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

Roman Pöschl for Mohammed Sohail Amjad

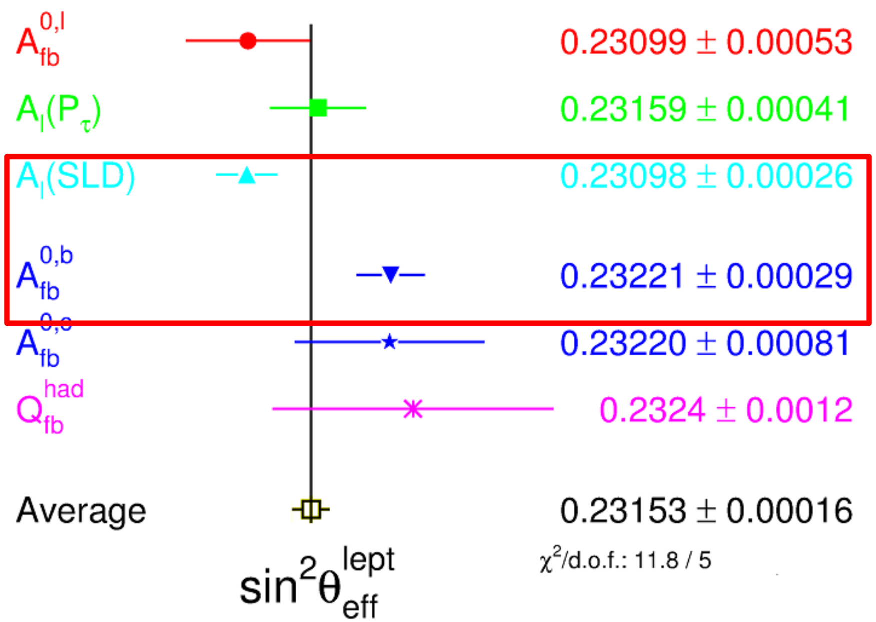
In collaboration with ...

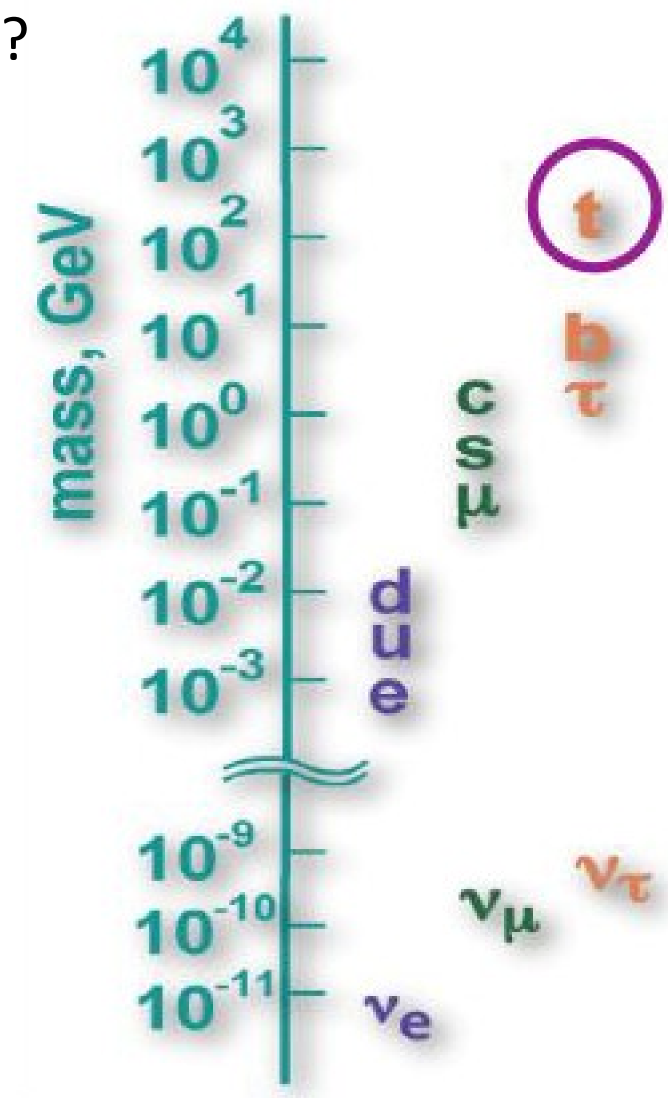
... and the ILD Detector concept

2eme Journées Collisionneur Linéaire – IRFU November 2013

The top quark and flavor hierarchy

- Flavor hierarchy ? Role of 3rd generation ?





- A_{FB} anomaly at LEP for b quark

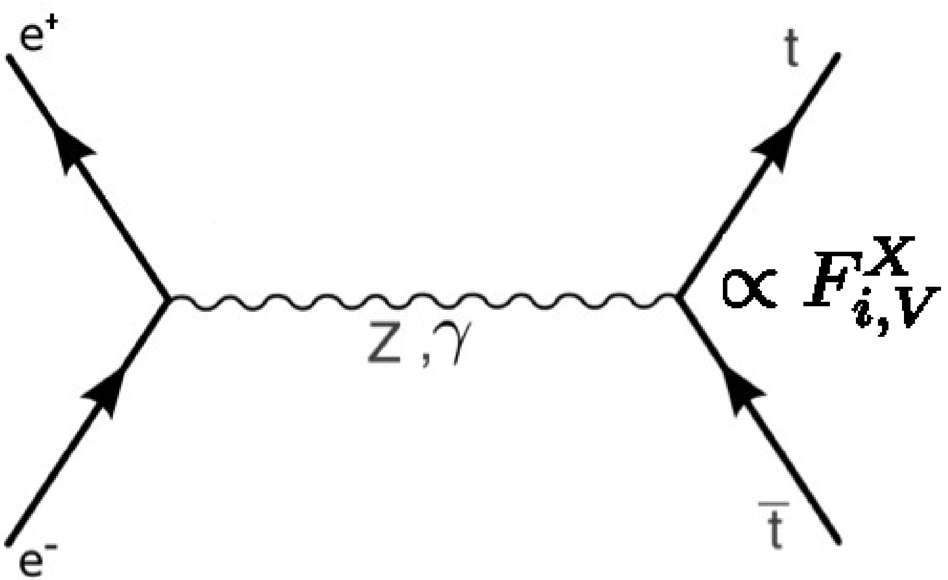
Tensions at Tevatron

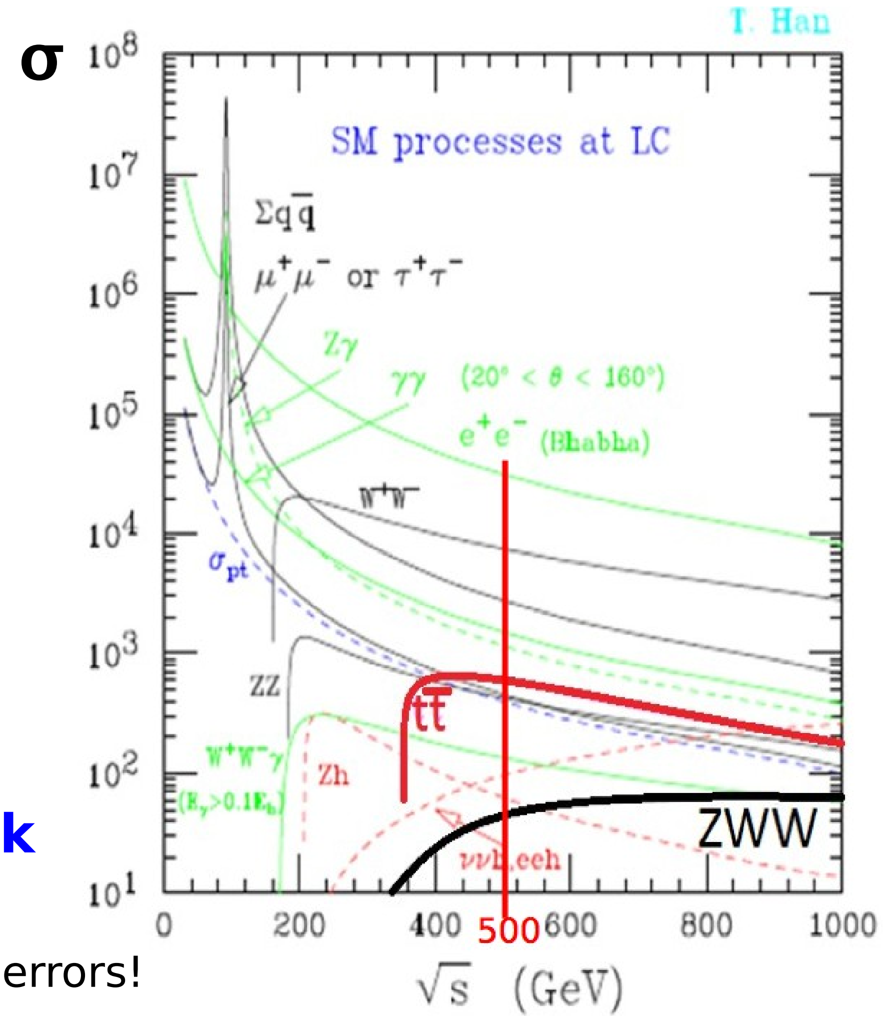
- Heavy fermion effect?

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





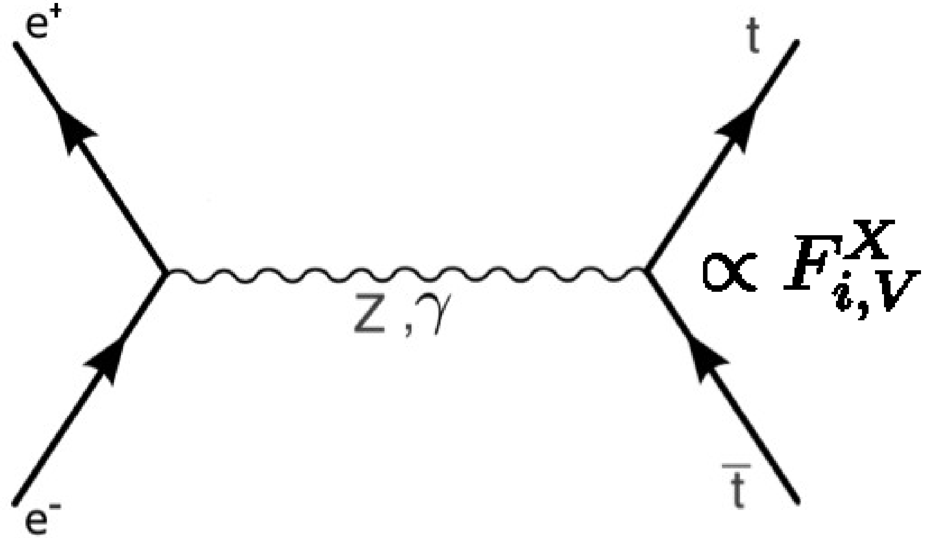
- Top quark production through **electroweak** processes,

  no competing QCD production => Small theoretical errors!

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

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

Testing the chiral structure of the Standard Model



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

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

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

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.

$$\sigma_I$$

x-section

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

Forward backward asymmetry

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

Fraction of right handed top quarks

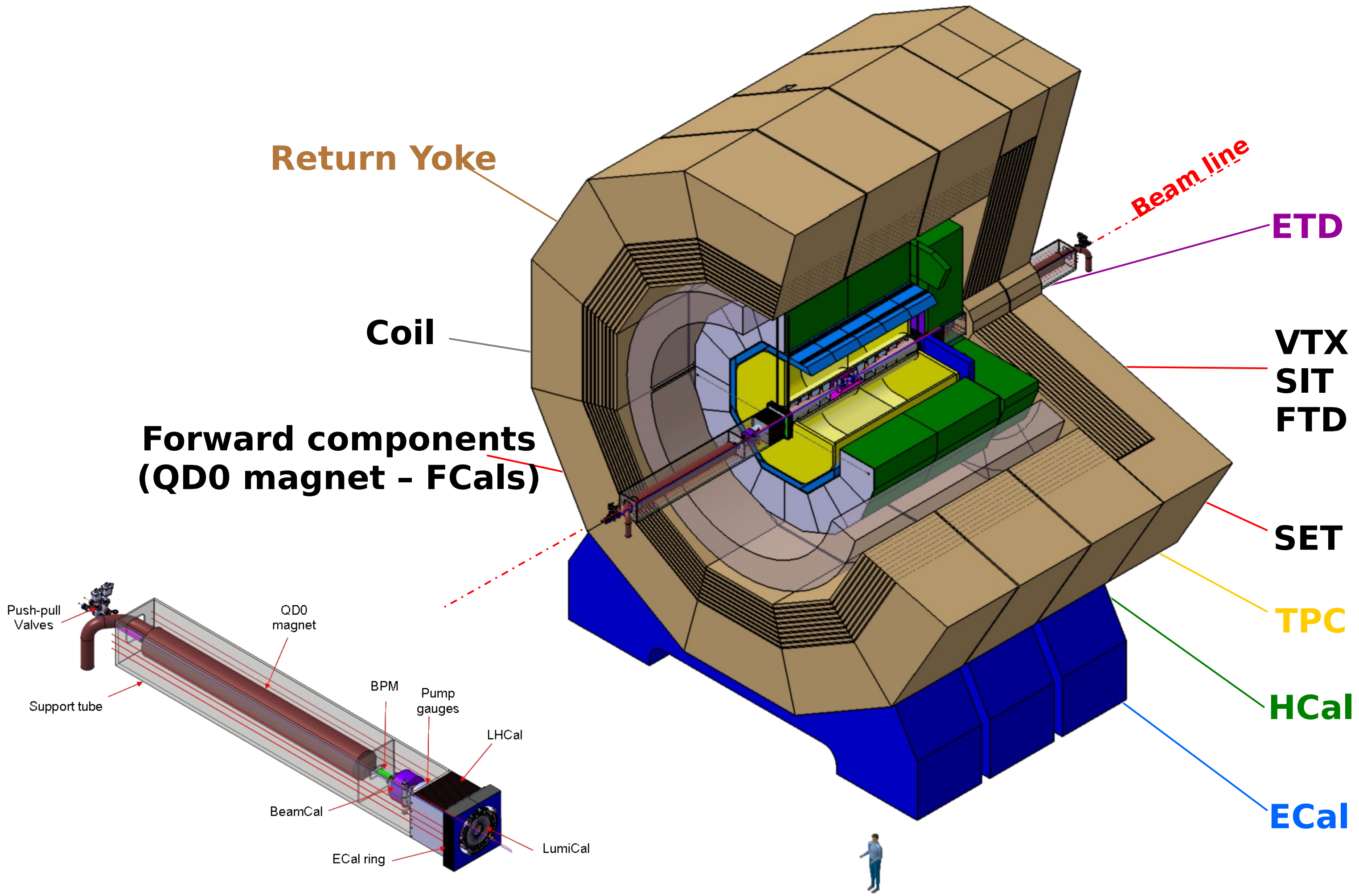
⇩

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 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:

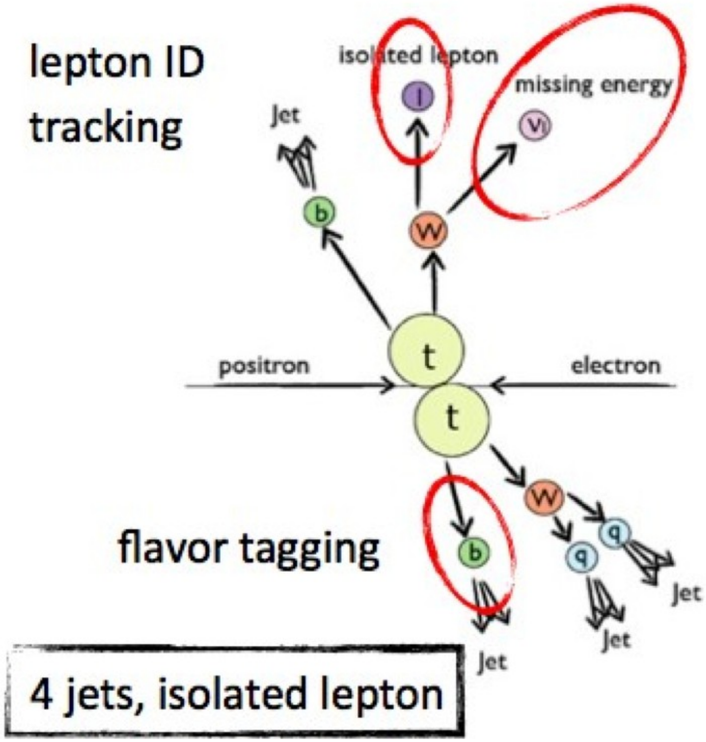
3-4% over
total energy range

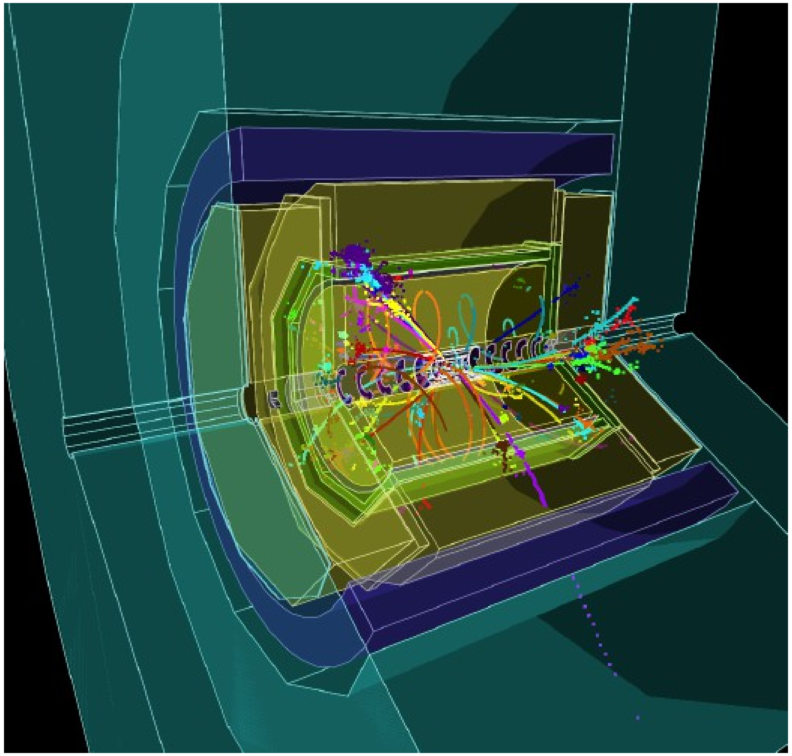
Detector Baseline Design 2013 – Based on full detector simulation

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

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

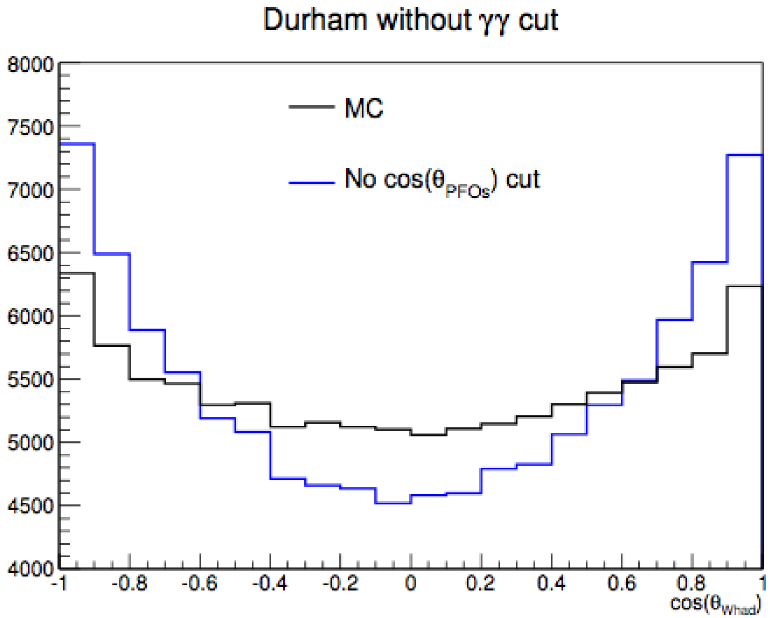
- Detector simulation is based on input from worldwide detector R&D

Discussion of pile up

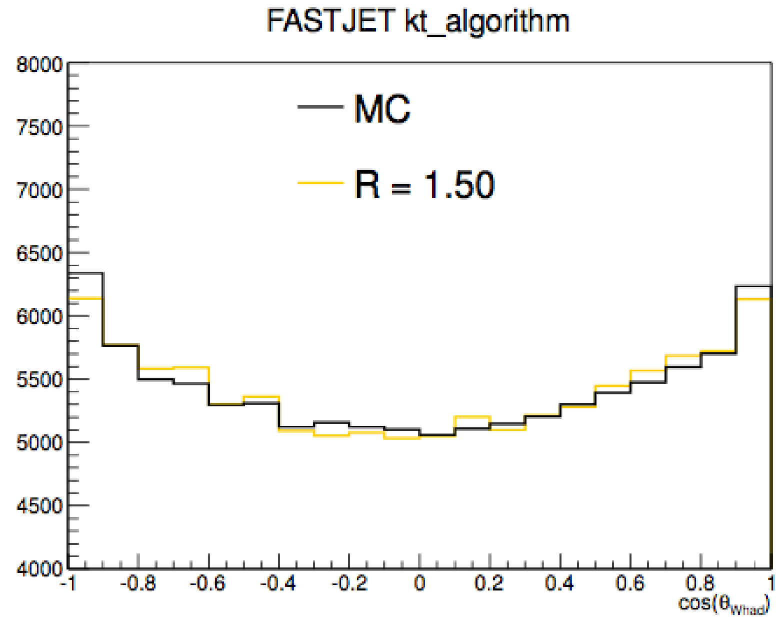
Main source of pile up: γγ -> hadrons

ILC about 1.7 evts. / bunchXing (including muons)

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



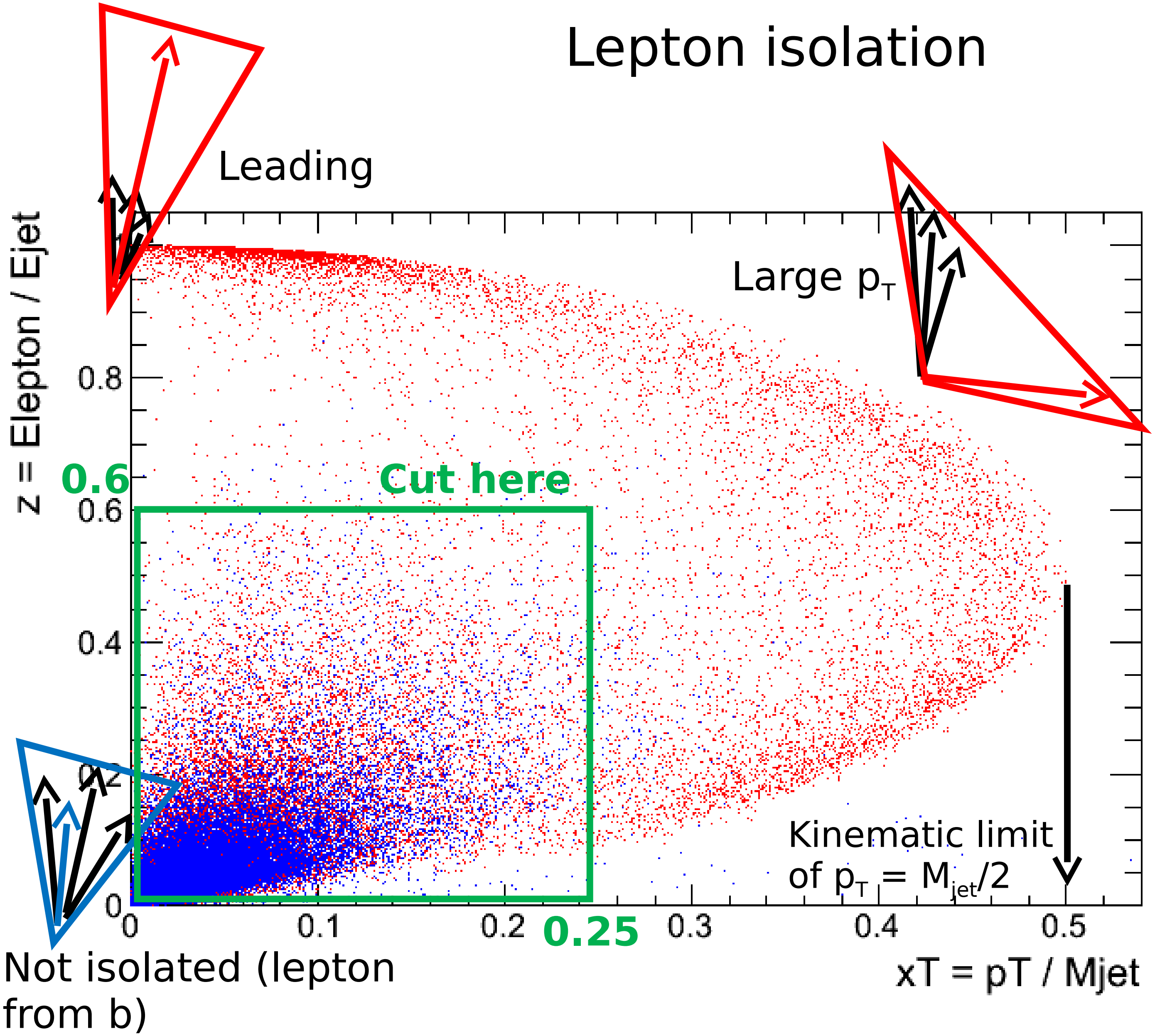
(a) Durham



(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



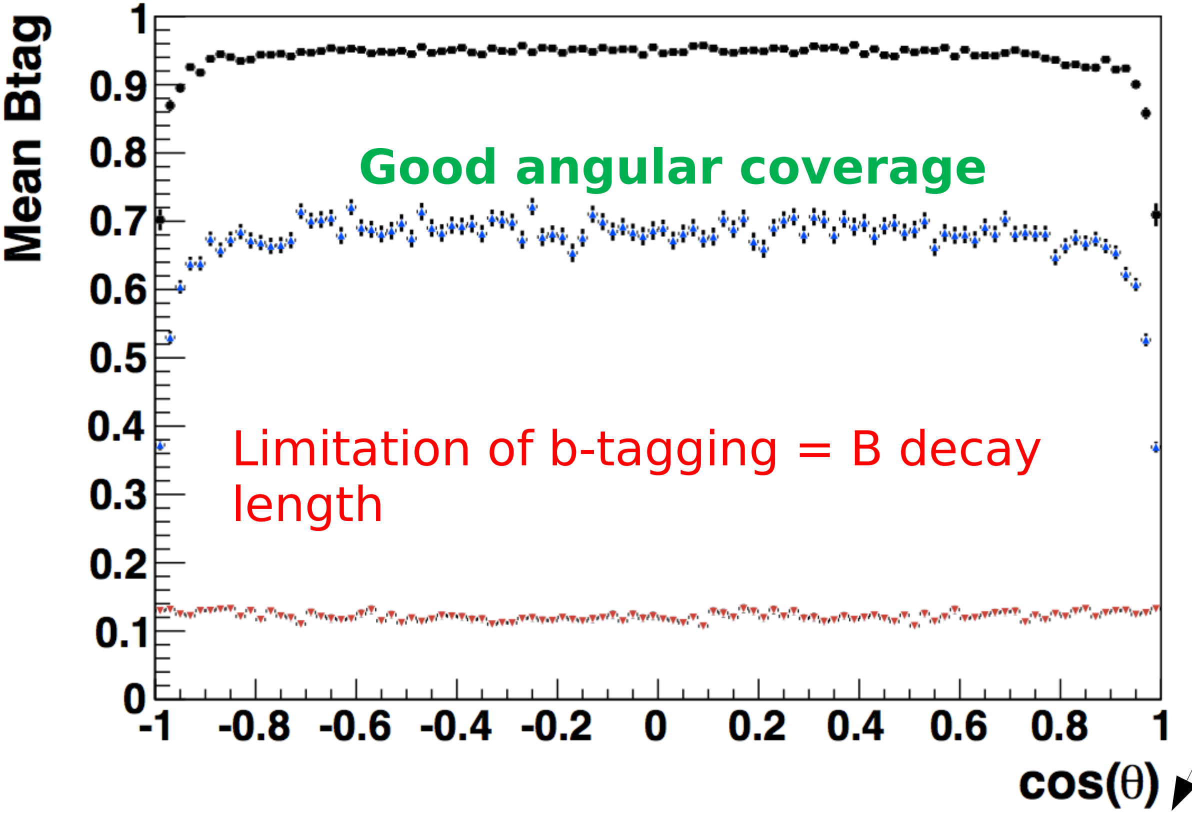
Red = leptons in semileptonic top events

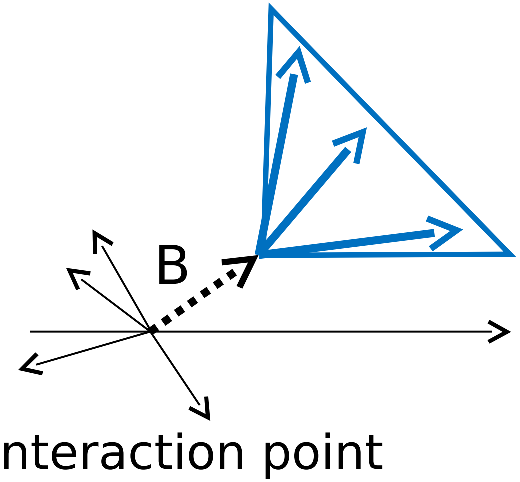
Blue = leptons in full hadronic top events = leptons from b

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**



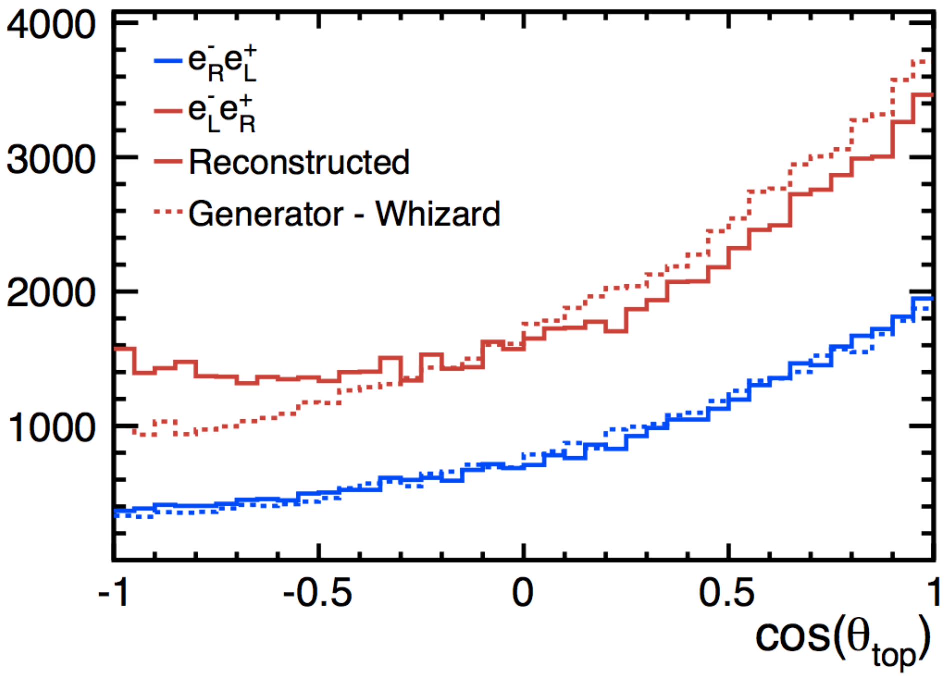


- 4 jets
- 2 highest Btag = b_1 & b_2
- 2 “light” jets = W

Polar angle of b-jet

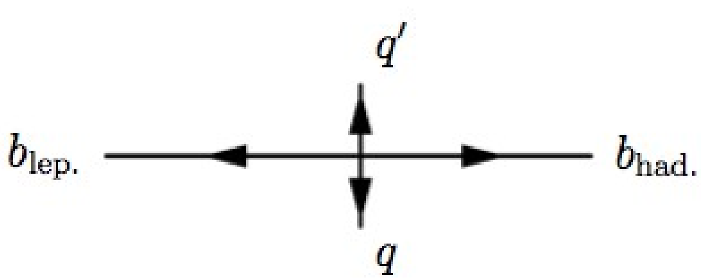
Clean e^+e^- environment allow for efficient b-tagging

Reconstruction of top quark production angle



Ambiguities in case of left handed electron beams

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:

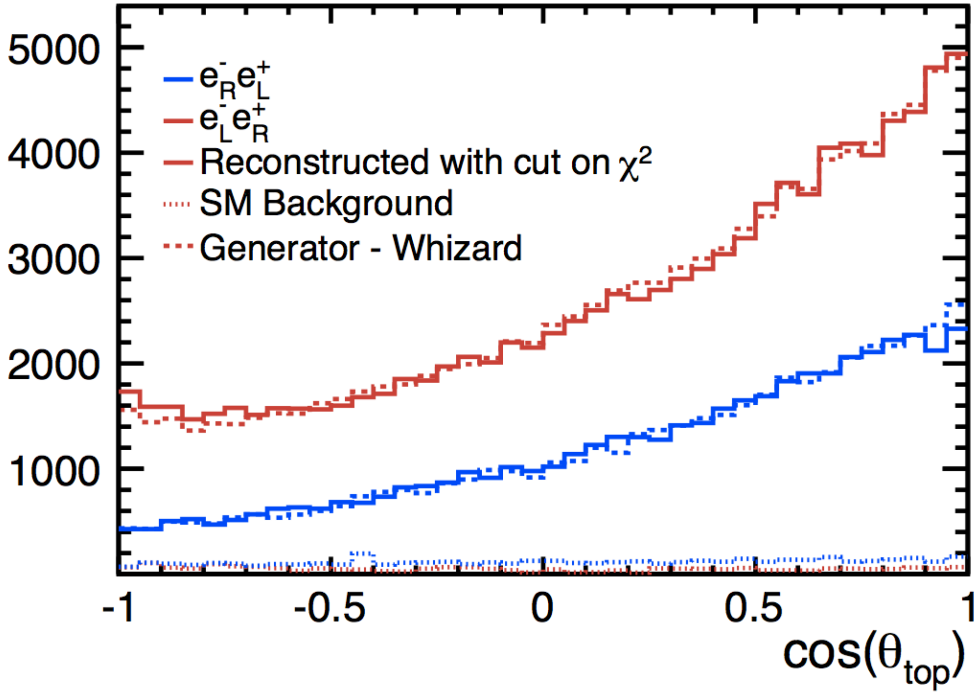
1) Select cleanly reconstructed events by kinematic fit or Chi2 analysis
2) Measure the b quark charge ("Golden way", to be pursued further)

Reconstruction of top quark production angle

(Current) remedy to address ambiguities:

Select cleanly reconstructed events by kinematic fit or χ^2 analysis

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

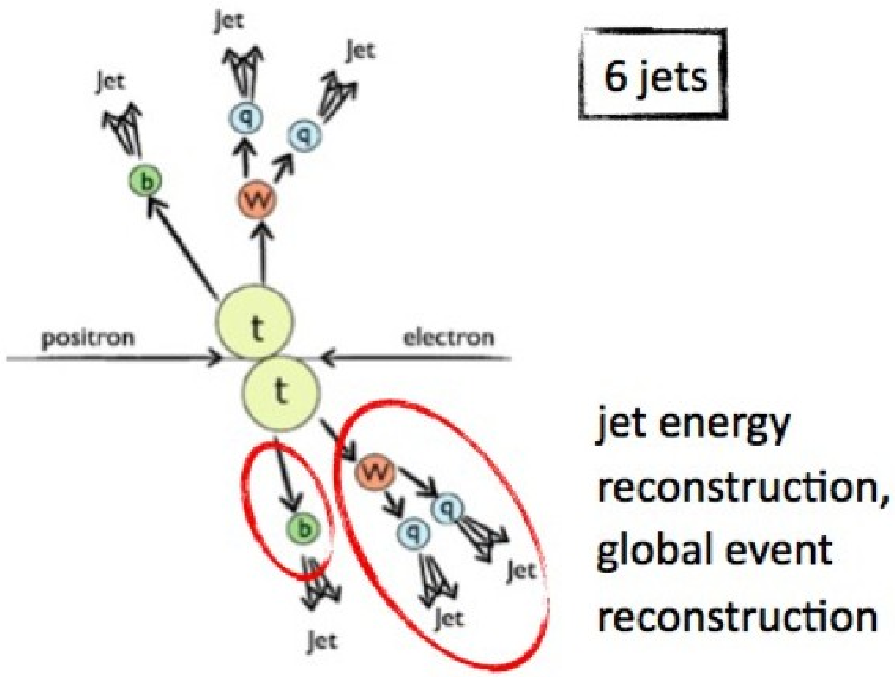


Precise reconstruction for both beam polarisations

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

Precision on A_{FB} ~ 2%

Intermezzo: Fully hadronic top decays



1) 6 jets with Durham jet finder

2) Vertexing and Btagging with LCFIPlus v00-05-02
Select jets with b tag > 0.3

3) W and b-jet reconstruction → Top reconstruction
Top = $W_i + b_k$ i,k=1,2 that minimise

$$\chi^2 = \left(\frac{m_t - 174}{\sigma_{m_t}}\right)^2 + \left(\frac{E_t - 250}{\sigma_{E_t}}\right)^2 + \left(\frac{p_b^* - 69}{\sigma_{p_b^*}}\right)^2$$

$\chi_1^2 < 20$

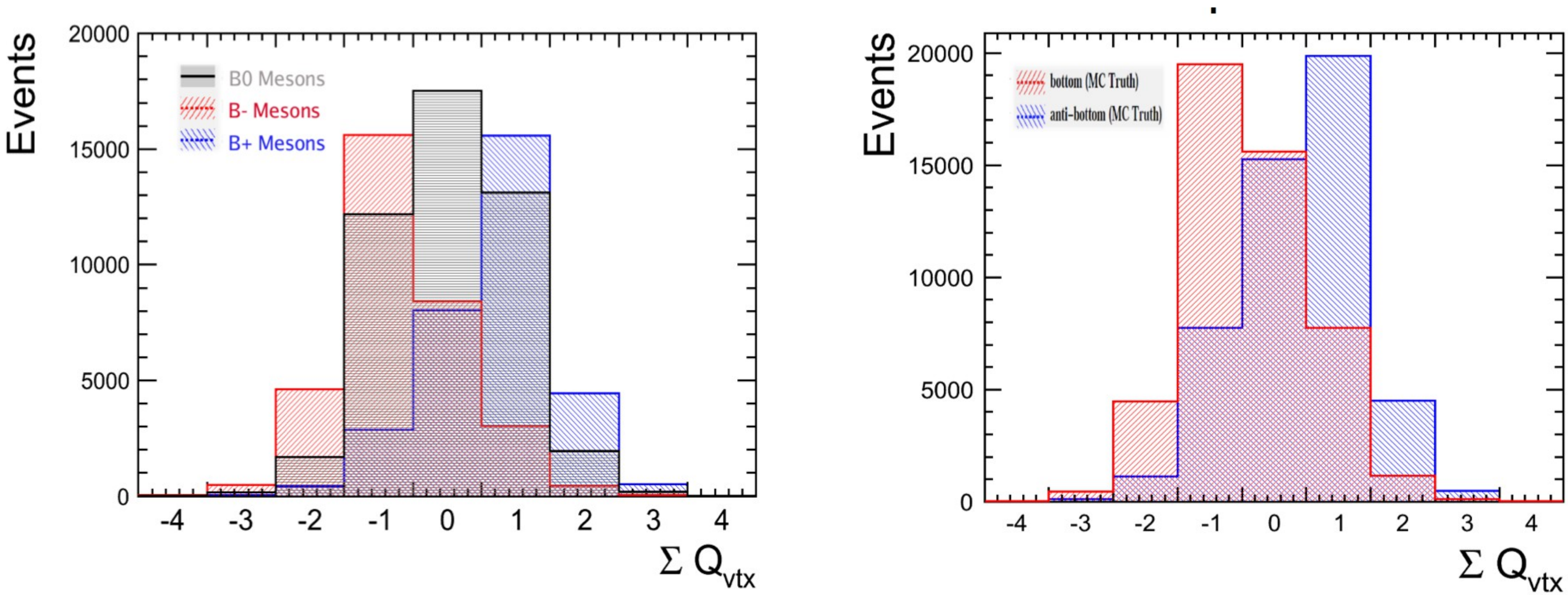
$\chi_2^2 < 40$

4)Vertex charge $|Q_b| < 5$

5) Event charge $C = Q_{b1} - Q_{b2} \neq 0$

Measurement of b quark charge

In fully hadronic top decays

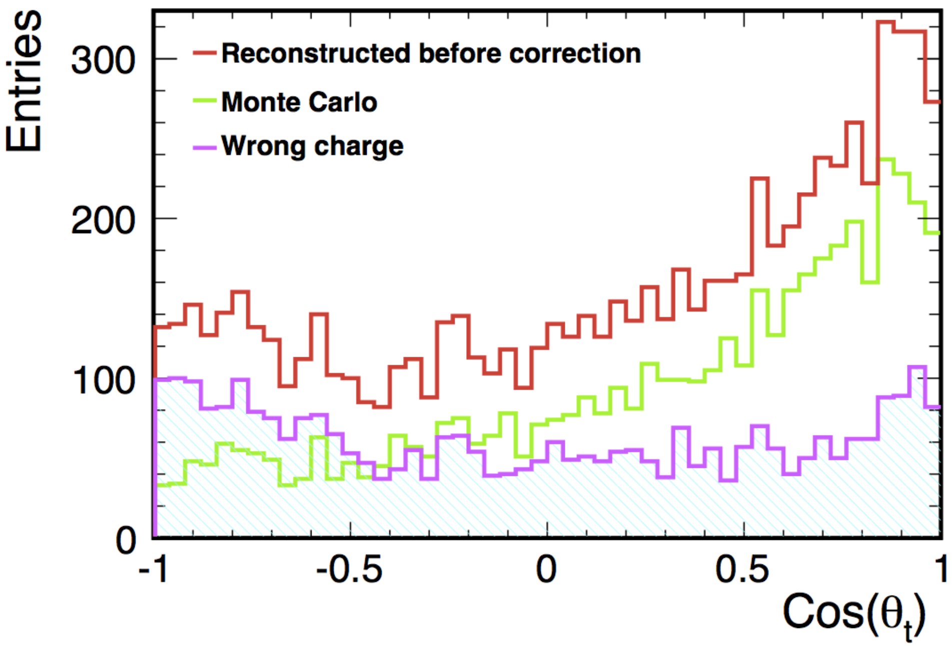


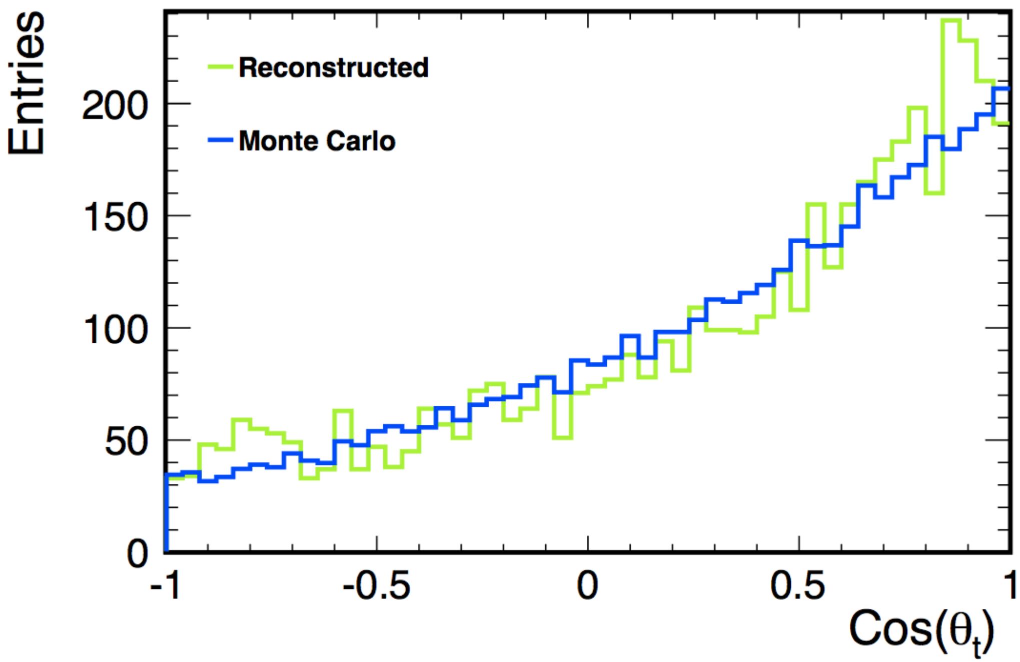
- Vertex charge measurement mandatory for fully hadronic top decays
- LC vertex and tracking system allows for determination of b-meson (b-quark) charge
  B-quark charge measured correctly in about 60% of the cases
- `LCFIPlus` package not yet optimised for vertex charge measurement

Optimisation of b-quark charge is major topic for future studies
(see talk by Jeremy)

Reconstruction of top quark production angle – Fully hadronic decays

Analysis for LC detector DBD





Relatively small selection efficiency (10%-20%)
Wrong b charge corrected with MC truth

=> Fully hadronic analysis (not yet) competitive with semi-leptonic analysis

However, very precious work in many aspects
→ Introduction to b charge measurement
→ Awareness of single top events
→ (Current) interface to Pythia hadronisation

End of Intermezzo -

Back to Semi-leptonic analysis

Measurement of top quark polarisation

Measure angle of decay lepton in top quark rest frame

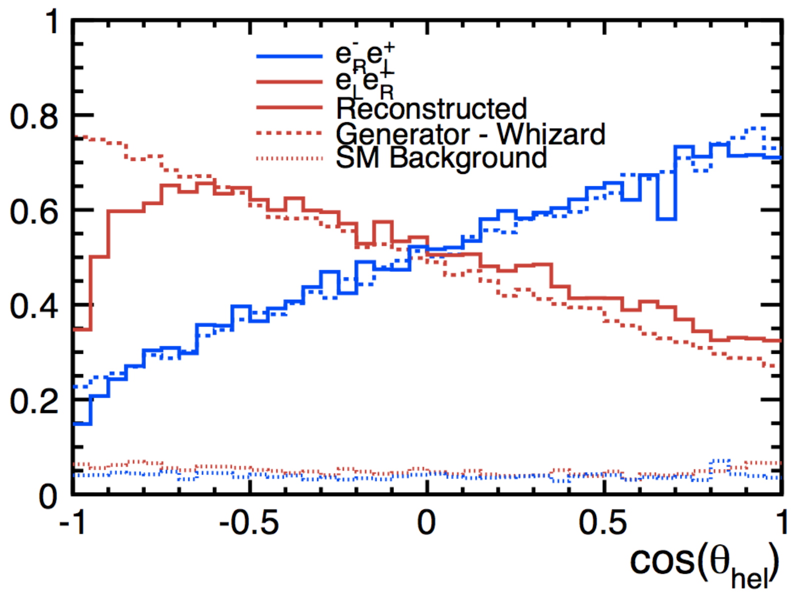
Lorentz transformation benefits from well known initial state

(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 $t_{R,L}$ 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:

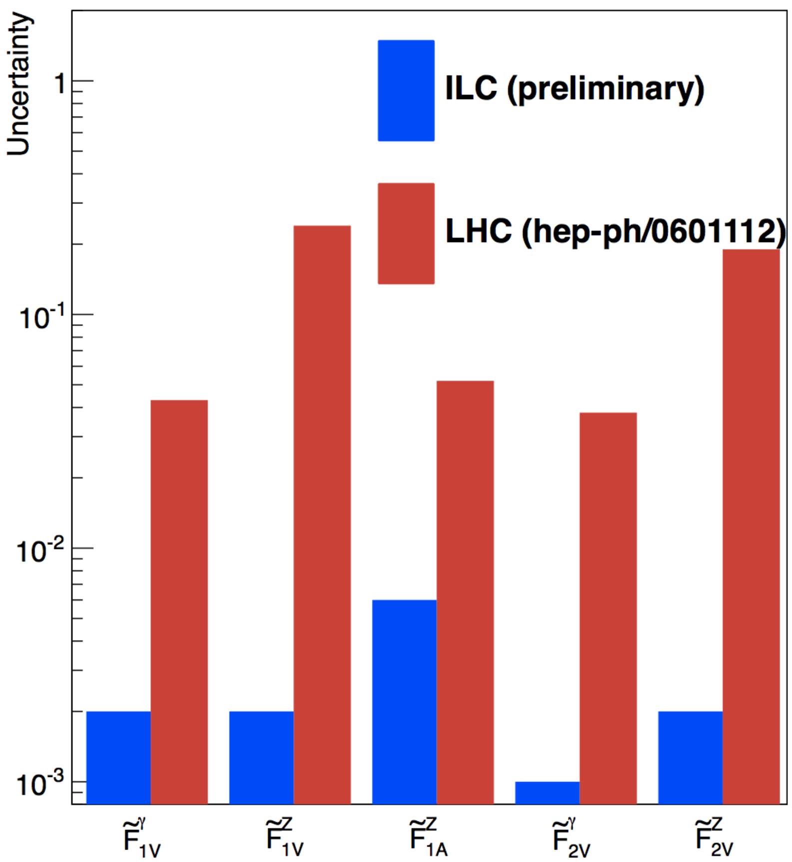
- Role of single top production (15% of 6f final state)
- Electroweak NLO predictions (Correction LO → NLO ~ 15%)

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

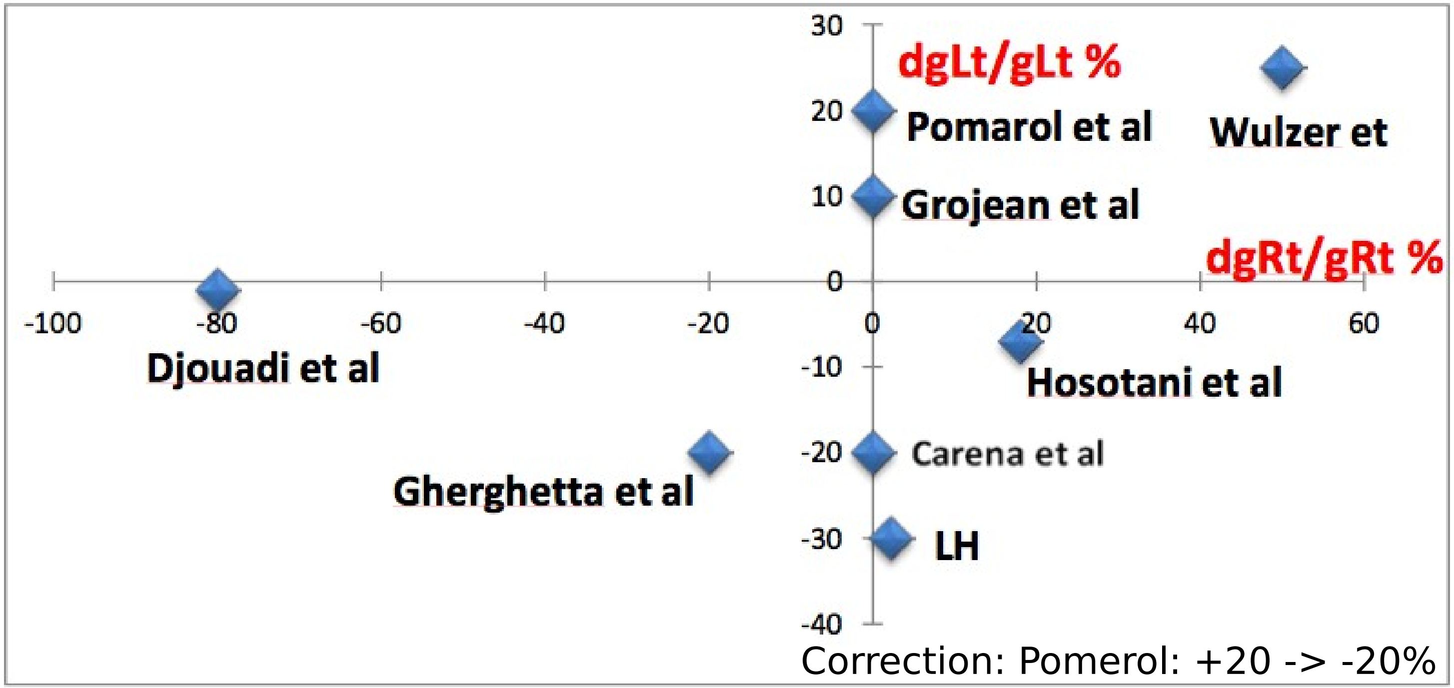
- Strong encouragement to update these numbers!
  First step is Phys. Rev. Lett. 110 (2013) 172002 by CMS

- Potential for CP violating couplings at ILC under study

ILC will be indeed high precision machine for electroweak top couplings

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)

- Precision on form factors of the order of 1%

No sign ambiguity

Large separation power between models!

Study on CP Violating Form Factors on going (not covered today, sorry)

- 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

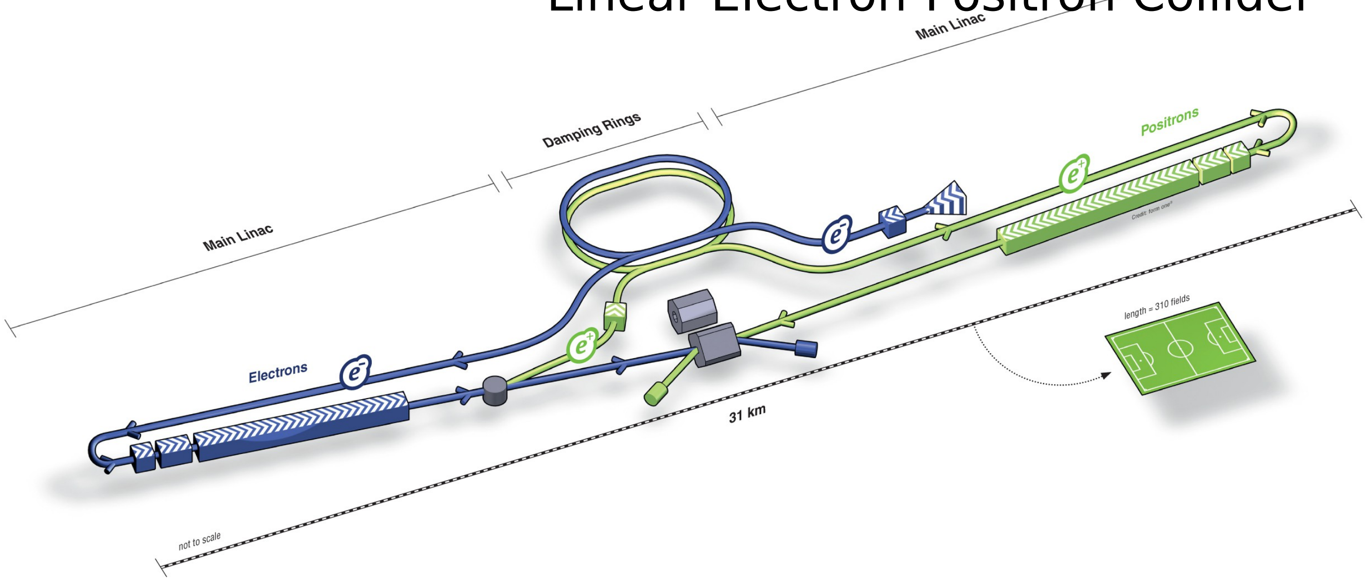
Reliable generators

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

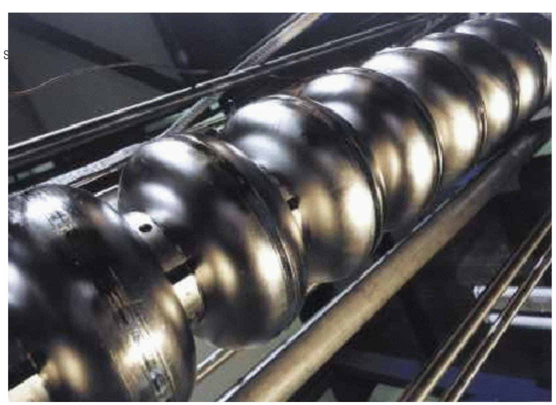
Backup

The 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 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 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

Equations for cross section, A_{FB} and F_R

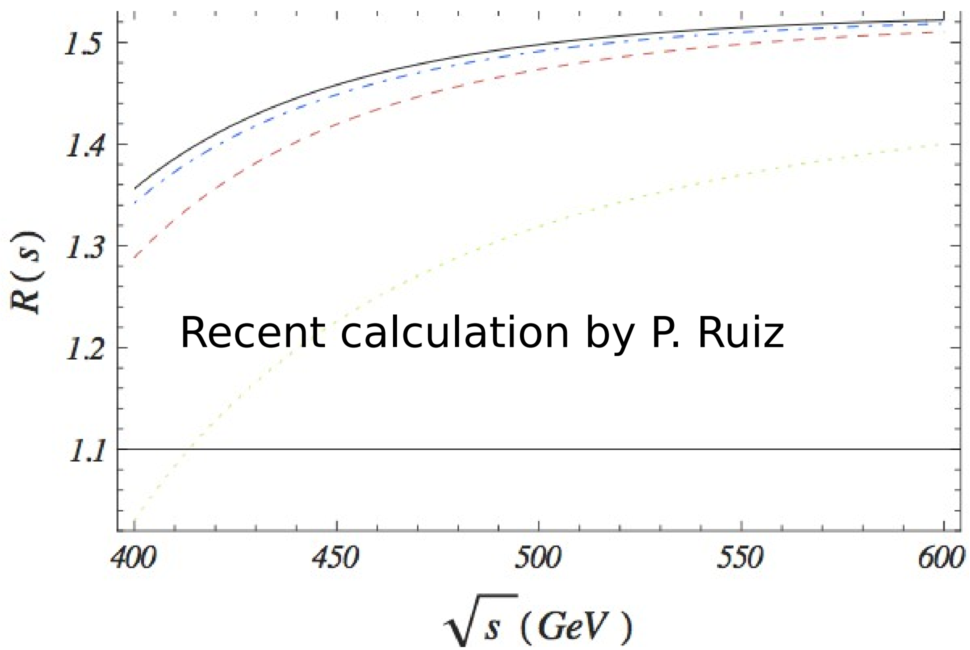
$$\sigma_I = 2\mathcal{A}N_c\beta\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right],$$

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

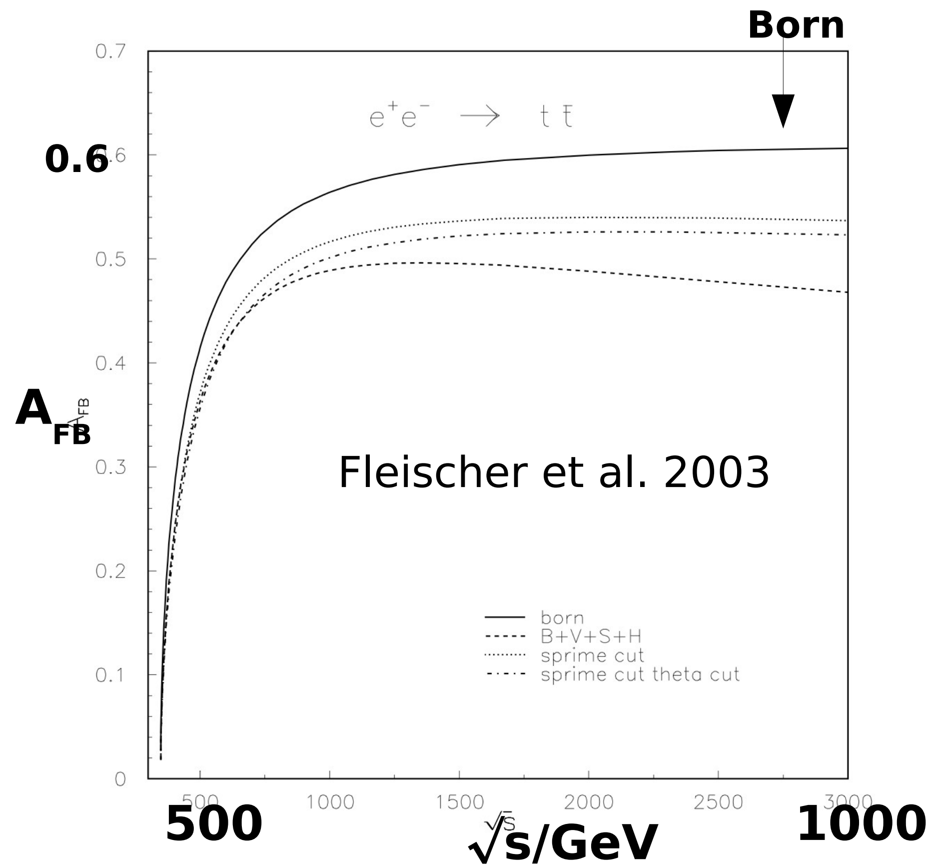
$$(F_R)_I = \frac{(\mathcal{F}^I_{1V})^2(1+0.5\gamma^{-2}) + (\mathcal{F}^{I'}_{1A})^2 + 2\mathcal{F}^I_{1V}\mathcal{F}^{I'}_{1A} + \mathcal{F}^I_{2V}(3\mathcal{F}^I_{1V} + 2\mathcal{F}^{I'}_{1A}) - \beta\mathcal{F}^I_{1V}\mathfrak{Re}(\mathcal{F}^I_{2A})}{2\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2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

SM correction to Born process

QCD up to $O(a_s^3)$



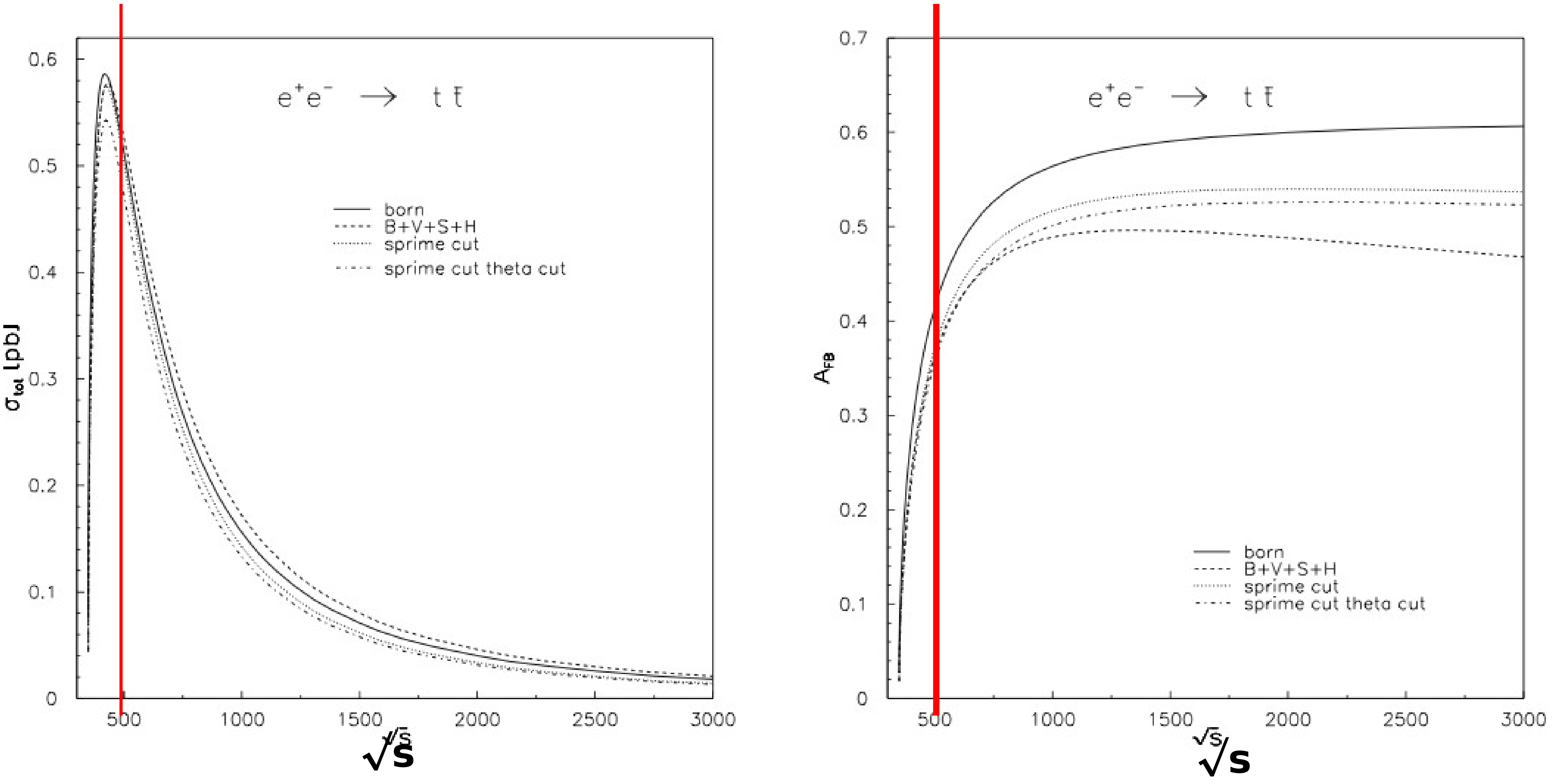
NLO electroweak



- 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%)
 More on electroweak corrections
 → Talk by Jeremy

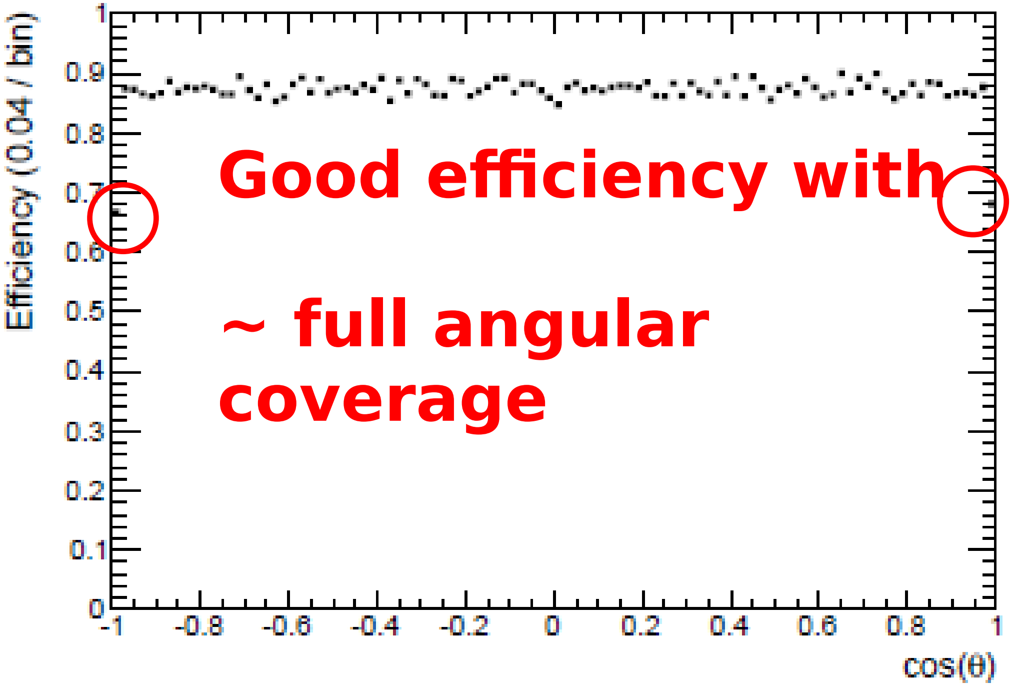
Why high(er) energies – e.g. 500 GeV

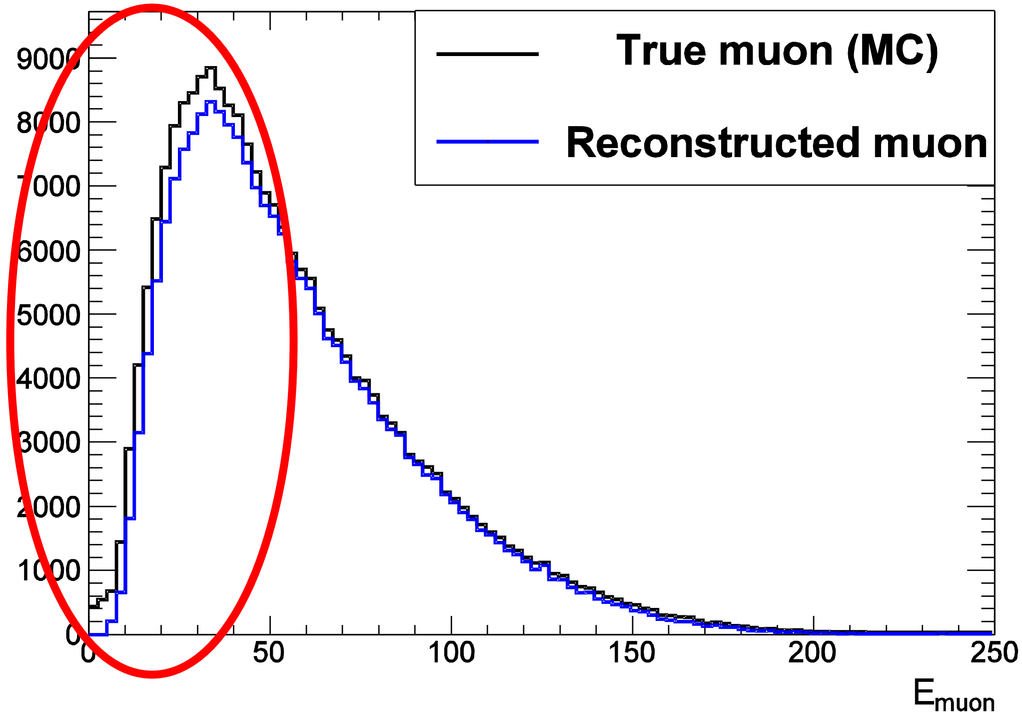


- Cross section close to maximum, A_{FB} well developed

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

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%

SL Analysis - Background suppression I

eL, eR: -0.8, +0.3

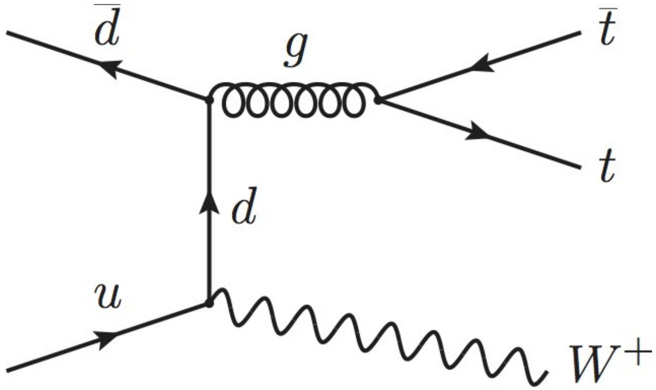
	TTsl	TTlep	TThad	WWsl	bb
Sigma (fb)	409.02	96.85	434.41	6618.63	718.08
Factor for L=250	0.99	0.868	1.08	3.74	0.642
Initial numbers	102255 (100%)	24212 (100%)	108602 (100%)	1654657 (100%)	179520 (100%)
NbLeptons == 1	68510 (67.0%)	9685 (40.0%)	3422 (3.15%)	986684 (59.6%)	17126 (9.54%)
Btag1,2>0.8,0.3	62354 (61.0%)	8853 (36.6%)	2953 (2.72%)	20234 (1.22%)	13231 (7.37%)
pfosThrust < 0.9	61901 (60.5%)	8450 (34.9%)	2948 (2.72%)	3247 (0.196%)	1840 (1.03%)
HadMass	60688 (59.4%)	5228 (21.6%)	2205 (2.03%)	1438 (0.0869%)	512 (0.286%)
Mw/Mtop	55637 (54.4%)	2498 (10.3%)	1809 (1.67%)	698 (0.0422%)	284 (0.158%)
chi2 < 15	29155 (28.5%)	190 (0.789%)	290 (0.268%)	41 (0.00248%)	43 (0.0243%)

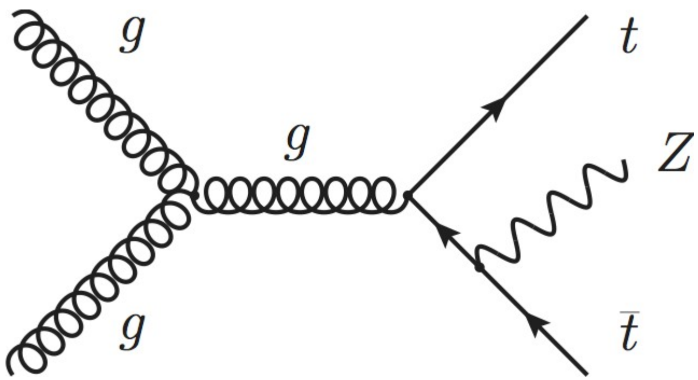
Background suppression II

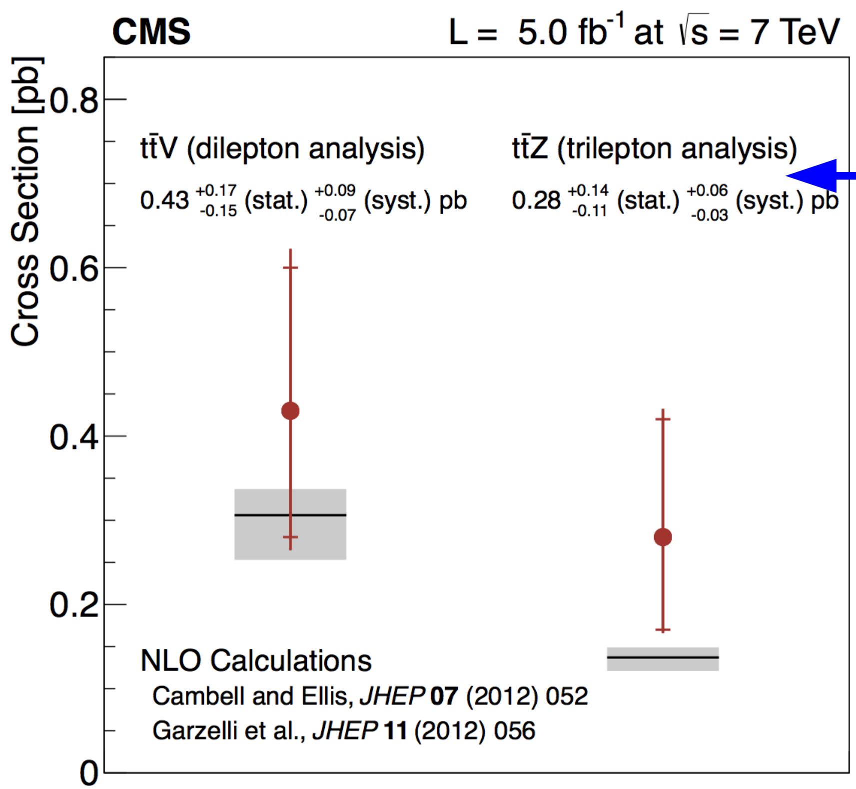
eL, eR: +0.8, -0.3

Sigma (fb)	**208.05**	**49.26**	**220.97**	**434.02**	**203.88**
Factor for L=250	**1.26**	**1.15**	**1.38**	**49.3**	**0.318**
Initial numbers	**52012 (100%)**	**12315 (100%)**	**55242 (100%)**	**108505 (100%)**	**50970 (100%)**
NbLeptons == 1	**34805 (66.9%)**	**4707 (38.2%)**	**1719 (3.11%)**	**71021 (65.5%)**	**5199 (10.2%)**
Btag1,2>0.8,0.3	**32475 (62.4%)**	**4441 (36.1%)**	**1455 (2.63%)**	**838 (0.773%)**	**3927 (7.71%)**
pfosThrust < 0.9	**32205 (61.9%)**	**4242 (34.4%)**	**1453 (2.63%)**	**591 (0.545%)**	**460 (0.903%)**
HadMass	**31547 (60.7%)**	**2476 (20.1%)**	**1067 (1.93%)**	**295 (0.273%)**	**84 (0.166%)**
Mw/Mtop	**29083 (55.9%)**	**1289 (10.5%)**	**852 (1.54%)**	**49 (0.0455%)**	**50 (0.0997%)**

First result on ttV by CMS







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

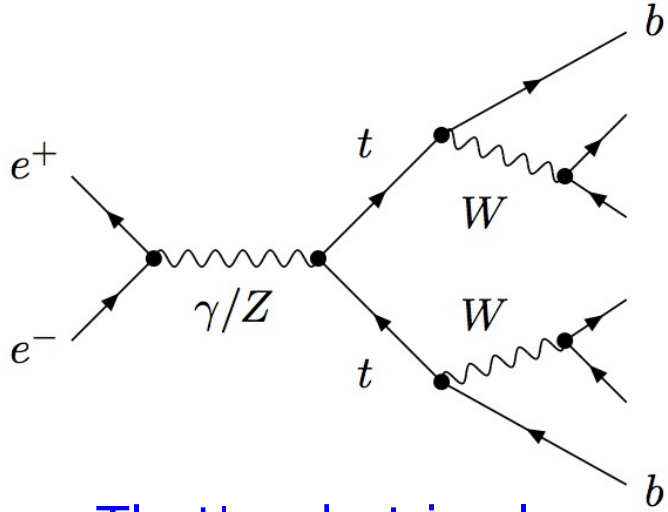
- Promising result
  N.B. NLO QCD has 10% uncertainty

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

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

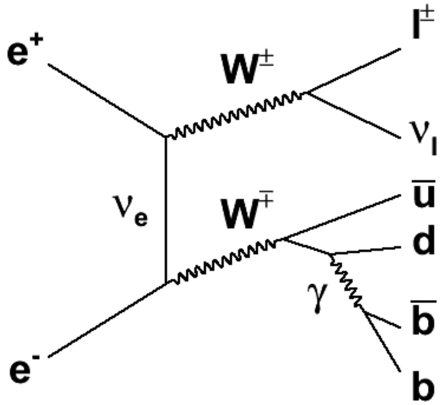
Closer look at ttbar production

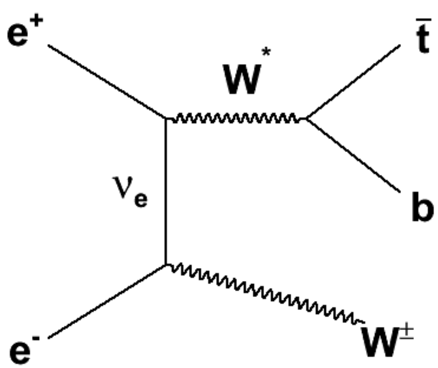
That's what we are interested in



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?

Event reconstruction for 6jet analysis

1) 6 jets with Durham jet finder

2) Vertexing and Btagging with LCFIPlus v00-05-02
Select jets with b tag > 0.3

3) W and b-jet reconstruction → Top reconstruction
Top = $W_i + b_k$ i,k=1,2 that minimise

$$\chi^2 = \left(\frac{m_t - 174}{\sigma_{m_t}}\right)^2 + \left(\frac{E_t - 250}{\sigma_{E_t}}\right)^2 + \left(\frac{p_b^* - 69}{\sigma_{p_b^*}}\right)^2$$

$$\chi_1^2 < 20$$

$$\chi_2^2 < 40$$

4)Vertex charge $|Q_b| < 5$

5) Event charge $C = Q_{b1} - Q_{b2} \neq 0$

$$C < 0 \Rightarrow t$$

$$C > 0 \Rightarrow \bar{t}$$