A precise determination of top quark electroweak couplings at the ILC

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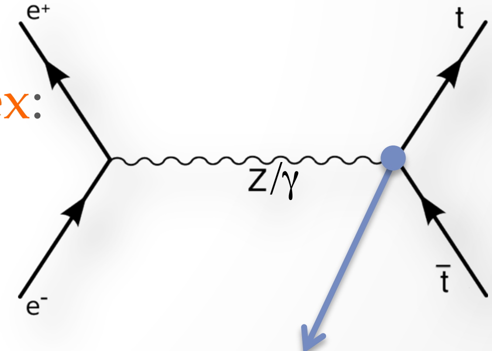
Theory

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

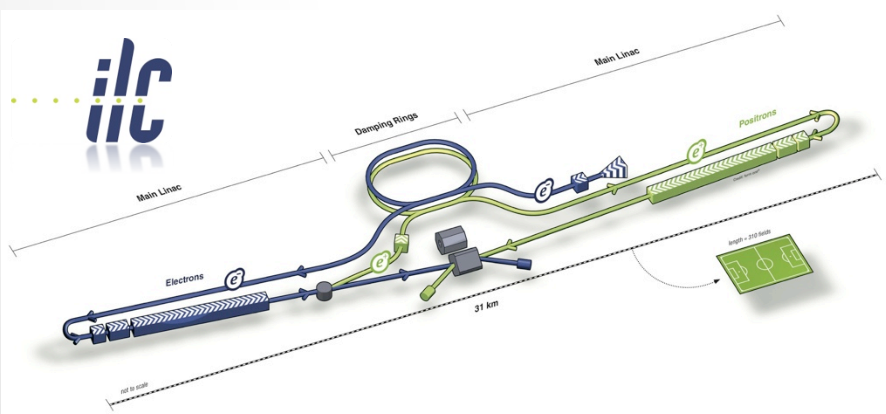
arxiv.org/abs/hep-ph/0601112



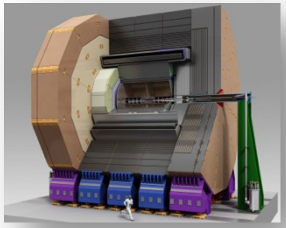
$$\Gamma_{\mu}^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu \left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2)\right)\right\}$$

International Linear Collider (ILC)

- The c.o.m. energy: **$\sqrt{s}$ = 500 GeV** (default design)
- **Luminosity**: **$\mathcal{L}$ = 500 fb^{-1}** = 5 x10^{5} pb^{-1} *(estimated for 4 years of running)*
- Beams are **polarised**: **P(e$^-$) ≈ ±80% , P(e$^+$) ≈ ±30%.**



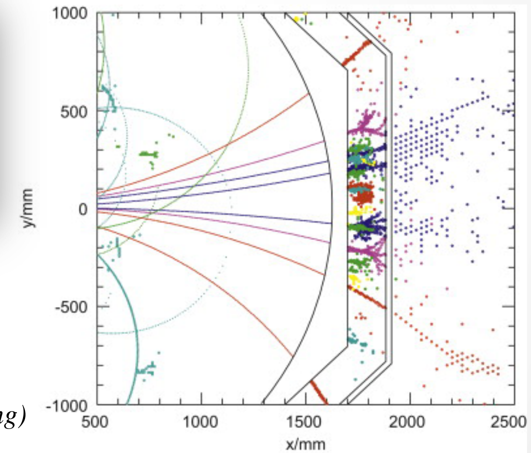
ILD detector is optimised for Particle Flow Algorithm (PFLOW), i.e. measure particles in jet in the best suited sub-detectors



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

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

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



So the expected energy resolution is:

$$\sigma_E / E \sim 3\%$$

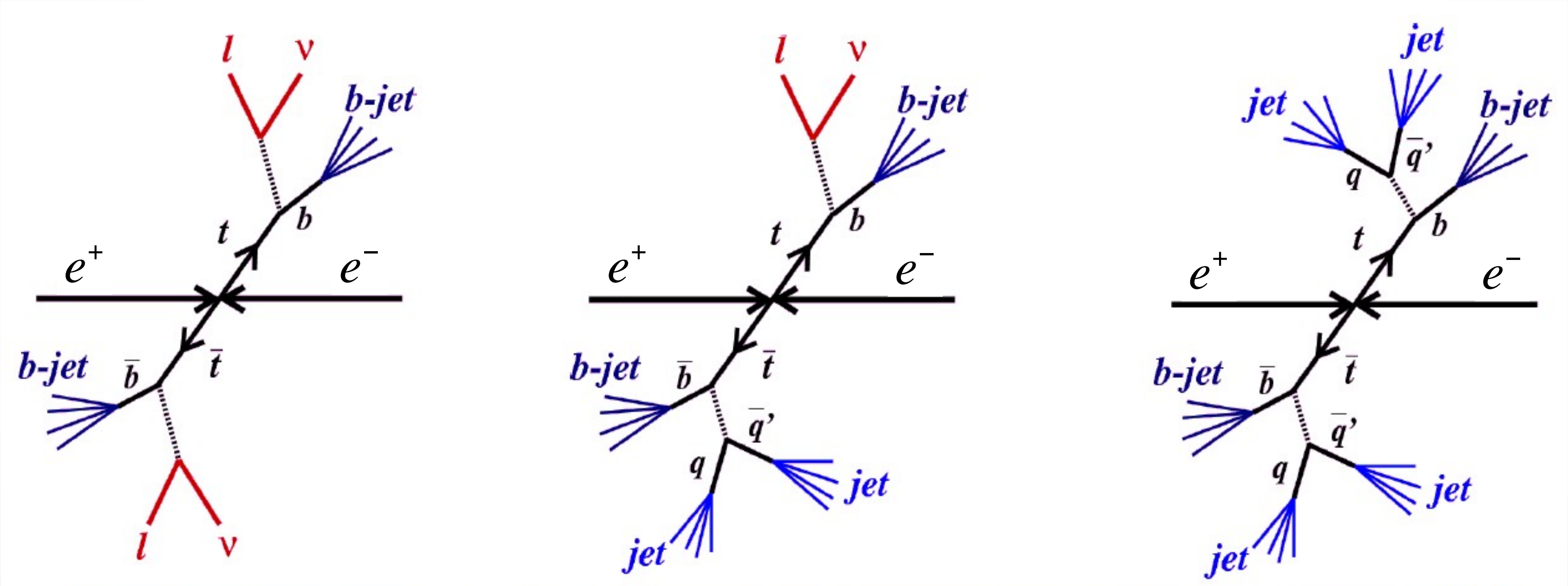
$t\bar{t}$ decay modes

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

Fully leptonic (10.3%)
2jets + 2 leptons + 2 neutrinos

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

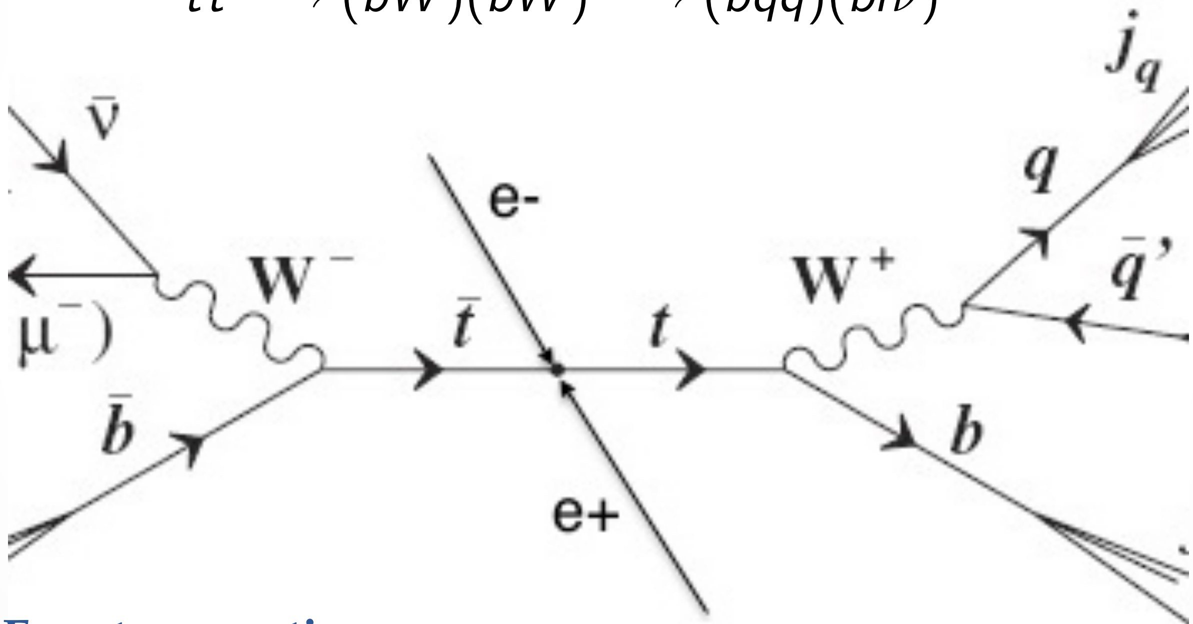
Fully hadronic (46.2%)
6 jets at final state



- This analysis concentrates mainly on events which have a **semi-leptonic final state**

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

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



Event generation

1) WHIZARD: event generation (*samples for the DBD*)

2) PYTHIA: Parton shower and hadronisation

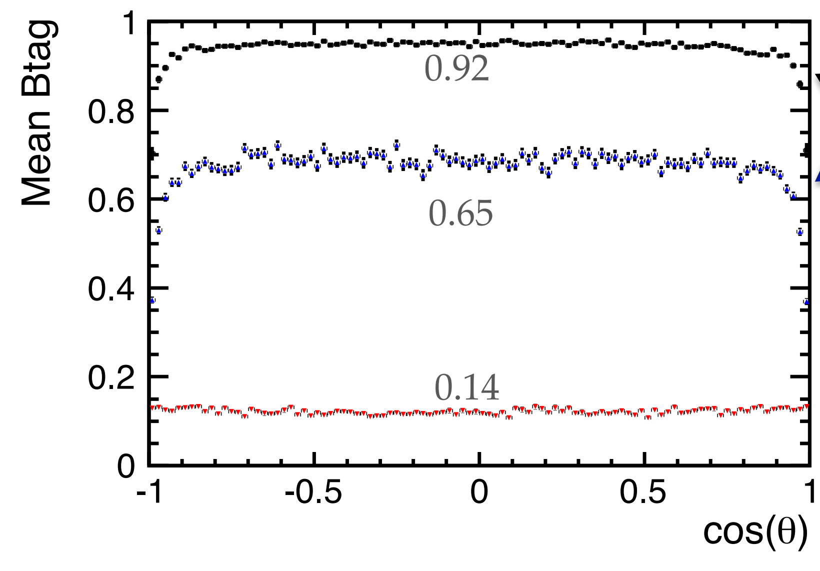
Event selection

- **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 τ 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.

$0 < b\text{-}tag < 1$



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-tag$_1$ > 0.8 & b-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** (σ)
- The **Forward-Backward Asymmetry** (A_{FB})
- **The slope of the distribution of the helicity angle** (λ_{hel})

But actually there are **6** independent observables = **3** observables x **2** polarisations

So once 6 observables are measured, we can obtain the following CP conserving 5 couplings of the top quark

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

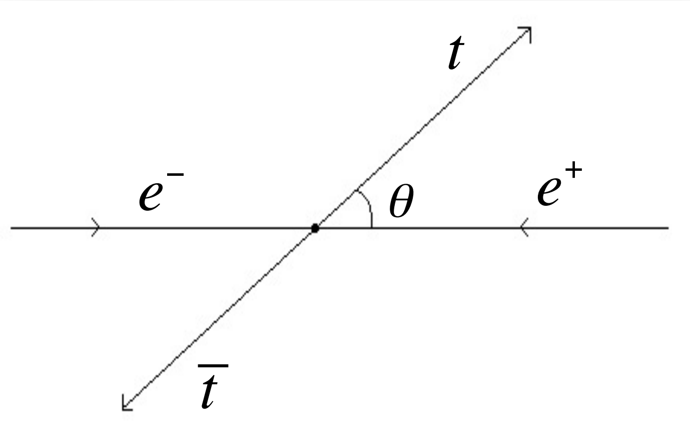
* $F_{1A}^{\gamma} = 0$ always because of the gauge invariance

Forward-Backward asymmetry: A_{FB}

- The Forward-Backward Asymmetry

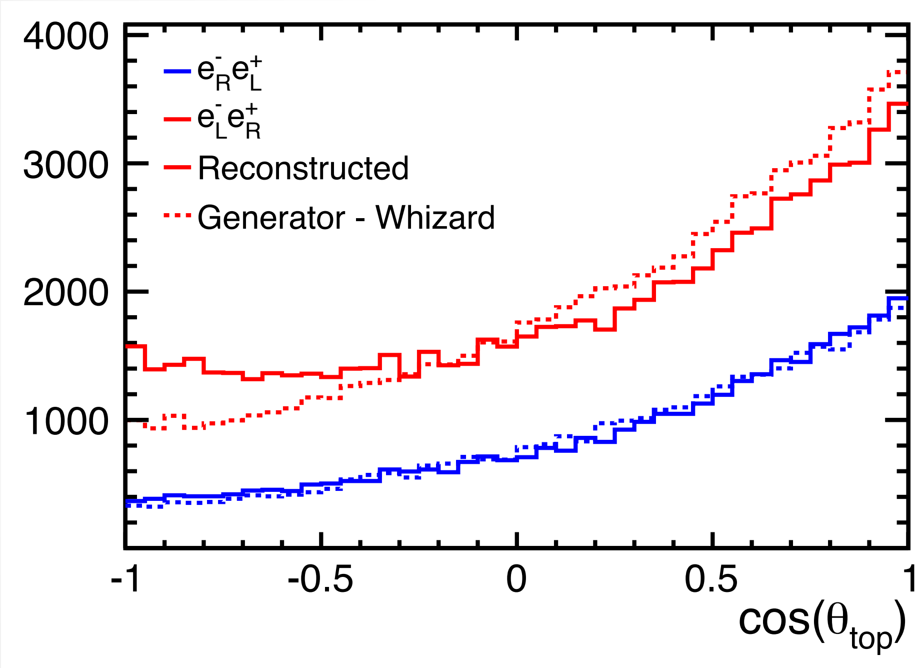
$$A_{FB} = \frac{N_{top}(\cos\theta > 0) - N_{top}(\cos\theta < 0)}{N_{top}(\cos\theta > 0) + N_{top}(\cos\theta < 0)}$$

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



- The sign of the top is the one of the lepton
- For $\bar{t}$ we change θ 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? χ^2 strategy

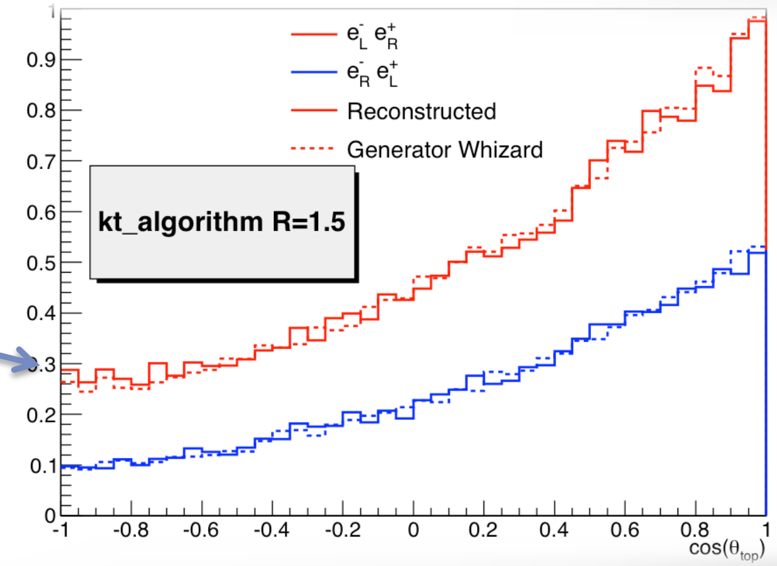
$$\chi^2 = \left(\frac{\gamma_t - 1.435}{\sigma_{\gamma_t}}\right)^2 + \left(\frac{E_b^* - 68}{\sigma_{E_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} - 0.26}{\sigma_{cos\theta_{bW}}}\right)^2$$

- If we cut on χ^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 $\mathcal{P}, \mathcal{P}' = +0.8, -0.3$)

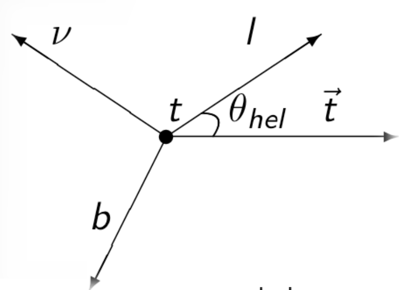
The χ^2 cut removes the migration effect

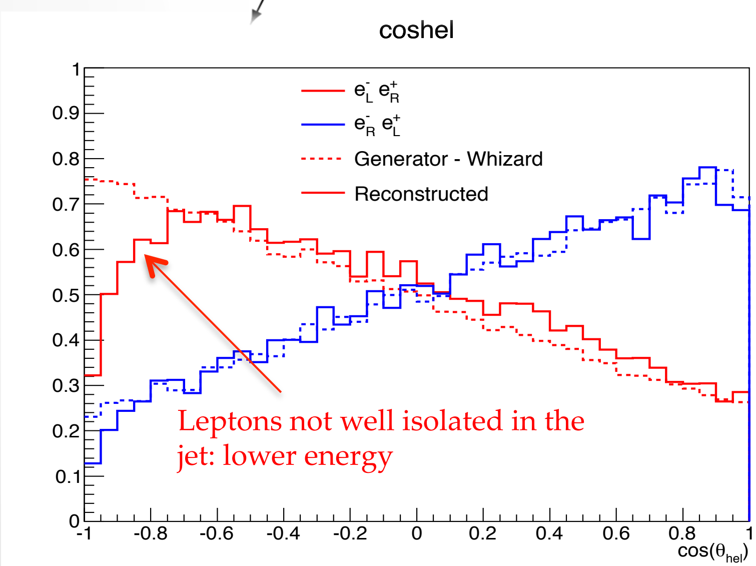
for left-handed electrons



Helicity angle (θ_{hel})

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





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

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

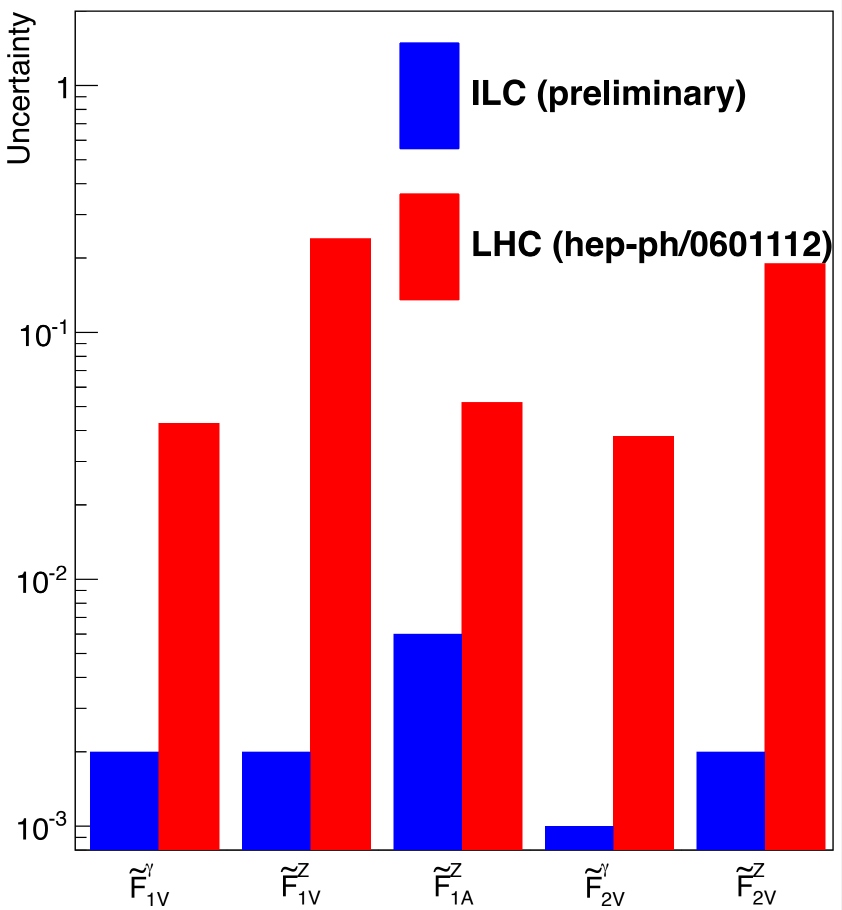
$$\lambda_t = 1 \text{ for } t_R \quad \lambda_t = -1 \text{ for } t_L$$

$\mathcal{P}, \mathcal{P}'$	$(\lambda_t)_{gen.}$	$(\lambda_t)_{rec.}$	$(\delta\lambda_t)_{stat.}$ 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

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 $\Delta F_{2V}^{(\gamma/Z)} = 0$
- $F_{2V}^{(\gamma/Z)}$ are extracted fixing all $F_1^{(\gamma/Z)}$ to their SM values



Conclusions

- **Polarisation** is a powerfull tool for analysis because it allows to **double** the number of **observables**
- **In LC with polarised beams** we can measure $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices with **accuracies** one or two orders of magnitude **better than LHC**
- **Current aim:** We are looking for **new observables** sensitive to the **CPV form factors $F_{2A}^{\gamma/Z}$.** For instance spin correlations between the lepton and the top.

Thanks for your attention

(you are free for leaving)

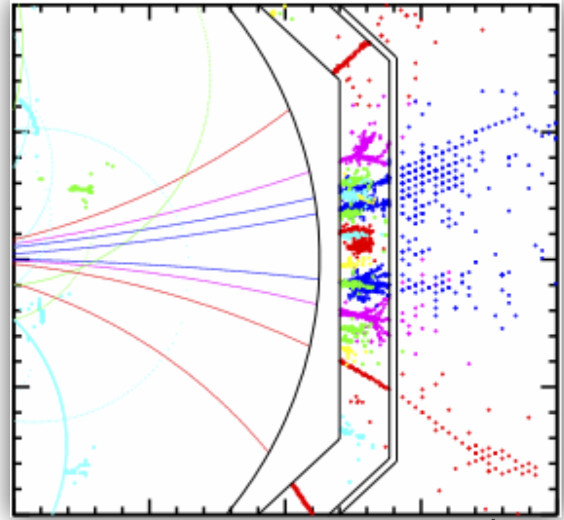
Particle Flow

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

- Measurement of the charged particle momentum in the tracker → charged component of the jet
- 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

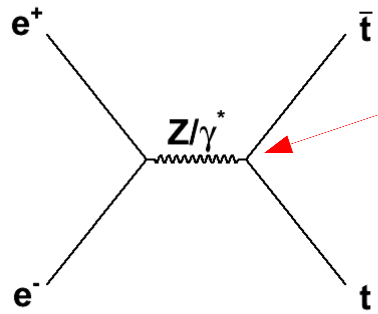
$$\sigma_E / E \approx 3\% \quad (E \text{ en GeV})$$

Great granularity of the calorimeters



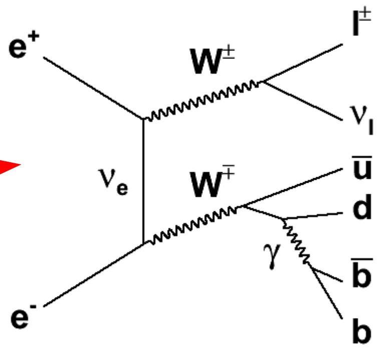
Calormeter (Silicon-Tungsten)

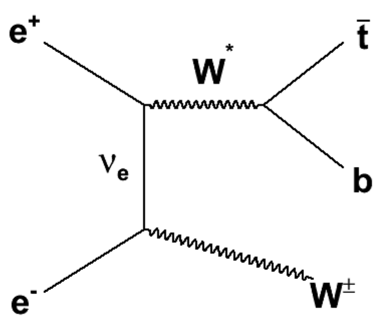
Single top



This is the vertex we want to probe

This is a background we can reduce

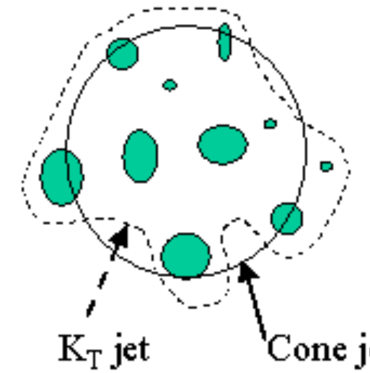




This is a problem

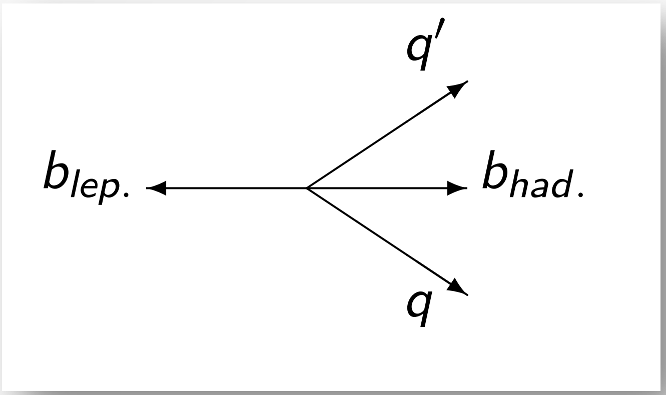
kt algorithm FastJet

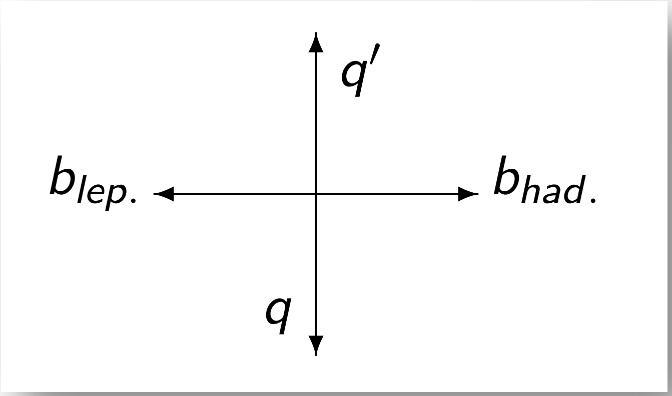
http://arxiv.org/pdf/1111.6097v1.pdf



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 ϕ_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

Observables SM values

- **Total cross section** (σ)
- The **Forward-Backward Asymmetry** (A_{FB})
- **The slope of the distribution of the helicity angle** (λ_{hel})

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

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

- The expected values in the Standard Model are:

Observables	$e^-_L e^+_R$	$e^-_R e^+_L$
σ(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

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