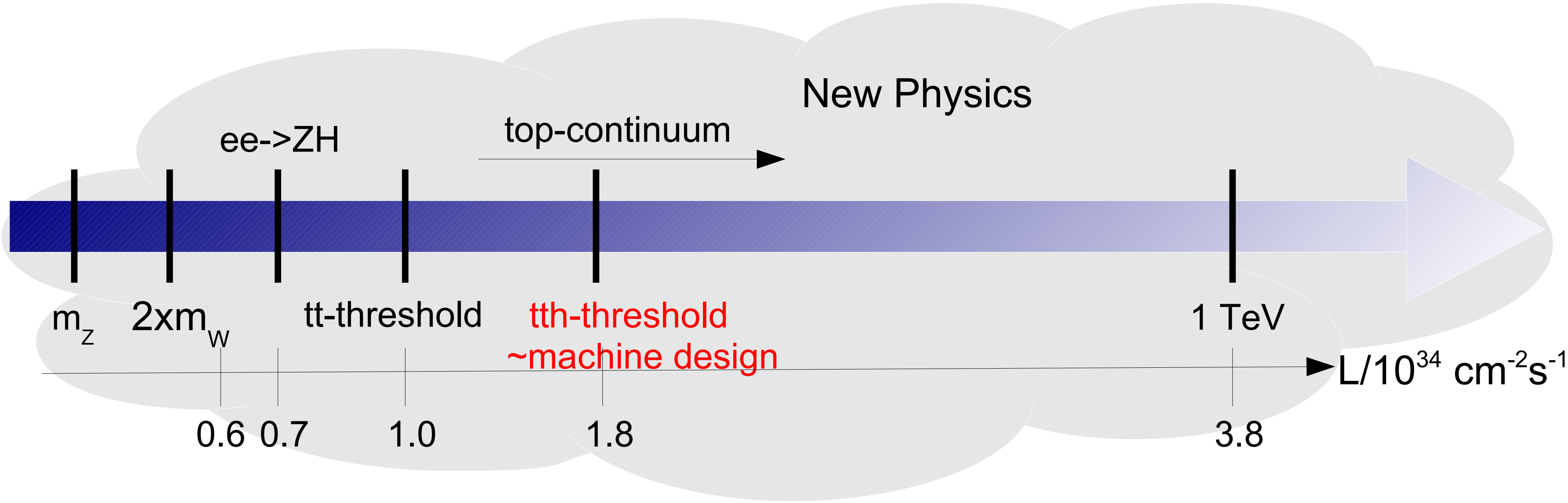
Top quark simulations at LC

Roman Pöschl

With major contributions from

2nd WHIZARD Workshop Würzburg – March 2015

(I)LC Physics program

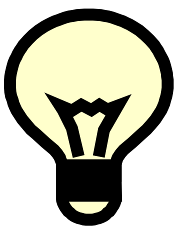


- All Standard Model particles within reach of (I)LC
  - High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation

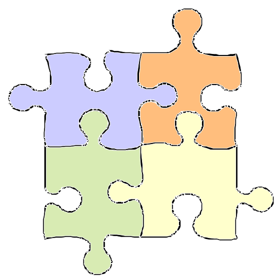
$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

- “Background free” searches for BSM through beam polarisation

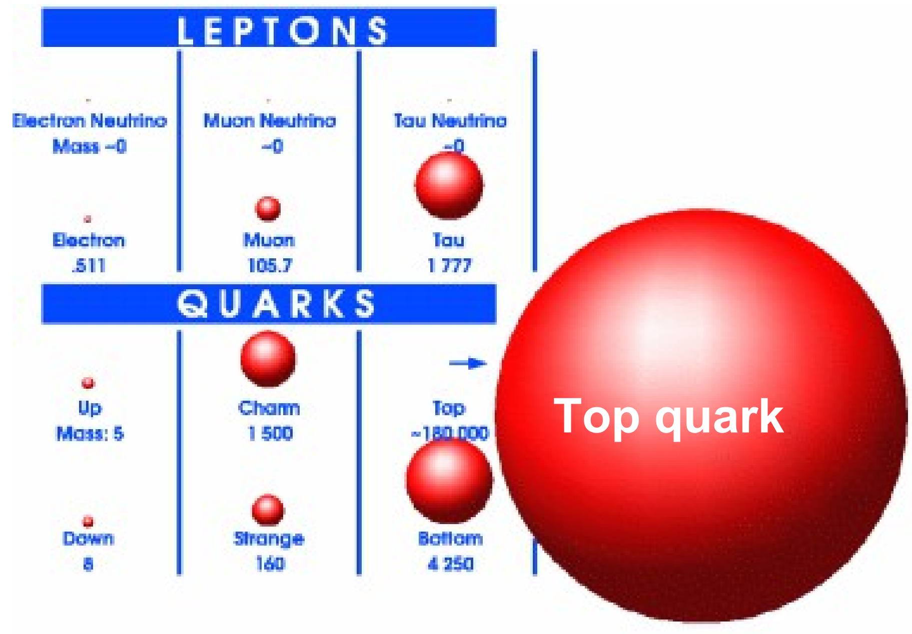
An enigmatic couple



Elementary Scalar?



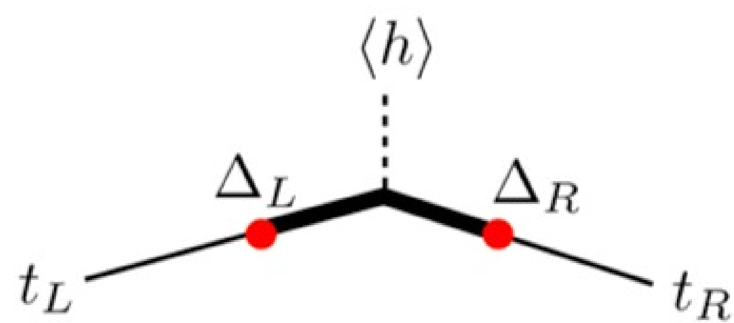
Composite object?



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

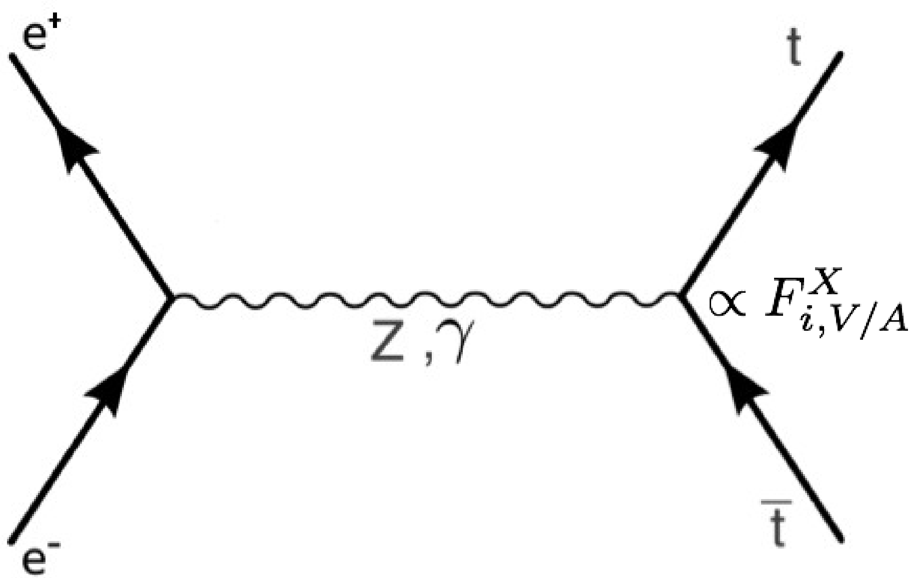
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

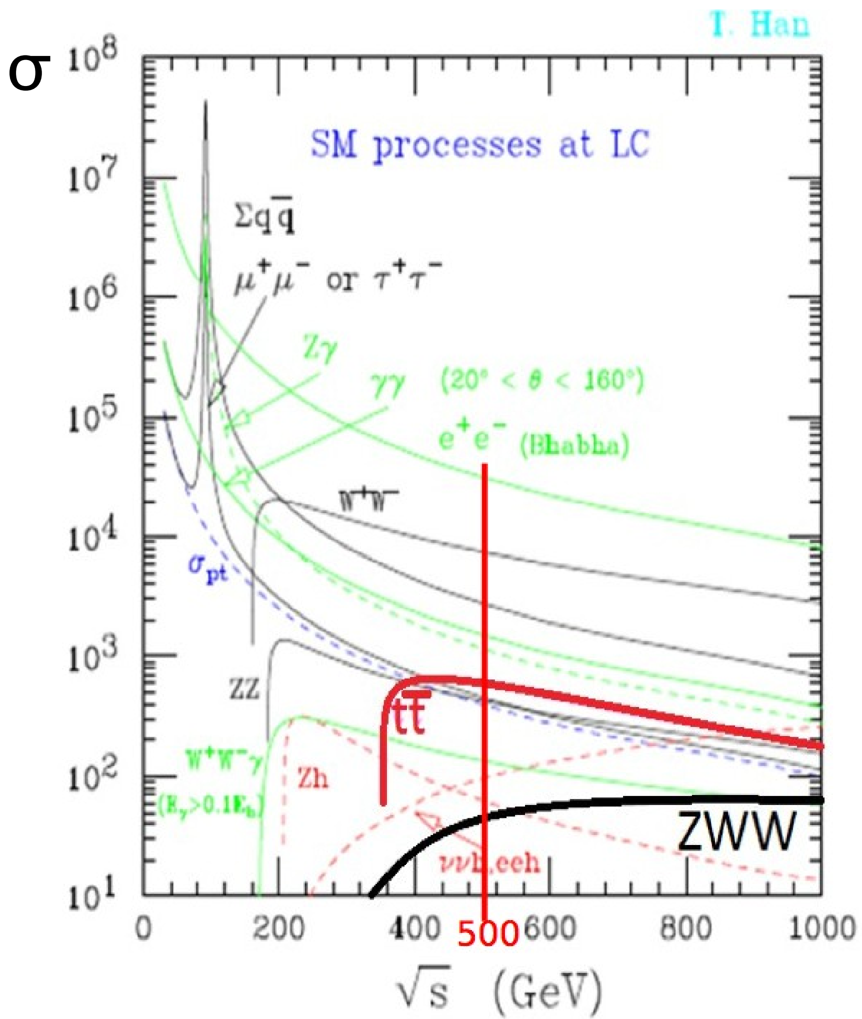
- LC perfectly suited to decipher both particles



Courtesy of S. Rychkov

Top Quark Physics at Electron-Positron Colliders





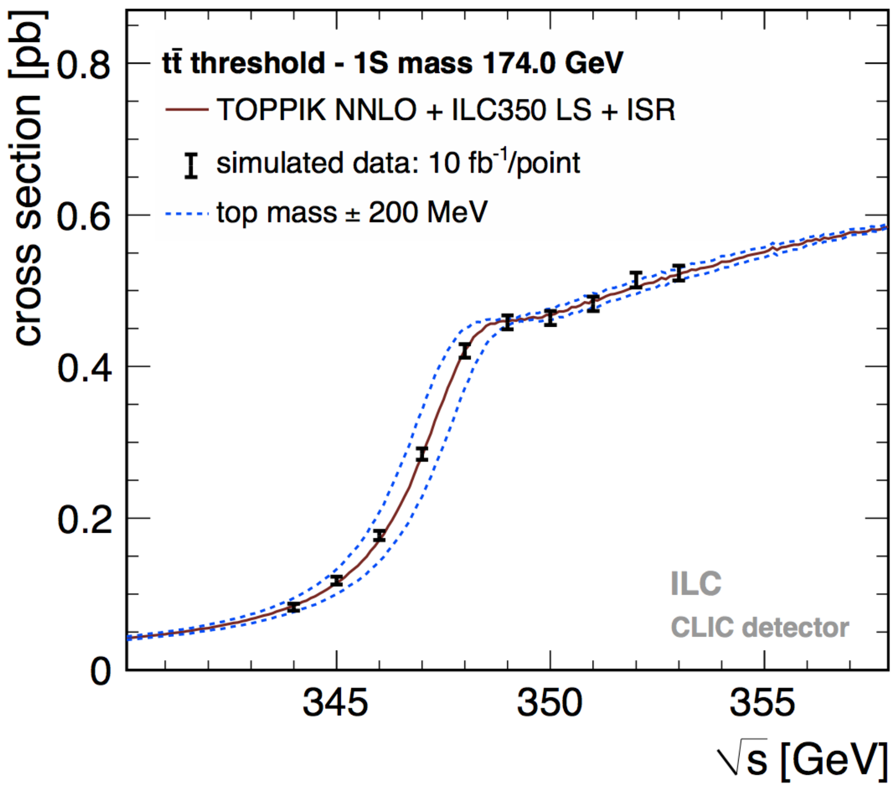
- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

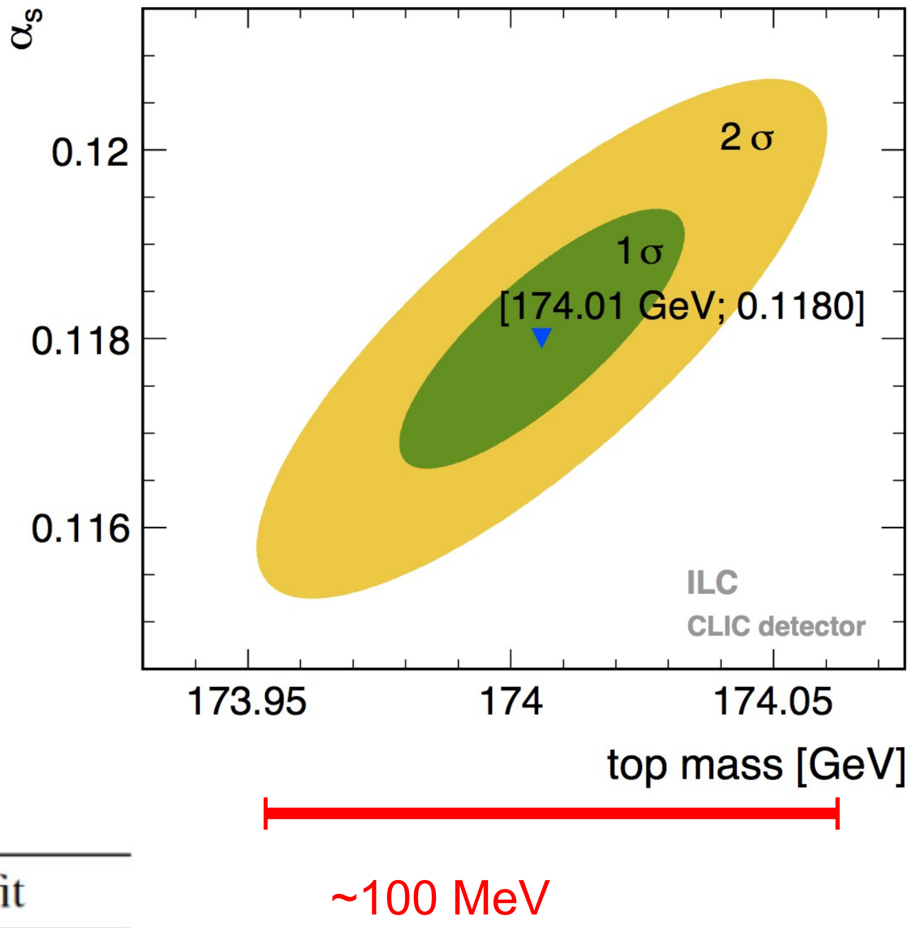
- High precision measurements
  - Top quark mass at ~ 350 GeV through threshold scan
  - Polarised beams allow testing chiral structure at ttX vertex
    => Precision on form factors F

Top Quark Mass – Results of Full Simulation Studies

Mass and α_s

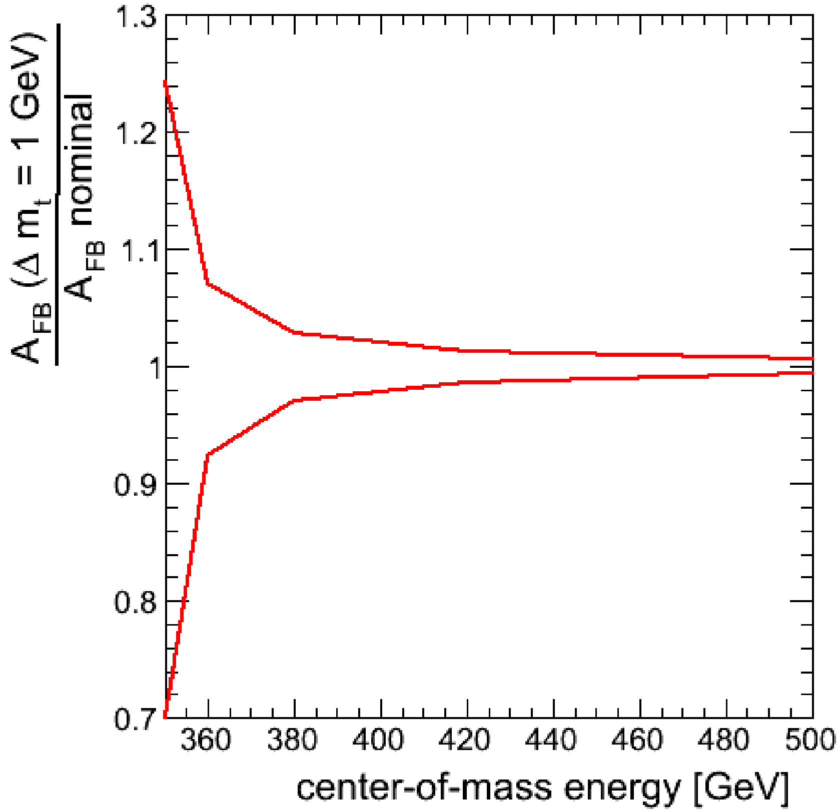
EPJC C73 (2013) 2530





1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

From threshold to continuum

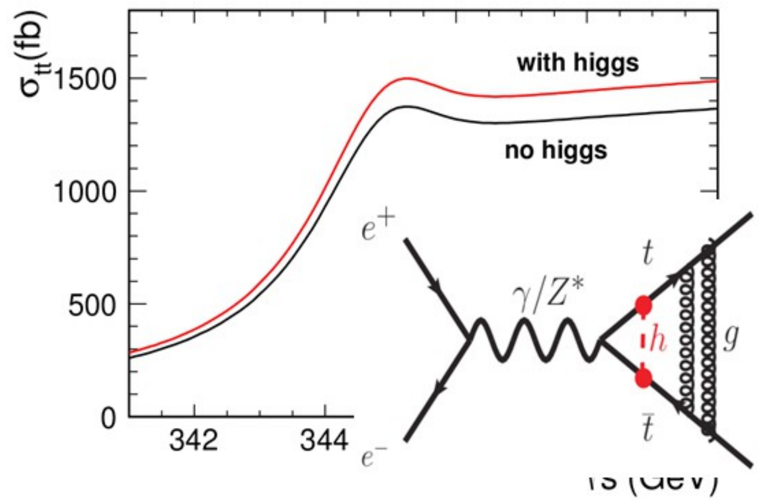


Influence of the top quark mass on x-sec and A_{FB}

- very pronounced below √s = 360 GeV
- 2.9%/GeV at √s = 380 GeV
- 1.3%/GeV at √s = 420 GeV
- 0.6%/GeV at √s = 500 GeV

With the assumption of a 100 MeV pole mass measurement at threshold, the remaining uncertainty is one per mil or less above 420 GeV

The template is prepared by floating top mass and width. Since the measurement of δyt is extracted from normalization of σtt, the normalization is also used for σtt fit.



- 2+1 param : **<u>2D fit</u>** <u>of mt and Γt</u>, yt is measured individually.
- 3 param : **3D fit** of mt, Γt and yt.

$\int \mathcal{L}dt = 100\ \mathrm{fb}^{-1}$

	(2 + 1) param fit	3 param fit
mt	19 MeV	29 MeV
Γt	38 MeV	39 MeV
yt	4.6%	5.9%

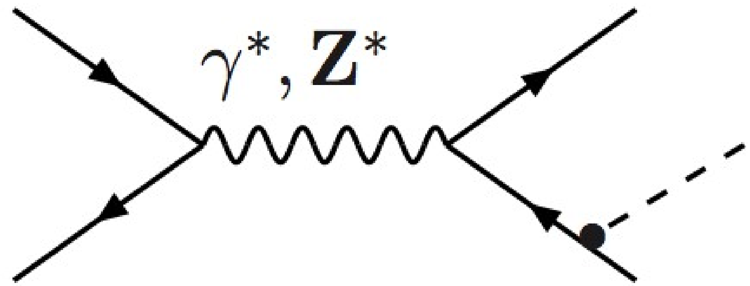
Stat. Uncertainties 'add' Theoretical uncertainties ~70 MeV

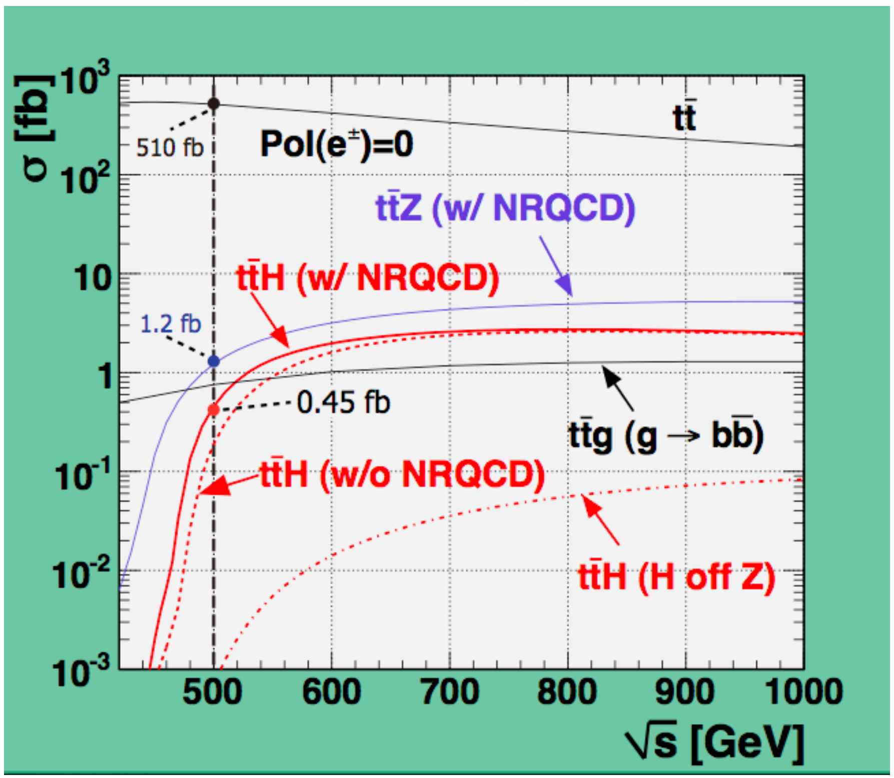
Total expected precision on m_t ~ 100 MeV

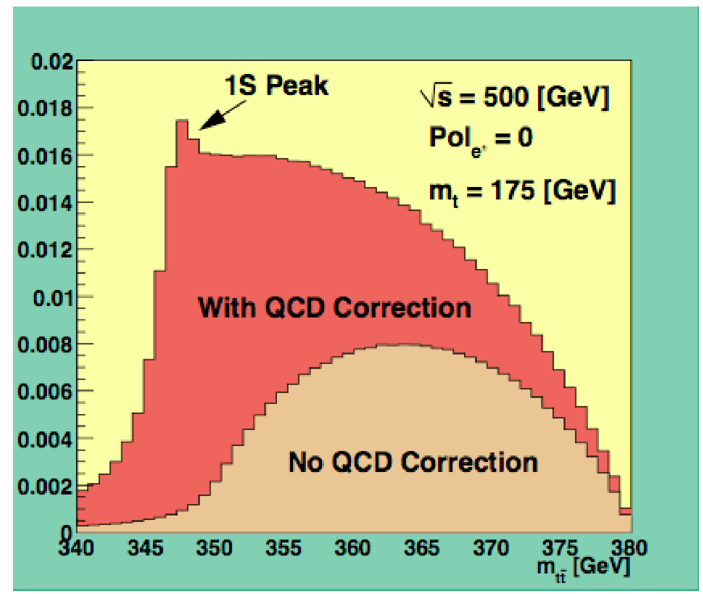
(very conservative estimation!!!)

T. Horiguchi

Top Yukawa Coupling above threshold







~ Factor 2 enhancement
From QCD bound states

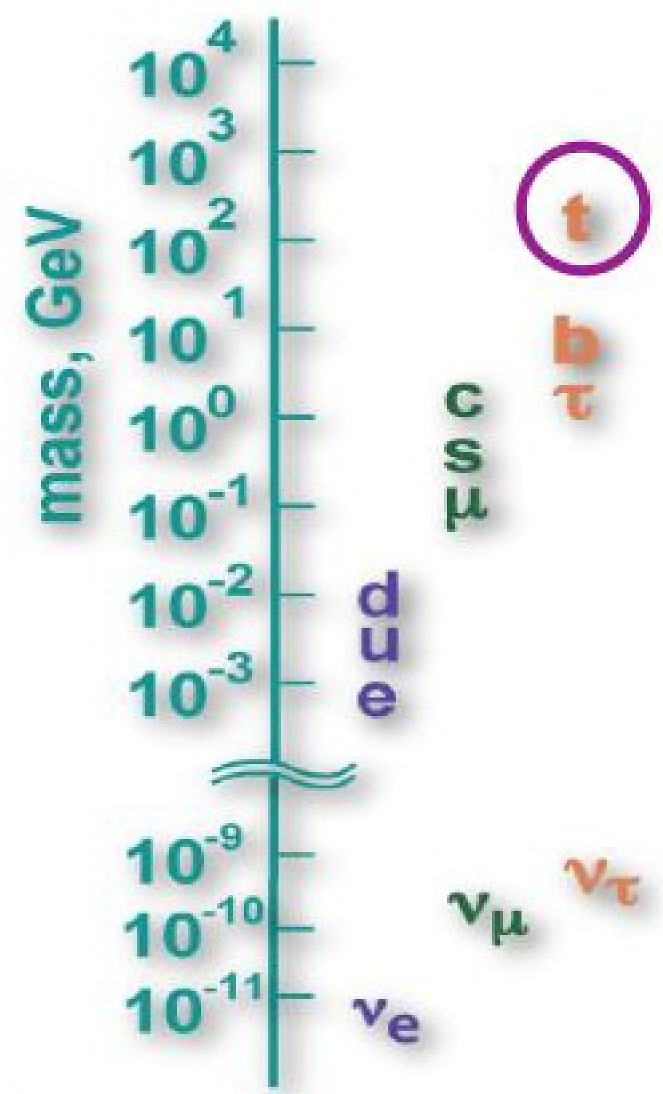
R. Yonamine et al.
T. Tanabe, T. Price

$\Delta g_{ttH} / g_{ttH}$	500 GeV	500 GeV + 1 TeV
Canonical	14%	3.2%
LumiUP	7.8%	2.0%

Canonical ← ILC TDR

LumiUP ← Technically possible

Top Quark and Flavor Hierarchy



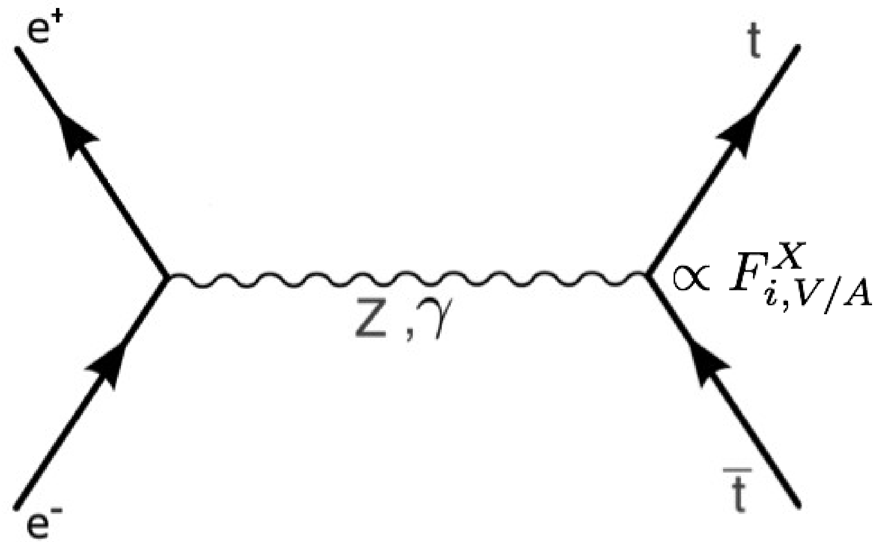
- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

- Fermion mass generation closely related to the origin electroweak symmetry breaking

- Expect residual effects for particles with masses closest to symmetry breaking scale
  - A_{FB} anomaly at LEP for b quark

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

Testing the Chiral Structure of the Standard Model



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

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

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

ILC 'provides' two beam polarisations

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

There exist 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 relevant unknowns

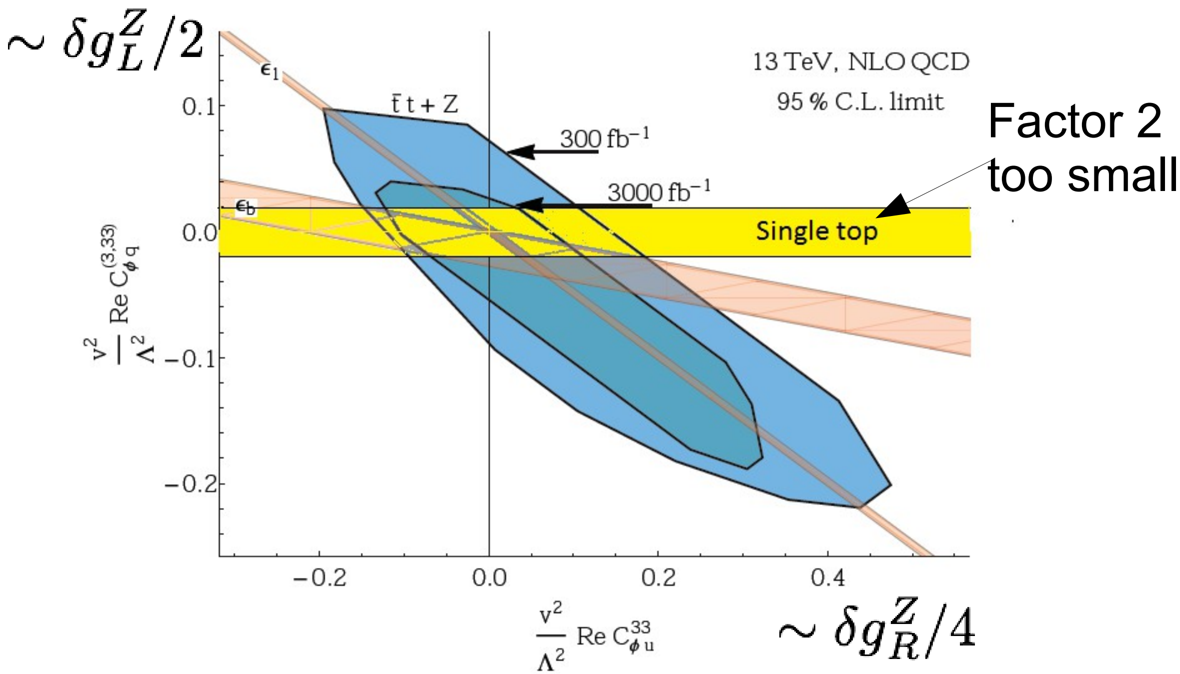
$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$
$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

or equivalently $g^{\gamma}_{L},\ g^{\gamma}_{R},\ g^{Z}_{L},\ g^{Z}_{R}$

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

ArXiv: 1307.8102

Accuracy on SM Z couplings compared with other experiments



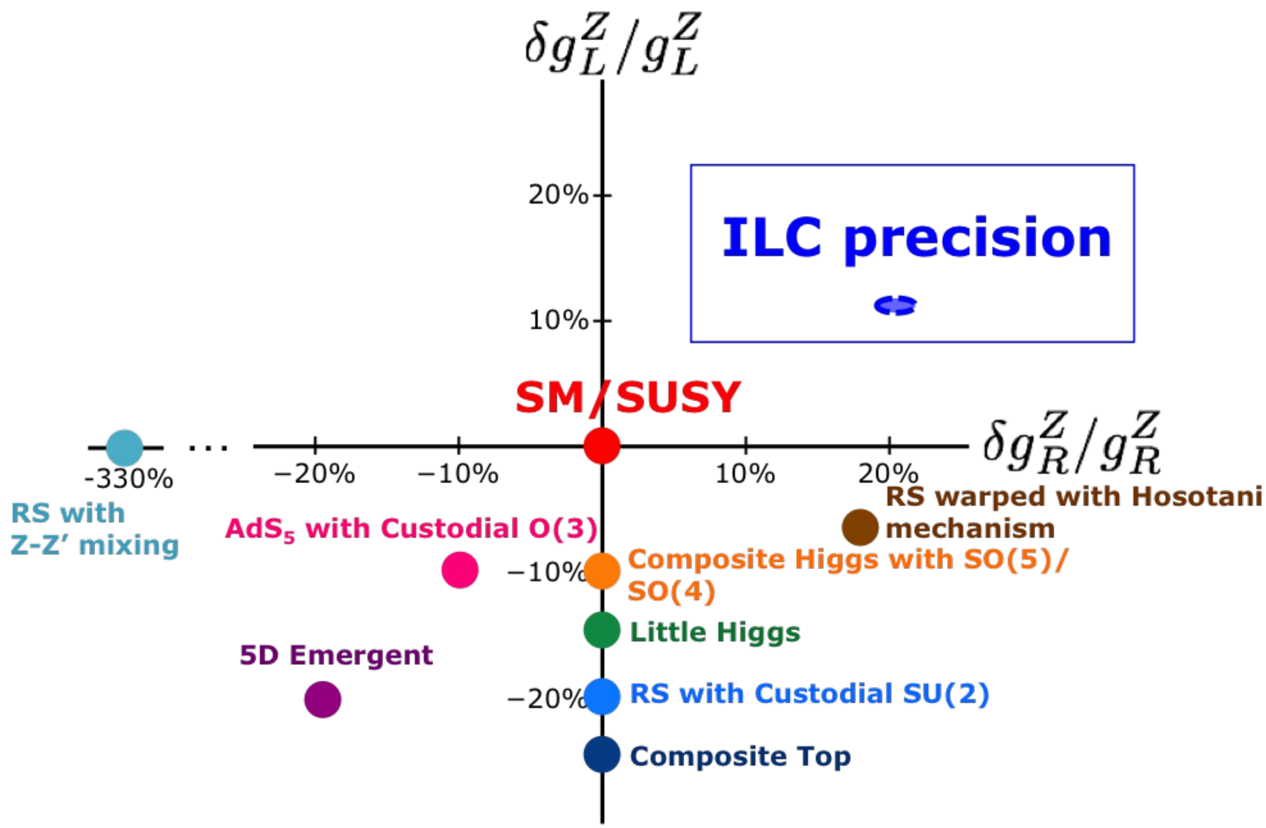
LHC 300. 3000 from 1404.1005
Flavor from 1408.0792
LHC Single top added by F. Richard

- ILC with polarised beams outperforms all present and future experiments (Stringent limits only from LEP)
- Before ILC single top at LHC and B factories can deliver complementary information
- In particular g_R can only be constrained by ILC!
- Maintaining this high level still requires substantial experimental and theoretical work

ILC promises to be high precision machine for electroweak top couplings

Sensitivity to New Physics

Top is primary candidate to be a messenger new physics in many BSM models
Incorporating compositeness and/or extra dimensions



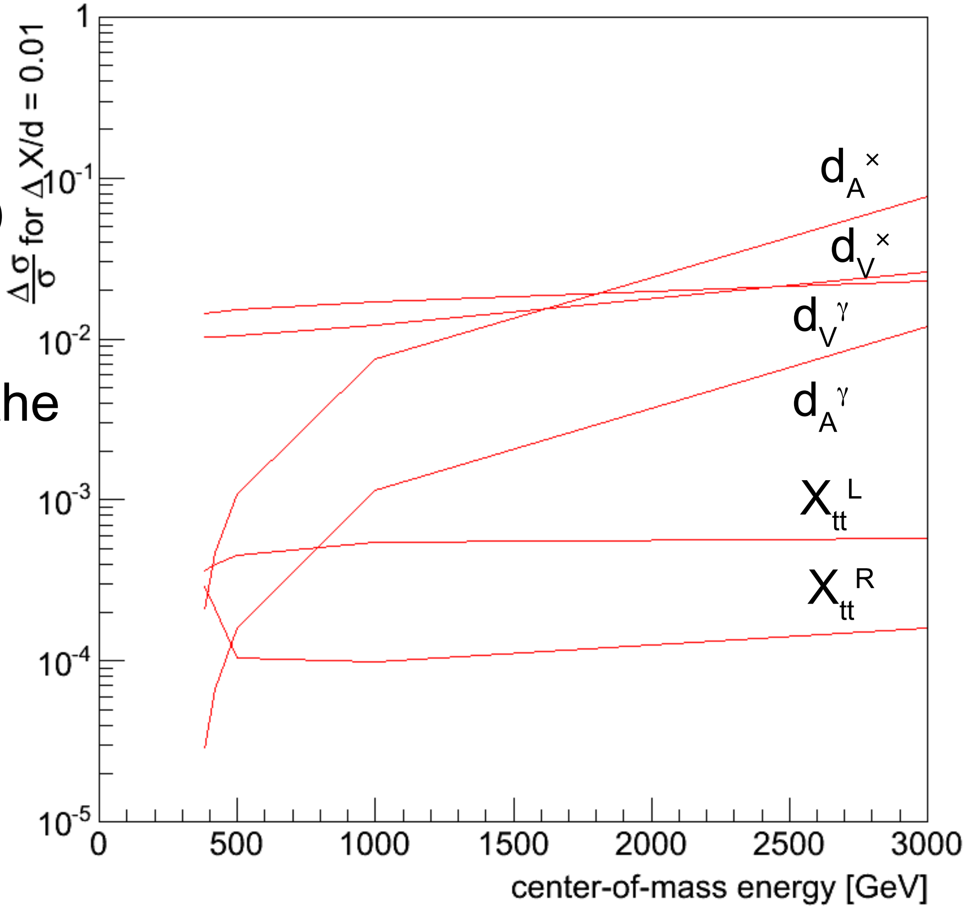
Precision expected for top quark couplings will allow to distinguish between models

Impact of x-section on New Physics

Dimension 6 effective operators
(~equivalent role to anomalous form factors)
have been implemented in WHIZARD...

Allow to map the dependence on √s of the impact of new physics on given observable

May help to explore the sensitivity of new/additional observables



Reminder - Input to study

- Event generator WHIZARD **(v1.95!!!)** 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

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

  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

Studies with WHIZARD 2.2.2

- Worry was that hard gluon radiation (not implemented in WHIZARD 1.95) detoriates results

- WHIZARD 2.2.2 allow for additional hard gluon radiation and test sensitivity of “our” observables to hard gluon emission (from top leg!?)
  Observables are cross section and forward-backward asymmetry

The generated samples are:

inclusive $e^+e^- \to t\bar{t}$

for both polarisations
$e^-_L e^+_R$ and $e^-_R e^+_L$

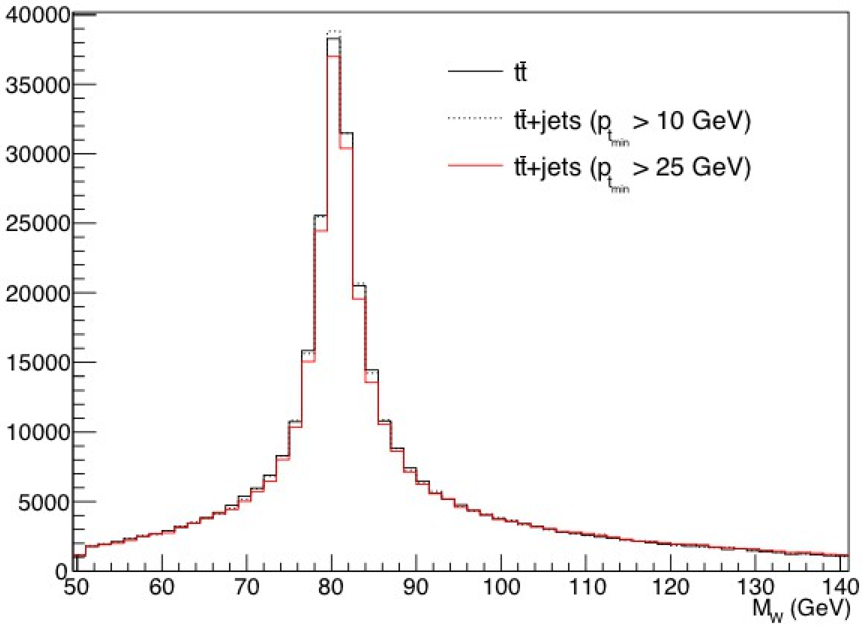
$e^+e^- \to t\bar{t} + t\bar{t}j + t\bar{t}jj + t\bar{t}jjj$

for different p_t of the additional jets
$(p_{t_{min}} > 10, 15, 20, 25\ \mathrm{GeV})$ for $e^-_L e^+_R$
$p_{t_{min}} > 10$ for $e^-_R e^+_L$

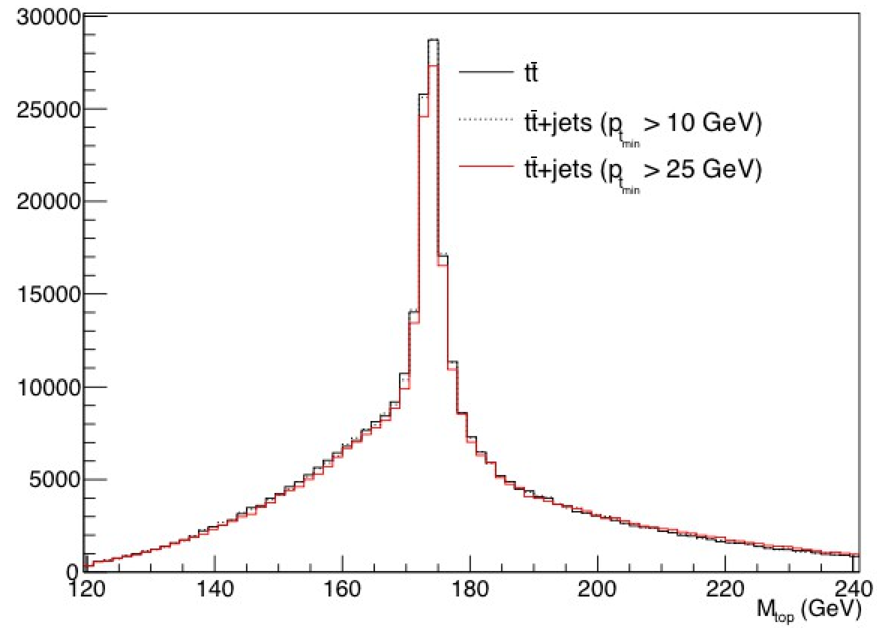
1 million of events per sample

- Events are passed to PYTHIA8 for parton showering and hadronisation

Studies with WHIZARD 2.2.2 – Observables I



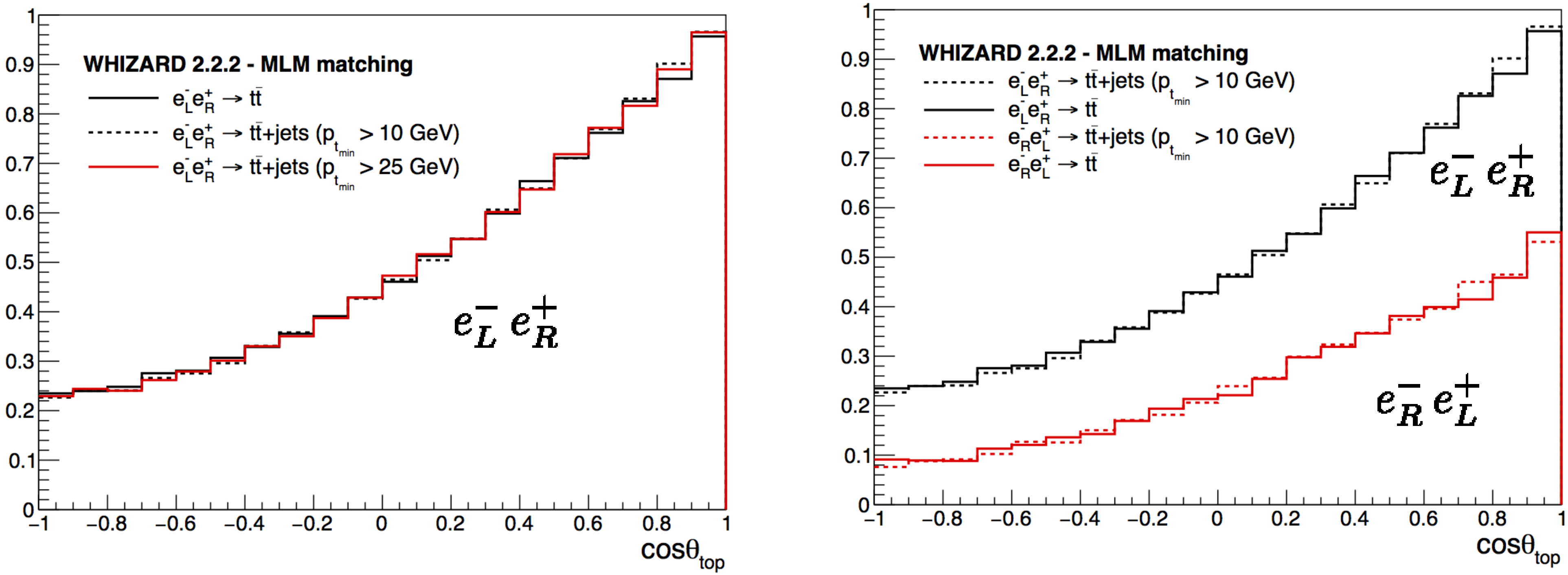
Reconstructed W mass



Reconstructed top mass

- No notable differences between different matched and unmatched distributions

Studies with WHIZARD 2.2.2 – Observables II

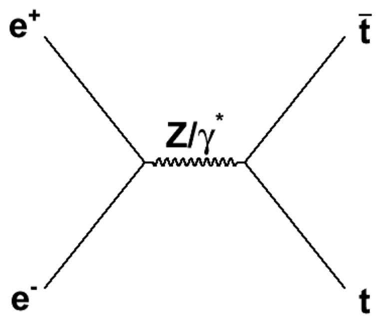


$\sqrt{s}$=500 GeV

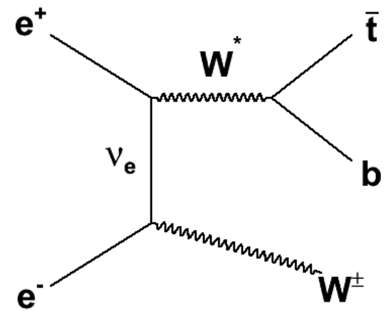
Difference between inclusive AFB and those with additional jets are small

=> Results with WHIZARD 1.95 are sufficiently accurate

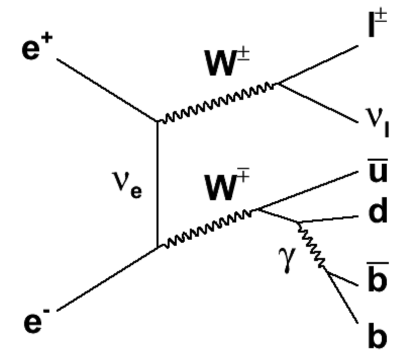
Top quark pairs and ...



Top quark pair production...



...Single top quark production...



...WWγ/Z/h...

... ...

Maximum x-section for pair production ~0.6 pb

peak well above threshold ~ 420 GeV

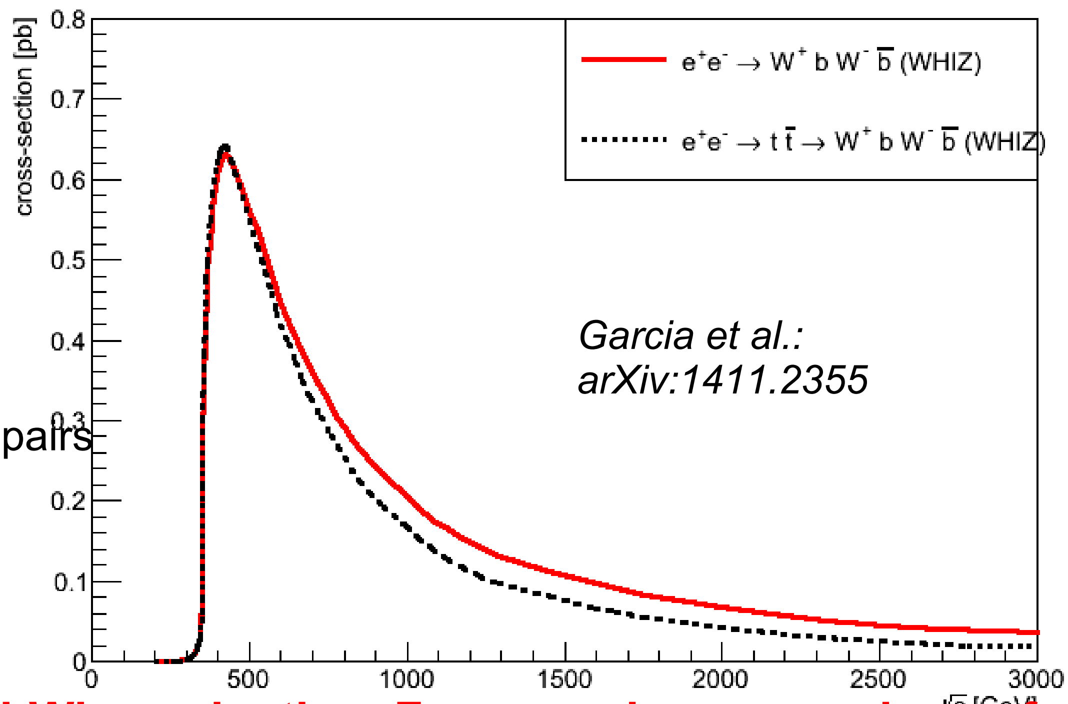
300.000 pairs after 4 years at 500 GeV

$e^+e^- \to$ WbWb $\to$ 6 fermions has several non-negligible sources

(at 500 GeV: tt ~ 90%, single top ~9%, WWγ/Z/h ~ 1%)

At 500 GeV single top is ~indistinguishable from pairs

The x-sec for WbWb is 5 to 50% larger than tt



Must measure rate and properties of WbWb production. For a precise comparison of data and prediction more theory work is needed!

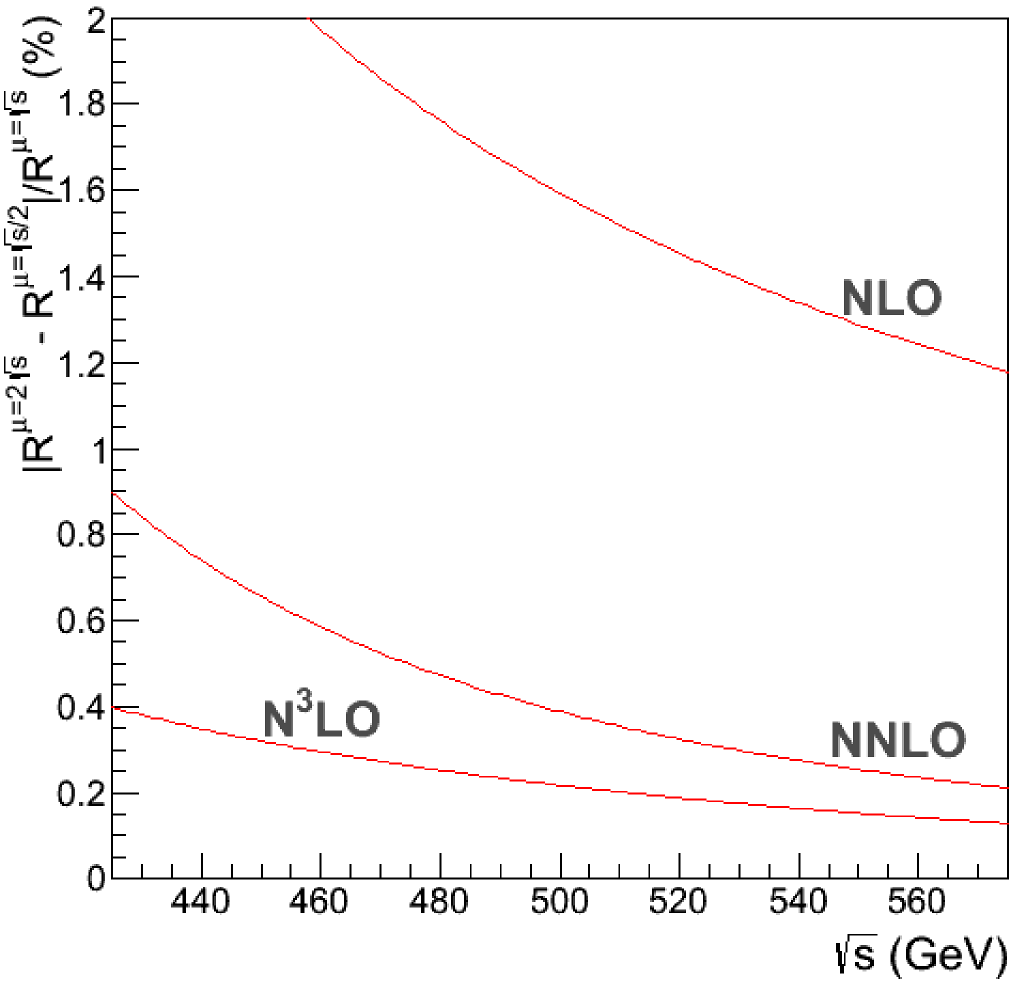
Theory calculations – What's in stock?

Precise calculations exist for
$e^+e^- \to tt$

QCD corrections calculated to N^2LO
Scale variations at N^3LO estimated at ~ 0.3%
Electroweak corrections are sizable, though.

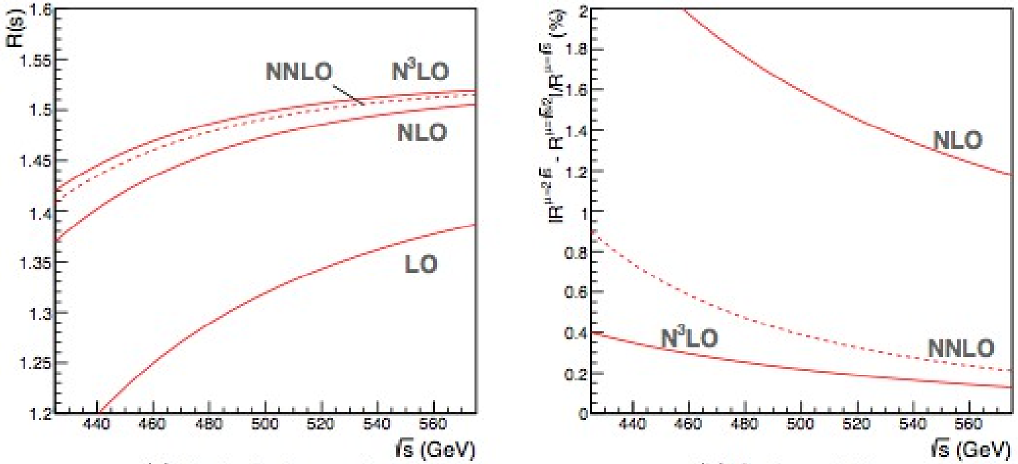
LO Monte Carlo exists for
$e^+e^- \to$ 6 fermions

WHIZARD-GoSam may bring this to NLO



Theoretical uncertainties

✶QCD corrections are known up to N³LO

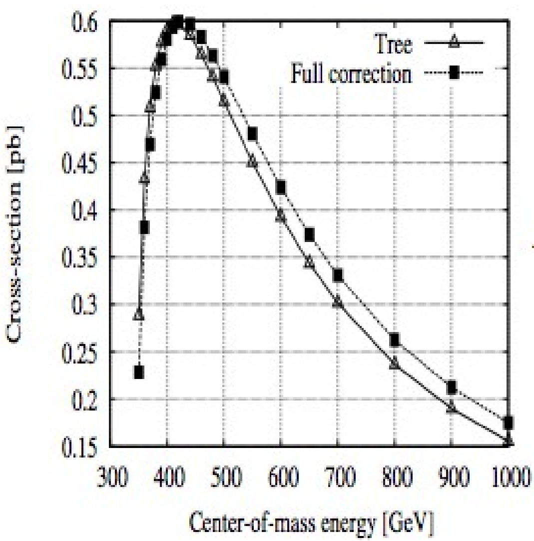


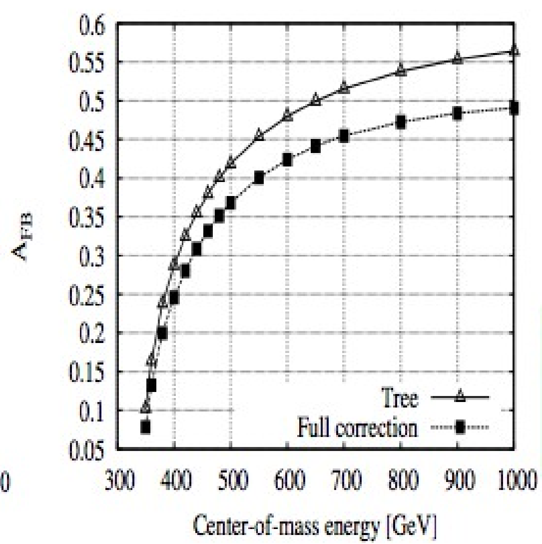
(a) Perturbation series (b) Scale variations

QCD correction (N³LO) 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



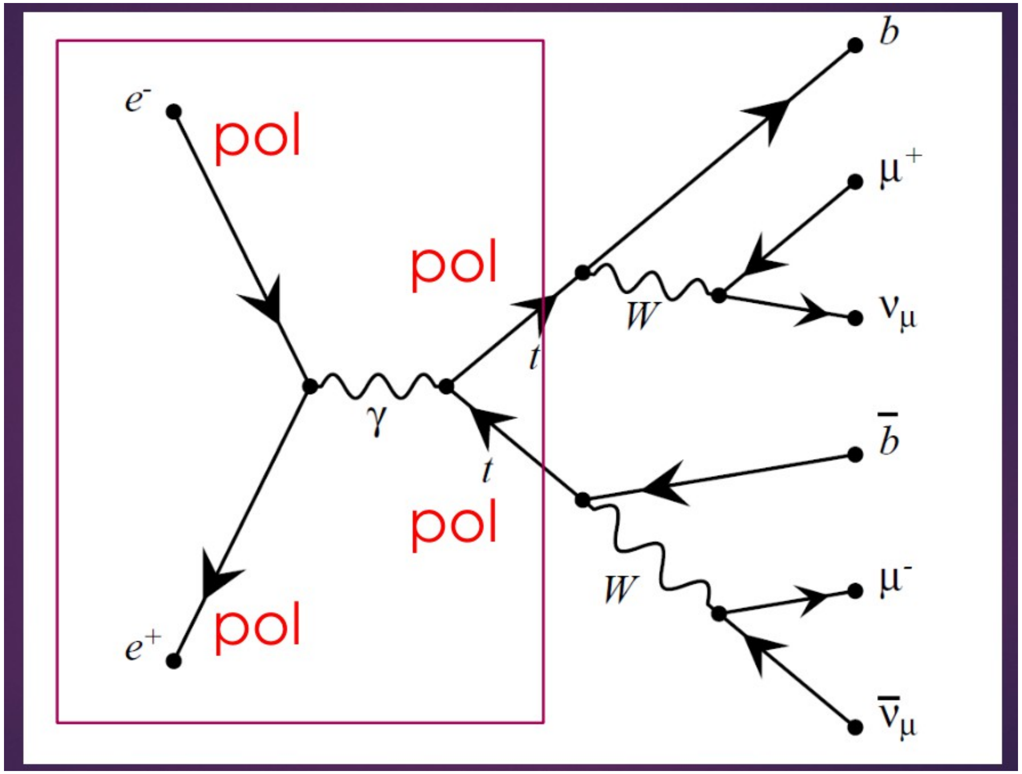


EW correction at one-loop is ~5% for cross section ~10% for A_{FB}

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

HO elw. corrections with GRACE

Elw. Corrections for polarised beams



Target:

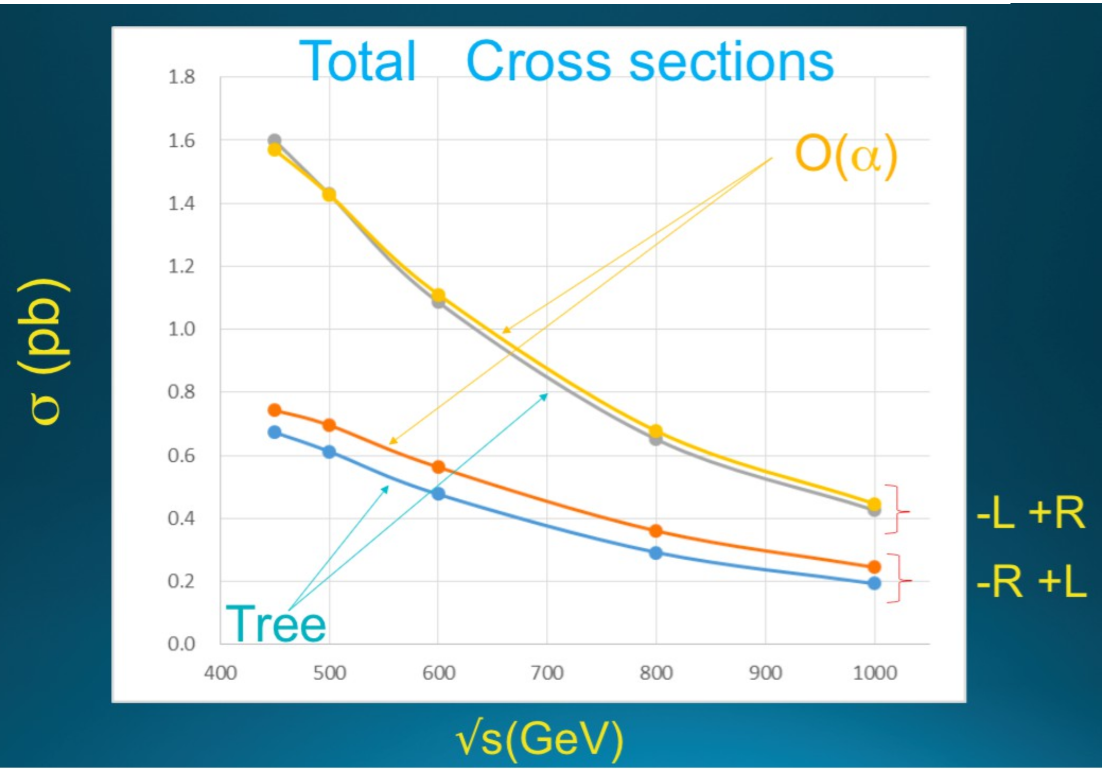
- $e^+e^- \to t\bar{t} \to b\bar{b}f\bar{f}f\bar{f}$ @ ILC
- Full *O*(α) electroweak corrections
- Beam polarization effects
- Finite width effects of top-quarks
- Matrix elements

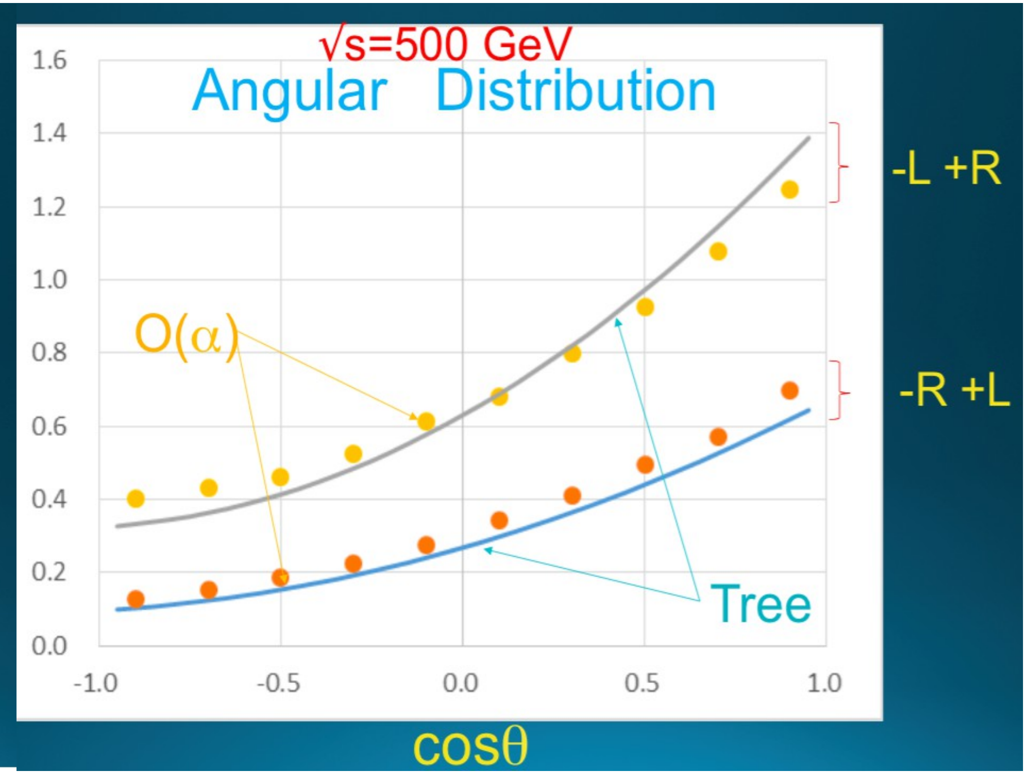
- Event generation ?
- *O*(α^2) electroweak corrections ???

Goal for accuracy < 1%

Collaboration within French-Japanese TYL/FJPPL research programme

GRACE – Some results





- Corrections on x-section more pronounced for: $e^-_R\, e^+_L$

- Higher orders deform angular distribution: $e^-_L\, e^+_R$

Beam polarisation essential to disentangle impact/origin of higher order corrections

Future

Decay Loop

Decay-Loop connection

Effects of a top-width

Higher order estimation

- Theoretial uncertainty

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, **Event generators play vital role in the endeavour**

  - Theoretical uncertainty on top mass >> Experimental uncertainty
  - Matchin between QCD dominated phase space region and continuum
  - tt production is in reality six-fermion final state
  - Uncertainty of theoretical prediction of AFB
    NLO with polarised beams
    NNLO would be 10 years of work !!!

Next Top@LC Workshop

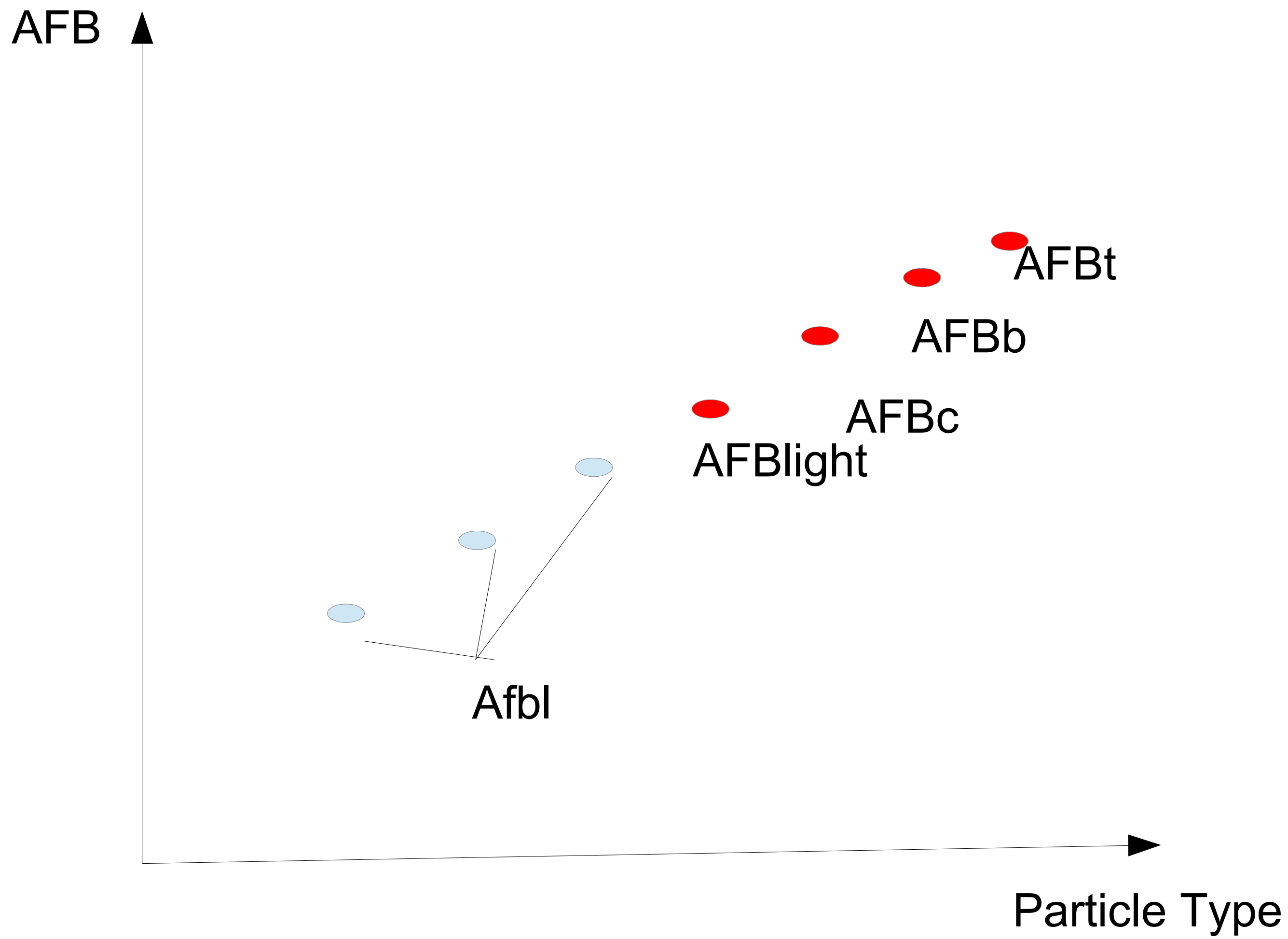
3rd workshop on LC Top Physics in Week 27 2015 (Week of 29/6/15) at IFIC Valencia

Mark your calendars and stay tuned

Backup

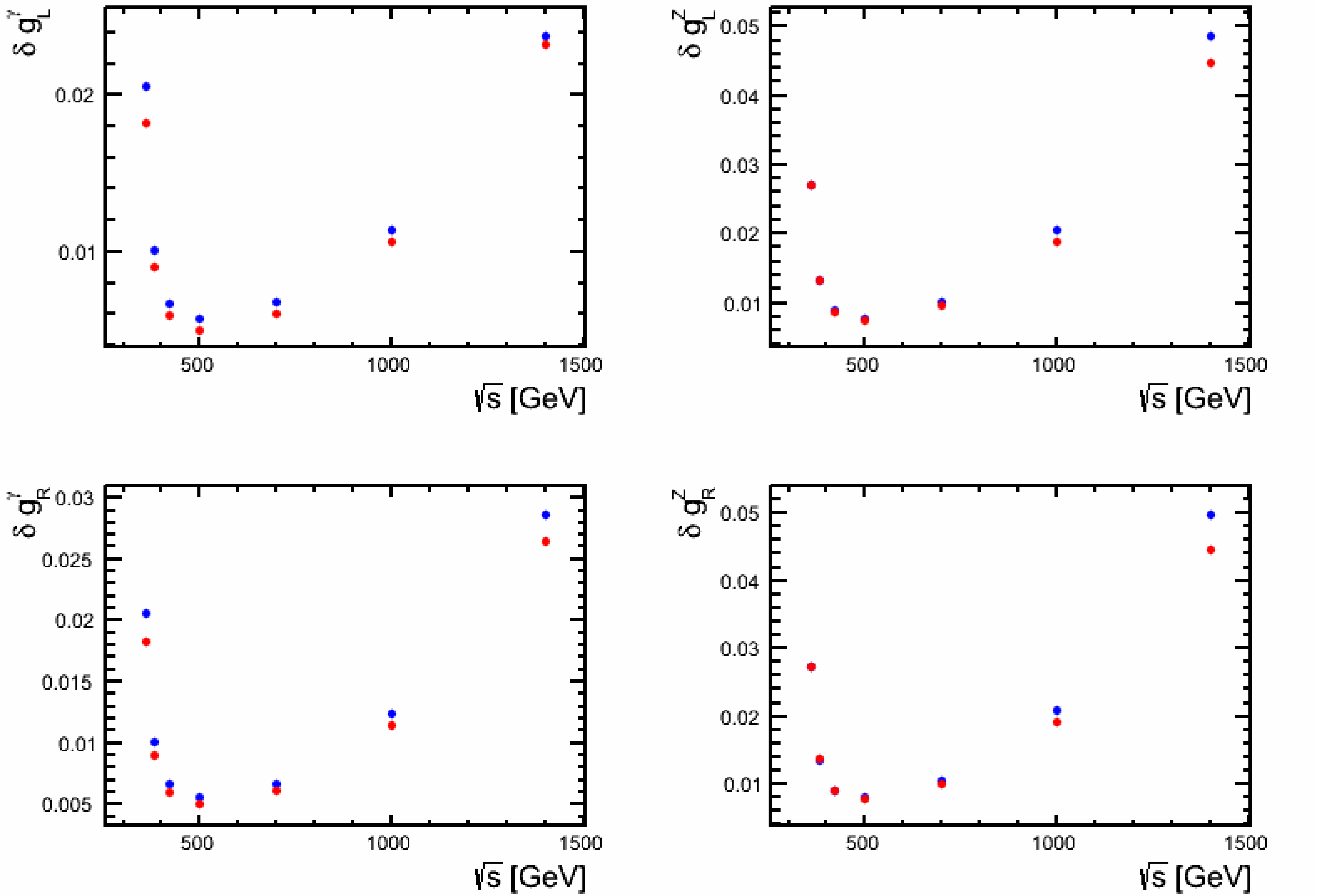
The “Dream”?

Question to theoreticians: What would you say if in ~two years from now we offer you something like this

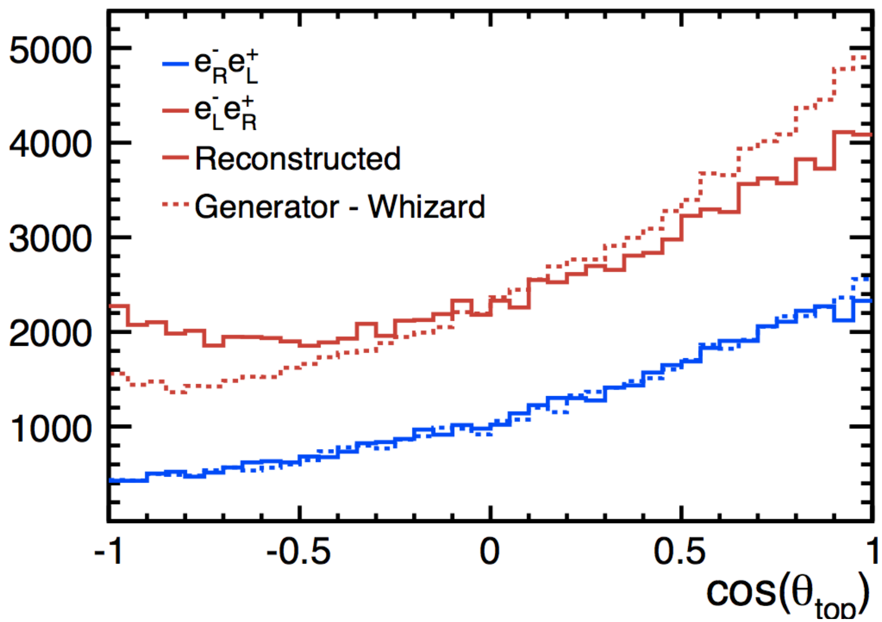


The “Higgs plot” for asymmetries

Energy dependence of couplings

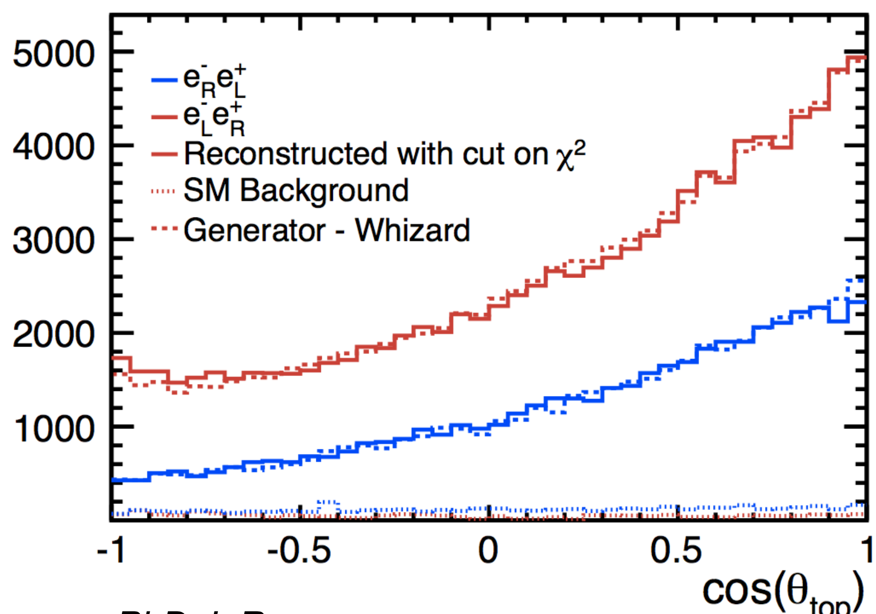


When do we run into QCD uncertainties at small energies?



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



PhD J. Rouene

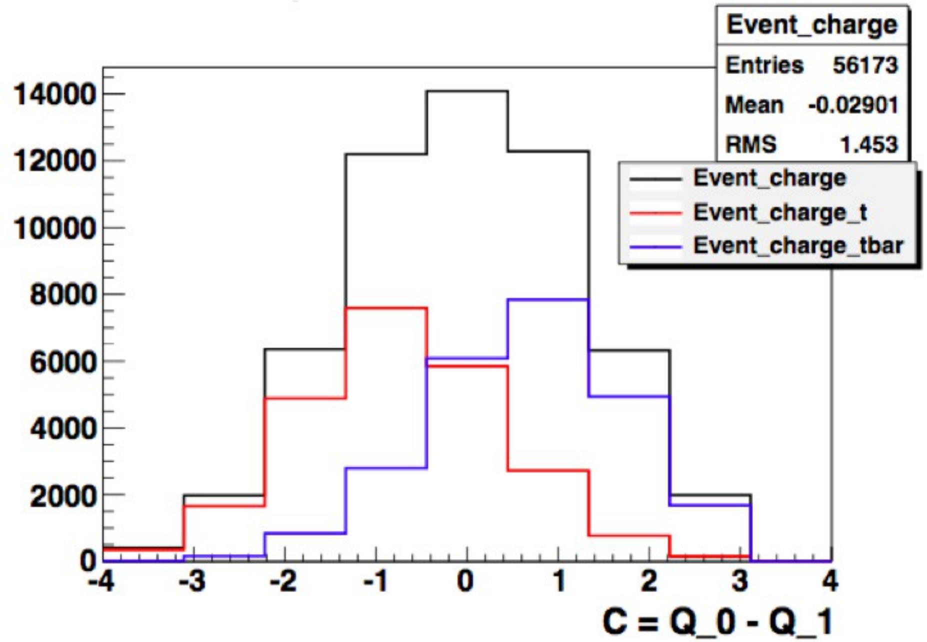
Remedy to address ambiguities:
Select cleanly reconstructed events by χ^2 analysis
or
Reconstruction of b quark charge

Precise reconstruction for both beam polarisations

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

Precision on $A_{FB} \sim 2\%$

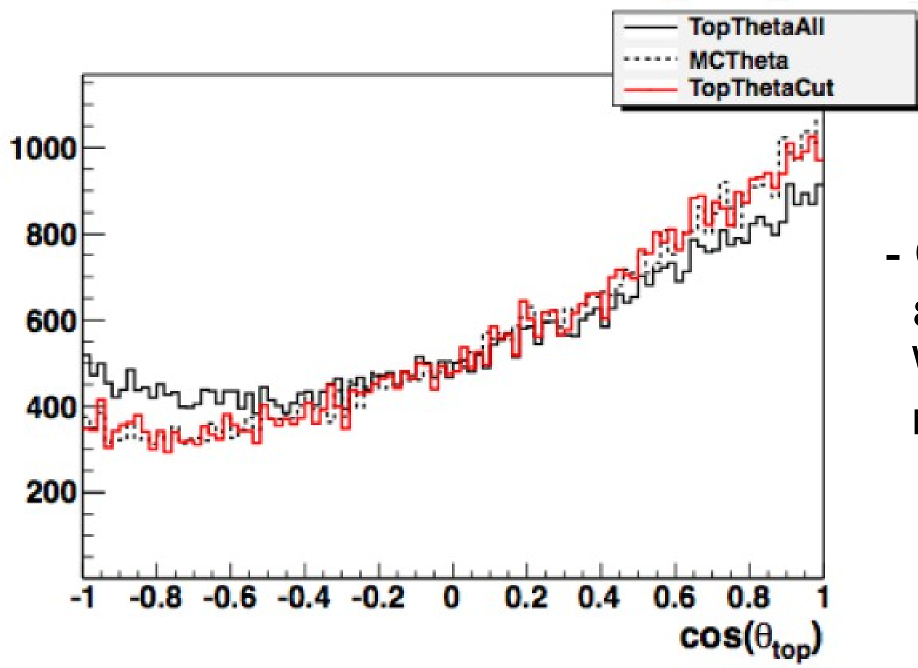
Top polar angle using b charge



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

-> Talks by Sviatoslav and Masakazu

LIA TYL ILC-top

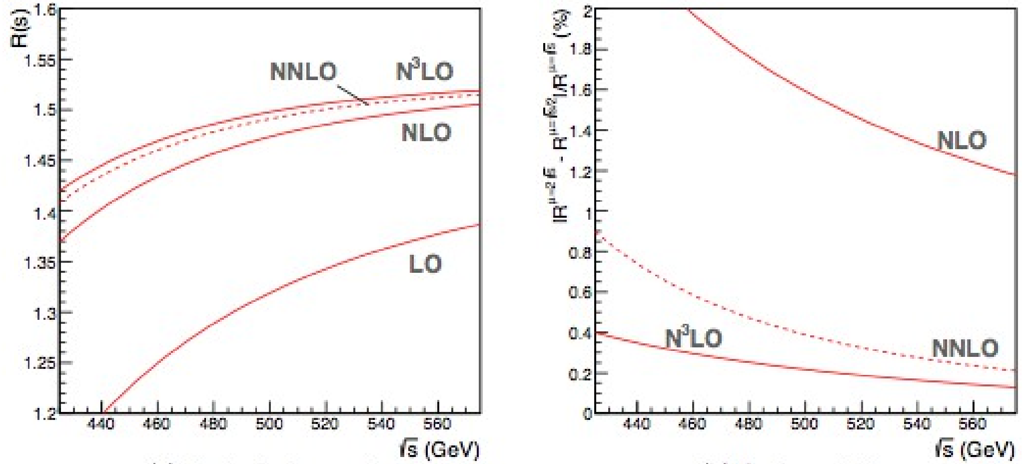
(one aspect of it)

$$e^+e^- \to t\,\bar{t} \to \mu^+\mu^- b\,\bar{b}\,\nu_\mu\bar{\nu}_\mu$$

The Matrix Element Method
Conjugate (optimal) variables
Results
Kinematics
Conclusion

See talk by Francois LeDiberder

✳QCD corrections are known up to N³LO



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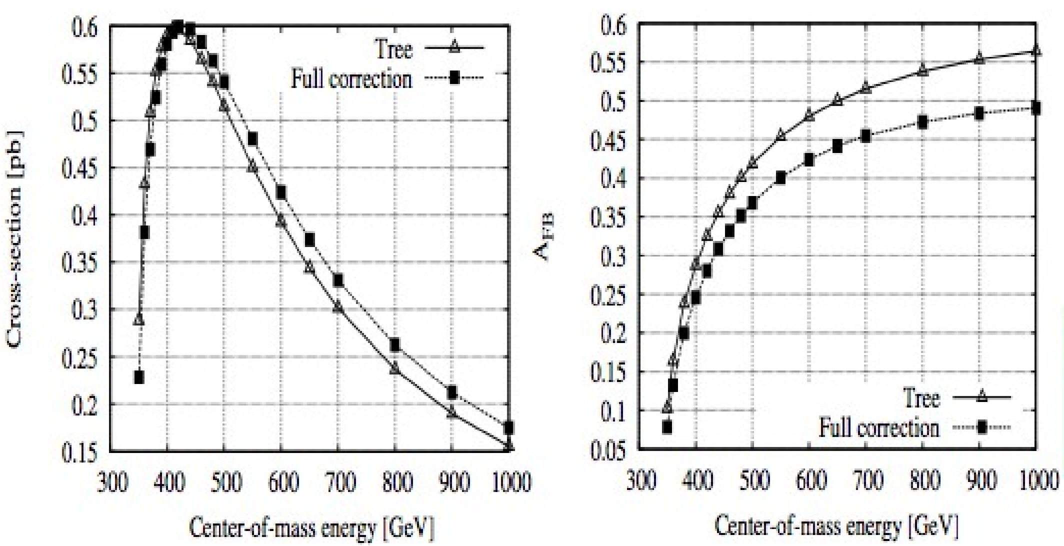
QCD correction (N³LO) is at the per mil level

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

Open topics for couplings study (Incomplete)

- Experimental study of matrix element method (Fully leptonic channel)
- Continuation of fully hadronic channel (would benefit massively from b charge and PiD)
- Studies at 1 TeV and higher (partially done by IFIC)
- CPV measurement at ~380 GeV

  380 GeV and > 1 TeV now addressed in CLIC study

- Influence of higher order corrections

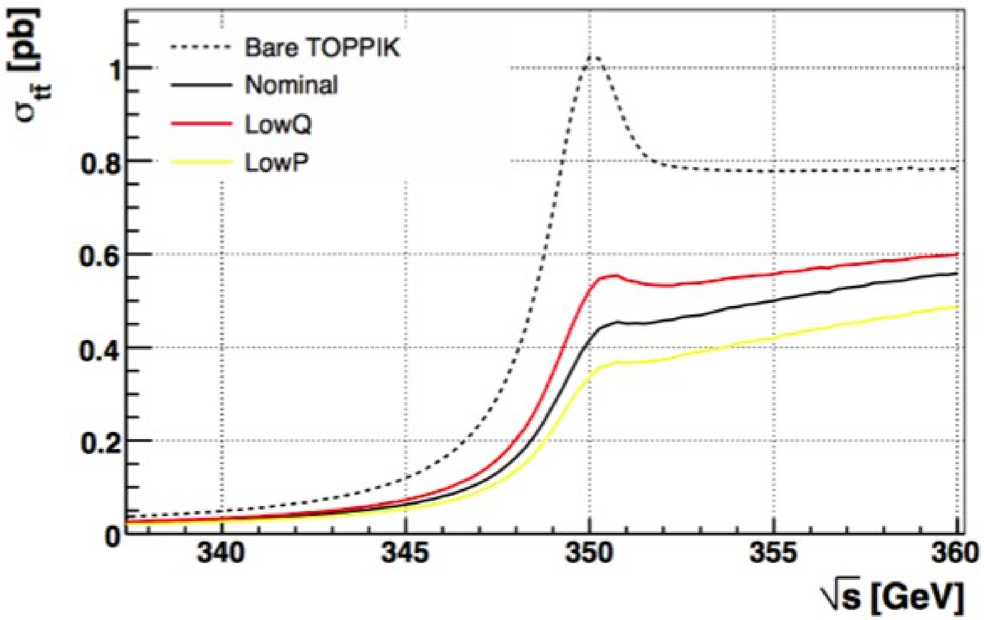
  Note Spanish Master thesis that claims that elw. NLO are no big deal!

- More on interpretation

  Note also studies by Roentsch et al. arXiv: 1501.05939

- Everything that I have forgotten

Total tt Cross Section in e+e- Collisions



Principle: m_t from $\sigma_{tt}(m_t)$

Advantages:

- count number of $t\bar{t}$ events
- color singlet state
- background is non-resonant
- physics well understood (renormalons, summations)

➢ Top decay protects from non-pert effects

Much of the discriminating power of the approach related to the strong mass-dependence (ttbar resonance).

Peak position very stable in theory predictions (threshold mass scheme).

Typical results:

$\rightarrow \delta m_t^{\rm exp} \simeq 50$ MeV

$\rightarrow \delta m_t^{\rm th} \simeq 100$ MeV

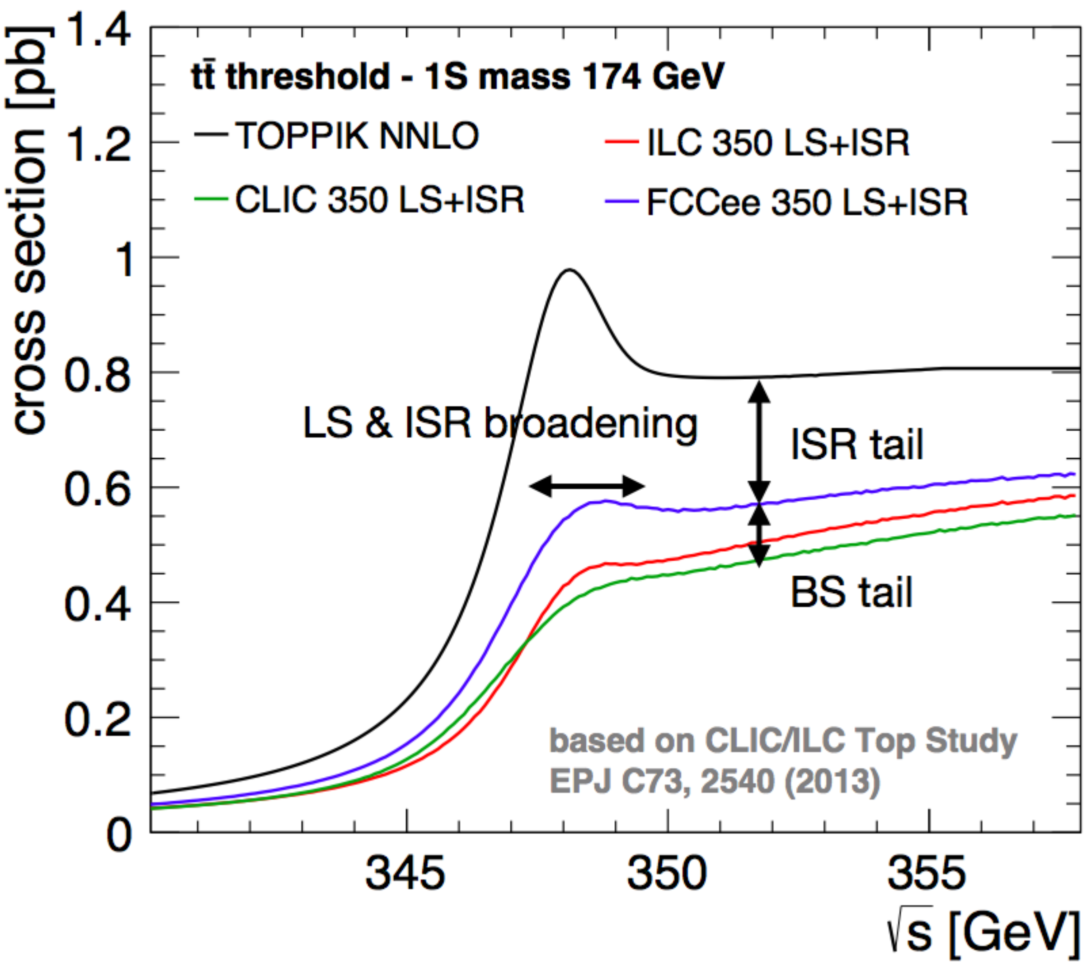
What mass?

$\sqrt{s}_{\rm rise} \sim 2m_t^{\rm thr}$ + pert.series

(short distance mass: 1S $\leftrightarrow \overline{\rm MS}$)

A. Hoang

Top Quark Mass – Influence of Luminosity Spectrum



- Initial State Radiation
  Lowers effective L at top energy
- BeamStrahlung
  Lowers effective L
  at top energy
  Not at FCCee Gaussian spectrum
- Luminosity spectrum & Initial State Radiation broadening
  Smearing of cross section
  Due to beam energy spread
  ILC and FCCee comparable
  Worse at CLIC

1) Main effect on L spectrum is ISR
   => Reduces Luminosity, smears out 1s bound state peak
2) LC somewhat smaller L due to BeamStrahlung

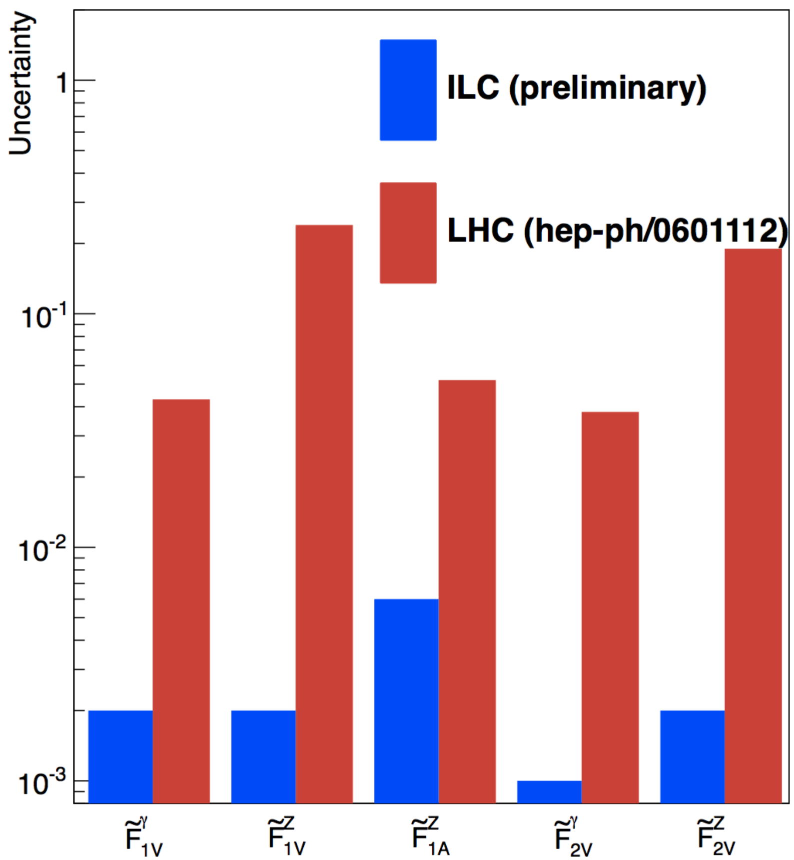
F. Simon
AWLC14

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



- 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

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

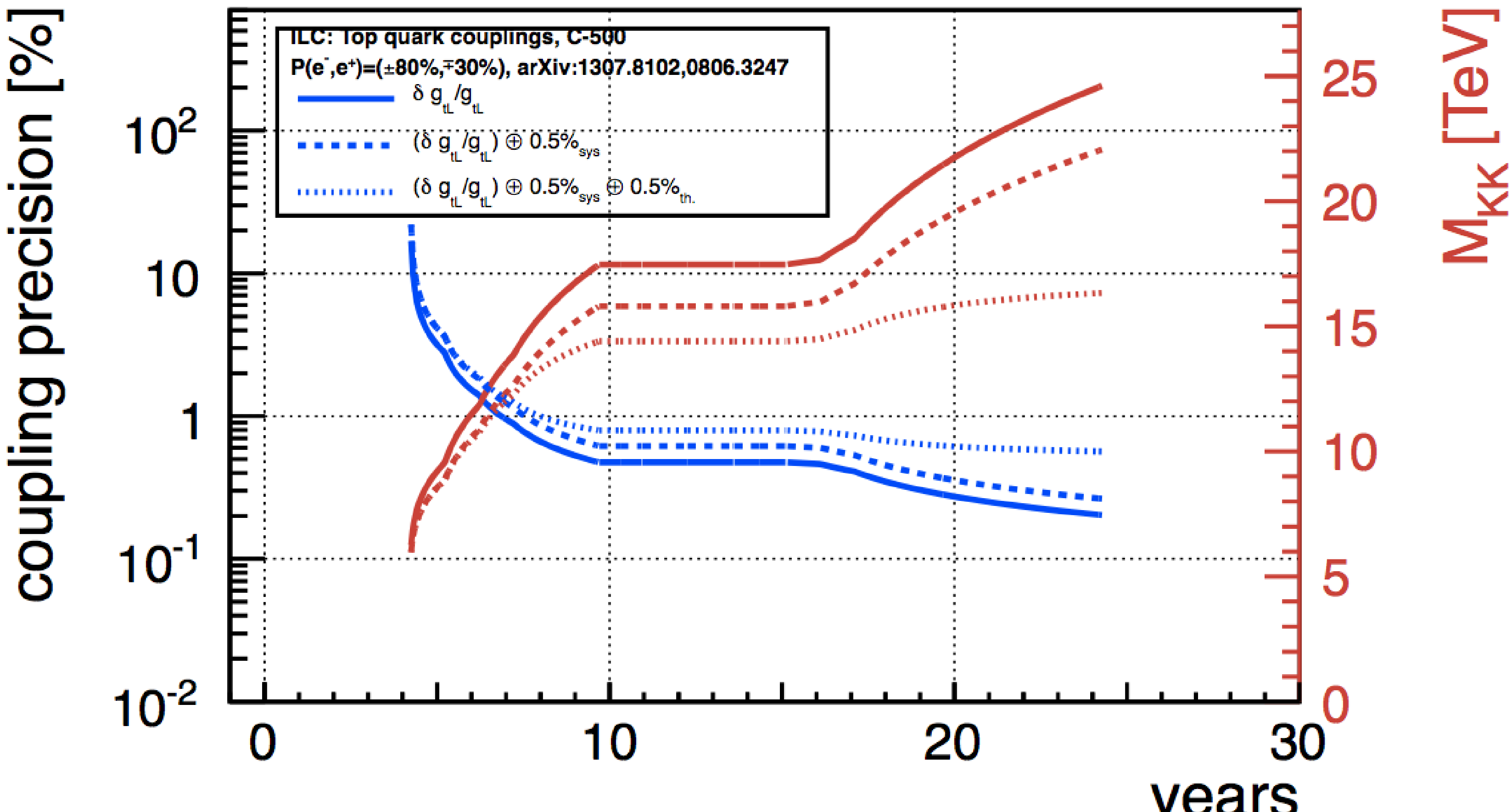
- Potential for CP violating couplings at ILC under study

ILC promises to be high precision machine for electroweak top couplings

Example for physics reach

New physics reach for typical BSM scenarios with composite Higgs/Top and or extra dimensions

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)

=> Important guidance for e.g. 100 TeV pp-collider