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(info@eps-hep2013.eu)

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

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Based on work in the groups of

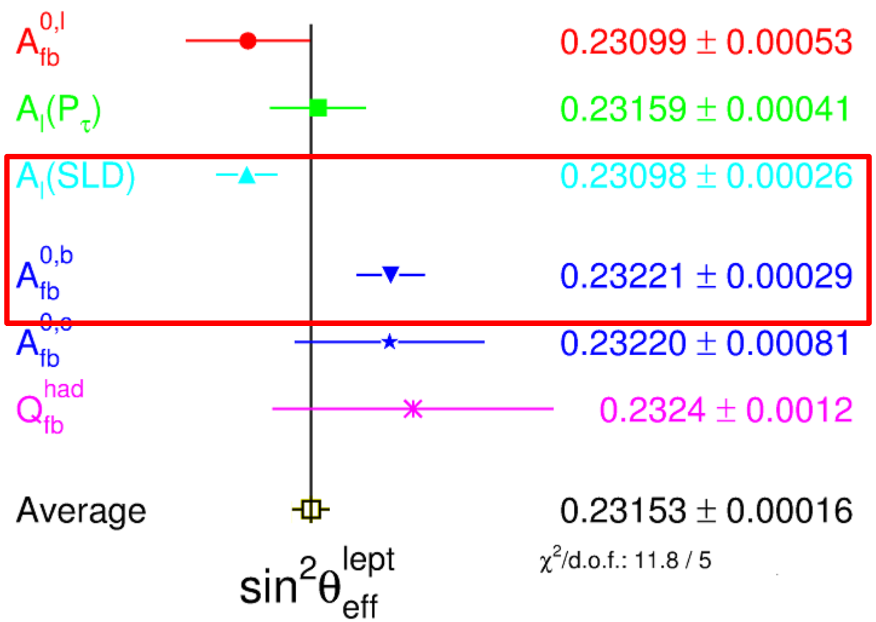
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE — UNIVERSITÉ PARIS SUD — UNIVERSITAT DE BARCELONA — ICCUB — SIC Sistemes d'Instrumentació i Comunicacions — IFIC INSTITUT DE FÍSICA CORPUSCULAR

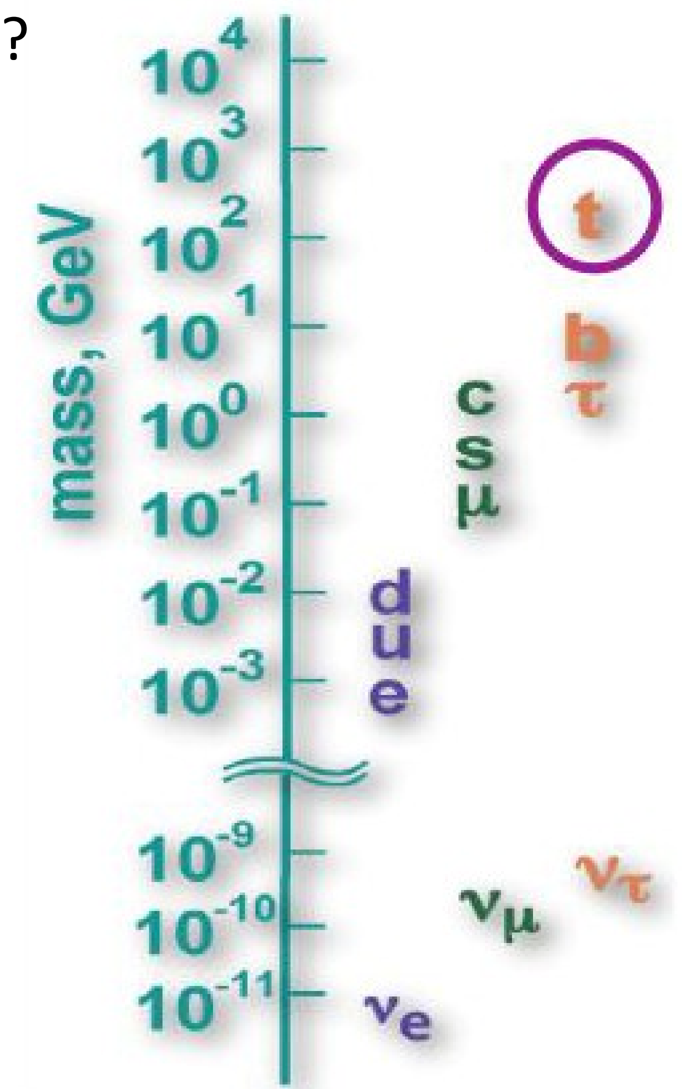
… and the ILD Detector concept

EPS-HEP - Stockholm July 2013

The top quark and flavor hierarchy

- Flavor hierarchy ? Role of 3rd generation ?





- A_{FB} anomaly at LEP for b quark

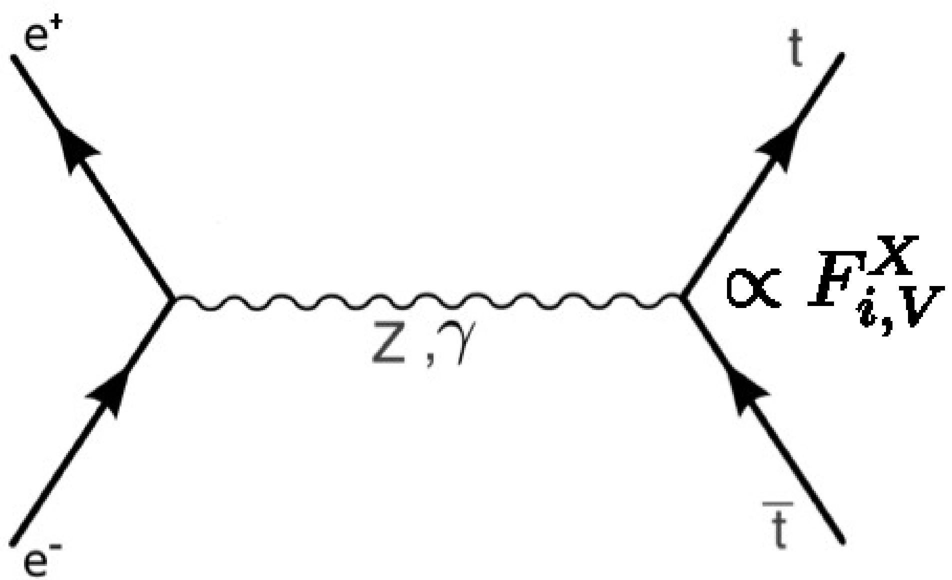
Tensions at Tevatron

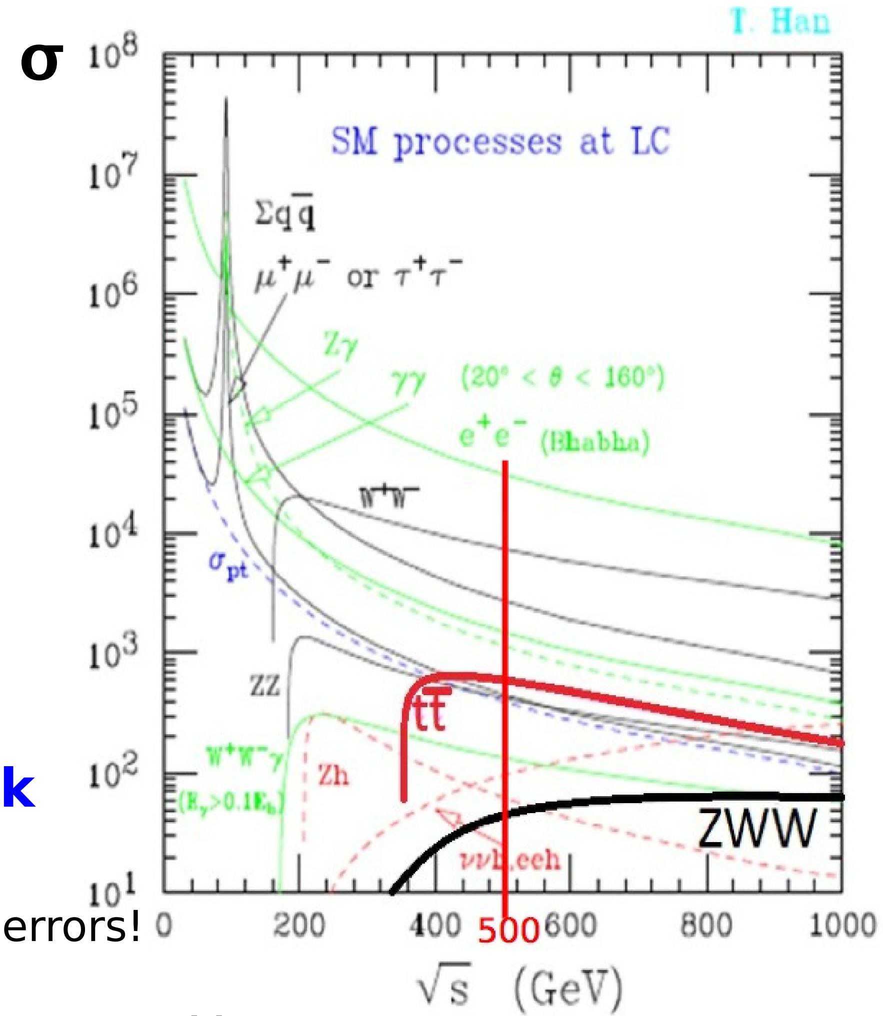
- Heavy fermion effect

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,

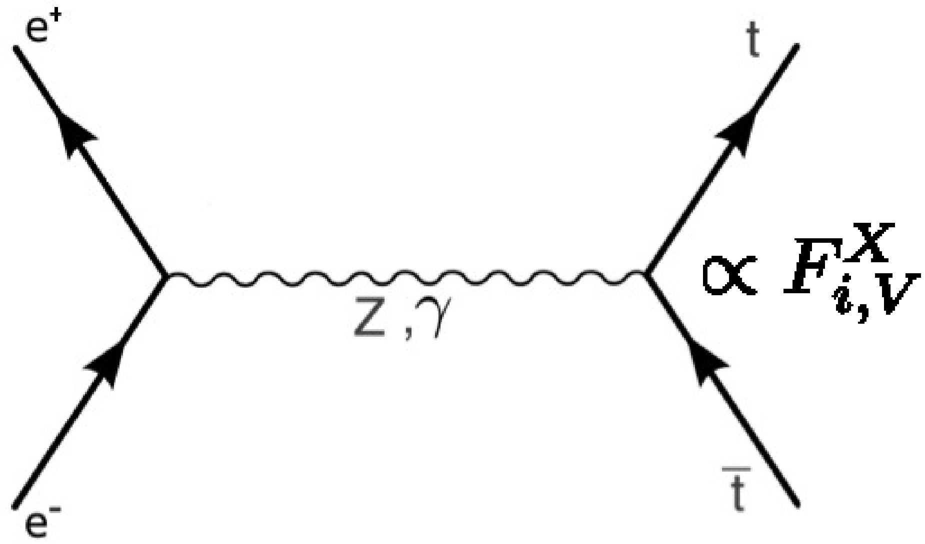
  no competing QCD production => Small theoretical errors!

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

  More on physics with polarised beams by G. Moortgat-Pick

-ILC is promising for high precision top quark 'tomography'
(See also talk on mass measurement by Philipp Roloff)

Testing the chiral structure of the Standard Model



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

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

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

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.

σ_I

$$A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

$$(F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$$

x-section

Forward backward asymmetry

Fraction of right handed top quarks

⇩

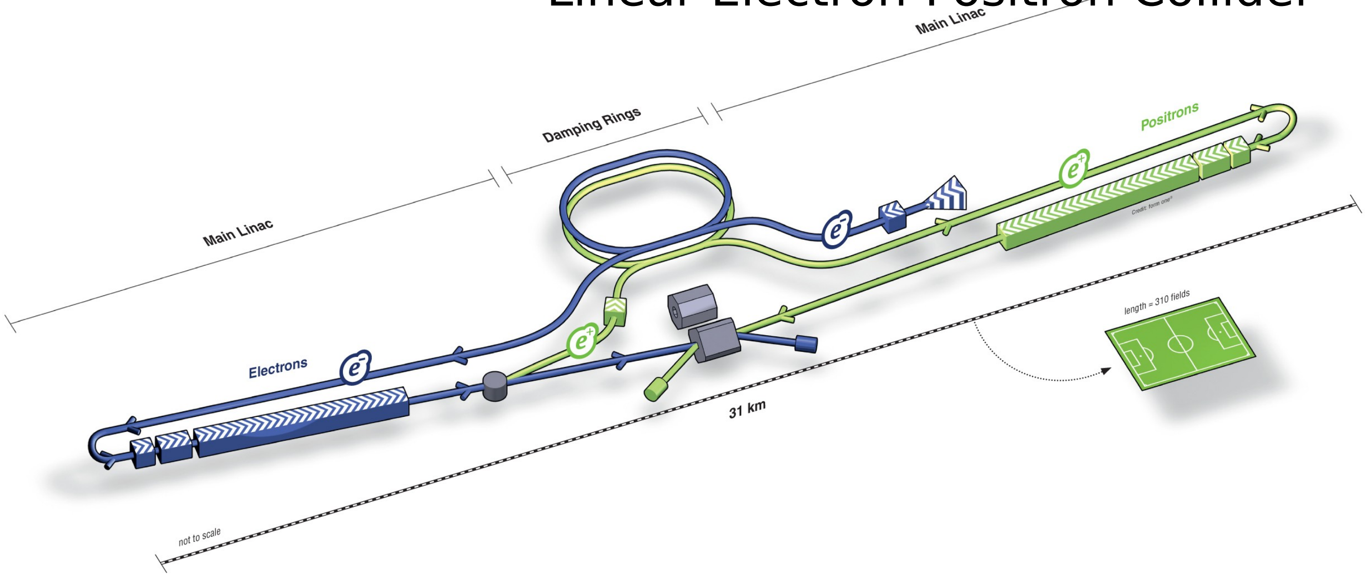
Extraction of six (five) unknowns

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

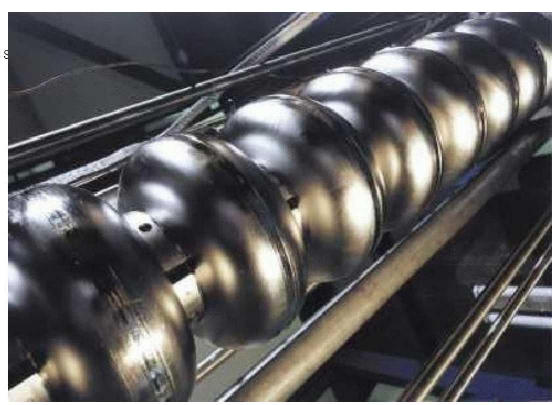
$F^{\gamma}_{2V},\ F^{Z}_{2V}$

The International Linear Collider ILC

Linear Electron-Positron Collider



Total footprint 31 km



Technology for main linac

Superconductive RF cavity

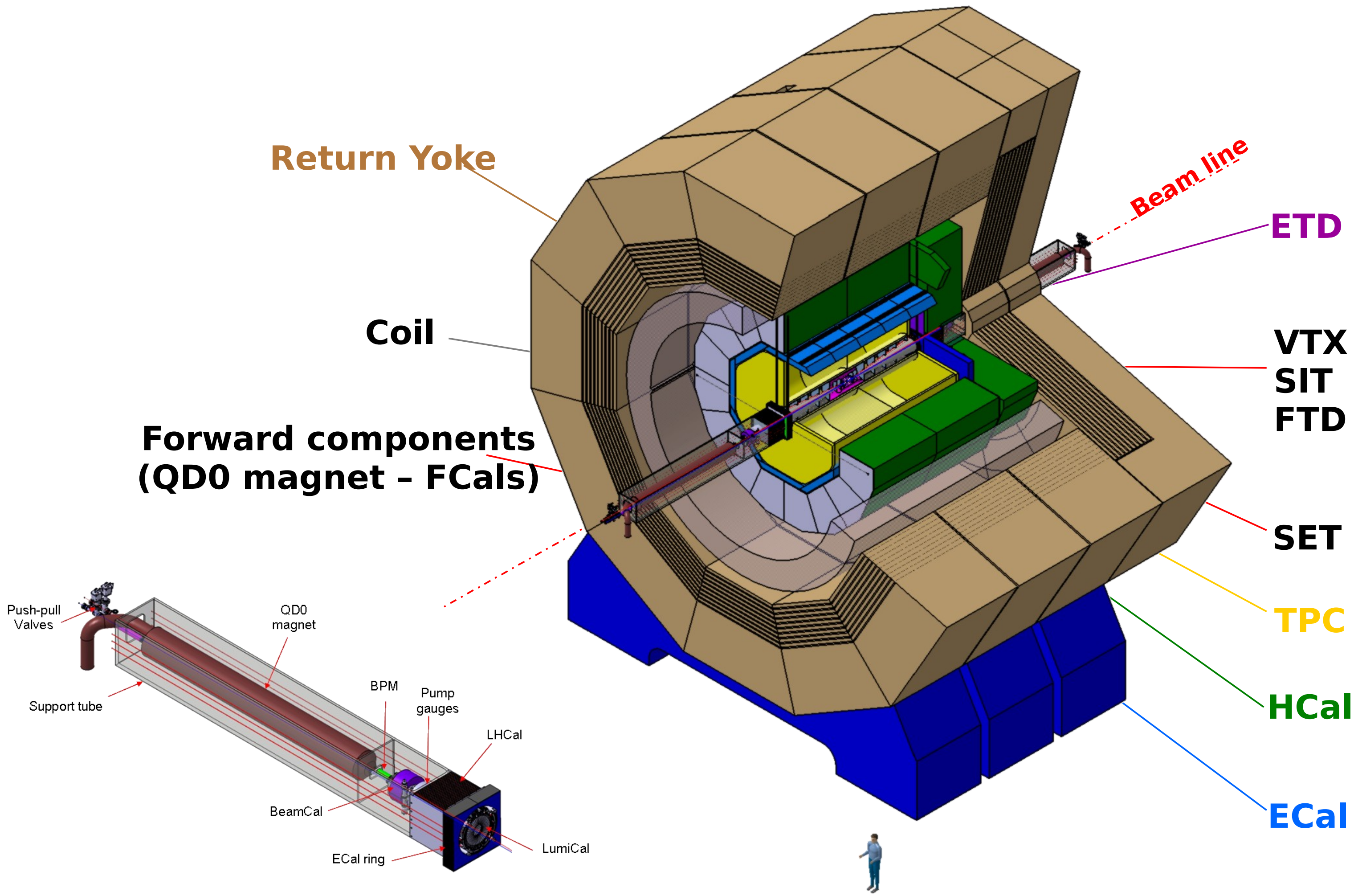
ITRP Recommendation 2004

Main parameters

- $\sqrt{s}$ adjustable from 200 – 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

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

Elements of top quark reconstruction

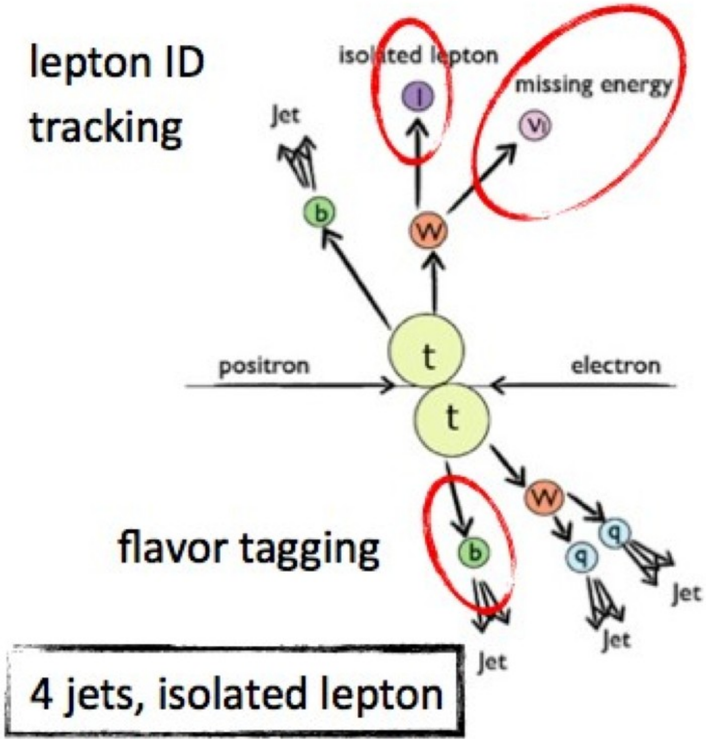
Three different final states:

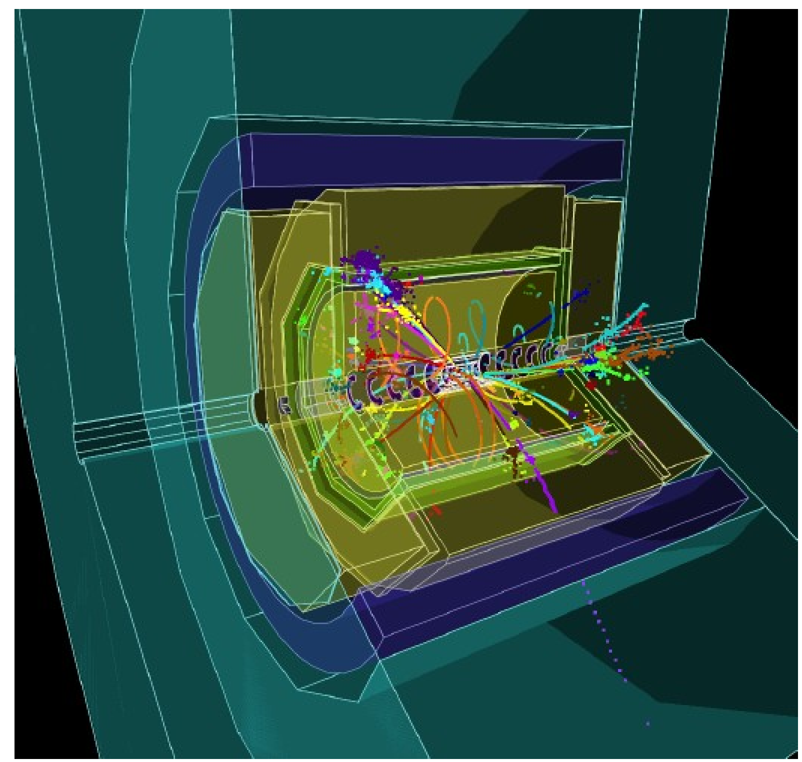
1) Fully hadronic (46.2%) → 6 jets

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

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

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

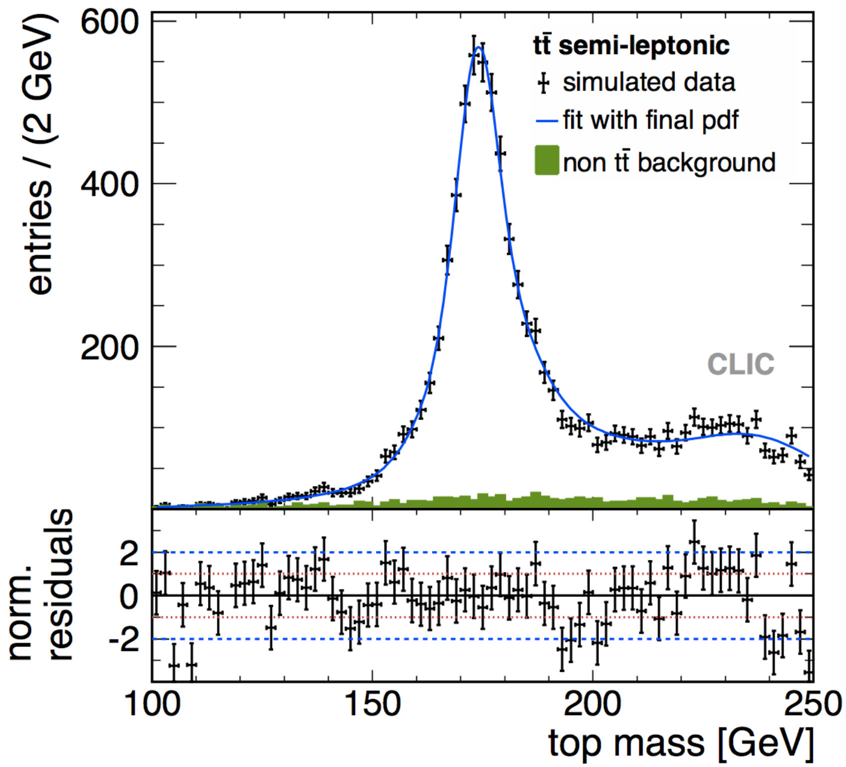


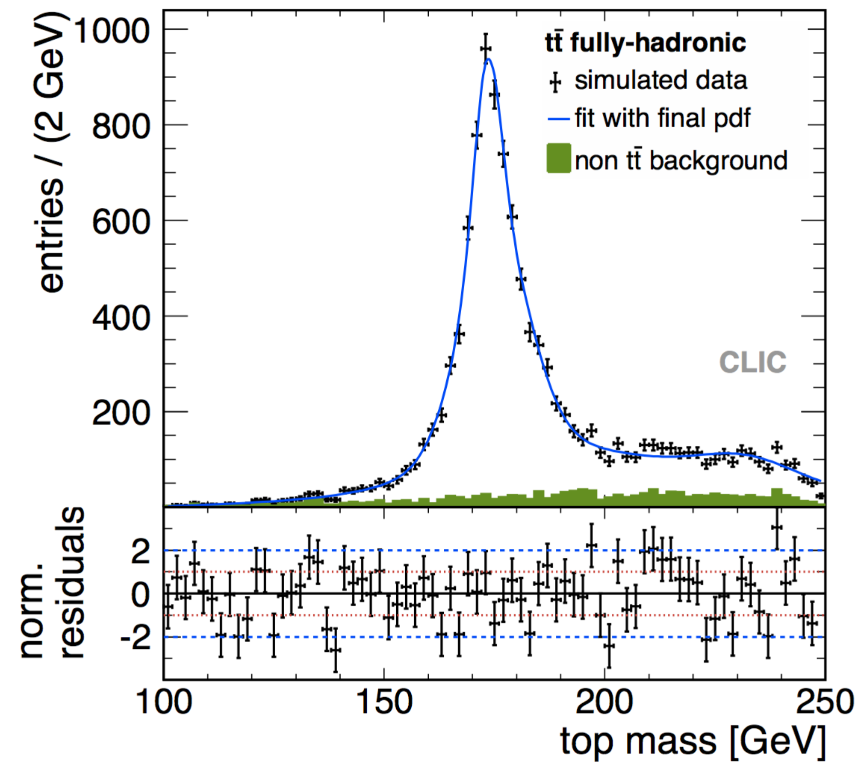


Final state reconstruction uses all detector aspects

Top mass spectrum in continuum – 500 GeV

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



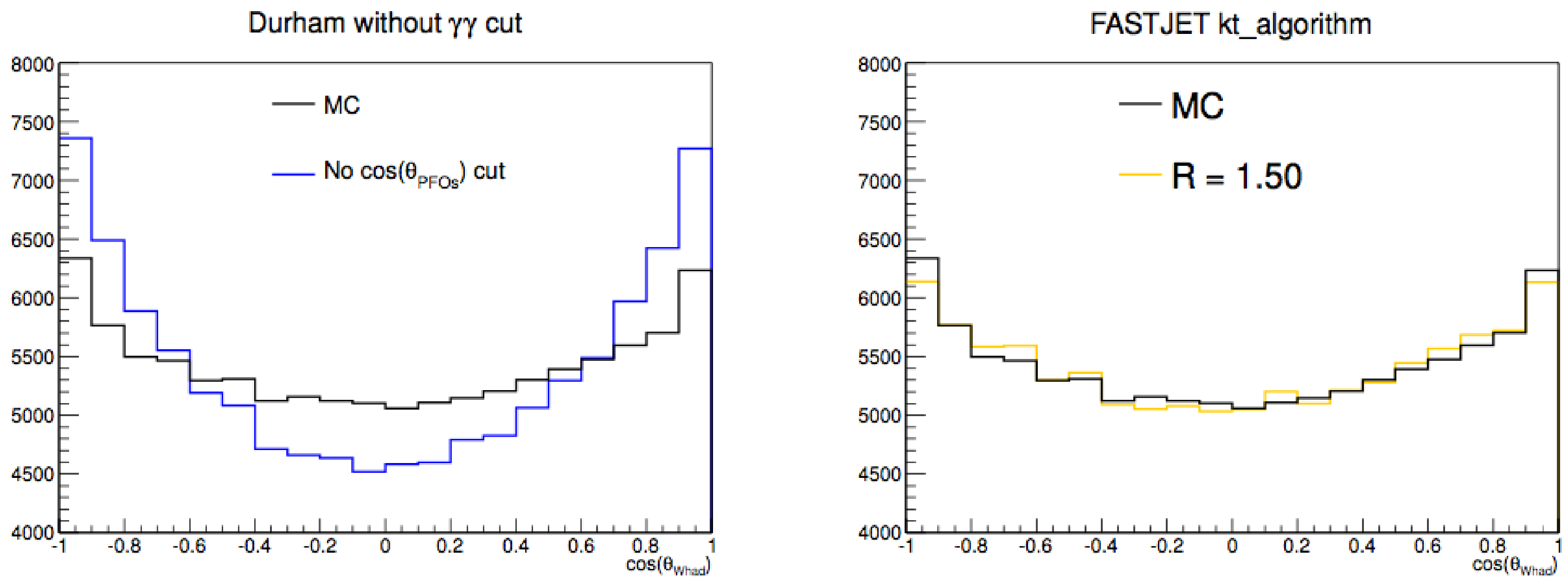


- (Almost) background free measurement

Discussion of pile up

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

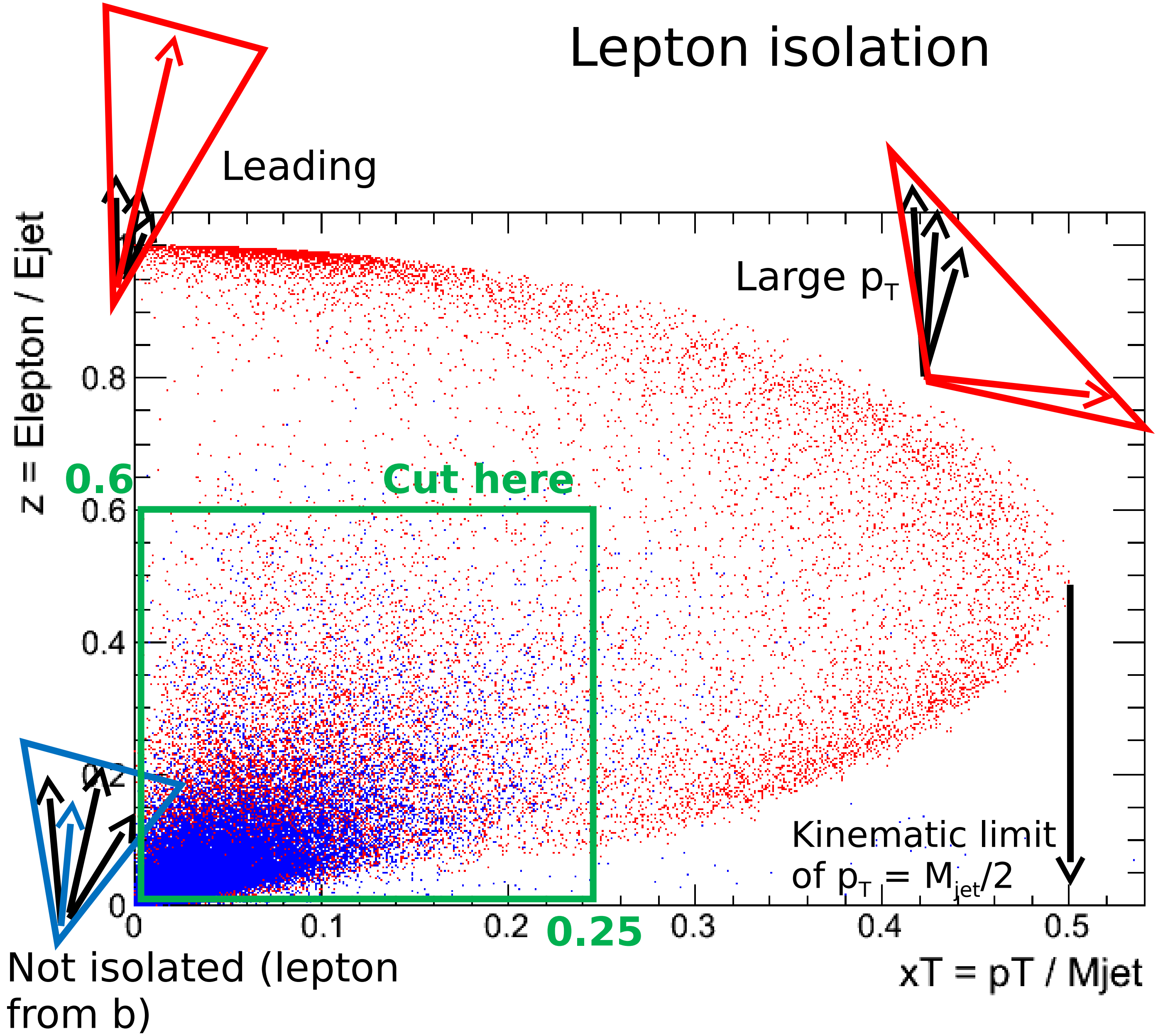
Study of different jet algorithms: Example polar angle of W boson



(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



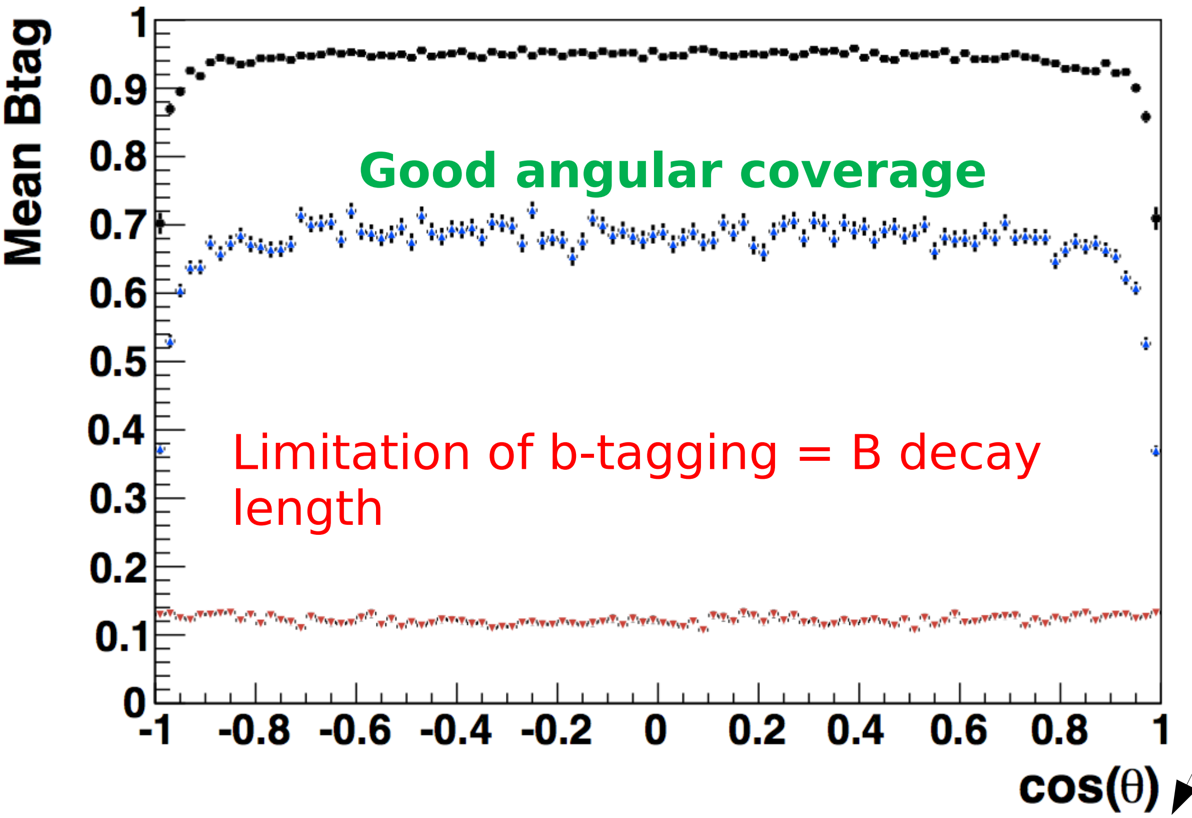
Red = leptons in semileptonic top events

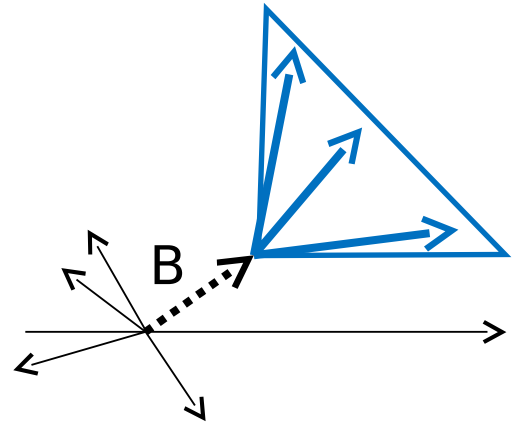
Blue = leptons in full hadronic top events = leptons from b

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



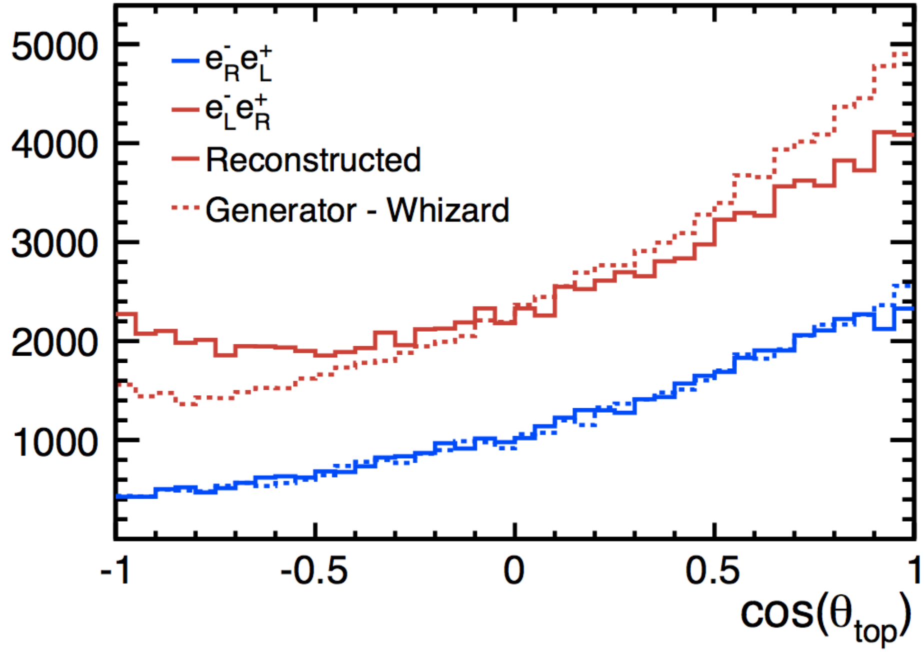


- 4 jets
- 2 highest Btag = b_1 & b_2
- 2 "light" jets = W

Polar angle of b-jet

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

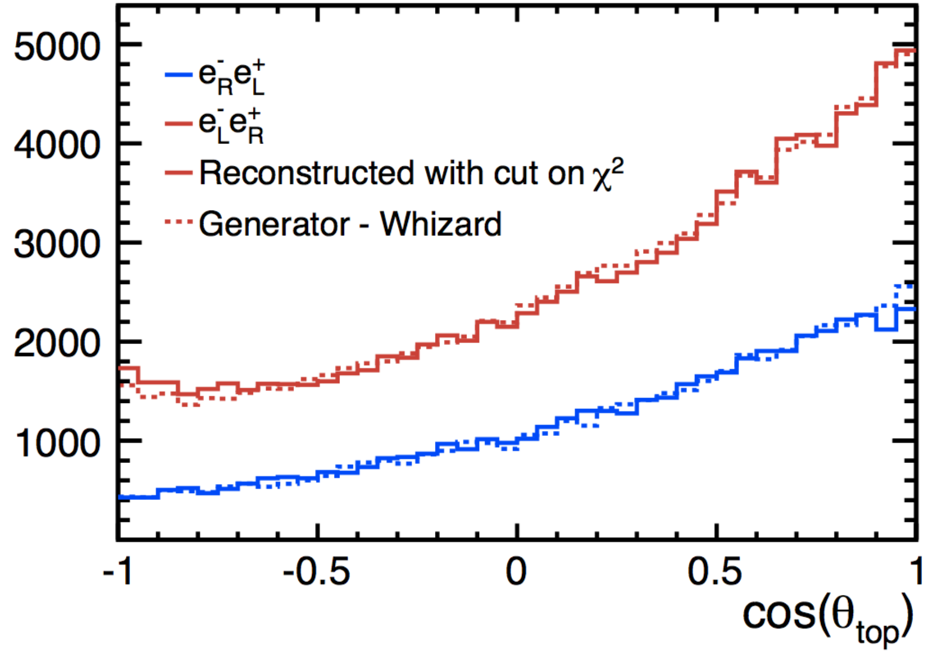
Reconstruction of top quark production angle



Ambiguities in case of
left handed electron beams
Due to V-A structure at ttX 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%

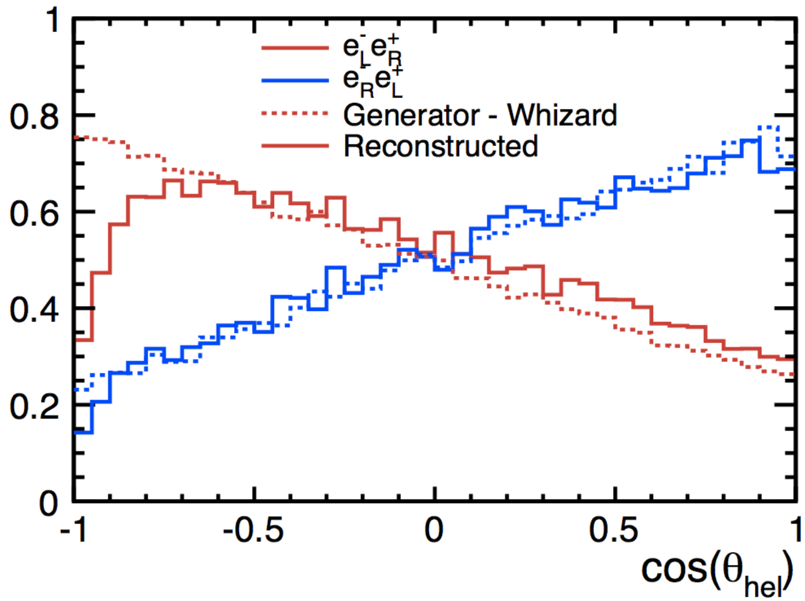
Measurement of top quark polarisation

Measure angle of decay lepton in <u>top quark rest frame</u>
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

- 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:

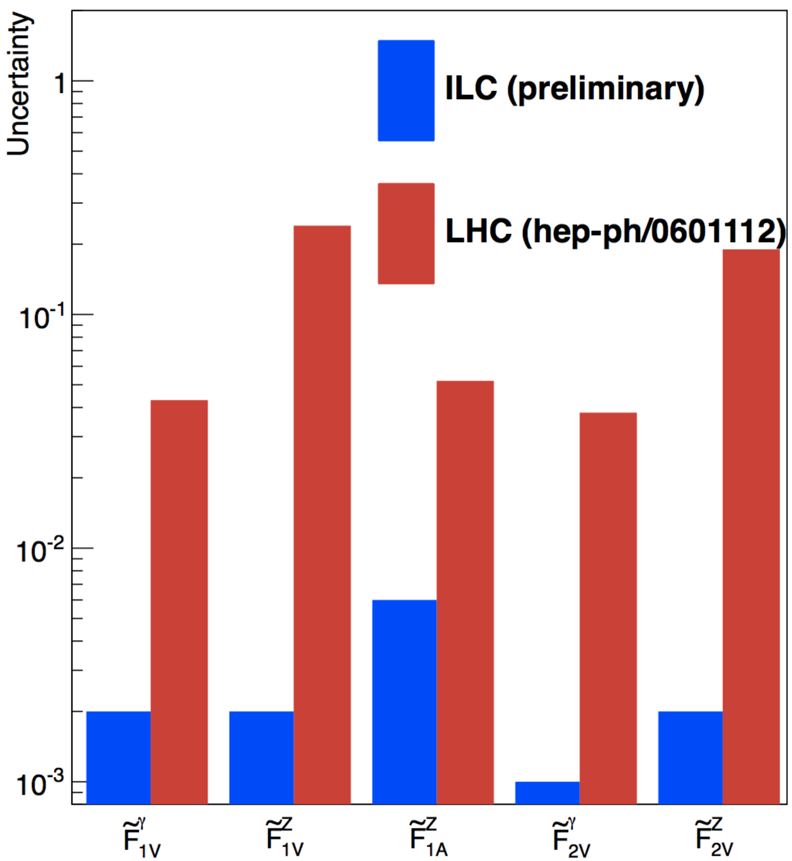
- Role of single top production (15% of 6f final state)
- Electroweak NLO predictions (Correction LO → NLO ~ 15%)

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

LC-REP-2013-007

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

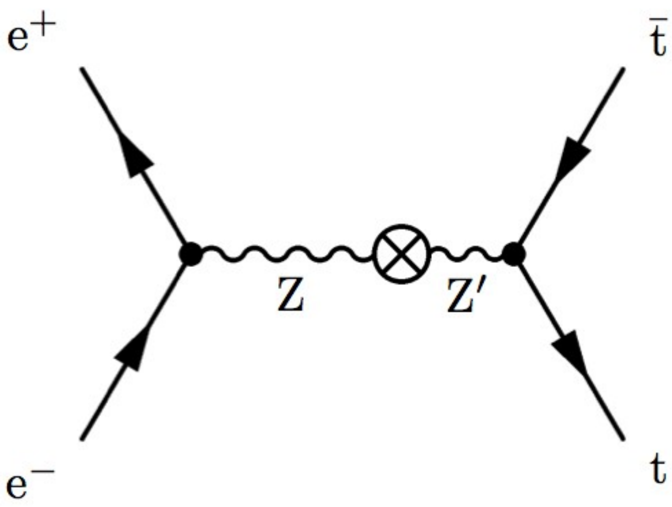
- Strong encouragement to update these numbers!
  First step is Phys. Rev. Lett. 110 (2013) 172002 by CMS

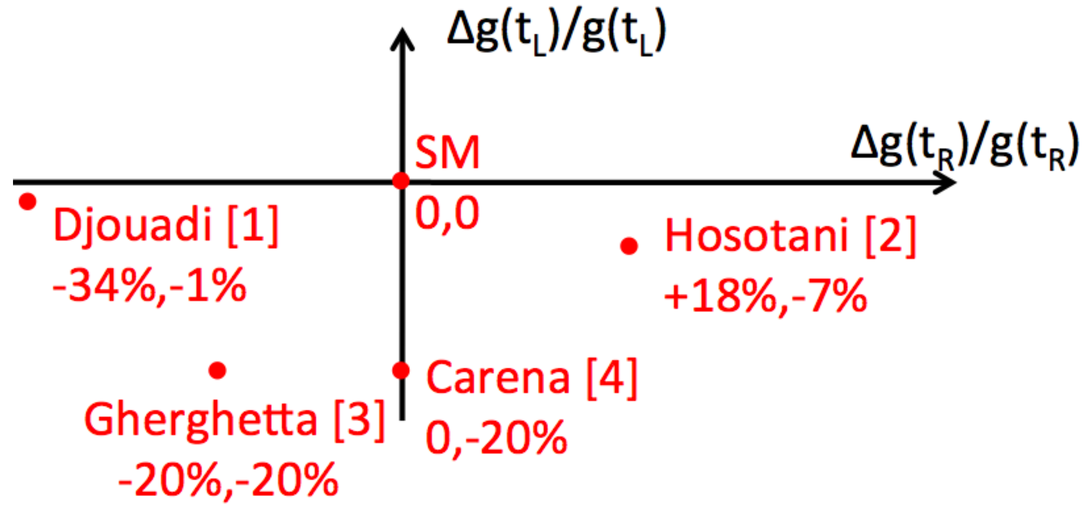
- Potential for CP violating couplings at ILC under study

ILC will be indeed high precision machine for electroweak top couplings

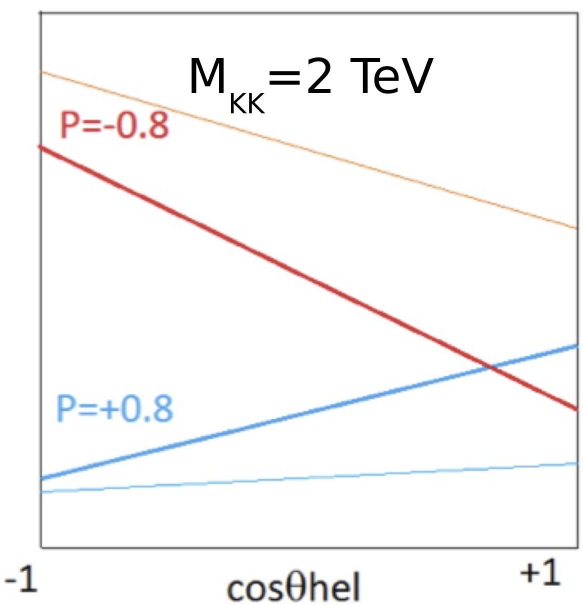
Top quark and new physics

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

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

  Sensitivity to new physics up to 100 TeV

  Btw.: Composite top (or Higgs) would be new physics

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

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

Backup

The solid pillars of the LC physics program

Top quark

Discovered 1995 at Tevatron

LHC and ILC are/would be
Top factories

W Boson

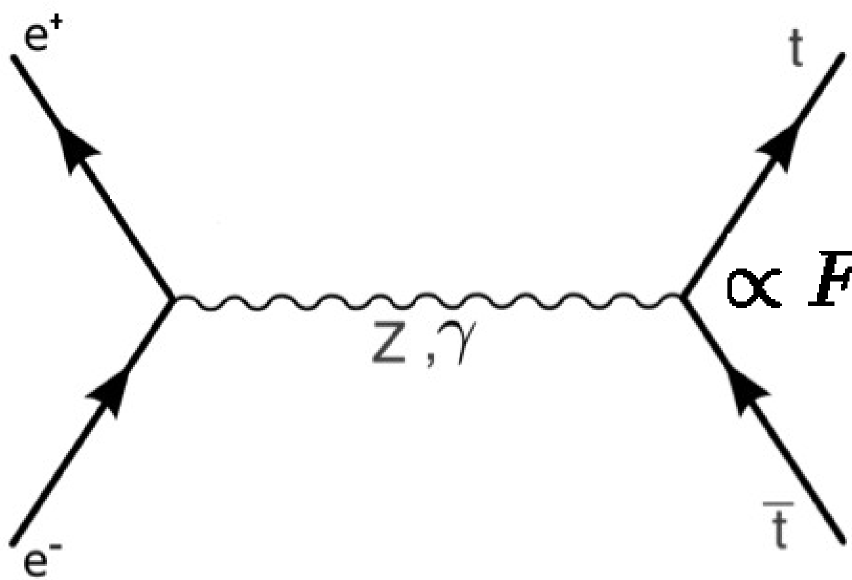
Discovered 1979 at SPS
Mass precisely at Tevatron
LHC and ILC are/would be
W factories

Higgs Boson

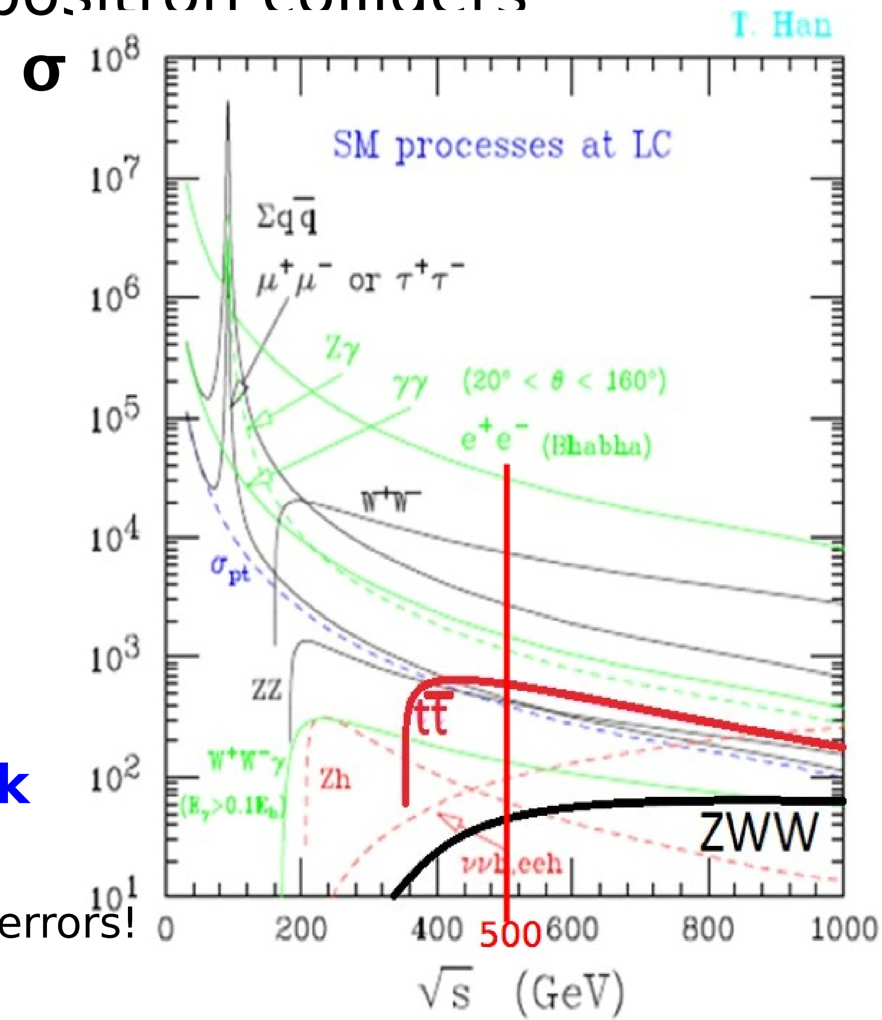
Discovered 2012 at LHC

LHC and ILC are/would be
Higgs factory

Top quark physics at electron-positron colliders



$\propto F^X_{i,V}$



- 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 (talk by ...)

  Polarised beams allow to test chiral structure at ttX vertex

  => Precision on form factors F (this talk)

- A major difference between LC and LHC is that an LC will run triggerless

  -> Unbiased event samples, all event selection happens off-line!

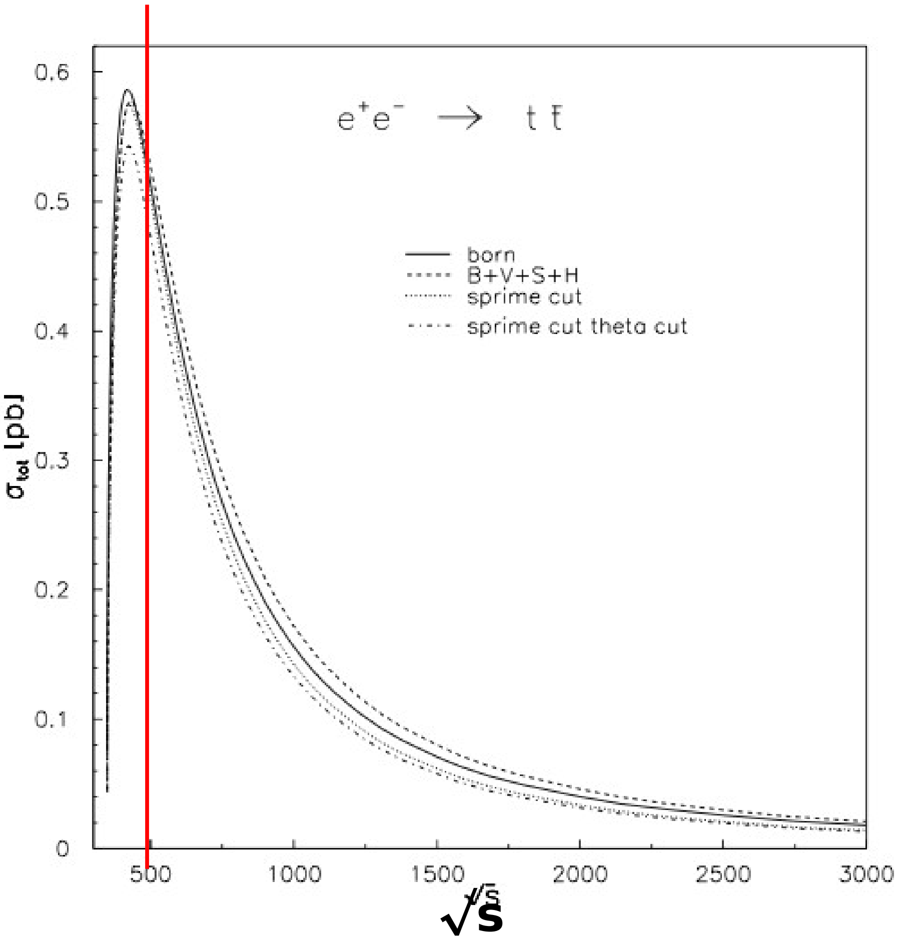
Equations for cross section, A_{FB} and F_R

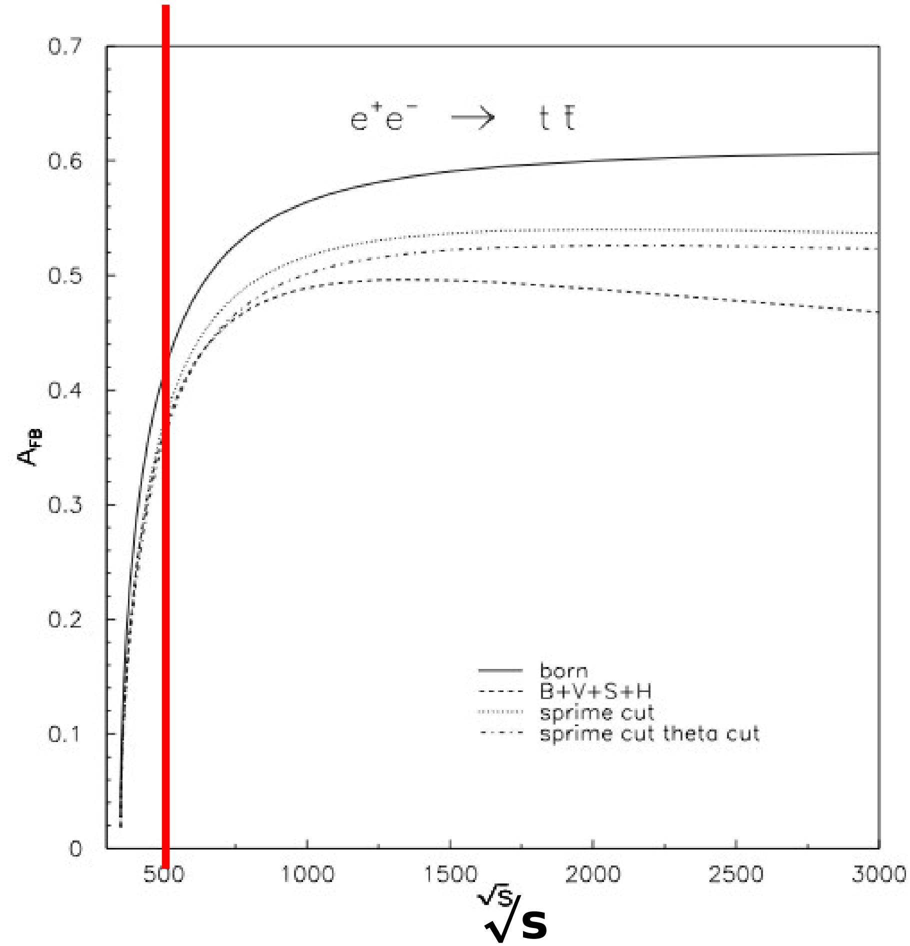
$$\sigma_I = 2\mathcal{A}N_c\beta\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right],$$

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

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

Why high(er) energies – e.g. 500 GeV



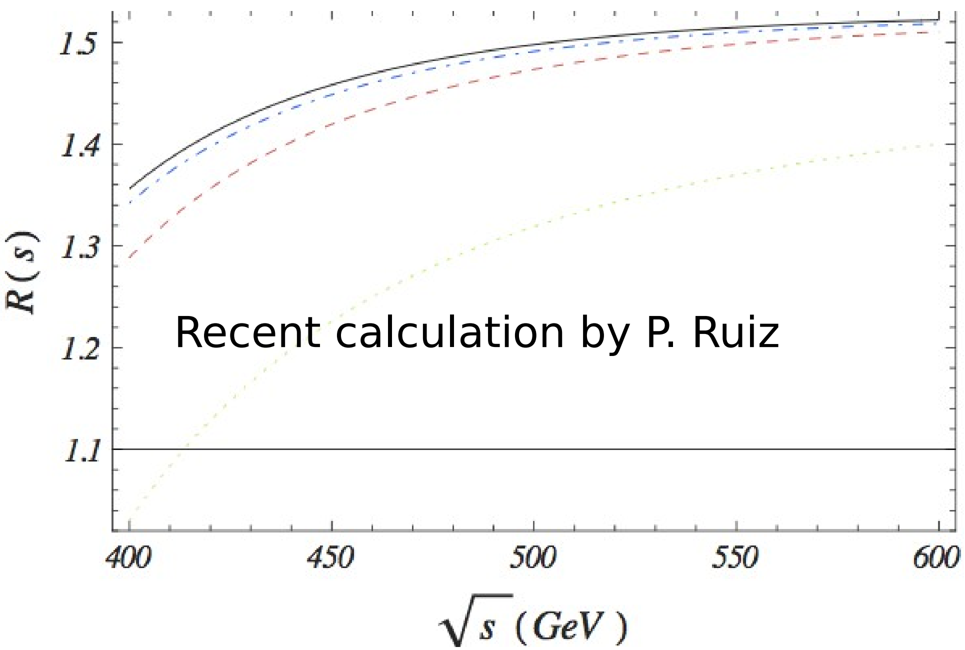


- Cross section close to maximum, A_{FB} well developed

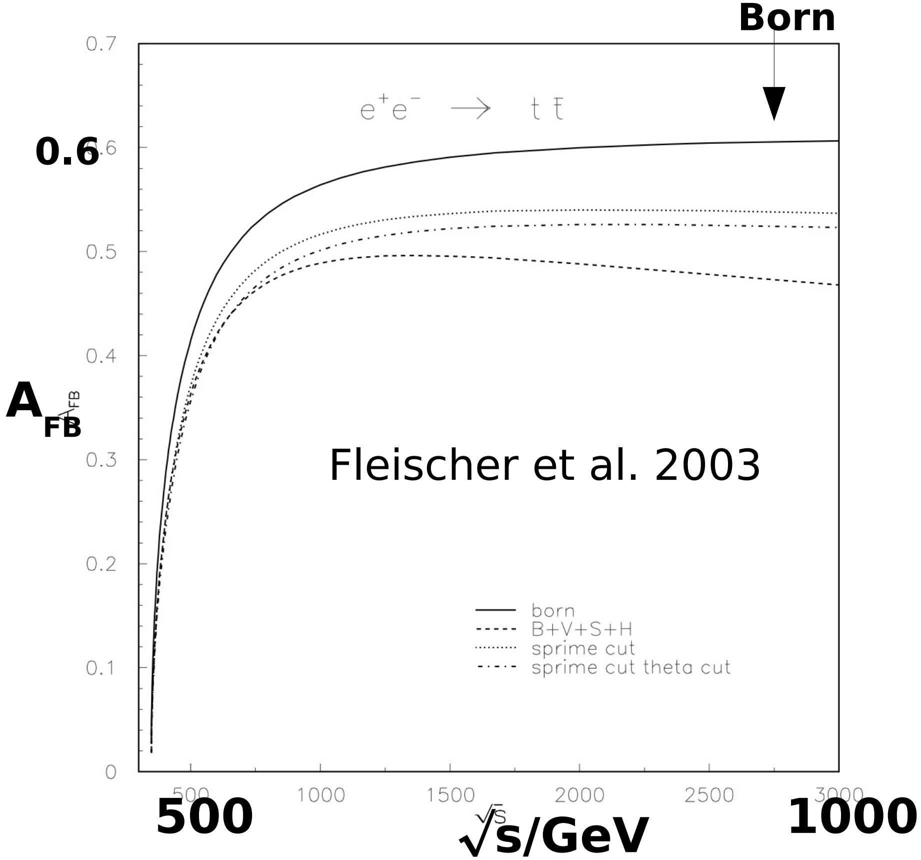
- Other remarks: Need some velocity to get sensitive to chiral obervables (see backup slides)

SM correction to Born process

QCD up to $O(a_s^3)$



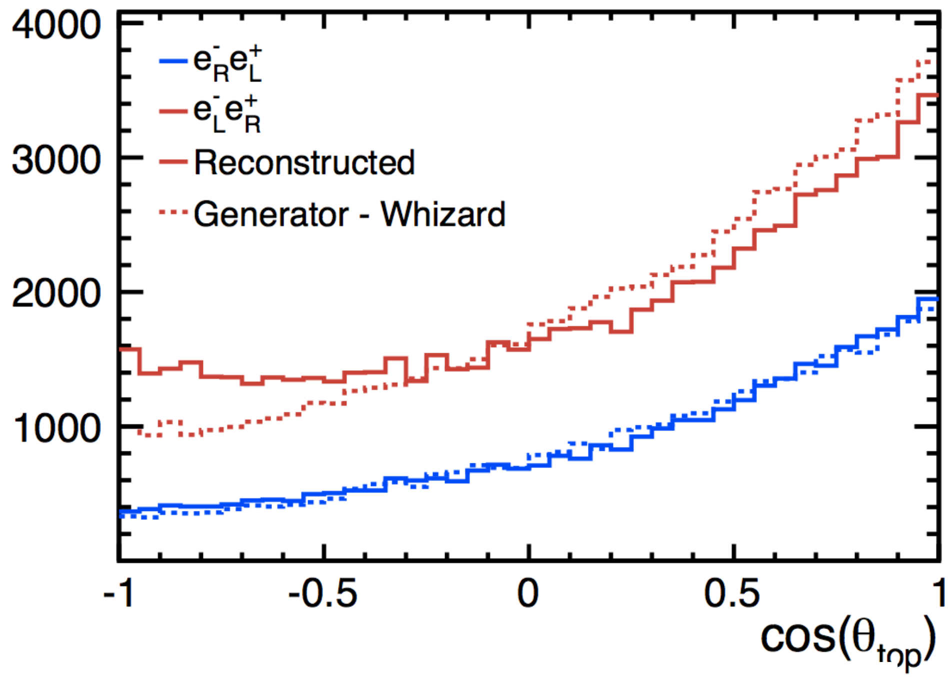
NLO electroweak



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

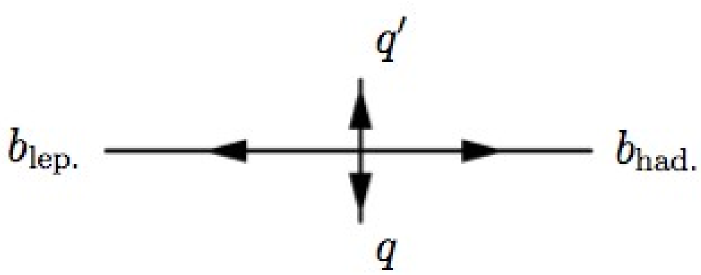
- Sizeable electroweak corrections to AFB (~15%)
- (To my knowledge) no estimation of size of next (i.e. NNLO correction) Needed for precision physics !(?)

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

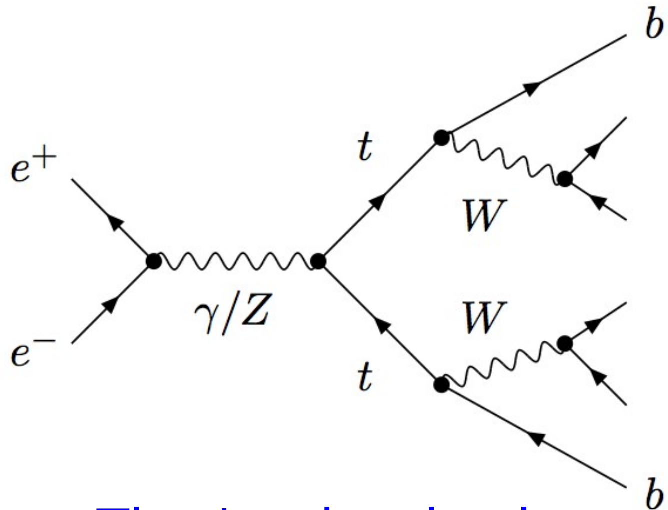
- top quark direction from hadronically decaying top (b+W)
- V-A structure of ttX vertex leads to soft W and hard b-quarks

=> 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)

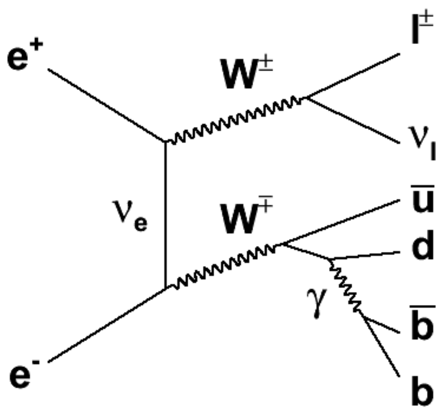
Closer look at ttbar production

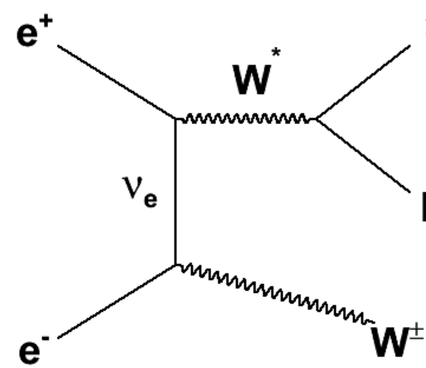
That's what we are interested in



Top pair production is effectively ee->6f process

That's what is also contributing to final state!



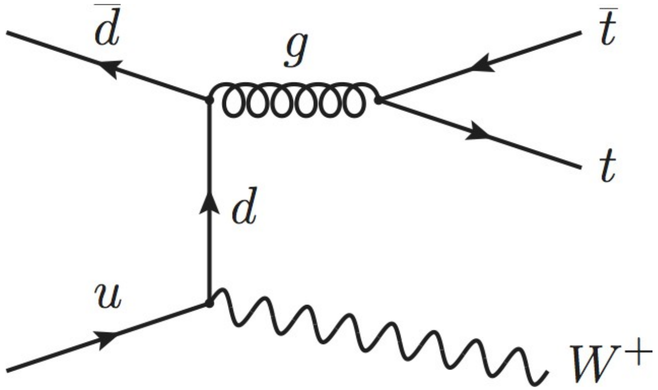


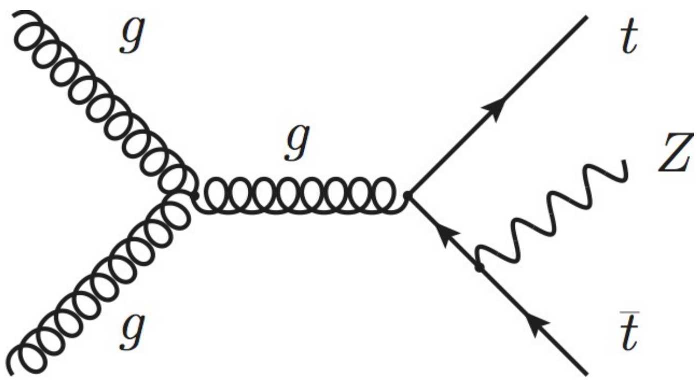
+ s-channel, t-channel only relevant for eL

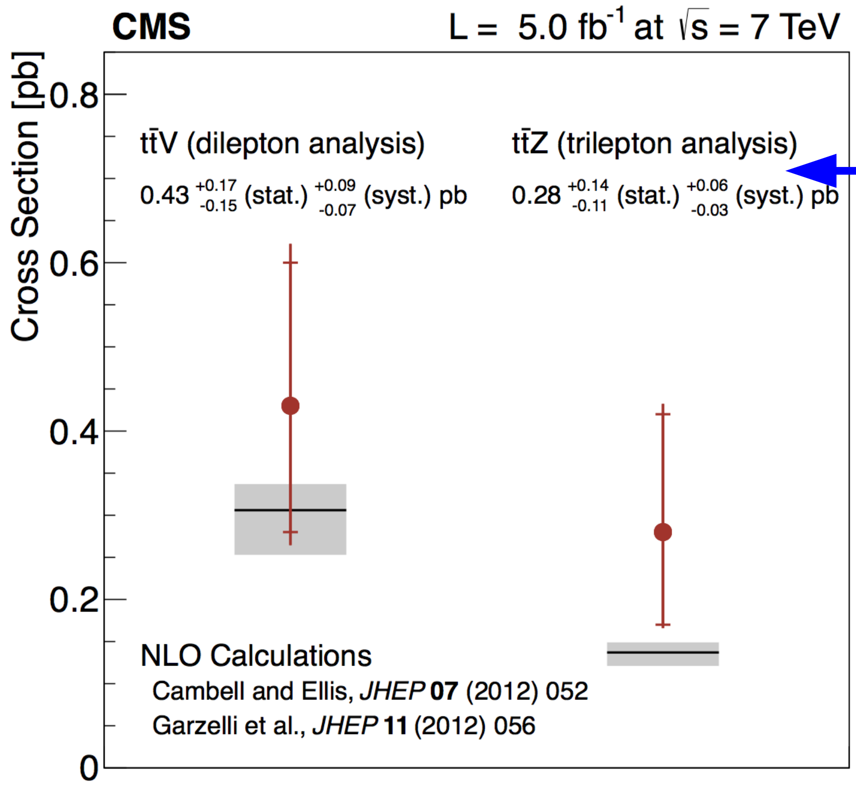
- Can one really speak about a ttbar cross section?
- If only 6f is relevant: What are relations to ttX couplings?
- What selection cuts are (theoretically) save?

The race is open !

Recent 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
- How will it evolve with higher Luminosity?
- Revision of 'old' estimations of precisions are needed!