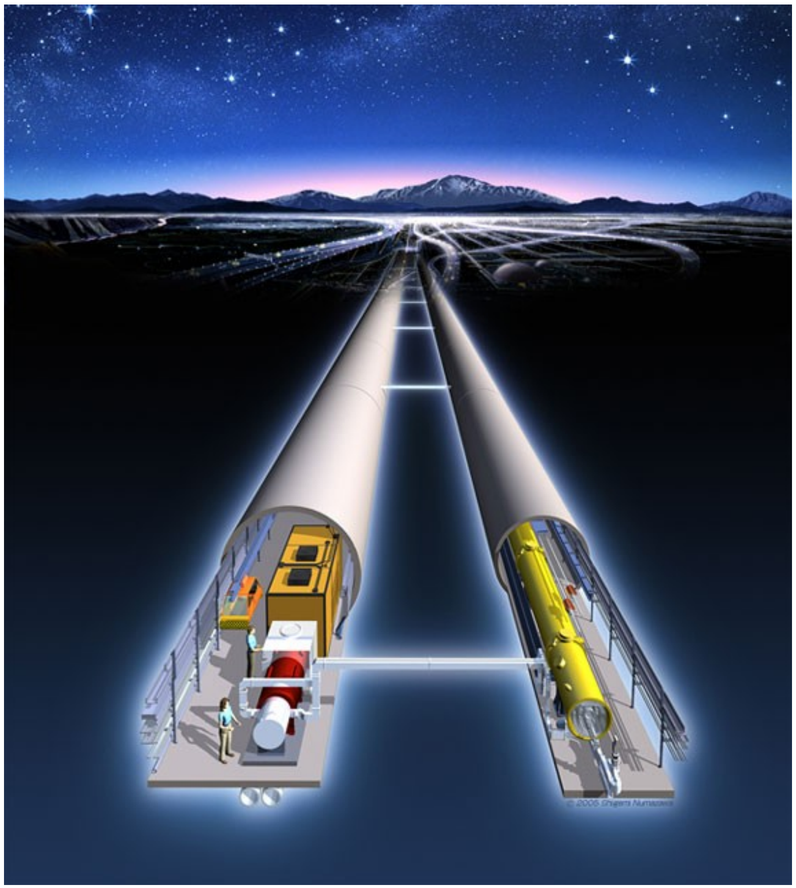
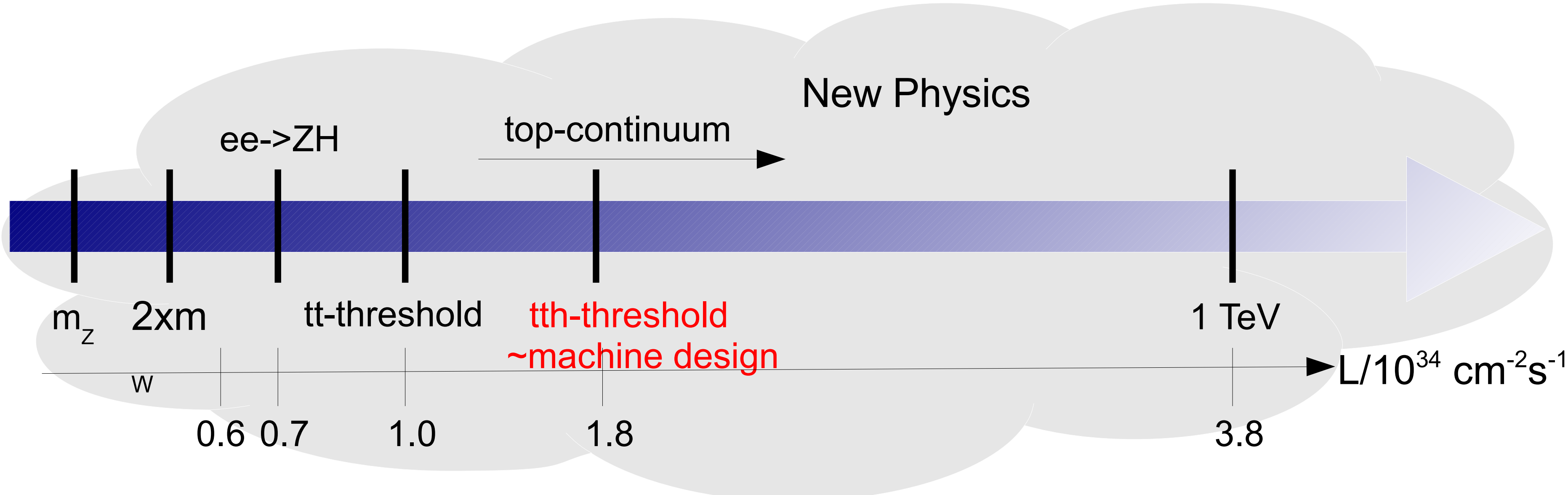
(Incomplete) Status of top quark studies



Roman Pöschl
Directeur de Recherche of CNRS

TYL FJPPL Meeting LAL – March 2015

ILC Physics program



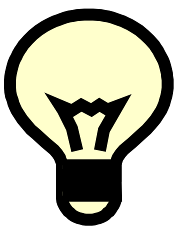
- All Standard Model particles within reach of ILC
  - High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be "tailored" for specific processes
  - Centre-of-Mass energy
  - Beam polarisation

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

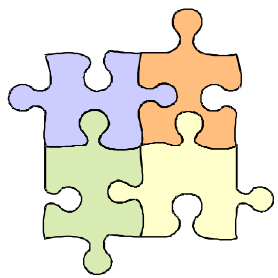
- "Background free" searches for BSM through beam polarisation

3. Top physics at the ILC

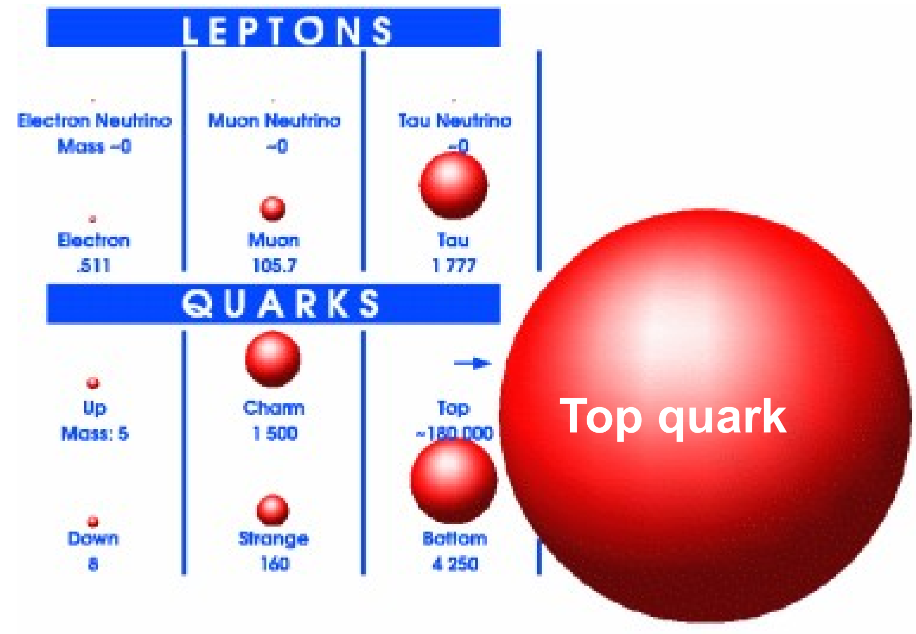
An enigmatic couple



Elementary Scalar?



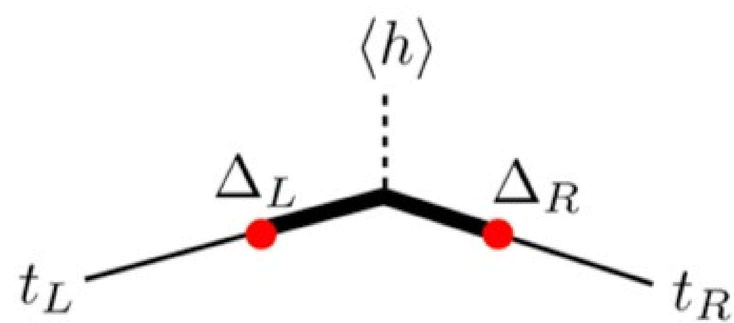
Composite object?



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

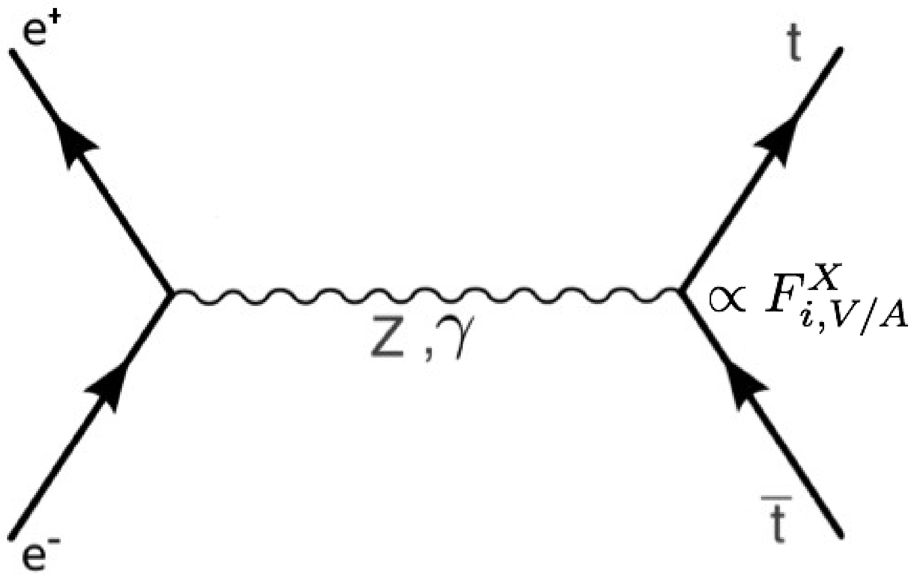
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

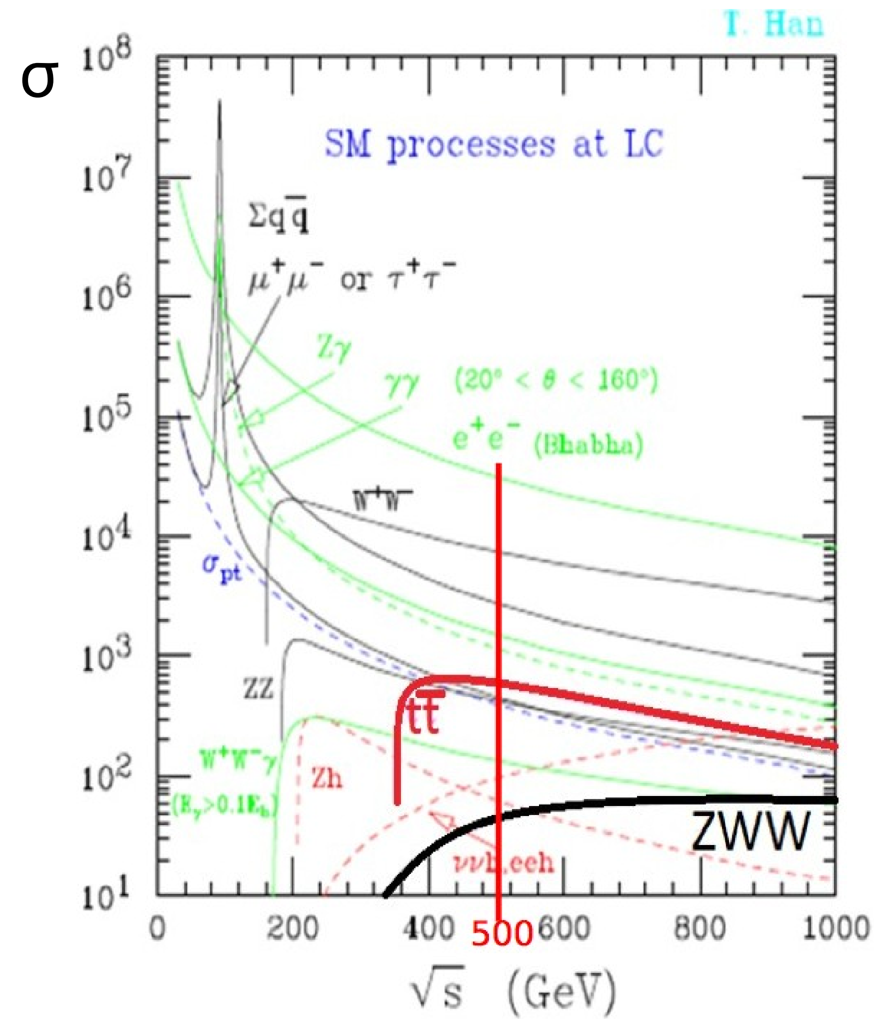
- LC perfectly suited to decipher both particles



Courtesy of S. Rychkov

Top Quark Physics at Electron-Positron Colliders





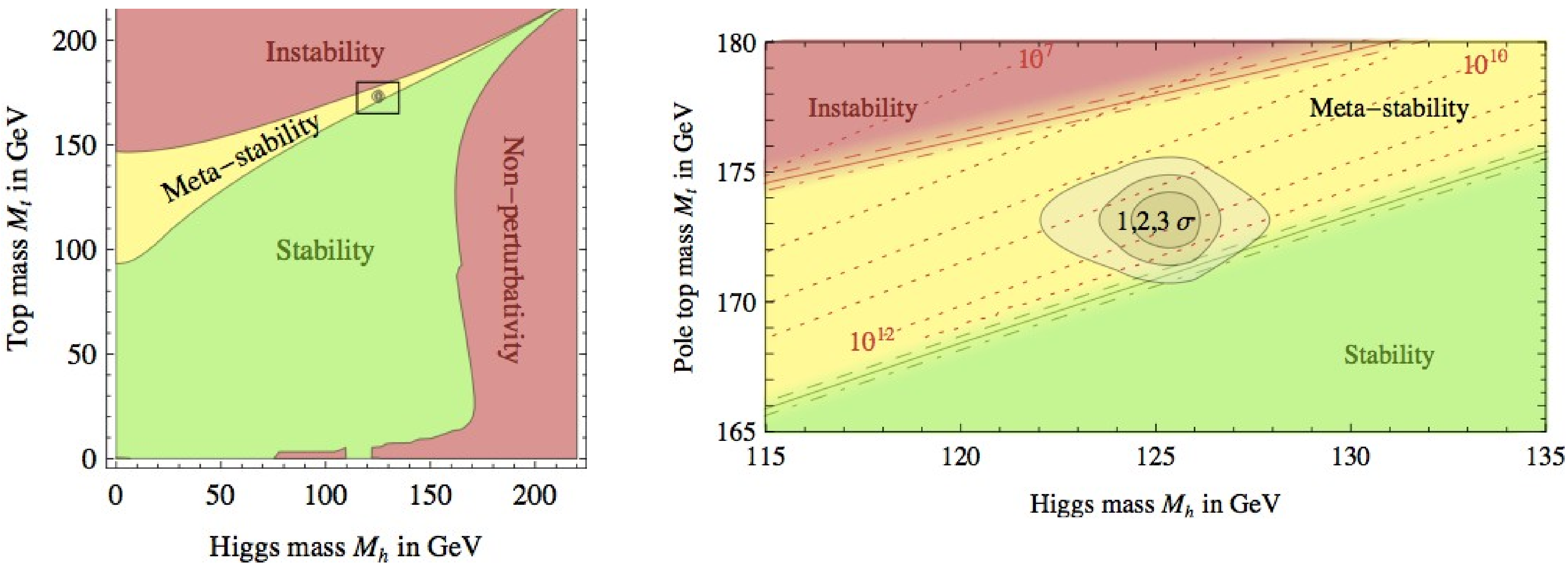
- Top quark production through electroweak processes
  no competing QCD production => Small theoretical errors!

- 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

Vacuum stability and Top Quark Mass

Degrassi et al. arXiv:1205.6497

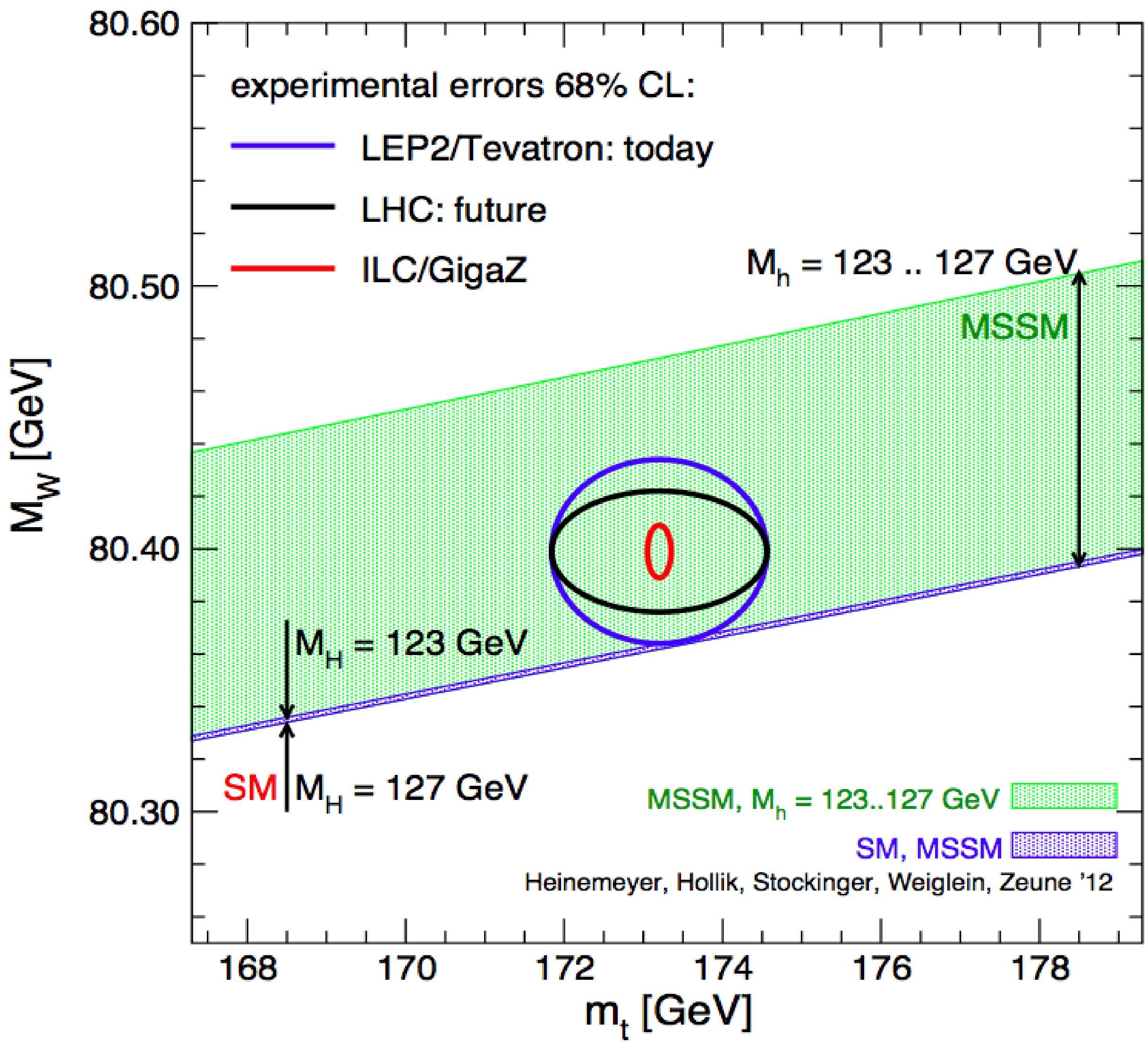
$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\ .$$



Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	±1.4 GeV
α_s	experimental uncertainty in α_s	±0.5 GeV
Experiment	**Total combined in quadrature**	**±1.5 GeV**
λ	scale variation in λ	±0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ correction to M_t	±0.6 GeV
y_t	QCD threshold at 4 loops	±0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	±0.2 GeV
Theory	**Total combined in quadrature**	**±1.0 GeV**

Uncertainty on **(pole)** top quark mass dominates uncertainty on stability conditions

Top Mass, Higgs Mass and BSM – SM vs. MSSM



Precise Top (and W) mass crucial to test compatibility of measured Higgs mass

MS might not be sufficient to explain Higgs mass

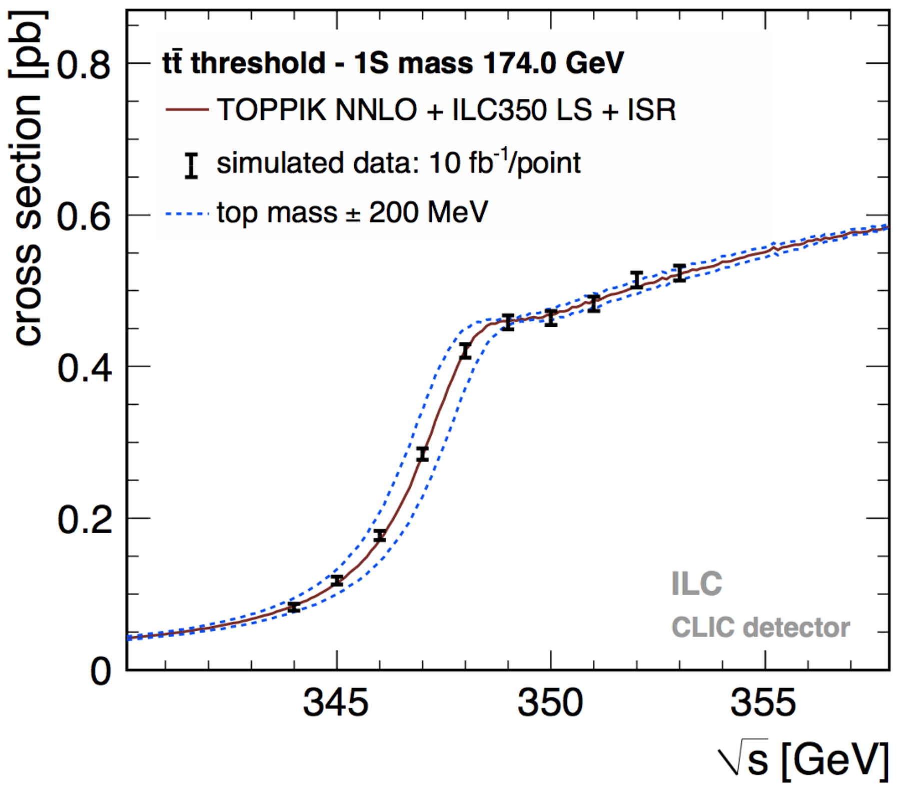
LHC may not reach sufficient discriminative power

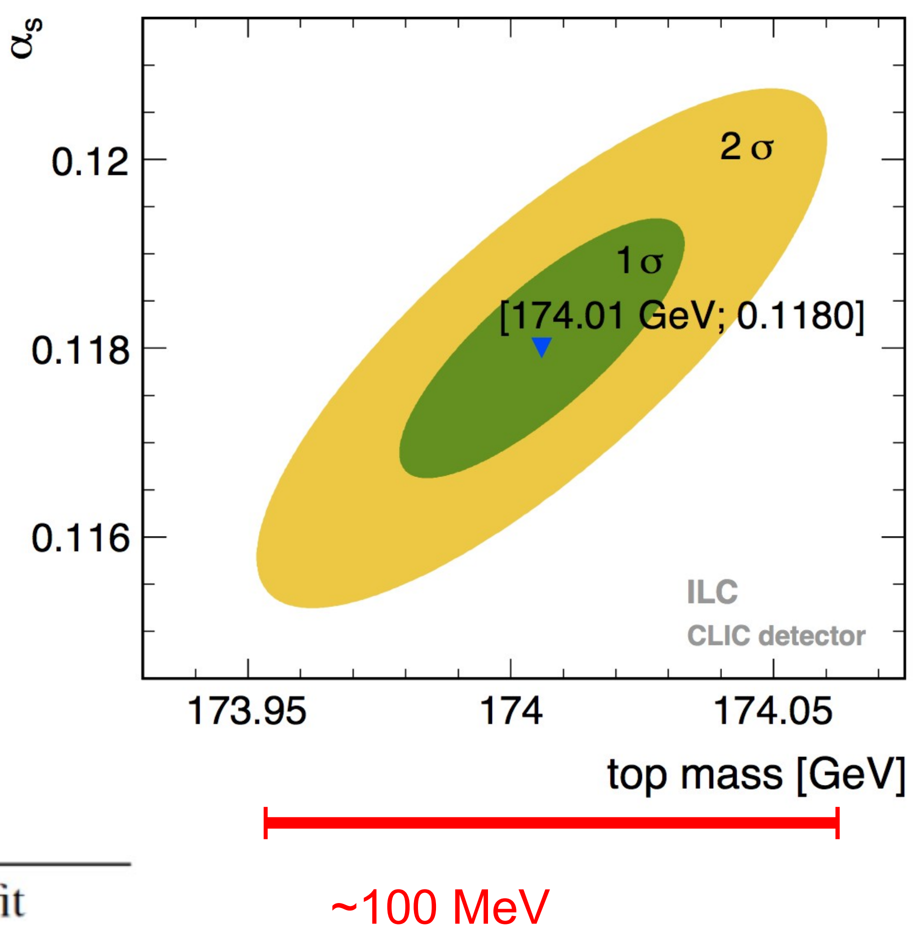
A lepton collider will

Top Quark Mass – Results of Full Simulation Studies

Mass and α_s

EPJC C73 (2013) 2530

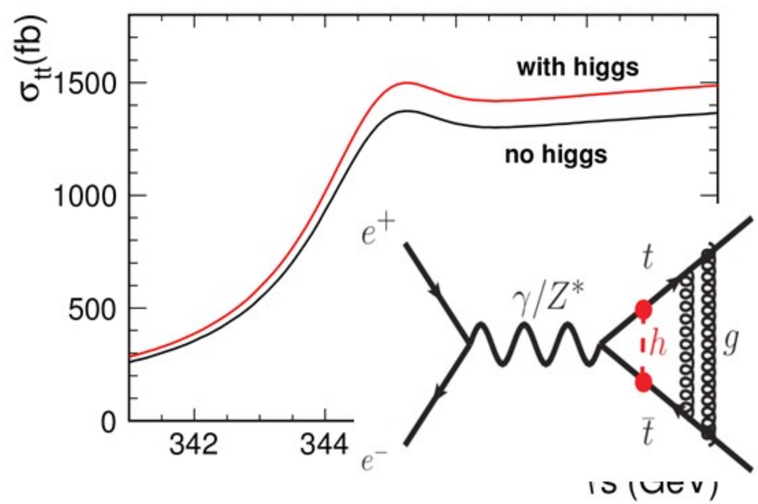




1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

Top mass and top Yukawa coupling at threshold

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 : **2D fit** of mt and Γt, yt is measured individually.
○ 3 param : **3D fit** of mt, Γt and yt.

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

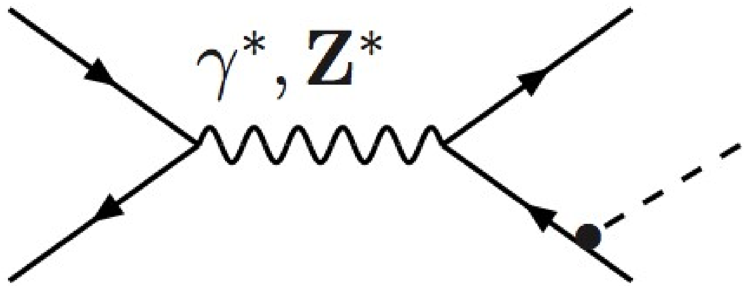
	(2 + 1) param fit	3 param fit
mt	19 MeV	29 MeV
Γt	38 MeV	39 MeV
yt	4.6%	5.9%

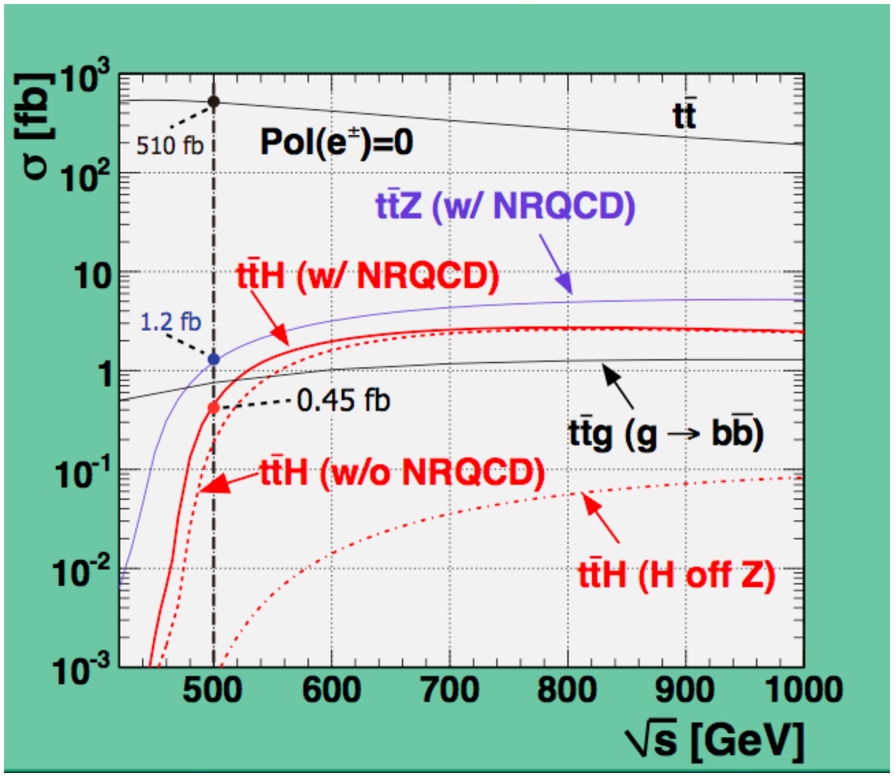
Stat. Uncertainties
'add'
Theoretical uncertainties ~70 MeV

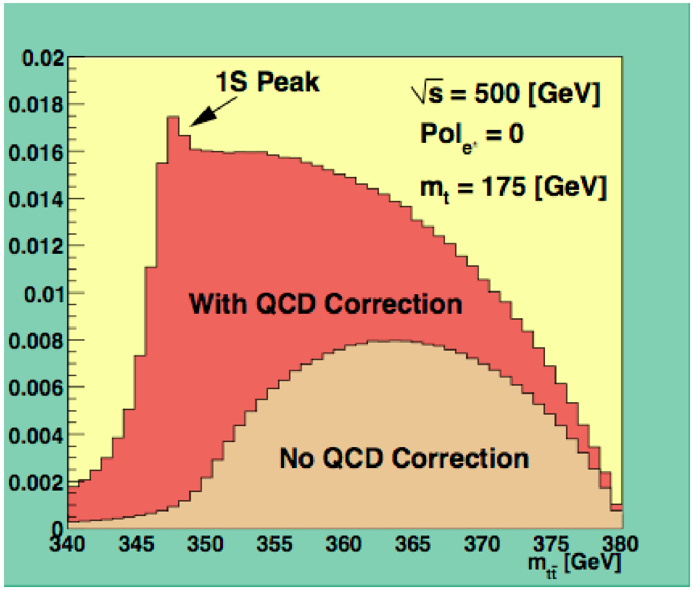
Total expected precision on m_t ~ 100 MeV
(very conservative estimation!!!)

T. Horiguchi

Top Yukawa Coupling above threshold







~ Factor 2 enhancement
From QCD bound states

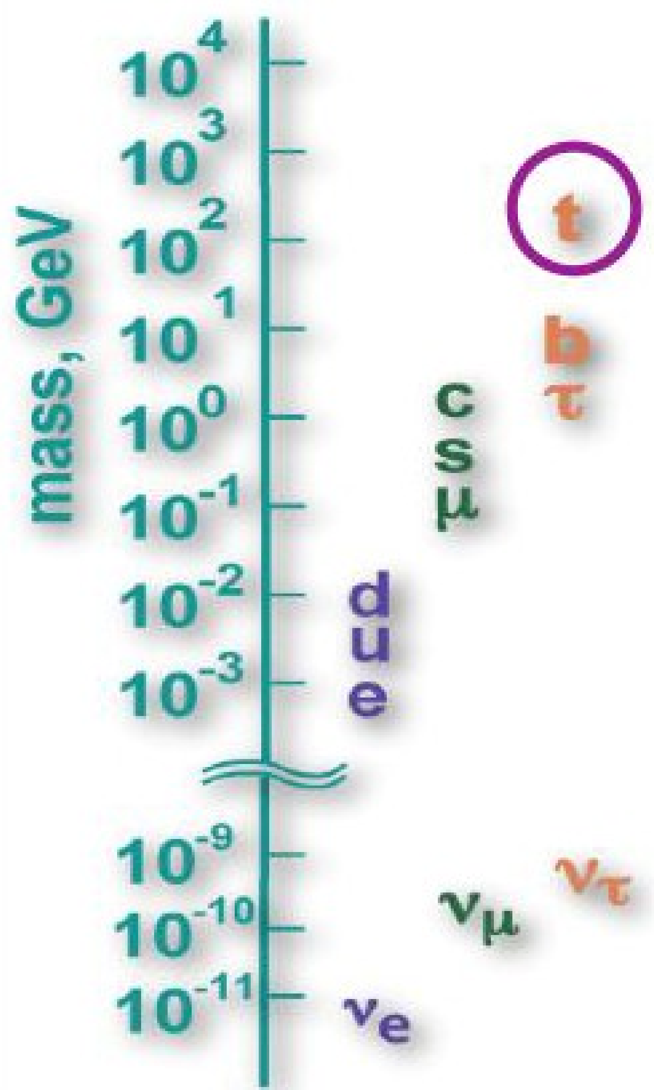
R. Yonamine et al.
T. Tanabe, T. Price

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

← ILC TDR

← Technically possible

Top Quark and Flavor Hierarchy



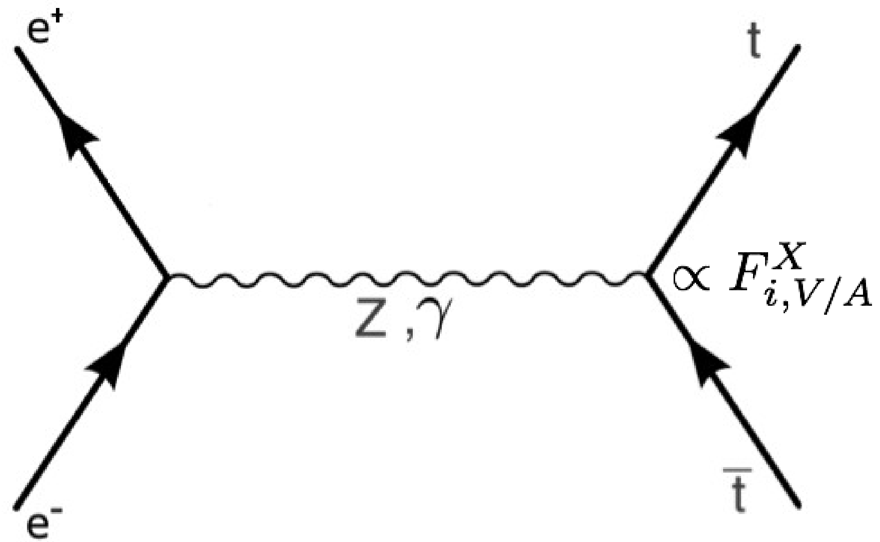
- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

- 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



$$\Gamma_\mu^{ttX}(k^2,q,\overline{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5F_{1A}^X(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^\mu\left(iF_{2V}^X(k^2)+\gamma_5F_{2A}^X(k^2)\right)\right\}, \quad (2)$$

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

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

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

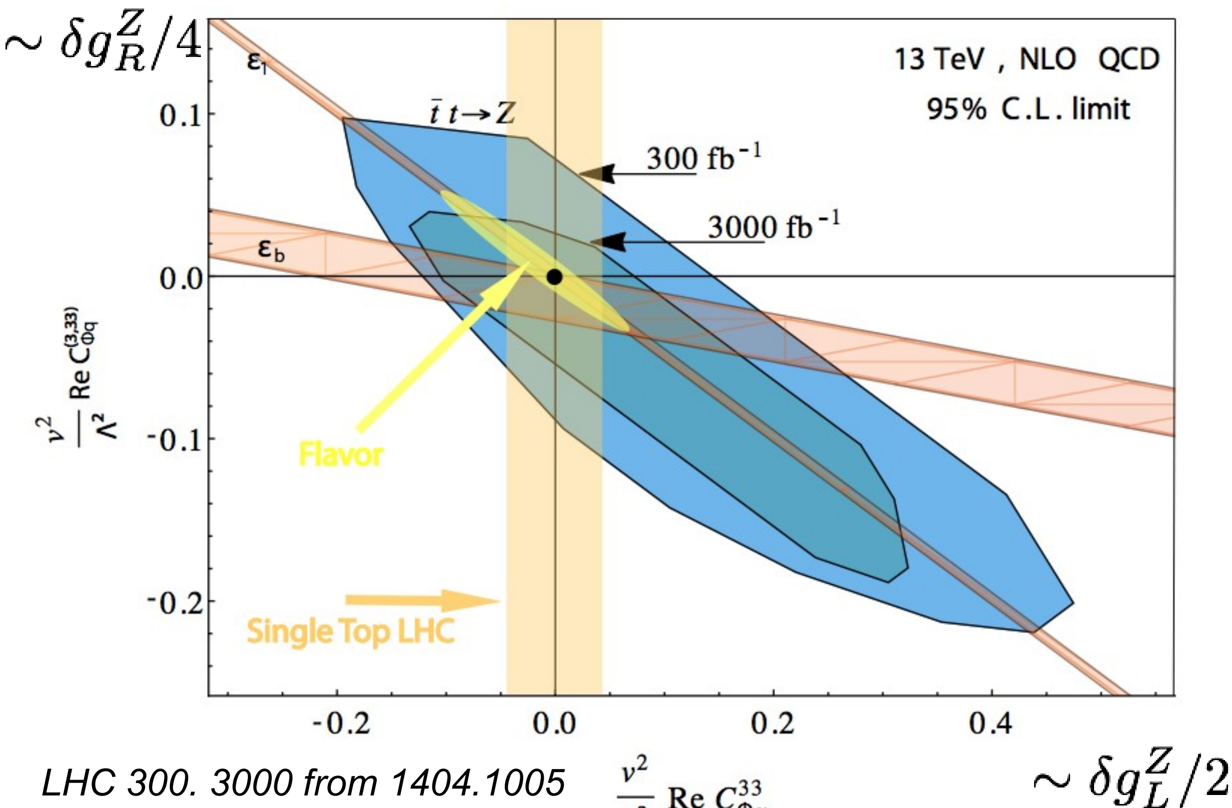
Results of full simulation study at $\sqrt{s}$ = 500 GeV and L=500 fb^{-1}

ArXiv: 1307.8102

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

(Good news results confirmed with recent WHIZARD version [IFIC])

Accuracy on SM Z couplings compared with other experiments



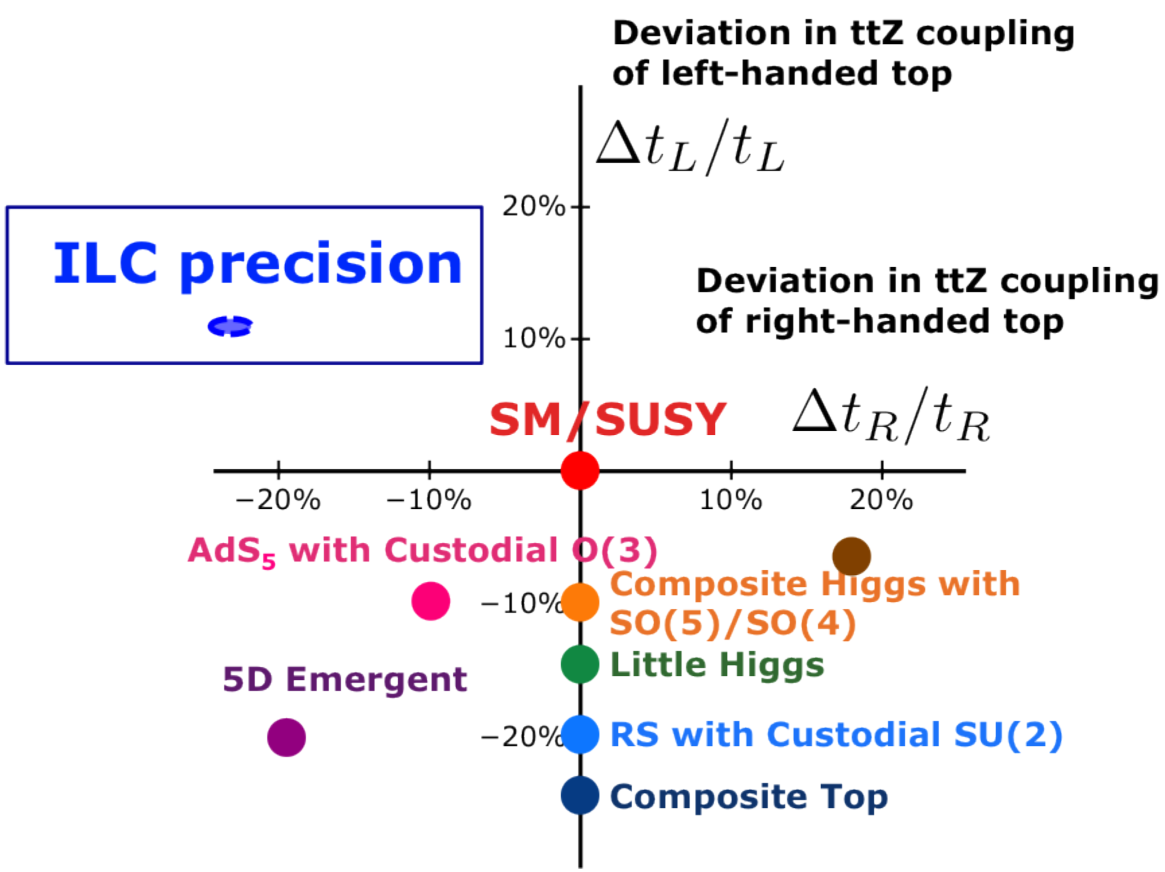
LHC 300. 3000 from 1404.1005
Flavor from 1408.0792
LHC Single top added by F. Richard

- 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

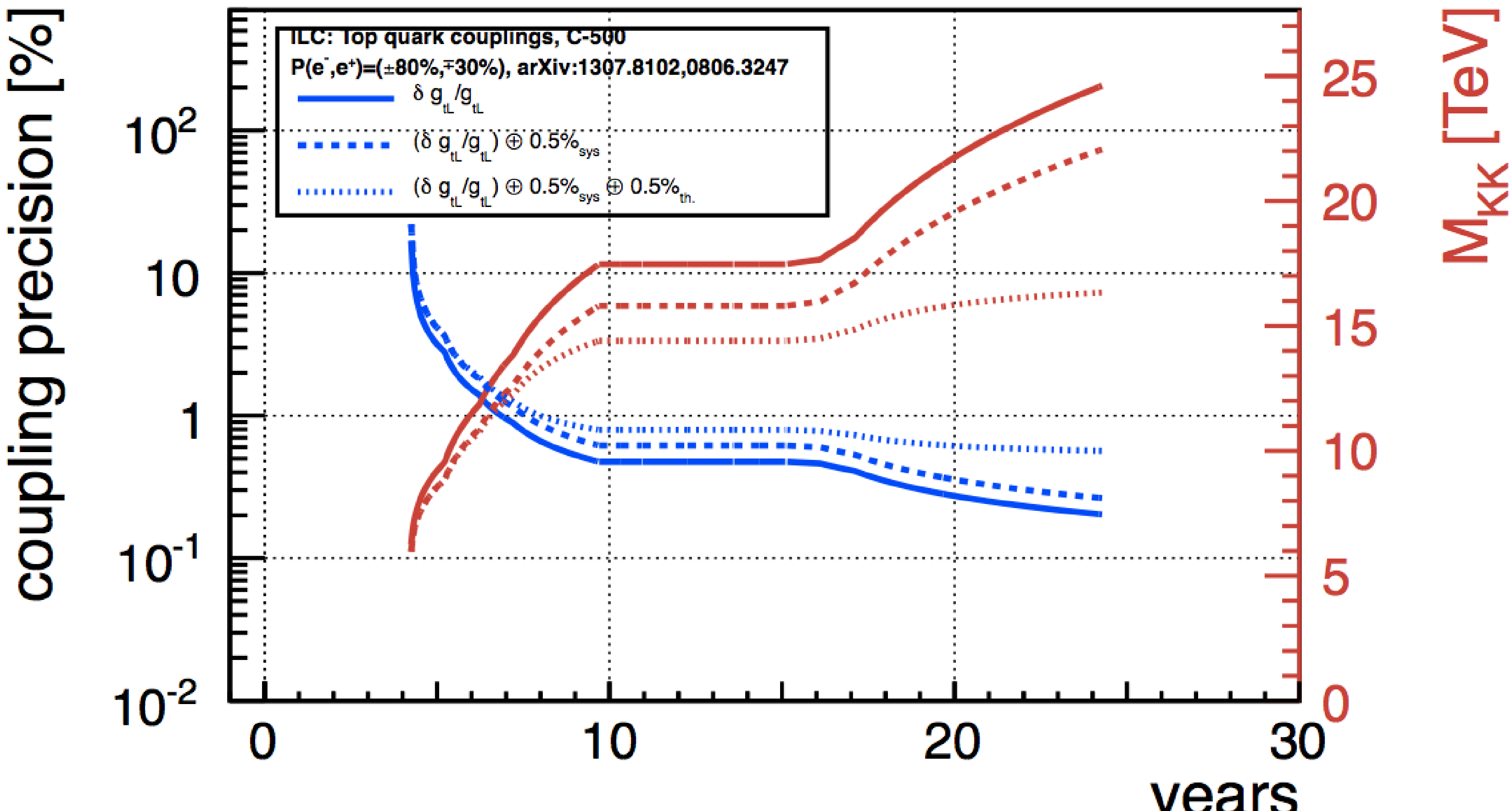


Precision expected for top quark couplings will allow to distinguish beween models

Example for physics reach

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

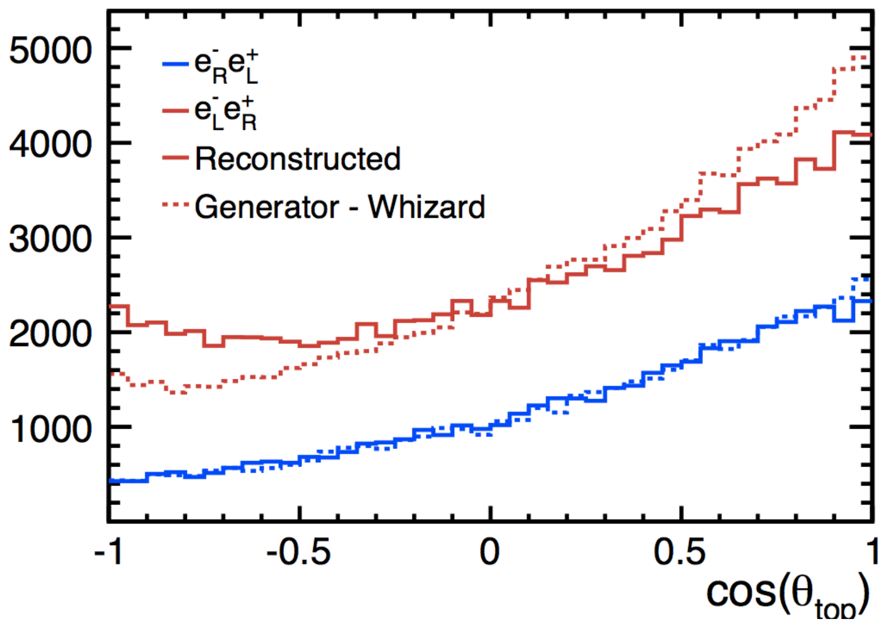
Based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 GeV for extreme scenarios)

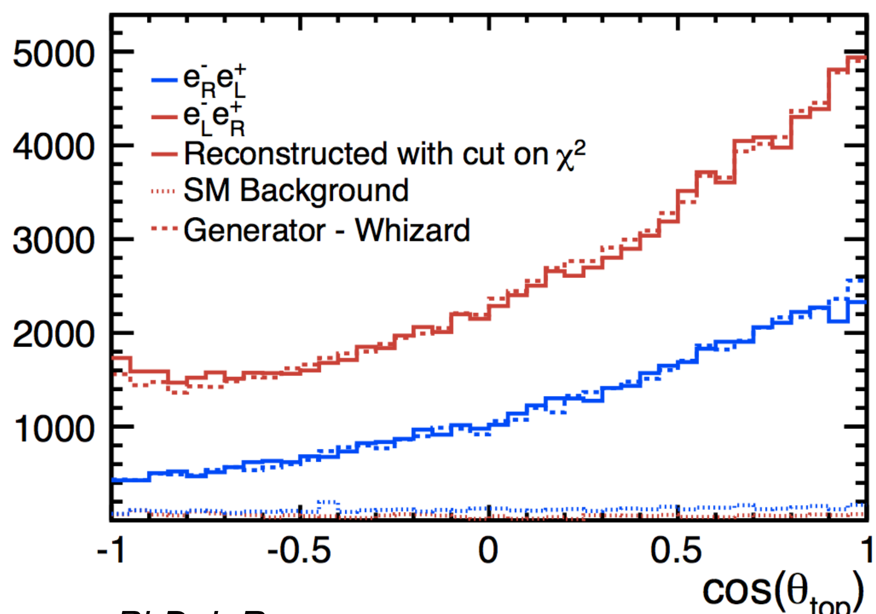
=> Important guidance for e.g. 100 TeV pp-collider



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



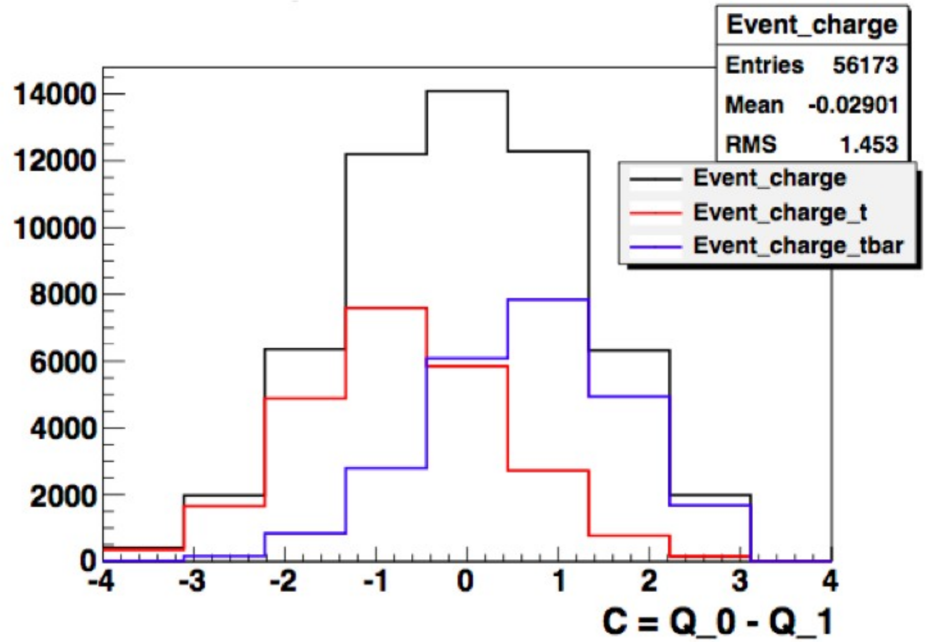
PhD J. Rouene

Precise reconstruction for both beam polarisations

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

Precision on A_{FB} ~ 2%

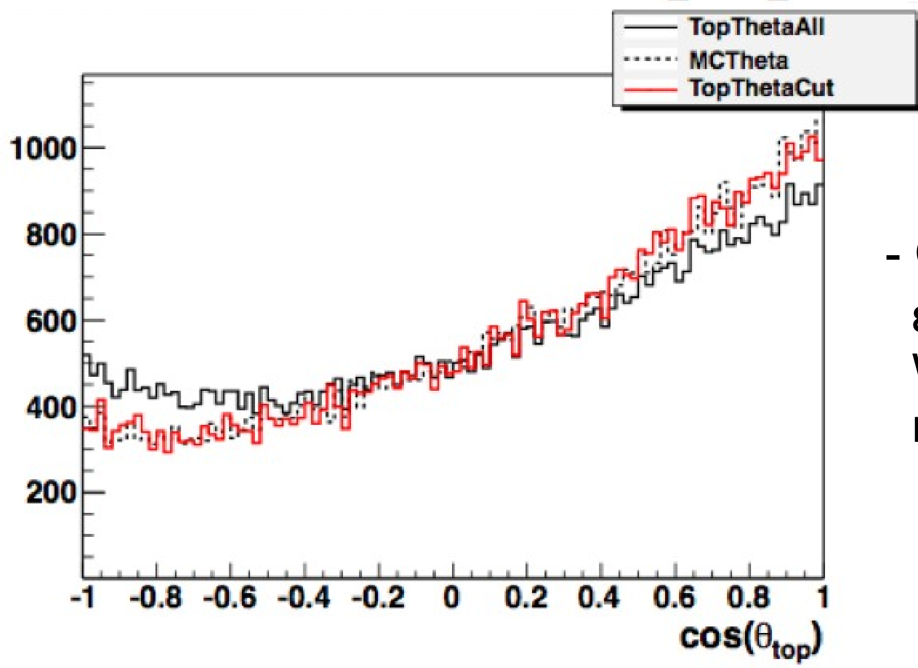
Top polar angle using b charge



Event charge C = b1 -b2

In SL can compare charge C with lepton charge t
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)

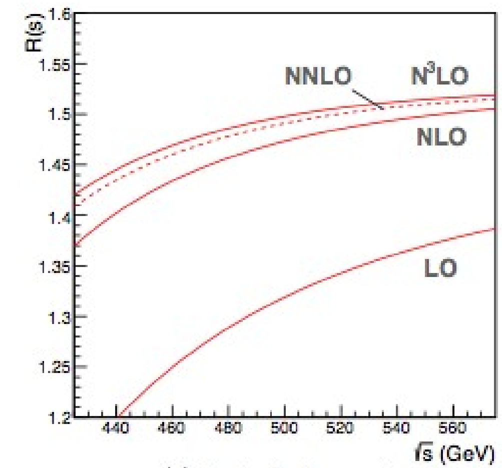
$$e^+e^- \rightarrow t\,\bar{t} \rightarrow \mu^+\mu^- b\,\bar{b}\,\nu_\mu\bar{\nu}_\mu$$

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

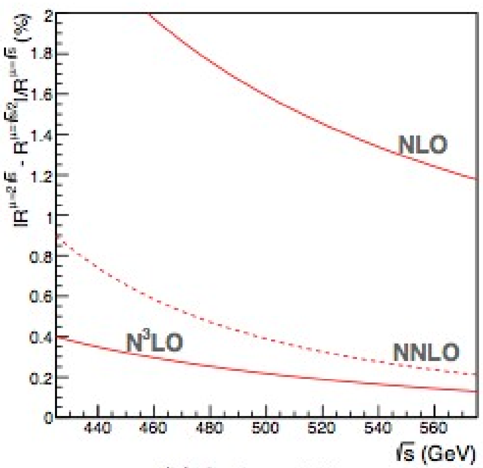
See talk by Francois LeDiberder

Theoretical uncertainties

- QCD corrections are known up to N^3LO



(a) Perturbation series

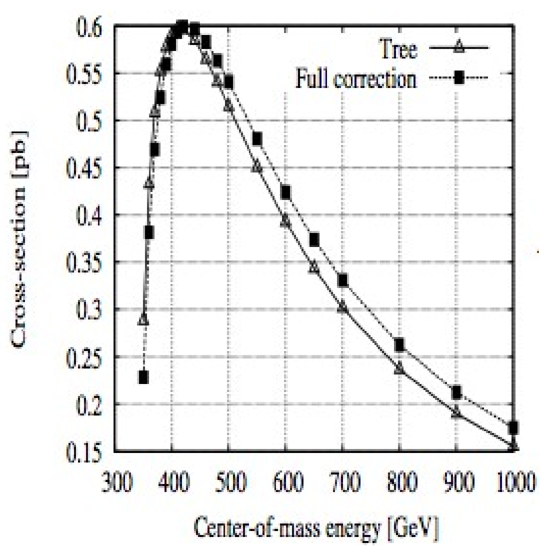


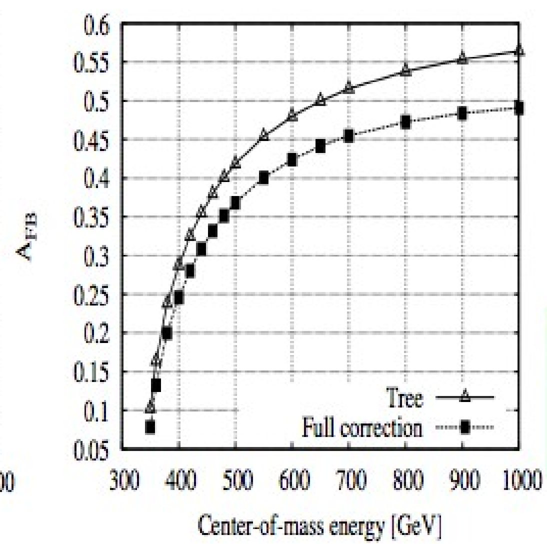
(b) Scale variations

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

Open topics for couplings study (Incomplete)

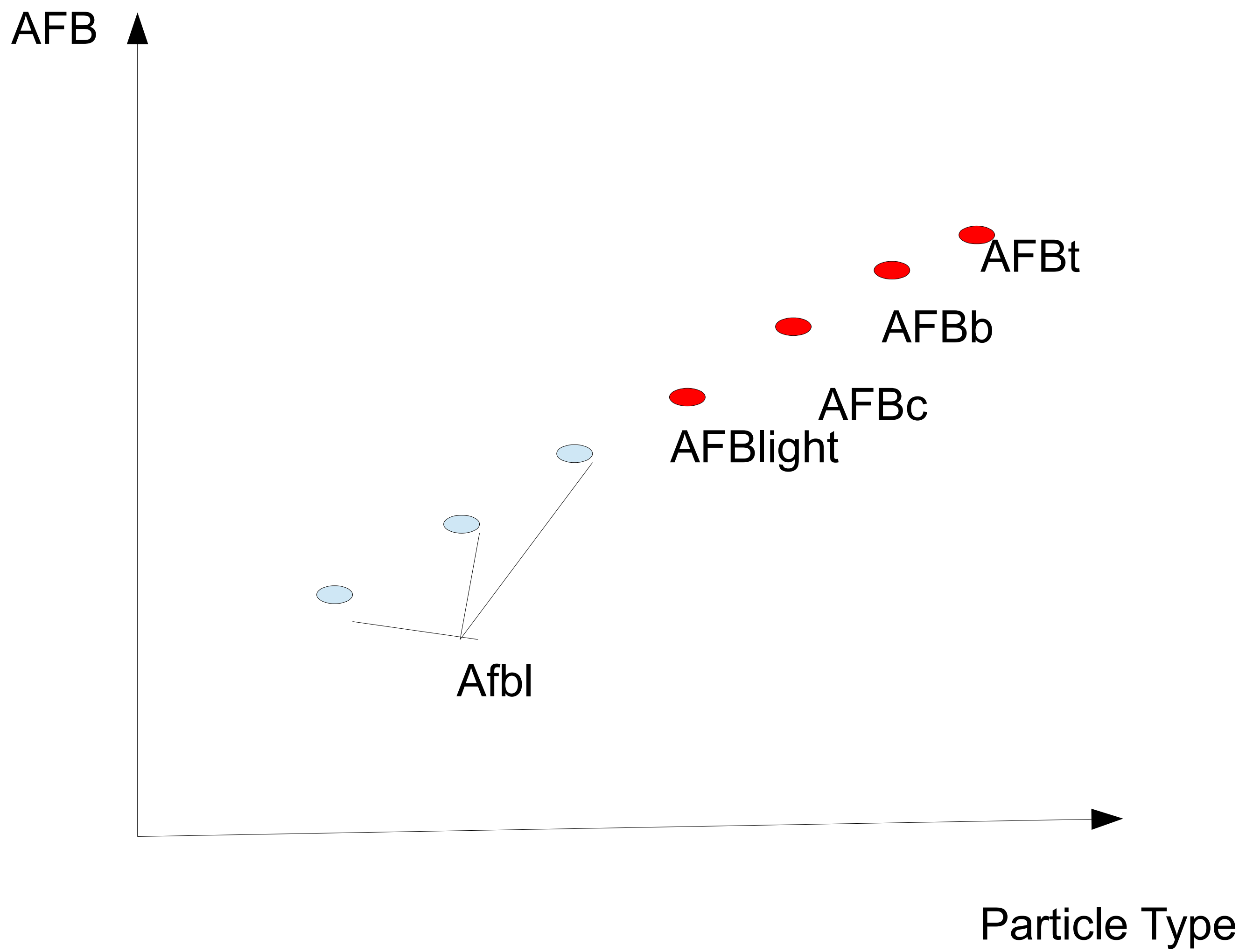
- Experimental study of matrix element method (Fully leptonic channel)
- Continuation of fully hadronic channel (would benefit massively from b charge and PiD)
- Studies at 1 TeV and higher (partially done by IFIC)
- CPV measurement at ~380 GeV

  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

The “Dream”?



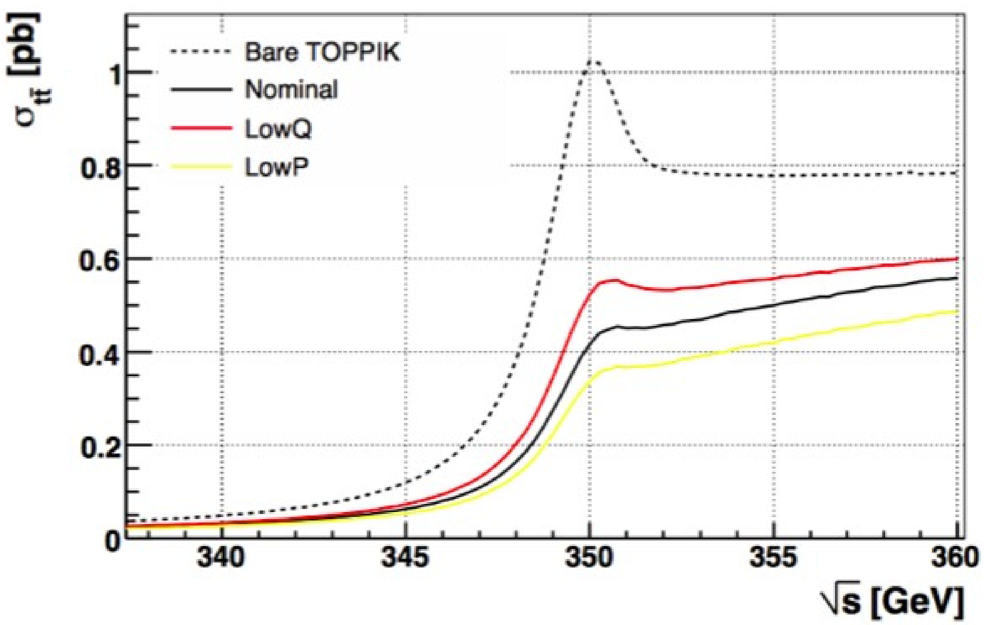
Summary

- Talk reflects status of ~November 2014

- New Aspects will be covered at this meeting

Backup ....

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:

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

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

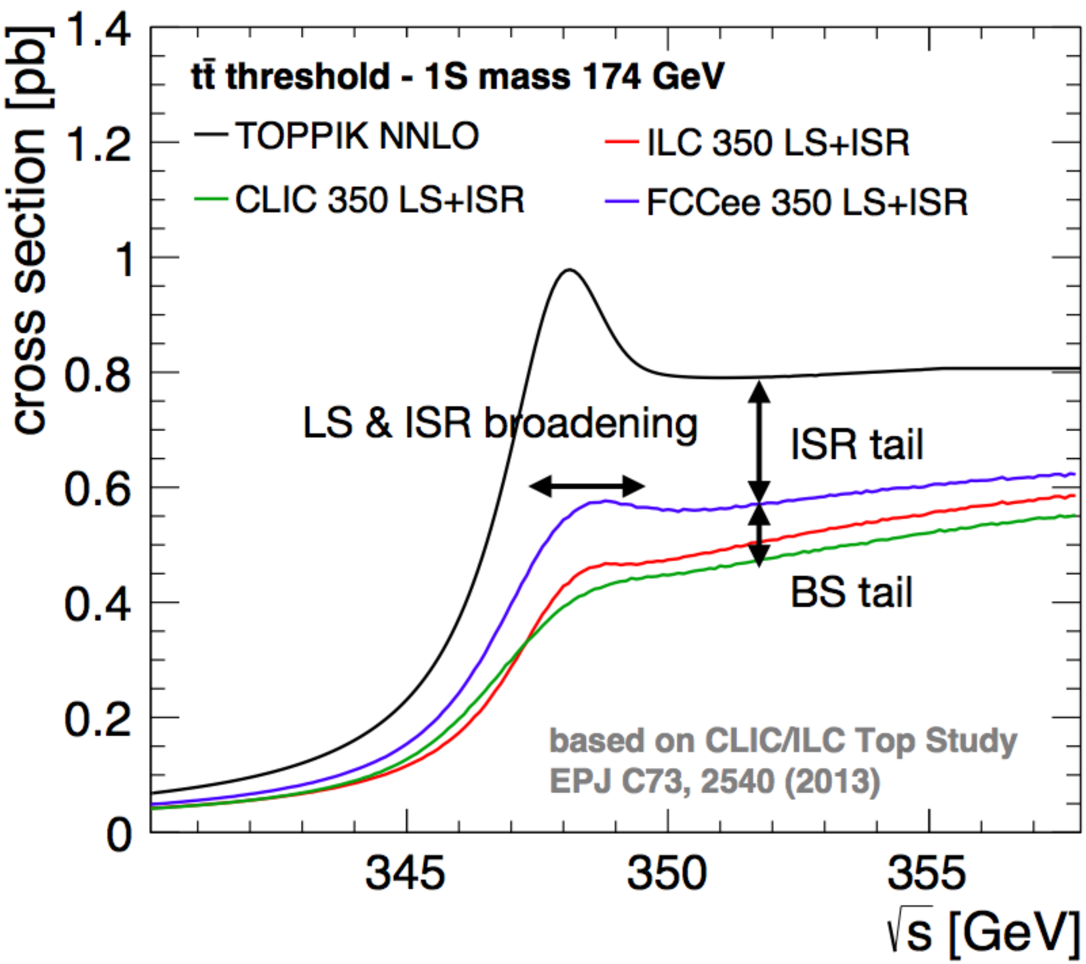
What mass?

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

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

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

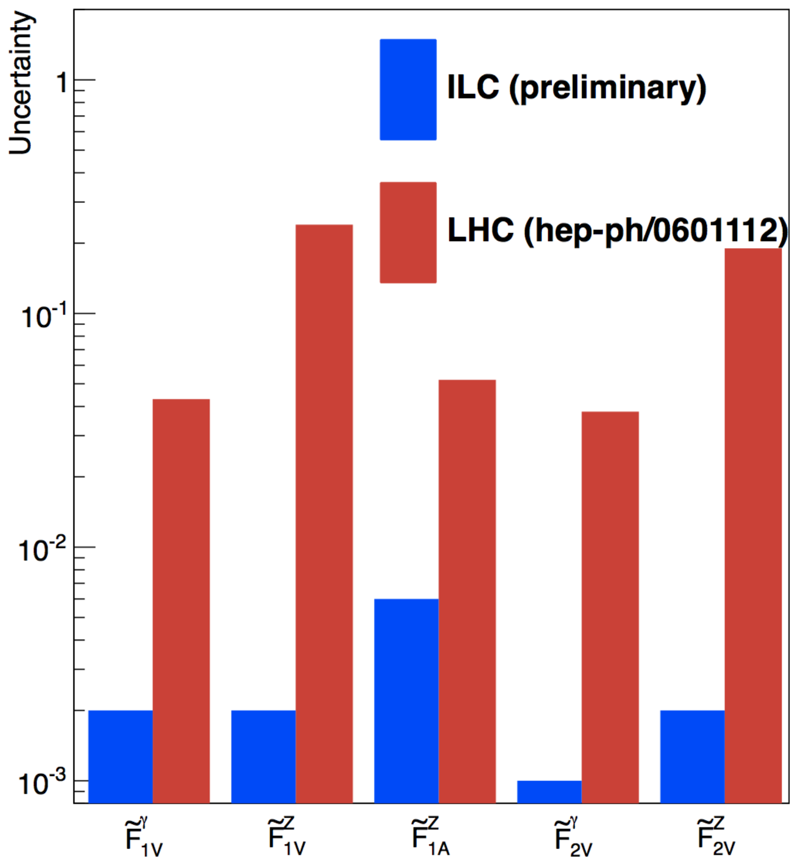
F. Simon
AWLC14

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