Asymmetries in Processes of Electron-Positron Annihilation

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Outline

MOTIVATION

Motivation:

- Development of the physical program for future high-energy e^+e^- colliders
- Having high-precision theoretical description of SM processes is of crucial importance
- Many of the future e^+e^- colliders foresee running with polarized beam(s)

QUESTIONS:

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

FUTURE e^+e^- COLLIDER PROJECTS

Linear Colliders

- ILC, CLIC
- ILC: technology is ready, might 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
- muon collider (?)

E_{tot}

- 91; 160; 240; 350 GeV

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

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

Beam polarization: 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

ASYMMETRIES

Asymmetries provide unique tests of SM predictions. They are sensitive to:

- Electroweak parameters and couplings including $\sin^2\vartheta_W$;
- C (and CP) parity violating effects;
- many kinds of new physics

Asymmetries are usually constructed as ratios of observed quantities, in which the bulk of experimental and theoretical systematic uncertainties is canceled out

PRELIMINARIES

Let's introduce some notation. For polarized beams

$$\begin{aligned}\sigma(P_{e^-},P_{e^+}) &= (1+P_{e^-})(1+P_{e^+})\sigma_{RR} + (1-P_{e^-})(1+P_{e^+})\sigma_{LR} \\ &+ (1+P_{e^-})(1-P_{e^+})\sigma_{RL} + (1-P_{e^-})(1-P_{e^+})\sigma_{LL}\end{aligned}$$

Effective polarization reads

$$P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-}P_{e^+}}$$

Useful combination A_f ($f = e, \mu, \tau$) of EW couplings

$$A_f \equiv 2\frac{g_{V_f} g_{A_f}}{g_{V_f}^2 + g_{A_f}^2}$$

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 $G_\mu^2\alpha(0)$

LEFT-RIGHT ASYMMETRY A_{LR} (I)

The polarized annihilation cross section (for $m_e \to 0$)

$$\sigma(P_{e^-}, P_{e^+}) = (1 - P_{e^-} P_{e^+})[1 - P_{\text{eff}} A_{\text{LR}}]\sigma_0$$

In the general case with partial polarizations

$$A_{\text{LR}} = \frac{1}{P_{\text{eff}}} \frac{\sigma(-P_{\text{eff}}) - \sigma(P_{\text{eff}})}{\sigma(-P_{\text{eff}}) + \sigma(P_{\text{eff}})}$$

For fully polarized initial particles ($|P_{e^\pm}| = 1$)

$$A_{\text{LR}} = \frac{\sigma_{L_e} - \sigma_{R_e}}{\sigma_{L_e} + \sigma_{R_e}}$$

At the Born level $A_{\text{LR}} \approx A_e$

LEFT-RIGHT ASYMMETRY A_{LR} (II)

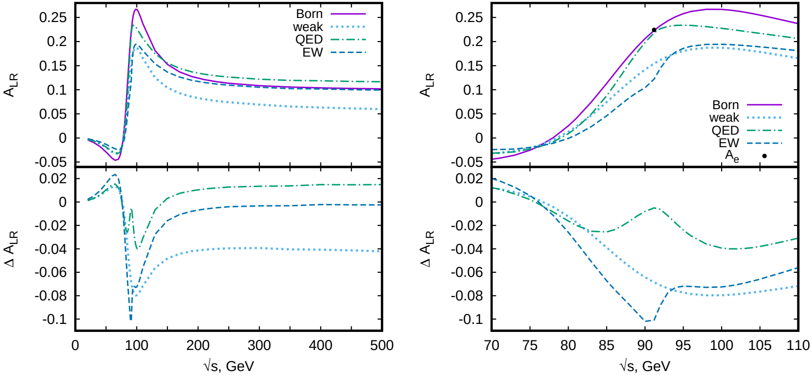


Figure: (**Left**) The A_{LR} asymmetry in the Born and 1-loop (weak, pure quantum electrodynamics (QED), and electroweak (EW)) approximations and ΔA_{LR} vs. center-of-mass system (c.m.s.) energy in a wide range; (**Right**) the same for the Z peak region.

LEFT-RIGHT ASYMMETRY A_{LR} (III)

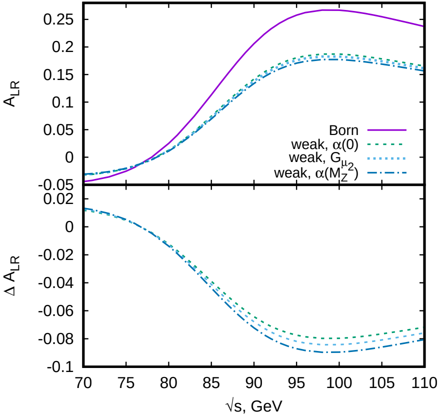


Figure: The A_{LR} asymmetry at the Born level and with 1-loop weak radiative corrections (RCs); the corresponding shifts ΔA_{LR} within $\alpha(0)$, G_μ, and $\alpha(M_Z^2)$ EW schemes vs. c.m.s. energy in the peak region.

NOTES ON A_{LR}

- A_{LR} is almost insensitive to the details of particle detection since they tend to cancel out in the ratio
- A_{LR} (almost) does not depend on the final state fermion couplings in the vicinity of the Z boson peak and can be measured for any final state with large statistics
- So, A_{LR} is good for extraction of $\sin^2\vartheta_W^{\mathrm{eff}}$
- At large energies QED and weak corrections ΔA_{LR} are large
- At the Z peak pure QED corrections are small but the weak ones are large

FORWARD–BACKWARD ASYMMETRY A_{FB} (I)

The forward–backward asymmetry is

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

$$\sigma_{\rm F} = \int_0^1 \frac{d\sigma}{d\cos\vartheta_f} d\cos\vartheta_f, \qquad \sigma_{\rm B} = \int_{-1}^0 \frac{d\sigma}{d\cos\vartheta_f} d\cos\vartheta_f$$

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 $A^b_{\rm FB}$ at LEP.

$$A_{\rm FB} \approx \frac{3}{4} A_e A_f$$

FORWARD–BACKWARD ASYMMETRY A_{FB} (II)

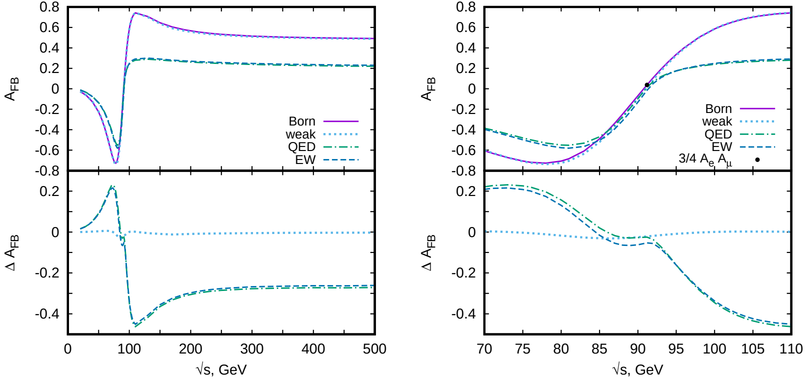


Figure: (**Left**) The A_{FB} asymmetry in the Born and 1-loop (weak, QED, EW) approximations and the corresponding shifts ΔA_{FB} for a wide c.m.s. energy range; (**Right**) the same for the Z peak region.

FORWARD–BACKWARD ASYMMETRY A_{FB} (III)

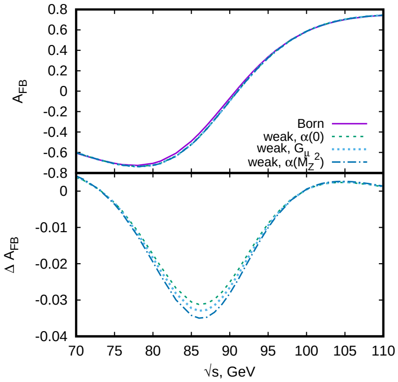


Figure: The $A_{\rm FB}$ asymmetry and $\Delta A_{\rm FB}$ in the Born and complete 1-loop EW approximations within the $\alpha(0)$, G_μ, and $\alpha(M_Z^2)$ EW schemes vs. the c.m.s energy.

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 also small but visible
- A_{FB} is strongly dependent on polarization degrees
- Pure QED corrections to A_{FB} in higher orders are known with high precision [S.Jadach, S.Yost, PRD 2019]
- There is an interesting idea [P.Janot, JHEP 2016] to use the A_{FB} asymmetry to get $\alpha(M_Z)$
- One-loop corrections to A_{FB} contain contributions proportional to m_f^1 which are relevant, e.g., for b quarks

LEFT–RIGHT FB ASYMMETRY A_{LRFB} (I)

To measure the weak couplings of the final state fermions, it was suggested to analyze the so-called left–right forward–backward asymmetry

$$A_{\text{LRFB}} = \frac{(\sigma_{L_e} - \sigma_{R_e})_F - (\sigma_{L_e} - \sigma_{R_e})_B}{(\sigma_{L_e} + \sigma_{R_e})_F + (\sigma_{L_e} + \sigma_{R_e})_B}$$

σ_L and σ_R are the cross sections with left and right handed helicities of the initial electrons.

In the case of unpolarized beams on the Z resonance peak, the Born-level asymmetry is

$$A_{\text{LRFB}} \approx \frac{3}{4} A_f$$

LEFT–RIGHT FB ASYMMETRY $A_{\mathbf{LRFB}}$ (II)

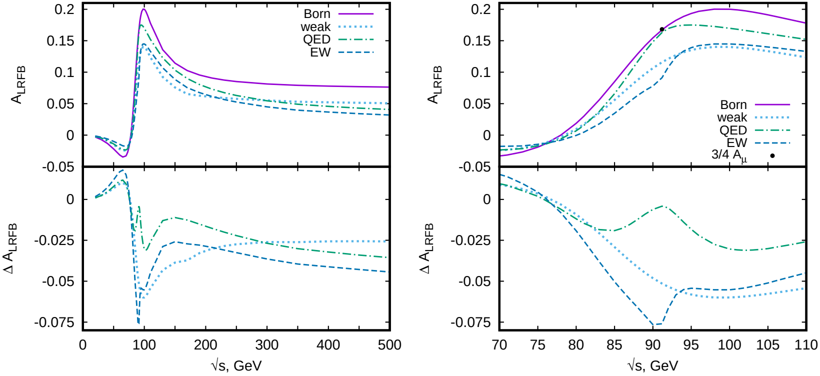


Figure: (**Left**) The A_{LRFB} asymmetry in the Born and 1-loop (weak, QED, EW) approximations and ΔA_{LRFB} for c.m.s. energy range; (**Right**) the same for the Z peak region.

LEFT–RIGHT FB ASYMMETRY A_{LRFB} (III)

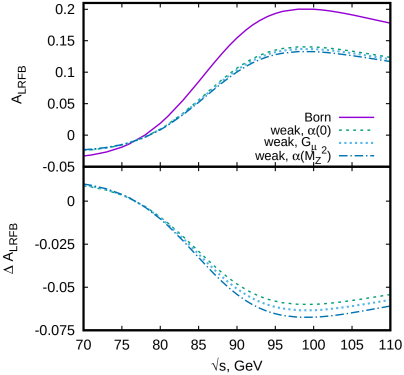


Figure: The A_{LRFB} asymmetry in the Born and 1-loop EW approximations and ΔA_{LRFB} within $\alpha(0)$, G_μ, and $\alpha(M_Z^2)$ EW schemes vs. c.m.s. energy in the Z peak region.

NOTES ON $A_{\mathbf{LRFB}}$

- $A_{\rm LRFB}$ asymmetry is more affected by weak corrections than $A_{\rm LR}$
- Formula $A_{\rm LRFB} \approx \frac{3}{4}A_f$ is very rough
- Shifts $\Delta A_{\rm LRFB}$ only slightly depend on EW scheme choice
- $A_{\rm LRFB}$ at Z boson peak can be used to measure weak couplings of μ and τ and compare with e^-, i.e., to check lepton universality

FINAL-STATE FERMION P_f (I)

The polarization of a final-state fermion $P_{f=\mu,\tau}$ can be found as

$$P_f = \frac{\sigma_{R_f} - \sigma_{L_f}}{\sigma_{R_f} + \sigma_{L_f}}$$

Experimentally it can be measured for the $\tau^+\tau^-$ channel by reconstructing τ polarization from the pion spectrum in the decay $\tau \to \pi\nu$. At LEP programs TAOLA and KORALZ were used for such an analysis

For unpolarized beams near Z peak

$$P_\tau(\cos\vartheta_\tau) \approx -\frac{A_\tau + \dfrac{2\cos\vartheta_\tau}{1+\cos^2\vartheta_\tau}A_e}{1 + \dfrac{2\cos\vartheta_\tau}{1+\cos^2\vartheta_\tau}A_e A_\tau}$$

Both A_τ and A_e can be extracted simultaneously

FINAL-STATE FERMION P_f (II)

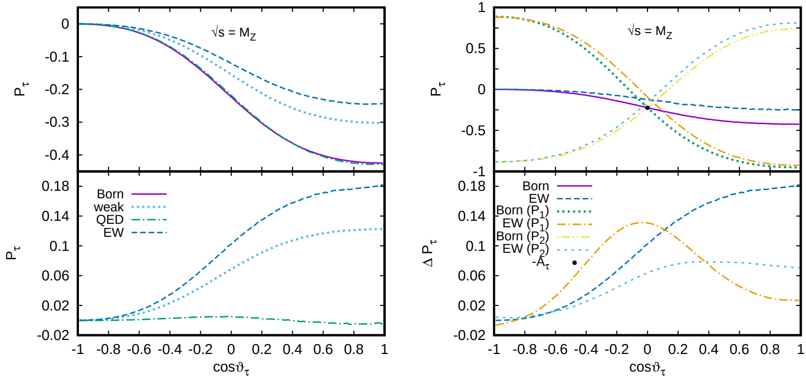
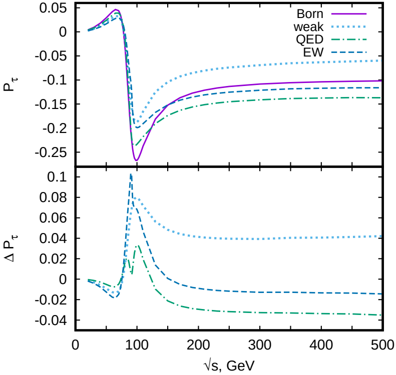


Figure: (**Left**) P_τ polarization in Born and 1-loop (weak, pure QED, and EW) approximations as a function of $\cos\vartheta_\tau$ at $\sqrt{s} = M_Z$. (**Right**) P_τ polarization for unpolarized and polarized cases with $P_1 = (-0.8, 0.3)$ and $P_2 = (0.8, -0.3)$ degrees of initial beam polarizations in Born and EW 1-loop approximations vs. cosine of the final τ lepton angle

FINAL-STATE FERMION P_f (III)



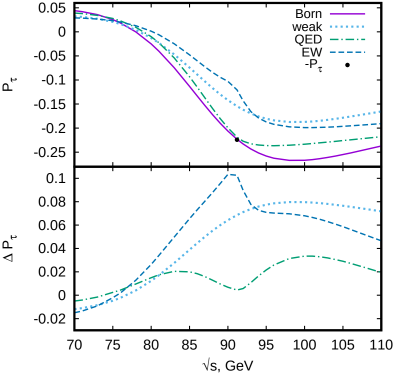


Figure: (**Left**) P_τ polarization in Born and 1-loop (weak, pure QED, and EW) approximations and ΔP_τ vs. c.m.s. energy in a wide range; (**Right**) the same for Z peak region. Black dot indicates the value P_τ at the Z resonance.

Notes on P_f

- The P_τ asymmetry is very sensitive to weak-interaction corrections
- The P_τ asymmetry is very sensitive also to the initial beam polarizations
- Near Z resonance, theoretical uncertainty of P_τ is determined by the interplay of uncertainties of large QED and weak contributions

OUTLOOK

- Asymmetries provide a powerful tool for high-precision tests of the Standard Model and for new physics searches
- Numerical results were obtained with the help of SANC Monte Carlo integrator and generator codes
- Numerical results show an interplay between the weak and QED contributions to asymmetries
- QED corrections including higher orders are in a good shape, but further work is required (higher-order NLO)
- Treatment of higher order EW effects should be improved see, e.g., [I.Dubovyk et al., JHEP 2019]