ILC Workshop, Snowmass, Colorado 27 August 2005

Summary of the Top/QCD Working Group

Convenors: Aurelio Juste, Yuichiro Kiyo, Frank Petriello, Thomas Teubner

- Introduction
- Top quark Threshold studies
- News about $t\bar{t}H$
- Anomalous top couplings
- QCD: Jets & α_s at the ILC
- Conclusions

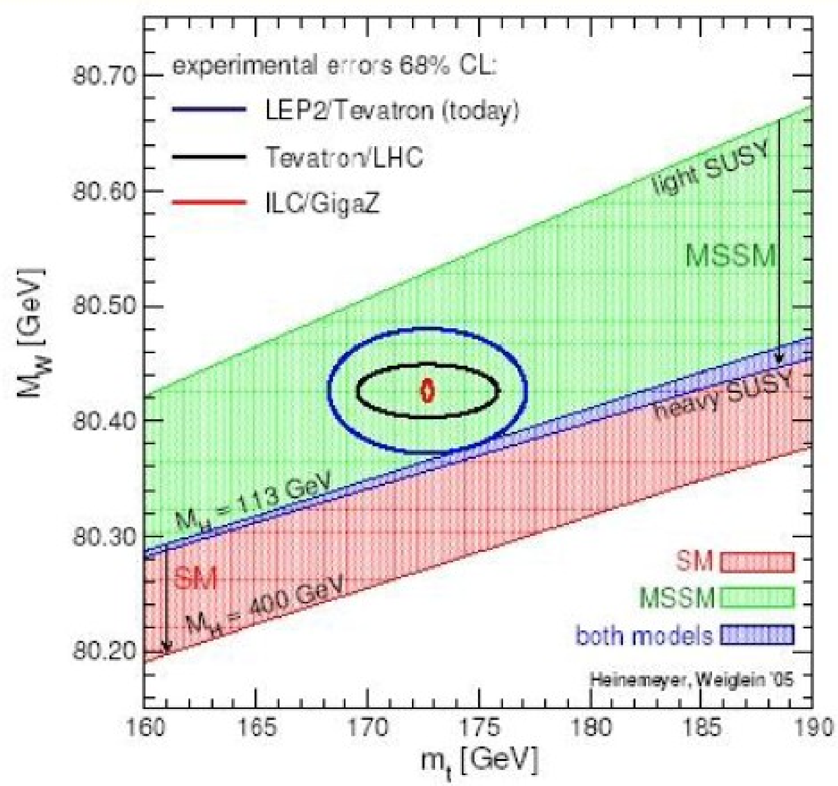
Motivation: Why is the top quark so interesting?

- Top quark sector of the SM is NOT established yet!
  - Possible anomalous couplings in $tbW, t\bar{t}Z/\gamma$
  - Does the top mass come from a single Higgs? $(y_t \Leftrightarrow m_t)$
- Top quark plays a key role in EWSB
  - Many models distinguish top from light quarks
  - Precise top mass determination is clue to New Physics

MSSM parameters varied

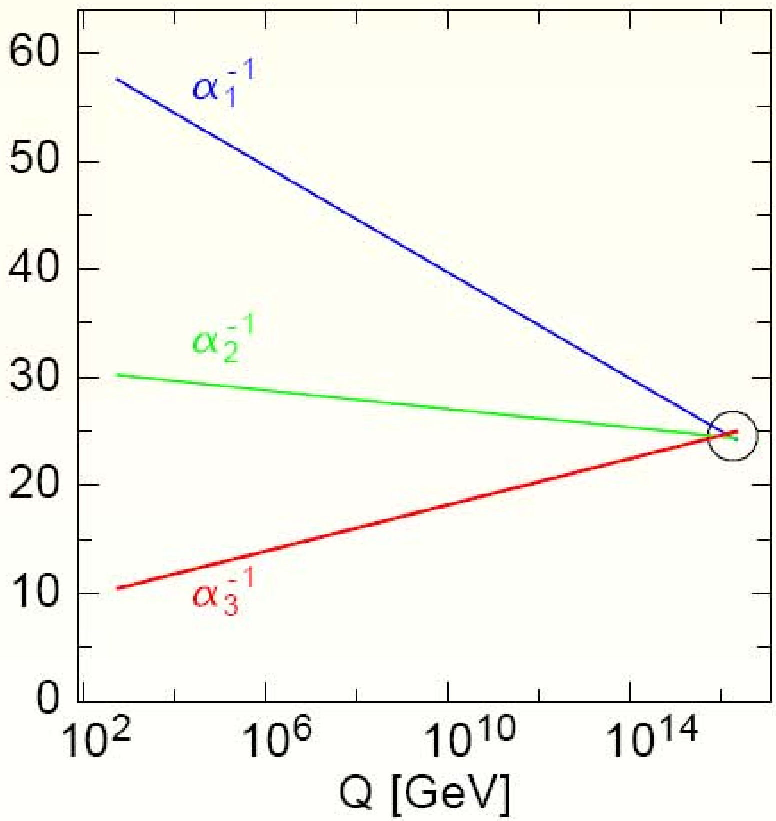
SM Higgs varied

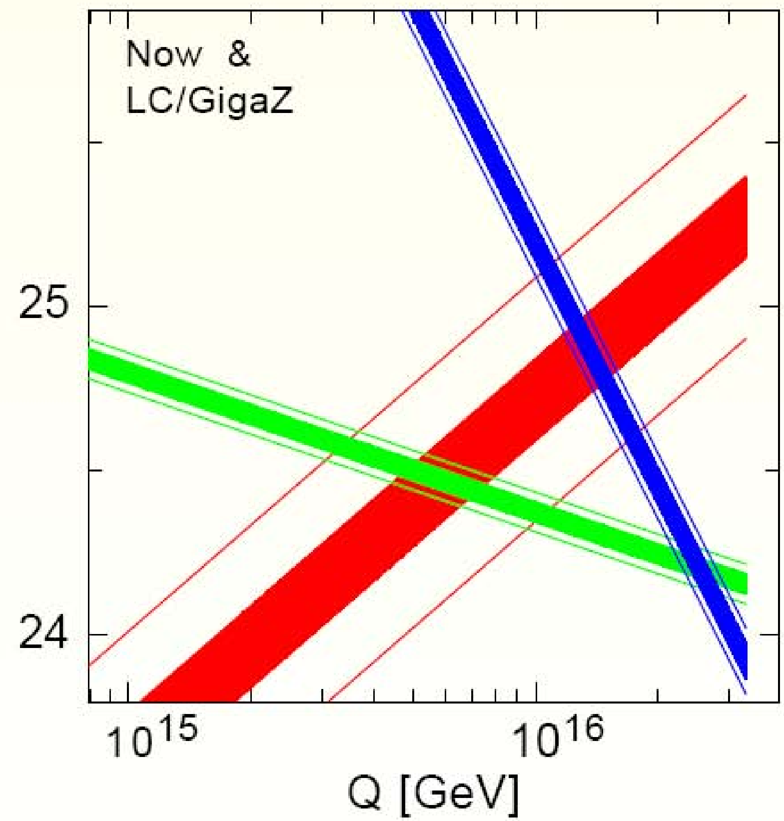
(Heinemeyer+Weiglein Snowmass)



Motivation: α_s measurement

- High precision α_s determination is crucial for accurate prediction of signal/background processes.
- α_s the least precise input for coupling unification in SUSY, GUT's:



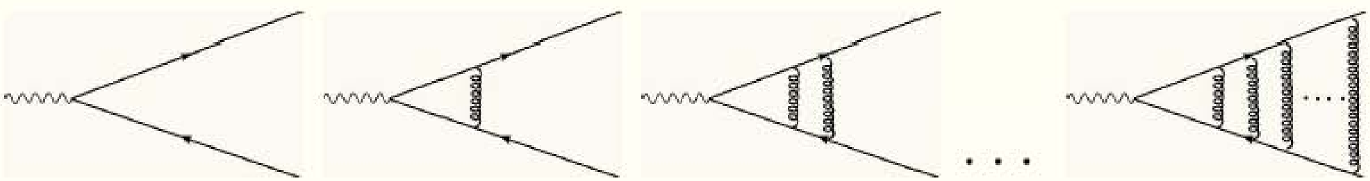


Threshold $t\bar{t}$ production; $E \equiv \sqrt{s} - 2m_t \sim 0$

Incredible experimental and theoretical precision is possible!

- Threshold scan of $\sigma(e^+e^- \to t\bar{t})$
  - Simple counting experiment of color singlet $t\bar{t}$ events
- $\Gamma_t \approx 1.5$ GeV $\gg \Lambda_{\rm QCD} \Rightarrow$ no hadronization
- $p_t = m_t v \approx 30\,\mathrm{GeV} \gg \Lambda_{\rm QCD} \Rightarrow t\bar{t}$ calculable perturbatively

Threshold cross section requires resummation of $\alpha_s/v \sim \mathcal{O}(1)$



✓ $\sigma_{LO} \sim 1 + \frac{\alpha_s}{v} + (\frac{\alpha_s}{v})^2 + \cdots \sim \Sigma_n (\frac{\alpha_s}{v})^n$

✓ $\sigma_{\rm NLO} \sim \Sigma_n \alpha_s \times (\frac{\alpha_s}{v})^n$

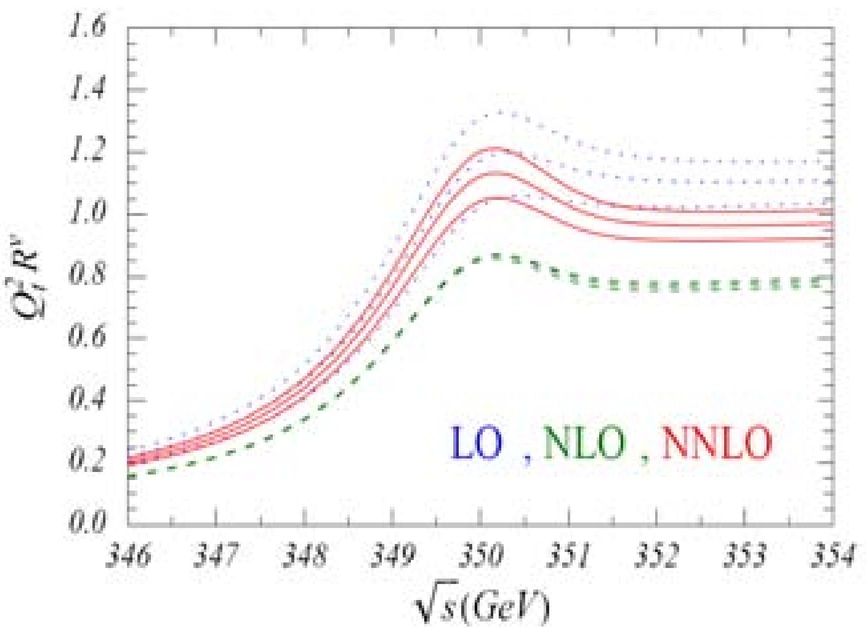
✓ $\sigma_{\rm NNLO} \sim \Sigma_n \alpha_s^2 \times (\frac{\alpha_s}{v})^n$

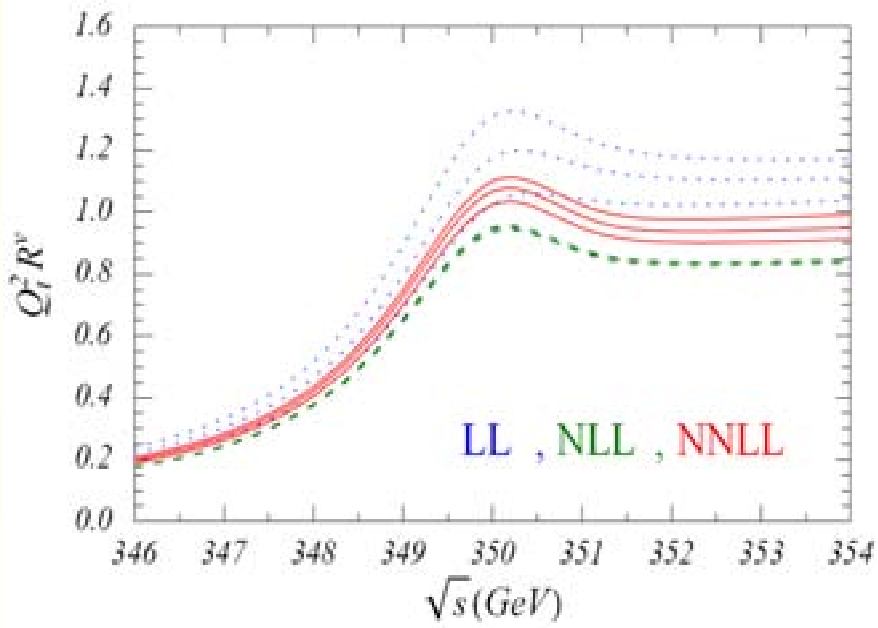
$\Rightarrow$ per mille top quark mass determination, $\Delta m_t \lesssim 50$ MeV

- NNLO was completed by several groups

  Hoang+T; Penin et al; Melnikov et al; Beneke et al; Sumino et al; Yakovlev
- First result towards NNNLO calculation: Y. Kiyo, et al.
- Renormalization Group resummation: A. Hoang, et al.

  $\sigma_{NNLL} \sim \alpha_s^2 \left(\frac{\alpha_s}{v}\right)^n \times (\alpha_s \ln(v))^m \;\Rightarrow\; \Delta\sigma_{t\bar{t}} \simeq 20\% \rightarrow 6\%$



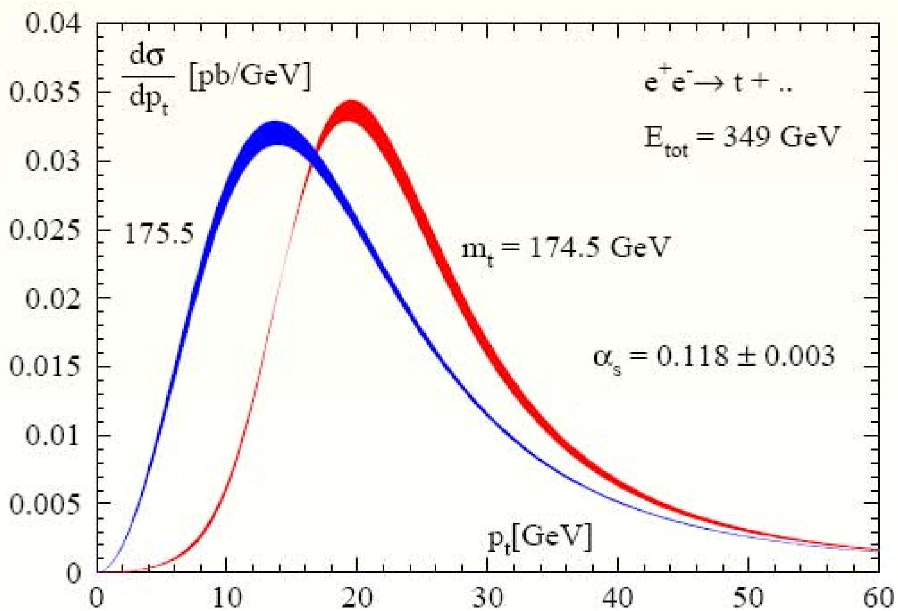


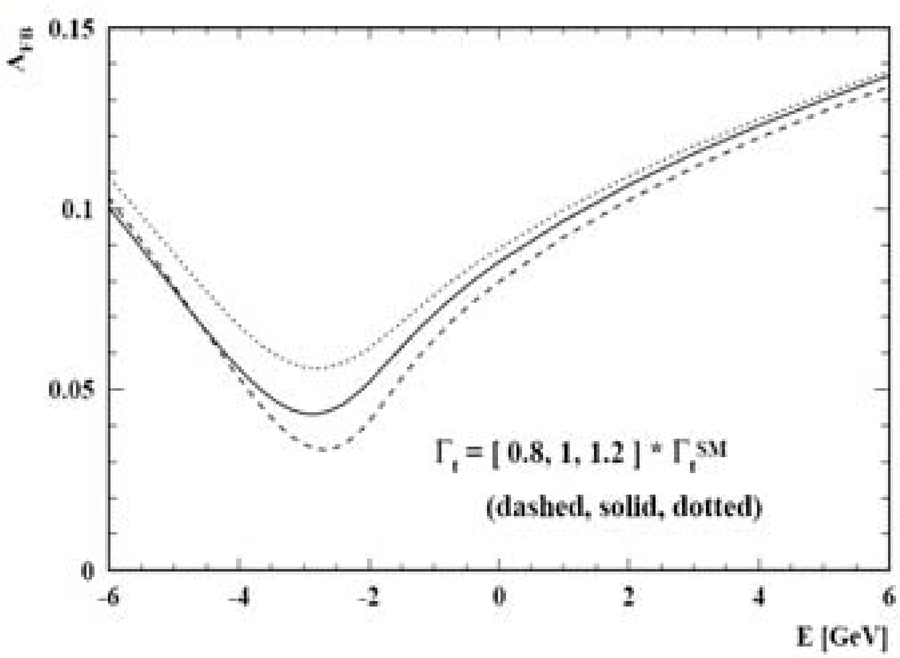
- Consistent treatment of EW effects near threshold
- top width beyond $E \to E + i\Gamma_t$, non-resonant $W^+bW^-\bar{b}$ contr.
- first result within effective field theory: A. Hoang, et al.
- see also talk from G. Zanderighi

Differential observables

Not only $\sigma_{t\bar{t}}$ but also differential observables are important!

- Needed for Monte Carlo event generators
  - Experimental cuts require exclusive cross section
- Make full use of experimental info with $A_{FB}, d\sigma_{t\bar{t}}/dp_t, \vec{s}_t$
  - additional constraints on $m_t, \alpha_s, \Gamma_t(, y_t)$
  - reduce correlations
- N(N)LO QCD corrections are available for these observables

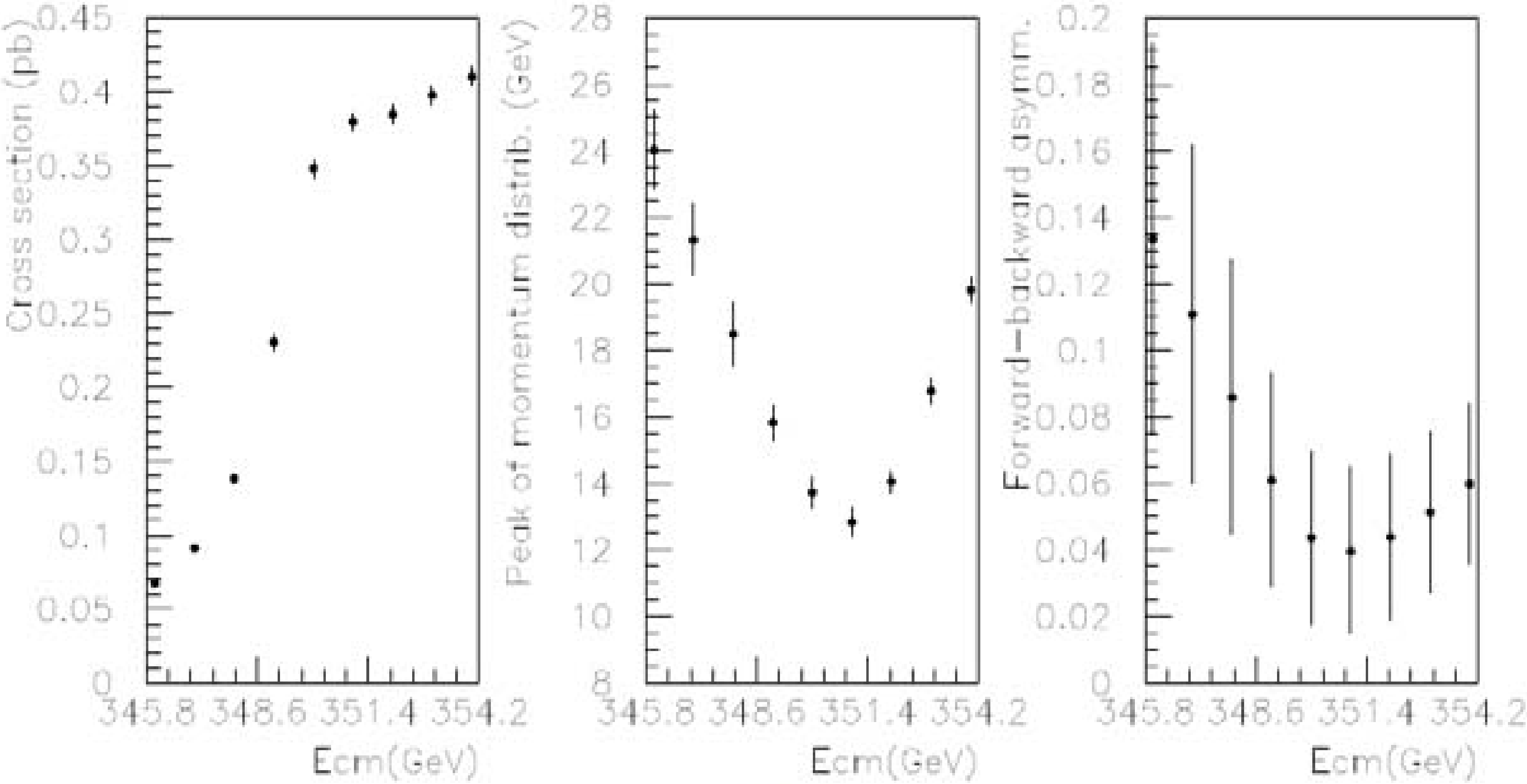




Top Threshold: experimental studies

9+1 point threshold scan at TESLA ($\mathcal{L} = 300$ fb^{-1}): Martinez + Miquel

Use of $\sigma_{\rm tot}$, peak of the top momentum distribution and A_{FB} as observables:



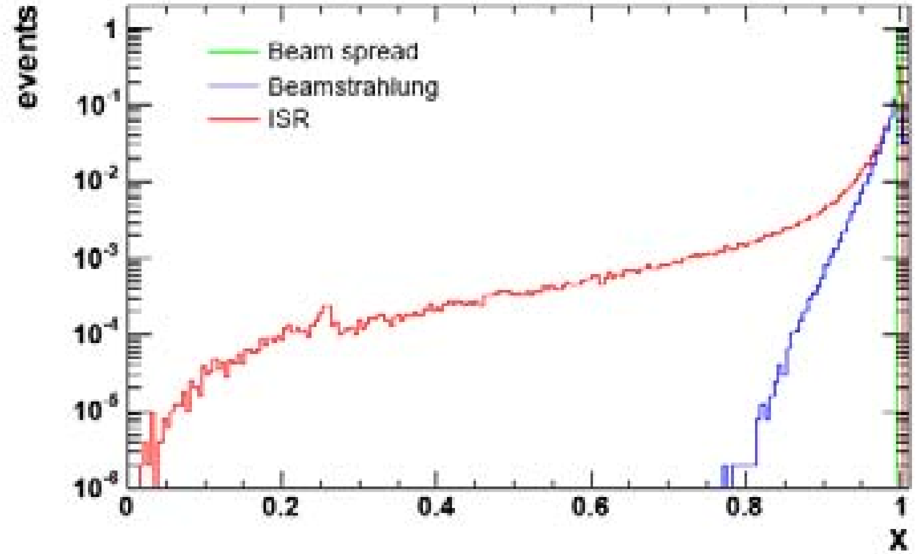
⋆ Exp. accuracy with multi-parameter fit (3% TH-error on $\sigma_{\rm tot}$, beam spectrum known):

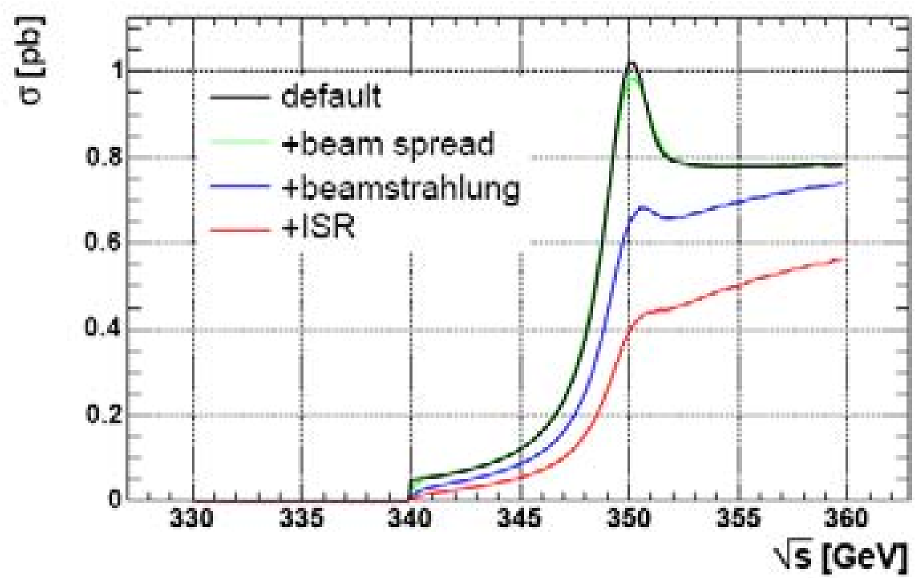
→ $\Delta m_t \sim 20$ MeV, $\Delta\Gamma_t \sim 30$ MeV, $\Delta\alpha_s \sim 0.0012$

▶ But: impact of limited knowledge of beam spectrum? Stewart Boogert

- Precision threshold measurements require:
  - Average c.m. energy $\langle\sqrt{s}\rangle$
    - Use of energy spectrometer → WG4
    - Calibrate with radiative return ($Z\gamma$)
  - Luminosity spectrum $\frac{\mathrm{d}L}{\mathrm{d}\sqrt{s}}$
    - Measure Bhabha acollinearity
      → Th.: Higher orders in MC's? (A. Penin)
      → Detector precision for Bhabha?
      [Forward calorimeter ok for FSR?]
  - Calculation of Initial State Radiation
    → Theoretical precision of ISR MC's?
- Effect on top cross section:

$$\sigma^{\mathrm{obs}}(\sqrt{s}) = \frac{1}{L_0}\int_0^1 L(x)\,\sigma(x\sqrt{s})\,\mathrm{d}x$$

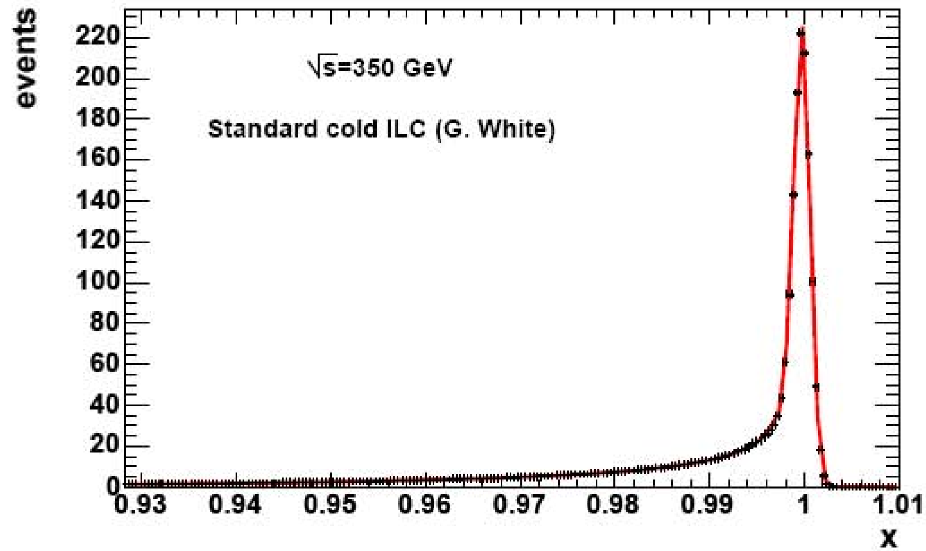




- Effect on top cross section:
  - Loss in effective luminosity
  - Shift in top mass; dominant systematic error?

▶ New simulation of beam spectrum:

  - $\sqrt{s} = 350$ GeV different from higher energies
  - new luminosity spectrum parameterization
  - will allow detailed study of systematic effects



- Top threshold is the benchmark for high precision analysis; impressive progress, but many details remain to be clarified.

  $\rightarrow$ Other cases (W^+W^-, SUSY thresholds) will benefit.

▶ Project started at Snowmass for updated full analysis:

  - use of differential distributions at (N)NLO
  - higher order MC for fully differential cross section
  - realistic beam spectrum; related systematics

- Error estimates (Th + Exp) are becoming reliable!

Top-Higgs Yukawa Coupling Measurement: Overview

- Largest coupling of the Higgs boson to fermions: $g_{ttH} \sim 0.7$ vs $g_{bbH} \sim 0.02$.
  Precise measurement very important since the top quark is the only "natural" fermion from the EWSB standpoint.

- Most promising method via σ_{ttH} measurement: $\sigma(e^+e^- \to t\bar{t}H) \sim g_{ttH}^2$
  Experimentally very challenging:
  - Spectacular signature: e.g. in $H \to bb$ decay mode $\Rightarrow$ 8j or $l\nu$+6j (4 b-jets)
  - Very low rate: σ_{ttH}~0.2(2.0) fb at $\sqrt{s}$=500(800) GeV for m_H=120 GeV.
  - Background more than 3 orders of magnitude larger: dominated by tt+jets

- LHC ($\oplus$ ILC input): $\Delta g_{ttH}/g_{ttH}$~12% for m_H=120-190 GeV, L=2x300 fb^{-1}. *M. Dührssen et al.*
- ILC direct measurement:

$\sqrt{s}$=800 GeV, L=1000 fb^{-1},
$\Delta g_{ttH}/g_{ttH}$~6(10)% for m_H=120(190) GeV

A. Juste and G. Merino (hep-ph/9910301)
A. Gay et al (4th ECFA/DESY Workshop)

Very important to investigate the sensitivity at $\sqrt{s}$=500 GeV (baseline machine).
A preliminary estimate (from 2002):

$\sqrt{s}$=500 GeV, L=1000 fb^{-1}
$\Delta g_{ttH}/g_{ttH}$~24% for m_H=120 GeV

A. Juste, Chicago LC Workshop, January 7-9, 2002

Work started at Snowmass to re-evaluate this estimate

Impact of tt Threshold Effects on ttH

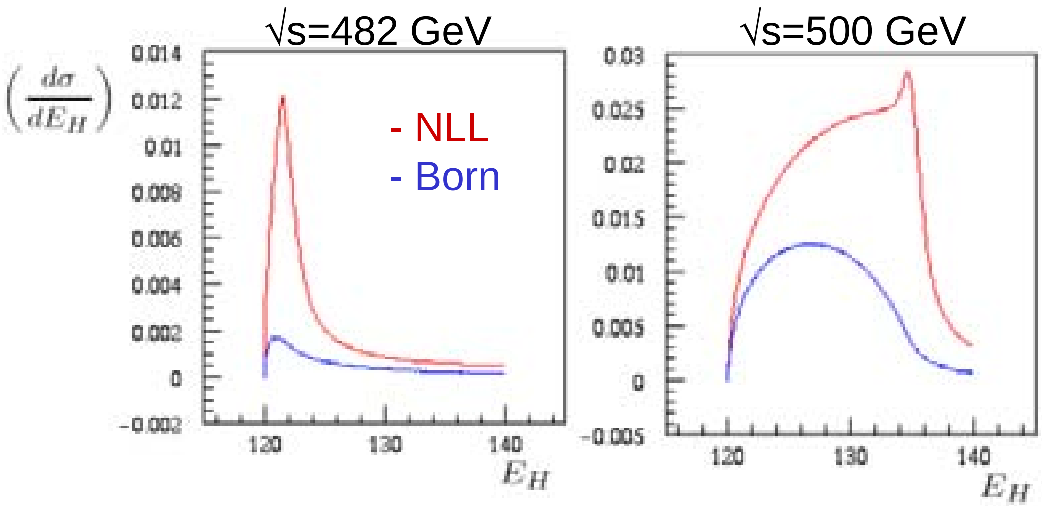
- At √s=500 GeV and for $m_h \geq 120$ GeV, the phase space region where the tt system is non-relativistic is enhanced.

  Important to take into account velocity-resummation effects (like at tt threshold).

  ⇒ Cross section enhancement.

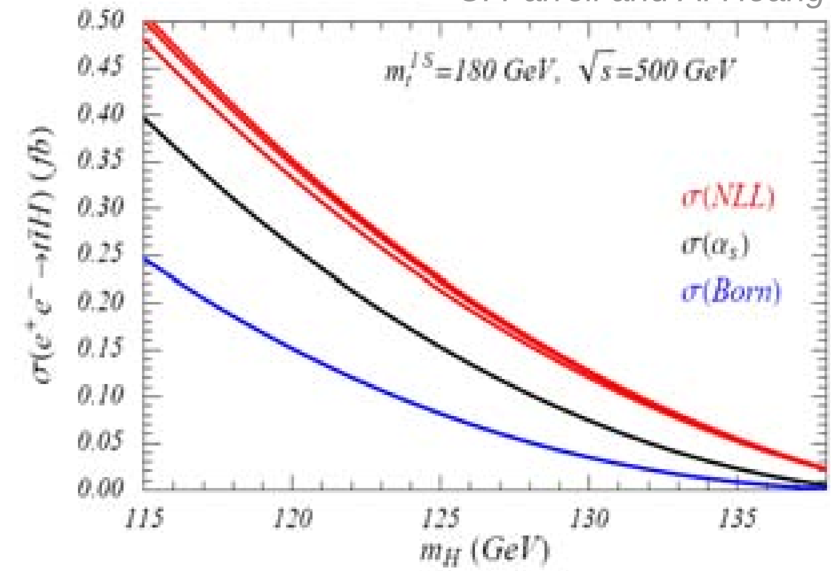
- NLL effects implemented in MC generator via E_H-dependent K-factor:

$$K(E_H, s) = \frac{(d\sigma / dE_H)^{NLL}}{(d\sigma / dE_H)^{LO}}$$



A. Juste

C. Farrell and A. Hoang



$$\sqrt{s} = 500\,\text{GeV}, m_t^{1S} = 180\,\text{GeV}, m_H = 120\,\text{GeV}$$

σ_{ttH}(fb)	Born	Born x K-factor	Increase
no ISR/BS	0.157(1)	0.357(2)	x2.27
BS	0.106(1)	0.252(3)	x2.38
ISR+BS	0.0735(8)	0.179(2)	x2.44

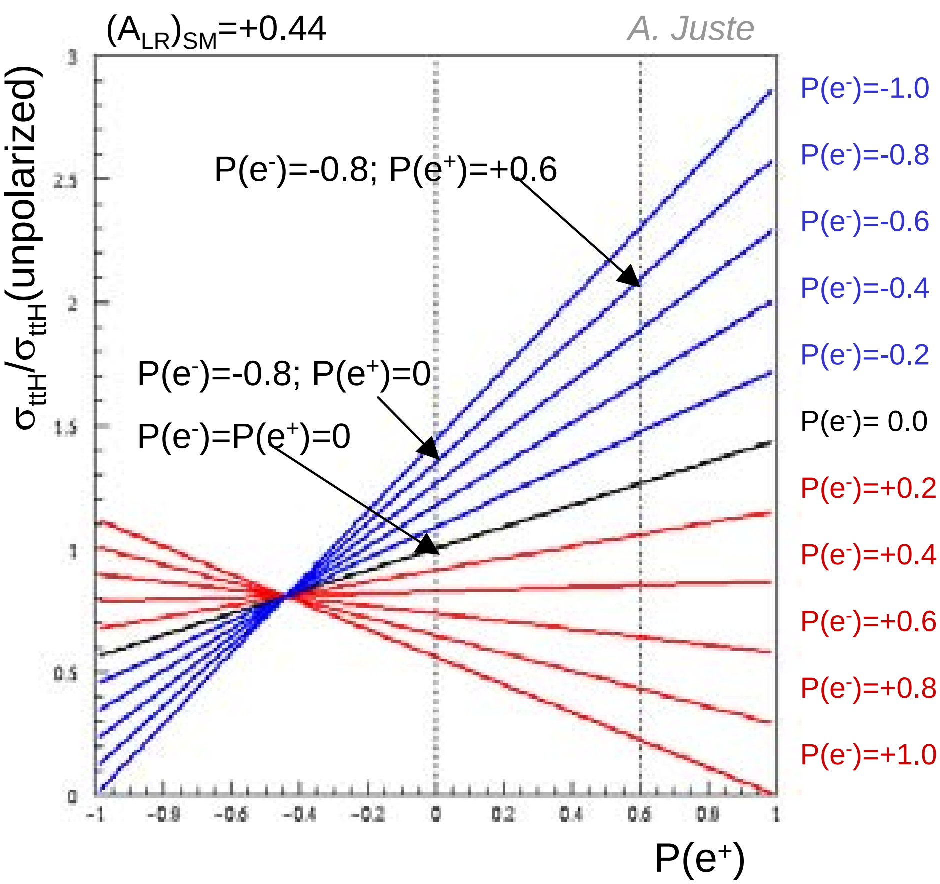
- Large effect of ISR+Beamstrahlung.

  Possible optimization of BS vs luminosity?
- Increase in cross section by ~x2.4 relative to Born.

Impact of Beam Polarization on ttH

- Baseline machine: $|P(e^-)| \sim 0.8$
  Option: add positron polarization $|P(e^+)| \sim 0.6$

Existing feasibility studies have not exploited beam polarization



- Choice of signs for $P(e^-)$ and $P(e^+)$ can only be done once the sign of A_{LR} is known
  $\Rightarrow A_{LR}$ must be measured first.

- For SM-like A_{LR}, optimal (realistic) beam polarization:
  $$[P(e^-),P(e^+)] = [-0.8,+0.6]$$
  $\Rightarrow$ increase in cross section relative to the unpolarized case by x2.1
  Additional motivation for positron polarization be part of the baseline machine.

- g_{ttH} measurement requires %-level and model-independent determination of $tt\gamma$ and ttZ couplings. This typically benefits from changing beam polarization. Desirable to optimize strategy to maintain cross section enhancement for ttH.

Top-Higgs Yukawa Coupling Measurement: Projection

- Folding into the previous estimate the new enhancement factors:
  - x2.4 from NLL prediction
  - x2.1 from beam polarization

  the preliminary estimated uncertainty on the top-Higgs Yukawa coupling measurement at $\sqrt{s}$=500 GeV is:

  A. Juste

$$\left(\frac{\Delta g_{tth}}{g_{tth}}\right) \approx 12\%$$

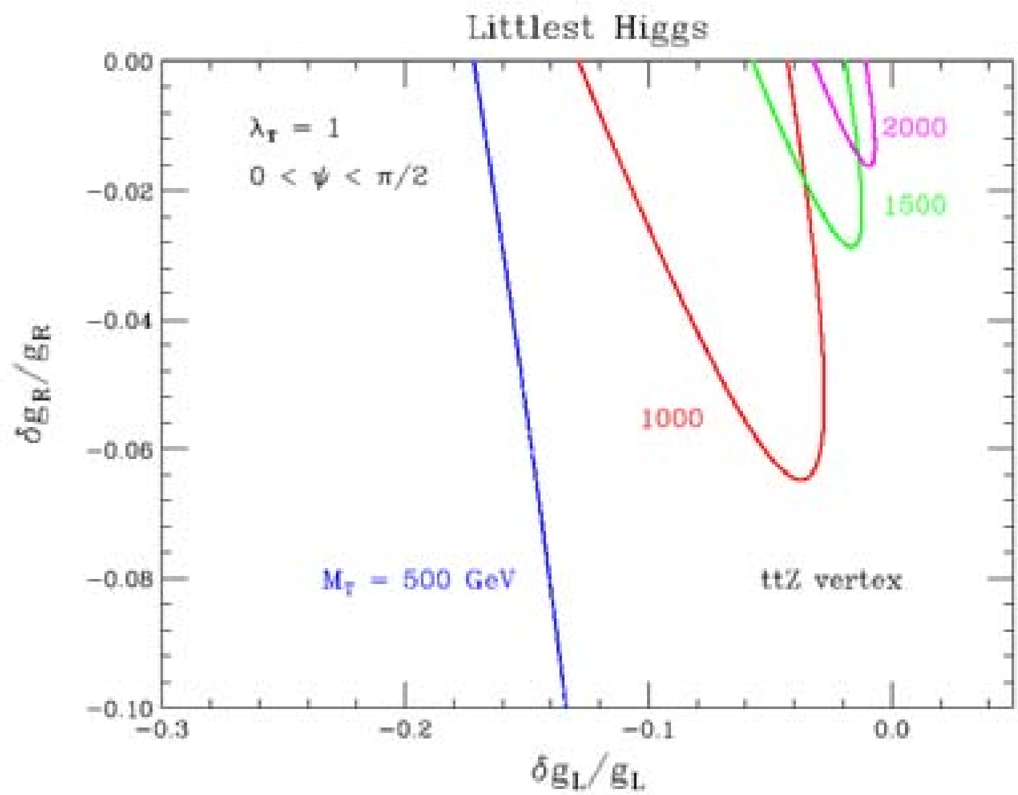
for m_H=120 GeV, L=1000 fb^{-1}

- Next step: redo feasibility study making an optimal use of b-tagging and kinematic information.
- There is a good chance that uncertainties ≤10% can be achieved for moderate m_H values (assuming L=1000 fb^{-1}). Stay tuned!

Anomalous couplings

- To explore connection to EWSB, search for anomalous couplings to EW gauge and Higgs bosons
- General form of ttV ($V = Z, \gamma$) vertex:

$$-ie\left\{\gamma_\mu\left(F_{1V}(q^2) + F_{1A}(q^2)\gamma_5\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q_t + q_{\bar{t}})\left(iF_{2V}(q^2) + F_{2A}(q^2)\right)\gamma_5\right)\right\}$$

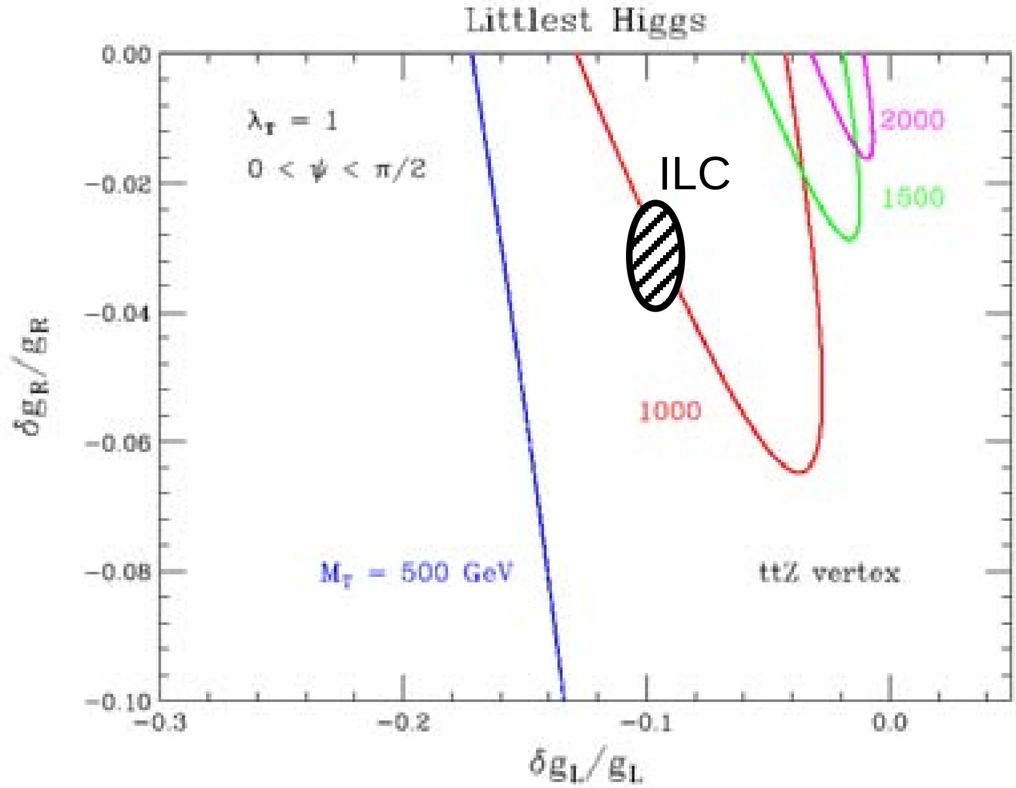


- Most new physics models predict significant top coupling shifts
- Need to get both a large top Yukawa and EW precision correct mandates this

⇐ Snowmass top-QCD/BSM project

ttV at the LHC and the ILC

coupling	LHC, 300 fb^{-1}	e^+e^-
$\Delta\tilde{F}^{\gamma}_{1V}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}
$\Delta\tilde{F}^{\gamma}_{1A}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}
$\Delta\tilde{F}^{\gamma}_{2V}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}
$\Delta\tilde{F}^{\gamma}_{2A}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}
$\Delta\tilde{F}^{Z}_{1V}$	$^{+0.34}_{-0.72}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\tilde{F}^{Z}_{1A}$	$^{+0.079}_{-0.091}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\tilde{F}^{Z}_{2V}$	$^{+0.26}_{-0.34}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\tilde{F}^{Z}_{2A}$	$^{+0.35}_{-0.35}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}



U. Baur

- Example: LHC (ILC) can measure F_{1Z} to 50% (1%), F_{2Z} to 8% (1%)
- Improvement from e^- polarization by a factor of 2-3 (talk by G. Moortgat-Pick)
  - ! Positron polarization not studied ⇒ needs to be done!
  - ! Correlated analysis done only for LHC; ILC study varies couplings independently

tbW and precision form factors

- Can measure V_{tb} to $\approx 8\%$ at the LHC (Stelzer et. al.)
- Can measure top width from threshold scan, but hard to access V_{tb} at an e^+e^- machine
- New proposal: determine V_{tb} from $e^+e^- \to tt^*$, with one top off-shell (T. Tait)

$\Rightarrow$ with top off-shell, dependence on Γ_t decreases

$\Rightarrow$ $4.3\,\mathrm{fb}^{-1}$ at 320 GeV before cuts, efficiencies $\Rightarrow$ worth studying further

- New calculation: Two-loop corrections to heavy quark form factors (T. Gehrmann et. al.)

	top ($\mu = m_t$)	bottom ($\mu = m_b$)	bottom ($\mu = m_Z$)
$(g-2)_Q^{\gamma,(1l)}$	$1.53 \cdot 10^{-2}$	$-1.52 \cdot 10^{-2}$	$-8.4 \cdot 10^{-3}$
$(g-2)_Q^{\gamma,(2l)}$	$4.7 \cdot 10^{-3}$	$-1.00 \cdot 10^{-2}$	$-6.6 \cdot 10^{-3}$
$(g-2)_Q^{Z,(1l)}$	$5.2 \cdot 10^{-3}$	$-1.87 \cdot 10^{-2}$	$-1.03 \cdot 10^{-2}$
$(g-2)_Q^{Z,(2l)}$	$1.6 \cdot 10^{-3}$	$-1.24 \cdot 10^{-2}$	$-8.1 \cdot 10^{-3}$
$(g-2)_Q^{\gamma}$	$2.00 \cdot 10^{-2}$	$-2.52 \cdot 10^{-2}$	$-1.50 \cdot 10^{-2}$
$(g-2)_Q^{Z}$	$6.8 \cdot 10^{-3}$	$-3.11 \cdot 10^{-2}$	$-1.85 \cdot 10^{-2}$
$G_{1,Q}$	$1 - 2.29 \cdot 10^{-2}$	$1 - 6.91 \cdot 10^{-2}$	$1 - 4.3 \cdot 10^{-2}$

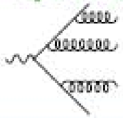
- QCD shifts reach 3%
- Must account for in precision analyses
- Much more work needed for precision description of top in the continuum!

Jets and α_s at the ILC

- Current limiting factor for α_s extraction from 3 jet event shapes is theory:

$$\alpha_s(M_Z) = 0.1202 \pm 0.0003\,(\text{stat}) \pm 0.0009\,(\text{sys}) \pm 0.0009\,(\text{had}) \pm 0.0047\,(\text{theory})$$

- Current theory is NLO; effort underway to obtain NNLO result (A. Gehrmann-De Ridder, T. Gehrmann et. al.)

Subprocess	partonic final state	partons in jets
$\gamma^* \to 3$ partons, 2 loop e.g. 	3 partons	(1) (1) (1)
$\gamma^* \to 4$ partons, 1 loop e.g. 	4 partons (3+1) partons	(2) (1) (1) (1) (1) (1)
$\gamma^* \to 5$ partons, tree e.g. 	5 partons (4+1) partons (3+2) partons	(3) (1) (1) (2) (2) (1) (2) (1) (1) (1) (1) (1)

- Complicated singular structure; at the frontier of perturbation theory
- Numerical results obtained for some color structures
- C_F^2 NNLO $< 1 - T >$ coefficient: -20.4 ± 4
- Estimated theory error after calculation: 2%

! Need more study of experimental aspects; calorimeter granularity, jet energy requirements?

- Promising methods for 1% extractions of α_s at the $t\bar{t}$ threshold and using R at Giga-Z (M. Winter)

Conclusions

- Small but active group
- Several projects started at Snowmass: new $t\bar{t}$ threshold studies, ttH Yukawa measurement at 500 GeV, survey of new physics predictions for top properties, tbW anomalous couplings below threshold, ...
- Need participation of more experimentalists!!
- Thanks to all our speakers and participants: Kaustubh Agashe, Malgorzata Awramik, Uli Baur, Carola Berger, Stewart Boogert, Jose Cembranos, Lance Dixon, Aude Gehrmann-De Ridder, Thomas Gehrmann, Steve Godfrey, Sonja Hillert, Andre Hoang, Swapan Majhi, Kirill Melnikov, Gudi Moortgat-Pick, Carmine Pagliarone, Michael Peskin, Peter Skands, Zack Sullivan, Tim Tait, Giulia Zanderighi