Measuring Tops at Future Colliders

Top & Detectors Working Group

Snowmass Energy Frontier

BNL Workshop

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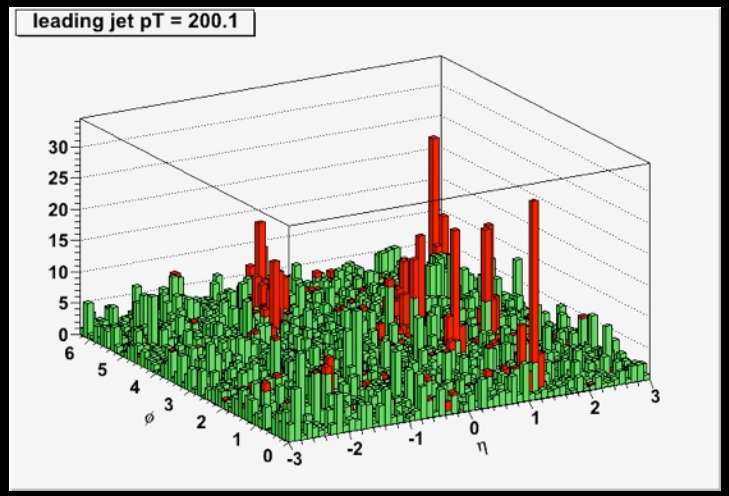
Challenges

- Hadron colliders
  - shorter-term (SLHC): very high pileup (~100)
  - longer-term (LHC33,VLHC): very high energy (p_T(top) ~ few TeV)
- Lepton colliders
  - how to maximize precision of kinematic reco?

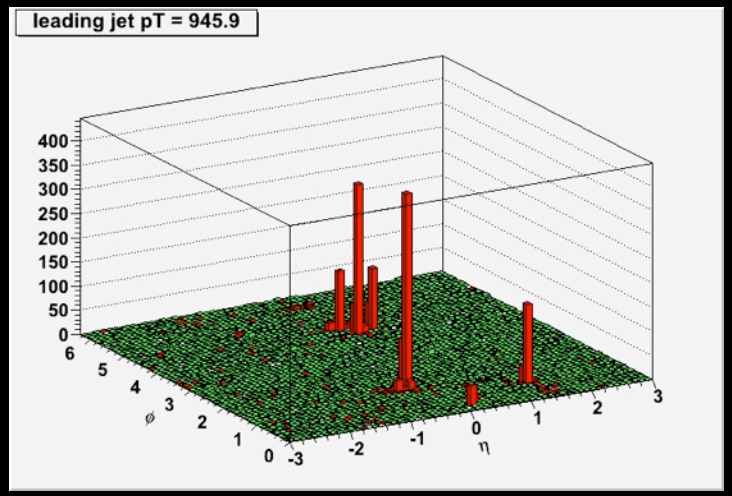
Hadron Colliders

Top Quarks in the Weeds

low-p_T top pair



high-p_T top pair

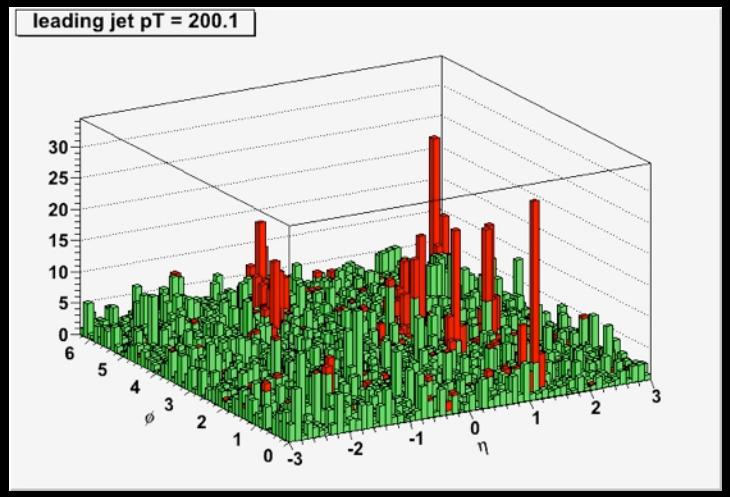


* Sergei's samples, 140 pileup events
(particle-level, not Delphes)

Pileup Mitigation Strategies

- Area corrections
  - subtract uniform “noise pedestal” from each jet
- Exploit tracking
  - can solve O(1) fraction of the problem
- Jet grooming / substructure
  - trimming, filtering, pruning, etc
  - should work great for high-p_T at least

full pileup



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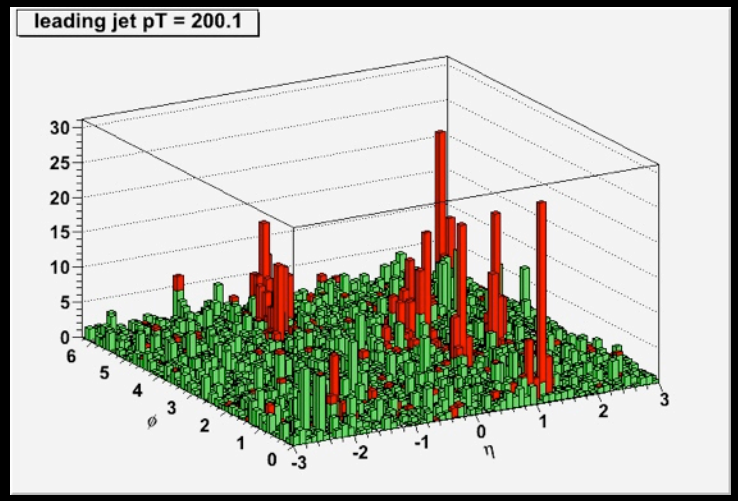
pileup neutrals only



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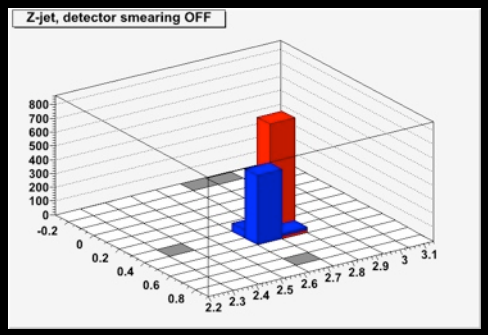
Exp Issues at Very High Energy

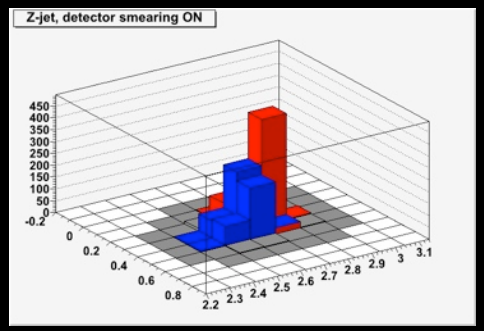
- Semilep decays: "isolation" tricky
  - exploit $m_t >> m_b$, m_c
  - muons straightforward, electrons hopeless?
- b-tagging
  - tiny opening angles, high track density
  - p_T ~ TeV: B-hadrons decay inside of tracker
  - semi-muonic decays should remain robust (BR~20%)
- Detector segmentation an unavoidable limitation
  - mitigated by particle flow (CMS), topo-clusters + tracks (ATLAS)
  - what to do for simple Snowmass detectors?

Theorists' ECAL Substructure

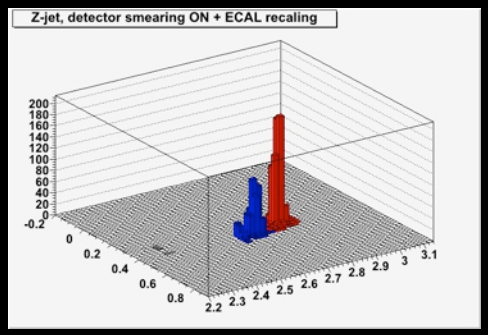
1.5 TeV Z-jet
perfect HCAL ("Delphes")



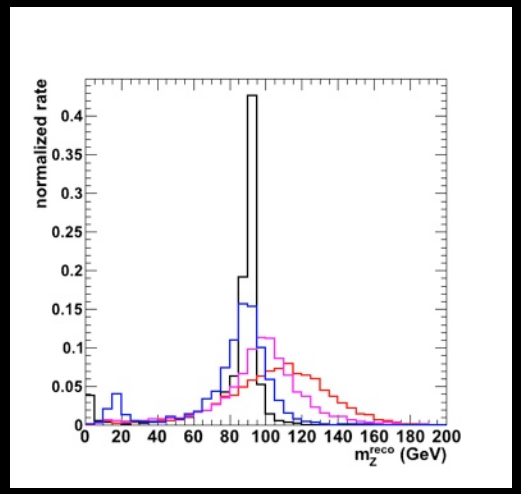
+ spatial smearing



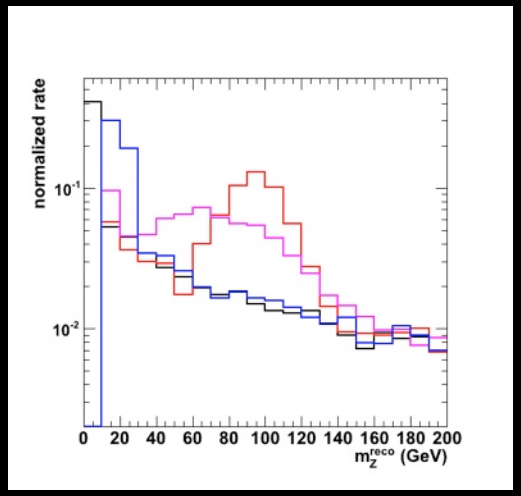
ECAL cells with
energy rescalings



1.5 TeV Z-jets (BDRS)



1.5 TeV QCD-jets



Particle-level
Raw calorimeter
Naive ECAL rescale
Minijet ECAL rescale

*also validated on boosted fully-hadronic h→WW

Other Issues at Very High Energy

- Top FSR
  - radiates gluons, just like a light quark or b-quark
  - how polluted is the "decay cone" ($\Delta R \sim m_t/p_T$)?
- Weakstrahlung
  - W/Z bosons "radiated like photons" from light quarks
  - problem for both semilep and hadronic decays
- Tops in the parton shower
  - analogy: for b-quarks inside high-p_T jets at LHC, radiative production is more important than prompt
  - another efficient way to produce W bosons in jets

Ideas for Snowmass Studies

- Address top-tagger robustness under extreme conditions
  - very high pileup
  - very high energy
- Obtain estimates of how backgrounds scale with energy
  - novelties like weak radiation

Questions

- Which top-taggers?
  - e.g., CMS-tagger and HEPTopTagger (retrofitted with Pruning or Trimming?)
  - not planning a “BOOST” style survey
- Which detector models?
  - Delphes clearly adequate for p_T < TeV studies w/ pileup
  - can address higher-p_T spatial resolution with next-to-minimal theorists’ calorimeter and/or Delphes particle flow
- Which colliders?
  - LHC14, LHC33, VLHC
- Physics benchmarks from NP group?

Lepton Colliders

Disclaimer:

Will concentrate mostly on experimental aspects of studies at 500 GeV and 500 fb^{-1} if not stated otherwise

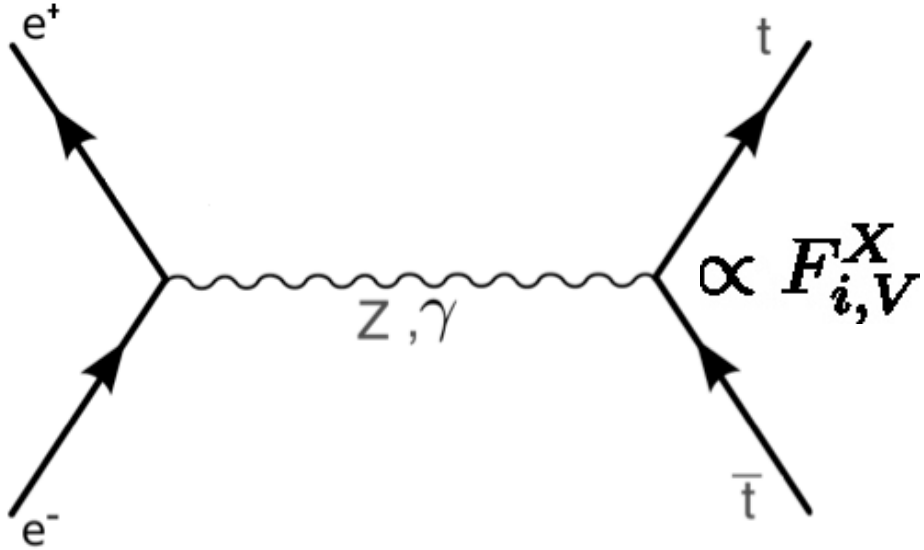
All results presented in the following are based on full simulation studies

- See also talks by Vos and Simon
- Material

LC Notes: LC-REP-2013-007 and LC-REP-2013-008
arXiv: 1303.3758

- Many methods apply also to tth (see e.g. talk by Yokoya for details)
- Lots of “Extras” slides in this talk

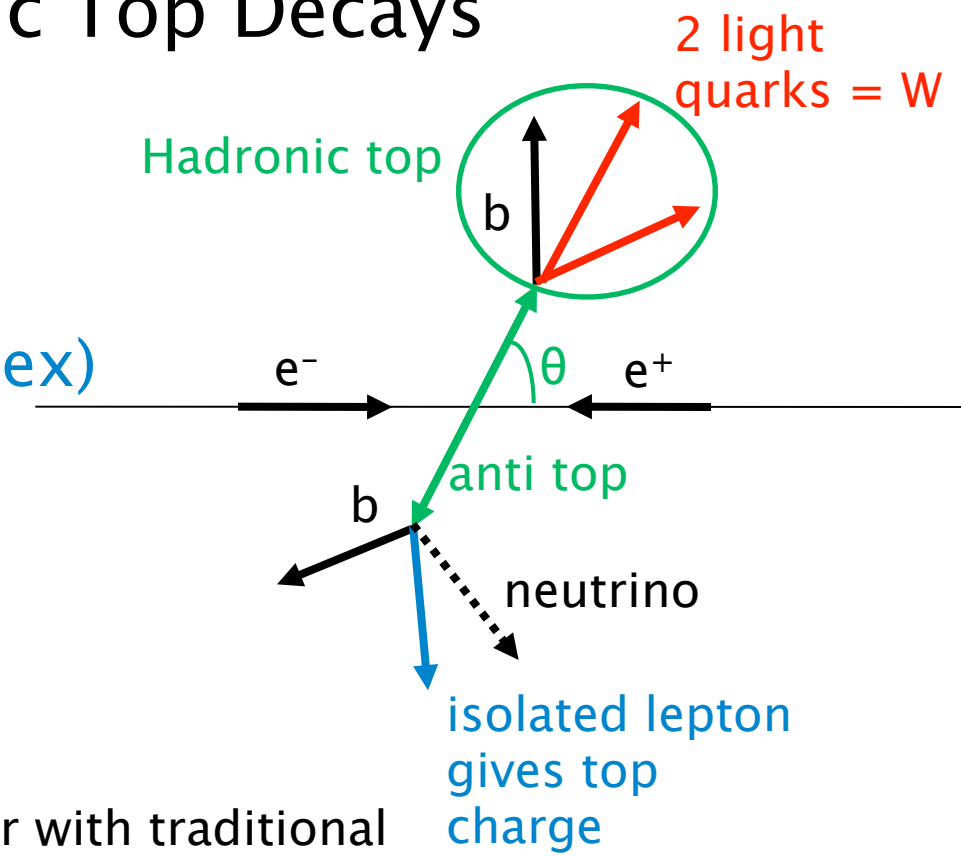
Top quark physics at electron-positron colliders



- 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** (Simon)
  Polarised beams allow to test chiral structure at ttX vertex
  => Precision on form factors F (Vos for studies at 500 GeV)

- Studies presented here deal with no or only mildly boosted tops, beta~0.7
  tth studies at 1 TeV do not reveal particular problems
- A major **difference between LC and LHC** is that an **LC** will run **triggerless**
  -> Unbiased event samples, all event selection happens off-line!

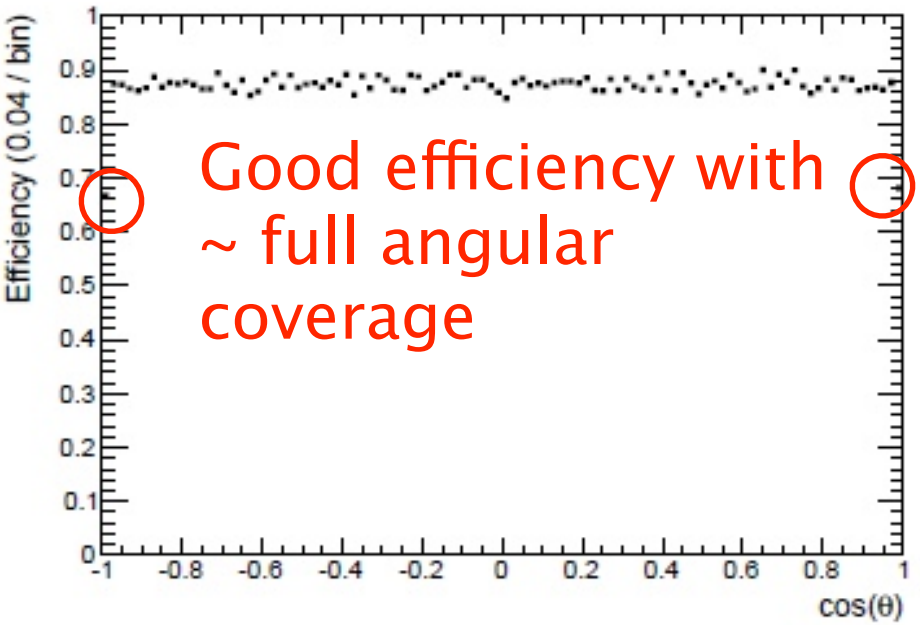
Semi-Leptonic Top Decays

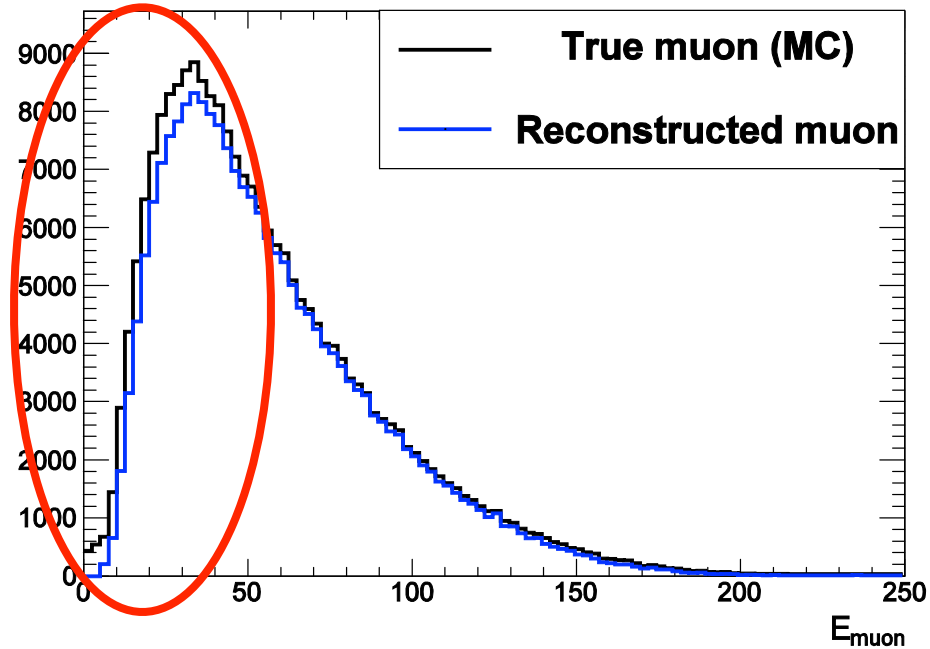


- tt→bbqqlν (l=e,μ)
  - Need at least 1 b jet (vertex)
  - Find 1 lepton (tracking)
- Method :
  - Find a lepton
  - Force 4 jets clustering

    Remark : Current studies rather with traditional Durham, alternatives ((anti) kT) are coming up !!!
  - 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

Lepton Efficiencies



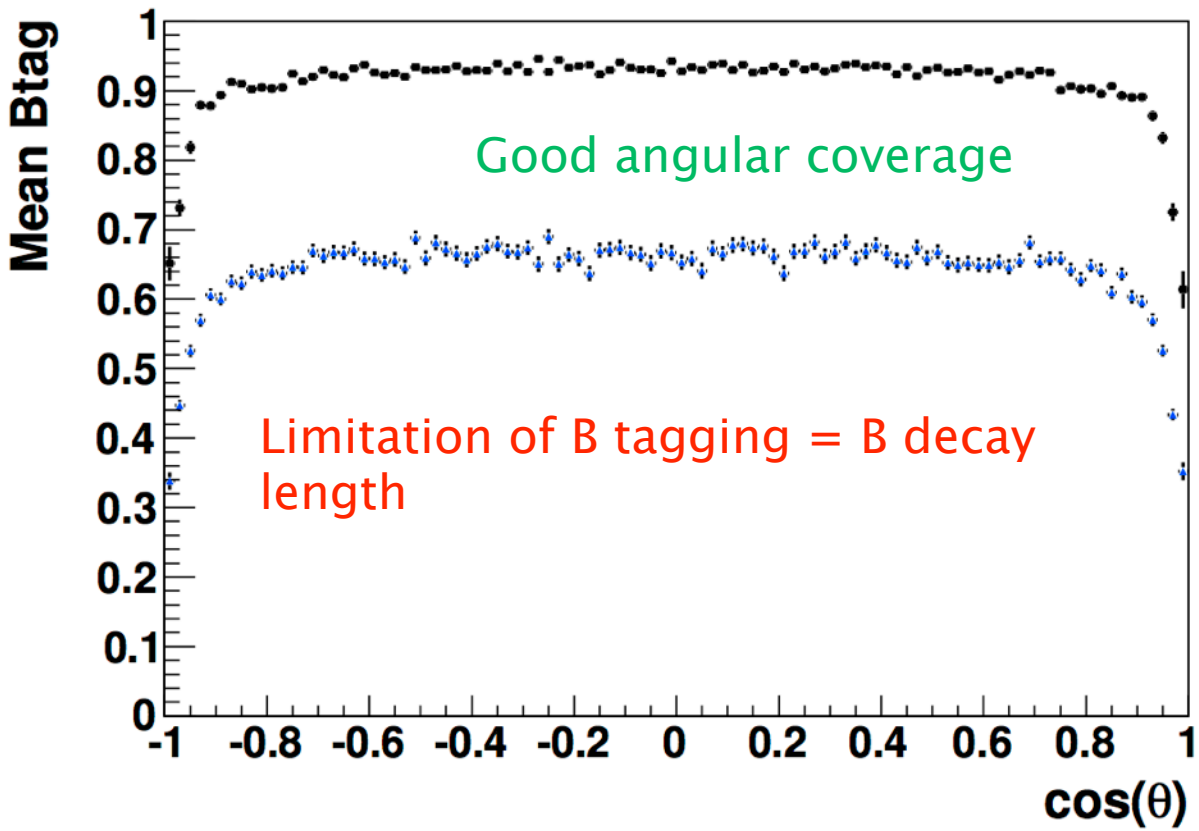


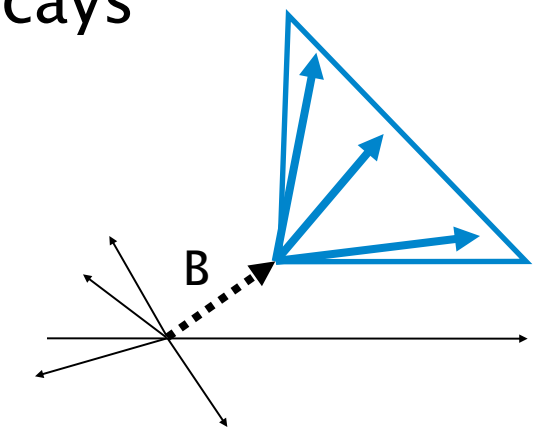
- Efficiencies under control :
  - Tracking worse in very forward regions
  - Leptons with small energies are suppressed by isolation cuts

Efficiency = 85%
Contamination = 0.3%

B tagging

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





Interaction point

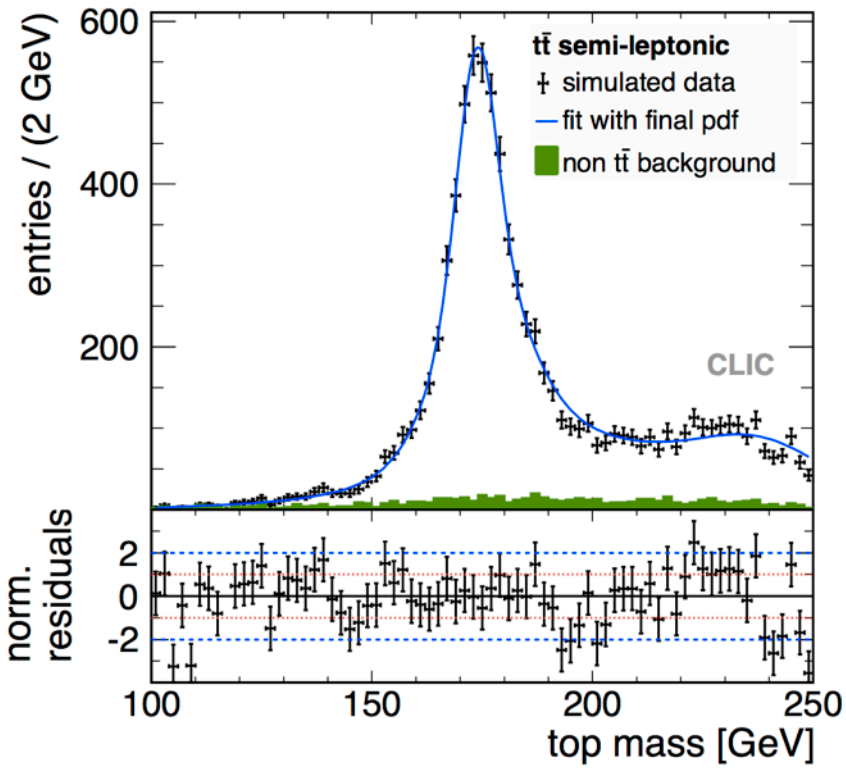
- 4 jets
- 2 highest Btag = b_1 & b_2
- 2 "light" jets = W

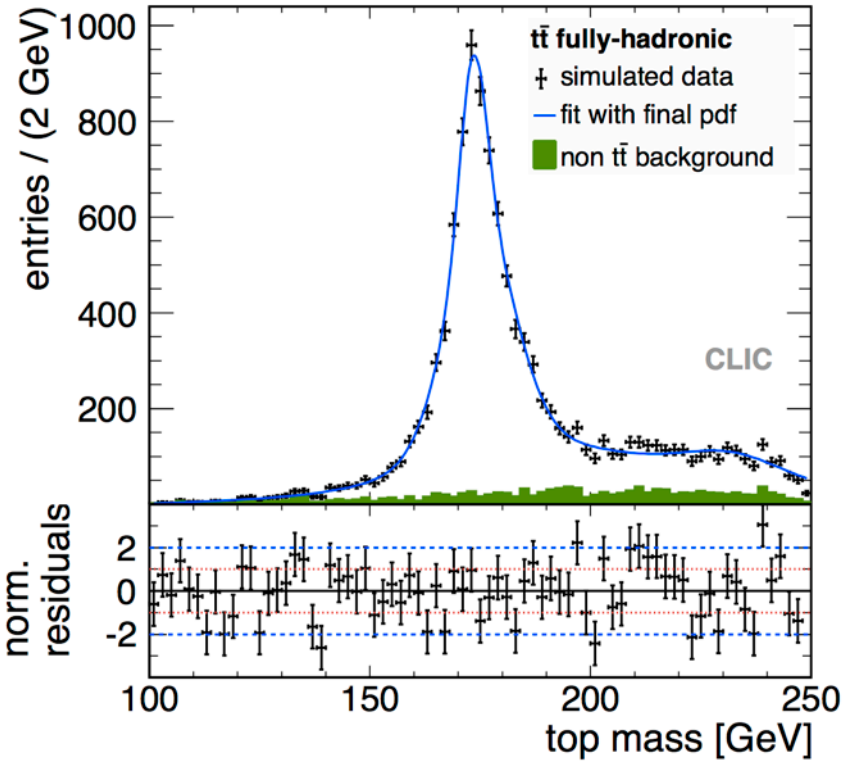
Polar angle of b-jet

Clean ee environment allow for efficient b-tagging
-> b-charge measurement later
-> Details on flavor tagging at LC see talk by Tomohiko Tanabe

Reconstructed Top Mass Spectrum

(500 GeV CLIC study but results very similar for ILC 100 fb^{-1})

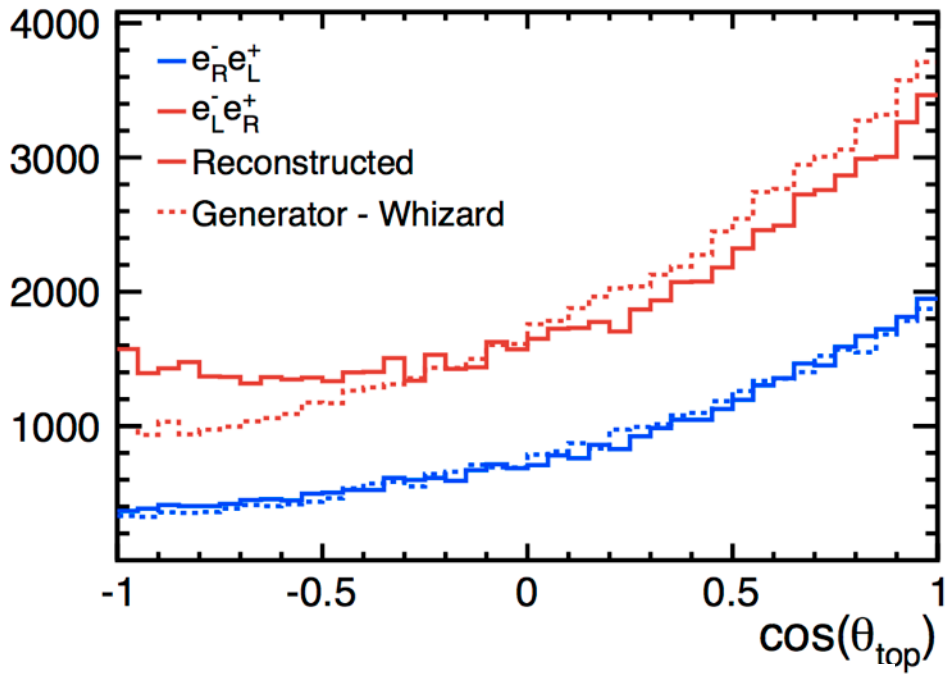




- (Almost) background free measurement of top mass
- Uncertainty on continuum top mass ~ 80 MeV

=> See talk by Simon for details

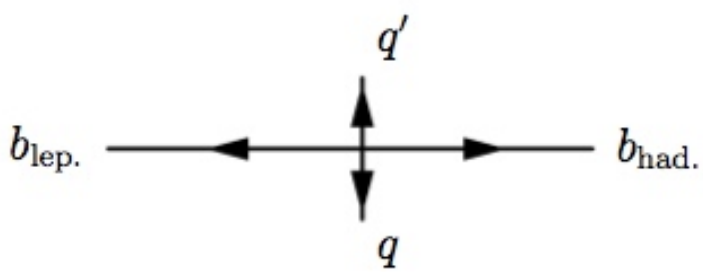
Reconstruction of top quark production angle



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

Precise reconstruction 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)
Measure the b quark charge
("Golden way", to be pursued further)

Discussion of Potential Systematic Errors

Experimental only – For theory errors see e.g. Vos

- Luminosity: Critical for cross section measurements
  Expected precision 0.1% @ 500 GeV

- Beam polarisation: Critical for asymmetry measurements
  Expected to be known to 0.1% for e- beam and 0.35% for e+ beam

- Migrations/Ambiguities: Critical for AFB:
  Need further studies but expect to control them better than the theoretical error

- 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

Extras

LC Detector Requirements

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

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

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

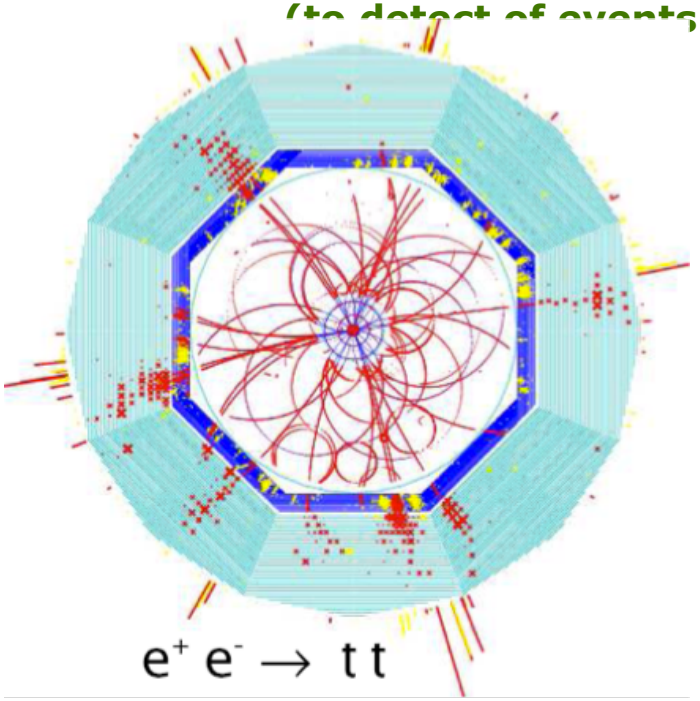
(c/b-tagging)

Jetenergy : $dE/E = 3\text{-}4\%$

(Measurement of W/Z Mass with Jets)

Hermeticity : $\theta_{min} = 5$ **mrad**

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



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**

Top quark cross section at LC

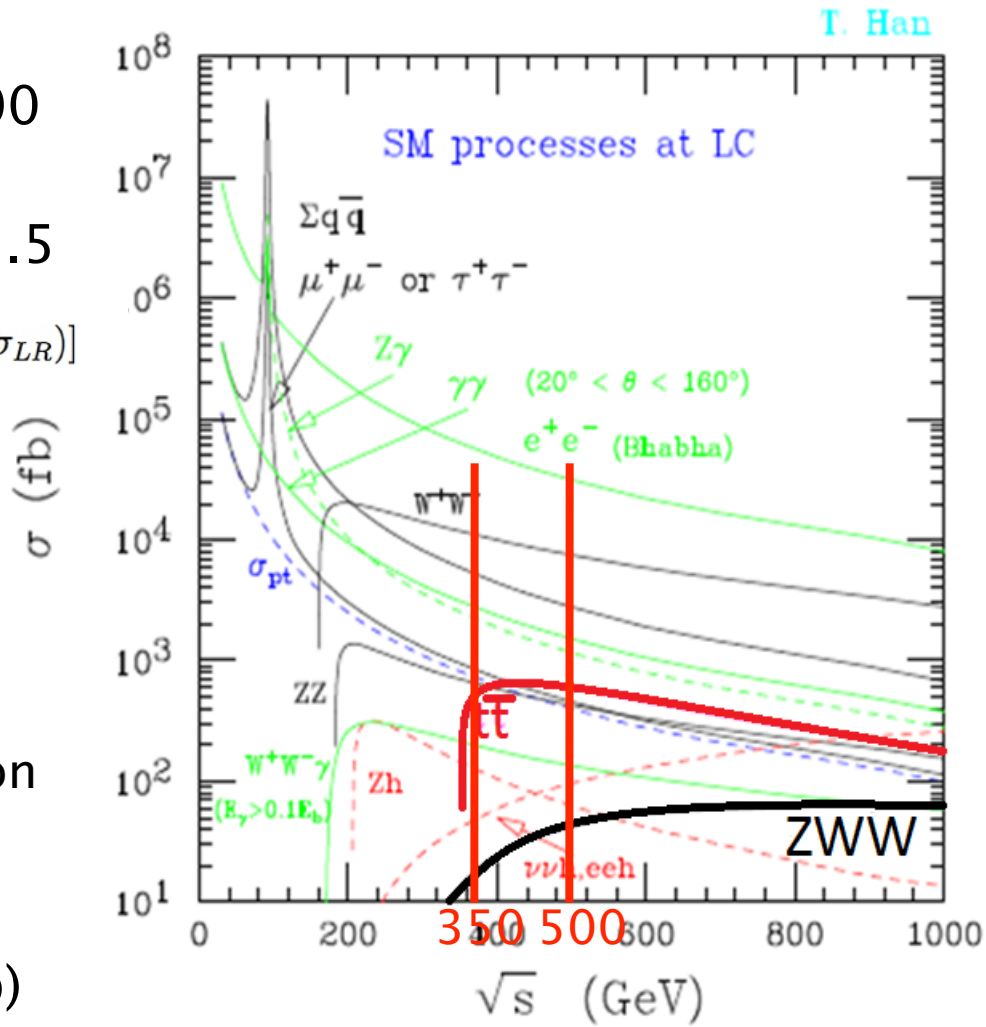
- Unpolarised σ(tt) ≈ 600 fb at 500 GeV
- Gain in statistics up to factor ~2.5

$$\sigma_{P,P'} = \frac{1}{4}\left[(1-PP')(\sigma_{LR}+\sigma_{RL}) + (P-P')(\sigma_{RL}-\sigma_{LR})\right]$$

Typical degree of polarisation :

80% for e− beam 30% for e+ beam

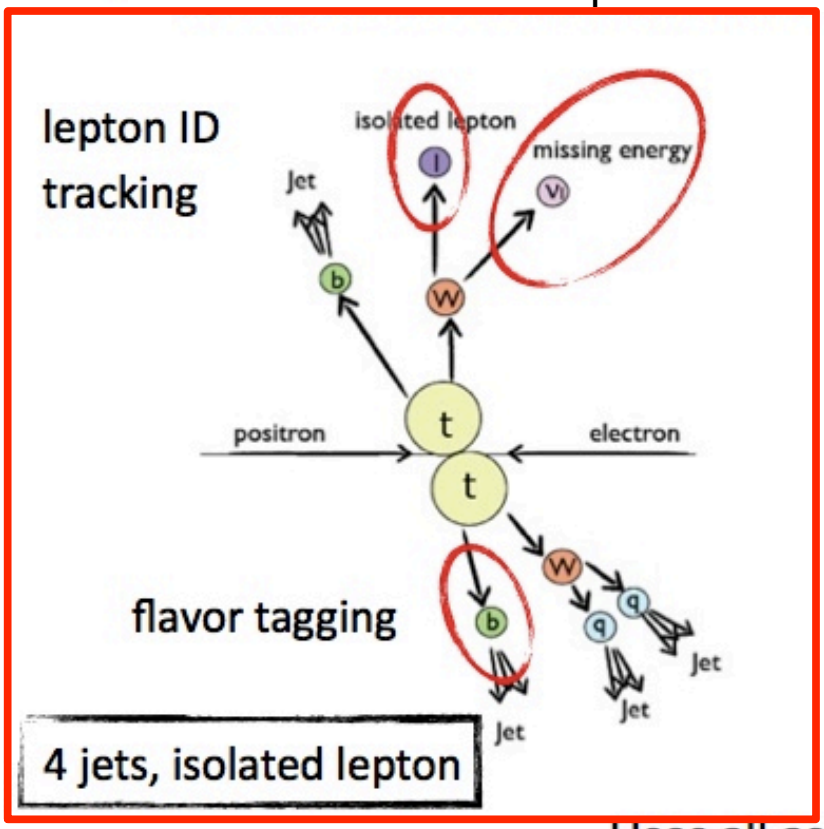
- Almost background free
  - Major background = other top channels → find 1 isolated lepton
  - WW → no b quark
  - bb → simple topology
- Major background : ZWW (Z→bb) ≈ 8 fb, same topology
  - Small but needs to be subtracted

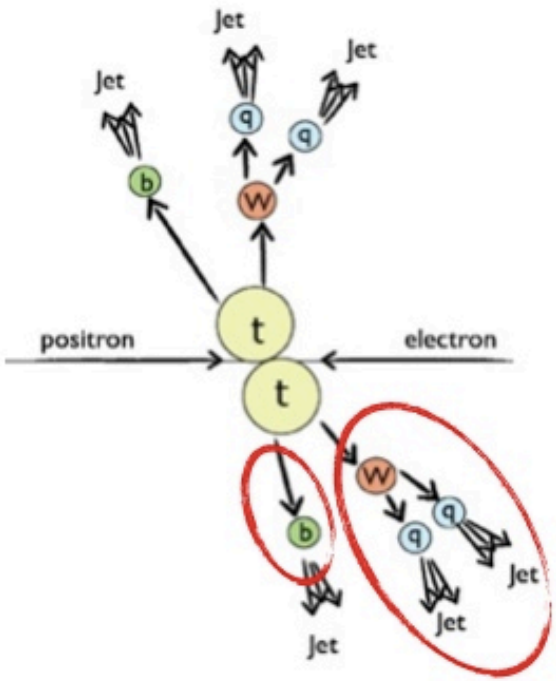


Elements of top quark reconstruction

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

Will concentrate in semi-leptonic channel



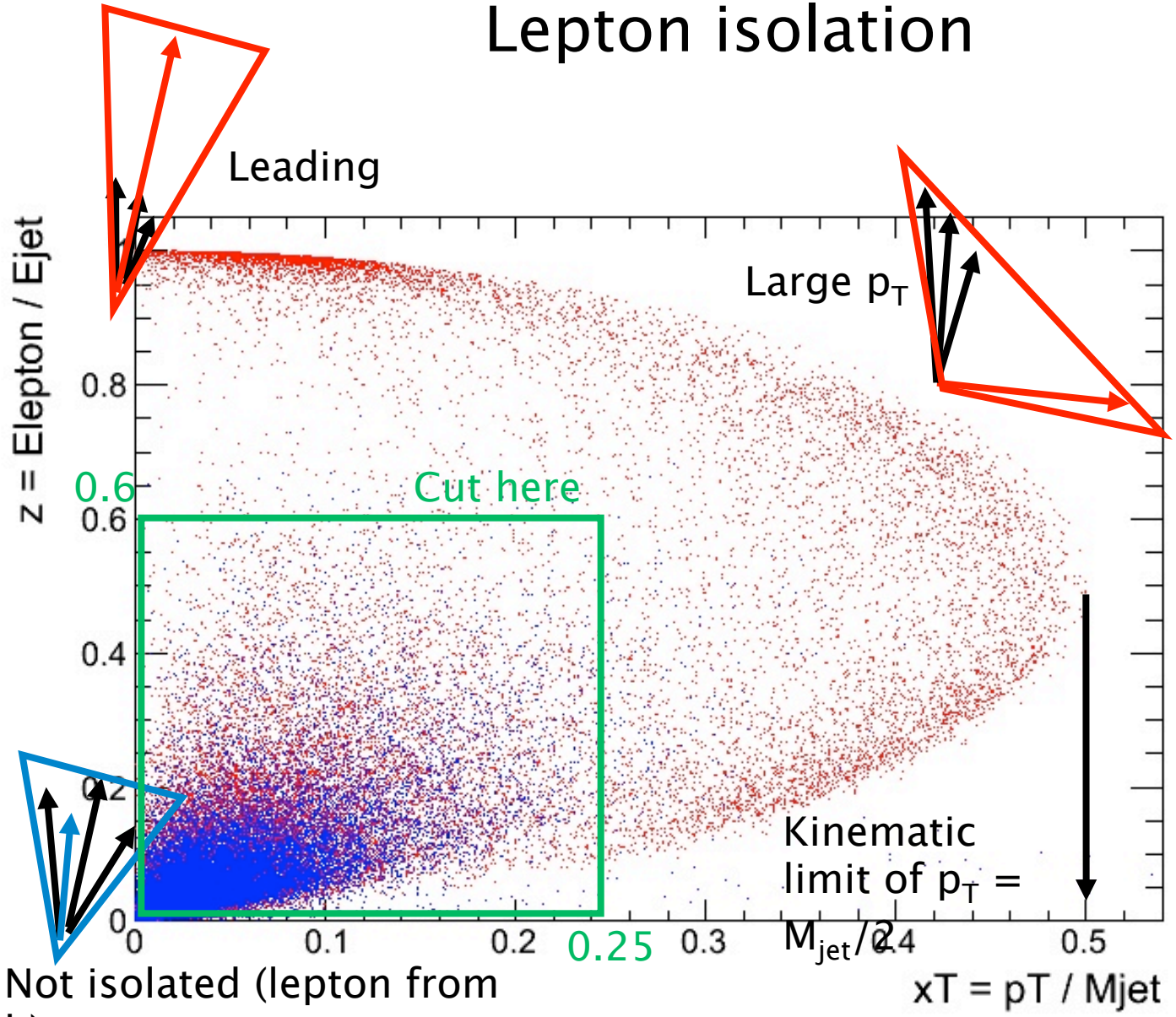


jet energy reconstruction, global event reconstruction

Uses all aspects of LC detectors!

Nice illustration stol
from Frank

Lepton isolation



Red = leptons in semileptonic top events

Blue = leptons in full hadronic top events = leptons from b

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

Efficiencies of top quark reconstruction

- Top quark reconstruction by combining W and b candidates

- Main backgrounds
  - Major background = other top channels → find 1 isolated lepton
  - 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

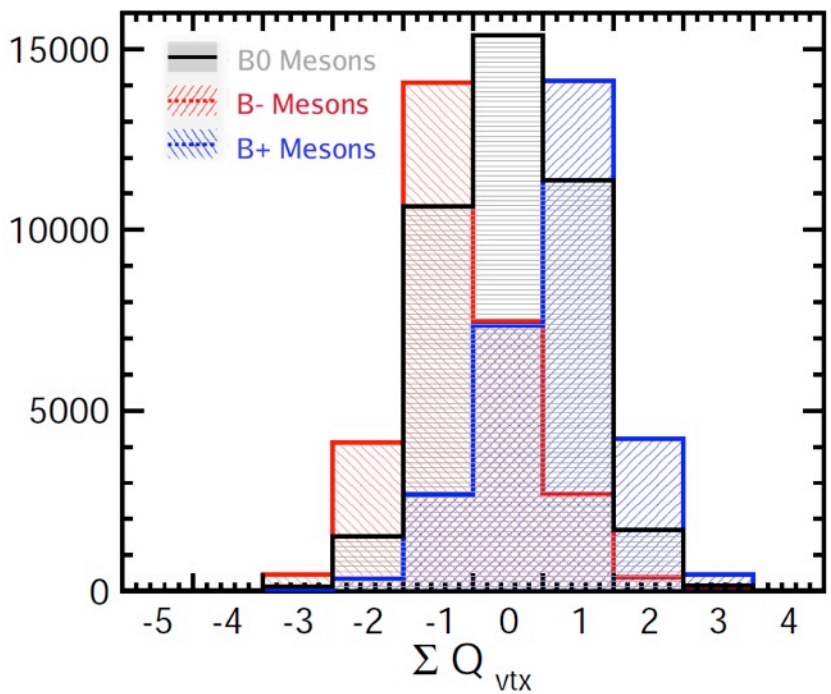
- Total selection efficiency: ~55% for semi-leptonic events, ~20%-30% for fully hadronic decays

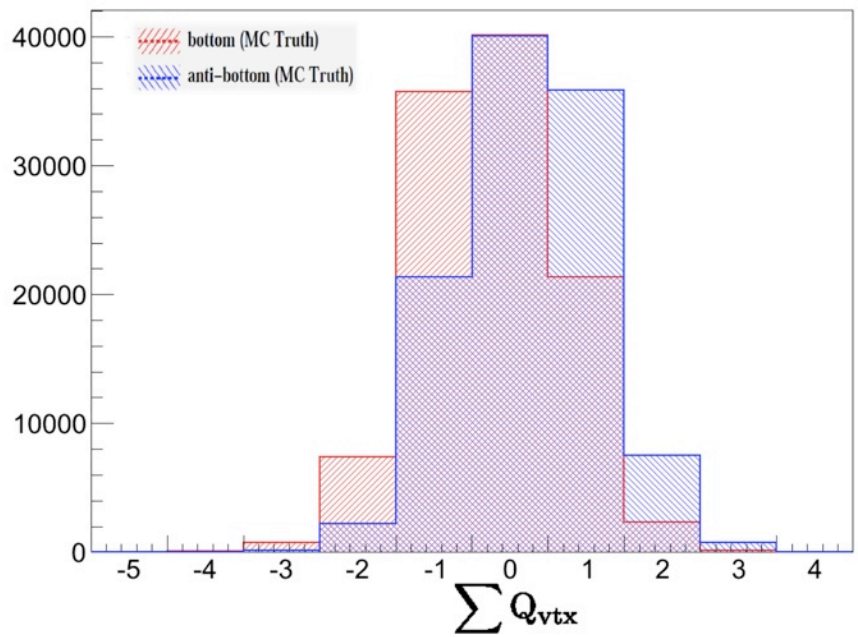
Remaining background almost negligible! -> See example for mass analysis

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

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
- `LCFIPlus` package not yet optimised for vertex charge measurement

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

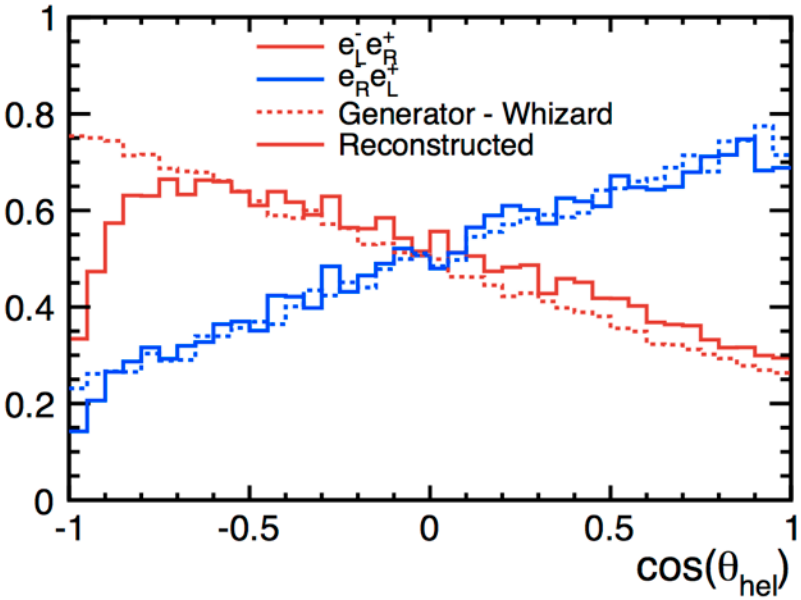
Measurement of top quark polarisation

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%