Production and measurement of $e^+e^- \rightarrow q\bar{q}$ signatures at ILC250

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LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

iJC Lab CNRS/IN2P3

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ILD

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Outline

Introduction

- EW Observables
- Selecting 2-quark samples

C-Quark case

- Measurement of the partial width Rc
  - Flavour Tagging
- Measuring the full differential angular cross section and the Afb
  - Flavour Tagging + Charge Measurement
- Results

Differences between c vs b studies.

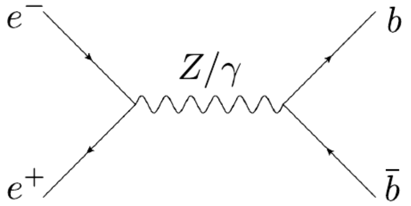
Publication plans

EW observables

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

$$R_q^0 = \Gamma_{q\bar{q}} / \Gamma_{had}$$
$$R_q^\mu = \Gamma_{q\bar{q}} / \Gamma_{\mu\mu}$$

→ Quark identification. No need to measure an angular distribution, a priori.



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

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

→ Angular Distribution.

Quark ID + charge measurement (quark – antiquark disentangling)

Gives access to all left/right couplings.

- These observables have been measured at **LEP/SLC at the Z-pole**
  - no access to the γ or Z/γ interferences
  - Moderated quark tagging and charge measurements.
  - Also moderated angular acceptance of the detectors: drop at cos(θ) ~0.6

Reconstruction of ee→ qq @ 250 GeV

Signal:

- 2 jets back-to-back topologies
  - All jets with similar energy of ~125 GeV

$$\cos(\theta_{\vec{p}_{\bar{q}\bar{q}}})=\cos(\theta_{b\bar{q}})\approx\frac{\cos(\theta_q)-\cos(\theta_{\bar{q}})}{2}\approx\cos(\theta_q)\approx-\cos(\theta_{\bar{q}})$$

Backgrounds:

- Radiative return ee→ γZ (ISR): Presence of the photon in the detector or invariant mass of the system <250GeV (Z-pole) 3 Jet like final states.
- WW: 4 jets final state or 2 jets + lepton + missing energy
- ZZ, HZ: 4 jets final state or 2 jets + 2 leptons
- None of them show back-to-back or two jet like final states.

	Cross section [pb] (LO)						
	bb	cc	uds	Rad Ret. (all flavours)	WW (hadrons)	ZZ (hadrons)	HZ (hadrons)
$e^-_L e^+_R$	5.6	8.0	17.7	97.8	14.1	1.4	0.3
$e^-_R e^+_L$	1.4	3.9	6.1	59.3	0.1	0.6	0.2

All studies are based on DBD samples and software releases

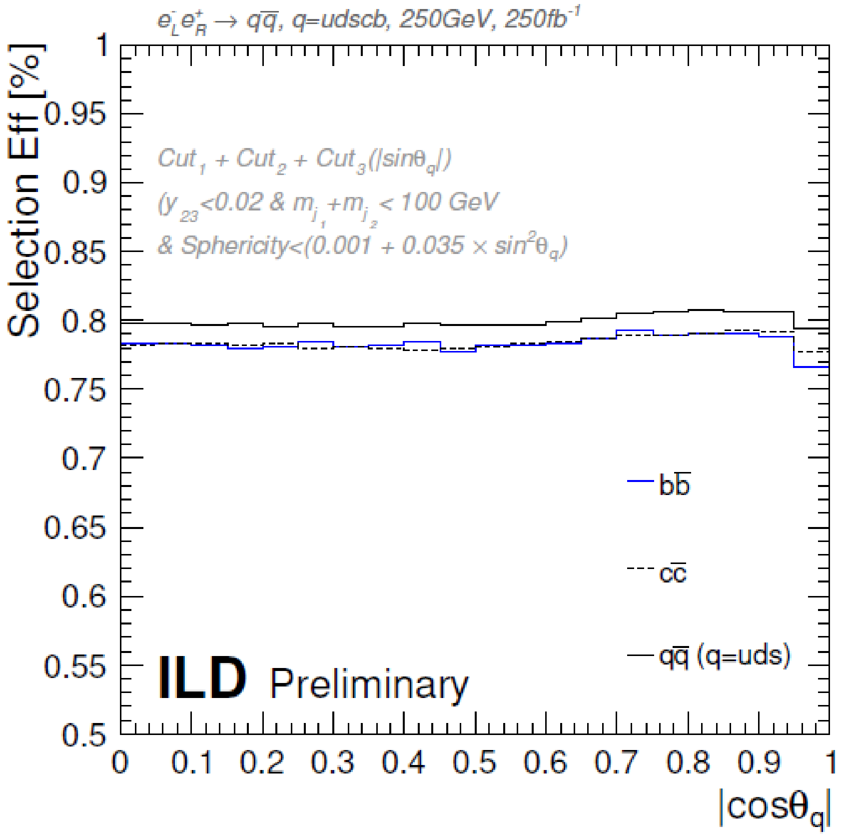
Measurement of the partial width

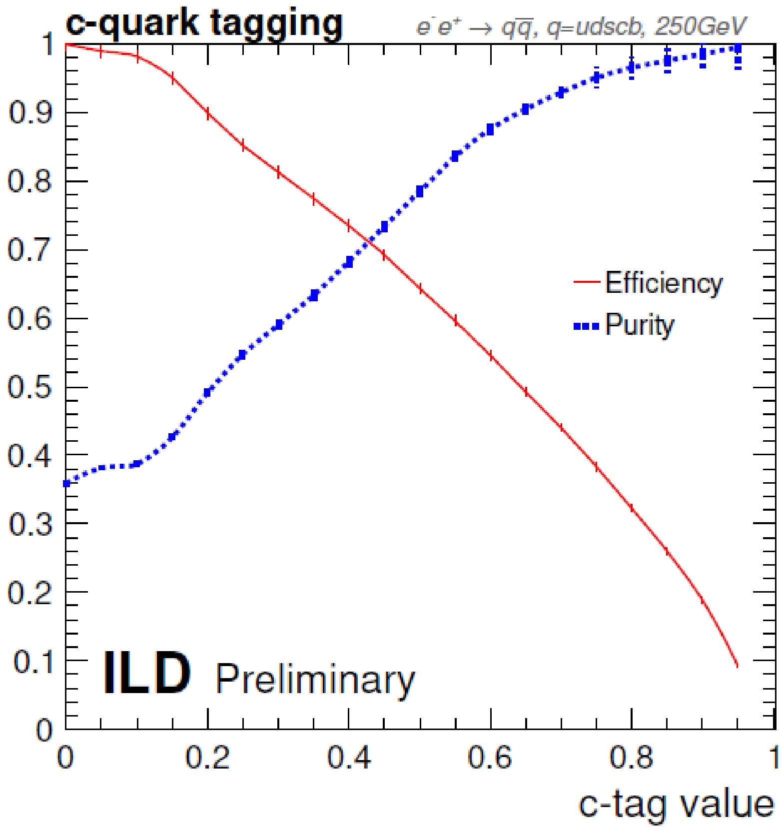
- We apply the same than LEP/SLD (i.e. Eur.Phys.J. C10 (1999) 415-442)
- We compare single vs double tagged topologies.
  - f_1 = fraction of events in which we had at least one jet b/c-tagged
  - f_2 = fraction of events in which we both jets are b/c-tagged

$$f_1 = \epsilon_c R_c + \epsilon_b R_b + \epsilon_{uds}(1 - R_c - R_b) + F(\epsilon_c, \epsilon_b, \epsilon_{uds}, BKG)$$
$$f_2 = \epsilon_c^2(1+\rho_c)R_c + \epsilon_b^2 R_b + \epsilon_{uds}^2(1 - R_c - R_b) + F(\epsilon_c^2, \epsilon_b^2, \epsilon_{uds}^2, BKG)$$

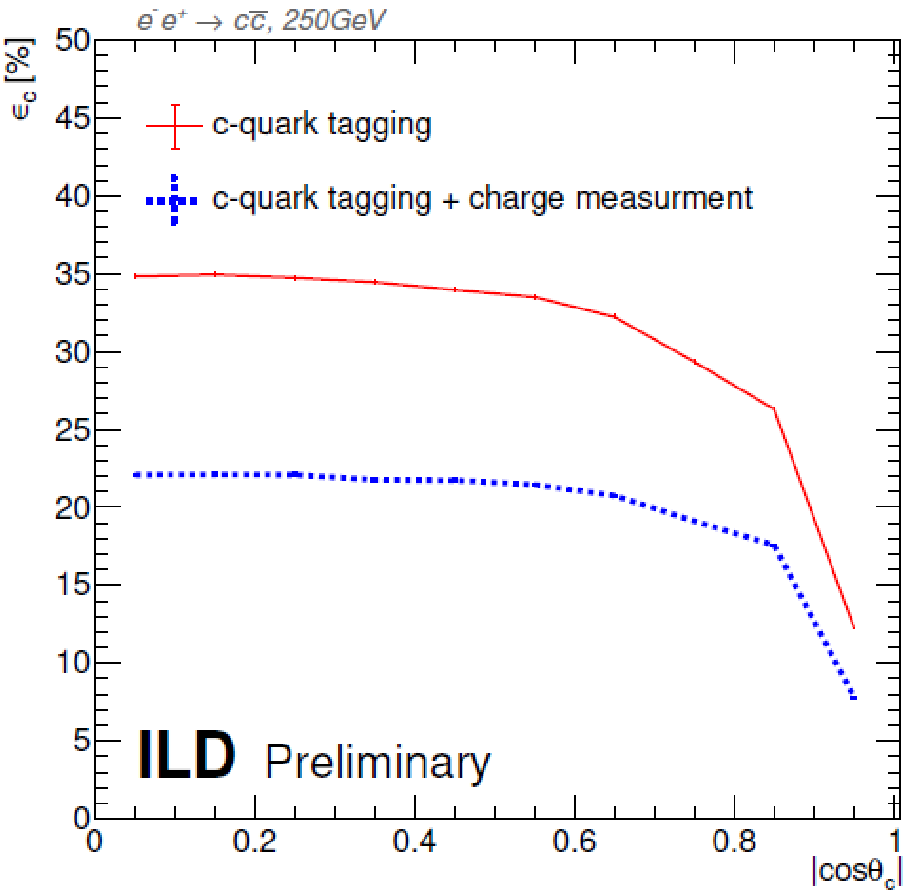
- Similar formula for b/c.
- Main source of systematic uncertainties (in the past)
  - **Correlation factor** → of the order of 0.5-3% in SLD and LEP. **Negligible for ILD** (small beam spot, excellent and very close to the beam pipe tracking)
- New Factor: running far from the Z-pole, we have contributions from other bakcgrounds ! Still, at low rates to be dominant but it adds a new complexity to the analysis..

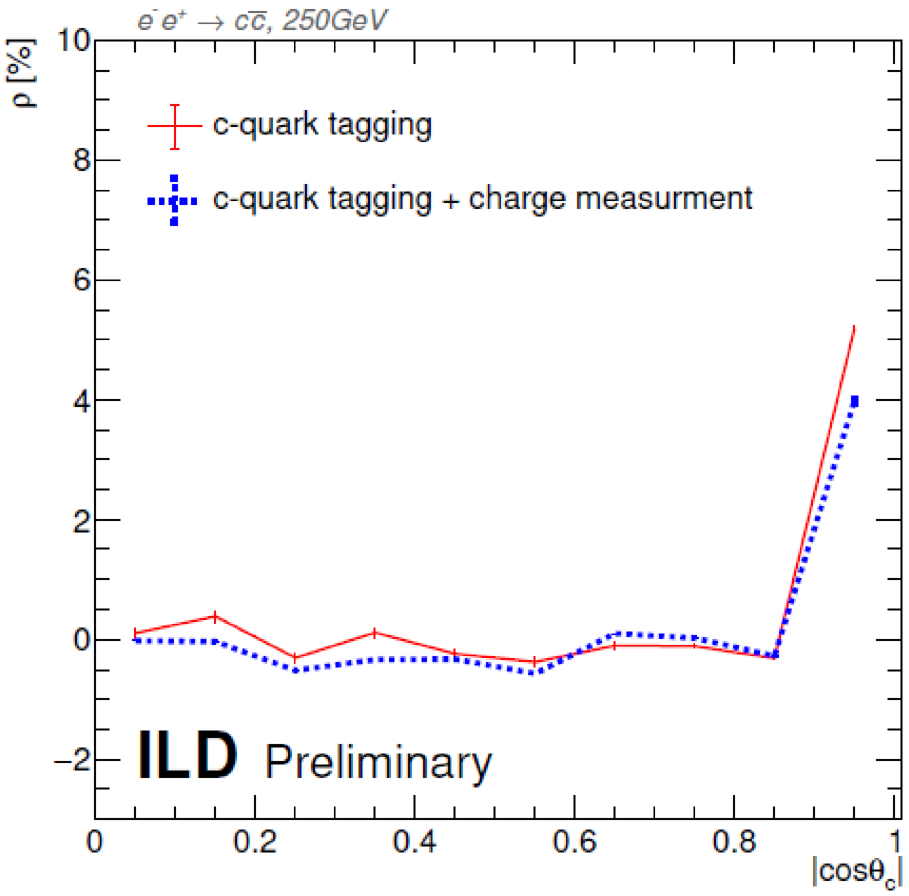
Measurement of the partial width



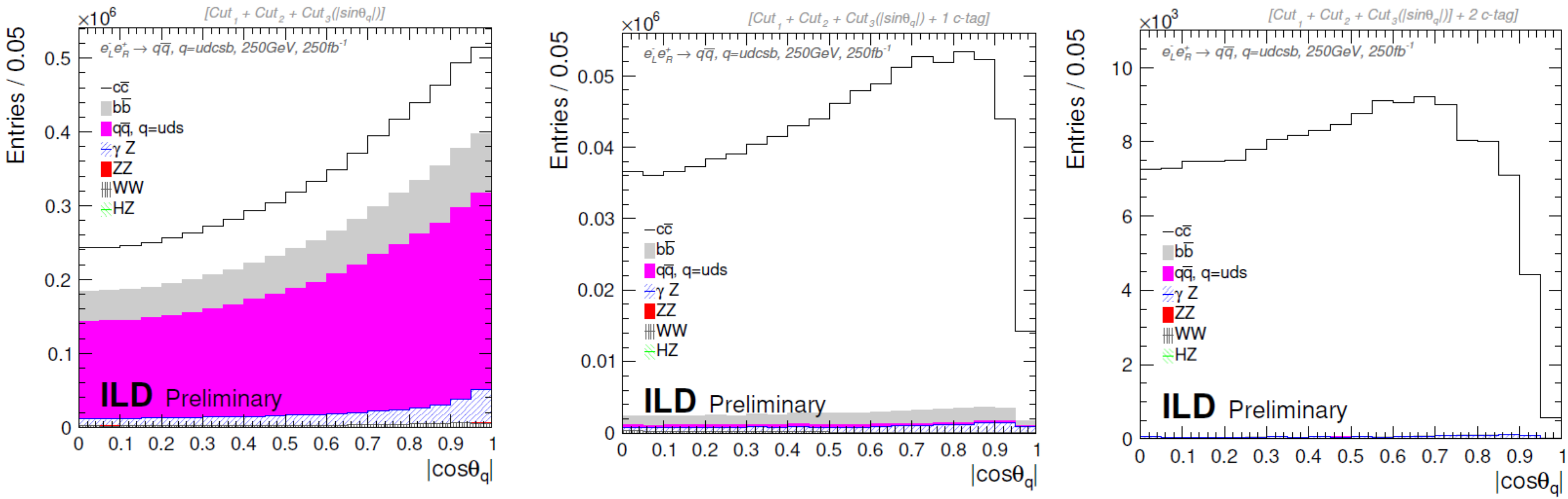


Measurement of the partial width





Measurement of the partial width



Preselection

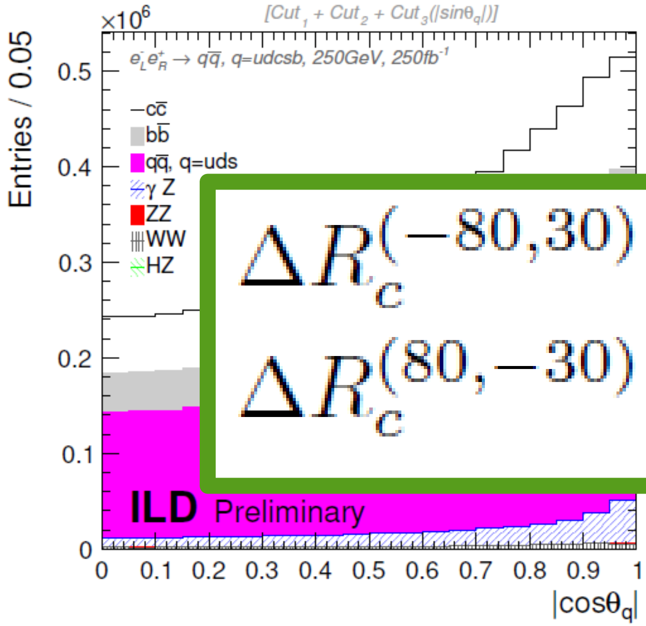
Preselection + 1 c-tag

Preselection + 2 c-tag

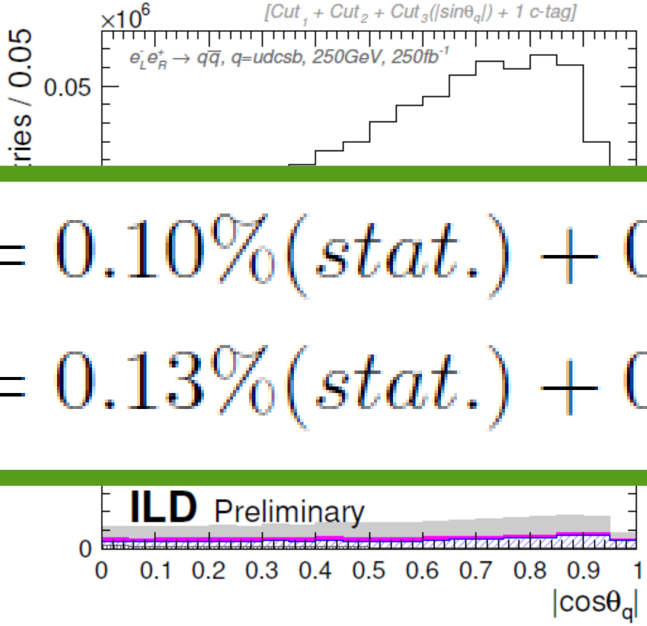
$$f_1 = \epsilon_c R_c + \epsilon_b R_b + \epsilon_{uds}(1 - R_c - R_b) + F(\epsilon_c, \epsilon_b, \epsilon_{uds}, BKG)$$

$$f_2 = \epsilon_c^2 (1 + \rho_c) R_c + \epsilon_b^2 R_b + \epsilon_{uds}^2 (1 - R_c - R_b) + F(\epsilon_c^2, \epsilon_b^2, \epsilon_{uds}^2, BKG)$$

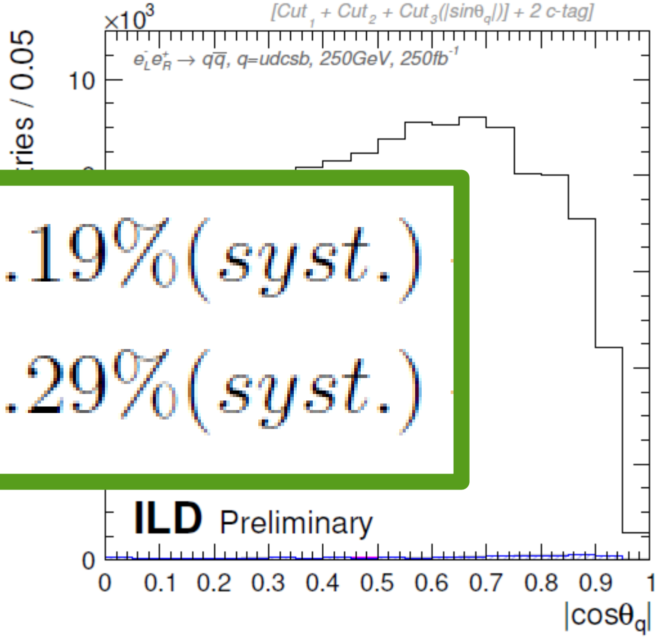
Measurement of the partial width



Preselection



Preselection + 1 c-tag



Preselection + 2 c-tag

$$\Delta R_c^{(-80,30)} = 0.10\%(stat.) + 0.19\%(syst.)$$

$$\Delta R_c^{(80,-30)} = 0.13\%(stat.) + 0.29\%(syst.)$$

$$f_1 = \epsilon_c R_c + \epsilon_b R_b + \epsilon_{uds}(1 - R_c - R_b) + F(\epsilon_c, \epsilon_b, \epsilon_{uds}, BKG)$$

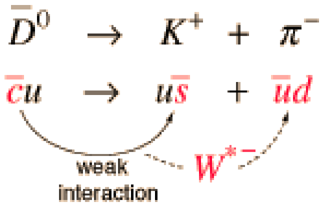
$$f_2 = \epsilon_c^2(1+\rho_c) R_c + \epsilon_b^2 R_b + \epsilon_{uds}^2(1 - R_c - R_b) + F(\epsilon_c^2, \epsilon_b^2, \epsilon_{uds}^2, BKG)$$

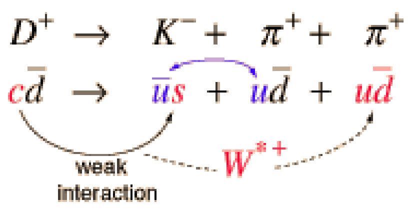
c-Jet Charge determination

- C-quark jets
  - D^0 mesons

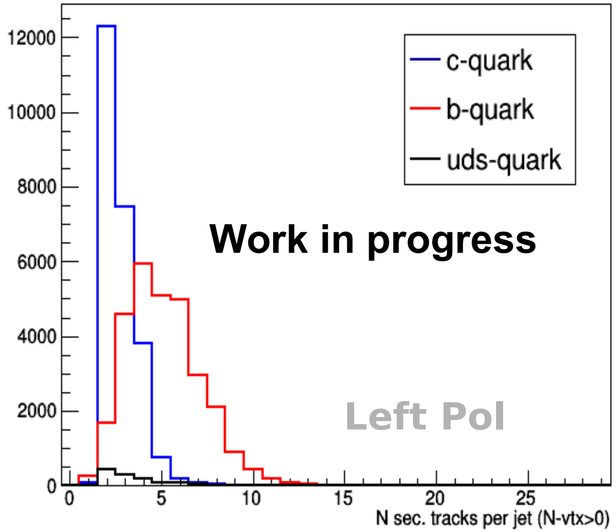
    70% have 2 prongs: -> **High purity offered by Kaons**

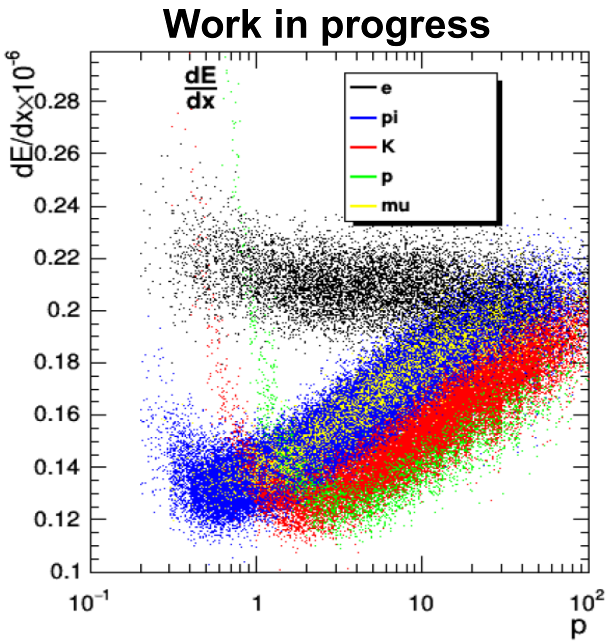
  - $D^{+/-}$, $D_s^{+/-}$: 1-3 prongs



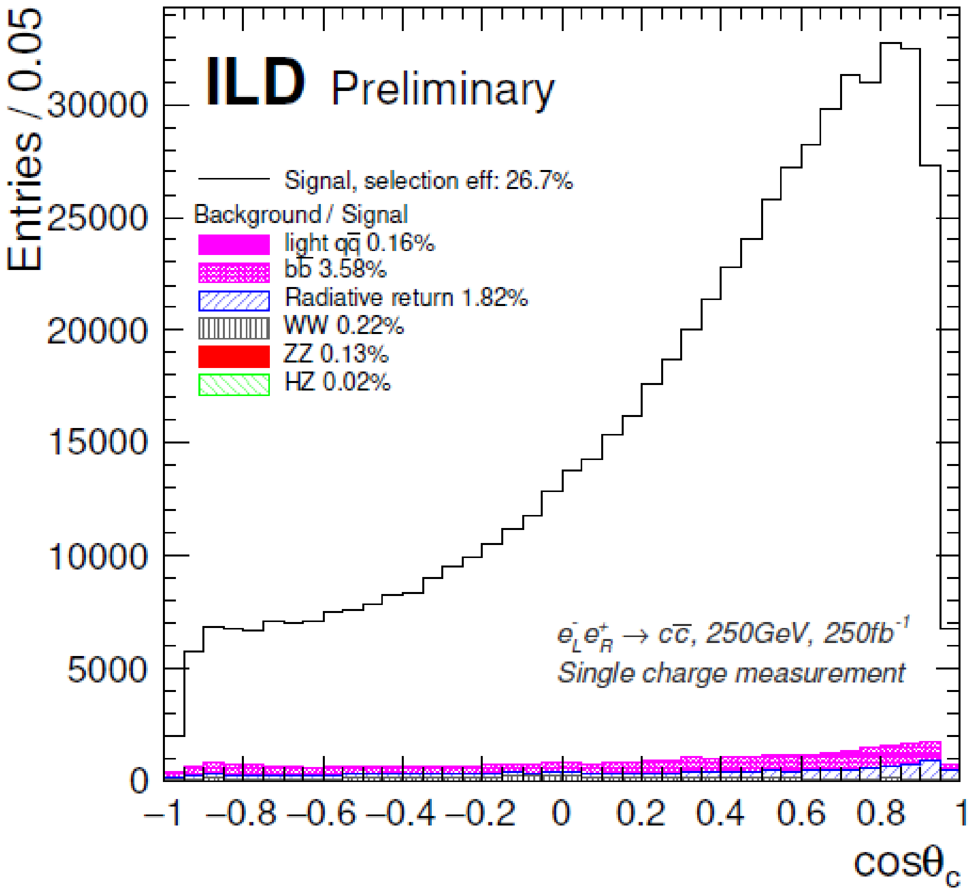


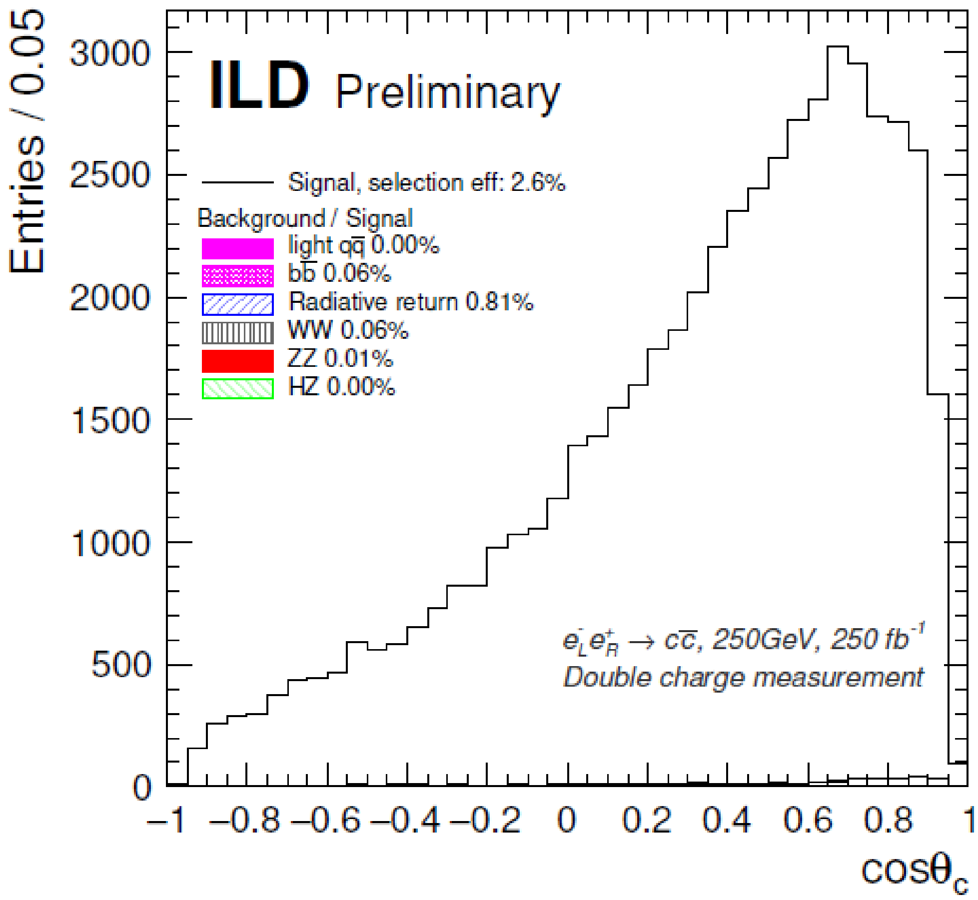
- The charge can be determined by:
  - Kaon ID (K method)
  - Full vertex charge measurement (Vtx method)





Final selection

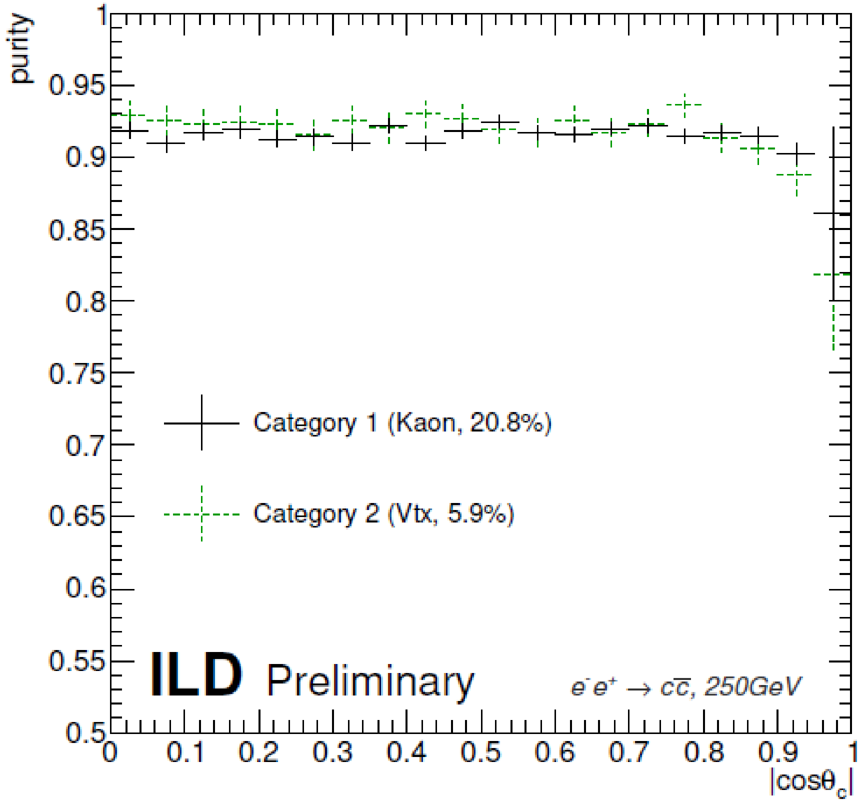


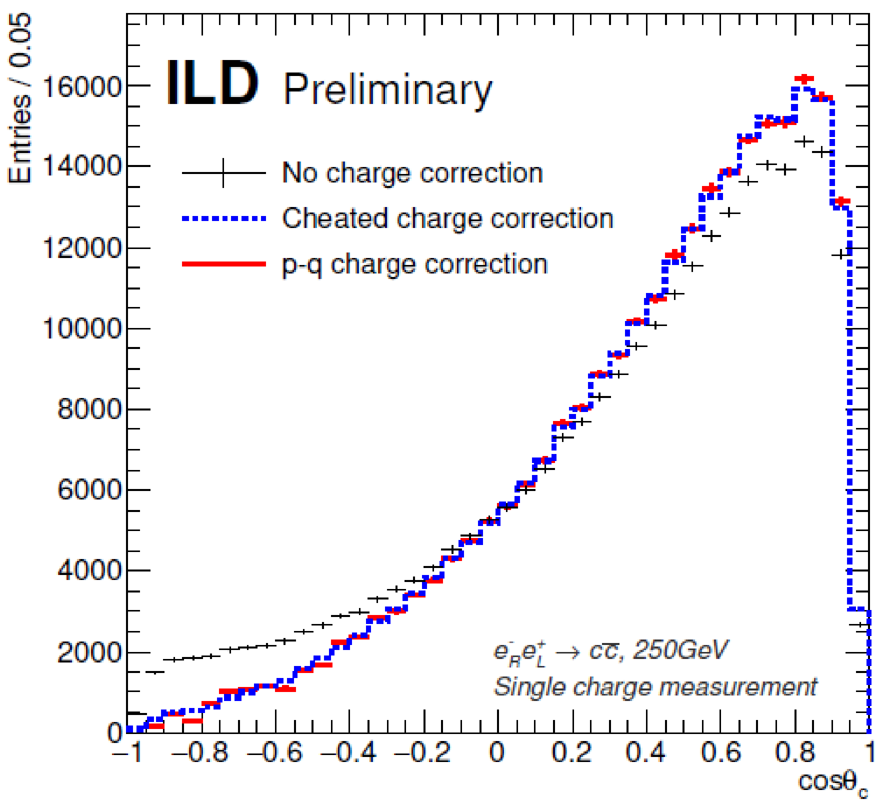


Calculating the purity of the charge measurement

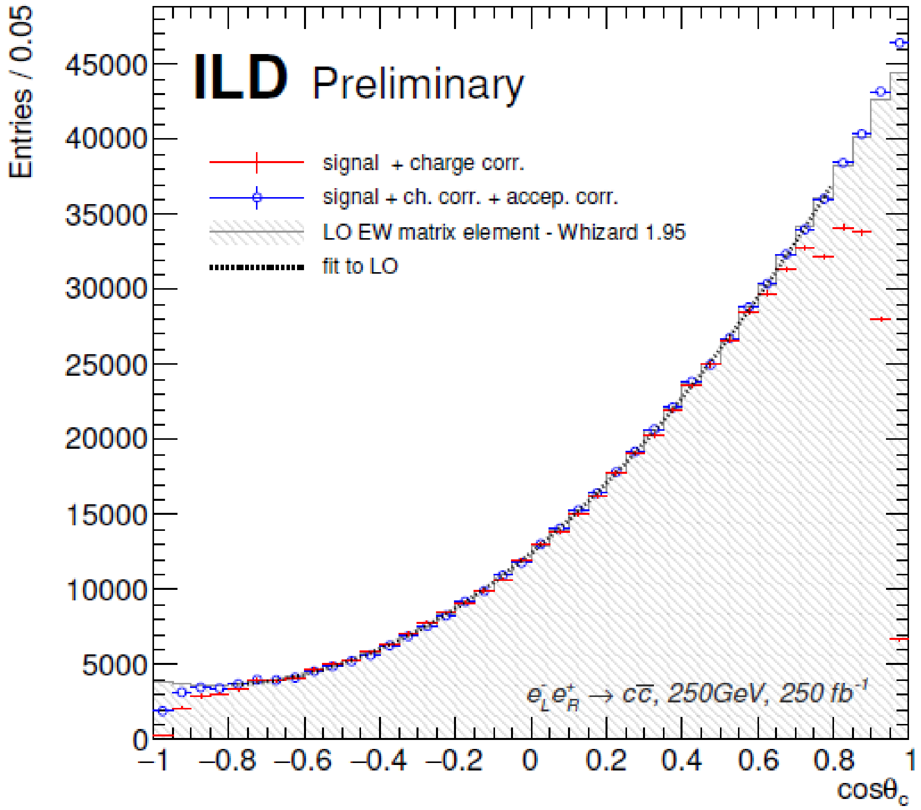
- The charge measurement can be incorrect (i.e. due to missing tracks)
- This will induce migrations: the event with the wrongly measured charge will move from positive to negative angles (or viceversa)
- These migration may look as New Physics !
- To fix this,
  - 1) we use double tagging events to calculate the purity of the method
  - 2) we use the measured purity (p) to correct for the migrations.

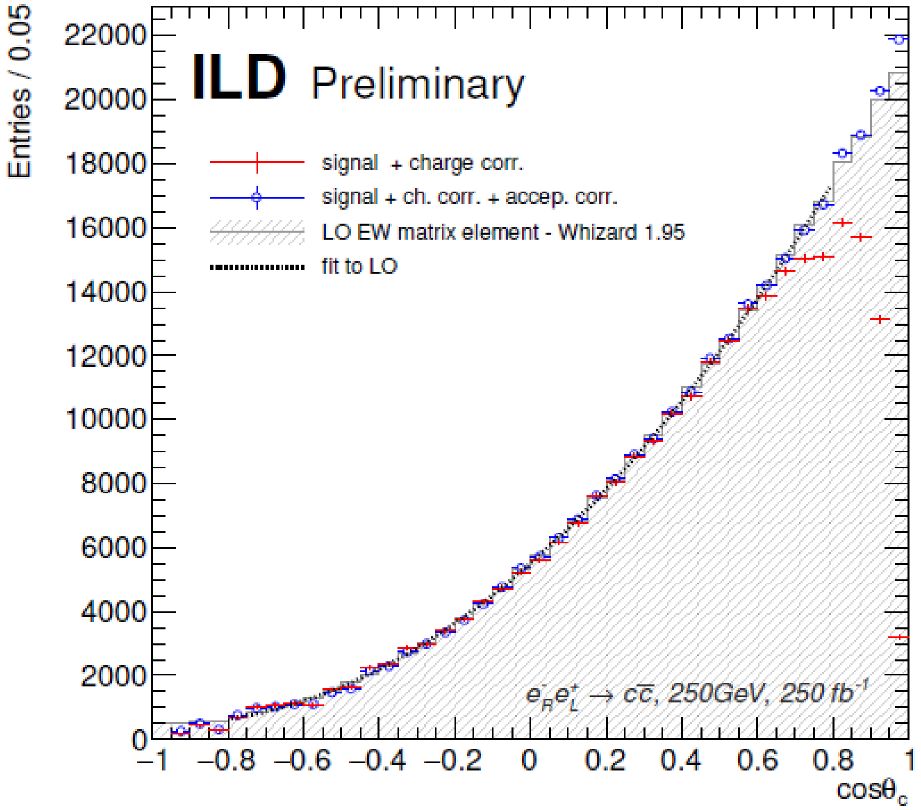
Calculating the purity of the charge measurement



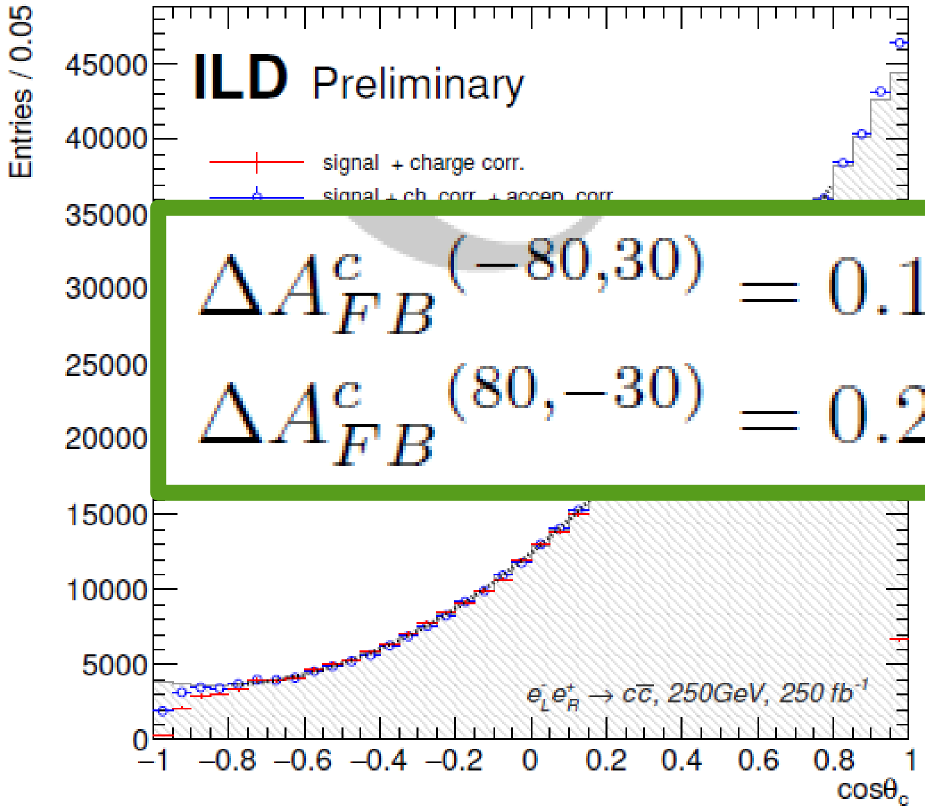


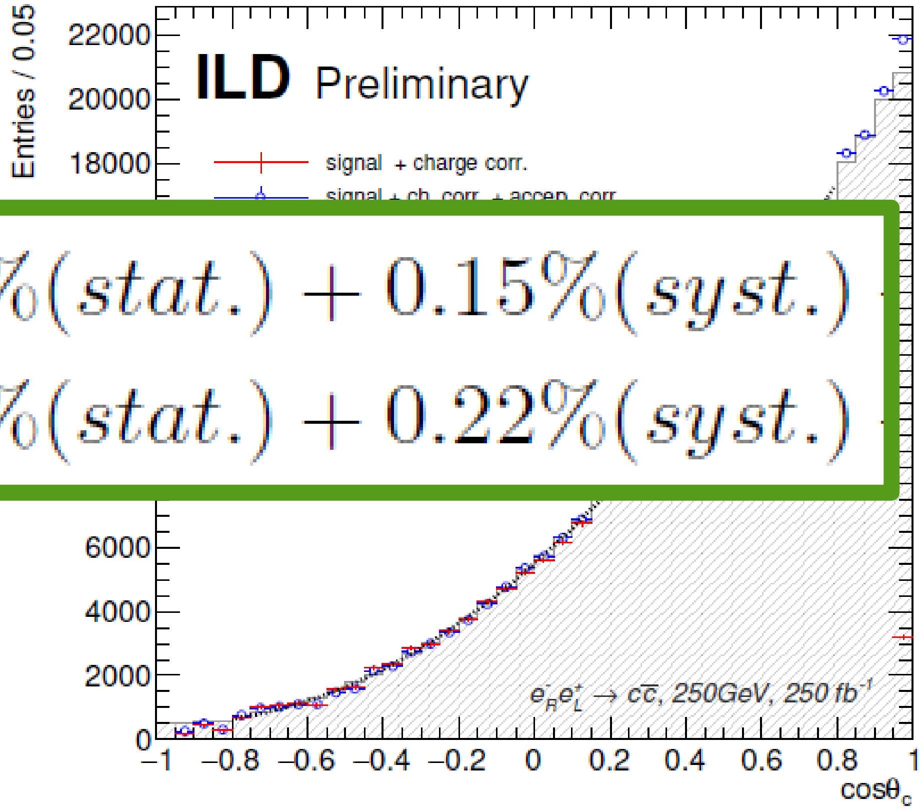
Final distributions (single charge measurement)





Final distributions (single charge measurement)

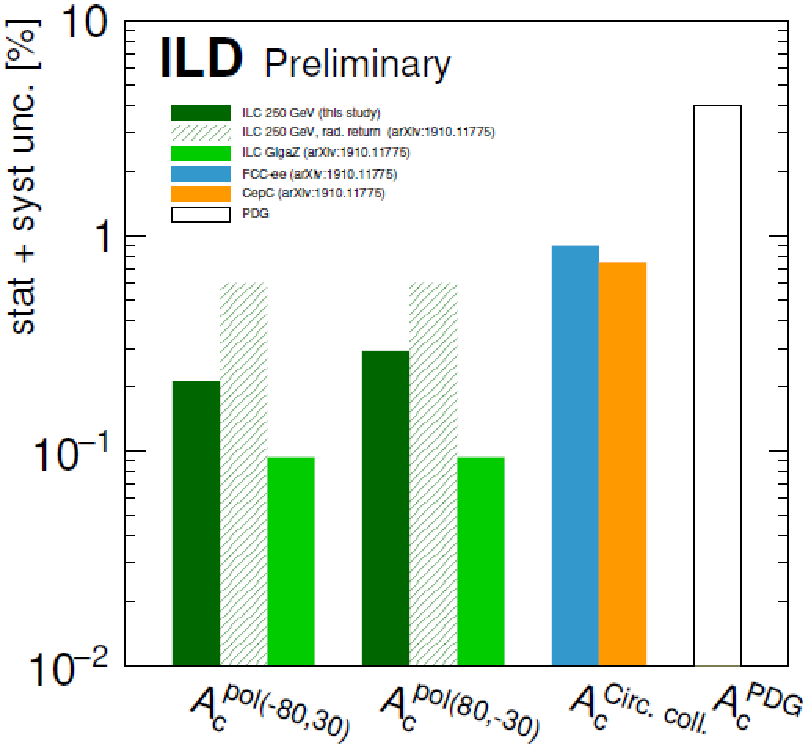


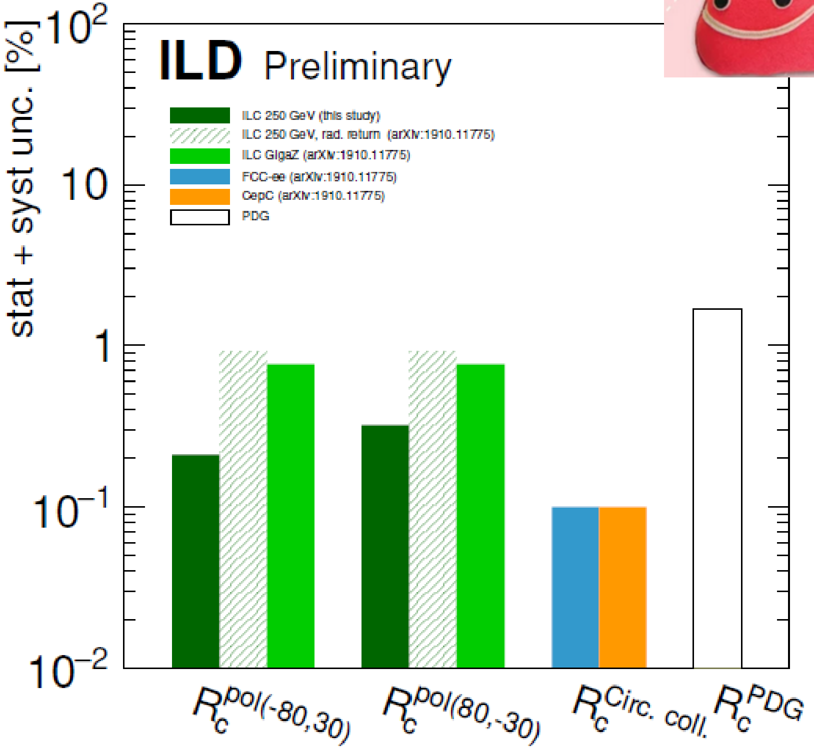


$$\Delta A_{FB}^{c}{}^{(-80,30)} = 0.16\%(stat.) + 0.15\%(syst.)$$

$$\Delta A_{FB}^{c}{}^{(80,-30)} = 0.20\%(stat.) + 0.22\%(syst.)$$

250 GeV vs Z-Pole resonance (Physics Briefing Book)





- Are the expectations for GigaZ just extrapolations from SLC?
- What are the systematics accounted by FCCee and CepC? What about the correlations/mistagging efficiencies?
  - Reminder: in our study the precission is already limited by systematics.

c vs b quarks

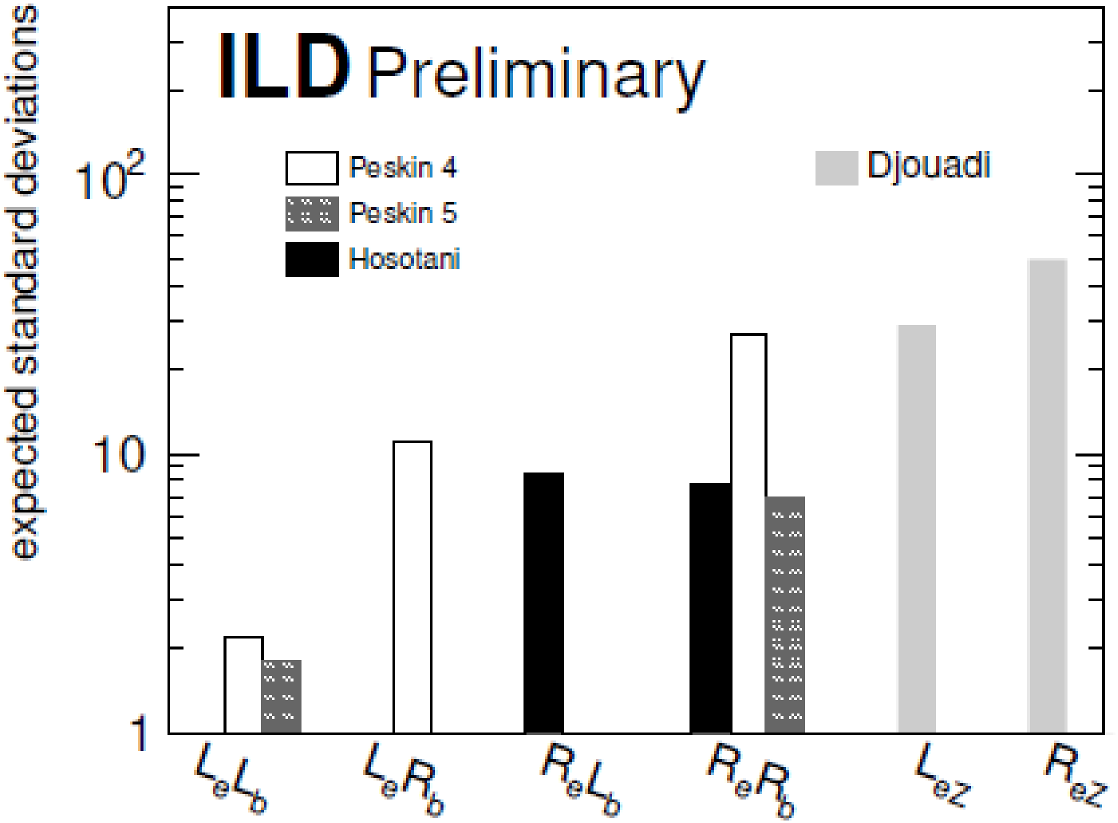
- More complicated charge calculation:
  - B- quark produce more tracks → Larger possibility to miss one.
  - B0s decay oscillate → change of charge of the final state.
- B-tagging efficiencies are 2 times better → we can use double tag even for the asymmetry measurement.
  - This largely compensates for the first point.
- Acceptance drop is more important for c-quarks (because missing a track in the forward regions means losing the event).

- We use same reconstruction process but we so far used “different” observable definition
  - C-quark : as LEP/SLC, using Afb and Rq observables to extract the EW couplings.
  - B-quark : using fit to fully differential distributions to extract EW couplings

Publication status & plans

- Sviatoslav's thesis (bb and tt)
- IDR contribution
- EPS19 Proceeding (b-quark)
- LCWS2019 (c-quark)
  - To be submitted the 15th February
- ILD note (b-quark) : work in progress
  - First draft already reviewed but several changes have been done since then → addressing the correlation issue, using Rb/Ab approach instead of the fit?
  - Very technical paper.
  - New draft efforts will start after the LCWS2019 proceeding is submitted.
- ILD note to be converted in a paper
- Similar process to be followed with the c-quark (shorter paper?)

Extraction of Z' couplings (only for the b)



- High mass new Z' can be probed at the ILC250 GeV (up to 20 TeV).
- Polarization enhances the New Physics discovery chances and is crucial to understand the new physics

Extraction of Z' couplings (b)

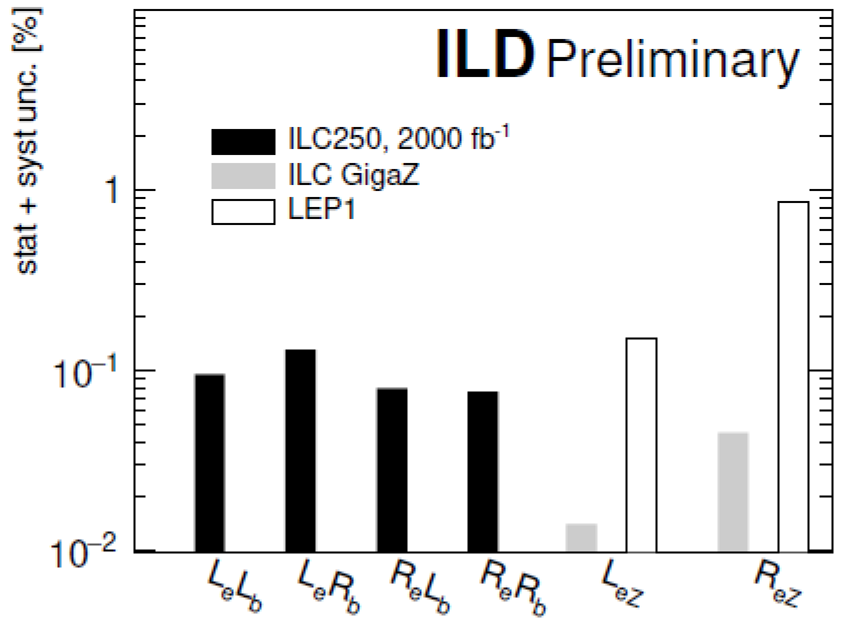
$$\frac{d\sigma}{d\cos\theta_b}(e^-_L e^+_R \to b\bar{b}) \sim (L_e L_b)^2(1+\cos\theta_b)^2 + (L_e R_b)^2(1-\cos\theta_b)^2$$
$$\frac{d\sigma}{d\cos\theta_b}(e^-_R e^+_L \to b\bar{b}) \sim (R_e R_b)^2(1+\cos\theta_b)^2 + (R_e L_b)^2(1-\cos\theta_b)^2$$

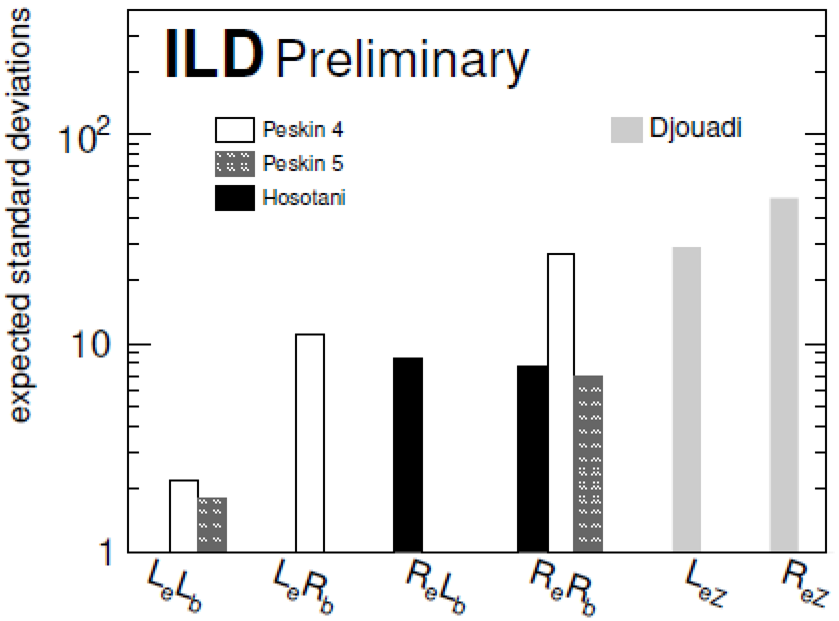
- $(L_e L_q)^2$ etc. are the helicity amplitudes that contain the information about the underlying physics e.g. the electroweak couplings to the photon and the Z (or to new bosons).
- A convenient rearrangement of these helicity terms:

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

$$\left(\begin{aligned} L_e L_b \propto \\ Q_e Q_b + \\ + \frac{L_{eZ} L_{bZ}}{\sin^2\theta_W \cos^2\theta_W} BWZ + \\ + \sum_{Z'} \frac{L_{eZ'} L_{bZ'}}{\sin^2\theta_W \cos^2\theta_W} BWZ' \end{aligned} \right)$$

Extraction of Z’ couplings (only for the b)





- High mass new Z’ can be probed at the ILC250 GeV (up to 20 TeV).
- Polarization enhances the New Physics discovery chances and is crucial to understand the new physics

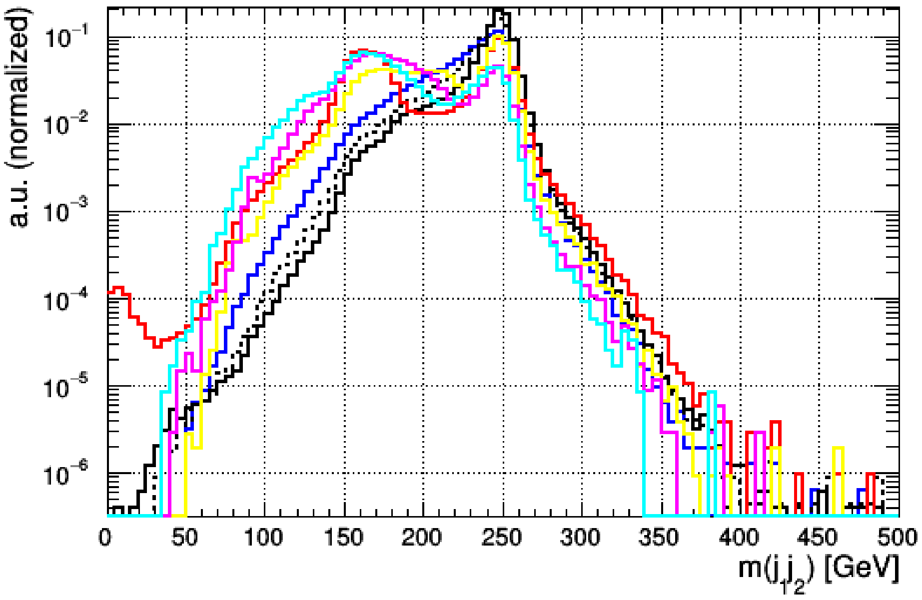
Back-up slides

Reconstruction of ee→ qq @ 250 GeV

Durham, 2 jets

- Note: most of the radiative return events are suppressed already at the generator level through an invariant mass cut..

- **Original strategy**: optimization of S/B through a cu on the invariant mass of the 2-jet system
  - Powerful against all bkg, specially the rad. return.
  - The shape of the tail is different for the different flavours → presence of neutrinos!



Reconstruction of ee→ qq @ 250 GeV

How can we improve the S/B ratio?

Looking a the jet substructure

- y23 (or d23) is defined as the distance at which a 2-jet system becomes a 3-jet system: it tells us about the substructure of the jets.
- Mass of the jets (hard non-collinear radiation artificially clustered in a jet will make “fat” jets)

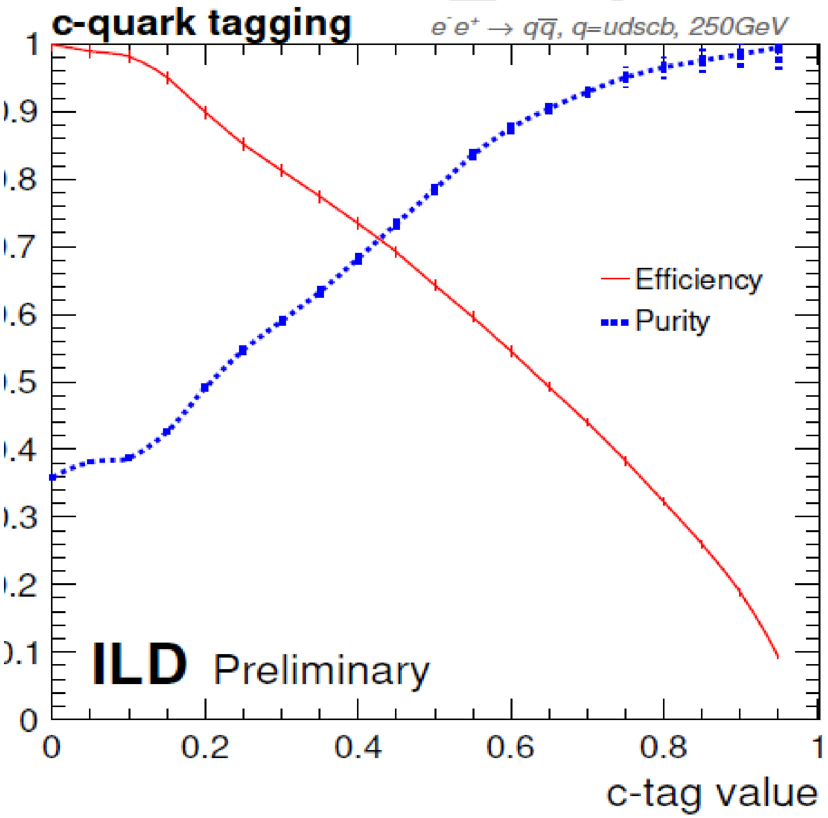
Event shape variables: sphericity

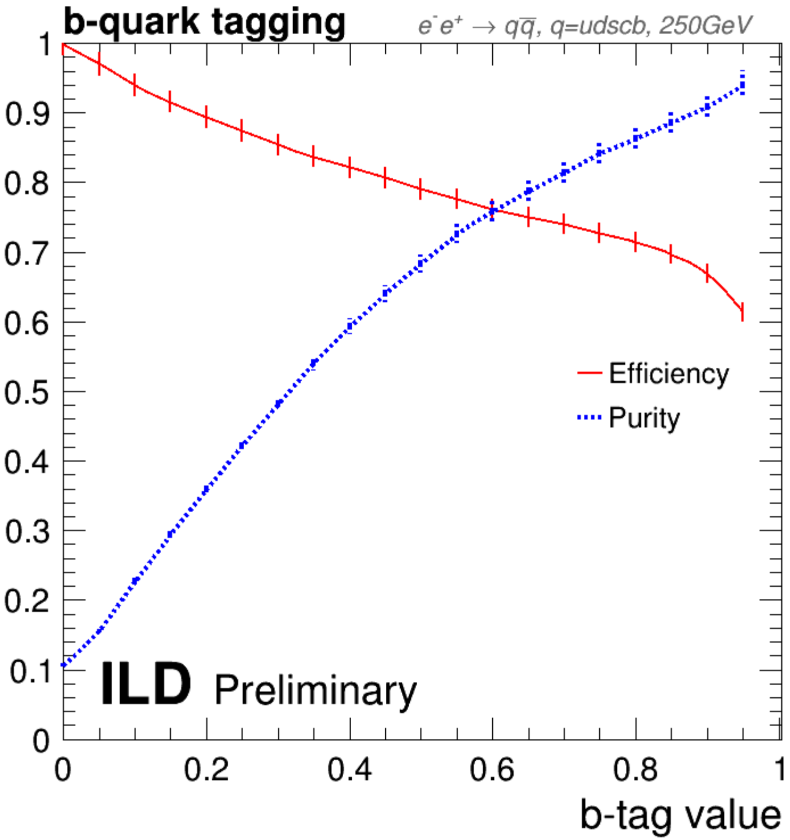
- Sphericity tensor

$$S^{\alpha\beta}=\frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\boldsymbol{p}_i|^2} \qquad \alpha,\beta=1,2,3$$

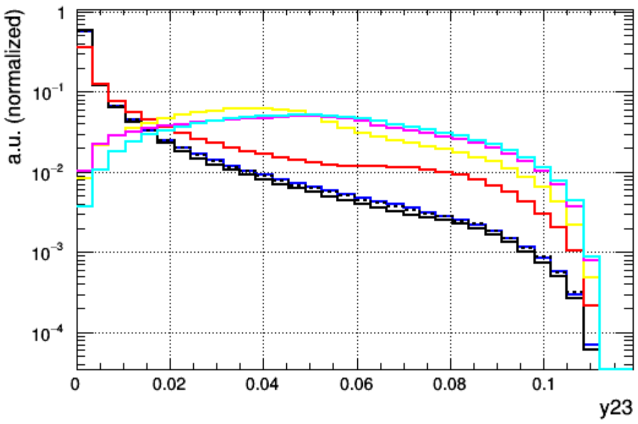
- Eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$ with $\lambda_1+\lambda_2+\lambda_3=1$
- Sphericity $S=\frac{3}{2}(\lambda_2+\lambda_3)$ with $0 \leq S \leq 1$
- 2-jet event: $S \approx 0$ isotropic event: $S \approx 1$

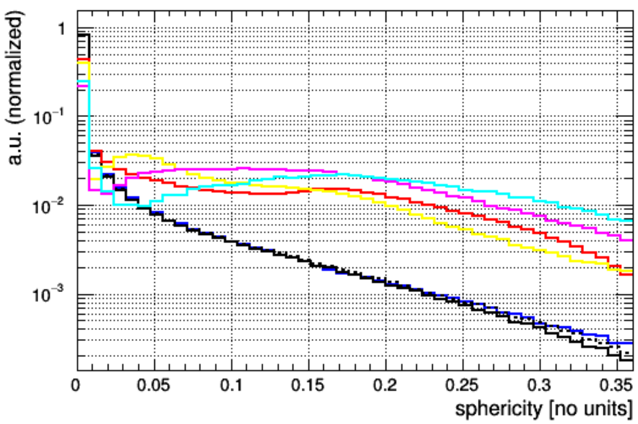
Measurement of the partial width

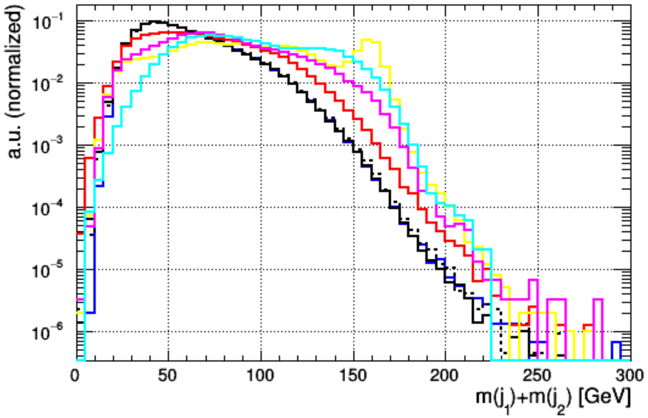




Reconstruction of ee→ qq @ 250 GeV (left pol)







- Preselection of qq final states using
  - y23<0.02 & S<cos(θ) & (mj1+mj2)<100 GeV
- Then, proceed to quark tagging (using LCFIPlus b and c tagger).

Measurement of the partial width

$e^-_L e^+_R \to b\bar{b}$							
	Signal [%]	Background processes [%] (B/S [%])					
	$c\bar{c}$	$b\bar{b}$	$q\bar{q}$ (uds)	$\gamma q\bar{q}$	ZZ	WW	HZ
Cut_1	85.6	85,2 (69,1)	87,2 (224,0)	69,0 (53,2)	15,4 (3,1)	16,7 (35,1)	11,0 (0,2)
$Cut_1 + Cut_2$	82,1	82,1 (69,4)	83,7 (224,4)	65,7 (52,8)	8,2 (1,7)	10,5 (23,1)	5,3 (0,1)
$Cut_1 + Cut_2 + Cut_3$	78.5	78,4 (69,4)	80,0 (224,4)	24,5 (20,6)	4,1 (0,9)	3,2 (7,4)	2,3 (0,0)
$Cut_1 + Cut_2 + Cut_3 + 1ctag$	38.9	2,1 (3,8)	0,2 (0,9)	1,1 (1,9)	0,3 (0,1)	0,2 (0,8)	0,1 (0,0)
$Cut_1 + Cut_2 + Cut_3 + 2ctag$	7.3	0,0 (0,2)	0,0 (0,0)	0,1 (0,7)	0,0 (0,0)	0,0 (0,1)	0,0 (0,0)

$e^-_R e^+_L \to b\bar{b}$							
	Signal [%]	Background processes [%] (B/S [%])					
	$c\bar{c}$	$b\bar{b}$	$q\bar{q}$ (uds)	$\gamma q\bar{q}$	ZZ	WW	HZ
Cut_1	85.6	85,1 (35,8)	87,1 (161,4)	69,0 (38,8)	17,7 (3,6)	7,8 (0,4)	10,9 (0,4)
$Cut_1 + Cut_2$	82.2	82,0 (36,0)	83,7 (161,5)	65,7 (38,5)	10,7 (2,3)	4,7 (0,2)	5,3 (0,2)
$Cut_1 + Cut_2 + Cut_3$	78.6	78,2 (35,9)	80,0 (161,5)	24,4 (15,0)	5,5 (1,2)	1,4 (0,1)	2,3 (0,1)
$Cut_1 + Cut_2 + Cut_3 + 1ctag$	38.9	2,1 (2,0)	0,2 (0,6)	1,3 (1,6)	0,4 (0,2)	0,2 (0,0)	0,1 (0,0)
$Cut_1 + Cut_2 + Cut_3 + 2ctag$	7.3	0,0 (0,1)	0,0 (0,0)	0,1 (0,7)	0,0 (0,1)	0,0 (0,0)	0,0 (0,0)

quark EW couplings determination

$$\frac{d\sigma}{\cos\theta}(e^-_L e^+_R \rightarrow q\bar{q}) \sim (L_e L_q)^2 (1+\cos\theta)^2 + (L_e R_q)^2 (1-\cos\theta)^2$$

$$\frac{d\sigma}{\cos\theta}(e^-_R e^+_L \rightarrow q\bar{q}) \sim (R_e R_q)^2 (1+\cos\theta)^2 + (R_e L_q)^2 (1-\cos\theta)^2$$

- $(L_e L_q)^2$ etc. are the helicity amplitudes that contain the information about the underlying physics e.g. the electroweak couplings to the photon and the Z (or to new bosons).
- At a linear collider with polarized beams and using vertex charge to distinguish **q** and **$\bar{q}$**, **all four of these functions** can be measured independently at a fixed c.m.e.
- A convenient rearrangement of these helicity terms:

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

Double charge measurements (b-quark)

- Mistakes in the charge calculation due to loss tracks (acceptance issues, mis reconstruction etc) have to be corrected and estimated using data → Mistakes produce migrations (flip of the cos(θ))
- 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

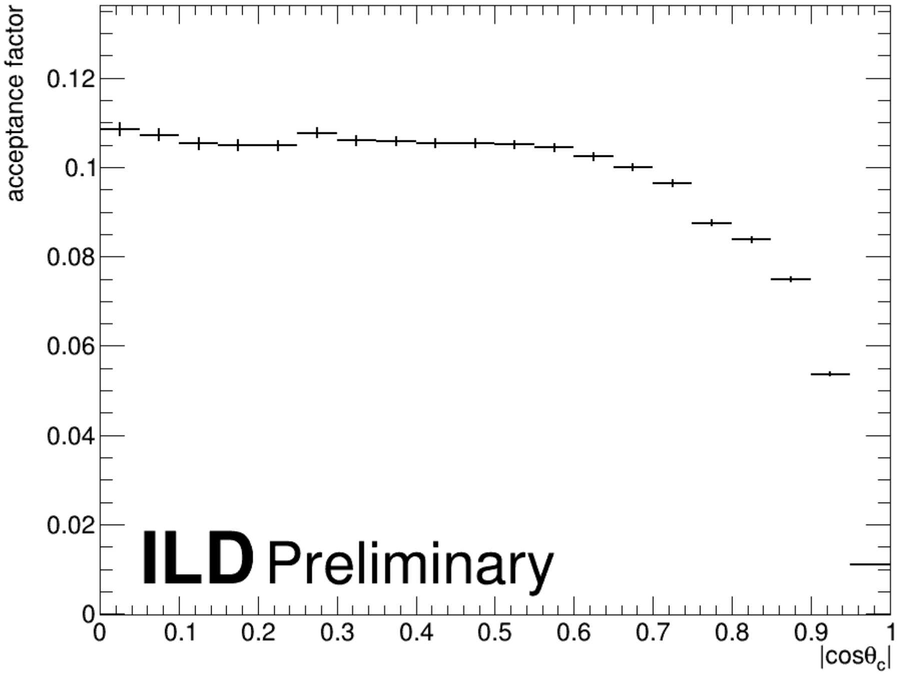
$$N_{acc} = Np^2 + Nq^2$$
$$N_{rej} = 2Npq$$
$$1 = p + q$$

pq-equation
Incognitas: pq and N.

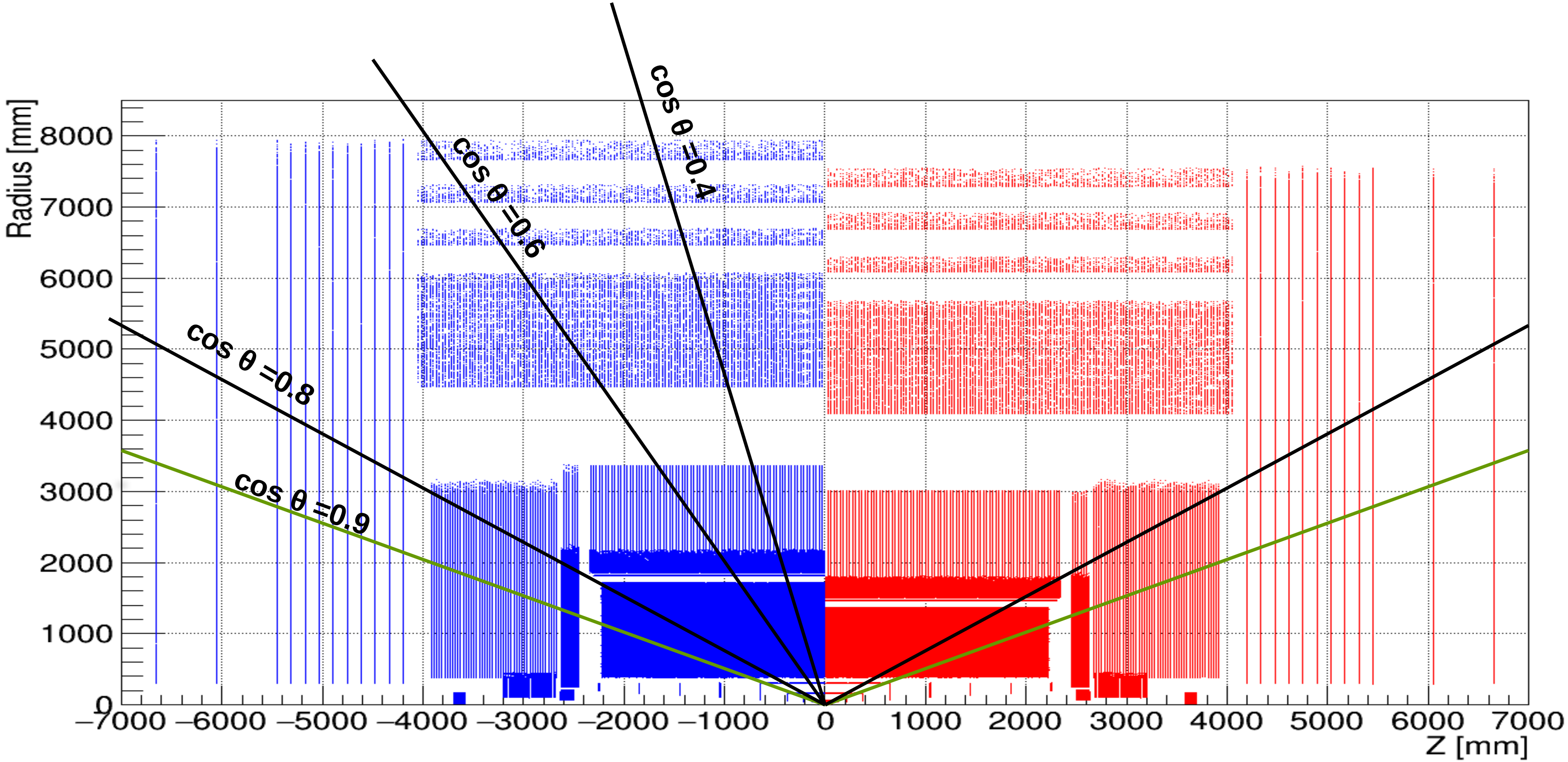
The **pq-equation** allows for correcting for migrations (finding the correct N) and in particular for the last and ultimate migration (dilution) due to B0 oscillations

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

Acceptance



- More dramatic acceptance issues for the c-quark than for b-quark case
  - Since most vertices have two tracks, if a track is lost, the full vertex is lost.
  - The correction starts to be large at cosθ ~0.7
- This signature is perfect for detector optimization & benchmarking
  - Simplicity of final state
  - Very sensitive to mis reconstruction issues
- To be investigated with the new samples and latest software releases.
  - And new forward trackers ideas?



Radius [mm]
8000
7000
6000
5000
4000
3000
2000
1000
0
−7000 −6000 −5000 −4000 −3000 −2000 −1000 0 1000 2000 3000 4000 5000 6000 7000
Z [mm]
cos θ =0.4
cos θ =0.6
cos θ =0.8
cos θ =0.9

The ILD Concept

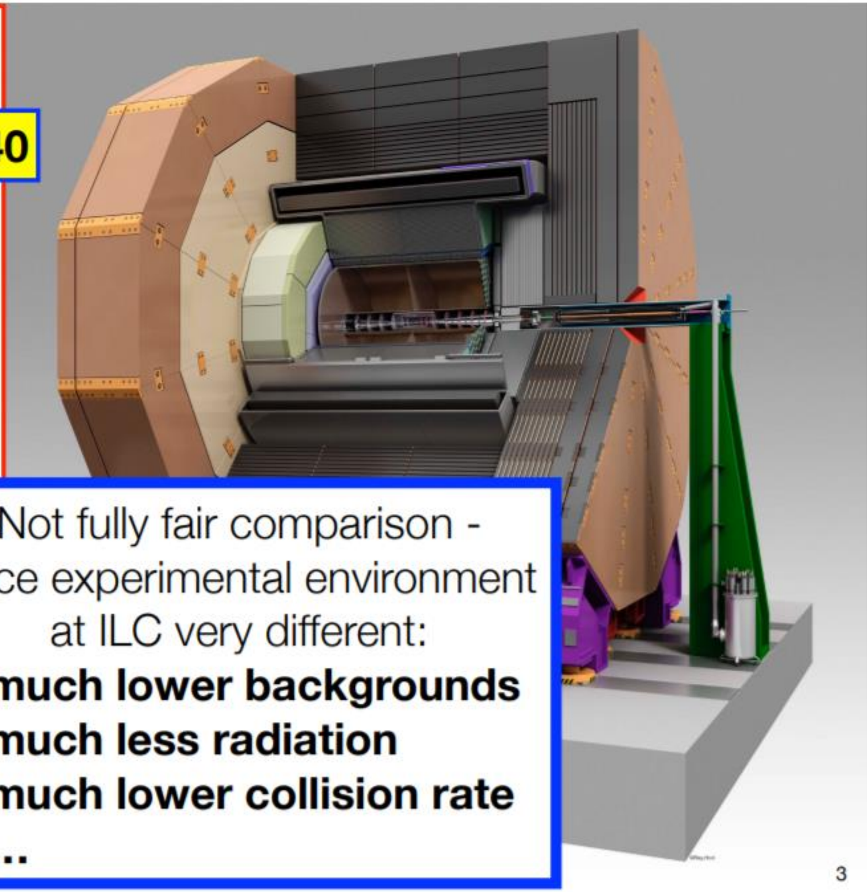
Jenny List, talk at LCWS2018

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** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
  ≈ CMS / 4
- **jet energy resolution** 3-4%
  ($H \rightarrow$ invisible)
  ≈ ATLAS / 2
- **hermeticity** θ_{min} = 5 mrad
  ($H \rightarrow$ 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	$\sigma^2_{r\phi} = (50^2 + 900^2 \sin^2\phi +$ $((25^2/22) \times (4T/B)^2 \sin\theta)(z/\text{cm}))\,\mu\text{m}^2$ $\sigma^2_z = (400^2 + 80^2 \times (z/\text{cm}))\,\mu\text{m}^2$ where ϕ and θ are the azimuthal and polar angle of the track direction

Tracking at ILD

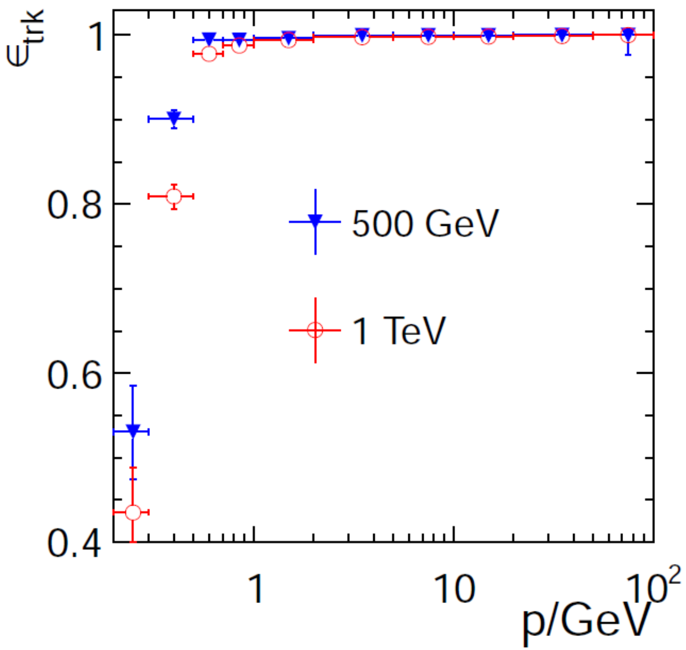


Figure 5. Tracking Efficiency for $t\bar{t} \rightarrow 6$ jets at 500 GeV and 1 TeV versus momentum in the presence of beam background.

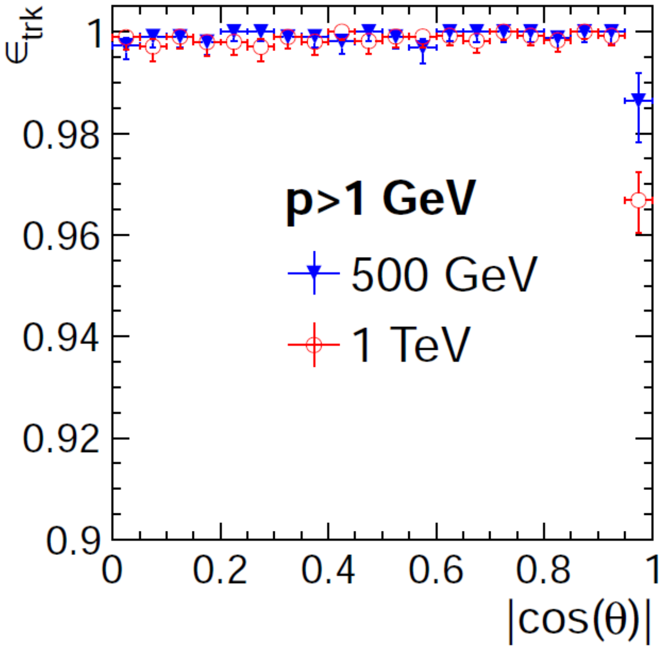
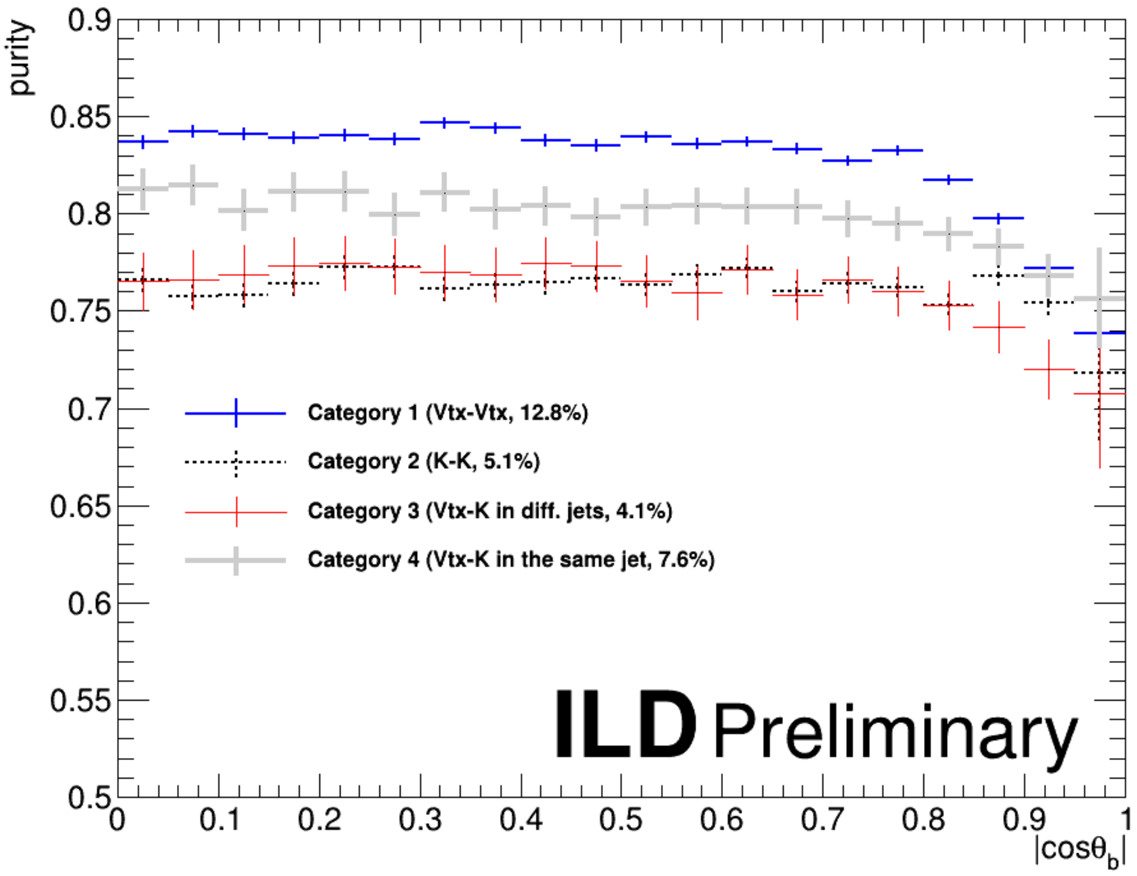


Figure 6. Tracking Efficiency for $t\bar{t} \rightarrow 6$ jets at 500 GeV and 1 TeV versus $|cos(\theta)|$ for particles with $p > 1$GeV in the presence of beam background

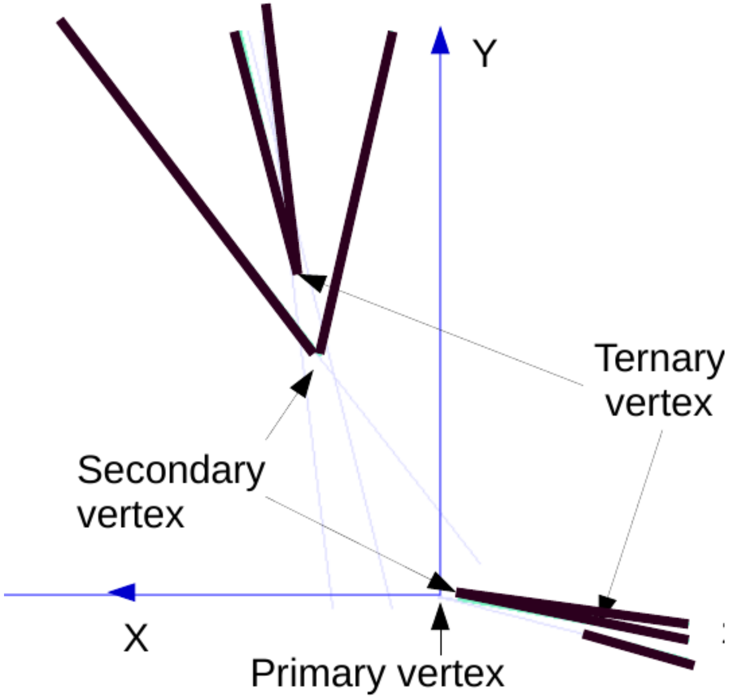
Double charge measurements

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



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)

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	0.5	0	−0.183	0	0	0	0	0
ν_μ			−0.183	0	0	0	0	0
ν_τ			−0.183	0	0	0	0	0
e	−0.2688	0.2312	0.099	0.916	0	−1.261	0.155	−1.665
μ			0.099	0.860	0	−1.193	0.155	−1.563
τ			0.099	0.814	0	−1.136	0.155	−1.479
u	0.3458	−0.1541	−0.127	−0.600	0	0.828	−0.103	1.090
c			−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	−0.4229	0.0771	0.155	0.300	0	−0.414	0.052	−0.545
s			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].