A precise determination of top quark electroweak couplings at the ILC operating at 500 GeV

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Arxiv: 1307.1802
1307.8265
(ILC white paper)

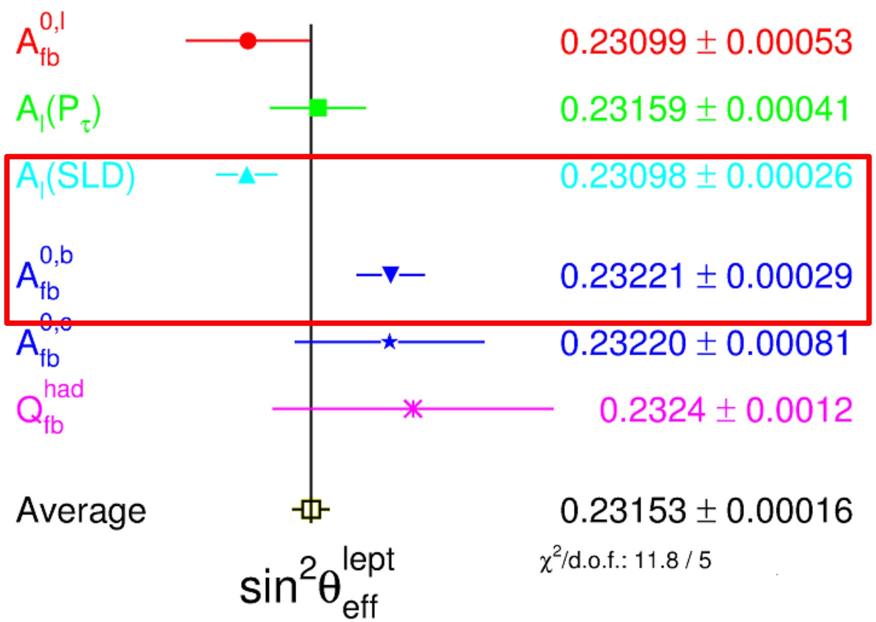
Based on work in the groups of

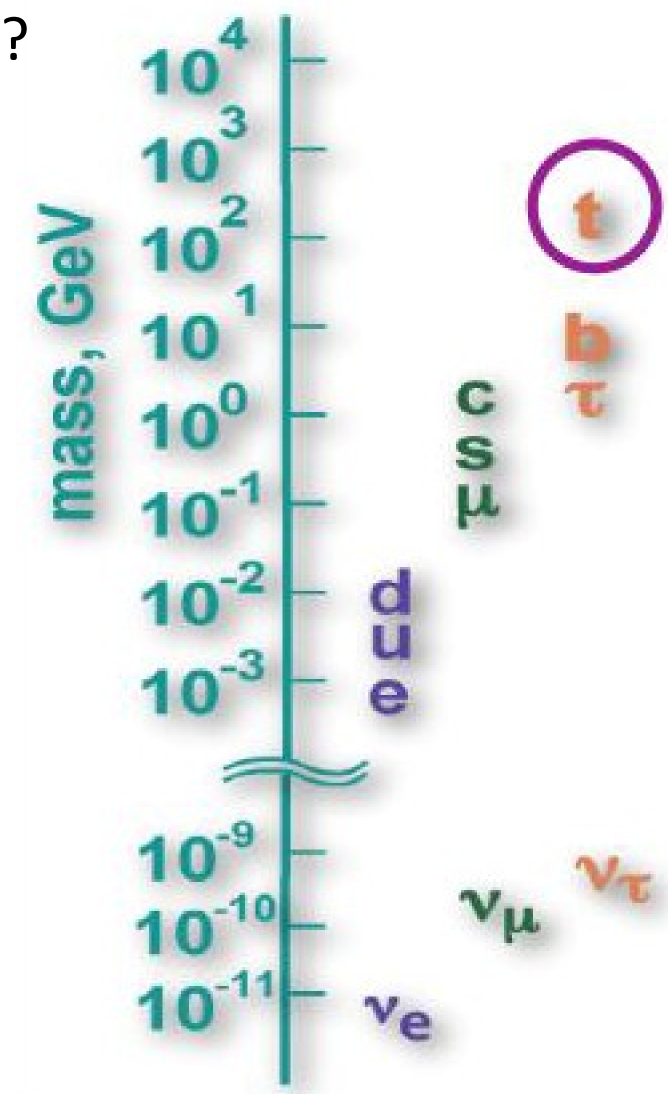
... and the ILD Detector concept

Snowmass CSS 2013 - Minneapolis/MN August 2013

The top quark and flavor hierarchy

- Flavor hierarchy ? Role of 3rd generation ?





- A_{FB} anomaly at LEP for b quark

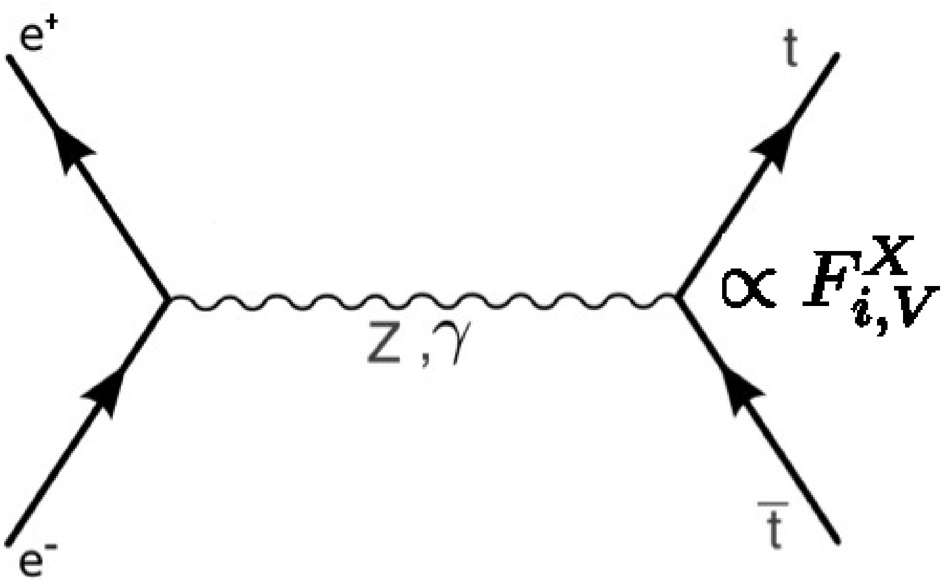
Tensions at Tevatron

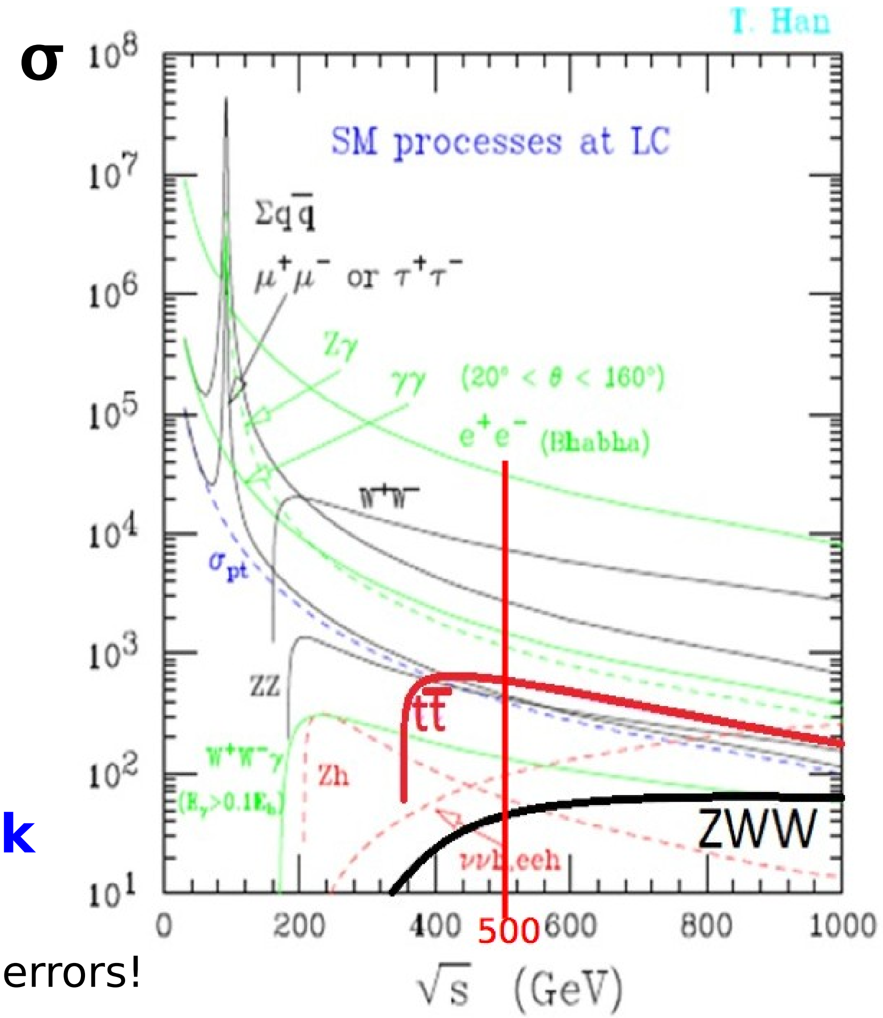
- Heavy fermion effect?

Strong motivation to study chiral structure of top vertex in high energy e+e- collisions

Why is it sooo heavy?

Top quark physics at (I)LC





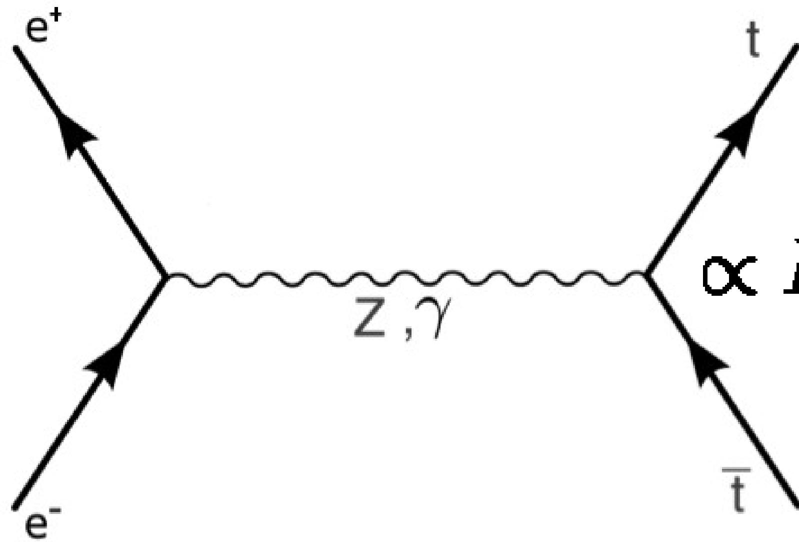
- Top quark production through **electroweak** processes,

  no competing QCD production => Small theoretical errors!

- Polarised beams allow to test chiral structure at ttX vertex
  => Precision on form factors F (this talk)

-ILC is promising for high precision top quark 'tomography'

Testing the chiral structure of the Standard Model



$$\propto F^{X}_{i,V}$$

$$\Gamma^{ttX}_{\mu}(k^2,q,\bar{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2)+\gamma_5 F^X_{1A}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu\left(iF^X_{2V}(k^2)+\gamma_5 F^X_{2A}(k^2)\right)\right\}, \quad (2)$$

$$\mathcal{F}^L_{ij} = -F^\gamma_{ij} + \left(\frac{-\frac{1}{2}+s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F^Z_{ij}$$

$$\mathcal{F}^R_{ij} = -F^\gamma_{ij} + \left(\frac{s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F^Z_{ij},$$

Pure γ or pure $Z^0 : \sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

Z^0/γ interference $: \sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

Disentangling

ILC 'provides' two beam polarisations

$P(e^-) = \pm 80\%$ $P(e^+) = \mp 30\%$

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

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

x-section | Forward backward asymmetry | Fraction of right handed top quarks

⇩

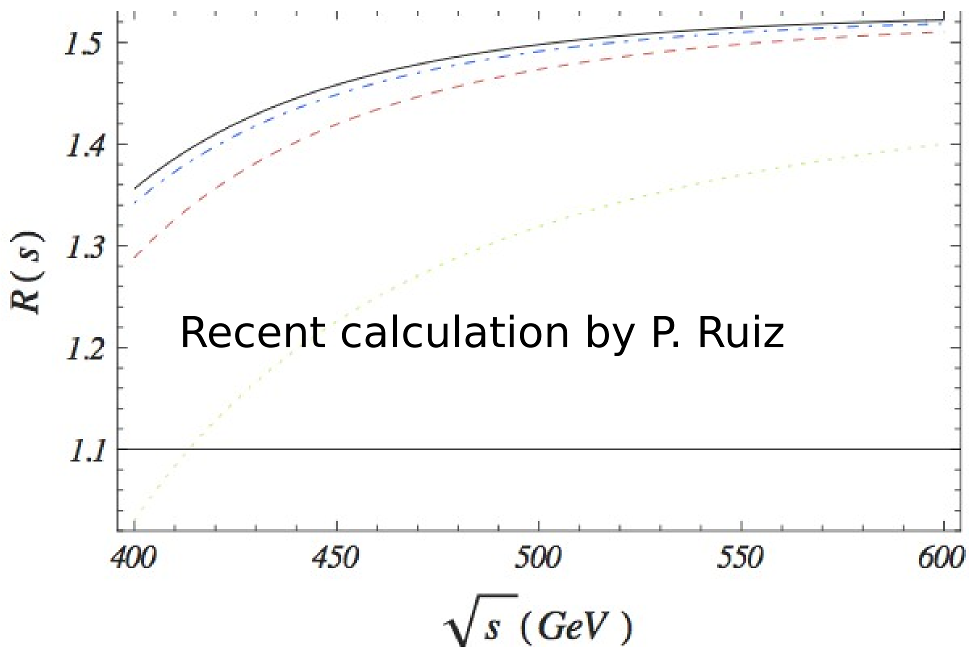
Extraction of six (five) unknowns

$$F^\gamma_{1V},\, F^Z_{1V},\, F^\gamma_{1A} = 0,\, F^Z_{1A}$$

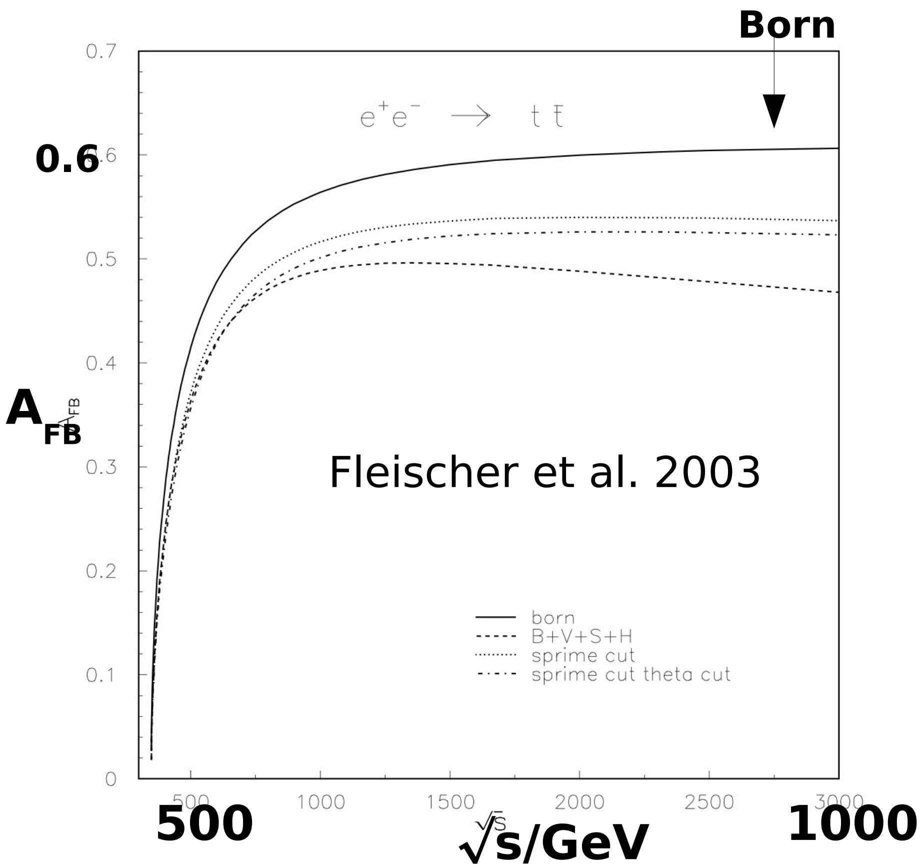
$$F^\gamma_{2V},\, F^Z_{2V}$$

SM correction to Born process

QCD up to $O(a_s^3)$



NLO electroweak

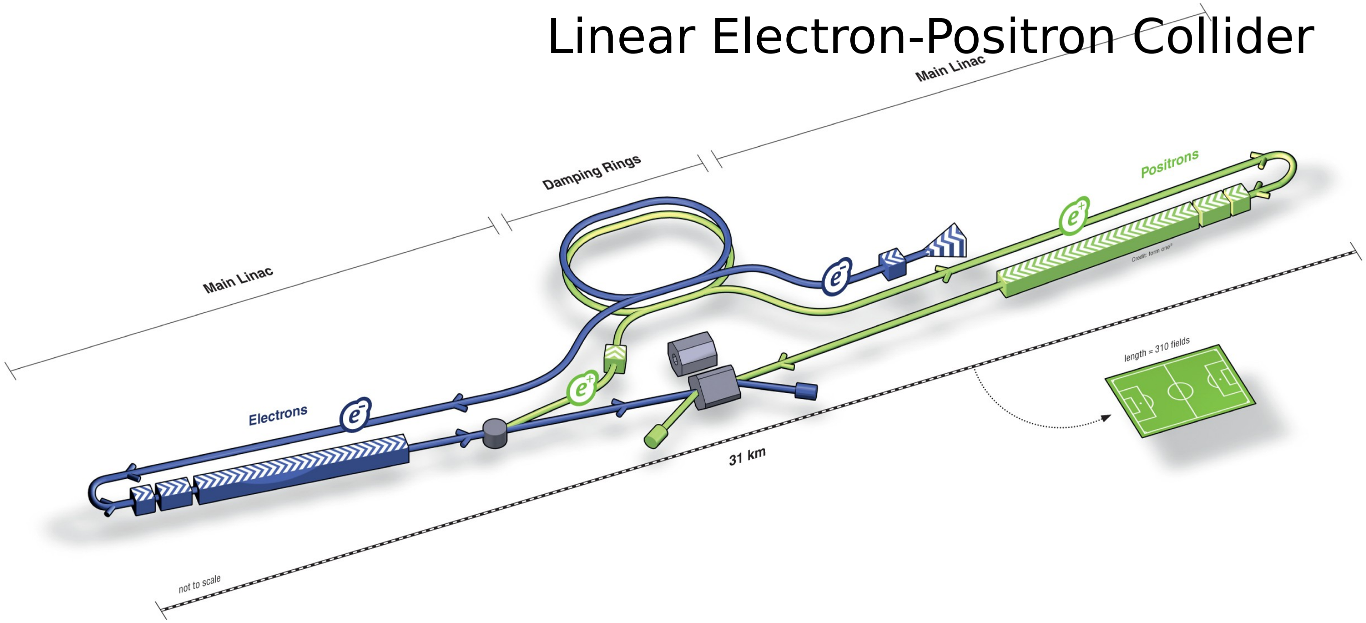


- Well behaving perturbation series
- Small scale uncertainties <1%
- Size of next correction expected to be Smaller than 0.3% at 500 GeV

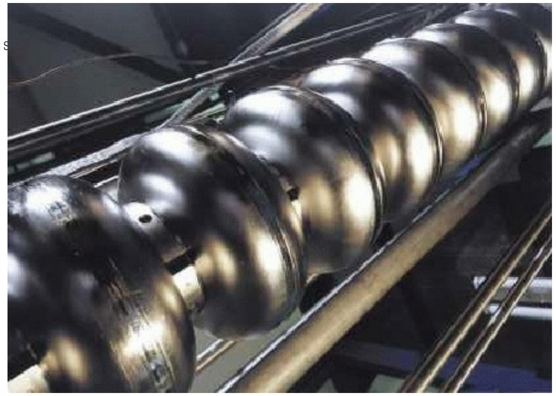
- Sizeable electroweak corrections to AFB (~15%)
- (To my knowledge) no estimation of size of next (i.e. NNLO correction) needed for precision physics !(?)

The International Linear Collider ILC

Linear Electron-Positron Collider



Total footprint 31 km



Technology for main linac

Superconductive RF cavity

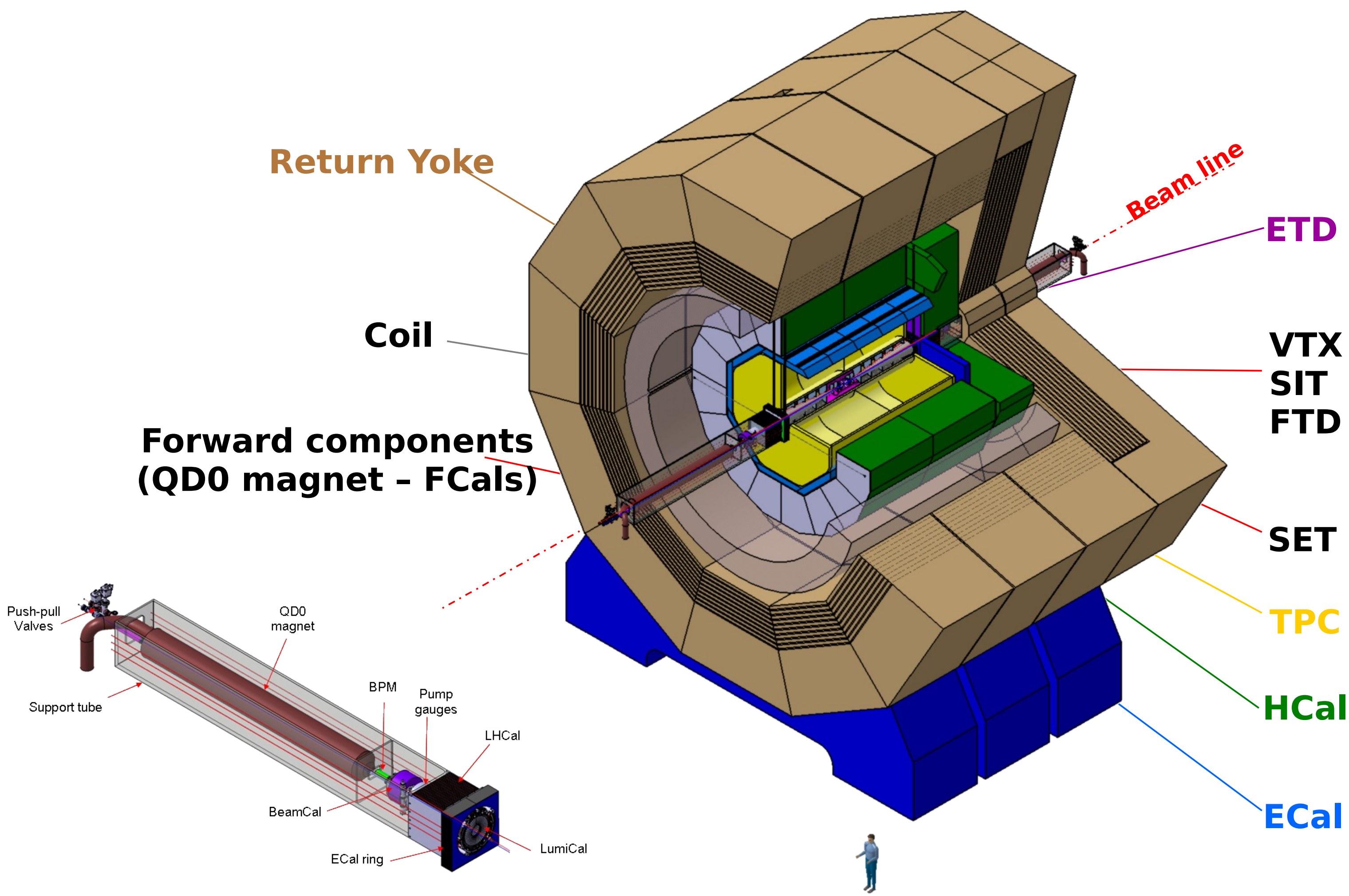
ITRP Recommendation 2004

Main parameters

- √s adjustable from 91 – 500 GeV
- Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarisation of at least 80%
  Option: polarised Positrons
- The machine must be upgradeable to 1 TeV

→ Technical design report published in 2013
→ R&D Project for higher energies CLIC

The ILD concept



Performance goals:

Impact parameter:

$$\sigma_b < 5 \oplus 10/p\sin^{3/2}\theta \mu m$$

Track momentum:

$$\sigma_{1/pt} = 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$$

Jet energy:

3-4% over
total energy range

Detector Baseline Design 2013 – Based on full detector simulation

Elements of top quark reconstruction

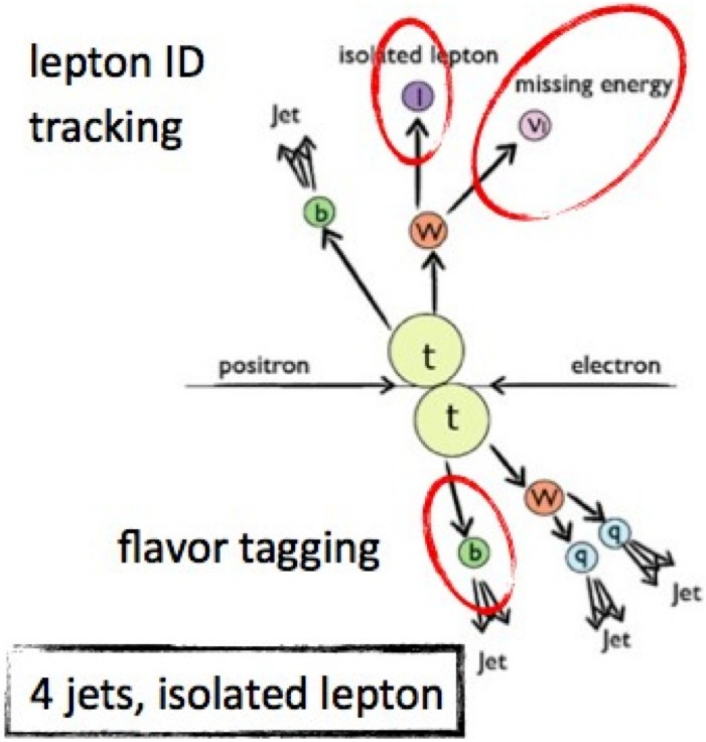
Three different final states:

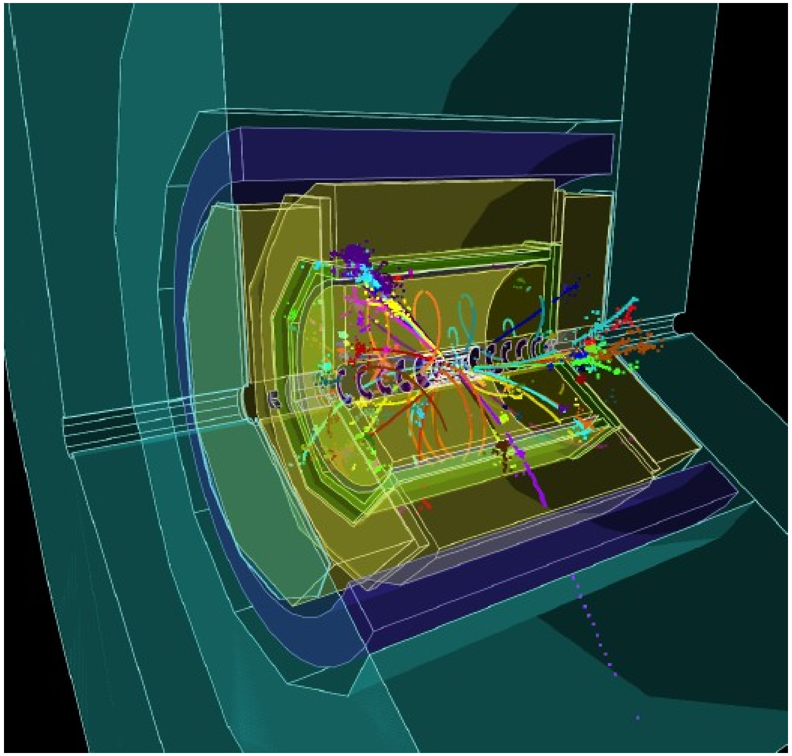
1) Fully hadronic (46.2%) → 6 jets

2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino

3) Fully leptonic (10.3%) → 2 jets + 4 leptons

$$t\bar{t} \to (bW)(bW) \to (bqq')(b\ell\nu)$$



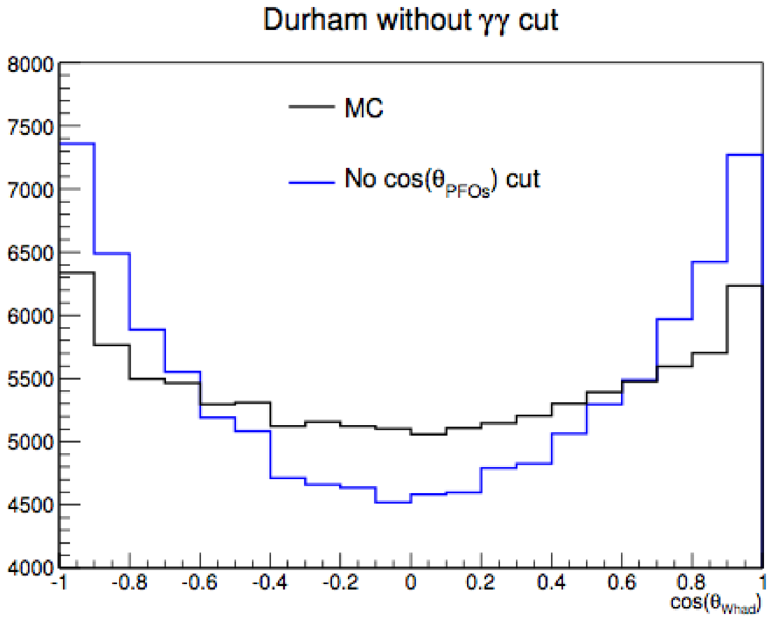


Final state reconstruction uses all detector aspects

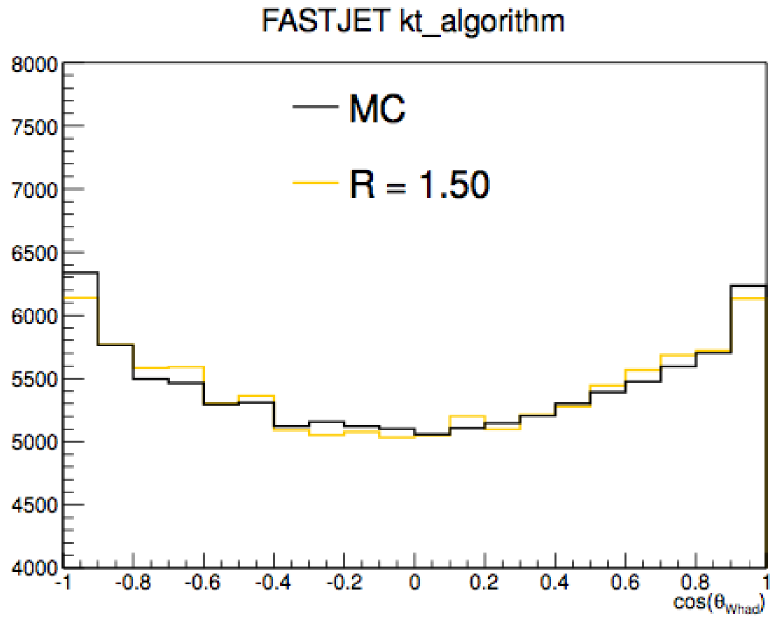
Discussion of pile up

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

Study of different jet algorithms: Example polar angle of W boson



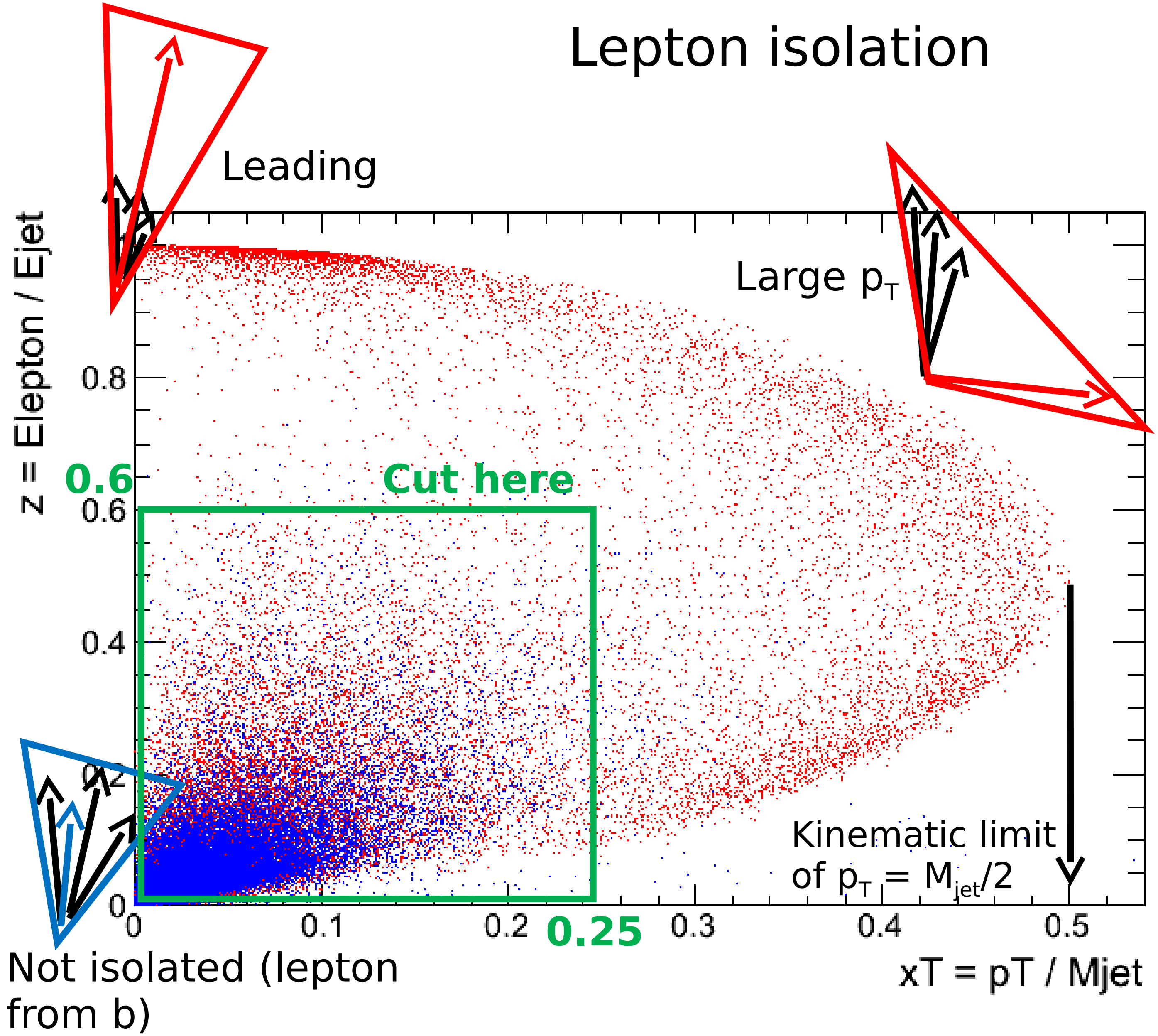
(a) Durham



(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)

Lepton isolation



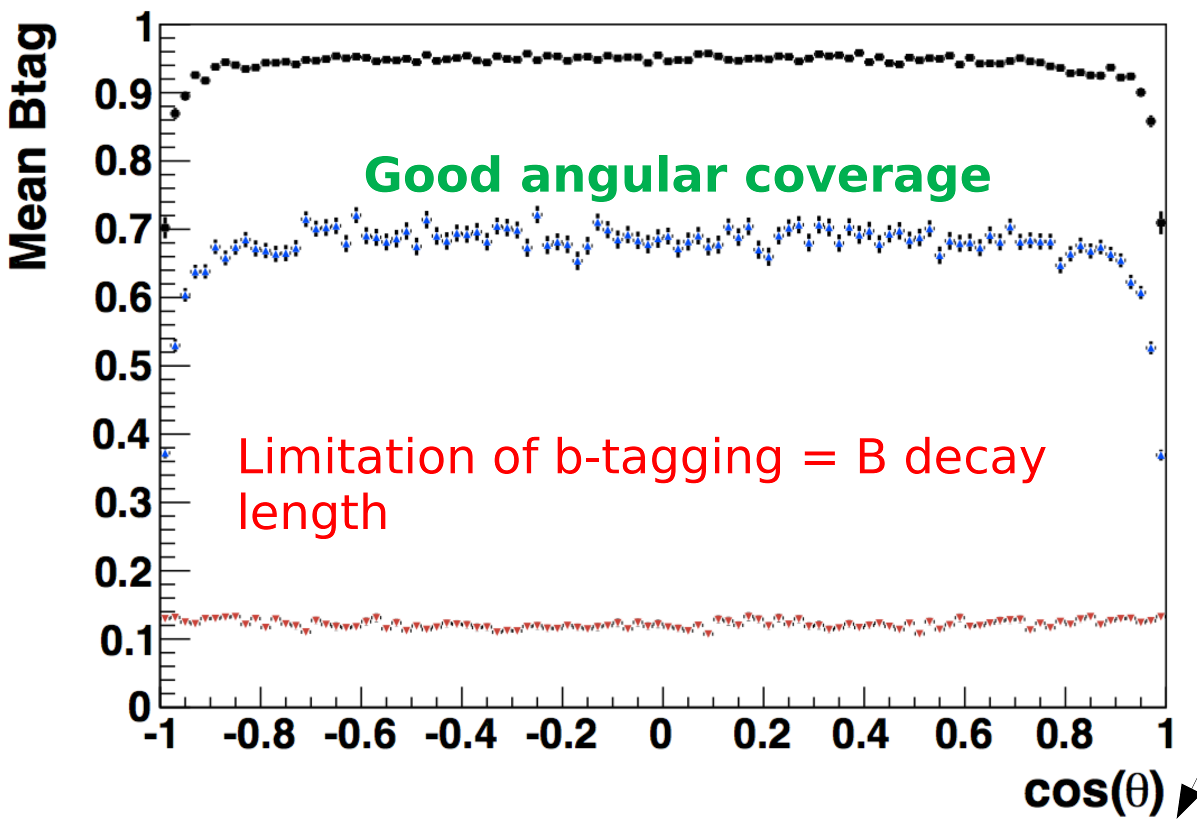
Red = leptons in semileptonic top events

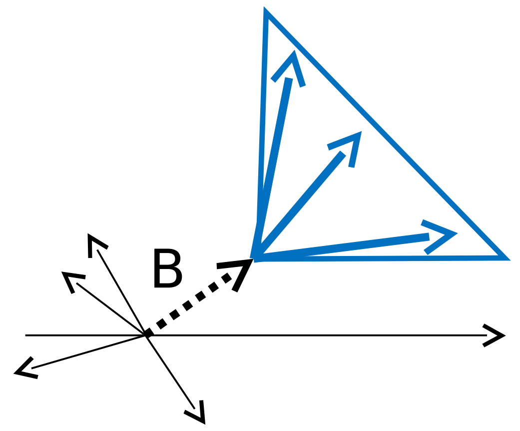
Blue = leptons in full hadronic top events = leptons from b

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

B tagging

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



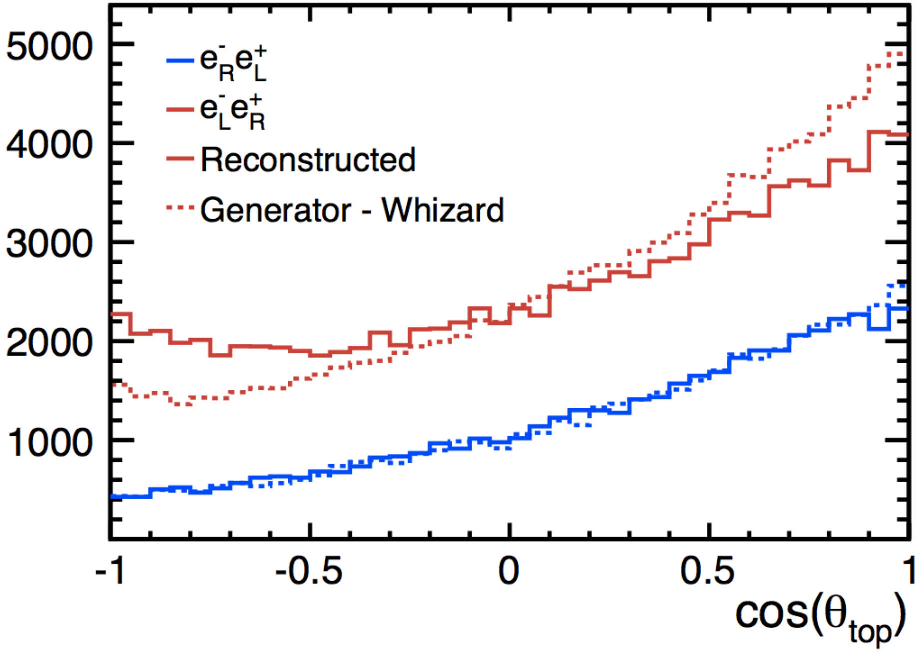


- 4 jets
- 2 highest Btag = b_1 & b_2
- 2 "light" jets = W

Polar angle of b-jet

Clean e^+e^- environment allow for efficient b-tagging

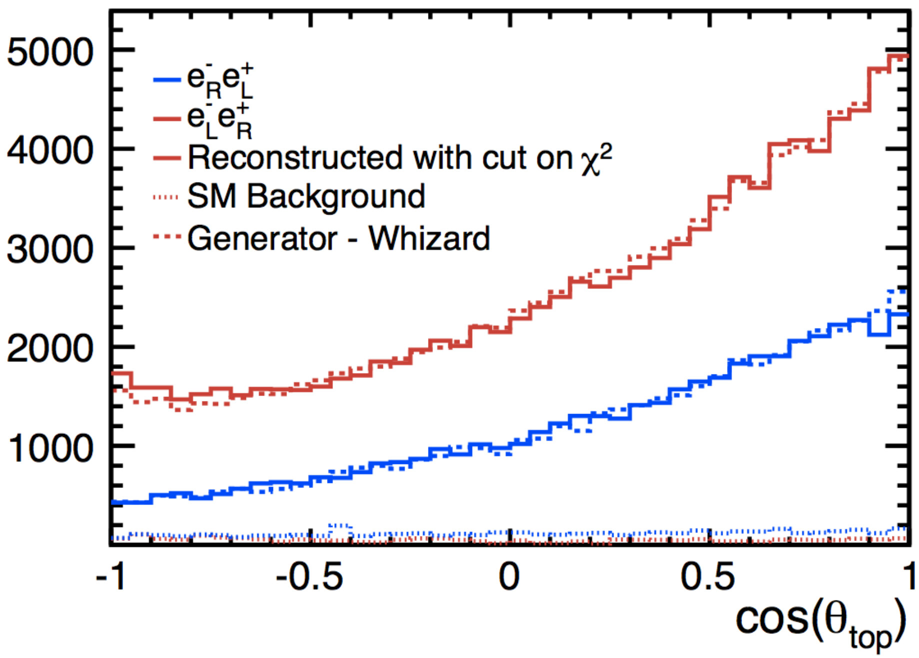
Reconstruction of top quark production angle



Ambiguities in case of left handed electron beams
Due to V-A structure at tbW vertex

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

(Current) remedy to address ambiguities:
Select cleanly reconstructed events by kinematic fit or χ^2 analysis



Precise reconstruction for both beam polarisations

- Efficiency Penalty for e_L
- ε_{tot}: $e_R \sim 50\%$, $e_L \sim 30\%$

Precision on A_{FB} ~ 2%

Measurement of top quark polarisation

Measure angle of decay lepton in top quark rest frame

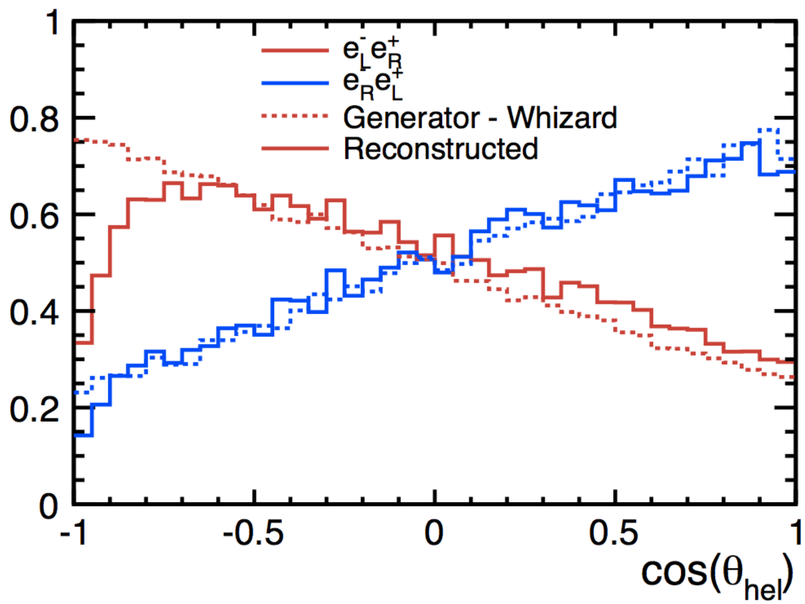
Lorentz transformation benefits from well known initial state

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

Differential decay rate

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

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 λ_t can be measured to an accuracy of about 3-4%

Discussion of potential systematic uncertainties

- 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

- Beamstrahlung/Beamenergy spread: uncritical

- Migrations/Ambiguities: Critical for A_{FB}:
  Need further studies but expect to control them better than the theoretical error
  Remedy may come from b charge measurement

- Other effects: b-tagging, passive material etc.
  LEP1 claims 0.2% error on R_b -> guiding line for LC

Under discussion with theory groups:

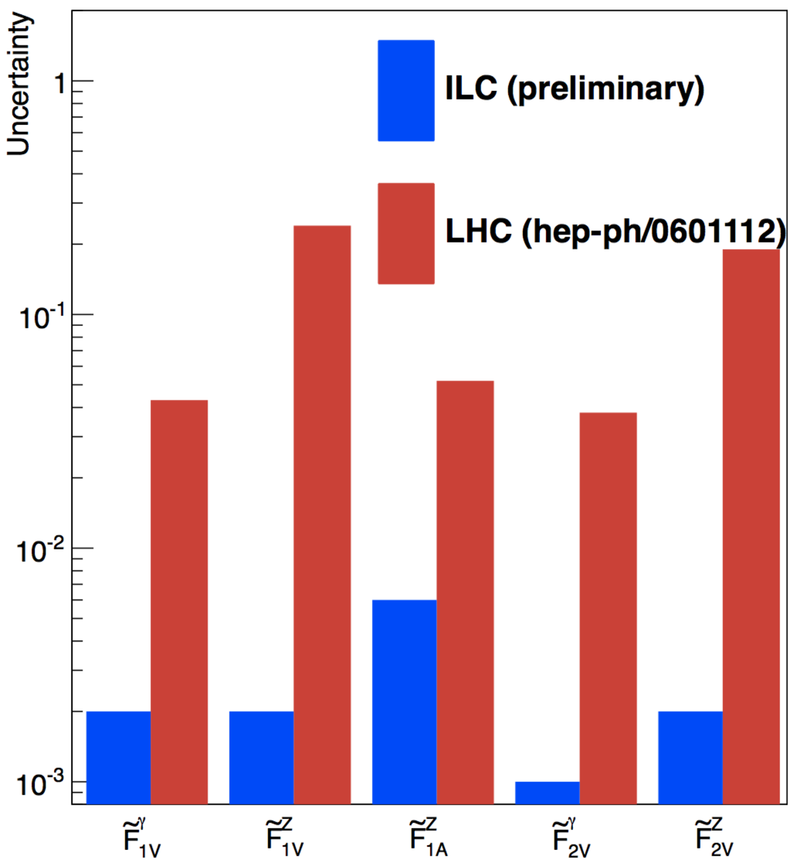
- Role of single top production (15% of 6f final state)
- Electroweak NLO predictions (Correction LO → NLO ~ 15%)

Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

Arxiv: 1307.1802

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

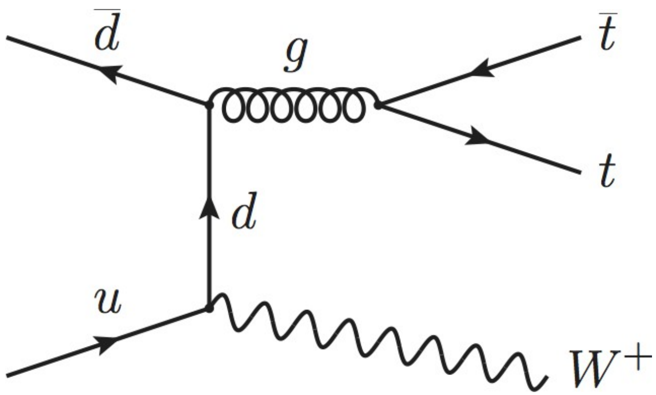
- However LHC projections from 8 years old study

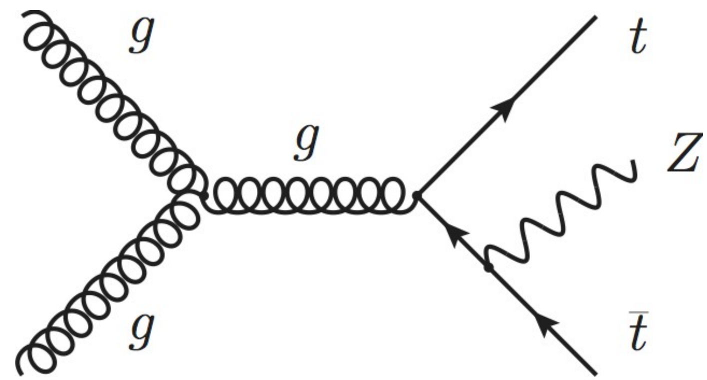
- Strong encouragement to update these numbers!
  First step is Phys. Rev. Lett. 110 (2013) 172002 by CMS

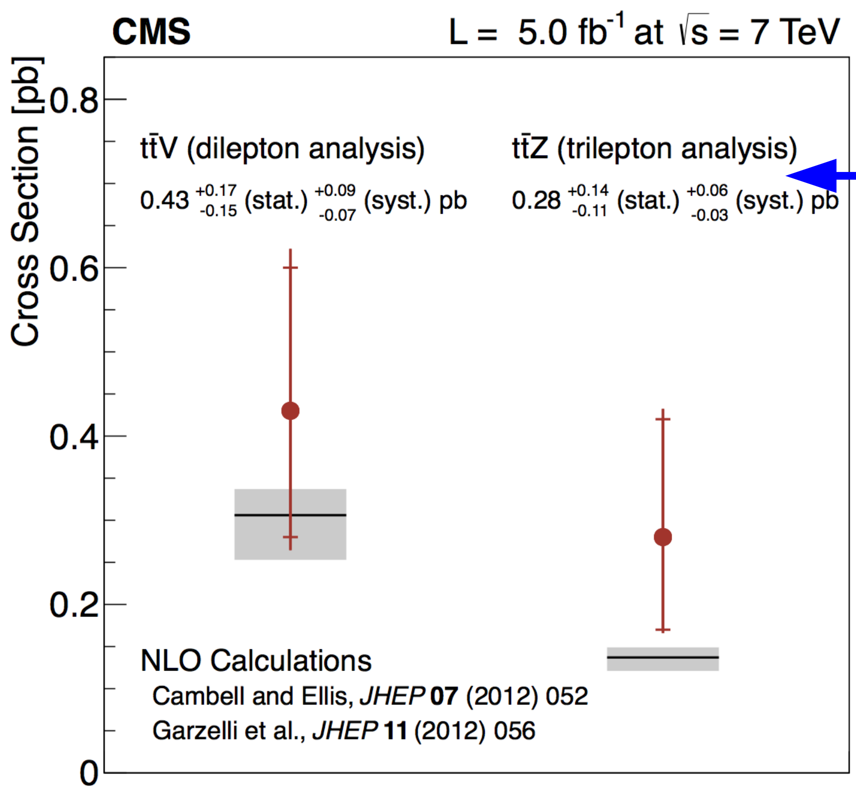
- Potential for CP violating couplings at ILC under study

ILC will be indeed high precision machine for electroweak top couplings

First result on ttV by CMS







$$\sigma(t\bar{t}Z) = 0.28^{+0.14}_{-0.11}\,(\text{stat.})\,^{+0.06}_{-0.03}\,(\text{syst.})\,\text{pb}$$

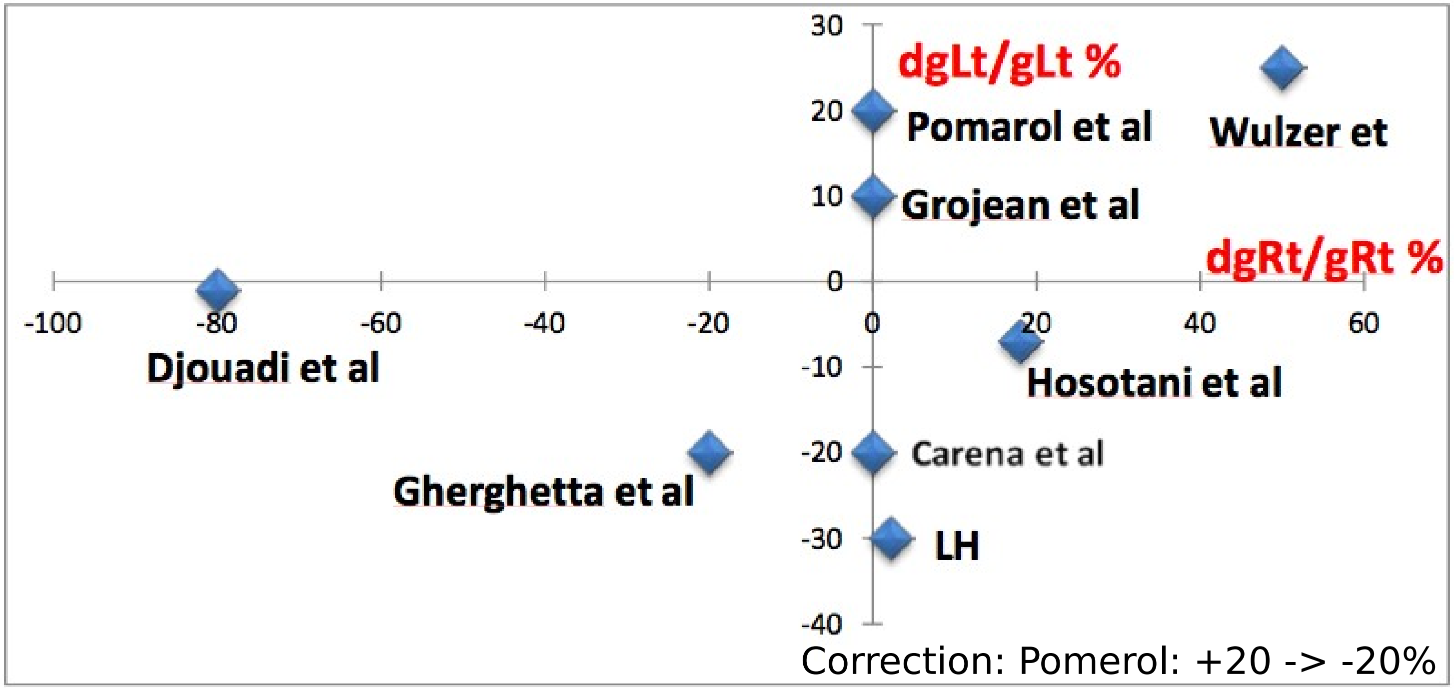
- Promising result
  N.B. NLO QCD has 10% uncertainty

- How will it evolve with higher Luminosity?
  Can entire uncertainty sys. + theor.
  get down to 10%

- Revision of 'old' estimations of precisions
  are needed!

Discussion of precisions (IFIC/LAL [F. Richard])

Models realising Top/Higgs compositeness and/or extra dimensions



Variety of models predicting modifications to
tL and tR due to couplings to new strong sector

Sensitivities and constraints

Model	dtR/tR %	dtL/tL %	dσZtt/σZtt %	LEP1
Carena	0	-20	-30% -3 sd	OK
Djouadi	-80	-1	-16%	-60
Gherghetta	-20	-20	-36% -3.6 sd	-15 for tL
Grojean	0	10	17%	OK
Hosotani	18	-7	-5%	OK
Little Higgs	2.2	-30	-32% -3 sd	-25
Pomarol	0	-20	-37% -3.7 sd	OK
Wulzer	50	25	68% 7 sd	NO

Assumption: $\frac{\delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}} \backsim 10\%$

LEP constraints: $|\delta F_{1A}^{Z}| < 0.2,\; Q_{t_L} \to Q_{t_L}^{SM}$

=> LHC may see deviations but cannot distinguish Models
=> ILC will be able to distinguish at several sigma level

Summary and outlook

- The ILC is the right machine for precision top physics

First machine to produce top pairs in electroweak production!!!

Essential pillar of ILC physics program

- Full simulation available for ILC detectors (here ILD)

=> Great deal of realism and confidence in perspectives

- Precision on form factors of the order of 1%

No sign ambiguity

Large separation power between models!

- Main experimental issues is control of migrations in A_{FB}

… but keeping the promises is maybe biggest challenge in coming years

- Need close contact with theory groups

EW NNLO for AFB

Role of single top production

Reliable generators

Full exploitation of top program at ILC requires a sustained program over many years

Backup

The solid pillars of the LC physics program

Top quark	W Boson	Higgs Boson
		
Discovered 1995 at Tevatron LHC and ILC are/would be Top factories	Discovered 1979 at SPS Mass precisely at Tevatron LHC and ILC are/would be W factories	Discovered 2012 at LHC LHC and ILC are/would be Higgs factory

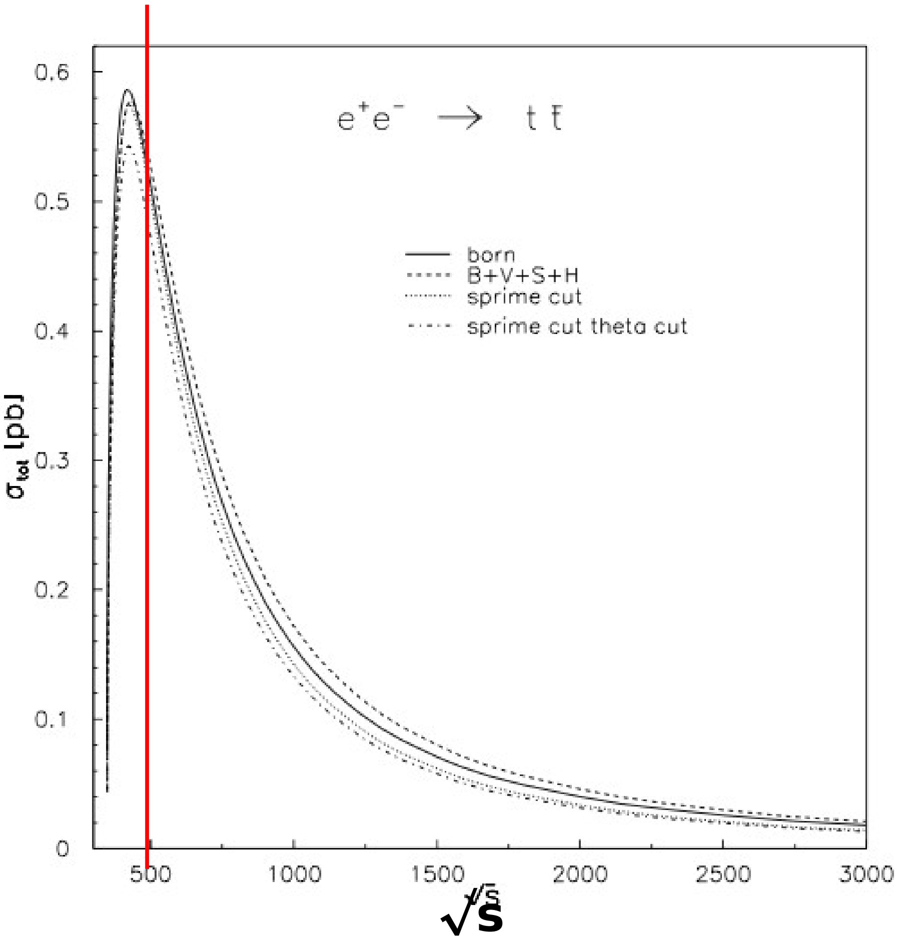
Equations for cross section, A_{FB} and F_R

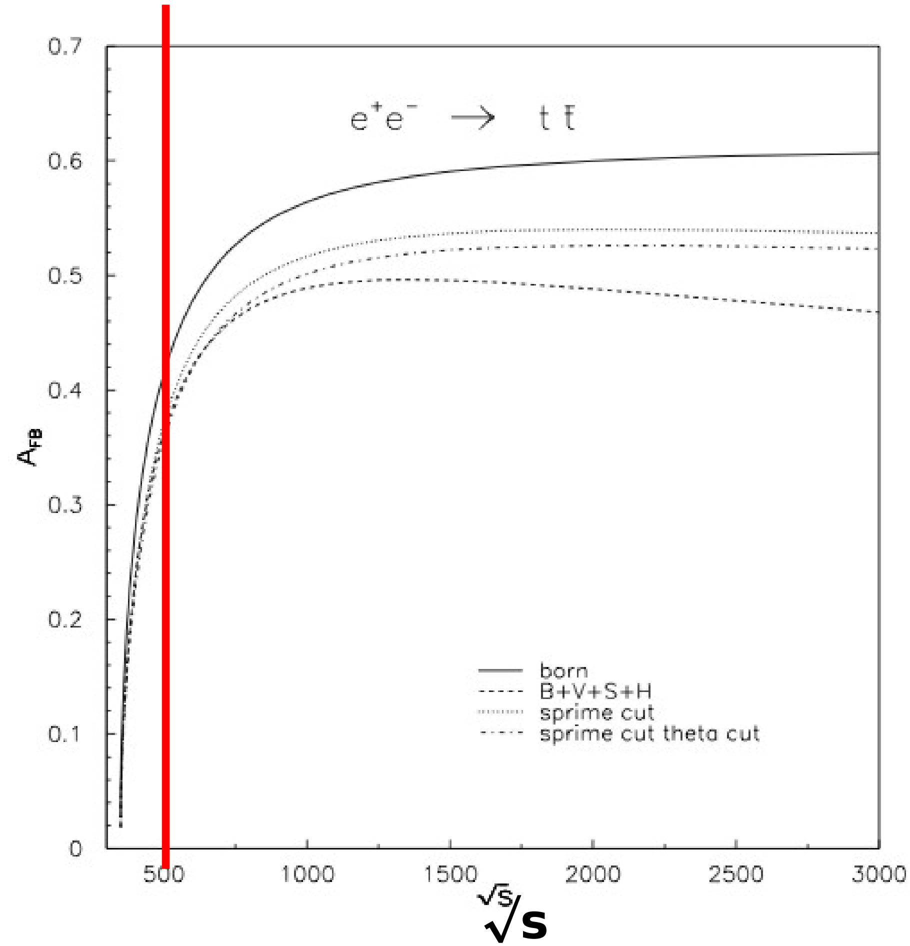
$$\sigma_I = 2\mathcal{A}N_c\beta\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right],$$

$$(A^t_{FB})_I = \frac{-3\mathcal{F}^{I'}_{1A}(\mathcal{F}^I_{1V}+\mathcal{F}^I_{2V})}{2\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right]},$$

$$(F_R)_I = \frac{(\mathcal{F}^I_{1V})^2(1+0.5\gamma^{-2}) + (\mathcal{F}^{I'}_{1A})^2 + 2\mathcal{F}^I_{1V}\mathcal{F}^{I'}_{1A} + \mathcal{F}^I_{2V}(3\mathcal{F}^I_{1V} + 2\mathcal{F}^{I'}_{1A}) - \beta\mathcal{F}^I_{1V}\mathfrak{Re}(\mathcal{F}^I_{2A})}{2\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right]}.$$

Why high(er) energies – e.g. 500 GeV





- Cross section close to maximum, A_{FB} well developed

- Other remarks: Need some velocity to get sensitive to chiral obervables (see backup slides)

Input to study

- Event generator WHIZARD interfaced to PYTHIA

  e^+e^- -> 6f: 250 fb^{-1} for two beam polarisations: $e_L^- e_R^+$ and $e_R^- e_L^+$

  Events were generated with full simulation and results were scaled for realistic beam polarisation $P, P' = \mp 0.8, \pm 0.3$

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

  Full Standard Model background
  Common samples for ILD and SiD studies

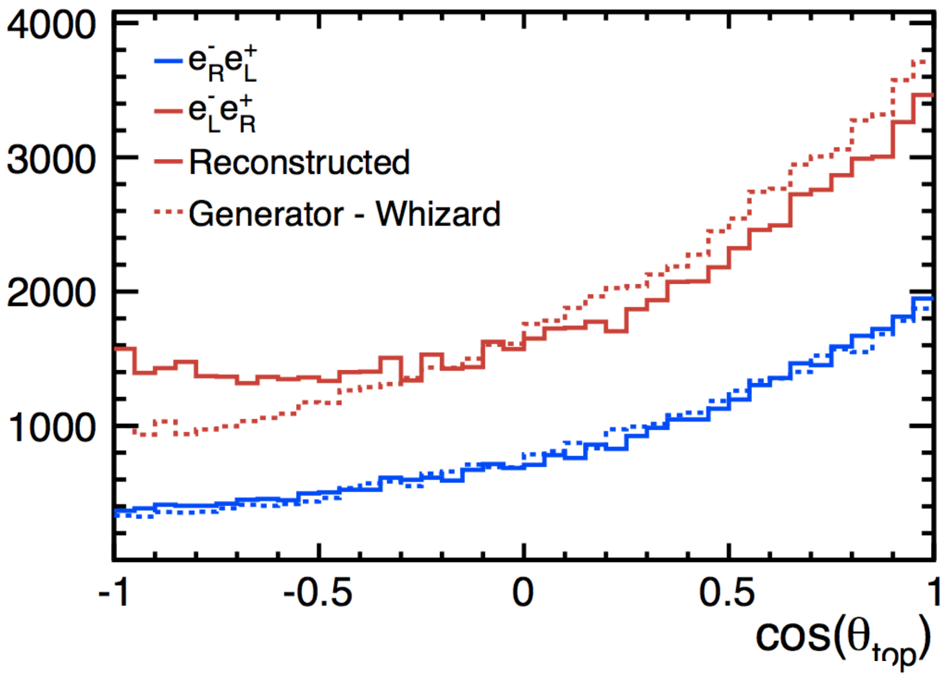
- GEANT4 and ILCSoft for detector simulation and reconstruction

- ILD features a full software suite

  - Mokka as geometry interface to GEANT4
  - MARLIN as analysis framework for event reconstruction
  - Interface to toolkits such as PandoraPFA or LCFIVertex

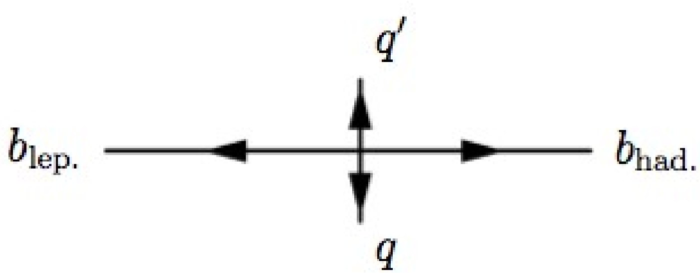
- Detector simulation is based on input from worldwide detector R&D

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



Left handed top quarks

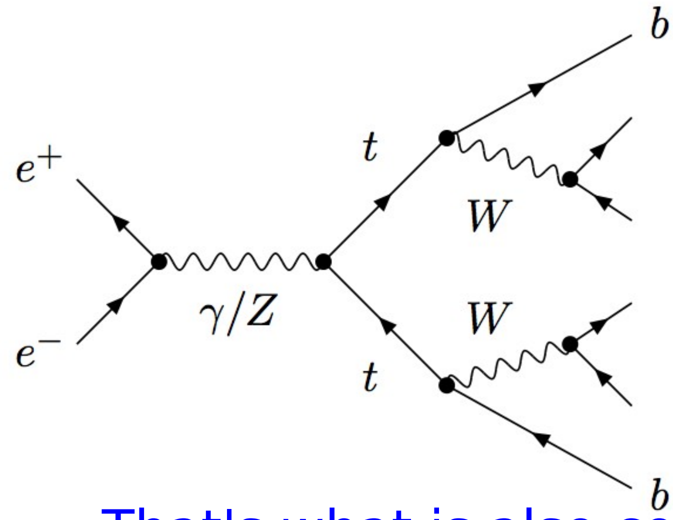
- top quark direction from hadronically decaying top (b+W)
- V-A structure of ttX vertex leads to soft W and hard b-quarks

=> 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)

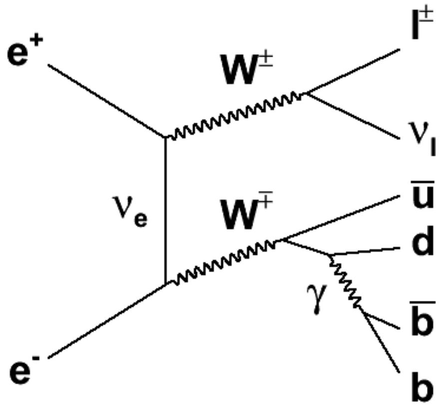
Closer look at ttbar production

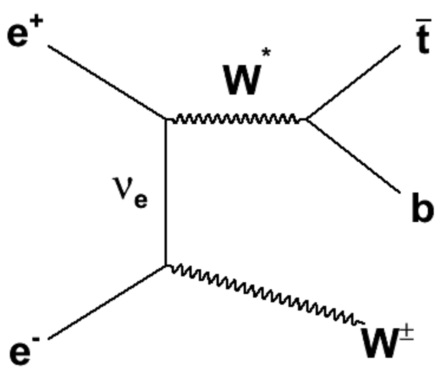
That's what we are interested in



Top pair production is effectively ee->6f process

That's what is also contributing to final state!



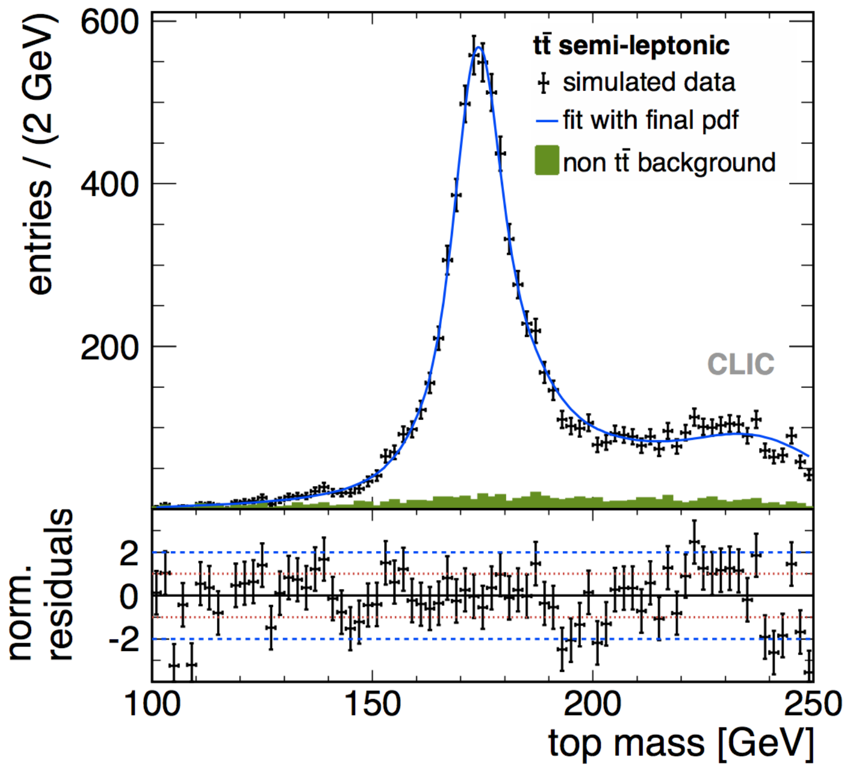


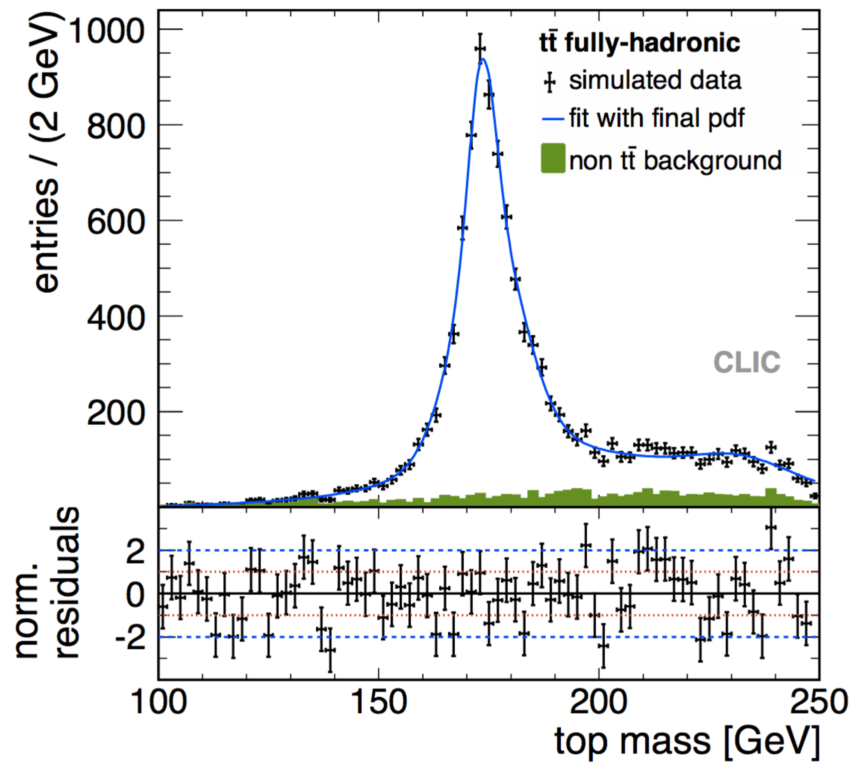
+ s-channel, t-channel only relevant for eL

- Can one really speak about a ttbar cross section?
- If only 6f is relevant: What are relations to ttX couplings?
- What selection cuts are (theoretically) save?

Top mass spectrum in continuum – 500 GeV

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

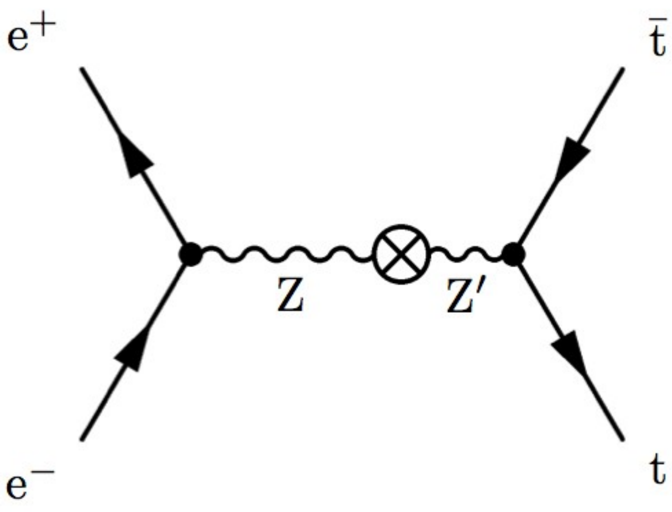


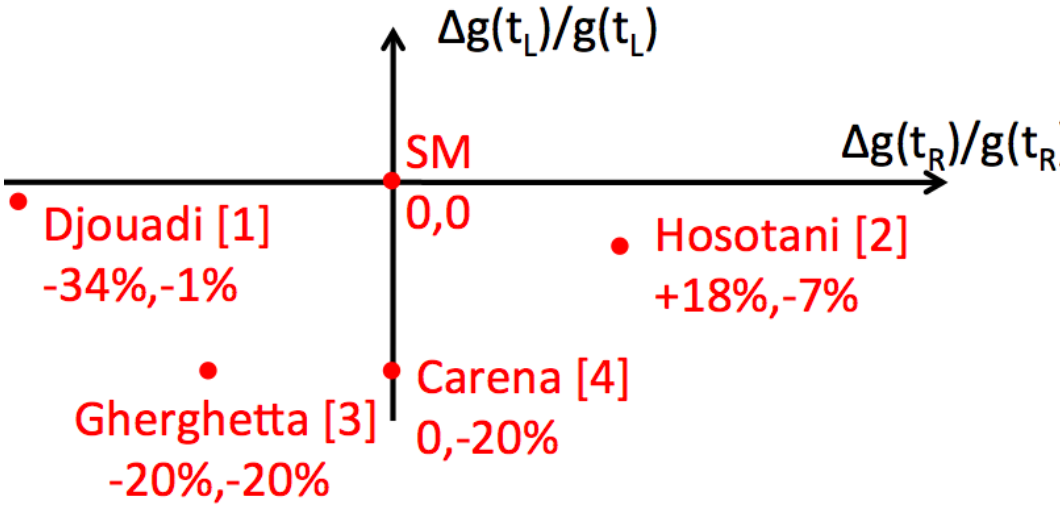


- (Almost) background free measurement

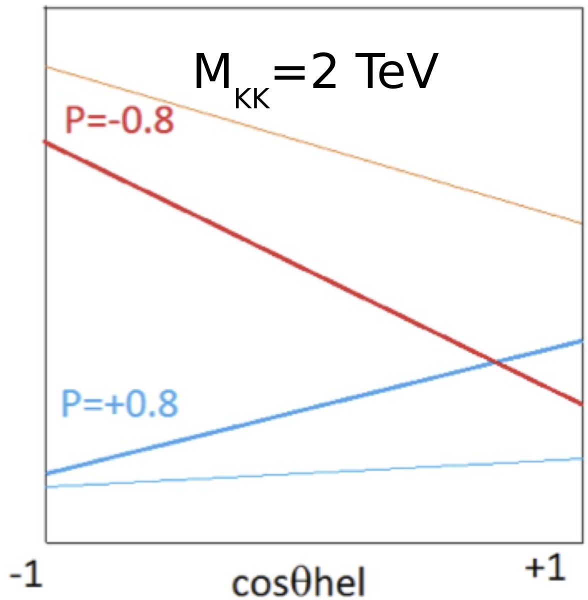
Top quark and new physics

New physics modify electroweak couplings to Z





Example: RS models with extra dimensions



ILC sensitive to M_{KK} masses up to 50 TeV

$(g\text{-}2)_t$

$$F_{2V}^{\gamma} = Q_t (g-2)_t / 2$$

$$\delta F_{2V}^{\gamma} = \delta (g-2)_t \approx 0.1$$

$$\delta (g-2)_t \approx 0.1\% \propto m_t / M$$

=> Test of compositeness scale M up to 100 TeV