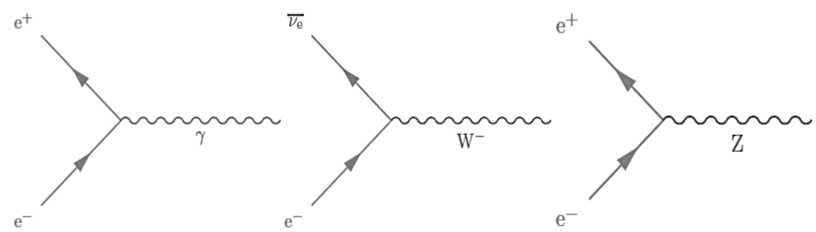
Precision measurements with polarized beams

Sabine Riemann, DESY

JINR Dubna, 23 July 2018 (Bardin's Day)

outline

It is long recognized that beam polarization is an essential feature for probing electroweak interactions



QED: γ Parity conserving
Charged Current: W Maximally parity violating
Neutral Current: Z Parity violating

In this talk:

- Introduction
- Collider projects and beam polarization
- Beam polarization at future e+e- colliders
  - Advantages and challenges
- Summary

A Choice of Dima Bardin's papers devoted explicitly to polarized scattering (without LEP/SLD)

One-loop electroweak radiative corrections to polarized Bhabha scattering

D. Bardin, Ya Dydyshka, L. Kalinovskaya, L. Rumyantsev , A. Arbuzov, R. Sadykov, S. Bondarenko ; Phys.Rev. D98 (2018) no.1, 013001

QED corrections for polarized elastic muon e scattering

Dmitri Yu. Bardin, Lida Kalinovskaya; DESY-97-230, e-Print: hep-ph/9712310

O(alpha) QED corrections to polarized elastic muon e and deep inelastic l N scattering

Dmitri Yu. Bardin, Johannes Blumlein, Penka Christova , Lida Kalinovskaya; Published in *Hamburg 1997, Physics with polarized protons at HERA* 44-53; e-Print: hep-ph/9711228

The Spin dependent structure function g1(x) of the deuteron from polarized deep inelastic muon scattering

Spin Muon (SMC) Collaboration (D. Adams et al.); Phys.Lett. B396 (1997) 338-348

O (alpha) QED corrections to neutral current polarized deep inelastic lepton - nucleon scattering

Dmitri Yu. Bardin Johannes Blumlein, Pena Christova Lida Kalinovskaya; Nucl.Phys. B506 (1997) 295-328

Radiative Corrections to P Odd Asymmetries in Deep Inelastic Scattering of Polarized Muons on Nucleons at TeV Energies

D.Yu. Bardin, O.M. Fedorenko, N.M. Shumeiko; J.Phys. G7 (1981) 1331; JINR-E2-80-503

Radiative Corrections To P Odd Asymmetries In Deep Inelastic Scattering Of Polarized Leptons And Anti-leptons On Nucleons

D.Yu. Bardin, O.M. Fedorenko, N.M. Shumeiko; JINR-E2-12761

On the Radiative Corrections to P Odd Asymmetry in Deep Inelastic Scattering of Polarized Leptons on Nucleons

D.Yu. Bardin, O.M. Fedorenko, N.M. Shumeiko (Dubna, JINR), Sov.J.Nucl.Phys. 32 (1980) 403, Yad.Fiz. 32 (1980) 782-795; JINR-E2-12564

MPI–PAE/PTh 32/90
PHE 90-9
June 1990

Bhabha scattering with higher order weak loop corrections

D. BARDIN

Joint Institute for Nuclear Research, Dubna,
Head Post Office, P.O. Box 79, SU-101000 Moscow, USSR

W. HOLLIK, T. RIEMANN*

Max-Planck-Institut für Physik und Astrophysik
– Werner-Heisenberg-Institut für Physik –
P.O.Box 40 12 12, Munich (Fed. Rep. Germany)

MPI-PAE/PTh 32/90
PHE 90-9
June 1990

Bhabha scattering with higher order weak loop corrections

D. BARDIN

Joint Institute for Nuclear Research, Dubna,
Head Post Office, P.O. Box 79, SU-101000 Moscow, USSR

W. HOLLIK, T. RIEMANN*

Max-Planck-Institut für Physik und Astrophysi
– Werner-Heisenberg-Institut für Physik –
P.O.Box 40 12 12, Munich (Fed. Rep. Germany

2. The lowest order Bhabha cross section

We consider the differential cross section for the Bhabha process with longitudinal polarisations of electrons (λ_-) and positrons (λ_+):

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} \cdot T,$$
$$T = f_0 + (\lambda_+ - \lambda_-) \cdot f_1 + \lambda_+\lambda_- \cdot f_2, \tag{2.1}$$

where the f_k derive from the squared sum of matrix elements $\mathcal{M}_u$ with s- and t-channel exchange of a photon ($n = 0$) or Z-boson ($n = 1$):

$$T \sim \sum_{h_+, h_-} |\mathcal{M}_s + \mathcal{M}_t|^2, \tag{2.2}$$

$$\mathcal{M}_s^0 = \frac{ie^2}{s} \sum_{n=0}^{1} [\bar{v}(\lambda_+) \cdot \Gamma_\mu^n \cdot u(\lambda_-)] \cdot [\bar{u}(h_-) \cdot \Gamma_n^\mu \cdot v(h_+)] \cdot \chi_n(s), \tag{2.3}$$

$$\mathcal{M}_t^0 = -\frac{ie^2}{t} \sum_{n=0}^{1} [\bar{v}(\lambda_+) \cdot \Gamma_\mu^n \cdot v(h_+)] \cdot [\bar{u}(h_-) \cdot \Gamma_n^\mu \cdot u(\lambda_-)] \cdot \chi_n(t). \tag{2.4}$$

Here, $h_\pm$ are the final state helicities, and s, t may be expressed by the beam energy

ZFITTER

An Analytical Program for Fermion Pair Production in e^+e^- Annihilation

Helicities and polarizations may be included in the Standard Model cross sections σ_A in a compact way for massless fermion production [3, 9]. To do this, one must replace the above couplings, $\mathcal{I}_A(m,n;s)$, with[10]

$$
\begin{aligned}
&C_T(m,n;\lambda_1,\lambda_2,h_1,h_2) = \\
&\quad \{\lambda_1[\bar{v}_e(m)\bar{v}_e^*(n)+\bar{a}_e(m)\bar{a}_e^*(n)] \;+\; \lambda_2[\bar{v}_e(m)\bar{a}_e^*(n)+\bar{v}_e^*(n)\bar{a}_e(m)]\} \;\times \\
&\quad \{h_1[\bar{v}_f(m)\bar{v}_f^*(n)+\bar{a}_f(m)\bar{a}_f^*(n)] \;+\; h_2[\bar{v}_f(m)\bar{a}_f^*(n)+\bar{v}_f^*(n)\bar{a}_f(m)]\},
\end{aligned} \tag{3.59}
$$

$$C_{FB}(m,n;\lambda_1,\lambda_2,h_1,h_2) = C_T(m,n;\lambda_2,\lambda_1,h_2,h_1). \tag{3.60}$$

The vector and axial-vector couplings $\bar{v}_f(0)$ and $\bar{a}_f(0)$ of the fermion to the photon are:

$$\bar{v}_f(0) = Q_f\, F_A(s), \qquad \bar{a}_f(0) = 0. \tag{3.61}$$

Here, we introduce the longitudinal polarizations of the electron (λ_-) and positron (λ_+) and the helicities of the final state fermions $h_\pm$ in the following combinations:

$$\lambda_1 = 1-\lambda_+\lambda_-, \qquad \lambda_2 = \lambda_+ - \lambda_-, \tag{3.62}$$

$$h_1 = \frac{1}{4}(1-h_+h_-), \qquad h_2 = \frac{1}{4}(h_+ - h_-). \tag{3.63}$$

Focus on lepton collider projects

Linear collider (e+e-)

- ILC; technology at hand, realization in Japan??
- CLIC

E_{cm}

- 250GeV – 1TeV (ILC)
- 350GeV – 3TeV (CLIC)

$L \approx 2\times10^{34}cm^{-2}s^{-1}$ ($\sim500fb^{-1}$/year)

→ Stat. uncertainty ~ $10^{-3}\ldots10^{-2}$

Beam polarization

e- beam P = 80-90%

e+ beam

ILC: P = 30% baseline;

60% upgrade

CLIC: P ≥ 60% upgrade

Circular collider

- FCC-ee
- CEPC
- μ Collider

E_{cm} (e+e-)

91 GeV, 160GeV, 240GeV, 350GeV

$L \approx 2\times10^{36}cm^{-2}s^{-1}$ (4 experiments)

→ Stat. uncertainty <10^{-3}

Beam polarization

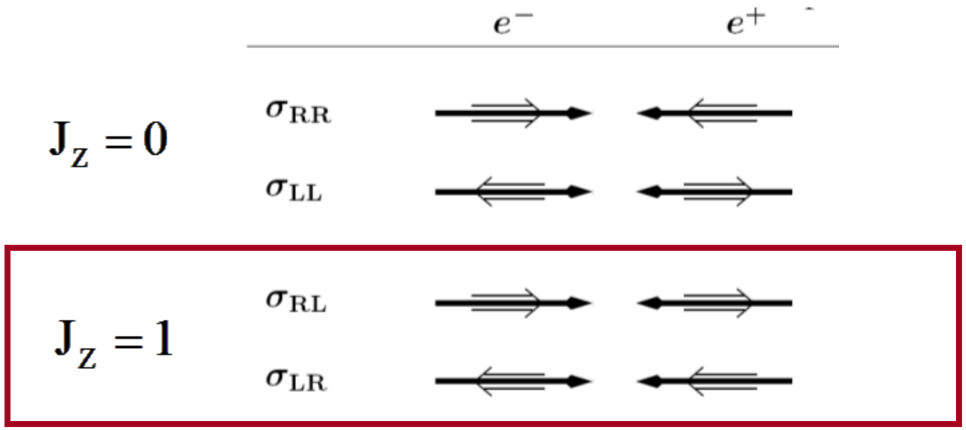
- Desired ??

Measurement in unpolarized colliders

- Circular e+e- colliders (PETRA, TRISTAN, LEP, FCC-ee, CEPC)
  - Measurement with unpolarized beams averages over all spin states:

$$\sigma_U = \frac{1}{4}\{\sigma_{LR} + \sigma_{RL} + \sigma_{LL} + \sigma_{RR}\}$$

The 4 individual contributions cannot be studied



- Only the J_z=1 configuration applies to s-channel γ and Z exchange
  - in case of unpolarized beams only 50% of the collisions are useful

Beam polarization at e+e- colliders (1)

- Longitudinal spin configurations in e+e- collisions:

		e^-	e^+	
$J_Z = 0$	σ_{RR}	$\Rightarrow$	$\Leftarrow$	$\frac{1+P_{e^-}}{2}\frac{1+P_{e^+}}{2}$
	σ_{LL}	$\Leftarrow$	$\Rightarrow$	$\frac{1-P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
$J_Z = 1$	σ_{RL}	$\Rightarrow$	$\Rightarrow$	$\frac{1+P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
	σ_{LR}	$\Leftarrow$	$\Leftarrow$	$\frac{1-P_{e^-}}{2}\frac{1+P_{e^+}}{2}$

P_{e-} = -1:
100% left-polarized e-
P_{e+} = -1:
100% right-polarized e+

- Cross section with polarized beams (≥ measurements: RL, LR, …)

$$\sigma(P_{e^-}, P_{e^+}) = \frac{1}{4}\{(1-P_{e^-})(1+P_{e^+})\sigma_{LR} + (1+P_{e^-})(1-P_{e^+})\sigma_{RL} + (1-P_{e^-})(1-P_{e^+})\sigma_{LL} + (1+P_{e^-})(1+P_{e^+})\sigma_{RR}\}$$

- Polarized e+ <u>and</u> polarized e-
  – Perform measurements of σ_{RL} and of σ_{LR}

$$L_{eff}/L_{unpol} = (1 - P_{e+}P_{e-})$$

→ enhance the effective luminosity

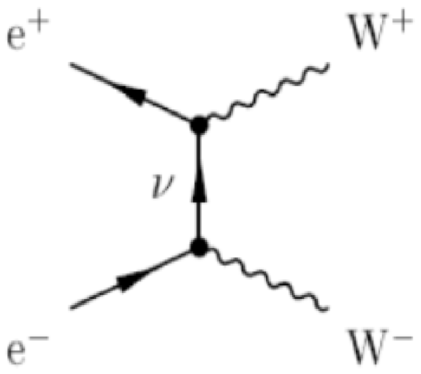
Beam polarization at e+e- colliders (2)

For processes where LR configuration essentially contributes (WW threshold), only 25% of the collisions are useful.

- Polarized e+ and polarized e- enhance the effective luminosity

  $$L'_{eff}/L_{unpol} = (1 - P_{e-})\,(1 + P_{e+})$$

- Use RL configuration to suppress the RL process (WW) and to measure the background



With a clever choice of beam polarization and running scenarios the statistics of the desired processes can be substantially increased

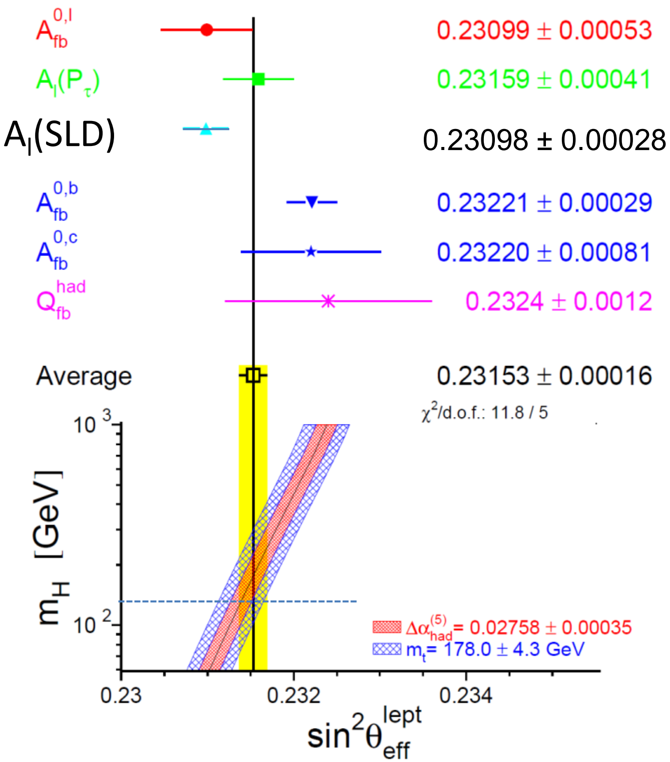
→ reduce the running time (cost saving)
→ Decrease the statistical uncertainty
→ Reduce systematic uncertainty by controlling the background
→ Construct asymmetry variables sensitive SM parameters and/or to physics scenarios beyond SM

Lesson from LEP/SLD: Measurement of $\sin^2\theta_{eff}$

Phys.Rep. 427(2006)257
[hep-ex/0509008]

LEP (circular collider)
- Unpolarized e+, e- beams, 17×10^6 Z events

SLD (linear collider)
- Polarized electron beam, 5×10^5 Z events

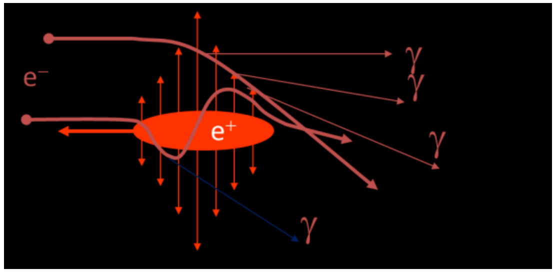


Improved precision with beam polarization

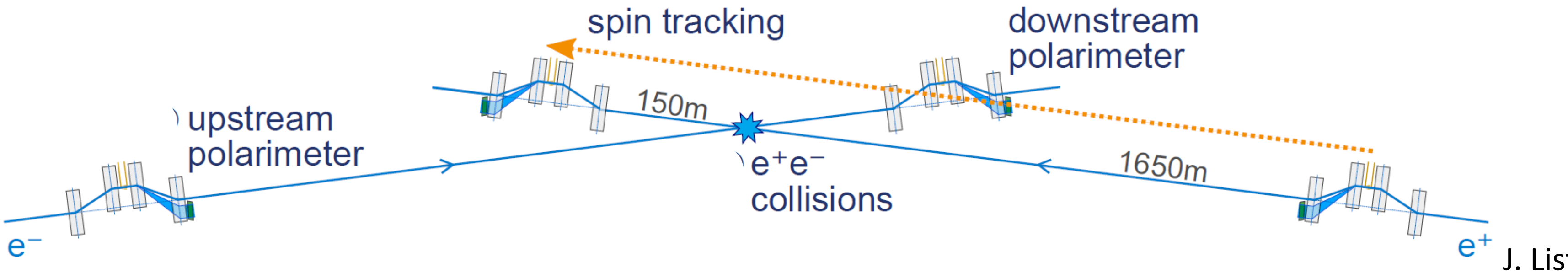
However, precision of beam polarization measurement could limit this advantage: SLD polarimeter: $\delta P = 0.5\%$,
ILC polarimeter: $\delta P \sim 0.25\%$ expected

Polarimetry at future linear e+e- colliders

- Small beam sizes at interaction point:
  - flat beams, at ILC:
    σ_x ~500 nm, σ_y ~ 6nm
  - Beamstrahlung → Some depolarization
  - Beams are disrupted after collision



- Compton polarimeters to measure e+ and e- polarization upstream and downstream the interaction point (IP)
- At ILC, (similar at CLIC):



→ spin tracking to relate the measurements in the polarimeters to the polarization at the IP

- For physics analyses the luminosity weighted polarization is required

Precision polarization measurement

- **Use polarized e- and polarized e+ beam ,**
- Perform 4 independent measurements with different helicity combinations; use also some luminosity for the "inefficient" helicity configurations $\sigma_{\pm\pm}$:

$$\sigma_{\pm\pm} = \frac{1}{4}\sigma_0[1 + P_{e+}P_{e-} + A_{LR}(\pm P_{e+} \pm P_{e-})]$$
$$\sigma_{\mp\pm} = \frac{1}{4}\sigma_0[1 - P_{e+}P_{e-} + A_{LR}(\mp P_{e+} \pm P_{e-})]$$

- determine simultaneously P_{e+} and P_{e-}, and A_{LR} directly measured from collision data

$$A_{LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$$

$$P_{e\pm} = \sqrt{\frac{(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})(-\sigma_{++}\pm\sigma_{-+}\mp\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})\ (+\sigma_{++}\mp\sigma_{-+}\pm\sigma_{+-}-\sigma_{--})}}$$

- the polarimeters are used to monitor the polarization

→ **Precision of $\delta P \sim 10^{-3}$ (and even below) is possible at high energies at ILC or CLIC**

  – Further studies are necessary to include the realistic beam properties and systematic effects (energy spread, uncertainty at helicity reversal, beam disruption,…)

Linear collider: Transverse polarization

- Matrix element for e+e- interaction with arbitrarily oriented polarization vector:

$$
\begin{aligned}
|\mathcal{M}|^2 \;=\; & \frac{1}{4}\Big\{(1-P_{e^-})(1+P_{e^+})|F_{\rm LR}|^2 + (1+P_{e^-})(1-P_{e^+})|F_{\rm RL}|^2 \\
& +(1-P_{e^-})(1-P_{e^+})|F_{\rm LL}|^2 + (1+P_{e^-})(1+P_{e^+})|F_{\rm RR}|^2 \\
& -2P^{\rm T}_{e^-}P^{\rm T}_{e^+}\{[\cos(\phi_- - \phi_+)\,{\rm Re}(F_{\rm RR}F^*_{\rm LL}) + \cos(\phi_- + \phi_+ - 2\phi)\,{\rm Re}(F_{\rm LR}F^*_{\rm RL})] \\
& \qquad + [\sin(\phi_- + \phi_+ - 2\phi)\,{\rm Im}(F_{\rm LR}F^*_{\rm RL}) + \sin(\phi_- - \phi_+)\,{\rm Im}(F^*_{\rm RR}F_{\rm LL})]\} \\
& +2P^{\rm T}_{e^-}\{\cos(\phi_- - \phi)[(1-P_{e^+})\,{\rm Re}(F_{\rm RL}F^*_{\rm LL}) + (1+P_{e^+})\,{\rm Re}(F_{\rm RR}F^*_{\rm LR})] \\
& \qquad - \sin(\phi_- - \phi)[(1-P_{e^+})\,{\rm Im}(F^*_{\rm RL}F_{\rm LL}) - (1+P_{e^+})\,{\rm Im}(F^*_{\rm RR}F_{\rm LR})]\} \\
& -2P^{\rm T}_{e^+}\{\cos(\phi_+ - \phi)[(1-P_{e^-})\,{\rm Re}(F_{\rm LR}F^*_{\rm LL}) + (1+P_{e^-})\,{\rm Re}(F_{\rm RR}F^*_{\rm RL})] \\
& \qquad + \sin(\phi_+ - \phi)[(1-P_{e^-})\,{\rm Im}(F^*_{\rm LR}F_{\rm LL}) - (1+P_{e^-})\,{\rm Im}(F^*_{\rm RR}F_{\rm RL})]\}\Big\}, \quad (1.14)
\end{aligned}
$$

  where the F_{ik} denote the helicity amplitudes, P_T gives the magnitude of transverse polarization and ϕ_+ and ϕ_- are the azimuthal orientations of the respective transverse polarizations, ϕ is the azimuthal angle of the reference momentum

- In a linear collider, ϕ_+ and ϕ_- are given by the experimental setup and can be changed independently
- Transverse polarization gives only measurable effects if both beams, e+ and e-, are polarized.
- New physics phenomena could show up as ϕ dependent modulation in the differential cross section remaining the ϕ averaged cross section unchanged

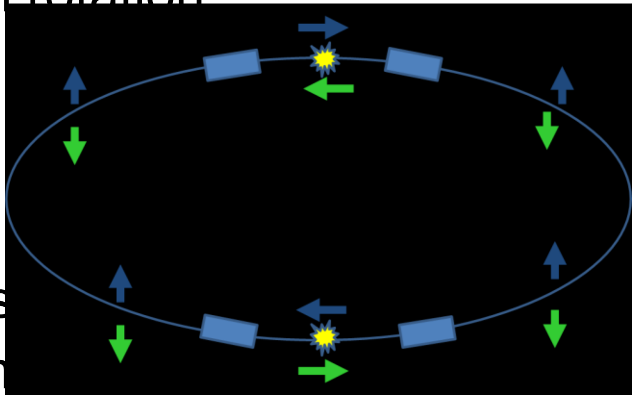
Beam polarization @ FCC-ee ?

- FCC-ee, Z pole measurements: 5×10^{12} Z bosons ⇔ statistical uncertainty is improved by 3 orders of magnitude compared to LEP;
- Coupling and widths measurements can be done with best precision ever

- Beam polarization ?
  - e+, e- circulate with spins aligned (anti-aligned) to the dipole field of the collider
  - To collide longitudinally polarized beams, spin rotation is necessary before and after beam crossing
  - Depolarization effects along the ring

  → beam polarization requires large effort

  → Knowledge of polarization could be much less precise than the statistical error of measurem



Summary (experimentalist's view)

- Future linear e+e- colliders will achieve a statistical precision of $\sim 10^{-3}$
- Physics analyses benefit from polarized beam(s)
  - spin related observables – sensitive to SM and models beyond
- Single beam polarization is an established aspect of linear colliders
- Polarization of both beams has distinct advantages and is desired for precision measurements at future linear e+e- colliders
  - Substantial enhancement of luminosity
  - Better control of systematic effects
  - More precise determination of polarization; in particular, with collision data an 'in situ' polarization measurement at the IP is possible

→ **It is crucial for the precision measurements at future linear colliders that MC generators and analysis tools include beam polarization**

- SANC is now implementing polarization effects
  - arXiv:1801.00125; "One-loop electroweak radiative corrections to polarized Bhabha scattering"; D. Bardin, A. Arbuzov, S. Bondarenko, Ya. Dydyshka, L. Kalinovskaya, L. Rumyantsev, R. Sadykov
- Project Advanced Research of Interactions in e+e- coLlisions

Many thanks to the organizers of Bardin’s Day and CALC2018, in particular Lida Kalinovskaya, Andriy Arbuzov and Alexander Bednyakov for the invitation and kind hospitality.