

Top quark measurements at



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Based on studies for the ILC DBD and the CLIC TDR

Remote contribution to Snowmass Pre-Meeting @ Seattle

SNOWMASS ENERGY FRONTIER WORKSHOP

June 30 – July 3, University of Washington, Seattle



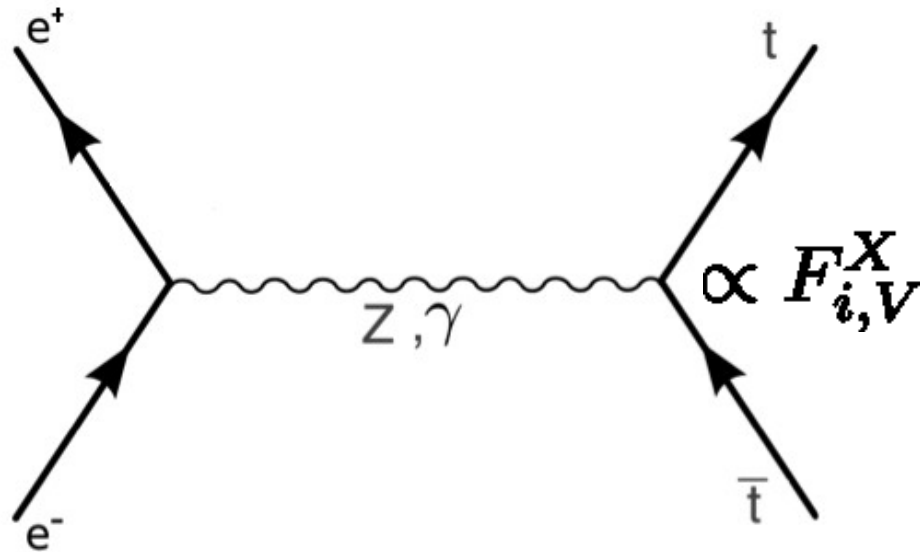
Disclaimer:

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

For the physics interpretation please see Gudi's talk in yesterday's Top lunch session

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 $t\bar{t}X$ vertex
 - => Form factors F for energies $>$ $t\bar{t}$ threshold (e.g. 500 GeV)
- Studies presented here deal with no or only mildly boosted tops, $\beta \sim 0.7$
 $t\bar{t}h$ 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!

Top quark cross section at LC

T. Han

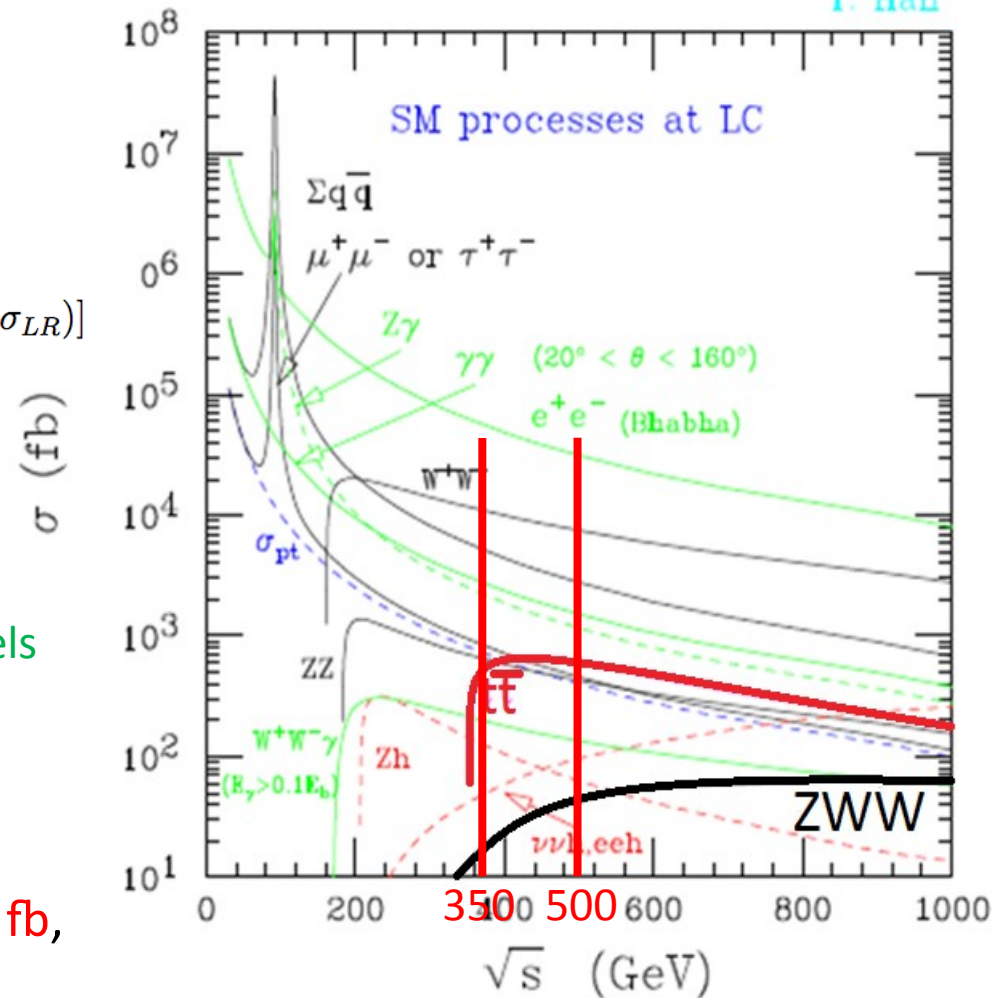
- Unpolarised $\sigma(tt) \approx 600$ fb at 500 GeV
- Gain in statistics up to factor ~ 2.5 by **polarised beams**

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

Typical degree of polarisation :

80% for e- beam 30% for e+ beam

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

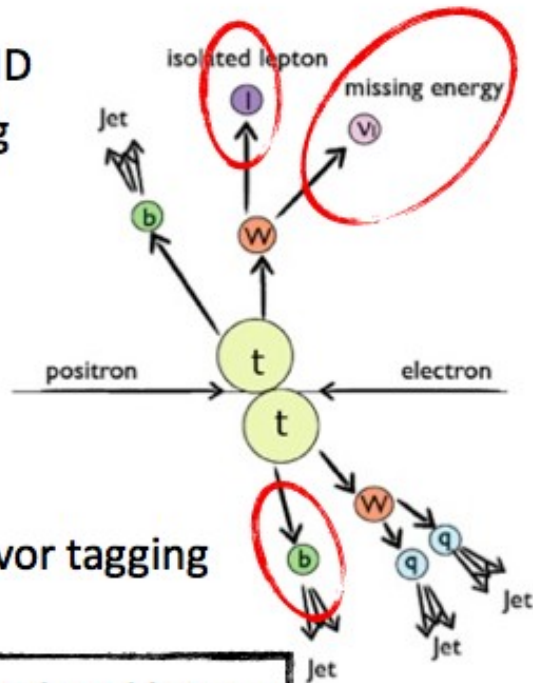


Elements of top quark reconstruction

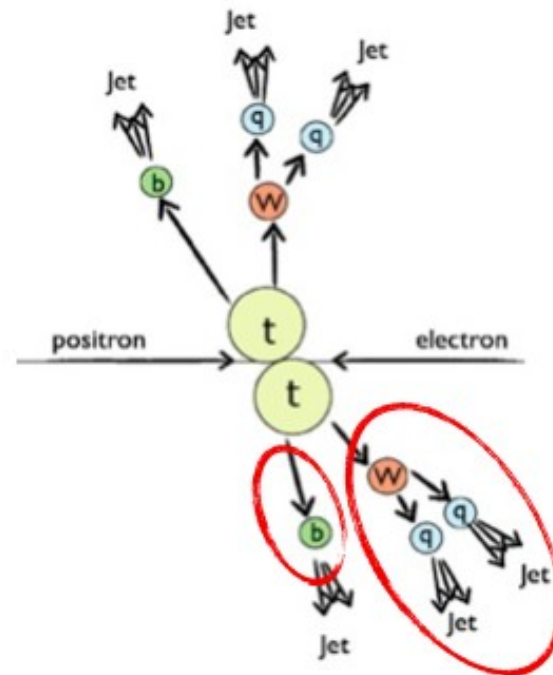
- By far dominating decays: All-hadronic (46%), semi-leptonic / lepton+jets (45%, 30% w/o τ)

Will concentrate on semi-leptonic channel

lepton ID tracking



4 jets, isolated lepton



6 jets

jet energy reconstruction, global event reconstruction

Uses all aspects of LC detectors!

Nice illustration stolen from Frank

Semi-leptonic top decays

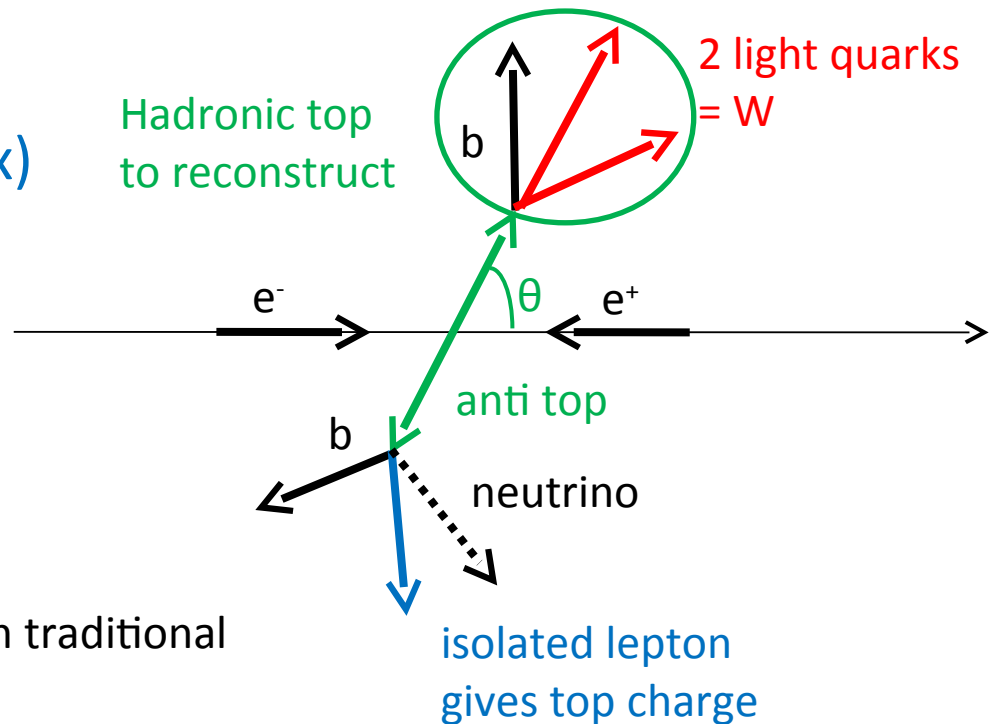
- $t\bar{t} \rightarrow b\bar{b}q\bar{q}l\nu$ ($l=e,\mu$)
 - Need at least 1 b jet (vertex)
 - Find 1 lepton (tracking)

- Method :

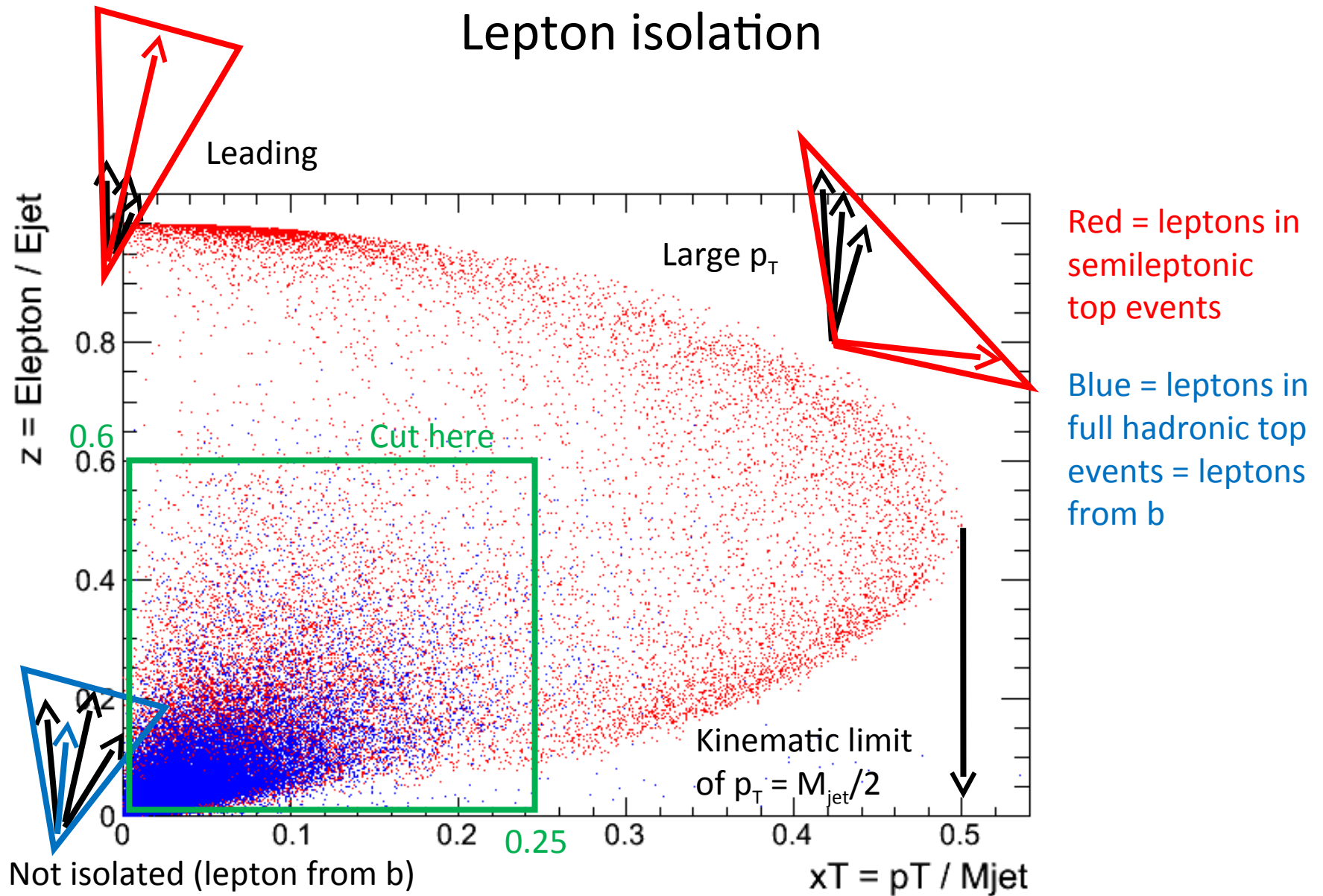
- Find a lepton
- Force 4 jets clustering

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



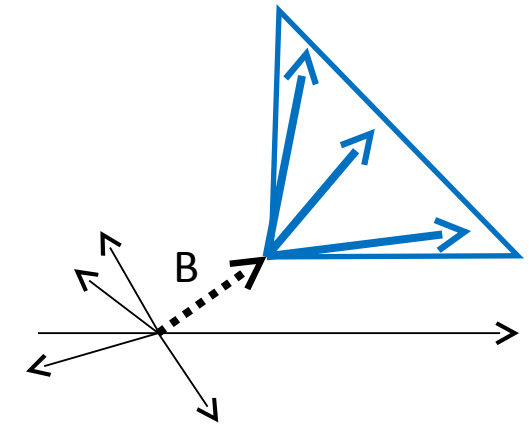
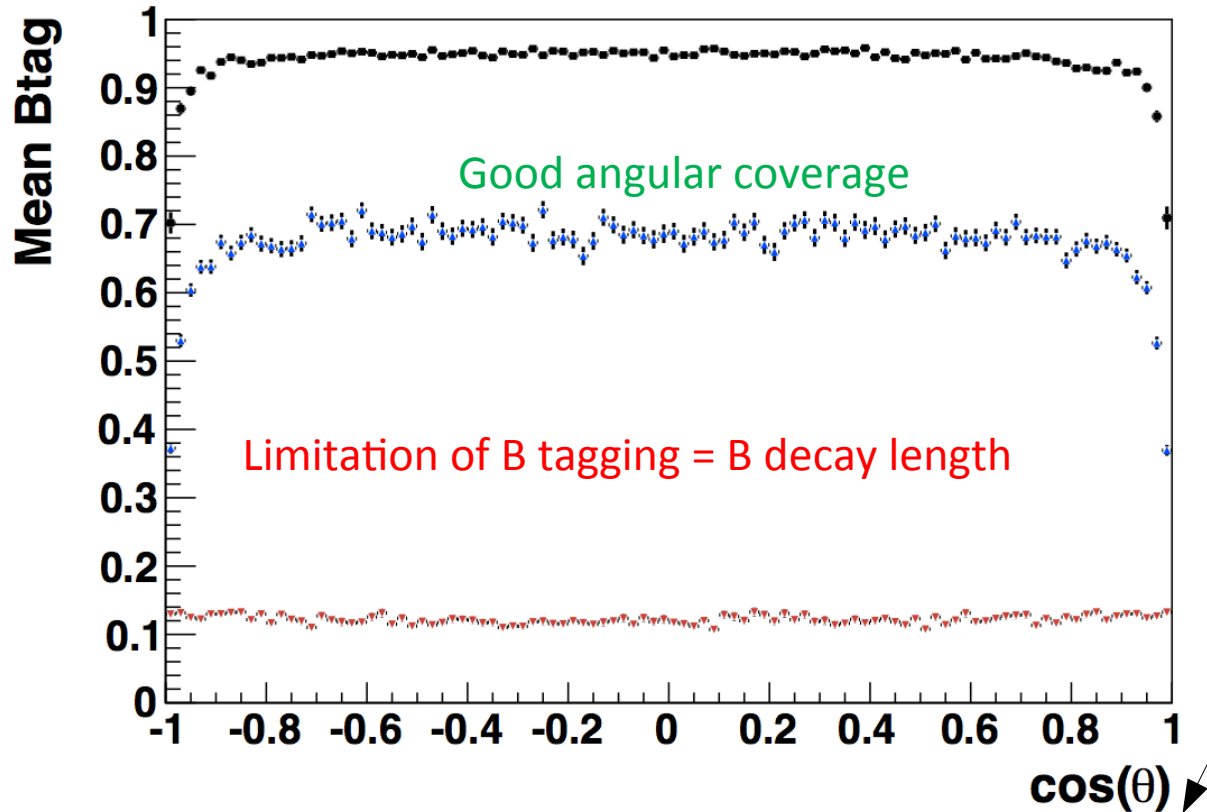
Lepton isolation



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

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

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

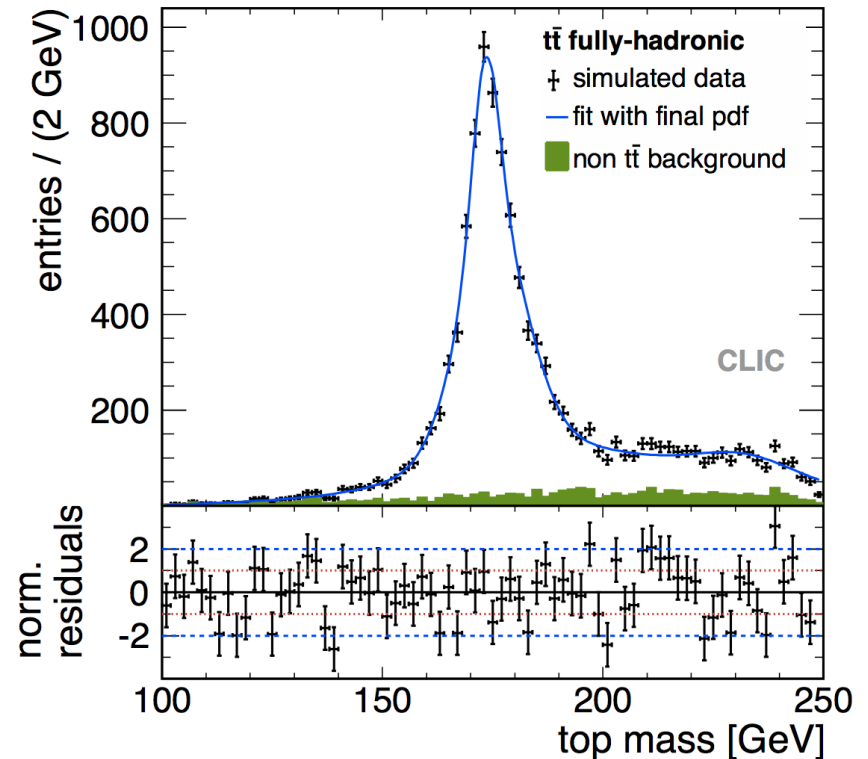
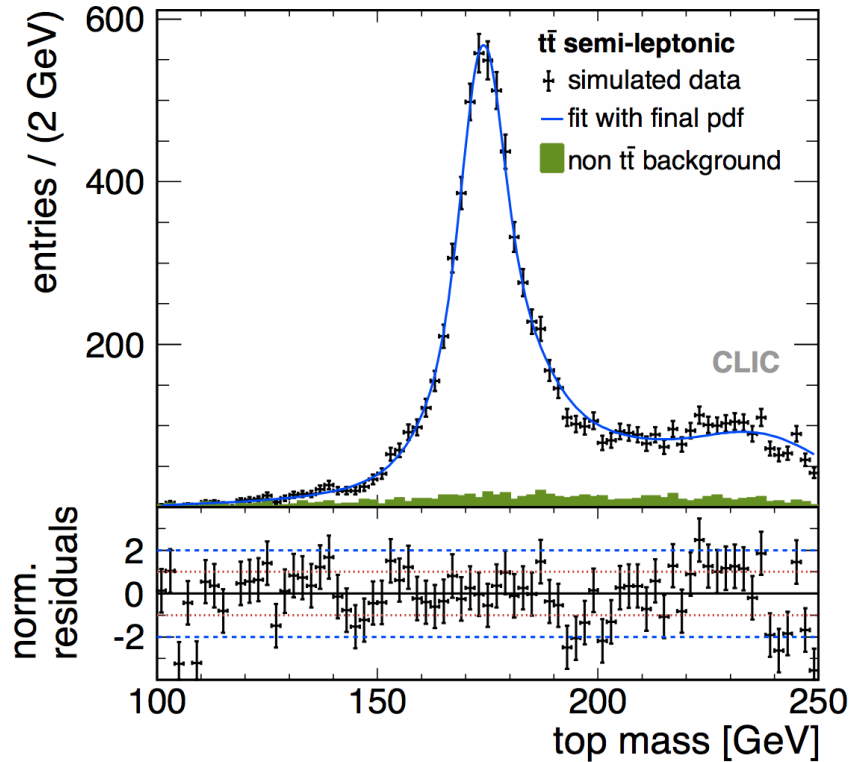
Remark: Selection efficiency depends also on purpose of analysis

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

Top mass spectrum in continuum – 500 GeV

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

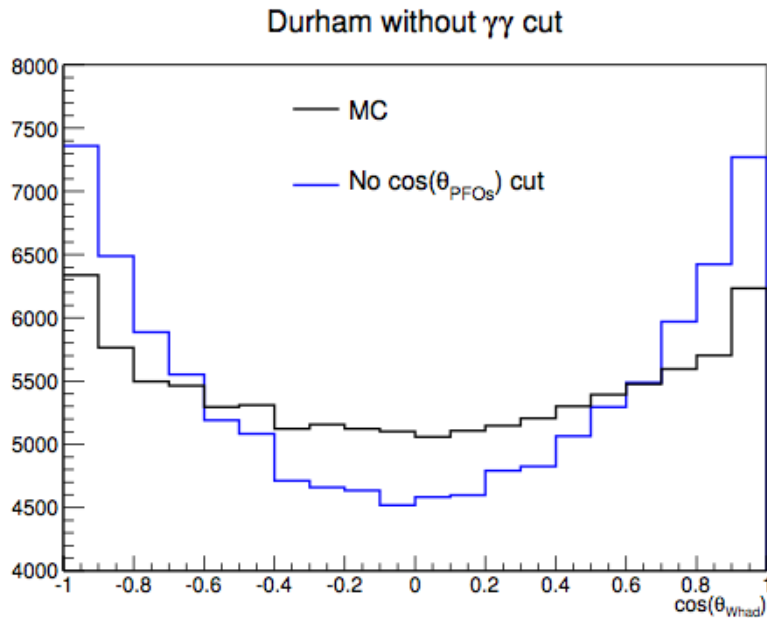


- (Almost) background free measurement of top mass
 - Uncertainty on continuum top mass ~ 80 MeV
- => See talk by Simon for details

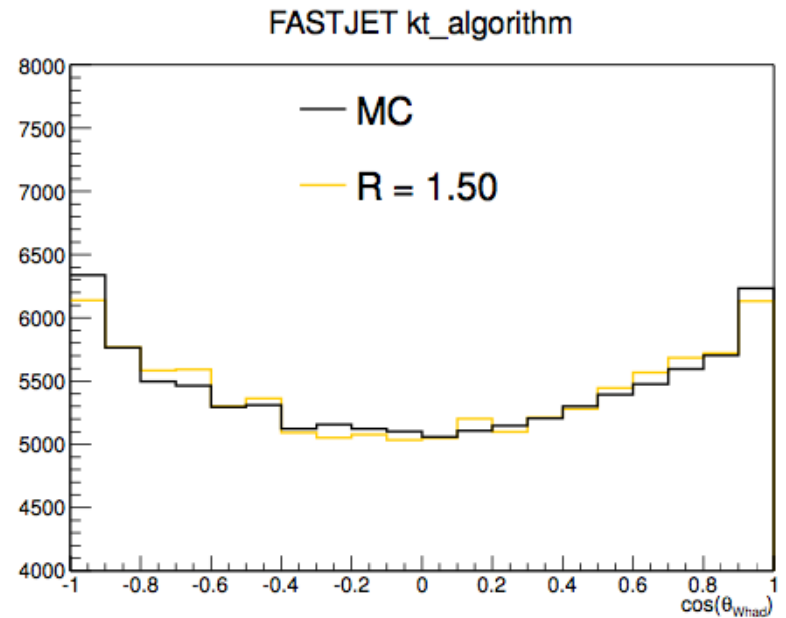
Discussion of pile up

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

Study different jet algorithms: Example polar angle of W boson



(a) Durham

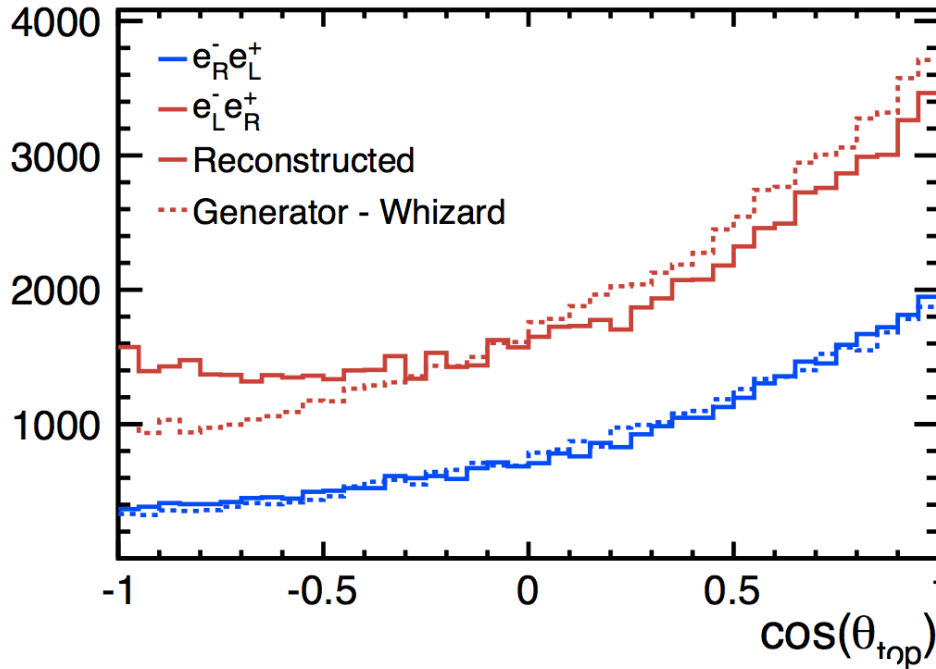


(b) k_t , $R = 1.5$

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

Result shown for ILC but similar result for CLIC energies

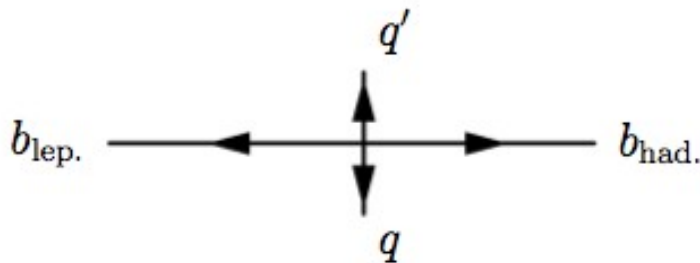
Reconstruction of top quark production angle



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

Precise reconstruction of θ_{top} in case of **right** handed electron beams

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

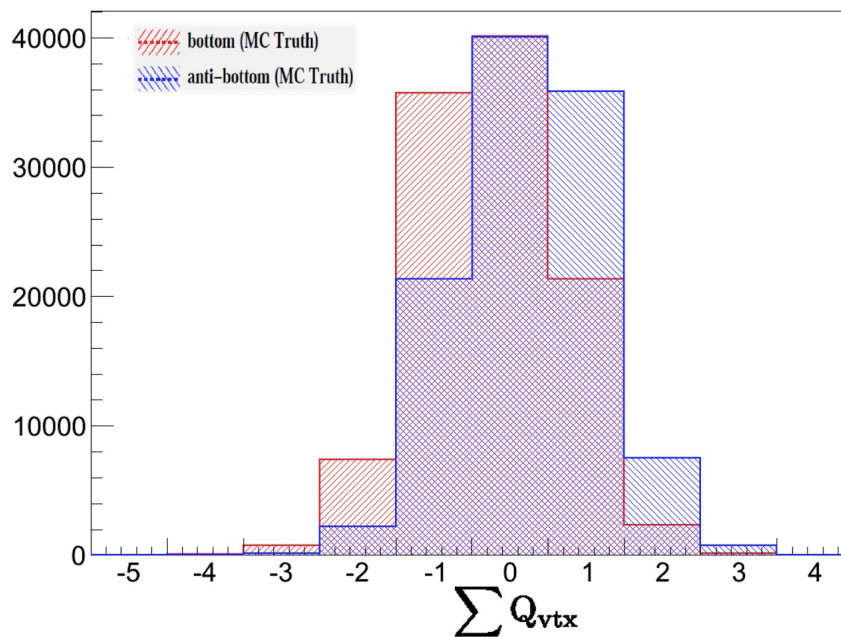
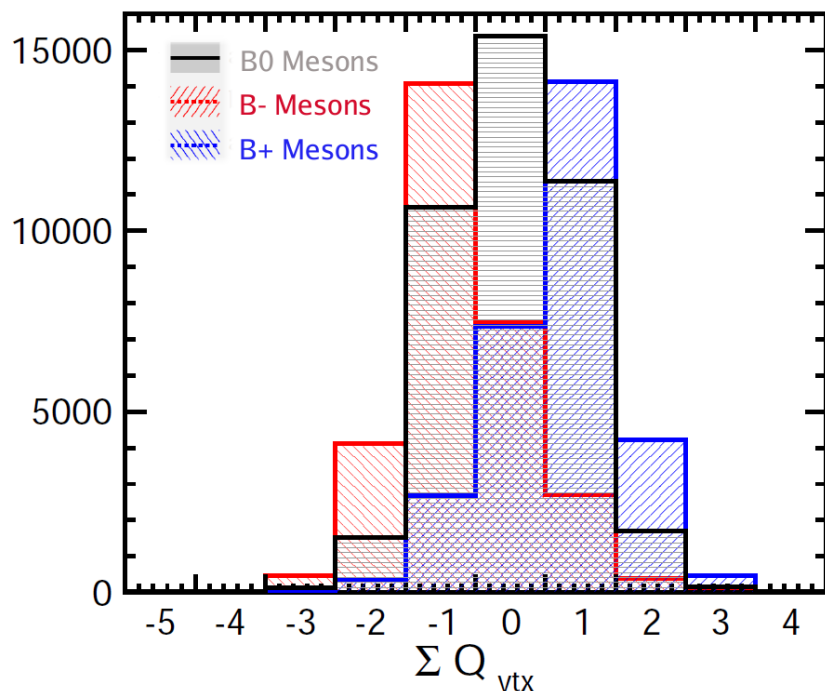


Left handed top quarks

- top quark direction from hadronically decaying top ($b+W$)
- V-A structure of $t\bar{t}X$ vertex leads to soft W and hard b-quarks
- => Wrong association leads to flip of top direction by π

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)

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

Measurement of top quark polarisation

Measure angle of decay lepton in top quark rest frame

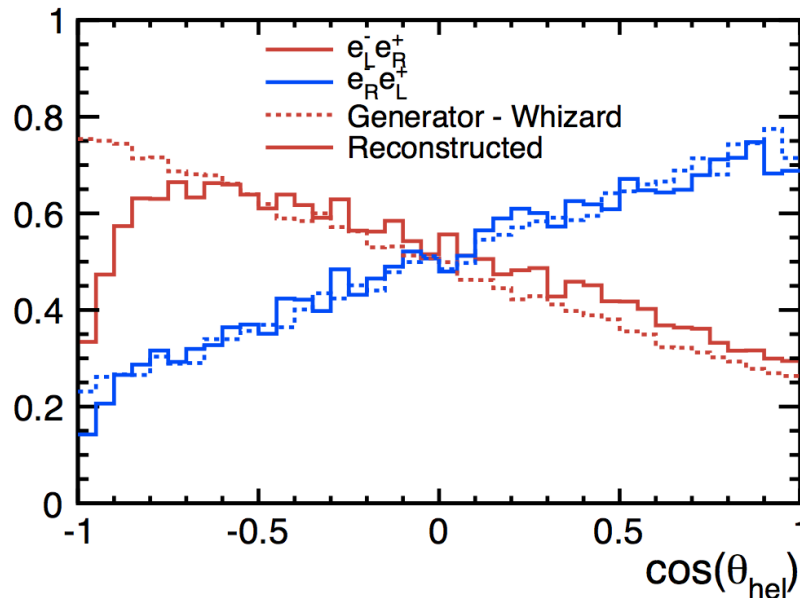
Lorentz transformation benefits from well known initial state

(N.B. : Proposal for hadron colliders applied to lepton colliders)

Differential decay rate

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

Slope measures fraction of $t_{R,L}$ 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%

Discussion of potential systematic errors

Experimental only:

- **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 \sim statistical error
- **Other effects**: B-tagging, passive material etc.
LEP claims 0.2% error on R_b -> guiding line for LC

Summary and Conclusion

- A future linear e^+e^- collider will allow for studying electroweak production of $t\bar{t}$ pairs.
- Physics backgrounds to $t\bar{t}$ production can be reduced to a negligible level. The needed selection cuts will always leave a signal sample of about 100 kEvents.
- Little event pile up. This is in particular true for the ILC.
Ongoing studies show that this residual pile-up can be controlled with adequate jet algorithms.
- The t quark mass can be measured to a statistical precision of better than 40 MeV
Adding up potential systematic and theory errors the precision will still be below 100 MeV
- A major asset of the linear collider are the polarized beams.
- Measurement of the b quark will be measured at a purity of 60% and better.
This is in particular beneficial for observables like AFB
- Electroweak couplings can be determined at the percent level.
It is important that experimental and theoretical errors are kept at the same level.
- In general the realization of machine and detectors must not compromise the precision physics. This is maybe the biggest challenge in the coming years.
- Expect a dedicated white paper on the physics potential of the LC w.r.t top quark physics for Minnesota
- Experimental details like these here will be summarised in the Top and algorithms working group summary

Backup

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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)

LC Detector Requirements

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

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

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

(c/b-tagging)

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

(Measurement of W/Z Mass with Jets)

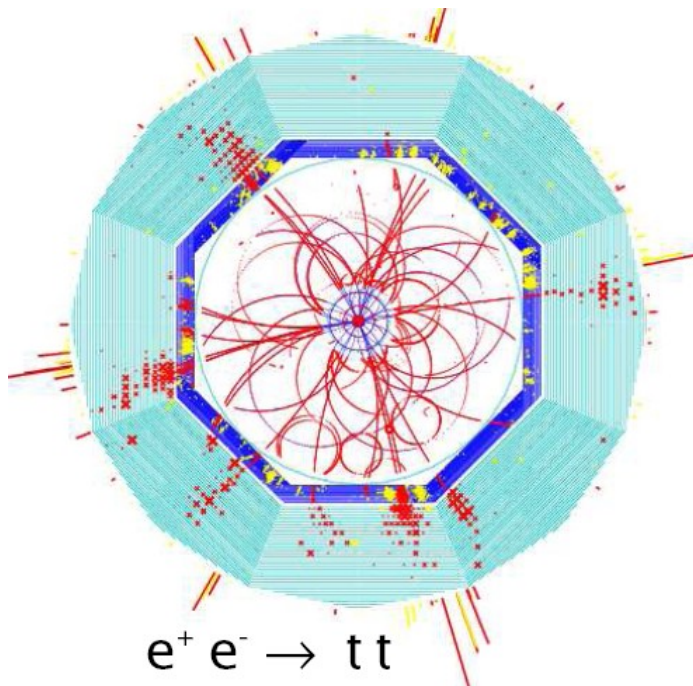
Hermeticity : $\theta_{\min} = 5 \text{ mrad}$

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

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

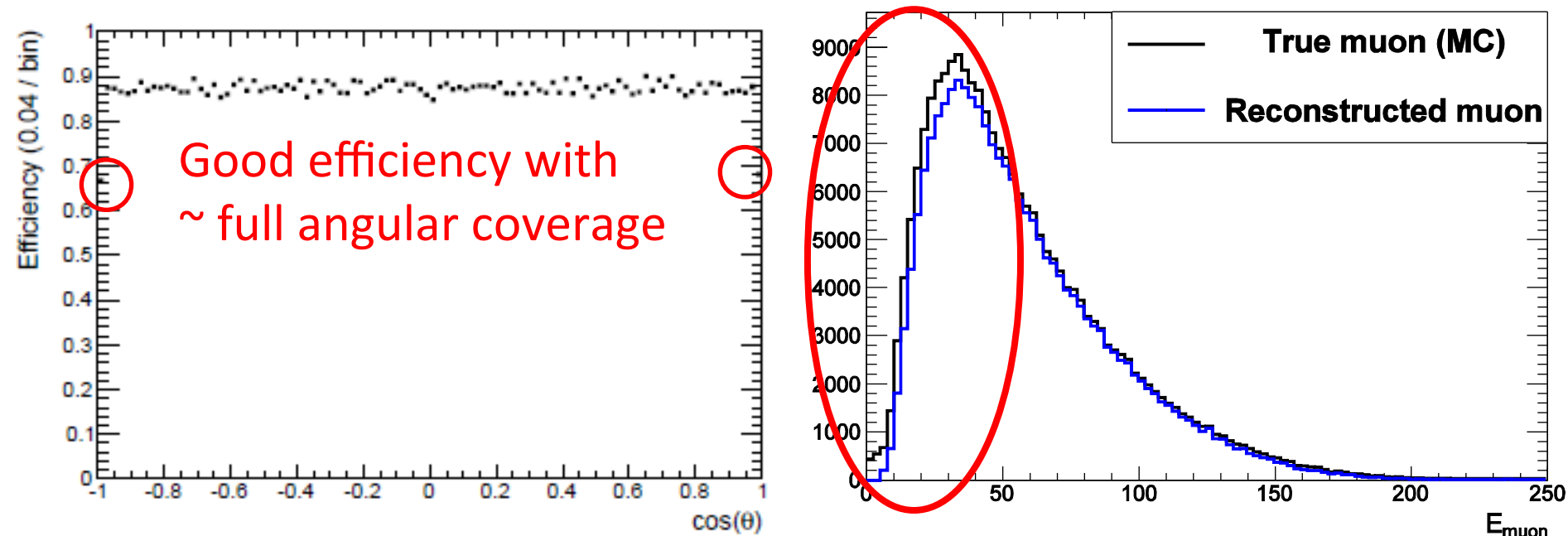
Therefore:

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



$e^+ e^- \rightarrow t \bar{t}$

Efficiencies : angular and energetic



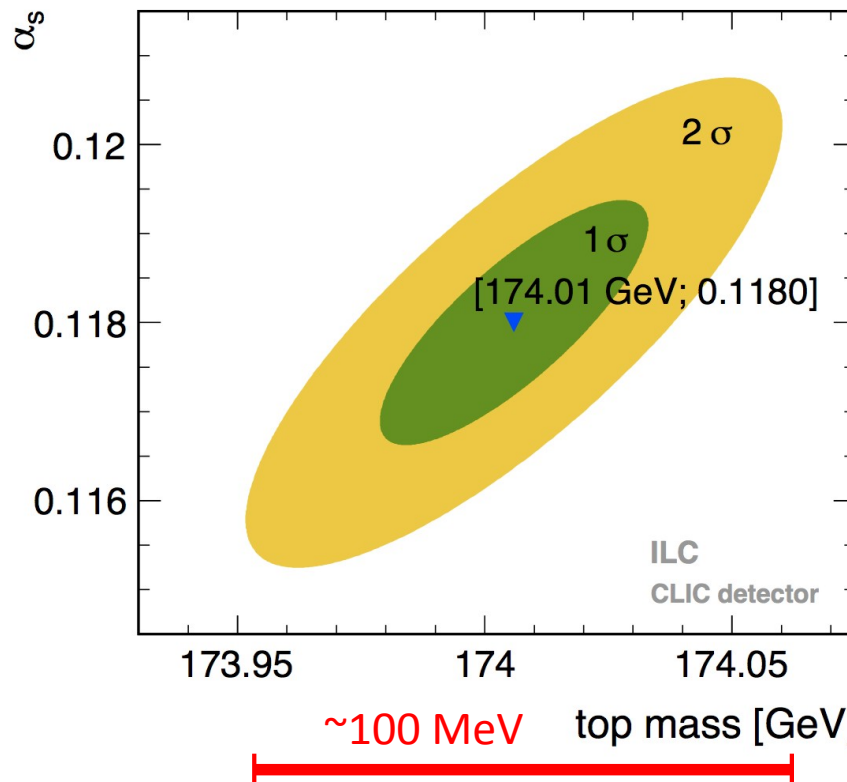
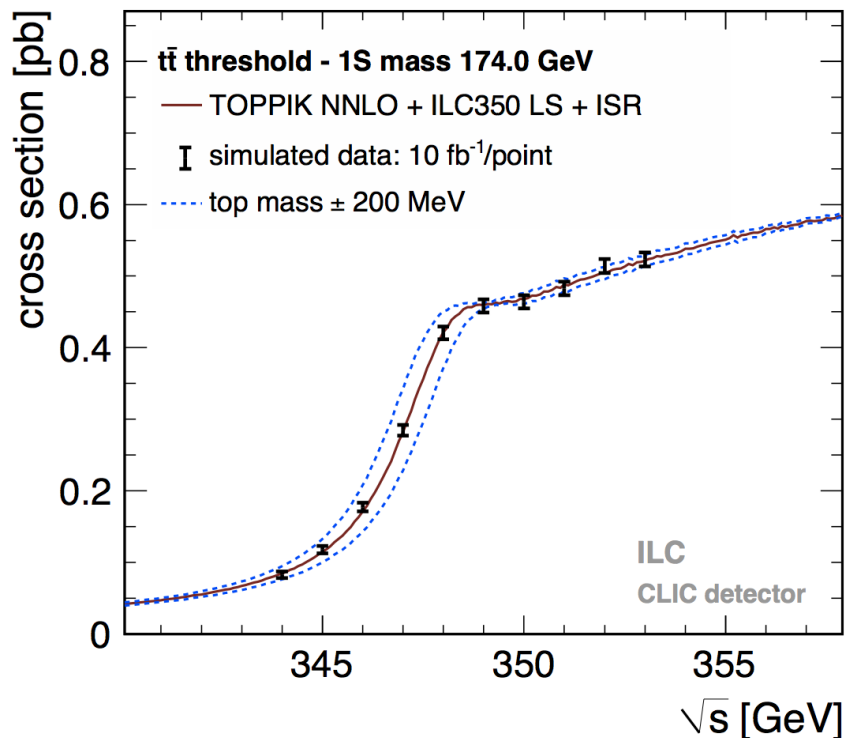
- Efficiencies under control :
 - Tracking worse in very forward regions
 - Leptons with small energies are suppressed by isolation cuts

Efficiency = 85%
Contamination = 0.3%

Top quark mass – Results of full simulation studies

Issue of CLIC study but adapted to ILC

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

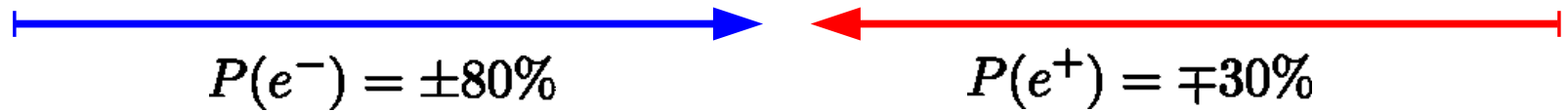
- Only one observable x-section
cf. Martinez et al. Used more observables and more lumi
- result include lumi spectrum of ILC
not much worse results for CLIC
- An additional source of error is knowledge of background

100 MeV is (conservative) estimate of expected precision

Disentangling

At ILC **no** separate access to ttZ or $t\bar{t}\gamma$ vertex, but ...

ILC 'provides' two beam polarisations



There exist a number of observables sensitive to chiral structure, e.g.

$$\sigma_I \quad A_{FB,I}^t = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \quad (F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$$

x-section

Forward backward asymmetry

Fraction of right handed top quarks



Extraction of six (five) unknowns

$$F_{1V}^\gamma, F_{1V}^Z, F_{1A}^\gamma = 0, F_{1A}^Z$$

$$F_{2V}^\gamma, F_{2V}^Z$$