Measurement of the Top Mass in a Threshold Scan at Linear Colliders

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Outline

Motivation & the goal

Top quark mass:

- cannot be calculated from the Standard Model, it is an input parameter
- important for calculation of electroweak radiative corrections
- connected to strong coupling constant, Higgs Yuakawa coupling, Higgs mass, etc.
- is not unambiguously defined

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⇒ determination of statistical and systematical uncertainties of the top quark mass and the strong coupling constant measurements at future linear colliders

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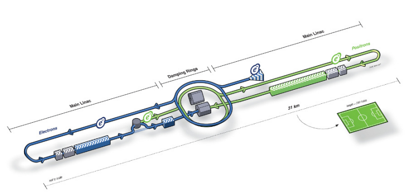
Method: scan of top quark production cross-section around production threshold energy (2$\times$ Top mass)

Future linear e^+e^- colliders

International Linear Collider (ILC):

- $\sqrt{s} = 500$ GeV, length 31 km
- $\sqrt{s} = 1$ TeV, length 53 km (upgrade)
- two interchangeable detector systems
- super-conducting RF cavities



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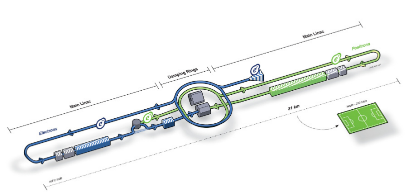
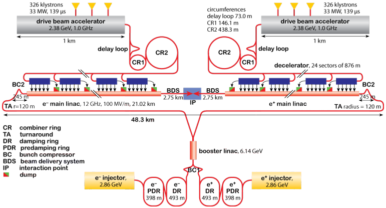


Compact Linear Collider (CLIC):



- $\sqrt{s} =$500 GeV, length 13 km
- $\sqrt{s} =$3 TeV, length 48 km (3rd stage)
- “two beam acceleration”
- 0.5 ns bunch spacing

Top mass measurement alternatives

- Top mass is not unambiguously defined

$\Rightarrow$ cross-check of several measurement methods needed

Invariant mass reconstruction

+ experimentally well defined
+ can be conducted at any above-threshold energy
+ high integrated luminosity
- cannot determine which Top mass was measured

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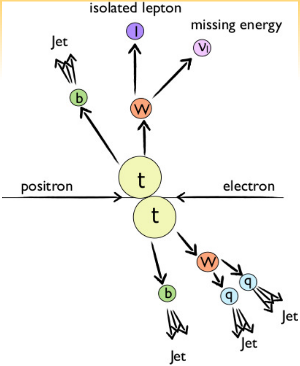
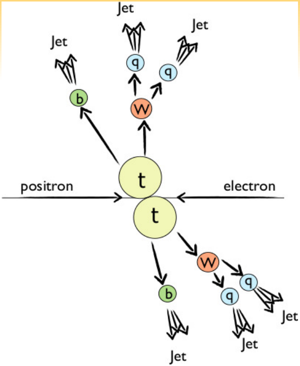
Threshold scan:

+ theoretically well understood
+ potential of simultaneous measurement of correlated quantities
+ together with known Top invariant mass can shed light on Top mass definitions
- needs a dedicated accelerator run

Top decays used for reconstruction



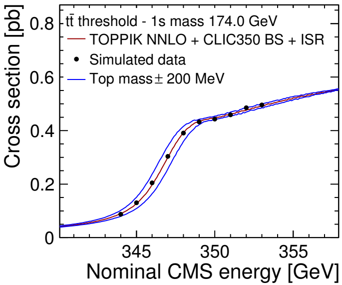


- 4-jet final state (BR = 45%)
- identified by isolated lepton and *b*-jet

- 6-jet final state (BR = 46%)
- identified by *b*-jet and reconstructed jet energy originating from *W* decay

Strategy of the threshold scan template fit

- top quark production cross-sections are "measured" around the expected $t\bar{t}$ pair creation threshold



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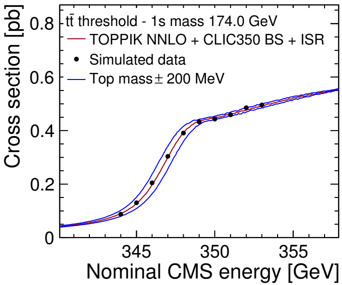
$\Rightarrow$ fit template



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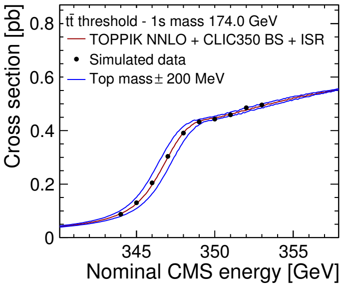

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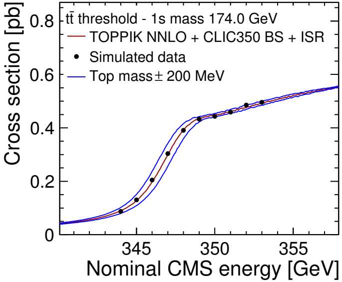
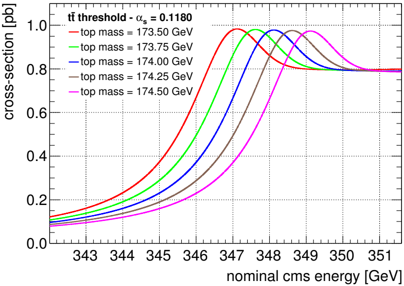
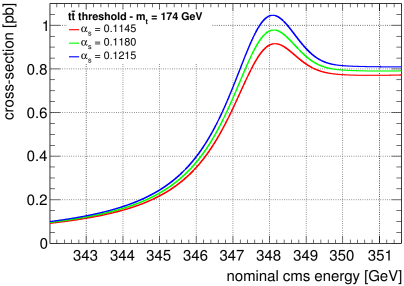


$t\bar{t}$ production cross-section generator

- theory based next-to-next-to-leading order (NNLO) calculation (“TOPPIK”)
- input parameters: Top mass, Top Width, strong coupling constant, Higgs mass, Yukawa coupling
- production channel: $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow t\bar{t}$



varying m_t



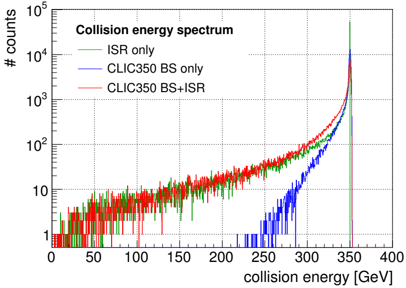
varying α_s

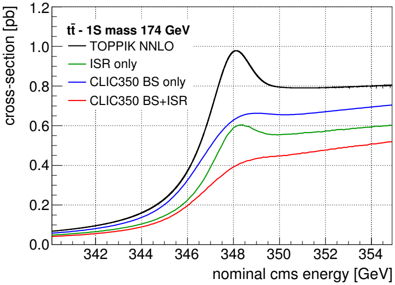
Effects of ISR and BS on cross-section shape

to get $t\bar{t}$ production cross-section at a e^+e^- collider, two effects have to be taken into account

- Initial State Radiation (ISR)
- Beam Spectra (BS)

these two distributions are folded with pure physical cross-section





Template χ^2 fit

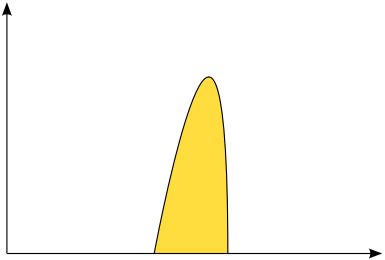
σ_n^{meas} .... measured cross-section

$\sigma_n^{template}$ ..... simulated cross-section

Γ_n^{meas} .... measured cross-section uncertainty

in n-th energy bin

$$\chi^2 = \sum_n^{Nbins} \left(\frac{\sigma_n^{meas} - \sigma_n^{template}}{\Gamma_n^{meas}} \right)^2$$



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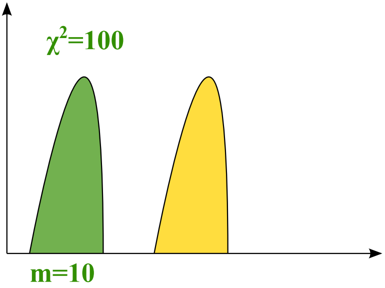

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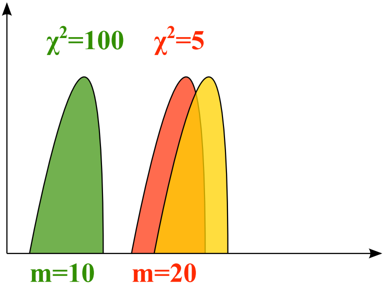

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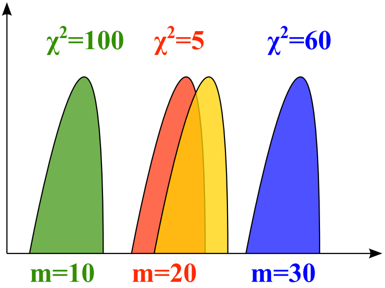

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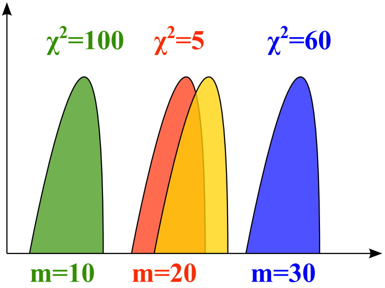

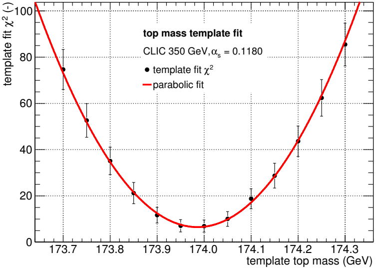

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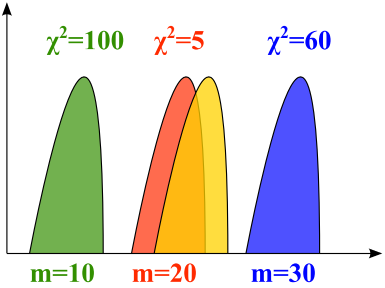
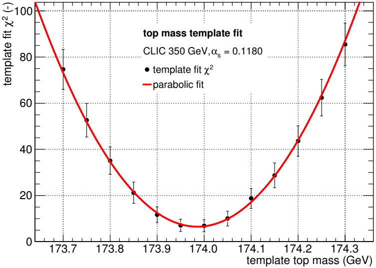




Repeat the fit 5000× with different measurement sets

⇒ statistical uncertainty

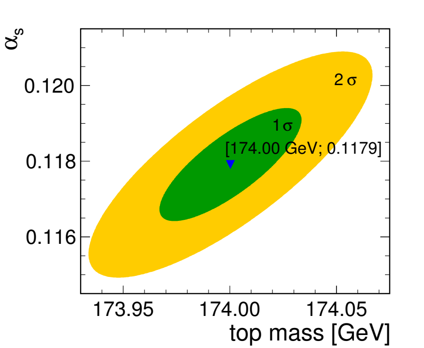
Top threshold scan results (at CLIC)

Simulation input

- $m_t = 174.000$ GeV
- $\alpha_s = 0.1180$

Simultaneous fit of m_t and α_s

- $m_t = 173.999 \pm 0.034$ GeV
- $\alpha_s = 0.1179 \pm 0.0009$



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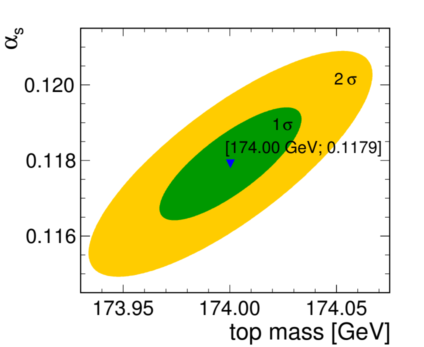

Further studies done:

- systematics induced by α_s and theory uncertainties
- influence caused by scan points position and number
- sensitivity to Top width, Yukawa coupling and Higgs mass

Summary

Future e^+e^- colliders:

- linear accelerators with program from 250 to 3000 GeV (ILC, CLIC)
- equipped with highly precise tracking systems and highly granular calorimeters to reach excellent jet-energy resolution
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Top threshold scan:

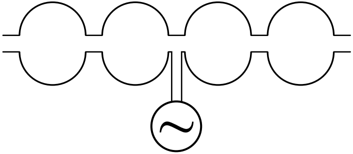
- $t\bar{t}$ pair production cross section measured around production threshold
- top quark mass can be extracted from that curve
- simulation for the CLIC and ILC has been completed
- top quark mass and strong coupling constant α_s have been obtained with a help of the template fit technique

Backup slides

Accelerating principles

ILC:

- should use technology of classical super-conducting RF cavities
- average electrical field gradient for $\sqrt{s} = 500$ GeV is 31.5 MV/m



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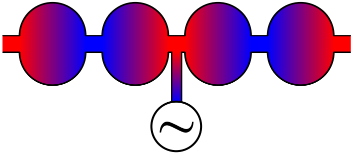

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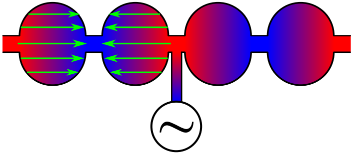

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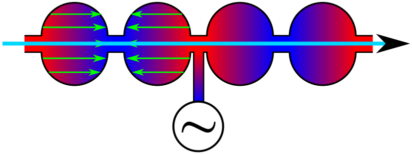

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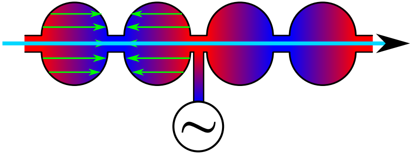

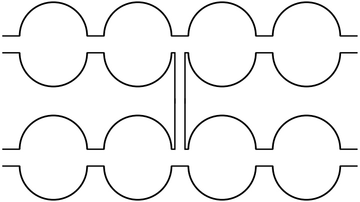

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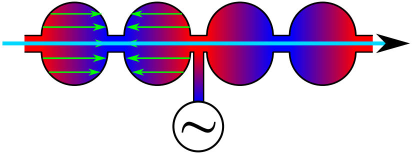

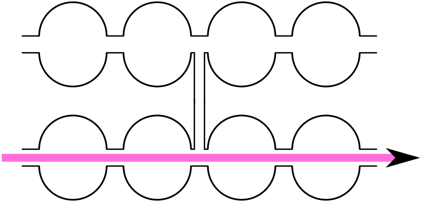

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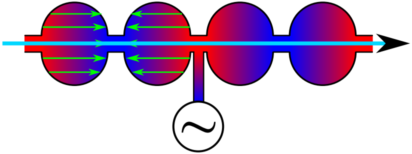

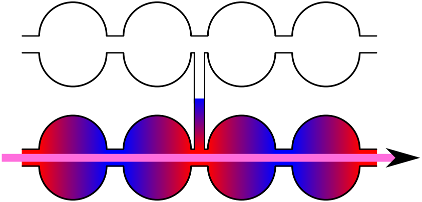

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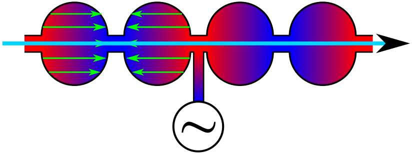

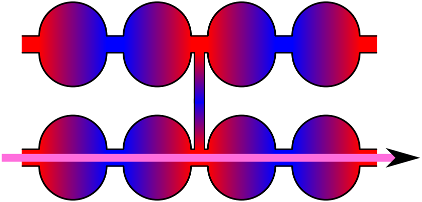

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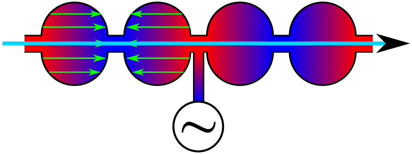

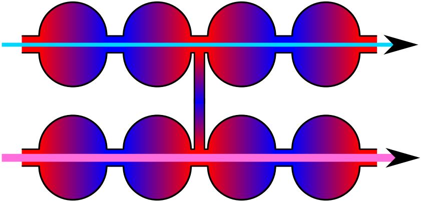

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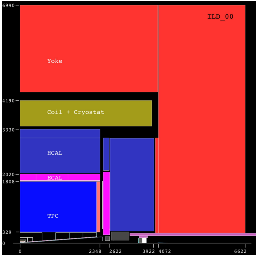
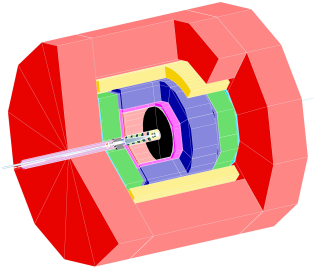
$\rightarrow$ high energy/low intensity beam

International Large Detector (ILD)

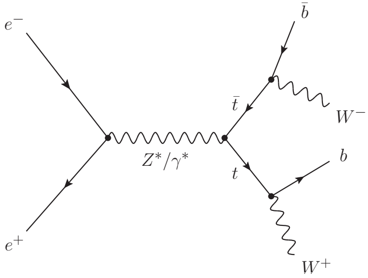
- effort of ILC and CLIC collaboration overlap extensively
- CLIC uses modified ILC detectors
- despite classical onion design of the detector, new concepts are employed to meet the demands
  - highly granular calorimeters
  - high resolution tracker

$\Rightarrow$ excellent jet energy resolution





Top quark properties



- mass: $m_t = 172.0 \pm 0.6_{(stat)} \pm 0.8_{(syst)}$ GeV
- width: $\Gamma_t < 13.1$ GeV
- lifetime: $\tau_{life} = 10^{-24}$ s
- hadronization time: $\tau_{had} = 10^{-23}$ s

$\Rightarrow$ decays before hadronization

$\Rightarrow$ Top mass can be measured directly by reconstructing decay products' invariant mass

- $t\bar{t}$ production cross-section (at $\sqrt{s_{e^+e_-}} = 2m_t$): 960 fb
- decay mode: $t \rightarrow Wb$, $BR > 96\%$

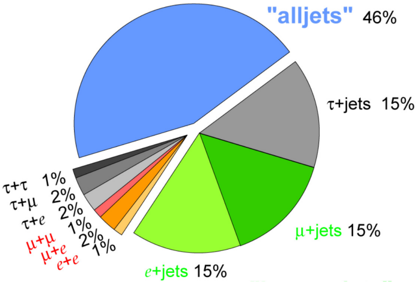
Top quark mass definitions

- pole mass
  - defined as the pole of the renormalized quark propagator for $p \to M$ ("rest mass")
  - has an internal ambiguity $\sim \Lambda_{QCD}$
  - usage at low energies is not completely correct
- $\overline{\mathrm{MS}}$ mass
  - obtained from "Minimal Subtraction" renormalization scheme
  - fits for calculations with energetic quarks
- $1S$ mass
  - defined as half of the mass of fictitious $^3S_1$ toponium ground state for a stable quark
  - position of the total $t\bar{t}$ production cross section peak remains stable if expressed in terms of $1S$ mass

Top decay products

- *b* quark creates always a *b*-jet

⇒ event signature is entirely given the *W* boson decay:



Hadron colliders:

- hard to pick out $t\bar{t}$ pairs from QCD background
- one and two-lepton final states are used

Lepton colliders:

- $t\bar{t}$ pairs easy to identify
- concentrate on large branching fractions
- low missing energy

Top mass reconstruction: signal and background at $\sqrt{s} = 350$ GeV

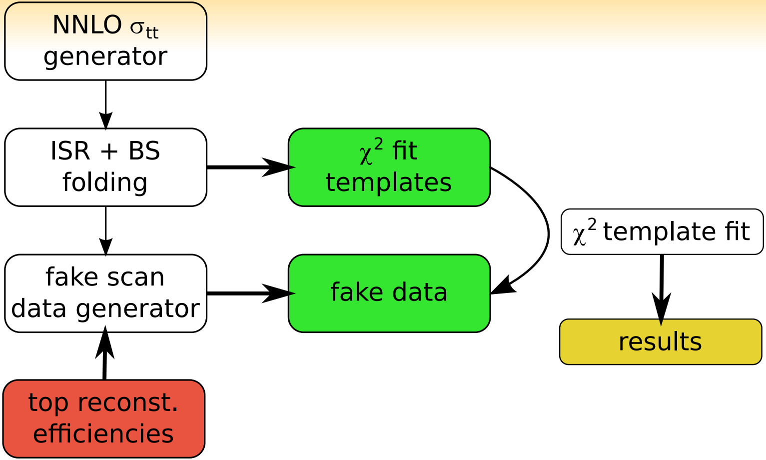
- signal and background events were simulated
- highly optimized Top reconstruction has been conducted

$\Rightarrow$ resulting Top reconstruction- and background rejection efficiencies were used for further simulation

process type	$e^+e^- \rightarrow$	cross-section* σ (fb)
signal	$t\bar{t}$	400
background	WW	11400
background	ZZ	673
background	WWZ	10
background	$q\bar{q}$	24500

* cross-sections corrected for Initial State Radiation (ISR) and beam spectrum

Simulation procedure scheme



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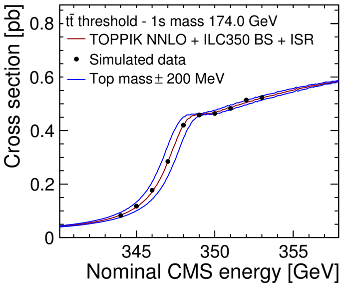
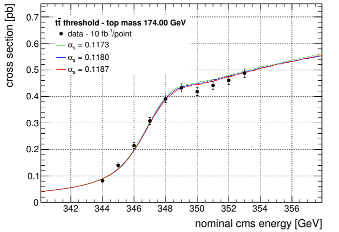
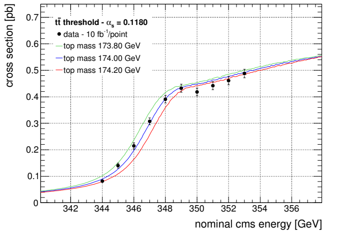
- top mass and α_s are extracted from the fits
- in principle, also further parameters fan be fitted, but would need higher measurement precision



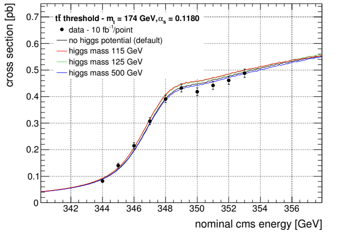
$\sigma t\bar{t}$ sensitivity to input parameters



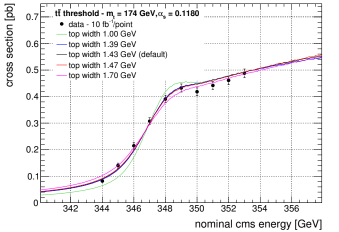
strong coupling const. α_s



Top mass m_t



Higgs mass m_H



Top width Γ_t

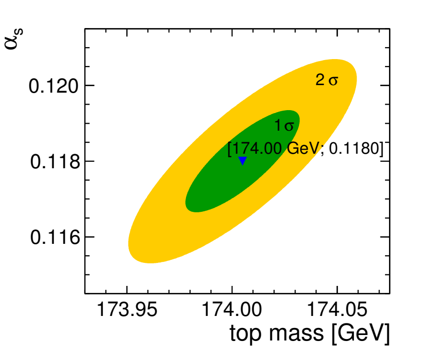
Top threshold scan results (at ILC)

Simulation input

- $m_t = 174.000$ GeV
- $\alpha_s = 0.1180$

Simultaneous fit of m_t and α_s

- $m_t = 174.005 \pm 0.027$ GeV
- $\alpha_s = 0.1180 \pm 0.0008$



Further studies done:

- systematics induced by α_s and theory uncertainties
- influence caused by scan points position and number
- sensitivity to Top width, Yukawa coupling and Higgs mass