*ALCPG LoopVerein, Fermilab, Oct 23, 2007*

# Tools for the ILC - What's Needed from Theorists?

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# The Power of Precision Physics

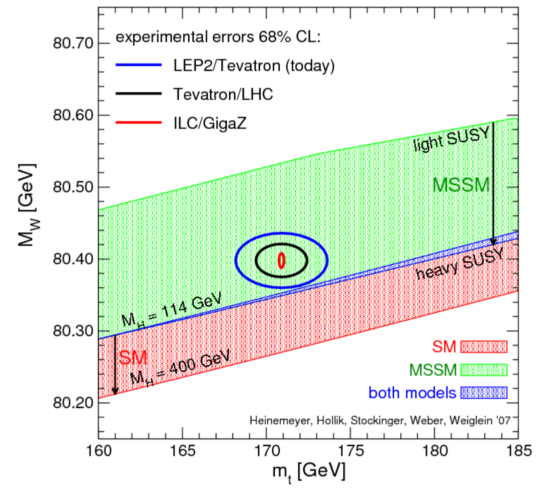
- The main strength of the ILC resides on its precision and model independence
  ⇒ will complement the LHC by providing essential information to interpret and exploit its discoveries.

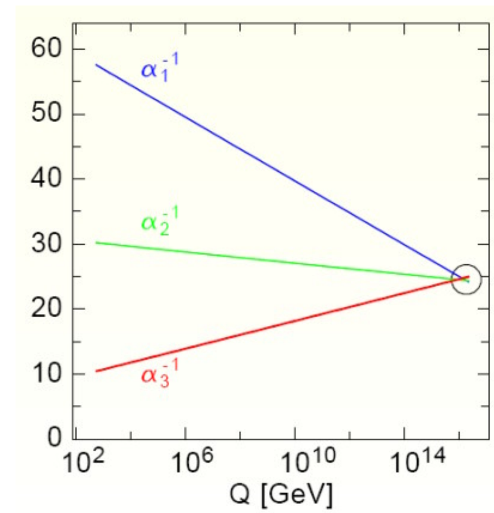
- Here I will focus on EW, Top/QCD and Higgs Physics.

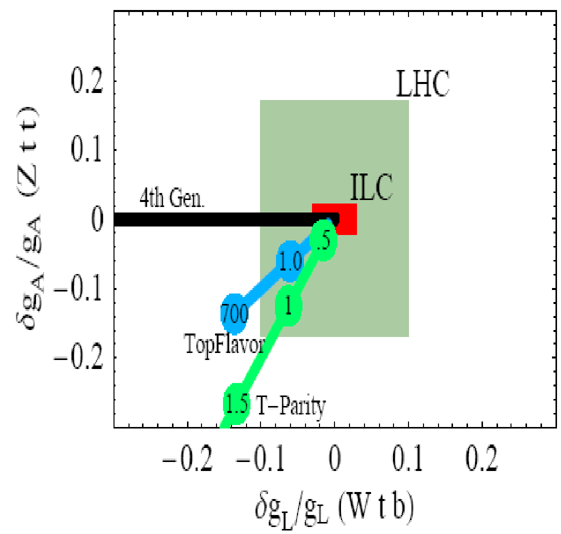
- Precise measurements of EW (e.g. $M_W$) and QCD (e.g. $\alpha_s$) parameters essential to provide precise theoretical calculations, constrain models of New Physics, extrapolate to GUT scale, …

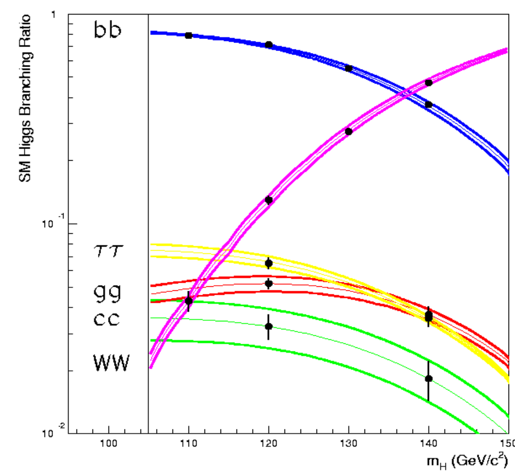
- Fully outlining the top quark and Higgs profiles will be critical to unravel the secrets of EWSB and/or flavor physics.

- The anticipated high experimental accuracy must be matched/exceeded by theoretical predictions. In many cases, this requires beyond state-of-art calculations/tools.



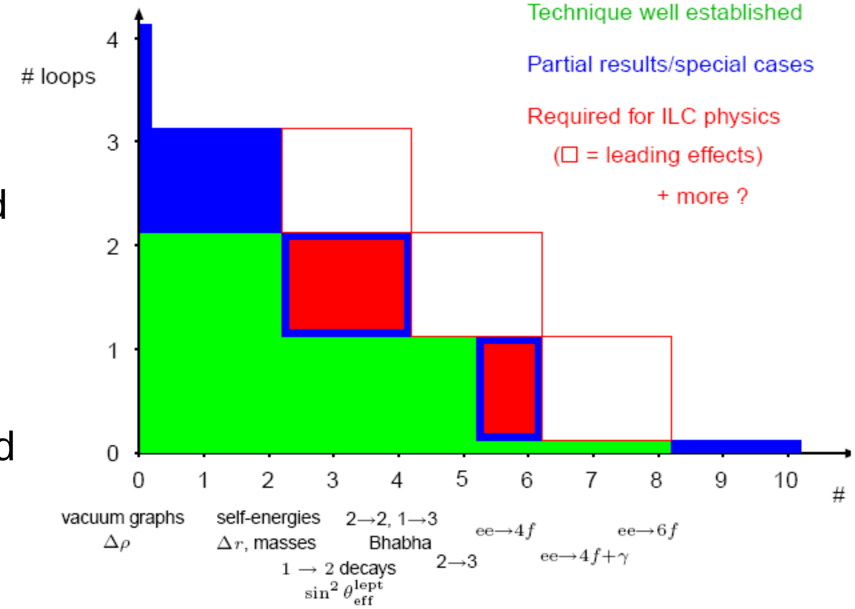



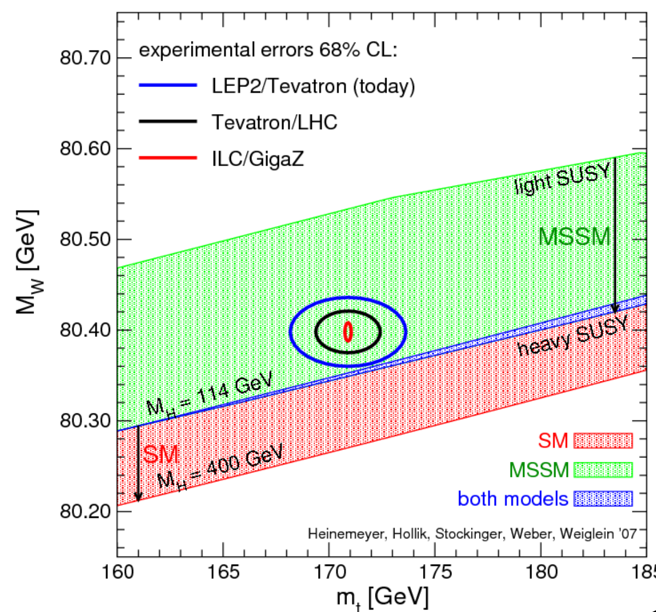
# What Kind of Tools?

Roughly three categories of tools:

1) Precise calculations of masses, mixing angles, couplings, partial decay rates, etc. Typically needed to a high order in perturbation theory.
2) Tools that allow to compute production rates and event kinematics for signal and background processes:
   - There is a tension between number of legs and the number of loops.
   - They become more and more useful the more differential the prediction is (e.g. allows to reweigh LO Monte Carlo predictions).
   - Most useful tools for experimentalists are MC event generators.
3) Tools that allow to combine measurements of different quantities in the context of a particular model to extract information on other model parameters.

In this talk I won't try to give an overview of existing tools, but rather use particular measurements at the ILC to illustrate the level of sophistication needed in these tools.



# Monte Carlo Event Generators

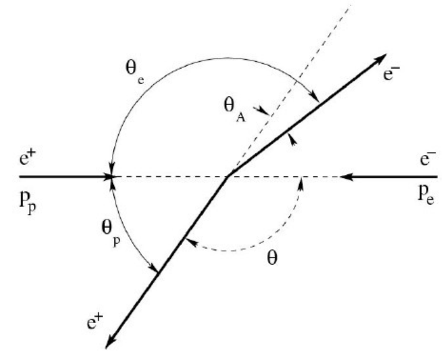
An experimentalist's wish list:

- Matrix element calculation:
  - Include radiative effects in the initial state
    - Beamstrahlung + beam energy spread (parameterized from data);
    - Bremsstrahlung (ideally ME calculation to NLO EW with soft-photon exponentiation).
  - Ability to select beam polarization.
  - Often
    - may be needed to $N^nLO$ EW and/or QCD ($n \geq 1$);
    - may be needed up to 10 external legs (e.g. ttH);
    - should avoid on-shell top/W/Z (ILC detectors have a a resolution $\leq \Gamma_{W,Z}$);
    - should include interfering backgrounds.
  - Full spin transmission in decay accounted for.
  - Explicit information on color flow in event and/or final state polarization.

- Parton shower
  - Interfaced to parton shower MC (PYTHIA, HERWIG,…)
  - Consistent matching between LO/NLO matrix element and PS (e.g. CKKW formalism)
- Hadronization model
  - Will it need to be retuned? Unclear how much of the tuning performed at LEP absorbed limitations in the ME/PS modeling…
- Particle decays
  - Interfaced to dedicated packages (EVTGEN, TAUOLA)

# Luminosity and Energy

- Precise measurements of luminosity and luminosity-weighted center-of-mass energy (<√s>) critical for many precision measurements.
- Luminosity spectrum:
  - Precision goal: ~0.1%
  - Interested in dL/d√s distribution and not only integral.
  - Via acollinearity in Bhabha events (~20-140 mrad)
  - Interested in extracting universal spectrum including ONLY beam energy spread and beamstrahlung components.

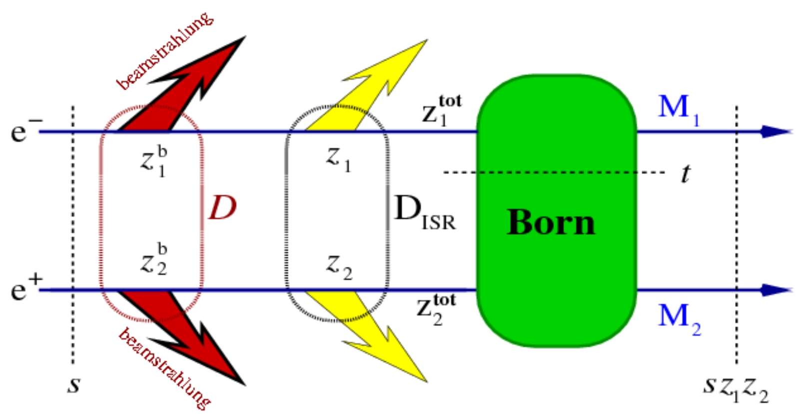



Frary-Miller

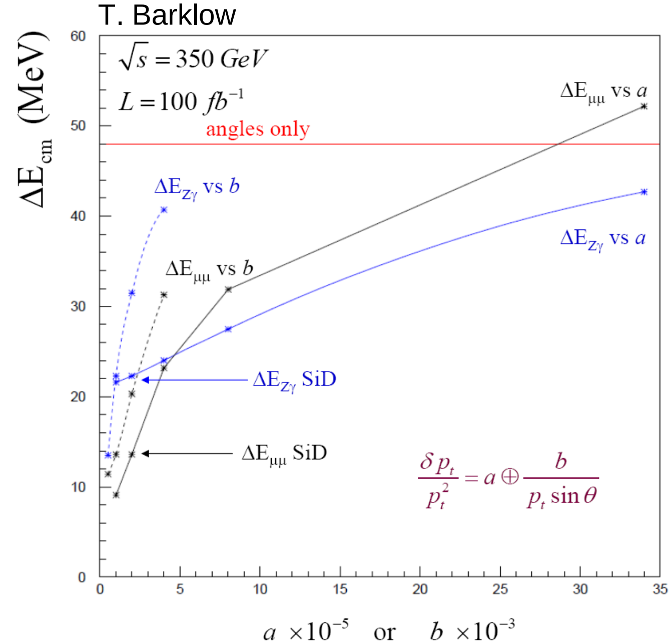
$$x = 1 - \frac{\theta_A}{2\sin\bar{\theta}}$$

K. Moenig

$$x = \sqrt{\cot\frac{\theta_p}{2}\cot\frac{\theta_e}{2}}$$




T. Barklow




- Luminosity-weighted center-of-mass energy:
  - Precision goal: ~$10^{-5}$ ($M_W$), ~$10^{-4}$ ($m_t$)
  - $e^+e^- \to Z\gamma \to \mu^+\mu^-\gamma$ (acollinearity method) or $e^+e^- \to \mu^+\mu^- (\gamma)$ (acollinearity + energy)
- Will need a very precise theoretical prediction: $e^+e^- \to f\bar{f}$ to $N^2LO$ EW in a MC event generator.

# The Role of Precision Observables

- The possibility to measure EW observables very precisely

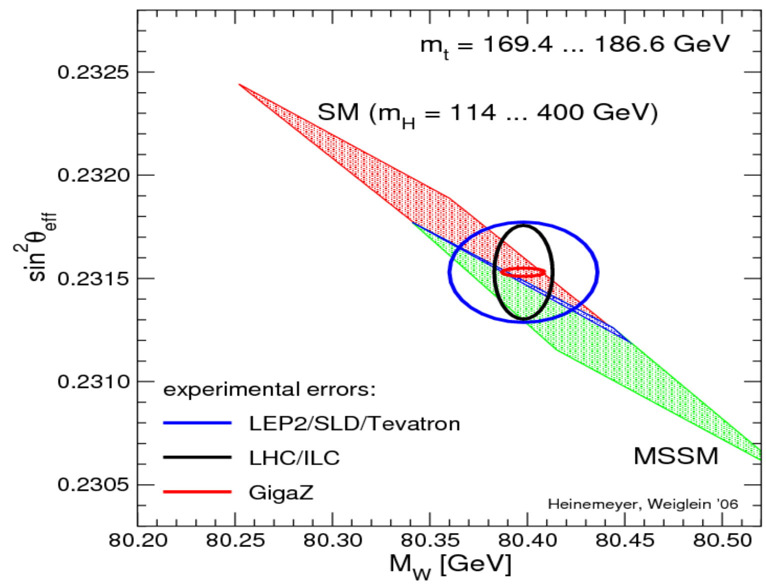
Experimental uncertainties

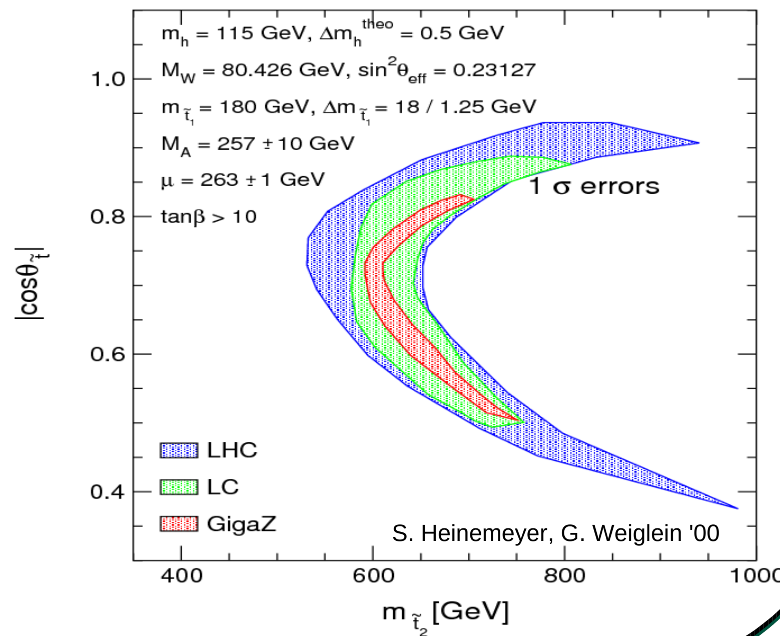
| | Today | Tevatron/LHC | ILC | Giga-Z |
|---|---|---|---|---|
| $\Delta\sin^2\theta_l^{eff}$ (x$10^5$) | 16 | 20 | (6) | 1.3 |
| $\Delta M_W$ [MeV] | 25 | 15-20 | (10) | 7 |
| $\Delta m_t$ [GeV] | 1.8 | 1.0-1.5 | 0.1 | |

opens new areas for high precision tests of EW theories:

- Within the SM: $\Delta m_H/m_H \sim 7\%$
- Within MSSM: in conjunction with other direct measurements, obtain information about new heavy states beyond direct reach.
- In general, place stringent constraints on extensions of the SM (e.g. S,T parameters)

- Very precise theoretical predictions required to fully exploit the anticipated experimental accuracy.



# The Role of Precision Observables

Three types of theoretical uncertainties:

- Primordial: associated with the extraction of the observable from the measured quantities.

  Example: $M_W$ from $\sigma_{WW}$ vs $\sqrt{s}$
  - Goal: $\Delta M_W^{th}\sim 1$ MeV $\Rightarrow (\Delta\sigma_{WW}/\sigma_{WW})^{th}\sim 0.05\%$ !!!
  - Full $O(\alpha)$ corrections to $e^+e^- \rightarrow 4f$ recently completed: ~2% effect compared to IBA at threshold!!
  - Remaining uncertainties:
    - NLL corrections: O(0.1%)
    - Higher order corrections to Coulomb singularity: O(0.2%)

  $\Rightarrow$ Still some work ahead…
- Parametric: due to dependence on other parameters, which are only known to limited precision (e.g. $M_W(m_t)$)

  $\Delta m_t = 1.5$ GeV $\Rightarrow \Delta M_W =$ 9 MeV, $\Delta\sin^2\theta_{eff} = 4.5\times10^{-5}$
  $= 0.1$ GeV $\Rightarrow \Delta M_W =$ 1 MeV, $\Delta\sin^2\theta_{eff} = 0.3\times10^{-5}$

  $\Rightarrow$ Will not likely be the limiting factor…
- Intrinsic: due to uncalculated higher order corrections.
  - $\Delta M_W^{intr}\sim 4$ MeV (SM), $\Delta M_W^{intr}\sim 5\text{-}11$ MeV (MSSM)
  - Full 2-loop corrections to $\sin^2\theta_l^{eff}$ recently completed (Awramik,Czakon, Freitas).
    - Estimated uncertainty (dominated by missing $O(\alpha^2\alpha_s)$) corrections): $\Delta\sin^2\theta_l^{eff}\sim 5\times10^{-5}$

  $\Rightarrow$ Still some work ahead…

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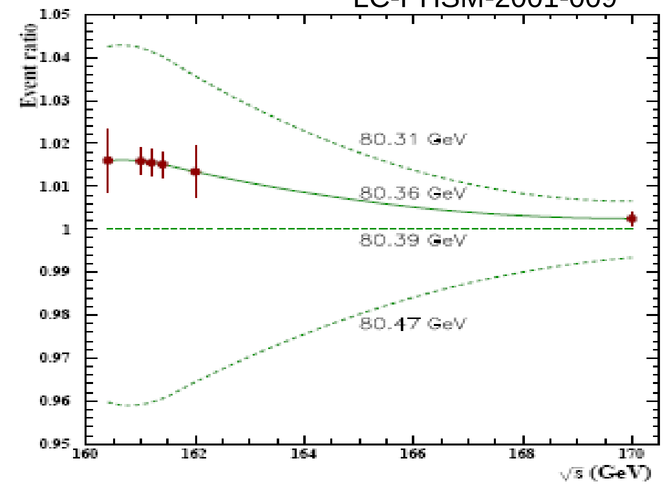


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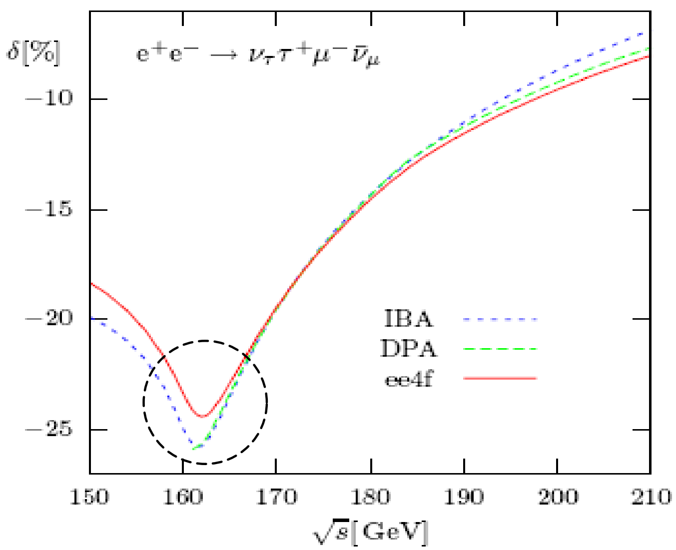


# Top Pair Production at Threshold

- Large $\Gamma_t$: cutoff for non-perturbative QCD effects
  - Top decays before top-flavored hadrons or tt-quarkonium bound states can form.
  - Use non-relativistic pQCD to compute $\sigma_{tt}$ near threshold.
- Remnants of toponium S-wave resonances induce a fast rise of $\sigma_{tt}$ near threshold.

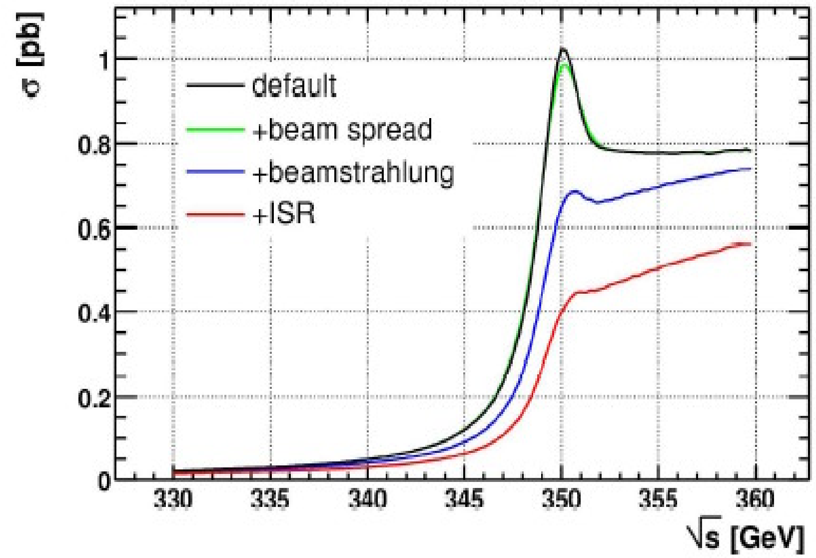
  Basic parameters: $\sigma_{tt}$ $(m_t, \alpha_s, \Gamma_t)$
- Lineshape significantly distorted due to:
  - Beamstrahlung: coherent radiation due to beam-beam interactions. Must be measured precisely (acollinearity in Bhabha events).
  - Bremsstrahlung (ISR): can be calculated accurately
  - Need precise determination of $dL/d\sqrt{s}$ and $\langle\sqrt{s}\rangle$.
- Convergence of calculation sensitive to $m_t$ definition used: pole mass is not IR-safe

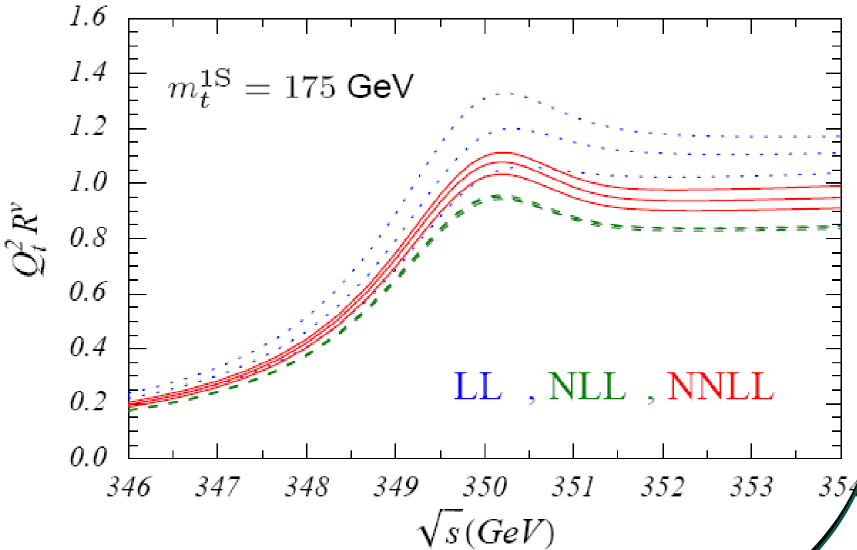
  $\Rightarrow \sigma_{tt}^{peak}$ not stable vs $\sqrt{s}$

  Solution is to use threshold masses: e.g. 1S mass (=1/2 the mass of the lowest tt bound state in the limit $\Gamma_t \rightarrow 0$).

  High accuracy in absolute normalization requires velocity resummation.

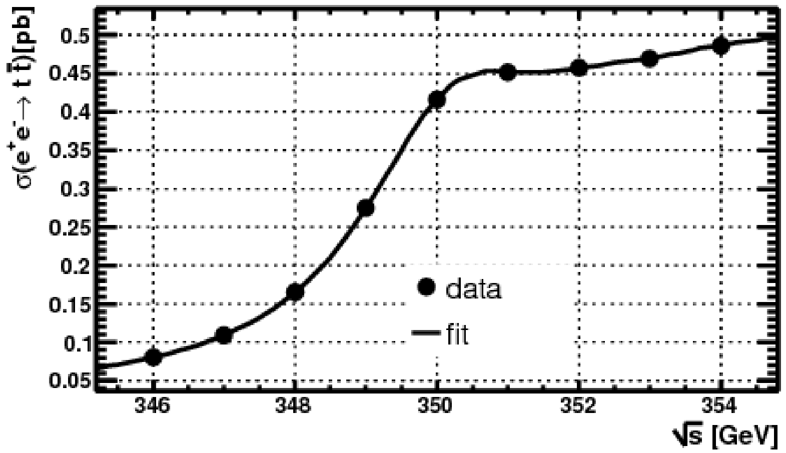
  State-of-art (NNLL): $(\Delta\sigma_{tt}/\sigma_{tt})_{QCD}$~6%



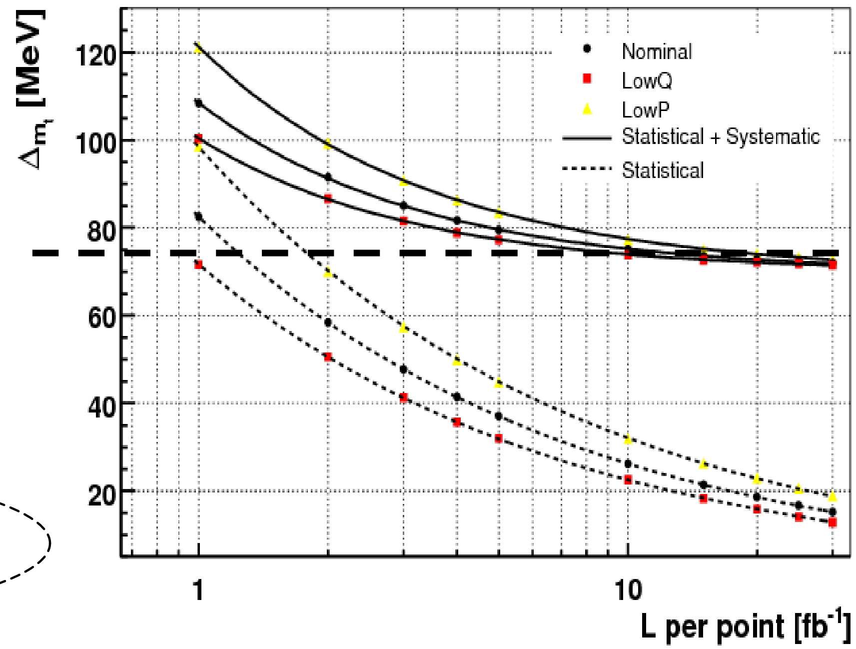
# $m_t$ from a Threshold Scan

- Center-of-mass energy scan: 9+1 points.
- Cross section measurement using lepton+jets and alljets final states.
- Simultaneous determination of $m_t$ and $\alpha_s$.
- A priori high precision expected (color singlet system, counting experiment,..).




- Estimated precision on $m_t^{1S}$:

| | |
|---|---|
| Statistical (10 $fb^{-1}$/point): 25 MeV | |
| Exp. Systematics | |
| - Beam energy | 35 MeV |
| - Luminosity spectrum | 50 MeV |
| Theory $\Delta\sigma_{tt}/\sigma_{tt}$~6% | 35 MeV |
| Total | 75 MeV |




- Estimated precision on $\overline{MS}$ $m_t$:
  - Perturbative expansion known to $O(\alpha_s^3)$
  - Also affected by uncertainty on $\alpha_s$

$$\Delta\overline{m}_t(\overline{m}_t) = \Delta m_t^{1S} \pm 70\,\mathrm{MeV}(pert) \pm 70\,\mathrm{MeV}\left(\frac{\Delta\alpha_s(M_Z)}{0.001}\right)$$

$\Rightarrow$ Room for further improvement

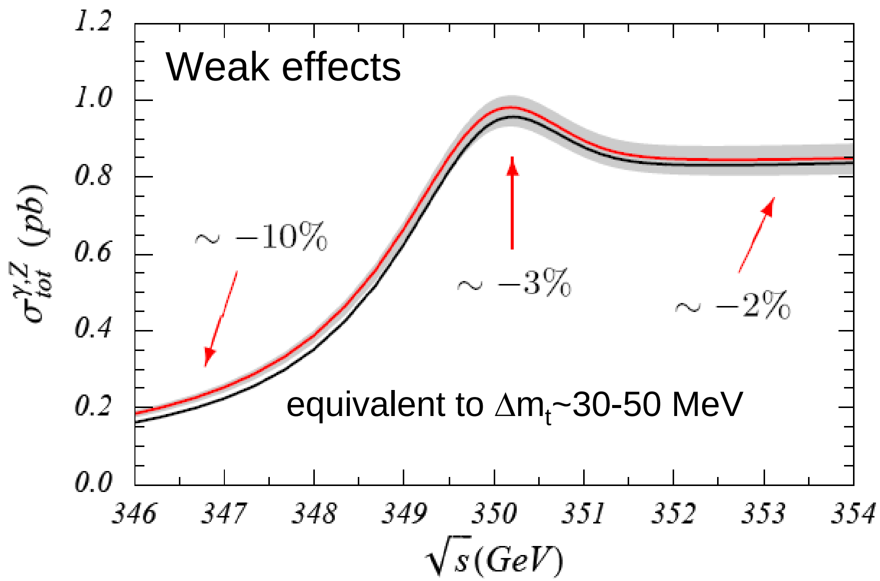
# Top Pair Production at Threshold

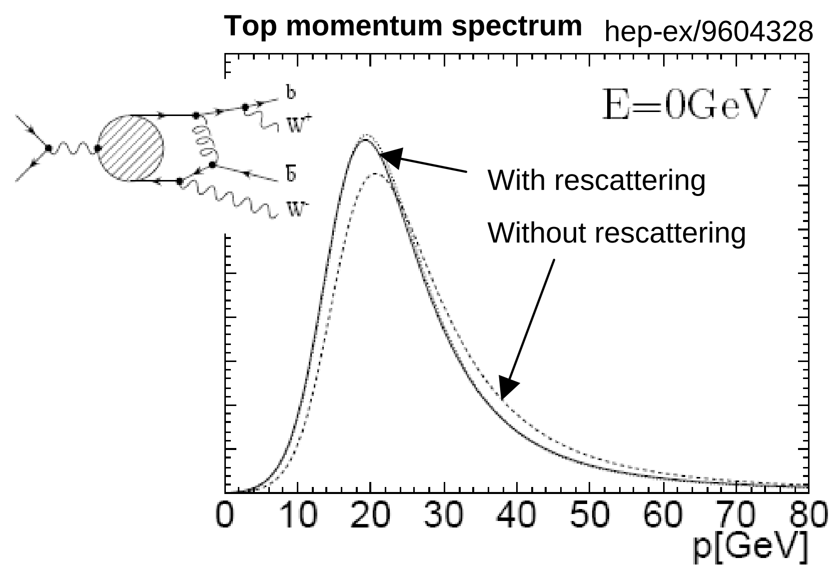
- Goal: 3% TOTAL precision $\Rightarrow$ important to take into account previously neglected %-level effects:

  Weak corrections ($\Gamma_t$ +non-resonant $W^+bW^-b$ background), QED corrections, interfering backgrounds $\Rightarrow$ a lot of work ahead!
- Another motivation for such precision is the possibility of a 1% measurement of $\alpha_s$.

- Finally, not only $\sigma_{tt}$ but also differential observables are important!
  - Exploit additional experimental information from $A_{FB}$, $d\sigma/dp_t$, $s_t$,…
    - Additional sensitivity to $m_t$, $\alpha_s$ and $\Gamma_t$
    - Reduce correlations

    $\Rightarrow$ Simultaneous determination of parameters possible when using all threshold observables.
  - Non-factorizable QCD corrections important in differential observables (NLO calculation available).
- Need MC event generator including current state-of-art, to perform detailed studies on differential observables (including the effect of experimental cuts/reconstruction).



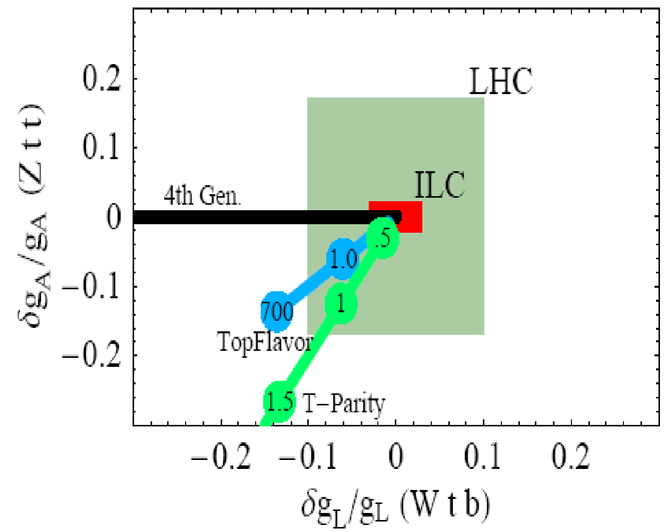
# Top Couplings to W/Z Bosons

- Precise (=per-cent level) and model-independent measurements of top quark interactions to W/Z could yield critical information on the mechanism for EWSB.
- Strengths of the ILC:
  - Large samples: ~200k events/year at $\sqrt{s}$=500 GeV
  - Beam polarization
  - High experimental accuracy
- Main observables:
  - Inclusive polarization observables: e.g. $A_{LR}$
  - Angular distributions of final state products
- Some of the available tools:
  - Total cross section to $N^2$LO QCD and NLO EW
  - Event generators:
    - $e^+e^- \to$6f LO (Lusifer, EETT6F)
    - $e^+e^- \to$tt to NLO EW (Topfit)
    - $e^+e^- \to$(tt)$\to$WbWb to NLO QCD (C. Macesanu, L. Orr)
  - Recently (hep-ph/060112): 2-loop QCD corrections to tt$\gamma$/Z vertex functions.

Combined

- Will need MC event generator for $e^+e^- \to$tt$\to$6f to at least NLO QCD and EW for precise measurement of top quark properties in the continuum (cross section, mass, couplings).

PRD 74, 054021 (2006)

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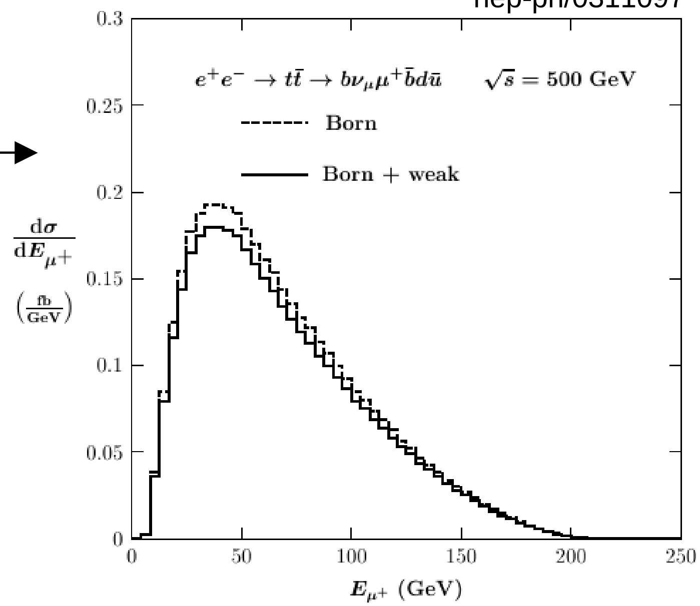
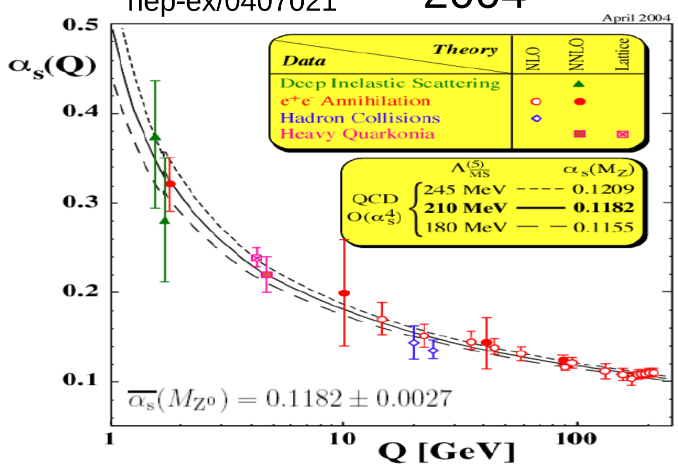
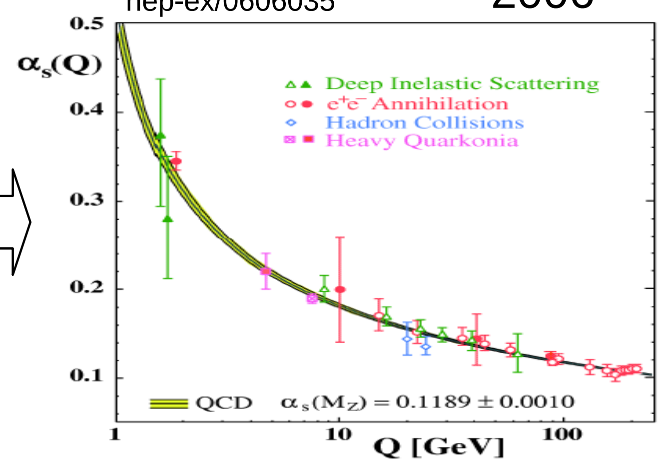


# Measurement of $\alpha_s$

hep-ex/0407021 2004




hep-ex/0606035 2006



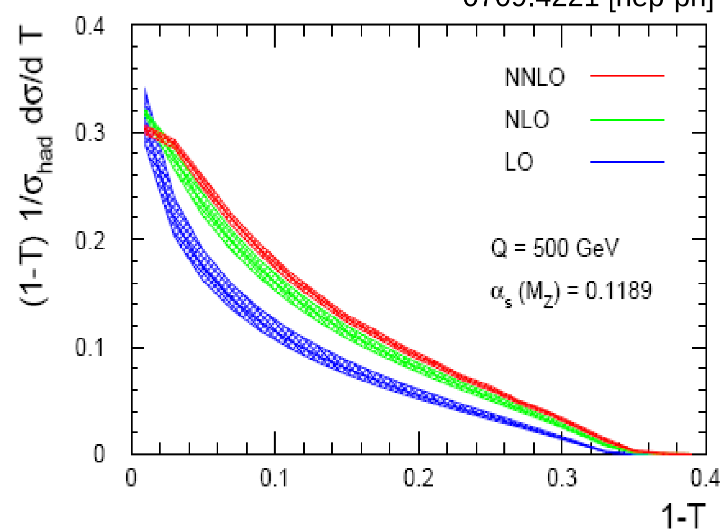

~1% precision!

Event shape observables

- Sensitive to the 3-jet nature of the particle flow: e.g. thrust, jet masses, jet rates, etc
- Procedure: form a differential distribution, correct for detector/hadronization effects and fit a pQCD prediction to the data, allowing $\alpha_s(M_Z)$ to vary. Till recently, state-of-art was NLO.
- Uncertainty dominated by theory:

  $\alpha_s(M_Z) = 0.121 \pm 0.001(\text{exp}) \pm 0.005(\text{theory})$ [S. Bethke 06]
- A 1% measurement is experimentally feasible but need to go beyond NLO.
- After a number of years, the NNLO calculation is finally available and implemented in EERAD3 program!
- Still need to evaluate whether this is sufficient for a 1% measurement.

0709.4221 [hep-ph]



# Measurement of $\alpha_s$

Ratio Method

- Make use of the inclusive ratios $\Gamma_z^{had}/\Gamma_z^{lept}$, $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$, which depend on $\alpha_s$ via radiative corrections. Current state of the art is NNLO.
- Pros: inclusive observables suffer from small experimental systematics
  (e.g. $\Delta\alpha_s$(exp syst)~0.001@ LEP/CLEO)
  Cons: require large statistics
  (e.g. $\Delta\alpha_s$(stat)~0.0025 @ LEP from 16M Z events using $\Gamma_z^{had}/\Gamma_z^{lept}$)

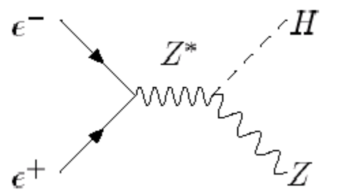
- GigaZ: ~$10^9$ Z events
  $\Gamma_z^{had}/\Gamma_z^{lept}$ : $\Delta\alpha_s$(stat)~0.0004, $\Delta\alpha_s$(exp syst)~0.0008
  Current estimates of theoretical uncertainties:
  - Conservative: last calculated term ($O(\alpha_s^3)$) ; $\Delta\alpha_s$(theo)~0.002
  - "Standard" (optimistic): estimated $O(\alpha_s^4)$ term; $\Delta\alpha_s$(theo)~0.0006
  - Scale variation: $m_Z/3 - 3\, m_Z$ ; $\Delta\alpha_s$(theo)~+0.002 –0.00016

  $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$ : $\Delta\alpha_s$(stat+exp syst)~0.001 already at LEP/CLEO!!!!
  Considerable debate about theoretical uncertainties: $\Delta\alpha_s$(theo)~0.001$\leftrightarrow$0.005
  If the theoretical uncertainties improved/clarified, this could offer a further 1%-level measurement.

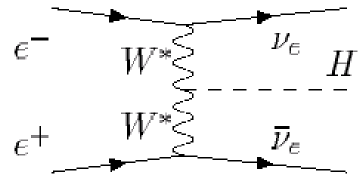
- Ongoing $N^3LO$ QCD calculations…

# Higgs Couplings

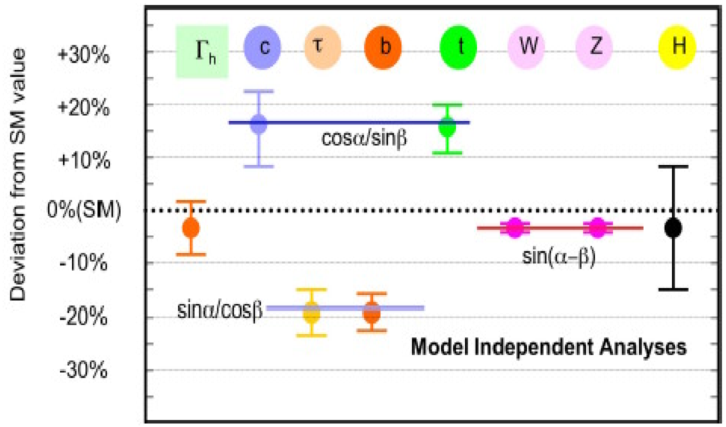
- Precise and model-independent measurements of Higgs couplings to gauge bosons and fermions crucial to determine the nature of the Higgs sector (SM, MSSM,…)
- Higgs production mechanims:



Higgsstrahlung
(dominant at √s=350 GeV)



WW-fusion
(dominant at √s=1 TeV)




- Measurement of Higgs couplings based on measurement of Higgs cross sections and BRs. Anticipated experimental accuracy ~few %.
- Need precise theoretical predictions for total cross sections and partial widths.
    - Basically already in place. Main limitation appears to be parametric theoretical uncertainties ($\alpha_s$, $m_b$, $m_c$) [See talk by Heather Logan]
    - Such calculations should be implemented in MC event generators so that experimental acceptance corrections can be precisely estimated as well.
- Also important is the development of global fitting tools (e.g. HFITTER), implementing state-of-art theoretical predictions, for optimal combination of observables and treatment of correlations.

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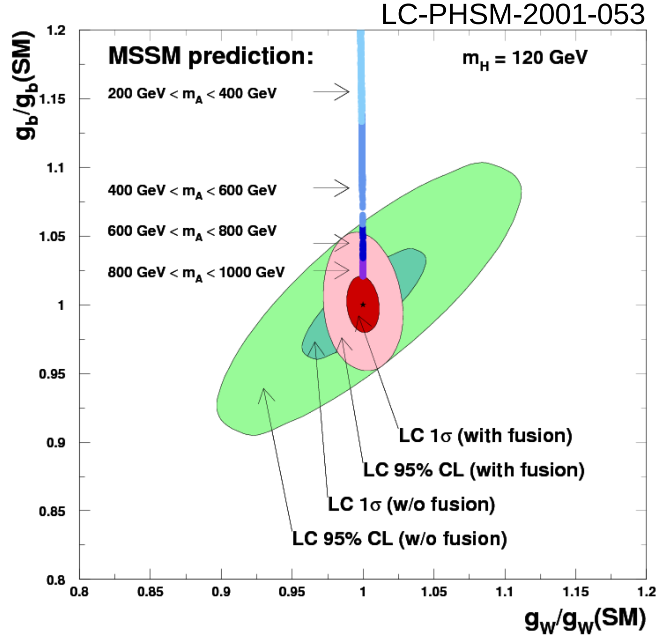
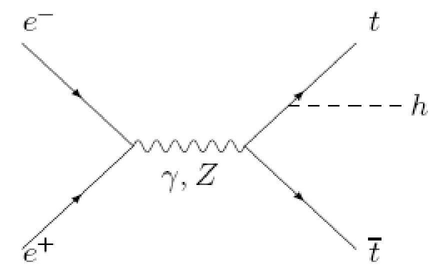


# Top-Higgs Yukawa Coupling




- The top-Higgs Yukawa coupling is the largest coupling of the Higgs boson to fermions. Precise measurement important since the top quark is the only “natural” fermion from the EWSB standpoint.
- Can be determined via cross section measurement: $\sigma_{tth} \propto g^2_{tth}$

  $\sigma_{tth}$(Born) ~ 0.2(2.5) fb at $\sqrt{s}$=500(800) GeV for $m_h$=120 GeV

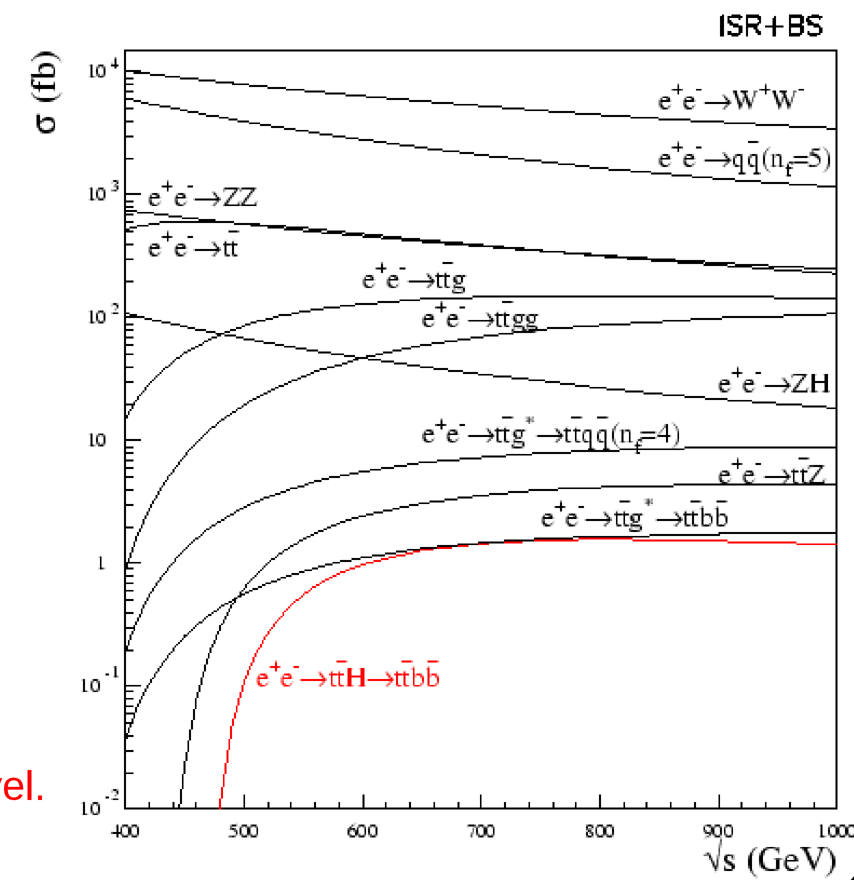
  (Includes only effects of BS and ISR via structure function approach)
- High luminosity required ($\geq$1 $ab^{-1}$) for a precise measurement:

  $\Rightarrow$ ~40(500) events/year at $\sqrt{s}$=500(800) GeV
- Spectacular signatures, e.g.
  - tth(h$\rightarrow$bb) $\rightarrow$ l+2j+4b, 4j+4b
  - tth(h$\rightarrow$WW) $\rightarrow$ l+6j+2b, $l^\pm l^\pm$+4j+2b
- Previous studies:

  $\sqrt{s}$=800 GeV, L=1 $ab^{-1}$, $\Delta g_{ttH}/g_{tth}$ ~ 6(10)% for $m_H$=120(190) GeV

  Use of b-tagging and sophisticated multivariate analyses crucial.

  Dominant background is tt+jets. Assumes it can be controlled in the tail of the distribution to the 5% level.



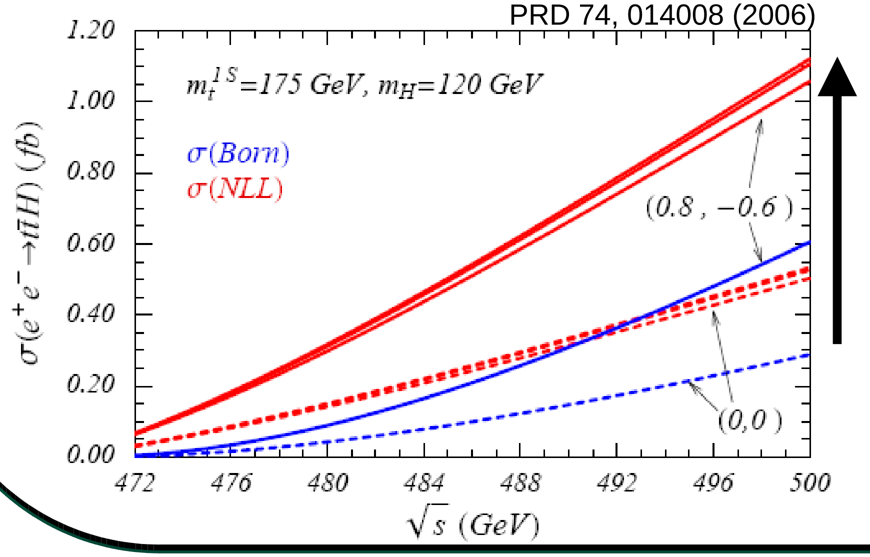
# Top-Higgs Yukawa Coupling

Issues:

- Signal cross section computed for 2 →3 process. Available:
  NLO QCD (large effects ~1.5 near tth threshold): uncertainty ~10% (too large)
  NLO EW (partial cancellation between photonic and weak corrections)
- Must improve significantly degree of sophistication of background prediction, e.g.:
  - 2→n (n≥6) LO ME calculation properly interfaced to parton shower. NON-TRIVIAL!!!
  - $e^+e^- \rightarrow$ (tt) → WbWbjj, WbWbQQ to NLO QCD, from where to extract HF k-factors
  - $e^+e^- \rightarrow$ ttZ to NLO EW
  - …

  ⇒ Not very different from the issues that basically killed ttH as a discovery channel at LHC…
- First top-Higgs Yukawa coupling will be at √s=500 GeV:
  - $\sigma_{ttH}$ down by x10, $\sigma_{tt}$ up by 70% wrt √s=800 GeV
  - tt dynamics is non-relativistic ⇒ must use vNRQCD as in the tt threshold.

PRD 74, 014008 (2006)




Considering $\sigma_{tth}$ enhancement due to:

- Large QCD resummation effect:
  ~x2.4 for $m_h$=120 GeV
  (theoretical uncertainty still not quantified)
- Use of beam polarization:
  ~x2.1 for $(P(e^-),P(e^+)) = (-0.8,+0.6)$

Taking this into consideration, anticipate:

$(\Delta g_{ttH}/g_{tth})_{stat}$~10% for $m_H$=120 GeV, L=1 $ab^{-1}$

hep-ph/0512246

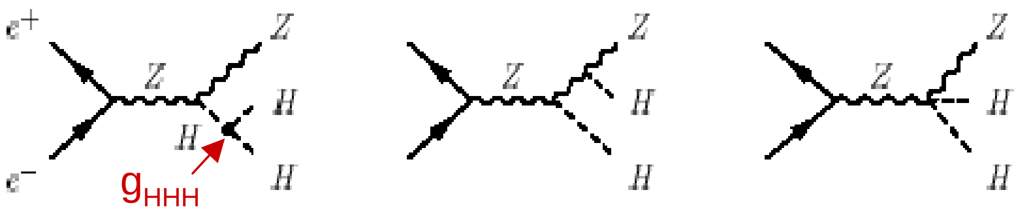
# Higgs Self-Coupling

- Unambiguous experimental verification of the Higgs mechanism as responsible for EWSB requires reconstruction of the Higgs self-energy potential.

$$V = \lambda\left(|\varphi|^2 - \tfrac{1}{2}v^2\right)^2 \Rightarrow V = \lambda v^2 H^2 + \lambda v H^3 + \tfrac{1}{4}\lambda H^4$$

$m_H^2/2$ $g_{HHH}$ $g_{HHHH}$

- Within the SM, $m_H$, $g_{HHH}$ and $g_{HHHH}$, are related to $\lambda$, at tree level.
  - Determination of $m_H$ provides indirect information on $\lambda$.
  - The cross-section for double (triple) Higgs production is sensitive to $g_{HHH}$ ($g_{HHHH}$).




$$\left(\frac{\Delta g_{HHH}}{g_{HHH}}\right) \sim 1.75 \times \left(\frac{\Delta\sigma_{ZHH}}{\sigma_{ZHH}}\right)$$

Dilution factor

- Triple Higgs coupling determined from ZHH events at $\sqrt{s}$=500 GeV with L=2000 $fb^{-1}$.

  $\sigma_{ZHH}$~0.2 fb for $m_h$=120 GeV
- Signature: qqbbbb, $\nu\nu$bbbb, $l^+l^-$bbbb.
- Challenging analysis:
  - Tiny signal and huge 6f backgrounds (S/B~$10^{-3}$).
  - Multivariate analysis mandatory
  - Dominant background is tt+jets.

  ⇒ Same background modeling issues as for ttH!!!
- Estimated statistical precision: 15-20% for $m_h$=120 GeV.

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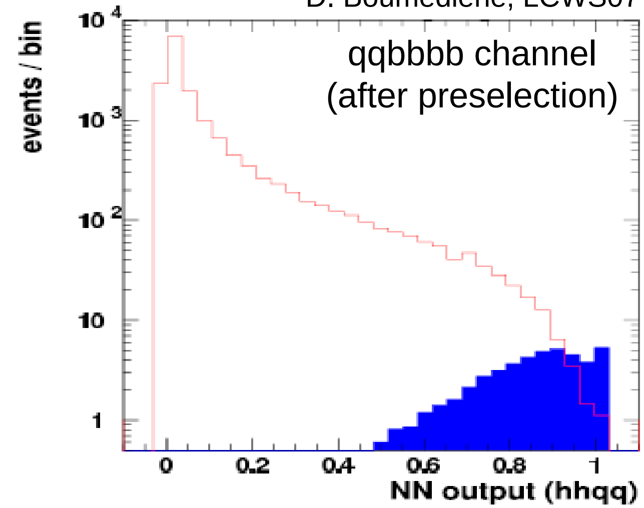

# Conclusions

- Precise theoretical predictions are critical to exploit the physics potential of the ILC.
- Significant progress has been made over the last few years, but still much remains to be done.
- In particular, MC event generators implementing higher order calculations should become “routine tools” at the ILC, and on this front we are still in a very early stage.
- The precise modeling of multi-jet final states via the interface of HO matrix element calculations and parton showers, especially when heavy quarks and/or unstable particles are involved, requires further work. This is particularly relevant for several high-profile measurements involving the top quark either as signal or background.
- These and many others are very challenging, and in many cases multi-year, projects but of a critical nature and which should receive strong support from the community and funding agencies.