Precision measurements with polarized beams at high-energy lepton colliders

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HEPKIT 2015

Shedding Light on our Understanding of Nature

HEPKIT2015:

"…the discussion and interpretation of LHC results in the SM and beyond, the presentation of new results and challenges in theoretical particle physics and the outlook on future research at upcoming colliders."

- What would a future e+e- collider add to the LHC results?
  - So far: discovery of a SM-like Higgs boson coupled with the absence of other phenomena
  - Are these 'new' phenomena to be found at higher energies, or have they escaped detection because of very small couplings?

→ Precision, model-independence of analyses

→ Discovery

- Precision measurements with lepton beams require:
  - High luminosity
  - known centre-of-mass energy
  - **Polarized beam(s**)

→ Well defined initial state

- Physics program of future e+e- colliders:
  - Higgs boson
  - W, Z boson physics
  - Top quark
  - Beyond the Standard Model
  - Physics at the Z pole

Details see also in:
ILC Technical Design Report, CLIC Conceptual Design Report, TESLA TDR, Snowmass study 2013,
Fuji et al., arXiv:1506.05992, Barklow et al., arXiv:1506.07830, and reference therein,
FCC-ee physics studies

Beam polarization at future lepton colliders needs effort…

- Benefit with polarized beams
- Beam polarization
- Polarimetry

Summary

Future lepton collider projects

Linear collider (e+e-)

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

E_{cm}

- ILC: 250GeV – 1TeV, 91GeV
  Length 31km
- 350GeV – 3TeV (CLIC)
  Length up to 50km

$L \approx 2\times10^{34}cm^{-2}s^{-1}$ (few $100fb^{-1}$/year)

→ Rel. stat. uncertainty ~ 10^{-3}…10^{-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

Projects are under study

- μ Collider

E_{cm} (FCC-ee)

91 GeV, 160GeV, 240GeV, 350GeV
~80km circumference

$L \approx 10^{36}cm^{-2}s^{-1}$ (Z pole)
$\approx 7\times10^{34}cm^{-2}s^{-1}$ (ttbar threshold)

Beam polarization

- Desired

Lessons from LEP/SLD

Measurement of $\sin^2\theta_W^{eff}$

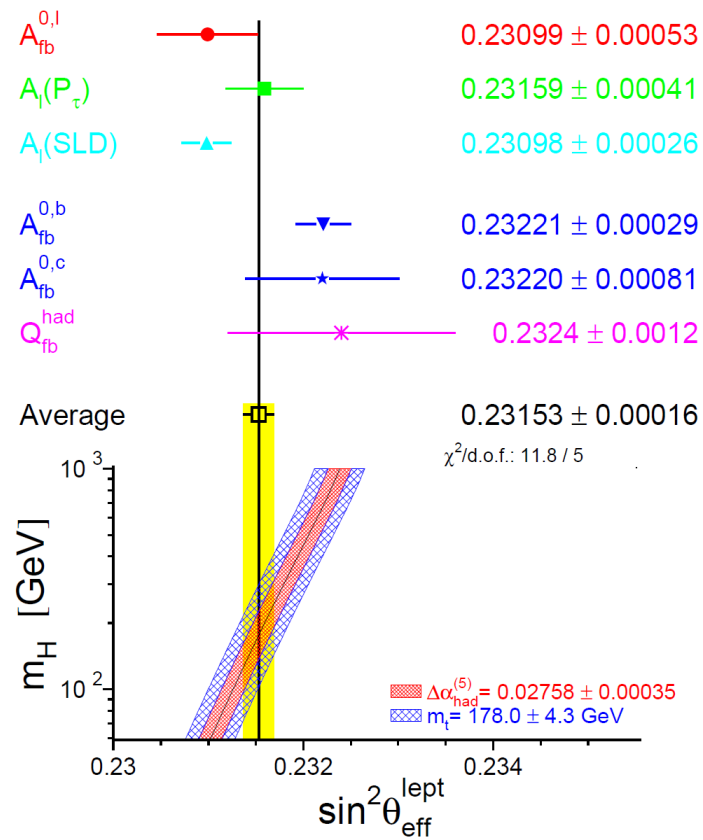
Phys.Rep. 427(2006)257
[hep-ex/0509008]

LEP

- Unpolarized e+, e- beams,
- 17×10^6 Z events
- relative precision on $\sin^2\theta_{eff(lept)}$
  - $\approx 1.8\times10^{-3}$ (A_{FB} lept final states)
  - $\approx 1.2\times10^{-3}$ (A_{FB} b-bbar final state)

SLD:

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



Beam polarization increases precision substantially

Polarized lepton beams

Goal

- Additional observables:
  - Left-right asymmetry
  - Forward-backward left-right asymmetr

  For example, at the Z pole:

$$A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

$$\left\langle P_\tau^0 \right\rangle = -A_\tau$$

$$A_{FB}^{pol,0} = -\frac{3}{4} A_e$$

$$A_{LR}^{0} = A_e$$

$$A_{LRFB}^{0,f} = \frac{3}{4} A_f$$

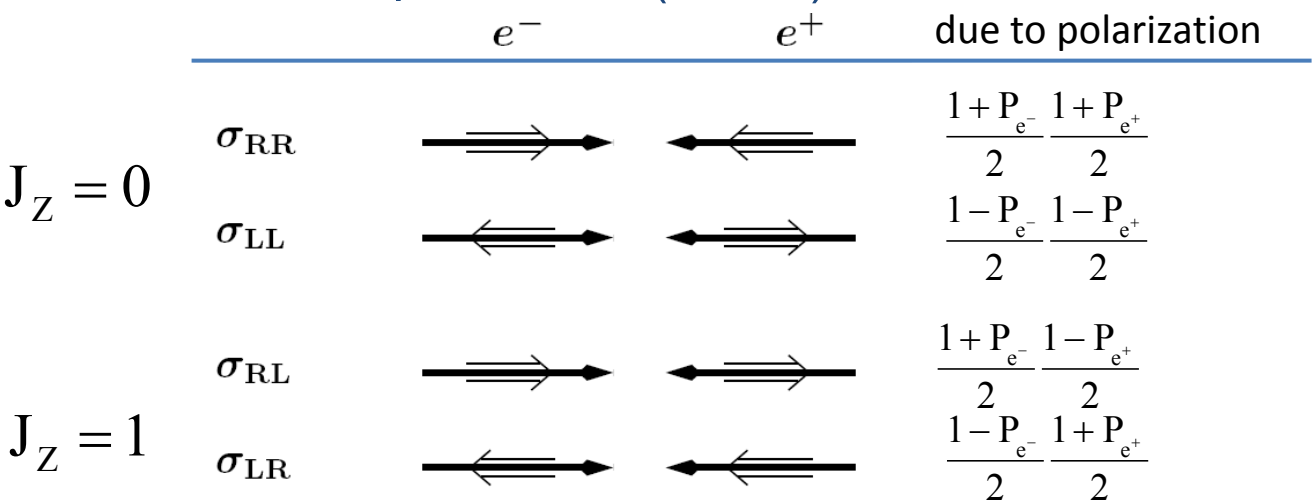
$$A_f = \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2} = \frac{g_{Lf}^2 + g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

$$\frac{g_{Vf}}{g_{Af}} = 1 - 4 \left| Q_f \right| \sin^2 \theta_{eff}^f$$

- Model–independent determination of left- and right-handed coupling
- Higher sensitivity to physics beyond the SM
- Suppression of background
- enhancement of signals

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

Consider s-channel processes (ee→ff)



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

If both beams are polarized

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

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

σ_0 - unpolarized cross section

If only e- beam is polarized, e+ beam unpolarized → measure only σ_L and σ_R

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

$$P_{e-}$$

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

Consider s-channel processes (ee→ff)

		e^-	e^+	Contribution due to polarization
$J_Z = 0$	σ_{RR}	$\Rightarrow$	$\Leftarrow$	$\frac{1+P_{e^-}}{2}\frac{1+P_{e^+}}{2}$
	σ_{LL}	$\Leftarrow$	$\Leftarrow$	$\frac{1-P_{e^-}}{2}\frac{1-P_{e^+}}{2}$
$J_Z = 1$	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+

If both beams are polarized

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

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

σ_0 - unpolarized cross section

Measurement with equal number of (+ -) and (- +) helicity pattern only increases effective luminosity

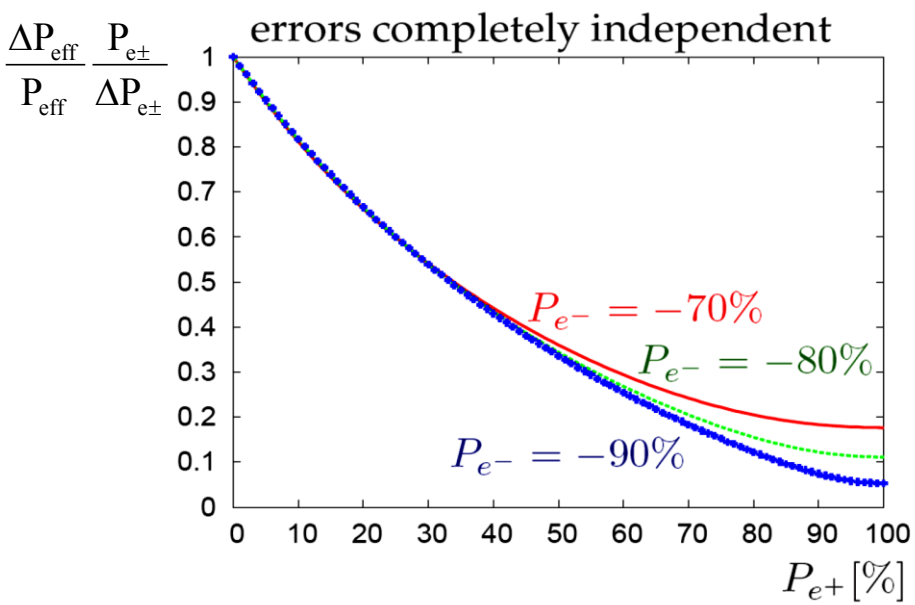
$L_{eff} = (1-P_{e+}P_{e-})$ → for $(P_{e+};P_{e-}) = (\mp 80\%; \pm 60\%)$: L is factor ~1.5 higher

Left-Right asymmetry A_{LR}

- A_{LR} is sensitive to parity violation

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

- 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)

Polarized lepton beams

Goal

- Additional observables:
  - Left-right asymmetry
  - Forward-backward left-right asymmetry
- Model–independent determination of left- and right-handed coupling
- Higher sensitivity to physics beyond the SM
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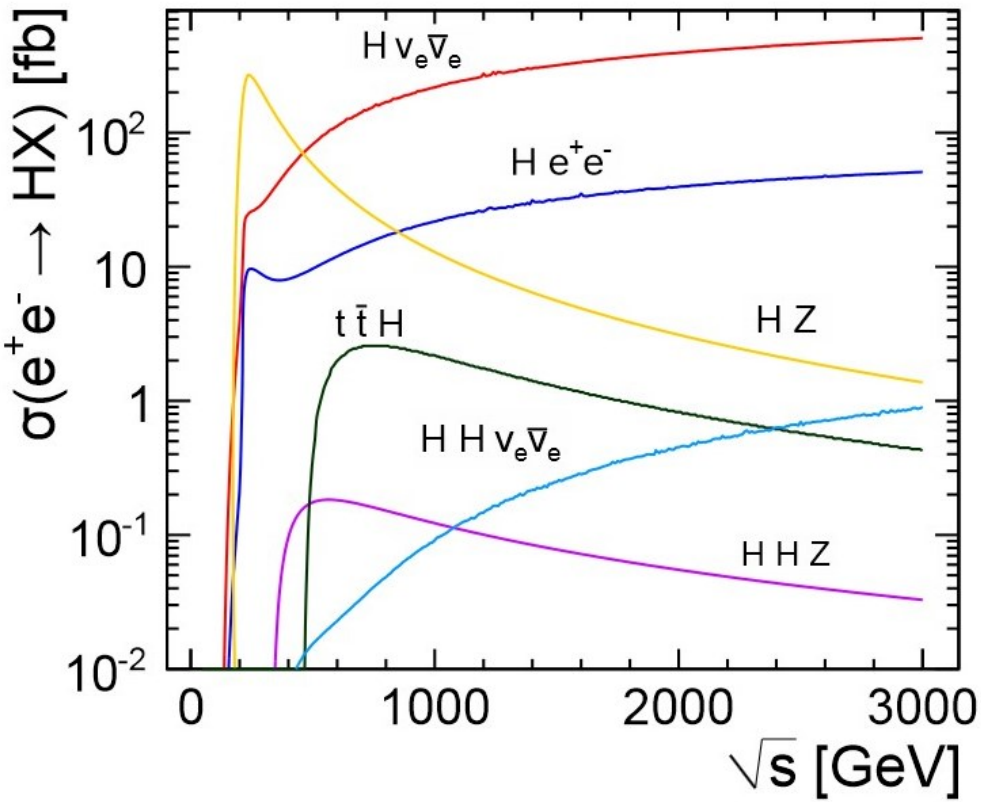
With polarized e+ <u>and</u> e- beam:

- Enhancement of luminosity ⇔ <u>important for linear colliders</u>
- Decrease of polarization uncertainty for LR asymmetry measurements

e+e- Colliders: Higgs factory

Higgs within achievable accuracy at LHC: SM-like

- Could be the only SM Higgs
- Could be a SUSY Higgs (one has to be close to a SM-like one)
- Could be a composite state



P(e+,e-) = (0,0)

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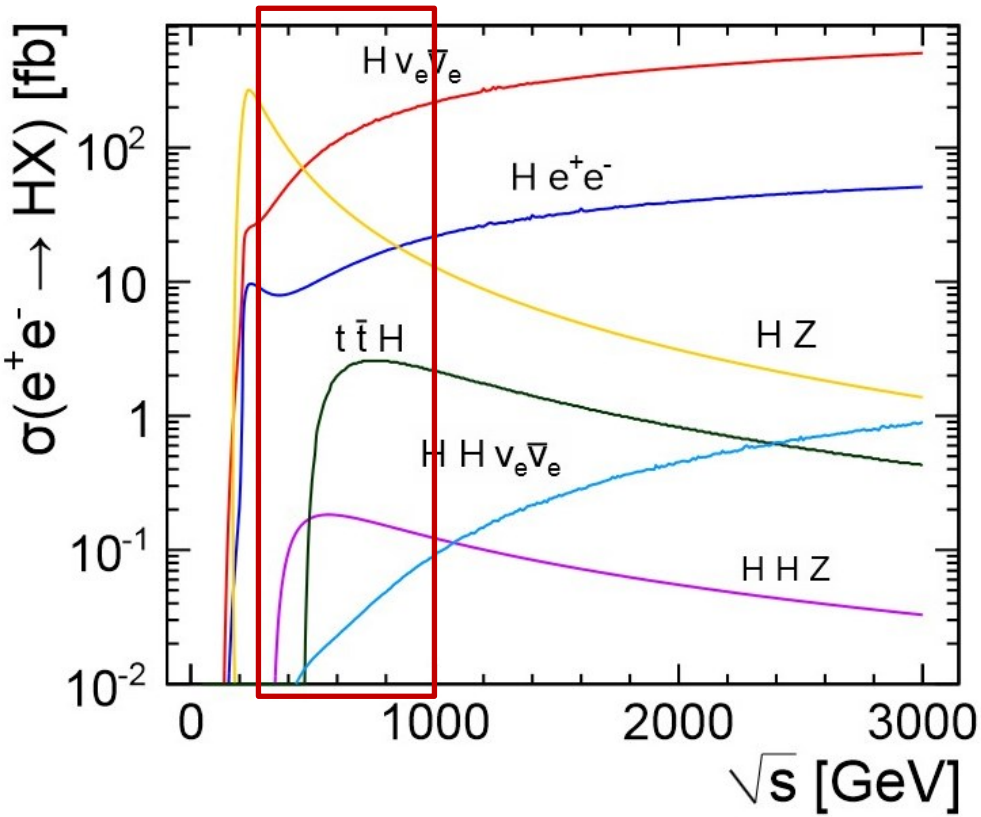


P(e+,e-) = (0,0)

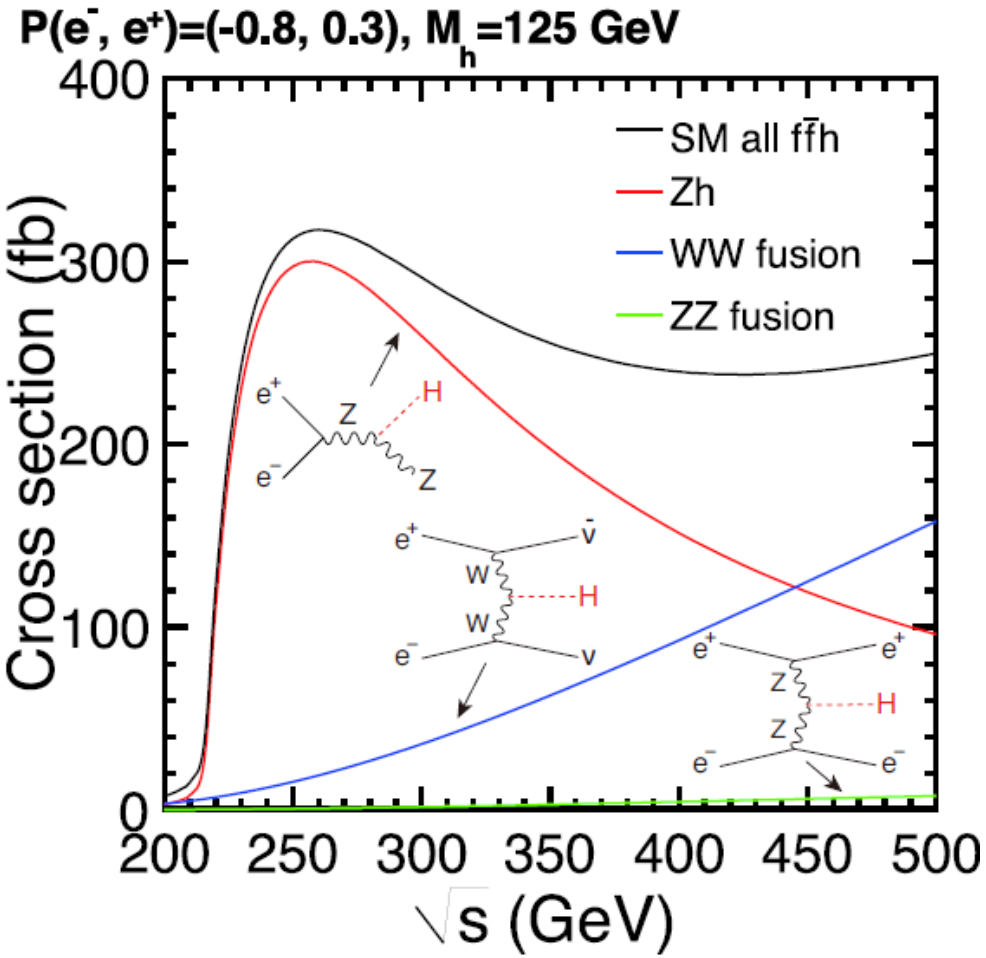
Goal with polarized beams

arXiv:1506.05992

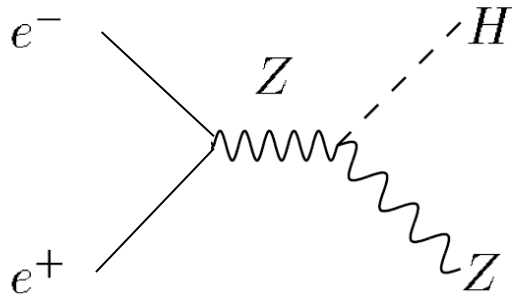
Linear collider with polarized beams:

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

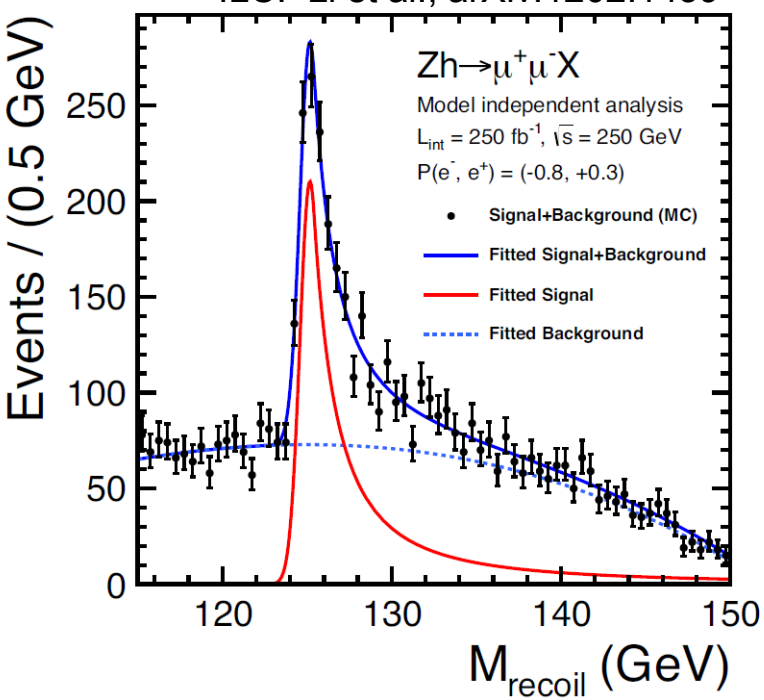
- Enhancement of WW, ZZ Fusion processes → selection of Higgs reactions



Higgsstrahlung: Coupling to the Z boson



ILC: Li et al., arXiv:1202.1439



arXiv:1506.05992

e+e- → ZH

- Reconstruct Z in lepton and quark channels
- Higgs becomes visible in the mass spectrum recoiling against the Z

$$M^2_{recoil} = (p_{e+e-} - p_Z)^2$$

→ Higgs mass and coupling:

(without reconstructing H)

Peak position ⇔ H mass, Δm_h < 30 MeV

Peak height ⇔ $\sigma_{HZZ} \sim g_{HZZ}^2$

→ Model-independent measurement of HZZ coupling

$\Delta g_{HZZ}/g_{HZZ} \approx 0.6\%$ (ILC 500)

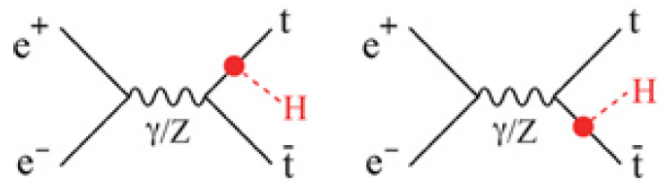
$\approx 0.3\%$ (ILC500 high L)

Higher lumi improves precision

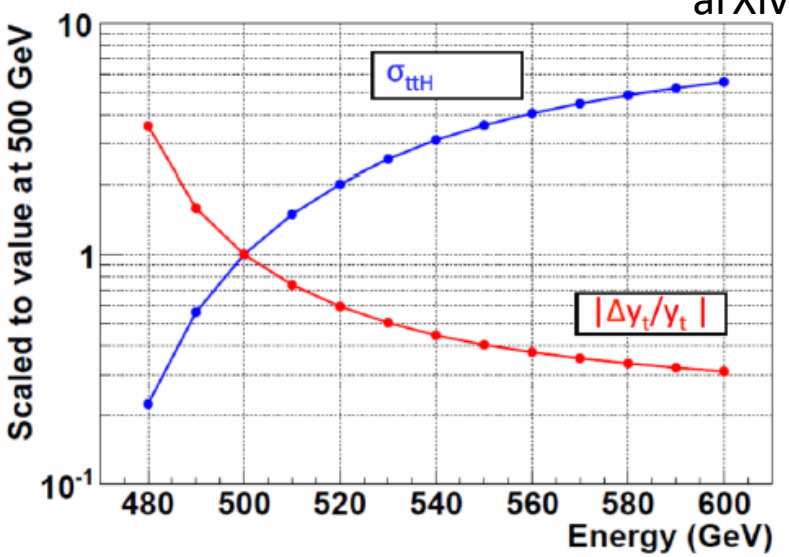
Top-quark Yukawa coupling at LC

- Strongest coupling to Higgs boson
- g_{Htt} is sensitive to unexpected effects
- Should be measured model-independent
- E > 480GeV is required

e+e- → Htt
H → bb



arXiv:1506.07830, Duerig EPS2015



σ_{tt} and relative precision of top Yukawa coupling

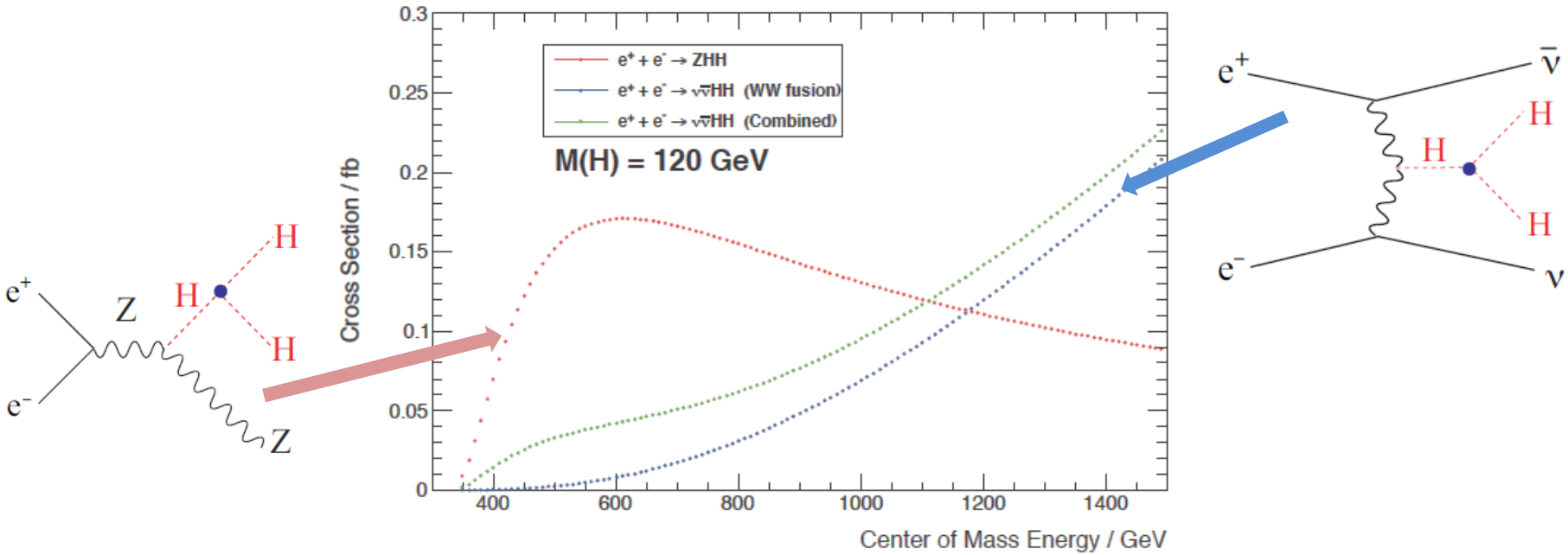
$\Delta g_{Htt}/g_{Htt}$	ILC 500 GeV	ILC 500GeV, Lumi upgrade
500GeV	18%	6.3%
550GeV	~9%	~3%

Increase √s by 10% → precision improves by factor 2 for same integrated luminosity

Higher lumi improves precision

Trilinear Higgs coupling at LC

arXiv:1506.05992



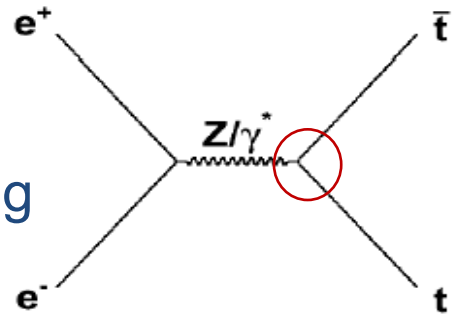
- Also at LC very challenging due to small rates ~0.2fb and huge background
- Full ILC data set (500GeV) → precision of 27% can be achieved
  - This would already be more than 3σ evidence for the existence of the Higgs self-coupling at the Standard Model value
- Upgrade to 1TeV: ~16% for 2000fb^{-1} and 10% for 5000fb^{-1}

Polarized e+ and e- beams improve selection of processes

Electromagn. and weak top quark coupling

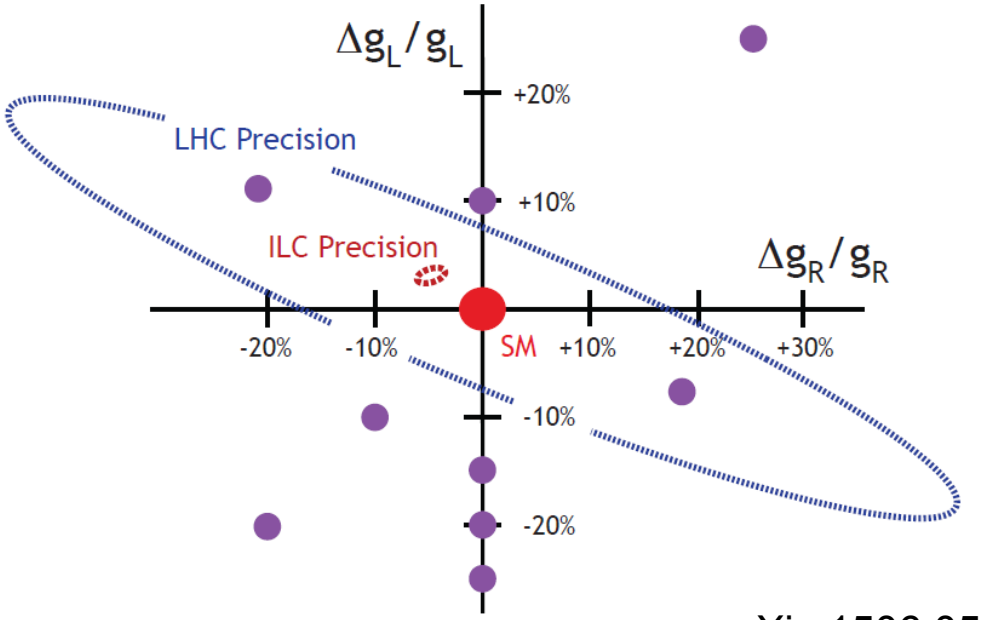
- Polarized beam, measure forward-backward asymmetry for two beam polarizations

→ measurement of left- and right-handed top coupling to γ and Z



Top coupling is sensitive to new physics:

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

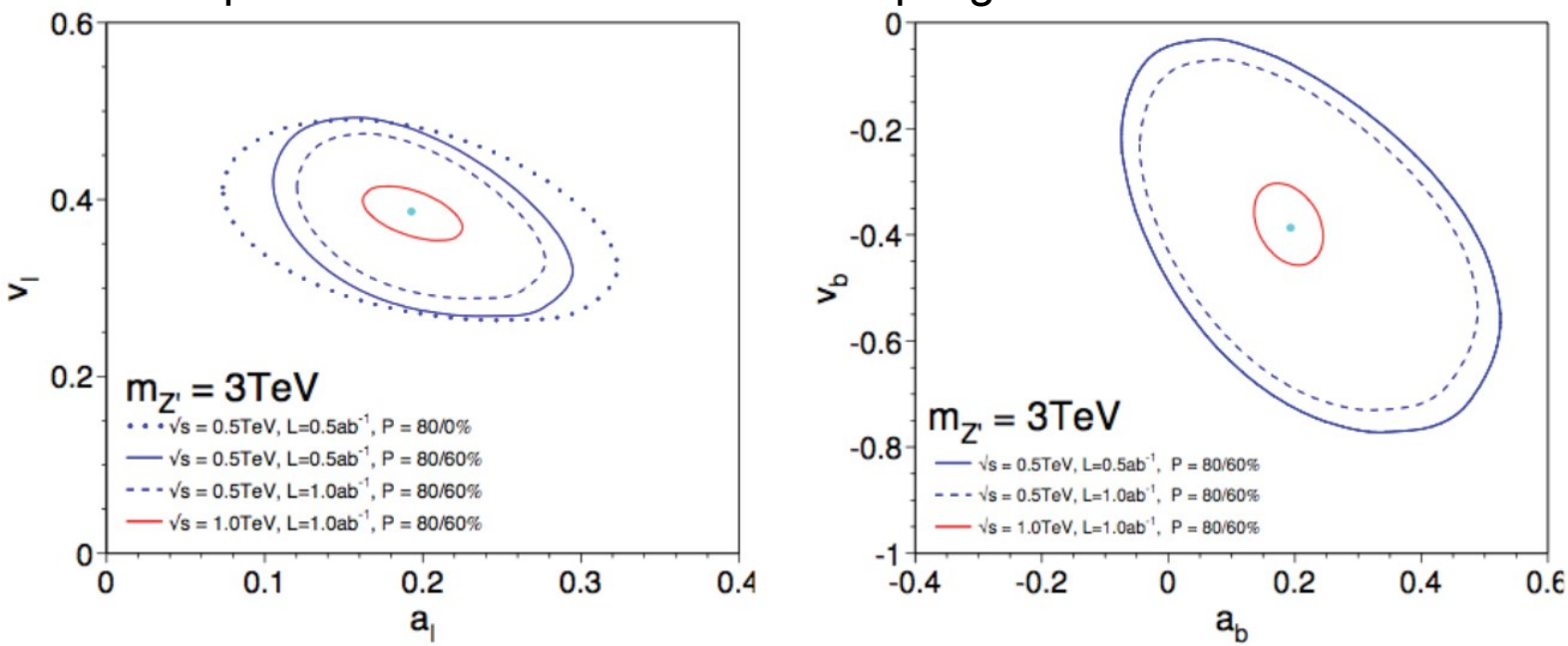


arXiv:1506.05992

Physics beyond the SM at LC

- Precision measurements allow indirect search for new phenomena, even beyond the LHC reach
- Deviations from SM prediction ⇔ new physics models
- Polarized beams ⇔ resolve ambiguities, improved distinction between models

Model-independent determination of Z' coupling



Z' vector and axial vector couplings to leptons and b quarks from fermion-pair production (χ model reproduced in a model-independent fit)

Physics at the Z Pole

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

A_{LR} measurement at the Z pole
"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) $$\frac{v_e}{a_e} = 1 - 2\sin^2\theta_{eff}^{lept}$$

polarization error ΔP could dominate ΔA_{LR}

- Perform 4 independent measurements with different helicity combinations

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

- determination of P_{e+} and P_{e-}, and A_{LR} simultaneously

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

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

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

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

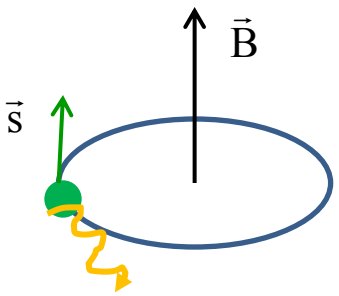
Energy	Reaction	Physics Goal	Polarization
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak	Left-Right asymmetry
160 GeV	$e^+e^- \to WW$	ultra-precision W mass	Enhancement of lumi
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings	
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings	Left-Right 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; lumi
	$e^+e^- \to t\bar{t}h$	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

Polarization in high energy e+e- colliders

- Longitudinal polarization for physics
- Precision measurement of energy
  - Storage rings:
    - Transverse beam polarization / LEP: Sokolov-Ternov effect
    - resonant depolarization (LEP: $\Delta E/E \sim 10^{-5}$)
  - linear e+e- colliders (ILC, CLIC)
    - Resonant depolarization does not work
    - Goal (ILC): $\Delta E/E \sim 1\text{-}2 \times 10^{-4}$
      - Energy spectrometers before and after collision point to measure energy distribution
- Precision polarimetry

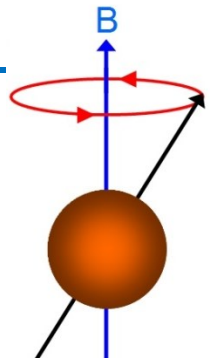
Polarization in storage rings

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 $$P_\infty = 0.924 \frac{1}{1+\tau_P/\tau_d}$$
  - In a real machine depolarization effects occur
    → asymptotic polarization is reduced and is achieved after effective polarization raise time $$\tau_p^{eff} = \frac{\tau_P}{1+\tau_P/\tau_d}$$
- Ideal storage ring: polarization is along vertical direction
- Real storage ring: perturbation → spin precession

Resonant depolarization



- Motion of spin vector of relativistic electron in presence of magnetic field ⇔ spin precession with f_{spin}

$$\frac{d\vec{s}}{dt} = \vec{\Omega}_{BMT} \times \vec{s} \quad \text{with } \vec{\Omega}_{BMT} = -\frac{e}{\gamma m_0}\left[(1+a\gamma)\vec{B}_{\perp} + (1+a)\vec{B}_{\parallel}\right] \quad \text{and } a = (g-2)/2$$

- number of spin oscillations per revolution is defined as spin tune ν (ideal storage ring)

$$\nu = \frac{f_{spin}}{f_{rev}} = \frac{a}{m_0 c^2} E_{beam} = \frac{E_{beam}[\text{MeV}]}{440.6486\ \text{MeV}}$$

  – spin tune is related to the energy of the particles
- If a perturbation is in phase with the nominal spin precession the polarization vector is resonantly rotated away from the vertical direction
- 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

Exciting depolarizing resonance f_{dep} → very precise beam energy measurement is possible; $\Delta E/E \sim 10^{-5} \ldots 10^{-6}$

Transverse polarization in FCC-ee

- Useful level for energy calibration: 5-10%; physics needs higher polarization
  - FCC-ee: beam energy 45 – max 175 GeV
  - long time to build up transverse polarization at Z pole

    $2\pi R$ = circumference of isomagnetic ring,
    ρ = bending radius

$$\tau_P = 98.66 \frac{\rho^3}{E^5} \frac{R}{\rho}$$

  τ_p **is ~270h for FCC-ee at Z pole** (Mane, arXiv:1406.0561)
- Introducing wiggler magnets (at least for the Z pole running)

  → increasing synchrotron radiation
  → decrease polarization build-up time
  But: wigglers increase beam energy spread

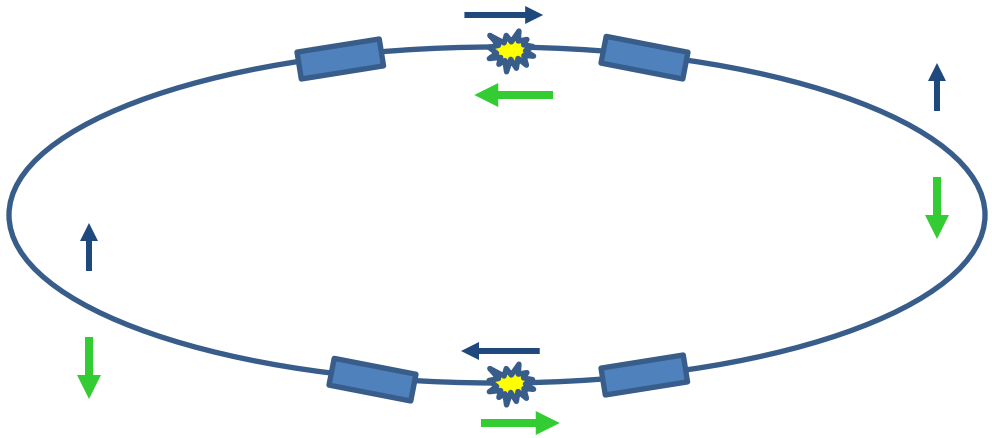
- Beam energy spread:
  - Beam energy spread enhances depolarization
  - At LEP beam energy spread destroyed polarization above 60 GeV;
  - energy spread rises with E^2_{beam}, it reached almost the same magnitude as the 440MeV energy spacing between two consecutive linear spin resonances

$$f_{dep} = (k \pm [\nu]) \cdot f_{rev} = \left(k \pm \left[\frac{E_{beam}[\mathrm{MeV}]}{440.6486\mathrm{MeV}} \right] \right) \cdot f_{rev}$$

- difficult to get higher P for E_{beam}>120GeV. P@FCC-ee is under study

Longitudinal polarization for physics

- Linear colliders (ILC, CLIC):
  - Sources generate longitudinally polarized e- and e+
  - Spin rotators at arcs/turnarounds
  - Very low depolarization in accelerator (one-way)
- FCC-ee
  - Use Sokolov-Ternov polarization, wigglers, or 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

Polarization measurement

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

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

- Compton polarimeters will be used to measure and to control e+ and e- polarization
- Blondel scheme → use annihilation data to determine beam polarization

- Goal
  - ILC: determine luminosity-weighted polarization at per-mille level ⇔ polarization error should not limit the precision of measurement. ΔP ~ 0.25% seems possible (see ILC TDR & related studies);
    at SLD ΔP ~ 0.5% was reached
  - FCC-ee: due to high statistics the uncertainty of the polarization measurement could limit the precision of observables . Studies needed.

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 huge effort

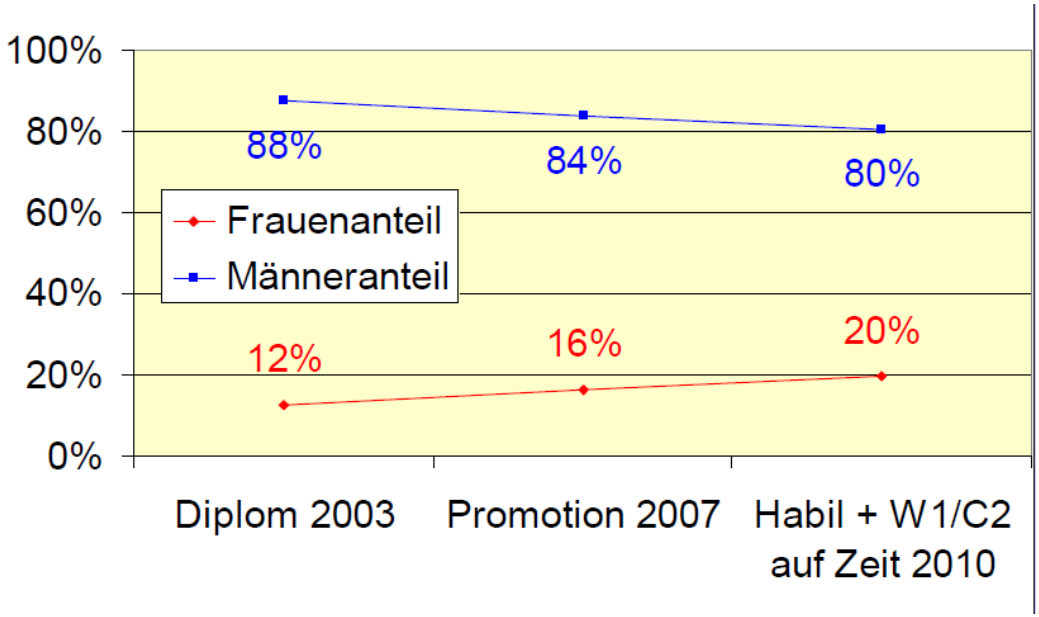
Summary

- Polarized beams at lepton colliders increase the physics potential and the precision of measurements
- Beam polarization is very useful to discriminate new physics phenomena; highest flexibility if both beams are polarized
- ILC, CLIC are designed with polarized e-, e+ sources
- polarization at ring colliders (FCC-ee) is a challenge and is under study
- Precision measurements with polarized beams require excellent polarimetry and spin tracking to determine the luminosity weighted polarization at the collision

Congratulations, Professor Muehlleitner!

Congratulations, Professor Muehlleitner!

Equal opportunity commissioner of the Faculty of Physics (KIT)



https://www.dpg-physik.de/dpg/gliederung/ak/akc/projekte/Meyer_Statistiken_DPT-2012.pdf

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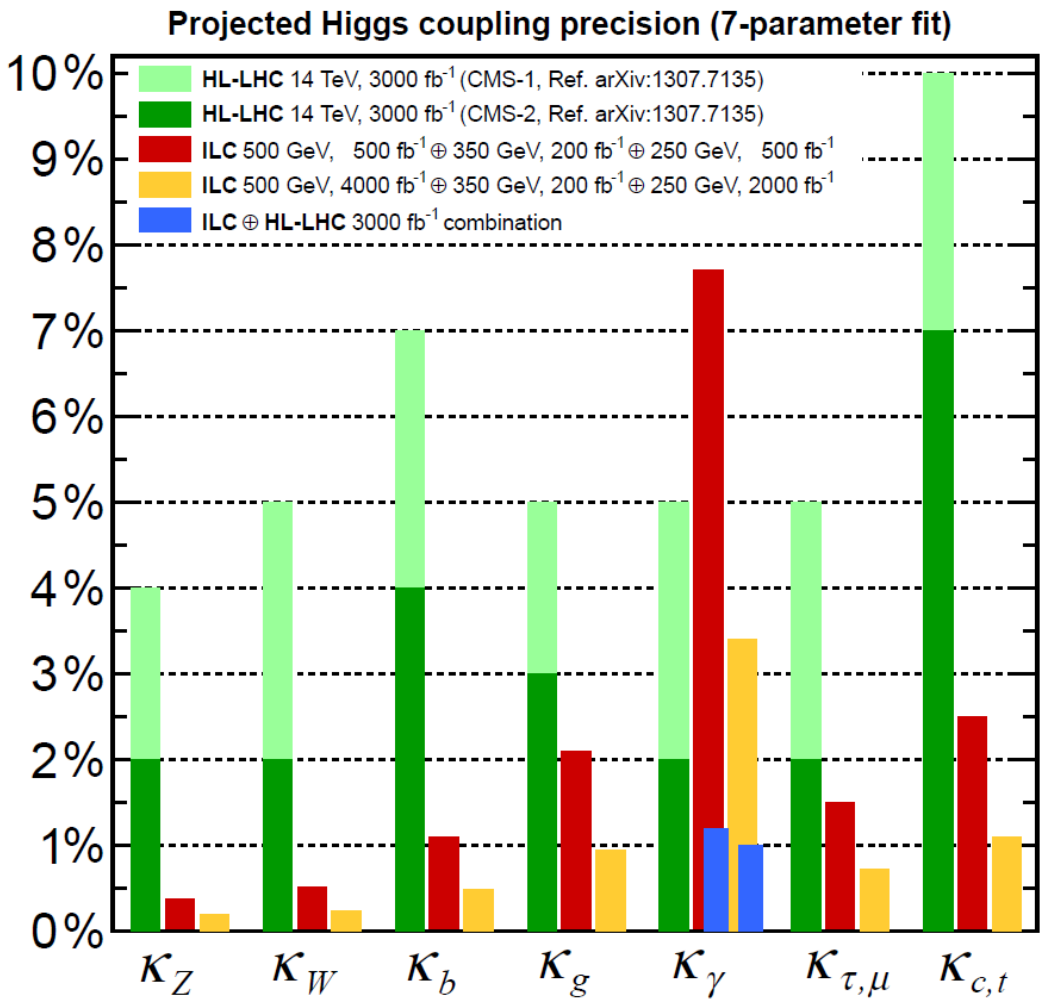
Precision of Higgs boson coupling

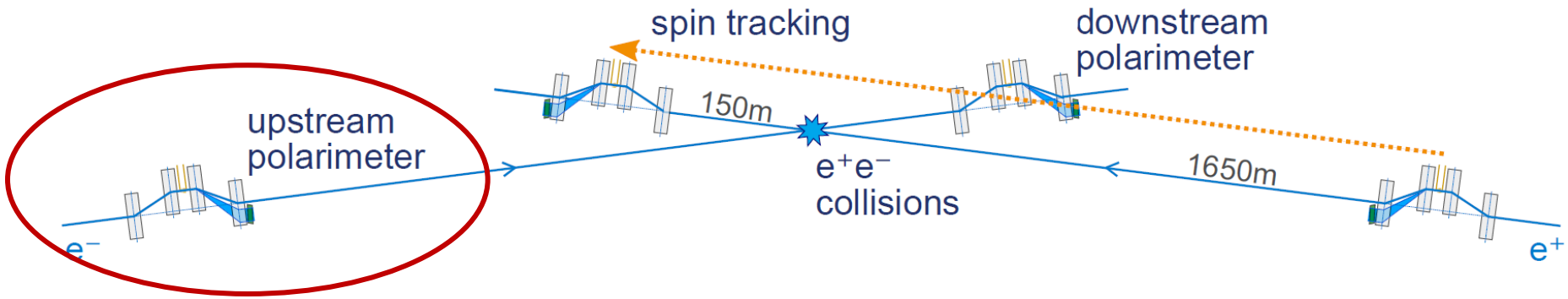
arXiv:1506.05992



Shown is the relative precision; $\kappa_A = \frac{g_{A\bar{A}h}}{g^{SM}_{A\bar{A}h}}$

Principle of polarization measurement at ILC

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



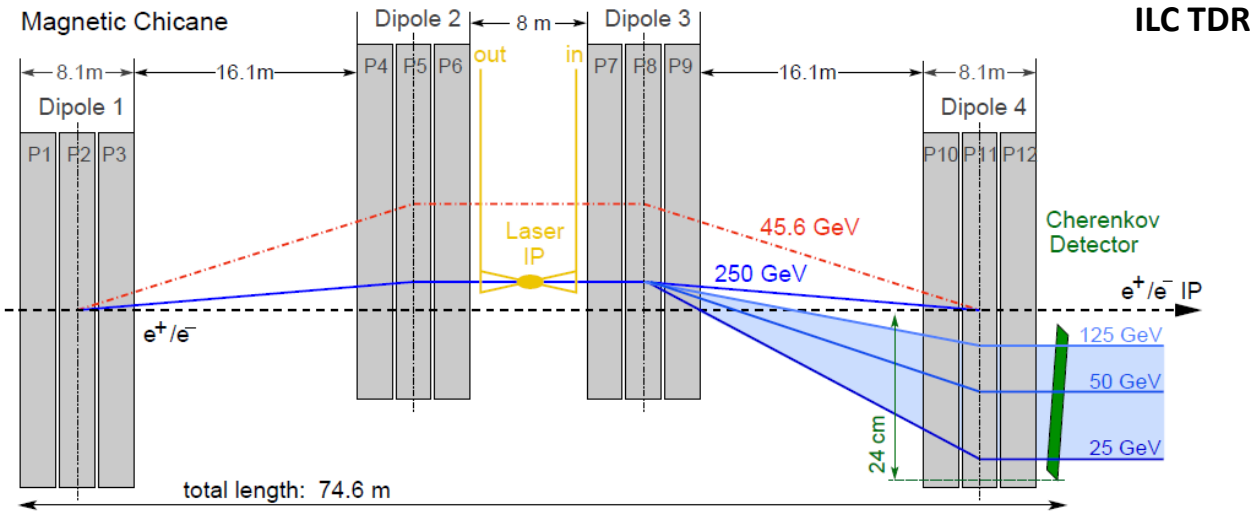
J. List

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

ILC: Upstream Compton polarimeter

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

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

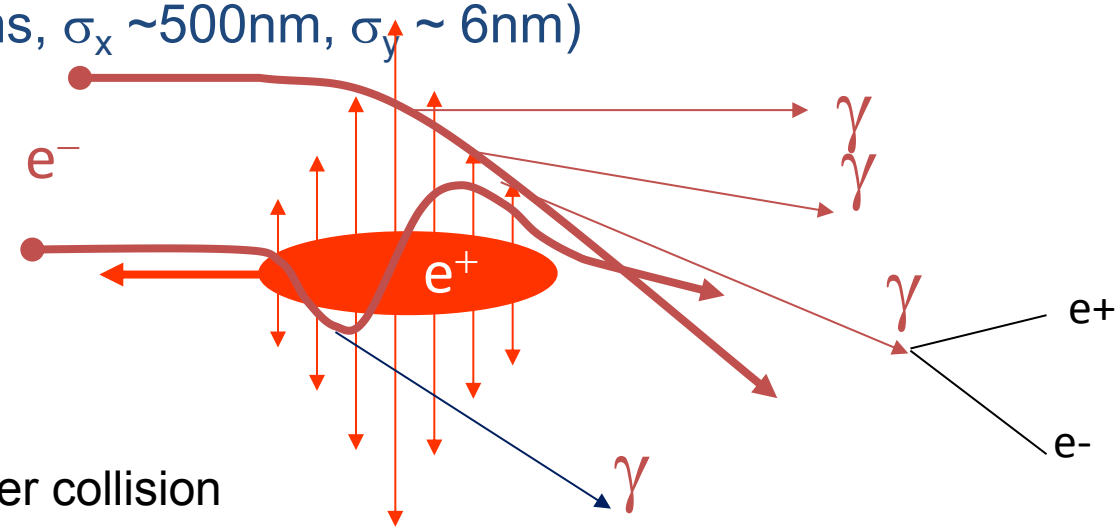


- Energy spectrum of scattered e- (e+) depends on product of circular polarization of laser P_γ (left, right) and longitudinal polarization Pe-, Pe+
- Spectrometer chicane (4 dipoles): energy distribution → position distribution
- Measure asymmetry of scattered e± for L, R laser polarization ➔ Pe±

Polarization measurement at ILC

- 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



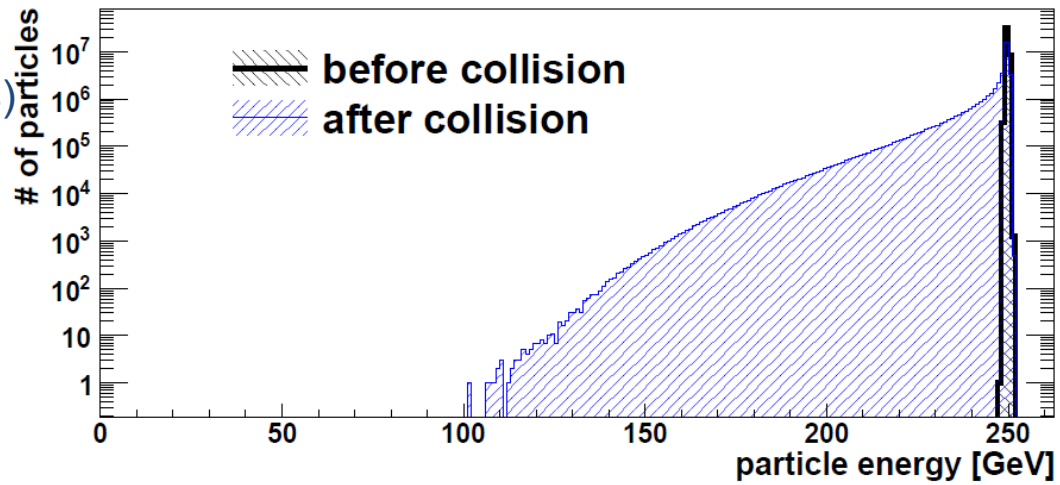
  - Beams are disrupted after collision

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

Polarization measurement at ILC

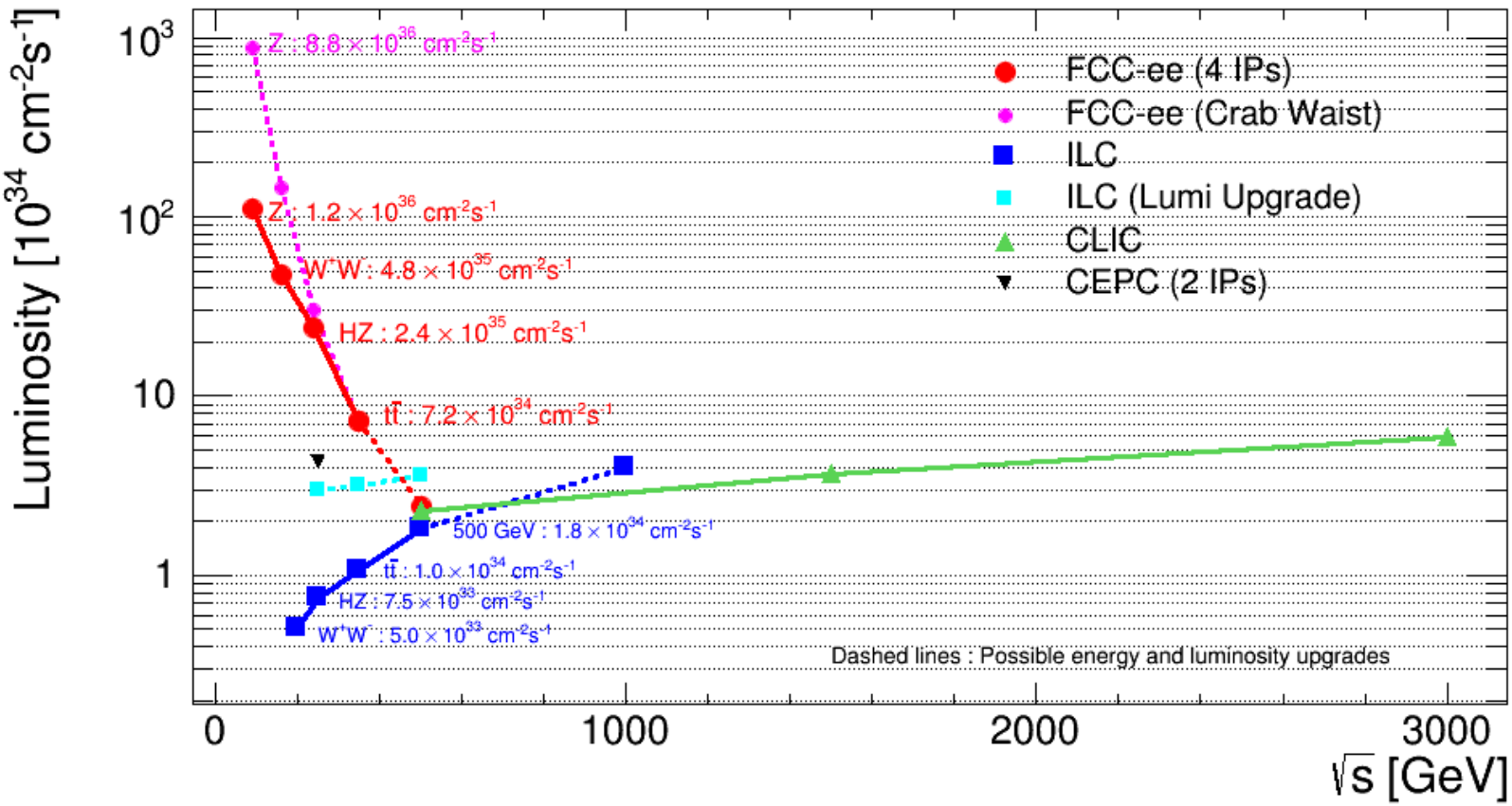
- Beam energy spectrum before and after collision (GuineaPig++, ILC RDR parameters)
- Beam is 'disrupted' → laser spot of Compton polarimeter hits only central part of the spent beam

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)

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

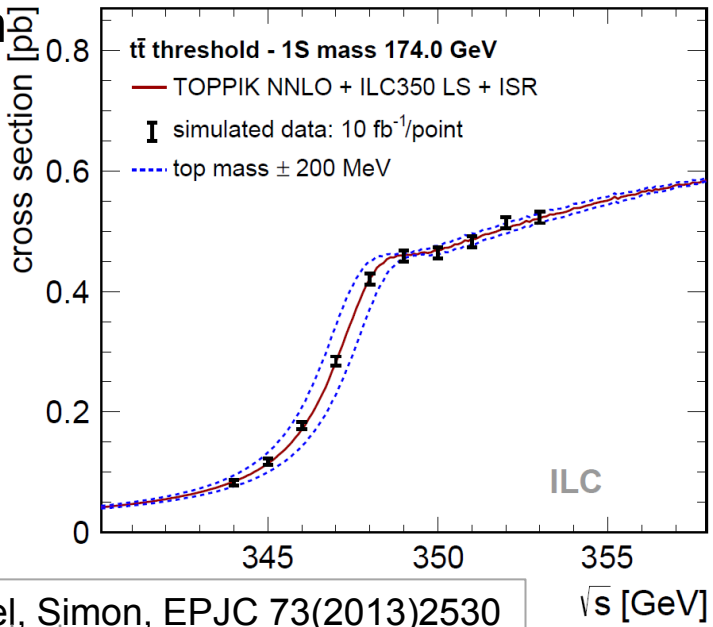


Top quark at LC

The top quark mass is a basic input parameter for the SM
So far, top quark has been directly studied at hadron colliders

ILC: ttbar threshold scan

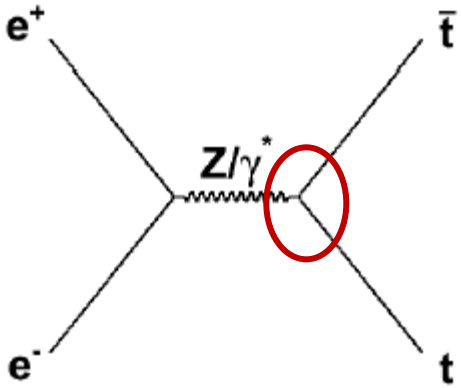
- The real part of the pole xs corresponding to the 1S bound state can be extracted
- This mass parameter can be determined to about 50 MeV
  The accuracy is limited by the precision of the theoretical prediction of the threshold shape
- Expect for the 200 fb^{-1} at ~350 GeV:
  (Barklow et al, arXiv:1506.07830)
  statistical errors (3-parameter fit)
  - 17 MeV for m_t,
  - 26 MeV for Γ_t



Seidel, Simon, EPJC 73(2013)2530

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):

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

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

$$\tilde{F}_{1A}^X = -F_{1A}^X \qquad \tilde{F}_{2A}^X = -iF_{2A}^X$$

$$F_{1A}^\gamma = 0 \qquad F_{1A}^Z = \frac{1}{4s_w c_w} \qquad F_{2A}^X \propto d_A^X$$

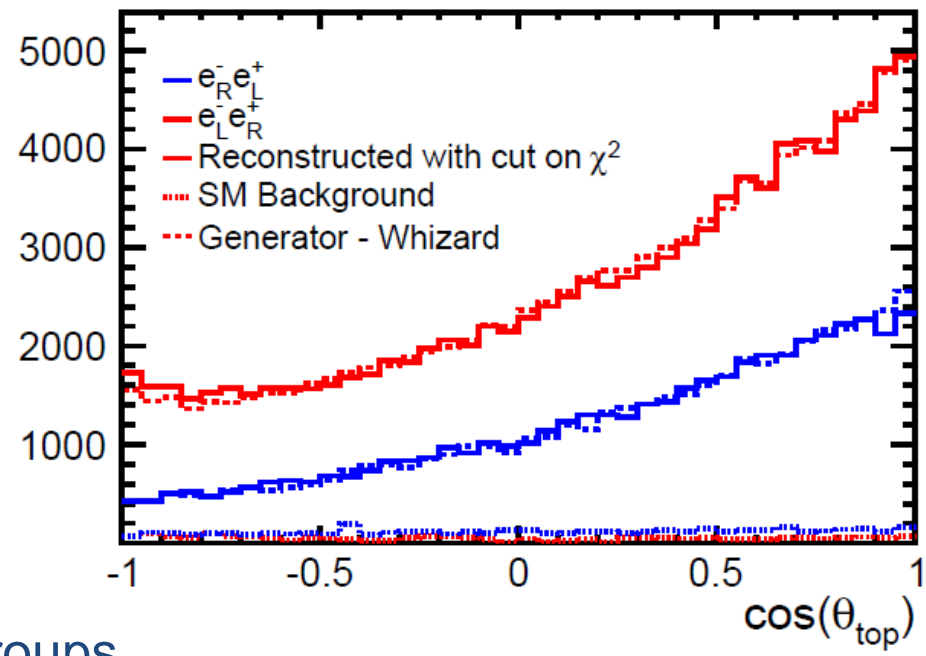
d = dipole moment;
F_{2A} violates CP

Top-quark coupling

- Polarized cross section for tt production

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

arXiv:1307.8102

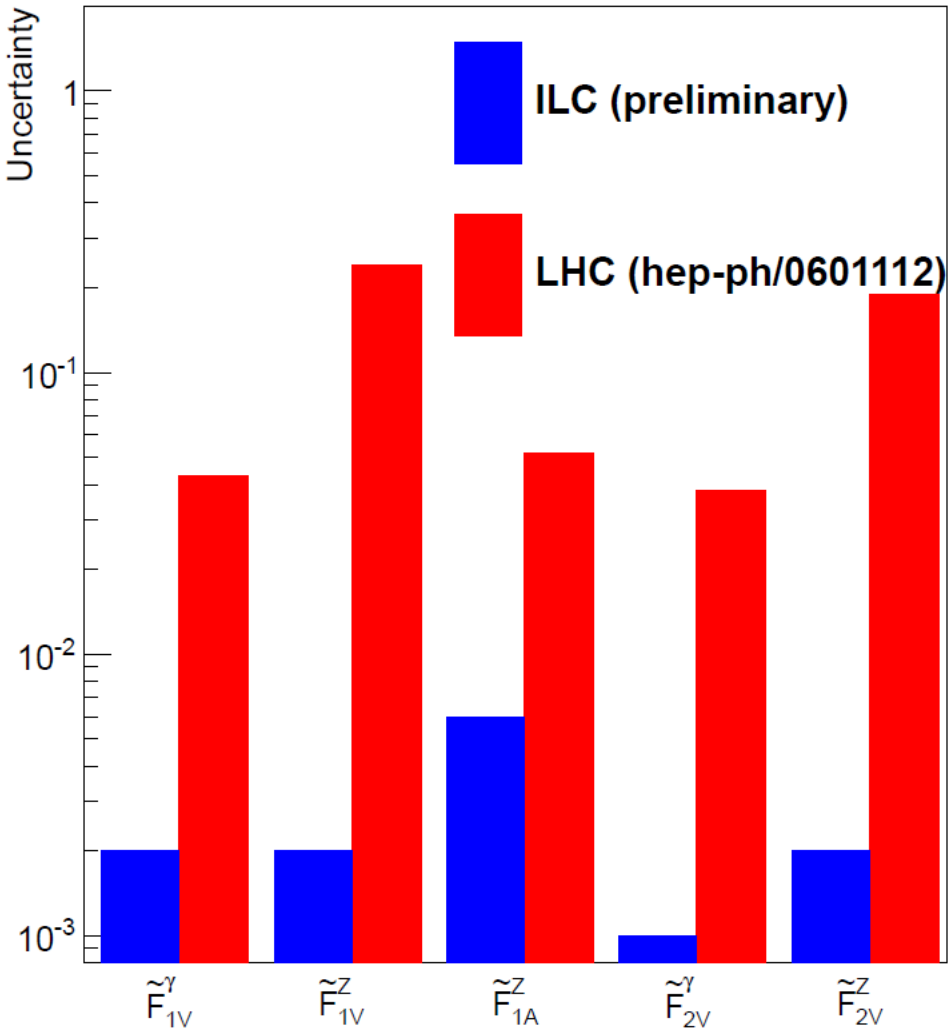


- measure forward-backward asymmetry for 2 beam polarizations
- Extract form factors in groups assuming SM for remaining groups
- Polarization is decisive to distinguish top coupling to Z and γ
- sign of form factors is fixed by γZ interference

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)