Heavy flavor physics at ILC

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LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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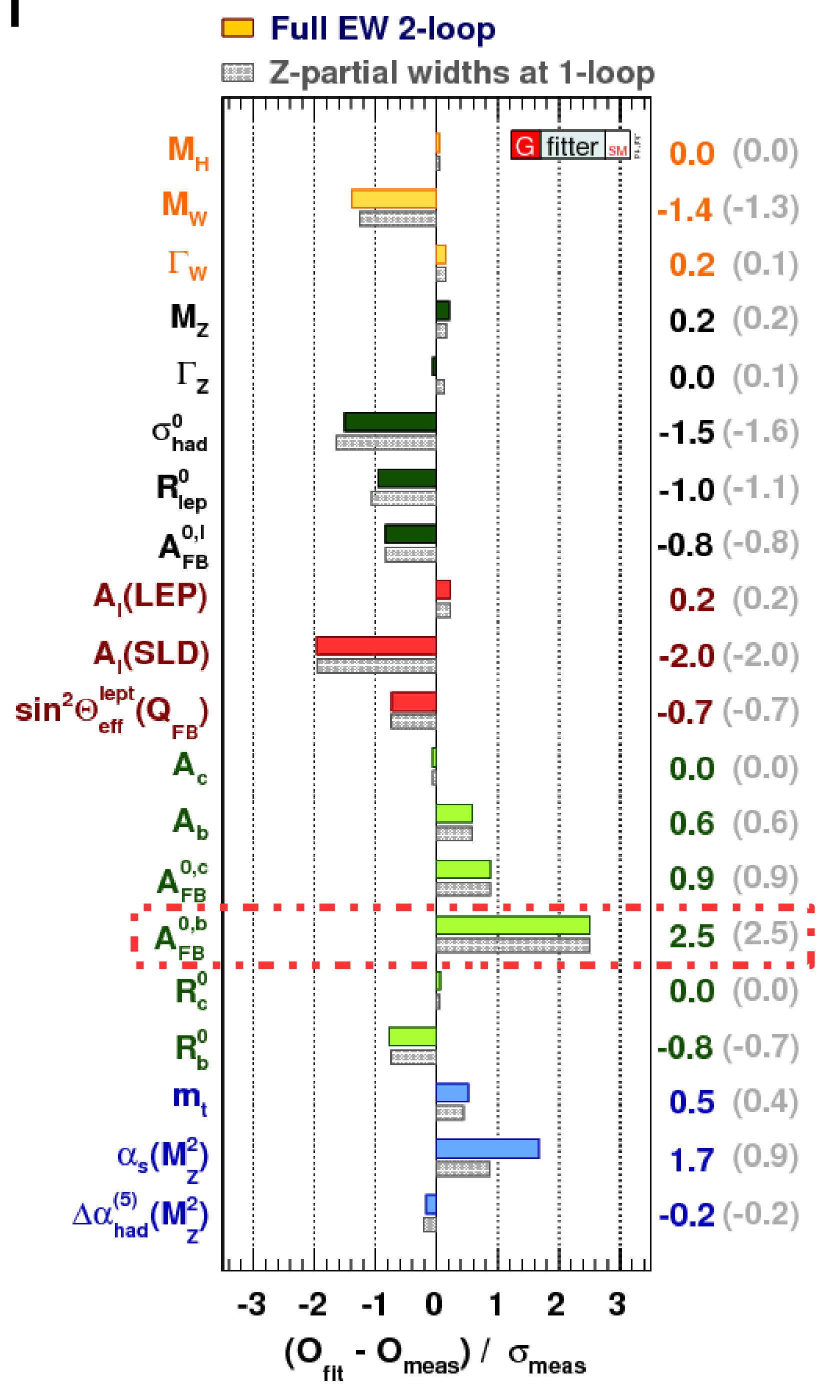
Motivation

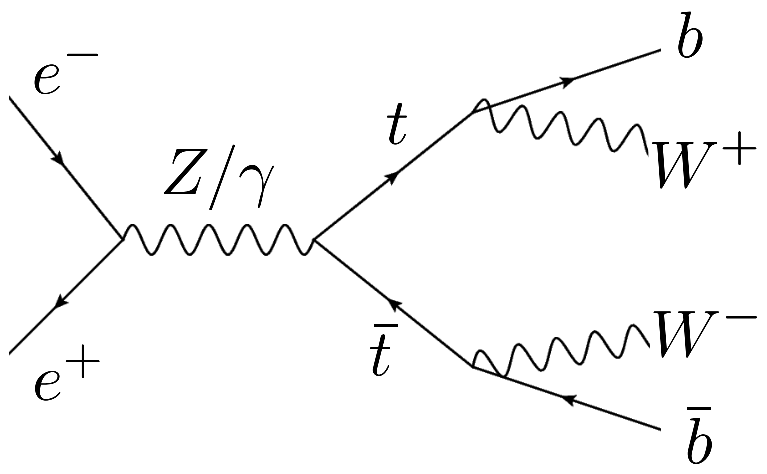
- Top quark is the heaviest elementary particle in the SM
- Top quark is subject of many BSM theories,
  - i.e. composite top or Randall-Sundrum models predict deviations for the EW couplings of the top quark
- The top and bottom quarks belong to one doublet
- Forward-backward asymmetry measurement at LEP has 2.5σ tension with the SM prediction
- We need to measure the heavy quark EW couplings
- We need to compute the theoretical predictions for the top quark production

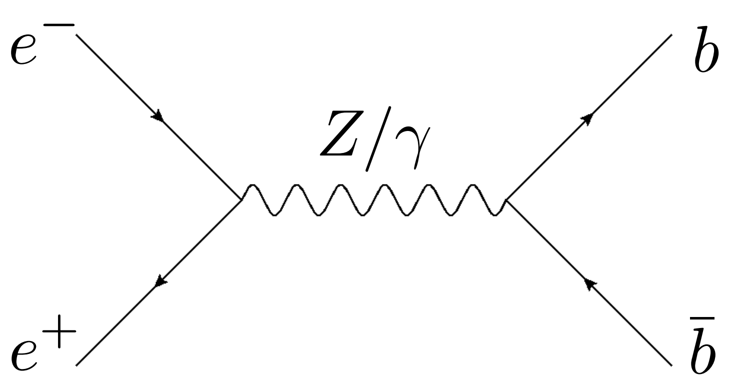


arxiv: 1407.3792v1

Heavy flavour at ILC

- Measurement of the heavy flavour quarks at the electron-positron machines:
  - Direct EW production
  - No competing QCD production
- Advantages of the ILC:
  - Operating at $\sqrt{s} = 500\,\mathrm{GeV}$ increases the sensitivity to top axial form factors, minimizes the QCD uncertainties
  - Polarized beams allow independent determination of the b-quark form factors
  - Highly granular 4π detectors allow for precise final state reconstruction using PFA





Content

- $e^+e^- \to b\bar{b}$ process
- Matrix element method for $e^+e^- \to t\bar{t}$
- NLO computation for $e^+e^- \to t\bar{t}$

$e^+e^- \to b\bar{b}$

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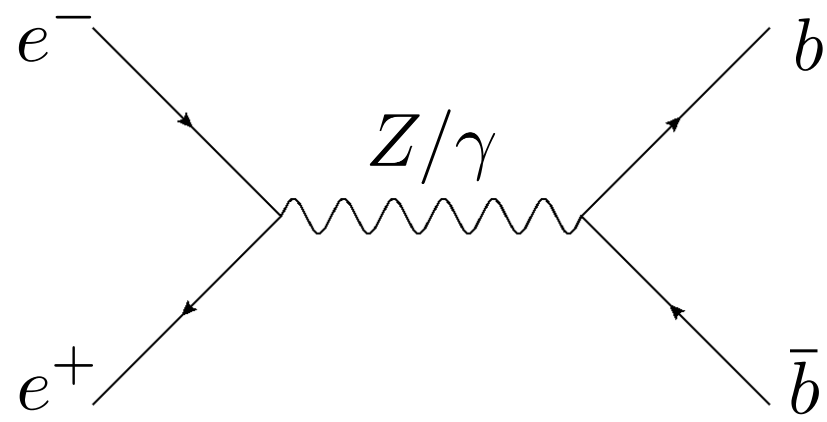
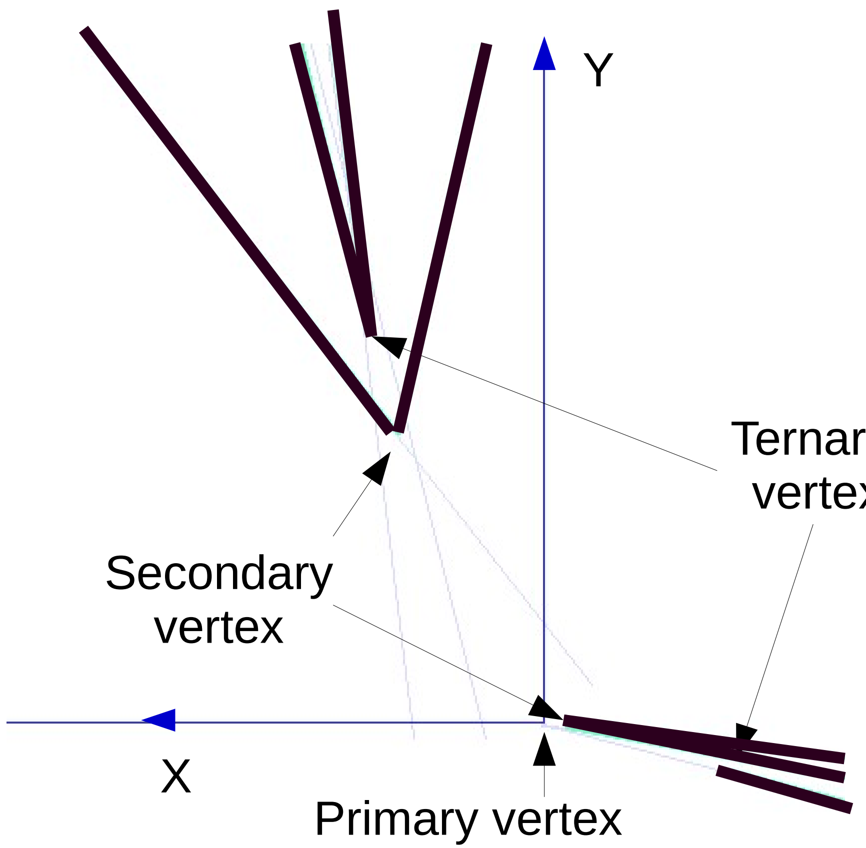
- Main purpose of this work is to define the electroweak couplings of the bottom quark using the b-quark polar angle measurement of the $e^+e^- \to b\bar{b}$ process
- Properties of decay products from the b-hadrons are used to determine the charge of initial b-quark
- Charge of the b-quark is calculated as a sum of the charges of secondary and ternary vertex particles
- The charge of K-mesons from reconstructed vertices is directly connected to the initial quark charge





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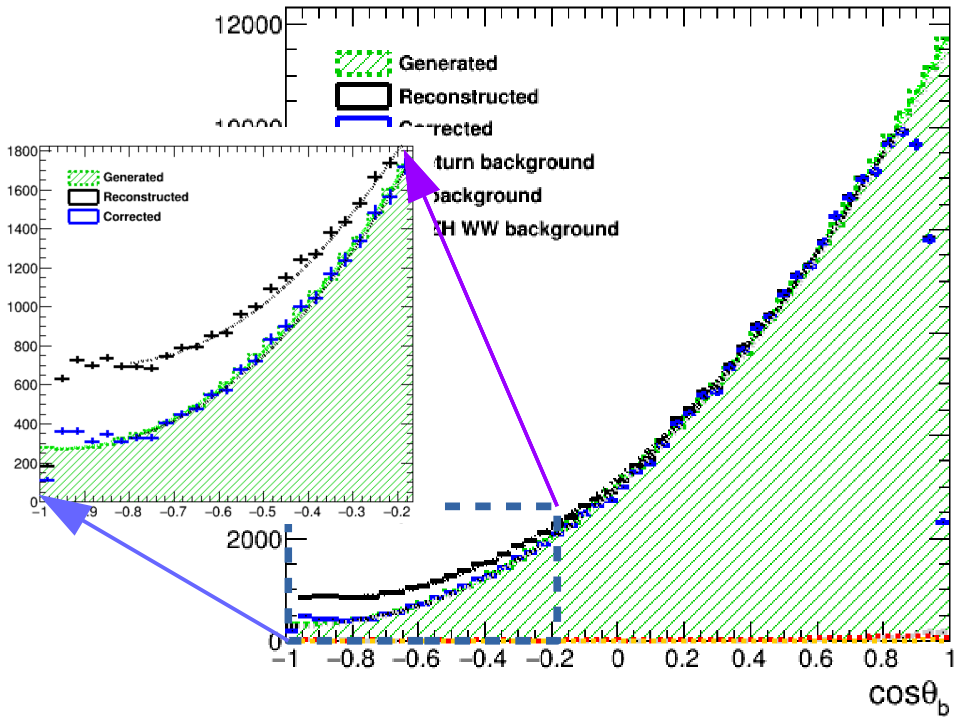
Bottom quark polar angle reconstruction

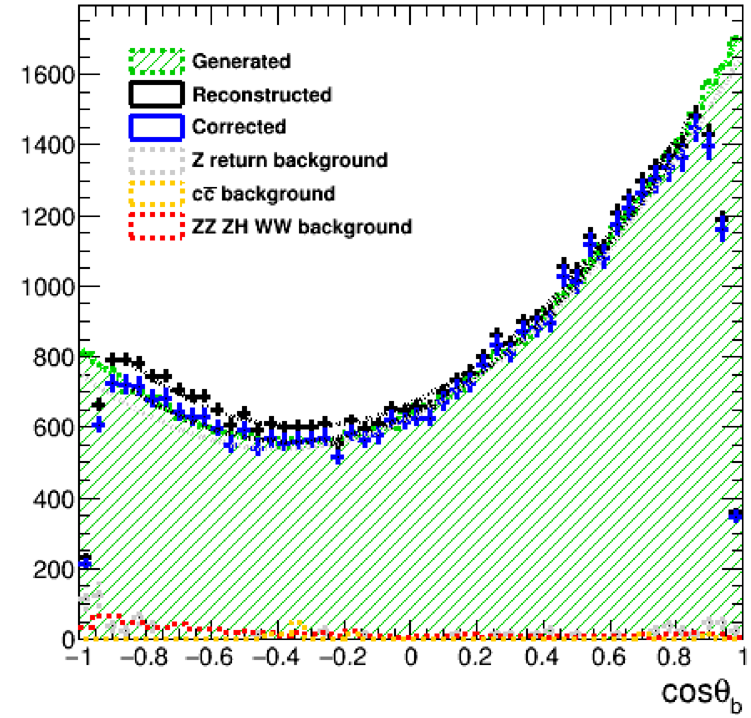
$$\sqrt{s} = 250\,\mathrm{GeV}\ \ L = 250\,\mathrm{fb}^{-1}$$

$e^-_L e^+_R \rightarrow b\bar{b}$



$A_{fb}^{rec}/A_{fb}^{gen} = 100.7\% \pm 0.62\%$

$e^-_R e^+_L \rightarrow b\bar{b}$



$A_{fb}^{rec}/A_{fb}^{gen} = 104.9\% \pm 2.25\%$

- The residual charge impurity cause a migration effect, which leads to discrepancy between the reconstructed and generated curves
- The developed correction procedure allows to measure the charge purity and correct for migrations using reconstructed events only

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Determination of the Form Factors

- We are measuring the differential cross section

$$\frac{d\sigma^I}{d\cos\theta} = A^I(1+\cos^2\theta) + B^I\cos\theta + C^I\sin^2\theta \qquad I = L, R$$

where the $A\ B\ C$ are

$$A^I \text{ cross section magnitude } \propto \mathcal{F}^I_{1V}, \mathcal{F}^I_{2V}, \mathcal{F}^I_{1A}$$

$$B^I \text{ asymmetry magnitude } \propto \mathcal{F}^I_{1A}, \mathcal{F}^I_{1V}, \mathcal{F}^I_{2V}$$

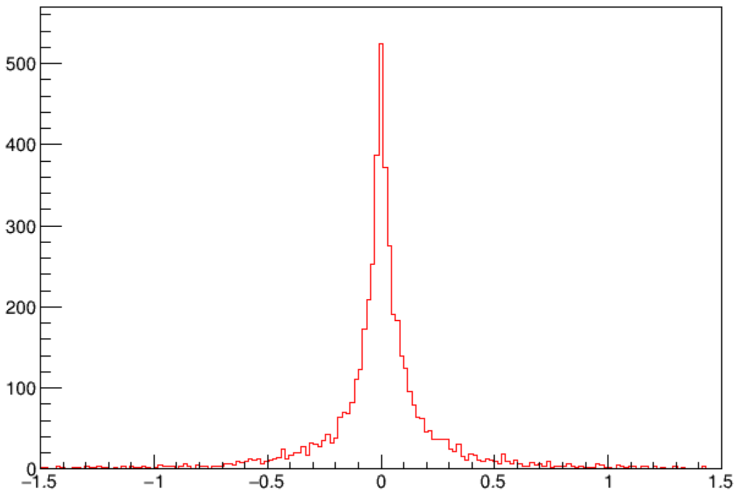
$$C^I \text{ spin flip } \propto \gamma^{-1}\mathcal{F}^I_{1V}, \gamma\mathcal{F}^I_{2V}$$

- One has 6 observables and 6 form factors to estimate
- Therefore, we can independently extract the form factors directly from the polar angle histograms
- PRELIMINARY: The expected precision on the form factors is ~0.5% for the left-handed polarization and ~1-2% for the right-handed polarization using two parameter fit

Matrix Element Method

MEM with di-leptonic state : $e^-e^+ \rightarrow t\bar{t} \rightarrow b\bar{b}l^-l^+\nu\bar{\nu}$

Full exploitation of all available information from decay products of top-pair



$\phi_{l^+,rec.} - \phi_{l^+,truth}$

* ϕ_{l^+} is one of angles associated with $t\bar{t}Z/\gamma$ vertex

Study based of the ILD full simulation

- $b, \bar{b}, l^-, l^+$ can be measured by the detectors
- Kinematical constraints (= 8):

  $\left(\sqrt{s}, \vec{P}_{\text{init.}}\right) = \left(500, \vec{0}\right), m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}$

→ Recover directions of $\nu, \bar{\nu}$ (= 6)

→ Two constraints in excess can be used to define the b-jet assignment

All final state particles can be reconstructed

Precision of form factors

Fit of all 10 form factors

di-muonic samples (~1/4 of di-leptonic state)

$\sqrt{s}$ = **500 GeV, 500 fb^{-1}**, (P_{e^-}, P_{e^+}) = **($\pm$0.8, $\mp$0.3)**

(eg.)	Precision of $\tilde{F}_{1V}^{\gamma}$	$N_{\text{signal}}/N_{\text{di-muonic}}$
This result	**0.0088**	**1**
Parton level study	**0.0037**	**~4**

- Precision is kept in good condition after considering the detector/hadronization effects.
- Some biases are observed (eg. $\tilde{F}_{1A}^{Z}, \tilde{F}_{2V}^{\gamma}$)

→ One can reduce them by convoluting the resolution function of angles with $|M|^2$

Preliminary

(efficiency = ~80 %)

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma} & -0.0047 \pm 0.0088 \\ \mathcal{R}e\ \delta\tilde{F}_{1V}^{Z} & -0.0236 \pm 0.0154 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma} & -0.0460 \pm 0.0126 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{Z} & +0.0631 \pm 0.0198 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma} & -0.0669 \pm 0.0253 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{Z} & -0.0206 \pm 0.0417 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma} & +0.0011 \pm 0.0160 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{Z} & -0.0370 \pm 0.0283 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma} & -0.0143 \pm 0.0163 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{Z} & -0.0110 \pm 0.0237 \end{bmatrix}$$

e+e-→t tbar @EW NLO

- **QCD corrections are known up to N^3LO**

- **Electroweak correction known up to NLO**

Y. Sato, F. Le Diberder, H. Yamamoto, A. Ishikawa, R. Poeschl, S. Bilokin

  - ✓ GRACE program (KEK) allows to compute NLO
  - ✓ EW NLO is large: 5 % in cross-section, 15 % in A_{FB}
  - ✓ Experimental sensitivity to couplings is at the per mill level
  - ✓ EW NNLO is impossible to compute as of today
  - ✓ Goal: to understand the origin of the large EW NLO (150 diagrams)

Y. Khiem, E. Kou, Y. Kurihara, B. Mecaj, T. Moskalets, N. Quach

- **Spin-correlation as a tool for precision**
  - ✓ ILC can have polarized e+ and e- (LR, RL)
  - ✓ Experimental study shows the ttbar spins (LR, RL, LL, RR) can be separated at a very high precision as well
  - ✓ EW correction (γ, Z, W) is sensitive to chirality of the particles: spin-correlation for pinning down the origin of NLO

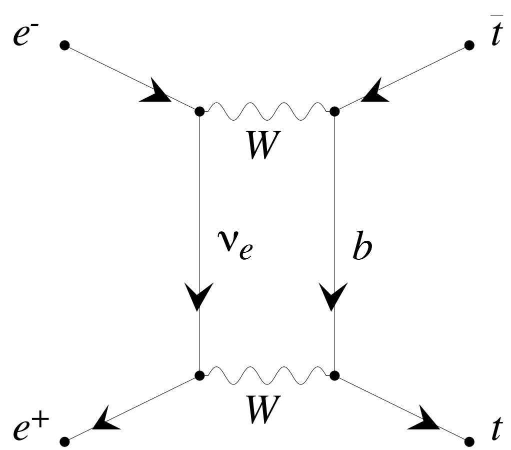
Anatomy of NLO contributions

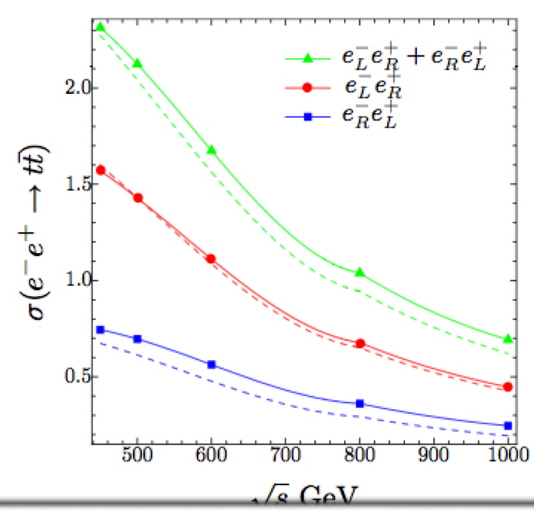
Y. Khiem, E. Kou, Y. Kurihara, B. Mecaj, T. Moskalets, N. Quach

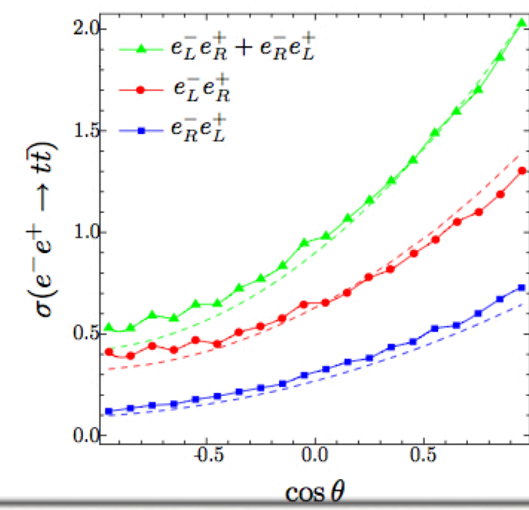
✳ **Which ttbar spin states receive more/less electroweak NLO corrections?**

GRACE : now both initial and final state polarization available (Kheim&Kurihar)

Graph 113







Example I : W does not couple to e^-_R. This results in

- ★ *NLO to cross section of $e^-_L e^+_R$ is very small*
- ★ *NLO to forward-backward asymmetry of of $e^-_R e^+_L$ is very small*

note: there is box-vertex cancelation

Anatomy of NLO contributions

Y. Khiem, E. Kou, Y. Kurihara, B. Mecaj, T. Moskalets, N. Quach

✳ **Which ttbar spin states receive more/less electroweak NLO corrections?**

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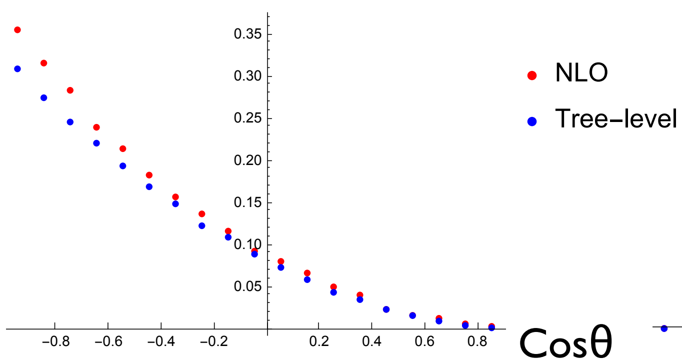
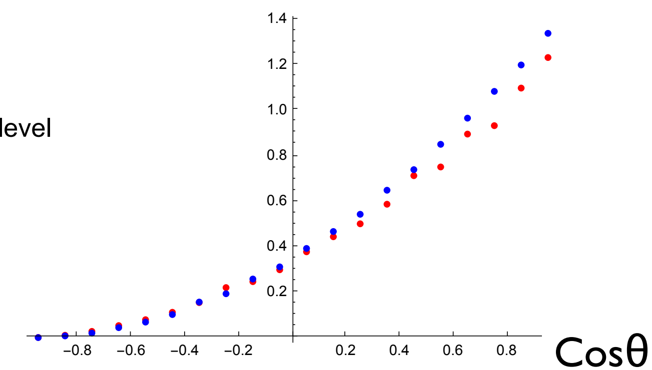
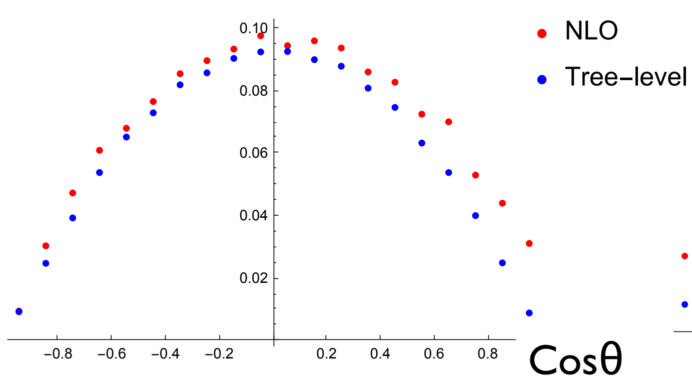
LRRL



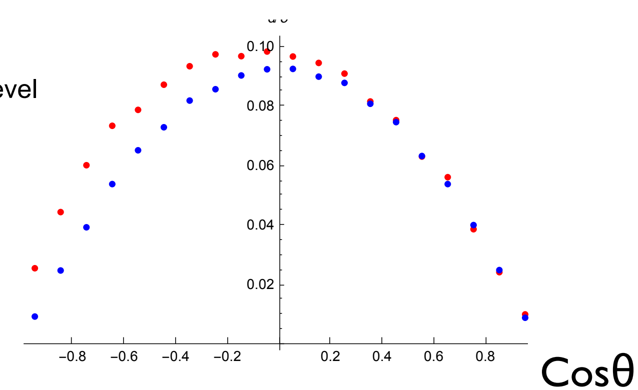
LRLR



LRLL



LRRR



✳ *Example II :*

Experimentally, the ttbar spins are measurable. We compute NLO corrections of the different spin combination of ttbar: pinning down the origin of the NLO corrections.

Conclusions

- The b-quark polar angle was reconstructed in the ILD environment
- The ILC will provide precise solution to the LEP tension
- At the ILC it will be possible to extract the b-quark form factors independently using the differential cross section

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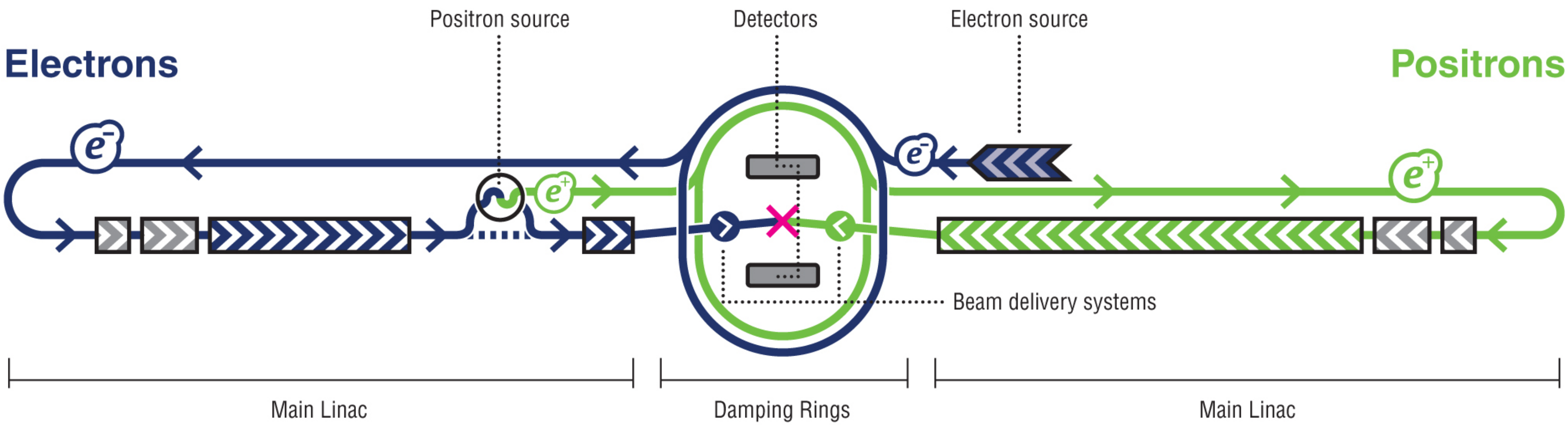
- FJPPL student exchange program was done in 2016

- The Matrix Element Method was successfully applied on full ILD simulation
  - ISR, FSR, hadronization effects are incorporated
- Method was checked with NLO events
- Next step → check with the background processes

- The box diagram causes the difference between left-handed and right-handed cross section
- The spin correlation analysis is now available in GRACE generator

Thank you!

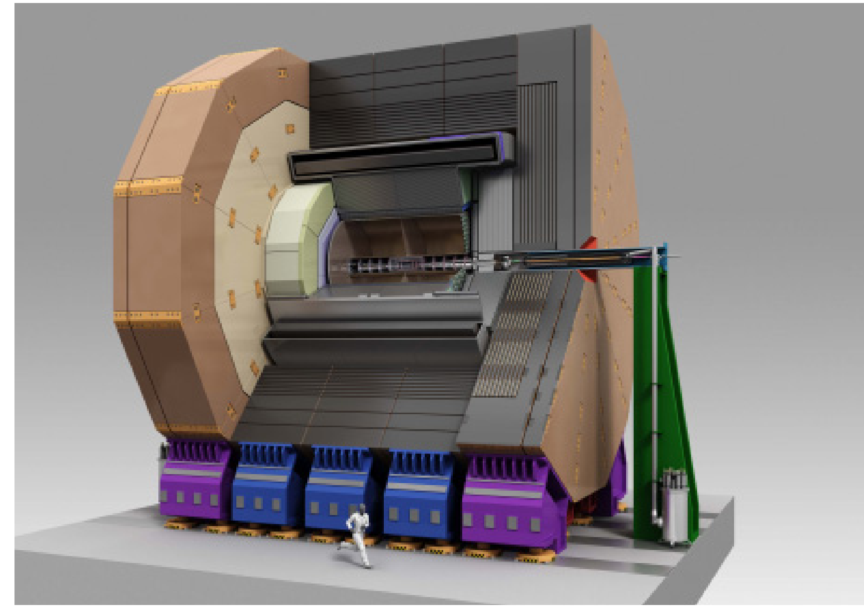
ILC project

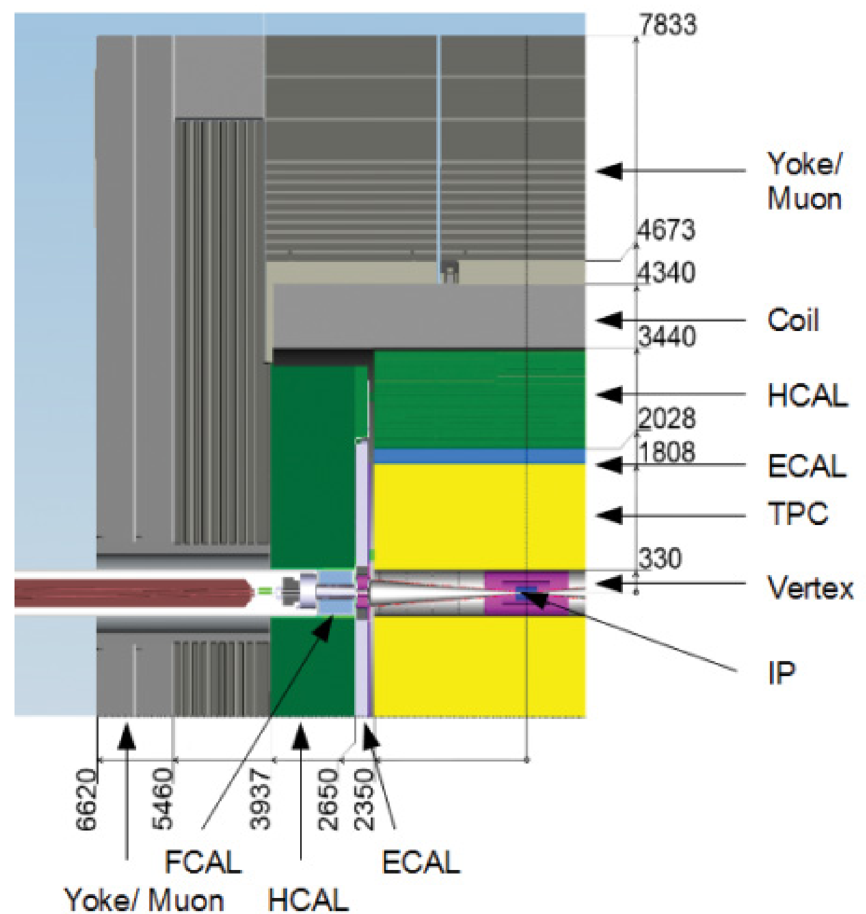


- Polarized electron and positron beams
- Center-of-mass energy of 250 – 500 GeV with a 1000 GeV upgrade option
- Two detectors, SiD and ILD
- Well known state of initial particles, low machine background
- Main goals:
  - Precision measurement of Standard Model parameters
  - Direct and indirect searches of Beyond Standard Model particles

ILD project

- Designed for Particle Flow algorithms that allow to reconstruct individual particles inside ILD
- Tracking system:
  - Vertex Detector composed of 3 double layers of silicon pixels
  - Time Projection Chamber with particle identification capabilities
  - Other devices
- Calorimeters:
  - High-granular silicon-tungsten Ecal (SiW Ecal)
  - Hcal with iron absorber
- 3.5T Solenoid
- Muon trackers
- Full GEANT4 simulation





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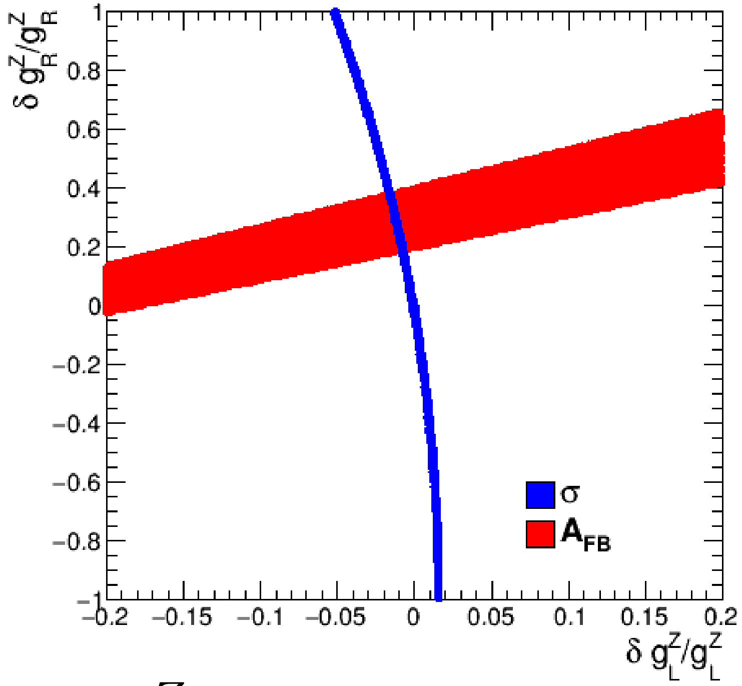
Precision on b-quark couplings

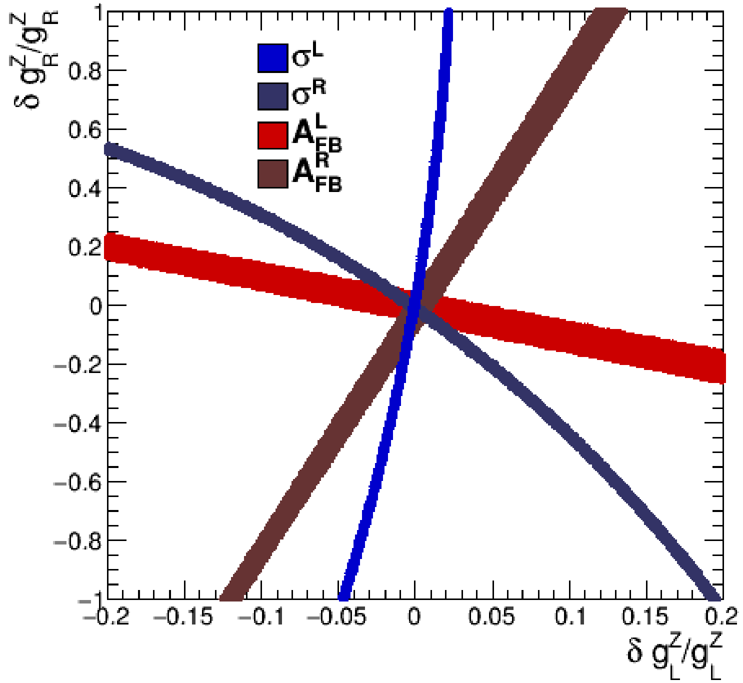
PRELIMINARY | WORK IN PROGRESS

Allowed 1σ regions for the tree level predictions

LEP



ILC



- g_L^Z is well defined
- g_R^Z sign flip is possible
- Allows for 20% g_R^Z variation

- Only one precise solution
- Better resolution on the g_R^Z value

- Assume only the $Zb\bar{b}$ coupling varies

Determination of the Form Factors

PRELIMINARY | WORK IN PROGRESS

$$\frac{d\sigma^I}{d\cos\theta} = A(1+\cos^2\theta) + B\cos\theta + C\sin^2\theta$$

$$e^-_L e^+_R \longrightarrow b\bar{b}$$

Reconstructed

Factor	Value	Error
A	3127.92	16.61
B	5933.01	22.7
C	9.74	22.61

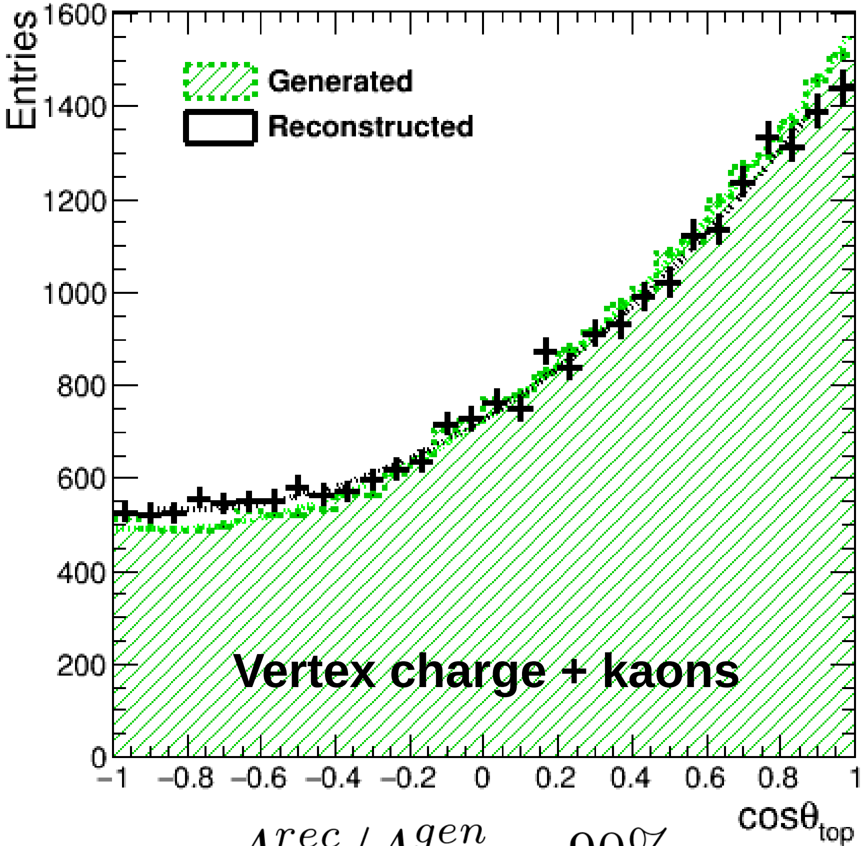
Generated

Factor	Value	Error
A	3058.95	2.52
B	5770.09	4.22
C	16.11	3.7

- Results depend on the number of events used – to be fixed
- There are 1-2% percent difference between the reconstructed and generated A and B values
- We get small C value as compared to A and B values as expected
- Errors on the A and C values are correlated
- Results and conclusions are similar for the right-handed polarization

Top polar angle reconstruction

$$e^+_R e^-_L \rightarrow t\bar{t}$$



$$A_{fb}^{rec}/A_{fb}^{gen} = 90\%$$

- Top polar angle reconstruction using kaons and vertex charge combination. **B-jet information only.**