Identification of particle interactions structure in experiments with polarized electron and positron beams

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XIV-th International School - Conference
“Actual Problems of Microworld Physics

Belarus, Grodno region, August 12-24, 2018

Outline:

1. **Introduction**
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3. **Benefits of positron beam polarization**
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Introduction

Recently, the plan for the International Linear Collider (ILC) has been revised to a staged machine design with the first stage at $\sqrt{s} = 250$ GeV.

L. Evans and S. Michizono, "The International Linear Collider Machine Staging Report 2017," arXiv:1711.00568 [physics.acc-ph])

The physics for such a staged machine, based on electron and positron beam polarization with 80% polarization of the electron beam and 30% polarization of the positron beam.

K. Fujii et al., "Physics Case for the 250 GeV Stage of the International Linear Collider," arXiv:1710.07621 [hep-ex];

C. Adolphsen et al., "The International Linear Collider Technical Design Report - Volume 3.II: Accelerator Baseline Design," arXiv:1306.6328 [physics.acc-ph])

Electron polarization is essential for all of the physics goals of the ILC. It plays an important role in the measurements proposed for every physics topic that will be studied at this machine .

H. Baer, et al., "The International Linear Collider Technical Design Report - Volume 2: Physics," arXiv:1306.6352 [hep-ph]

Linear collider (LC) provides unique possibilities for carrying out of precision measurements and search of signals of new physics.

The striking features of the LC are

- **The clean experimental environment**
- **Tunable collision energy**
- **Polarized beams**
- **New additional observables**

In the recent past, the availability of a polarized beam at the SLC (SLAC Linear Collider), the prototype for the ILC, enabled it to compensate in some respects for the fact that it had a lower luminosity than LEP (Large Electron Positron collider).

The report aim is
to show why polarization of both collision beams is needed

The role of positron polarization at future e^+e^- colliders has been reviewed in great detail in

G. Moortgat-Pick et al., "The Role of polarized positrons and electrons in revealing fundamental interactions at the linear collider," Phys. Rept. 460 (2008) 131 [hep-ph/0507011].
K. Fujii et al., (LCC Physics Working Group), "The role of positron polarization for the initial 250 Gev stage of the International Linear Colliders," arXiv 1801.02840vl [hep-ph]

Three main benefits of positron polarization:

1. **Positron polarization allows us to obtain subsamples of the data with higher rates for interesting physics processes and lower rates for backgrounds.**

2. **Positron polarization offers four distinct data sets instead of the two available if only the electron beam can be polarized.**

3. **The likely most important effect is the control of systematic uncertainties: The precisions aimed for at the ILC can only be reached if all relevant systematic uncertainties are controlled to the same level as the statistical uncertainties or better.**

Polarization at e^+e^- Collider

As weak interactions are chiral, i.e. $W^\pm$ and Z bosons couple differently to left-handed and right-handed fermions, and only left-handed fermions take part in charged weak interactions, polarization effects play an important role in strategies to extract information from e^+e^- reactions. Since all the strong motivations to search for physics beyond the Standard Model (SM) of particles physics relate to its electroweak sector, there is every reason to expect that also new phenomena will depend on the chirality of the involved particles. Any real particle beam will contain a mixture of N_L left- and N_R right-handed particles, given by the longitudinal beam polarization

$$P = \frac{N_R - N_L}{N_R + N_L}$$

Depending on the orientation of the full polarization vector, there can also be transverse polarization. The spin rotator systems of the ILC, which are needed to turn the polarization into the vertical before the damping rings and back into the longitudinal direction afterwards, have been designed carefully to allow any orientation of the polarization vectors at the e^+e^- interaction point.

Experiments with longitudinally-polarized beams

Cross section at an e^+e^- collider with longitudinally–polarized beams:

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

One has to distinguish two cases:

● in annihilation diagrams (s- canal) the helicity of the incoming beams are coupled to each other;

● in exchange diagrams (t-, u- canal) the helicities of the incoming beams are directly coupled to the helicities of the final particles

Effective polarization: $$P_{eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}$$

Effective luminosity: $$\mathcal{L}_{eff} = \frac{1}{2}(1 - P_{e^-}P_{e^+})\mathcal{L}$$

The left-right asymmetry $$A_{LR} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}}$$

Cross-section: $$\boxed{\sigma_{P_{e}-P_{e^+}} = 2\sigma_o\,(\mathcal{L}_{eff}/\mathcal{L})\,[1 - P_{eff}A_{LR}]}$$

Positron polarization increases effective polarization P_{eff} and effective luminosity $\mathcal{L}_{eff}$

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

P_{e^-} \ P_{e^+}	0	0,22	0,34	0,60
-0.8	-0.8	-0.86	-0.89	-0.95
-0.9	-0.9	-0.93	-0.95	-0.97

$$\mathcal{L}_{eff} = \frac{1}{2}(1 - P_{e^-} P_{e^+})\,\mathcal{L}$$

P_{e^-} \ P_{e^+}	0	0,22	0,34	0,60
-0.8	0.5 $\mathcal{L}$	0.59 $\mathcal{L}$	0,63 $\mathcal{L}$	0,75 $\mathcal{L}$
-0.9	0.5 $\mathcal{L}$	0.60 $\mathcal{L}$	0.65 $\mathcal{L}$	0.77 $\mathcal{L}$

Types of processes which are the most importance for the ILC physics programme

s-channel Z/γ exchange:

For the s-channel exchange of a vector boson, the spin of the incoming particles have to add up to a total spin-1 configuration, therefore only σ_{LR} and σ_{RL} are non-zero.
The polarized cross section simplifies to:

$$\sigma(P_{e^-}, P_{e^+}) = 2\sigma_0(\mathcal{L}_{eff}/\mathcal{L})(1\text{-}P_{eff}A_{LR})$$

Important examples: Higgs production via Higgs -strahlung and $f\bar{f}$ production.

t-channel W or ν_e exchange:

Since only left-handed fermions and right-handed anti-fermions take part in the charged weak interaction, only σ_{LR} is non-zero in this case, or in other words $A_{LR} = 1$, thus

$$\sigma(P_{e^-}, P_{e^+}) = 2\sigma_0(\mathcal{L}_{eff}/\mathcal{L})(1\text{-}P_{eff})$$

Important examples: Higgs production via WW fusion , W pair production,
neutrino pair production as background for missing energy signatures.

The impact of $\mathcal{L}_{eff}$ and P_{eff} for $P_{e^-} = -0.8$ and $P_{e^+} = +0.3$ the cross section increases by 30% in comparison with $P_{e^+} = 0$ In the opposite sign configuration, which in case of WW measurements serves as in-situ background determination, $P_{e^-} = +0.8$ and $P_{e^+} = -0.3$ gives a 30% reduction of the remaining signal pollution in comparison with $P_{e^+} = 0$.

Formalism

G. Moortgat-Pick [et al.], Physics Reports. – 2008. – Vol. 460 – P. 131–243.
F.M. Renard, Basic of electron positron collisions./Dreux, France: Editions Frontieres. – 1981. – 238p.
H.E. Haber, In «Spin structure in high energy processes», Stanford. –1993. – P.231–272.
K. I. Hikasa, Phys. Rev. – 1986. –Vol. D33. – P.3203–3223.

Main task:

- show how to include beam polarization in the calculation of e^+e^- reactions
- show what configurations of beam polarizations can occur in the general case

ILC processes: $\boldsymbol{e^-(p_{e^-}, \lambda_{e^-})\, e^+(p_{e^+}, \lambda_{e^+}) \rightarrow X}$

The helicity amplitude can be written as

$$F_{\lambda_{e^-}\lambda_{e^+}} = \bar{v}\,(p_{e^+}, \lambda_{e^+})\,\Gamma\, u(p_{e^-}, \lambda_{e^-}),$$

where

$$\Gamma = \sum \Gamma_k\, \mathcal{A}_k,$$

$$\Gamma_k = (\gamma_\mu, \gamma_\mu\gamma_5, \mathbb{I}, \gamma_5, \sigma_{\mu\nu}) \equiv (\mathbf{V},\ \mathbf{A},\ \mathbf{S},\ \mathbf{P},\ \mathbf{T})$$

$\mathcal{A}_k$ - the transition amplitude which depend on the respective final state

Transition probability is given as

$$|\mathcal{M}|^2 = \sum_{\lambda_{e^-}\,\lambda_{e^+}\,\lambda'_{e^-}\lambda'_{e^+}} \rho_{\lambda_{e^-}\,\lambda'_{e^-}}\, \rho_{\lambda_{e^+}\,\lambda'_{e^+}}\, F_{\lambda_{e^-}\,\lambda_{e^+}}\, \bar{F}_{\lambda'_{e^-}\,\lambda'_{e^+}}$$

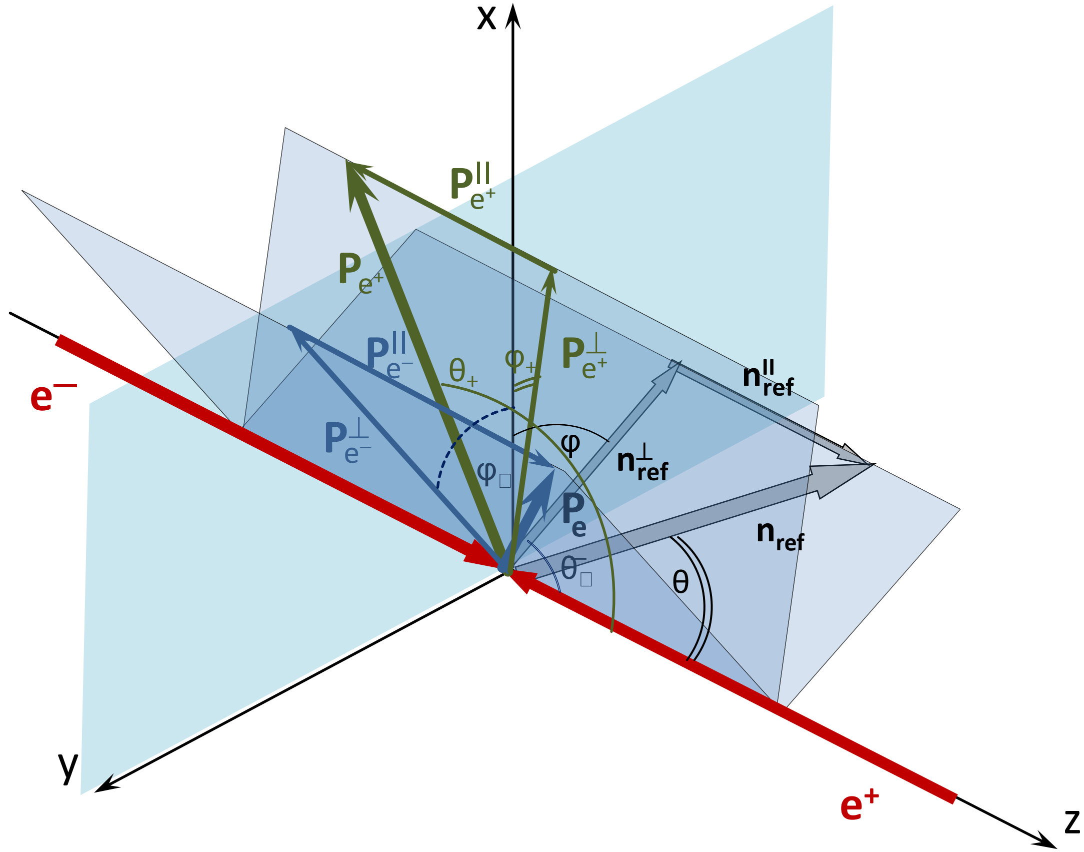

Fig.1. Decomposition of the $e^{\pm}$polarization vectors $\mathbf{P}_{e^{\pm}}$ into a longitudinal components $\mathbf{P}^{||}_{e^{\pm}}$ in the direction of the electron/positron momentum and transverse components $\mathbf{P}^{\perp}_{e^{\pm}}$ with respect to a fixed coordinate system. The z-axis is in the direction of the electron momentum, and $\boldsymbol{n}_{\mathbf{ref}}$ is the reference direction.

The matrix element squared for a process at an e^+e^- collider with polarized beam

$$|\mathcal{M}|^2 = \frac{1}{4}\Big\{(1-P_{e^-})\,(1+P_{e^+})\,|F_{LR}|^2 + (1+P_{e^-})\,(1-P_{e^+})\,|F_{RL}|^2 + (1-P_{e^-})\,(1-P_{e^+})\,|F_{LL}|^2 + (1+P_{e^-})\,(1+P_{e^+})\,|F_{RR}|^2 - 2\,P^T_{e^-}\,P^T_{e^+}\,\{[cos(\varphi_- - \varphi_+)\,\mathrm{Re}(F_{RR}\,F^*_{LL}) + cos(\varphi_- + \varphi_+ - 2\varphi)\,\mathrm{Re}(F_{LR}\,F^*_{RL})]$$

Comments to illustrate the formula:

- the F's contain the dependence on polar angle θ and on $\sqrt{s}$
- the contribution of different helicity configurations add up incoherently for longitudinally-polarized beams
- transversely-polarized beams generate interference term between left- and right-helicity amplitude

Dependence on beam polarization of the transition probability, for (pseudo) scalar-, (axial) vector- and tensor-interaction in the limit $m_e \to 0$

Interaction structure		Longitudinal		Transverse		Longitudinal – transverse
Γ_k	$\bar{\Gamma}_l$	Bilinear	Linear	Bilinear	Linear	Interference
S	S	$\sim P_{e^-}P_{e^+}$	—	$\sim P^T_{e^-}P^T_{e^+}$	—	—
S	P	—	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	—	—
S	V,A	—	—	—	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
S	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	—	—
P	P	$\sim P_{e^-}P_{e^+}$	—	$\sim P^T_{e^-}P^T_{e^+}$	—	—
P	V,A	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
P	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	—	—
V,A	V,A	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	—	—
V,A	T	—	—	—	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
T	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	—	—

Major physics processes and physics goals to be studied by the ILC at various energies. The last column gives the motivation for the use of polarized beams [from **ILC TDR – 2013**]

Energy , GeV	Reaction	Physics Goal	Polarization
91	$e^+e^- \to Z$	ultra-precision electroweak	A the beam polarization asymmetry is a crucially information observables
160	$e^+e^- \to WW$	ultra-precision W mass	B opposite polarization of e^+ and e^- beams enhance the luminosity
250	$e^+e^- \to Z\,H$	precision Higgs coupling	B
350-400	$e^+e^- \to t\bar{t}$ $e^+e^- \to WW$ $e^+e^- \to \nu\bar{\nu}H$	t quark mass and couplings precision W couplings precision Higgs couplings	A B B
500	$e^+e^- \to f\bar{f}$ $e^+e^- \to t\bar{t}H$ $e^+e^- \to Z\,H\,H$ $e^+e^- \to \bar{\chi}\,\bar{\chi}$ $e^+e^- \to AH, H^+,H^-$	precision search for Z' Higgs coupling to t quark Higgs self-couplings search for supersymmetry search for extended Higgs states	A B B C use of the polarization state $e_R^-\, e_L^+$ to suppress SM background C
700-1000	$e^+e^- \to \nu\bar{\nu}HH$ $e^+e^- \to \nu\bar{\nu}VV$ $e^+e^- \to \nu\nu t\bar{t}$ $e^+e^- \to t\bar{t}^*$	Higgs self-coupling composite Higgs sector composite Higgs and t quark search for supersymmetry	D use of the polarization state $e_L^-\, e_R^+$ to greatly enhances the rate D D C

Positron beam polarization and systematic errors

Higher precision of the measurements of all kind electroweak observables will allow to probe higher energy scales. In order to reduce the impact of systematic uncertainties to a minimum, it will be necessary to constrain the actual observables of interest simultaneously with many so-called nuisance parameters, which model possible systematic effects. Classic examples comprise

- **the luminosity,**
- **the beam polarizations,**
- **selection efficiencies**
- **theoretical or parametric uncertainties.**

Only recently a study to demonstrate the simultaneous extraction of total cross sections, left-right asymmetries and beam polarizations from differential distributions of all kinds of electroweak processes at the ILC was started:

R. Karl and J. List, "Polarimetry at the ILC," arXiv:1703.00214 [hep-ex]

A fit is performed and the following parameters are extracted:

- **the total unpolarized cross section for each process,**
- **the left-right asymmetry for each process,**
- **the beam polarizations separately for e^- and e^+,**

Fit include 16 parameters.

Conclusions from the fit.

- In all the configurations studied so far, the electron polarization was always well determined to sub-per mille precision.

- Without a constraint on the positron polarization from the polarimeters, the positron polarization can only be constrained to 0.5% in the $P_{e^+} = 0$ case. This is a factor 5 worse than usually assumed as systematic uncertainty. At the same time, the resulting uncertainties on the total cross sections and on the left-right asymmetries grow by typically one order of magnitude compared to the case of $P_{e^+} = 0.3$.

- When adding the polarimeter constraint for the positron polarization, assuming no bias, the effects are partially mitigated: The polarimeter uncertainty propagates nearly one-to-one onto the positron polarization obtained from the fit, so with the polarimeter measuring $P_{e^+} = 0 \pm 0.0025$, the final uncertainty is still 0.0024. The same applies for the total cross sections for w pair and single- w processes and the left-right asymmetries for the 2-fermion processes, which still are a factor 2-3 worse than in the $P_{e^+} = 0.3$ case.

- If now a bias of 2.5 per mille is assumed between the polarimeter and the IP, thus $P_{e^+} = 0.0025 \pm 0.0025$. The observe effects: In the case of $P_{e^+} = 0.3$ the fitted cross sections and asymmetries receive a bias of typically − 0.5σ, thus covered by the uncertainty. Larger discrepancy could be revealed by comparison with the results from a fit without the polarimeter constraint, which in case of $P_{e^+} = 0.3$ is, for sufficiently large data-sets, of similar precision. In the case of $P_{e^+} = 0$ however, all total cross sections and three out of the six considered asymmetries receive biases between −1 and −1.5σ. Since the uncertainties without the polarimeter constraint are an order of magnitude larger, as described in the previous bullet, the opportunity of an independent consistency check does not exist in the case of $P_{e^+} = 0$.

Positron beam polarization and BSM physics

The ILC, even at 250 GeV, has an interesting window for new particle discovery consistent with the exclusions of new particles reported by the LHC experiments. However, still, these particles might not appear. The role of positron polarization in BSM physics is sometimes discussed separately for discovery or exclusion, on one hand, and for characterization of the signal once it has been found, on the other hand, implying that e.g. in case of the ILC a polarized source could be built once a discovery has been made.

In general, though, and especially for the highest accessible masse s and the lowest detectable couplings, one could very well end up in a situation where a deviation from the SM becomes visible only with the full dataset, possibly even with a medium significance between 3 and 5σ. In such cases, the ability to test the "characterization" part of the BSM program by exploiting the extra observables provided by positron polarization would give important and in some cases even crucial hints for convincing ourselves that the observed effect is indeed new physics, and would narrow down the possible interpretations. In other words, only in special cases is there a strict separation between "discover first" and "characterize later", while in real life, both are often intertwined. Thus, there are examples where a discovery of new particle might be missed without the assistance of positron polarization. The most important of these are the following:

- **Invisible particles;**
- **Heavy Leptons;**
- **R -Parity Violating SUSY;**
- **Contact Interactions.**

Summary

- **The full potential of the linear collider could be realized only with the polarized electron and positron beams**
- the scalar - scalar or pseudo scalar – pseudo scalar interactions structure can be detectable only if both electron and positron beams are polarized
- In case of pure V,A,-interactions for $m_e \to 0$ the effects from transverse beam polarization occur only if both beams are polarized
- double beam polarization enables better statistics to be obtained and the dominant systematics errors in indirect searches to be reduced
- The option with transverse polarized beams provides new and efficient observables for the detection of possible sources of new physics (sources of CP violation, the effects of massive gravitons, distinguishing between models with extra spatial dimensions and so on).

"New directions in science are launched by new tools much more often that by new concept. The effects of concept–driven revolutions is to explain old things in new ways. The effect of tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson,
Imagined Worlds, 1997

Undoubtedly all scientists hope that the future LC will be such tool, tool with unprecedented versatility!

The Standard Model is not enough. I would like to write down 7 concrete physical arguments for this:	
1).	The electroweak vacuum is not stable in the SM, if one take at face value the measurements of m_t and m_H and extrapolates naively to high scales without introducing new physics
2).	The SM has no candidate for cosmological dark matter
3).	The SM does not explain the origin of matter
4).	The SM does not include mixing and masses of the neutrinos
5).	The SM does not explain the origin and naturalness of the hierarchy of mass scale in physics
6).	The SM does not accommodate cosmological inflation
7).	The SM does not include a quantum theory of gravity

John Ellis,
Summary and Outlook
International Symposium on Lepton Photon Interactions at High Energies 17-22 August 2015
University of Ljubljana, Slovenia
ArXiv:1509.1733 6v1[hep-ph]