The top quark pair cross-section at the threshold at the FCC-ee

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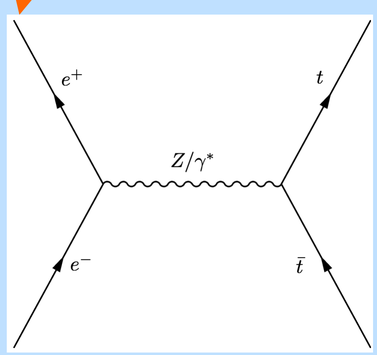
1 Abstract

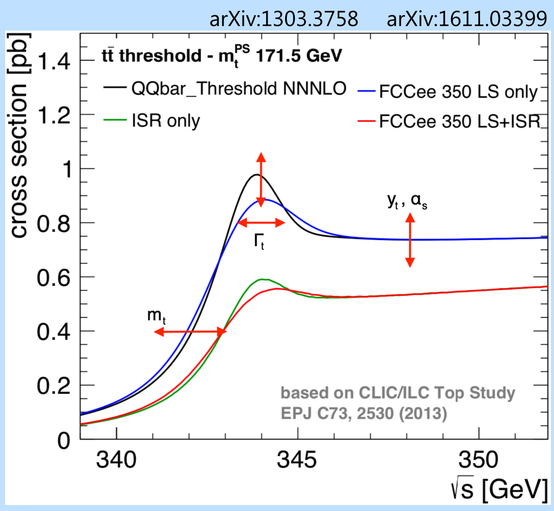
An analysis study of the the semi-leptonic $t\bar{t}$ process at the FCC-ee is performed. Samples for $t\bar{t}$ events and backgrounds were simulated including the detector response, using a fast simulation approach and subjected to a succession of kinematic cuts to obtain data consisting primarily of signal. A selection efficiency of 10 % and 81 % purity was chosen after selection. The selection process was studied in function of $\sqrt{s}$ and the simulated top quark mass. The efficiency to select $t\bar{t}$ events in the semi-leptonic channel is relatively independent of these parameters and around 10 %. The statistical uncertainty on the cross-section improves with higher $\sqrt{s}$ and stabilises in the continuum. The analysis aims to contribute to the effort of optimising the FCC-ee top quark program.

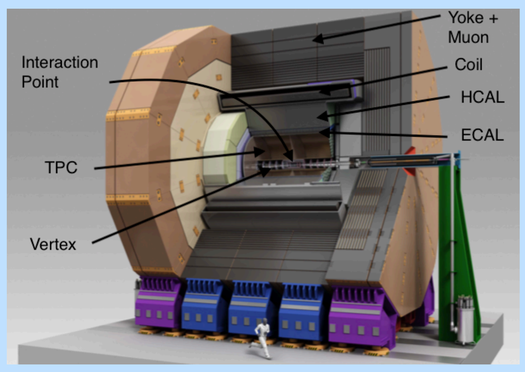
2 Top quark production at lepton colliders



- Production of top quark pairs occurs predominantly via the s-channel Feynman diagrams. No top quarks have been produced yet at lepton colliders due to the high collision energy required.

The cross-section at threshold mainly depends on four SM parameters. The top quark mass $\mathrm{m_t}$ changes the location of the peak, the width Γ_t broadens the peak and the Yukawa coupling y_t and strong coupling α_s affect the height of the continuum region past $\sqrt{s} > 2\mathrm{m_t}$.





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- The detector used for this analysis is the International Large Detector. The detector has a very similar design to Compact Muon Solenoid detector at the LHC. Similar performance is expected for the CLiC-like Detector.

3 Event pre-selection

cuts	$t\bar{t}$ semi-lep	$t\bar{t}$ di-lep	$t\bar{t}$ had	HZ	ZZ	WW
Generated	95000	100000	90000	100000	95000	100000
Scaled	48352	11428	50111	26000	100000	1000000
1 lep & 4 ptcles	13505 ± 82	1621 ± 13	977 ± 23	2964 ± 27	5923 ± 78	303420 ± 1741
$\mathrm{m_{4j}} > 150$	13467 ± 82	666 ± 8	977 ± 23	1984 ± 22	2607 ± 52	13310 ± 364
$\mathrm{m_{4j}} < 270$	13445 ± 82	666 ± 8	43 ± 4	1396 ± 19	1607 ± 41	11890 ± 344
$\mathrm{m_{2j}^{min}} > 10$	13443 ± 82	567 ± 8	43 ± 4	1336 ± 18	1332 ± 37	9510 ± 308
$\mathrm{m_{2j}^{2nd\,min}} > 20$	13442 ± 82	491 ± 7	43 ± 4	1311 ± 18	1256 ± 36	8560 ± 292
$\mathrm{E_{lepton}} < 100$	13432 ± 82	491 ± 7	43 ± 4	1258 ± 18	1120 ± 34	6480 ± 254
$\not{E}^{\mathrm{reco}} > 20$	13410 ± 82	491 ± 7	42 ± 4	1222 ± 17	1010 ± 32	6370 ± 252

$L_{\mathrm{int}} = 0.2\,\mathrm{ab}^{-1}$

The analysis focuses on the semi-leptonic decay channel for the $t\bar{t}$ process. The signature to look for contains four jets, of which two b-jets, one isolated lepton and missing energy for the neutrino. The events are generated at LO using Pythia8 then scaled for their respective cross-sections and branching ratios. The integrated luminosity of $L_{\mathrm{int}} = 0.2\,\mathrm{ab}^{-1}$ was chosen according the the threshold scan at the FCC-ee for one year. The detector response and reconstruction were simulated with the PAPAS Fast Simulation. The background processes all have different topologies and kinematic distributions. A succession of cuts are then applied to reduce the backgrounds while maintaining the signal. The cuts eliminate 99.2 % of the background while leaving 27 % of the signal.

4 Selection process

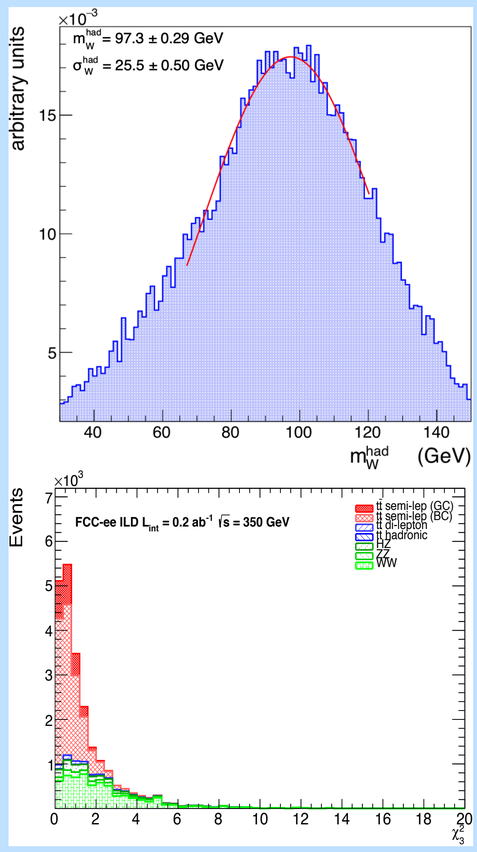
$$\chi^2_3 = \left(\frac{\mathrm{m_t^{had}} - \mathrm{m_{t,reco}^{had}}}{\sigma_\mathrm{t}^{\mathrm{had}}}\right)^2 + \left(\frac{\mathrm{m_t^{lep}} - \mathrm{m_{t,reco}^{lep}}}{\sigma_\mathrm{t}^{\mathrm{lep}}}\right)^2 + \left(\frac{\mathrm{m_W^{had}} - \mathrm{m_{W,reco}^{had}}}{\sigma_\mathrm{W}^{\mathrm{had}}}\right)^2$$

$$\chi^2_4 = \chi^2_3 + \left(\frac{\mathrm{m_W^{lep}} - \mathrm{m_{W,reco}^{lep}}}{\sigma_\mathrm{W}^{\mathrm{lep}}}\right)^2$$

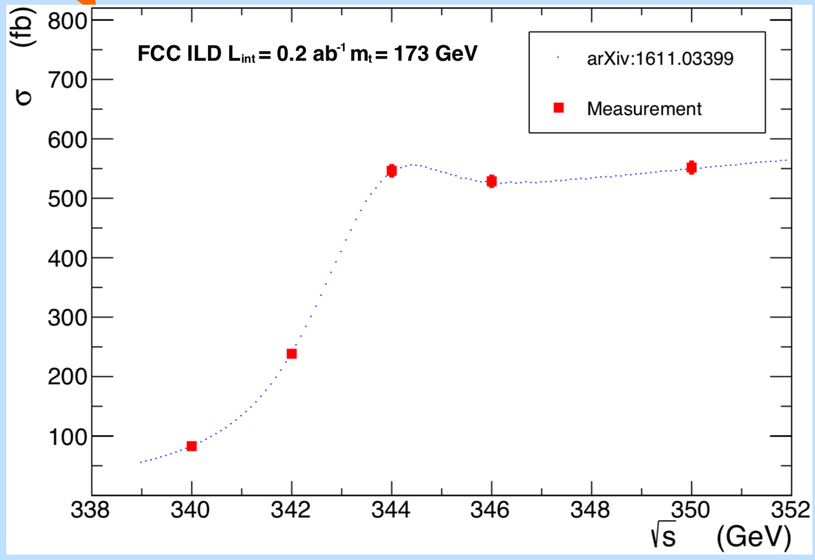
$$\chi^2_5 = \chi^2_4 + \left(\frac{(\mathrm{m_t^{had}} + \mathrm{m_t^{lep}}) - (\mathrm{m_{t,reco}^{had}} + \mathrm{m_{t,reco}^{lep}})}{\sigma_\mathrm{t}^{\mathrm{had}} + \sigma_\mathrm{t}^{\mathrm{lep}}}\right)^2$$

The variables $\chi^2_{3,4,5}$ are compared to obtain a purer sample of top quark events, based on the sum of χ^2 terms. The necessary resolutions are determined using events where the simulation matched the reconstruction. χ^2_3 offers the best statistical uncertainty on the cross-section and performance overall. The efficiency here is defined with respect to the pre-selection. The final χ^2_3 distribution is given.

Variable	Cut	Signal efficiency (%)	Purity (%)	$(\Delta\sigma/\sigma)_{\mathrm{stat}}$ (%)
χ^2_3	0.45	29.43	81.0	1.76
χ^2_4	1.35	29.96	81.1	1.86
χ^2_5	1.50	30.00	81.0	1.85



5 Cross-section measurement



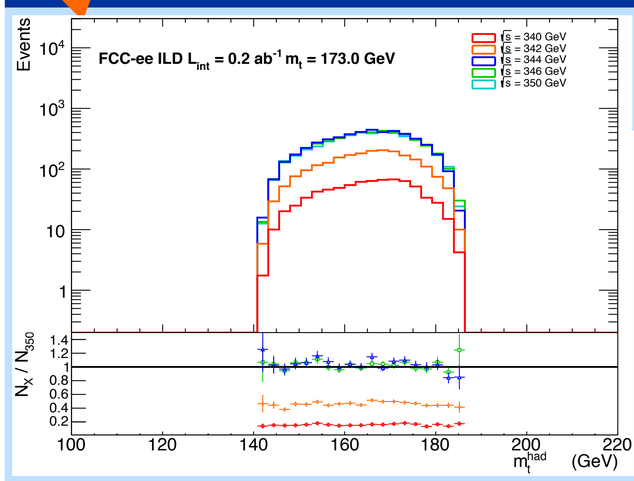
The cross-section is calculated using

$$\sigma = \frac{N_{\mathrm{total}} - N_{\mathrm{BG}}}{\varepsilon \cdot L_{\mathrm{int}}}$$

where the events and efficiencies are determined for different top quark mass and centre of mass energies.

The measured cross-section values for the top threshold are compared to the latest predictions. The error bars represent only the statistical uncertainties on signal and background, for which the luminosity, branching ratio and efficiency are assumed to be known perfectly. The measurements are very close to the predicted value which gives confidence in the result. This is to be expected as the reference values to produce the red points were the latest predictions.

6 Influence of centre of mass energies and top quark mass on measurements



Statistical uncertainty on the cross-section in %. $\left(\frac{\Delta\sigma}{\sigma}\right)_{\mathrm{stat}} = \sigma^{-1} \cdot \left(\sqrt{\frac{N_{\mathrm{total}}}{(\varepsilon L_{\mathrm{int}} \mathrm{BR})^2} + \frac{N_{\mathrm{BG}}}{(\varepsilon L_{\mathrm{int}} \mathrm{BR})^2}}\right)$

$\sqrt{s}$ \ m_t	171.8	172.6	173.0	173.4	174.2
340	7.66	7.67	7.81	7.64	7.69
342	3.07	3.11	3.08	3.14	3.12
344	1.75	1.74	1.74	1.74	1.72
346	1.79	1.79	1.77	1.8	1.78
350	1.81	1.81	1.81	1.8	1.79

The shape of the reconstructed top quark mass distributions as well as χ^2_3 are not affected by the changes in $\sqrt{s}$ and $\mathrm{m_t}$.

The efficiency of the selection on the signal with respect to the scaled events remains fairly stable with a slight downward trend past the continuum region $\sqrt{s} > 344\,\mathrm{GeV}$.

$\sqrt{s}$ \ m_t	171.8	172.6	173.0	173.4	174.2
340	$0.1034^{+0.0036}_{-0.0035}$	$0.1031^{+0.0036}_{-0.0035}$	$0.1011^{+0.0036}_{-0.0035}$	$0.1037^{+0.0036}_{-0.0035}$	$0.1029^{+0.0036}_{-0.0035}$
342	$0.1039^{+0.0021}_{-0.0021}$	$0.1023^{+0.0021}_{-0.0021}$	$0.1033^{+0.0021}_{-0.0021}$	$0.1011^{+0.0021}_{-0.0021}$	$0.1020^{+0.0021}_{-0.0021}$
344	$0.0994^{+0.0014}_{-0.0014}$	$0.1011^{+0.0014}_{-0.0014}$	$0.1007^{+0.0014}_{-0.0014}$	$0.1010^{+0.0014}_{-0.0014}$	$0.1026^{+0.0014}_{-0.0014}$
346	$0.1003^{+0.0014}_{-0.0014}$	$0.1003^{+0.0014}_{-0.0014}$	$0.1017^{+0.0014}_{-0.0014}$	$0.0995^{+0.0014}_{-0.0014}$	$0.1012^{+0.0014}_{-0.0014}$
350	$0.0955^{+0.0013}_{-0.0013}$	$0.0955^{+0.0013}_{-0.0013}$	$0.0953^{+0.0013}_{-0.0013}$	$0.0963^{+0.0014}_{-0.0013}$	$0.0972^{+0.0014}_{-0.0013}$