High precision tests of the Standard Model at future e+e- colliders

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Outline

1. Motivation
2. e^+e^- colliders
3. What do we have?
4. What do we need?
5. Outlook

Motivation

- We don't have clear hints for new physics energy scales
- To be honest, most likely no any new physics will be found at the LHC
- But we do need a new collider to scrutinize the SM
- That should be a e^+e^- machine
- Having high-precision theoretical description of SM processes is of crucial importance
- It is time to develop the physical program for future high-energy e^+e^- colliders

Questions

QUESTIONS:

- What do we have?
- What do we need?
- What to do?
- How to do?

Future e^+e^- collider projects

Linear Colliders

- ILC, CLIC
- ILC: technology is ready, might not 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 $\sim 10^{-3}$

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

Circular Colliders

- FCC-ee, TLEP
- CEPC
- $\mu^+\mu^-$ collider (?)

E_{tot}

- 91; 160; 240; 350 GeV

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

Stat. uncertainty $< 10^{-3}$

e^- beam polarization is desirable

SUPER CHARM-TAU FACTORY PROJECTS

Budker Institute of Nuclear Physics in Novosibirsk (Sarov) and/or China

Colliding electron-positron beams with c.m.s. energies from 2 to 8 GeV with unprecedented high luminosity $10^{35} cm^{-2} c^{-1}$

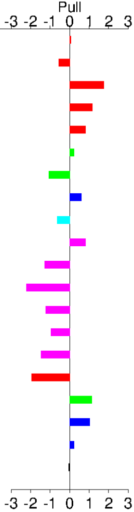
The electron beam will be longitudinally polarized

The main goal of experiments at the Super Charm-Tau factory is to study the processes charmed mesons and tau leptons, using a data set that is 2 orders of magnitude more than the one collected by BESIII

LEP RESULTS

Stanford 1999

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.20
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05



Calculations and computer codes

- 1.5–loop (+) in QED and EW
- NNLO (+) in QCD
- mixed $\alpha\alpha_s$ corrections
- a progress in methods of perturbative (and non-perturbative) calculations
- semi-analytic codes: ZFITTER, DIZET, TOPAZ0, Gfitter, …
- Monte Carlo event generators: KKMC, BHLUMI, ReneSANCe, …

But that is not enough for FCC-ee

FORWARD–BACKWARD ASYMMETRY A_{FB} (I)

The forward–backward asymmetry is

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

$$\sigma_{\mathrm{F}} = \int\limits_0^1 \frac{d\sigma}{d\cos\vartheta_f} d\cos\vartheta_f, \qquad \sigma_{\mathrm{B}} = \int\limits_{-1}^0 \frac{d\sigma}{d\cos\vartheta_f} d\cos\vartheta_f$$

ϑ_f is the angle between momenta of incoming e^- and outgoing f^-.

For high-precision test the most convenient channels are $f = e, \mu$.

Cases $f = \tau,\ b,\ c$ are also very interesting. Remind A_{FB}^b at LEP.

$$A_{\mathrm{FB}} \approx \frac{3}{4} A_e A_f, \qquad A_f \equiv 2\frac{g_{V_f} g_{A_f}}{g_{V_f}^2 + g_{A_f}^2}$$

Forward–Backward Asymmetry A_{FB} (II)

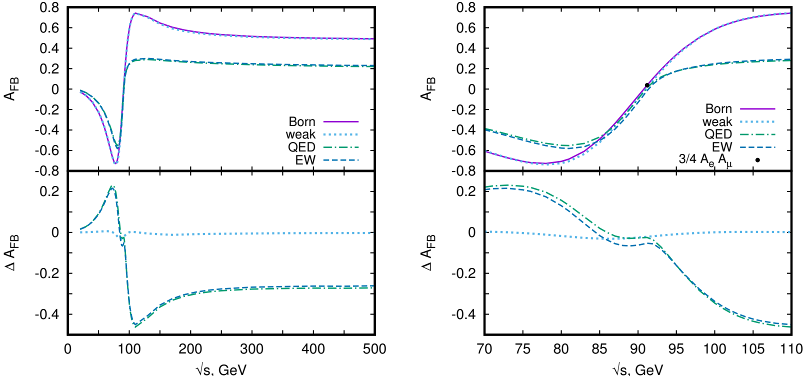


Figure: (**Left**) The A_{FB} asymmetry in the Born and 1-loop (weak, QED, EW) approximations and the corresponding shifts ΔA_{FB} for a wide c.m.s. energy range; (**Right**) the same for the Z peak region.

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

Electroweak schemes

1. $\alpha(0)$ scheme: fine-structure constant $\alpha(0)$ is used as input. Running of α gives a large correction
2. $\alpha(M_Z^2)$ scheme: effective electromagnetic constant $\alpha(M_Z^2)$ is used at Born level while virtual 1-loop and real photon bremsstrahlung contributions are proportional to $\alpha^2(M_Z^2)\alpha(0)$
3. G_μ scheme: the Fermi coupling constant G_μ is used at the Born level while the virtual 1-loop and real photon bremsstrahlung contributions are proportional to $G_\mu^2\alpha(0)$

FORWARD–BACKWARD ASYMMETRY A_{FB} (III)

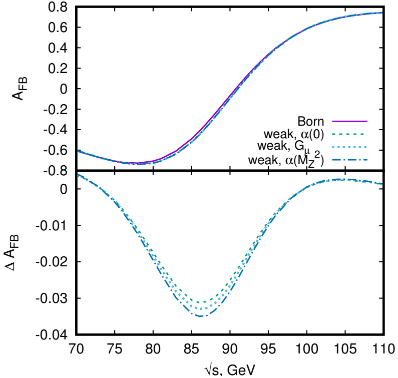


Figure: The A_{FB} asymmetry and ΔA_{FB} in the Born and complete 1-loop EW approximations within the $\alpha(0)$, G_μ, and $\alpha(M_Z^2)$ EW schemes vs. the c.m.s energy.

NOTES ON A_{FB}

- Pure weak contributions are rather small at all energies
- But they are numerically relevant at the peak region because of high statistics there. EW scheme dependence is relevant
- $A_{\rm FB}$ is strongly dependent on polarization degrees
- Pure QED corrections to $A_{\rm FB}$ in higher orders are known with high precision [S.Jadach, S.Yost, PRD 2019], [J.Blumlein, A.De Freitas, K.Schönwald, PLB 2021]
- There is an interesting idea [P.Janot, JHEP 2016] to use the $A_{\rm FB}$ asymmetry to get $\alpha(M_Z)$
- One-loop corrections to $A_{\rm FB}$ contain contributions proportional to m_f^1 which are relevant, e.g., for b quarks

FCC PHYSICS OPPORTUNITIES

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
M_Z (keV/c^2)	91186700 ± 2200	5	100
Γ_Z (keV)	2495200 ± 2300	8	100
$\alpha_s(M_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.45-1.6
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	231480 ± 160	3	2–5
N_ν ($\times 10^3$)	2920 ± 50	0.8	small
A_{FB}^b ($\times 10^4$)	992 ± 16	0.02	1–3
m_t (MeV/c^2)	172740 ± 500	20	small
Γ_t (MeV/c^2)	1410 ± 190	40	small
$\lambda_t/\lambda_t^{\text{SM}}$	1.2 ± 0.3	0.08	small

The Higgs self-coupling with an error of 32%

[A.Abada,. . . , A.A. et al. EPJC '2019]

PRECISION ESTIMATES

Now:

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2\theta^l_{eff}[10^{-5}]$	4.5	16
Γ_Z [MeV]	0.5	2.3
$R_b[10^{-5}]$	15	66

Quantity	ILC	FCC-ee	CEPC	Projected theory error
M_W [MeV]	3–4	1	3	1
$\sin^2\theta^l_{eff}[10^{-5}]$	1	0.6	2.3	1.5
Γ_Z [MeV]	0.8	0.1	0.5	0.2
$R_b[10^{-5}]$	14	6	17	5–10

The estimated error for the theoretical predictions of these quantities is given, under the assumption that $O(\alpha\alpha_s^2)$, fermionic $O(\alpha^2\alpha_s)$, fermionic $O(\alpha^3)$, and leading four-loop corrections entering through the ρ-parameter will become available.

OUTLOOK

- Studies of the SM physics are of ultimate importance regardless any new physics searches
- A circular e^+e^- collider should be built
- Adequately accurate theoretical predictions within the SM should be constructed
- Independent calculations and their comparisons are necessary
- Working groups are (self)organized
- Both Monte Carlo and semi-analytic codes are required
- Treatment of higher order EW effects should be improved see, e.g., [I.Dubovyk et al., JHEP 2019]
- We need 2-loop EW form factors