Top quark physics and Electroweak measurements at the ILC

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Journees Collisionneur Lineaire - Lyon Mai 2013

The solid pillars of the LC phyics program

Top quark

Discovered 1995 at Tevatron

LHC and ILC are/would be
Top factories

W Boson

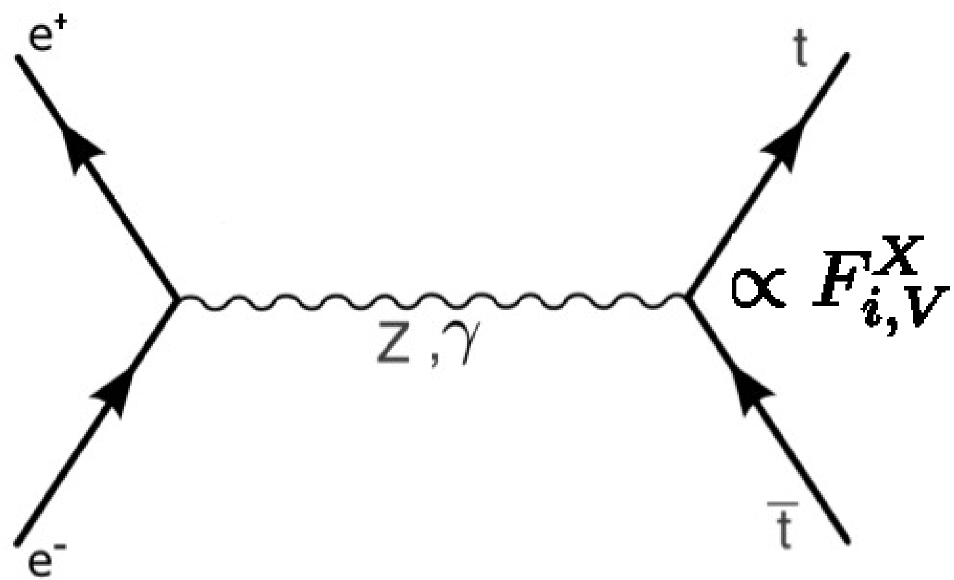
Discovered 1979 at SPS
Mass precisely at Tevatron
LHC and ILC are/would be
W factories

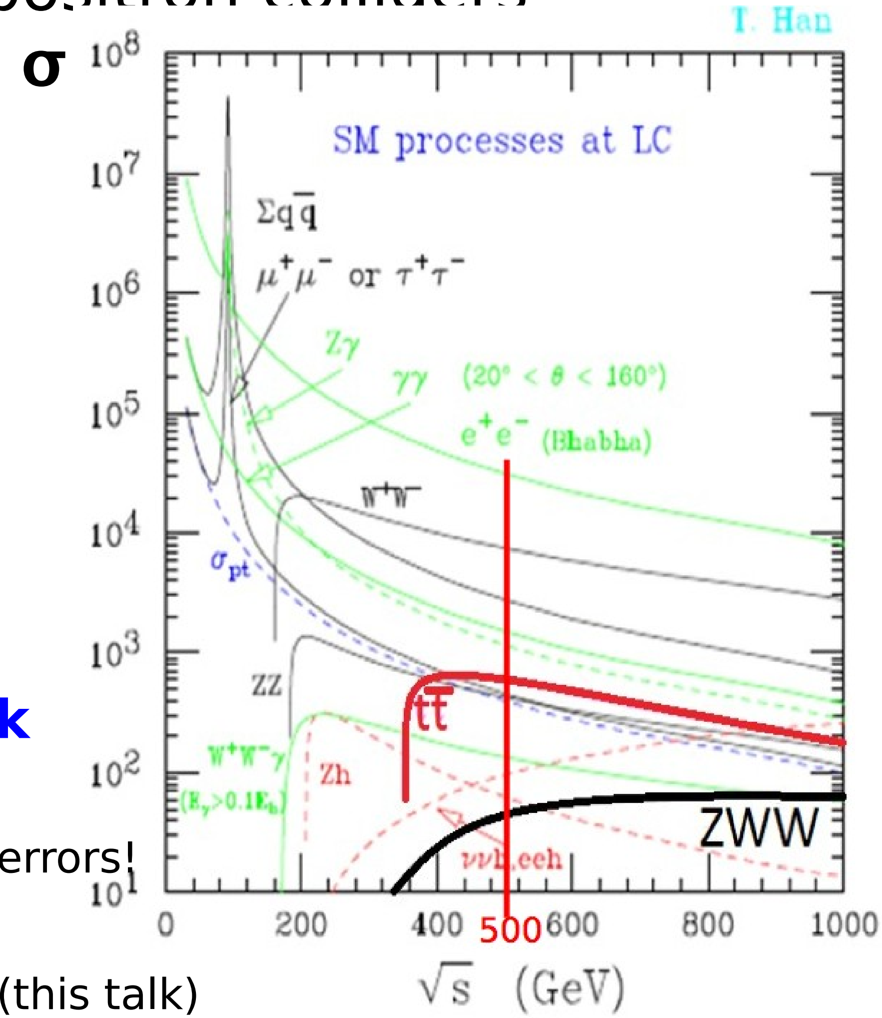
Higgs Boson

Discovered 2012 at LHC

ILC are/would be
Higgs factories
See talk by Klaus

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 (this talk)

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

- 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

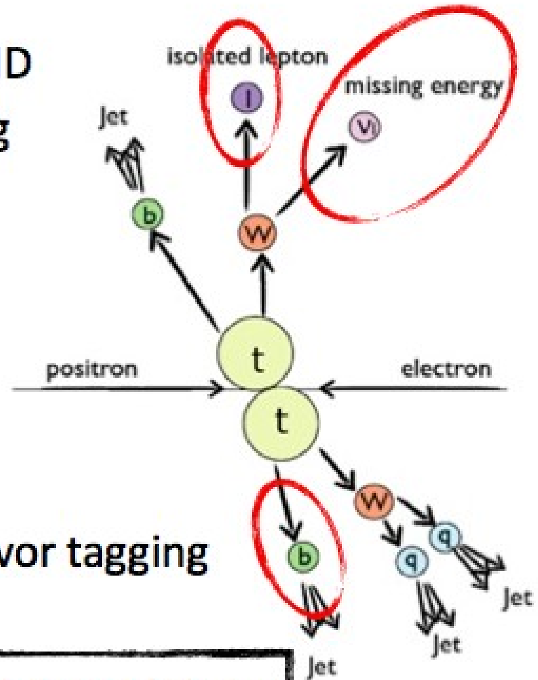
  -> Unbiased event samples, all event selection happens off-line!

Elements of top quark reconstruction

See also talk by Jeremy

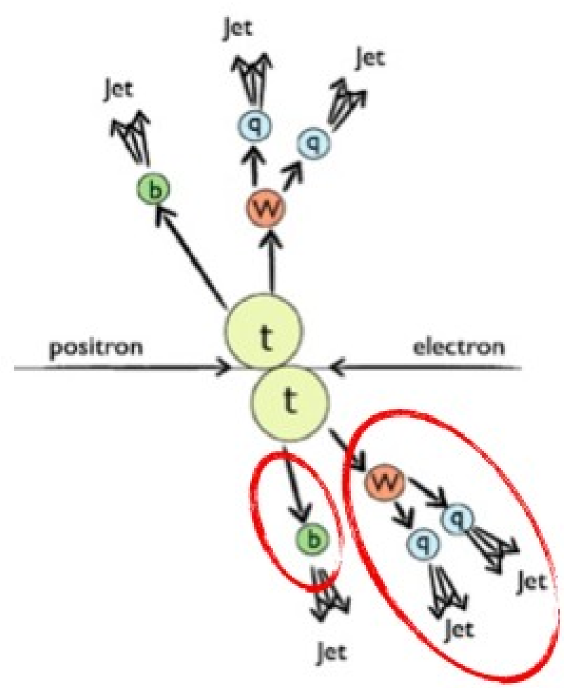
- By far dominating decays: All-hadronic (46%), semi-leptonic / lepton+jets (45%, 30% w/o τ)
  - try to avoid decays into τ, increased uncertainties from additional neutrino

lepton ID
tracking



flavor tagging

4 jets, isolated lepton



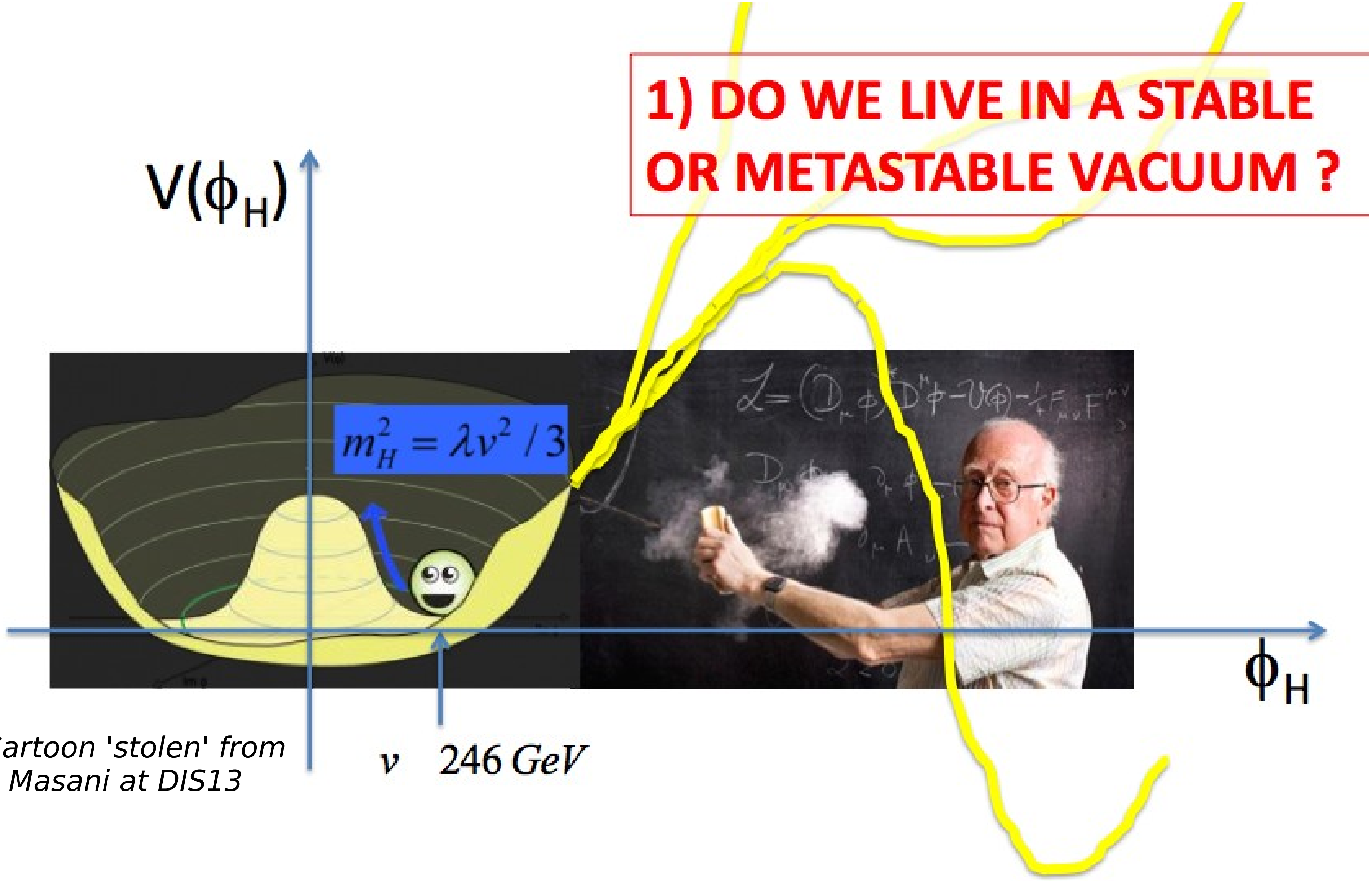
6 jets

jet energy reconstruction, global event reconstruction

Uses all aspects of LC detectors!

Nice illustration stolen from Frank

Motivation for precise top quark mass

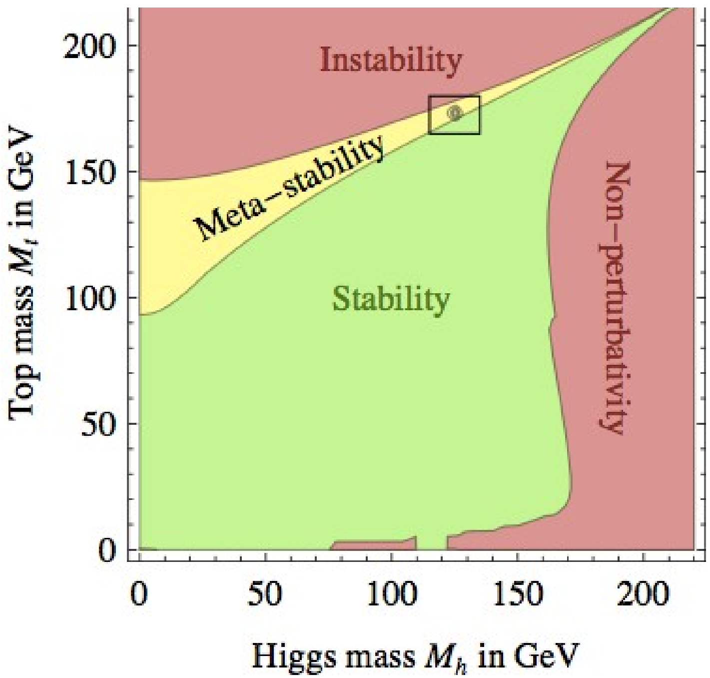


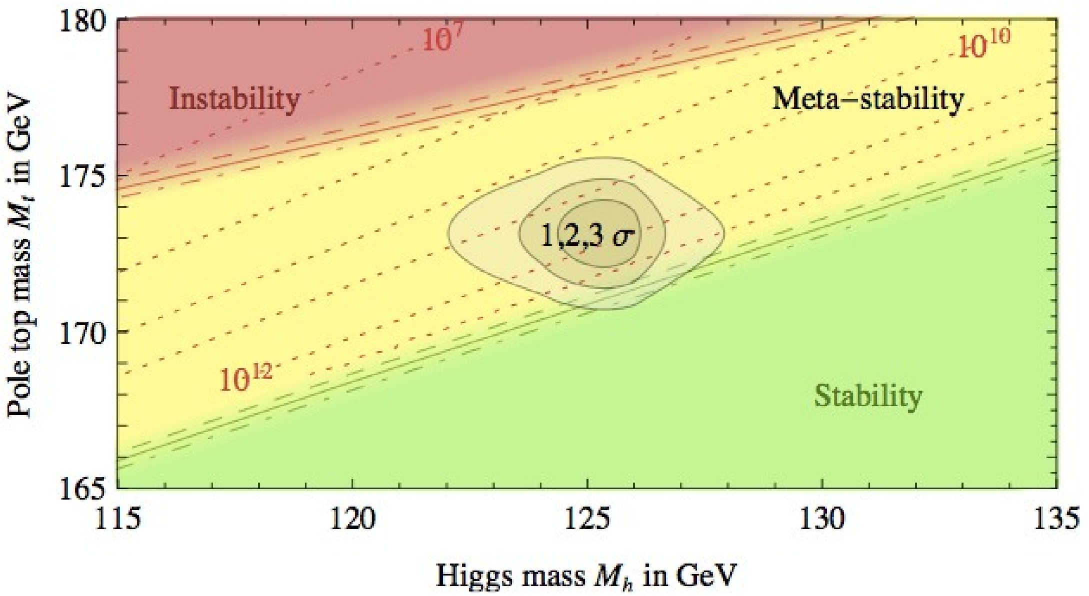
Cartoon 'stolen' from
I. Masani at DIS13

Vacuum stability and top quark mass

Degrassi et al.
arXiv:1205.6497

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





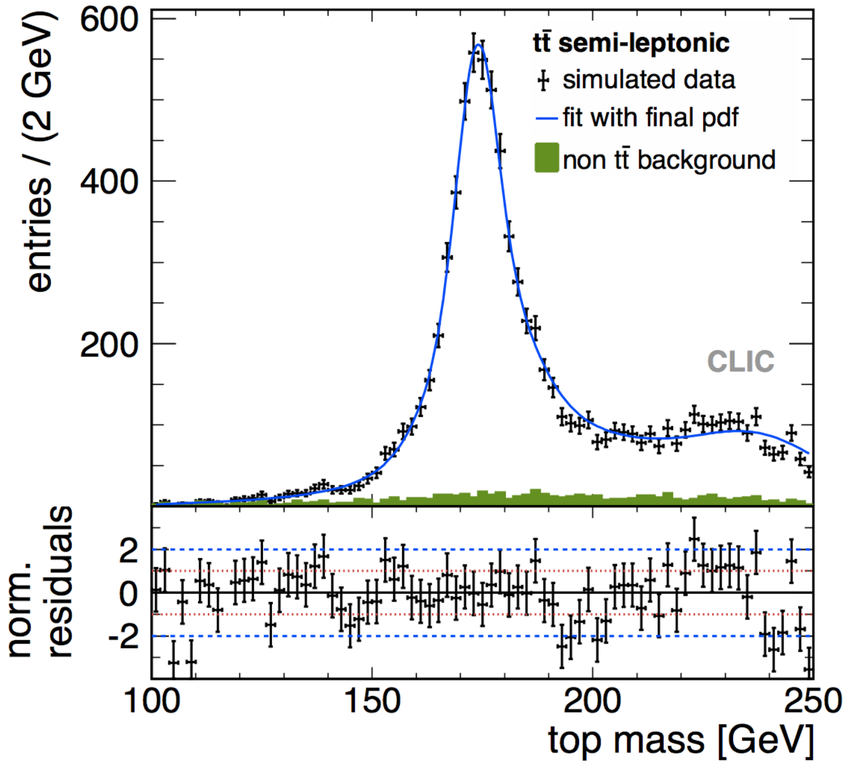
Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	**Total combined in quadrature**	**± 1.5 GeV**
λ	scale variation in λ	± 0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ correction to M_t	± 0.6 GeV
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**

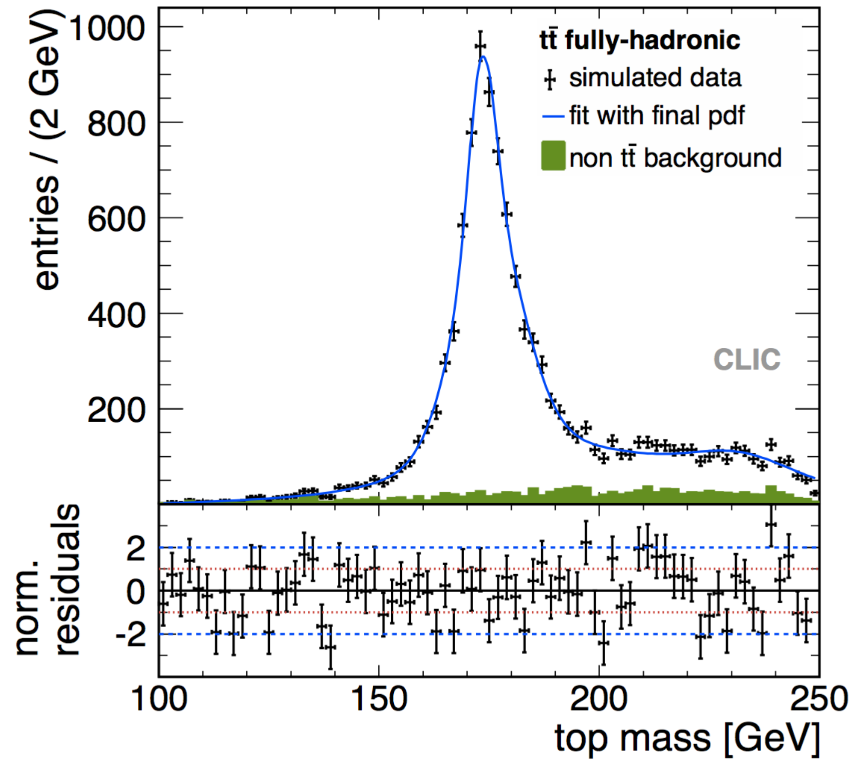
Uncertainty on **(pole)** top quark mass dominates uncertainty on stability conditions

(argument is repeated In literature!)

Top mass spectrum in continuum – 500 GeV

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

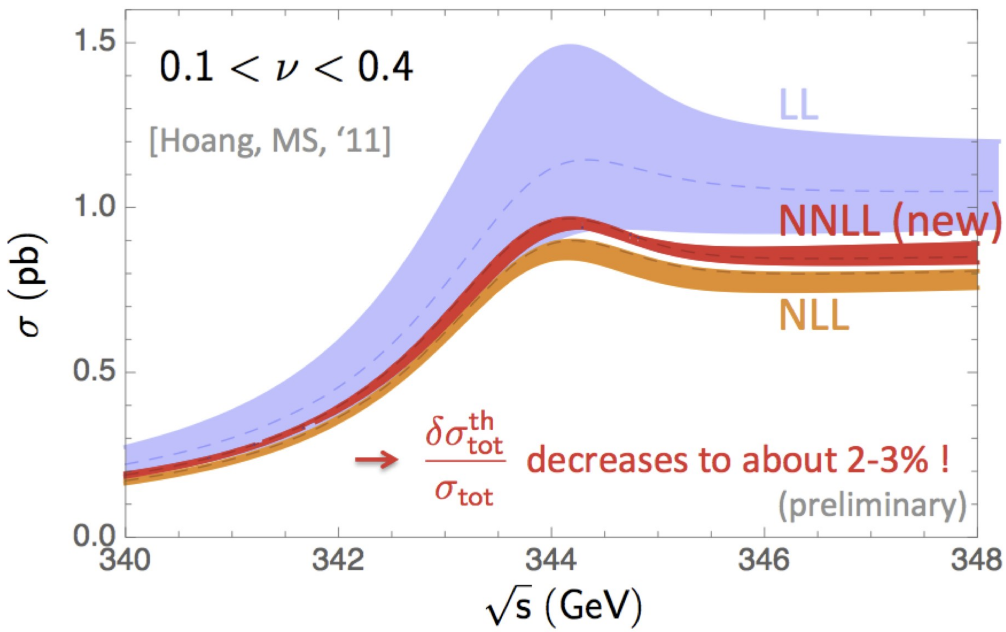




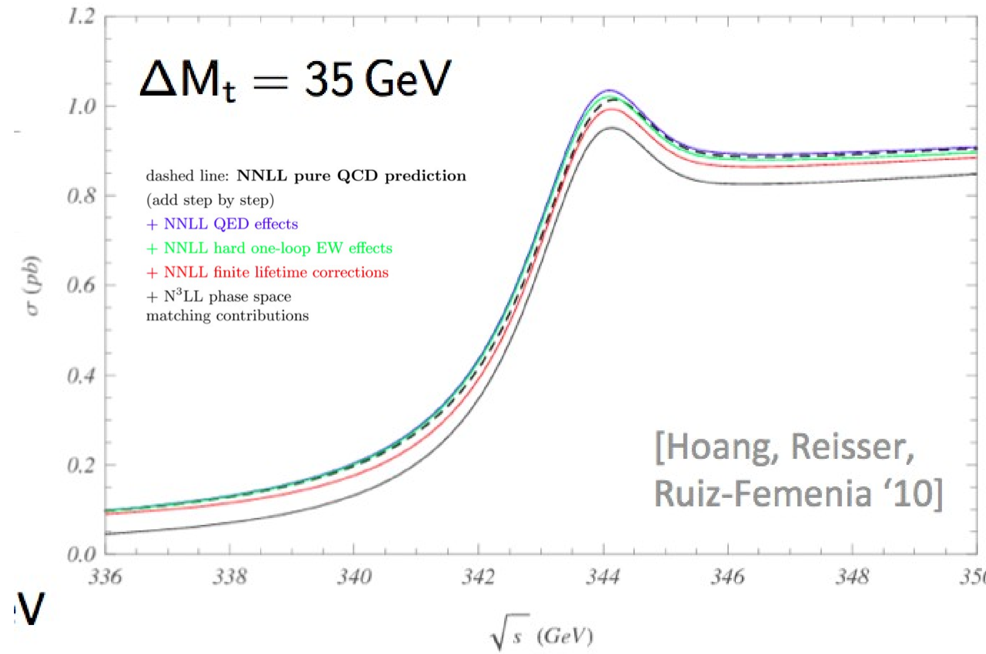
- (Almost) background free measurement of top mass
- However, continuum mass theoretically not well Defined (Renormalisation scheme dependent) Similar issues at Lepton and hadron colliders

Top quark mass – Theoretical accuracies

QCD



QCD + electroweak

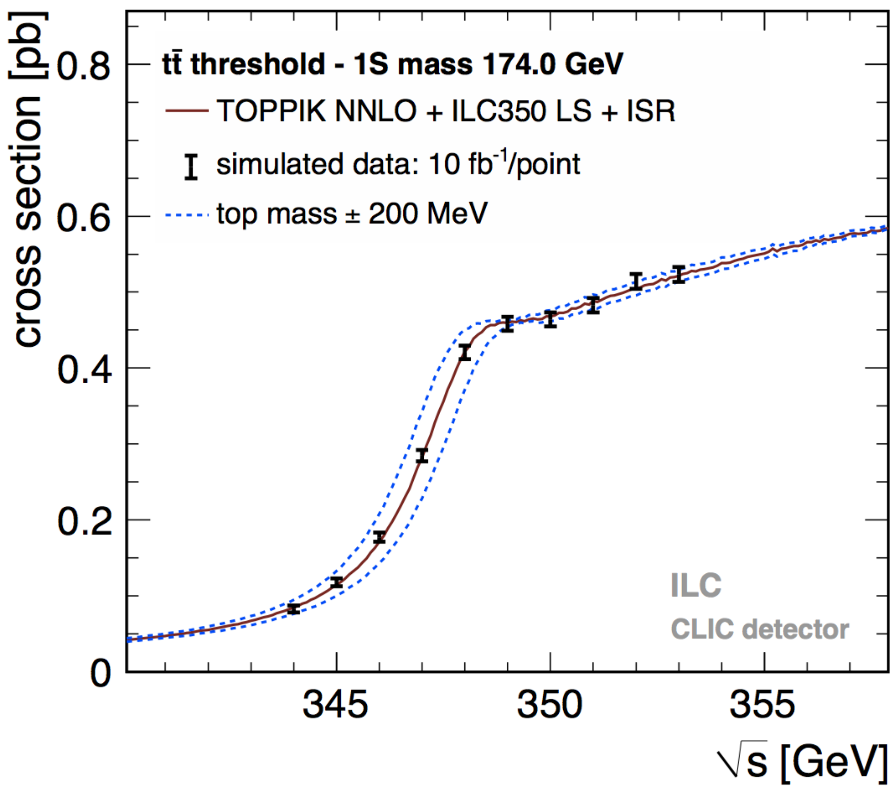


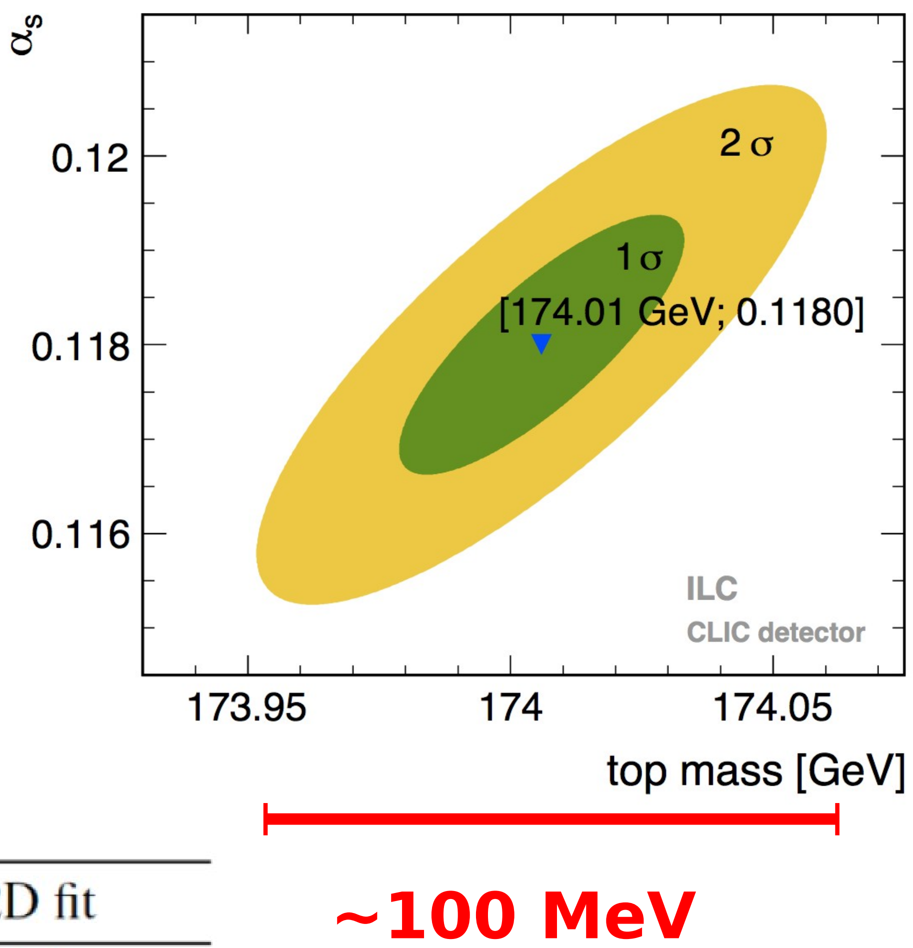
Correct resummation of
Non relativistic logs ~v

Theoretical uncertainties at the 2-3% level
=> Threshold scan theoretically well understood

Top quark mass – Results of full simulation studies

arXiv:1303.3758

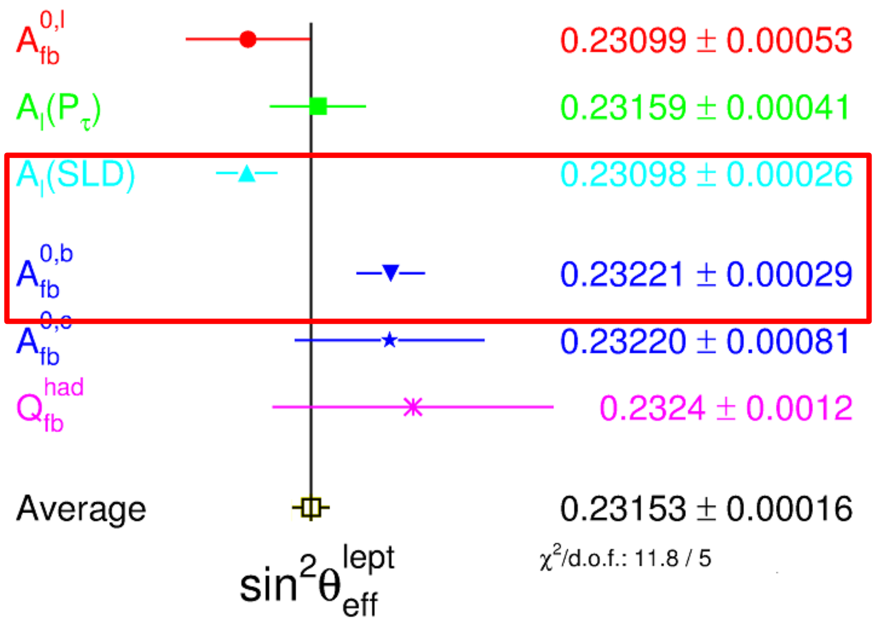




1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

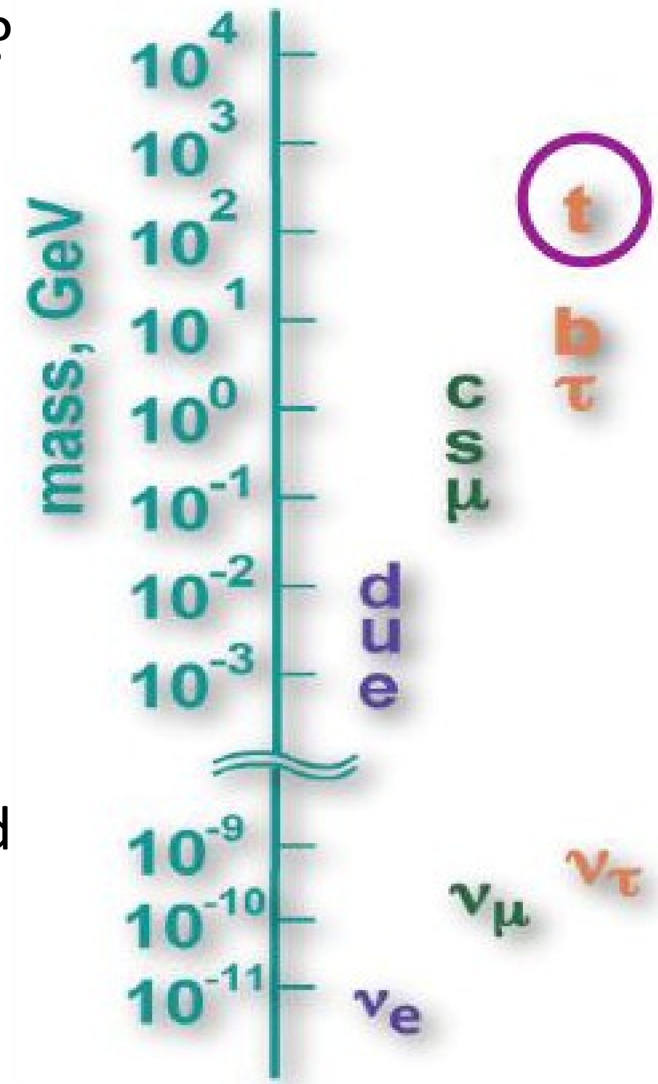
The top quark and flavor hierarchy

- Flavor hierarchy ? Role of 3rd generation ?

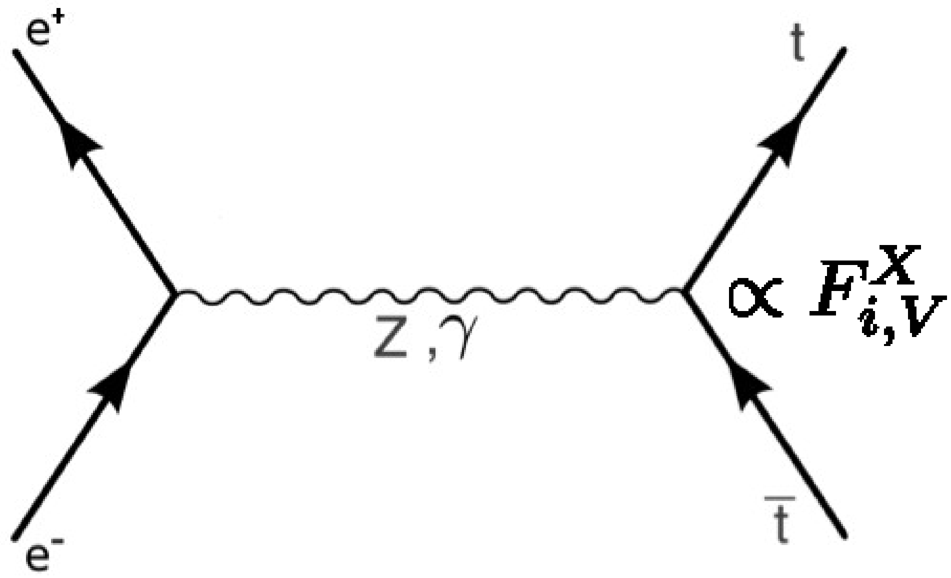


- Top quark : no hadronisation → clean and detailed observations

- Redo measurements of A_{LR} and A_{FB} with the top



Testing the chiral structure of the Standard Model



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

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

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

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

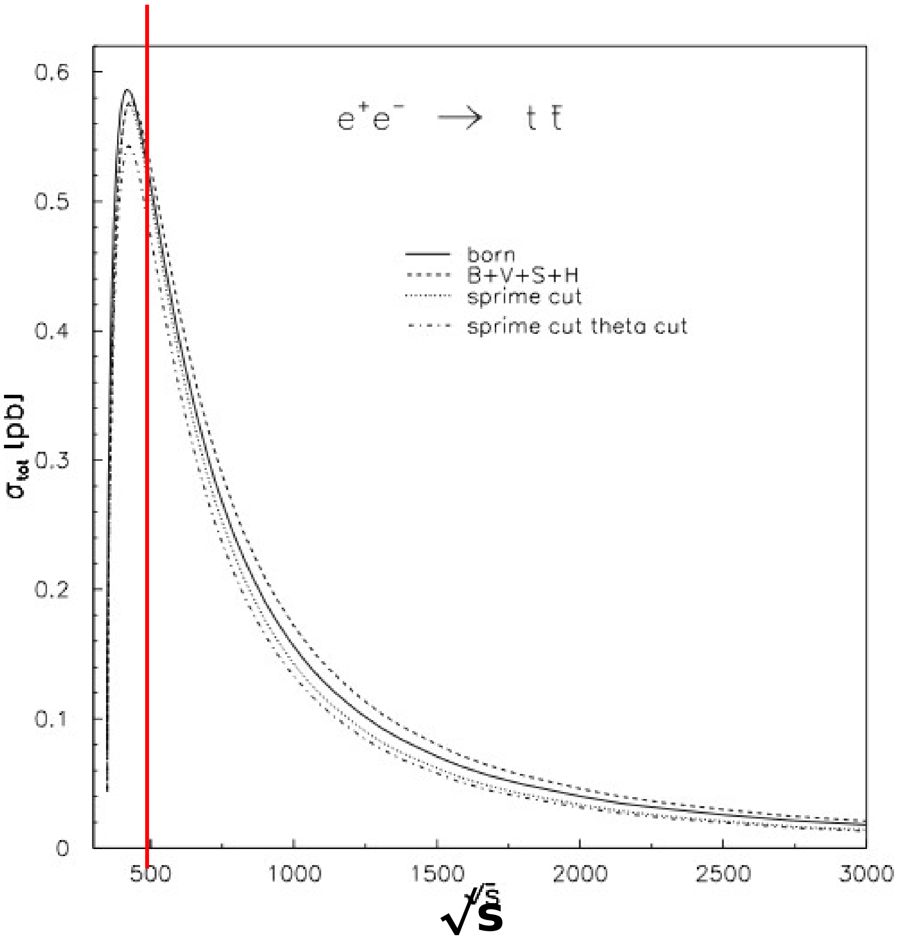
⇩

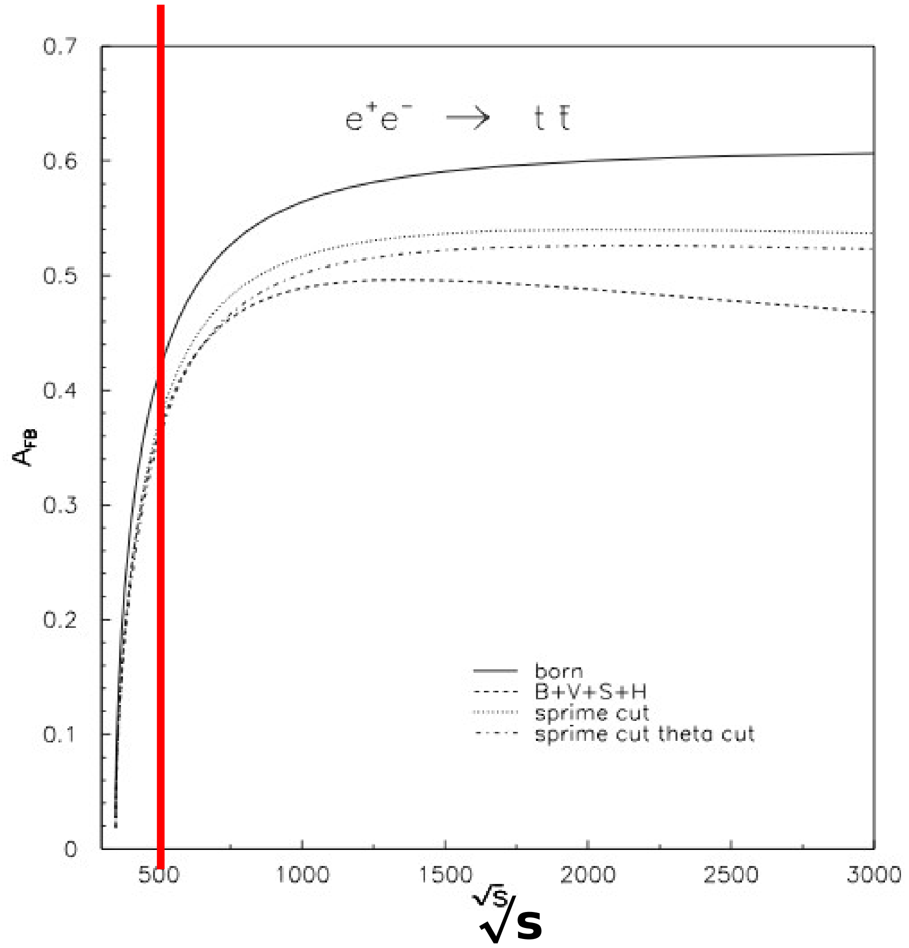
Extraction of six (five) unknowns

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

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

500 GeV – Answers to yesterday's questions



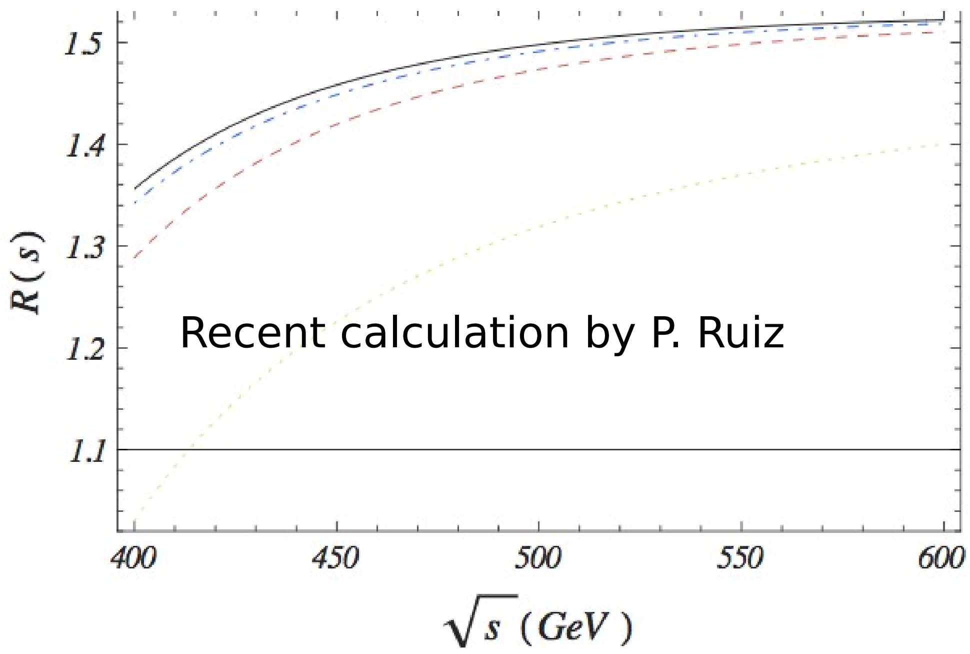


- Cross section close to maximum, A_{FB} well developed

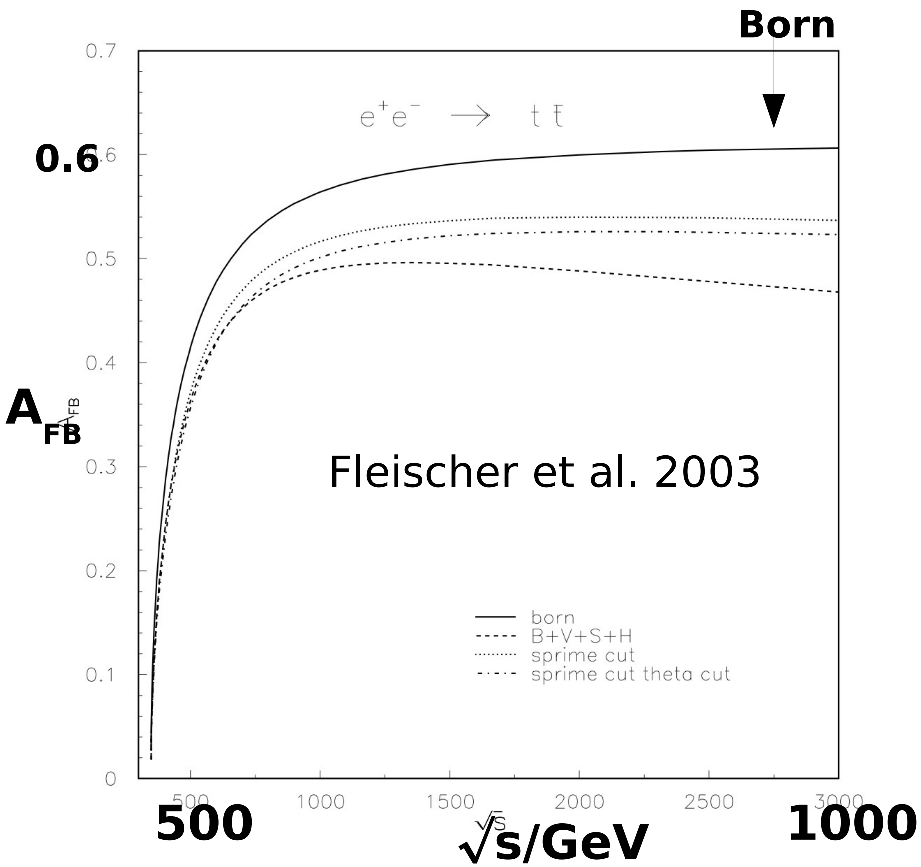
- Other remarks: Need some velocity to get sensitive to chiral obervables (see backup slides)

SM correction to Born process

QCD up to $O(a_s^3)$



NLO electroweak



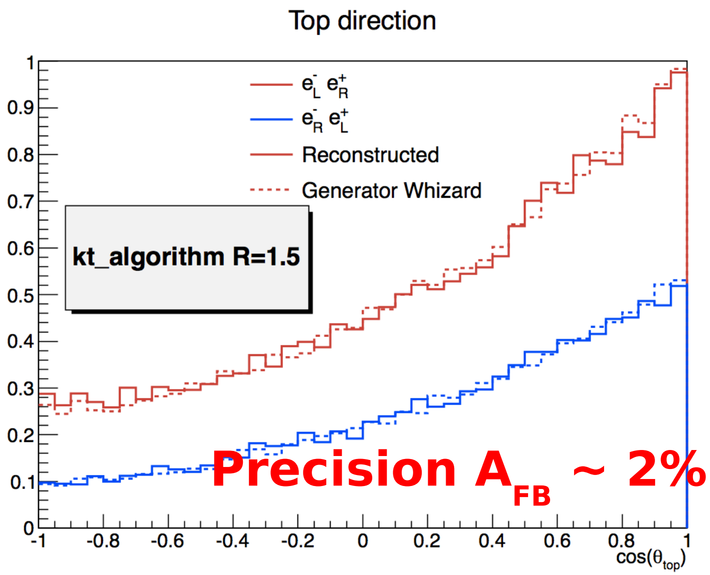
- Well behaving perturbation series
- Small scale uncertainties <1%
- Size of next correction expected to be Smaller than 0.3% at 500 GeV

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

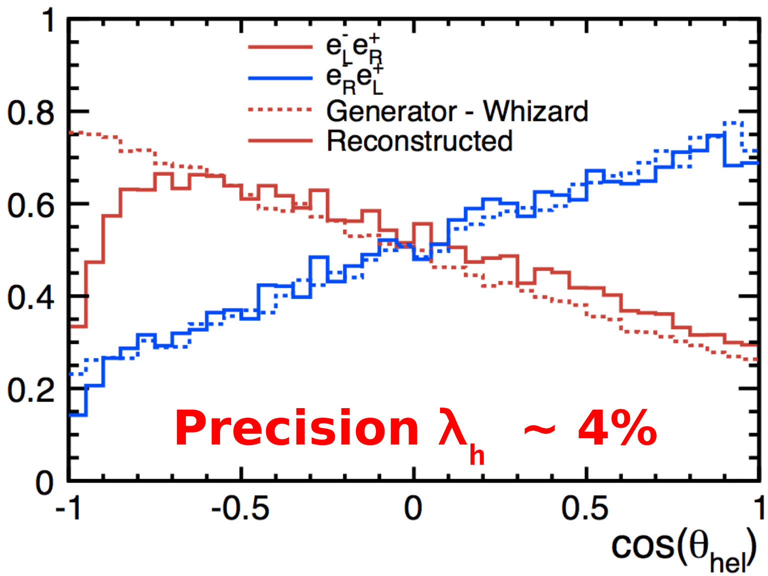
Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

LC-REP-2013-007

Precision: x section ~ 0.5%



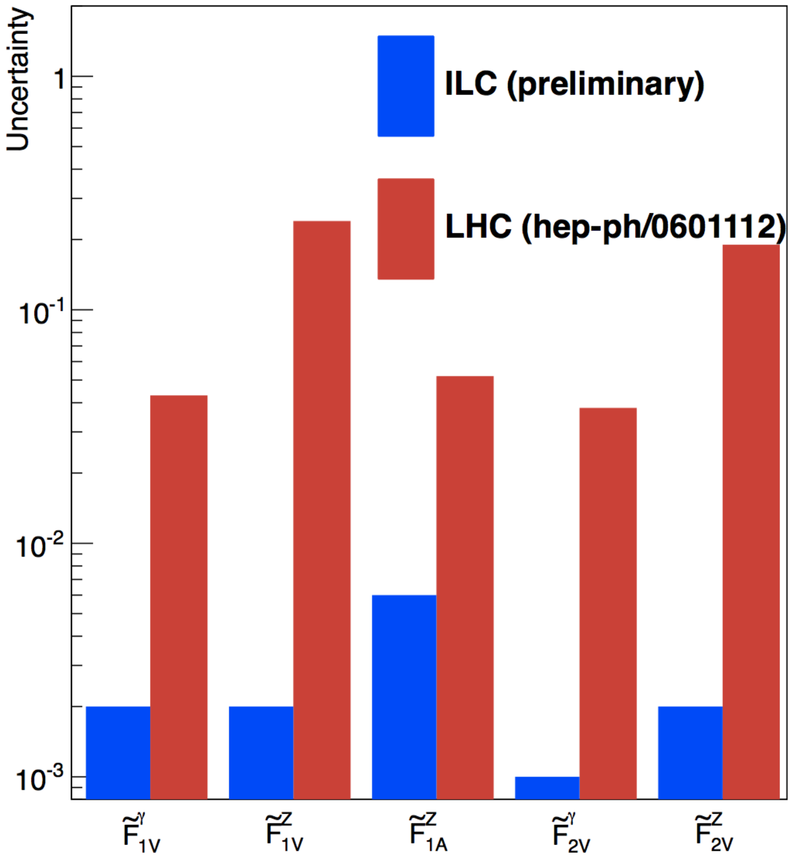
Precision A_{FB} ~ 2%



Precision λ_h ~ 4%

=>

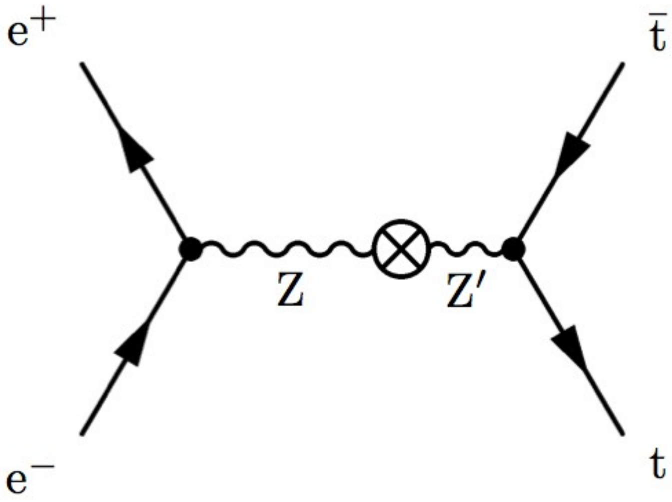
Precision of couplings

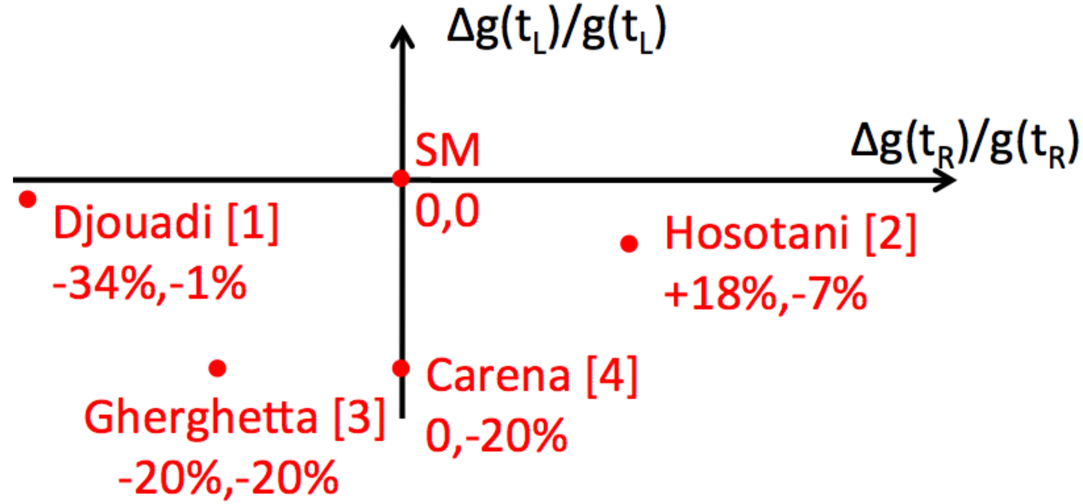


ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})

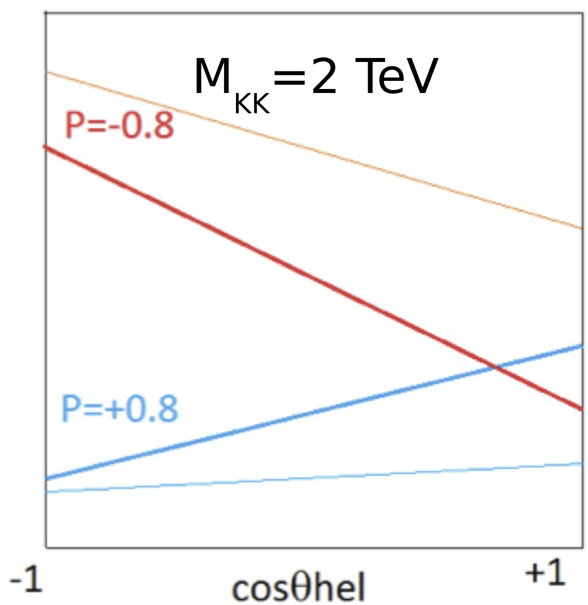
Top quark and new physics

New physics modify electroweak couplings to Z





Example: RS models with extra dimensions



ILC sensitive to M_{KK} masses up to 50 TeV

$(g\text{-}2)_t$

$$F_{2V}^{\gamma} = Q_t (g-2)_t/2$$

$$\delta F_{2V}^{\gamma} = \delta (g-2)_t \approx 0.1$$

$$\delta (g-2)_t \approx 0.1\% \propto m_t/M$$

=> Test of compositeness scale M up to 100 TeV

Discussion of potential systematic uncertainties

Experimental (see also talk by Rouene)

- 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

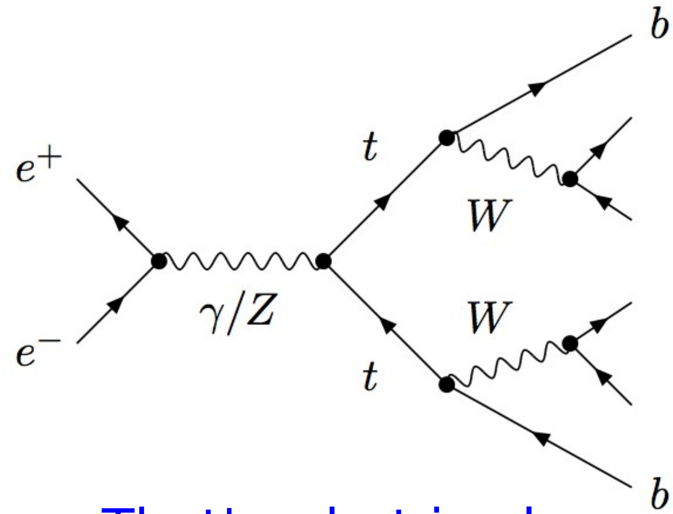
- Other effects: B-tagging, passive material etc.
  LEP claims 0.2% error on R_b -> guiding line for LC

Theory:

- see above and in the following

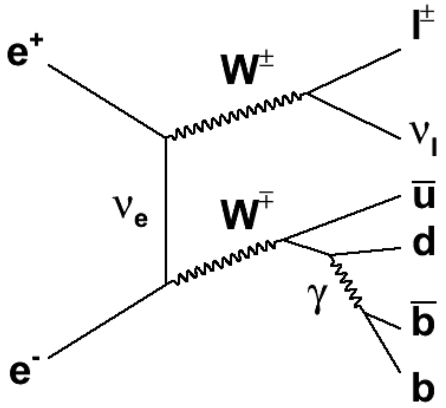
Closer look at ttbar production

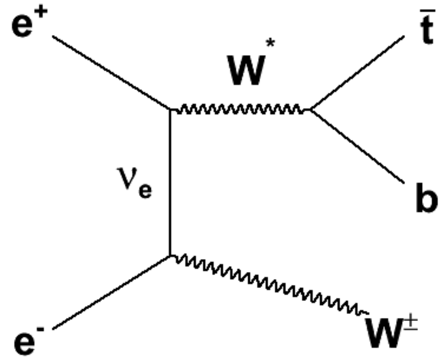
That's what we are interested in



Top pair production is effectively ee->6f process

That's what is also contributing to final state!



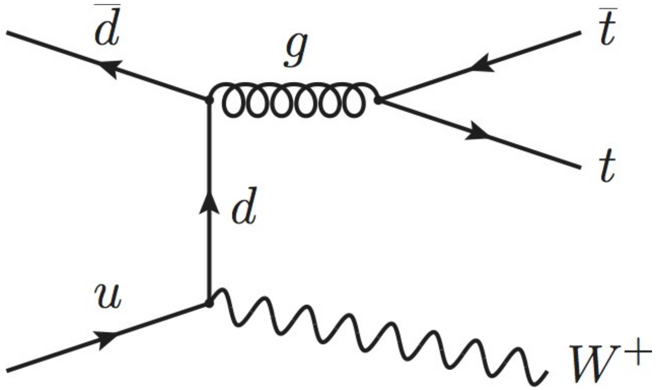


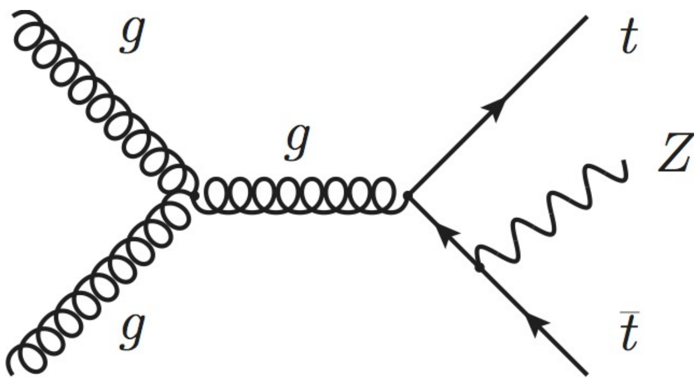
+ s-channel, t-channel only relevant for eL

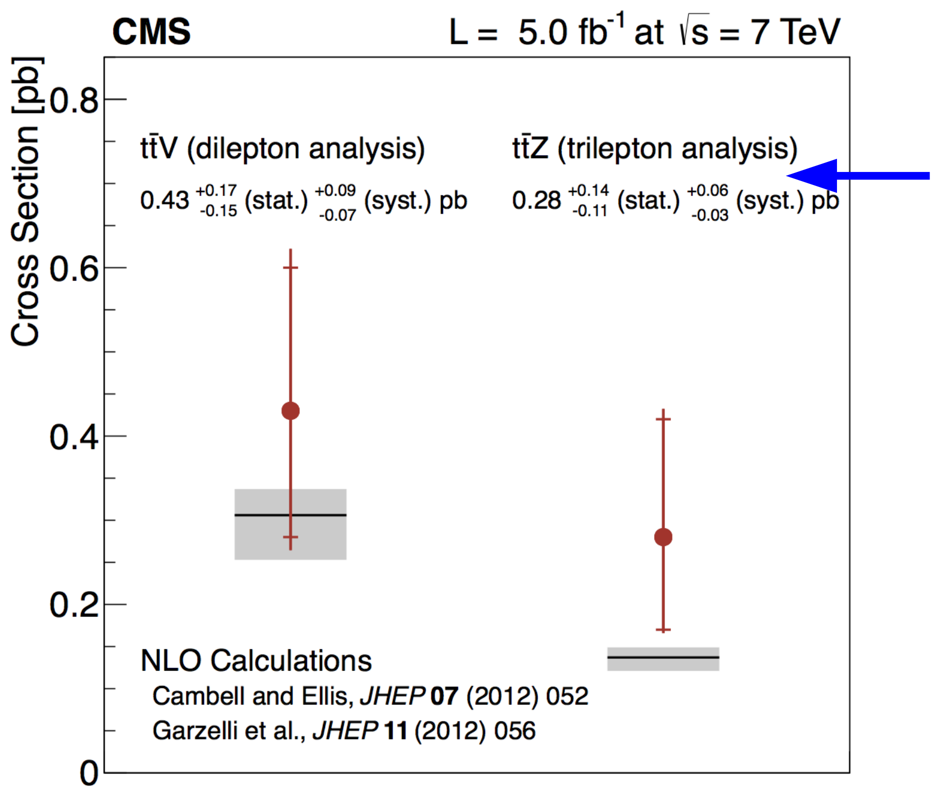
- Can one really speak about a ttbar cross section?
- If only 6f is relevant: What are relations to ttX couplings?
- What selection cuts are (theoretically) save?

The race is open !

Recent result on ttV by CMS





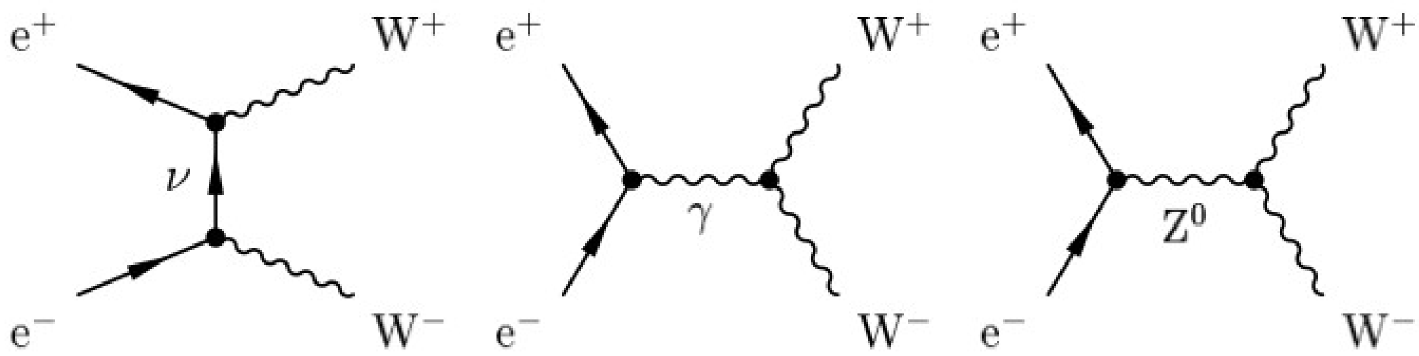


$$\sigma(t\bar{t}Z) = 0.28^{+0.14}_{-0.11}\,(\text{stat.})\,^{+0.06}_{-0.03}\,(\text{syst.})\,\text{pb}$$

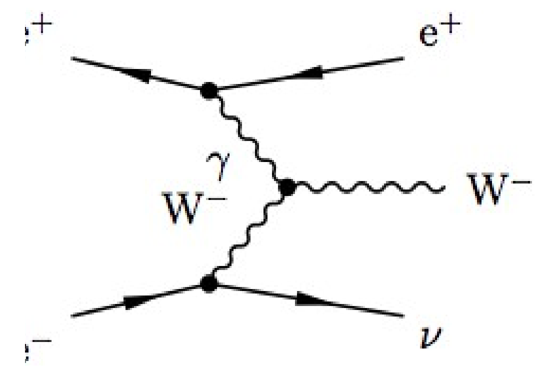
- Clearly, promising result
- How will it evolve with higher Luminosity?
- Revision of 'old' estimations of precisions are needed!

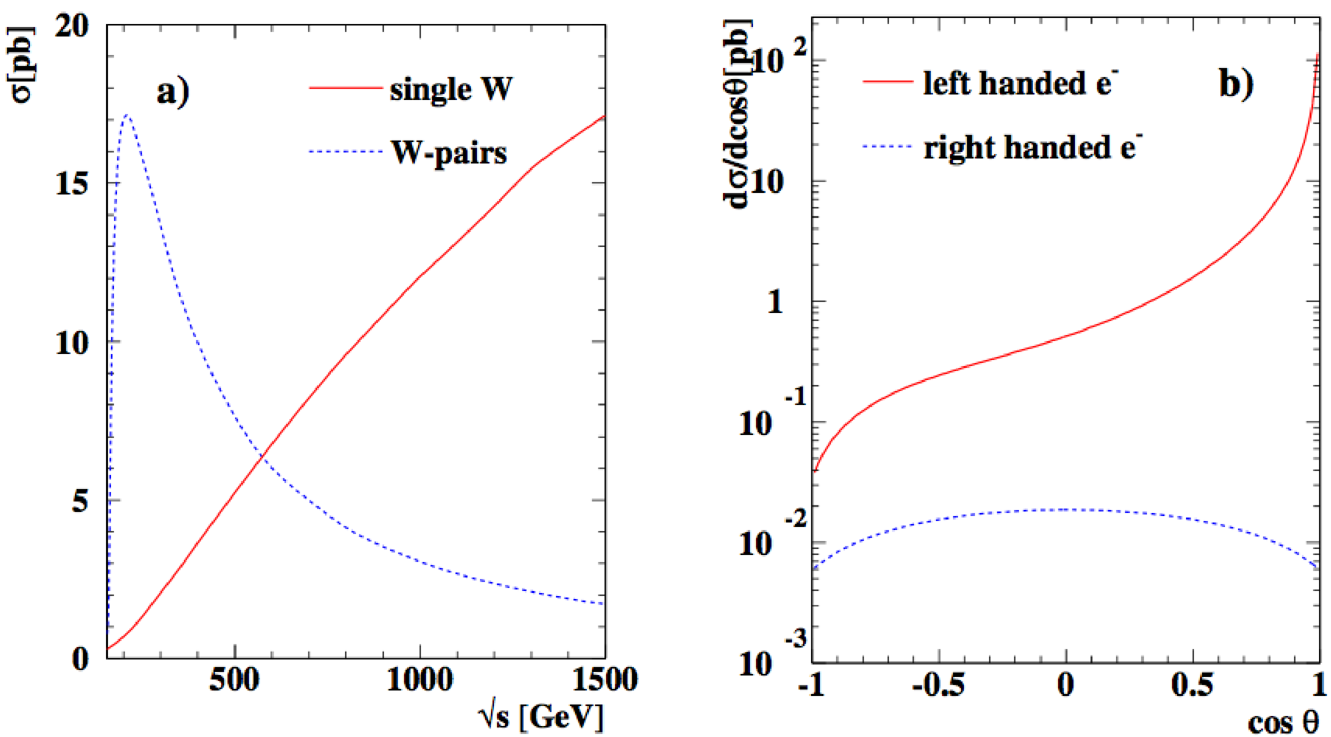
W physics

W pair production



Single W production





- Sensitivity to Triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

=> Enrich different helicity modes of W
=> in situ measurement of beam polarisation

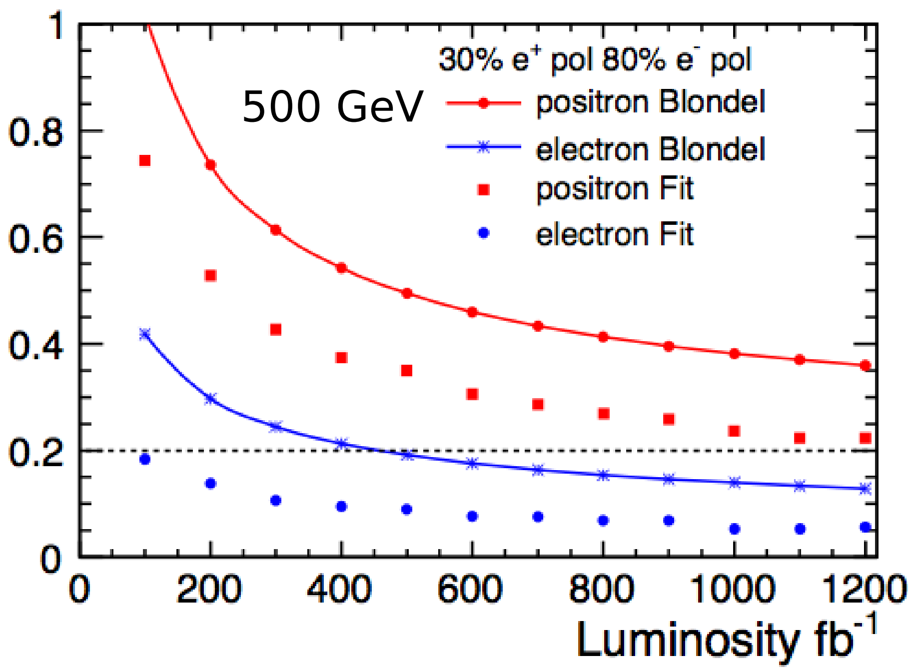
W production and beam polarisation

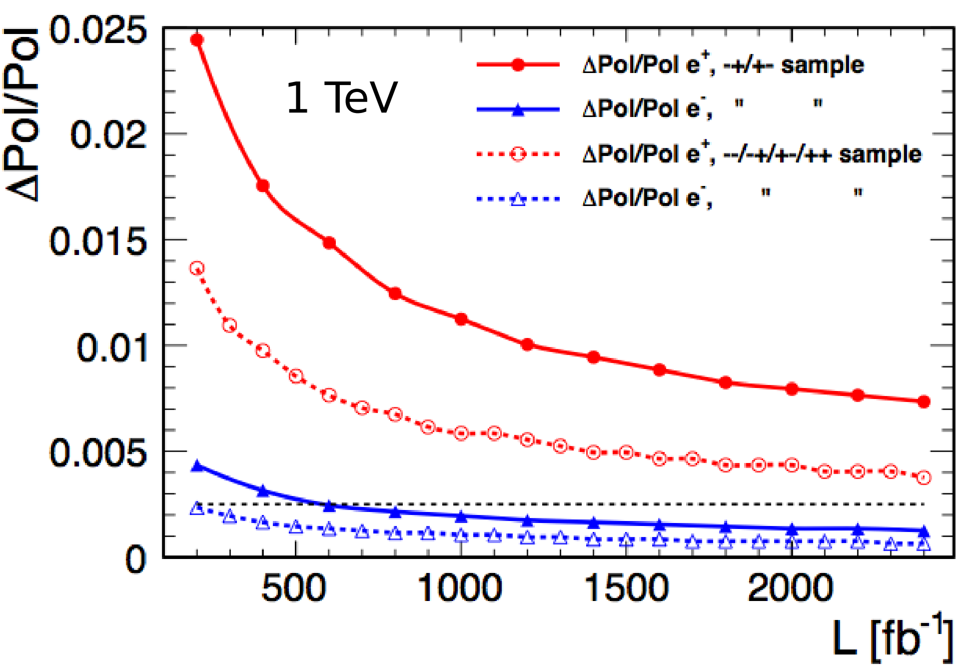
Polarisation measurement requires running at all combinations of beam polarisation: **++, +-,-+,--**

'Traditionally' – Blondel scheme

$$|P_{e^\pm}| = \sqrt{\frac{(\sigma_{-+}+\sigma_{+-}-\sigma_{--}-\sigma_{++})(\pm\sigma_{-+}\mp\sigma_{+-}+\sigma_{--}-\sigma_{++})}{(\sigma_{-+}+\sigma_{+-}+\sigma_{--}+\sigma_{++})(\pm\sigma_{-+}\mp\sigma_{+-}-\sigma_{--}+\sigma_{++})}},$$

Alternative: Fit to angular distributions (see PhD thesis I. Marchesini or LC-REP-2013-009)

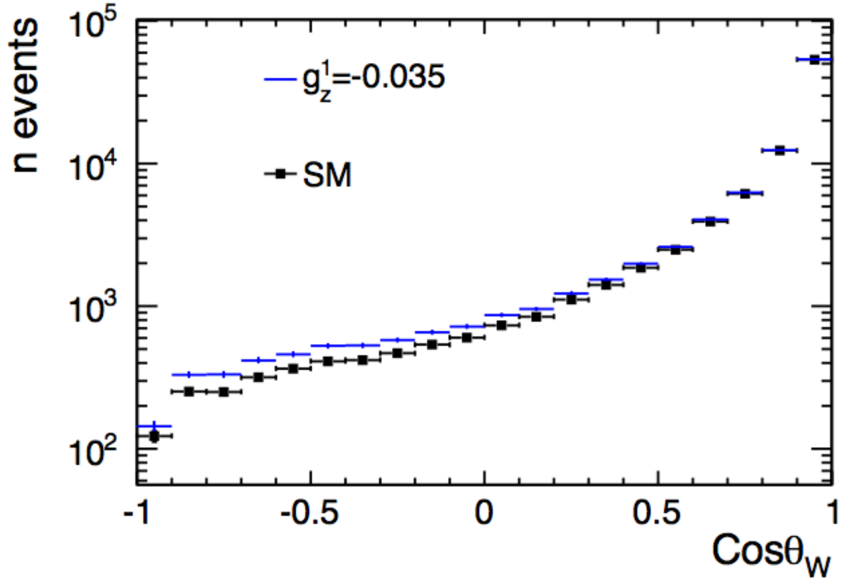




- Precisions: <0.2% for P(e-), ~0.35% for P(e+)
- Angular fit superior to Blondel scheme

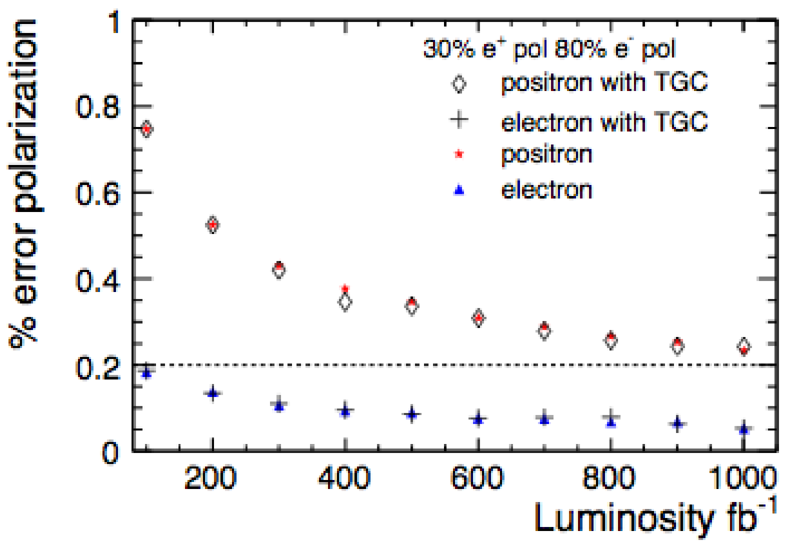
Angular fit scheme does not need running at ++,-- (albeit it benefit from it)

W production and TGCs

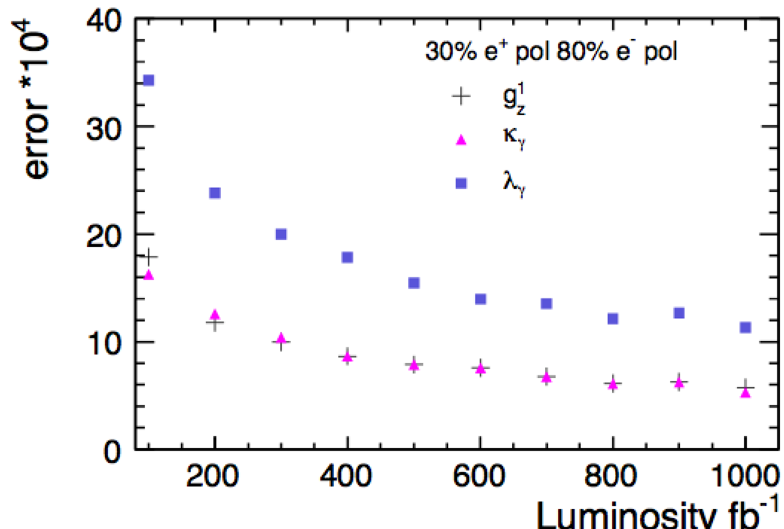


Example: Influence of **anomalous WZ coupling** on W scattering angle

Impact on P-measurement



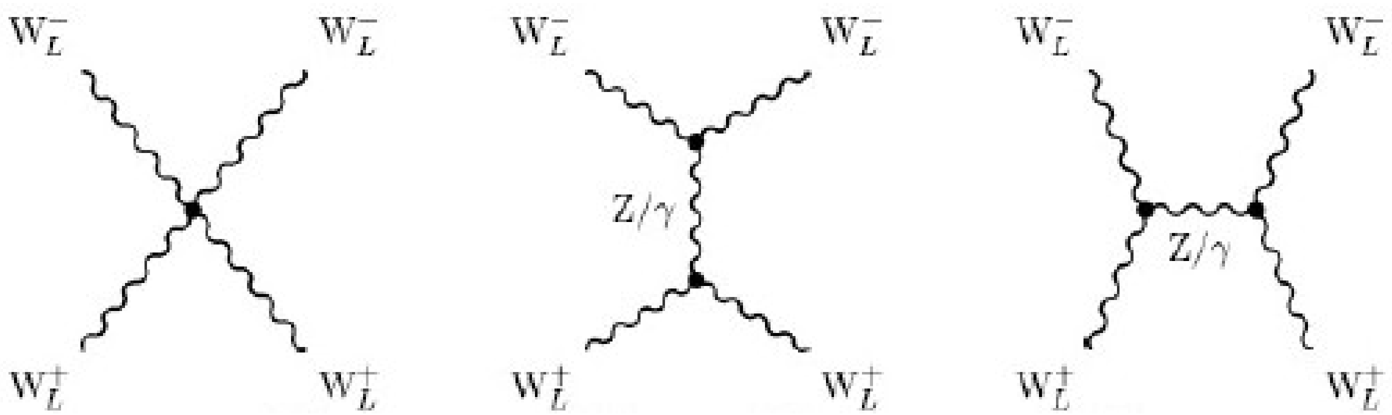
Precisions on TGC



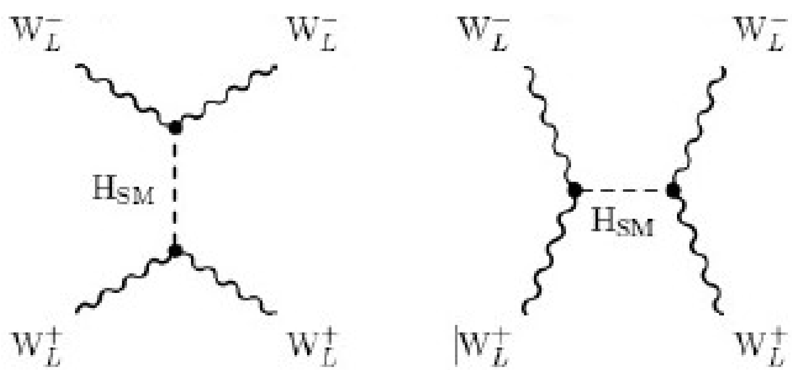
Anomalous TGC do not compromise precision

Uncertainty ~10^{-3}

Scattering of (longitudinally polarised) W Bosons



Violation of unitarity @ $\sqrt{s} \approx 1$ TeV



Counter terms

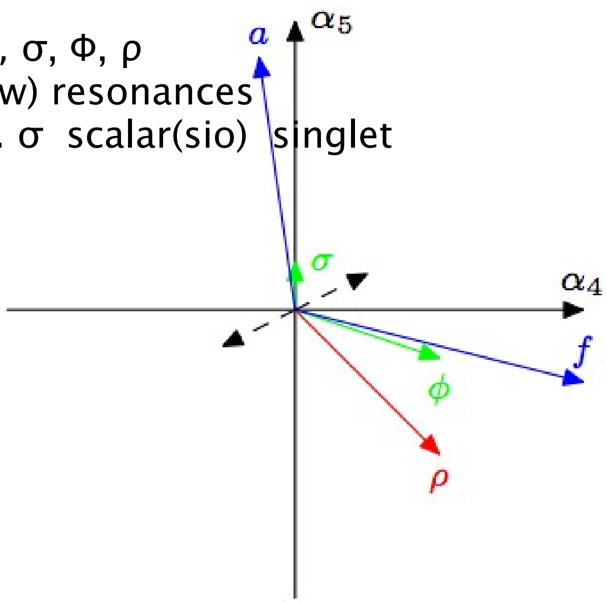
- **Before 4th of July 2012 one of the strongest motivations for a light Higgs**
- **Still “one of the most important physical observables in the EW sector”**
  → Search for deviations from the electroweak structure of the SM
  → Sensitive to new physics, i.e. Strongly interaction light Higgs

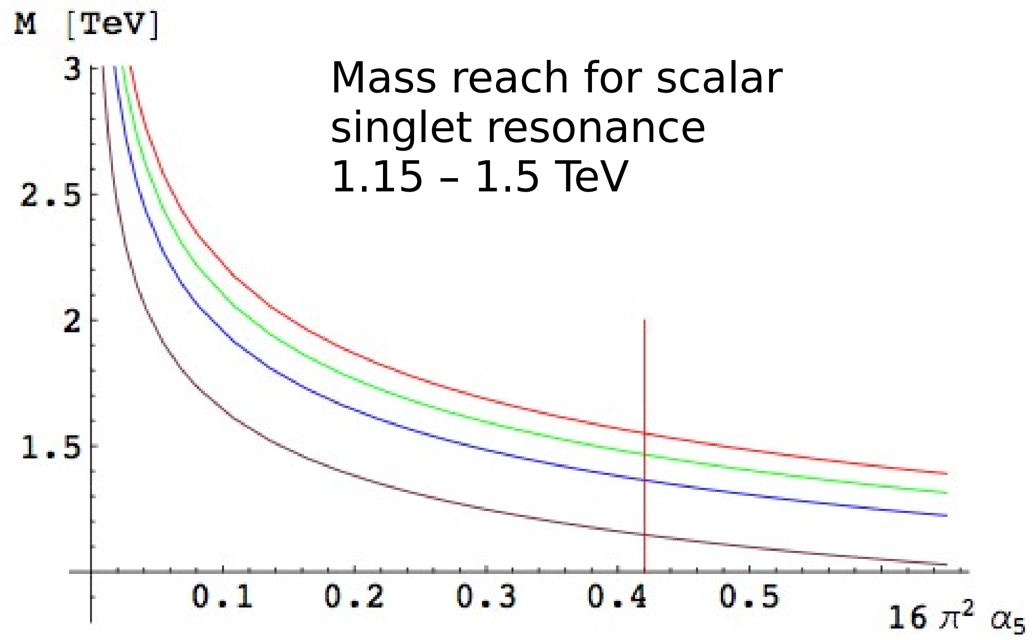
Analyses WW -> WW scattering

Existing analysis in terms of chiral Lagrangian
No Higgs but can be easily added

Deviation from
SM couplings expressed as ai

a, f, σ, Φ, ρ
(New) resonances
e.g. σ scalar(sio) singlet





Mass reach for scalar
singlet resonance
1.15 – 1.5 TeV

Up to ~ 5 TeV for other types of resonances

General remarks:
- Study most important to unveil electroweak structure
- Analysis at 1 TeV
- Results taken from hep-ph/0604048 (fast simulation)
- Analysis made no attempt to isolate WL bosons

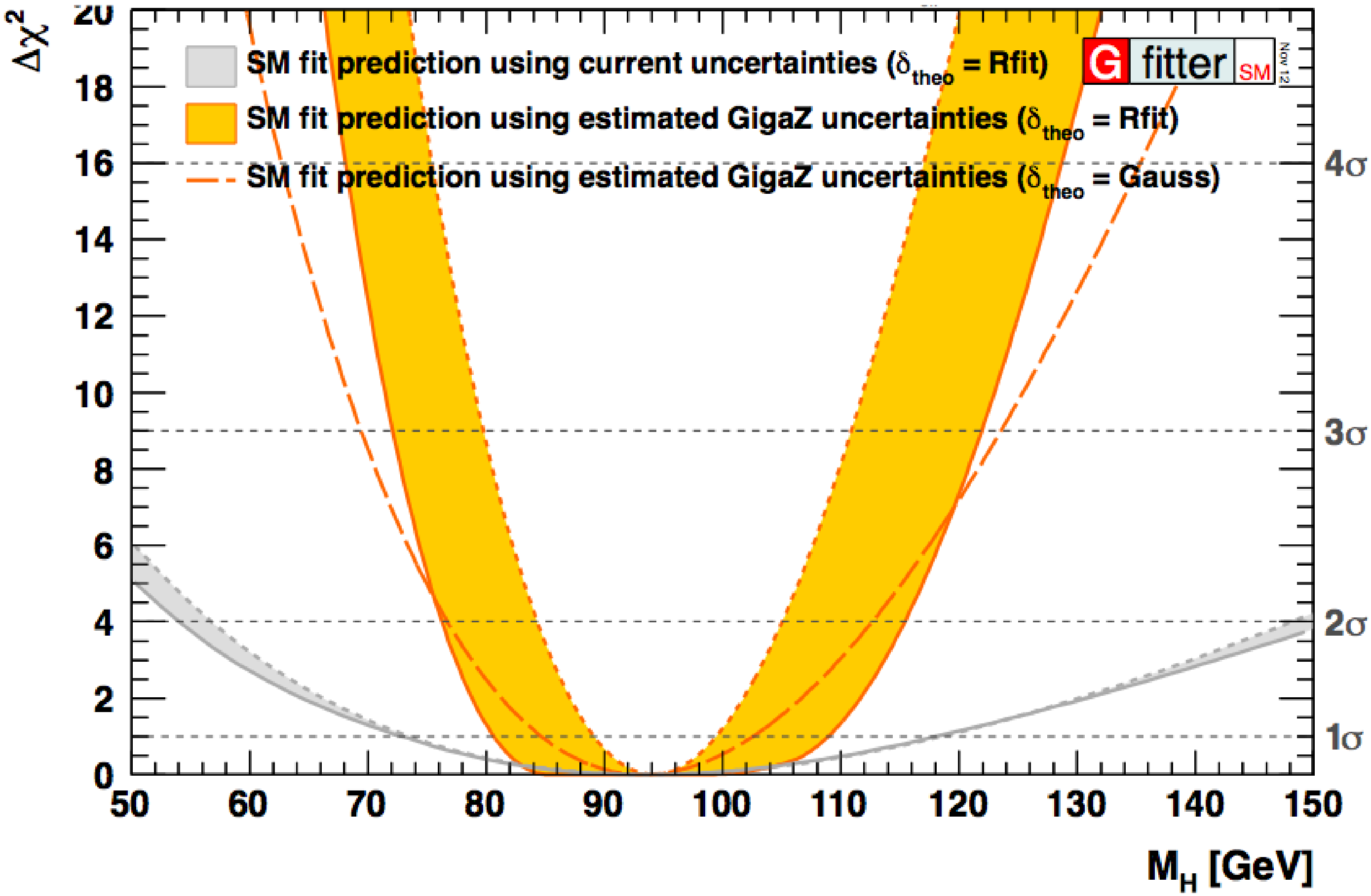
Giga Z

Running on Z-pole would allow for 'LEP/SLD' within a couple of days

Again polarised beams

Example I: W mass could be determined to about 6 MeV

Example II: Electroweak fit based on GigaZ



$$m_h = 92.3^{+16.6}_{-11.6}\,\mathrm{GeV}$$

=> Nearly 4σ deviation
From mass of scalar
Resonance discovered
At LHC

Summary and outlook

- The ILC is the right machine for precision physics in the range m_Z – 1 TeV

- 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
    Sensitivity to new physics up to 100 TeV
    Btw.: Composite top (or Higgs) would be new physics

- W physics is essential part of electroweak tests
  - New resonances or (not discussed here) extra dimensions
    Sensitivity up to 5 TeV
  - WW->WW studies need update with full simulation

- Both, top and W programme would benefit from running at 1 TeV

- Both programmes need consistent work on experimental but also on theoretical side !!!

- GigaZ would be ideally complement to precision physics at higher energies

Backup

Equations for cross section, A_{FB} and F_R

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

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

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

ILC in a staged approach

- If LHC discovers a light Higgs it is the “duty” of the ILC to determine all the relevant parameters

This would favor a machine at initially 250 GeV

(at initially lower cost)

Higgs Factory

- ILC @ 500 GeV could then be considered as a first upgrade
  (Crossing the) tt-threshold, ZHH final states

- ILC @ 1 TeV would be then the second upgrade phase
  ttH, unitarity bounds,
  new particles (?), e.g. colorless supersymmetric particles
  Sensitivity versus extra dimensions up to several TeV