Precision measurements with polarized beams

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outline

Precision measurements with polarized lepton beams

- Future collider projects - see talk of J. Mnich, 20 July
  - Physics with polarized beams at lepton colliders
- Precision measurements
  - Beam polarization
  - Polarimetry
  - Luminosity
- Summary

Future lepton collider projects (see also talk of J. Mnich)

Linear collider (e+e-)

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

E_{cm}

- 250GeV – 1TeV, 91GeV (ILC)
- 500GeV – 3TeV (CLIC)

$L \approx 2\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (~$500\mathrm{fb}^{-1}$/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, TLEP
- CEPC

μ Collider

Projects under study

E_{cm}

91 GeV, 160GeV, 240GeV, 350GeV

$L \approx 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (4 experiments)

→ Stat. uncertainty $\leq 10^{-3}$

Beam polarization

- Desired (?)

Precision measurements

- Precise theoretical predictions
- The right machine (E_{cm}, L, P) + detector
  - Energy from Z pole up to TeV
  - Luminosity – as high as possible
  - Polarization
    - Enhancement and suppression of processes
    - Polarization of e- beam only or of both, e+ and e- beam ?
- Precise measurements & diagnostics

High flexibility to be ready for the unexpected

Goal of polarization at SLD

Lessons from LEP/SLD: Measurement of $\sin^2\theta_W^{eff}$

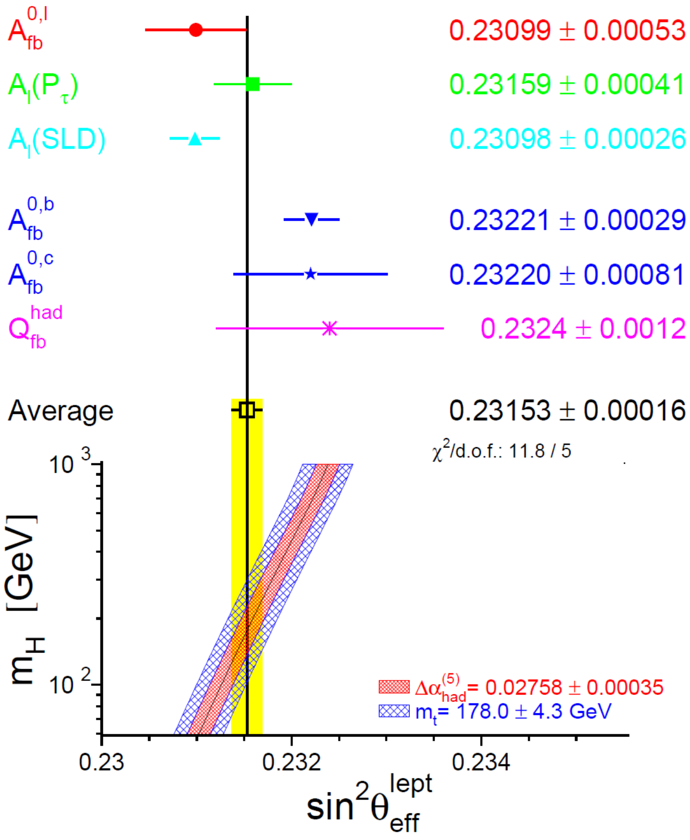
Phys.Rep. 427(2006)257
[hep-ex/0509008]

LEP

- Unpolarized e+, e- beams,
- 17×10^6 Z events
- relative precision on $\sin^2\theta_{eff(lept)} \approx 1.8\times10^{-3}$

SLD:

- Polarized e- beam
- 5×10^5 Z events
- relative precision on $\sin^2\theta_{eff(lept)} \approx 1.1\times10^{-3}$



Beam polarization can increase precision substantially

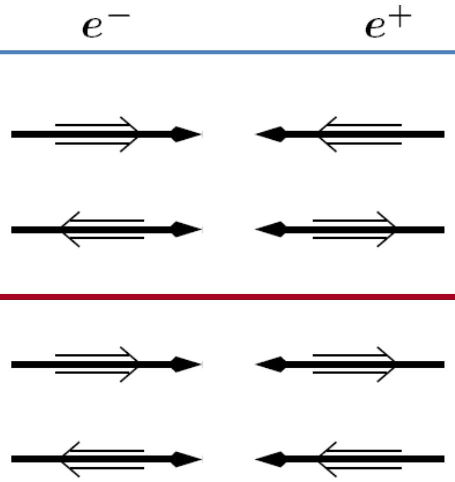
Beam polarization ($P_{e\pm}$)

Physics goal with polarized lepton beams: a short (but incomplete) overview

- Some facts
- Some example processes

Beam polarization ($P_{e\pm}$)

Consider s-channel processes (ee→ff)



		Contibution due to polarization
$J_Z = 0$	σ_{RR}	$\frac{1+P_{e^-}}{2}\frac{1+P_{e^+}}{2}$
	σ_{LL}	$\frac{1-P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
$J_Z = 1$	σ_{RL}	$\frac{1+P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
	σ_{LR}	$\frac{1-P_{e^-}}{2}\frac{1+P_{e^+}}{2}$

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

$$\sigma_{ij}^{meas} = \sigma_0 \left(1 - P_{e-}P_{e+}\right)\left(1 + A_{LR} P_{eff}\right)$$

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

σ_0 - unpolarized cross section

- Measurement with equal number of (+ -) and (- +) helicity pattern only increases statistics if both beams are polarized

→ Enhancement of effective luminosity with e+ polarization:

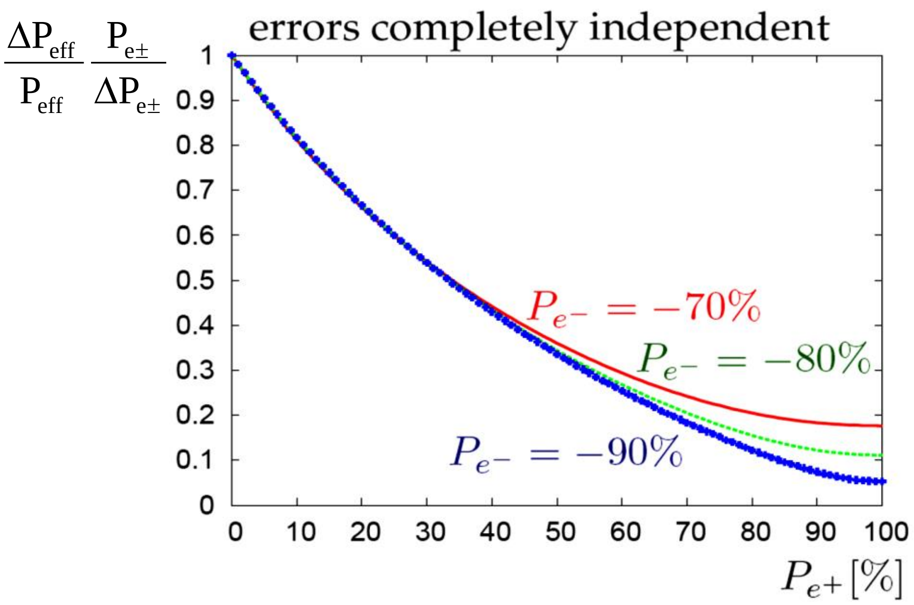
$L_{eff} = (1-P_{e+}P_{e-})$ → for (P_{e+};P_{e-}) = (∓80%; ±60%): L is factor ~1.5 higher

Left-Right asymmetry A_{LR}

- A_{LR} is sensitive to parity violation

$$A_{LR} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}} \cdot \frac{1}{P_{eff}} \cong \frac{N_{LR} - N_{RL}}{N_{LR} + N_{RL}} \cdot \frac{1}{P_{eff}^{lumi}}$$

- Effective polarization P_{eff} is larger than e- polarization
- At measurements with high statistics polarization uncertainty could dominate ΔA_{LR} → limited precision
- Error propagation ⇔ $\Delta P_{eff} < \Delta P_{e\pm}$ → e+ polarization helps!!



SLD: (Phys.Rept. **427**(2006)257)

$\Delta P/P \sim 0.50\%$

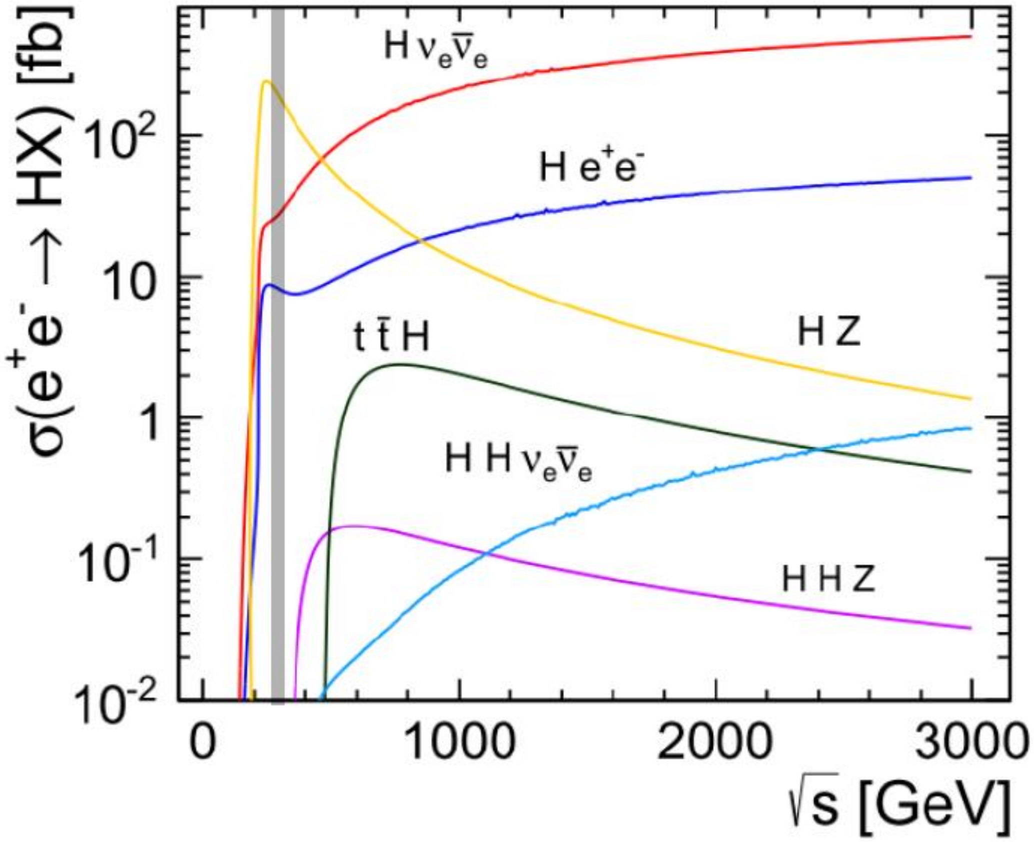
ILC (goal): (List et al., JINST 4:P10015,2009)

$\Delta P_e/P_e = 0.25\%$

$\Delta P_{eff}/P_{eff} = 0.12\%$ (P_{e-}=0.8, P_{e+} =0.3)

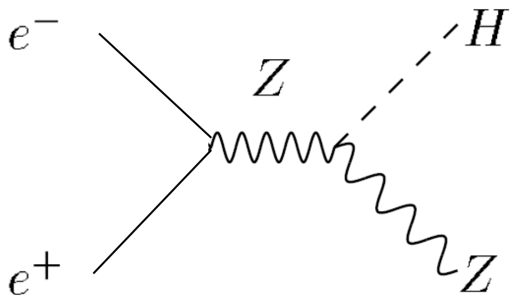
e+e- Higgs factory

ILC TDR

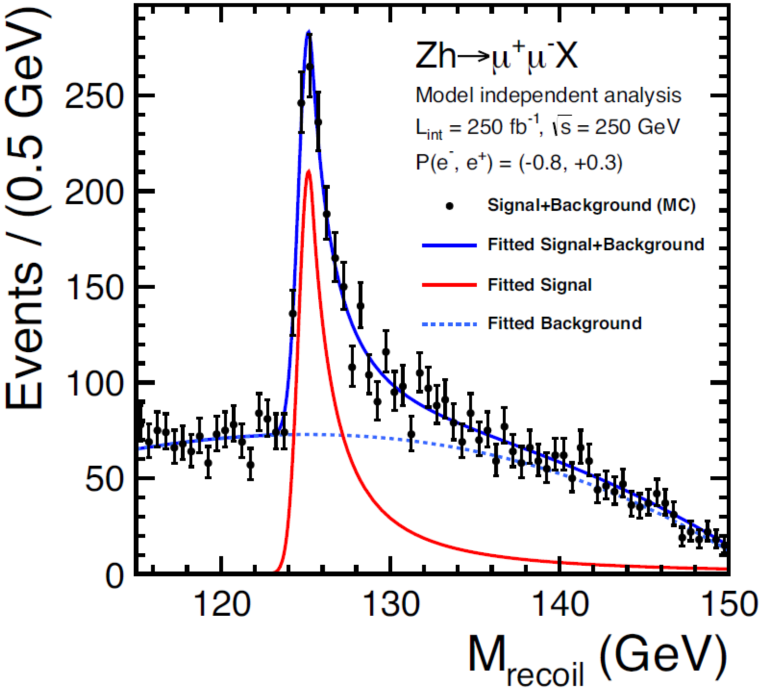


Higgs Coupling to the Z

arXiv:1506.05992



ILC: Li et al., arXiv:1202.1439



Select events:

e+e- → Zh and Z → $\mu\mu$,ee

Fit to the spectrum of recoil mass of both leptons ➔ Higgs mass and coupling

Peak position ⬄ Higgs mass

$\Delta m_h < 30$ MeV

Peak height ⬄ $\sigma_{Zh} \sim g_{Zh}^2$

→ Model-independent measurement of Zh coupling (percent-level)

→ Higgs total decay width

Higher lumi improves precision

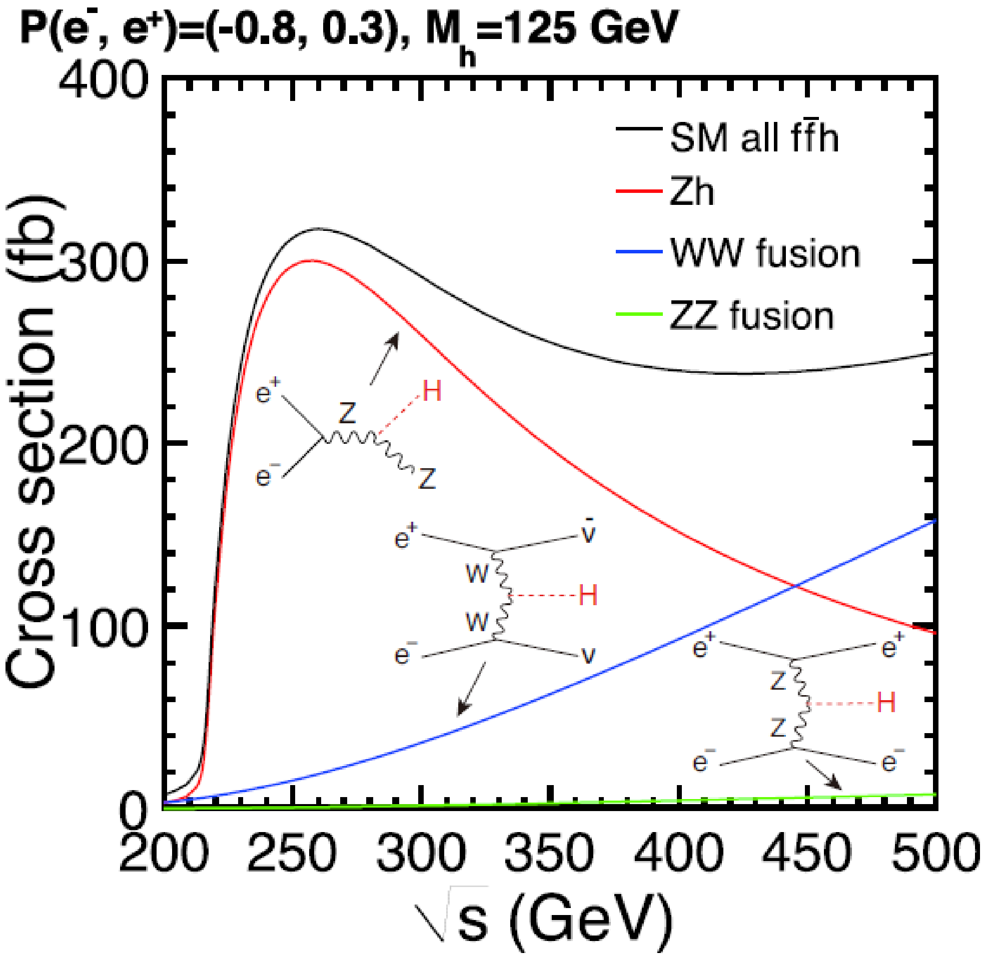
Goal with polarized beams

with polarized beams:

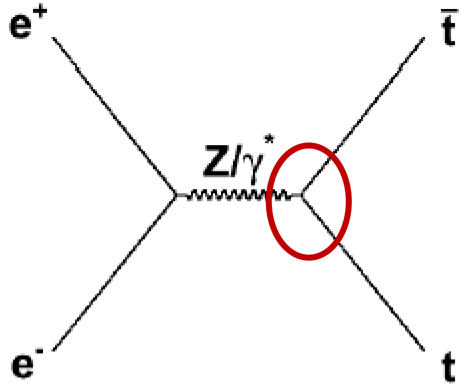
- Enhancement of Higgs Strahlungs process by factor $(1-P_{e-}P_{e+})$ if e+ and e- are polarized ($e^+_L\ e^-_L$ and $e^+_R\ e^-_R$ are suppressed)

- Enhancement of WW, ZZ Fusion processes

arXiv:1506.05992



Top-Quark coupling: ttX



- Idea (Amjad et al.,arXiv:1307.8102):
  - – use polarized beams
  - – Discriminate top coupling to Z and γ
- ttX vertex :

$$\Gamma_\mu^{t\bar{t}X} = ie\left[\gamma_\mu\left(\tilde{F}_{1V}^X + \gamma_5\tilde{F}_{1A}^X\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\tilde{F}_{2V}^X + \gamma_5\tilde{F}_{2A}^X\right)\right]$$

Form factors and their SM values (Born level):

$$\tilde{F}_{1V}^X = -\left(F_{1V}^X + F_{2V}^X\right)$$

$$F_{1V}^\gamma = -\frac{2}{3} \qquad F_{1V}^Z = -\frac{1}{4s_W c_W}\left(1-\frac{8}{3}s_W^2\right)$$

$$\tilde{F}_{2V}^X = F_{2V}^X$$

$$F_{2V}^\gamma = Q_t\frac{(g\text{-}2)}{2} \qquad F_{2V}^Z$$

$$\tilde{F}_{1A}^X = -F_{1A}^X$$

$$F_{1A}^\gamma = 0 \qquad F_{1A}^Z = \frac{1}{4s_w c_w}$$

$$\tilde{F}_{2A}^X = -iF_{2A}^X$$

$$F_{2A}^X \propto d_A^X$$

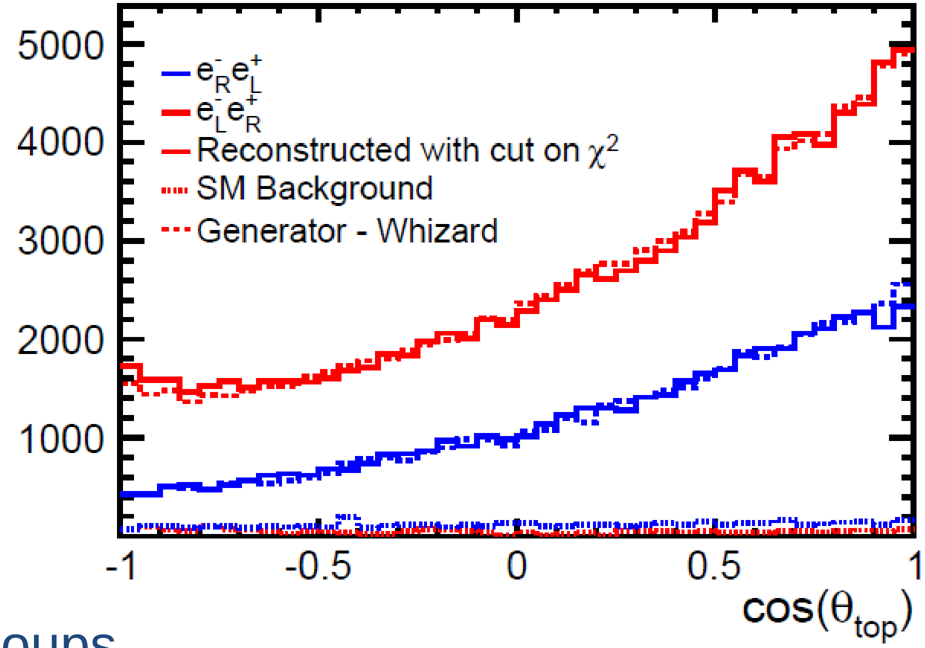
d = dipole moment;
F_{2A} violates CP

Top-quark coupling

- Polarized cross section for tt production

  (polar angle of top from decay products in the hadronic decay branch)

arXiv:1307.8102



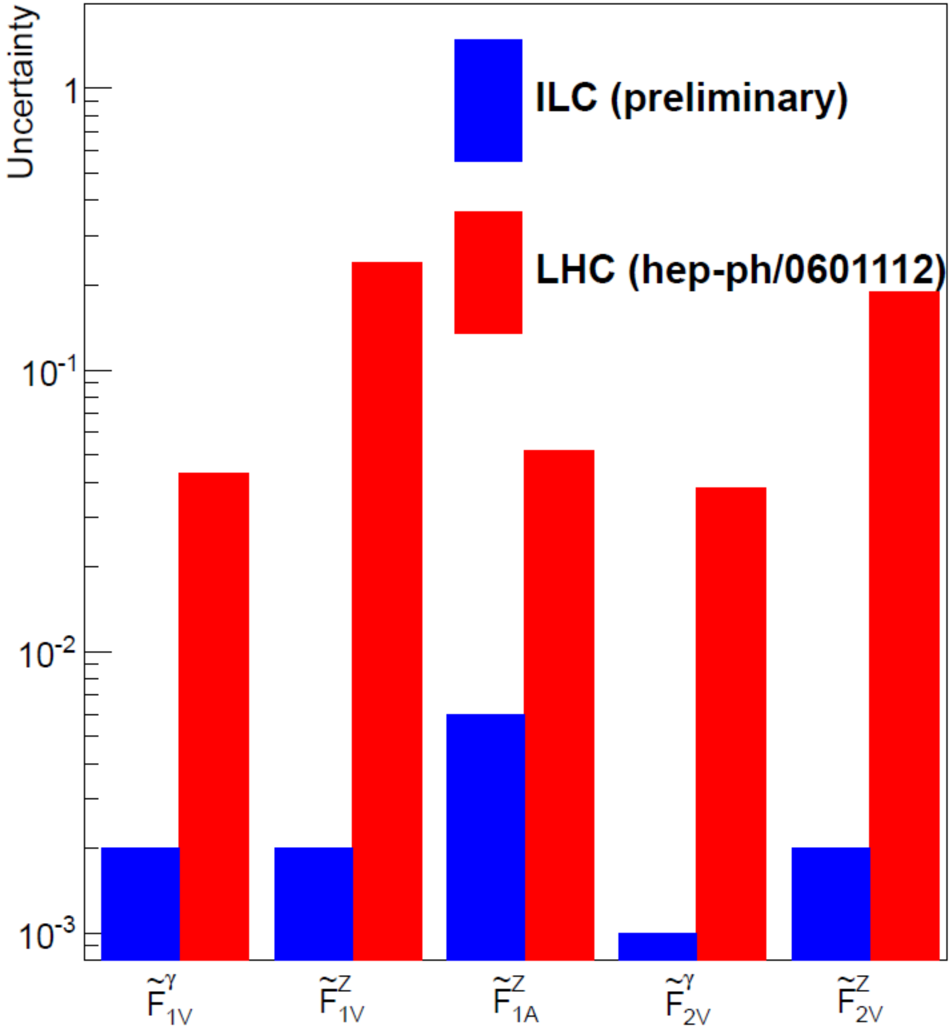
- measure forward-backward asymmetry for 2 beam polarizations

- Extract form factors in groups assuming SM for remaining groups
- Polarization is decisive to distinguish top coupling to Z and γ
- sign of form factors is fixed by γZ interference

Achieved in this study: relative uncertainty of ttX coupling ≤1%

Top-quark coupling

arXiv:1307.8102



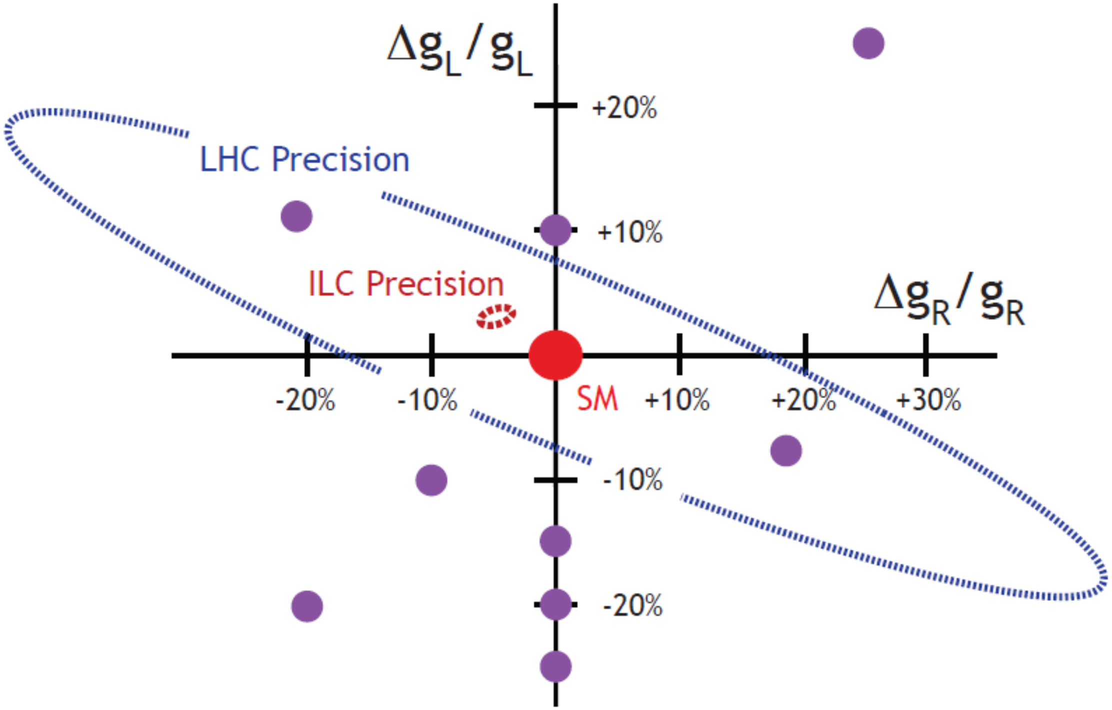
arXiv:1307.8102

Statistical precision on CP conserving form factors expected at LHC (3000fb^{-1}) and ILC (500fb^{-1}, Pe+=±0.8,Pe+= ±0.3)

New physics

Top coupling is sensitive to new physics:

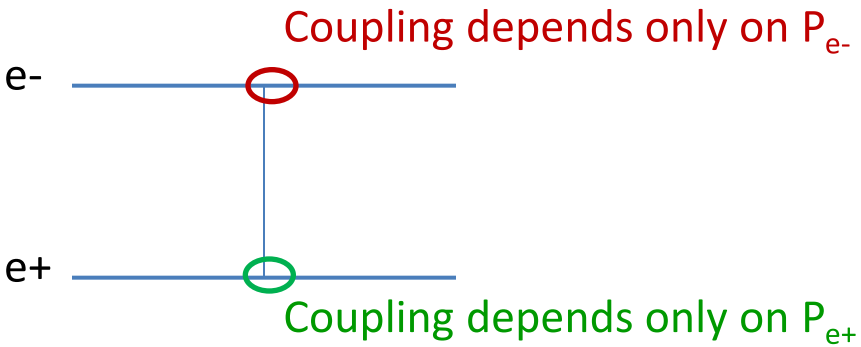
arXiv:1506.05992



Comparison of g_L,g_R (SM) with composite Higgs models

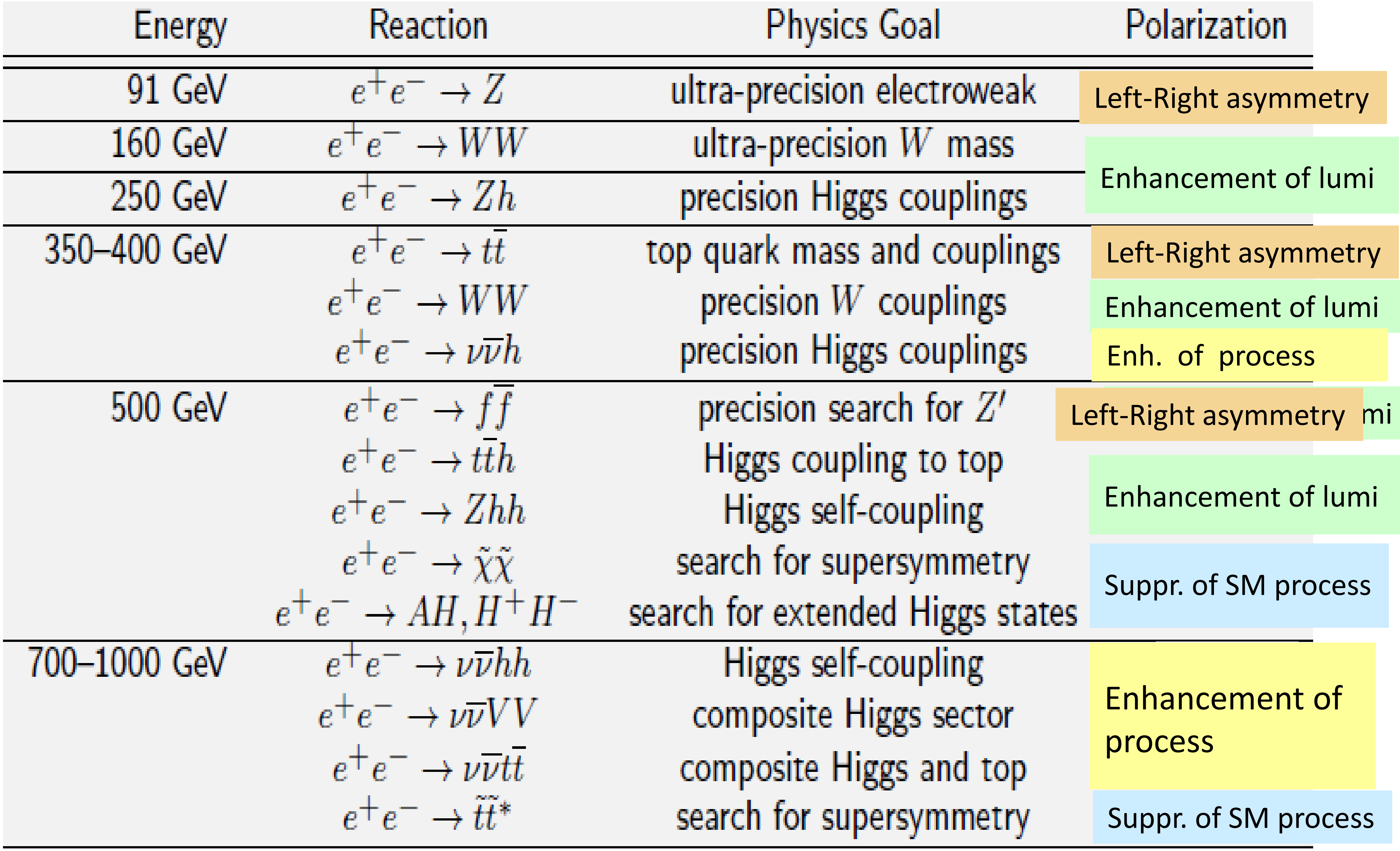
Further example: t-channel processes:

- helicities of initial and final state are directly coupled, but independent of the helicity of the second incoming beam particle



- As a unique feature of Bhabha scattering, the J=0 state can isolate the t-channel for vector currents from scalar s-channel exchange

Key physics explorations at high-energy e+e- colliders



Energy	Reaction	Physics Goal	Polarization
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak	Left-Right asymmetry
160 GeV	$e^+e^- \to WW$	ultra-precision W mass	Enhancement of lumi
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings	
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings	Left-Right asymmetry
	$e^+e^- \to WW$	precision W couplings	Enhancement of lumi
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings	Enh. of process
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'	Left-Right asymmetry mi
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top	Enhancement of lumi
	$e^+e^- \to Zhh$	Higgs self-coupling	
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry	Suppr. of SM process
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states	
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling	Enhancement of process
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector	
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top	
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry	Suppr. of SM process

Physics at the Z Pole

- Ultra-precision electroweak measurements
- Planned Luminosity
  - GigaZ (ILC): 10^9 Z bosons
  - FCC-ee (TLEP): up to 10^{13} Z bosons
- Beam polarization important for
  - A_{LR} measurement
  - Energy measurement (ring collider)

A_{LR} measurement at Z peak

“Blondel Scheme” with polarized e+ and e-

- Most sensitive to weak mixing angle: A_{LR}

$$A_{LR} = \frac{A_{LR}^{meas}}{P} = A_e = \frac{2 v_e a_e}{v_e^2 + a_e^2}$$

(independent of the final state)

$$\frac{v_e}{a_e} = 1 - 2\sin^2\theta_{eff}^{lept}$$

- Perform 4 independent measurements with different helicity combinations

$$\sigma_{\pm\pm} = \tfrac{1}{4}\sigma_0\left[1 + P_{e^+}P_{e-} + A_{LR}\left(\pm P_{e^+} \pm P_{e-}\right)\right]$$

=0 (SM) if both beams 100% polarized

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

- determination of P_{e+} and P_{e-}, and A_{LR} simultaneously ($A_{LR} \neq 0$) (equal polarization for + and – helicity):

$$A_{LR} = \left[\frac{\left(\sigma_{++} + \sigma_{-+} - \sigma_{+-} - \sigma_{--}\right)}{\left(\sigma_{+-} + \sigma_{-+} + \sigma_{++} + \sigma_{--}\right)} \cdot \frac{\left(-\sigma_{+-} + \sigma_{-+} - \sigma_{++} + \sigma_{--}\right)}{\left(-\sigma_{+-} + \sigma_{-+} + \sigma_{+-} - \sigma_{--}\right)}\right]^{1/2}$$

$$P_{e^\pm} = \left[\frac{\left(\sigma_{+-} + \sigma_{-+} - \sigma_{++} - \sigma_{--}\right)}{\left(\sigma_{+-} + \sigma_{-+} + \sigma_{++} + \sigma_{--}\right)} \cdot \frac{\left(\mp\sigma_{+-} \pm \sigma_{-+} - \sigma_{++} + \sigma_{--}\right)}{\left(\mp\sigma_{+-} \pm \sigma_{-+} + \sigma_{++} - \sigma_{--}\right)}\right]^{1/2}$$

- A_{LR} can be measured independently from polarimeters
- Loss in precision is small if only 10% of luminosity is used for σ_{++} and σ_{--}

A_{LR} measurement at Z peak (cont'd)

- However, some corrections are necessary…
  - Blondel scheme assumes that
    - polarization for + and – helicity state is the same;
    - e+ and e- beam polarizations are uncorrelated

  → difference of absolute values of helicity states has to be known; need polarimeters at IP for measuring polarization difference between + and – helicity states
  - Beamstrahlung effects, …

- Expectation:

  GigaZ (ILC): $\Delta\sin^2\theta$eff is improved by factor ~1/13 to LEP/SLD

- Circular colliders (FCC-ee, CEPC):
  - need polarized beams to measure A_{LR}

Polarization in circular high energy e+e- colliders

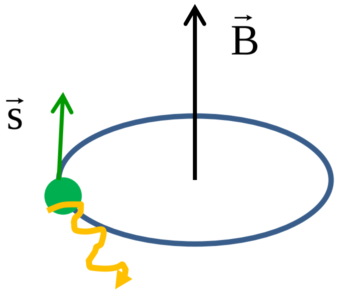
- Transverse polarization in storage rings
  - Sokolov-Ternov effect
  - Beam energy measurement using resonant depolarization
  - Transverse polarization at FCC-ee
- Longitudinal polarization for physics

- Precision measurement of energy at LEP:
  - Highest precision using method of resonant depolarisation
  - $\Delta E/E \sim 10^{-5}$

  → precision Δm_z = 2.1MeV with 1.7 MeV from energy measurement
- Measurement of energy at linear e+e- colliders (ILC, CLIC)
  - method of resonant depolarization does not work
  - Goal (ILC): $1\text{-}2 \times 10^{-4}$
  - Energy spectrometers before and after collision point to measure energy distribution

Polarization in storage rings

Transverse polarization



- Spin ½ particle in homogeneous magnetic field
  → 2 stable states: $\vec{s} \uparrow\uparrow \vec{B}$ $\vec{s} \uparrow\downarrow \vec{B}$

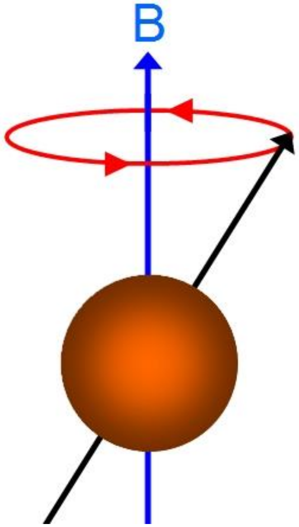
- **Sokolov-Ternov effect**:
  - Synchrotron emission has a small spin-flip probability, with large asymmetry in favor of orienting the magnetic moment of the particles along the guiding magnetic dipole field.
    → **self polarization**
  - In a perfect machine large asymptotic transverse polarization (max 92.4%) builds up
  - In a real machine depolarization effects occur → asymptotic polarization is reduced ($P_\infty < P_{ST} = 0.924$); is achieved after effective polarization raise time τ_p^{eff}

$$P_\infty = 0.924 \frac{1}{1 + \frac{\tau_P}{\tau_d}} \qquad \tau_p^{eff} = \tau_P \frac{1}{1 + \frac{\tau_P}{\tau_d}}$$

- Ideal storage ring: polarization is along vertical direction
- Real storage ring: perturbation → spin precession

Spin precession

Motion of spin vector of relativistic electron in presence of magnetic and electric field is described by Thomas-BMT (Bargmann, Michel, Telegdi) equation



$$\frac{d\vec{s}}{dt} = \vec{\Omega}_{BMT} \times \vec{s}$$

with (neglecting electrical fields)

$$\vec{\Omega}_{BMT} = -\frac{e}{\gamma m_0}\left[(1+a\gamma)\vec{B}_{\perp} + (1+a)\vec{B}_{\parallel}\right]$$

$$a = (g-2)/2$$

- Average over all particles of the number of spin oscillations per revolution is defined as spin tune (ideal storage ring)

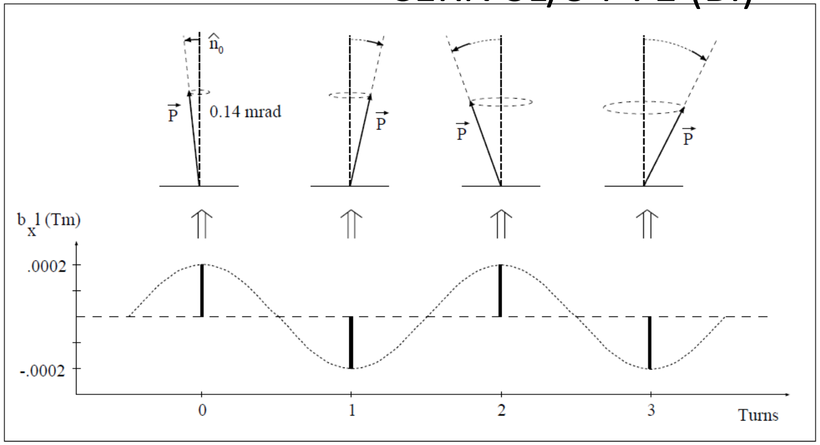
$$\boxed{\nu = \frac{f_{spin}}{f_{rev}} = \frac{a}{m_0 c^2} E_{beam}}$$

- **spin tune is related to the energy of the particle**

Resonant depolarization

If a perturbation is in phase with the nominal spin precession the polarization vector is resonantly rotated away from the vertical direction

CERN SL/94-71 (BI)



(in this example *fdep* = 0.5 · *frev*).

- The RF-magnet field oscillating at a frequency f_{dep} is in resonance with the spin precession if:

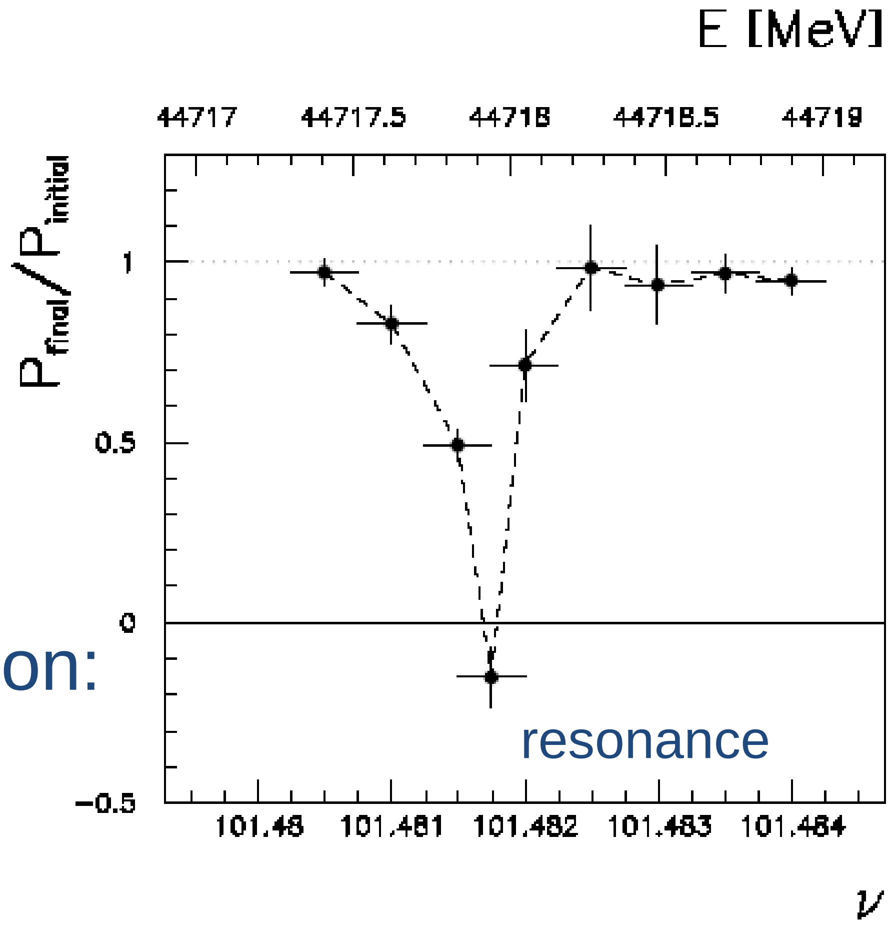
$$f_{dep} = (k \pm [\nu]) \cdot f_{rev}$$

k = integer,
f_{rev} = revolution frequency in the ring

➔ **Depolarization**

With exciting artificial depolarizing resonance f_{dep} very precise beam energy measurement; $\Delta E/E \sim 10^{-5} \ldots 10^{-6}$

Measurements of the artificially excited spin resonance (LEP):



CERN SL/94-71 (BI)

Standard energy calibration:

The slightly asymmetric shape is due to tidal changes of the beam energy during the 12 minutes of measurement

Transverse polarization in FCC-ee

- FCC: large radius, beam energy 45 – 80 GeV:
  - extremely long time to build up transverse polarization
  - Depolarization due to imperfections along the ring

- Useful level for energy calibration: 5-10%

  → Sokolov-Ternov effect is not the best option to polarize beams (at least for E_{beam} = 45GeV)
  - introducing wiggler magnets
    - → increasing synchrotron radiation
    - → decrease polarization build-up time
  - But: wigglers increase beam energy spread

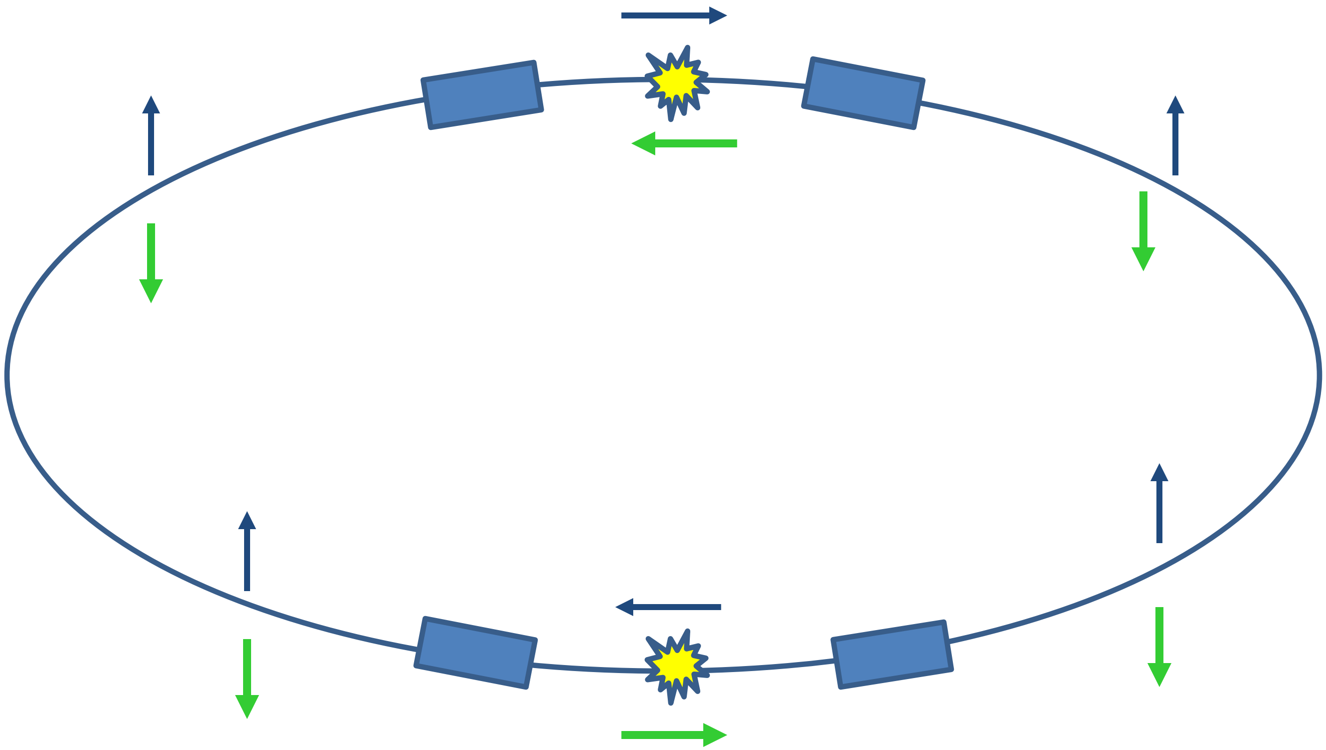
- Beam energy spread:
  - Beam spread enhances depolarization due to synchrotron motion
  - At LEP beam energy spread destroyed polarization above 60 GeV

- Polarization at FCC-ee is under study

Longitudinal polarization for physics

- Linear colliders (ILC, CLIC):
  - Sources generate longitudinally polarized e- (e+)
  - Spin rotators at arcs/turnarounds
  - Very low depolarization in accelerator (one-way)

- FCC-ee
  - Inject polarized beams
  - Spin manipulation: Spin rotators must be installed on either side of the interaction points to rotate the polarization direction from the vertical plane to the longitudinal plane and back. (→ 4×3,000 times per second)
  - Needs studies and careful calculations based on details of a realistic design



- Spin rotation from transverse to longitudinal polarization before and after interaction point
- ‘Frequent’ helicity reversal to minimize systematic effects

- Polarization measurement
    - Principle
    - Precision
- Luminosity measurement

Polarization measurement

- Measurement of polarized cross section ⇔ measurement of polarization

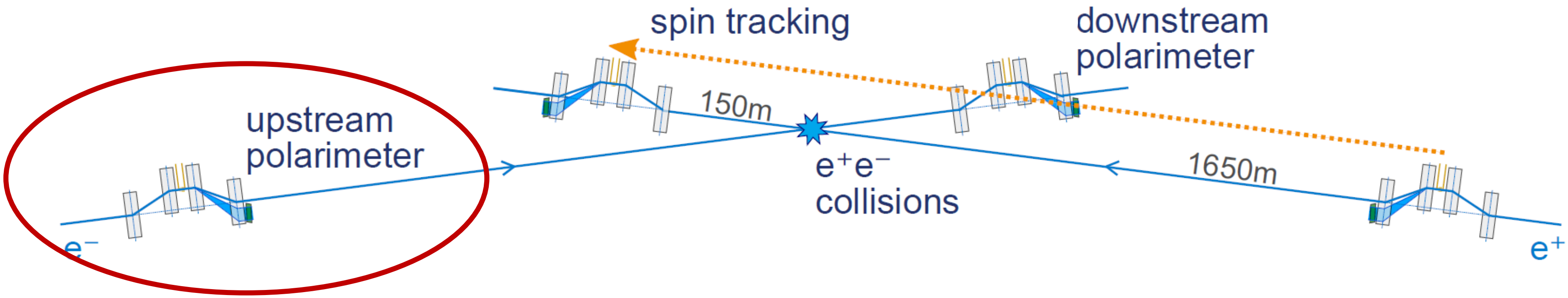
- To be measured: luminosity weighted average polarization at the interaction point
  - So far, all studies assume that this average polarization is known

$$\langle P_Z \rangle_{IP} = \frac{\int P_Z(t) L(t) dt}{\int L(t) dt}$$

- Goal (ILC)
  - determine luminosity-weighted polarization at per-mille level ⇔ polarization error should not limit the precision of measurement

Principle of polarization measurement

- Compton polarimeters to measure e+ and e- polarization upstream and downstream the interaction point (IP)



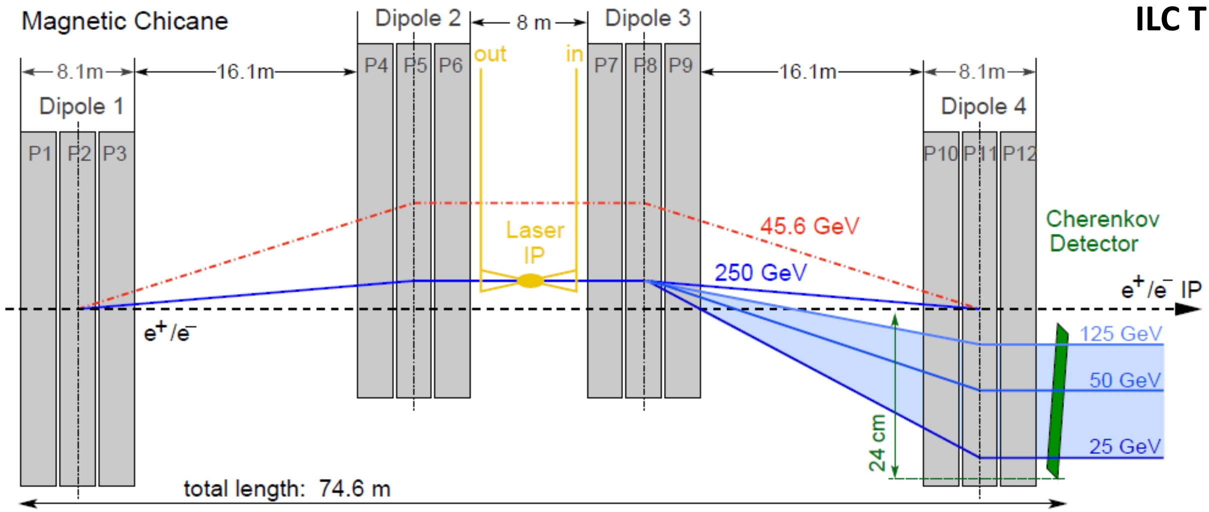
J. List

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

Upstream Compton polarimeter

Compton scattering of polarized laser photons on e+, e-

- fast measurement ⇔ O(10^6) Compton scattering events per second



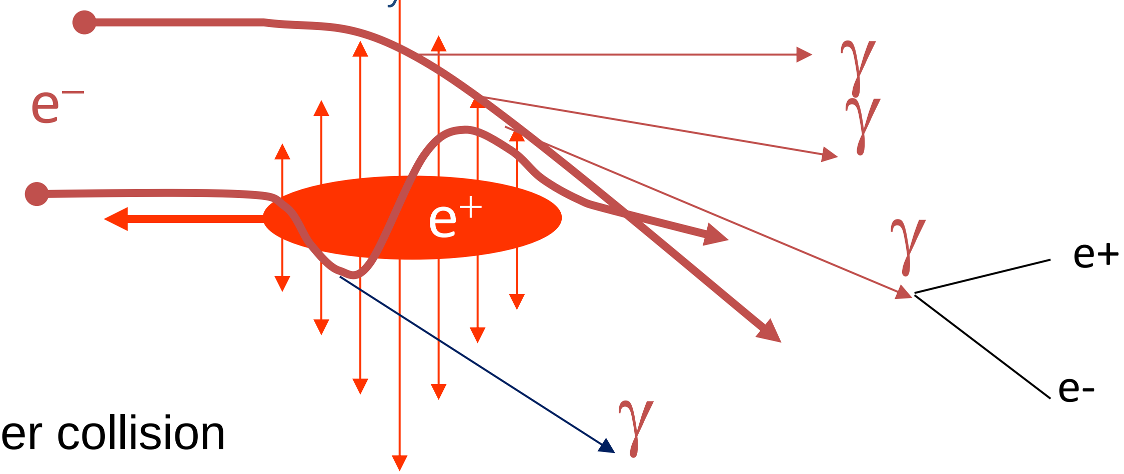
ILC TDR

- Energy spectrum of scattered e- (e+) depends on product of circular polarization of laser P_γ (left, right) and longitudinal polarization Pe-, Pe+
- Spectrometer chicane (4 dipoles): energy distribution → position distribution
- Measure asymmetry of scattered e± for L, R laser polarization ➔ Pe±

Polarization measurement

- Upstream Compton – Polarimeter: $\Delta P/P = 0.25\%$
  - For comparison: SLD achieved $\Delta P/P = 0.5\%$

- polarimeters measure the beam polarization 1.8km upstream and 140m downstream the IP
- Transport of polarized beam through beam delivery system ⇔ spin manipulation
- Beam crossing (flat beams, σ_x ~500nm, σ_y ~ 6nm)
  - Beamstrahlung
    → Some depolarization



  - Beams are disrupted after collision

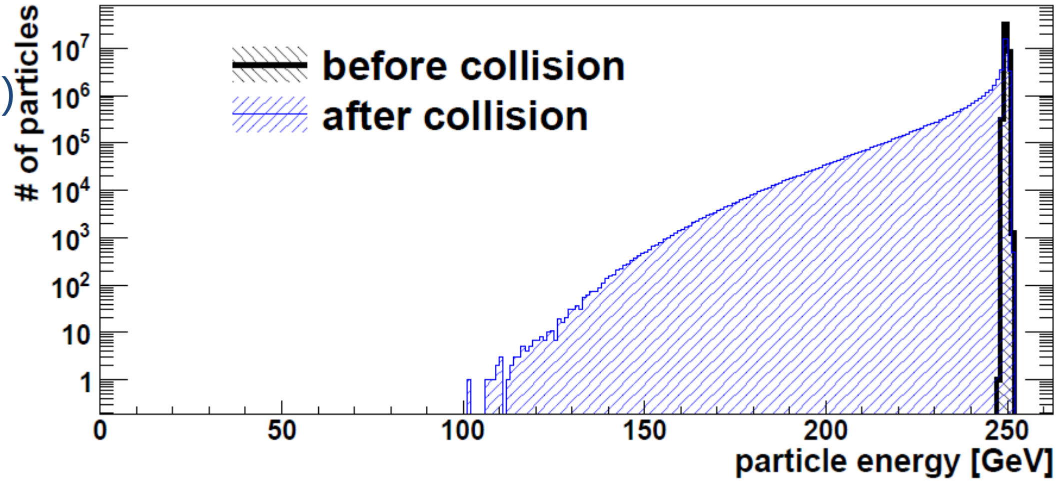
→ Need the second polarimeter
to measure polarization of spent beam (Dowstream polarimeter)

Polarization measurement

- Beam energy spectrum before and after collision (GuineaPig++, ILC RDR parameters)

- Beam is ‘disrupted’ → laser spot of Compton polarimeter hits only central part of the spent beam

M. Beckmann, DESY-THESIS-2013-053



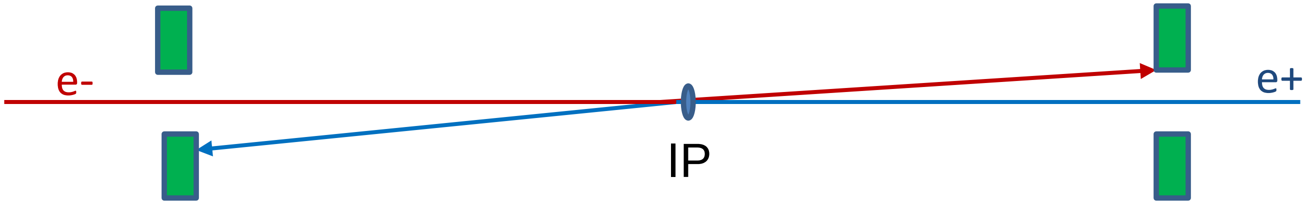
- Correction of this effect to get the luminosity-weighted polarization:
  - Extremely careful alignment of beam, laser and polarimeter required
  - Precise monitoring of luminosity, beam parameters, upstream polarimeter
  - More details see M. Beckmann, DESY-THESIS-2013-053

- Explore long-term polarization measurement from collision data (Blondel scheme, WW production)

Luminosity measurement

Luminosity measured using Bhabha scattering $L = \frac{N_{Bhabha}}{\sigma_{Bhabha}}$

- Cross section at small angles $\sigma_{\text{Bhabha}} \propto \frac{1}{s}\left(\frac{1}{\theta_{\min}} - \frac{1}{\theta_{\max}}\right)$
- Forward peak
  - precise knowledge of θ_{min} ⇔ Very precisely positioned luminosity monitor
    - ILC: θ_{min} = 31mrad, θ_{max} = 78mrad



  - Precise theoretical prediction
- Required precision of luminosity measurement
  - ILC: $\Delta L/L < 10^{-3}$ (LEP: lumi monitoring ~ 10^{-4})
  - ILC/GigaZ: $\Delta L/L \sim 10^{-4}$
  - TLEP: ? Even better…

Bhabha scattering generators

- BHLUMI for small-angle Bhabha scattering
  - S. Jadach, W. Placzek, E. Richter-Was, Z. Was
  - Theoretical error of low angle Bhabha scattering at LEP: 0.05 – 0.07%; room for improvement exists (vacuum polarization)
  - GigaZ,…: Substantial improvement of theory precision below experimental error seems feasible

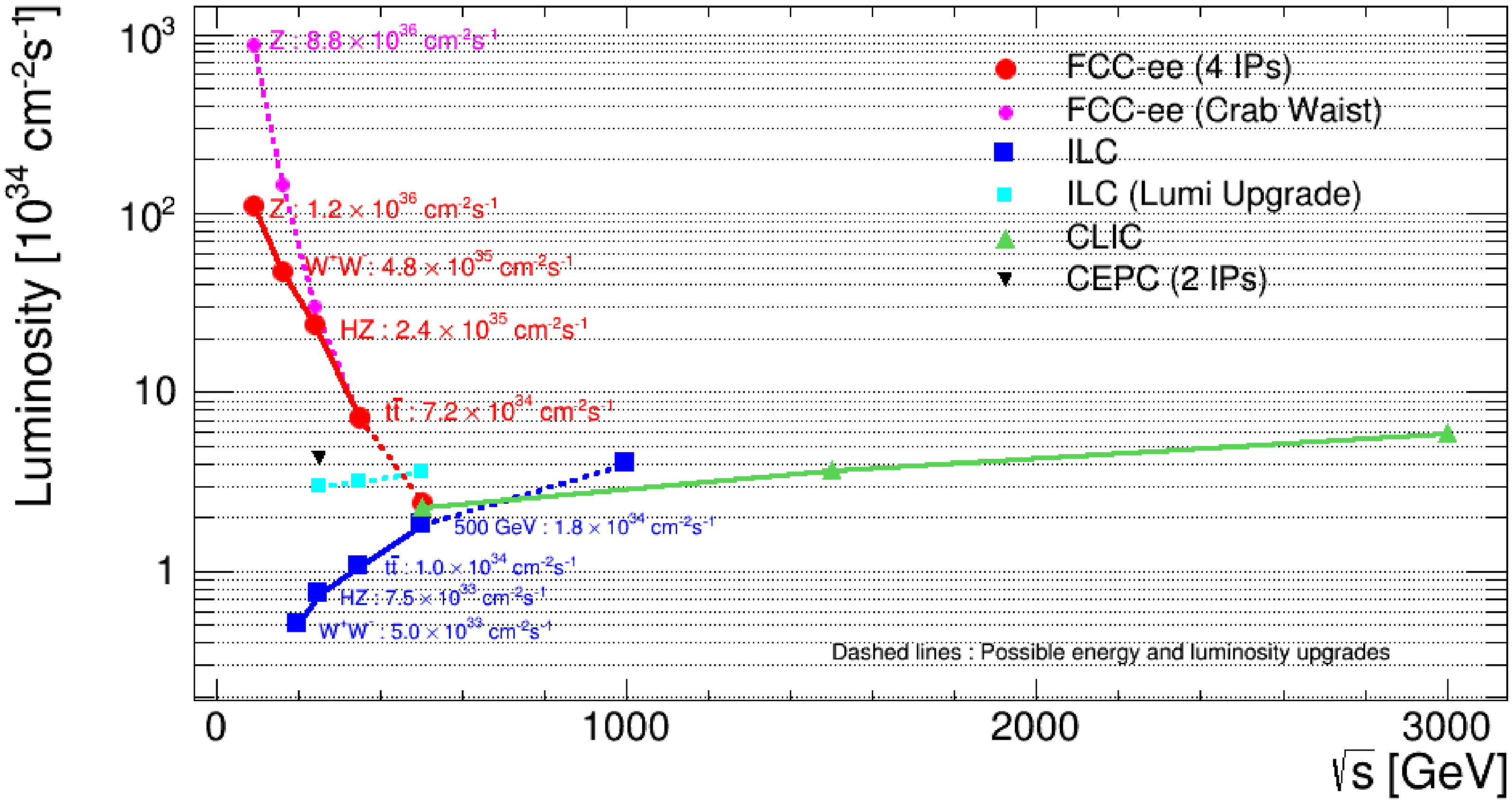
- BHWIDE generator for wide-angle Bhabha scattering
  - S. Jadach, W. Plazcek, Z. Was
  - precision up to 0.11% at LEP1

- But:
  - Both generators do not include beamstrahlung spectra
  - Both generators do not include explicitly beam polarization

Work done/in progress:

- Higher order corrections for Bhabha scattering (Gluza, Penin, Riemann)
- New Bhabha generator with polarization: Vladimir Makarenko (NC PHEP BSU, Minsk)

Energy and distribution of luminosity across the possible working points of e+e- colliders



Polarized beams in μ collider

- Muons have short lifetime ⇔ self-polarization is excluded
- Muons are born polarized → maintain polarization
- However, muons come from π decay (in flight)
  - μ polarization depends on energy
  - have to separate muons with high energy

  → Reduced luminosity
- Longitudinal polarization in interaction region → spin manipulation
- Polarized muon collider should be possible but needs large effort

Summary

- Polarized beams at lepton colliders increase the potential and the precision of measurements
- Beam polarization is very useful to discriminate new physics phenomena
- ILC, CLIC designed with polarized e- (e+) beams
- Precision measurements with polarized beams
  - Require excellent polarimetry and spin tracking to determine the luminosity weighted polarization at the collision
  - relative uncertainty of polarimeters at per-mille level required
- Polarization in very large circular lepton colliders (FCC-ee,…) is a challenge