SNOWMASS ENERGY FRONTIER WORKSHOP
June 30 – July 3, University of Washington, Seattle

Top physics in e^+e^- collisions at CLIC

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on behalf of the CLIC Detector and Physics Study

1. Top quark mass
   - $\sqrt{s}$ = 350 GeV threshold scan
   - $\sqrt{s}$ = 500 GeV invariant mass measurement

Established analysis
arxiv:1303.3768v1
submitted to EPJC

2. Top Yukawa coupling
   - $\sqrt{s}$ =1.4 TeV ttH cross section measurement

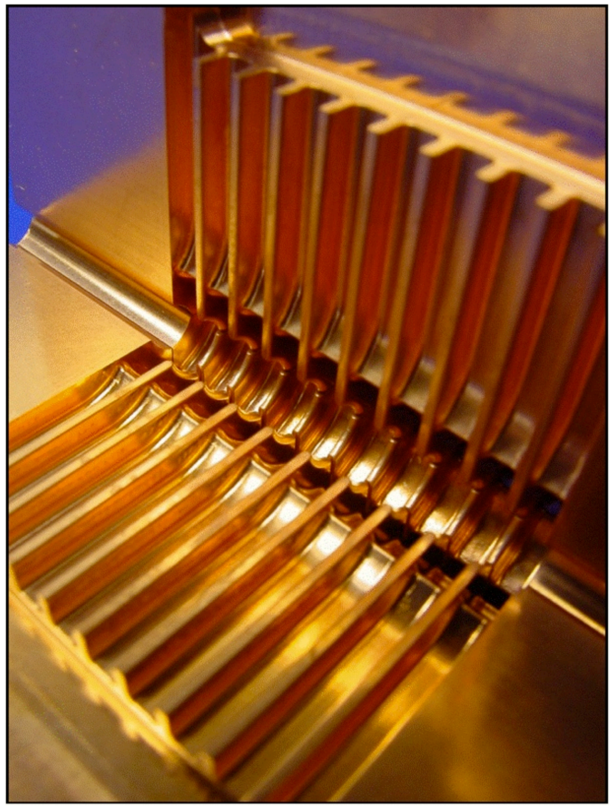
New analysis
preliminary result

3. Top as a probe for new physics
   - $\sqrt{s}$ = 1-3 TeV

Subject of studies
in the near future

CLIC - a brief introduction

CLIC: The most mature option for a multi-TeV e^+e^- collider

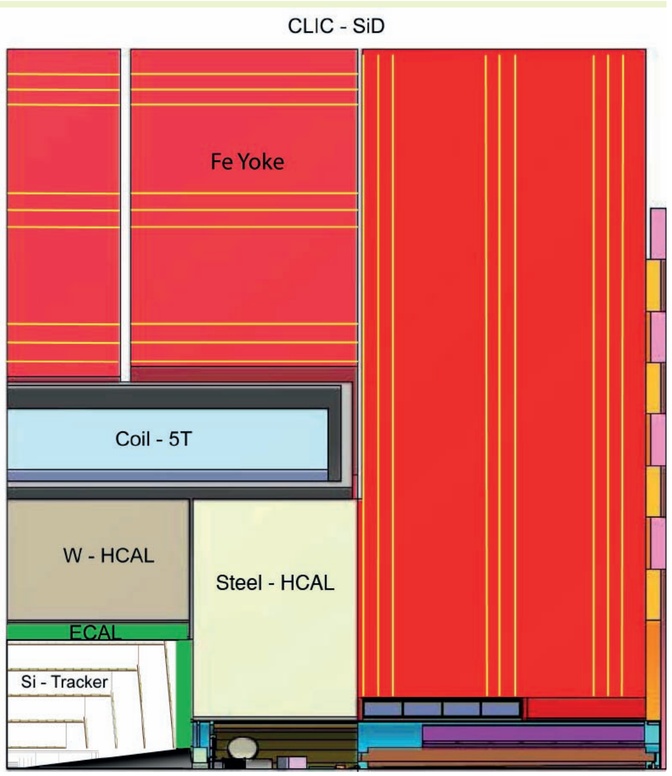


CLIC Accelerator:

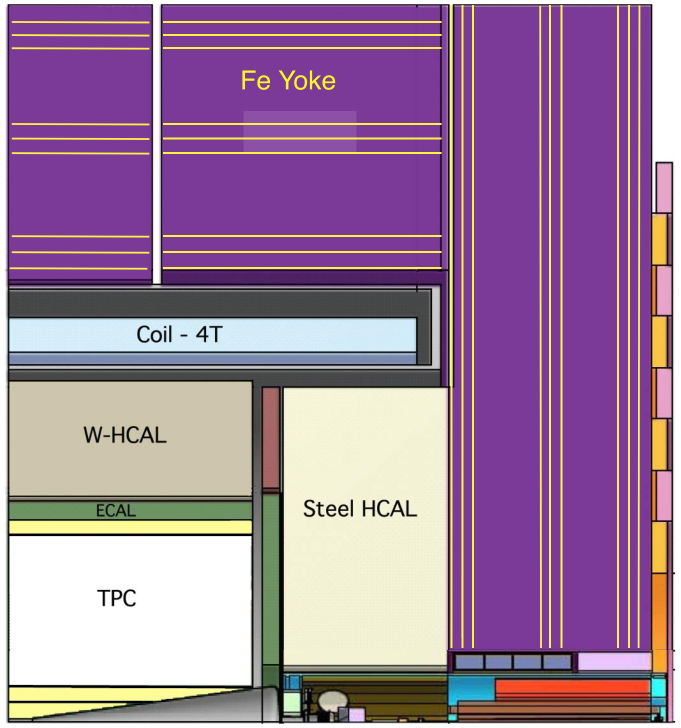
- $\sqrt{s}$ = 3 TeV with two lower energy stages
- Two-beam acceleration, warm RF, gradient 100 MV/m
- Polarised electron beam, luminosity >10^{34} $cm^{-2}s^{-1}$

CLIC Detectors:

- Two detector concepts based on ILC designs, adapted to CLIC conditions
  - ultra low mass vertexing
  - particle flow calorimetry
  - 4-5 T solenoids

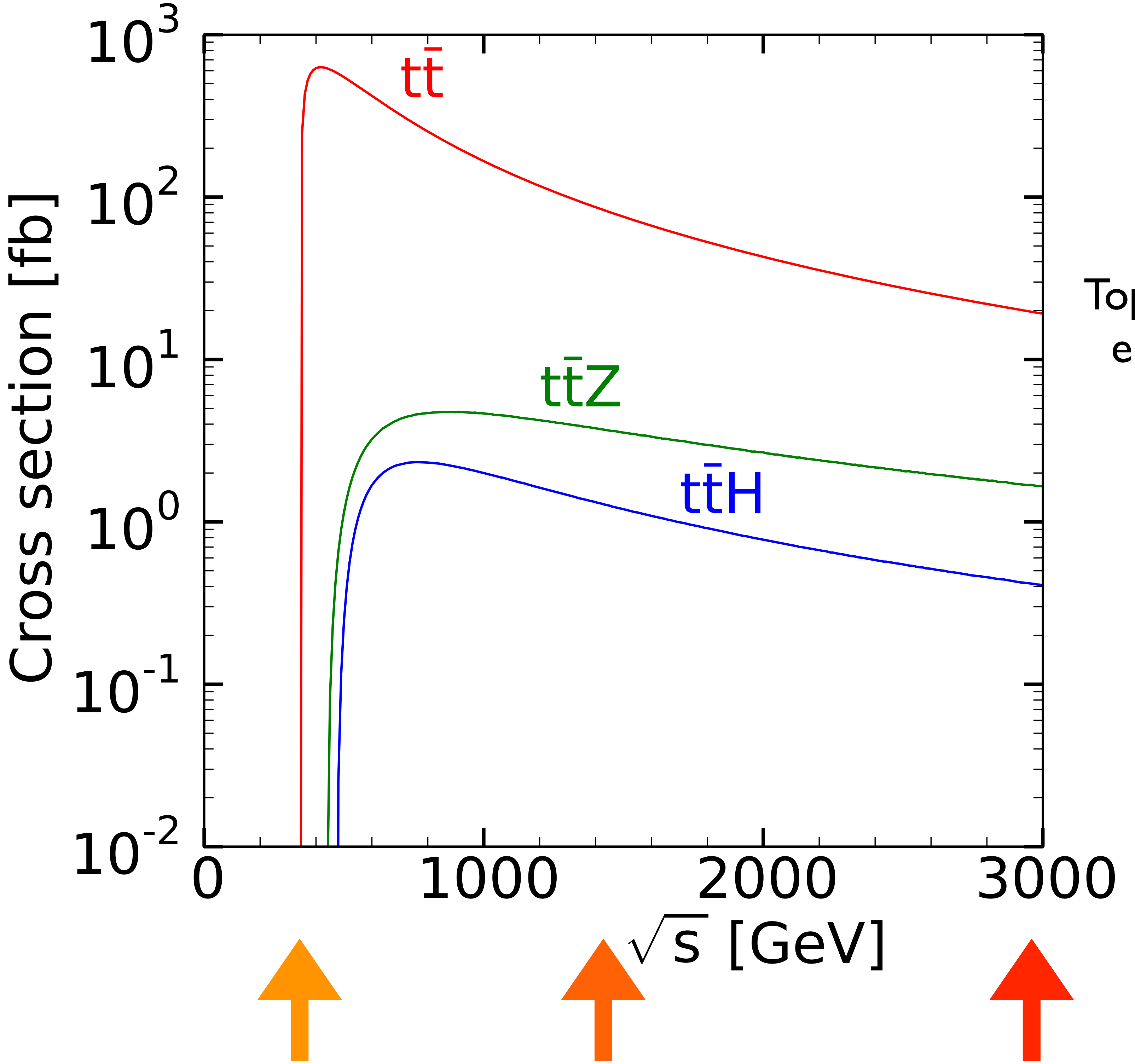


CLIC - ILD



CLIC CDR completed: feasibility of machine and precision physics demonstrated

Top physics at CLIC



Top physics interest at all energy stages of CLIC

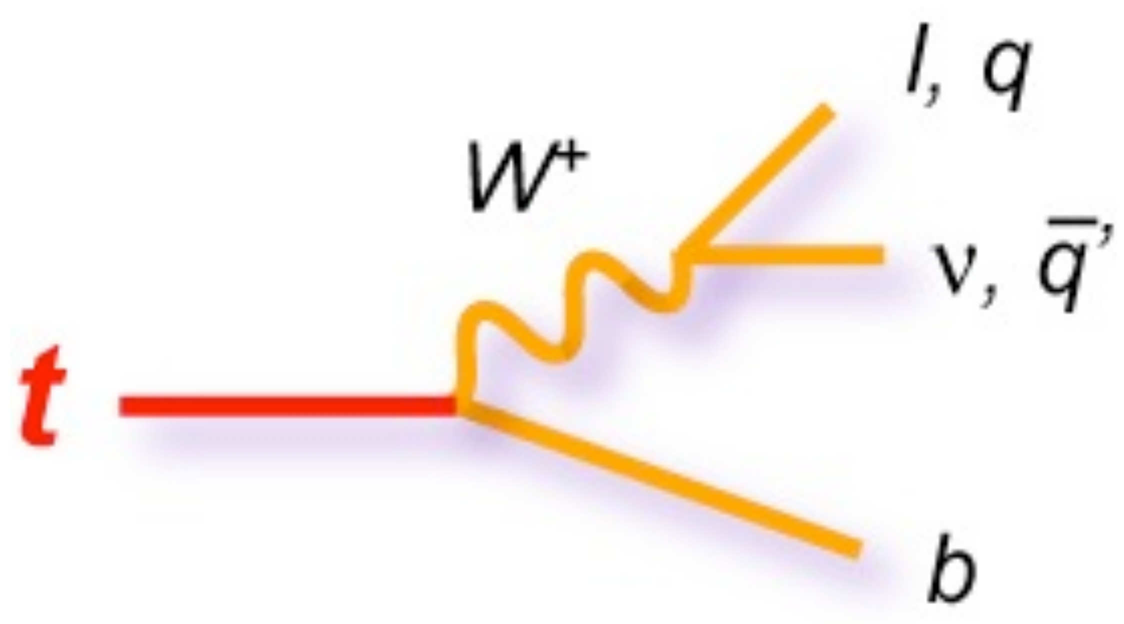
Stage 1: $\sqrt{s}$ = ~375 GeV
Top mass measurement and threshold scan

Stage 2: $\sqrt{s}$ = 1.4 TeV
Top Yukawa coupling

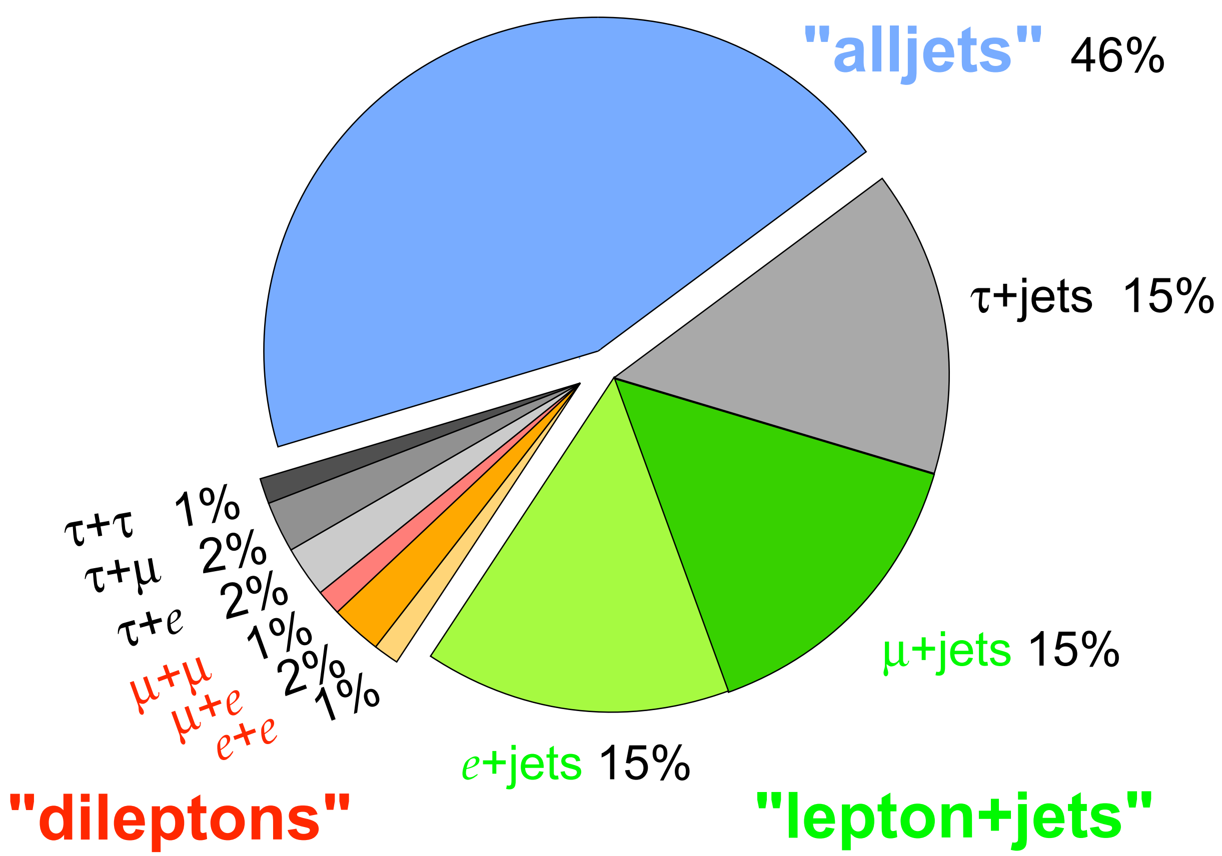
Stage 3: $\sqrt{s}$ = 3 TeV
Top in combination with new physics

Top quarks at CLIC

- Event signature given by the decay of the W bosons
- At lepton colliders:
    - top pairs are easily identifiable
    - concentrate on large branching fractions to fully hadronic and semi-leptonic states, with controllable missing energy



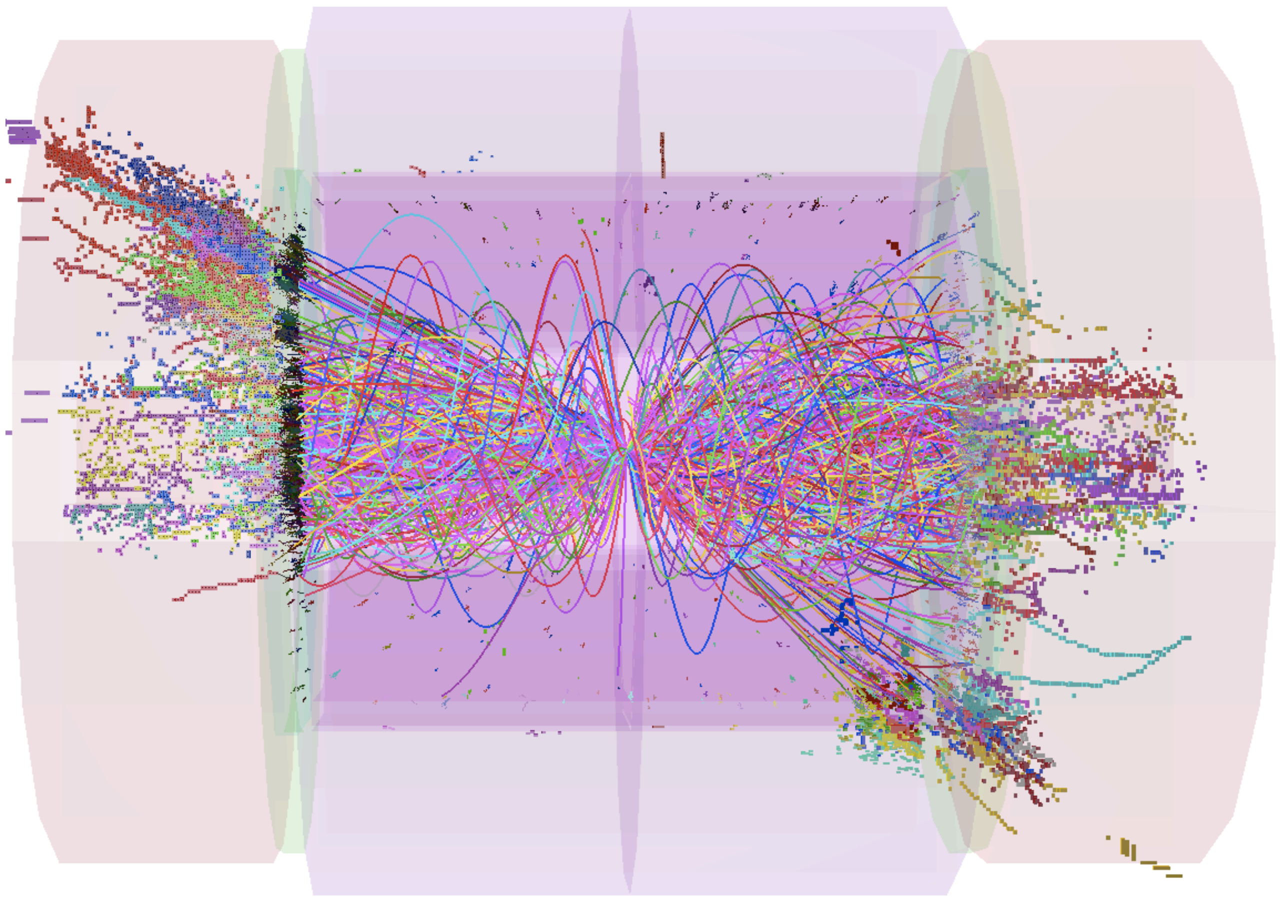
Top Pair Branching Fractions



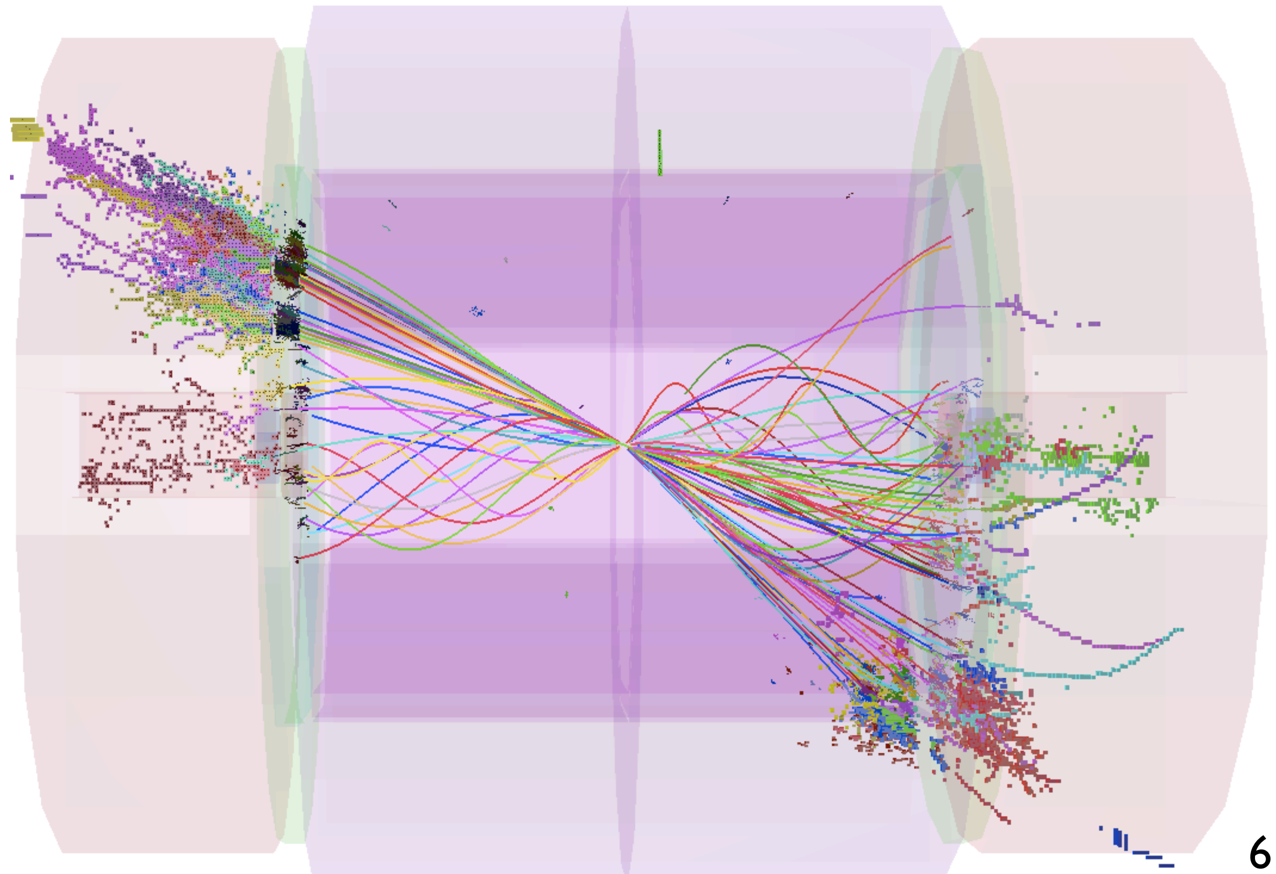
Analysis challenges at CLIC

- Key reconstruction challenge: pile-up of $\gamma\gamma \rightarrow$hadrons background
- Rejected beam-induced backgrounds with timing & p_t cuts
- Jet finding based on hadron collider k_t algorithm (two additional beam jets)
- Analyses fully simulated in GEANT4 including beam background overlays

No background suppression



Background suppression



Top mass at CLIC

Established analysis
arxiv:1303.3768v1
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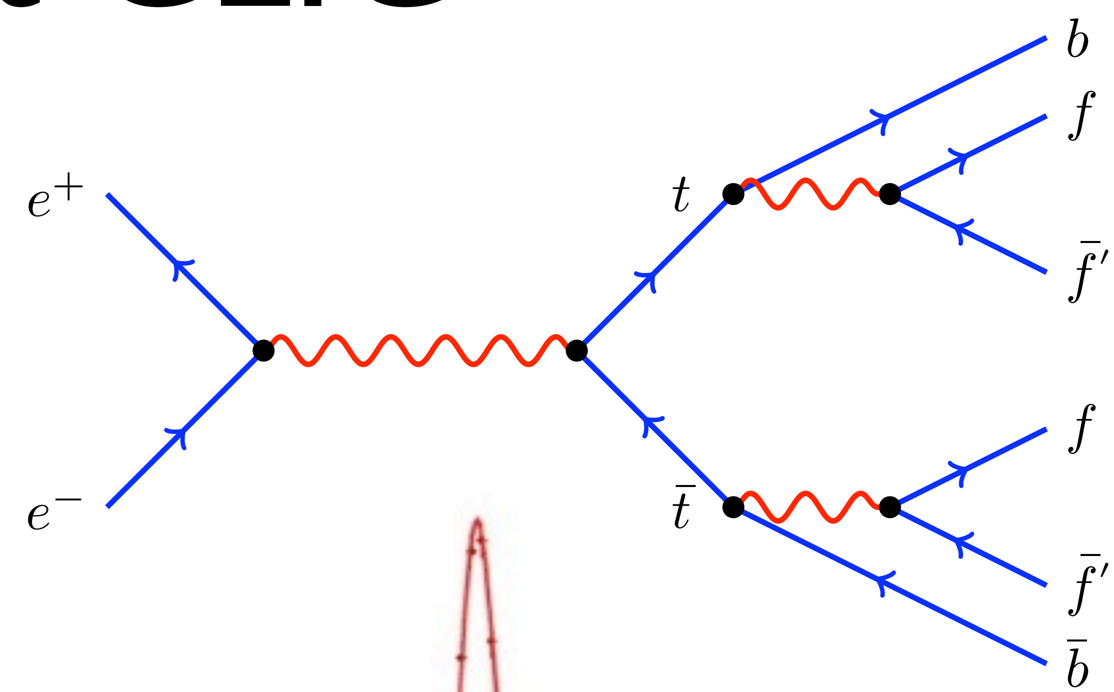
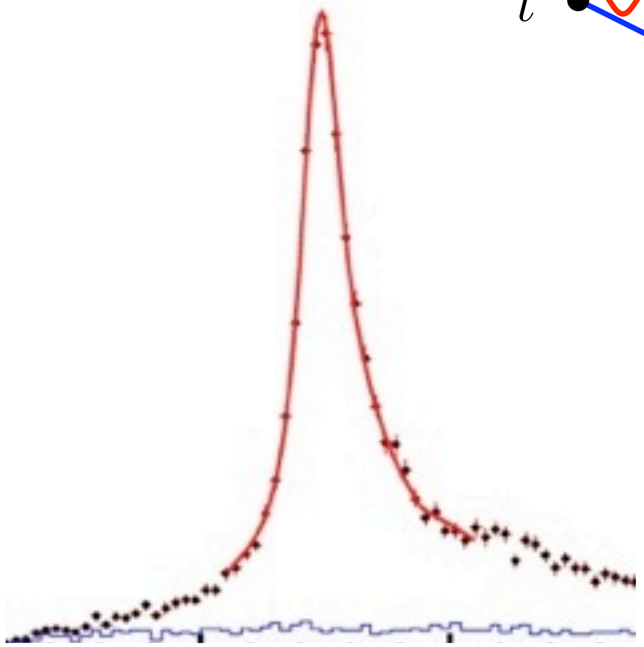
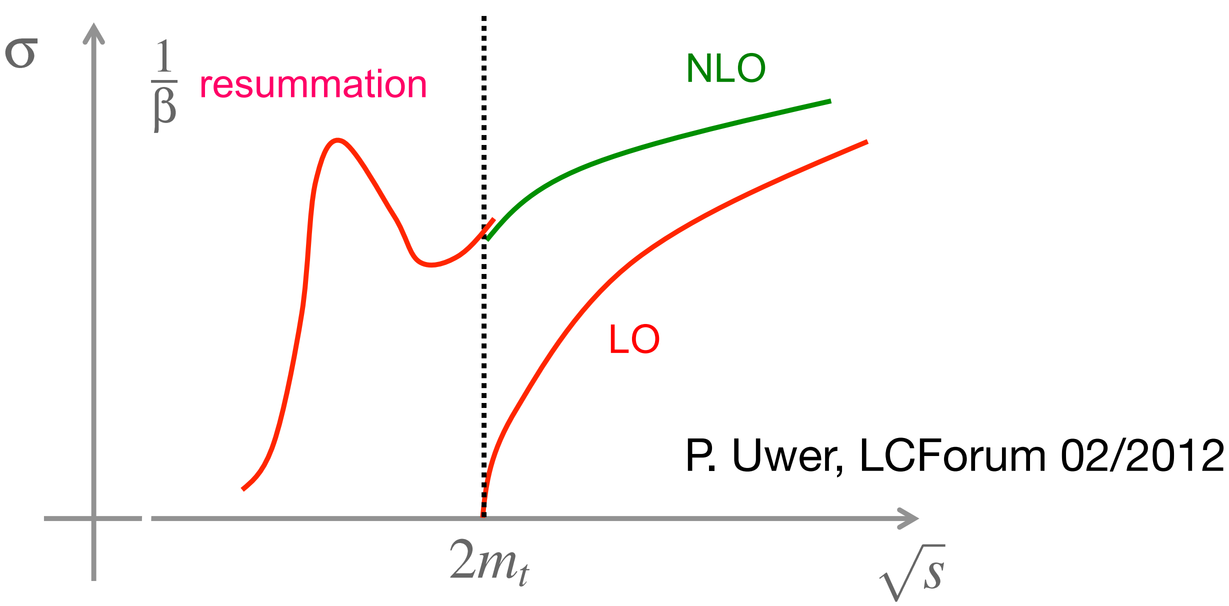


- Measure the top mass in top pair production
- Two complementary methods

1) Invariant mass at $\sqrt{s}$ = 500 GeV (100 fb^{-1})
   - can be performed at arbitrary energy above threshold: high integrated luminosity
   - experimentally well defined (but not theoretically - “PYTHIA” mass)

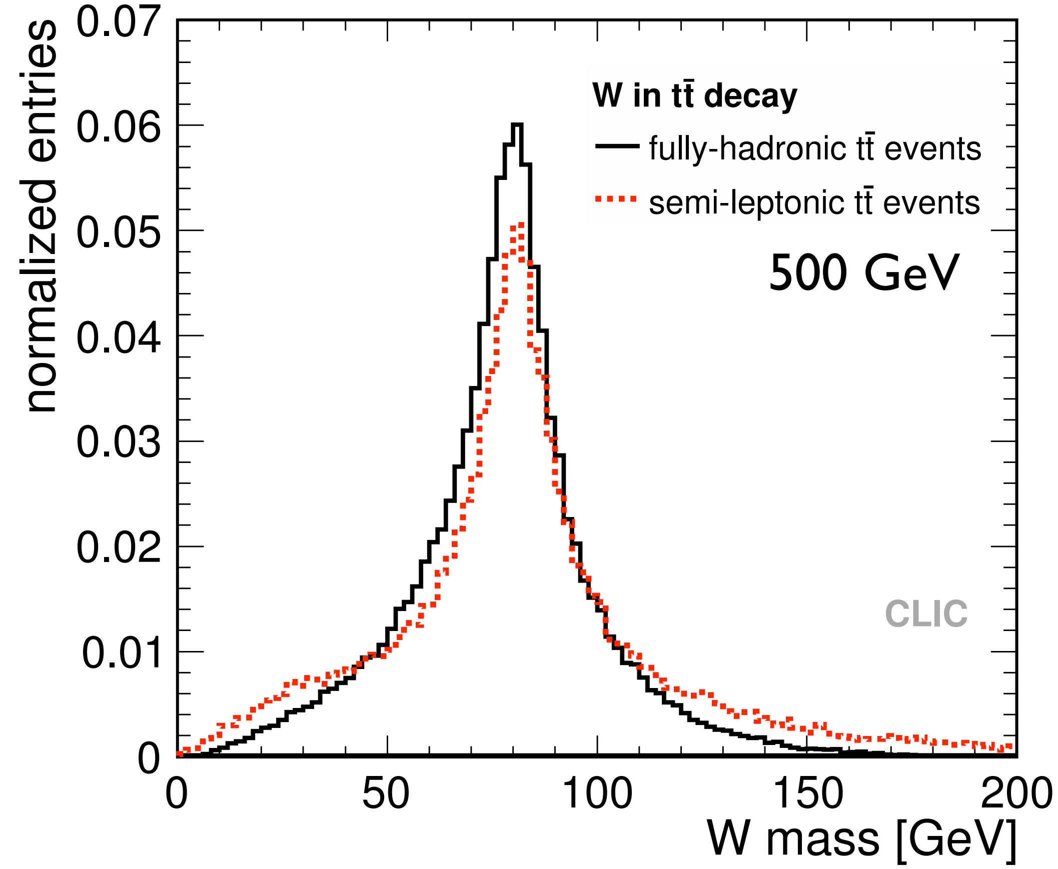


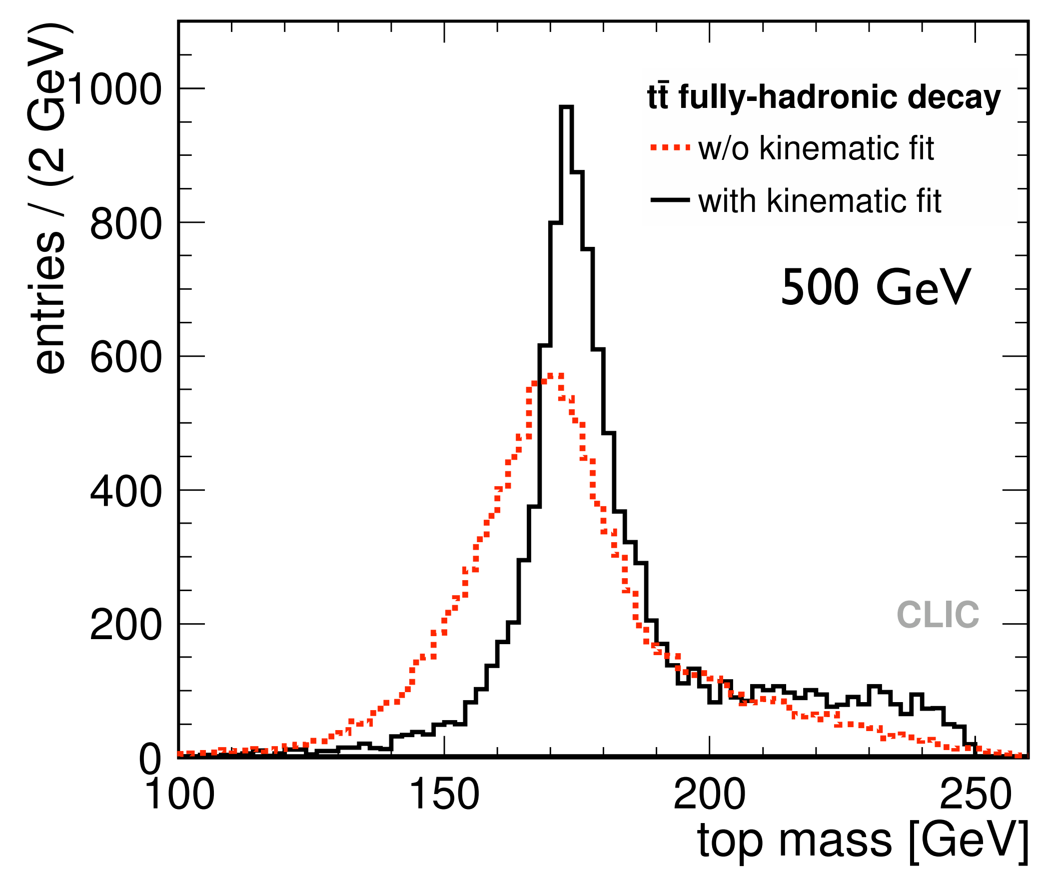
2) Threshold scan at $\sqrt{s}$ = 350 GeV (10×10 fb^{-1})
   - theoretically well understood, can be calculated to higher orders
   - needs dedicated accelerator time



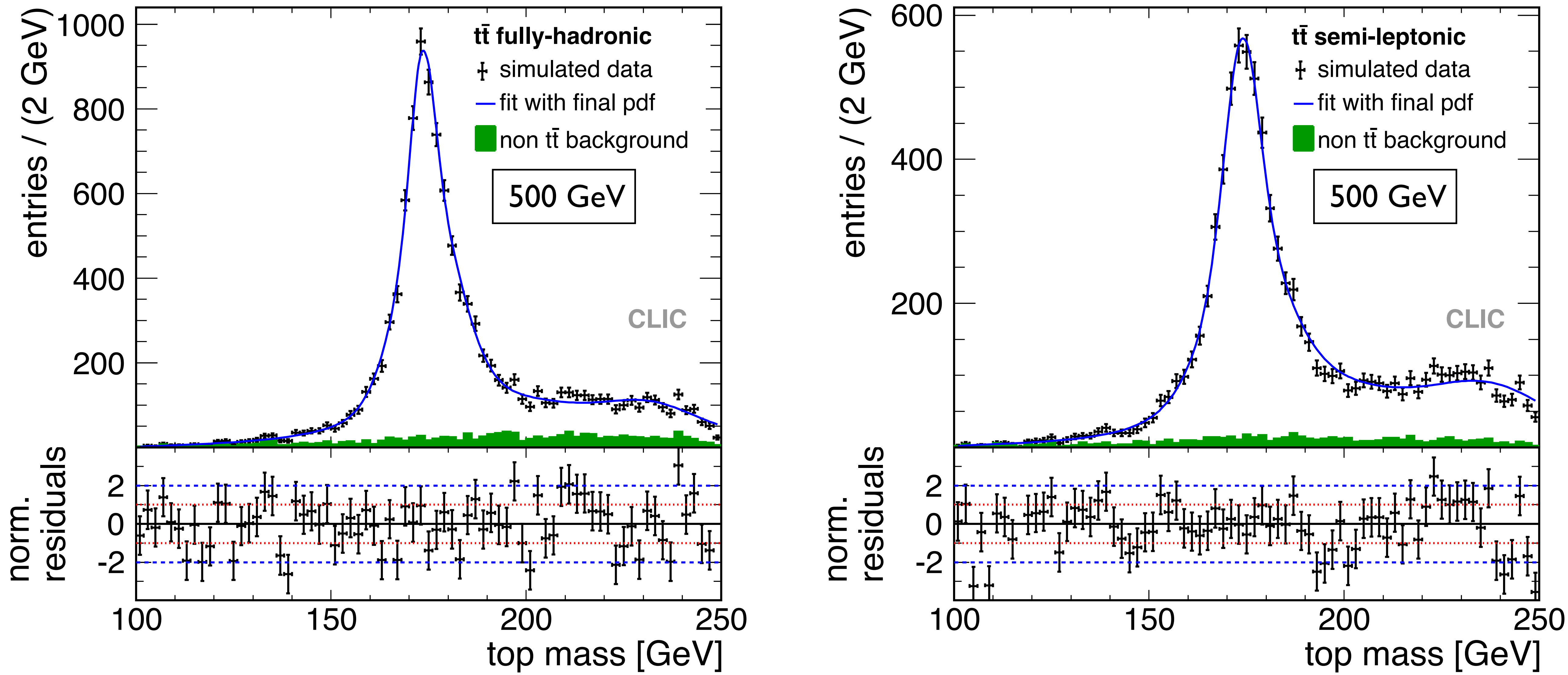
Top quark reconstruction

1) Lepton finding
   - classifies event: semi-leptonic / fully hadronic
2) Jet clustering
3) Flavour tagging
4) W reconstruction
   - FH: take best jet pairing
   - SL: neutrino absorbs uncertainties - tail
5) Kinematic fitting
   - constrain W masses, momentum conservation
   - substantially improves mass resolution, reduces impact of uncertainties
   - provides background rejection





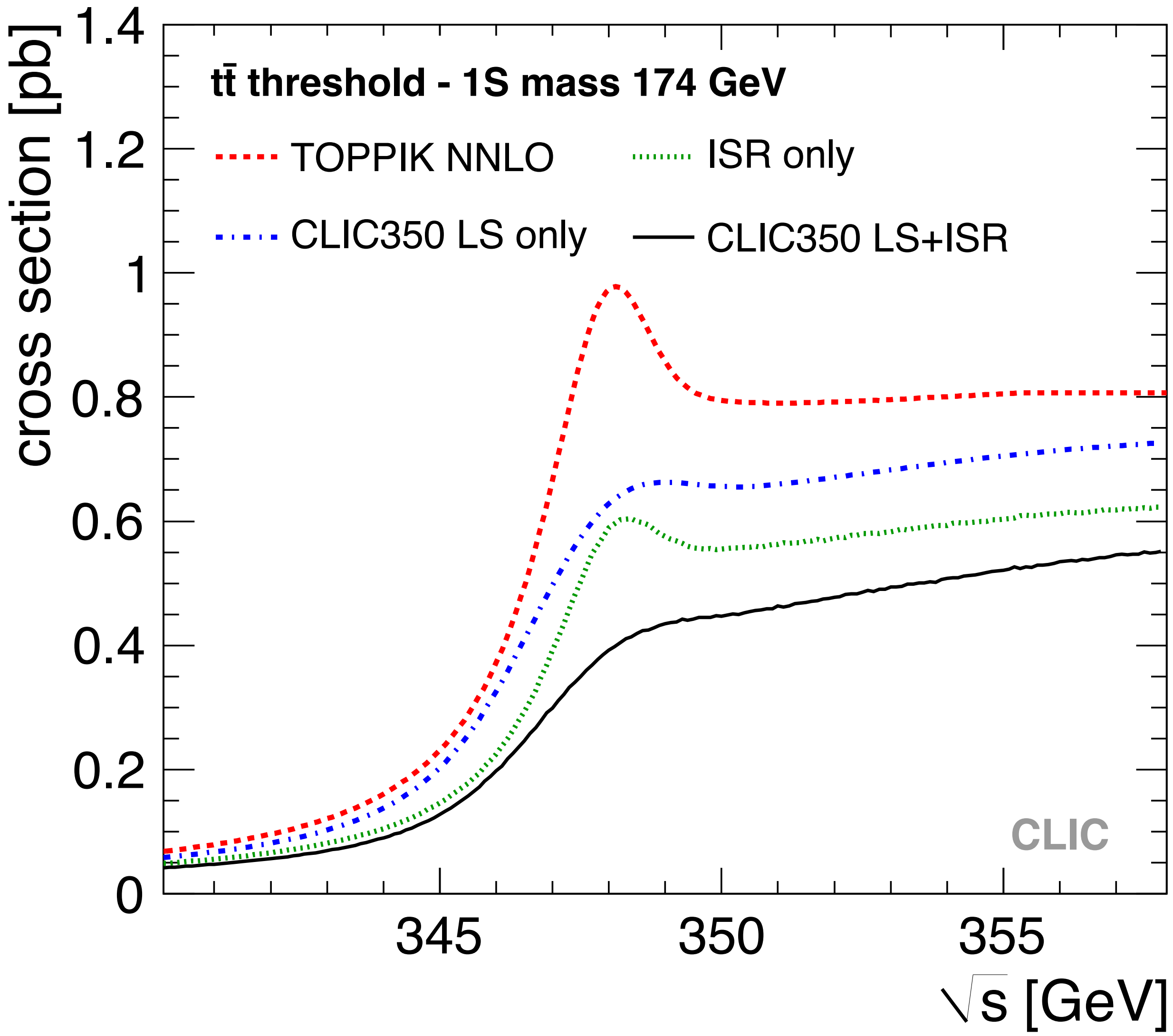
Invariant mass measurement

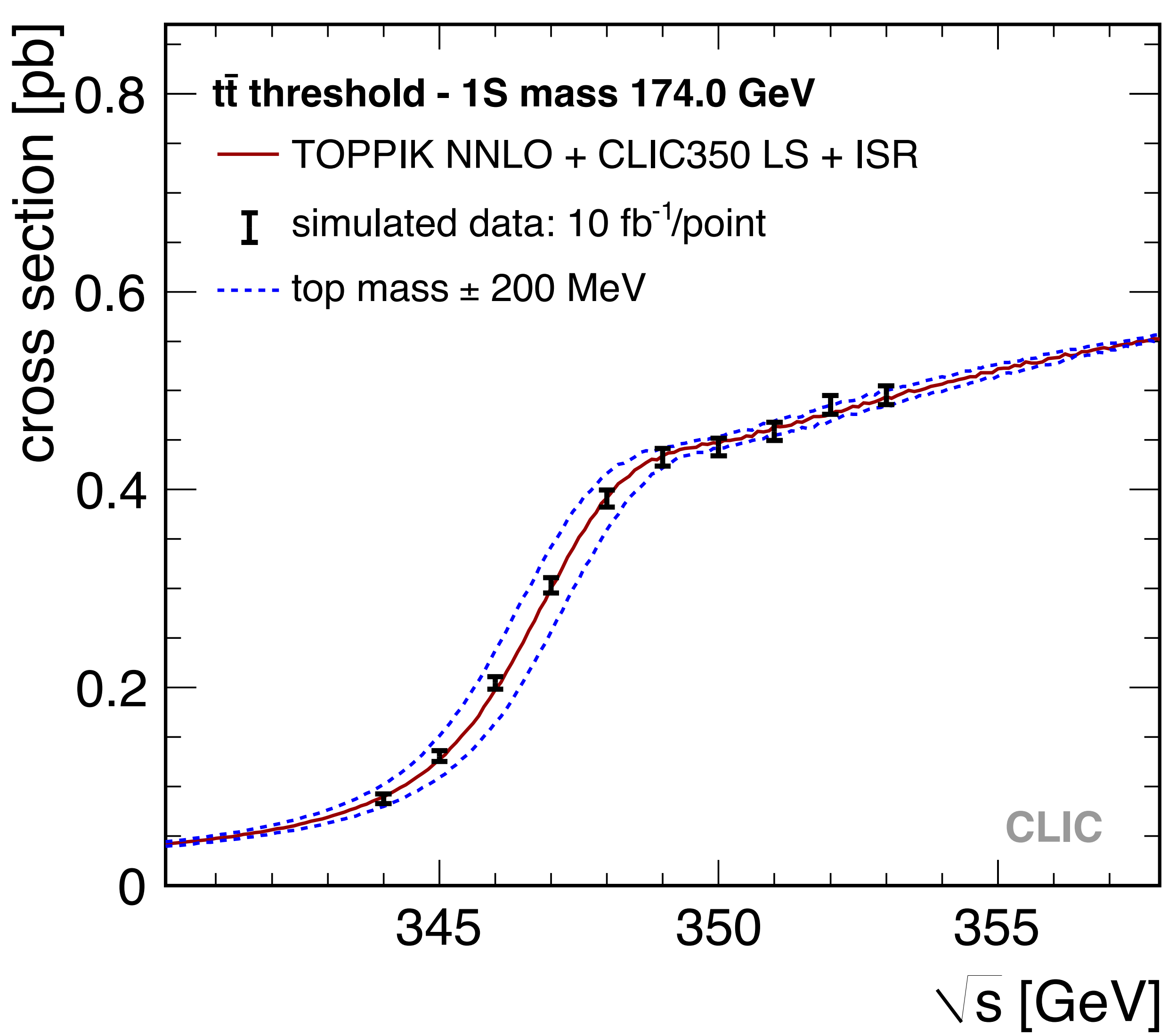


channel	m_{top}	Δm_{top}	Γ_{top}	$\Delta\Gamma_{top}$
fully-hadronic	174.049	0.099	1.47	0.27
semi-leptonic	174.293	0.137	1.70	0.40
combined	174.133	0.080	1.55	0.22

Threshold scan

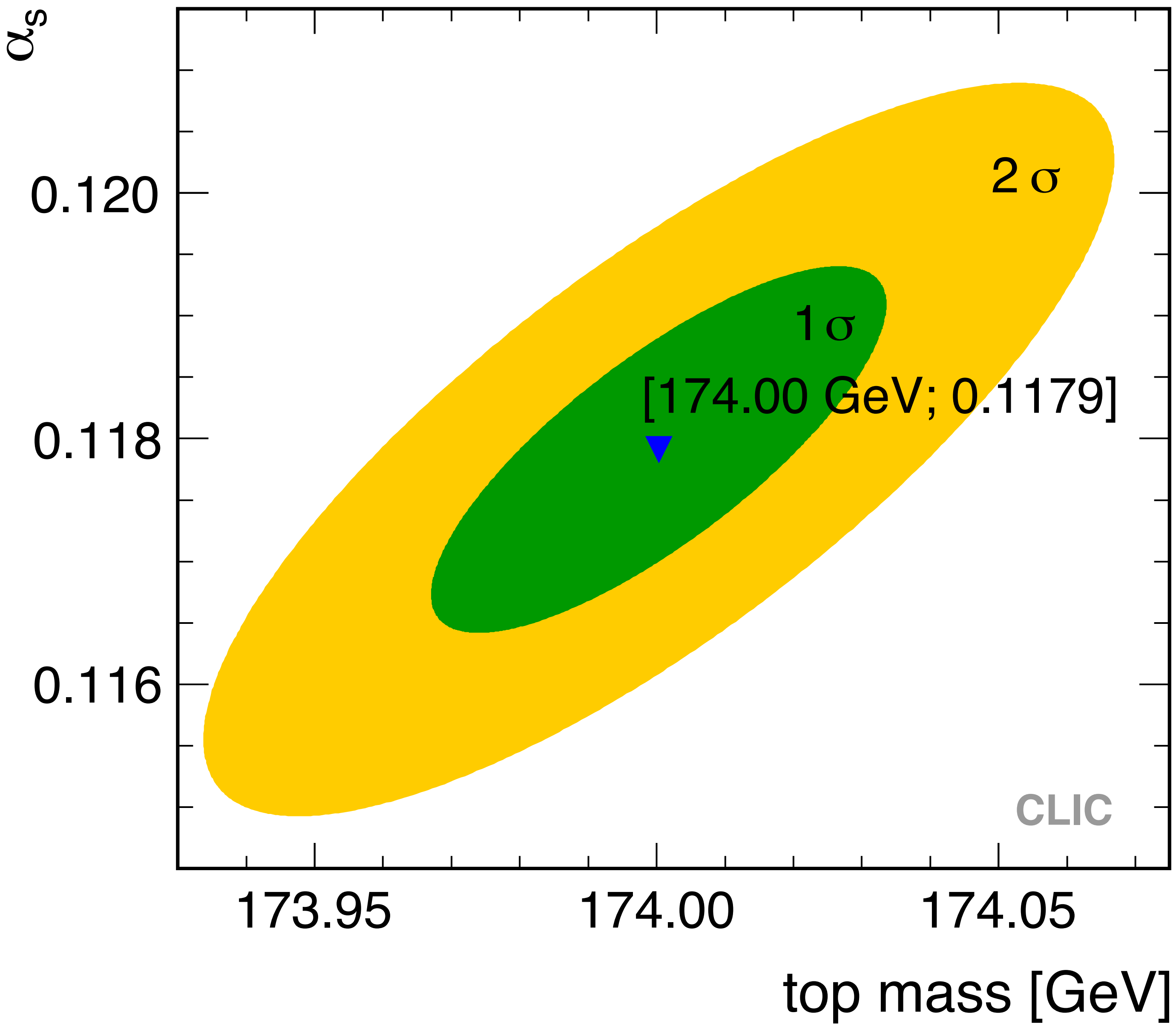
- Pure NNLO cross section (calculated with TOPPIK [Hoang & Teubner]) distorted by ISR and luminosity spectrum
- Combined with selection efficiency and background contamination from full simulations: Simulated data points





Threshold mass and α_s

- Threshold behaviour of the cross section depends on the strong coupling constant
- 2D template fit to cross section used to extract m_t, and α_s



1S top mass and α_s combined 2D fit	
m_t stat. error	34 MeV
m_t theory syst. (1%/3%)	5 MeV / 8 MeV
α_s stat. error	0.0009
α_s theory syst. (1%/3%)	0.0008 / 0.0022

Top mass systematics

Invariant mass

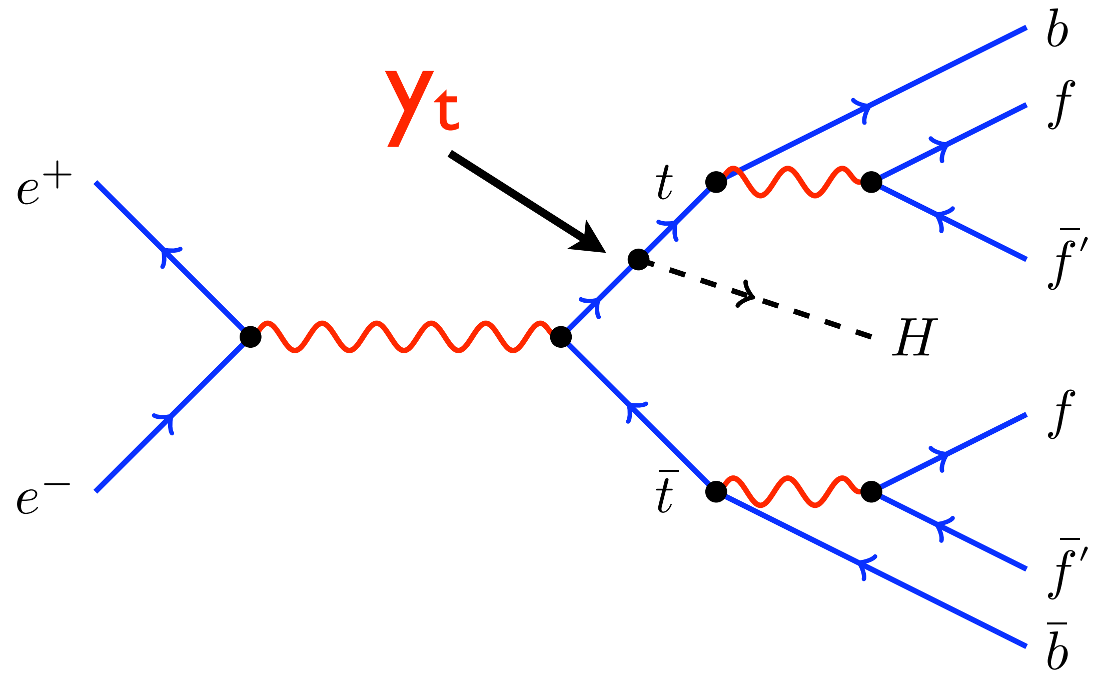
Threshold scan

1) Bias from top mass and width assumptions in generator
   - effect is below the statistical uncertainty, no bias found
2) Jet energy scale
   - 1% for light jets (W events), similar for b jets (Z, ZZ events)
   - effect is below statistical uncertainties of the measurement
3) Beam energy:
   - Expect 10^{-4} precision on CMS energy: 30 MeV uncertainty on top mass (also applies to invariant mass due to kinematic fit)
4) Non-ttbar background:
   - 5% background uncertainty results in 18 MeV uncertainty on top mass
5) Luminosity spectrum:
   - e.g. 20% uncertainty on luminosity peak width results in 75 MeV uncertainty on top mass. Achievable precision still under investigation

Top Yukawa coupling

New analysis
preliminary result

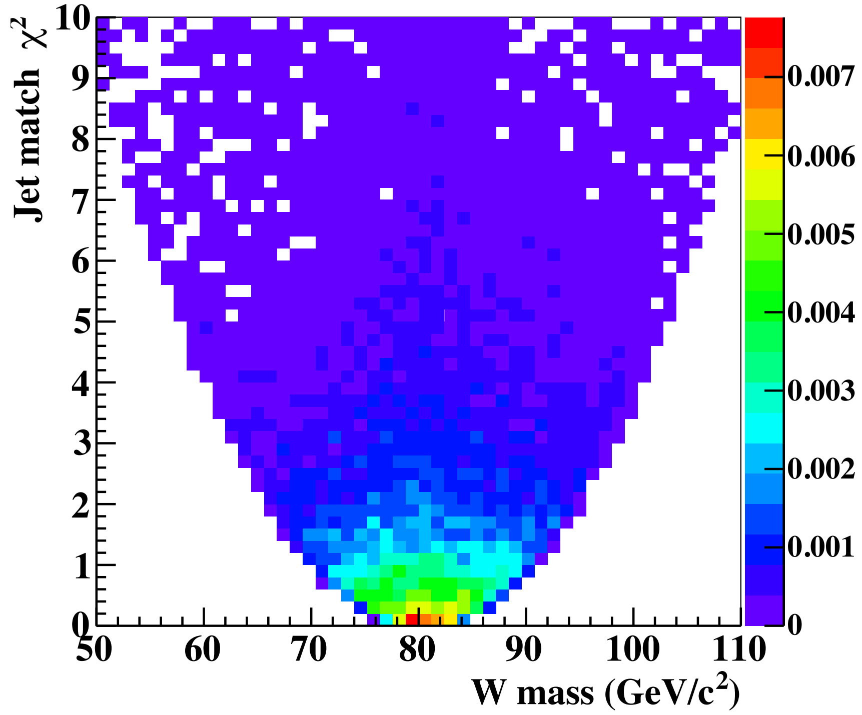
- Heaviest SM particle, couples most strongly to the Higgs field
- Measurement of ttH cross section allows extraction of top Yukawa coupling
- New physics could induce sizeable deviation from SM expectation **[arXiv:1206.3560]**



Direct measurement
Sensitive to NP at tree level
Complex final state

tth reconstruction

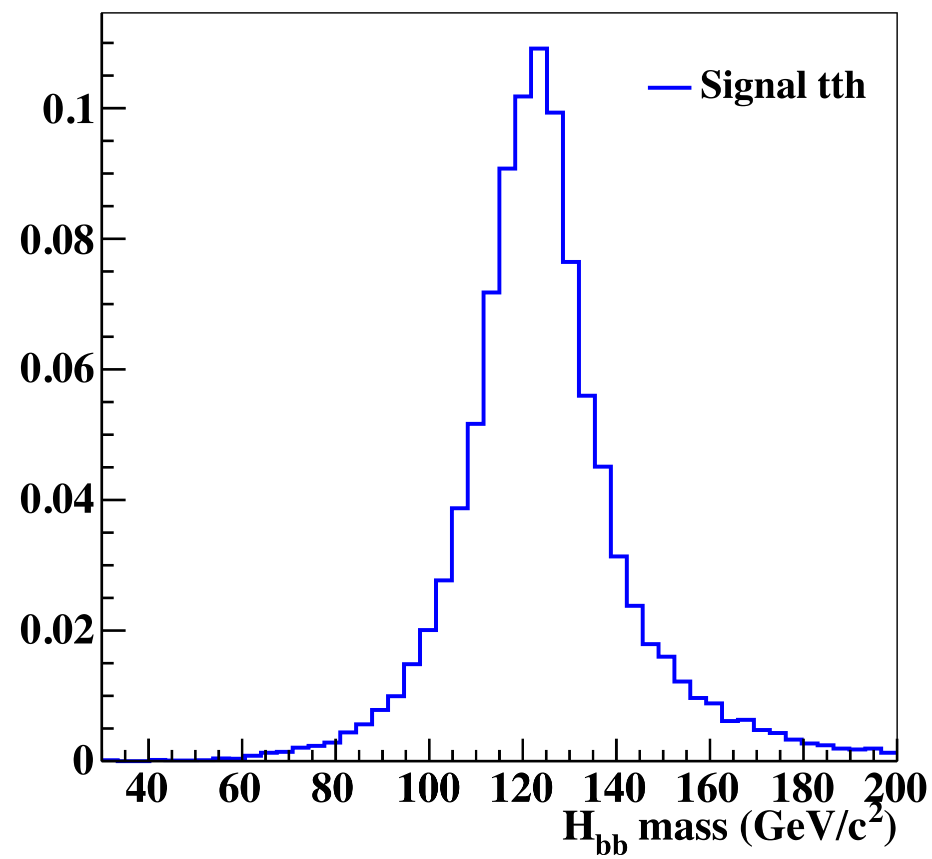
- Similar reconstruction strategy to tt events - addition of two b jets
- Eight fermion final state! Fully hadronic or semi-leptonic



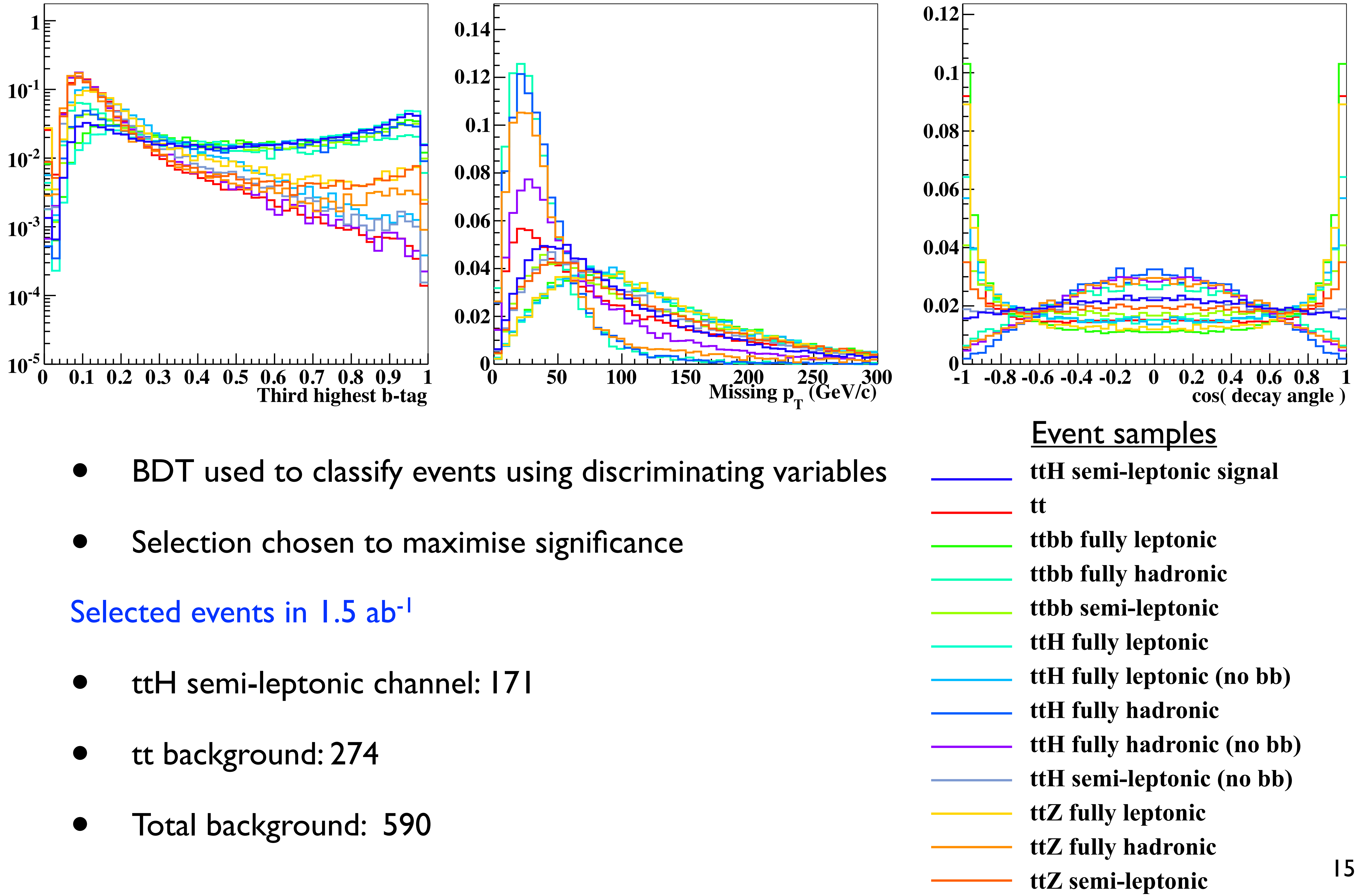
1) Lepton finding
2) Jet clustering
3) Flavour tagging
   - 4 b jets!
4) Jet pairing
   - Choose permutation with smallest chi^2:

$$\chi^2 = \frac{(M_{12} - M_W)^2}{\sigma_W^2} + \frac{(M_{123} - M_t)^2}{\sigma_t^2} + \frac{(M_{45} - M_h)^2}{\sigma_h^2}$$

   - Provides background rejection



Semi-leptonic selection



- BDT used to classify events using discriminating variables
- Selection chosen to maximise significance

Selected events in 1.5 ab^{-1}

- ttH semi-leptonic channel: 171
- tt background: 274
- Total background: 590

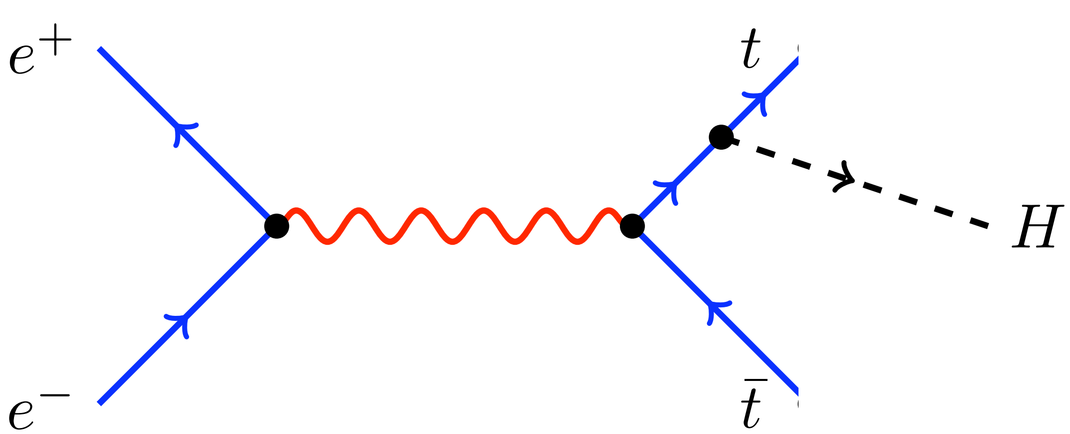
Preliminary result (semi-leptonic channel)

New analysis preliminary result

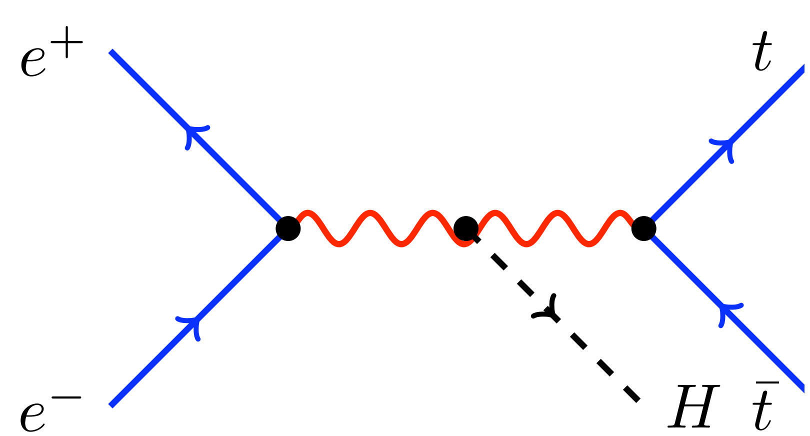
- ttH cross section measurement at $\sqrt{s}$ =1.4 TeV, using 1.5 ab^{-1}
- Statistical uncertainty of 16.1% at CLIC

Next:

- Improve semi-leptonic analysis
- Combine with fully hadronic channel (higher statistics)
- Need to account for Higgsstrahlung to extract top Yukawa coupling:



t radiates Higgs
sensitive to top Yukawa coupling



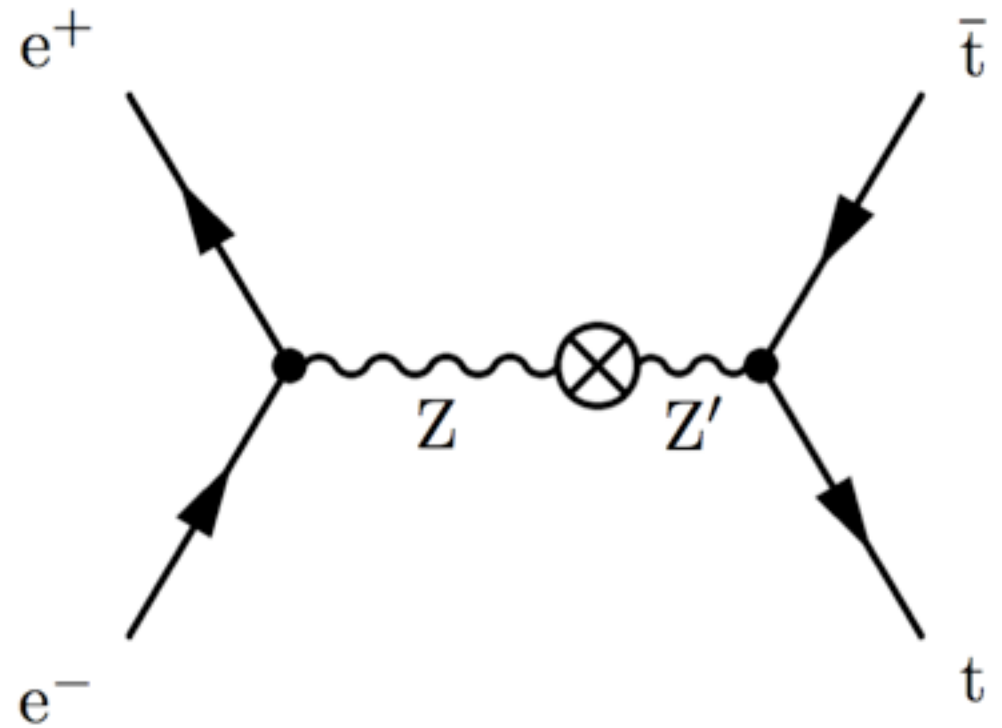
Higgsstrahlung
not sensitive to top Yukawa coupling

Top as a probe for new physics

Subject of studies in the near future

New physics effects

- Probe ttZ vertex to search for additional gauge bosons, extra dimensions
- A_{FB}: modified vertex gives different A_{FB} than predicted by SM
- A_{LR}: use polarised electron beam to enhance t_L / t_R. Measure change in cross section for different polarisations



ILC $\sqrt{s}$ = 500 GeV, 500 fb^{-1} study

- Precision on A_{FB} and A_{LR} of 1-1.5% [arxiv:1202.6659]

Advantages at CLIC

- Sensitivity to new physics improves at higher centre of mass energy: E^2/Λ^2
- Highly boosted top quarks - easier jet association

On the CLIC top physics agenda:
A_{FB}, A_{LR}, couplings to bosons, CP violation, FCNC top decays

Summary

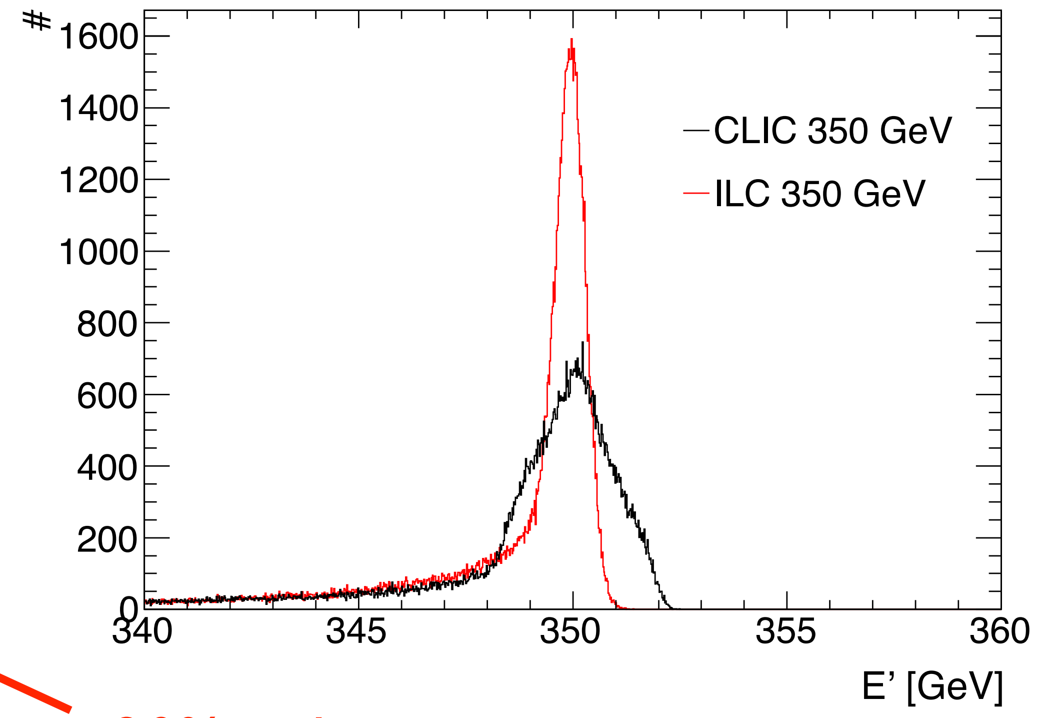
- ☑ Top physics present at every energy stage of CLIC design
- ☑ Top quark mass measurement:
  - Invariant mass at $\sqrt{s}$ = 500 GeV uncertainty 80 MeV/c^2
  - Threshold scan at $\sqrt{s}$ = 350 GeV uncertainty 34 MeV/c^2
- ☑ Top Yukawa coupling
  - ttH semi-leptonic cross section measurement at $\sqrt{s}$ = 1.4 TeV uncertainty 16.1%
- ☑ Top as a probe for new physics
  - Exploit polarised electron beam, benefit from $\sqrt{s}$ = 3 TeV

Backup

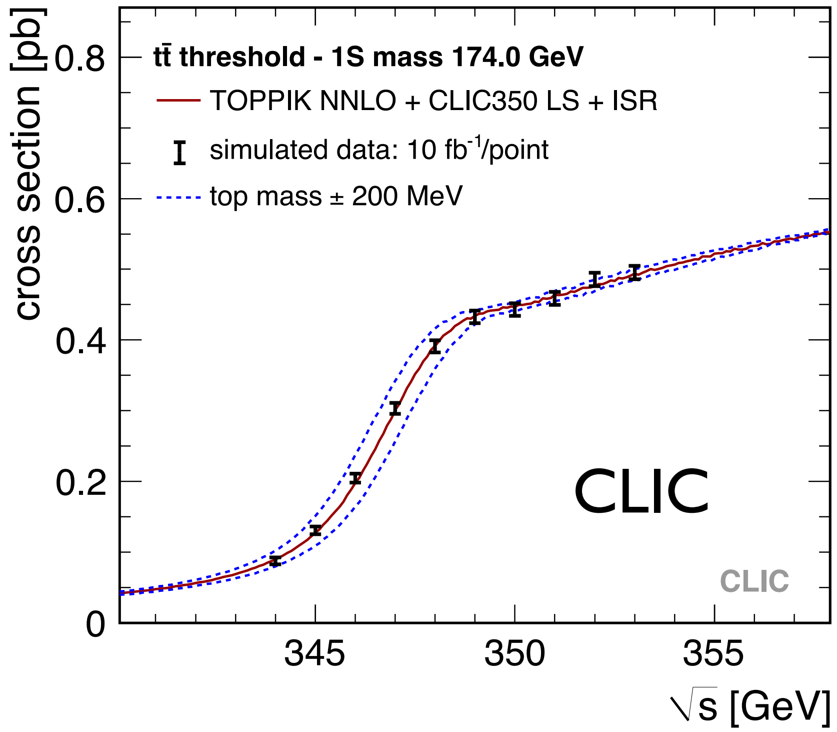
Effect of luminosity spectrum

- Same analysis - but using ILC luminosity spectrum
- Identical 2D extraction of m_t, α_s

1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022



20% reduction in statistical uncertainty on mass



ILC luminosity spectrum