# A precise determination of top quark electroweak couplings at the ILC

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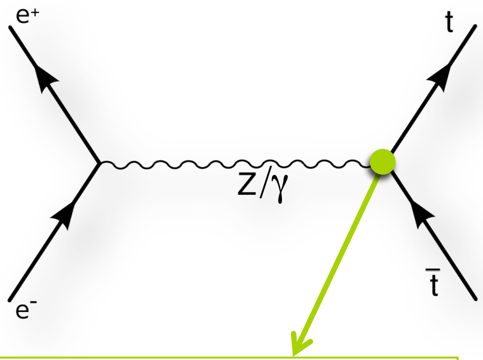
# Theory

- The top quark is the heaviest elementary particle and it is the most strongly coupled to the mechanism of electroweak symmetry breaking.

- In contrast to the situation at hadron colliders, the dominant pair production process $e^+e^-\to t\bar{t}$ involves only $t\bar{t}Z^0$ and $t\bar{t}\gamma$ primary vertices

- A way to describe the current at the $t\bar{t}X$ vertex:
  - $X = Z^0, \gamma$
  - *V = Vector coupling*
  - *A = Axial coupling*

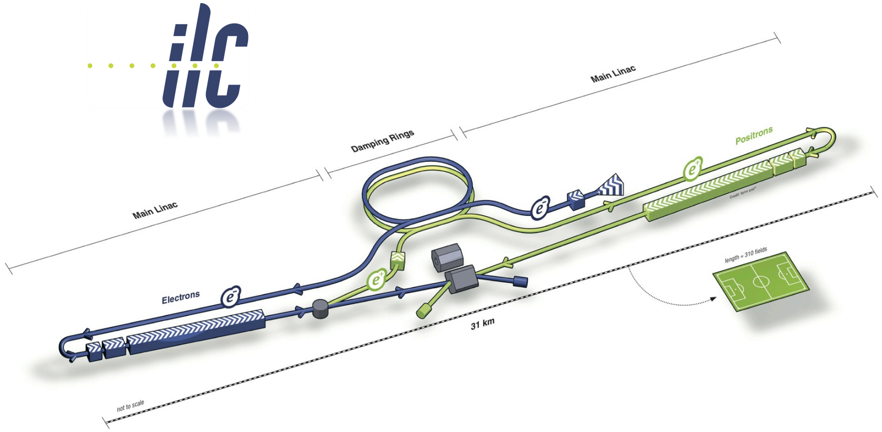
arxiv.org/abs/hep-ph/0601112



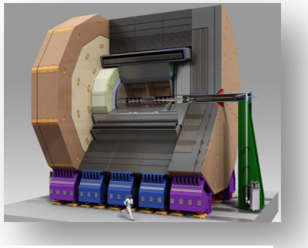
$$\Gamma_\mu^{ttX}(k^2,\, q,\, \overline{q}) = ie\left\{\gamma_\mu \left(\widetilde{F}_{1V}^X(k^2)+\gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\overline{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2)+\gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$

# International Linear Collider (ILC)

- **The c.o.m. energy**: **$\sqrt{s}$ = 500 GeV** **(default design)**
- **Luminosity**: **$\mathcal{L}$ = 500 $\mathrm{fb}^{-1}$** = 5 $\times 10^5$ $\mathrm{pb}^{-1}$ *(estimated for 4 years of running)*
- Beams are **polarised**: **$P(e^-) \approx \pm 80\%$ , $P(e^+) \approx \pm 30\%$.**



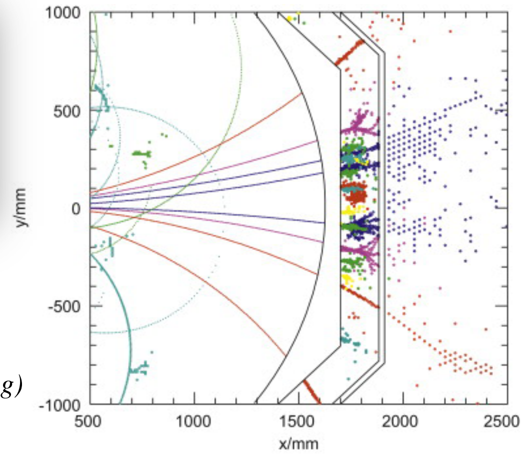
ILD detector is optimised for Particle Flow Algorithm (PFLOW), i.e. measure particles in jet in the best suited sub-detectors



$$\sigma(d_0)=\left[5\oplus\frac{1}{p_T}\frac{10}{\sqrt{\sin\theta}}\right]\mu m$$

$$\sigma(p_T)/p_T \approx 2\cdot 10^{-5}\, p_T \oplus a$$

$a = 1\cdot 10^{-4}$ (multiple scattering)



So the expected energy resolution is:

$$\boxed{\sigma_E / E \sim 3\%}$$

# Decay modes

$e^+e^- \rightarrow t\bar{t}$ gives three different final states:

1) Fully hadronic (46.2%) → *6 jets at final state*

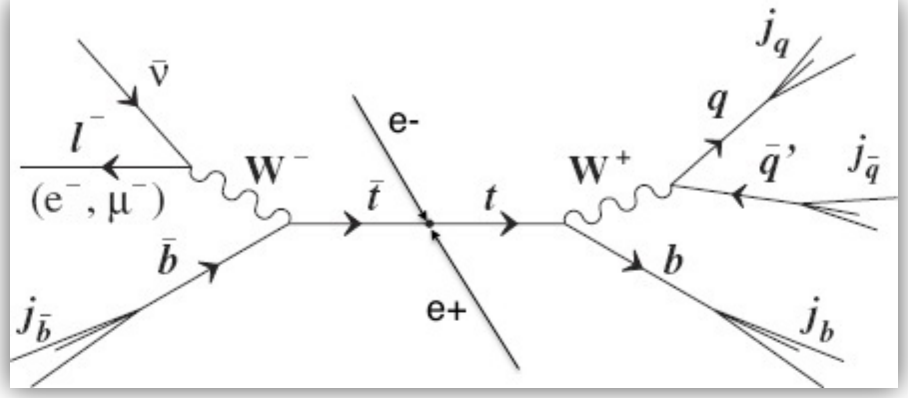
http://www-flc.desy.de/lcnotes/ LC-REP-2013-008

2) Semi-leptonic (43.5%) → *4 jets + lepton + neutrino*

http://www-flc.desy.de/lcnotes/ LC-REP-2013-007

3) Fully leptonic (10.3%) → *2jets + 2 leptons + 2 neutrinos*

- This analysis is concentrate mainly on the events which have a **semi-leptonic final state**



$$t\bar{t} \longrightarrow (bW)(bW) \longrightarrow (bqq)(bl\nu)$$

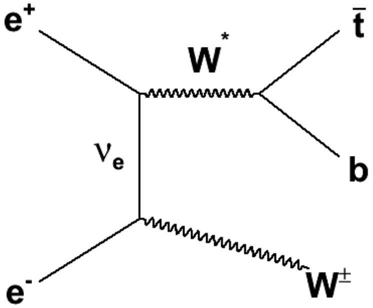
# Event generation and technical remarks

## Event generation

- WHIZARD: event generation (*samples for the DBD*)
- PYTHIA: Generation of parton shower and hadronisation
- The input top mass to WHIZARD is 174 GeV

## Latest improvements

- Single top background ~15%
    - It has been studied but its final state it's so similar to $e^+e^- \to t\bar{t}$ and it seems no posible to distinguish these events.



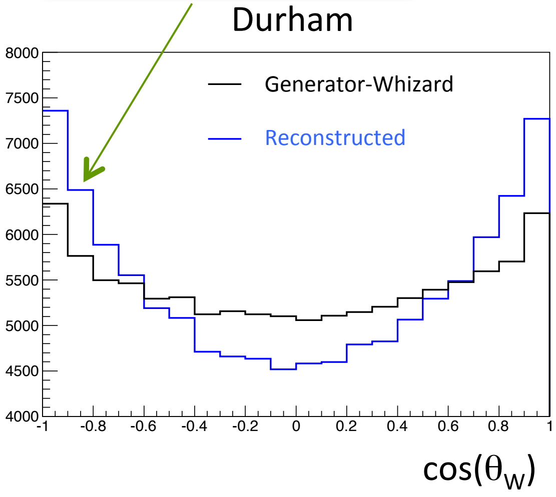
- γγ→hadrons. Is a process superposed to $e^+e^- \to t\bar{t}$ which degrades severaly the angular distributions. It has been reduced with *kt* jet algorithm.

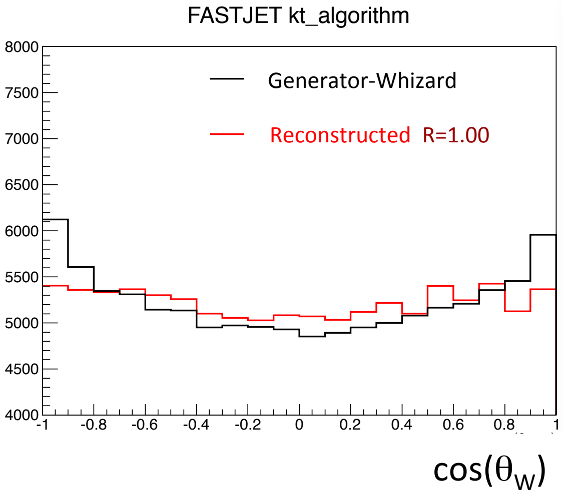
# γγ to hadrons

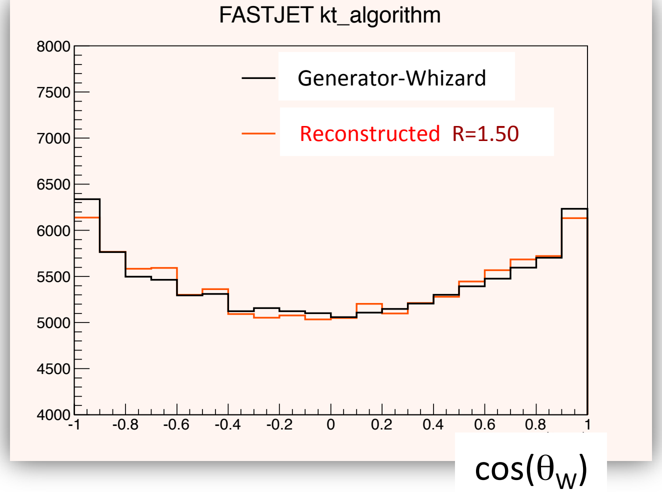
- This background appears mainly in the very **forward region**.
- **Durham** (1st jet algorithm) includes these particles in the jets.
- **Second jet clustering** with ***kt* algorithm** → creates the so called **beam-jets** where very forward particles are included and **reduces the impact** in the final jets.

***kt* algorithm** with a jet size of **R=1.50** gives the best results

Excess of particles in the **forward region**







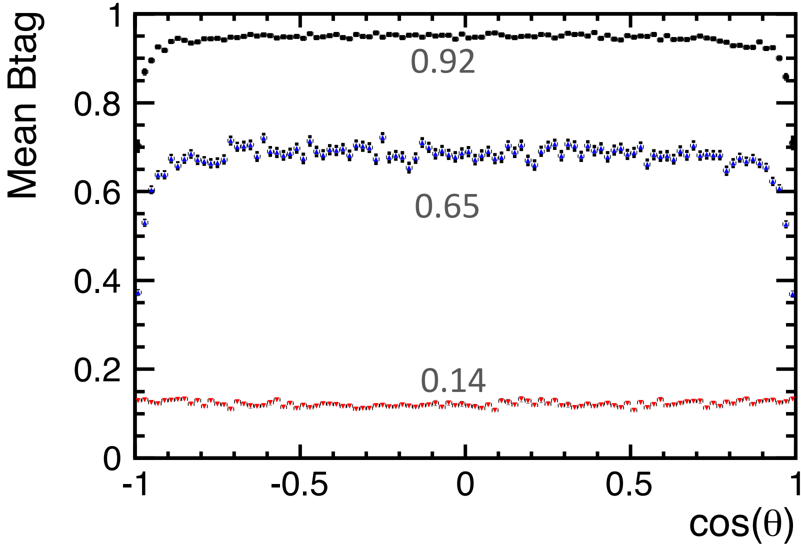
# Event selection

- **Lepton identification** criteria:
  - *Lepton is isolated from a jet* $x_T = p_{T,lepton}/M_{jet} > 0.25$ and $z = E_{lepton}/E_{jet} > 0.6$

    Taking into account the $\tau$ leptons → **Eff ~ 70%**

- ***b*-likeness or *b-tag*** is determined analysing secondary vertices → jet mass, decay length and particle multiplicity. A *b-tag* value is assigned to each jet.

0 < *b-tag* < 1



***Tagged as b-jets***

The 2 jets with higher *b-tag* value

***Non b-jet***

# Event selection

- The signal is reconstructed by choosing the combination of *b* quark jet and W boson that minimises the following equation:

$$d^2 = \left(\frac{m_{cand.} - m_t}{\sigma_{m_t}}\right)^2 + \left(\frac{E_{cand.} - E_{beam}}{\sigma_{E_{cand.}}}\right)^2 + \left(\frac{p_b^* - 68}{\sigma_{p_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} - 0.23}{\sigma_{cos\theta_{bW}}}\right)^2$$

- Some cuts:
  - Hadronic mass of the final state: $180 < m_{had.} < 420\,\mathrm{GeV}$
  - Reconstructed W mass: $50 < m_W < 250\,\mathrm{GeV}$
  - Reconstructed top mass: $120 < m_t < 270\,\mathrm{GeV}$
  - Isolated lepton: *the best candidate*
  - b-tag values: $b\text{-}tag_1 > 0.8$ & $b\text{-}tag_2 > 0.3$

- The **entire selection** retains:
  - **51.9%** for the configuration P,P’ = -1,+1 (Left-handed electrons)
  - **55.0%** for P,P’ = +1, -1 (Right-handed electrons)

# Observables

- **Total cross section** ($\sigma$)
- The **Forward-Backward Asymmetry** ($A_{FB}$)
- **The slope of the distribution of the helicity angle** ($\lambda_{hel}$)

But actually there are **6** independent observables →

$$\boxed{\begin{array}{cccc} \sigma(+) & A_{FB}(+) & \lambda_{hel}(+) & (+=e_R^-) \\ \sigma(-) & A_{FB}(-) & \lambda_{hel}(-) & (-=e_L^-) \end{array}}$$

- The expected values in the Standard Model are:

| Observables | $e^-_L e^+_R$ | $e^-_R e^+_L$ |
|---|---|---|
| **$\sigma$(fb)** | **1564** | **724** |
| **$A_{FB}$** | **0.38** | **0.47** |
| **$F_R$** | **0.25** | **0.76** |

where $F_R$ is the fraction of right-handed tops

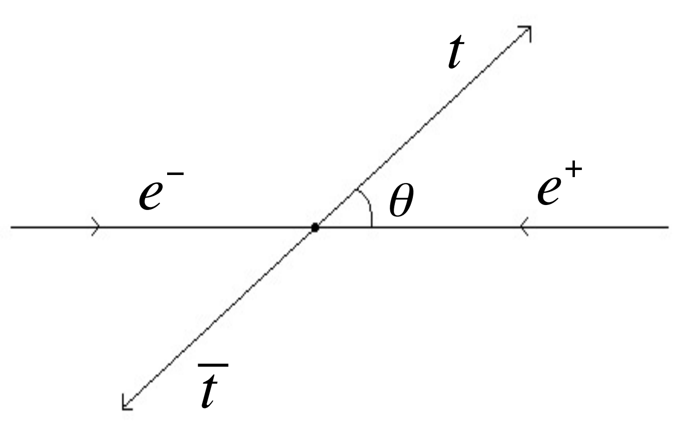
← $$\boxed{\lambda_{hel} = 2F_R - 1}$$

# Forward-Backward asymmetry: $A_{FB}$

- The Forward-Backward Asymmetry

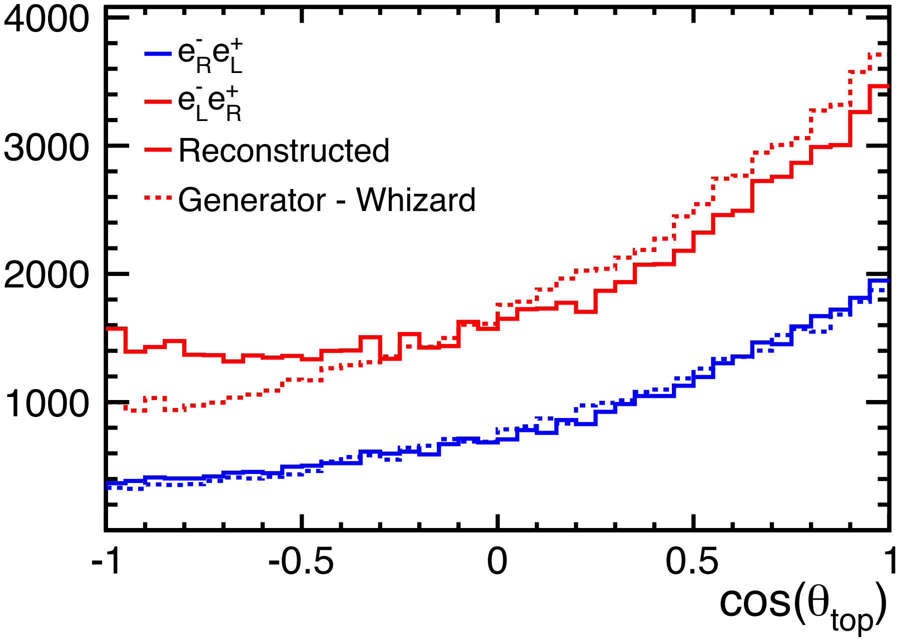
$$A_{FB} = \frac{N_{top}(\cos\theta > 0) - N_{top}(\cos\theta < 0)}{N_{top}(\cos\theta > 0) + N_{top}(\cos\theta < 0)}$$

$$\boxed{-1 < A_{FB} < 1}$$



- The sign of the top is the one of the lepton
- For $\bar{t}$ we change $\theta$ to $\theta + \pi$

# Results for $A_{FB}$



← We can see a clear **migration effect** for left-handed electrons

- This migration comes from the **wrong combination** of the **W** and the **b-jet** to **reconstruct the top** quark
- It occurs in about **30%** of the times.

- This gives a wrong direction of the reconstructed top and produces the migration effect.

# How to cure migration? $\chi^2$ **strategy**

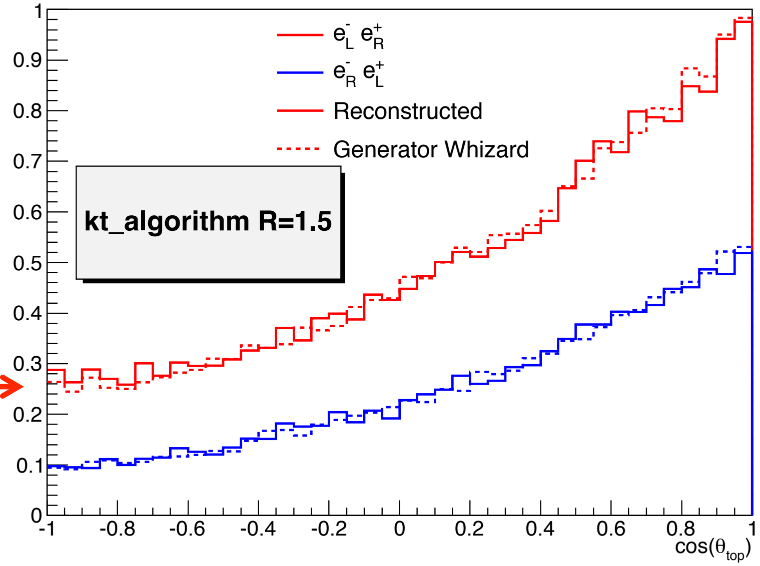
$$\chi^2 = \left(\frac{\gamma_t - 1.435}{\sigma_{\gamma_t}}\right)^2 + \left(\frac{E_b^* - 68}{\sigma_{E_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} - 0.26}{\sigma_{cos\theta_{bW}}}\right)^2$$

- If we cut on $\chi^2$ we reduce the number of wrong combinations of W and b-jet
- $\chi^2$ **< 15** → Reconstruction efficency : **29.6%**

| $\mathcal{P}, \mathcal{P}'$ | $(A^t_{FB})_{gen.}$ | $A^t_{FB}$ | $(\delta_{A_{FB}}/A_{FB})_{stat.}$ [%] |
|---|---|---|---|
| $-1, +1$ | 0.360 | 0.344 | 1.7 (for $\mathcal{P}, \mathcal{P}' = -0.8, +0.3$) |
| $+1, -1$ | 0.433 | 0.428 | 1.3 (for $\mathcal{P}, \mathcal{P}' = +0.8, -0.3$) |

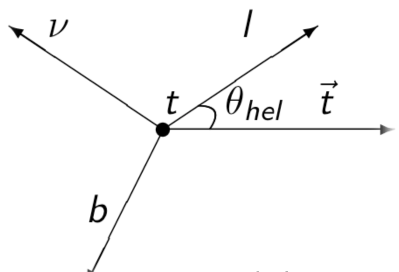
The $\chi^2$ cut removes the migration effect

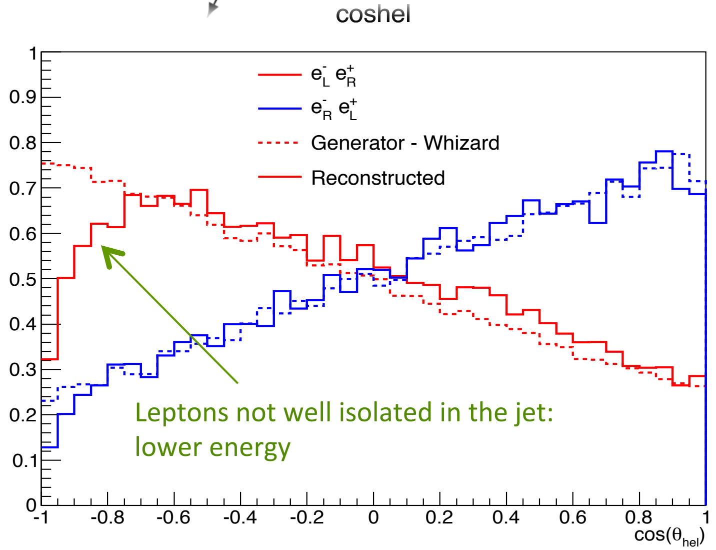
for left-handed electrons



# Helicity angle ($\theta_{hel}$)

- In the rest frame of the top, $\theta_{hel}$ **is the angle between the initial direction of the top and the lepton**





Leptons not well isolated in the jet: lower energy

- The slope ($\lambda_t$) of the distribution gives the fraction of $t_L$ and $t_R$ in the sample.

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_{hel}} = \frac{1+\lambda_t cos\theta_{hel}}{2} = \frac{1}{2} + (2F_R - 1)\frac{cos\theta_{hel}}{2}$$

$$\lambda_t = 1 \text{ for } t_R \quad \lambda_t = -1 \text{ for } t_L$$

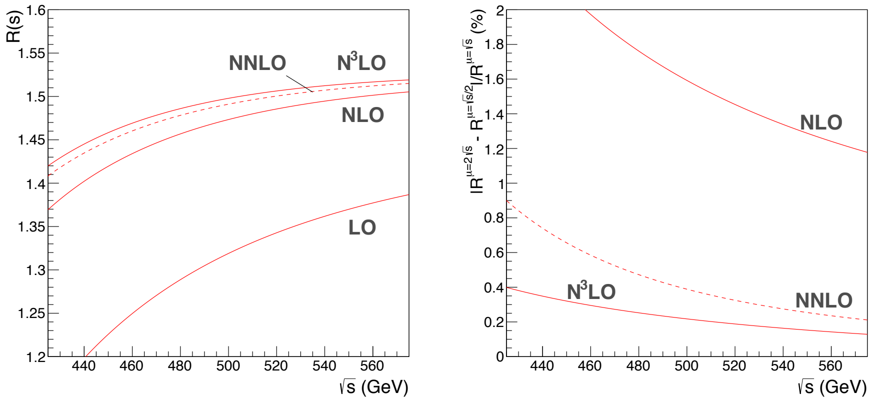
| $\mathcal{P},\mathcal{P}'$ | $(\lambda_t)_{gen.}$ | $(\lambda_t)_{rec.}$ | $(\delta\lambda_t)_{stat.}$ for $\mathcal{P},\mathcal{P}' = \mp 0.8, \pm 0.3$ | $(\delta\lambda_t)_{syst.}$ |
|---|---|---|---|---|
| $-1,+1$ | -0.519 | -0.489 | 0.016 | 0.011 |
| $+1,-1$ | 0.544 | 0.547 | 0.016 | 0.010 |

# Systematic uncertainties

- **Luminosity**
  - It can be controlled to 0.1%
- **Polarisation**
  - DBD studies → 0.1% e- beam, 0.35% e+ beam
  - $\sigma_{P,P'=-0.8,+0.3}$ : 0.25% and $\sigma_{P,P'=+0.8,-0.3}$: 0.18%
- **Migrations**
  - Cure migration in $A_{FBL}$ leads to a penalty in efficiency
- **Theory**
  - Electroweak and QCD corrections (ongoing)

# Theoretical uncertainties

- QCD uncertainties are lower than statistical errors



(a) Perturbation series (b) Scale variations

$N^3LO$ → $\delta\sigma^{QCD}$ ~ 3‰ and $\delta A_{FB}{}^{QCD}$ ~ 1%

- EW uncertainties are large for one-loop but lower values are expected for two-loops (not done yet)

- Calculation is done for $e^+e^- \rightarrow t\bar{t}$ process, not for top decay modes

# Extraction of the Physics

- ☐ So once 6 observables are mesured, we can obtain the following 5 couplings of the top quark

$$\left.\begin{matrix} \sigma(+) & A_{FB}(+) & \lambda_{hel}(+) & (+=e_R^-) \\ \sigma(-) & A_{FB}(-) & \lambda_{hel}(-) & (-=e_L^-) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F_{1V}^{\gamma} & * & F_{2V}^{\gamma} \\ F_{1V}^{Z} & F_{1A}^{Z} & F_{2V}^{Z} \end{matrix}\right\}$$

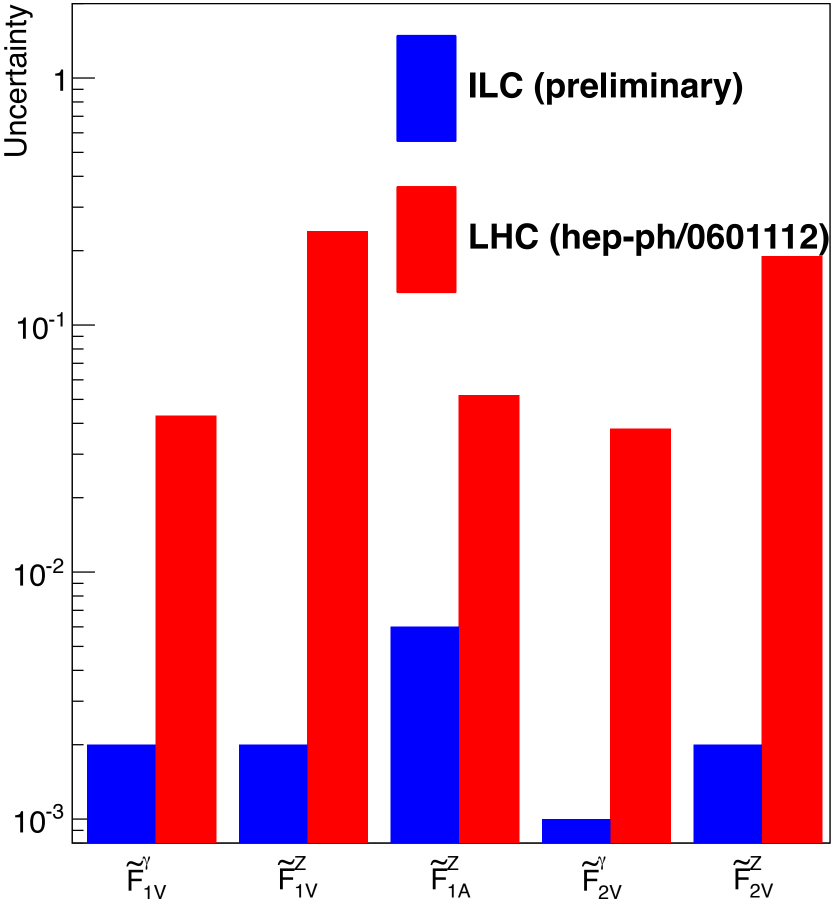
* $F_{1A}^{\gamma} = 0$ always because of the gauge invariance

# Summary of the results

| Coupling | SM value | LHC [1] $\mathcal{L} = 300$ fb$^{-1}$ | $e^+e^-$ [6] $\mathcal{L} = 300$ fb$^{-1}$ $\mathcal{P}, \mathcal{P}' = -0.8, 0$ | $e^+e^-$[*ILC DBD*] $\mathcal{L} = 500$ fb$^{-1}$ $\mathcal{P}, \mathcal{P}' = \pm0.8, \mp0.3$ |
|---|---|---|---|---|
| $\Delta\widetilde{F}^{\gamma}_{1V}$ | 0.66 | $^{+0.043}_{-0.041}$ | $^{-}_{-}$ | $^{+0.002}_{-0.002}$ |
| $\Delta\widetilde{F}^{Z}_{1V}$ | 0.23 | $^{+0.240}_{-0.620}$ | $^{+0.004}_{-0.004}$ | $^{+0.002}_{-0.002}$ |
| $\Delta\widetilde{F}^{Z}_{1A}$ | -0.59 | $^{+0.052}_{-0.060}$ | $^{+0.009}_{-0.013}$ | $^{+0.006}_{-0.006}$ |
| $\Delta\widetilde{F}^{\gamma}_{2V}$ | 0.015 | $^{+0.038}_{-0.035}$ | $^{+0.004}_{-0.004}$ | $^{+0.001}_{-0.001}$ |
| $\Delta\widetilde{F}^{Z}_{2V}$ | 0.018 | $^{+0.270}_{-0.190}$ | $^{+0.004}_{-0.004}$ | $^{+0.002}_{-0.002}$ |

- $F_1^{(\gamma/Z)}$ form factors can be extracted simultaneously considering $\Delta F_{2V}^{(\gamma/Z)} = 0$

- And $F_{2V}^{(\gamma/Z)}$ are extracted fixing all $F_1^{(\gamma/Z)}$ to their SM values



# Outlook

- $\chi2$ optimisation
- Theoretical errors (EW and QCD) → *help from theoreticians is needed!*
- CP violation form factors *($F_{2A}^{X}$)*→ looking for new observables
- Posibilities to measure the b-quark charge
  - b-quark charge measurement for fully hadronic top decays

    http://www-flc.desy.de/lcnotes/ LC-REP-2013-008
  - It is measured correctly in about 60% of the cases
  - Include this method in the semi-leptonic top decays

# Conclusions

- Polarisation allows to double the number of observables
- **Semi-leptonic events** can be selected with an **efficiency** about **55%**
    - The cross section can be measured to a statistical precision of about 0.5%
    - The forward-backward asymmetry to a precision better than 2% for both polarisations
    - The slope of helicity distribution to a precision of about 4%
- **LC** can characterize ttZ ttγ vertices with **accuracies** one or two orders of magnitude **better than LHC**

# Thanks for your attention

# BACKUP SLIDES

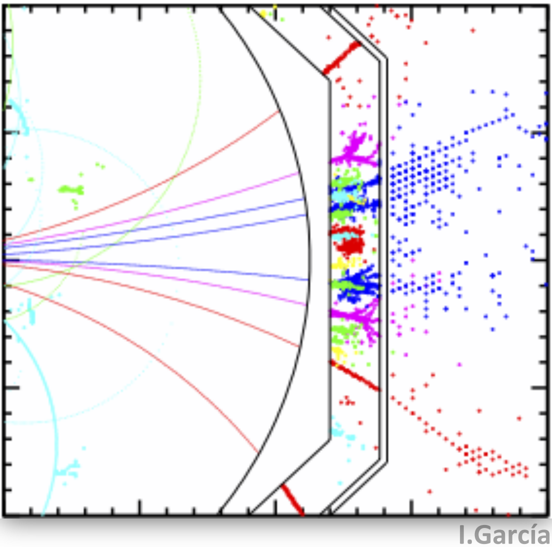
# Particle Flow

Particle Flow (a powerful tool to measure the energy of the jets)

- Measurement of the charged particle momentum in the tracker → <u>charged component of the jet</u>
- Measurement of the momentum of the neutral component of the jet = total energy measured in the calorimetry – energy of the charged particles in the calorimeter.
- Total energy of the jet = charged component + neutral component

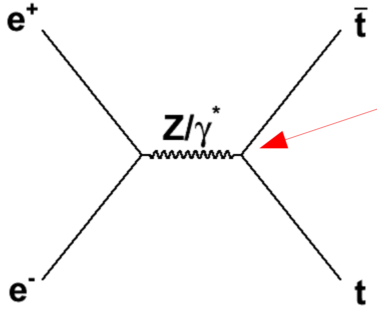
$$\boxed{\sigma_E / E \approx 3\% \quad (E\ en\ GeV)}$$

Great granularity of the calorimeters



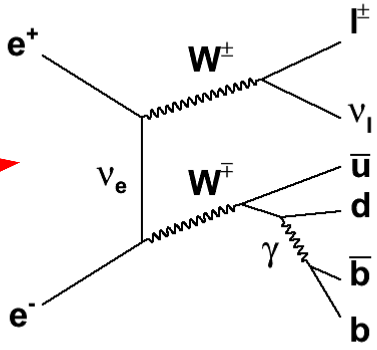
*Calormeter (Silicon-Tungsten)*

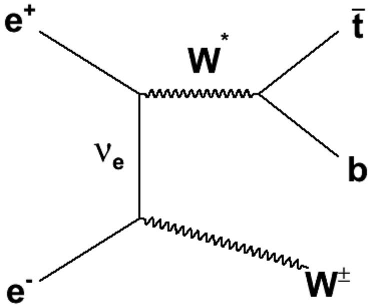
# Single top



This is the vertex we want to probe

This is a background we can reduce

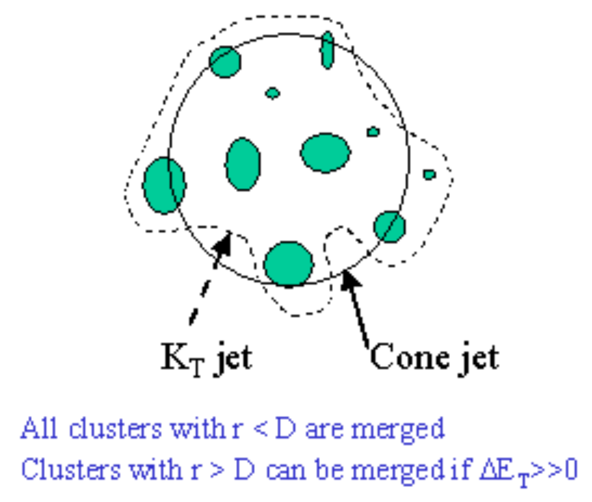




This is a problem

# *kt* algorithm FastJet

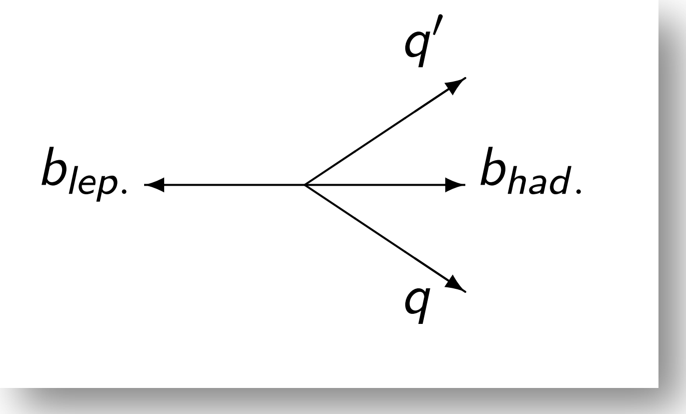
http://arxiv.org/pdf/1111.6097v1.pdf

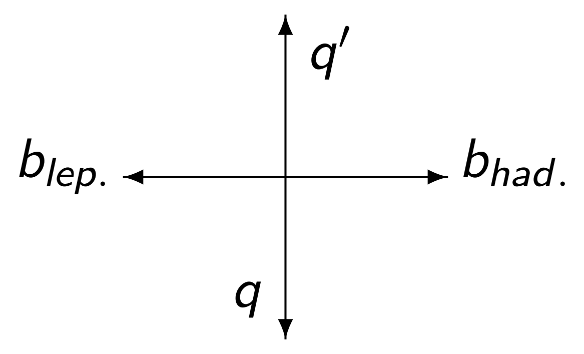


All clusters with r < D are merged
Clusters with r > D can be merged if $\Delta E_T >> 0$

1. For each pair of particles $i$, $j$ work out the $k_t$ distance
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\,\Delta R_{ij}^2/R^2$$
with $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, where $k_{ti}$, $y_i$ and $\phi_i$ are the transverse momentum, rapidity and azimuth of particle $i$ and $R$ is a jet-radius parameter usually taken of order 1; for each parton $i$ also work out the beam distance $d_{iB} = k_{ti}^2$.
2. Find the minimum $d_{\min}$ of all the $d_{ij}, d_{iB}$. If $d_{\min}$ is a $d_{ij}$ merge particles $i$ and $j$ into a single particle, summing their four-momenta (this is $E$-scheme recombination); if it is a $d_{iB}$ then declare particle $i$ to be a final jet and remove it from the list.
3. Repeat from step 1 until no particles are left.

# Where does this migration comes from?





- Right-handed electron beam:
  - The W is emitted into the flight direction of the top togheter with a soft *b*
- In the case is the W is easily combine to good b to reconstruct the top

- Left-handed electron beam:
  - The W is emitted almost at rest togheter with a hard *b*
- In the case it is harder to combine the W and the good b to reconstruct the top