QCD and Precision Calculations at the ILC

Doreen Wackeroth

University at Buffalo
The State University of New York

Vancouver Linear Collider Workshop/GDE meeting

July 21, 2006

Resources

- A. Juste *et al.*, *Report of the 2005 Snowmass top/QCD working group*, hep-ph/0601112.
- S. Heinemeyer *et al.*, *Toward high precision Higgs-boson measurements at the international linear e^+e^- collider*, hep-ph/0511332.
- G. Weiglein *et al.* [LHC/LC Study Group], *Physics interplay of the LHC and the ILC*, hep-ph/0410364.
- W.Hollik *et al.*, *Electroweak Physics*, hep-ph/0501246.
- T. Abe *et al.* [American Linear Collider Working Group], *Linear collider physics resource book for Snowmass 2001*, SLAC-R-570.
- LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/.
- Talks at LoopFest meetings, http://quark.phy.bnl.gov/lcwg

The power of precision physics

Precision measurements of electroweak and strong observables at LEP/SLC and the Tevatron enabled us to

- probe the SM of electroweak and strong interactions as a fully-fledged Quantum Field Theory,
- test the consistency of the SM by comparing direct with indirect measurements of model parameters, e.g., $m_t, M_W, sin^2\theta_{eff}.$,
- constrain the SM Higgs boson mass,
- search for indirect signals of new physics in form of small deviations from SM predictions, and
- exclude or constrain new physics models.

The power of precision physics

With the anticipated discoveries at the LHC and the increase in experimental precision at the ILC we will be able to

- identify the nature of the non-standard physics discovered at the LHC by precisely measuring mass, couplings, spin,
- check the consistency of the underlying theoretical framework by comparing direct and indirect measurements of model parameters, e.g., $M_H, M_{SUSY}, \ldots$
- constrain model parameters not directly accessible, such as masses of heavy particles, and
- search for small deviations from predictions due to the virtual presence of new particles and constrain new physics.

with great opportunities come great challenges

Theoretical prerequisites

- Predictions for signal and background processes in the SM and beyond including all relevant higher-order corrections,
- Proper interface between resummed and fixed order calculations.
- Estimate of residual theoretical uncertainties.
- Total cross sections and kinematic distributions with application of realistic cuts and inclusion of dominant initial-state related effects (beamstrahlung).
- Implementation in event generators, or if not feasible or practical, a recommendation for a procedure to properly take into account higher order effects, e.g., K-factors.
- All available calculations for one process in one code: Electroweak, QCD, and new physics contributions (in the spirit of MC@NLO and MCFM).

Theoretical challenges

To meet the precision at the ILC, we are faced with an increased complexity of calculations:

- $2 \to 2, 3$ processes at 2-loop and leading 3-loop.
  Complete electroweak 2-loop calculation; exclusive distributions at NNLO QCD.
- $2 \to 3, 4, 6 \ldots$ processes via e.g., $ZH, t\bar{t}, \ldots$ production at complete 1-loop. Leading contributions resummed (QED, threshold, EW Sudakov).
  Complete electroweak 1-loop calculation to $2 \to 6$.
- Higher complexity in models beyond the SM, e.g., loop calculations in the MSSM.
- Alternative initial states: $\gamma\gamma, \gamma e, e^- e^-$

More challenges . . .

These calculations pose technical/computational challenges, e.g. when going from $\mathcal{O}(100)$ to $\mathcal{O}$(several 10000) diagrams (more legs, more loops),
and theoretical/conceptual problems:

- Gauge-invariant treatment (or consistent perturbative expansion) of unstable particles.
- Realistic treatment of electroweak Sudakov logarithms ($\alpha/\pi \log^2(s/M_V^2)$) (higher orders, resummation).
- Renormalization in the MSSM (restoring supersymmetry).
- Consistent framework to go beyond tree-level, if not the MSSM.

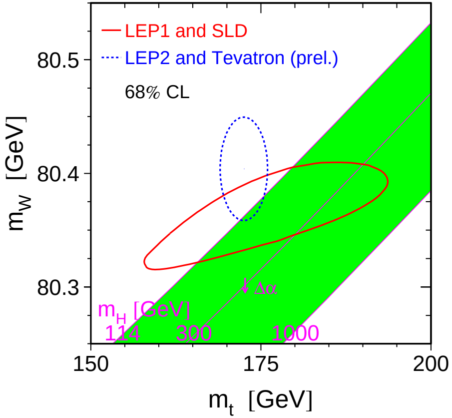
What can we learn from an incredible precise knowledge of SM parameters ?

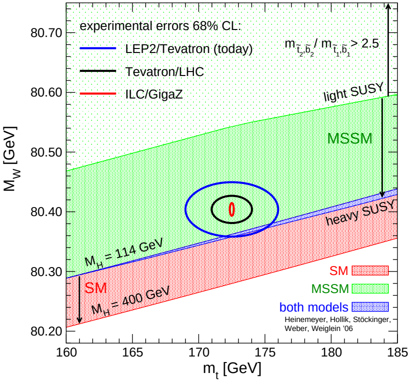
"Global fit pitfalls":
not including all relevant radiative corrections or only selecting subsets of precision observables may give completely different results than performing a complete global fit analysis.

see also talks by S.Heinemeyer at this meeting !

Electroweak precision observables: m_t, M_W, $sin^2\theta_{eff}$

Constraint on M_H and sensitivity to new physics:





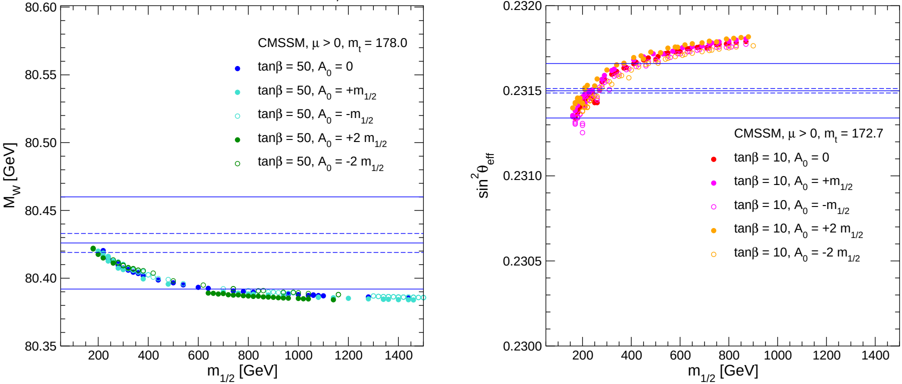
CERN-PH-EP/2005-051 (update: LEPEWWG webpage) S.Heinemeyer *et al.*, hep-ph/0604147

From global fit to all EW precision data:

$$M_H = 89^{+42}_{-30} \text{ GeV at 68 \% C.L.; } M_H < 207 \text{ GeV at 95 \% C.L.}$$

Global fit to electroweak precision data within the CMSSM

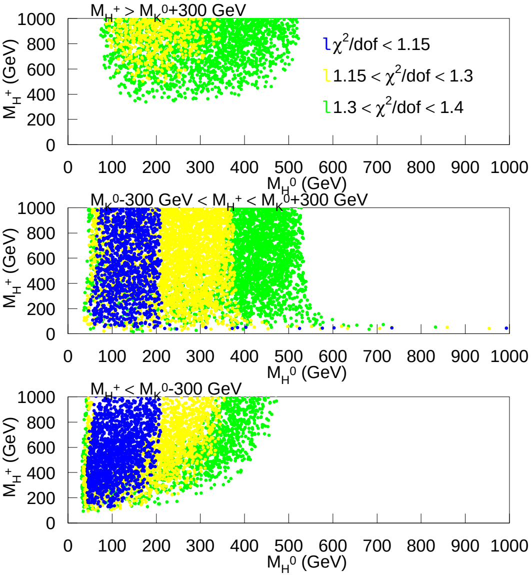
M_W vs. $M_{1/2}$ in different CMSSM scenarios



Ellis, Heinemeyer, Olive, Weiglein, hep-ph/0604180

Electroweak precision data including $g-2$ and $b \to s\gamma$ prefer $M_{1/2}$ between 300 and 600 GeV.

Global fit to electroweak precision observables in models with an additional Higgs triplet



Allowed parameter space in M_{H^+}, M_{H^0}.

Chen, Dawson, Kuprovnickas, hep-ph/0604102

Fit without Γ_Z:
M_{H^0} up to 1 TeV allowed.

All data, including rad. corr.:
EW precision data prefer
100 GeV $< M_{H^0} <$ 200 GeV.

Anticipated experimental precision of M_W, m_t, $sin^2\theta_{eff}$, M_H

	now	LHC	LC	GigaZ
$\delta \sin\theta_{eff} (\times 10^5)$	17	14–20	(6)	1.3
δM_W [MeV]	30	15	10	7
δm_t [GeV]	2.3	1.0	0.2	0.13
δM_H [MeV]$*$	–	100	50	50

$*$ assuming $M_H = 115$ GeV

from U.Baur *et al.*, hep-ph/0111314

For GigaZ precision we will need full control over electroweak 2-loop and leading 3-loop corrections to predictions for M_W and $\sin^2\theta_{eff}$ in SMand beyond.

Theoretical uncertainties due to missing higher order corrections

Theory uncertainties in predictions (*theory*) for $sin^2\theta_{eff}$ and M_W and in predictions for the observables (*experiment*) from which $\sin^2\theta_{eff}$ and M_W (LEPII(Tevatron)) are extracted.

	theory	*experiment*	GigaZ/MegaW $*$
$\delta\sin\theta_{eff}(\times 10^5)$	5	–	1.7
δM_W [MeV]	4	5(10)	3
$\delta M_H/M_H$ [%] (from all data)	47	–	8

from U.Baur *et al.*, hep-ph/0111314

$*$ Assuming that full two-loop electroweak corrections are known and $\delta\alpha(M_Z) = 7\times 10^{-5}$.

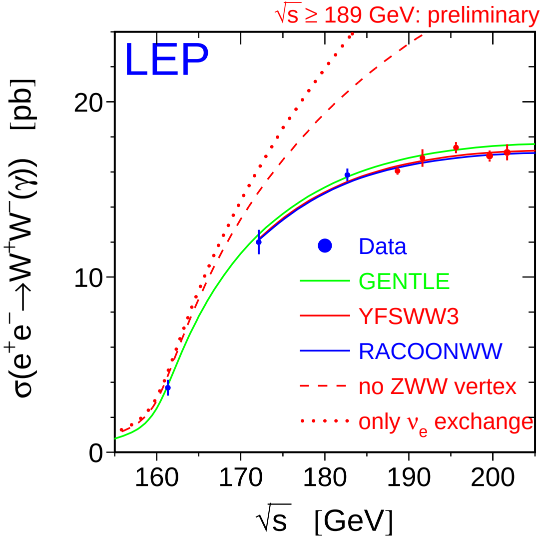
How do we achieve this incredible precision measurements of SM parameters ?

"W pair production: the history of a higher-order calculation": Experimental capabilities drive the need for more and more sophisticated calculations.

By meeting the theoretical challenges we are probing "deeper and deeper" in barely explored regions of the theoretical framework.

W-pair production at e^+e^- colliders at LEPII

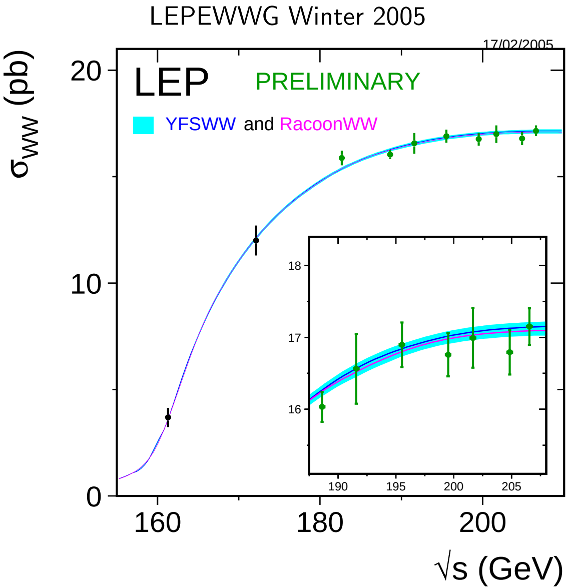
LEPEWWG Summer 2002



Predictions in improved Born approximation (GENTLE) consistently 2% higher than data.

σ_{WW} measurement is sensitive to pure non-universal electroweak corrections.

W-pair production at e^+e^- colliders at LEPII



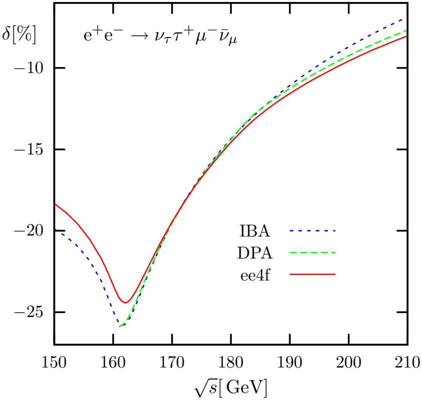
Theory includes complete $\mathcal{O}(\alpha)$ corrections to $e^+e^- \to WW \to 4f$ in Double Pole Approximation (DPA)

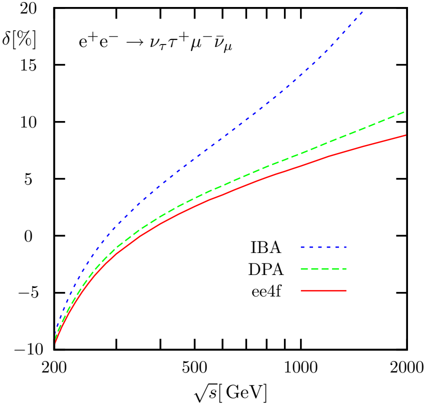
Theory uncertainty:
$\Delta M_W = 5$ MeV

DPA not valid at *WW* threshold !

Full electroweak $\mathcal{O}(\alpha)$ corrections to $e^+e^- \to 4f$

The impact of electroweak radiative corrections on σ_{WW} (in %) at different levels of sophistication:

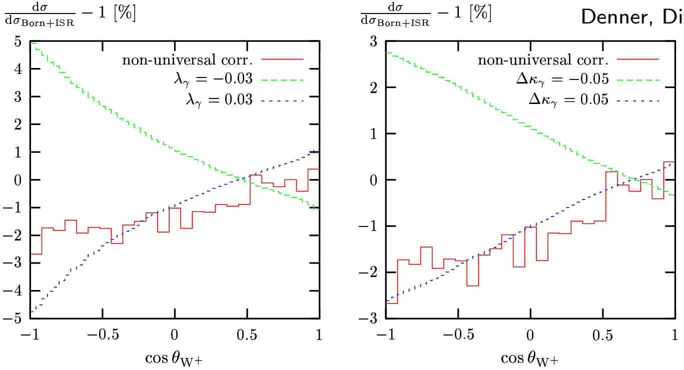




Denner, Dittmaier,Roth,Wieders, hep-ph/0505042

Anomalous triple gauge boson couplings at LEPII

A window to the dynamics of electroweak symmetry breaking: new strong interaction will affect EW gauge boson self couplings.



Denner, Dittmaier, Roth, Wackeroth

hep-ph/0110402

Non-universal corrections can fake anomalous TGC !

LEPII bound: $\lambda_\gamma = -0.028 \pm 0.02$ LEPTGCWG (2005)
Theory uncertainty (DPA): $\Delta\lambda_\gamma = 0.005$ at LEPII energies
Brunelier *et al.*, hep-ph/0201304

Anticipated experimental uncertainty at ILC: $\Delta\lambda_\gamma = 0.0005$ (!)

High energies and kinematic thresholds: how to properly take into account enhanced radiative corrections ?

A "different look" at the perturbation expansion reveals how to deal with "slow" particles and soft and collinear radiation of heavy particles.

see talks by T.Becher and A.Hoang at this meeting !

Enhanced electroweak corrections at high energies

- At energies $\sqrt{s} \gg M_{W,Z}(M_{SUSY})$, EW corrections are enhanced by

  $$\alpha^L \log^N(\frac{s}{M_V^2}) \;\; ; \;\; 1 \leq N \leq 2L \; (L = 1(1-loop), \ldots)$$

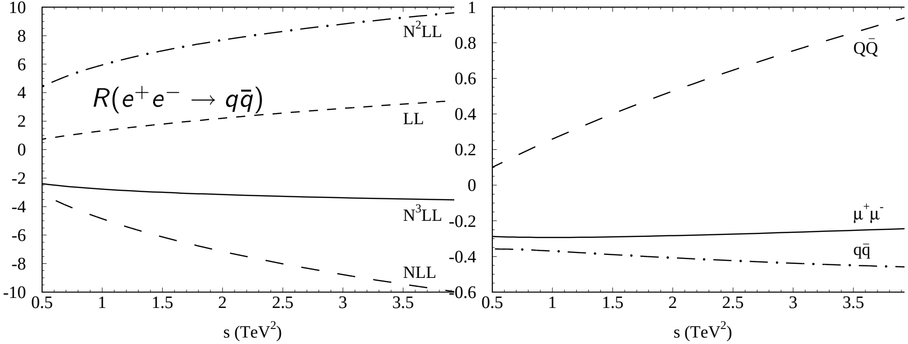
  Origin: Remnants of UV singularities after renormalization + soft/collinear ISR and FSR emission of virtual and real W/Z bosons.
  In contrast to QED,QCD, Bloch-Nordsiek theorem is violated, i.e. also in inclusive observable these corrections do not completely cancel.
  W/Z mass is physical cut-off: real W/Z is usually not included since it leads to a different initial/final state.

- EW logarithmic corrections to 4-fermion processes are known up to 2-loop N^3LL order and are available in form of compact analytical formula.

  For a review see, e.g., J.Kühn's talk at Radcor 2005: `http://www-conf.kek.jp/radcor05`

Leading electroweak corrections to $e^+e^- \to 2f$

Logarithmic electroweak corrections to $R = \sigma/\sigma_{Born}$ (in %) up to two-loop N^3LL order:



1-loop: 4% at 500 GeV for $q\bar{q}$, $Q\bar{Q}$

Jantzen,Kühn,Penin,Smirnov, hep-ph/0509157

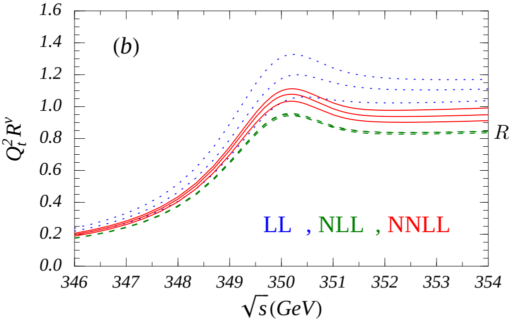
$t\bar{t}$ threshold at the ILC

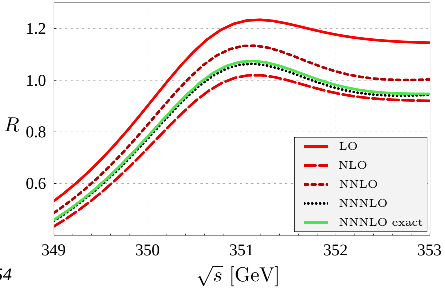
m_t: $\delta m_t(1S) < 100$ MeV can be reached

$\sigma_{t\bar{t}}$: QCD at NNLO and NNLL (not yet complete), first steps toward NNNLO, EW at NNLL.

QCD normalization of $\sigma_{t\bar{t}}$ needs to be known at the few percent level (now: 6%). How about distributions ?

NRQCD effects to the total $t\bar{t}$ cross section





Hoang, hep-ph/0604185

Beneke,Kiyo,Schuller, hep-ph/0501289

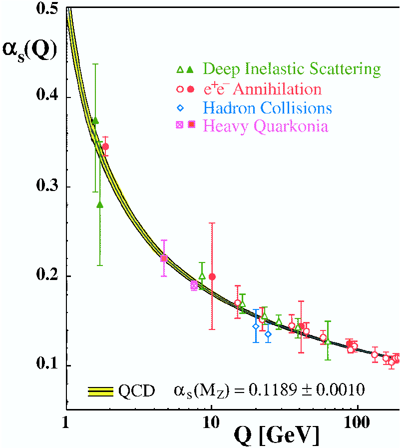
Frontier in multi-loops:

What can we learn from a incredible precise α_s measurement and how hard do theorist have to work for it ?

Running of α_s

- ILC: evolution of α_s over wide range of energies, threshold effects due to new physics ?
- GigaZ: $\delta\alpha_s(M_Z) = 0.0005 - 0.0008$ hep-ph/0106315

S.Bethke: "NNLO calculations are eagerly awaited by experimentalists."



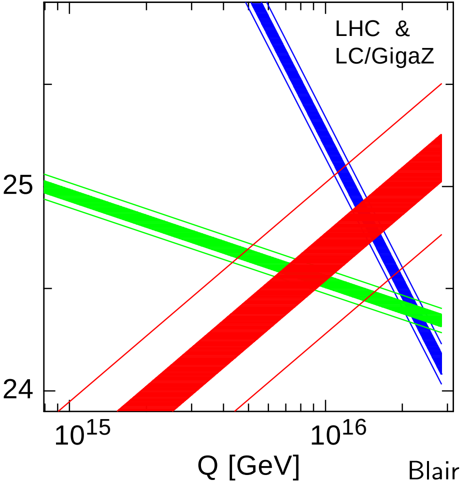
Bethke, hep-ex/0606035

$\alpha_s = 0.1189 \pm 0.0010$

Gauge-coupling unification in mSUGRA

Study of gauge and Yukawa coupling unification may provide hints about SUSY breaking mechanisms, if initial gauge couplings and masses are precisely measured.

Present uncertainties versus anticipated GigaZ improvements:



Blair *et al.*, hep-ph/0512084

Toward $e^+e^- \to 3$ jets event shapes at NNLO QCD and R at $O(\alpha_s^4)$

Estimated theory uncertainty in α_s from missing $\mathcal{O}(\alpha_s^4)$ corrections: $\delta\alpha_s(M_Z) = 0.0006$

- $e^+e^- \to 3$ jets event shapes:
  First numerical results for QED-like contributions available and leading color contributions is work in progress.
  (see, e.g., LoopFest V talk by T.Gehrmann, hep-ph/0607042)

- σ_{had} at $O(\alpha_s^4)$:
  a number of intermediate results available, final result may take a few more years.
  Many challenges: 28 master integrals, extremely CPU intensive ("10 years on single 1.5 GHz and 15 month on 32 CPU cluster").
  Baikov,Chetyrkin,Kühn, hep-ph/0602126

Frontier in multi-legs:
Tree-level is hard enough. Universal corrections should not be a problem, but

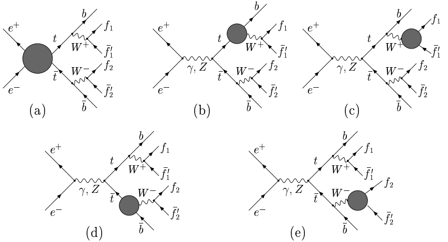
Do we really need non-universal radiative corrections to $2 \longrightarrow 6$ *processes?*

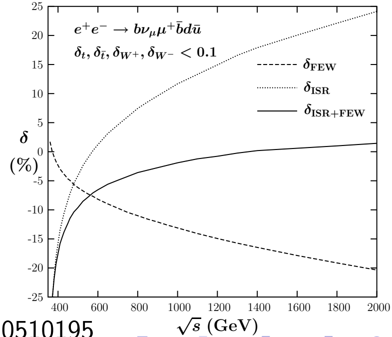
see also talk by F.Gounaris at this meeting !

$t\bar{t}$ production in the continuum at the ILC

- On-shell $t\bar{t}$ production: QCD at NLO and first steps toward NNLO, EW at NLO, QCD+EW at NLO.
- NLO QCD to $e^+e^- \to t\bar{t} \to WWbb$ in DPA Macesanu, hep-ph/0112142 .

Impact of factorizable EW $O(\alpha)$ corrections on the total cross section in the pole scheme to the full $2 \to 6$ process:





Kołodziej, Staroń,Lorca,Riemann, hep-ph/0510195

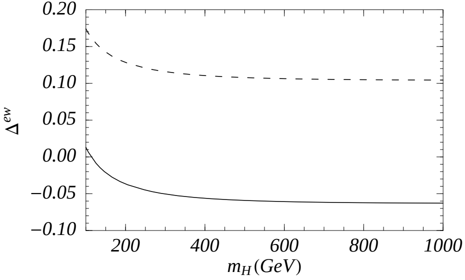
If there is a Higgs, its nature and the nature of the electroweak symmetry breaking mechanism will be finally revealed to us.

Do we really know how well we will be able to reconstruct the Higgs potential and measure couplings to the top ?

Top Yukawa coupling from $e^+e^- \to t\bar{t}h$

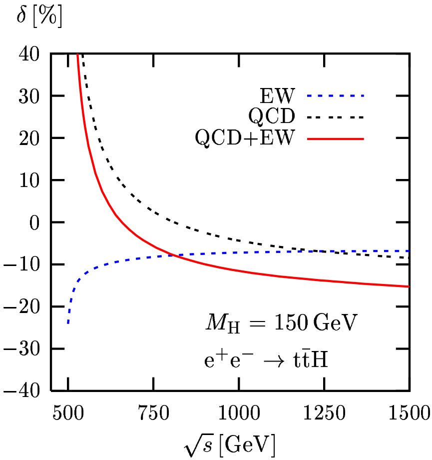
Impact of

NLL EW corr. on $\sigma_{t\bar{t}h}$ at threshold



Hoang, hep-ph/0604185

NL0 EW+QCD corr. on σ_{tth} in %

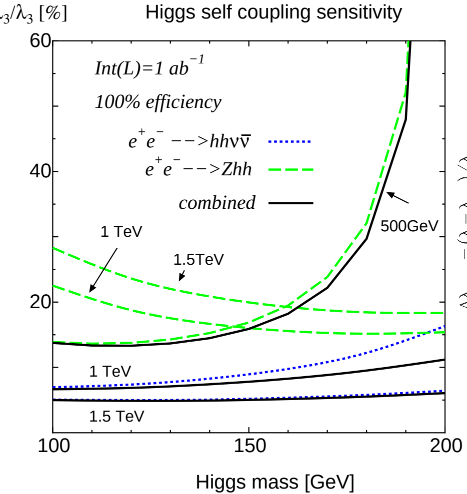


Denner,Dittmaier,Roth,Weber hep-ph/0406335

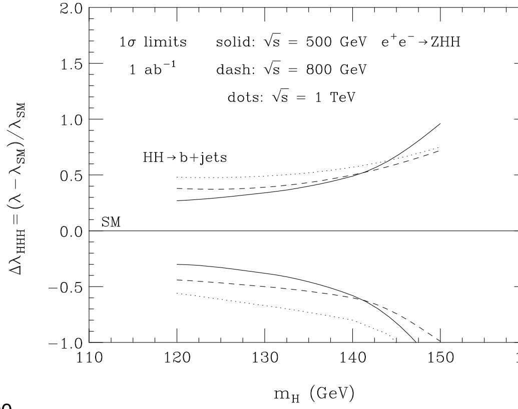
$\delta y_t/y_t = 10\%$ at 500 GeV, 1000 fb^{-1}. Juste, hep-ph/0512246

Higgs self-couplings from $e^+e^- \to ZHH, \nu\nu HH$

Measuring the Higgs potential will tell us about the nature of the Higgs and EWSB.



Heinemeyer *et al.*, hep-ph/0511332



Baur,Plehn,Rainwater, hep-ph/0304015

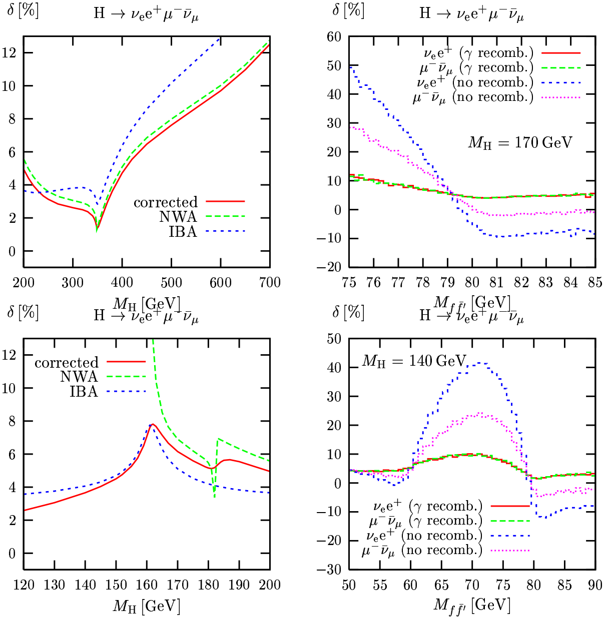
An finally, some examples for new developments crucial for incredible precise measurements of Higgs and SUSY particle masses.

Are additional improvements needed for percent(permille) level mass measurements ?

EW one-loop corrections to $H \to WW \to 4f$

NWA ok above

WW threshold



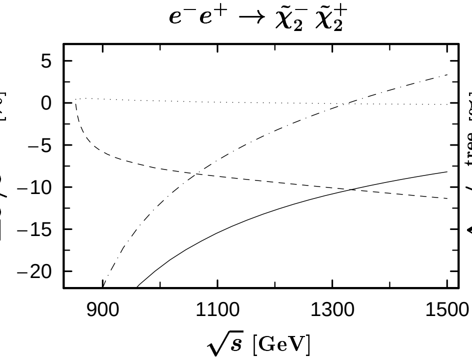
Size of EW corr.:

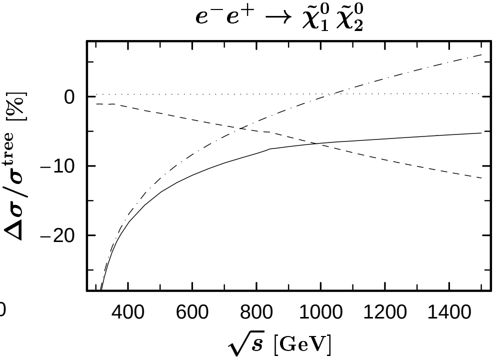
about 5-10 %

Bredenstein, Denner, Dittmaier, Weber, hep-ph/0604011

Neutralino and Chargino pair production

Impact of electroweak $\mathcal{O}(\alpha)$ corrections on the total cross section:





Öller,Eberl,Majerotto, hep-ph/0504109

(full, dashed, dotted, dash-dotted) line corresponds to (complete, weak, non-universal QED, universal QED)

Conclusions

- No matter what will happen at the LHC, the ILC will enable us to fully exploit the power of precision physics for testing the underlying model at the quantum level and to search for new physics.
- After discovery of new physics at the LHC, at the ILC we can look forward to the exciting process of identifying its nature and probing physics scenarios at the GUT/Planck scale.

Provided the necessary theoretical tools are in place and realistic predictions with unprecedented high precision for "bread and butter" physics and within the new model(s) are available.

In this process we will have gained deeper insight into the theoretical framework within the SM and beyond.

see, e.g., talk by C.Berger at this meeting !

with great challenges come great opportunities