Production and electroweak couplings of 3rd generation quarks at the ILC

Adrián Irles*, on behalf the ILD collaboration

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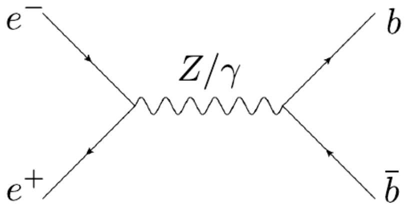
Outline of the talk

- What do we want to measure and why?
- Where? International Linear Collider, **ILC250**, and the International Large Detector **ILD**
- **b-quark electroweak couplings** extracted from **differential cross section** measurements
- Few words about the t-quark

Motivation

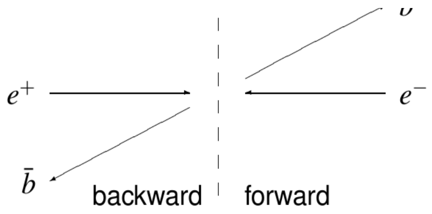
- Quark (fermion) **electroweak couplings** can be **inferred from cross section** and forward backward asymmetry (**AFB**) observables.

$$\frac{d\sigma^I}{d\cos\theta}$$



The b-quark polar angle is defined as a polar angle of the vector

$$\vec{p}_{b\bar{b}} = \vec{p}_b - \vec{p}_{\bar{b}},$$

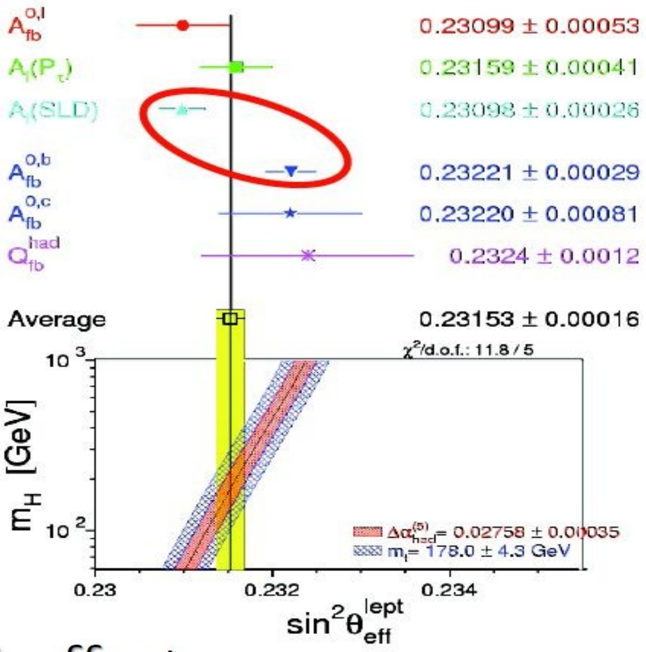


$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

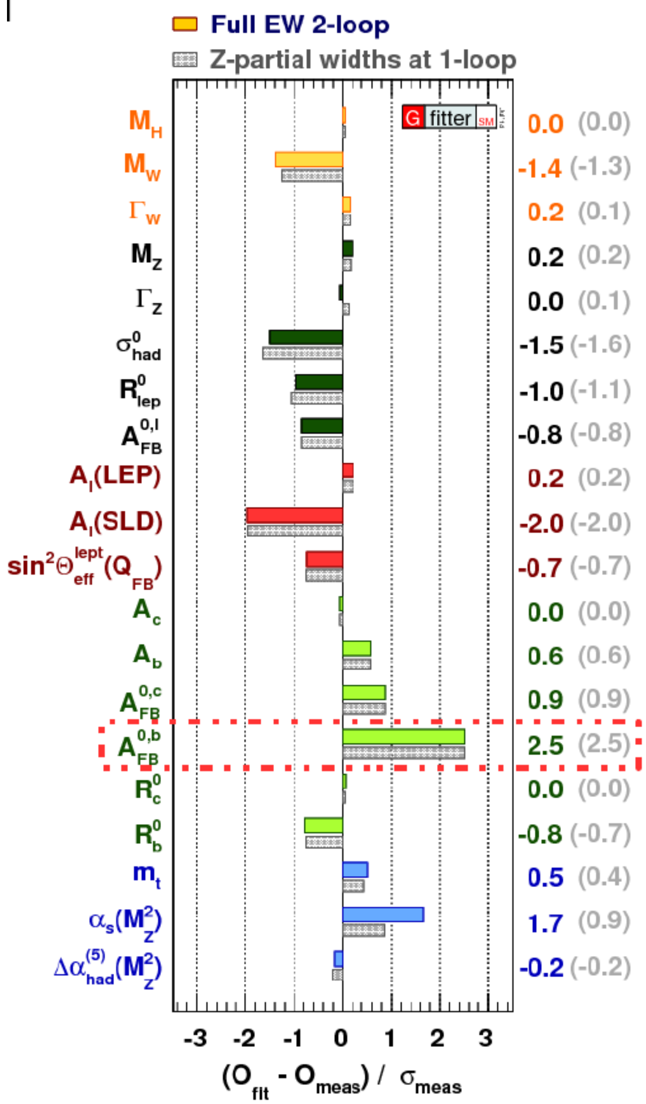
- These observables have been measured at LEP/SLC at the Z-pole (no access to the γ or Z/γ interferences)

Motivation

- Current LEP & SLC **measurements** show **tension** between their **AFB** (b-quark) measurement
- This measurement is the one with **largest tension with the SM fit.**



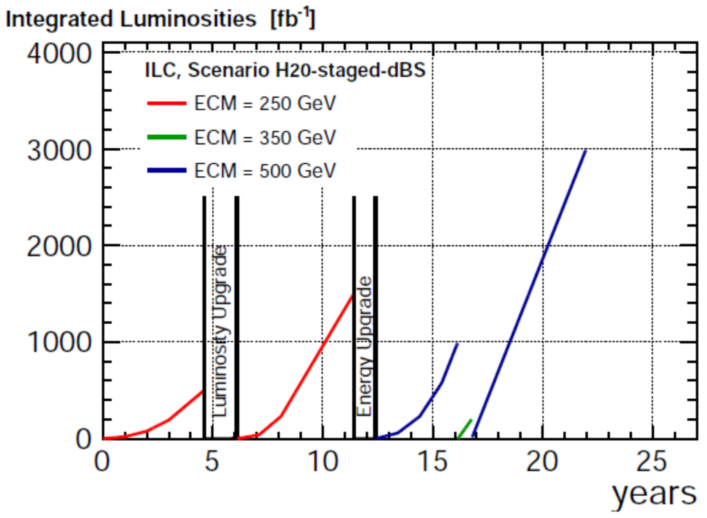
LEP1 effect

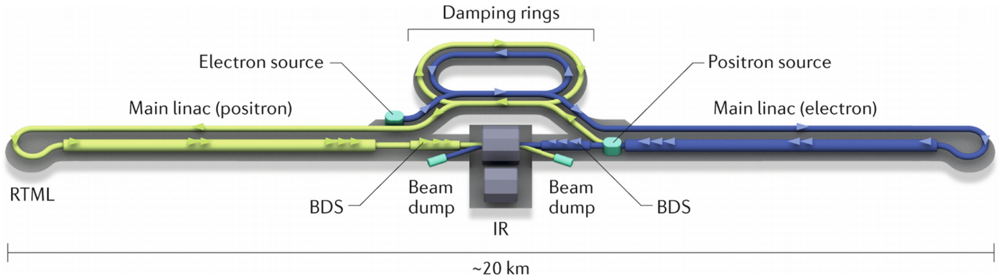


arxiv: 1407.3792v1

The International Linear Collider, ILC 250GeV

- It is a Linear Collider Project, to be hosted in Japan.
  - Matured technollogy: TDR (accelerator + detectors) since 2013.
- e+e- collider with both beams polarized
  - (30%,80%) respectively at 250GeV
- Stage 250GeV:
  - 2000fb-1 in 10-15 years,
  - luminosity shared among different polarization configurations.
- Proposed detector concepts: ILD and SiD.



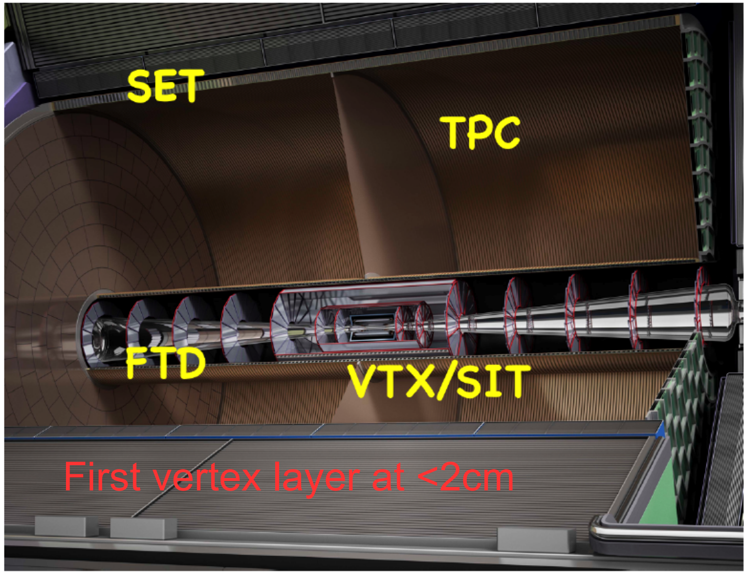


- One of the proposed running scenarios for a staged ILC starting at 250GeV

*GigaZ (running at Z-pole) is a serious option for ILC and the results shown here are the backbone for the estimation of the physics potential in terms of heavy quarks.

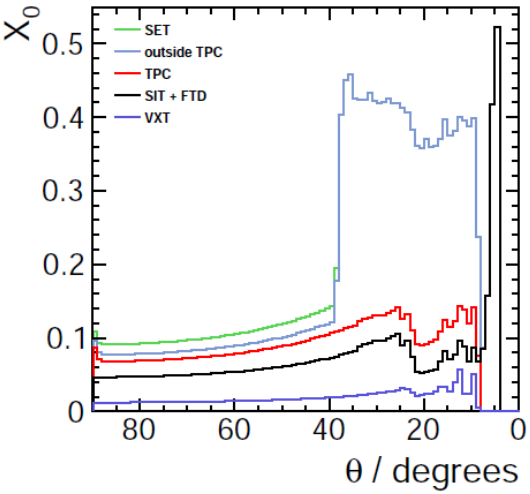
Measuring heavy quark jets with the ILD

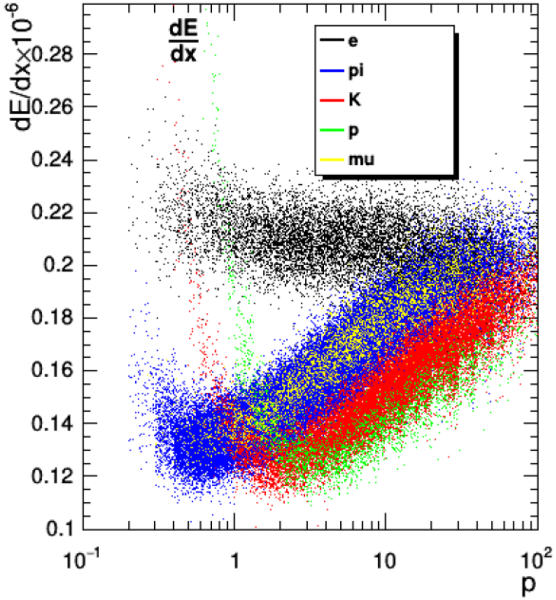
- The goal is to measure the asymmetry basically by measuring the **direction and charge** of the two final state jets. **How?**



- **High** angular **coverage** with **minimum material budget** and **PID (TPC)**

- ILC experiments, as the **ILD**, will provide excellent:
  - Beam IP constraint
  - **Secondary vertex separation and flavour tagging**
  - Tracking **efficiency** (>99%)



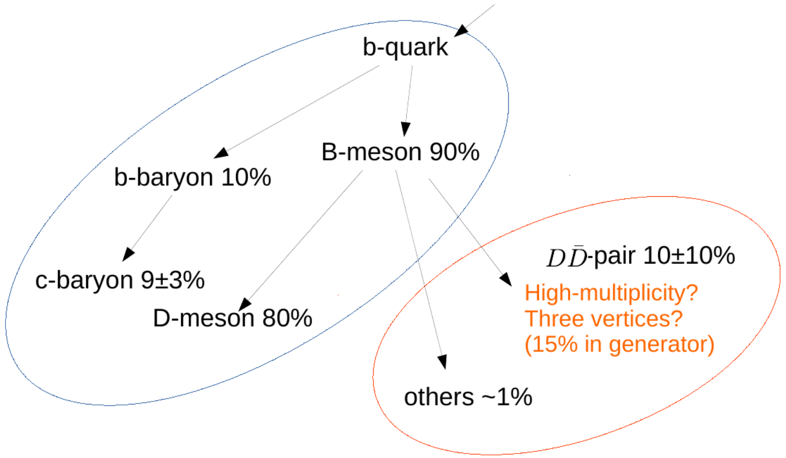


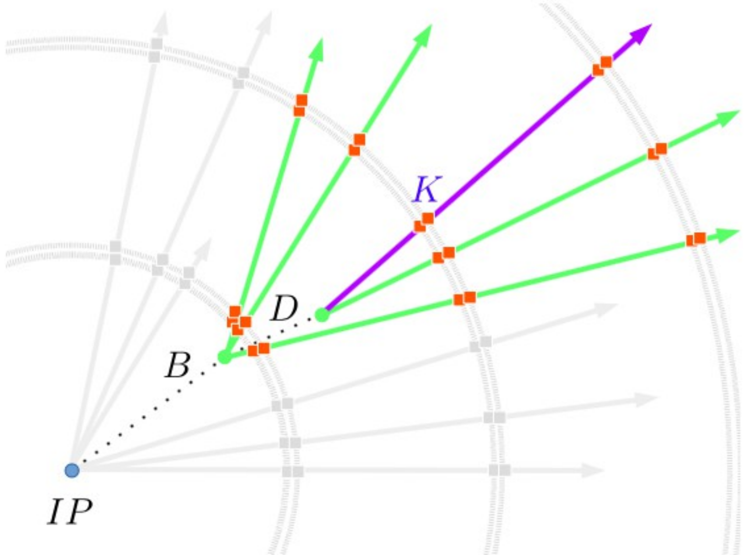
Measuring two b-quark jets with the ILD

- Direct measurement of the charge of charged B-hadrons decay products produced by the b-quark hadronization by measuring the charge of the secondary vertexes.

Process overview

- Hadronization and decay modes of b-quark:





Only the kaon identification (~85% eff and 90% purity) allows to measure the b-quark charge when it decays in neutral B_0 or D_0

Event Pre-Selection

- Event pre-selection is based in the **double b-tagging.**
- Additional kinematic cuts are applied to reduce background and QCD effects
  - Cut 1: Radiative return removal cut 1(reject events with m(j1j2)<180GeV)
  - Cut 2: Radiative return removal cut 2 (reject events with a photon with E>40GeV)
  - Cut 3: Against QCD FSR and “fat jets” in ZZ signatures (m(j1)+m(j2)<120 GeV)

	Pure left polarization, 250GeV						
	Signal	Backgrounds (B/S) %					
	bb	Lighter qq	Radiative Z	WW	ZZ	HZ	Total
Full sample	100.0%	541.0%	14.9%	259.6%	24.6%	2.1%	842.2%
Double btag	73.5%	0.6%	11.0%	0.2%	5.0%	1.1%	18.0%
+Cut 1	70.4%	0.5%	4.5%	0.1%	2.0%	0.5%	7.7%
+Cut 2	63.4%	0.5%	1.6%	0.1%	2.0%	0.5%	4.8%
+Cut 3	62.1%	0.5%	1.5%	0.1%	1.1%	0.2%	3.4%

- O(10^6) of b-quark pairs (excluding rad. return) are going to be produced by ILC250 !

Double charge measurements

- Not all b-jets provide b-quark charge information and also **mis-measurmenets** on the **charge** lead to **large migrations** in the final distribution.
- The **migrations are restored** by determining the purity of the charge calculation using double charge measurements
  - Accepted events, N_{acc}, with (-,+) compatible charges
  - Rejected events, N_{rej}, non compatible (–,++) charges

$$N_{acc} = Np^2 + Nq^2$$
$$N_{rej} = 2Npq$$
$$1 = p + q$$

pq-equation
Incognitas: pq and N.

The **pq-equation** allows for correcting for migrations (findinf the correct N) and in particular for the last and ultimate migration (dilution) due to B0 oscillations

Final selection after double charge measurements is still very large. ~30%

b-quark EW couplings determination

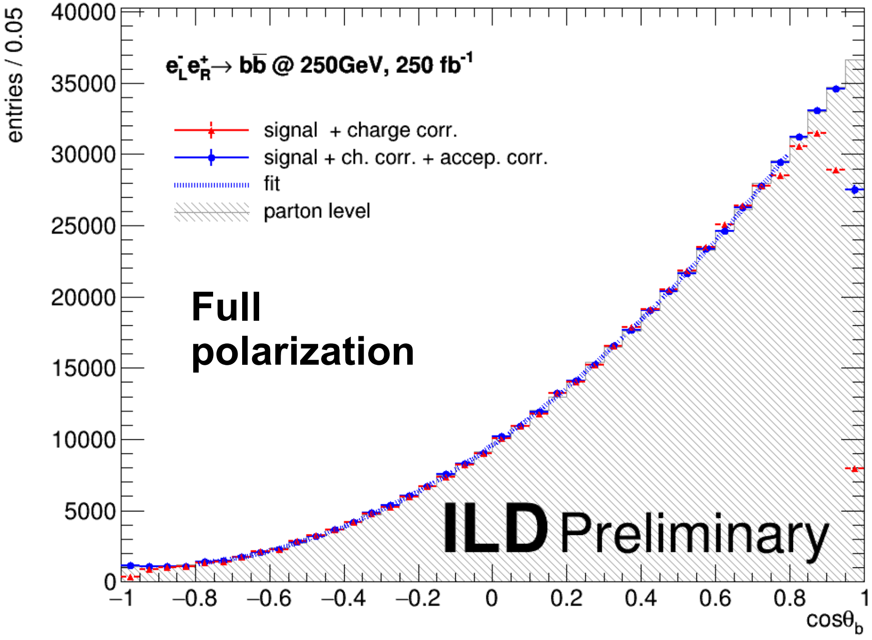
$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to b\bar{b}) = L_e L_b (1+\cos\theta)^2 + L_e R_b (1-\cos\theta)^2$$

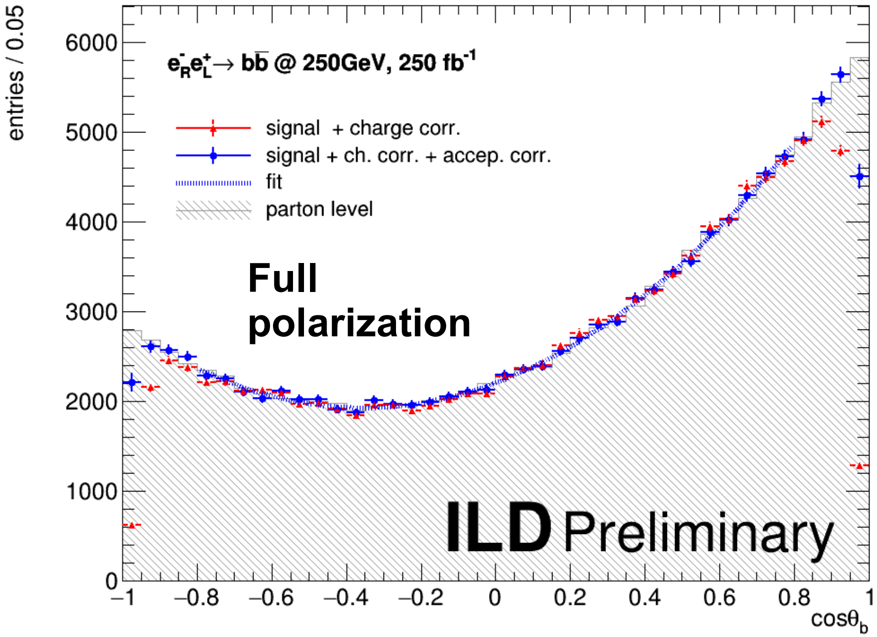
$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to b\bar{b}) = R_e L_b (1+\cos\theta)^2 + R_e R_b (1-\cos\theta)^2$$

- $L_e L_b$, $L_e R_b$ are associated with the production of $b_L \bar{b}_R$; Similar for $R_e L_b$, $R_e R_b$.
- At a linear collider with polarized beams and using vertex charge to distinguish b and $\bar{b}$, **all four of these functions** can be measured independently at a fixed c.m.e.
- Also, traditionally, these helicity terms can rearranged in 'simpler' ways, I.e.

$$f_{LR/RL}(S,A) = S_{LR/RL}(1+\cos^2\theta) + A_{LR/RL}\cos\theta$$

b-quark EW couplings determination





- **Long lever arm** to extract the relevant quantities (i.e. S,A)

- **2000 fb-1,**
- assuming no new resonances.

Polarizations (e-, e+)	**(-80,+30) %**	**(+80,-30) %**
Selection Eff (%)	30	30
L (fb-1)	900	900
εS (syst + stat) %	0.095+0.15	0.20+0.17
εA (syst + stat) %	0.13+0.15	0.77+0.26

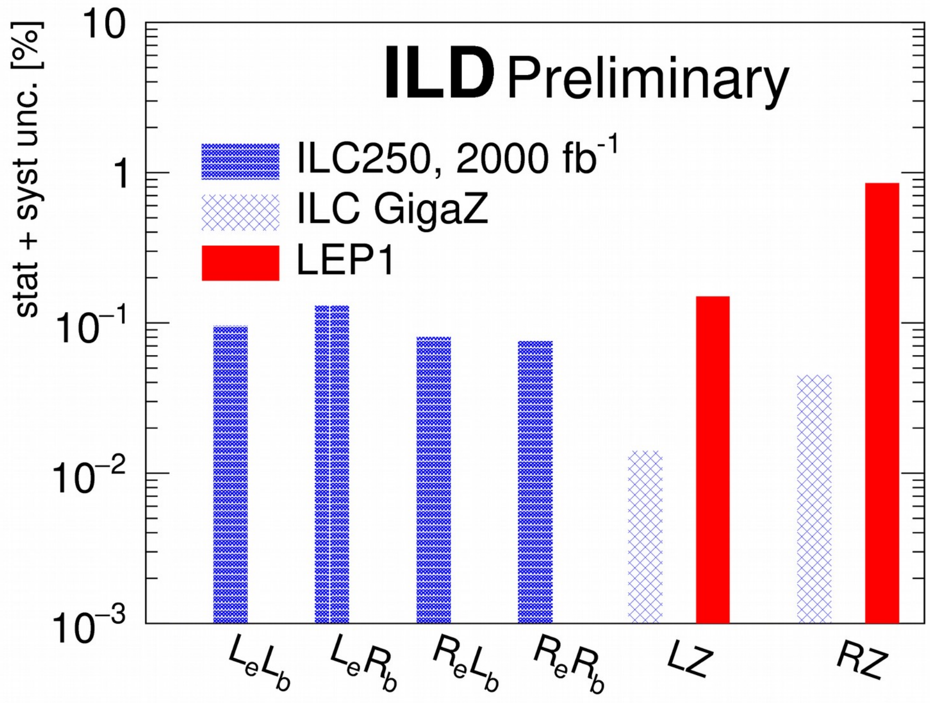
Interpreting the results in the context of new RS resonances

- Closer look to the helicity amplitudes.
- The origin of new resonances is sustained by RS models.
  - Top-philics

    Djouadi, Moreau and Richard (hep-ph/0610173)

    Yoon and Peskin (arXiv:1811.07877)
  - Predict deviations for all fermion specias

    Hosotani et al (Phys.Lett. B775 (2017) 297-302)



$$\mathrm{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w}BWZ + \sum_{Z'}\frac{LeZ'LbZ'}{s^2wc^2w}BWZ'$$

ILC250 SM GigaZ New Resonances

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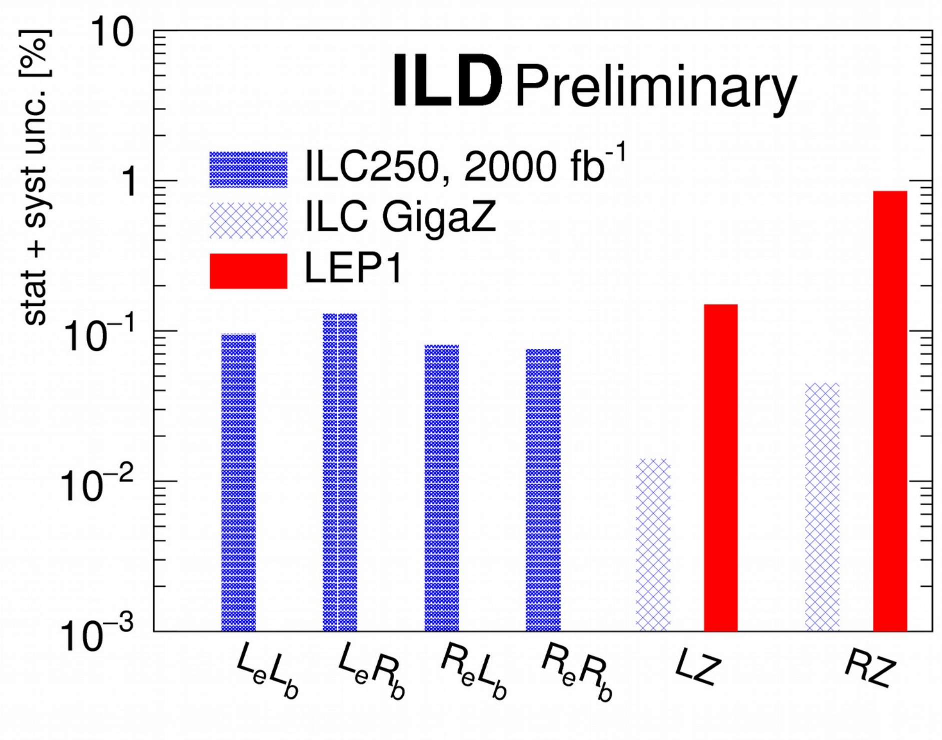
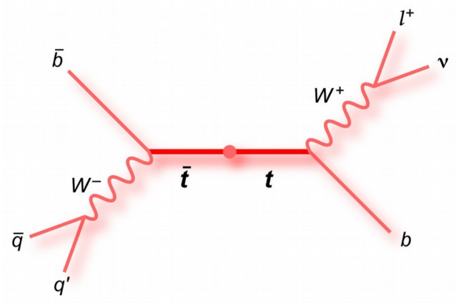
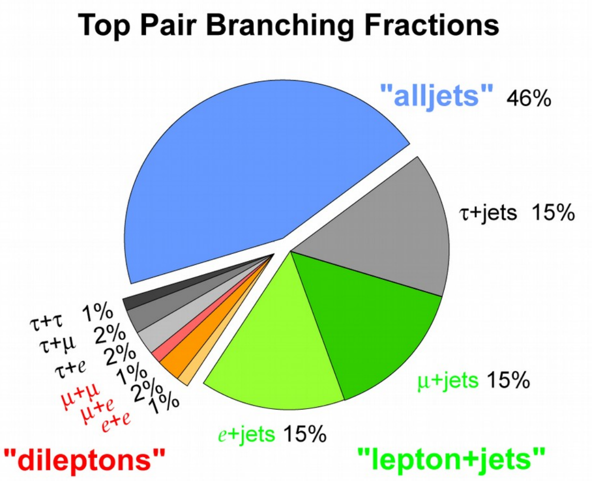


- **ILC250 + GigaZ can discover RS signals and distinguish between models that predict Z-Z' mixing or not.**

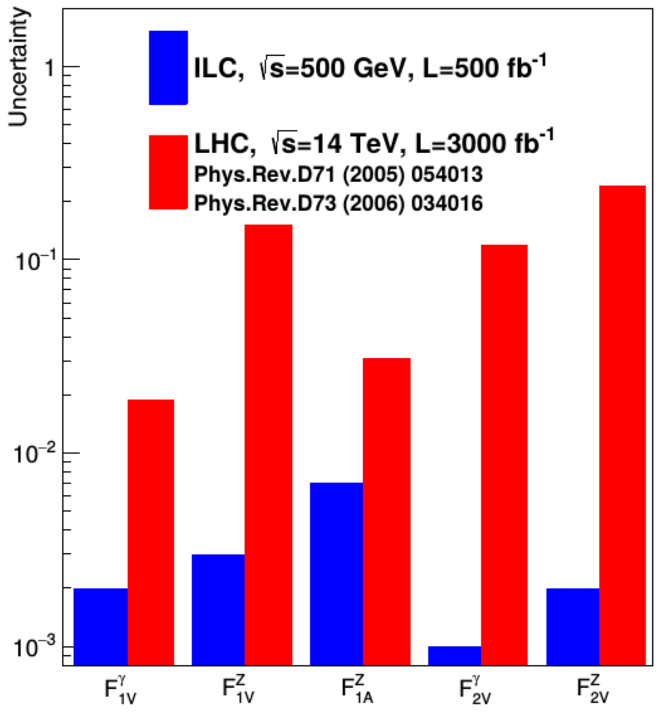
t-quark EW couplings determination

- Potential upgrades of ILC250 are: Z-pole, tt-threshold, **500GeV**, 1TeV
- For tt: at 500 GeV one works in a theoretically safe domain that is free from threshold effects with particular sensitivity to axial couplings.
- **Tops decay** before hadronizing: Analysis based on lepton & b-quark selection and charge measurement.
- **Current prospects** are based on the analysis of the **semileptonic decay modes.** The major uncertainty is still the statistical one.



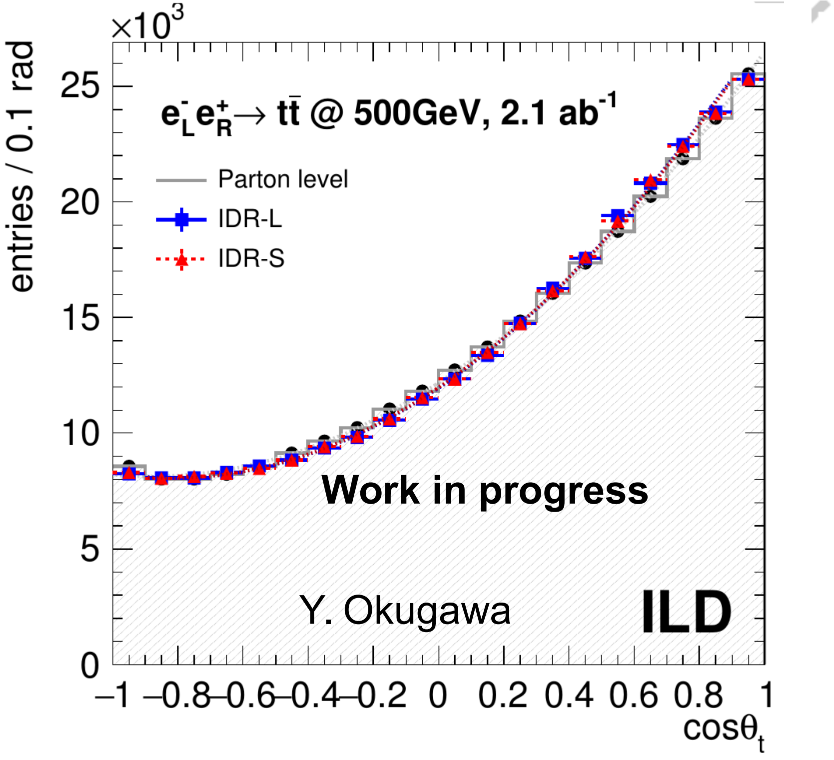


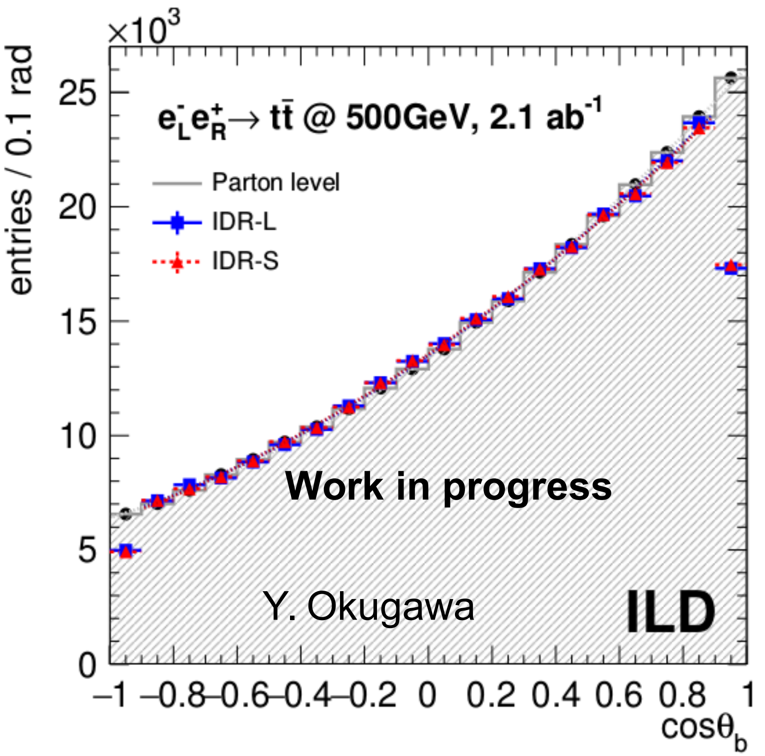
arxiv:1505.06020



t-quark EW couplings determination

- We are working on an **update** of the published analysis with **2000 fb-1.**
- **The improvements on the measurement of the** b-quark charge will soon allow us to take the **fully hadronic** decay modes into account.





Conclusions & Prospects

- **Two fermion final states** are an important ingredient to the **physics program at the ILC.**
- **ILC** will fully **solve the LEP1 effect** and the LEP/SLC disagreements.
- **Heavy quarks are sensitive to new physics effects,** as for example those inspired by **RS** models
  - Heavy quarks are at the cross roads between top-philic models and those that predict deviations for all fermions species.
- These measurements constitute important **benchmarks** for **detector optimization**
  - Clean measurement requires double tagging and vertex charge measurement both is possible with ILD
- Full exploitation of physics potential require adequate experimental setup: **polarised beams, reach in energy (Z-pole to 1 TeV)**

- Stay tuned for more results of EW couplings (b, t) for different running scenarios and also for the second generation of quarks.

Back-up slides

The ILD Concept

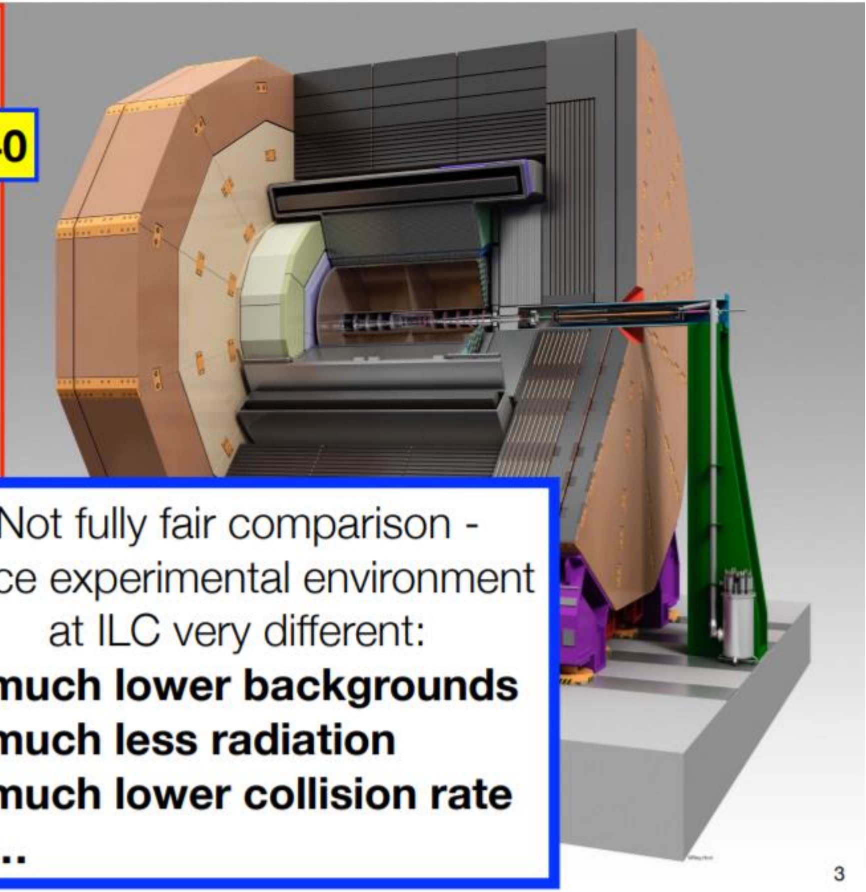
Jenny List, talk at LCWS2018

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$ **≈ CMS / 40**
- **vertexing** (H → bb/cc/ττ)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu\mathrm{m}$ **≈ CMS / 4**
- **jet energy resolution** 3-4%
  (H → invisible) **≈ ATLAS / 2**
- **hermeticity** θ_{min} = 5 mrad
  (H → invis, BSM) **≈ ATLAS / 3**

To key features of the **detector**:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



Not fully fair comparison - since experimental environment at ILC very different:

- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**
- **...**

Tracking at ILD

Table 1. The ILD tracking detectors and their key parameters [2].

detector	geometry	description	single point resolution
VTX	$r_{in} = 16$ mm $r_{out} = 60$ mm $z = 125$ mm	3 double layers Si-pixel sensors	$\sigma_{r\phi,z} = 2.8\mu$m (layer 1) $\sigma_{r\phi,z} = 6.0\mu$m (layer 2) $\sigma_{r\phi,z} = 4.0\mu$m (layers 3-6)
SIT	$r_{in} = 153$ mm $r_{out} = 300$ mm $z = 644$ mm	2 double layers Si-strip sensors	$\sigma_{\alpha_z} = 7.0\mu$m $\alpha_z = \pm 7.0°$ (angle with z-axis)
SET	$r = 1811$ mm $z = 2300$ mm	1 double layer Si-strip sensors	$\sigma_{\alpha_z} = 7.0\mu$m $\alpha_z = \pm 7.0°$ (angle with z-axis)
FTD_{pixel}	$z_{min} = 230$ mm $z_{max} = 371$ mm	2 disks Si-pixel sensors	$\sigma_r = 3.0\mu$m $\sigma_{r_\perp} = 3.0\mu$m
FTD_{strip}	$z_{min} = 644$ mm $z_{max} = 2249$ mm	5 disks - double Si-strip sensors	$\sigma_{\alpha_r} = 7.0\mu$m $\alpha_r = \pm 5.0°$ (angle with radial direction)
TPC	$r_{in} = 330$ mm $r_{out} = 1808$ mm $z = 2350$ mm	MPGD readout > 220 layers 1 x 6 mm^2 pads	$\sigma^2_{r\phi} = (50^2 + 900^2 \sin^2\phi +$ $((25^2/22) \times (4T/B)^2 \sin\theta)\,(z/\mathrm{cm}))\,\mu\mathrm{m}^2$ $\sigma^2_z = (400^2 + 80^2 \times (z/\mathrm{cm}))\,\mu\mathrm{m}^2$ where ϕ and θ are the azimuthal and polar angle of the track direction

Tracking at ILD

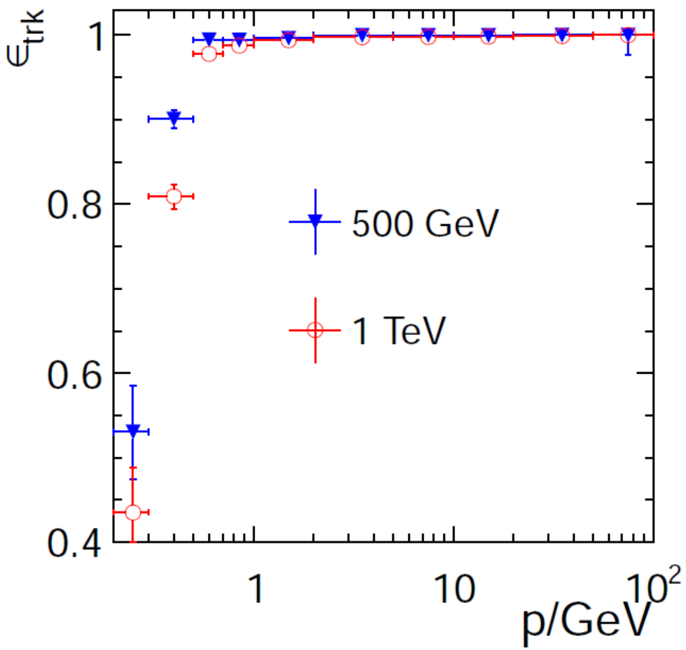


Figure 5. Tracking Efficiency for $t\bar{t} \to 6$ jets at 500 GeV and 1 TeV versus momentum in the presence of beam background.

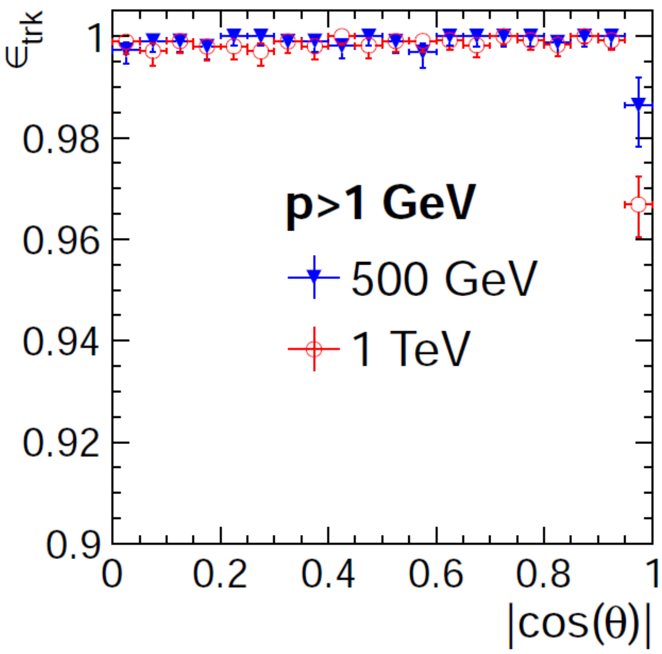
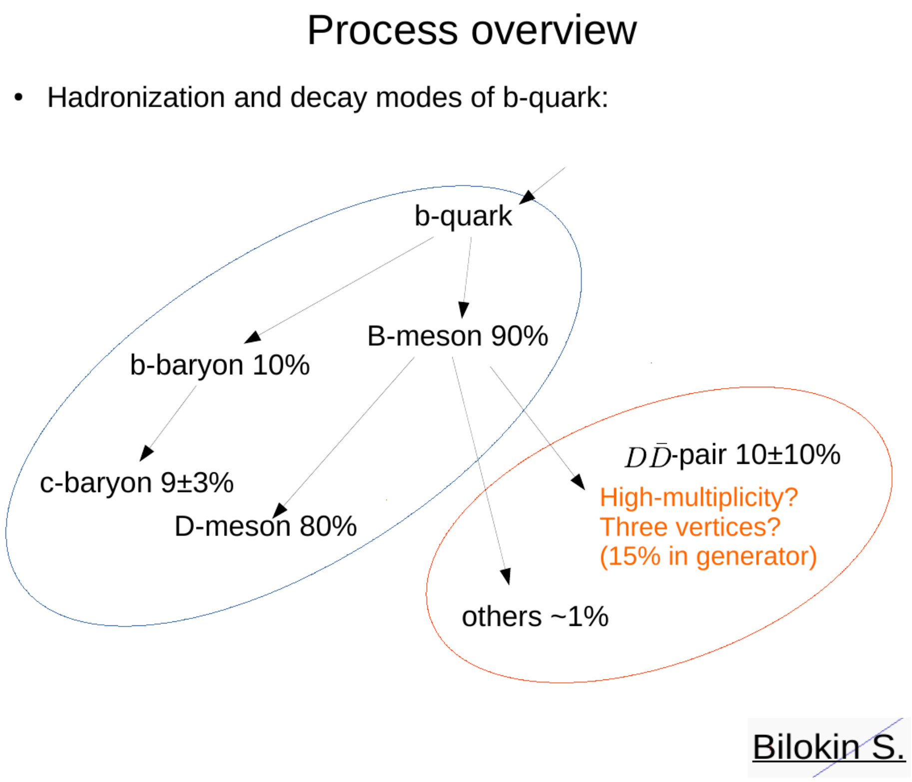
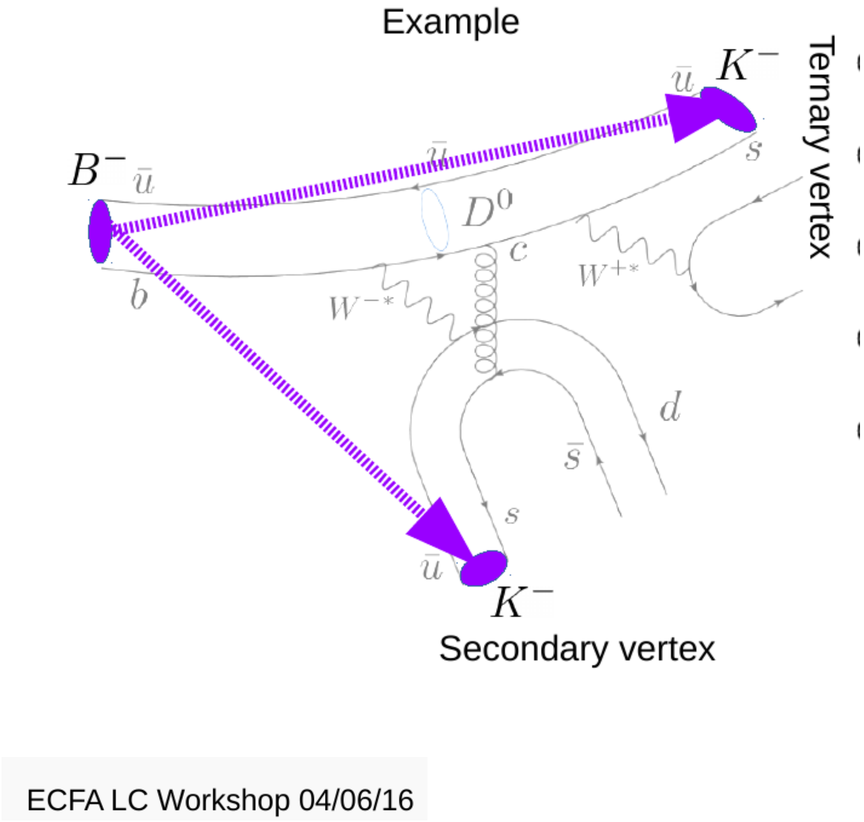


Figure 6. Tracking Efficiency for $t\bar{t} \to 6$ jets at 500 GeV and 1 TeV versus $|cos(\theta)|$ for particles with $p > 1$GeV in the presence of beam background

Process overview

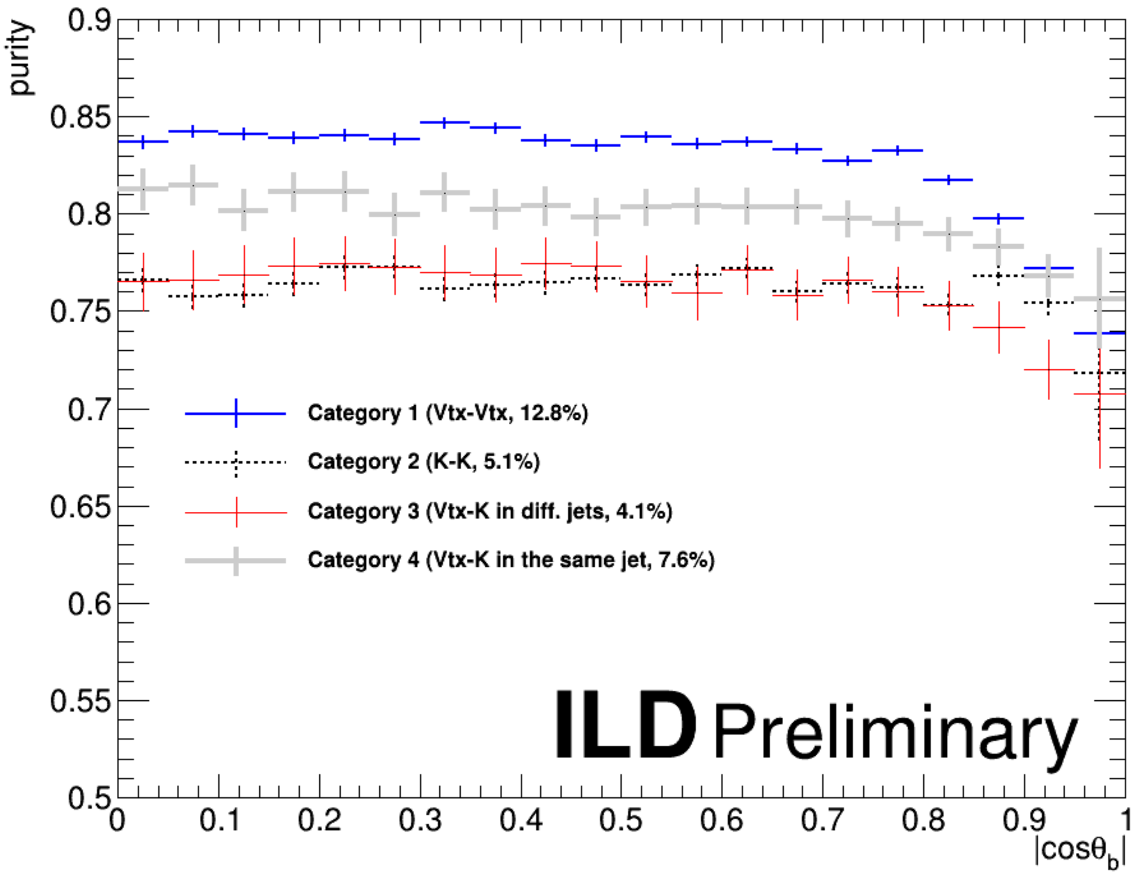
- The goal is to measure the asymmetry basically by measuring the **direction** of the two final state jets and their **charge**. **How?**





Double charge measurements

- Final selection after double charge measurements is still very large.
  - ~30%



Double tagging

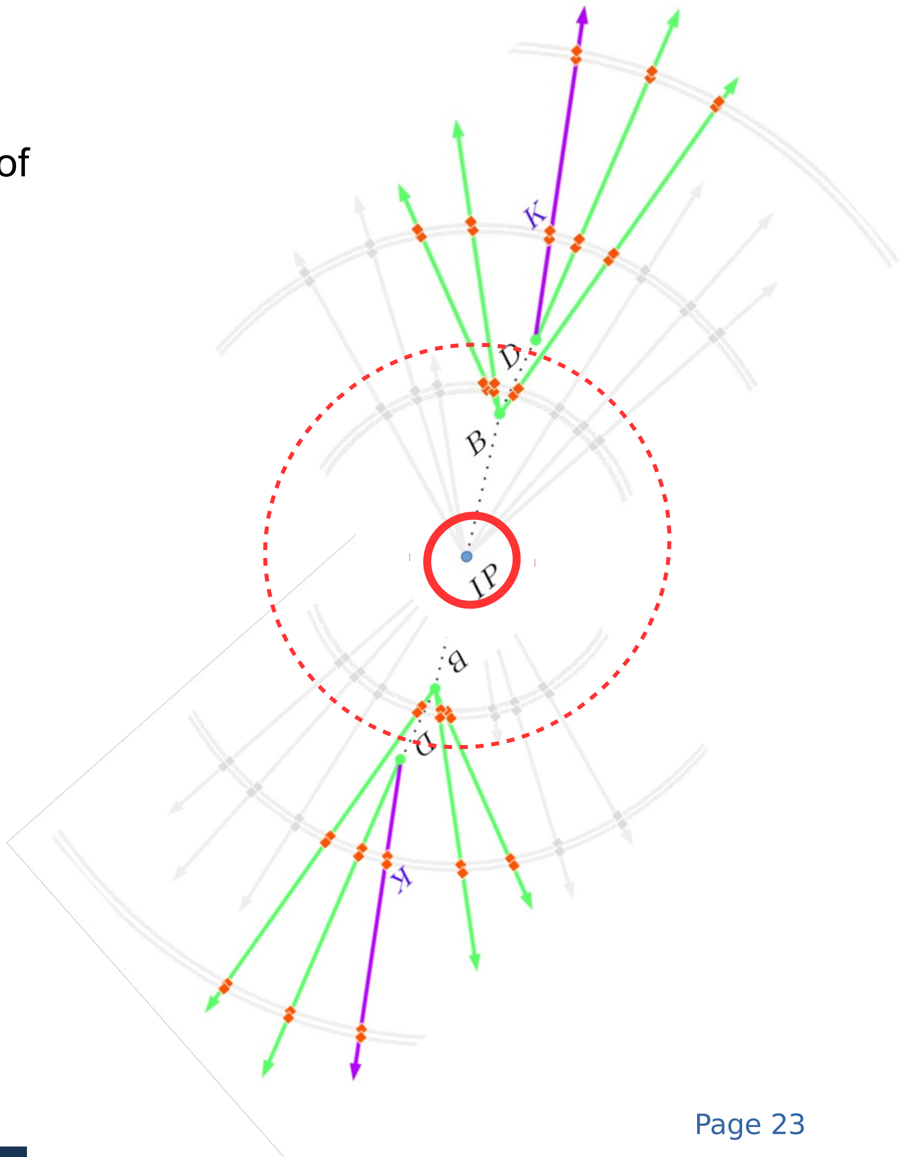
- Important systematic error is associated to the knowledge of tagging efficiency ε_q
- Can be derived from data if tagging is independent in two hemispheres, i.e. if

$$C_q = \frac{\epsilon_{double}}{\epsilon_q^2} \approx 1$$

  - If $C_q \neq 1$ → Hemisphere correlations → systematic error

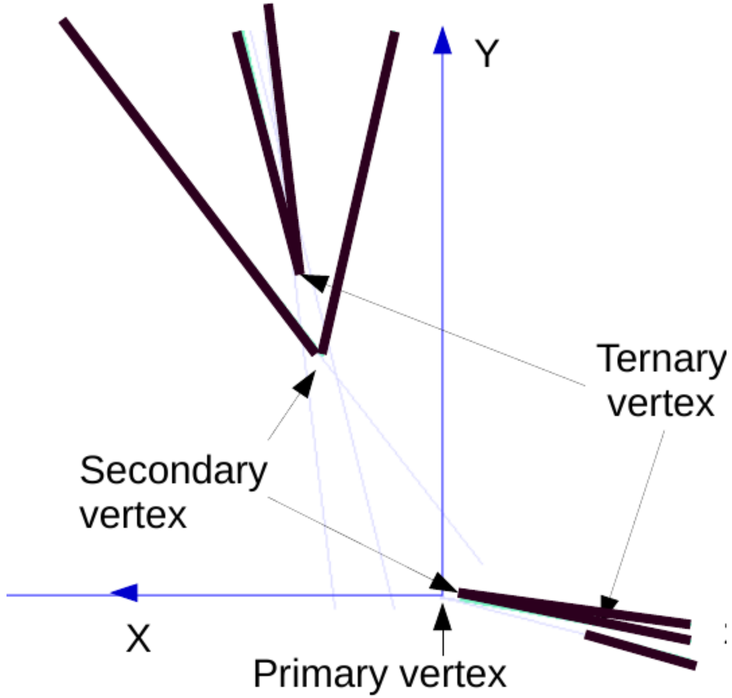
- For example:
  - LEP (large beam spot): C_q-1 ≈ 3% → ΔR_b ≈ 0.2%
  - SLC (smaller beam spot): C_q-1 < 1% → ΔR_b ≈ 0.07%
  - ILC (tiny beam spot): Expect C_q-1 ≈0 → ΔR_b ≈ 0

    to be verified however



b-asymmetry measurement

- The goal is to measure the asymmetry basically by measuring the direction of the two final state jets and their charge. **How?**



- We have two methods to identify b-jet charge:
  - With the charge of the b-quark, calculated as a sum of the charges of secondary and tertiary vertex

    → we call this method the Bc method (or vtx method)

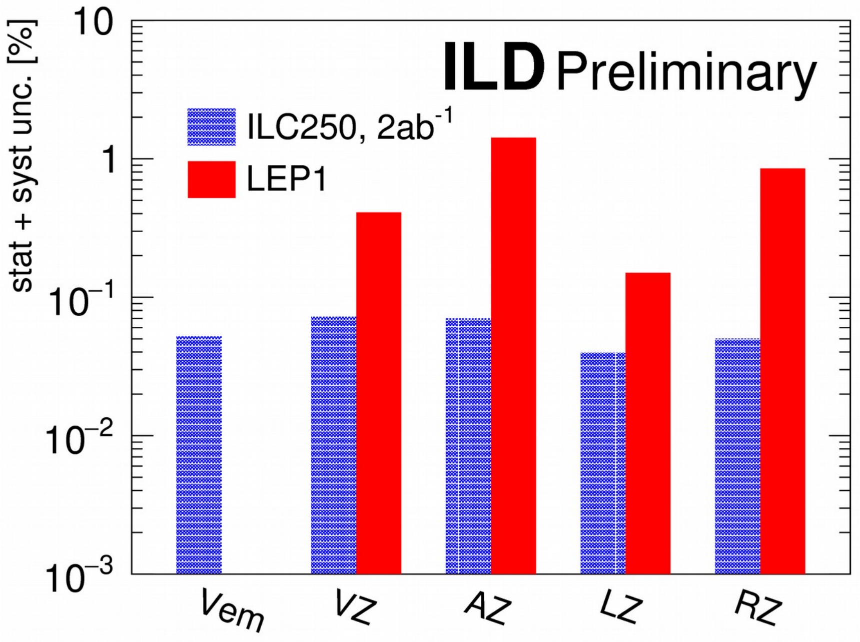
  - With the charge of K-mesons, from B-decays, in secondary and tertiary vertexes

    → we call this method the Kc method (or kaon method)

b-quark EW couplings determination

- For 2000 fb-1, the measurements are already systematics limited.

Polarisations P P'	-80% +30%	+80% -30%
Efficiency %	30	30
Luminosity fb^{-1}	900	900
Cross section fb	3342	1012
Background(S) %	1.5	5
Syst for S % L+eff+Pol+back	0.1+0.1+0.0+0.0	0.1+0.1+0.08+0.05
S stat+syst %	0.095+0.15	0.20+0.17
Syst for A % L+eff+Pol+back	0.1+0.1+0.0+0.0	0.1+0.1+0.2+0.1
A stat+syst %	0.13+0.15	0.77+0.26



- EW b-quark form factors and couplings

- The **LEP1 anomalies** measured in RZ and LZ (~3σ away of SM) will be completely confirmed or discarded
- These results are obtained assuming no **new resonances.** If so, assuming, improved measurements at Z-pole, **ILC250GeV** will **have access to Z' of ~20TeV.**

$$\text{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w}BWZ + \sum_{Z'}\frac{LeZ'LbZ'}{s^2wc^2w}BWZ'$$

ILC250 SM GigaZ New resonances

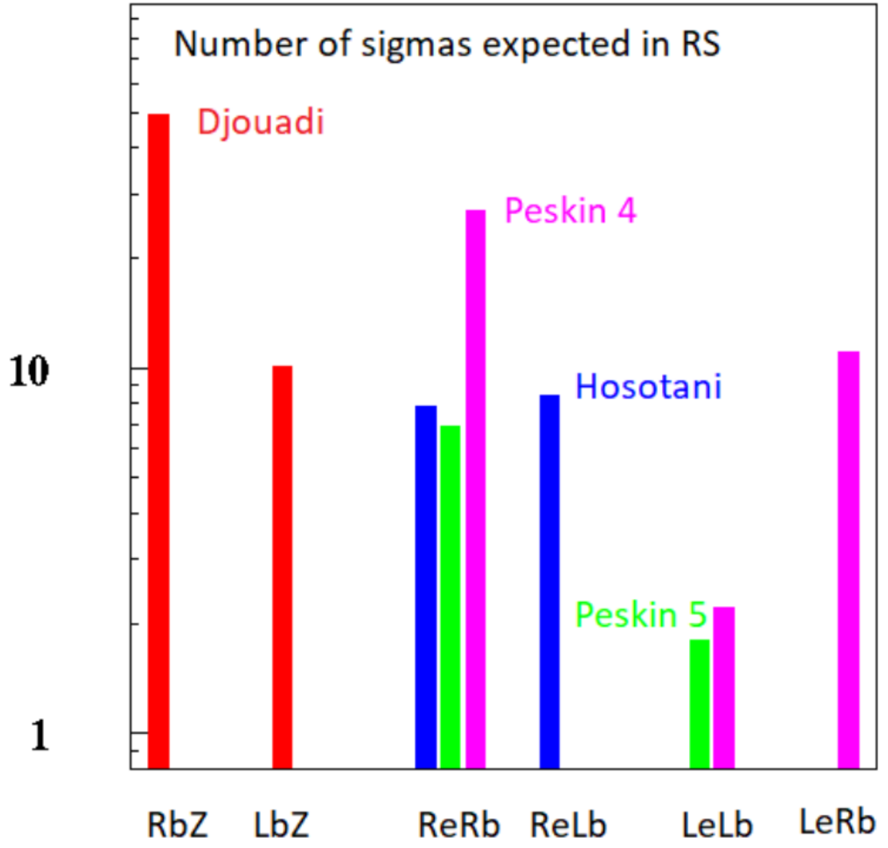
Couplings to Z′

$$\frac{g_w}{\cos\theta_W} Z'_\mu \{ \hat{g}_L \bar{f}_L \gamma^\mu f_L + \hat{g}_R \bar{f}_R \gamma^\mu f_R \}$$

$\theta_H = 0.0917$

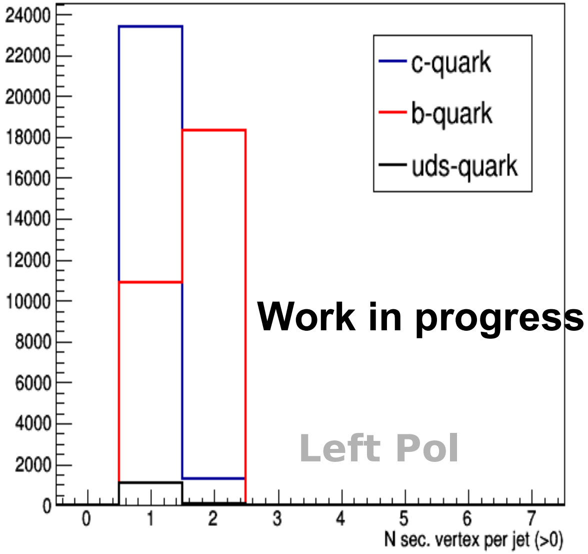
	SM: Z		$Z^{(1)}$		$Z_R^{(1)}$		$\gamma^{(1)}$	
	Left	Right	Left	Right	Left	Right	Left	Right
ν_e			−0.183	0	0	0	0	0
ν_μ	0.5	0	−0.183	0	0	0	0	0
ν_τ			−0.183	0	0	0	0	0
e			0.099	0.916	0	−1.261	0.155	−1.665
μ	−0.2688	0.2312	0.099	0.860	0	−1.193	0.155	−1.563
τ			0.099	0.814	0	−1.136	0.155	−1.479
u			−0.127	−0.600	0	0.828	−0.103	1.090
c	0.3458	−0.1541	−0.130	−0.555	0	0.773	−0.103	1.009
t			0.494	−0.372	0.985	0.549	0.404	0.678
d			0.155	0.300	0	−0.414	0.052	−0.545
s	−0.4229	0.0771	0.155	0.277	0	−0.387	0.052	−0.504
b			−0.610	0.186	0.984	−0.274	−0.202	−0.339

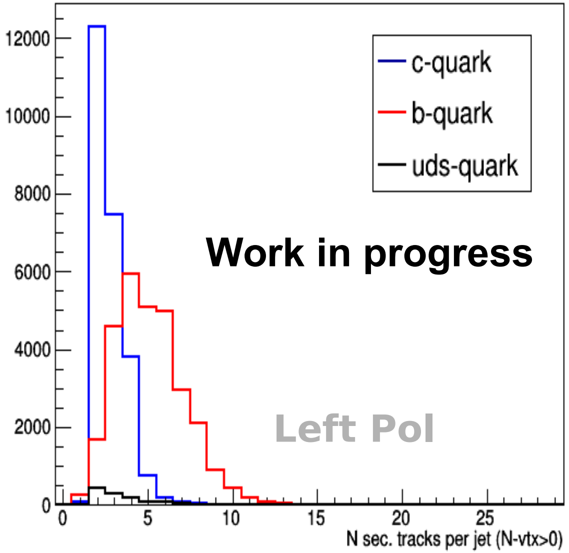
Figure 9: Predictions of the Z' couplings from the Hosotani et al. model [12].

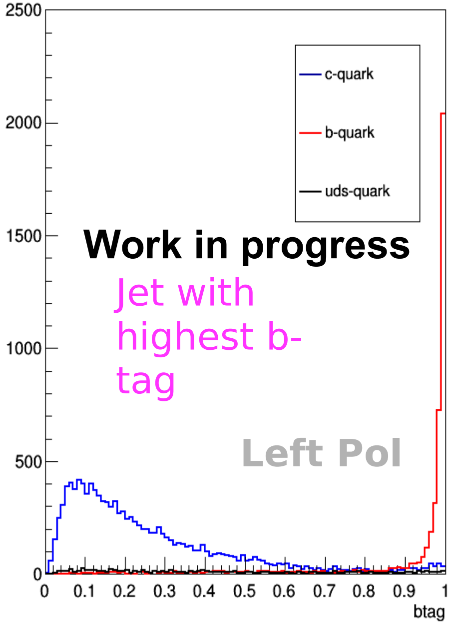


What about lighter quarks ? c-quark

- We started to explore the c-tagging capabilities following first principles and exploiting the tools developped for the b-bbar analysis
- C-tagging (and anti uds and b tagging) seems feasible in jet per jet basis.

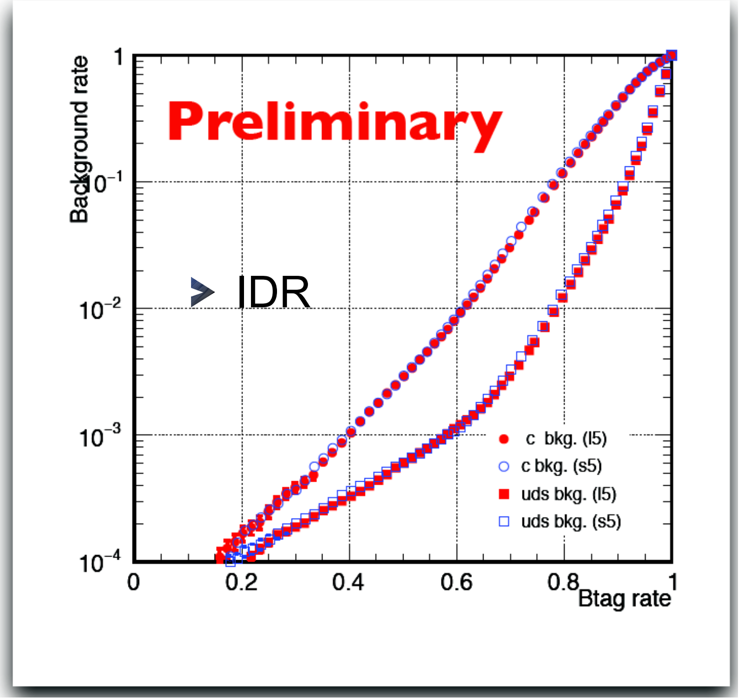


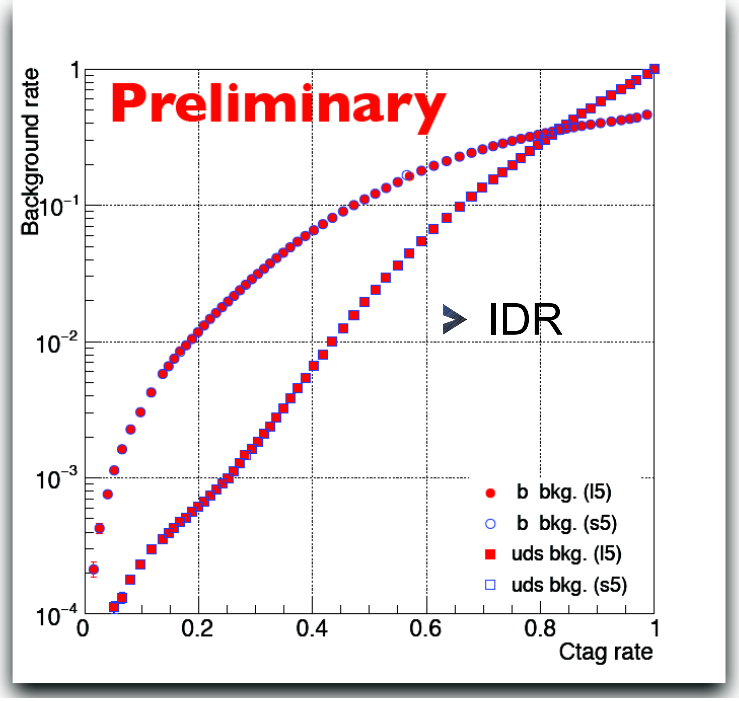




- Studies just started and show the potential of reaching ~>20% efficiency of selection using double tagged events
  - Similar efficiency than SLC but they were using only single tagged events.!

LCFIPlus C-tagging



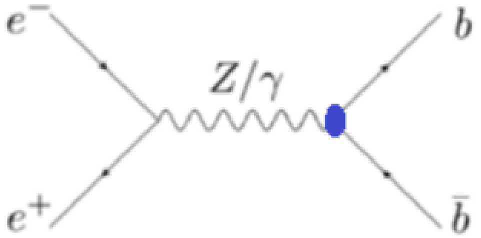


- R. Yonamine's slides, ILD benchmarking days 2019.

6b, 500 GeV, w/ beam bkg.

b-quark EW couplings determination

- The Zbb vertex can be interpreted as a function of the F form factors, which enter in the S & A fit parameters



$$\Gamma_{\mu}^{Z/\gamma} = e[\gamma_{\mu}(F_{1V}^{Z/\gamma} + \gamma_5 F_{1A}^{Z/\gamma}) + \frac{i\sigma_{\mu\nu}q^{\nu}}{2m_b}(F_{2V}^{Z/\gamma} + \gamma_5 F_{2A}^{Z/\gamma})]$$

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