Precision QCD and top quark physics at a linear e^+e^- collider;

summary of the top, QCD and Loopverein WG

Marcel Vos
IFIC (U. Valencia/CSIC), Spain

QCD and Loopverein

Christoph Schwan,
Numerical NLO calculations in QCD with many jets

The first calculation of 5,6,7 jet rates at an e^+e^- collider, PRL 108 (2012) 032005

Dominik Stoeckinger,

Nondecoupling two-loop contributions to g-2 of the muon from heavy squarks

Two-loop contributions $a_\mu^{2L\tilde{f}f}$ to muon g-2 computed. A large contribution to g-2 in split SUSY scenarios with heavy colored s-particles and a light s-muon,

Sven Heinemeyer,

LC precision in the MSSM, getting it under control

Calculation of decay widths and BR in the cMSSM to LC precision, PRD86 (2012) 075023

Joint top-Higgs

Impact of m_t measurements on precision tests of the SM and the MSSM
Sven Heinemeyer

Top anomalous magnetic moment and Higgs decays
Lance Labun

See Keisuke Fuji's summary for LC prospect on top Yukawa couplings:

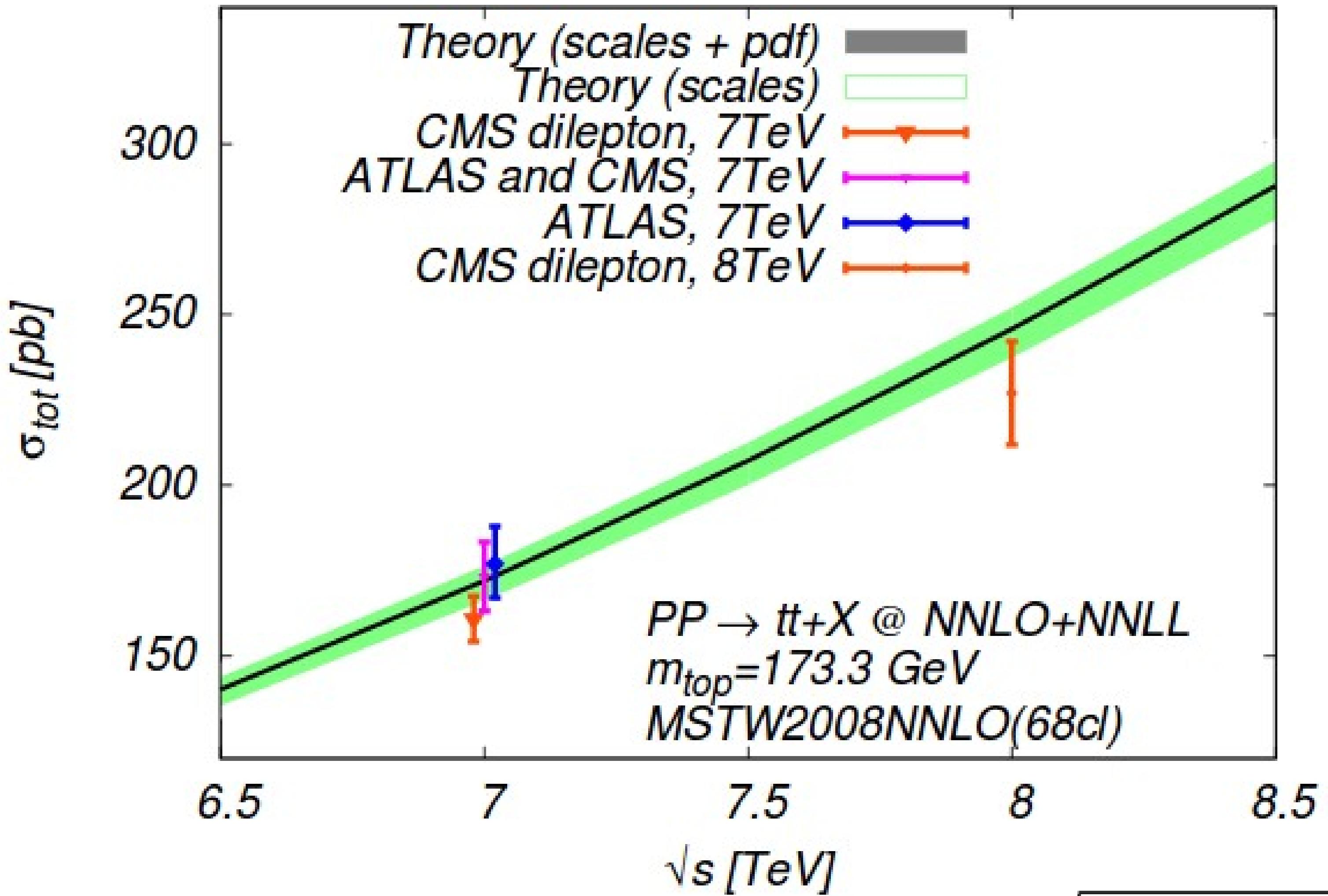
Associated production of the Higgs boson with a top pair at the ILC
Tomohiko Tanabe

Measurement of the top Yukawa coupling at sqrt(s) = 1 TeV using the SiD detector
Philipp Roloff

Measurement of the top Yukawa coupling at a 1.4 TeV CLIC collider
Sophie Redford

Status of top physics

Introduction by Sven Moch



Theory milestone:
full NNLO and NNLL result for top quark pair production at hadron colliders

K-factor (NLO → NNLO) ~ 10%
Scale stability ~ 5 %

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$+0.259(3.7\%)$ $-0.374(5.3\%)$	$+0.169(2.4\%)$ $-0.121(1.7\%)$
LHC 7 TeV	167.0	$+6.7(4.0\%)$ $-10.7(6.4\%)$	$+4.6(2.8\%)$ $-4.7(2.8\%)$
LHC 8 TeV	239.1	$+9.2(3.9\%)$ $-14.8(6.2\%)$	$+6.1(2.5\%)$ $-6.2(2.6\%)$
LHC 14 TeV	933.0	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$

Status of top physics

ATLAS and CMS reviews by Gaetano Barone and Andreas Meyer

5 million top quark pairs produced at the LHC

Pair production:
- $t\bar{t}$ cross-section to 4-7%
- differential measurements in p_T, m_{tt}, rapidity, jet multiplicity
- Spin correlations established (no correlation excluded at 5.1 σ level)
- Polarization 0.47 $\pm$ 0.03 compatible with SM

Decay:
- R=BR(tWB)/BR(tWq) > 0.945 (from b-tag multiplicity in di-lepton channel)
- W helicity fractions confirm V-A structure of tWb vertex

+ 1 million top quarks from electro-weak single-top production

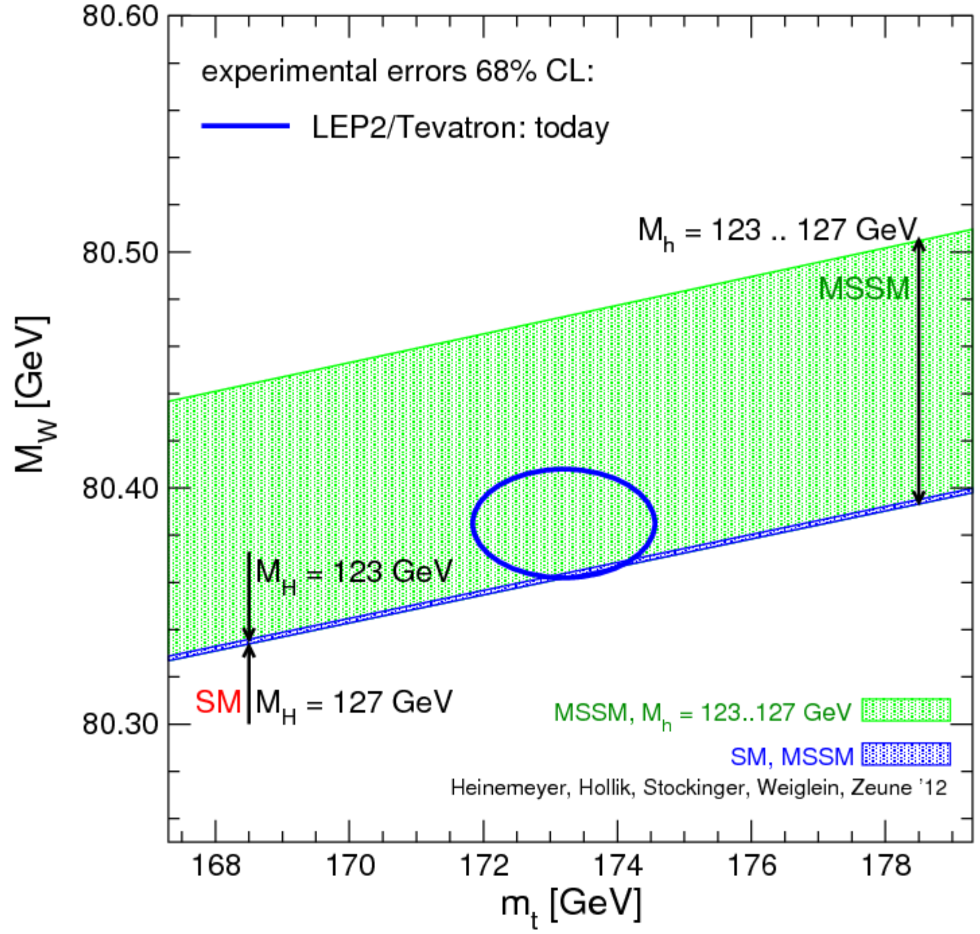
- x-sections for t-channel (to 20%) and tW (to 30%)
  (s-channel accessible soon)
- found no CP violation: $-0.2 < I(g_R) < 0.30$

Searches:
- $t\bar{t}$ resonances: $m_{Z'} > 2$ TeV (was 900 GeV)
- t' → Wb, Zt, Ht (m>790 GeV)
- b* → Wt (m > 780 GeV)
- W' → tb (m > 1.5 TeV)

Top quark mass: motivation

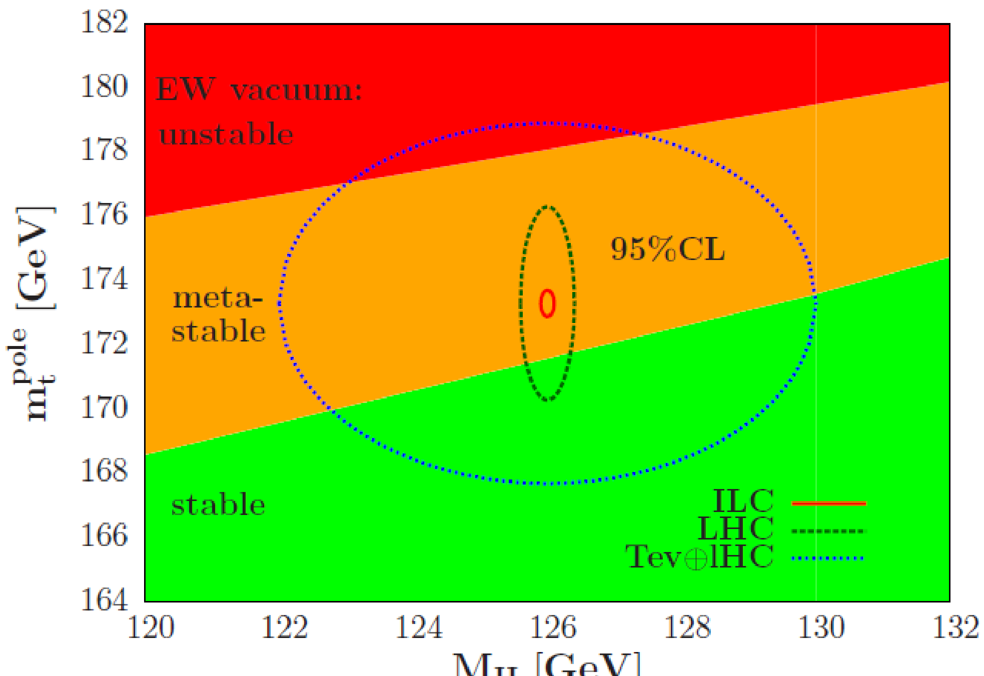
Precision test of the SM (Sven Heinemeyer)

- SM EW fit yields relations between m_H, m_t and m_W
- Currently limited by m_W, must improve also α_s, $\sin^2\theta$, m_Z



Fate of the universe (Sven Moch)

- Depending on the value of the top quark mass the Higgs potential may go negative somewhere between EW and Planck scale (in the SM)



Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice et al. '12; Alekhin, Djouadi, S.M. '12; Masina '12

Top quark mass

Tevatron: 173.2 ± 0.51 ± 0.71 GeV

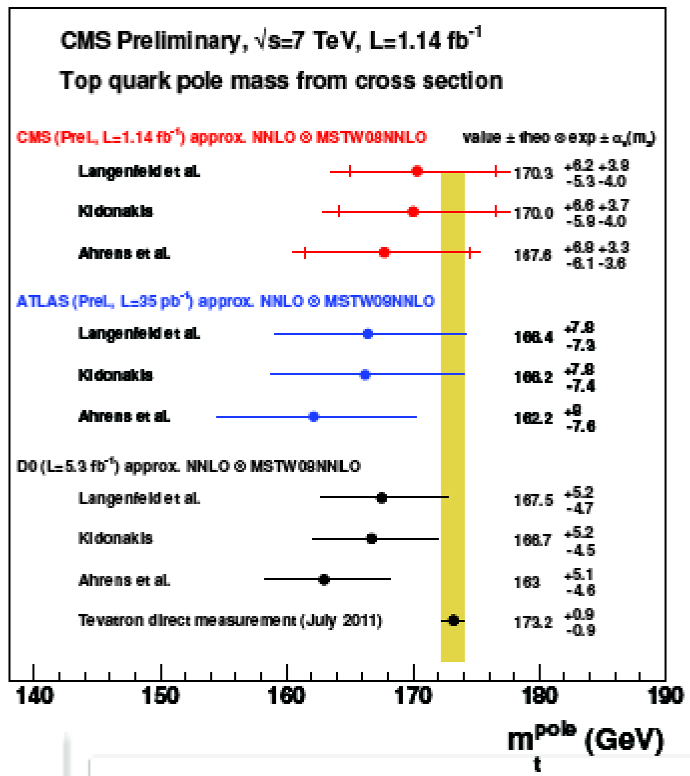
LHC: 173.3 ± 0.5 ± 1.3 GeV

} Kinematic mass, MC mass

Prospects: LHC surpasses Tevatron precision soon

Better understanding of interpretation

- kinematic mass ~ pole mass
  - » Color reconnection uncertainty (500 MeV)
  - » Stability in different channels and kinematic regimes



Alternative methods:

Endpoint measurement

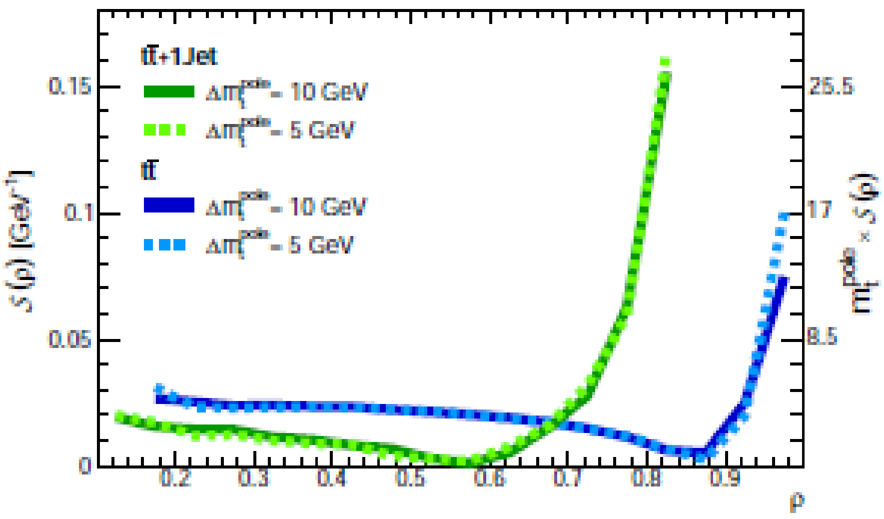
(CMS, arXiv:1304.5783, currently 2 GeV uncertainty)

Extraction from J/psi spectra, m_{bl}

Extracted from total cross section

$$\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \approx 5\frac{\Delta m_t}{m_t}$$ (currently > 5 GeV uncertainty)

$t\bar{t}g$ cross-section (arXiv:1303.6415)



Threshold scan

A scan of the beam energy through the $t\bar{t}$ production threshold

(nominally: 10 points of 10/fb each)

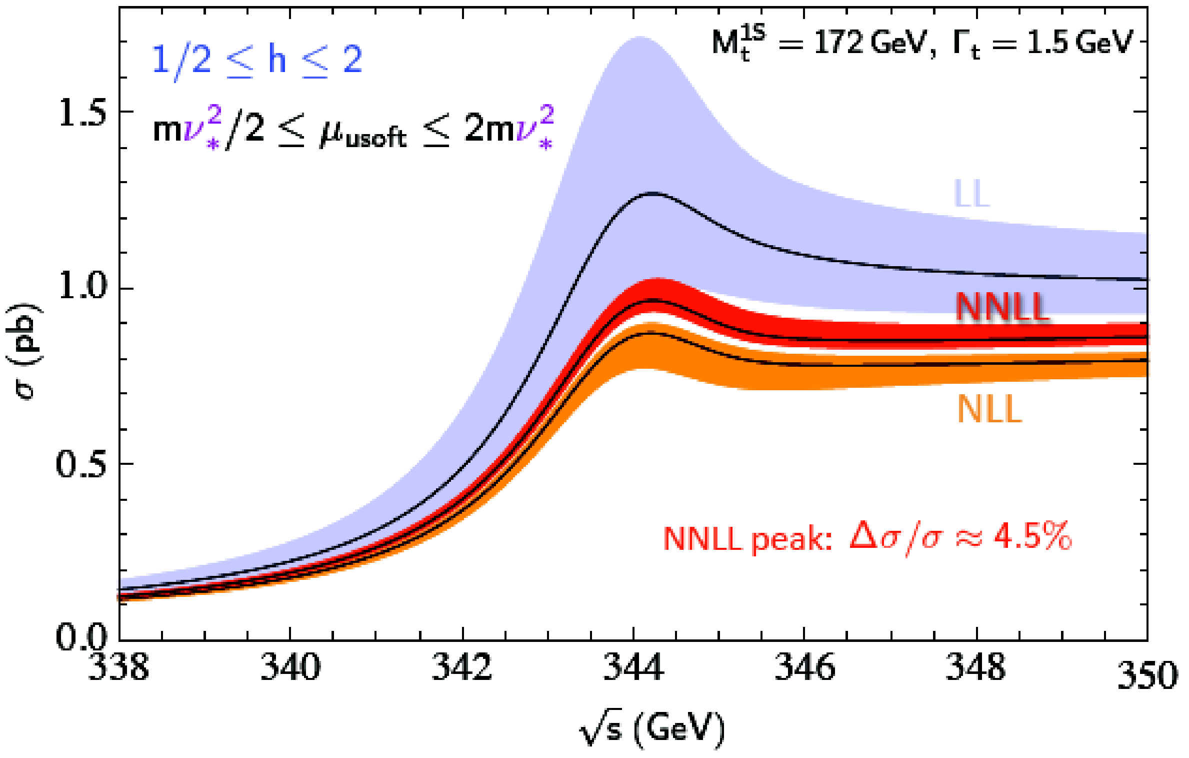
Sven Moch → introduction

Maximilian Stahlhofen → NNLL calculation

Pedro Ruiz-Femenia → NNLO non-resonant

Tomohiro Horiguchi → top Yukawa extraction

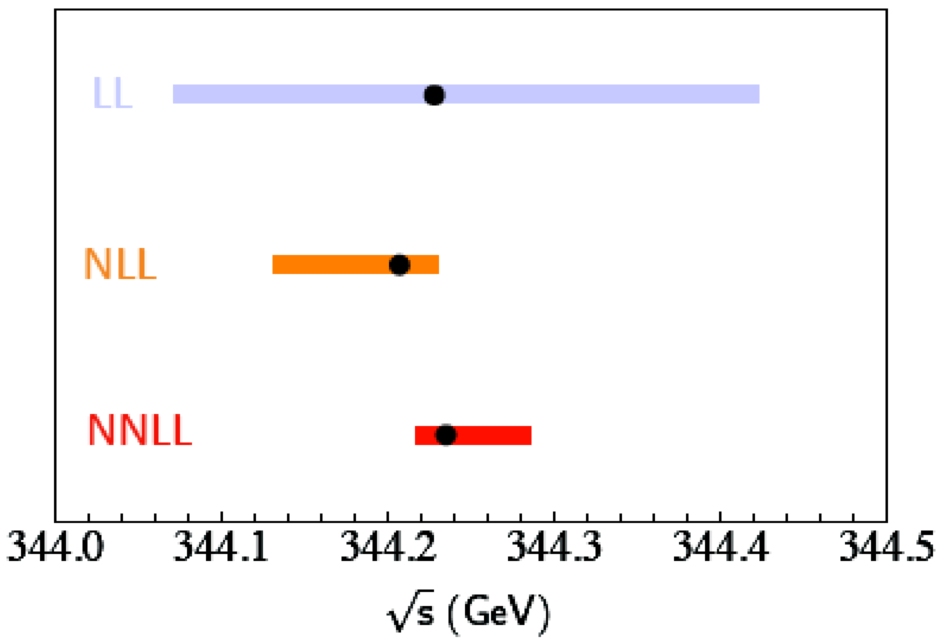
Frank Simon → LC analysis



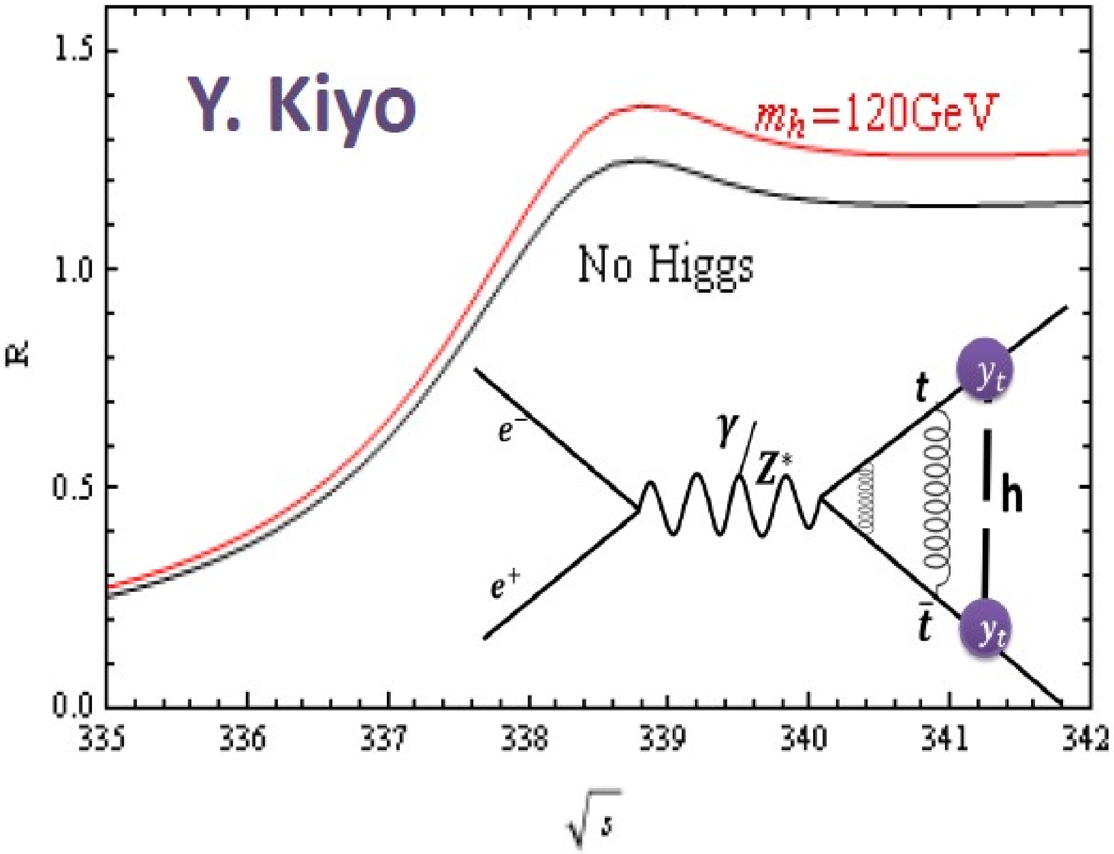
Threshold scan: theory

Non-relativistic effective theory. Progress is impressive, but we still need more...

Maximilian Stahlhofen → NNLL calculation

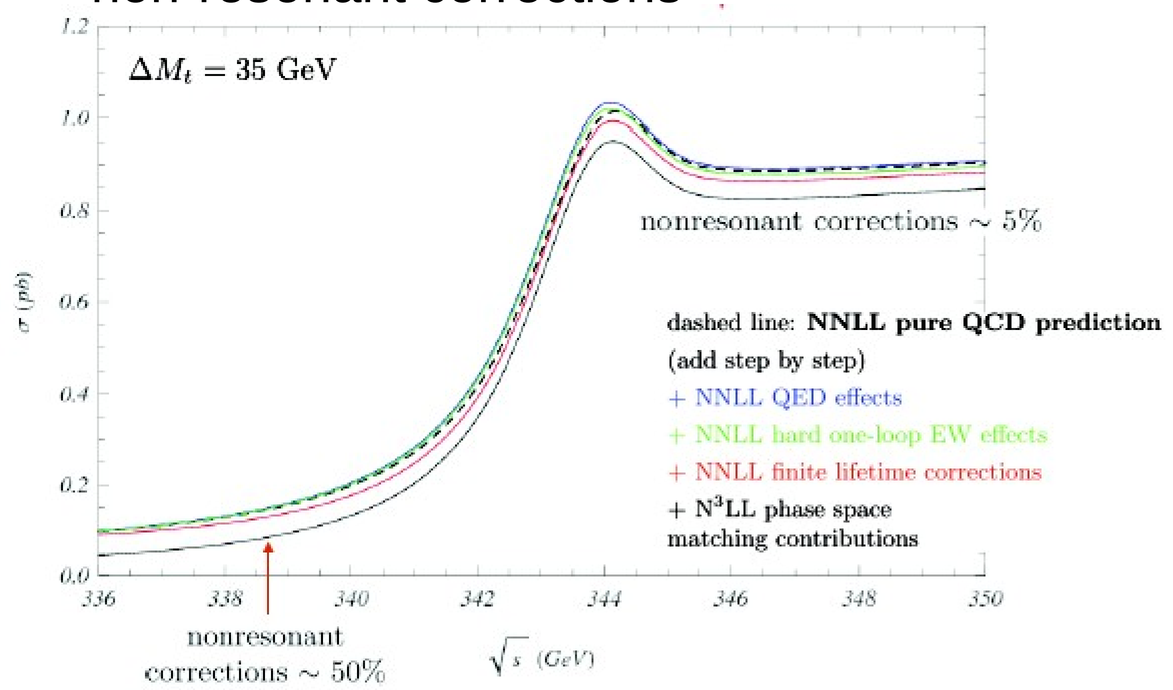


Tomohiro Horiguchi → top Yukawa extraction

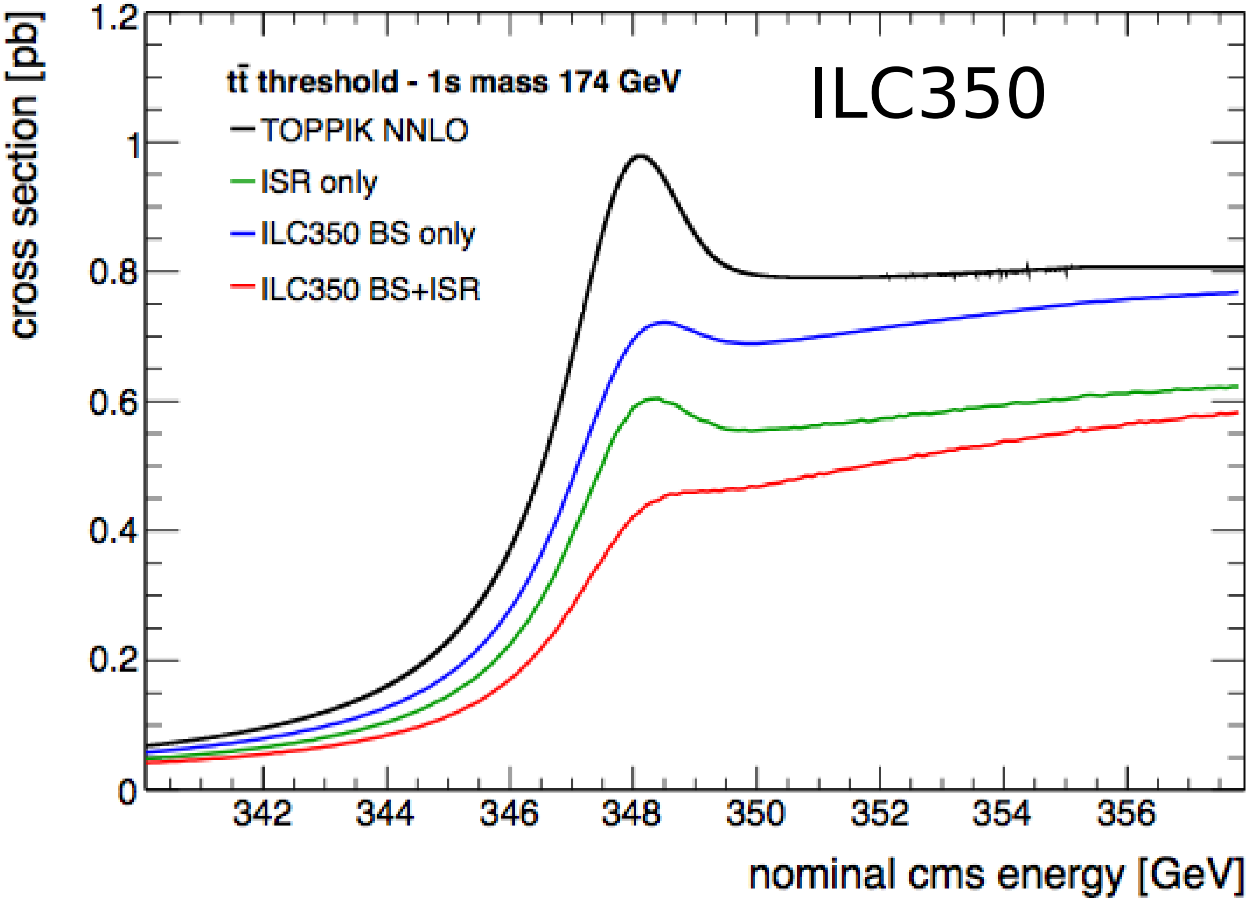


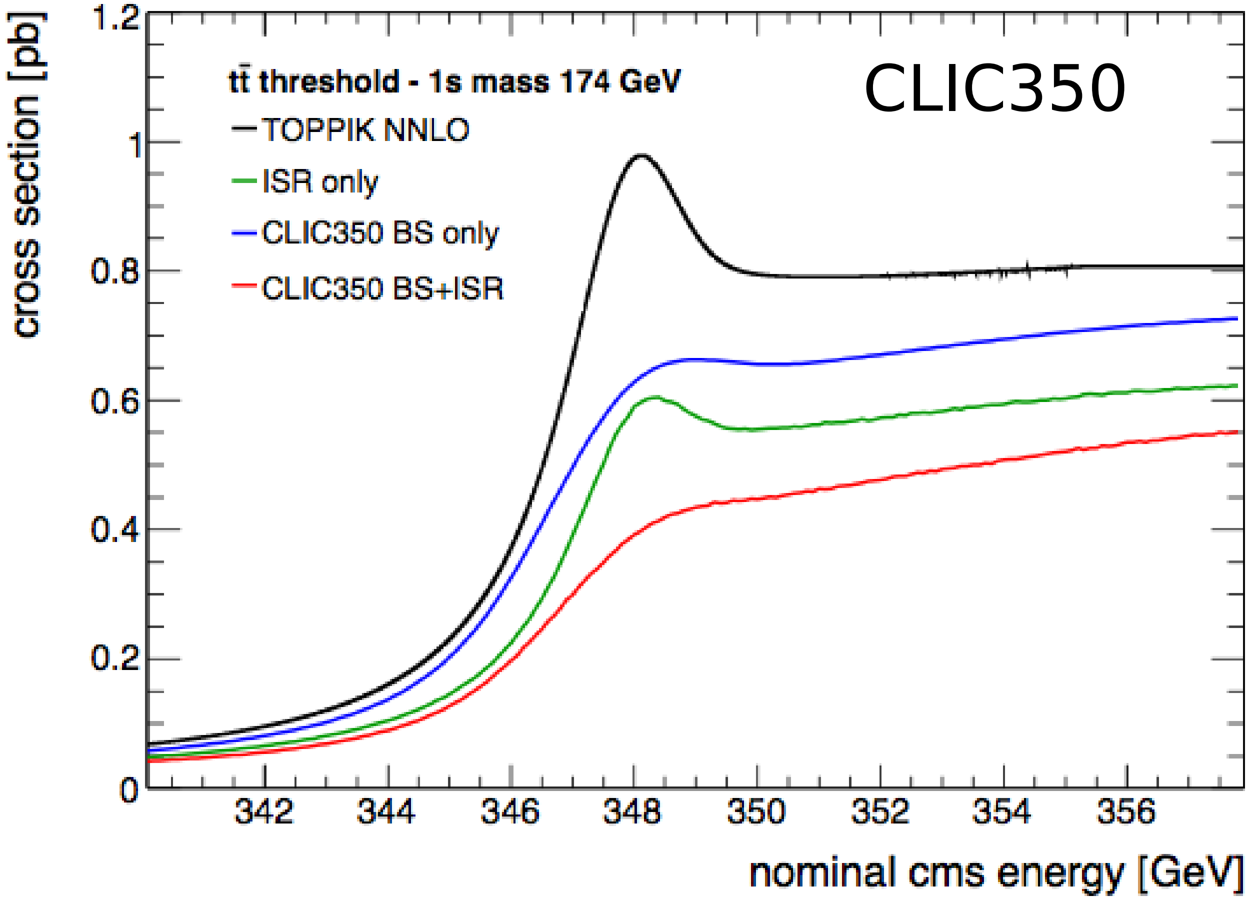
Pedro Ruiz-Femenia → NNLO

non-resonant corrections



Threshold scan





Realistic beam energy spectrum (ILC & CLIC)

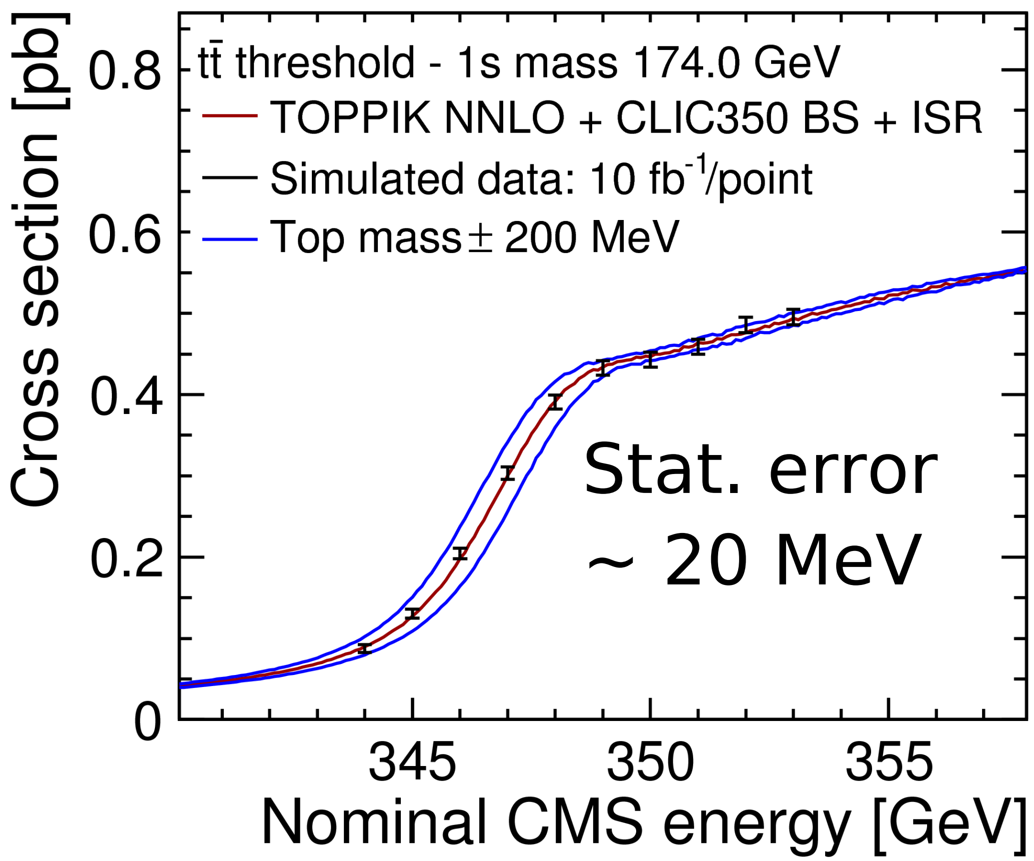
Frank Simon

Full simulation & reconstruction, including background

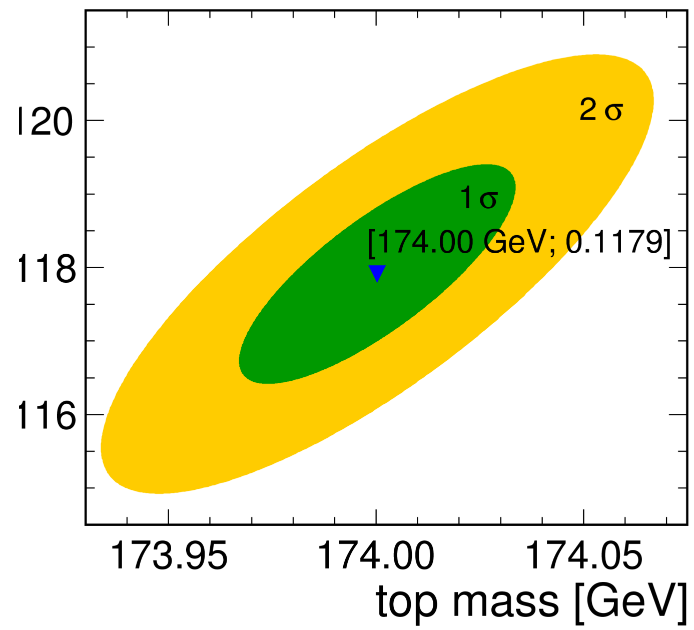
Evaluation/discussion of systematics

Action: evaluate impact of uncertainties on normalization and shape in current state-of-the-art calculations in a realistic fit

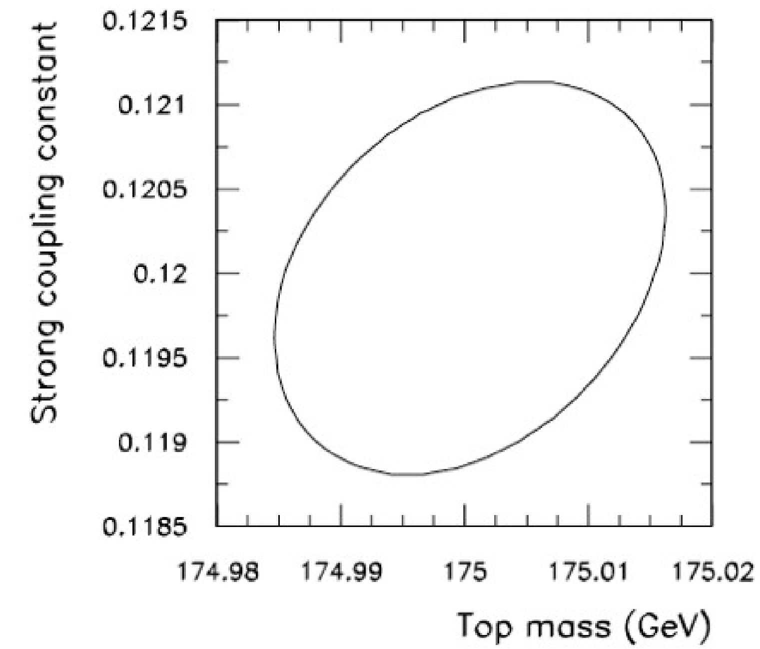
Top quark mass



Seidel, Simon, Tesar, Poss



Martinez, Miquel, EPJ C27, 49 (2003)



No dependence on location of scan energy
5% uncertainty non-tt bkg → 18 MeV
10^{-4} precision on √s → 30 MeV
20% uncertainty on lumi-spectrum → 75 MeV

1S top mass and α_s combined 2D fit	
m_t stat. error	34 MeV
m_t theory syst. (1%/3%)	5 MeV / 8 MeV
α_s stat. error	0.0009
α_s theory syst. (1%/3%)	0.0008 / 0.0022

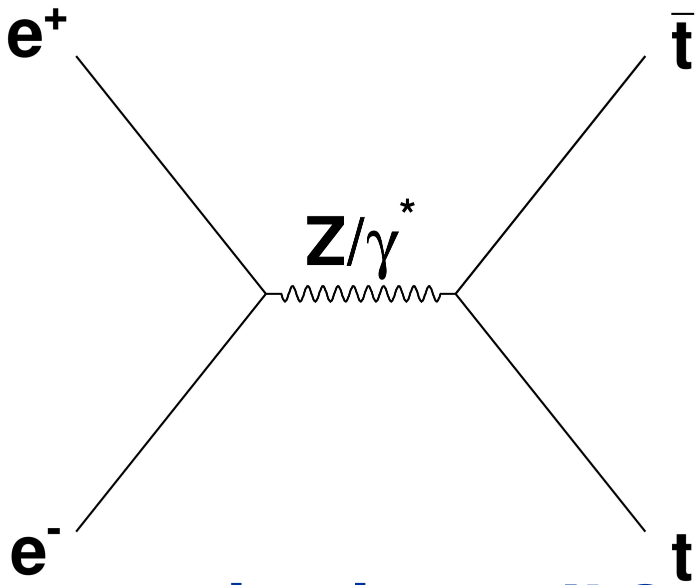
A precise measurement ($\Delta\ m_t$ < 100 MeV) can be achieved

+ $\Delta\ \alpha s$ < 0.001 (+ $\Delta\ \Gamma_t$ < 30 MeV) (+ $\Delta\ y_t/y_t$ ~ 35% *)

Frank Simon, arXiv:1303.3758

* Tomohiro Horiguchi shows stat. error on y_t can be much smaller

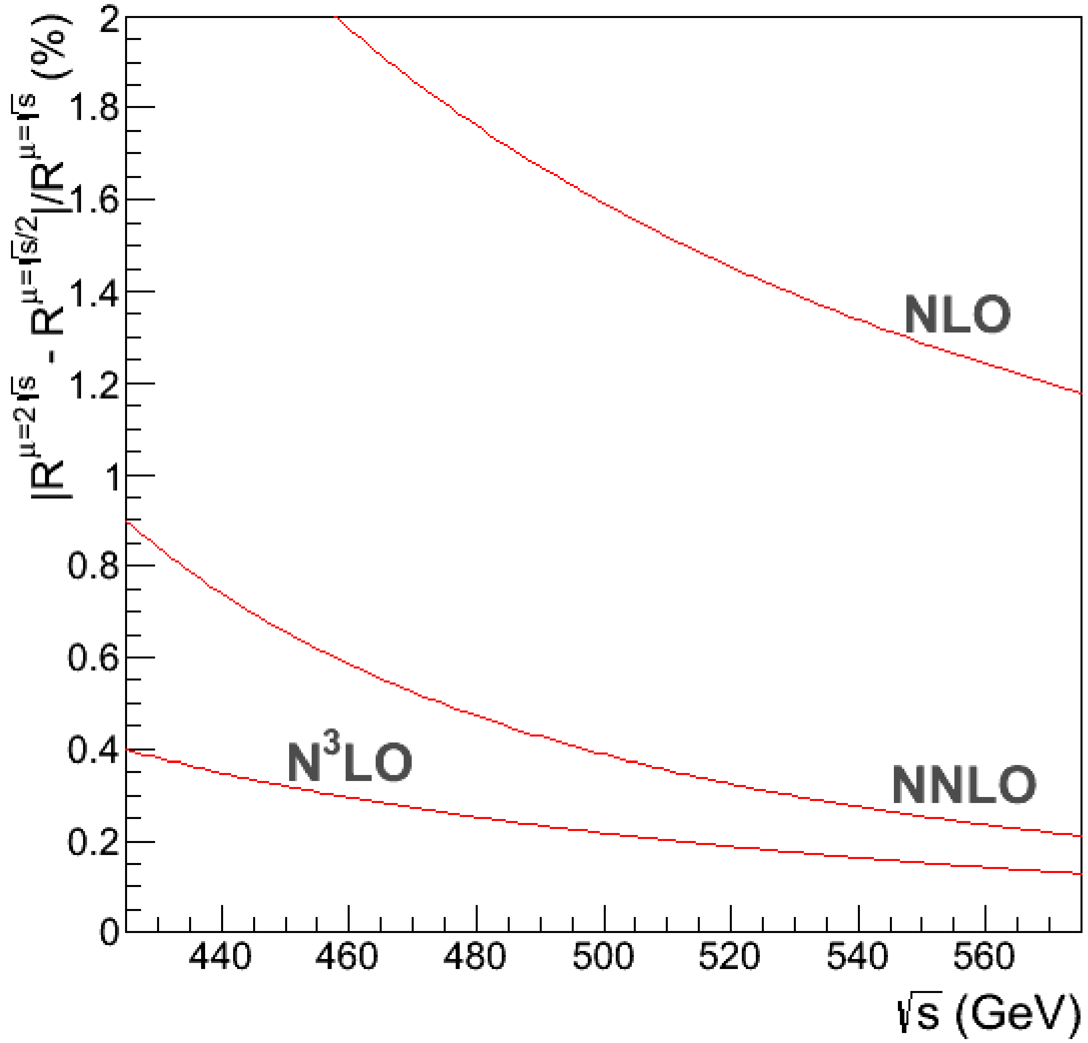
Top quark pair production in the continuum



tt production at ILC:
σ~0.6 pb
at √s = 500 GeV
~0.2 pb
at √s = 1000 GeV

300.000 tt̄ events in 4 years @ 500 GeV

Variation in predicted x-section due to scale variations



A 5% uncertainty in the cross-section prediction at the LHC is impressive, but for true precision there is nothing like e^+e^-

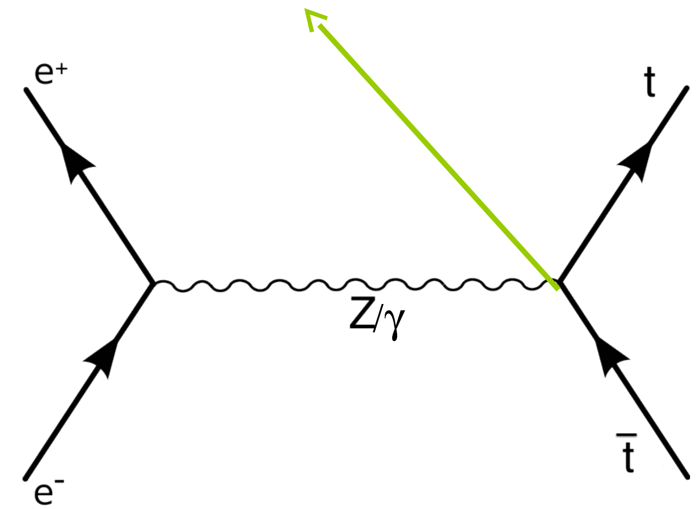
However, one-loop electroweak corrections are sizable

Action: estimate size of two-loop corrections

Electroweak couplings

The current at the $t\bar{t}X$ vertex:

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



At the LHC electroweak production cannot be isolated, but vertex can be probed in **associated production**

CMS establishes $t\bar{t}V$ signal at 4.7 σ (V=W,Z)
$\sigma(t\bar{t}Z)$ = 0.28 +0.14 -0.11 (stat) +0.06 -0.03 (syst)
PRL 110 (2013) 172002

Nacho García

Long-term LHC prospects by Baur, Juste et al. (Snowmass 2005) Phys.Rev. D71 (2005) 054013

For a good argument to measure the top magnetic moment, see Lance Labun's talk.

Electroweak couplings

Measure 6 observables, extract 5 form factors

Nacho García
Gudrid Moortgat-Pick

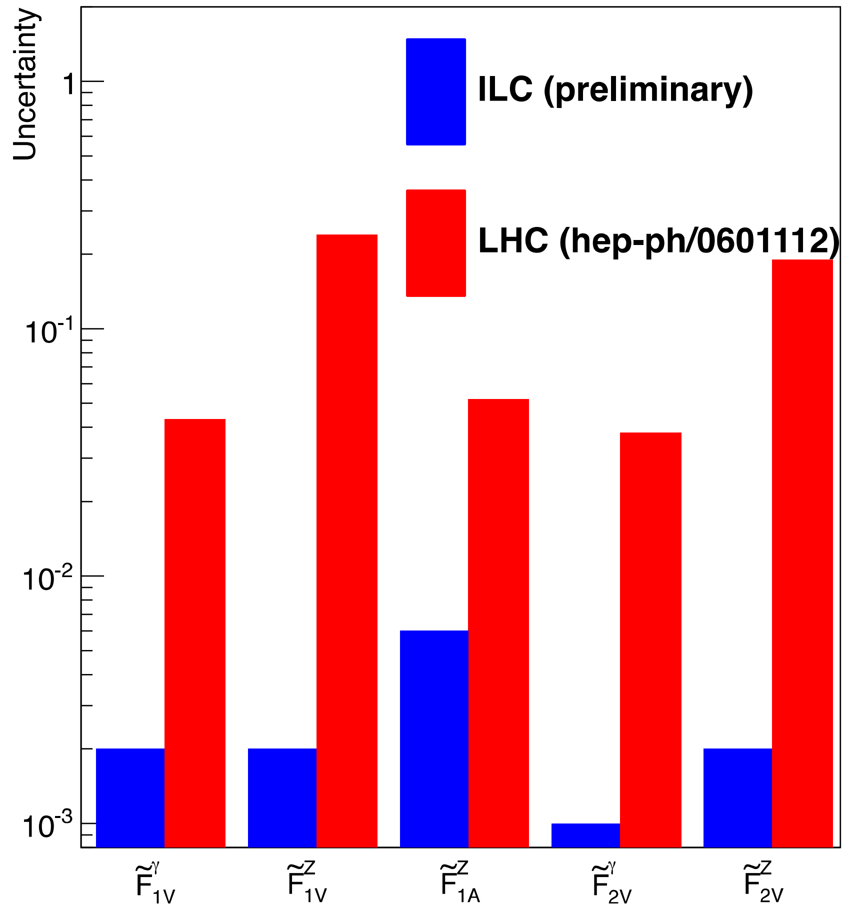
$$\left.\begin{matrix} \sigma(+) & A_{FB}(+) & \lambda_{hel}(+) & (+ = e^-_R) \\ \sigma(-) & A_{FB}(-) & \lambda_{hel}(-) & (- = e^-_L) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F^{\gamma}_{1V} & * & F^{\gamma}_{2V} \\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V} \end{matrix}\right\}$$

The cross section can be measured to 0.5% (stat. + lumi)

The forward-backward asymmetry to 2% (stat. + syst.)

The slope of helicity distribution to ~4% (stat. + syst.)

LC-REP-2013-007



500/fb at 500 GeV yields 1-2 orders of magnitude better sensitivity than the LHC (300/fb at 14 TeV)

Similar results to TESLA TDR, but:
- simultaneous extraction of photon and Z form factors
- full simulation & reconstruction
- discussion of systematic effects
    (knowledge of polarization, energy, ...)

Summary

Two highlights of the LHC top programme:

Precise top quark mass (100 MeV) with rigorous interpretation

Precise top quark electroweak couplings

$\delta F_{1V}^{\gamma,Z}, \delta F_{1A}^{\gamma,Z}$ ~1% An order of magnitude better than LHC prospects!

All LC strong points conspire to achieve this:

- calculability, theory errors at few per mil level
- controlled initial state, center-of-mass energy and polarization
- excellent detectors to reduce exp. systematics

These prospects now rest on even more solid ground:

– full simulation & sophisticated reconstruction

– Evaluation of dominant systematic uncertainties