Top Quark Mass from Radiative Events

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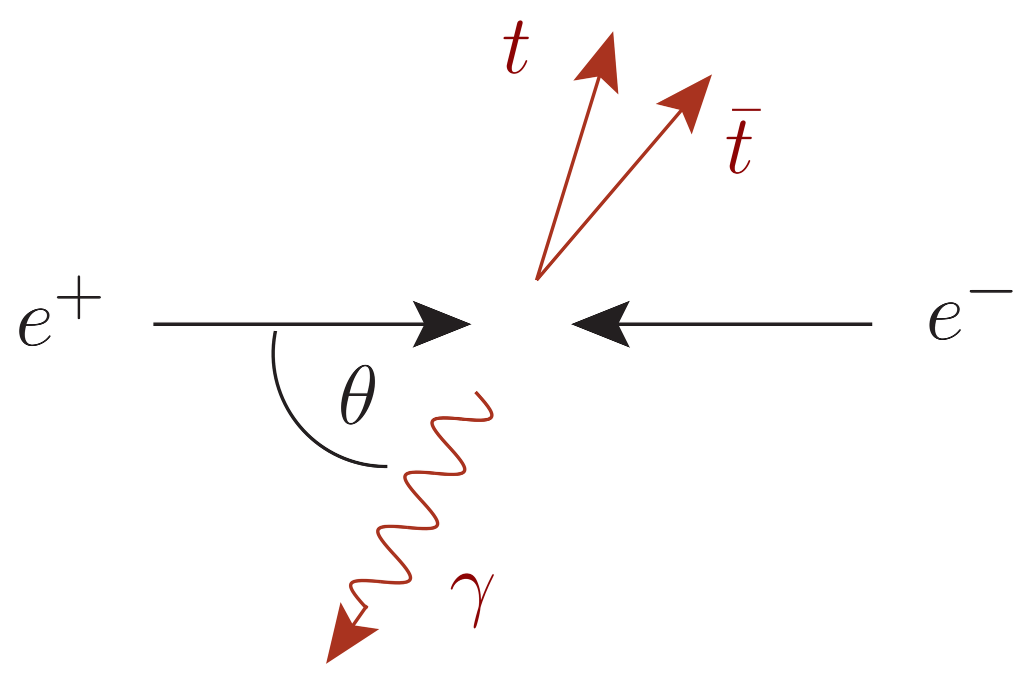
Doktoratskolleg Particles and Interactions

Main Results

1) Radiative events allow for high precision determinations of the top quark mass in a **well-defined short-distance mass scheme** ($\overline{\text{MS}}$ mass $\overline{m}_t(\overline{m}_t)$ or MSR mass $m_t^{\text{MSR}}(R)$) at the two planned high-energy linear colliders CLIC (Compact Linear Collider) and ILC (International Linear Collider) for center-of-mass (CM) energies $\sqrt{s}$ of 380 GeV and 500 GeV, respectively:

   - CLIC run at $\sqrt{s} = 380\text{ GeV}$: precision $\Delta m_t = 110\text{ MeV}$
   - ILC run at $\sqrt{s} = 500\text{ GeV}$: precision $\Delta m_t = 150\text{ MeV}$

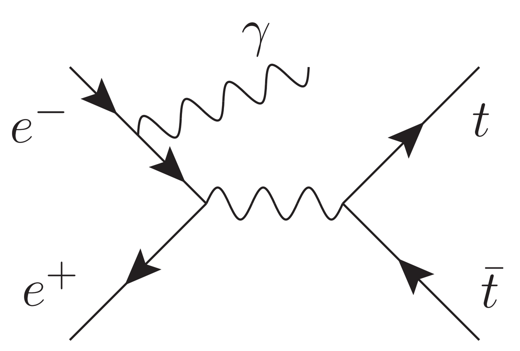
2) The running of the top quark MSR mass can be tested with a significance of over $5\,\sigma$ for the $\sqrt{s} = 500\text{ GeV}$ run of ILC.



Radiative Event at a Lepton Collider

1 Our Method

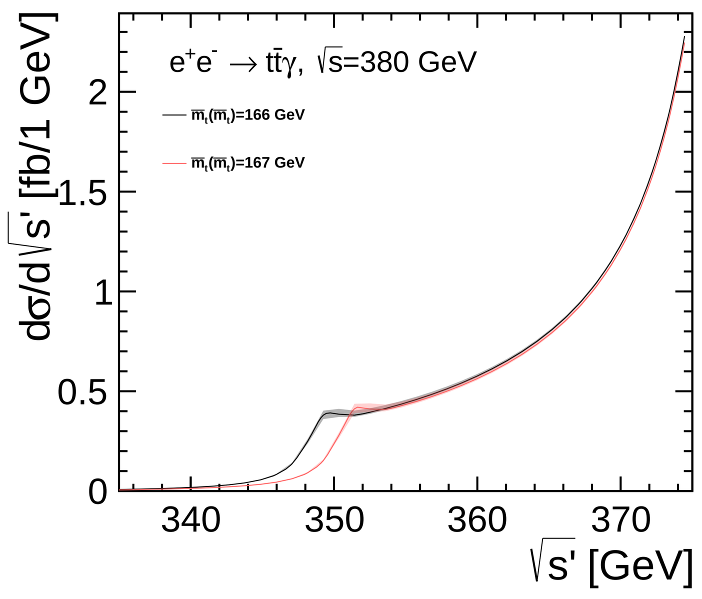
At the top quark pair production threshold ($2\,m_t \approx 350\text{ GeV}$) the cross section $\sigma(e^+e^- \to t\bar{t})$ is highly sensitive to the top quark mass. At higher CM energies, it is possible to radiatively return to the production threshold by considering the process $\sigma(e^+e^- \to t\bar{t}\gamma)$, where the radiation of an initial state photon (ISR) lowers the invariant mass $\sqrt{s'}$ of the top quark pair:



$$s = (p_{e^+} + p_{e^-})^2$$

$$s' = (p_t + p_{\bar{t}})^2 = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

The cross section for this process factorizes (for ISR) into the pair production cross section $\sigma_{t\bar{t}}$ and a part depending on the photon energy:



Cross Section with Theory Errors

$$\frac{\mathrm{d}\sigma_{t\bar{t}\gamma}}{\mathrm{d}\sqrt{s'}} = \frac{\alpha_{\text{em}}}{\pi}\, g(E_\gamma, s)\, \sigma_{t\bar{t}}(s')$$

$$g(E_\gamma,\, s) = \int_{8^\circ}^{172^\circ} d\theta\, \sqrt{\frac{1-2x}{s}}\, \frac{2}{x\sin\theta}\left[1 - 2x + (1+\cos^2\theta)\, x^2\right],$$

$$x = E_\gamma/\sqrt{s}$$

Apart from identifying the top quark pair, only the photon energy has to be measured in the experiment, which can be done with high accuracy in the main electromagnetic calorimeters. Their coverage region is taken into account by limiting the photon angle θ from $8^\circ - 172^\circ$ in the cross section calculation.

For $\sigma_{t\bar{t}}$ in the equation above we use a matched cross section [3]. It combines N^{3}LO fixed-order terms with a renormalization group improved NNLL threshold calculation, which resums QCD enhanced terms coming from bound-state effects. Double-counted terms are subtracted and the bound-state effects are switched off with a switch-function $f_s(\sqrt{s'})$, which interpolates between $f_s = 1$ at the threshold and $f_s = 0$ at high invariant masses:

$$\sigma_{t\bar{t}}^{\text{matched}} = \sigma_{\text{N}^3\text{LO}}^{\text{fixed-order}} + \left(\sigma_{\text{NNLL}}^{\text{threshold}} - \sigma^{\text{double-counted}}\right) \cdot f_s(\sqrt{s'})$$

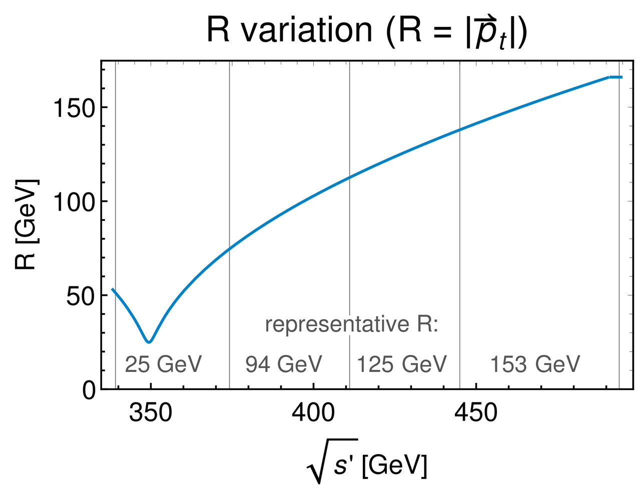
2 Top Quark Mass Uncertainties

We extract the mass for realistic operating scenarios of CLIC and ILC, taking into account the acceptance, selection efficiency, photon energy resolution, photon energy scale, luminosity spectrum, and the theory uncertainties.

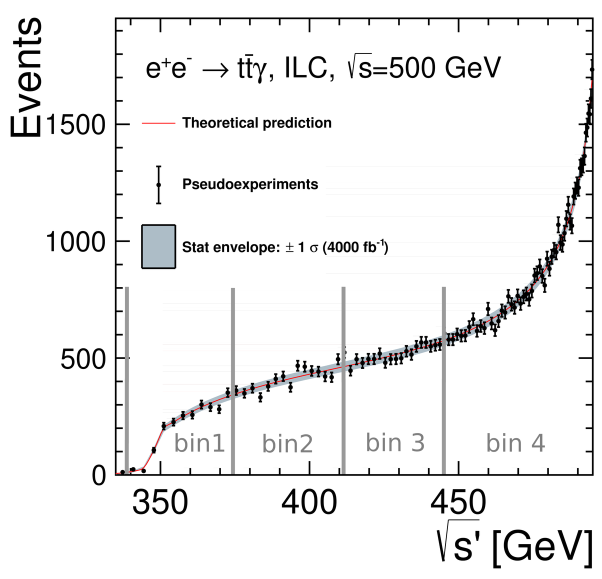
cms energy	CLIC, $\sqrt{s} = 380\,\text{GeV}$		ILC, $\sqrt{s} = 500\,\text{GeV}$	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

3 Running of the Top Quark Mass

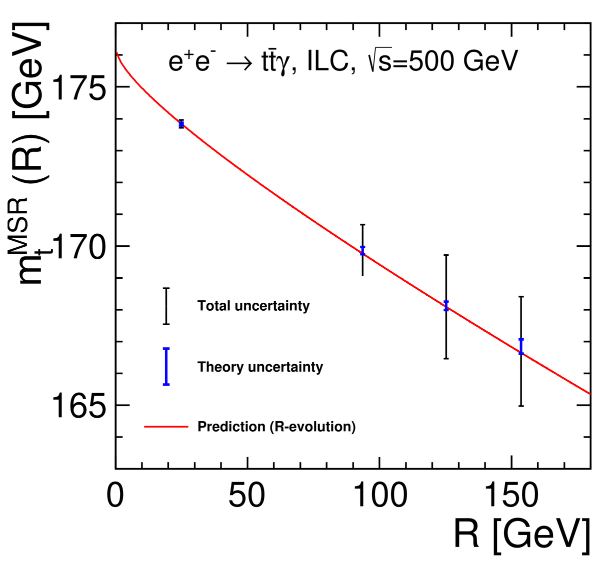
For the top pair production cross section $\sigma_{t\bar{t}}$ we use the scale-dependent MSR mass $m_t^{\text{MSR}}(R)$ which is a renormalon-free short-distance mass. Through its dependence on the scale R, which depends on the $t\bar{t}$ kinematics, the MSR mass $m_t^{\text{MSR}}(R)$ serves as a short-distance mass for the threshold region ($\sqrt{s'} = 2m_t$) as well as for the high-energy region ($\sqrt{s'} >> 2m_t$) in a smoothly connected way. The scale R is chosen of the order of the three-momentum $|\vec{p}_t|$ of the top quark in the $t\bar{t}$ CM frame.



Extracting the mass from four bins in different invariant mass $\sqrt{s'}$ regions gives a measurement of the running of the MSR mass and provides a consistency check of QCD with the running mass.



For the ILC run at 500 GeV, the running can be extracted with a significance of over $5\,\sigma$. The uncertainties are dominated by the experimental uncertainties.



4 References

[1] **CLICdp** Collaboration, H. Abramowicz *et al.*, "Top-Quark Physics at the CLIC Electron-Positron Linear Collider," *JHEP* **11** (2019) 003.

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[3] B. Dehnadi, A. H. Hoang, V. Mateu, M. Stahlhofen, and A. Widl, "Threshold continuum matching for the top pair production cross section in electron-positron annihilation," *Work in Progress* .