

Production and measurement of $e^+e^- \rightarrow c\bar{c}$ signatures at ILC 250

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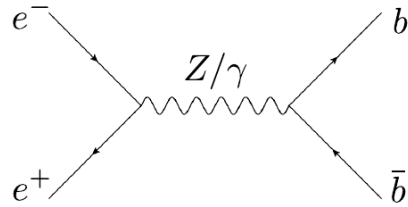
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Outline

- Introduction
- Reconstructing $ee \rightarrow qq$ @ 250 GeV
 - Signal and background: different topologies
- Charge calculation
 - And correction of mistakes in the calculation (data driven method)
- Results

Introduction

- Quark (fermion) **electroweak couplings** can be **inferred from cross section, R_q** 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 → **see Prof. Hosotani's talk** (*ILC Pheno of Gauge Higgs Unification*)
 - Moderated (compared with ILC detectors) quark tagging and charge measurements.
 - Also moderated angular acceptance of the detectors.

→ **see R. Poeschl talk** (*Study of systematic errors in high precision heavy quark analyses*)

Reconstruction of $ee \rightarrow qq$ @ 250 GeV

Signal:

➤ 2 jets back-to-back topologies

- All jets with similar energy of ~125 GeV

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

Backgrounds:

- Radiative return $ee \rightarrow \gamma Z$ (ISR): Presence of the photon in the detector or invariant mass of the system < 250 GeV (Z-pole)
- 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

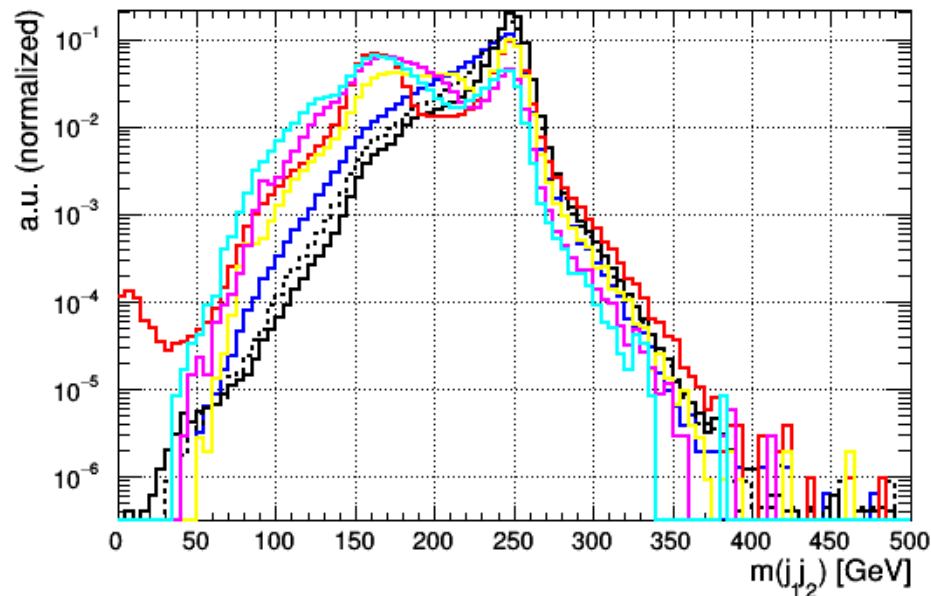
Reconstruction of $ee \rightarrow qq$ @ 250 GeV

Durham, 2 jets

$$Eff = \frac{N_{q\bar{q}}^{reco}}{N_{q\bar{q}}^{gen}}$$

$$S/N = \frac{N_{BKG}^{reco}}{N_{q\bar{q}(all\ flav)}^{reco}}$$

—	$b\bar{b}$, 100.0%
⋯	$c\bar{c}$, 100.0%
—	$q\bar{q}$, $q=uds$, 100.0%
—	γZ ($Z \rightarrow q\bar{q}$, $q=udscb$), 11.5%
—	ZZ , 4.2%
—	WW , 44.1%
—	HZ , 0.4%



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

➤ Optimization of S/B through a cut 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.

Reconstruction of $ee \rightarrow qq$ @ 250 GeV

How can we improve the S/B ratio?

➤ Looking at the jet substructure

- y_{23} (or d_{23}) 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)

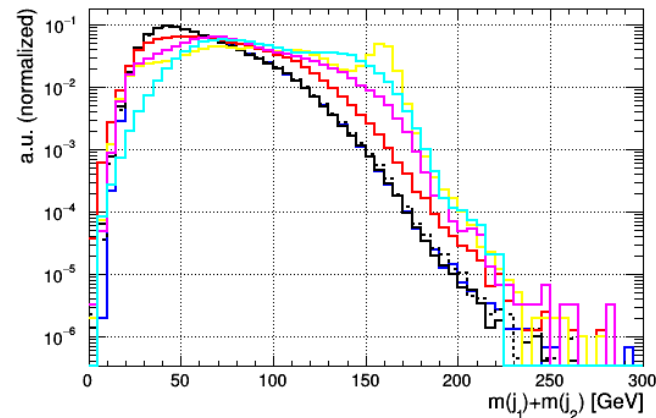
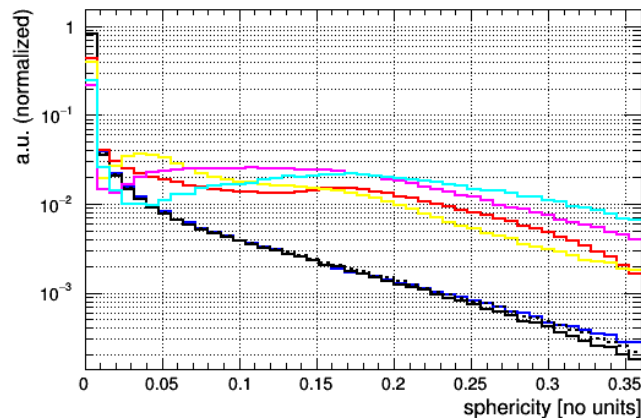
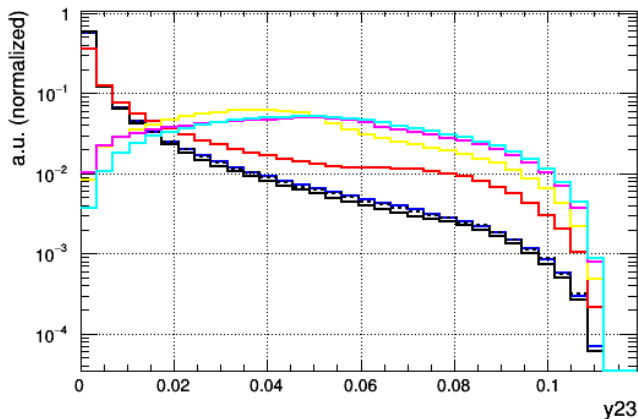
➤ Event shape variables: sphericity

- Sphericity tensor

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

- 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: $S \approx 1$

Reconstruction of $ee \rightarrow qq$ @ 250 GeV (left pol)



➤ Preselection of qq final states using

- $y_{23} < 0.02$ & $S < 0.012$ & $(m_{j1} + m_{j2}) < 120$ GeV

➤ Then, proceed to quark tagging (using LCFIPlus b and c tagger).

$$Eff = \frac{N_{qq}^{reco}}{N_{qq}^{gen}}$$

$$S/N = \frac{N_{BKG}^{reco}}{N_{qq(all\ flav)}^{reco}}$$

➤ Numbers before selection.

- $b\bar{b}$, 100.0%
- $c\bar{c}$, 100.0%
- $q\bar{q}$, $q=u,d,s$, 100.0%
- γZ ($Z \rightarrow q\bar{q}$, $q=u,d,s,c,b$), 11.5%
- ZZ , 4.2%
- WW , 44.1%
- HZ , 0.4%

Final selection

	100 % eL ⁻ polarization								
	Signal Eff [%]				BKG / S [%]				
	qq	bb	cc	light	Z rad	ZZ	WW	HZ	Total
y23 cut	85,7%	84,3%	85,0%	86,4%	9,2%	0,7%	8,6%	0,0%	18,5%
y23, S	77,5%	75,9%	77,1%	78,2%	5,0%	0,5%	4,3%	0,0%	9,9%
y23, s, jet M	77,0%	75,5%	76,5%	77,6%	4,9%	0,4%	3,0%	0,0%	8,4%
1-ctag		0,0%	11,8%	0,1%	3,0%	0,8%	2,3%	0,1%	6,2%
2-ctag		0,0%	6,9%	0,0%	0,6%	0,5%	0,0%	0,1%	1,2%

- Quite homogeneous selection for all quark flavours.
- Moderated efficiency for the c-tagging but with minimal background contamination.
 - Eff ~ 1/3 of the b-quark case.
 - Compensated by higher cc cross section.

c-Jet Charge determination

➤ C-quark jets

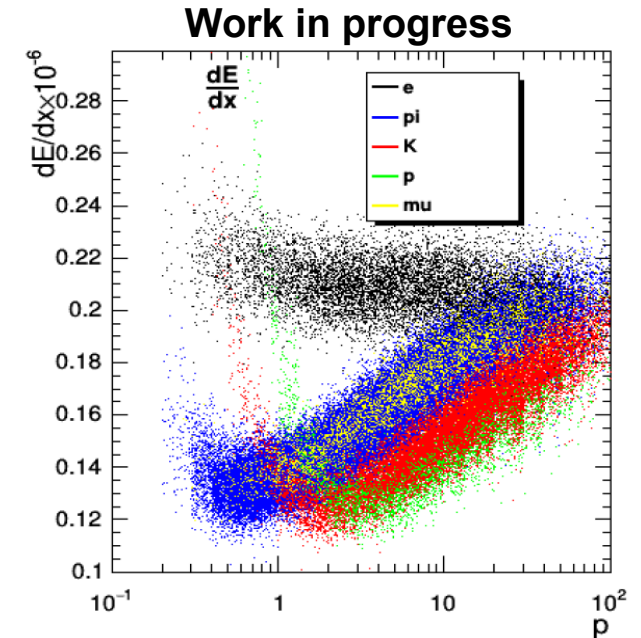
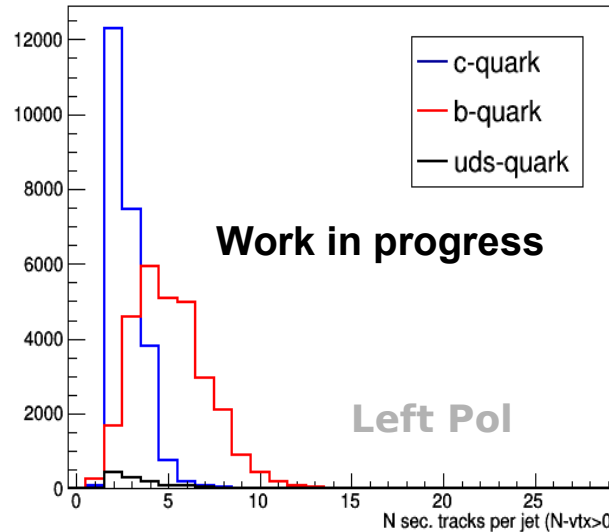
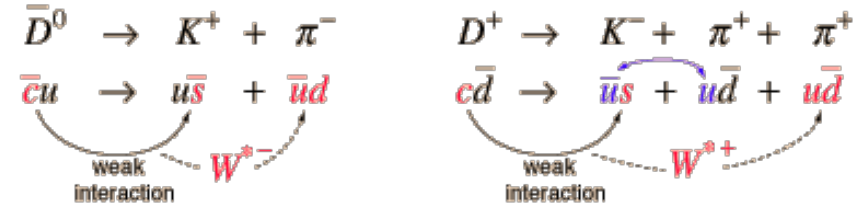
- D^0 mesons

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

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

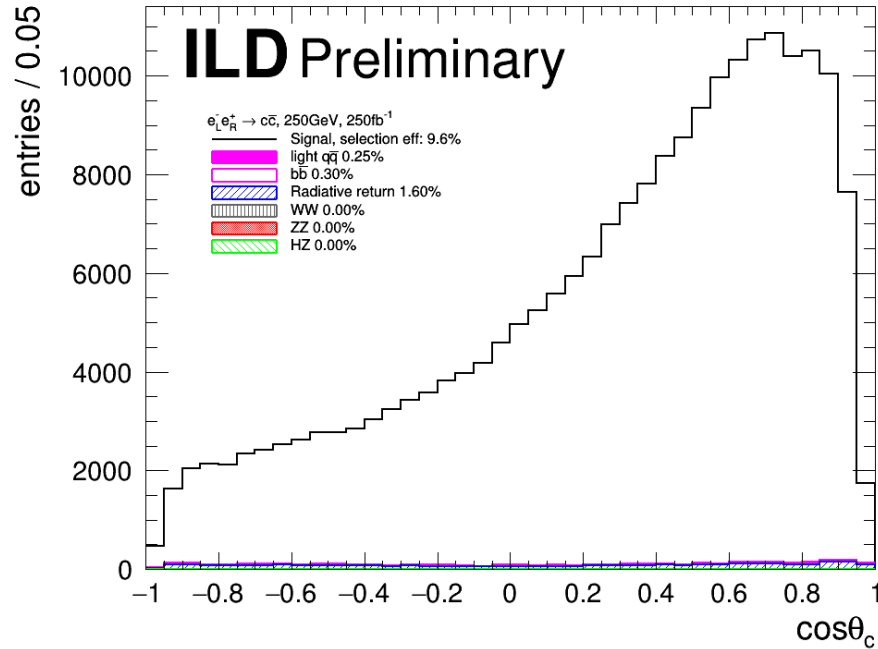
➤ The charge can be determined by:

- Kaon ID (K method)
- Full vertex charge measurement (Vtx method)

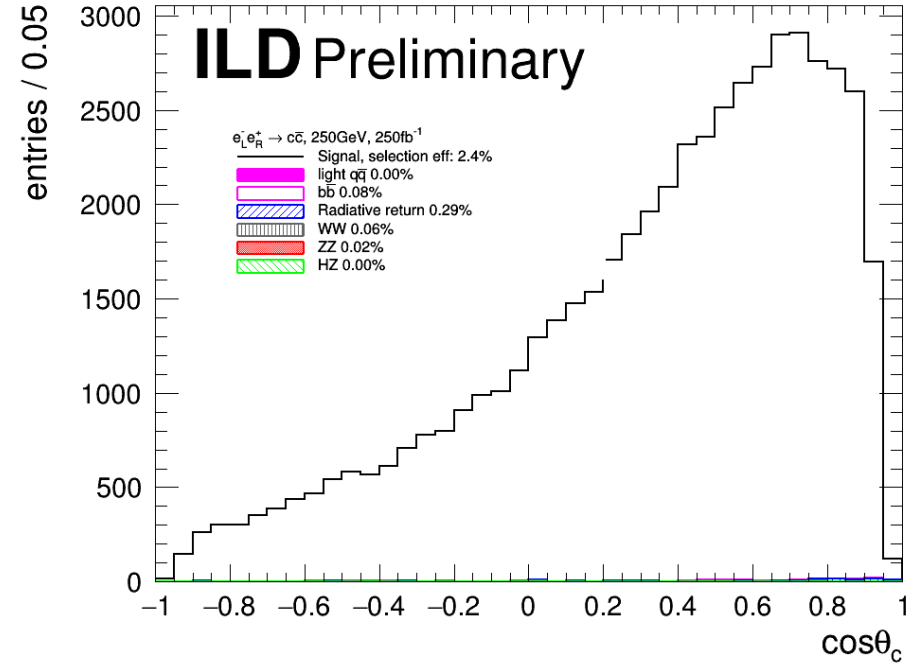


Final selection

➤ Only one jet with c-charge measurement



➤ The two jets with c-charge measurement

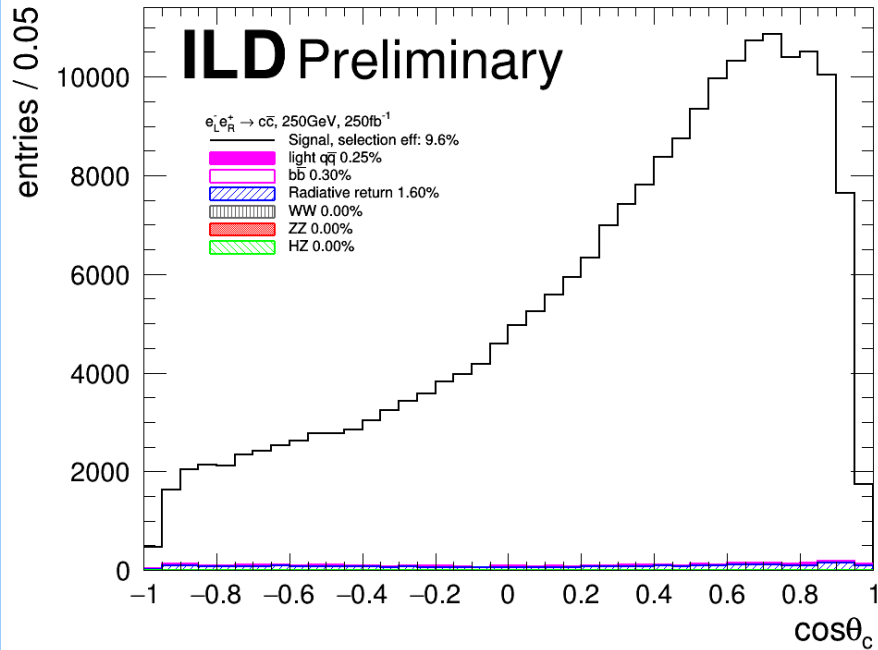


➤ Final efficiencies of 2.5-10 % in the cc- reconstruction.

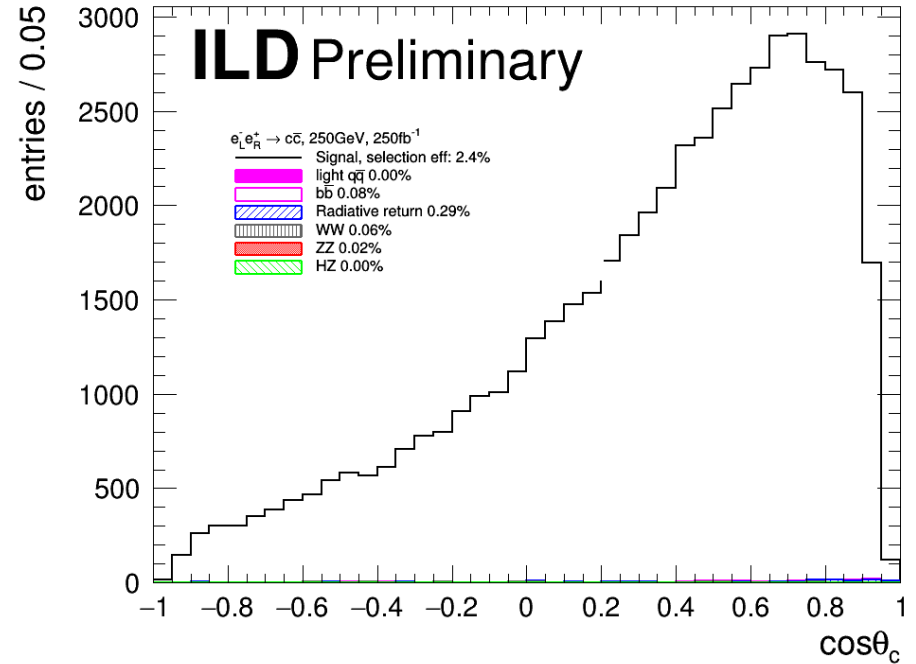
- Small BKG contamination in both cases.

Final selection

➤ Only one jet with c-charge measurement



➤ The two jets with c-charge measurement

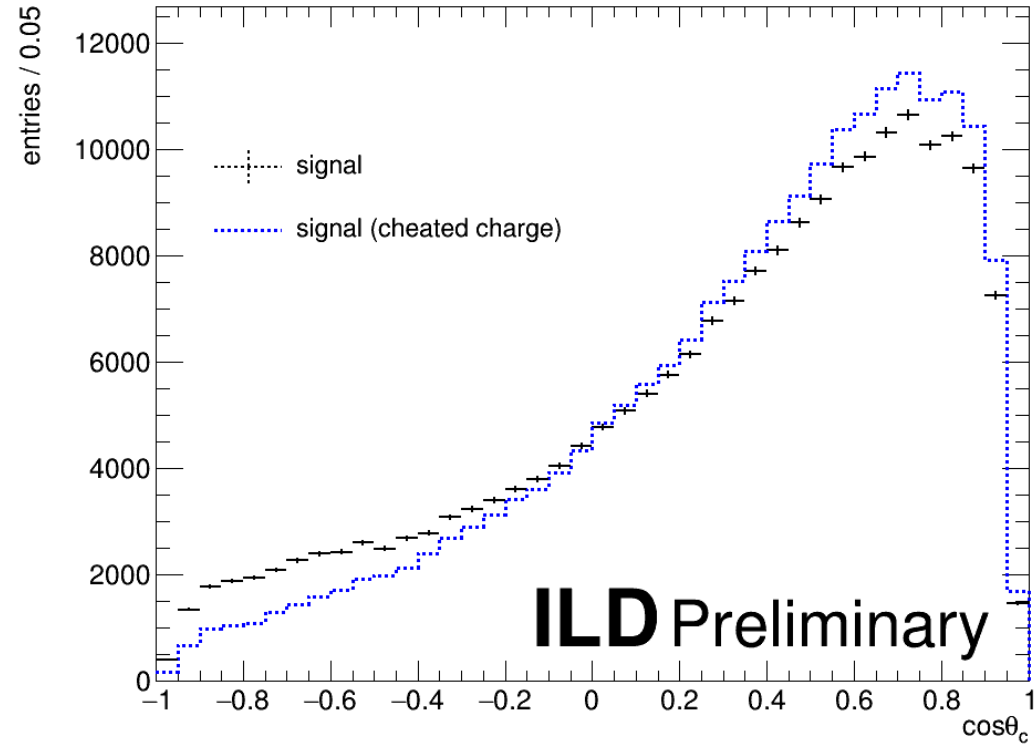


➤ Final efficiencies of 2.5-10 % in the cc- reconstruction.

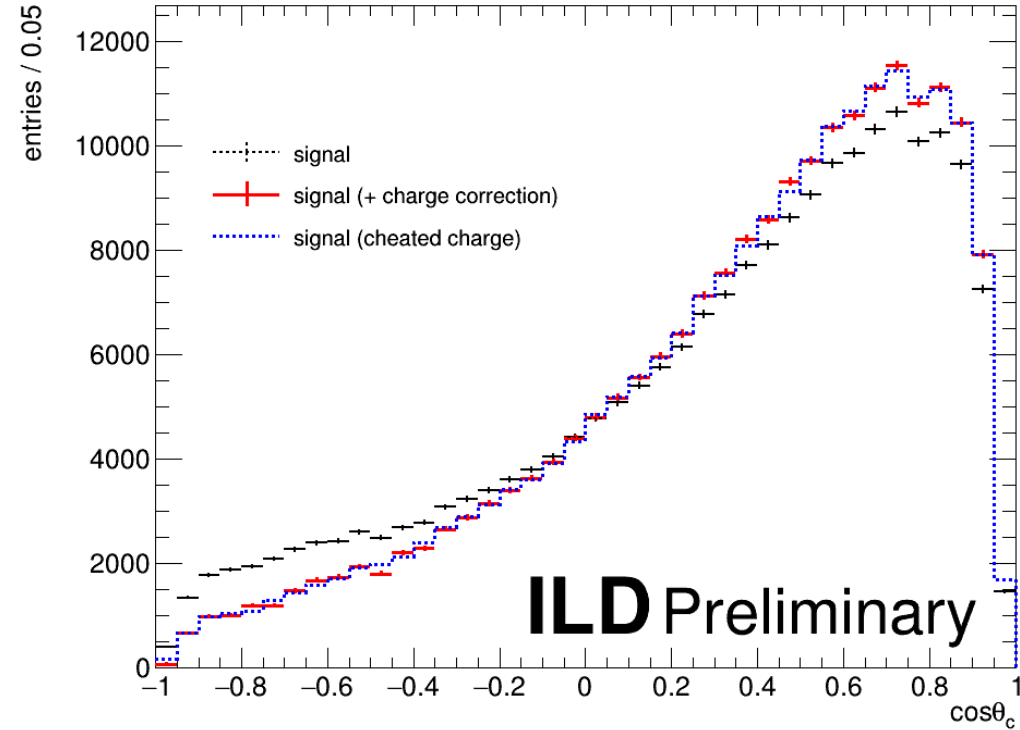
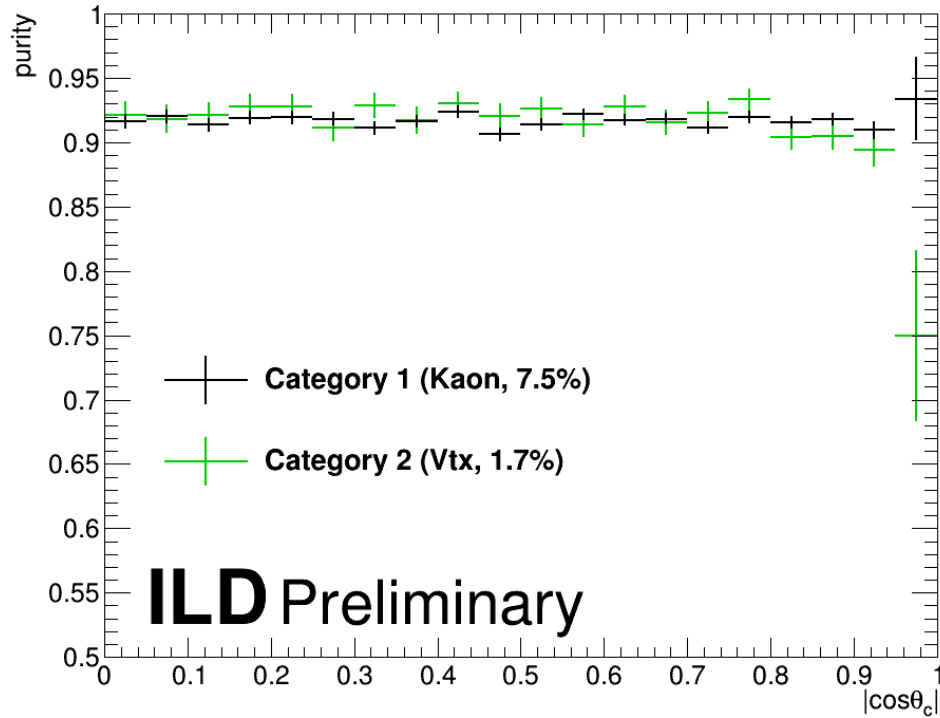
- Small BKG contamination in both cases.

Mis-measurements of the charge

- Mis-measurements of the jet charge produce a flip of the sign in the differential distribution: **migrations**.
 - Mistakes due to lost tracks, mis-identification of kaons...
- Migrations look as “new physics” → we need to correct them
 - Using data: double charge measurements with same and opposite charges (see back-up slides)
 - We calculate the probability to reconstruct correctly the charge (purity) and use it for correction
 - DATA DRIVEN METHOD.

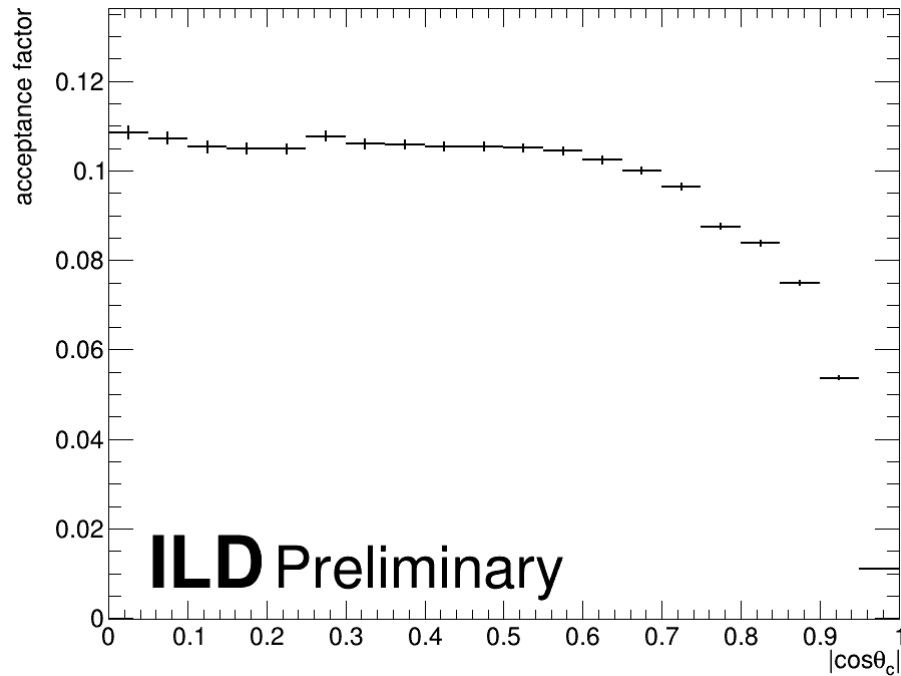


Migration correction



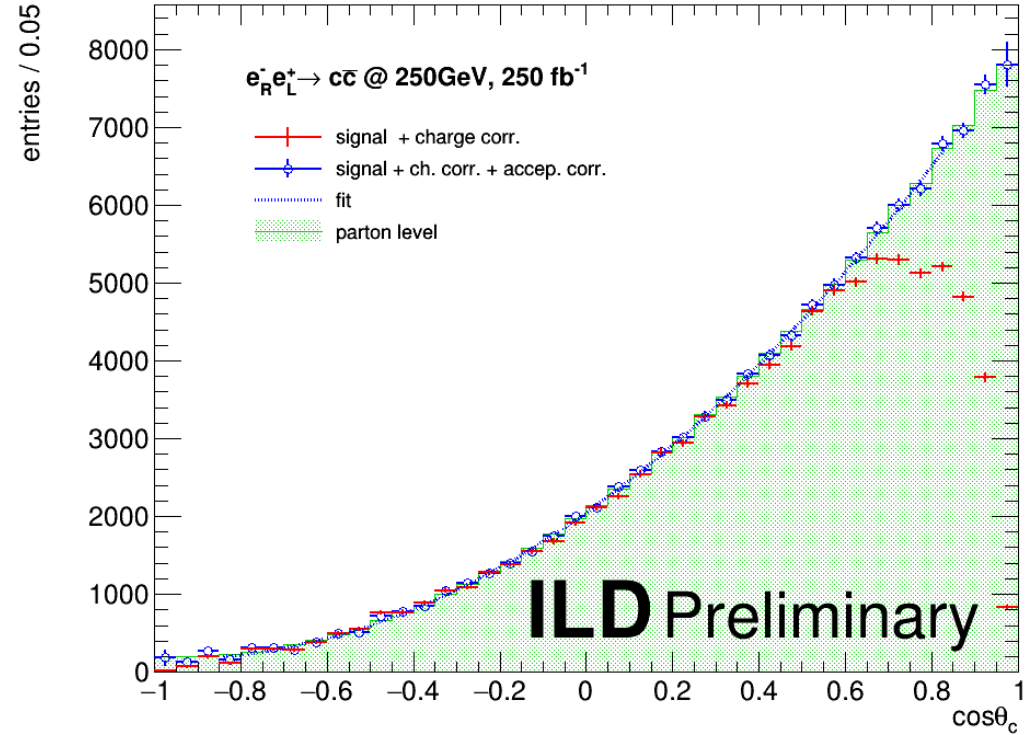
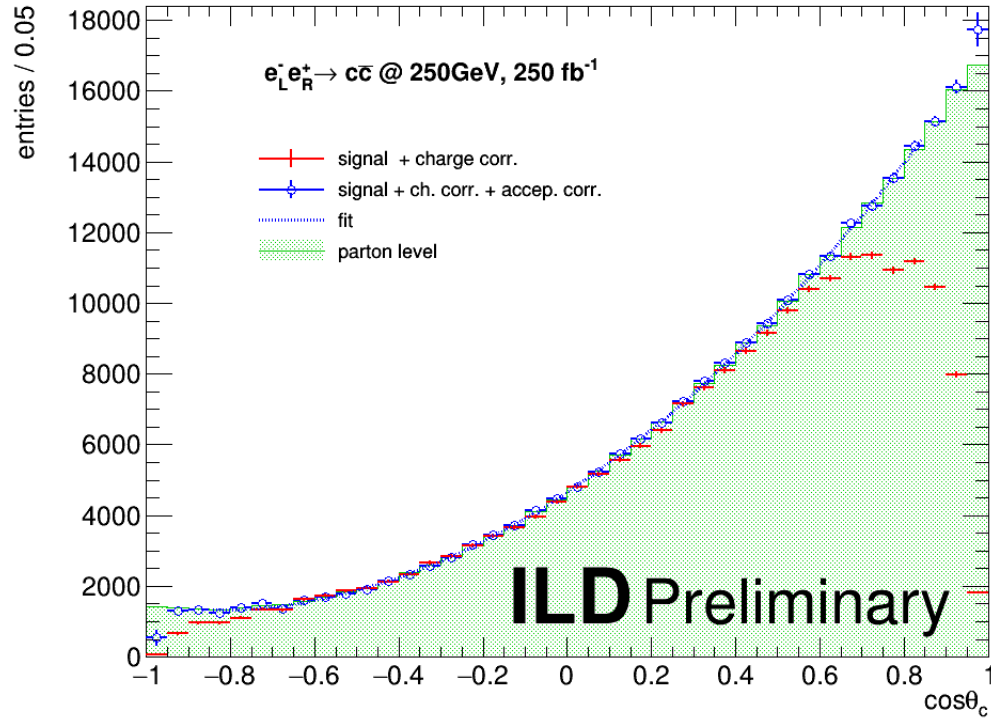
- Purities of ~ 0.92 in the full detector.
- For the b-quark, the purities are smaller (~ 0.75 - 0.85) and start dropping at large angles ($\cos\theta \sim 0.75$)

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 $\cos\theta \sim 0.7$
- 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?

Final distributions



► Long lever arm to extract form factor or couplings

$$\frac{d\sigma^I}{d\cos\theta} = S^I(1 + \cos^2\theta) + A^I \cos\theta \quad I = L, R$$

Summary

- The EW couplings to quarks can be studied in deep by the ILD.
 - Probe the SM, cross check LEP and SLC results and search of BSM (i.e. compositeness, etc).
- We will be able to measure angular cross sections with high efficiency:
 - 10% for c-quarks and 30% for b-quarks
 - Thanks to the high resolution of the TPC (Kaon ID) and the excellent vertexing capabilities of ILD.
- Careful estimation of reachable precisions on the EW couplings, including the systematic uncertainties have been carried out around the b-quark case → **see R. Poeschl talk** (*Study of systematic errors in high precision heavy quark analyses*)
 - For the c-quark, we expect similar values.
 - Ongoing activity
- This signature is shows a great potential to be used as detector optimization.
 - Relatively simple signatures but that require excellent vertexing, particle ID, quark tagging... in the full detector volume.

Back-up slides

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)

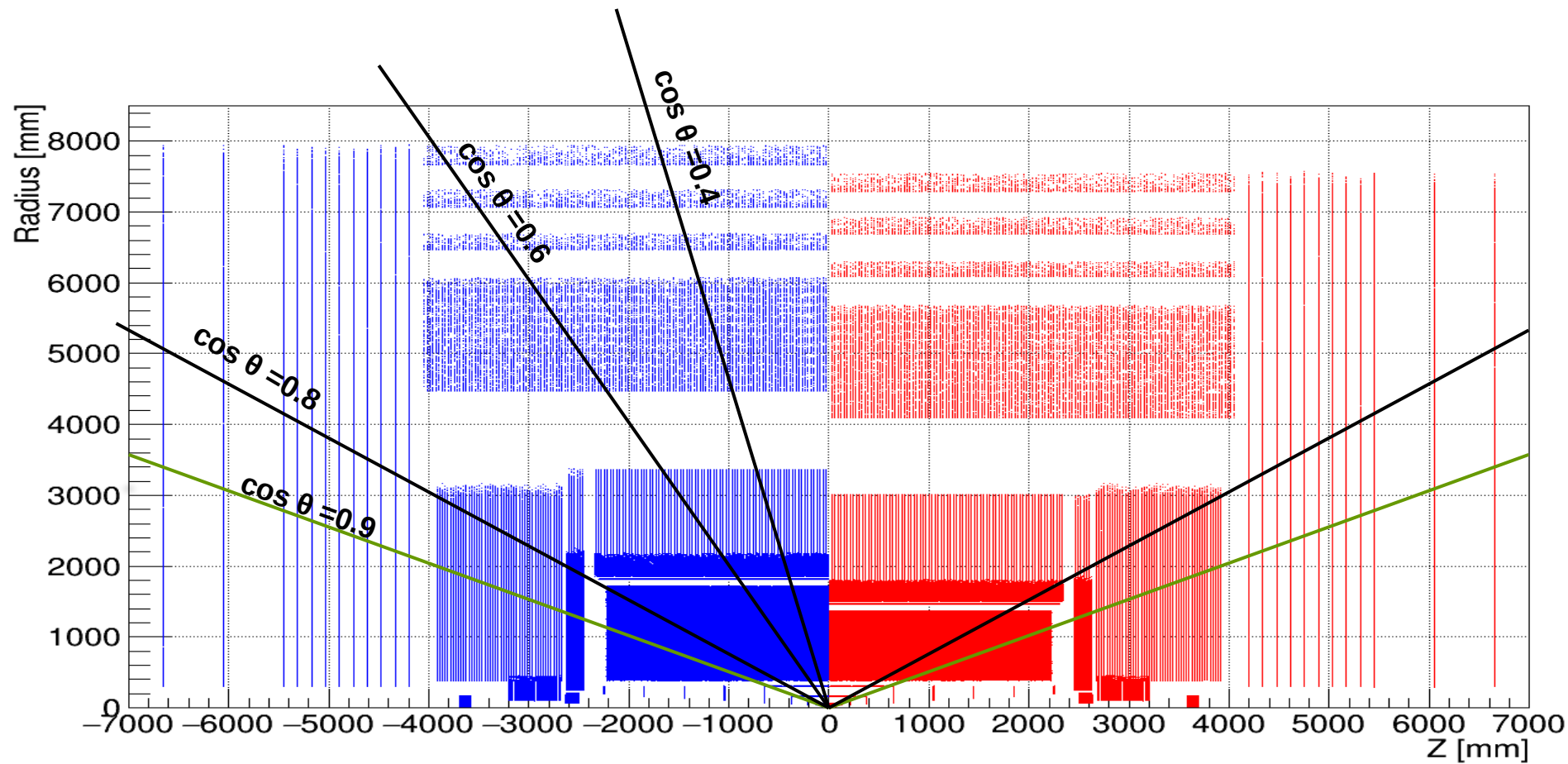
- Mistakes in the charge calculation due to loss tracks (acceptance issues, mis reconstruction etc) have to be corrected and estimated using data → Mistakes produce migrations (flip of the $\cos(\theta)$)
- The **migrations are restored** by determining the purity of the charge calculation using double charge measurements
 - Accepted events, N_{acc} , with $(-,+)$ compatible charges
 - Rejected events, N_{rej} , non compatible $(-,++)$ charges

pq-equation
Incognitas: pq and N .

$$\begin{aligned}N_{acc} &= Np^2 + Nq^2 \\ N_{rej} &= 2Npq \\ 1 &= p + q\end{aligned}$$

The **pq-equation** allows for correcting for migrations (finding the correct N) and in particular for the last and ultimate migration (dilution) due to B^0 oscillations

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



The ILD Concept

Jenny List, talk at LCWS2018

From key requirements from **physics**:

- **p_t resolution** (total ZH x-section)

$$\sigma(1/p_t) = 2 \times 10^{-5} \text{ GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2} \theta)$$

$\approx \text{CMS} / 40$

- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)

$$\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2} \theta) \mu\text{m}$$

$\approx \text{CMS} / 4$

- **jet energy resolution** 3-4%
($H \rightarrow \text{invisible}$)

$\approx \text{ATLAS} / 2$

- **hermeticity** $\theta_{\min} = 5 \text{ mrad}$
($H \rightarrow \text{invis, BSM}$)

$\approx \text{ATLAS} / 3$

To key features of the **detector**:

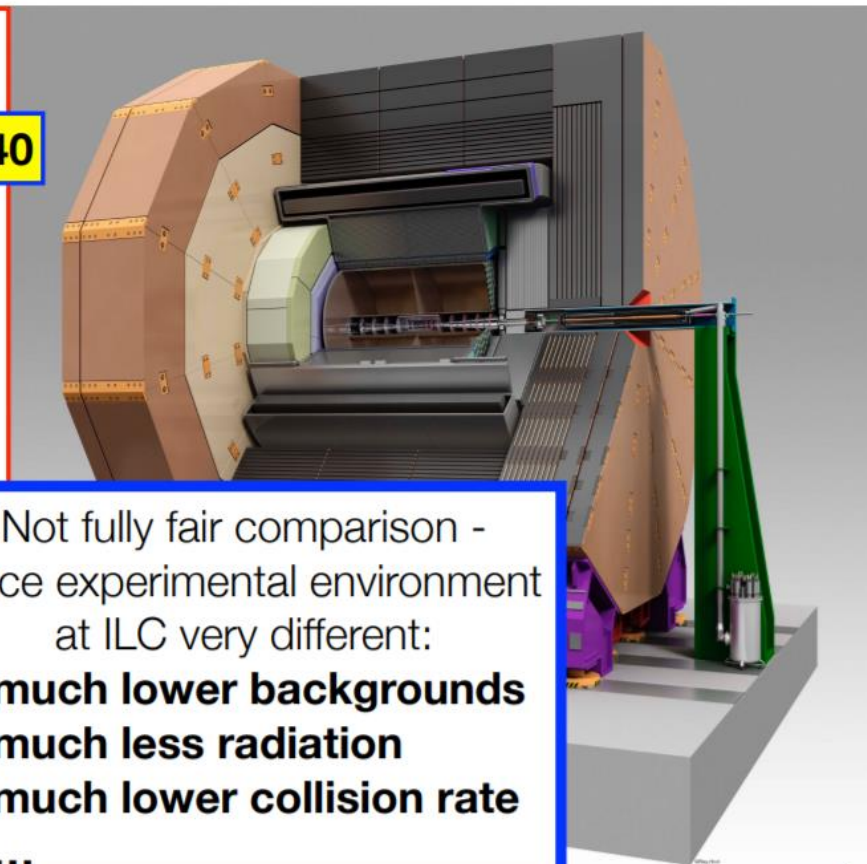
- **low mass tracker:**

- 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	$\sigma_{r\phi,z} = 2.8\mu\text{m}$ (layer 1) $\sigma_{r\phi,z} = 6.0\mu\text{m}$ (layer 2) $\sigma_{r\phi,z} = 4.0\mu\text{m}$ (layers 3-6)
SIT	$r_{in} = 153$ mm $r_{out} = 300$ mm $z = 644$ mm	2 double layers Si-strip sensors	$\sigma_{\alpha_z} = 7.0\mu\text{m}$ $\alpha_z = \pm 7.0^\circ$ (angle with z-axis)
SET	$r = 1811$ mm $z = 2300$ mm	1 double layer Si-strip sensors	$\sigma_{\alpha_z} = 7.0\mu\text{m}$ $\alpha_z = \pm 7.0^\circ$ (angle with z-axis)
FTD _{pixel}	$z_{min} = 230$ mm $z_{max} = 371$ mm	2 disks Si-pixel sensors	$\sigma_r = 3.0\mu\text{m}$ $\sigma_{r\perp} = 3.0\mu\text{m}$
FTD _{strip}	$z_{min} = 644$ mm $z_{max} = 2249$ mm	5 disks - double Si-strip sensors	$\sigma_{\alpha_r} = 7.0\mu\text{m}$ $\alpha_r = \pm 5.0^\circ$ (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	$\sigma_{r\phi}^2 = (50^2 + 900^2 \sin^2 \phi + ((25^2/22) \times (4T/B)^2 \sin \theta) (z/\text{cm})) \mu\text{m}^2$ $\sigma_z^2 = (400^2 + 80^2 \times (z/\text{cm})) \mu\text{m}^2$ where ϕ and θ are the azimuthal and polar angle of the track direction

Tracking at ILD

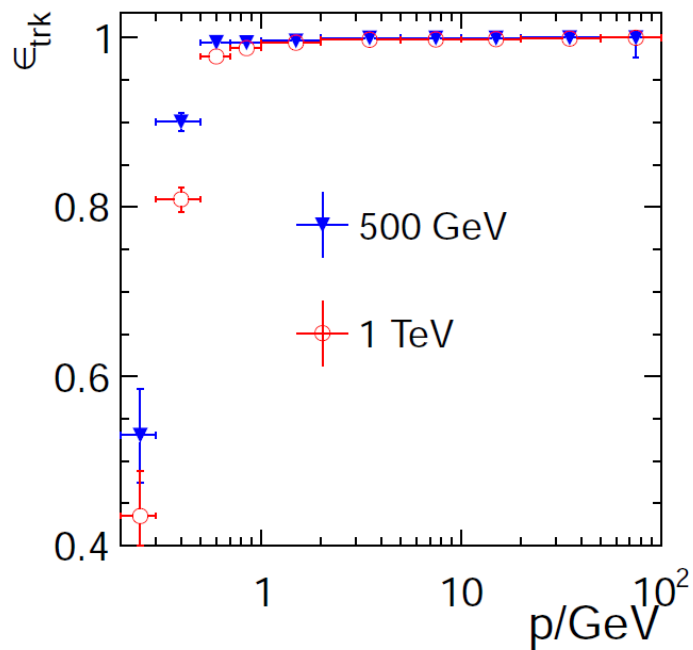


Figure 5. Tracking Efficiency for $t\bar{t} \rightarrow 6$ jets at 500 GeV and 1 TeV versus momentum in the presence of beam background.

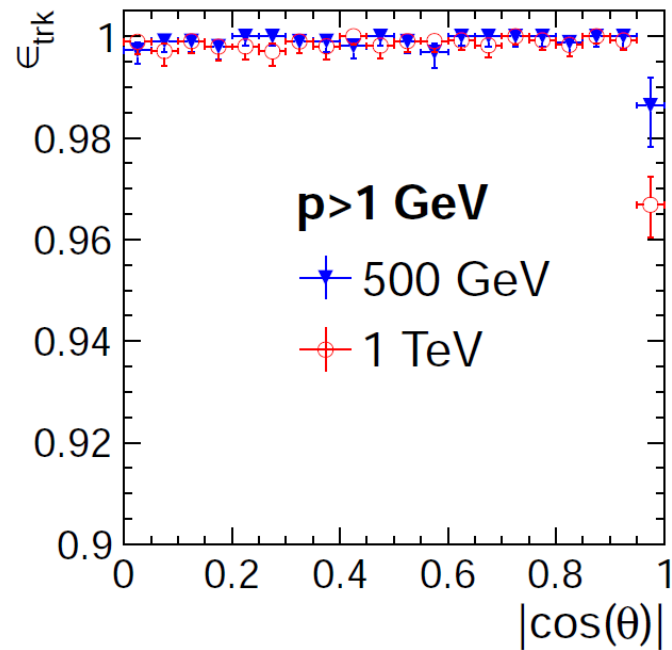
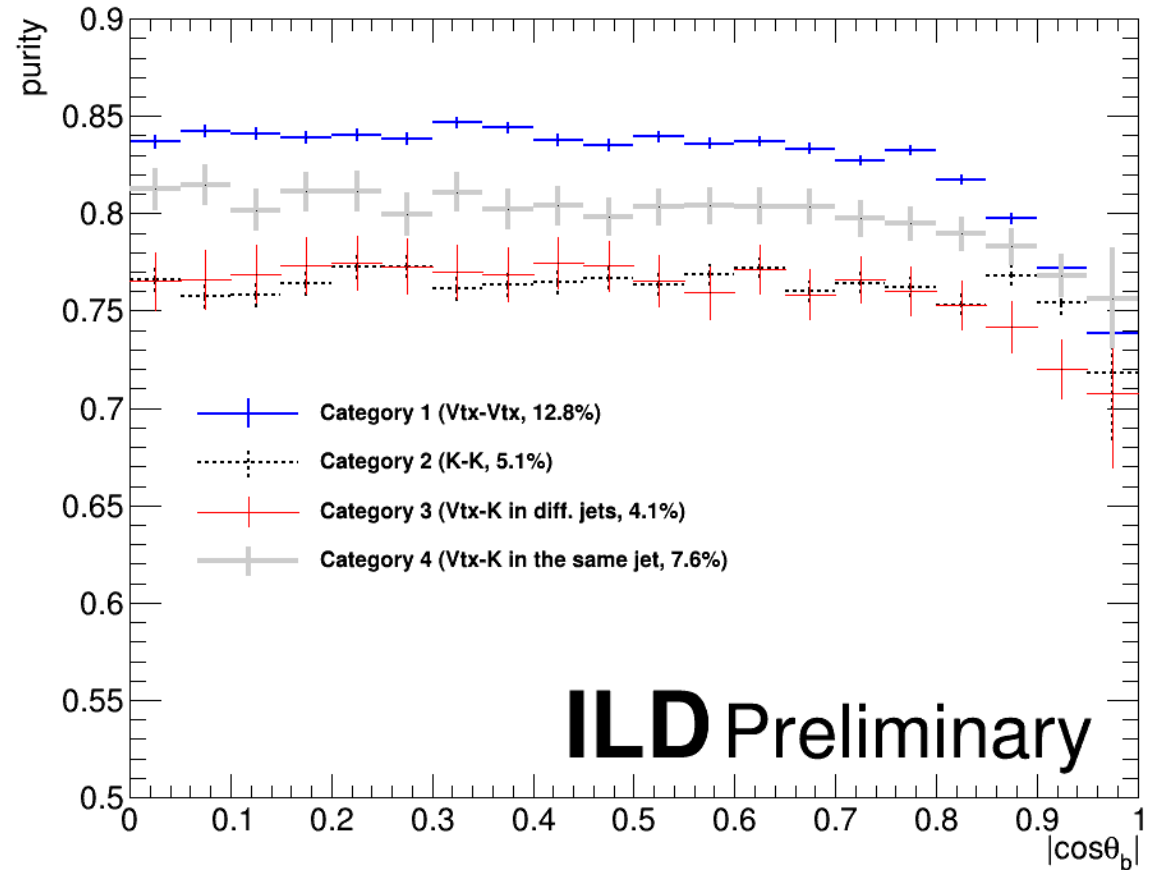


Figure 6. Tracking Efficiency for $t\bar{t} \rightarrow 6$ jets at 500 GeV and 1 TeV versus $|\cos(\theta)|$ for particles with $p > 1\text{ GeV}$ in the presence of beam background

Double charge measurements

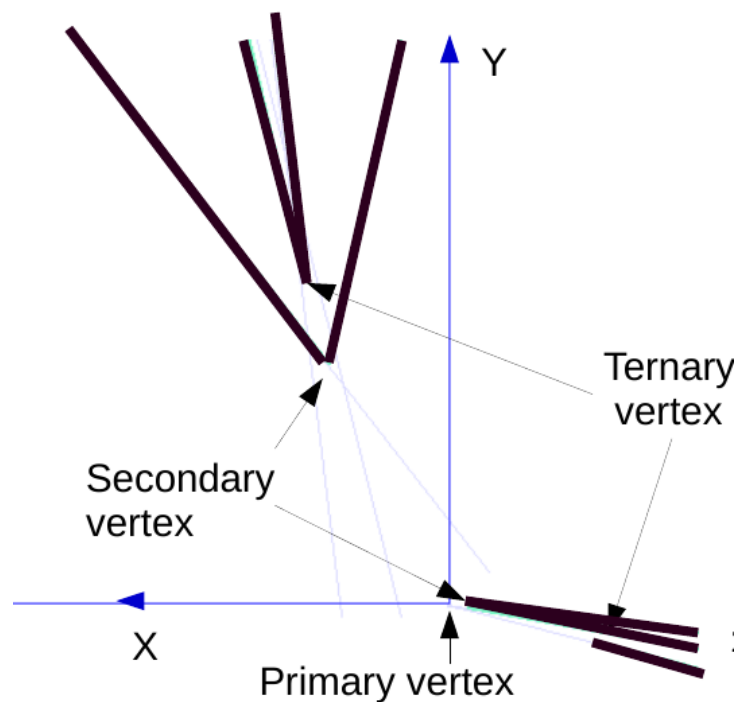
➤ Final selection after double charge measurements is still very large.

- ~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].