Top quark measurements at

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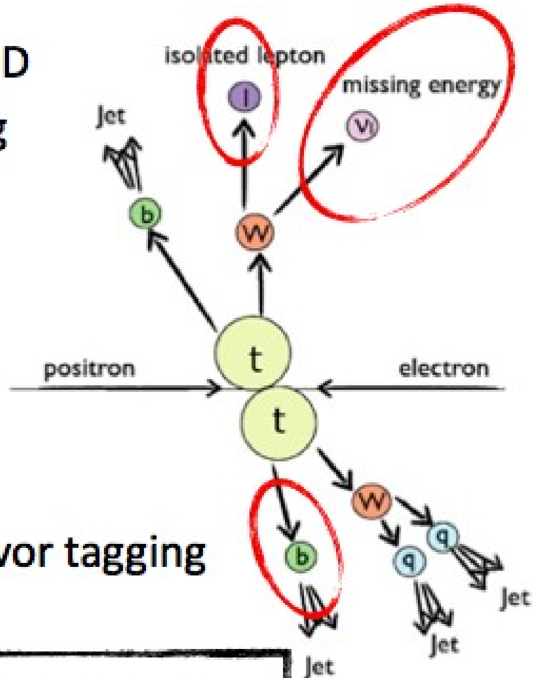
Based on studies for the ILC DBD (and the CLIC TDR)

ILD Meeting Cracow/Poland September 2013

Elements of top quark reconstruction

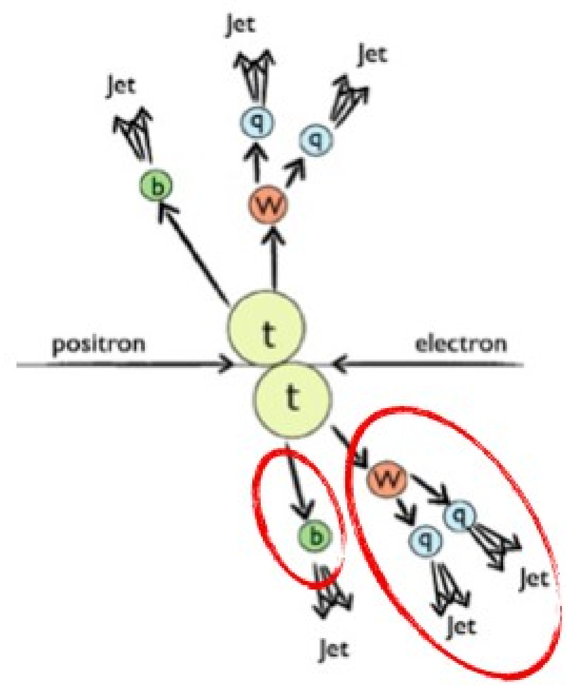
- By far dominating decays: All-hadronic (46%), semi-leptonic / lepton+jets (45%, 30% w/o τ)

lepton ID
tracking



flavor tagging

4 jets, isolated lepton



6 jets

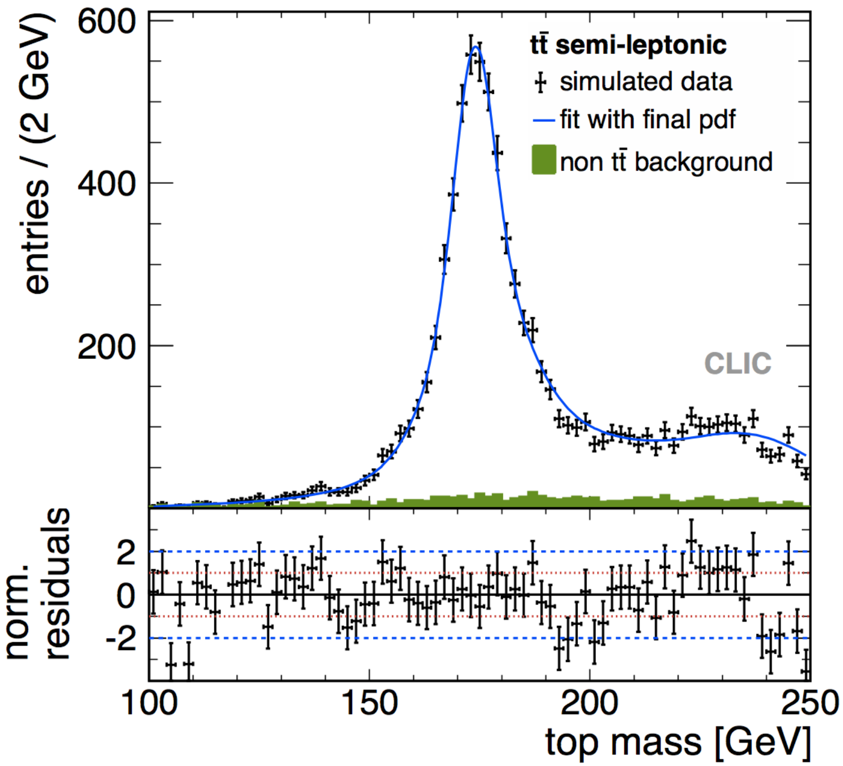
jet energy
reconstruction,
global event
reconstruction

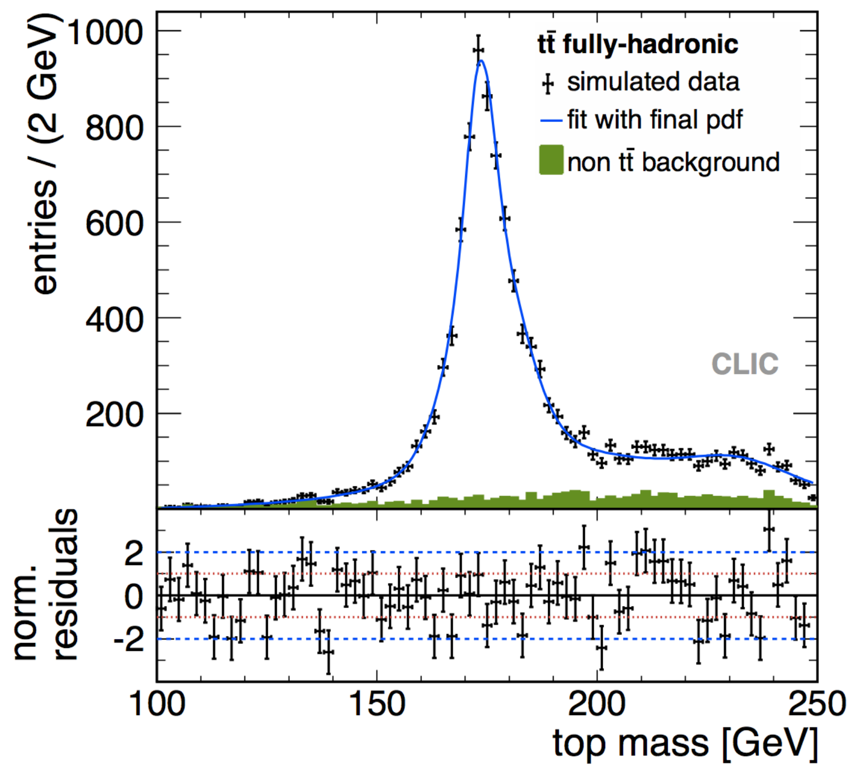
Uses all aspects of LC detectors!

Nice illustration stolen from Frank

Brief reminder on results I – Top mass in continuum

CLIC study but results very similar for ILC – L=100 fb-1

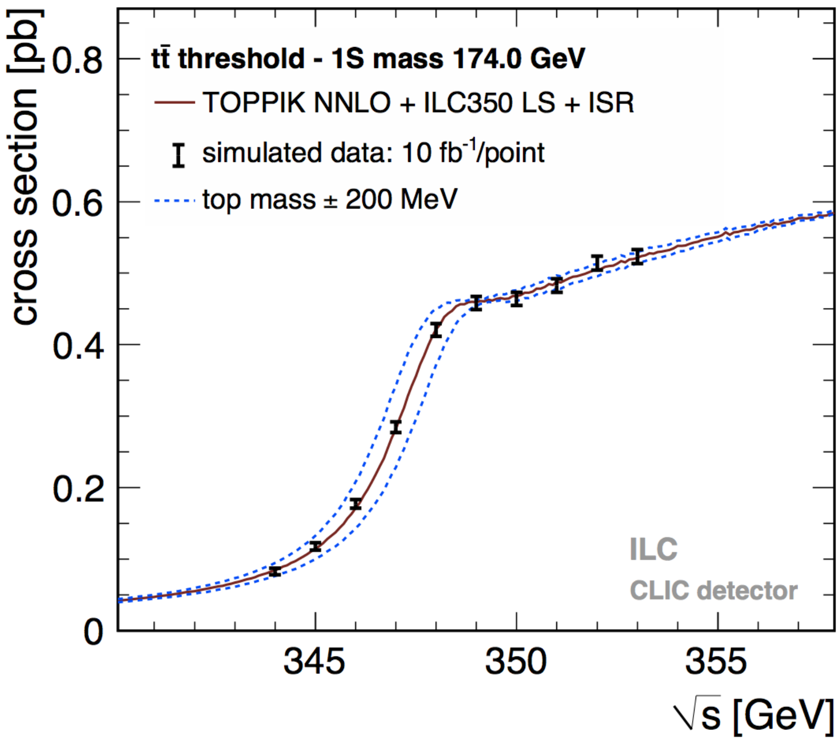


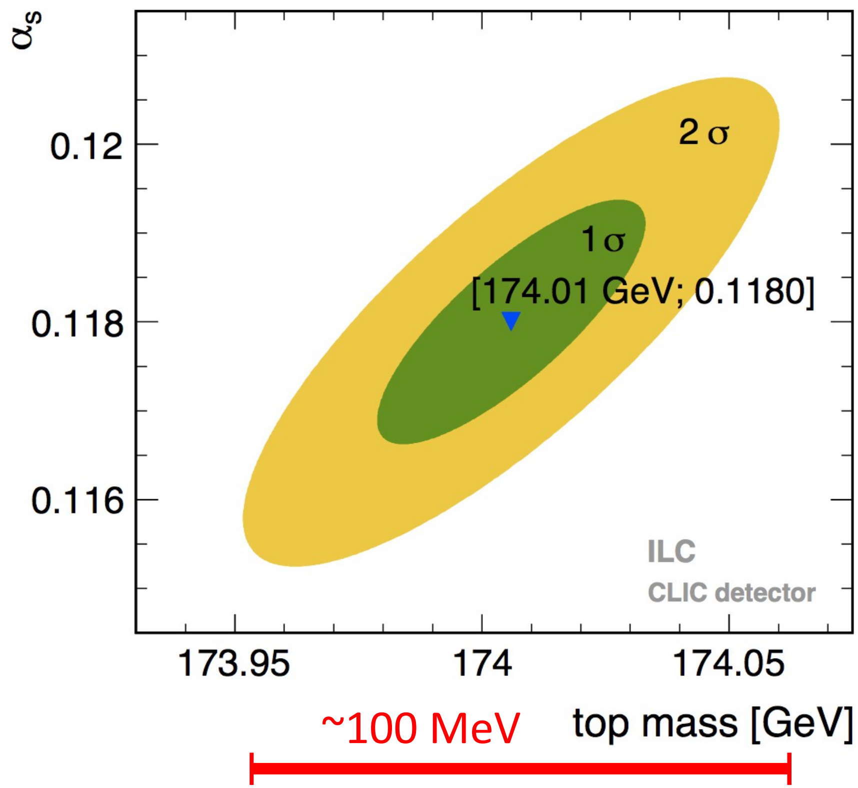


- (Almost) background free measurement of top mass
- Uncertainty on continuum top mass ~ 80 MeV

Brief reminder on results II – Top mass in threshold scan

arXiv:1303.3758





1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

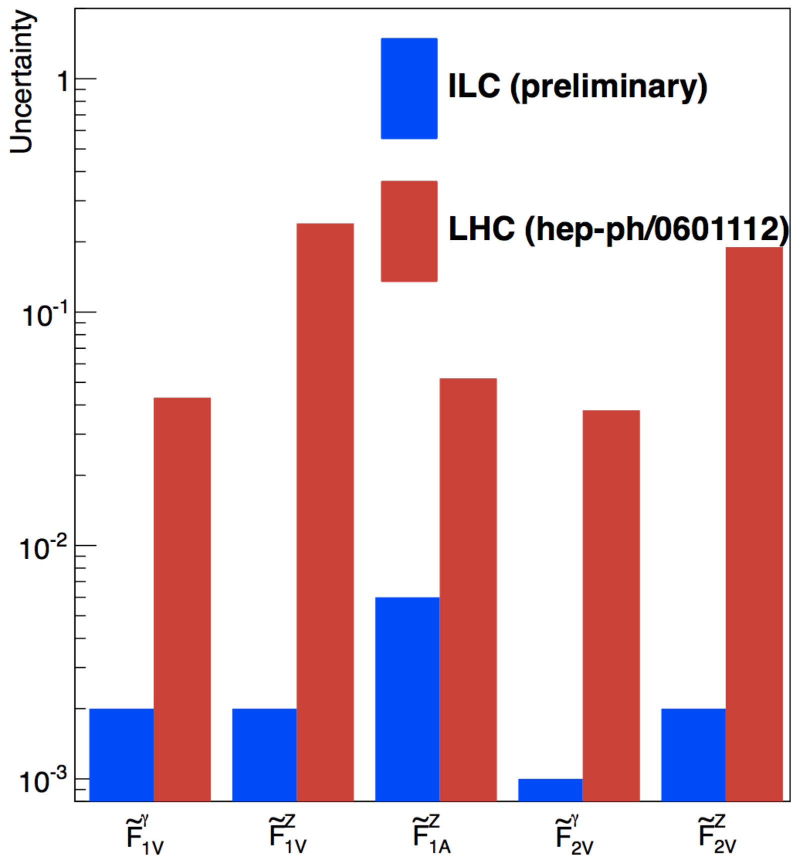
- Only one observable x-section
  cf. Martinez et al. Used more observables and more lumi
- result include lumi spectrum of ILC
  not much worse results for CLIC
- An additional source of error is knowledge of background

100 MeV is (conservative) estimate of expected precision

Brief reminder on results III – (CP conserving) elw. Couplings (arXiv:1307.8102)

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings



- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})

  Disentangling of couplings for ILC

  One variable at a time For LHC

- However LHC projections from 8 years old study

- Strong encouragement to update these numbers!

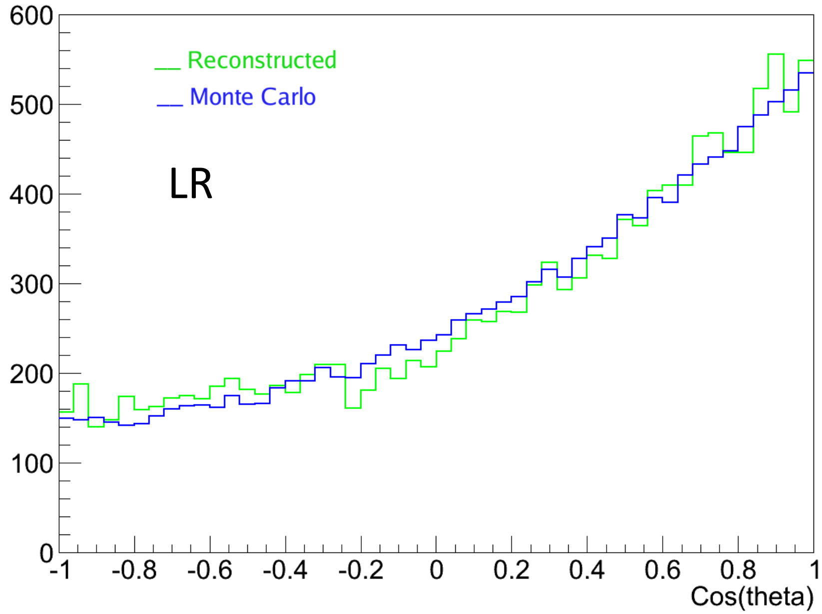
  First step is Phys. Rev. Lett. 110 (2013) 172002 by CMS

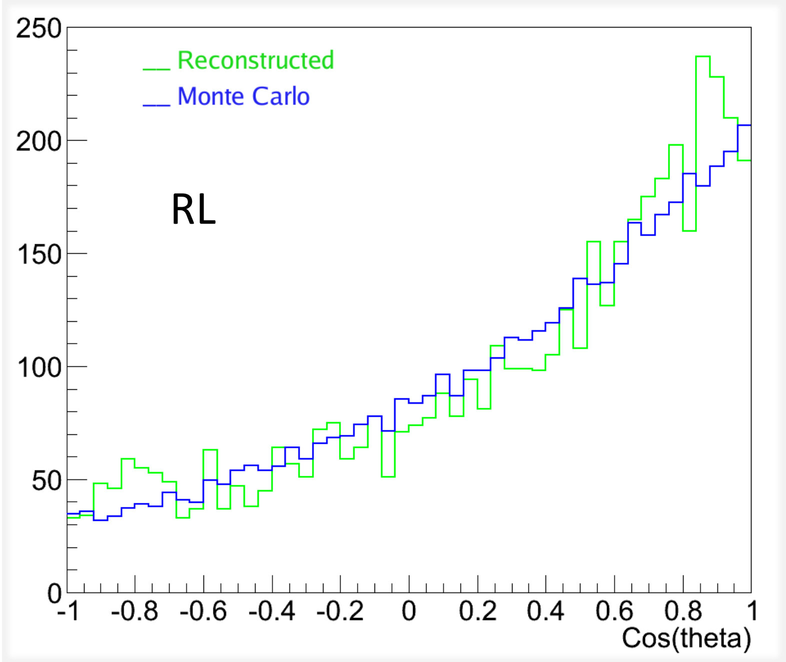
- Potential for CP violating couplings at ILC under study

ILC will be indeed high precision machine for electroweak top couplings

Brief reminder on results IV – AFB fully hadronic (Benchmark analysis)

Charge: Repetition of one LOI analysis
Fully hadronic channel, full polarisation eLpR





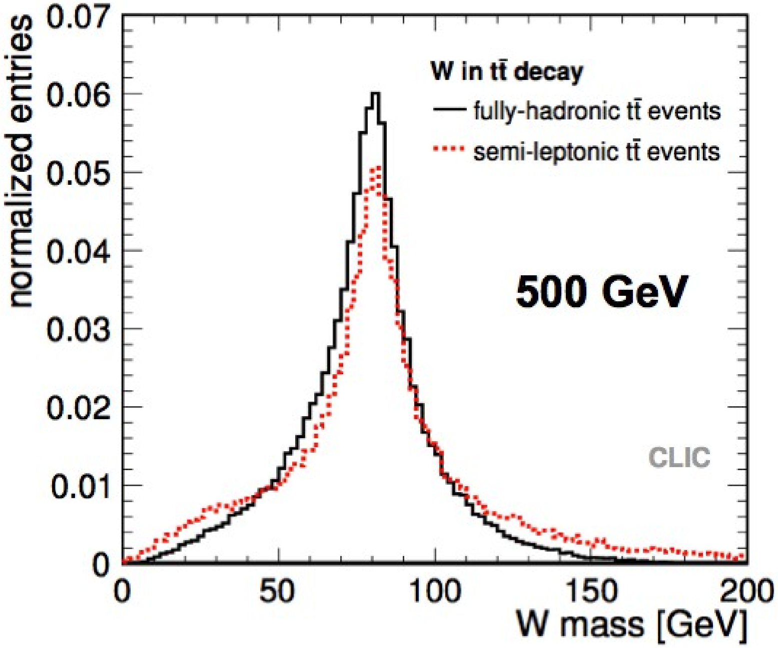
$P(e^-)$, $P(e^+)$	$(A^t_{FB})_{gen.}$	A^t_{FB}	$(\delta_{A_{FB}}/A_{FB})_{stat.}$ [%]	$(\delta_{A_{FB}}/A_{FB})_{syst.}$ [%]
−80%, +30%	0.355	0.344	2.9	0.8
+80%, −30%	0.438	0.443	3.2	0.3

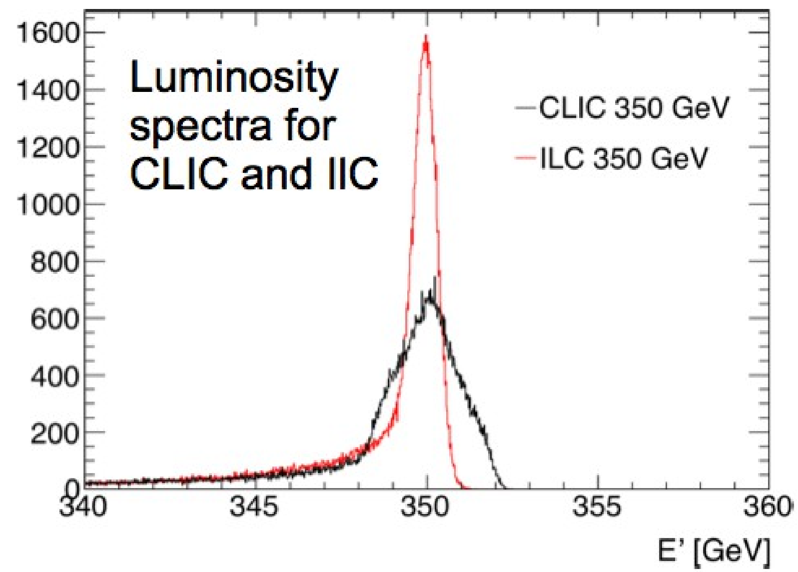
SiD: 0.371

SiD: 0.441

Main issues for top mass measurements

From P. Roloff's talk at eps



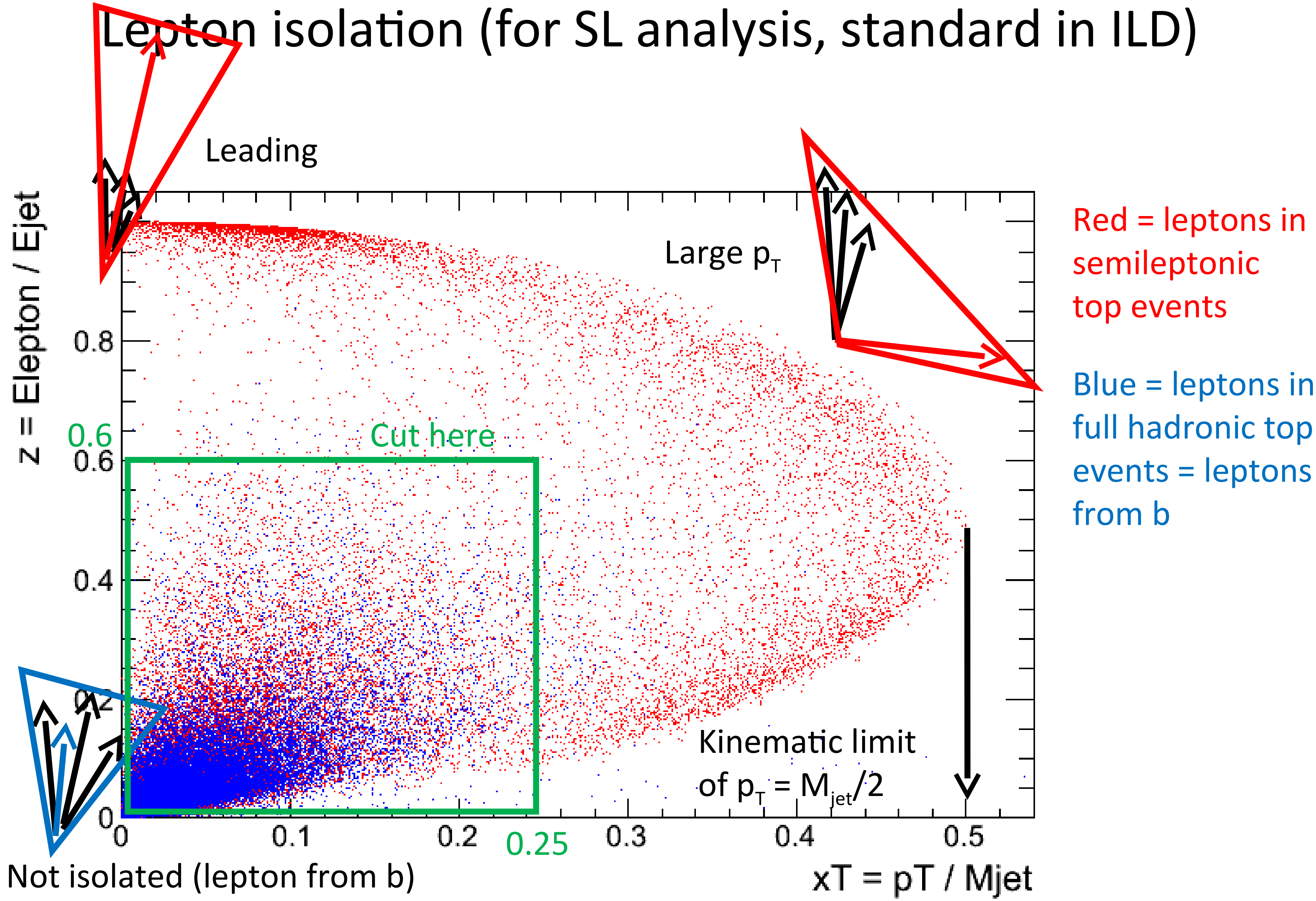


- Width of W peak
- Jet clustering more important Than actual PFLOW

Mainly important for continuum analysis

- Lumi spectrum (maybe one of the biggest Impact on threshold scan) May require comtrol of Bhabha electrons In Central Tracker

Lepton isolation (for SL analysis, standard in ILD)

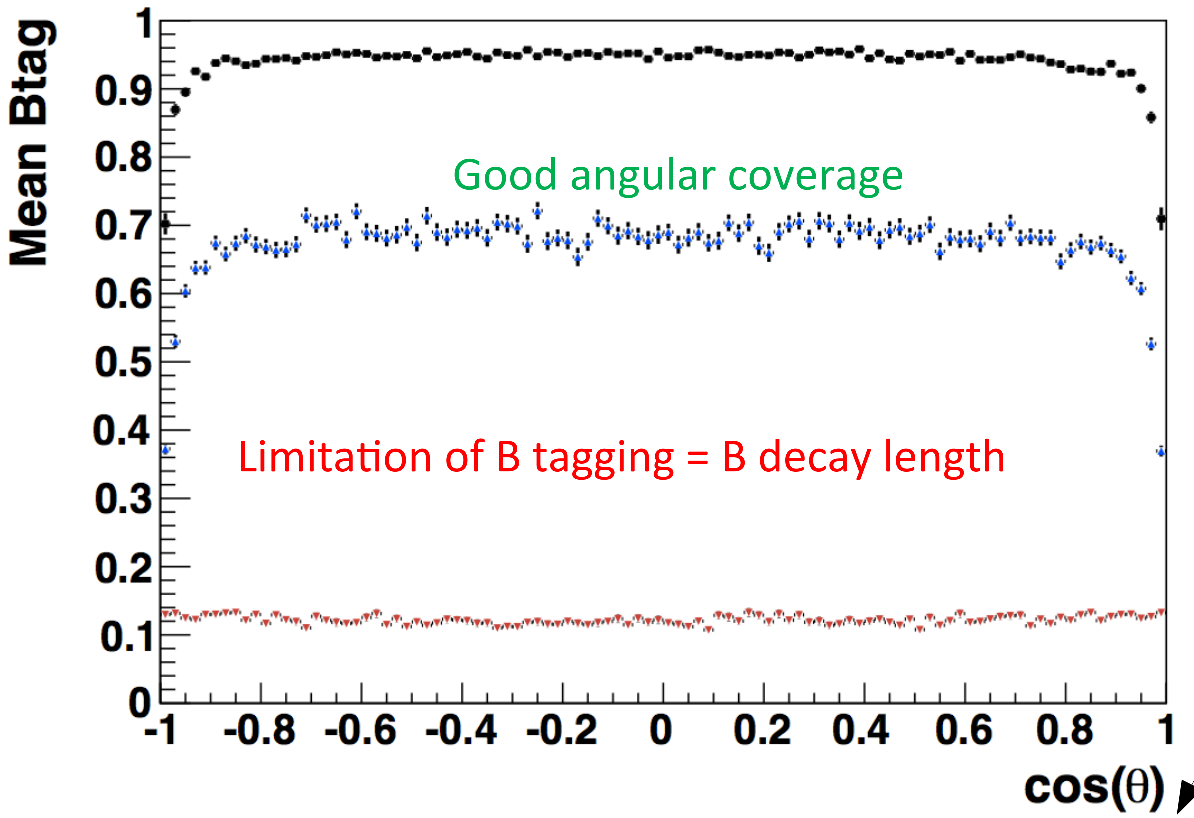


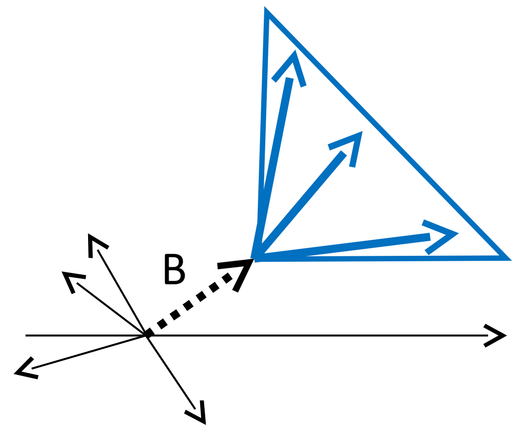
Efficiency to find decay lepton: ~85% (e mu only), ~70% (e, mu, tau)

Remark: Top mass analysis uses cone to isolate leptons

B tagging

- Vertex detector → measure offset, multiplicity and mass of jets to separate b from c decays





- 4 jets
- 2 highest Btag = b_1 & b_2
- 2 "light" jets = W

Polar angle of b-jet

Clean ee environment allow for efficient b-tagging
-> b-charge measurement later

Elements of top quark reconstruction

- Top quark reconstruction by combining W and b candidates to minimise e.g.

$$d^2 = \left(\frac{m_{cand.} - m_t}{\sigma_{m_t}}\right)^2 + \left(\frac{E_{cand.} - E_{beam}}{\sigma_{E_{cand.}}}\right)^2 + \left(\frac{p_b^* - 68}{\sigma_{p_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} - 0.23}{\sigma_{cos\theta_{bW}}}\right)^2$$

- Main backgrounds
  - Major background = other top channels
  - WW → no b quark
  - bb → simple topology

Further cuts against background:
Cut based: Jet Thrust < 0.9, mass of hadronic final state, mass windows for top and W mass
Alternative: Binned likelihood technique

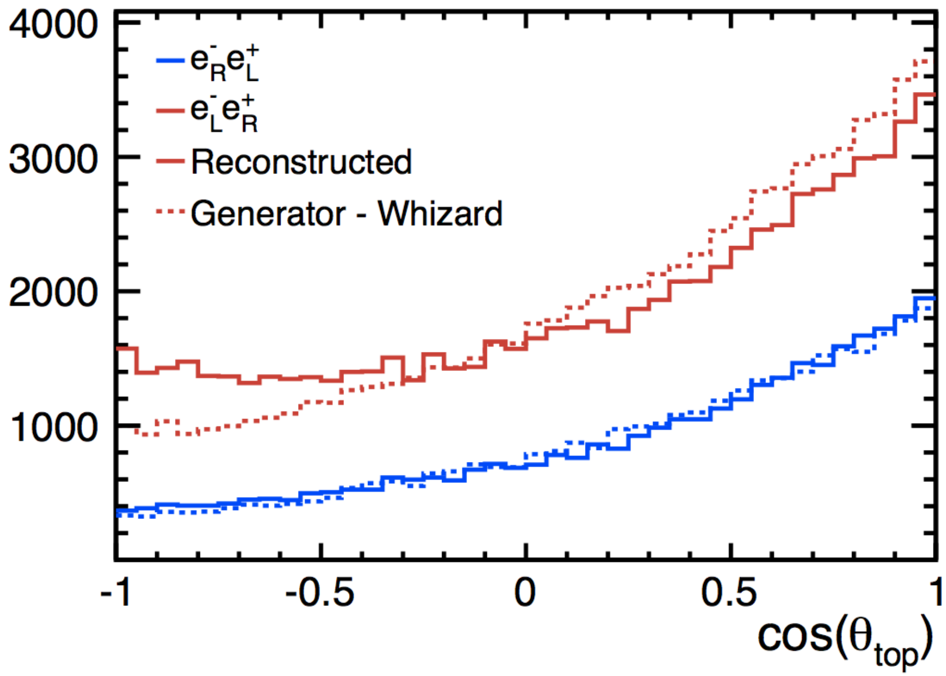
- Total selection efficiency: ~55% for semi-leptonic events, ~20%-30% for fully hadronic decays

Remaining background almost negligible!

Remark: Selection efficiency depends also on purpose of analysis
e.g. Top mass would preferably select in tt peak and discard tau events from analysis

High selection efficiencies lead to statistical uncertainties of order of 1-2% for relevant observables

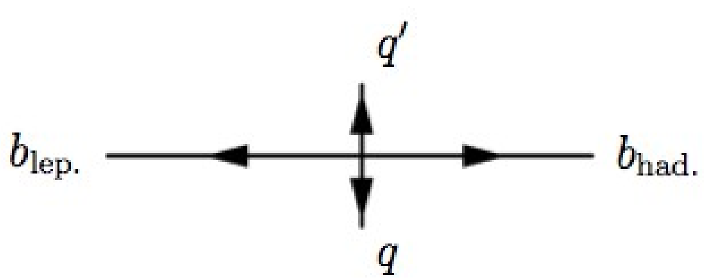
Reconstruction of top quark production angle



Ambiguities in case of **left** handed electron beams

Precise reconstruction of theta_top in case of **right** handed electron beams

Precise measurement of polar angle
=> Accuracy on A_{FB} ~ 1-2%

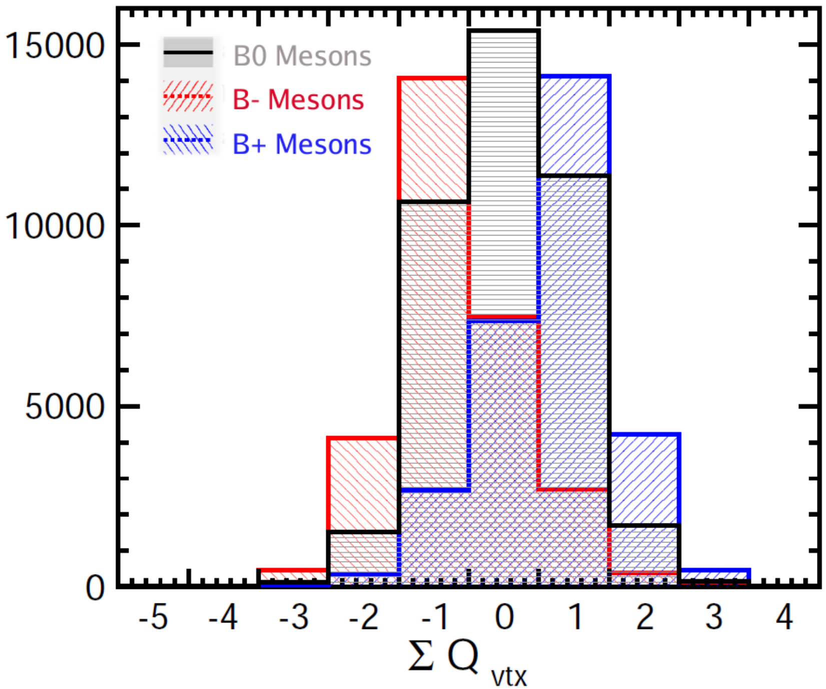


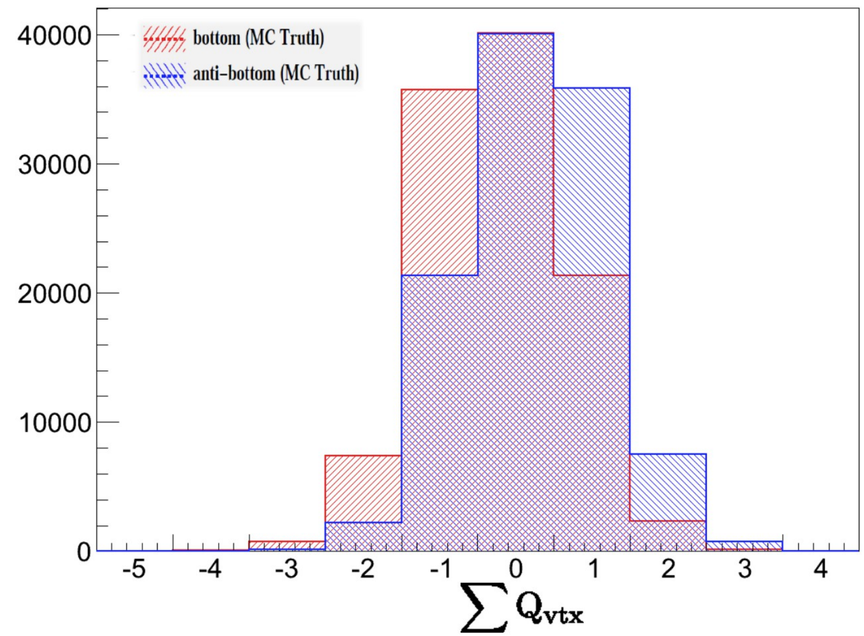
Left handed top quarks
- top quark direction from hadronically decaying top (b+W)
- V-A structure of ttX vertex leads to soft W and hard b-quarks

=> Wrong association leads to flip of top direction by pi

Remedies to address ambiguities: Select cleanly reconstructed events by kinematic fit or Chi2 analysis (so far applied, penalty on selection)
Measure the b quark charge
("Golden way", to be pursued further)

Measurement of b quark charge





- Vertex charge measurement mandatory for fully hadronic top decays
- LC vertex and tracking system allows for determination of b-meson (b-quark) charge
  B-quark charge measured correctly in about 60% of the cases
  Can be increased to 'arbitrary' purity on the expense of smaller statistics
- `LCFIPlus` package not yet optimised for vertex charge measurement

Optimisation of b-quark charge is major topic for future studies

Potential systematic errors

Experimental only:

- Luminosity:

Value: Critical for cross all section measurements

Expected precision 0.1% @ 500 GeV

Spectrum: **Critical** for top threshold mass

- Beam polarisation: Critical for asymmetry measurements

Expected to be known to 0.1% for e- beam and 0.35% for e+ beam

- (angular) Migrations/Ambiguities: Critical for AFB:

Need further studies

PFLOW important for selection of 'clean events' but maybe subleading w.r.t. jet clustering (as for top mass measurement)

Control of b charge is most relevant topic !!!!

- Jet energy scale: Critical for top mass determination

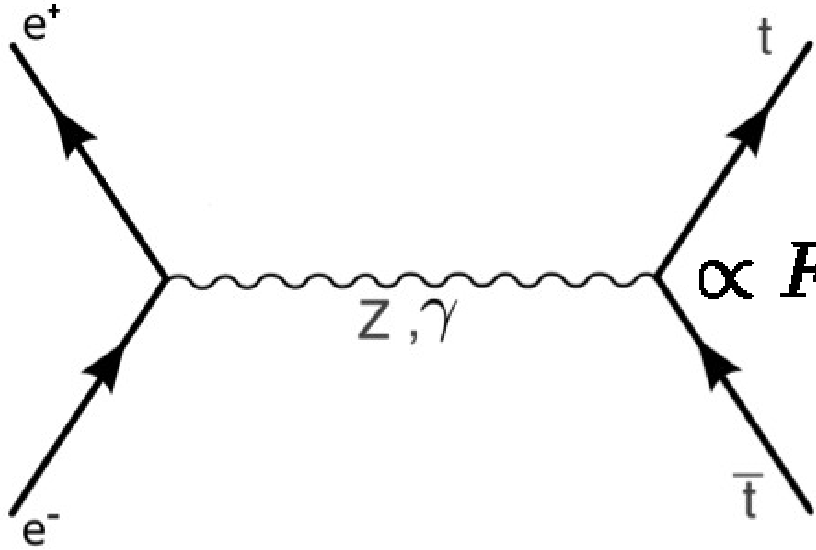
Systematic study CLIC states systematic error ~ statistical error

- Other effects: B-tagging, passive material etc.

LEP claims 0.2% error on R_b -> guiding line for LC

Backup

Top quark physics at electron-positron colliders



$\propto F_{i,V}^{X}$

- Top quark production through electroweak processes, no competing QCD production => Small theoretical errors!
- **High precision measurements**

Top quark mass at ~ 350 GeV through **threshold scan**

Polarised beams allow to test chiral structure at ttX vertex

=> Form factors F for energies > tt threshold (e.g. 500 GeV)

Systematic uncertainties: invariant mass

No full study of systematic uncertainties yet, but key issues were investigated:

• **Possible bias from top mass and width assumptions in detector resolutions:** below statistical uncertainty if varied → no bias found

• **Jet energy scale:** can be constrained in-situ to better than 1% for light quark jets using the reconstructed W mass, similar performance expected for b-jets using Z and ZZ events
→ resulting uncertainties smaller than statistical precision of the measurement

The interpretation of the measurement currently leads to theoretical uncertainties large compared to the experimental error

Systematic uncertainties: threshold scan

In addition to the theory normalisation uncertainty other sources of systematic uncertainty were studied:

- **Shift of measurement points to higher energies by 0.5 GeV:** results unchanged → precision of LHC sufficient to define range

- **Normalisation of non-$t\bar{t}$ background**: 5% variation leads to 18 MeV shift in top mass

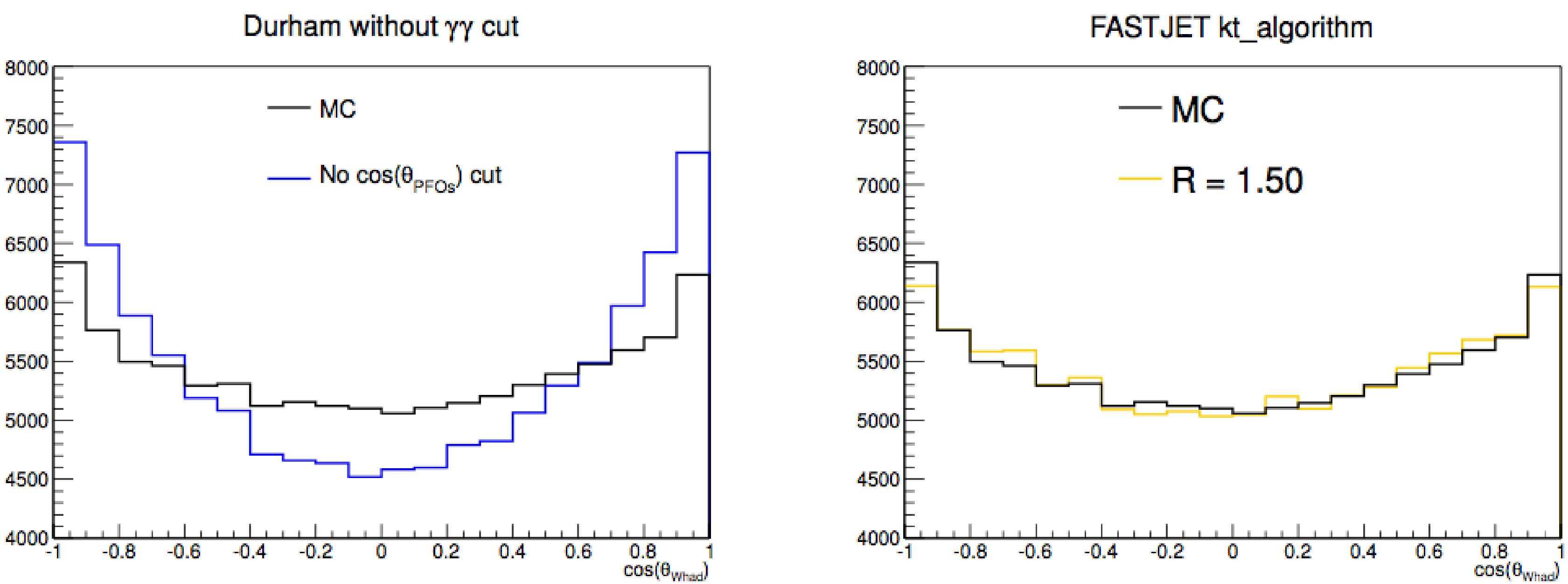
- **Beam energy:** 10^{-4} uncertainty on the centre-of-mass energy leads to a 30 MeV uncertainty on the mass

- **Luminosity spectrum:** 20% uncertainty of the RMS width of the main luminosity peak leads to 75 MeV uncertainty on top mass, realistic studies of the uncertainties on the CLIC luminosity spectrum ongoing

Discussion of pile up

- Main source of pile up: $\gamma\gamma$ -> hadrons
  ILC about 1.7 evts. / bunchXing (including muons)

Study different jet algorithms: Example polar angle of W boson



(a) Durham   (b) k_t, $R = 1.5$

- “Traditional” e+e- jet algorithm fails to remove hadron background
- Successful removal using kT algorithm (hadron collider algorithm)

Result shown for ILC but similar result for CLIC energies

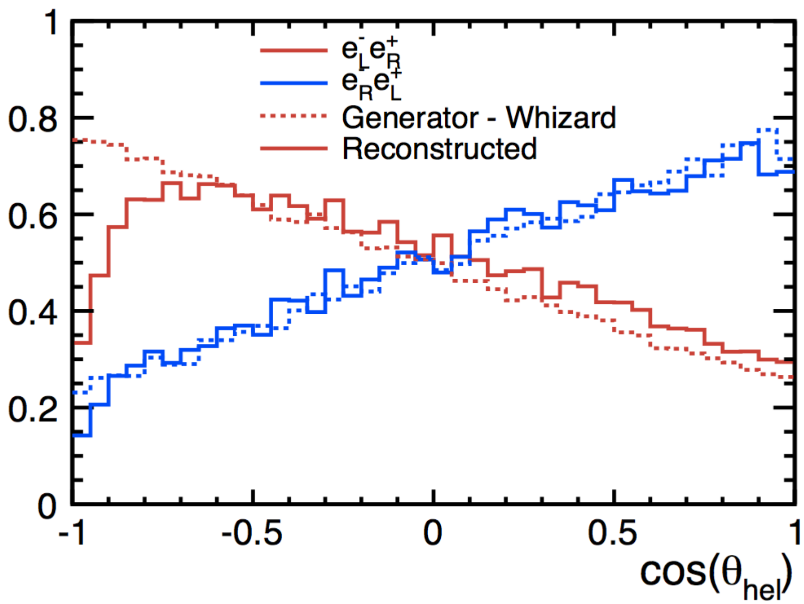
Measurement of top quark polarisation

Measure angle of decay lepton in top quark rest frame
Lorentz transformation benefits from well known initial state
(N.B. : Proposal for hadron colliders applied to lepton colliders)

Differential decay rate

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_\ell} = \frac{1+\lambda_t cos\theta_\ell}{2} \quad \text{with } \lambda_t = 1 \text{ for } t_R \text{ and } \lambda_t = 1 \text{ for } t_L$$

Slope measures fraction of tR,L in sample



- Measurement of decay lepton almost 'trivial' at LC
  High reconstruction efficiency for leptons
- Reconstructed slope coincides with generated slope

Slope can be measured with an accuracy of about 2%

LC Detector Requirements

Track Momentum: $\sigma_{1/p}$ **< 5 x 10^{-5}/GeV** **(1/10 x LEP)**

(e.g. Z-Mass Measurement with charged Leptons)

Impactparameter: σ_{d0} **< 5 $\oplus$ 10/(p[GeV]sin$^{3/2}\theta$) μm** **(1/3 x SLD)**

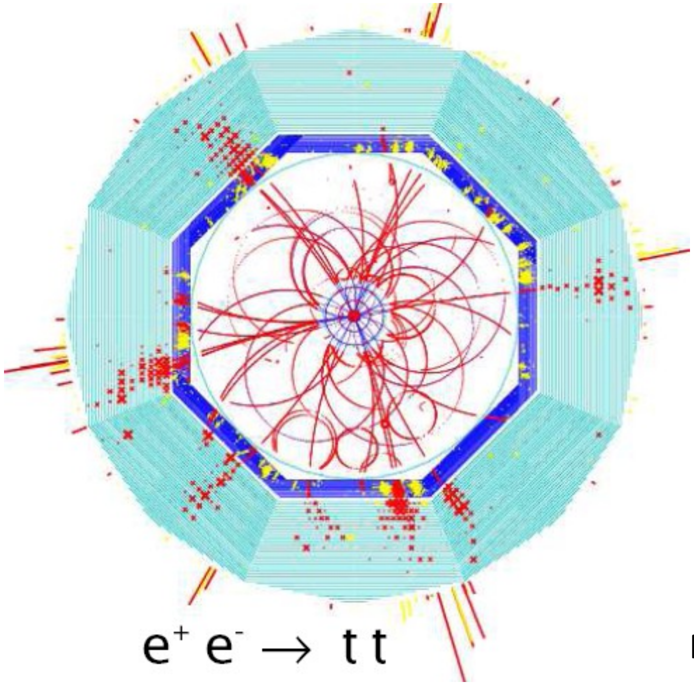
(c/b-tagging)

Jetenergy : **dE/E = 3-4%**

(Measurement of W/Z Mass with Jets)

Hermeticity : θ_{min} **= 5 mrad**

(to detect of events with missing energy e.g. SUSY)



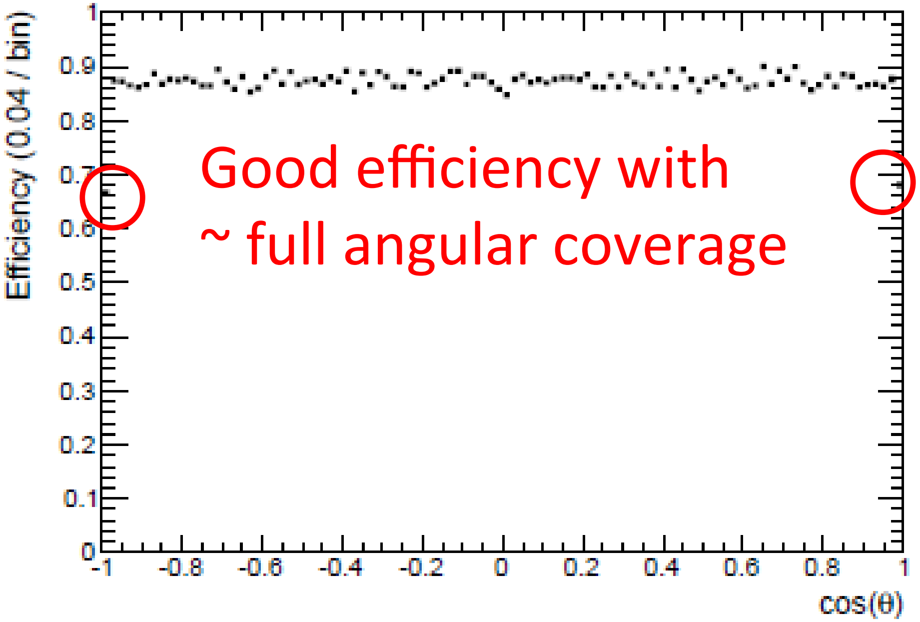
$e^+ e^- \rightarrow t t$

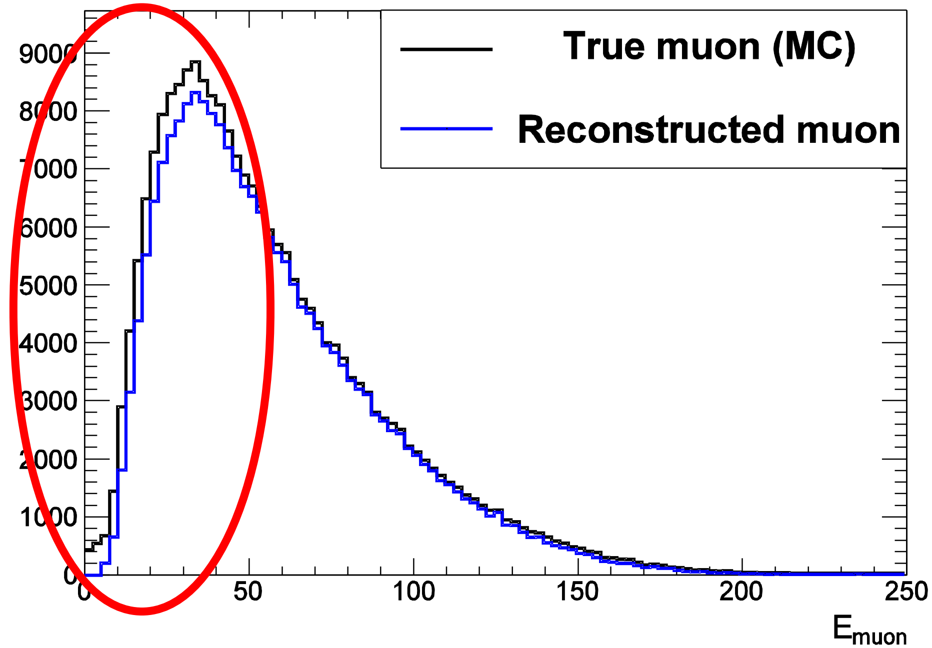
Events with large track multiplicity and a large number of Jets (6+) are expected.

Therefore:

- **high Granularity**
- **good track Measurement**
- **good Track Separation**
- **"Particle Flow" detectors**

Efficiencies : angular and energetic





- Effiencies under control :
  - Tracking worse in very forward regions
  - Leptons with small energies are suppressed by isolation cuts

Efficiency = 85%
Contamination = 0.3%

Semi-leptonic top decays

- tt→bbqqlv (l=e,μ)
  - Need at least 1 b jet (vertex)
  - Find 1 lepton (tracking)
- Method :
  - Find a lepton
  - Force 4 jets clustering

    Remark : Current studies rather with traditional

    Durham
  - Find at least 1 (or 2) b jets
  - Form the top with one b jet + 2 non-b jets left,
    lepton charge gives the opposite sign of the top