Physics at future electron-positron Z boson factories

Andrej Arbuzov

JINR, Dubna

Workshop on Physics at Future High-Energy e^+e^- Colliders

5th June 2025

Outline

1. Motivation

2. e^+e^- colliders

General motivation

- The Standard Model is the most successful physical model ever
- But there are still many open questions to it
- We believe that it is only an effective theory, but its applicability domain might be limited just by the Planck mass scale
- The primary goal of HEP is to study the physics of our actual microworld
- Discovering physics beyond SM is our hope
- In any case, the research in HEP will not stop by the end of LHC
- Logically, the next step should be a e^+e^- collider

Future e^+e^- collider projects

Linear Colliders

- ILC, CLIC

not to be built in Japan (?)

E_{tot}

- ILC: 91; 250 GeV — 1 TeV
- CLIC: 500 GeV — 3 TeV

$\mathcal{L} \approx 2 \cdot 10^{34}$ cm^{-2}s^{-1}

Stat. uncertainty $\sim 10^{-4}$

Beam polarization:
e^-beam: $P = 80 - 90\%$
e^+beam: $P = 30 - 60\%$

Circular Colliders

- FCC-ee, CEPC
- Z-factory (ZUNK, LEP3, LEP-Z)
- Super Charm-Tau Factory
- $\mu^+\mu^-$ collider

E_{tot}

- 91; 160; 240; 350 GeV

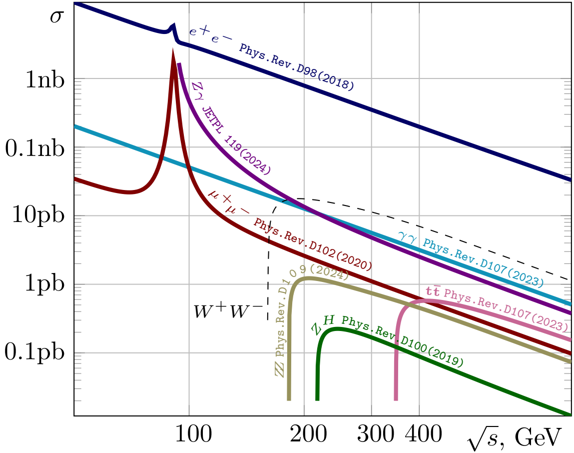
$\mathcal{L} \approx 2 \cdot 10^{36}$ cm^{-2}s^{-1} (4 exp.)

Stat. uncertainty $\sim 10^{-6}$

Tera-Z mode!

Beam polarization: desirable

Basic processes of SM for e^+e^- annihilation

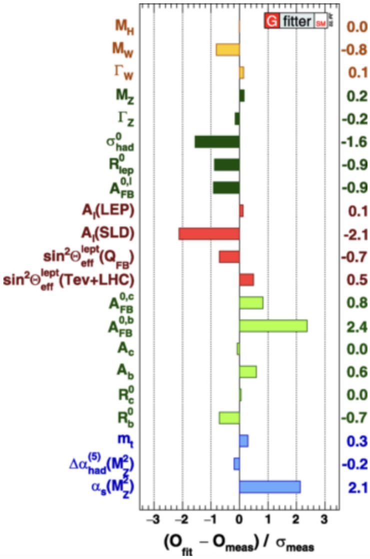


The cross sections are given for polar angles between $10^\circ < \theta < 170^\circ$ in the final state.

Physics possibilities at the Z peak

- Indeep verification of the EW sector of the SM
- Unique possibilities for QCD at the EW scale
- Searches for new physics of SMEFT and other types
- Photon-photon physics
- Properties of tau lepton
- Physics of (exotic) mesons
- N.B. Effective B-factory and Charm-tau factory

Where are we now with the SM



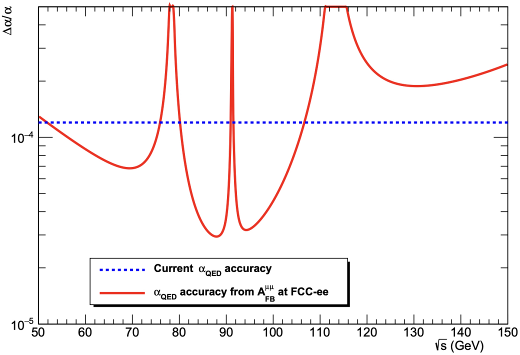
Weak mixing angle

An experimental precision better than 5×10^{-6} is therefore a robust target for the measurement of $\sin^2 \theta_W^{\text{eff}}$ at FCC-ee, corresponding to more than a thirty-fold improvement with respect to the current precision of 1.6×10^{-4}.

Individual measurements of leptonic and heavy quark couplings are achievable, with a factor of several hundred improvement on statistical errors and, with the help of detectors providing better particle identification and vertexing, by up to two orders of magnitude on systematic uncertainties.

[FCC Coll. EPJC'2019]

$\alpha_{QED}(m_Z^2)$



An experimental relative accuracy of 3×10^{-5} on $\alpha_{QED}(m_Z^2)$ can be achieved at FCC-ee, from the measurement of the muon forward-backward asymmetry at energies ~ 3 GeV below and ~ 3 GeV above the Z pole. The corresponding parametric uncertainties on other SM parameters and observables will be reduced. [FCC Coll. EPJC'2019]

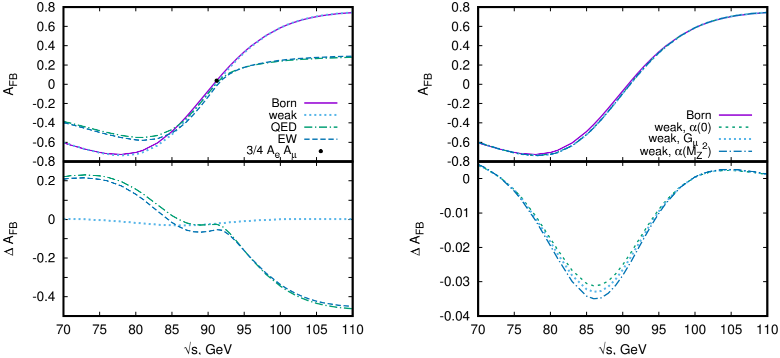
Z boson mass and width; R_l

Overall experimental uncertainties of 0.1 MeV or better are achievable for the Z mass and width measurements at FCC-ee. The corresponding parametric uncertainties on $\sin^2\theta_W^{\rm eff}$ and m_W SM predictions are accordingly reduced to 6×10^{-7} and 0.12 MeV, respectively.

An absolute (relative) uncertainty of 0.001 (5×10^{-5}) on the ratio of the Z hadronic-to-leptonic partial widths (R_l) can be reached. The same relative uncertainty is expected for the ratios of the Z leptonic widths, which allows a stringent test of lepton universality.

[FCC Coll. EPJC'2019]

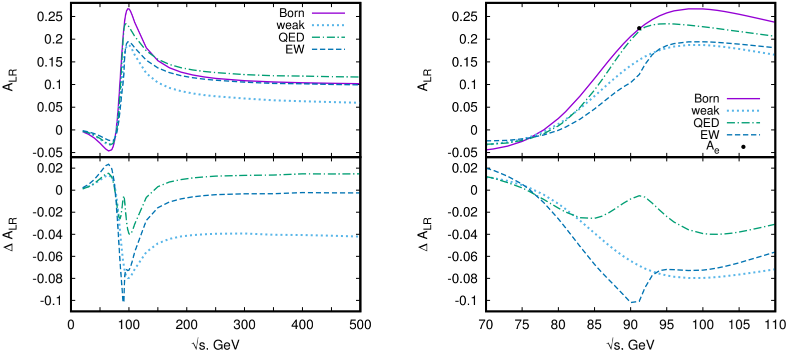
Forward-Backward Asymmetry



$$A_f = \frac{2 g_V g_A}{g_V^2 + g_A^2} \qquad \text{for the given fermion } f$$

[A.A., S.Bondarenko, L.Kalinovskaya, Symmetry'2020]

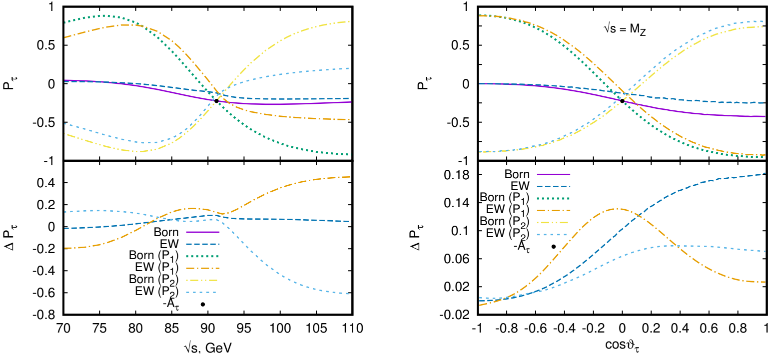
Left-Right Asymmetry



$$A_{LR} = \frac{1}{P_{\rm eff}} \frac{\sigma(-P_{\rm eff}) - \sigma(P_{\rm eff})}{\sigma(-P_{\rm eff}) + \sigma(P_{\rm eff})}, \qquad P_{\rm eff} \equiv \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-} P_{e^+}}$$

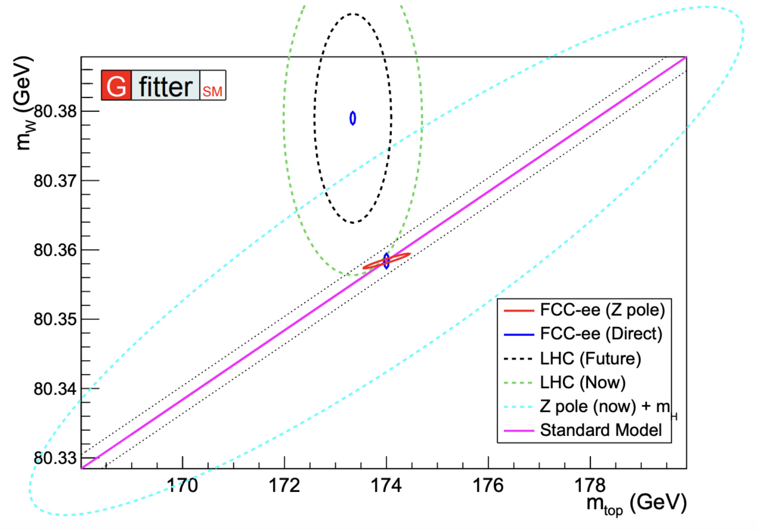
[A.A., S.Bondarenko, L.Kalinovskaya, Symmetry'2020]

Tau lepton polarization



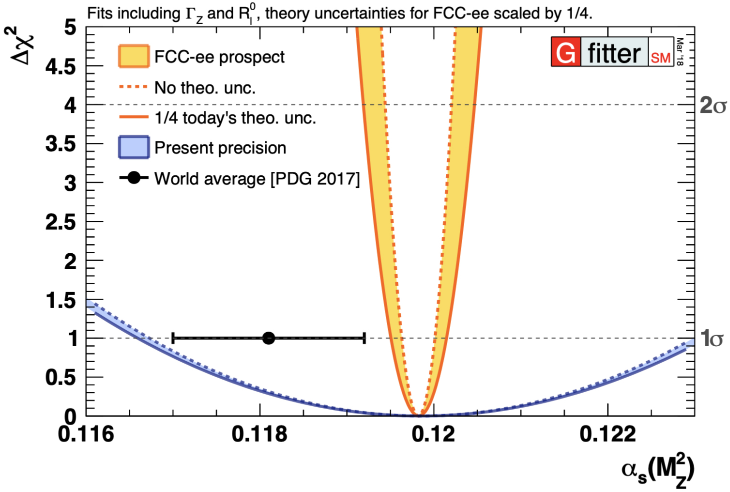
[A.A., S.Bondarenko, L.Kalinovskaya, Symmetry'2020]

Indirect measurements



[FCC Coll. EPJC'2019]

Alpha QCD



[FCC Coll. EPJC'2019]

EW quasi observables (I)

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)	Source and dominant experimental error
$\mathrm{m_Z}$ (keV/c^2)	91 186 700	±	2200	5	100	Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 200	±	2300	8	100	Z line shape scan Beam energy calibration
$\mathrm{R}_\ell^\mathrm{Z}$ ($\times 10^3$)	20 767	±	25	0.06	1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(\mathrm{m_Z})$ ($\times 10^4$)	1196	±	30	0.1	1.6	$\mathrm{R}_\ell^\mathrm{Z}$ above
$\mathrm{R_b}$ ($\times 10^6$)	216 290	±	660	0.3	<60	Ratio of $\mathrm{b\bar{b}}$ to hadrons Stat. extrapol. from SLD [7]
σ^0_had ($\times 10^3$) (nb)	41 541	±	37	0.1	4	Peak hadronic cross-section Luminosity measurement
N_ν($\times 10^3$)	2991	±	7	0.005	1	Z peak cross-sections Luminosity measurement
$\sin^2\theta_\mathrm{W}^\mathrm{eff}$($\times 10^6$)	231 480	±	160	3	2–5	$\mathrm{A_{FB}^{\mu\mu}}$ at Z peak Beam energy calibration
$1/\alpha_\mathrm{QED}(\mathrm{m_Z})$($\times 10^3$)	128 952	±	14	4	Small	$\mathrm{A_{FB}^{\mu\mu}}$ off peak
$\mathrm{A_{FB}^{b,0}}$ ($\times 10^4$)	992	±	16	0.02	<1	b quark asymmetry at Z pole Jet charge

[A.Blondel et al., CERN YR 2019]

EW quasi observables (II)

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)	Source and dominant experimental error
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498	±	49	0.15	<2	τ polar. and charge asymm. τ decay physics
m_W (keV/c^2)	803 500	±	15 000	600	300	WW threshold scan Beam energy calibration
Γ_W (keV)	208 500	±	42 000	1500	300	WW threshold scan Beam energy calibration
$\alpha_s(m_W)(\times 10^4)$	1170	±	420	3	Small	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)	172 740	±	500	20	Small	$t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410	±	190	40	Small	$t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	$m = 1.2$	±	0.3	0.08	Small	$t\bar{t}$ threshold scan QCD errors dominate
$t\bar{t}Z$ couplings		±	30%	<2%	Small	$E_{CM} = 365$ GeV run

[A.Blondel et al., CERN YR 2019]

SMEFT

Possible deviations from SM predictions in differential and inclusive observables to be fit within SMEFT extension of the SM by 6 dim. operators

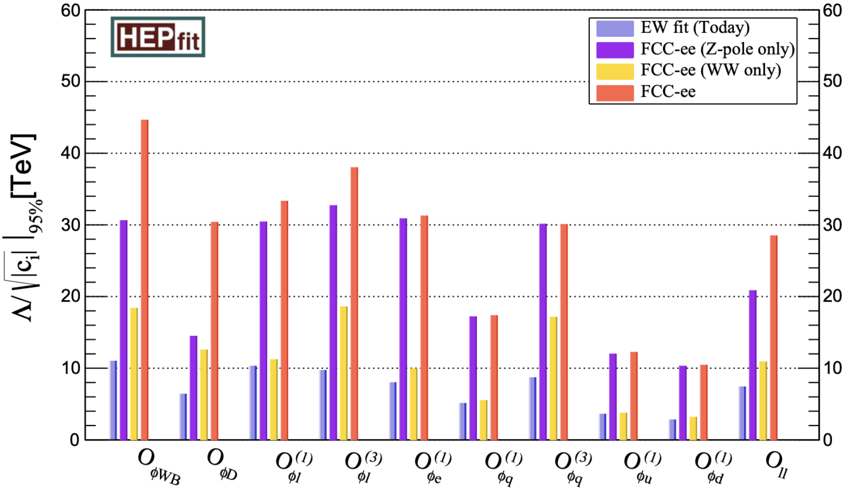
Remind three oblique Peskin–Takeuchi parameters used at LEP.
At a Z-factory one can (should) do a much more detailed study

Scenarios of specific new physics models can be also verified, e.g. with long-lived particles

N.B. Having polarized beams would help a lot

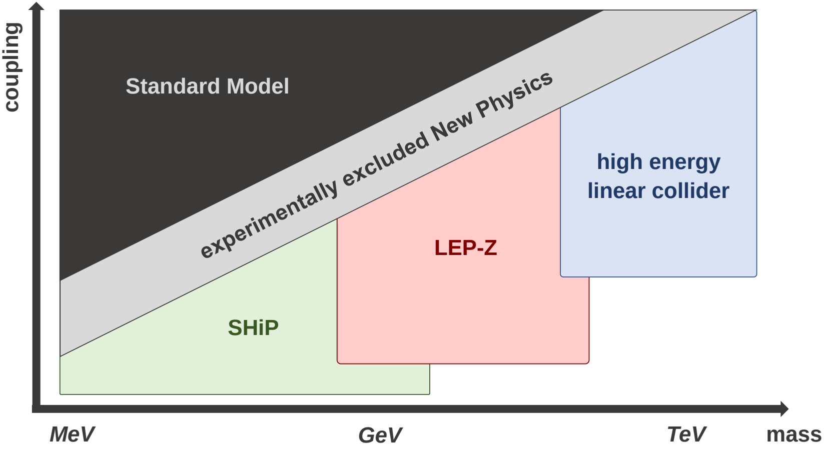
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SME}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{C_j^{(6)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots$$

Sensitivity to new physics scale



[FCC Coll. EPJC'2019]

Direct searches of new particles



[M. Drewes, E. Shaposhnikova and M. Shaposhnikov, “A Possible Future Use of the LHC Tunnel,” arXiv:2503.17081]

To-do list for theory

- Develop physical program on SM verification and new physics searches
- Compute 2-loop QED and EW + higher-order QCD radiative corrections to differential distributions of key processes: Bhabha scattering, $e^+e^- \to \mu^+\mu^-$; $\tau^+\tau^-$; $t\bar{t}$; $\gamma\gamma$; ZH etc.
- Estimate higher-order contributions within some approximations
- Account for interplay with QCD and electroweak effects
- Construct reliable Monte Carlo codes

Outlook

- A new high-energy e^+e^- collider is well motivated by the necessity to study SM in more detail and new physics searches
- A new Z-factory provides unique possibilities for progress in HEP
- Complementarity to hadron-hadron, lepton-hadron machines and to fixed target experiments is essential
- New theoretical calculations of higher-order corrections in SM are required
- Chains of interfaced Monte Carlo codes to be developed
- The work is started, but there are still many tasks

Thank you for attention!