{\mathrm{param.}} \text{ from top, Z, H, } \alpha_{\mathrm{s}}, \alpha_{\mathrm{em}})$$

WW threshold $e^+e^- \rightarrow W^+W^-$ ($\rightarrow 4f$).
E.g. Complete two-loop EW needed?

FCC-ee-W, Physics at LEP2, Yellow report CERN/96-01, February 1996

https://arxiv.org/abs/hep-ph/0005309

High Energy Physics - Phenomenology

Four-Fermion Production in Electron-Positron Collisions

Martin W. Gruenewald, Giampiero Passarino, E. Accomando, A. Ballestrero, P. Bambade, D. Bardin, W. Beenakker, F. Berends, E. Boos, A. Chapovsky, A. Denner, S. Dittmaier, M. Dubinin, J. B. Hansen, V. Ilyin, S. Jadach, Y. Kurihara, M. Kuroda, E. Maina, G. Montagna, M. Moretti, O. Nicrosini, A. Olshevsky, M. Osmo, A. Pallavicini, C. G. Papadopoulos, H. T. Phillips, F. Piccinini, R. Pittau, W. Placzek, T. Riemann, M. Roth, A. S. Schmidt-Kaerst, Y. Shimizu, M. Skrzypek, R. Tanaka, M. Verzocchi, D. Wackeroth, B. F. L. Ward, Z. Was

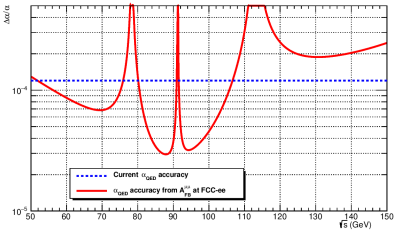
(Submitted on 30 May 2000)

This report summarises the results of the four-fermion working group of the LEP2-MC workshop, held at CERN from 1999 to 2000. Recent developments in the calculation of four-fermion processes in electron-positron collisions at LEP-2 centre-of-mass energies are presented, concentrating on predictions for four main reactions: W-pair production, visible photons in four-fermion events, single-W production and Z-pair production. Based on a comparison of results derived within different approaches, theoretical uncertainties on these predictions are established.

Comments: 150 pages, 73 figures, 45 tables
Subjects: **High Energy Physics - Phenomenology (hep-ph)**
Cite as: **arXiv:hep-ph/0005309**

FCC-ee-H, FCC-ee-t

1. FCC-ee-H. $\delta m_H \sim 20$ MeV. Talks on SM Higgs physics, decays, couplings.
2. FCC-ee-t. $\delta m_t \sim 50$ MeV (LHC: 500 MeV). **Needed higher order effects, resummations,...**
3. $\alpha_{QED}(M_Z^2)$ - $A_{FB}^{\mu\mu}$ at FCC-ee (P. Janot), **higher order EW corrections to FB asymmetry needed.**



The best accuracy is obtained for one year of running either just below or just above the Z pole, at 87.9 and 94.3 GeV, respectively.

4. $\alpha_{QCD}(m_Z^2)$ - e.g. Z,W,τ hadronic decays at FCC-ee. **What about theory precision?**

One theory session will be devoted to methods and tools

"New directions in science are launched by new tools much more often than by new concepts."

Freeman Dyson.

Multi-loop methods and tools in general are not universal and especially new ideas and tools should be explored, to be finally used in practical calculations.

Looking forward for talks on analytical and numerical methods and software.

Plus one **plenary** session on MC generators

This is a difficult issue as generators constitute a connection between theory and experiment.

- W-physics
- tau physics,
- luminosity.

Finally, several talks on beyond SM

"The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson.

We need to explore and understand many, many things around.

Talks:

- SMEFT approach.
- Neutrinos,
- DM, axions.

Good motivation for being here (by one of participated students)

"I am interested in FCC because, I am totally involved myself to the Quantum Physics, and understand that physics beyond the Standard Model is exactly what I want to study."

"As for me, FCC - is that project which will be run by the time when I will be a mature scientist. And before that moment I want to develop myself and help develop this project."

"This workshop will help me to understand the project deeper: at what stage is it located now and what contribution can I make to the FCC in the future."

Some final thoughts.

- FCC-ee is a very ambitious experimental project and needs strong focus on theory side, and a lot of ingenious and hard work.
- We are just at the beginning.
- Looking forward for talks, discussions during this workshop and summary sessions on Friday.