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

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MAX-PLANCK-GESELLSCHAFT

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.
- issues regarding top mass definitions

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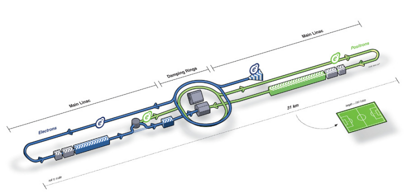
Method: $t\bar{t}$ production threshold scan

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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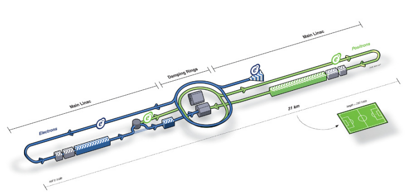
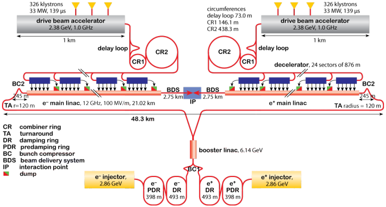


Compact Linear Collider (CLIC):

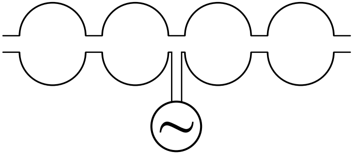


- $\sqrt{s}$ =500 GeV, length 13 km
- $\sqrt{s}$ =3 TeV, length 48 km (3rd stage)
- “two beam acceleration”
- 0.5 ns bunch spacing

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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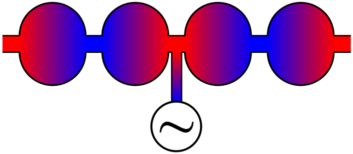

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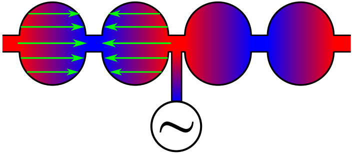

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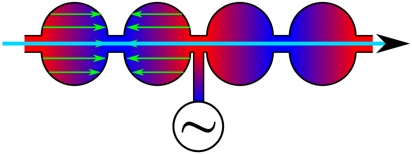

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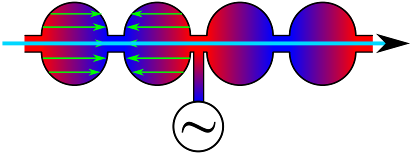

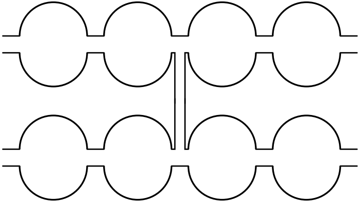

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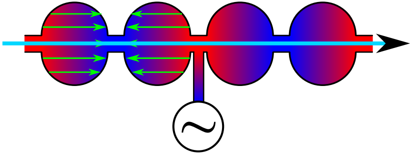

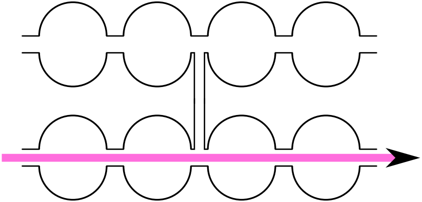

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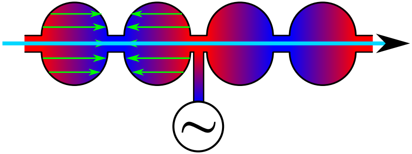

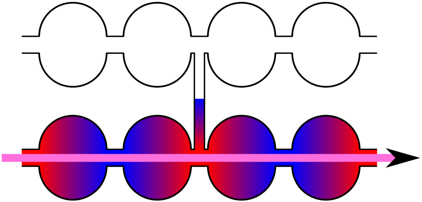

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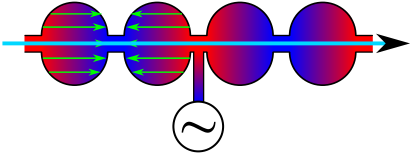

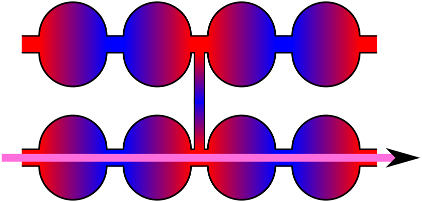

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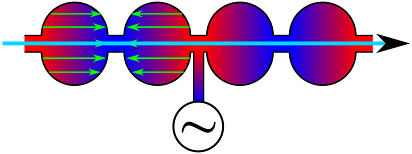

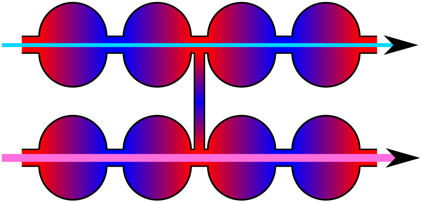

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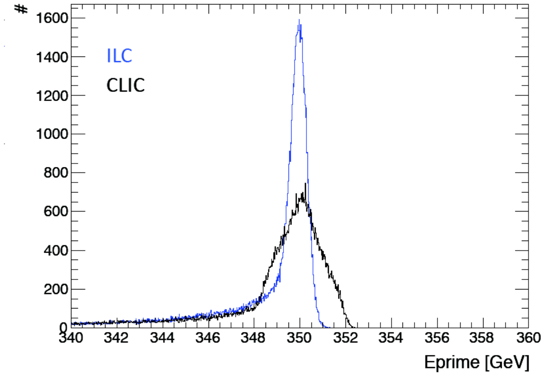
ILC anc CLIC beam spectra (BS)



- the CLIC beam spectrum has a broader peak then ILC BS

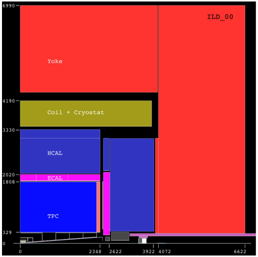
Question:

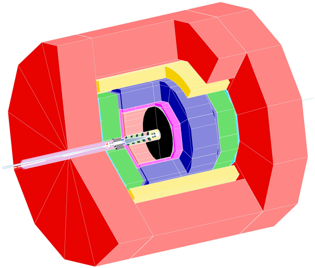
is it possible at all to conduct a top threshold scan at the CLIC?

International Large Detector (ILD)

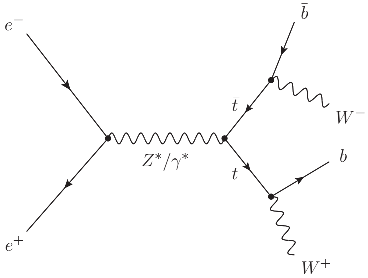
- effort of ILC and CLIC collaboration overlap extensively
- CLIC uses modified ILC detectors
- despite classical onion design of the detector, new concepts are employed to meet the demands
  - highly granular calorimeters
  - high resolution tracker

$\Rightarrow$ excellent jet energy resolution





Top quark properties



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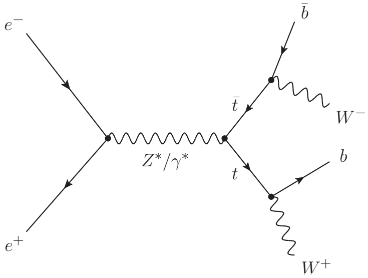

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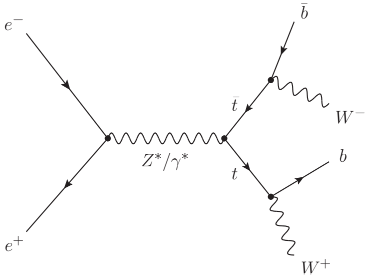

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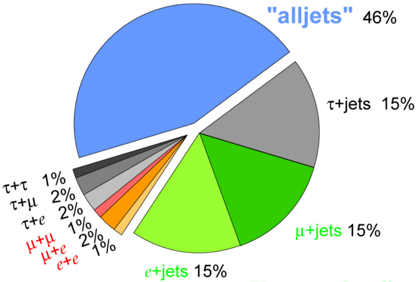
Top decay products

- b quark creates always a b-jet

⇒ event signature is entirely given the W boson decay:



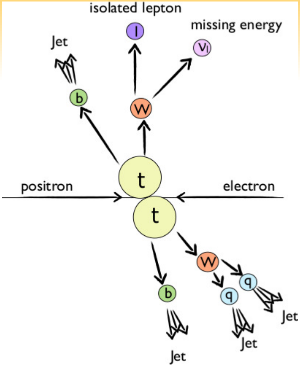
Hadron colliders:

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

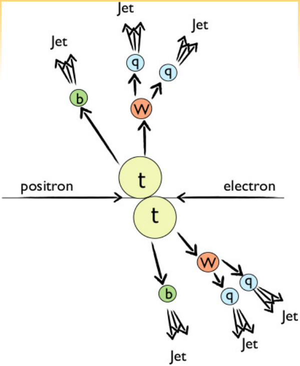
Lepton colliders:

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

W 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

Top quark mass definitions

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  - has an internal ambiguity $\sim \Lambda_{QCD}$
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- $1S$ 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 quark reconstruction

- top quark decays ($t \rightarrow Wb$) before it hadronizes

$\Rightarrow$ its mass can be determined directly from its decay products

- $W \rightarrow$ 2 jets or jet + lepton
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Hadron accelerators

- experiments must deal with high QCD background

$\Rightarrow$ usually, final states with one or two leptons are used for the analyses

$\Rightarrow$ missing energy taken out by neutrino

$\Rightarrow$ lower total branching fraction $\to$ lower integrated luminosity

Top quark measurement at linear lepton colliders

- lepton collider experimental conditions are favorable for the top mass measurement
  - low background compared to hadron colliders
  - better defined initial state of the collision
- thanks to low background at e^+e^- accelerators, so called "particle flow" algorithms can be employed

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Two top mass measurement alternatives:

- invariant mass reconstruction
- threshold scan

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
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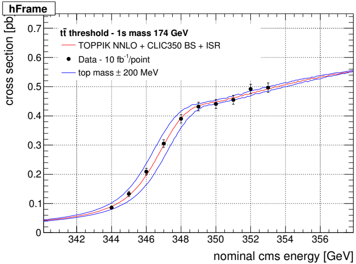
Threshold scan:

+ 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 (Higgs measurements also possible)

Principle 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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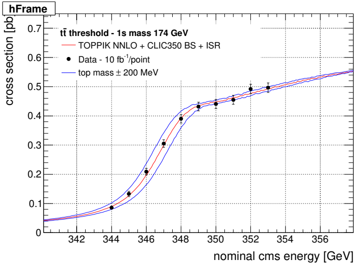
$\Rightarrow$ fit template



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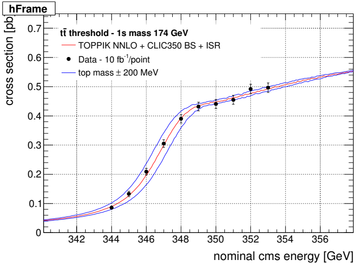
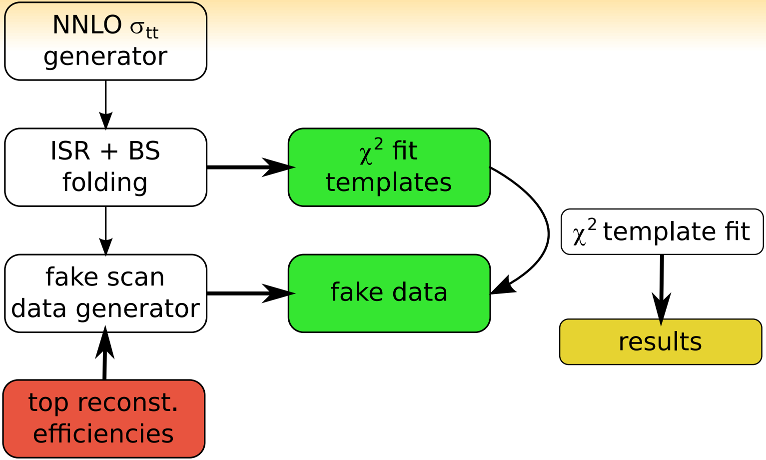
- the “measured” data points are fitted with the templates
- top mass and α_s are extracted from the fits



Simulation procedure scheme



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

- signal and background events were simulated
- highly optimized top reconstruction has been conducted (by Katja Seidel)

process type	$e^+e^- \to$	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

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

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⇒ resulting top reconstruction- and background rejection efficiencies were used for further simulation

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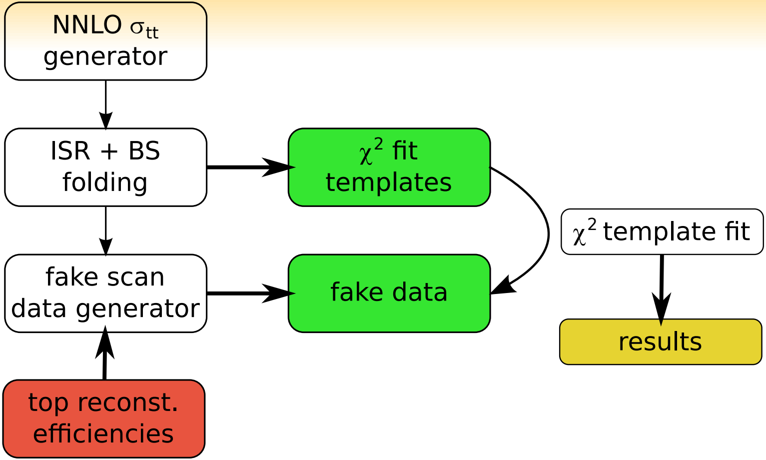
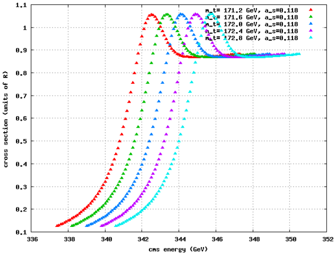
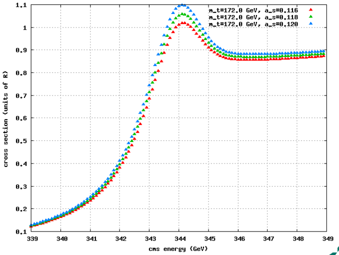


$t\bar{t}$ production cross-section generator

- theory based next-to-next-to-leading order (NNLO) calculation ("TOPPIK" by Hoang & Teubner, Phys.Rev.D60:114027,1999)
- input parameters: top mass, top Width, strong coupling constant, Higgs mass, Yukawa coupling, (LO, NLO, NNLO)
- production channel: $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow t\bar{t}$



varying m_t



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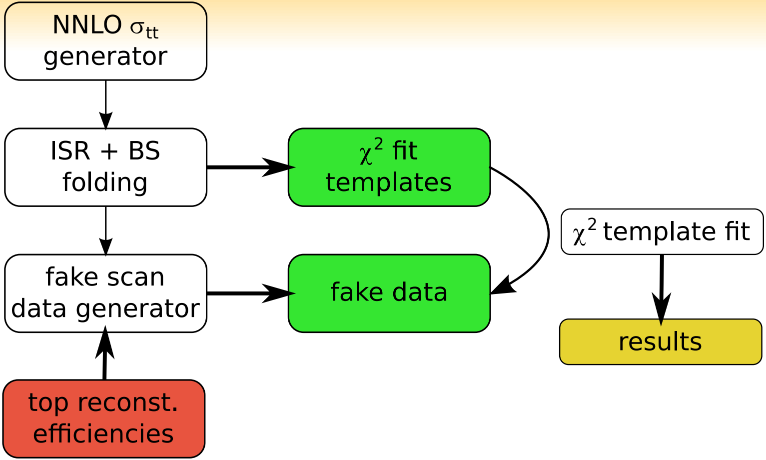
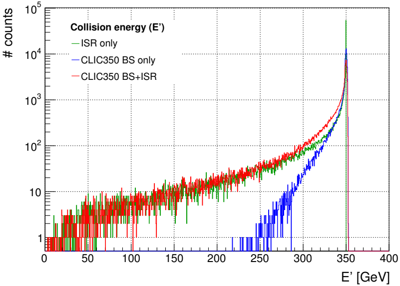


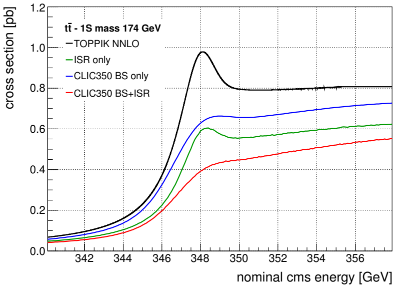
Effects of ISR and BS on cross-section shape

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





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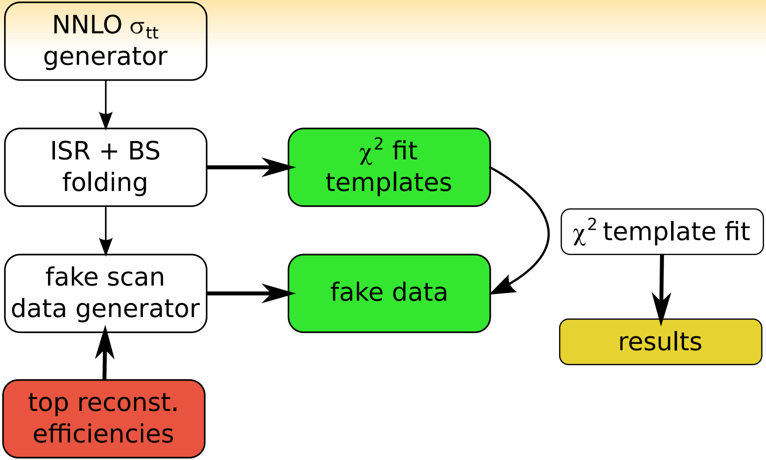

Template χ^2 fit

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

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

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

in n-th energy bin

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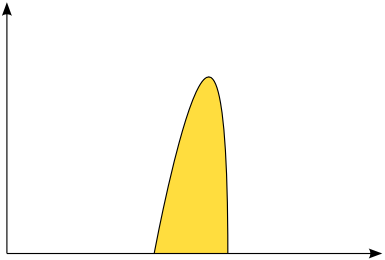

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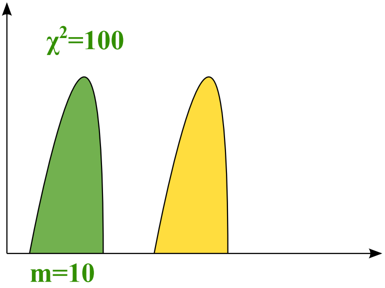

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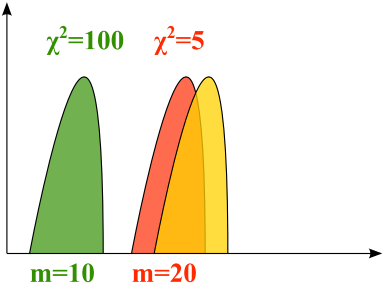

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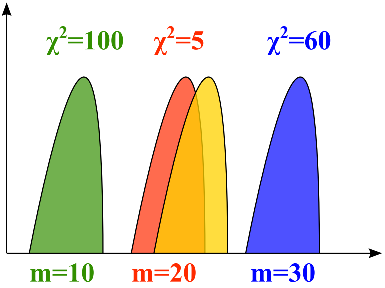

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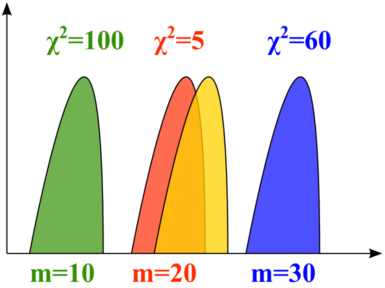
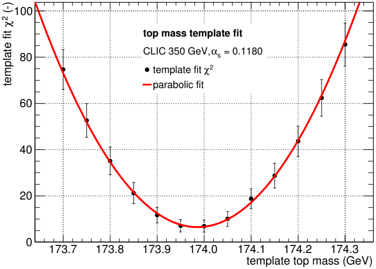




Template χ^2 fit

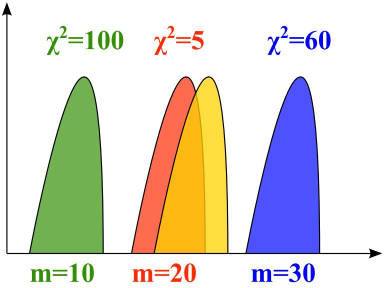
σ_n^{meas} .... measured cross-section

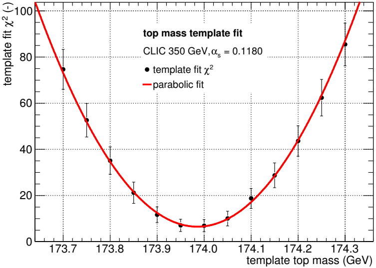
$\sigma_n^{template}$ ..... simulated cross-section

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

in n-th energy bin

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





Repeat the fit 5000× with different measurement sets

⇒ statistical uncertainty

Recent hadron collider uncertainties of the top mass

CDF, Tevatron

$$\delta m_t^{(inv)} = 510_{(\mathrm{stat.})} \oplus 710_{(\mathrm{syst.})}\,\mathrm{MeV}$$

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CMS, LHC

$$\delta m_t^{(inv)} = 380_{(\mathrm{stat.})} \oplus 910_{(\mathrm{syst.})}\,\mathrm{MeV}$$

$$\Rightarrow\ \delta m_t^{(\overline{\mathrm{MS}})} = \mathcal{O}(1)\,\mathrm{GeV}$$

CLIC threshold scan uncertainties

1D fit result (external input: $\delta\alpha_s = 0.0007$, $\alpha_s = 0.1180$)

$$\delta m_t^{(1S)} = 21_{(\text{stat.})} \pm 6_{(\text{thr. syst.})} \pm 11_{(\text{bkg. syst.})} \pm 21_{(\alpha_s\ \text{syst.})}\ \text{MeV}$$

$$\delta m_t^{(1S)} = 21_{(\text{stat.})} \oplus 43_{(\text{syst.})}\ \text{MeV}$$

$$\Rightarrow\ \delta m_t^{(\overline{\text{MS}})} = 100\ \text{MeV}$$

CLIC threshold scan uncertainties

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$$\delta m_t^{(1S)} = 21_{\text{(stat.)}} \pm 6_{\text{(thr. syst.)}} \pm 11_{\text{(bkg. syst.)}} \pm 21_{(\alpha_s\,\text{syst.})}\,\text{MeV}$$

$$\delta m_t^{(1S)} = 21_{\text{(stat.)}} \oplus 43_{\text{(syst.)}}\,\text{MeV}$$

$$\Rightarrow\ \delta m_t^{(\overline{\text{MS}})} = 100\,\text{MeV}$$

2D fit result (from fit: $\delta\alpha_s = 0.0015$)

$$\delta m_t^{(1S)} = 33_{\text{(stat.)}} \pm 6_{\text{(thr. syst.)}} \pm 16_{\text{(bkg. syst.)}}\,\text{MeV}$$

$$\delta m_t^{(1S)} = 33_{\text{(stat.)}} \oplus 17_{\text{(syst.)}}\,\text{MeV}$$

$$\Rightarrow\ \delta m_t^{(\overline{\text{MS}})} = 142\,\text{MeV}$$

Conclusions

- Top threshold scan in feasible at the CLIC
- m_t statistical uncertainty for the ILC is by 22 % lower
- precise knowledge of the beam spectrum is more important than a narrow distribution

$\Rightarrow$ CLIC beam spectrum is good enough

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Further performed studies:

- sensitivity to top width, Yukawa coupling and Higgs mass is not high enough
- 1σ luminosity-spectrum-induced systematic uncertainty of the top mass is $\approx 6\,MeV$

Summary

Future e^+e^- colliders:

- linear accelerators with $\sqrt{s}$ of 500 to 3000 GeV (ILC, CLIC)
- equipped with highly precise tracking systems and highly granular calorimeters to reach excellent jet-energy resolution
- offer clean experimental environment for precise measurement of the top quark mass

Summary

Future e^+e^- colliders:

- linear accelerators with $\sqrt{s}$ of 500 to 3000 GeV (ILC, CLIC)
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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 can obtained with a help of the template fit technique
- statistical and systematical uncertainties detrmined