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

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Outline

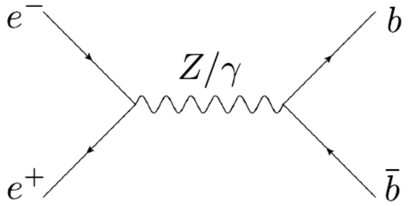
- Introduction
- Reconstructing ee→ qq @ 250 GeV
  - Signal and background: different topologies
- Charge calculation
  - And correction of mistakes in the calculation (data driven method)
- Results

Introduction

- Quark (fermion) **electroweak couplings** can be **inferred from cross section, 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 → **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→ qq @ 250 GeV

Signal:

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

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

Backgrounds:

- Radiative return ee→ γZ (ISR): Presence of the photon in the detector or invariant mass of the system <250GeV (Z-pole)
- 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

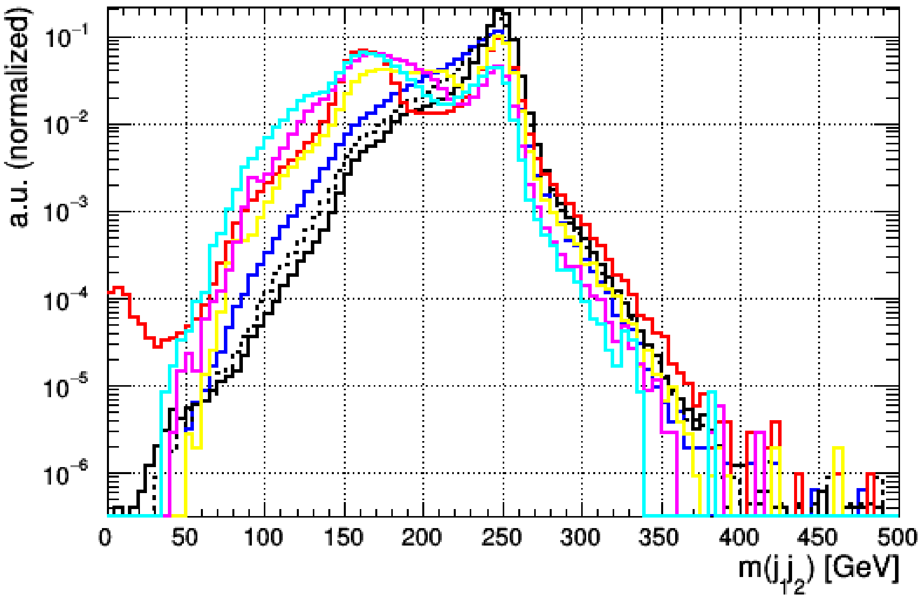
Reconstruction of ee→ qq @ 250 GeV

Durham, 2 jets

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

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

- $b\bar{b}$, 100.0%
- $c\bar{c}$, 100.0%
- $q\bar{q}$, q=uds, 100.0%
- γ Z (Z→ $q\bar{q}$, 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.

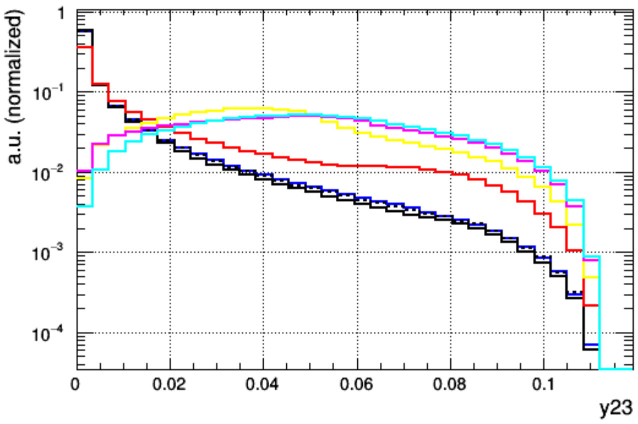
Reconstruction of ee→ qq @ 250 GeV

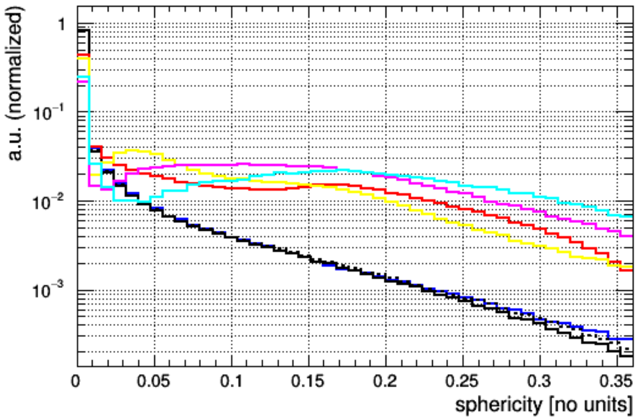
How can we improve the S/B ratio?

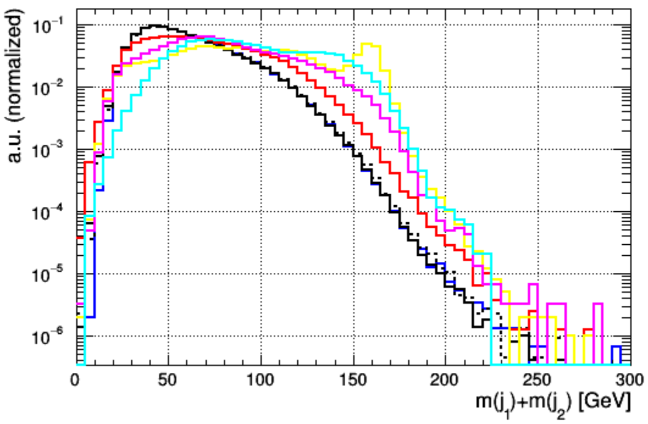
- Looking a the jet substructure
  - y23 (or d23) is defined as the distance at which a 2-jet system becomes a 3-jet system: it tells us about the substructure of the jets.
  - Mass of the jets (hard non-collinear radiation artificially clustered in a jet will make “fat” jets)

- 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: $S \approx 1$

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







- Preselection of qq final states using
  - y23<0.02 & S<0.012 & (mj1+mj2)<120 GeV
- Then, proceed to quark tagging (using LCFIPlus b and c tagger).

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

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

- Numbers before selection.

blue solid	$b\bar{b}$, 100.0%
black dotted	$c\bar{c}$, 100.0%
black solid	$q\bar{q}$, q=uds, 100.0%
red	γ Z (Z→ $q\bar{q}$, q=udscb), 11.5%
magenta	ZZ, 4.2%
yellow	WW, 44.1%
cyan	HZ, 0.4%

Final selection

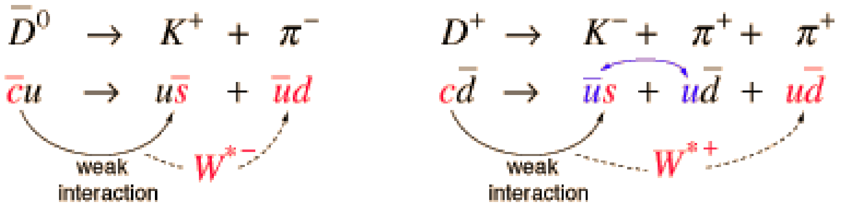
	100 % eL⁻ polarization								
	Signal Eff [%]				BKG / S [%]				
	qq	bb	cc	light	Z rad	ZZ	WW	HZ	Total
y23 cut	**85,7%**	84,3%	85,0%	86,4%	9,2%	0,7%	8,6%	0,0%	**18,5%**
y23, S	**77,5%**	75,9%	77,1%	78,2%	5,0%	0,5%	4,3%	0,0%	**9,9%**
y23, s, jet M	**77,0%**	75,5%	76,5%	77,6%	4,9%	0,4%	3,0%	0,0%	**8,4%**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

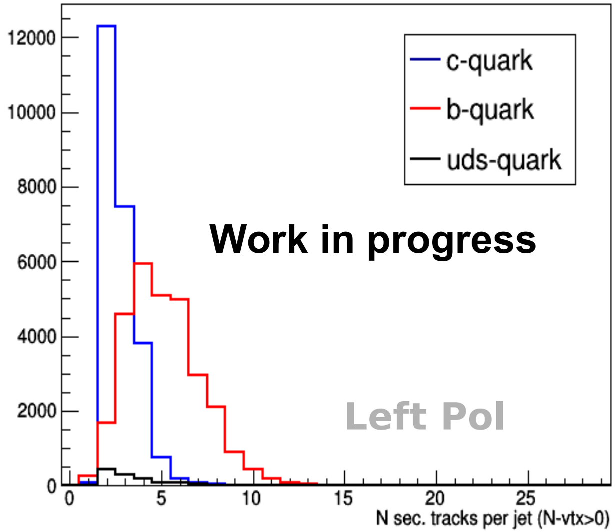
- C-quark jets
  - D^0 mesons

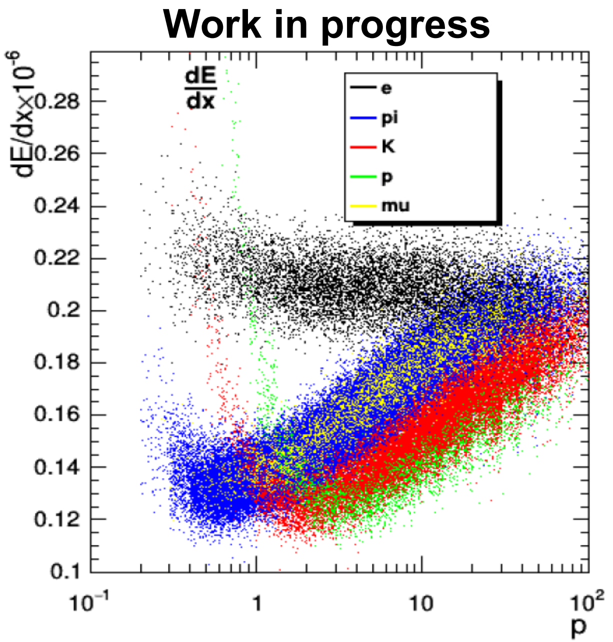
    70% have 2 prongs: -> **High purity offered by Kaons**
  - $D^{+/-}$, $D_s^{+/-}$: 1-3 prongs



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

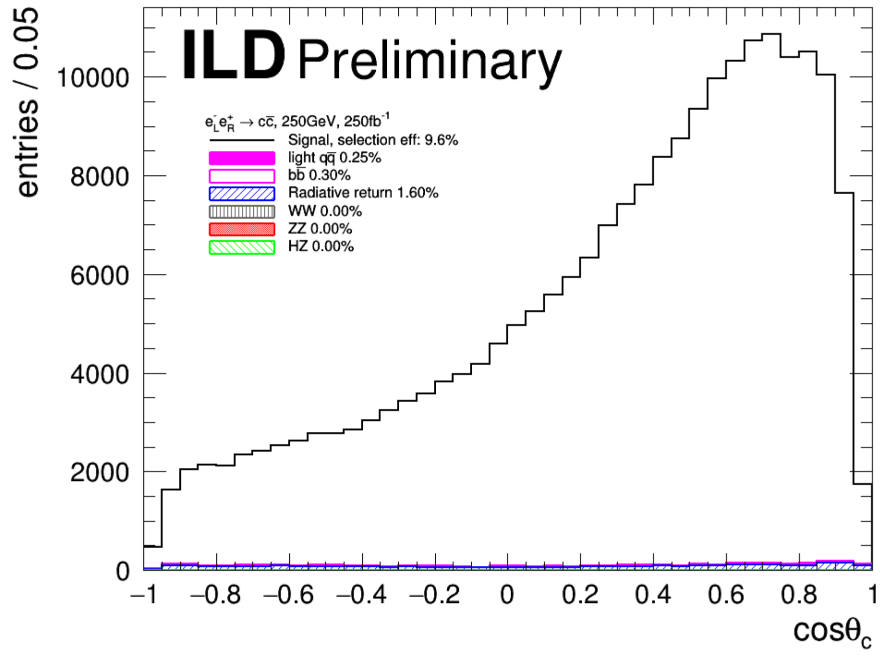
    (Vtx method)



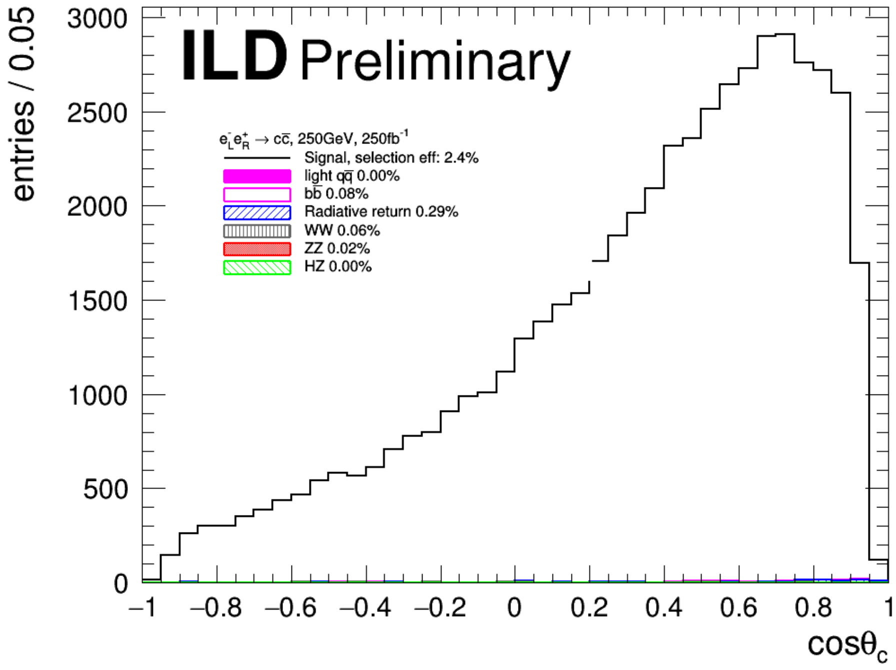


Final selection

- Only one jet with c-charge measurement



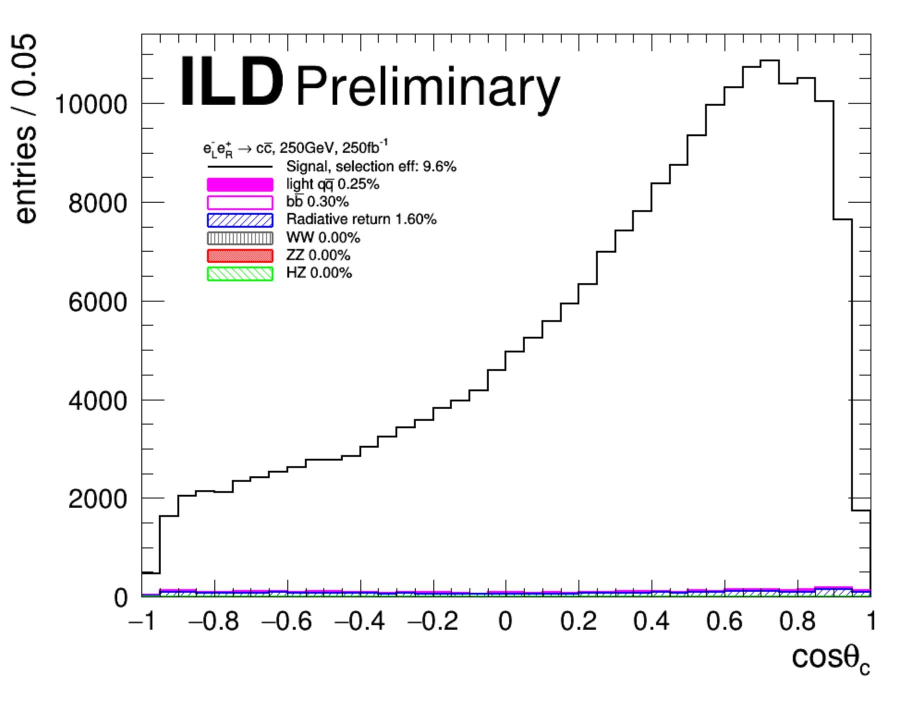
- The two jets with c-charge measurement



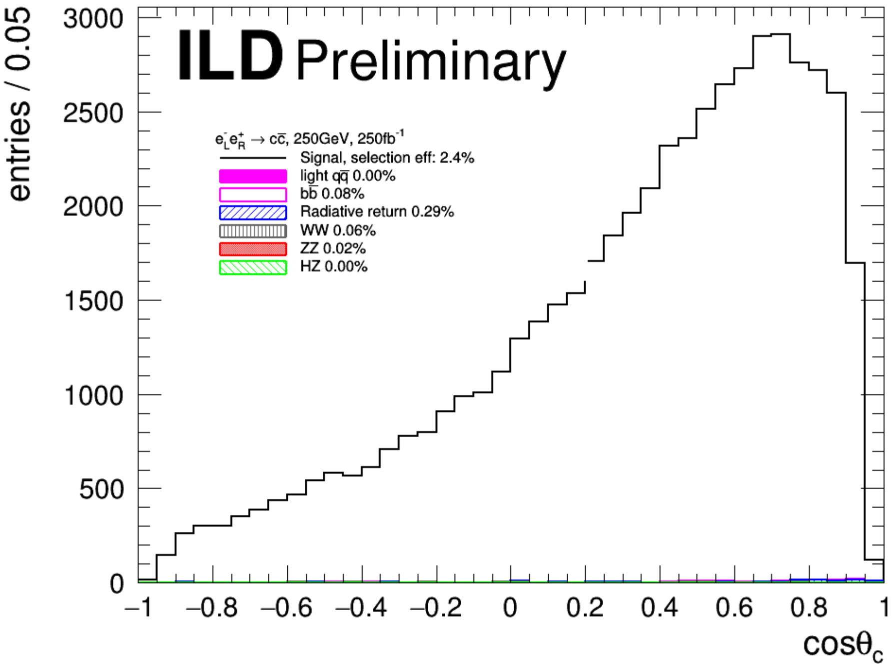
- Final efficiencies of 2.5-10 % in the cc- reconstruction.
  - Small BKG contamination in both cases.

Final selection

- Only one jet with c-charge measurement



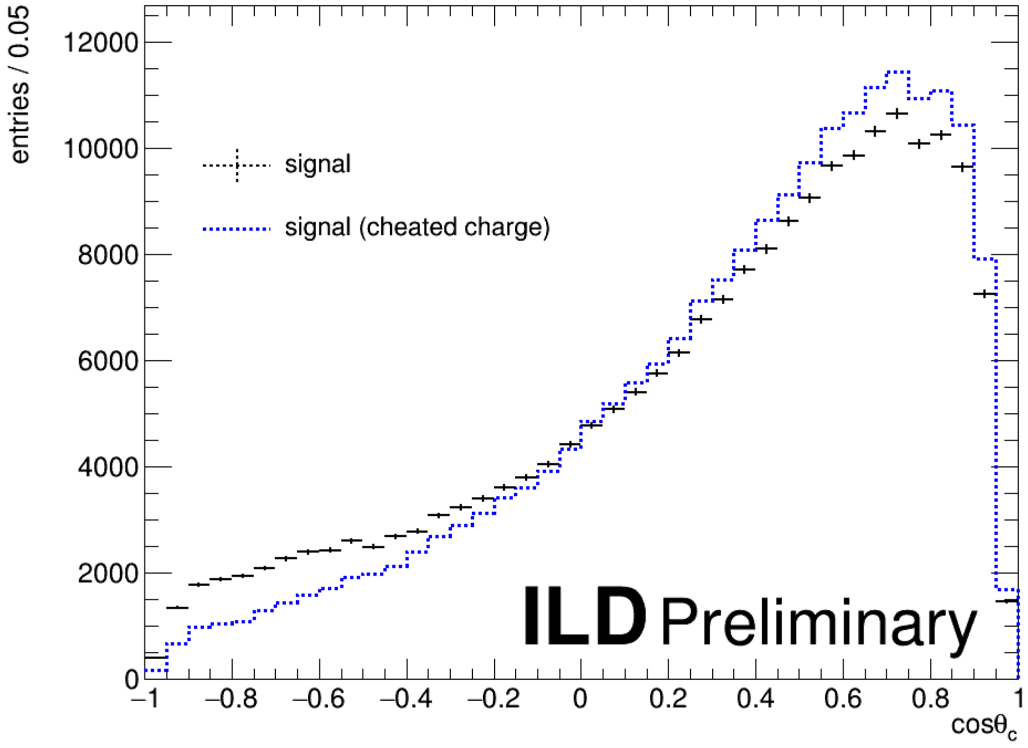
- The two jets with c-charge measurement



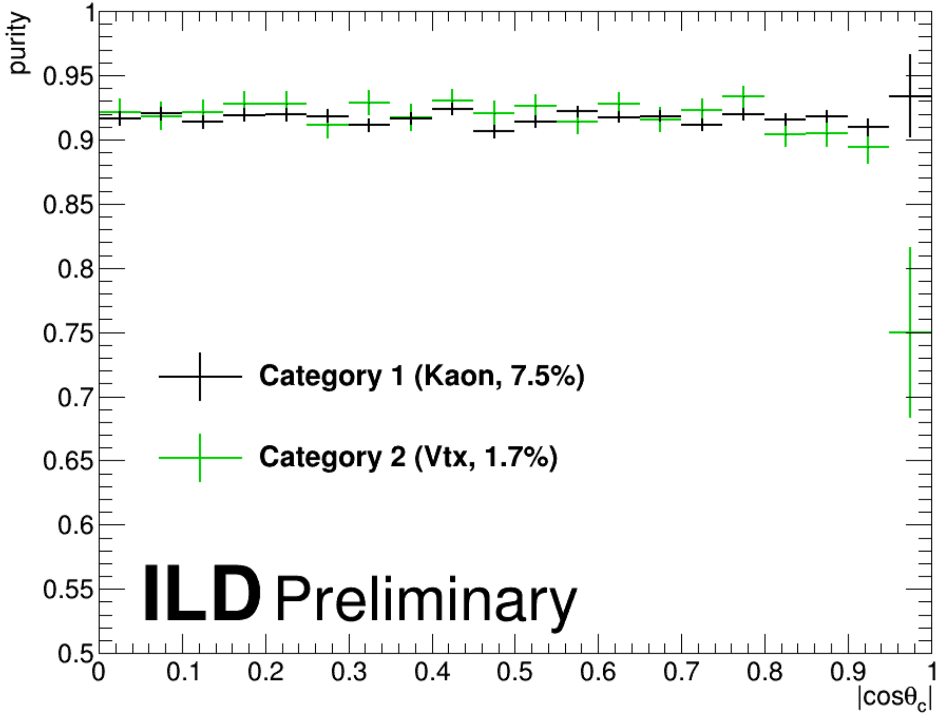
- Final efficiencies of 2.5-10 % in the cc- reconstruction.
  - Small BKG contamination in both cases.

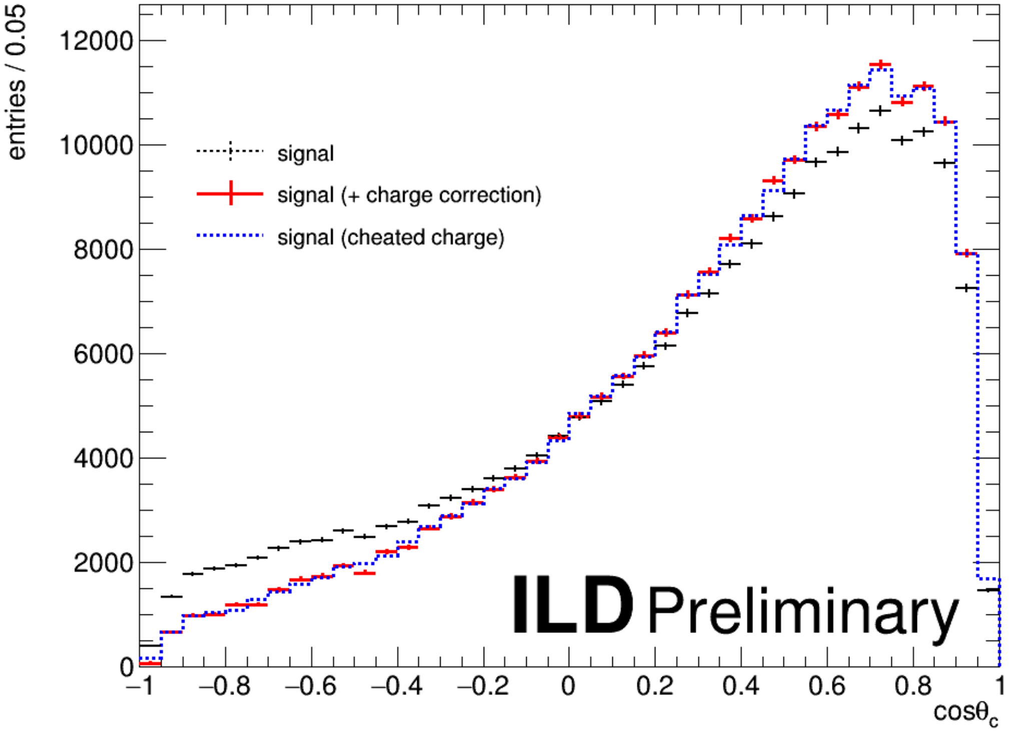
Mis-measurements of the charge

- 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.



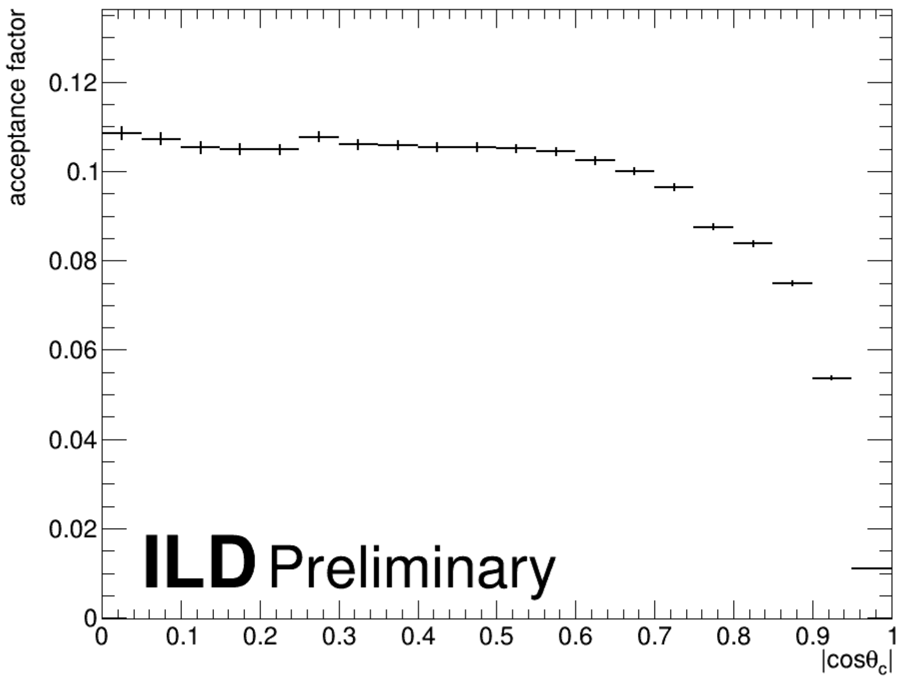
Migration correction





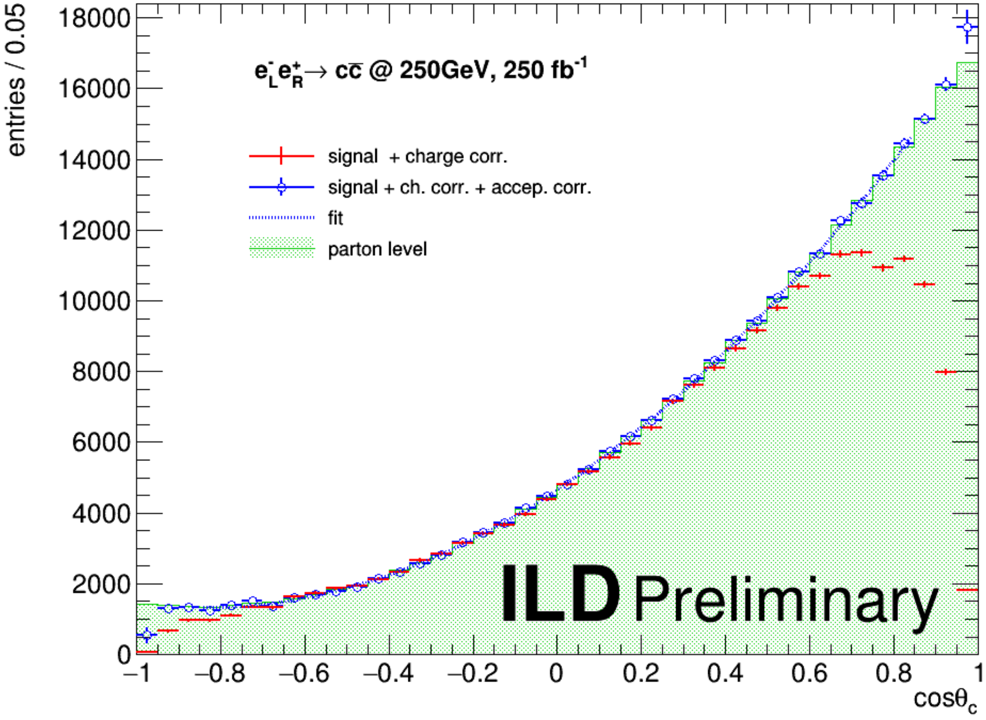
- Purities of ~ 0.92 in the full detector.
- For the b-quark, the purities are smaller (~0.75-0.85) and start dropping at large angles (cosθ ~0.75)

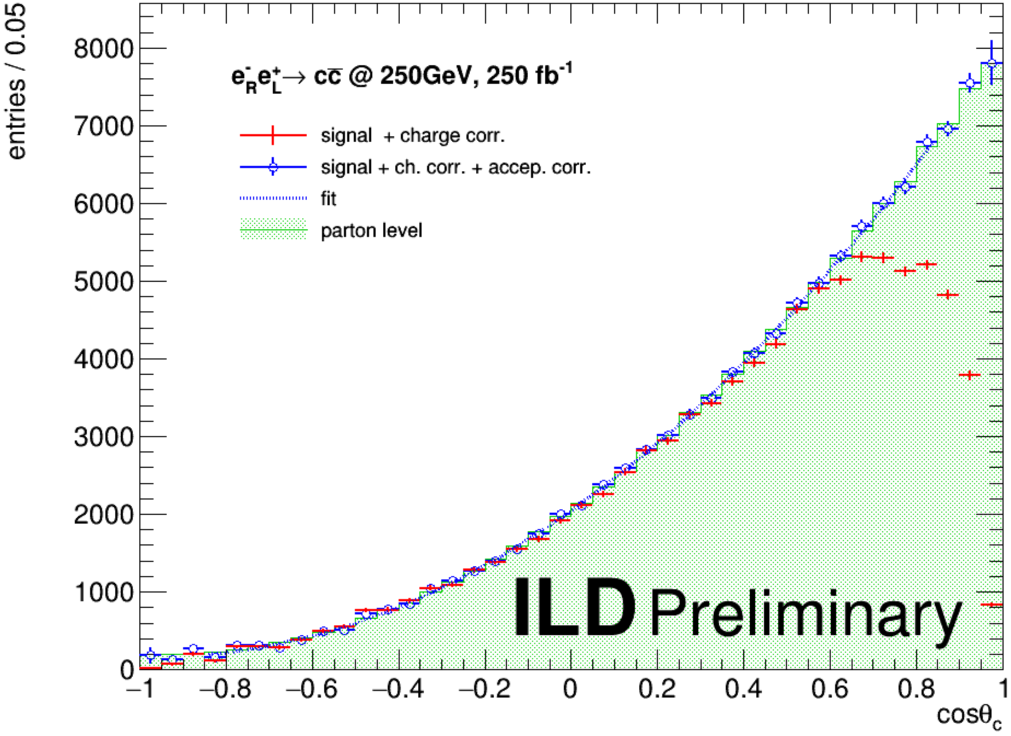
Acceptance



- 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 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?

Final distributions





- Long lever arm to extract form factor or couplings

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

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 $\bar{\mathbf{q}}$, **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)

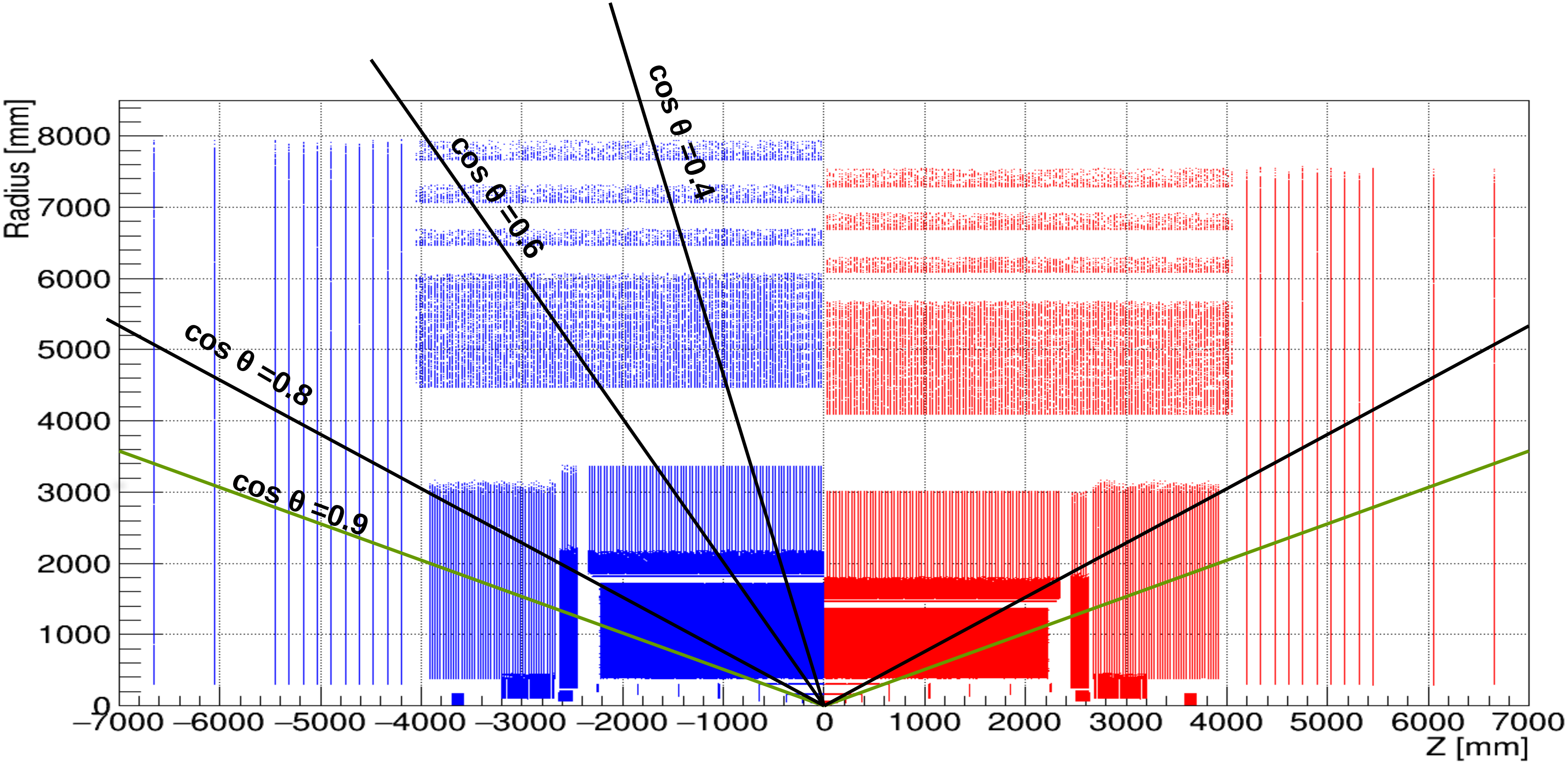
- Mistakes in the charge calculation due to loss tracks (acceptance issues, mis reconstruction etc) have to be corrected and estimated using data → Mistakes produce migrations (flip of the cos(θ))
- The **migrations are restored** by determining the purity of the charge calculation using double charge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

pq-equation
Incognitas: pq and N.

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

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%



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

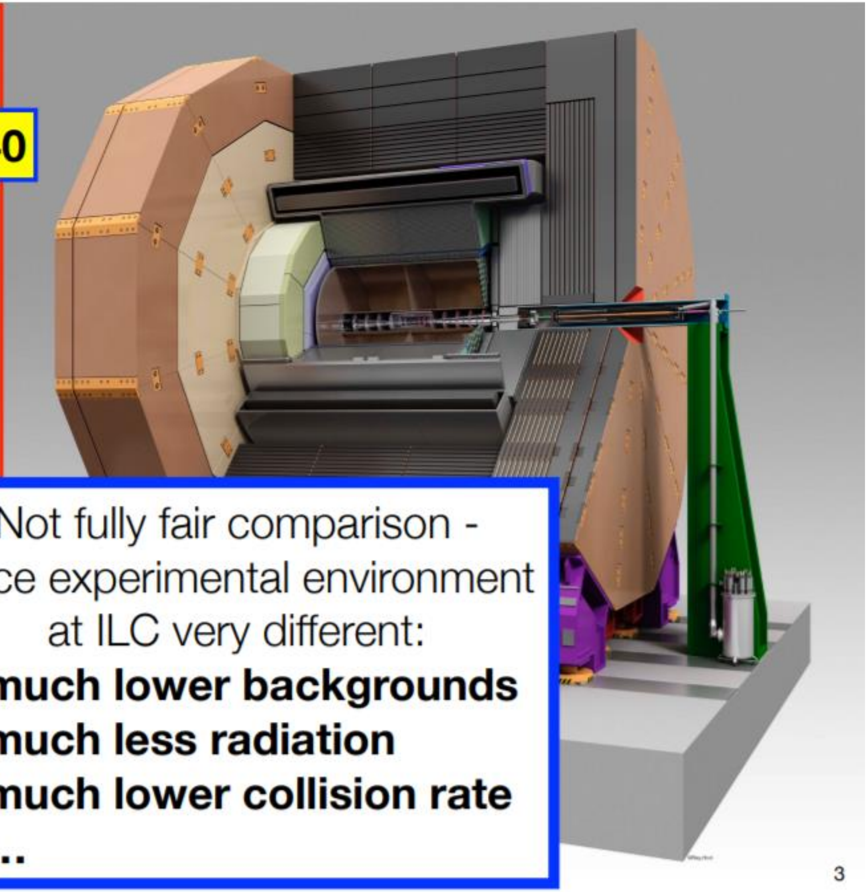
Jenny List, talk at LCWS2018

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \text{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
  ≈ CMS / 40
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta)\ \mu m$
  ≈ 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	$\sigma^2_{r\phi} = (50^2 + 900^2 \sin^2\phi +$ $((25^2/22) \times (4T/B)^2 \sin\theta)(z/cm))\,\mu m^2$ $\sigma^2_z = (400^2 + 80^2 \times (z/cm))\,\mu m^2$ where ϕ and θ are the azimuthal and polar angle of the track direction

Tracking at ILD

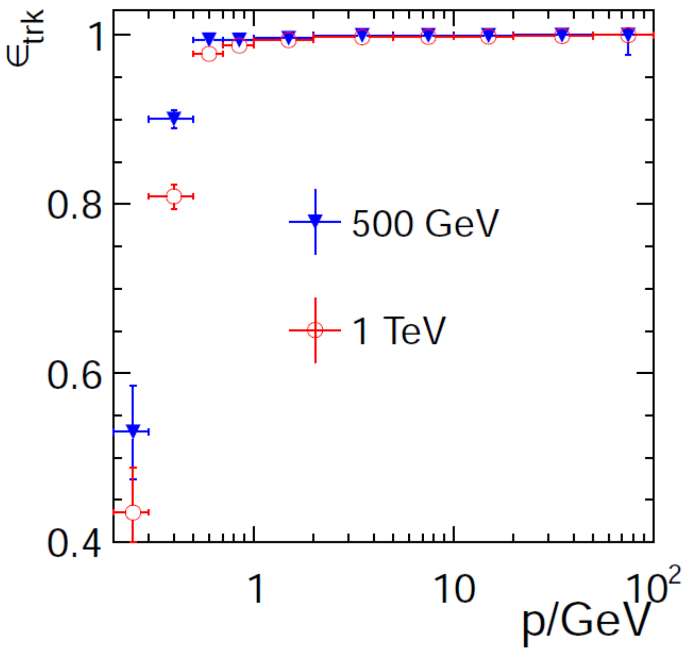


Figure 5. Tracking Efficiency for $t\bar{t} \rightarrow 6$ jets at 500 GeV and 1 TeV versus momentum in the presence of beam background.

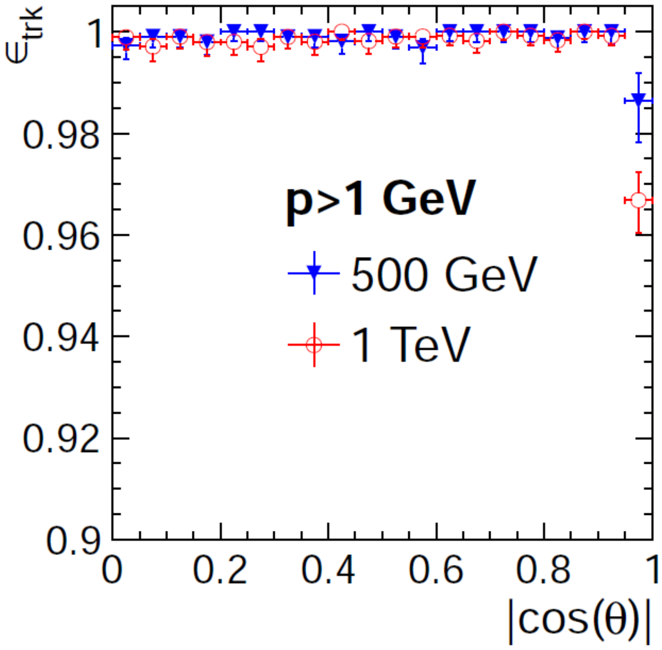
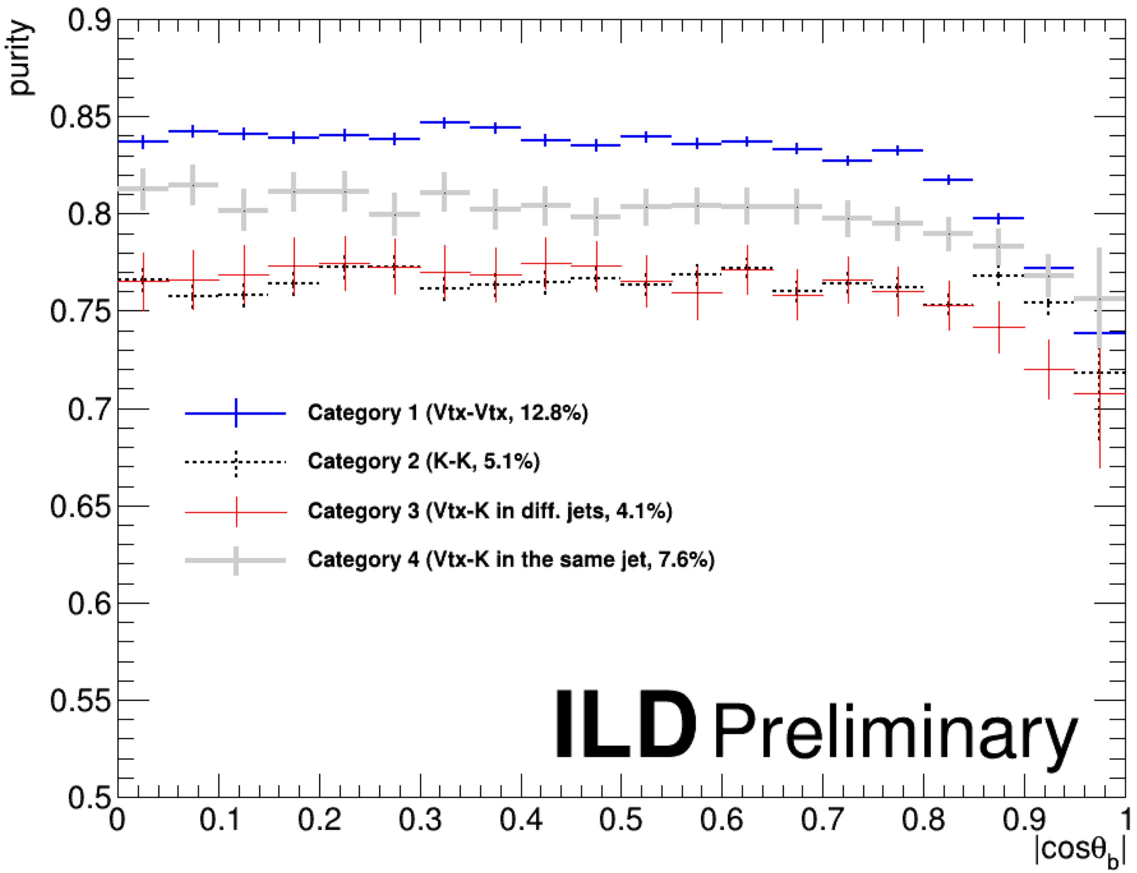


Figure 6. Tracking Efficiency for $t\bar{t} \rightarrow 6$ jets at 500 GeV and 1 TeV versus $|cos(\theta)|$ for particles with $p > 1\text{GeV}$ in the presence of beam background

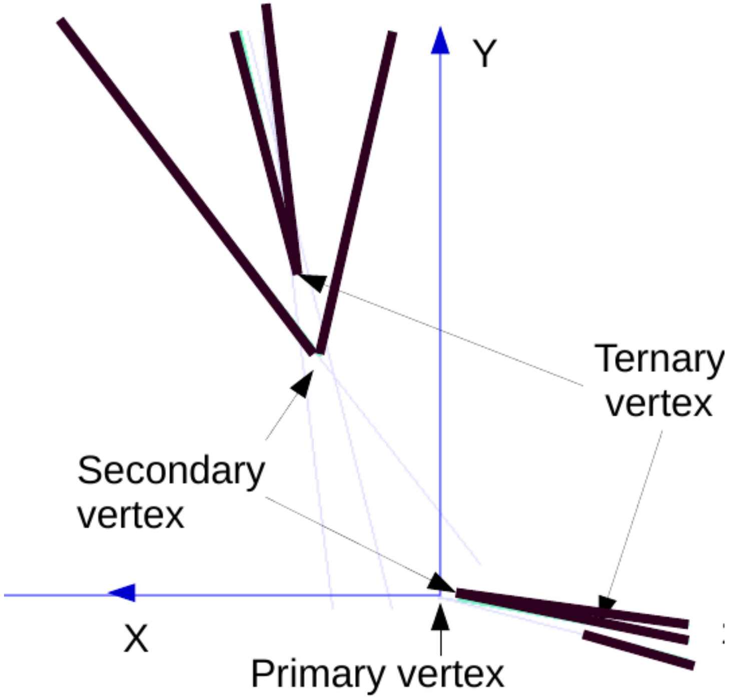
Double charge measurements

- 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].