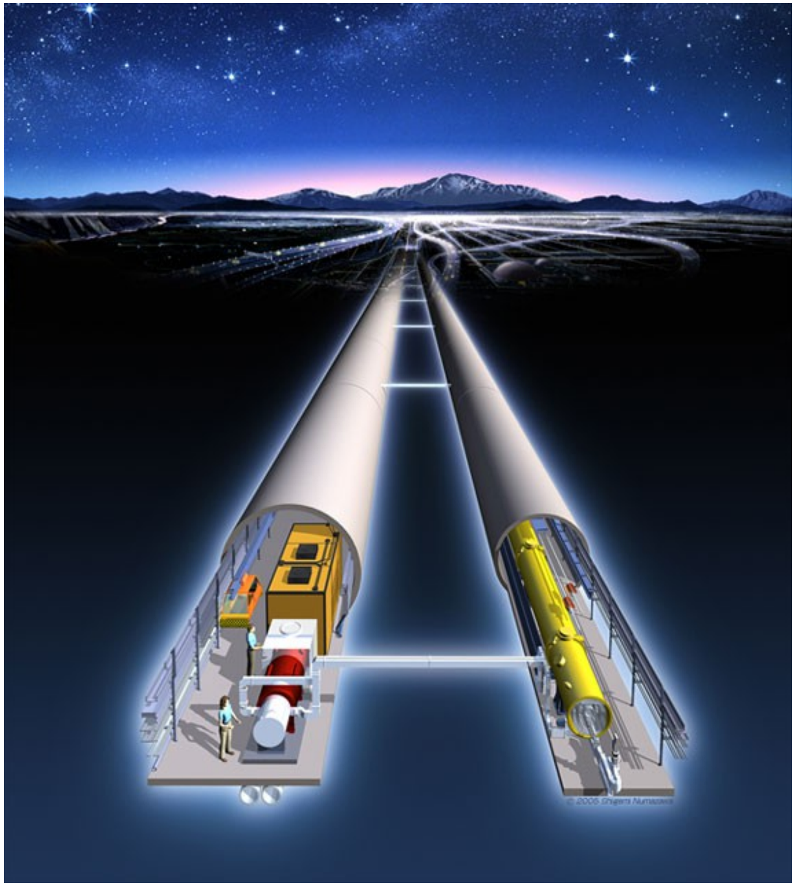
Top quark coupling at LC
- Experimental issues -



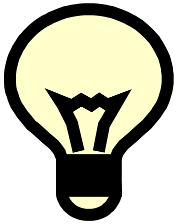
Roman Pöschl

Based on collaboration
With IFIC Valencia

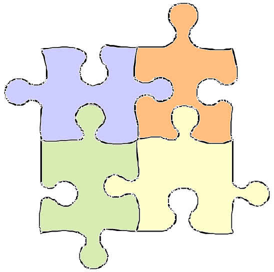
3rd Journées Collisionneur Linéaire – LPSC/Grenoble Dec. 2014

An enigmatic couple ...

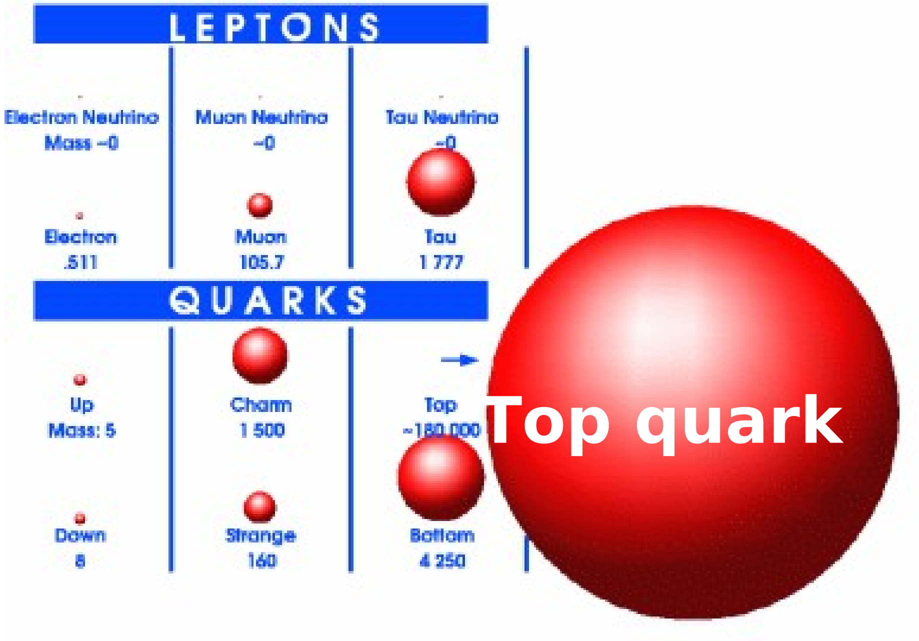
Higgs Boson



Elementary Scalar?



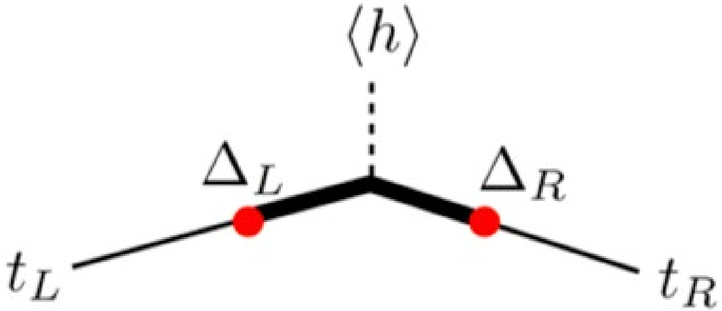
Composite object?



- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter

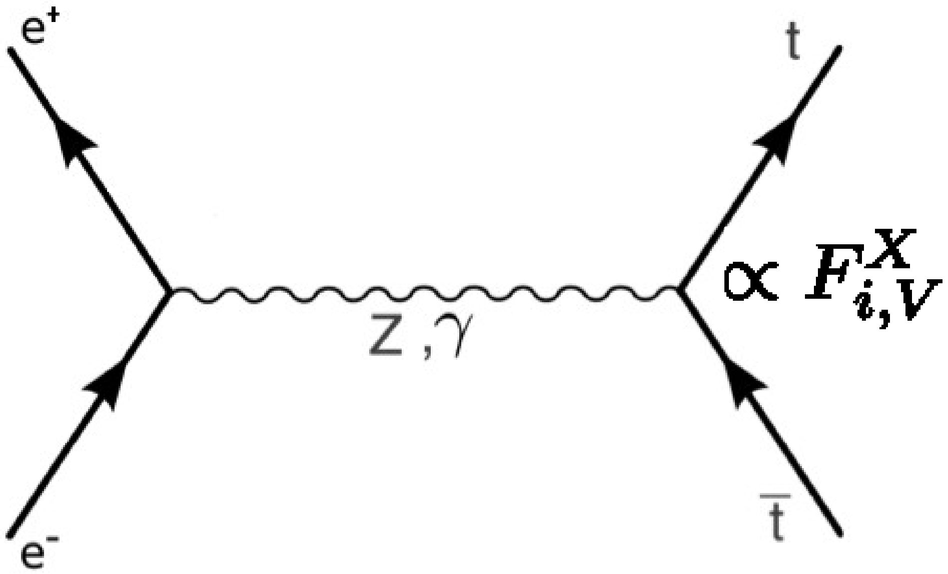
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

- **LC perfectly suited to decipher both particles**

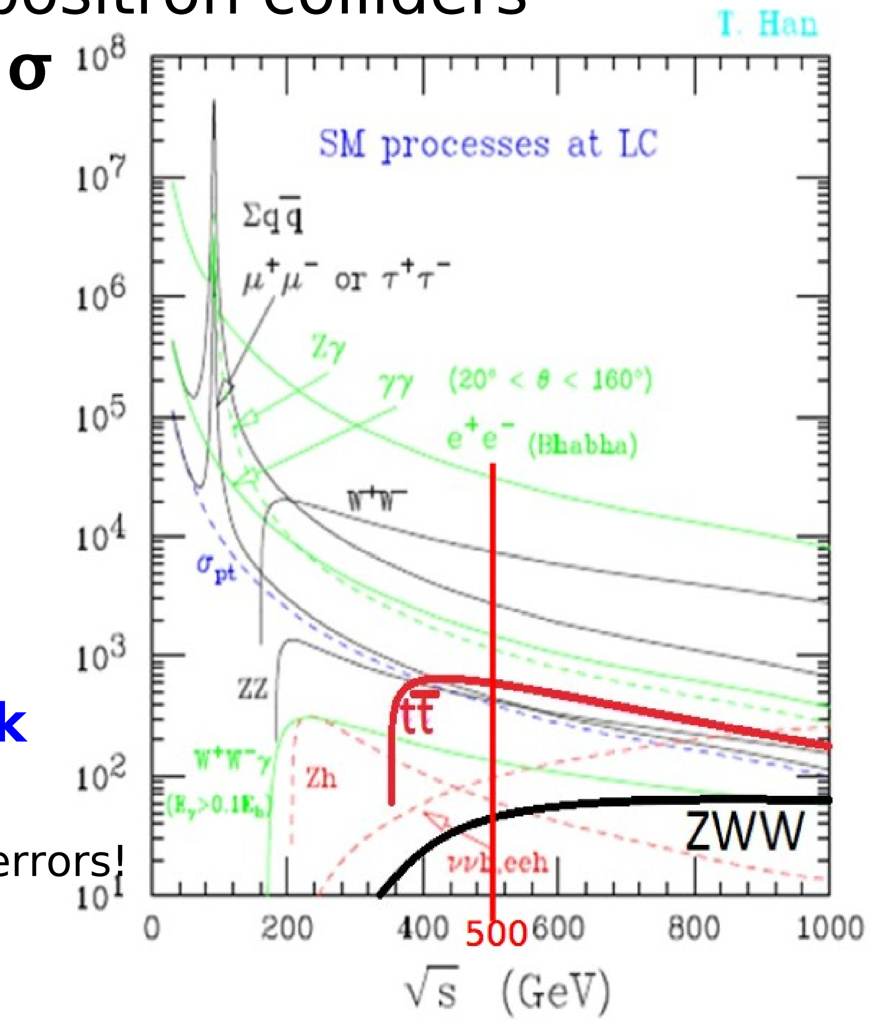


Courtesy of S. Rychkov

Top quark physics at electron-positron colliders



$\propto F_{i,V}^{X}$



- 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

  Polarised beams allow testing chiral structure at ttX vertex
  => Precision on form factors F

- Studies presented here deal with no or only mildly boosted tops, beta~0.7
  - A major difference between LC and LHC is that an LC will run triggerless

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

Detector parameters

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

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)]$ μm(1/3 x SLD)

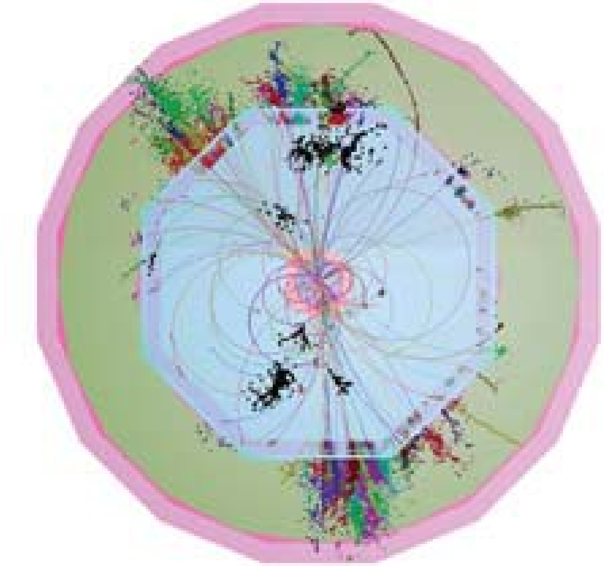
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(\mathrm{GeV}))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

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

(for events with missing energy e.g. SUSY)



Final state will comprise events with a large number of charged tracks and jets(6+).

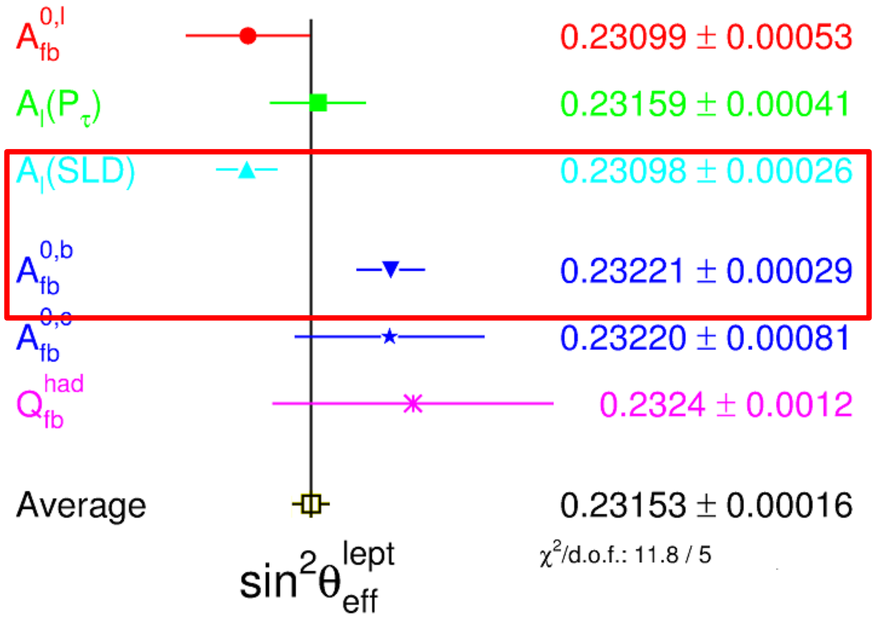
- **High granularity**
- **Excellent momentum measurement**
- **High separation power for particles**

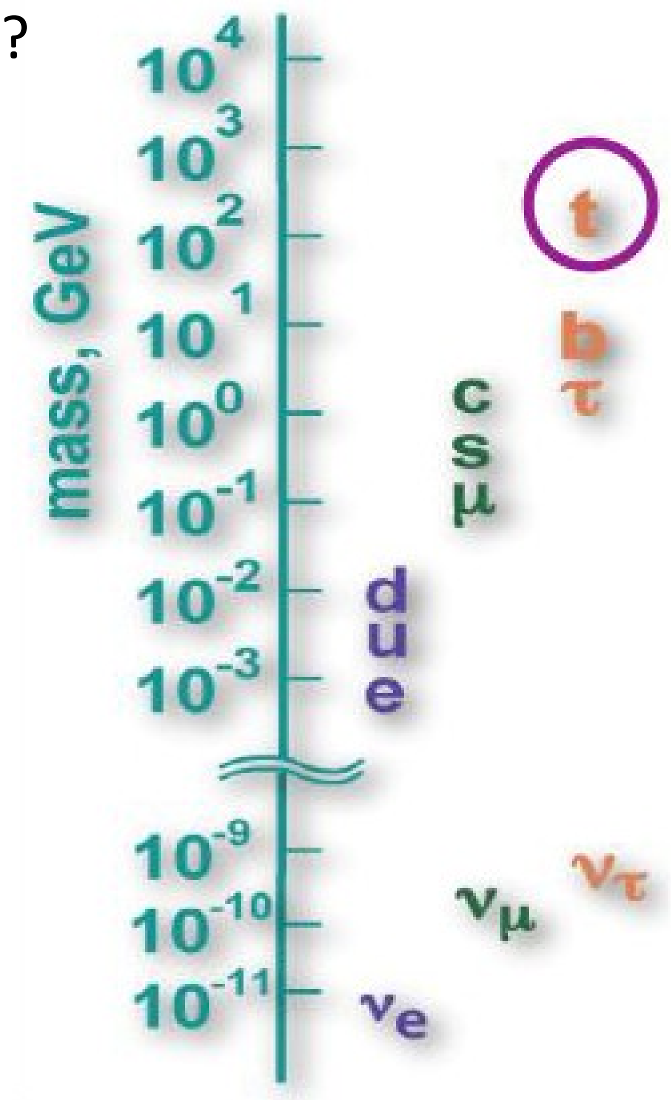
2> **Two different approaches**

Detector concepts SiD et ILD

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

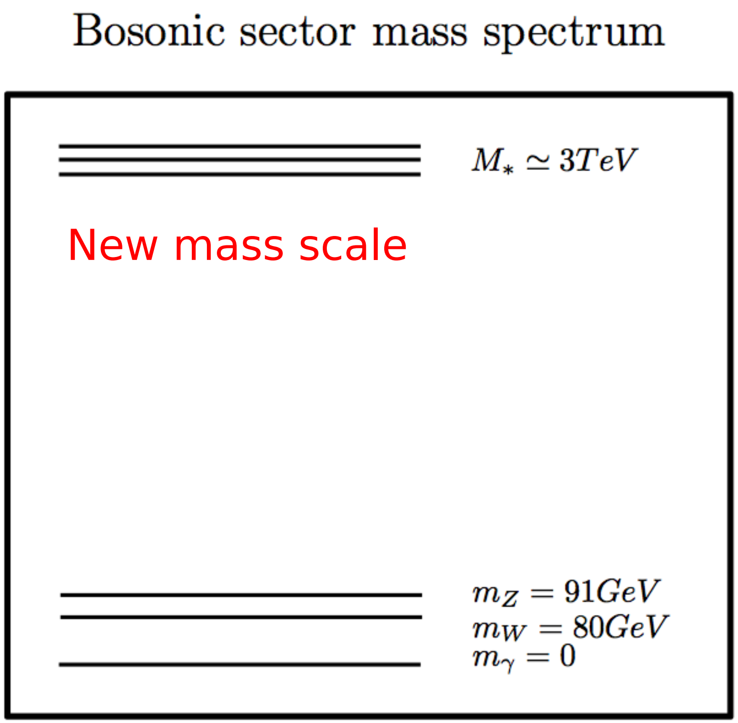
Why is it sooo heavy?

Towards New Physics

à la G.M. Pruna, LC 13, Trento

Compositeness:

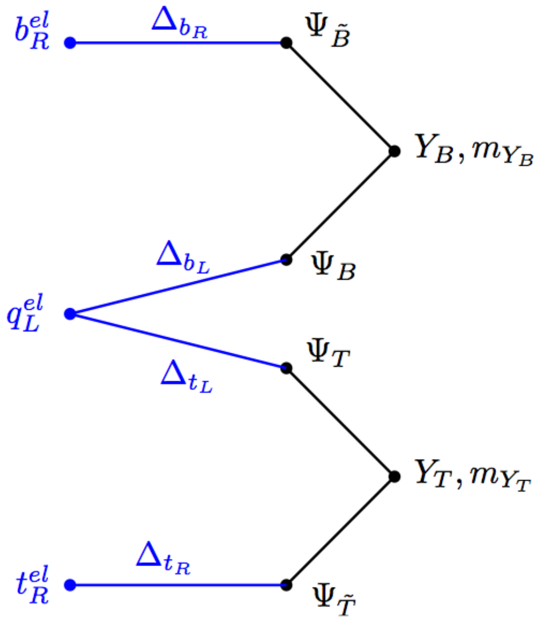
- ... provides elegant solution for naturalness
- ... few tensions with SM predictions
- ... composite Higgs hypothesis has only been marginally studied in comparison with other “fundamental” scenarios
- ... **all** scalar objects observed in nature turned out to be bound states of fermions



New mass scale

Fermionic resonances

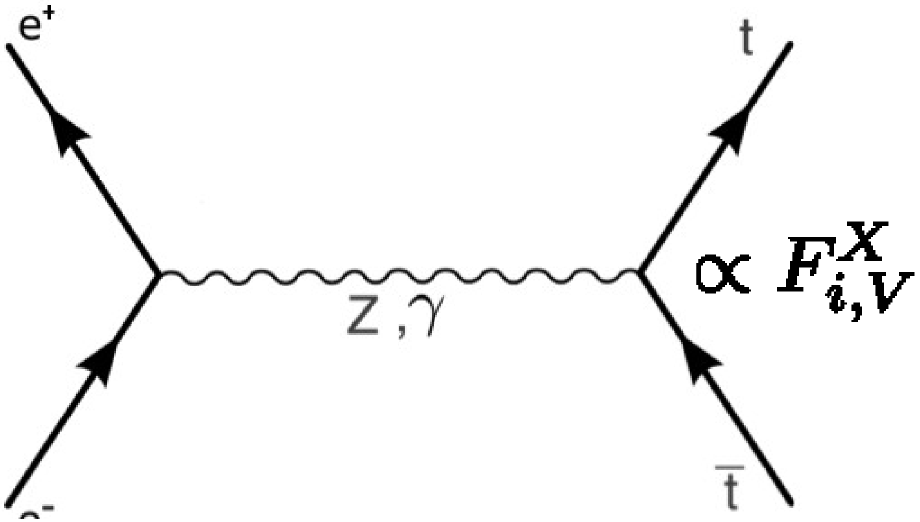
From heavy left handed SM doublet and heavy right handed SM singlet



Physics modify Yukawa couplings and Ztt, Zbb

Heavy fermion effect!

Testing the chiral structure of the Standard Model



$$\Gamma_{\mu}^{ttX}(k^2,q,\overline{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^{X}(k^2)+\gamma_5 F_{1A}^{X}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^{\mu}\left(iF_{2V}^{X}(k^2)+\gamma_5 F_{2A}^{X}(k^2)\right)\right\}, \tag{2}$$

$$\begin{aligned}\mathcal{F}_{ij}^{L} &= -F_{ij}^{\gamma}+\left(\frac{-\frac{1}{2}+s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F_{ij}^{Z}\\ \mathcal{F}_{ij}^{R} &= -F_{ij}^{\gamma}+\left(\frac{s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F_{ij}^{Z}\ ,\end{aligned}$$

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

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

Disentangling

At ILC **no** separate access to ttZ or ttγ vertex, but ...

ILC 'provides' two beam polarisations

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

There exist 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

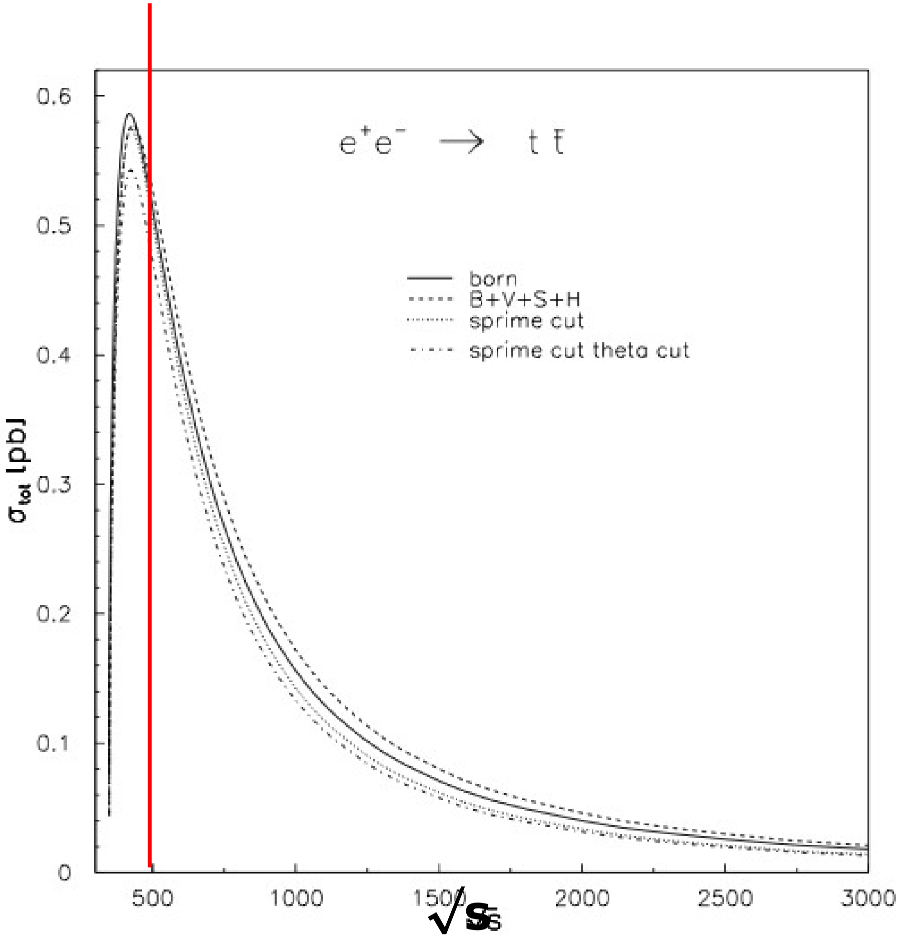
⇩

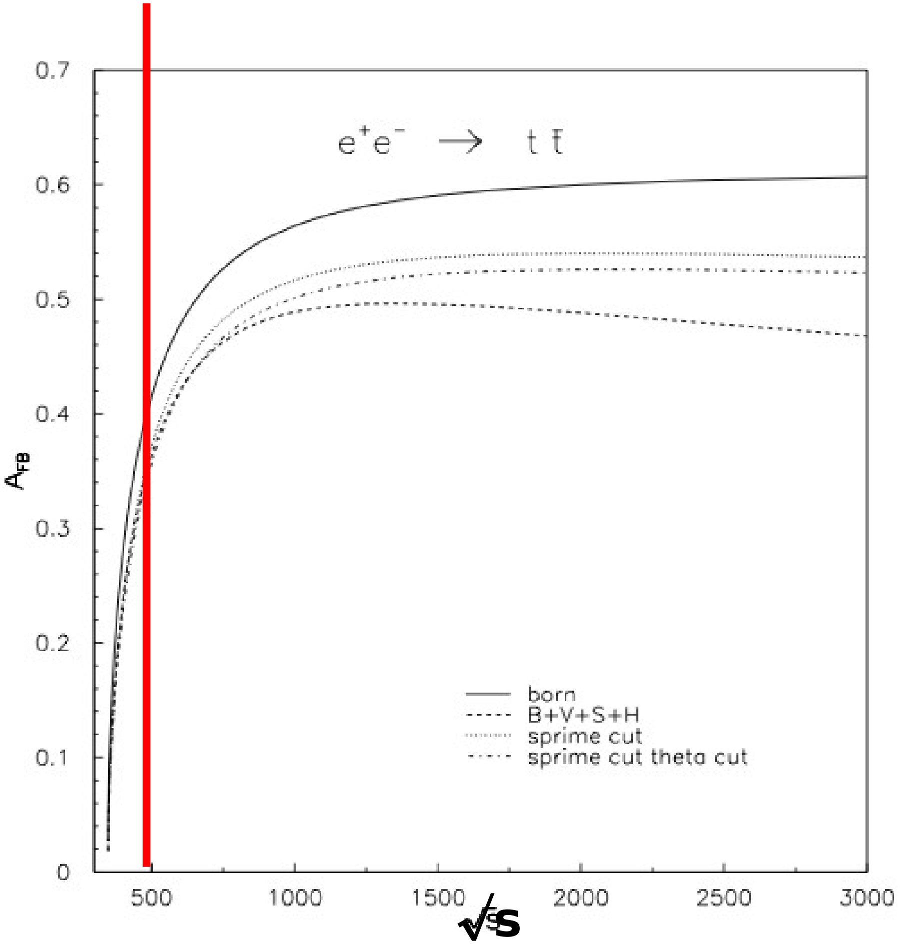
Extraction of up to six (five) unknowns

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

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

Measuring at 500 GeV



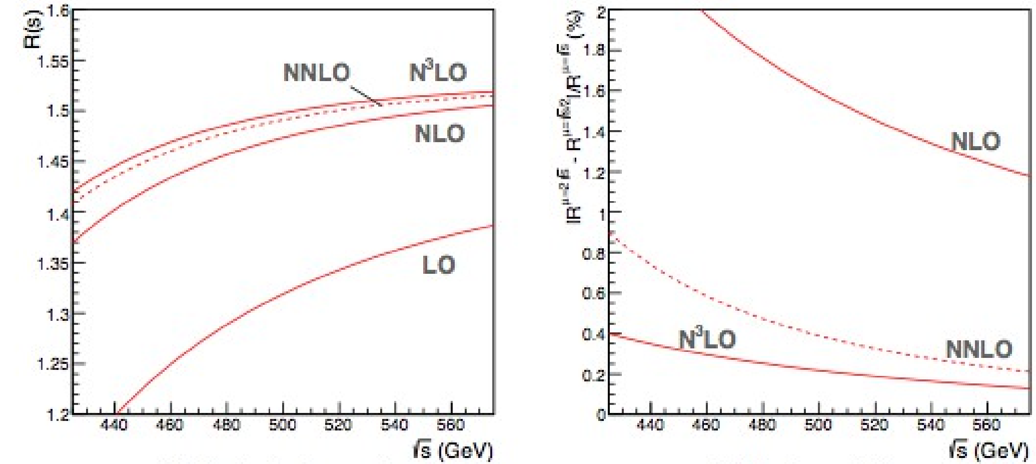


- Cross section close to maximum, A_{FB} well developed

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

Theoretical uncertainties

- QCD corrections are known up to N^3LO

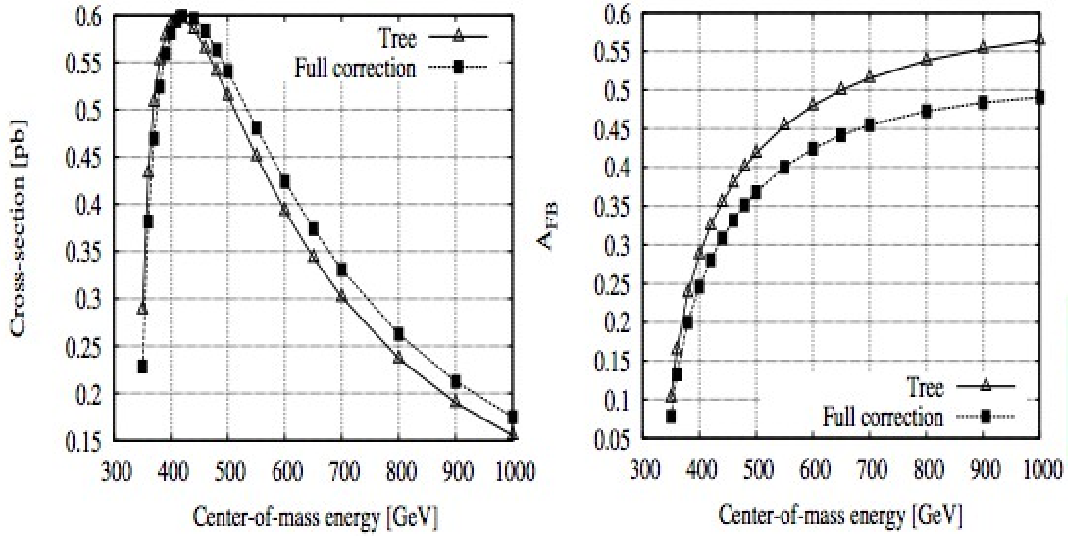


(a) Perturbation series (b) Scale variations

QCD correction (N^3LO) is at the per mil level

Kiyo, Maier, Maierhofer, Marquard, NCP B823 ('09)
Bernreuther, Bonciani, Gehrmann, Heinesch, Leineweber. NPB750 ('06)
Hoang, Mateu, Zebarjad, NPB813 ('09)

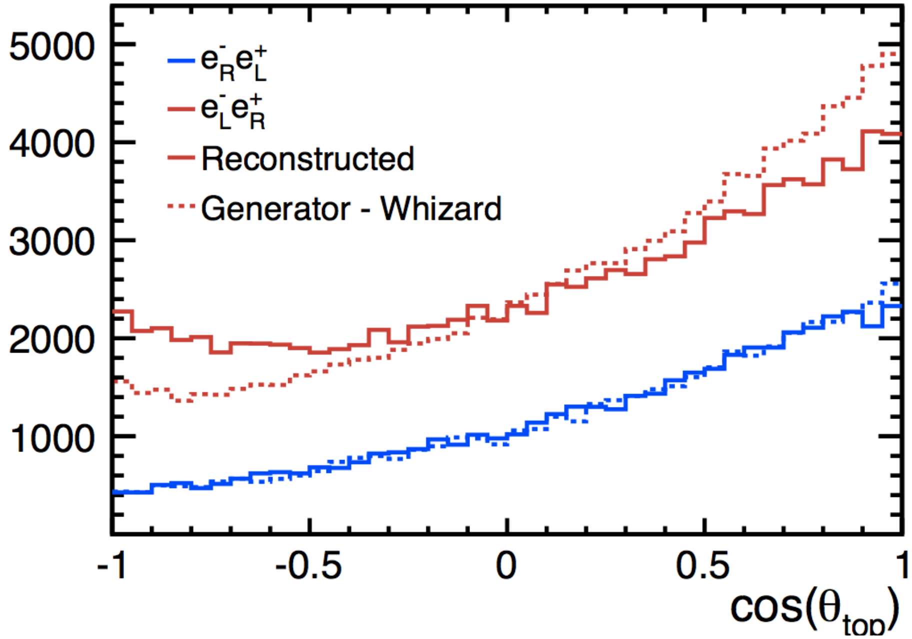
- Electroweak corrections are known at one-loop level



EW correction at one-loop is ~5% for cross section ~10% for A_{FB}

Fleischer, Leike, Riemann, Werthenbach, EJPC31 ('03)
Kheim, Fujimoto, Ishikawa, Kaneko, Kato, arXive:1211.1112

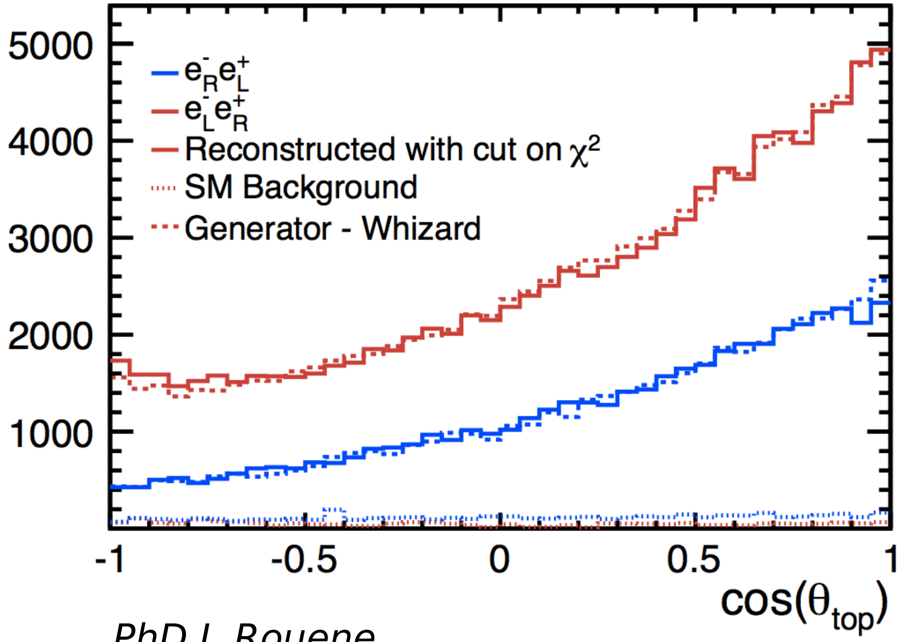
Semi Leptonic Analysis - Reconstruction of top quark production angle



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

Remedy to address ambiguities:
Select cleanly reconstructed events by χ^2 analysis
or
Reconstruction of b quark charge



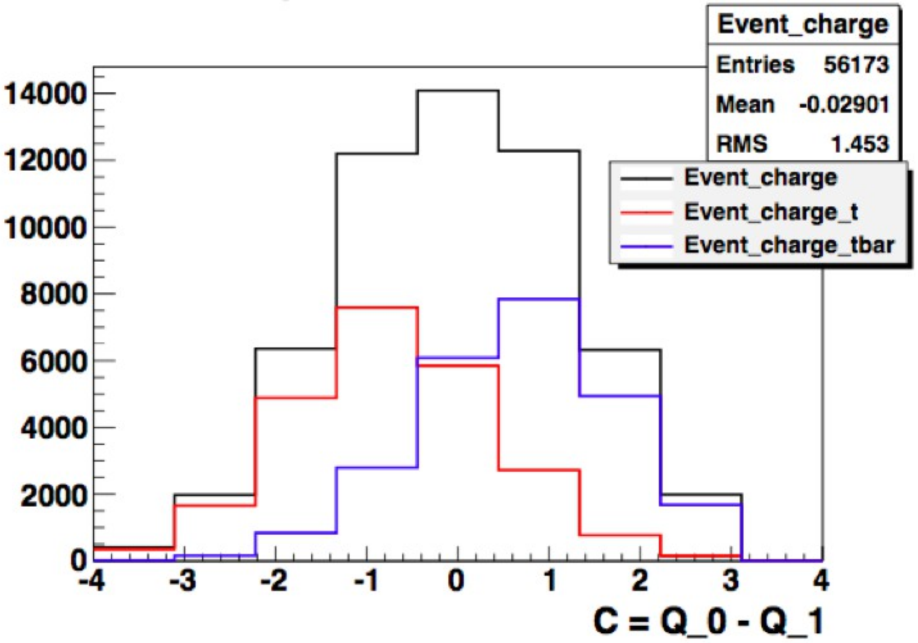
Precise reconstruction for both beam polarisations

- Efficiency Penalty for e_L
- ε_{tot}: e_R ~ 50%, e_L ~ 30%

Precision on A_{FB} ~ 2%

Top polar angle using b charge

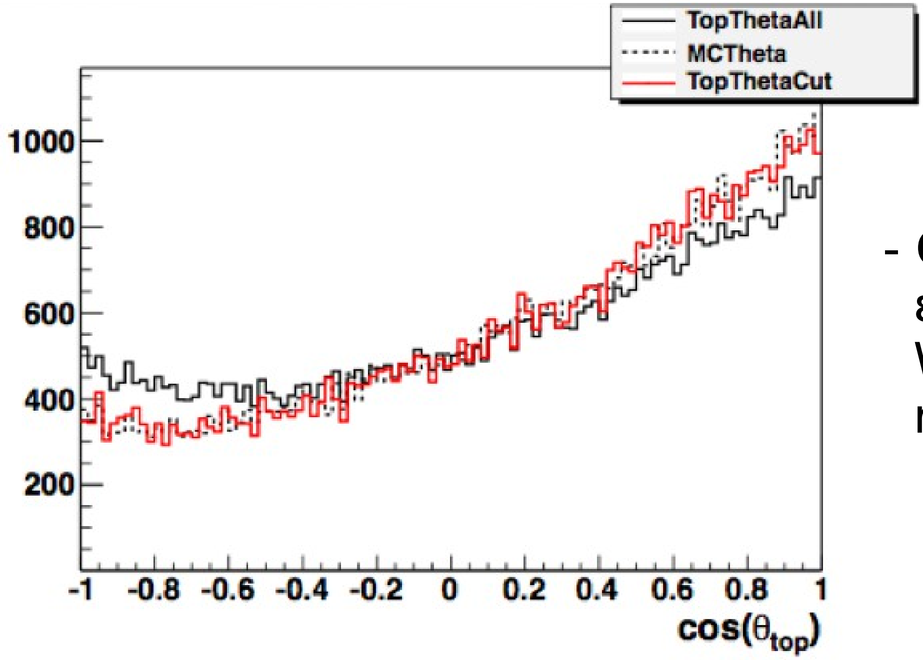
(SL Analysis)



Event charge C = b1 -b2

In SL can compare charge C with lepton charge to select clean sample

Use only events with correct C or C=0 (plus another cut on the Lorentz Factor)



- Clean reconstruction of top quark direction
  ε ~ 30%
  Will improve with improving charge reconstruction

B charge measurement - Potential

- b quark hadronises to about

~40% to charged B mesons
~50% to neutral B mesons
~10% to Baryons
=> 64% cases where there is at least one charged b => Should be recognisable

- neutral B mesons decay to about

~ 50% into charged D Mesons => measurable
~ 50% into neutral D mesons
    ~64% of these D neutral undergo prong decays => charged particles => measurable
=> Out of 36% cases remaining above ~75% can (in principle) be retrieved

=> 91% of the charges from top quark decays lead to signatures that are in principle measurable

Two tasks:

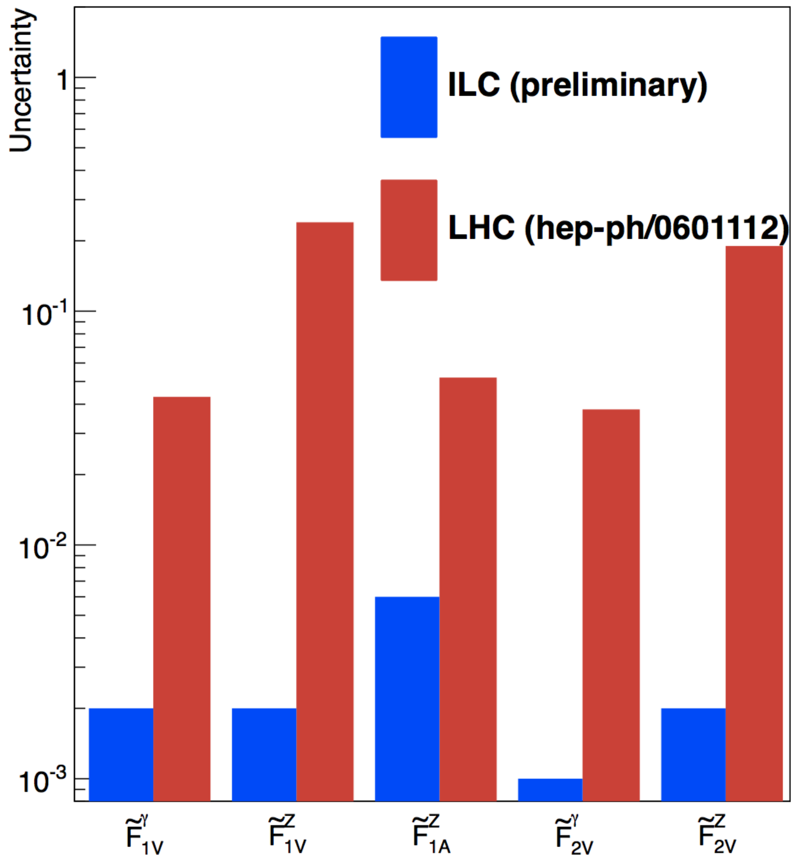
1) Understand why final state with charged B Meson are wrongly reconstructed
Exact fraction depends on final state, looks as if SL is somewhat easier than fully hadronic
2) Tertiary vertices for neutral B Mesons

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

ArXiv: 1307.8102

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings



Results validated by several independent cross checks

- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of vecto/axial vectol couplings for ILC
  One variable at a time For LHC
  However LHC projections from 8 years old study

- Need to control experimental (e.g. Top angle) and theoretical uncertainties (e.g. Electroweak corrections)
  -> Dedicated work has started

- Journal paper of results in preparation

ILC will be indeed high precision machine for electroweak top couplings

Discussion of potential systematic uncertainties

Experimental

- 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

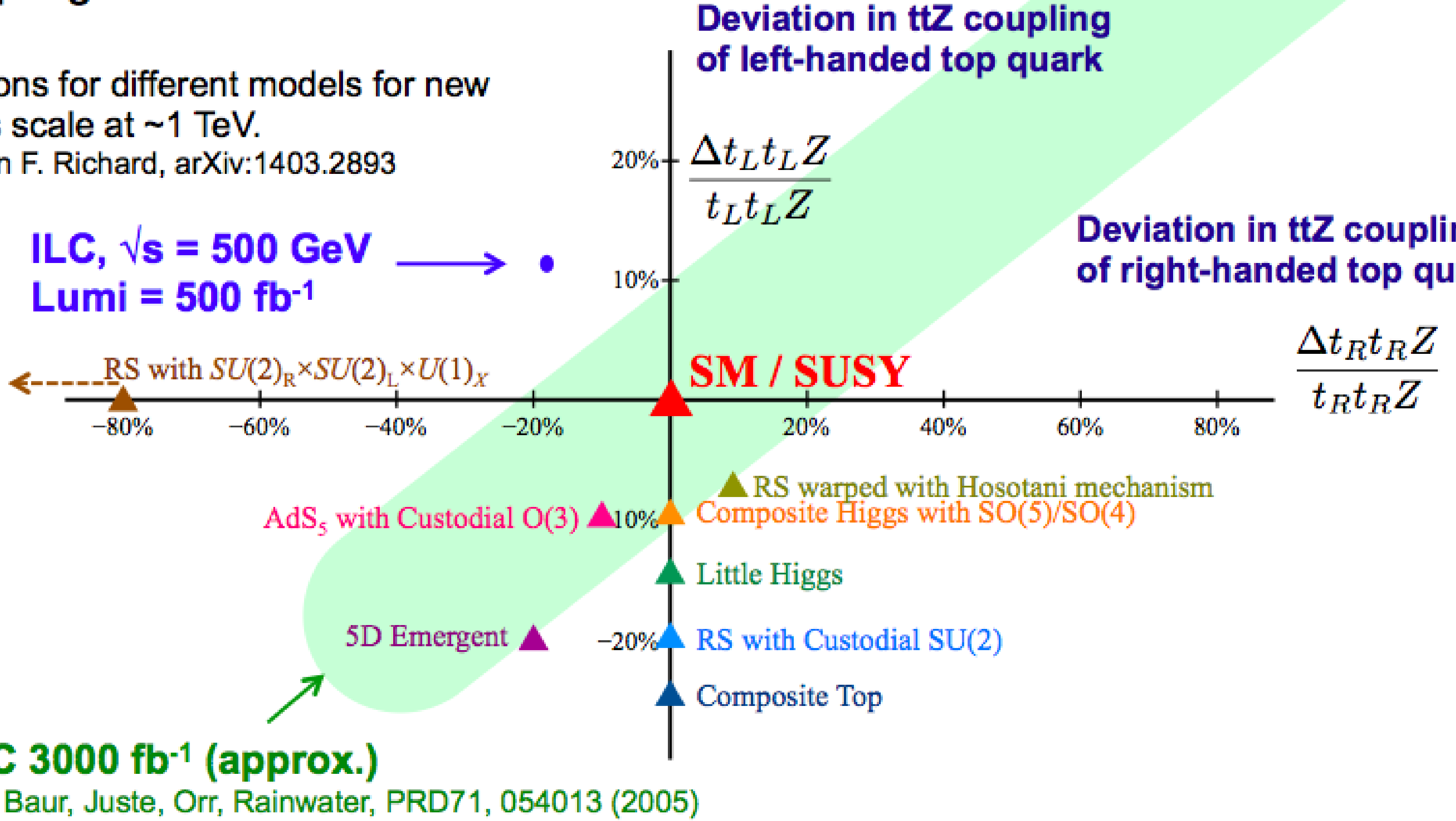
- Other effects: B-tagging, passive material etc.
  LEP claims 0.2% error on R_b -> guiding line for LC

Theory:
- See above
– Issue of single top under study

Sensitivity to New Physics

Composite Higgs theories have an impact on the top sector. Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization (both e- and e+) is essential to distinguish the ttZ and ttγ couplings.

Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893



Deviation in ttZ coupling of left-handed top quark

$$\frac{\Delta t_L t_L Z}{t_L t_L Z}$$

Deviation in ttZ coupling of right-handed top quark

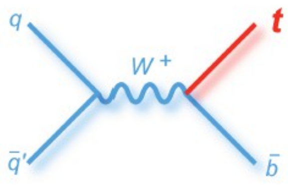
$$\frac{\Delta t_R t_R Z}{t_R t_R Z}$$

ILC, √s = 500 GeV
Lumi = 500 fb^{-1}

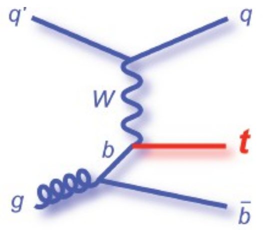
HL-LHC 3000 fb^{-1} (approx.)
Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

Remark: Ongoing discussion to understand contribution/constraints from LEP, LHC and B-Physics

Sensitivities and constraints



s-channel



t-channel

Model	dtR/tR %	dtL/tL %	dtLbL/tLbL %	dεb/εb	dε1/ε1	dꙨZtt/ꙨZtt %
Carena	0	-20	-14	0.8	1.1	-30
Djouadi	-330	0	0	-1.4	1.1	70
Gherghetta	-20	-20	-14	0.7	2.1	-36
Grojean	0	10	7	-0.4	-1.0	17
Hosotani	18	-7	-5	-0.4	-0.8	-5
Little Higgs	0	-15	-10	0.6	1.0	-23
Pomarol	0	-25	-17	1.0	1.2	-37
Wulzer 1	25	25	17	-1.1	5.8	56
Wulzer 2	-10	-10	-7	0.4	1.3	-20

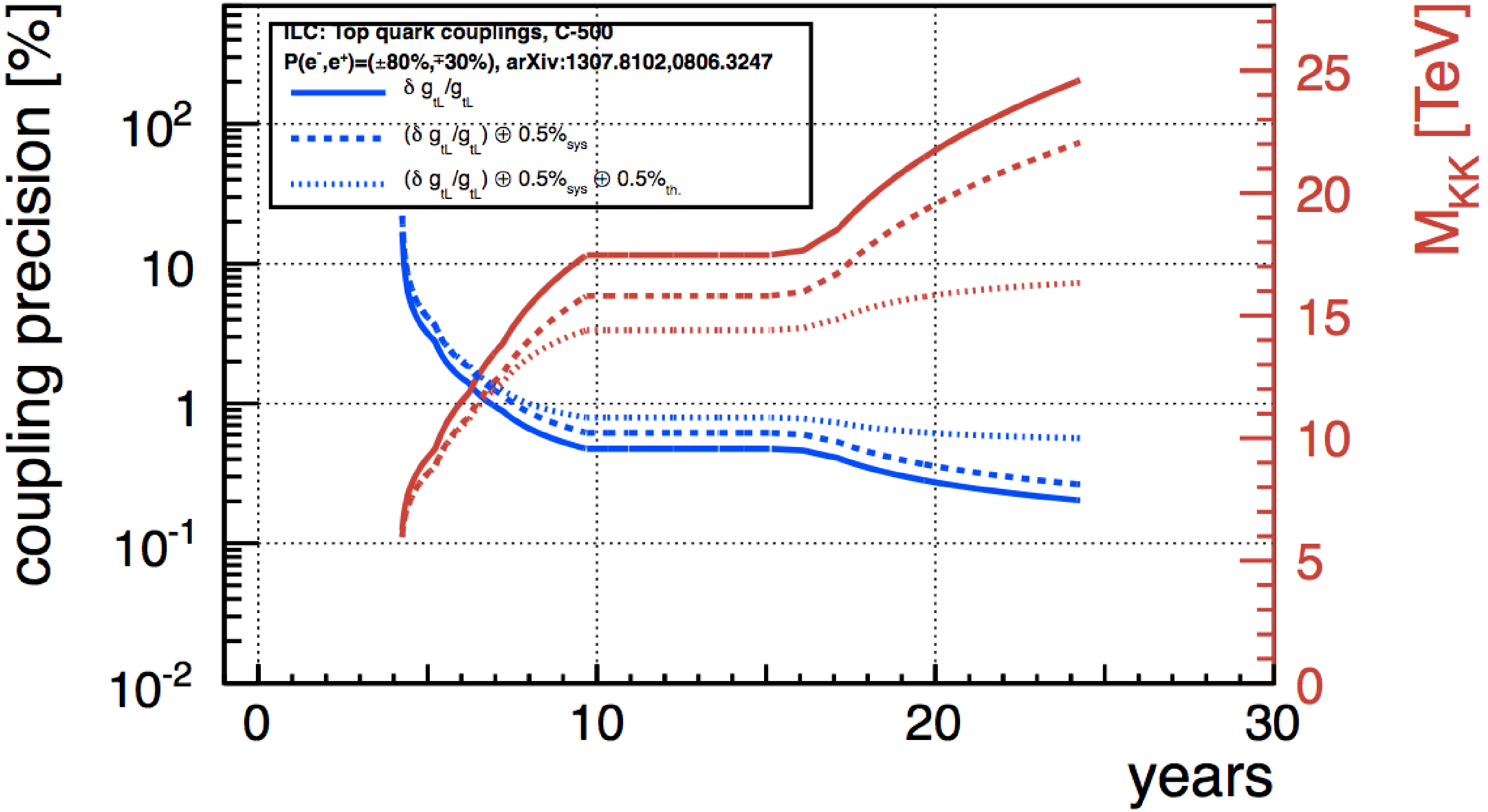
LEP constraints: $|\delta F_{1A}^{Z}| < 0.2,\ Q_{t_L} \to Q_{t_L}^{SM}$

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

Example for physics reach

New physics reach for typical BSM scenarios with composite Higgs/Top And or extra dimenssions

Based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~25 TeV in typical scenarios
(… and up tp 80 GeV for extreme scenarios)

Summary and outlook

- A LC is **the** machine for precision top physics

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

  Essential pillar of LC physics program

- Rich program of top quark physics with 'exciting' prospects

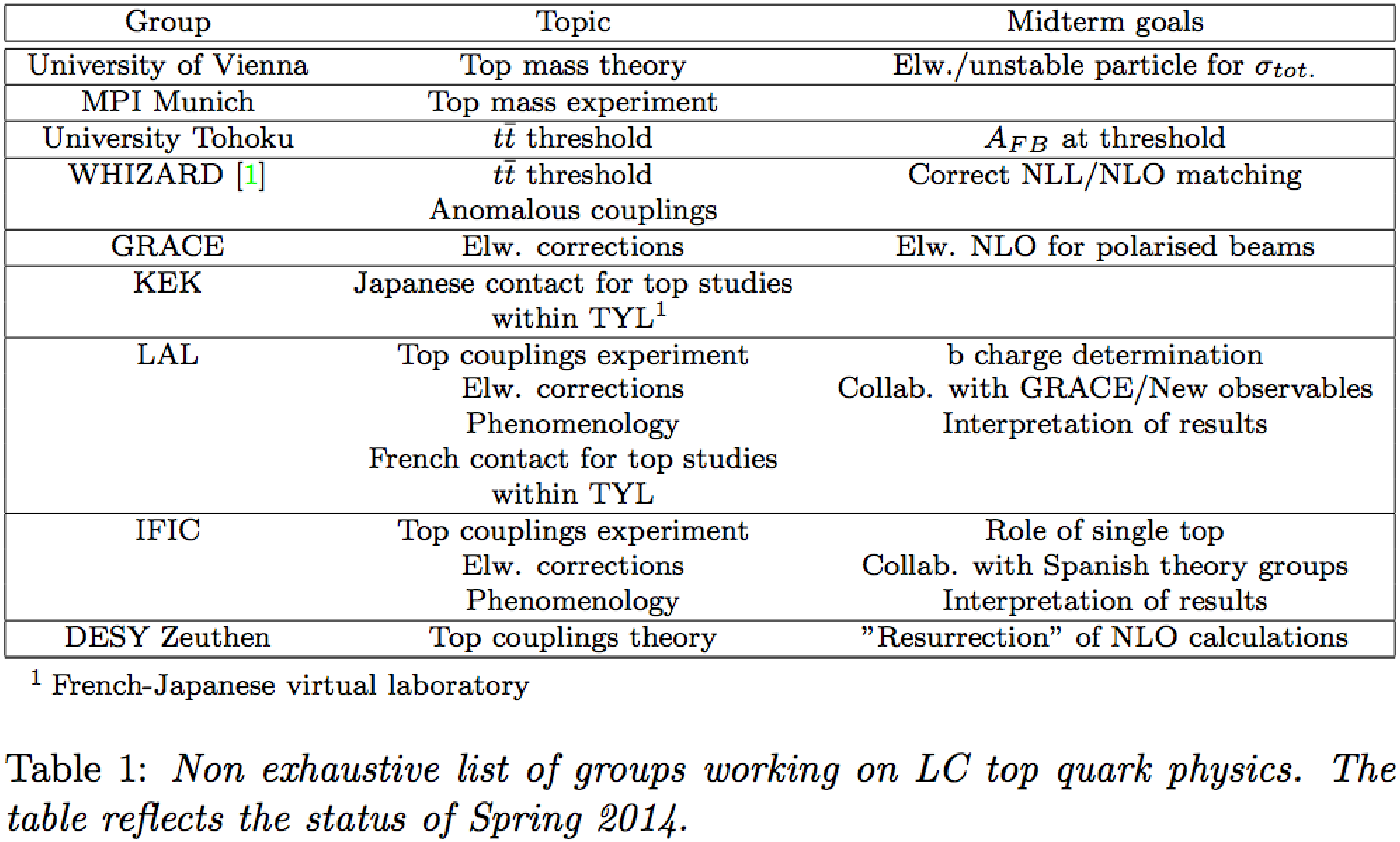
  -Precision on top mass ~50 MeV =>
  'Final word' on vacuum stability of the universe
  - Test of models with extra dimensions and/or compositeness
  - Top elw. Measurements are complementary to Higgs coupling Measurements

- Exploitation of potential requires huge experimental and theoretical efforts

  - Theoretical uncertainty on top mass >> Experimental uncertainty
  - Uncertainty of theoretical prediction of AFB
    NNLO would be 10 years of work !!!
  - Measurement of b quark charge still in infancy, may need revision of algorithms and detector
  – In general experimentalists will have to make sure that systematic errors can be kept small

Towards a coherent approach (Theory and experiment)

1st workshop on top physics at LC – March 2013 at LPNHE/Paris



Group	Topic	Midterm goals
University of Vienna	Top mass theory	Elw./unstable particle for σ_{tot}.
MPI Munich	Top mass experiment	
University Tohoku	$t\bar{t}$ threshold	A_{FB} at threshold
WHIZARD [1]	$t\bar{t}$ threshold Anomalous couplings	Correct NLL/NLO matching
GRACE	Elw. corrections	Elw. NLO for polarised beams
KEK	Japanese contact for top studies within TYL[1]	
LAL	Top couplings experiment Elw. corrections Phenomenology French contact for top studies within TYL	b charge determination Collab. with GRACE/New observables Interpretation of results
IFIC	Top couplings experiment Elw. corrections Phenomenology	Role of single top Collab. with Spanish theory groups Interpretation of results
DESY Zeuthen	Top couplings theory	"Resurrection" of NLO calculations

[1] French-Japanese virtual laboratory

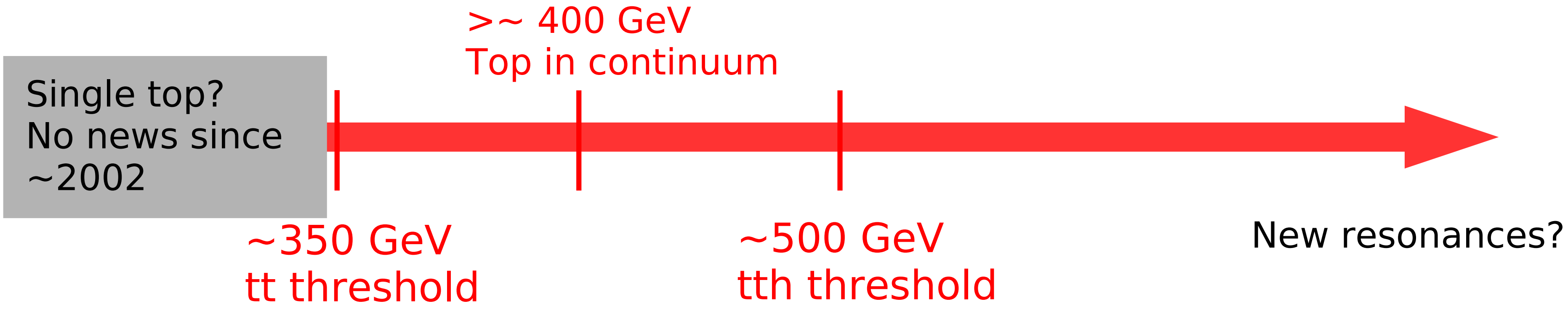
Table 1: *Non exhaustive list of groups working on LC top quark physics. The table reflects the status of Spring 2014.*

- Mailing list: topatlc-l@in2p3.fr

  No new structure but lightweight forum on issues of top physics
- Stay tuned for 2nd workshop in Spring 2015

Backup

Relevant scales for Top physics and LC Physics programme



Single top?
No news since
~2002

>~ 400 GeV
Top in continuum

~350 GeV
tt threshold

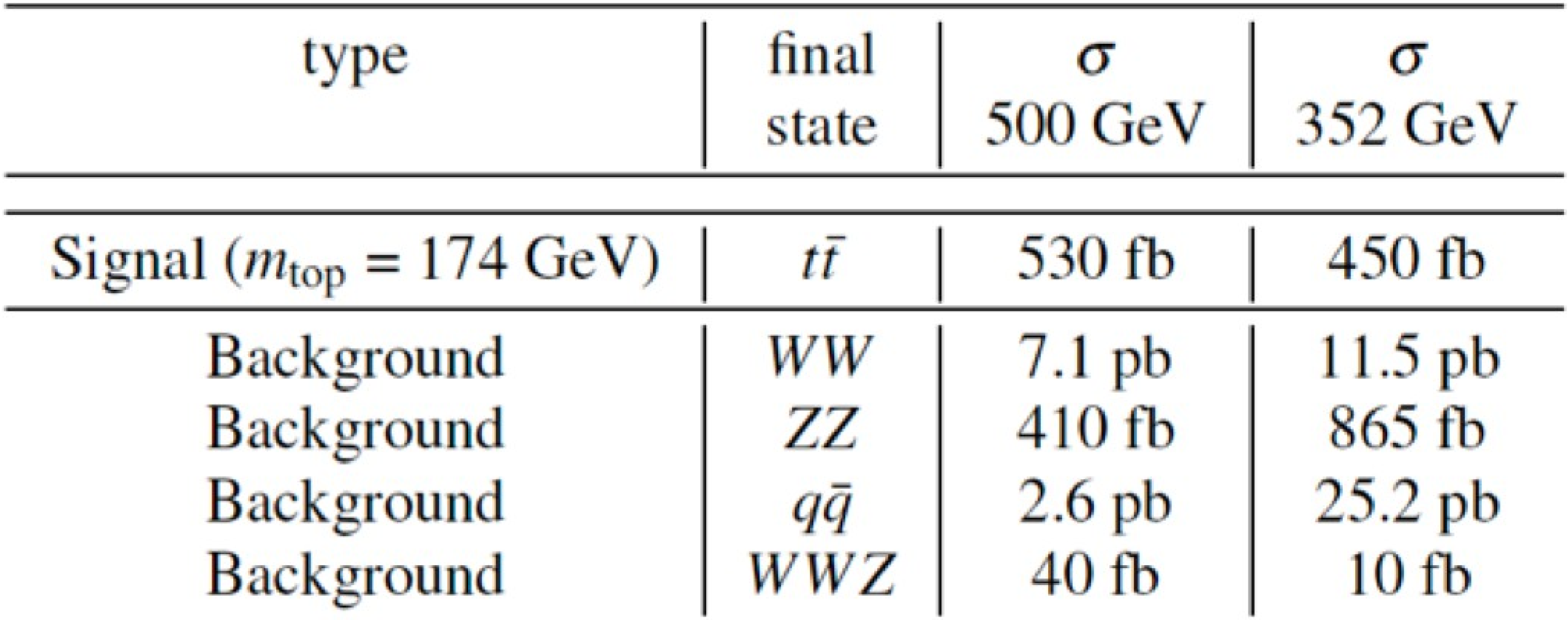
~500 GeV
tth threshold

New resonances?

- After TDR and Japanese initiative, programme for ILC under discussion
  ILC in staged approach but which is first stage?

- Arguments to start at 350 GeV include Top physics programme

Relevant cross sections



type	final state	σ 500 GeV	σ 352 GeV
Signal (m_{top} = 174 GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

Remarks:

- LC will have polarised beams
  => $(\sigma_{tt})_L \sim 1565\text{fb}^{-1}$, $(\sigma_{tt})_R \sim 724\text{fb}^{-1}$ at 500 GeV
- Background varies differently with polarisations
  e.g. WW-Background → 26000fb^{-1} for e_L and 150fb^{-1} for e_R

Form Factors and observables I

Form factors from previous pages re-written:

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

$$\longrightarrow$$

$$\mathcal{F}^L_{1V} = Q_e Q_t + c^e_L f(s) F^Z_{1V},\quad \mathcal{F}^L_{1A} = c^e_L f(s) F^Z_{1A}$$

$$\mathcal{F}^R_{1V} = Q_e Q_t + c^e_R f(s) F^Z_{1V},\quad \mathcal{F}^R_{1A} = c^e_r f(s) F^Z_{1A}$$

Cross section more explicitly (Stay in SM for the moment):

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

$$=$$

Z/γ interference

$$\begin{aligned}\sigma_I &= 2\mathcal{A}N_c\beta\left[(1+0.5\gamma^{-2})((Q_eQ_t)^2\right.\\ &+ 2Q_eQ_tc^e_Lf(s)F^Z_{1V}\\ &+ \left.(c^e_Lf(s)F^Z_{1V})^2) + (\beta\mathcal{F}^I_{1A})^2 + \ldots\right]\end{aligned}$$

Form Factors and observables II

Differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left[A_0(1+\cos^2\theta) + A_1\cos\theta\right]\begin{cases} \sim (1+\cos^2\theta) & \text{'Usual' Vector current, symmetric in } \cos\theta \\ \backsim \cos\theta & \text{Axial Vector current, asymmetric in } \cos\theta \end{cases}$$

Forward Backward Asymmetry

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

- Key observable to test chiral structure of Ztt (Zff) vertex

- Sensitive to amount of left-right asymmetry in interaction
  New physics may reduce asymmetry (→ left-right symmetric)

More on Form Factors

Vector/axial vector Form factors SM values (Better known as c_V, c_A):

$$F_{1V}^{Z} = \frac{2}{3} = Q_t, \quad F_{1V}^{Z} = \frac{1}{4} - \frac{2}{3}\sin^2\theta_W/(\sin\theta_W\cos\theta_W), \quad F_{1A}^{Z} = -\frac{1}{4}/(\sin\theta_W\cos\theta_W)$$

$$F_{1A}^{\gamma} = 0$$

… and <u>always</u> 0 in SM
No axial coupling to photon, QED gauge invariance

Tensorial couplings (all 0 at tree level):

Magnetic Dipole Moment:

$$F_{2V}^{\gamma}(0) = Q_t\frac{(g_t - 2)}{2}$$

(Anomalous) magnetic moment of top quark
Scattering of particle in magnetic field,
(g_t -2) ≠ 0 due to higher order corrections, 'not pointlike' anymore)
Similar interpretation holds for F_{2V}^{Z}

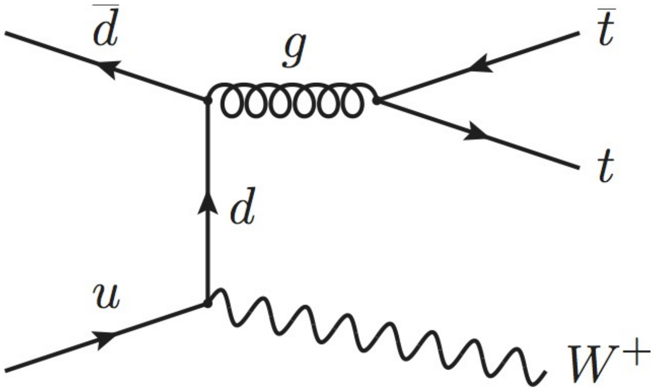
Electrical Dipole Moment:

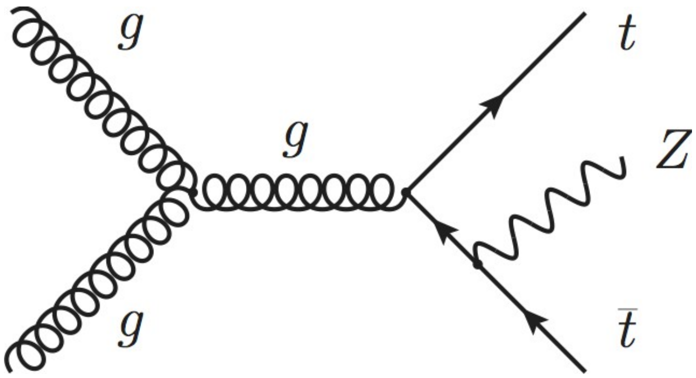
$$F_{2A}^{\gamma}(0) = ed_t^{\gamma}$$

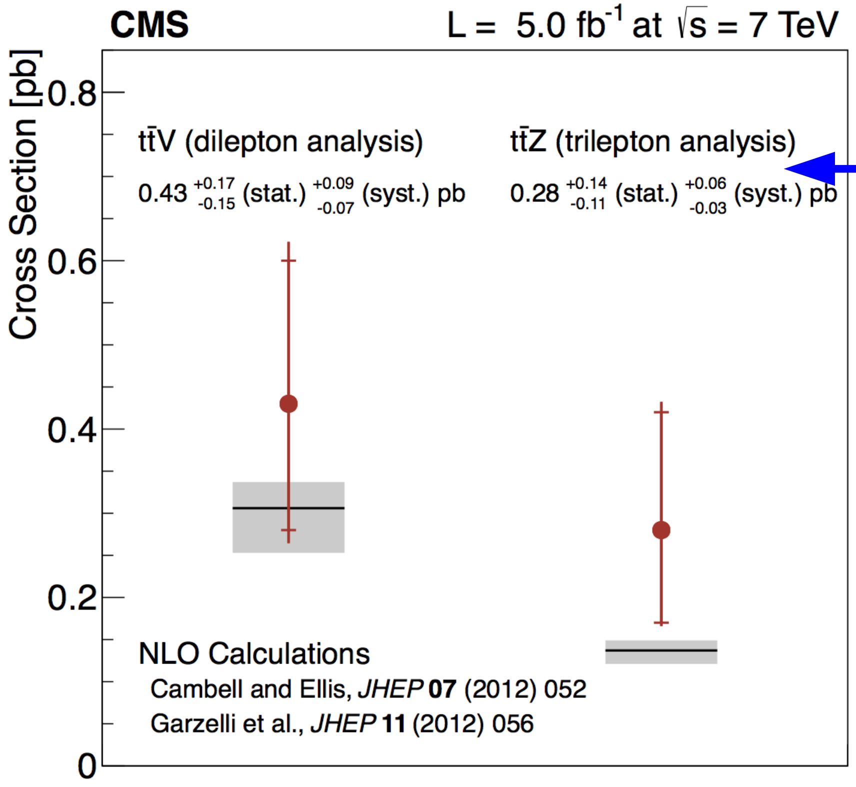
Bound state effects (e.g. vertex corrections) may create electrical dipole
d extremely small in SM, O(10^{-14})
CP Violating
Any non-zero value measured 'today' is sign of BSM
May receive contributions from CP Violating Higgs
Similar interpretation holds for F_{2A}^{Z}

The race is open !

Recent result on ttV by CMS







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

- Clearly, promising result
- How will it evolve with higher Luminosity?
- Revision of 'old' estimations of precisions are needed!

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

Equations for cross section, A_{FB} and F_R

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

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

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

Elements of top quark reconstruction

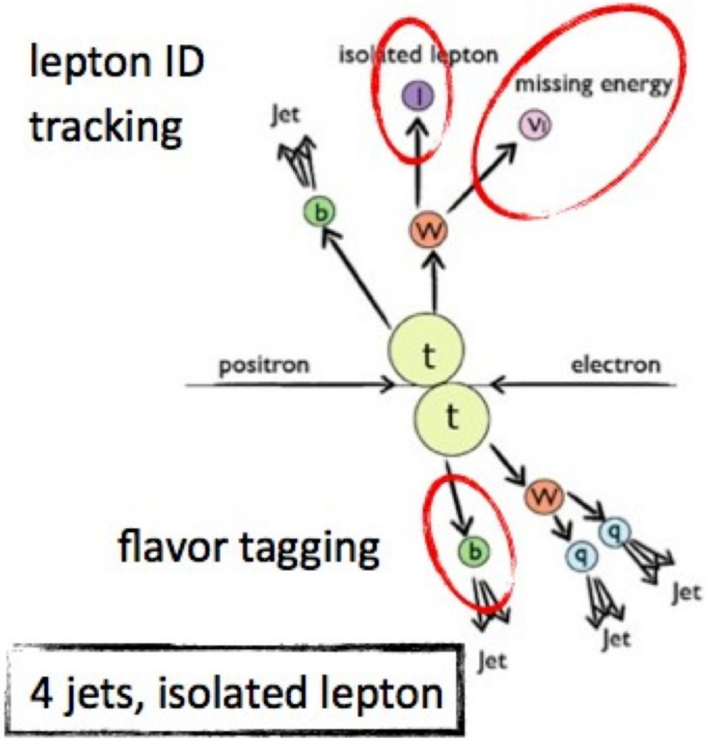
Three different final states:

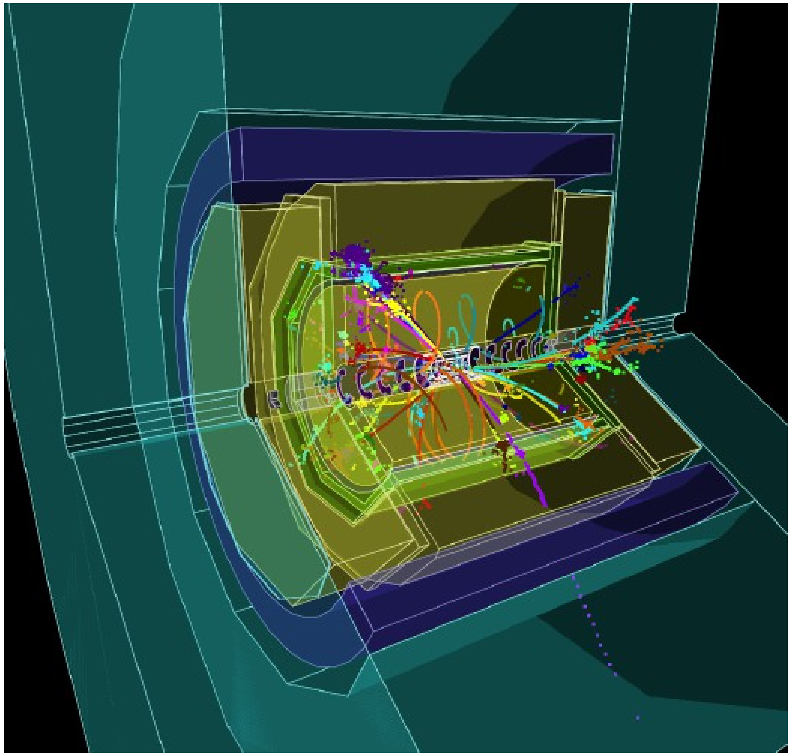
1) Fully hadronic (46.2%) → 6 jets

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

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

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

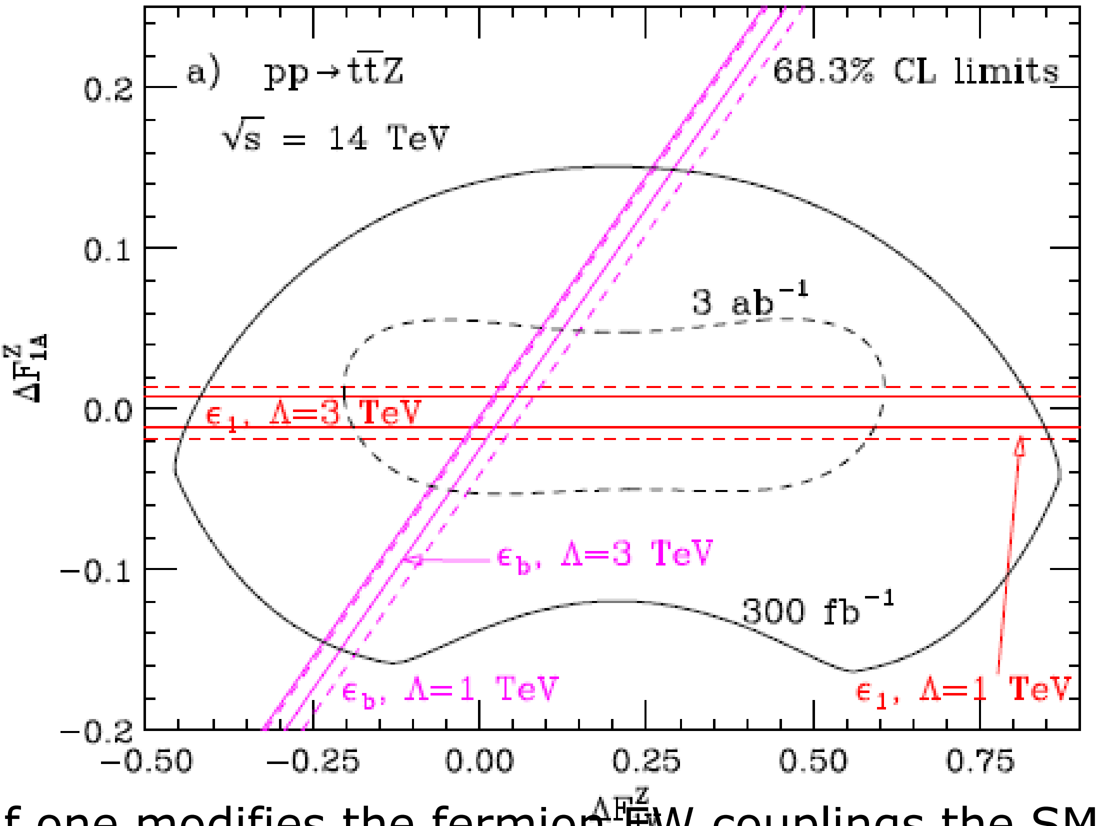




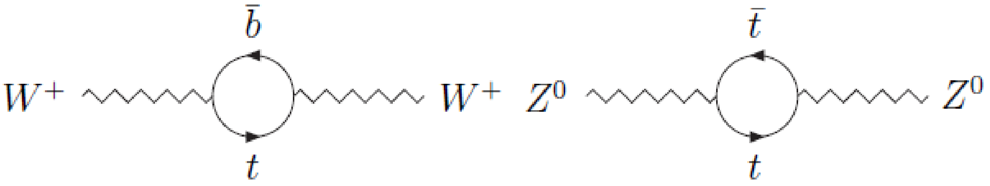
Results in the following mainly based on semi-leptonic decay

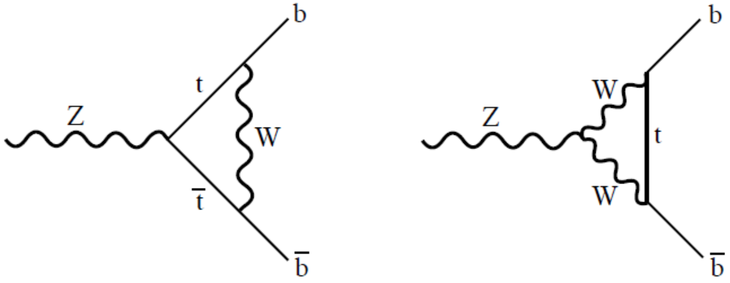
Do however integrate results from fully hadronic study

Recap: LEP/SLD Constraints



- Recall that if one modifies the fermion EW couplings the SM loops becomes UV divergent and this requires introducing a **cutoff π~TeV** to compute these contributions
- Given this cutoff the top EW **couplings anomalies** are limited by LEP/SLD measurements





Constraints due to Gauge Invariance

- Gauge invariance relates ZtLtL to WtLbL and ZbLbL

$$\kappa_{bL}^{NC} + \kappa_{tL}^{NC} \sim \kappa_{tL}^{NC} = 2\kappa_{tLbL}^{CC}$$

- From LEP1 we know that ZbLbL has no anomaly meaning that

$$\frac{\delta WtLbL}{WtLbL} = 0.72\frac{\delta ZtLtL}{ZtLtL}$$

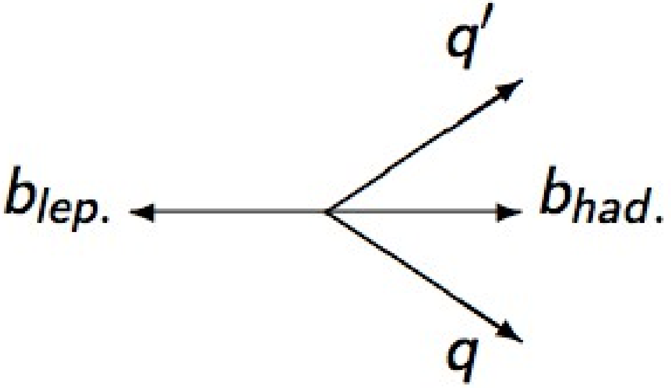
- ʃε1 and ʃεb only depend on neutral couplings ZbLbL and ZbRbR
- Loop contributions therefore fully constrain ZtLtL and ZtRtR and the only freedom left comes from BSM compensating contributions to ε1 and εb

F. Richard

Experimental challenge b-charge reconstruction - Motivation

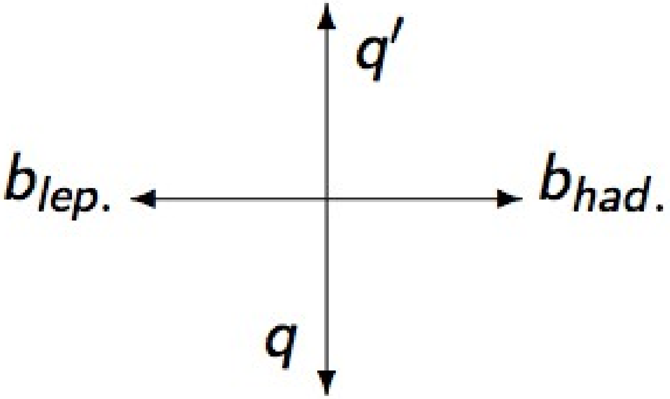
- To measure A_{FB} in fully hadronic decays there is no choice

- In semi-leptonic decays there is the charged lepton but ….



Right handed electron beam:

- mainly right handed tops In final state (V-A)
- Hard W in flight direction of Top and soft b's
- Flight direction of t from flight direction of W



Left handed electron beam:

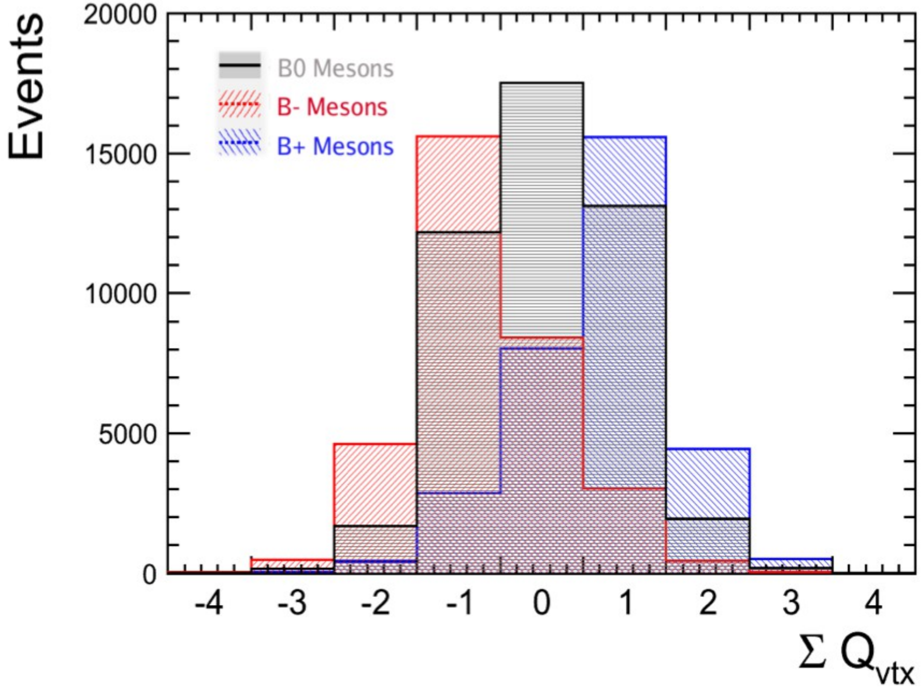
- mainly left handed tops
- Hard b in flight direction of Top and soft W's
- Flight direction of t from flight direction of b

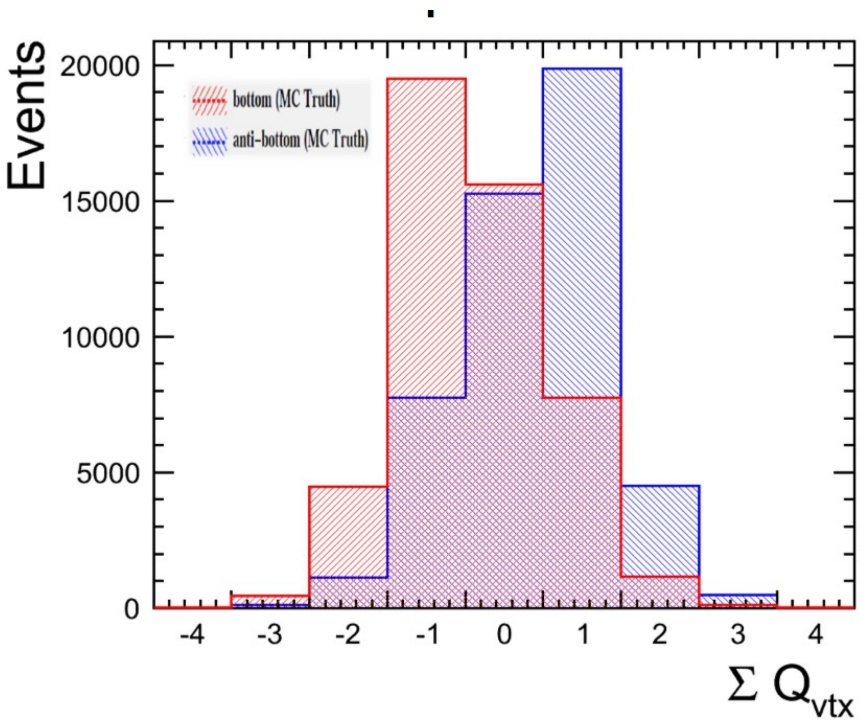
=> Wrong association ↔ top flip

Measurement of b-charge to resolve ambiguities

Measurement of b quark charge

(N.B. At example of fully hadronic analysis, PhD M.S. Amjad)

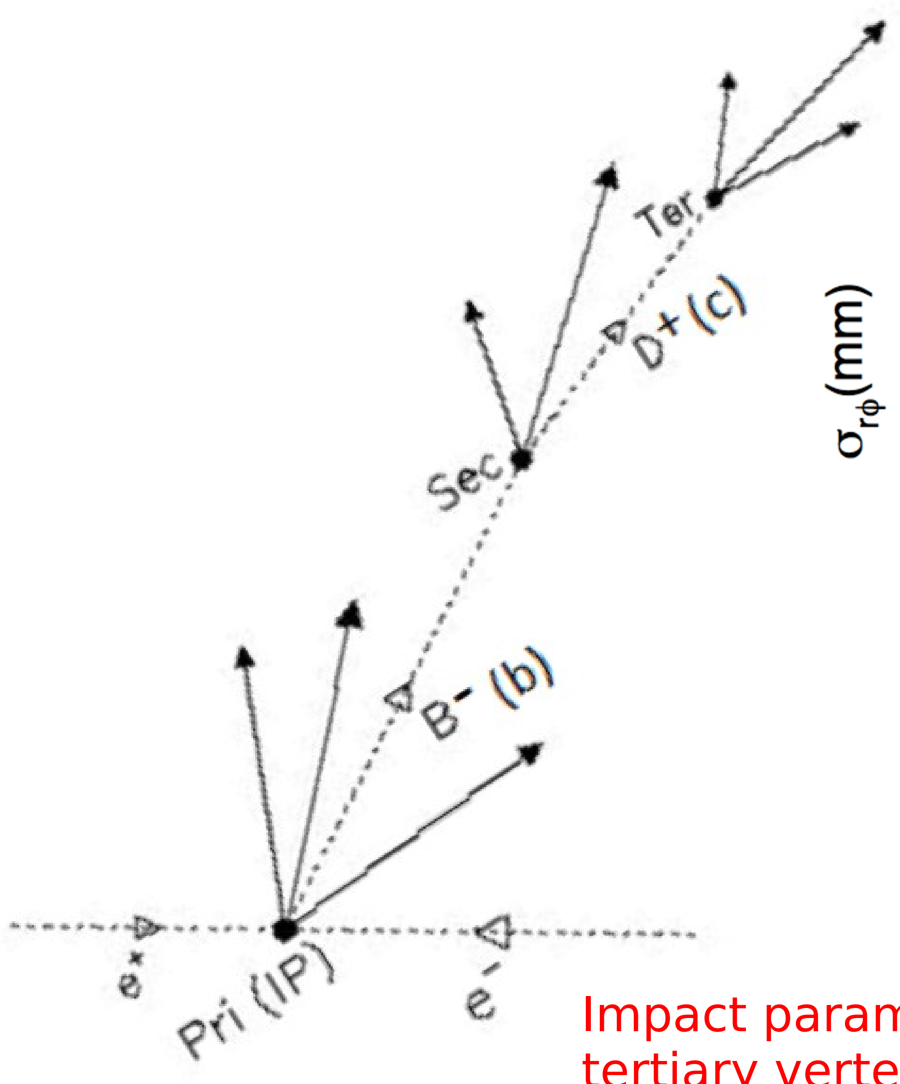




- Vertex charge measurement mandatory for fully hadronic top decays
- LC vertex and tracking system allows for determination of b-meson (b-quark) charge
  B-quark charge measured correctly in about 60% of the cases
  Can be increased to 'arbitrary' purity on the expense of smaller statistics
- `LCFIPlus` package not yet optimised for vertex charge measurement

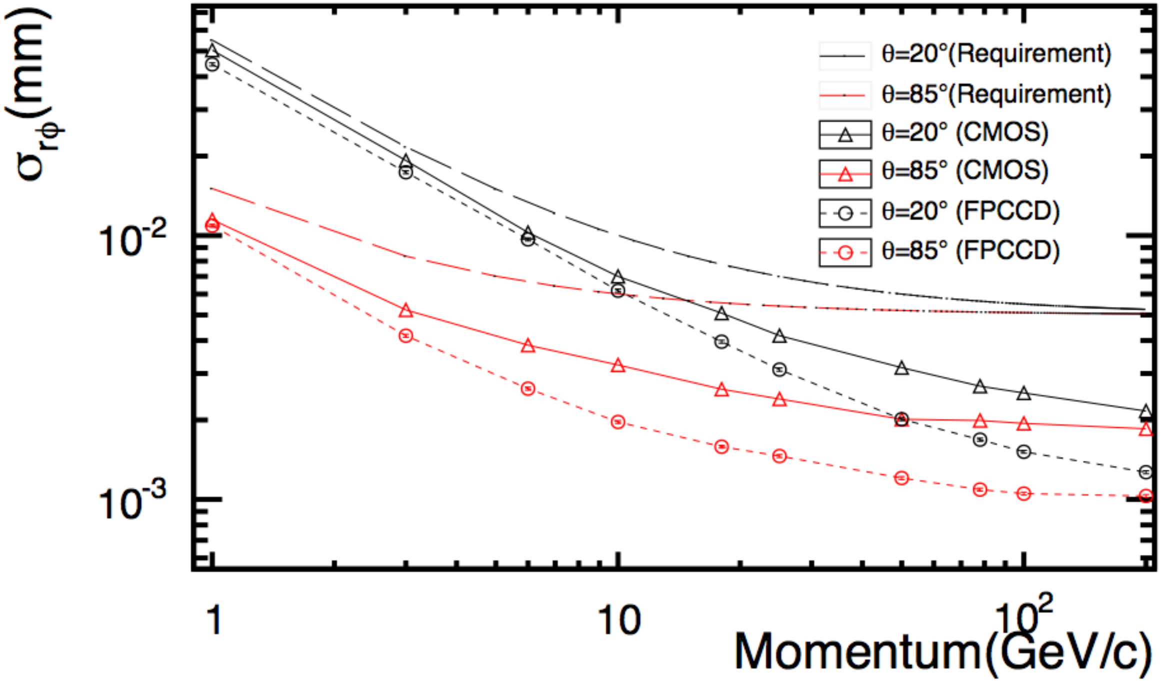
Optimisation of b-quark charge is major topic for future studies

Tertiary vertices – Principal considerations



Decay length of neutral D
cτ ≈ 120µm

Decay length of charged D
cτ ≈ 310 µm



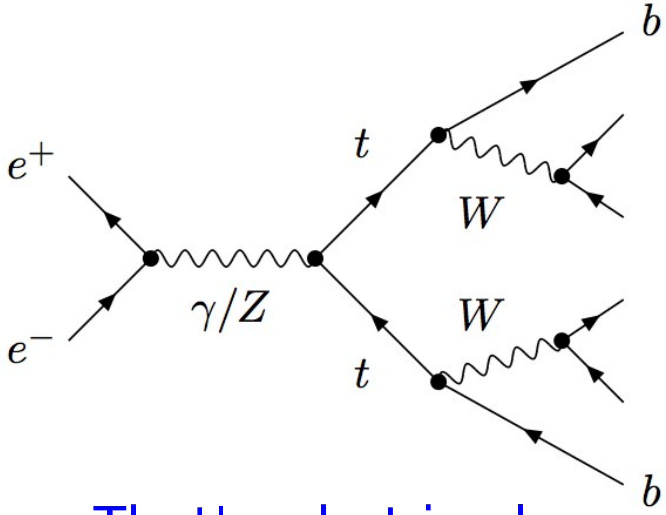
Impact parameter resolution of < 10 µm should permit tertiary vertex resonstruction ...

- Long lived charged particles via central tracking

N.B.: Both measurements are not part of ILD DBD

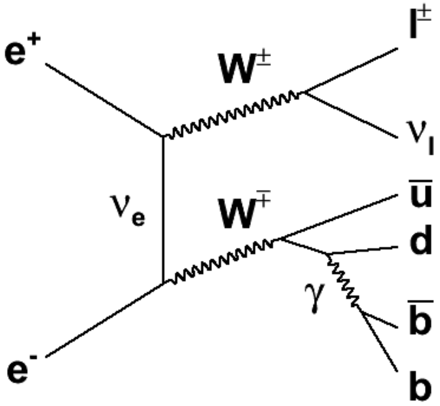
Closer look at ttbar production

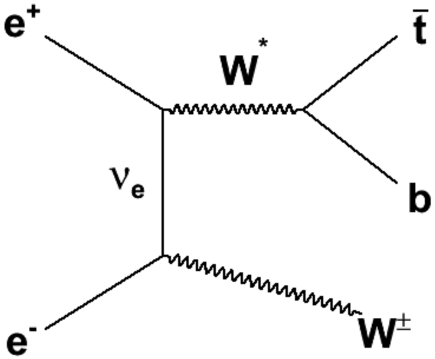
That's what we are interested in



Top pair production is effectively ee->6f process

That's what is also contributing to final state!

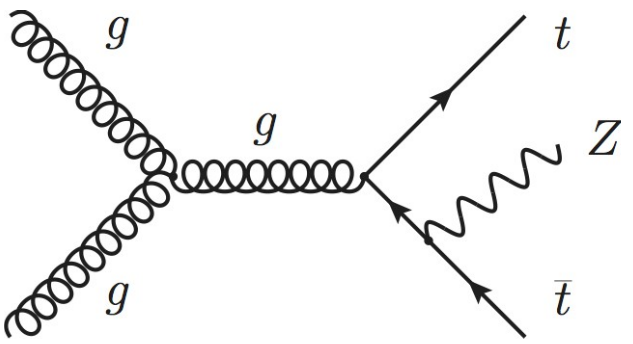


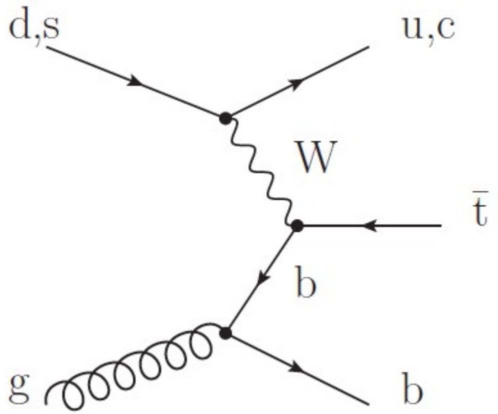


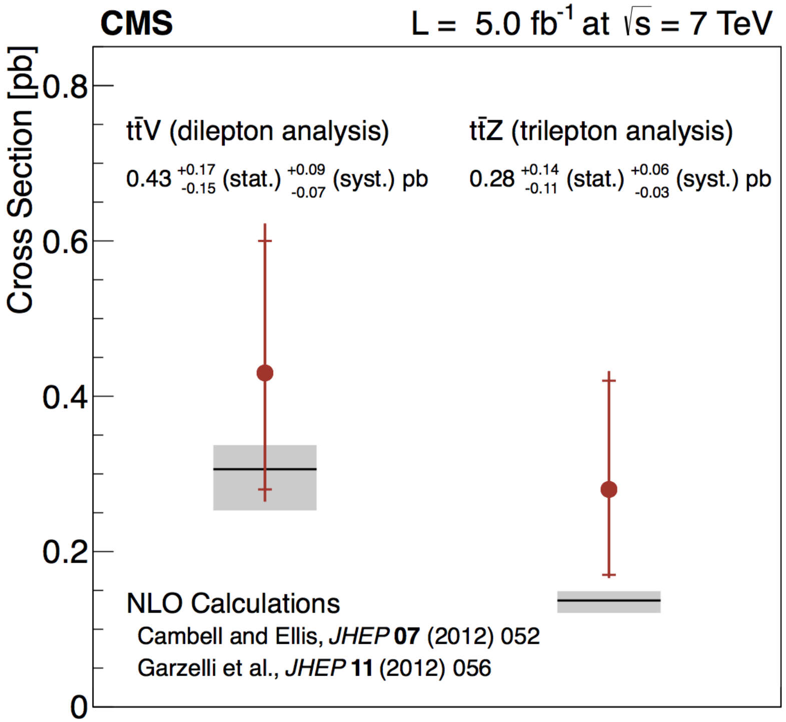
+ s-channel, t-channel only relevant for eL

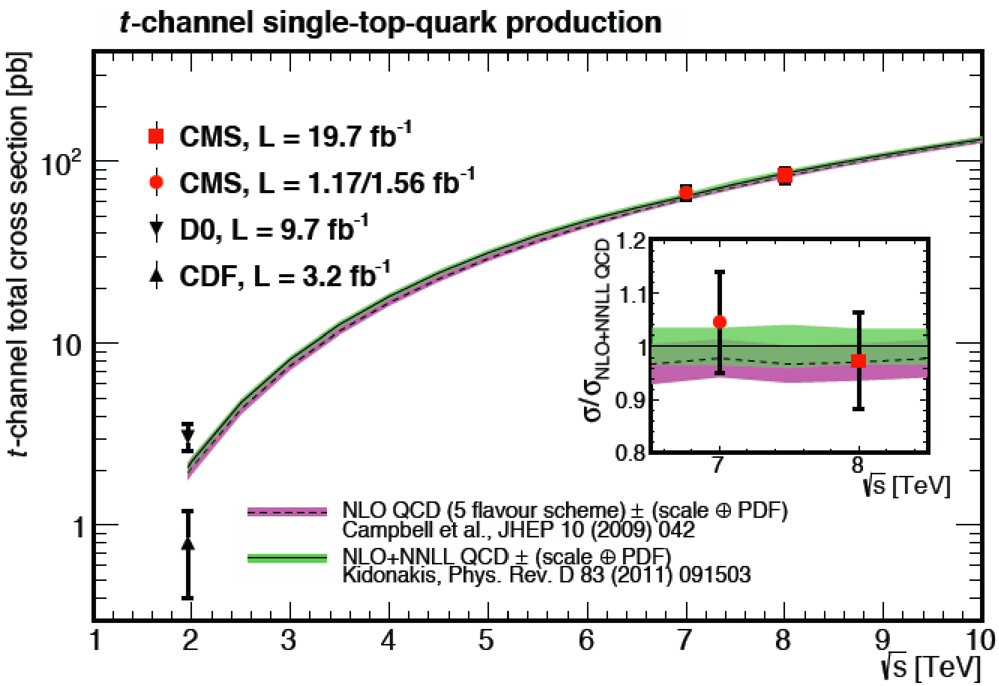
- Can one really speak about a ttbar cross section?
- If only 6f is relevant: What are relations to ttX couplings?
- What selection cuts are (theoretically) save?

Electroweak couplings – LHC contributions









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

=> $\delta V_{tb} \sim 5\%$

May expect: $\frac{\delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}} \backsim 10\%$?

=> Constraints on left handed top couplings

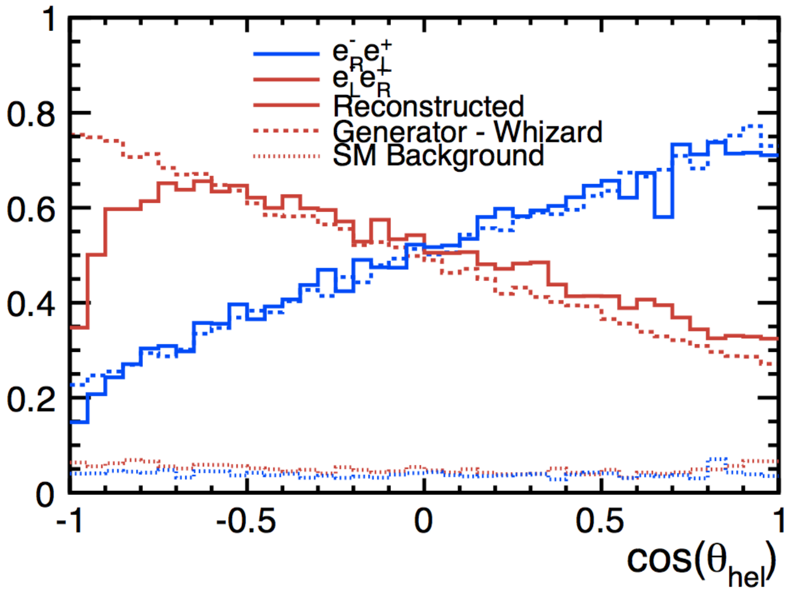
Measurement of top quark polarisation

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

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

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%

$$F_{2A}^{\gamma}(0) = Q_t d_t^{\gamma}$$