# Top quark threshold scan at future linear accelerators

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Max-Planck-Intitut für Physik

Young Scientist Workshop

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# Outline

1. Introduction
2. Future linear colliders
3. The top quark
4. Top threshold scan
5. Summary

# 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:** scan of top quark production cross-section around production threshold energy (2× Top mass)

# Top quark reconstruction

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

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

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## Hadron accelerators

- experiments must deal with high QCD background

⇒ usually, final states with one or two leptons are used for the analyses

⇒ missing energy taken out by neutrino

⇒ lower total branching fraction → 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

⇒ high jet energy resolution

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**Two Top mass measurement alternatives:**

- invariant mass reconstruction
- threshold scan

# Top mass measurement alternatives

- Top mass is not unambiguously defined

⇒ 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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**Invariant mass reconstruction**

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+ can be conducted at any above-threshold energy
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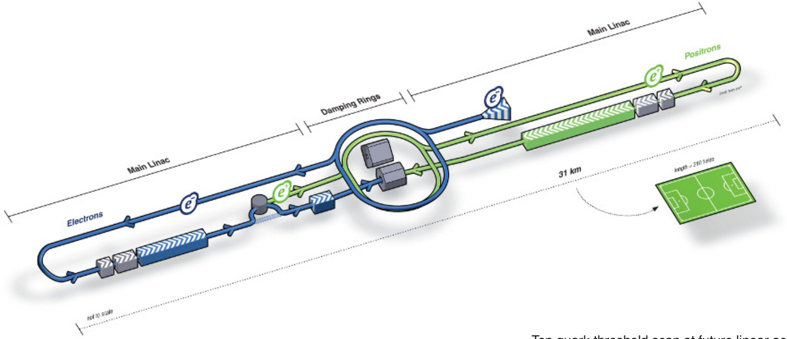
**Threshold scan:**

+ 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)

# International Linear Collider (ILC)

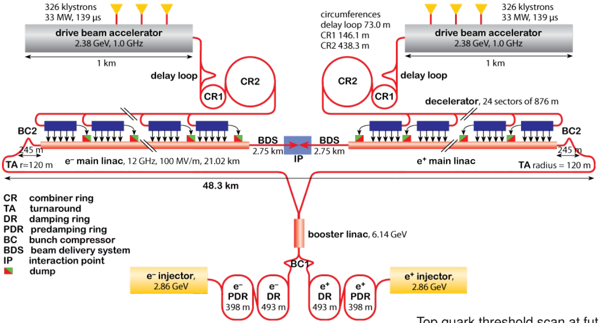
- $\sqrt{s} = 500$ GeV, length 31 km
- $\sqrt{s} = 1$ TeV, length ~53 km (after upgrade)
- two interchangeable detector systems
- acceleration by classical super-conducting RF cavities



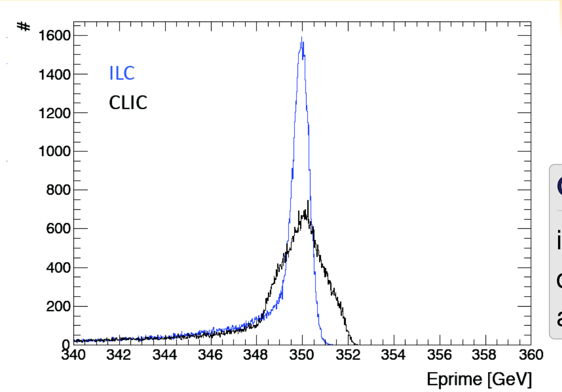
# Compact Linear Collider (CLIC)

- $\sqrt{s}$ =500 GeV, length 13 km (first construction stage)
- $\sqrt{s}$ =3 TeV, length 48 km (after extension)
- “two beam acceleration” technology
- extremely short bunch spacing (0.5 ns)

⇒ high demands on detector systems



# ILC anc CLIC beam spectra (BS)



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

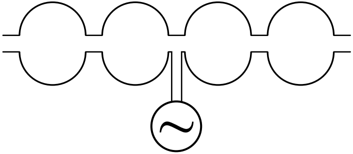
**Question:**

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

# 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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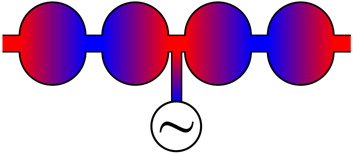

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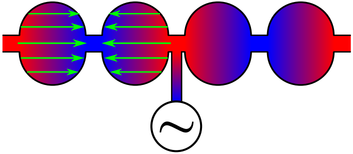

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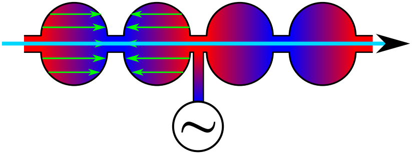

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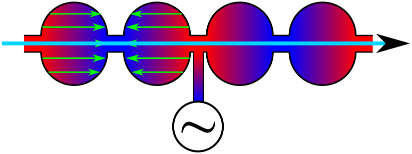

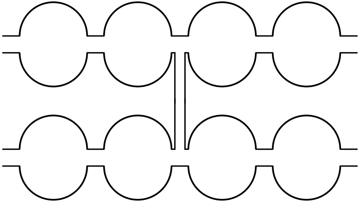

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- due to limitations of RF cavities:

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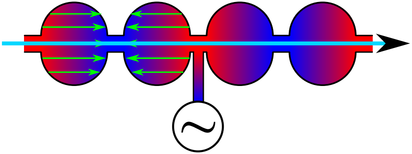

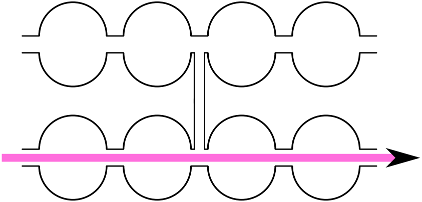

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- low energy/high intensity beam →

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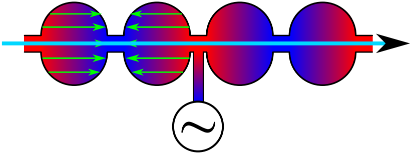

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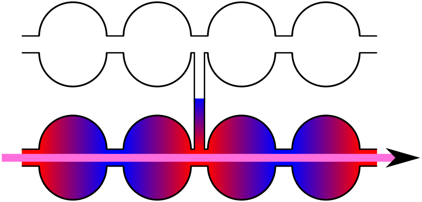

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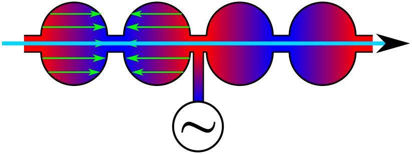

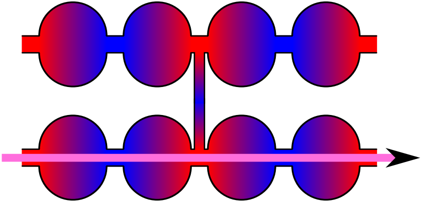

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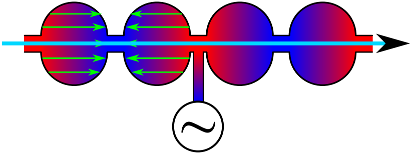

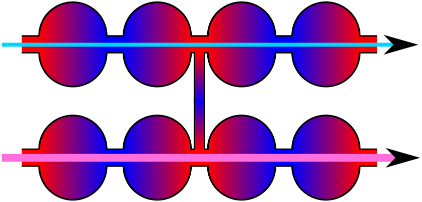

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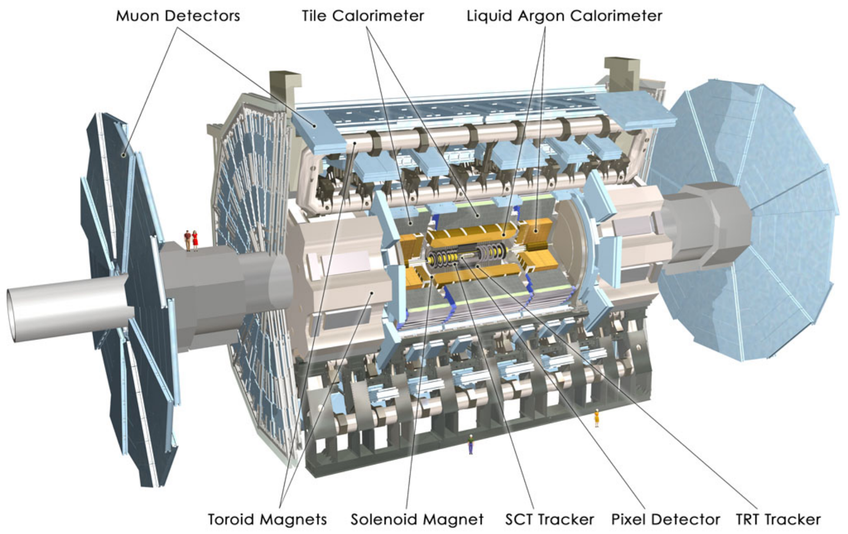
→ high energy/low intensity beam

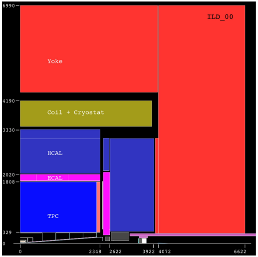
# The ATLAS detector

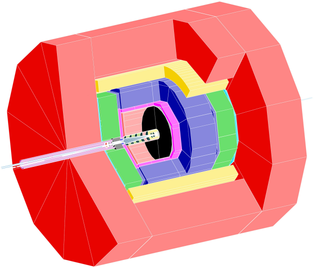


# International Large Detector (ILD)

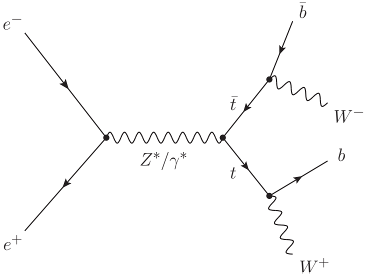
- effort of ILC and CLIC collaboration overlap extensively
- CLIC uses modified ILC detectors
- despite classical onion design of the detector, new concepts are employed to meet the demands
    - highly granular calorimeters
    - high resolution tracker

⇒ 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
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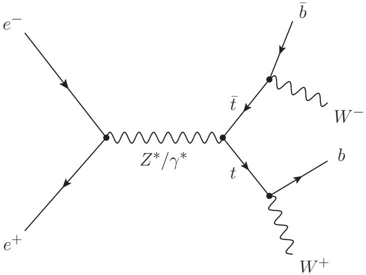

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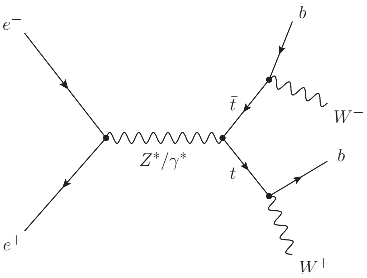

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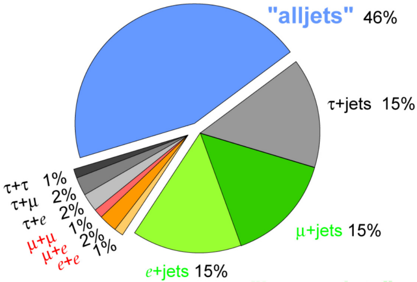
- $t\bar{t}$ production cross-section (at $\sqrt{s_{e^+e_-}} = 2m_t$): 960 fb
- decay mode: $t \rightarrow Wb$

# Top decay products

- $b$ quark creates always a $b$-jet

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



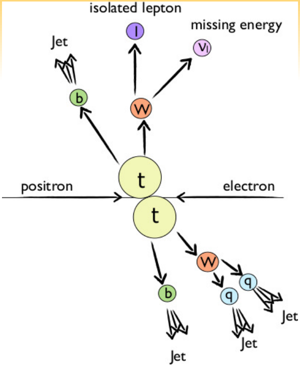
## Hadron colliders:

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

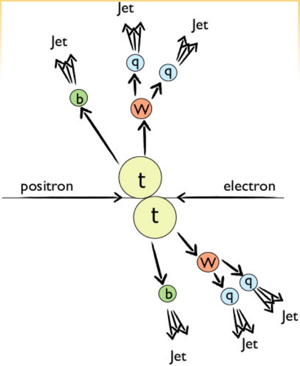
## Lepton colliders:

- $t\bar{t}$ 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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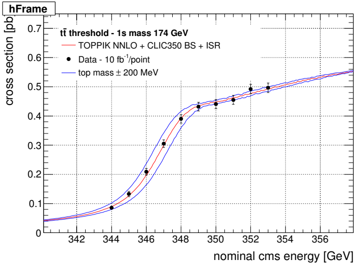
- $1S$ mass
  - defined as half of the mass of fictitious ${}^3S_1$ toponium ground state for a stable quark
  - position of the total $t\bar{t}$ production cross section peak remains stable if expressed in terms of $1S$ mass

# 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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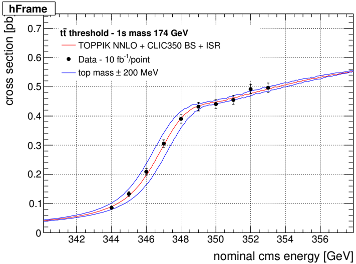
- in parallel, the many of these dependencies are simulated with different parameter values ($m_t$, $\alpha_s$, ...)

⇒ fit template



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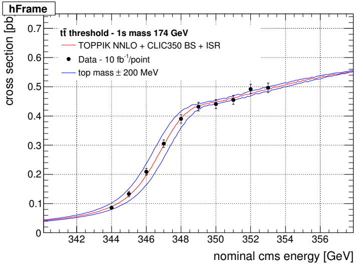
- the "measured" data points are fitted with the templates
- top mass and $\alpha_s$ are extracted from the fits



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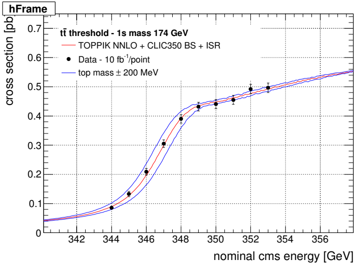
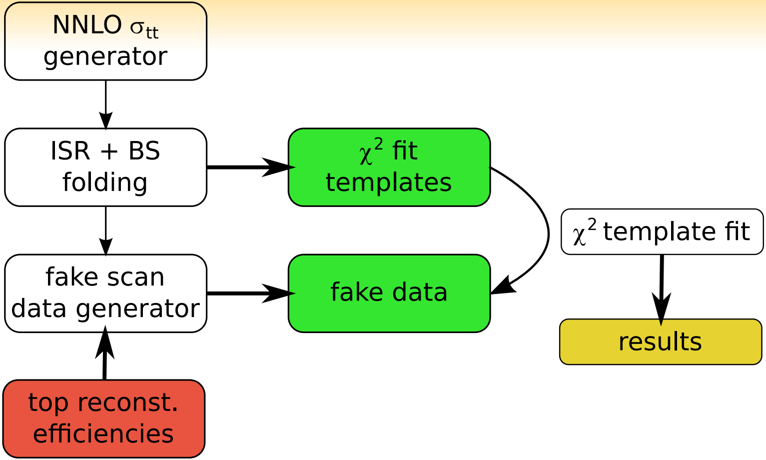
- in principle, also further parameters fan be fitted, but would need higher measurement precision



# Simulation procedure scheme



NNLO $\sigma_{tt}$ generator

ISR + BS folding

fake scan data generator

top reconst. efficiencies

$\chi^2$ fit templates

fake data

$\chi^2$ template fit

results

# 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 | $e^+e^- \rightarrow$ | cross-section* $\sigma$ (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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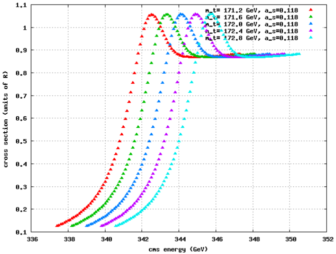
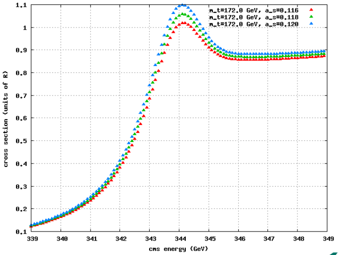
# $t\bar{t}$ production cross-section generator

- 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 $m_t$



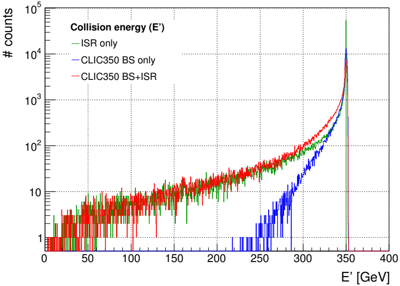
varying $\alpha_s$

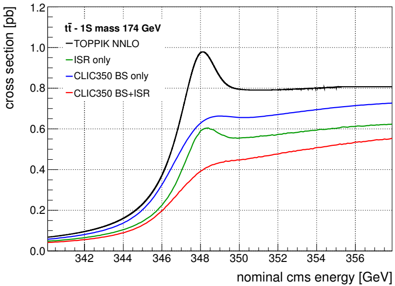
# Effects of ISR and BS on cross-section shape

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 $\chi^2$ fit

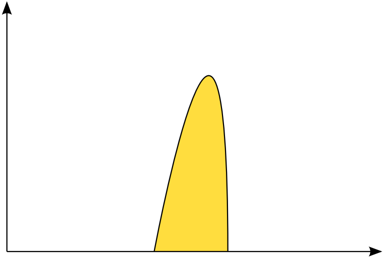
$\sigma_n^{meas}$ ....... measured cross-section

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

$\Gamma_n^{meas}$ ....... 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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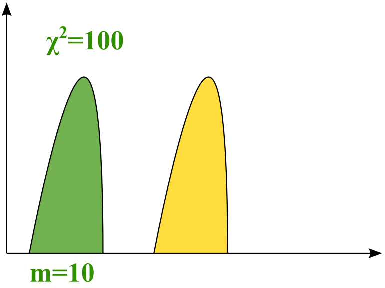

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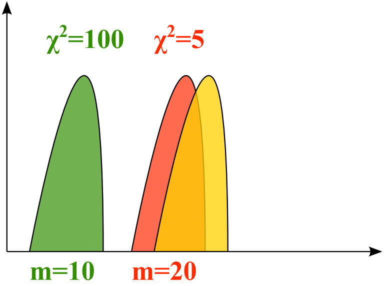

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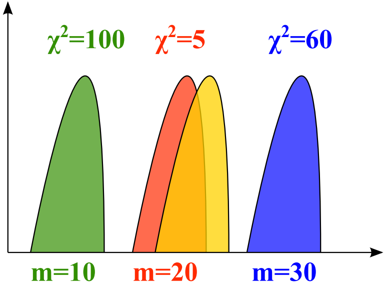

# Template $\chi^2$ fit

$\sigma_n^{meas}$ ....... measured cross-section

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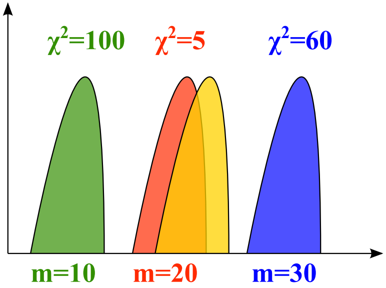

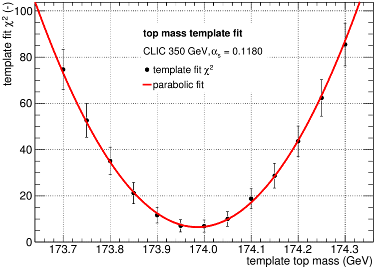

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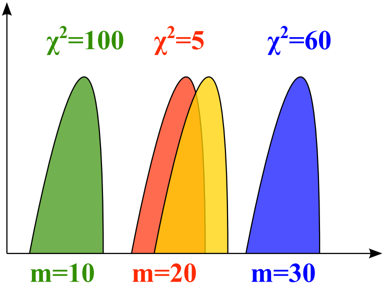
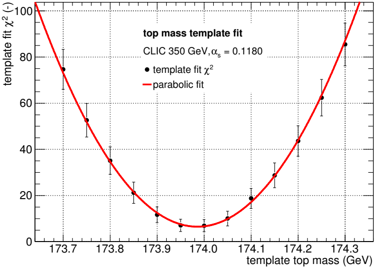




Repeat the fit 5000× with different measurement sets
⇒ statistical uncertainty

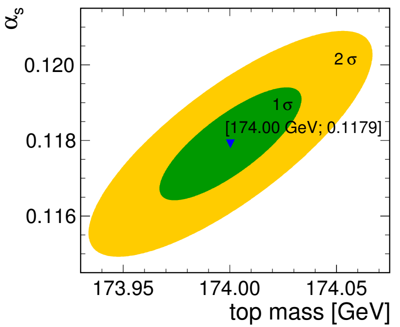
# Top threshold scan results

**Simulation input**

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

**Simultaneous fit of $m_t$ and $\alpha_s$**

- $m_t = 174.000 \pm 0.033$ GeV
- $\alpha_s = 0.1179 \pm 0.0009$



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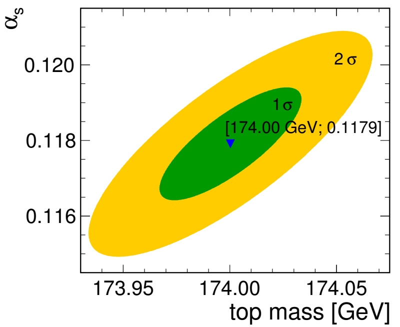

Further studies done:

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

# Systematics and beam effects

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

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# 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
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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 has been completed
- Top quark mass and strong coupling constant $\alpha_s$ have been obtained with a help of the template fit technique
- statistical and systematical uncertainties acquired too

# Thank you for your attention!