Top Mass at Linear Colliders

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on behalf of the Linear Collider Detector and Physics Study

based on K. Seidel, F. Simon, M. Tesar, S. Poss, arXiv:1303.3758

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

- What are we measuring?
- Top quark production at Linear Colliders
- Top reconstruction
- Mass measurement above threshold
- Mass measurement in a threshold scan
- Systematics
- Summary

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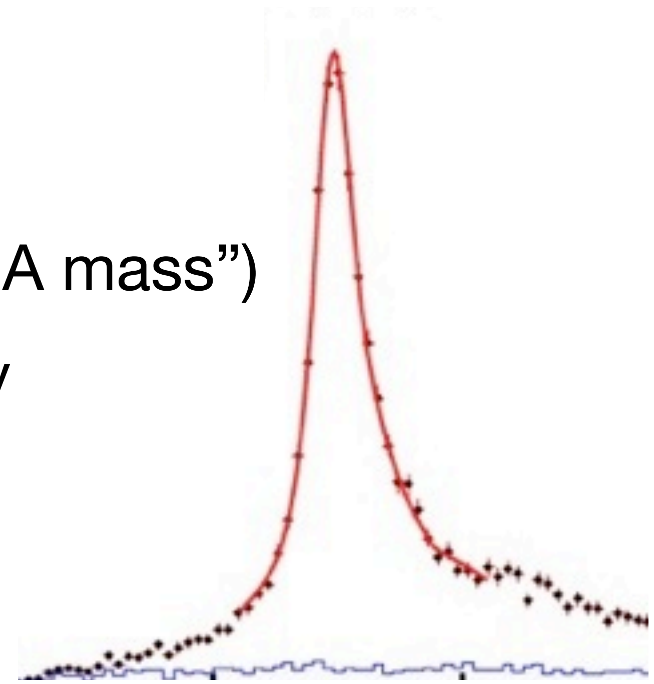
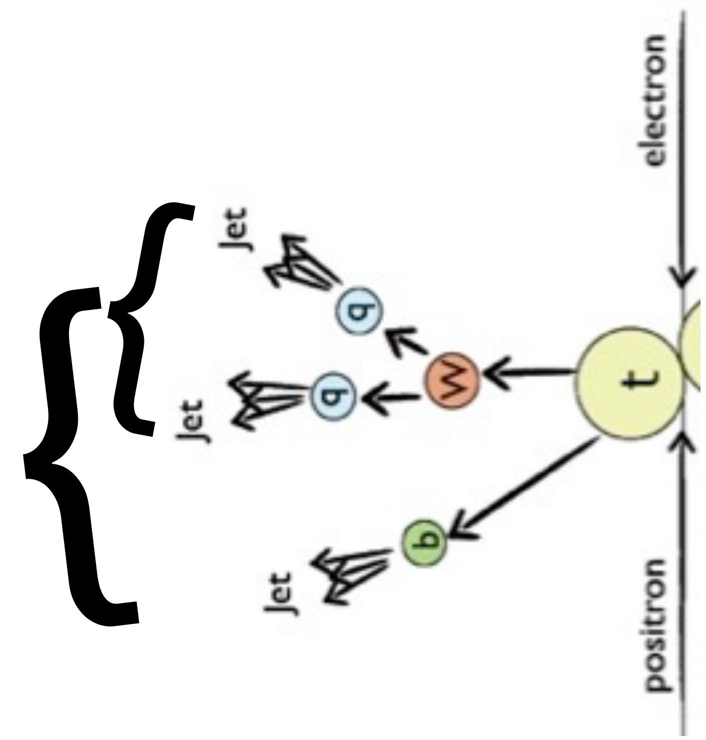
Based on results obtained in the framework of the CLIC CDR studies - But in general also applicable to ILC

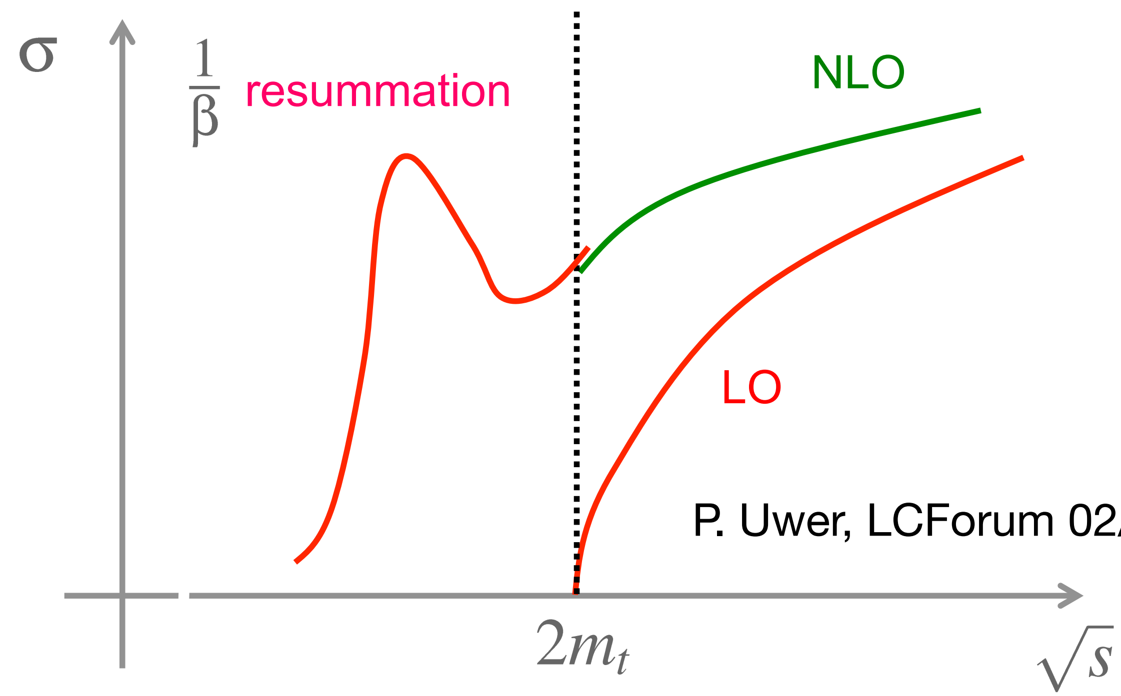
Top Mass at Linear Colliders

- Measurement in top pair production, two possibilities, each with advantages and dis-advantages:
  - Invariant mass
    - experimentally well defined (but not theoretically: “PYTHIA mass”)
    - can be performed at arbitrary energy above threshold: high integrated luminosity



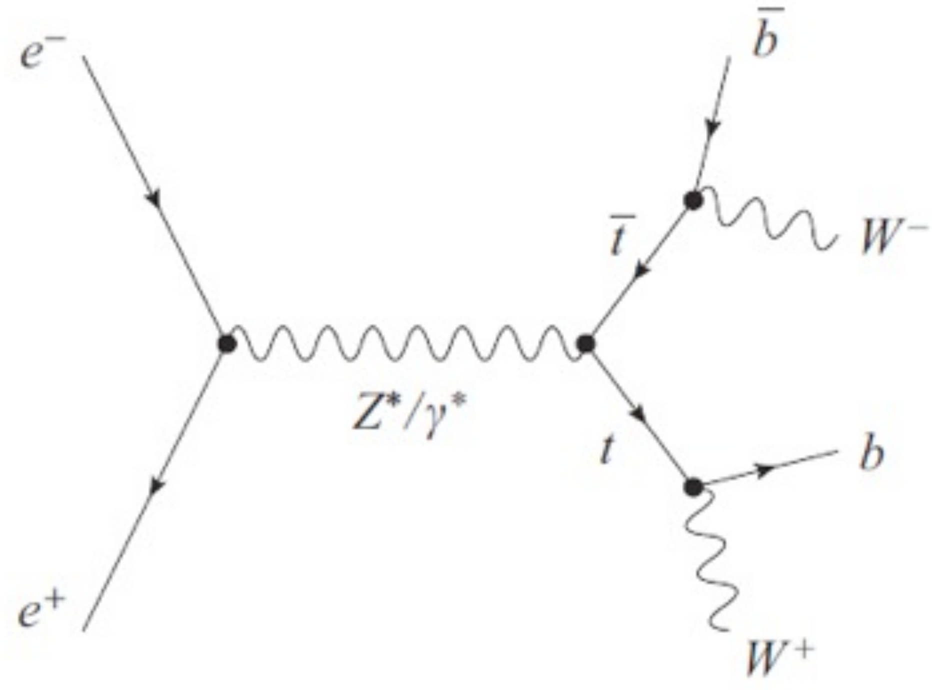


  - Threshold scan
    - theoretically well understood, can be calculated to higher orders
    - needs dedicated running of the accelerator (but is also in a sweet spot for Higgs physics)



Reconstructing Top Quarks at Lepton Colliders

- Driven by production and decay:
  - Production in pairs, decay to W and b



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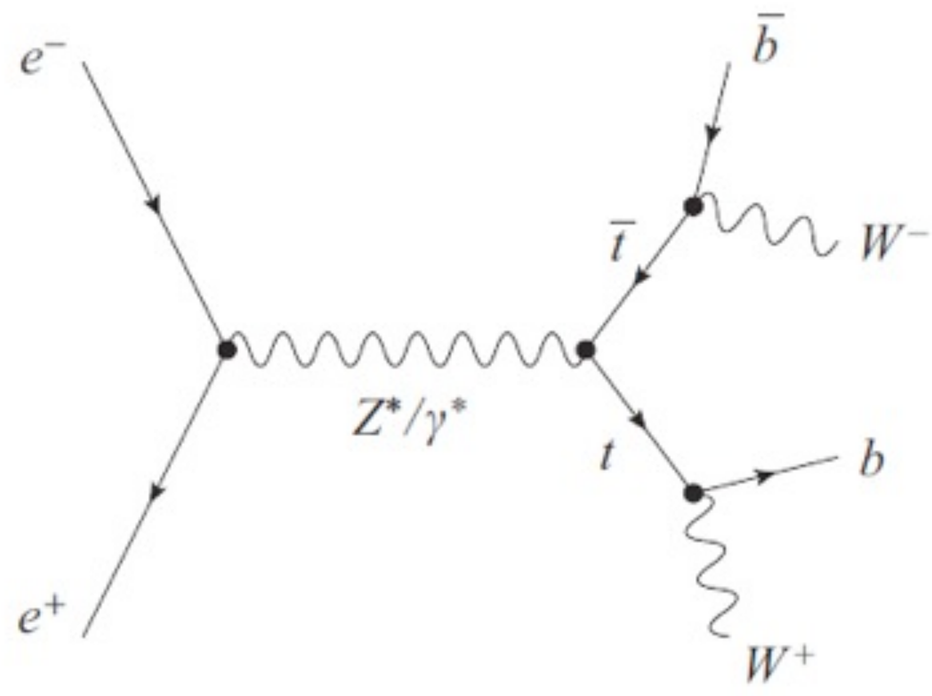
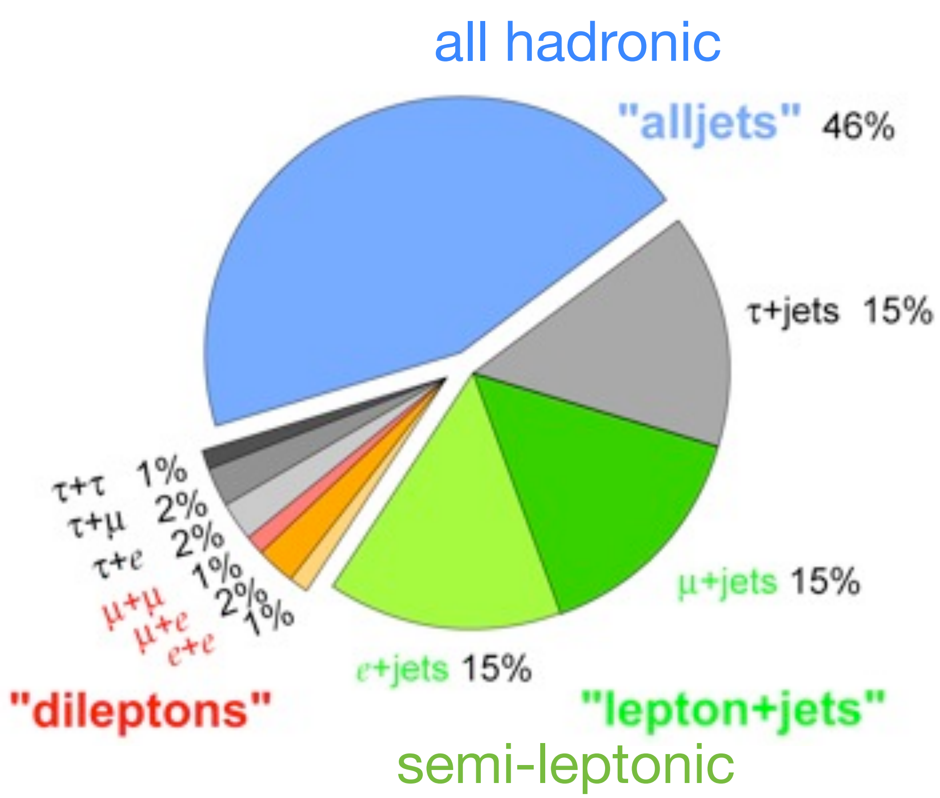


Event signature entirely given by the decay of the W bosons:



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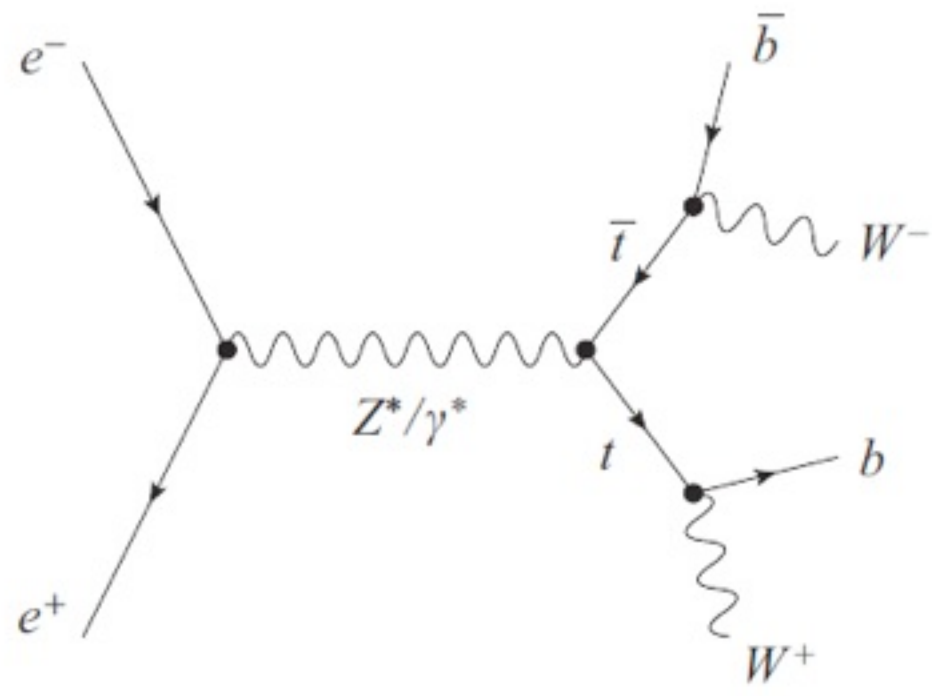

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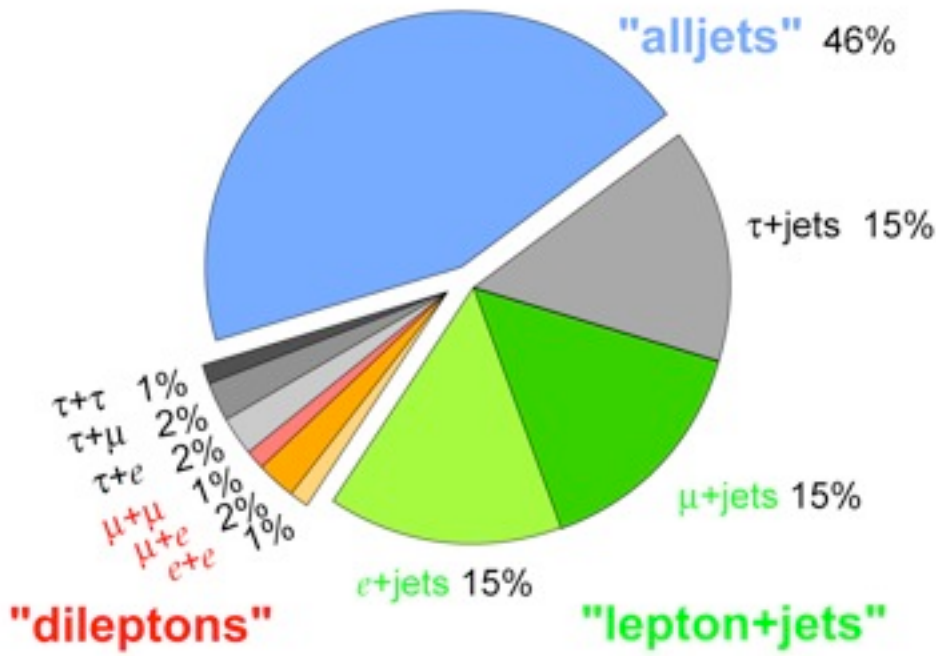


- At hadron colliders: Hard to pick out top pairs from QCD background - Use one and two-lepton final states
- At lepton colliders: Top pairs easy to identify, concentrate on large branching fractions and controllable missing energy (not more than one neutrino!)

Analysis Challenges & Event Simulation

- Key reconstruction challenge at CLIC: pile-up of γγ -> hadrons background, rejected with timing & p_t cuts and with jet finding based on k_t algorithm
  - Also relevant for ILC: No pile-up, but several γγ -> hadrons events / BX - Jet finding now follows CLIC experience

- Event generation with PYTHIA and WHIZARD, depending on final state
- Full GEANT4 detector simulation
- Reconstruction with PandoraPFA

no direct simulation of threshold - using NNLO cross sections

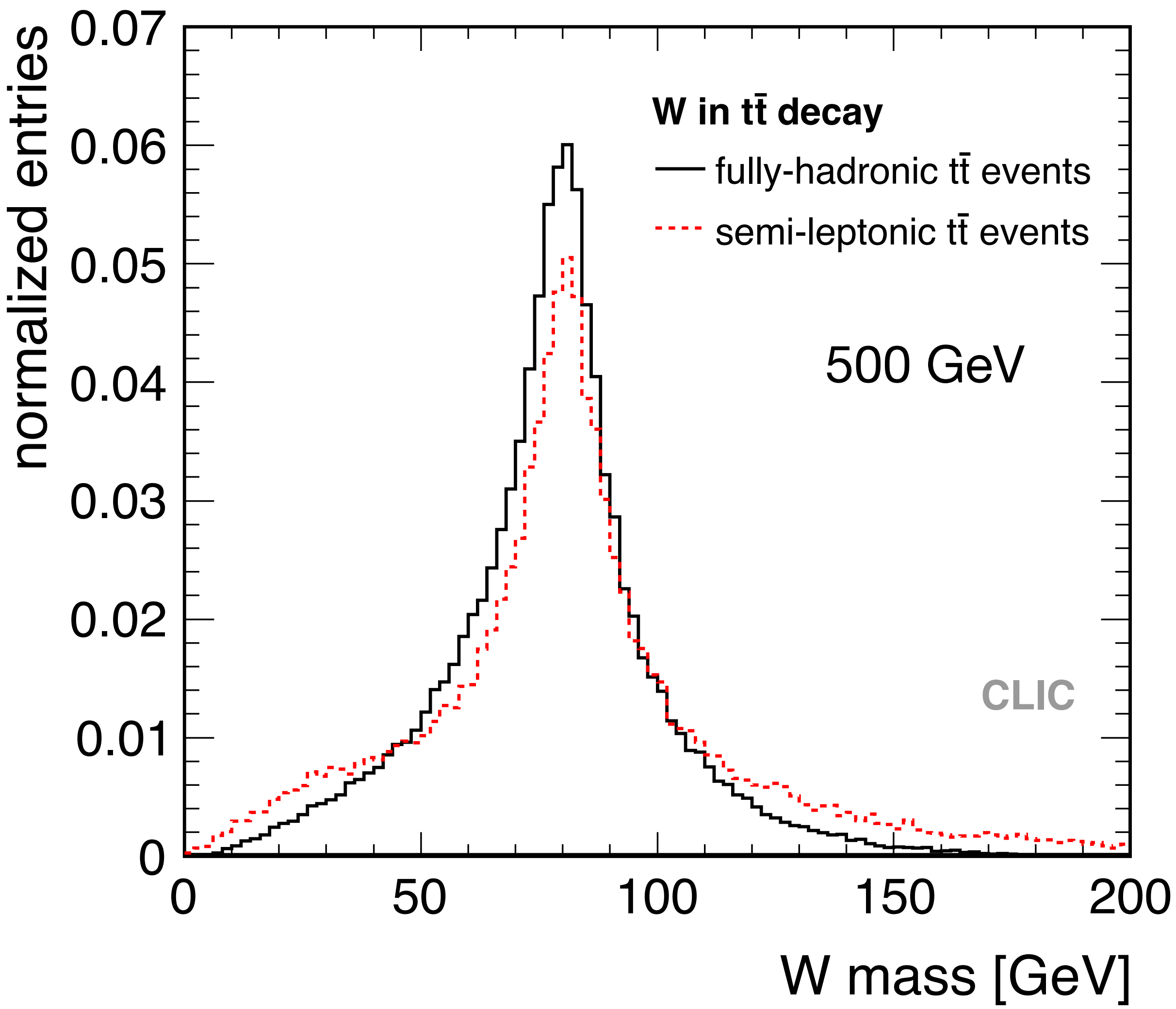
type	final state	σ 500 GeV	σ 352 GeV
Signal (m_{top} = 174 GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

both at and above threshold 100 fb^{-1} assumed

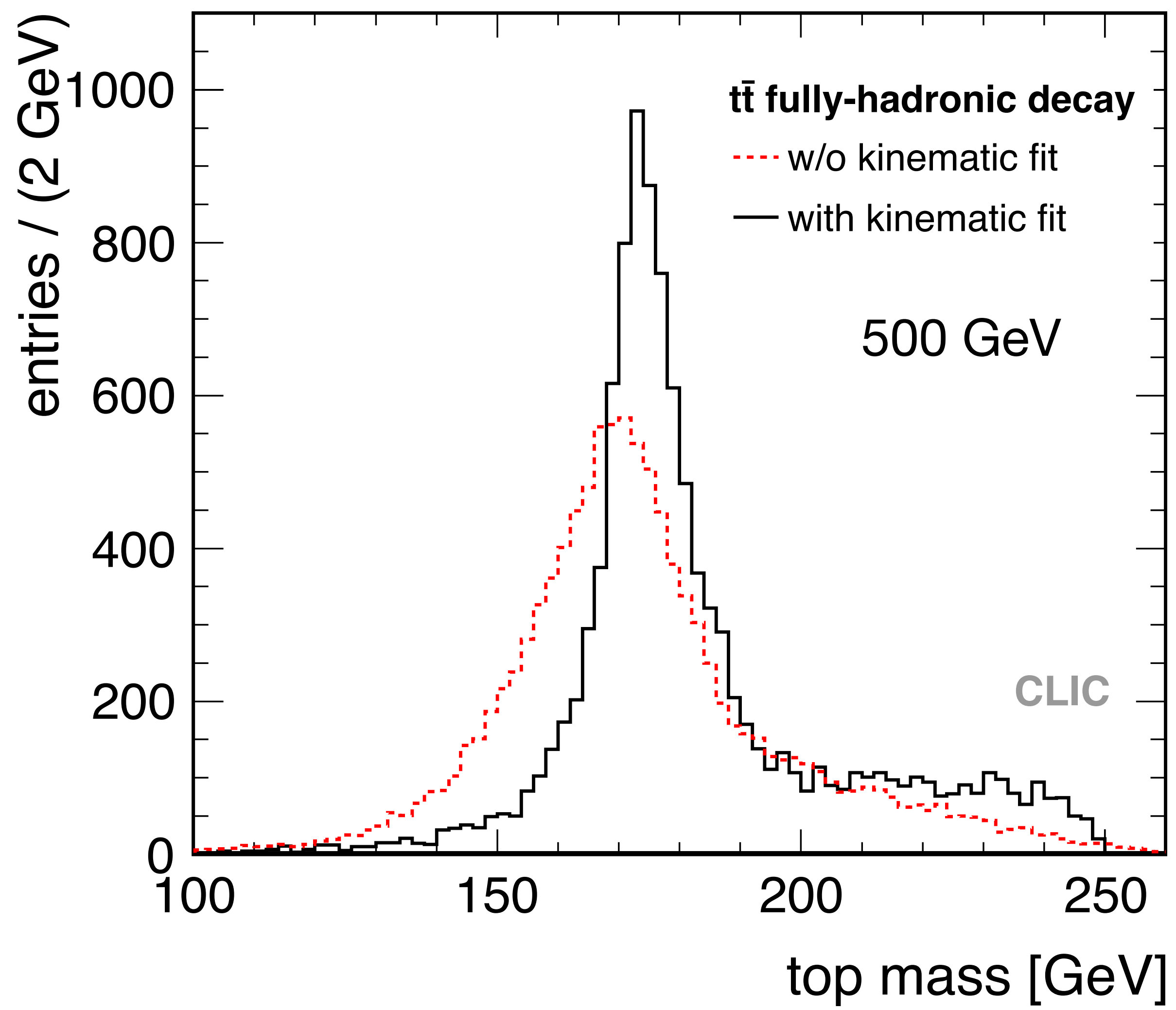
Analysis Strategy

- Identify the type of top decay according to number of isolated leptons
  - all-hadronic (0 leptons), semi-leptonic (1 lepton), leptonic (>1 lepton) -> rejected
- Jet clustering (exclusive k_t algorithm) according to classification: 6 or 4 jets
- Flavor-tagging: Identify the two most likely b-jet candidates
- W pairing: Jets / leptons into W bosons
  - Unique in the semi-leptonic case: 1 W from two light jets, 1 W from lepton & missing Energy
  - 3 possibilities (4 light jets) in all-hadronic case - Pick combination with minimal deviation from nominal W mass
- Kinematic fit - Use Energy/momentum conservation to constrain event
  - Performs the matching of W bosons an b-Jets to t candidates
  - Enforces equal t and anti-t mass: Only one mass measurement per event
  - Provides already good rejection on non-tt background
- Additional background rejection with likelihood method based on event variables (sphericity, b-tags, multiplicity, W masses, d_{cut}, top mass w/o kin fit)

Reconstruction Details

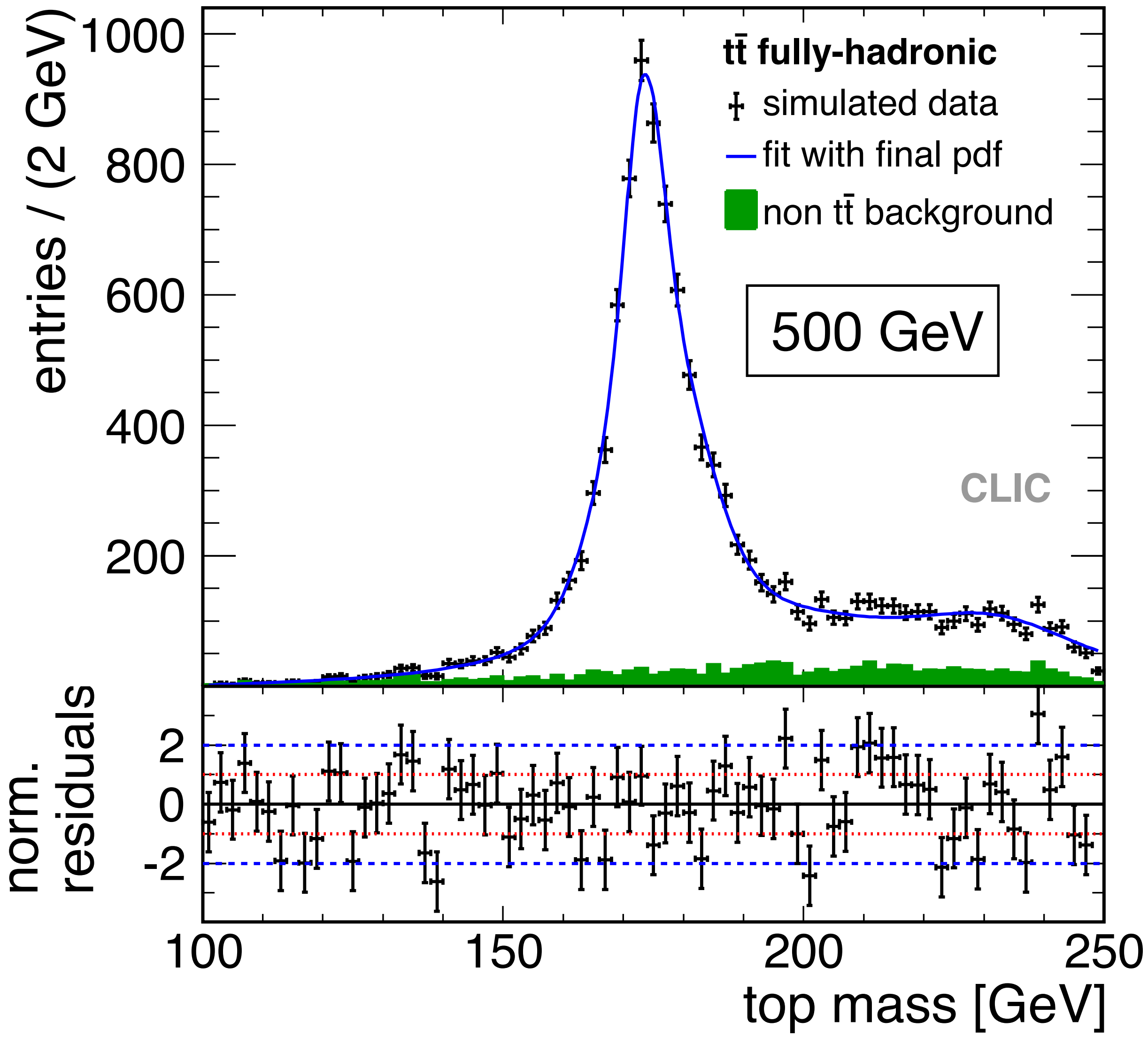


- Direct W reconstruction: sub-100 MeV precision on reconstructed mass: < 1 % uncertainty on JES



- The power of kinematic fitting: Substantially improved mass resolution, reduction of impact of uncertainties

Top Reconstruction - Performance

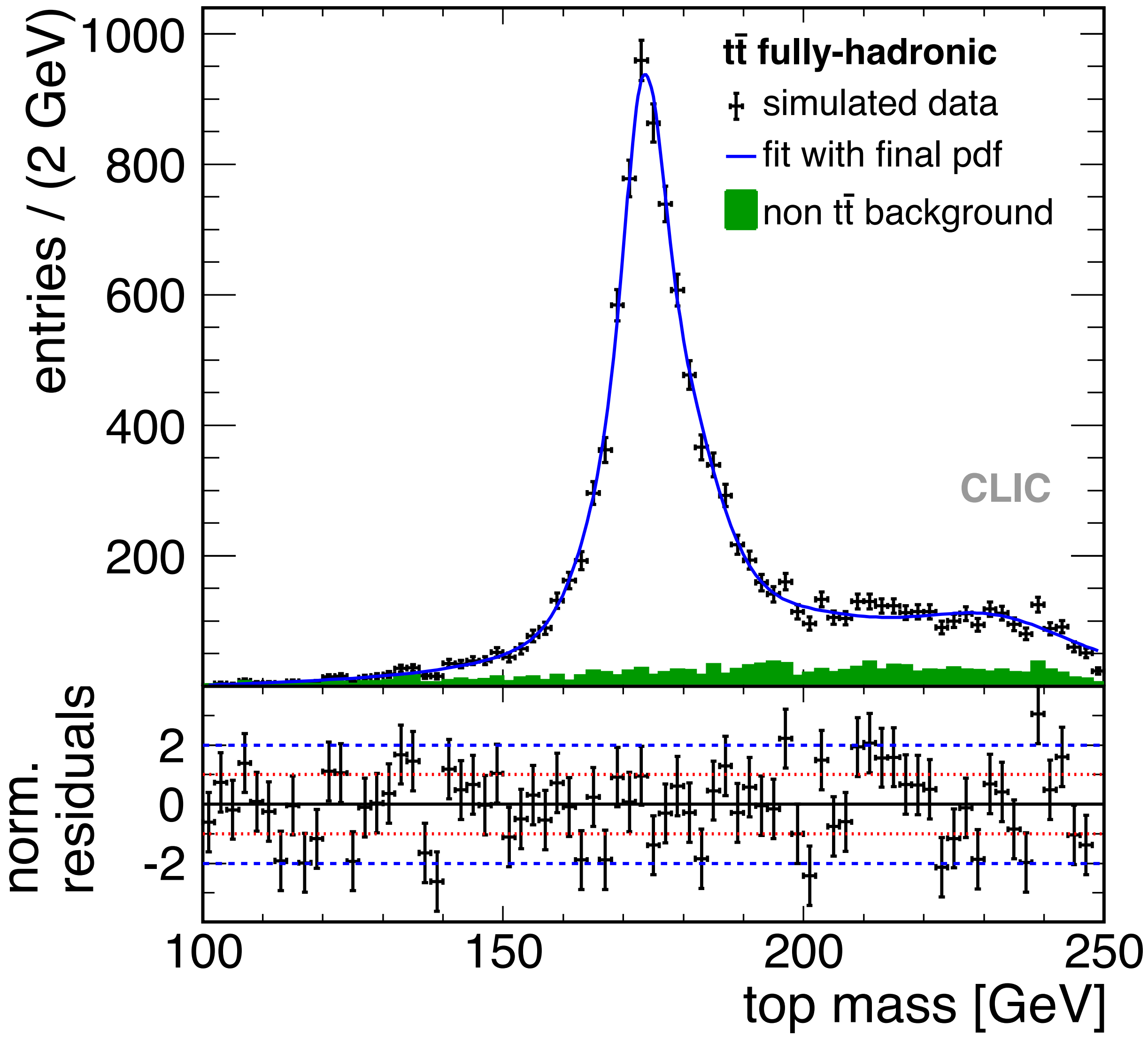


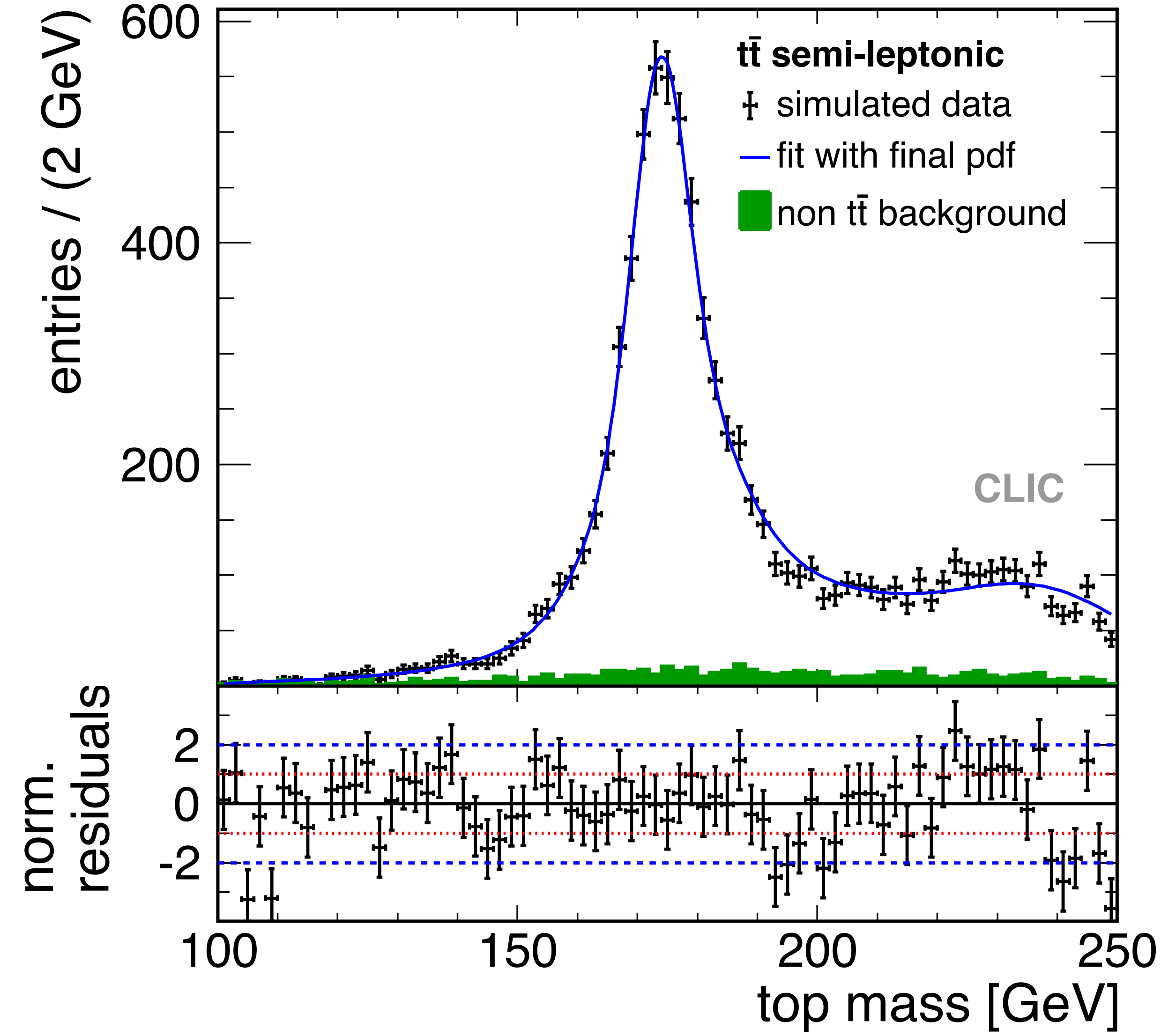
- Very low non-ttbar background
  - S/B ~8.5 (12) for FH (SL) at 500 GeV
  - S/B ~4.5 directly above threshold
- High reconstruction efficiency
  - 34% (44%) for FH (SL) at 500 GeV
  - 92% for selected decay modes at threshold

Analysis at threshold optimized for significance, not highest reconstruction quality

Overall similar performance expected at ILC (somewhat higher efficiencies obtained in 500 GeV LOI-studies without $\gamma\gamma \rightarrow$ hadrons background)

Mass Reconstruction Above Threshold

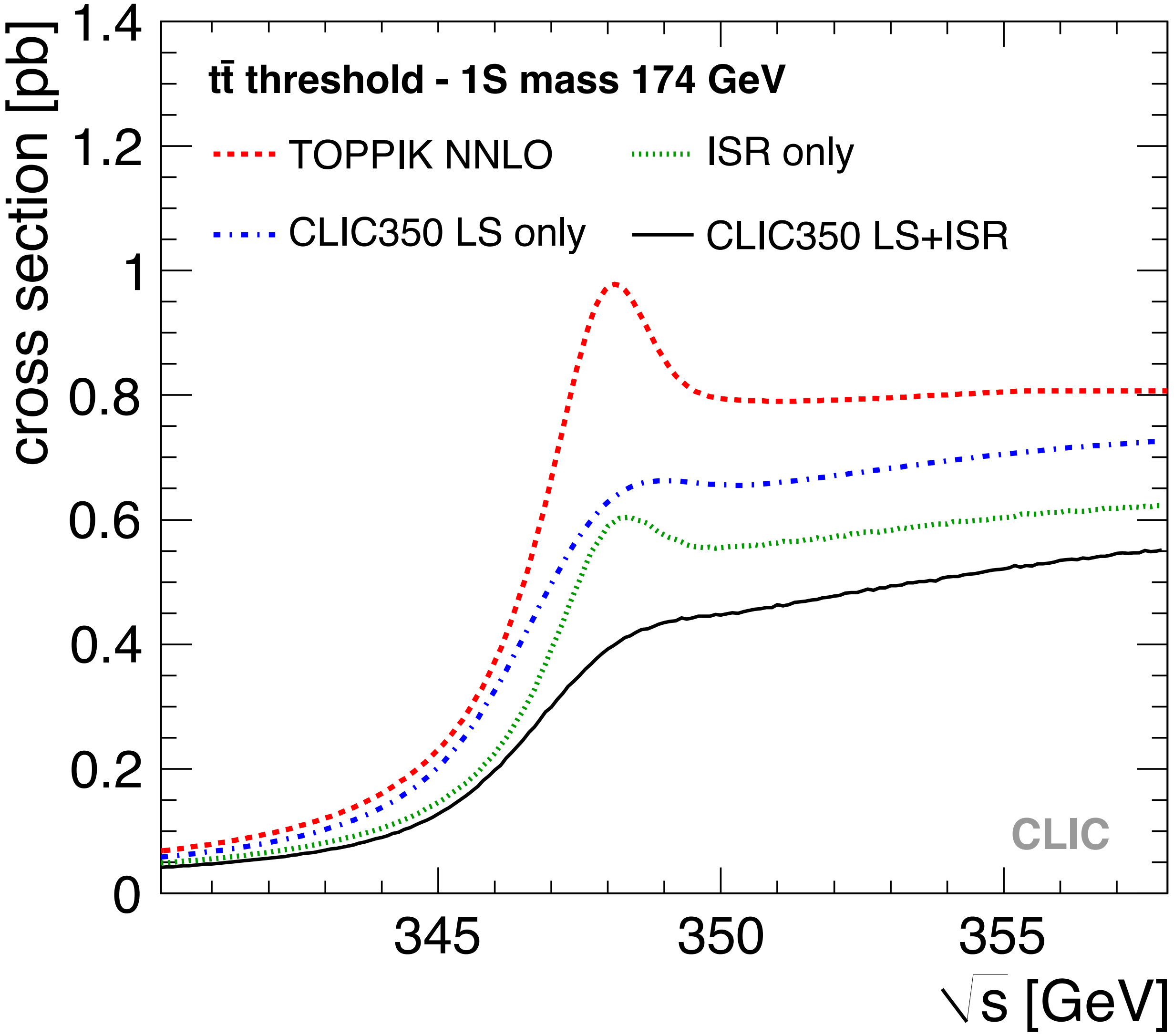




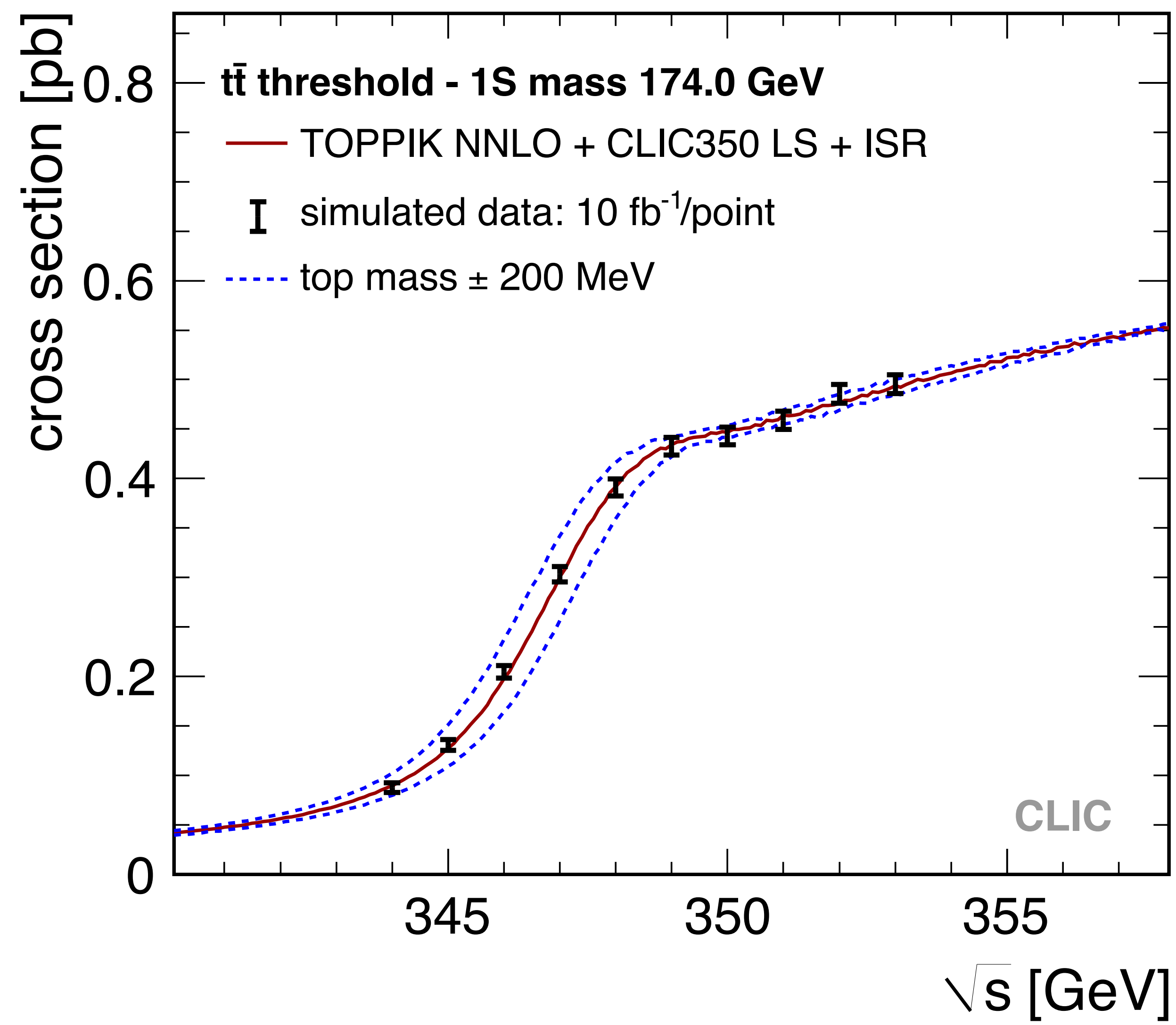
- Width less constrained than mass: substantial detector effects (peak width ~ 5 GeV compared to 1.4 GeV top width)

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

A ttbar Threshold Scan at CLIC



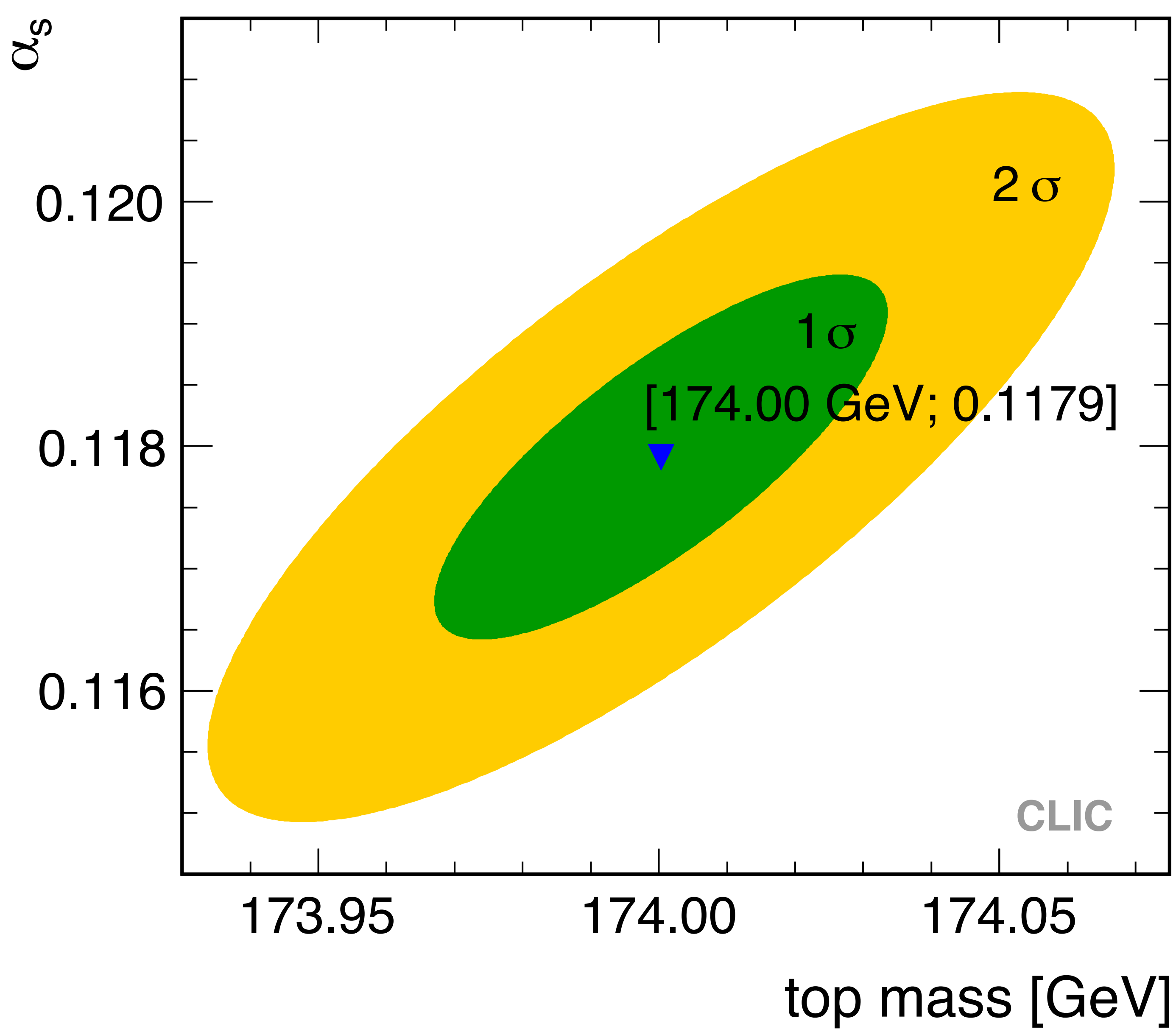
- Pure NNLO cross section (calculated with TOPPIK [Hoang & Teubner]) distorted by ISR and luminosity spectrum



- Combined with selection efficiency and background contamination from full simulations: Simulated data points

Measuring Top Mass and Strong Coupling

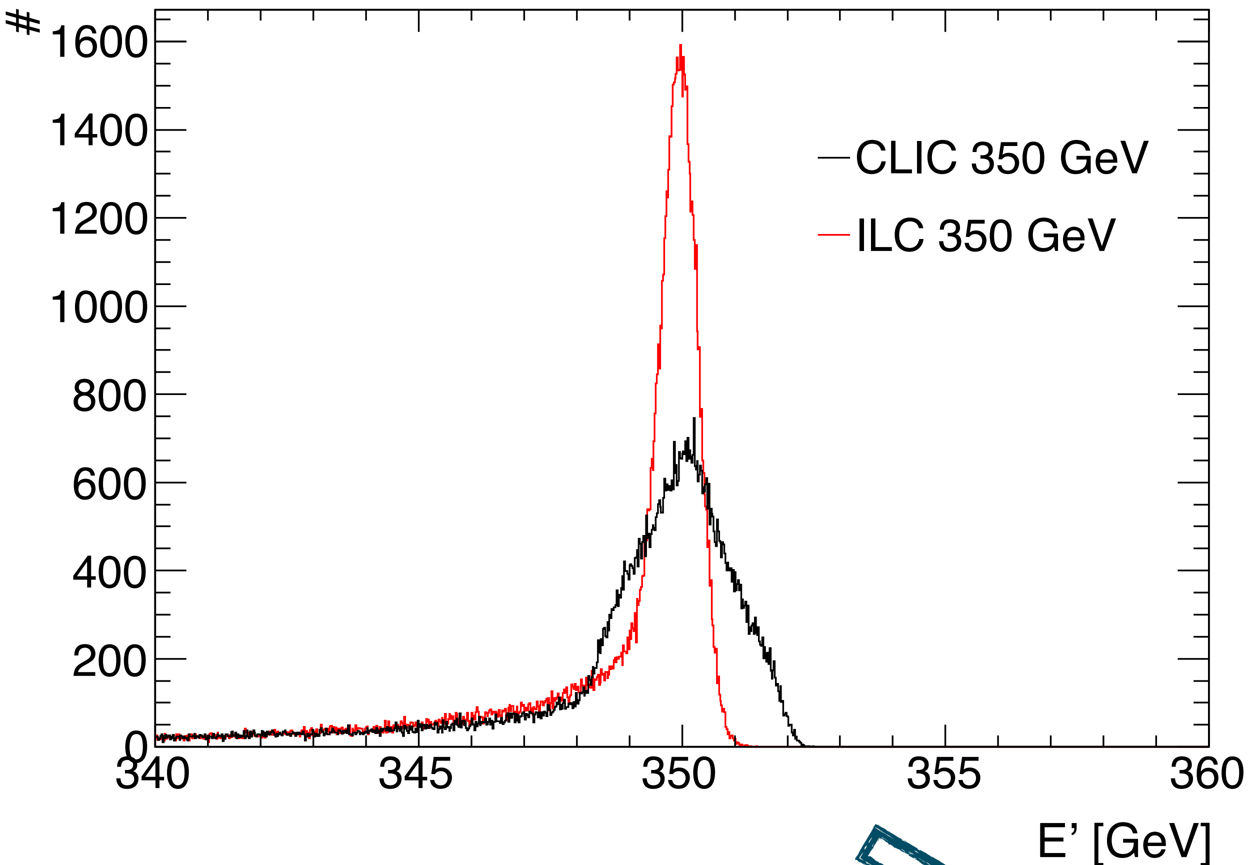
- 2D template fit to cross section

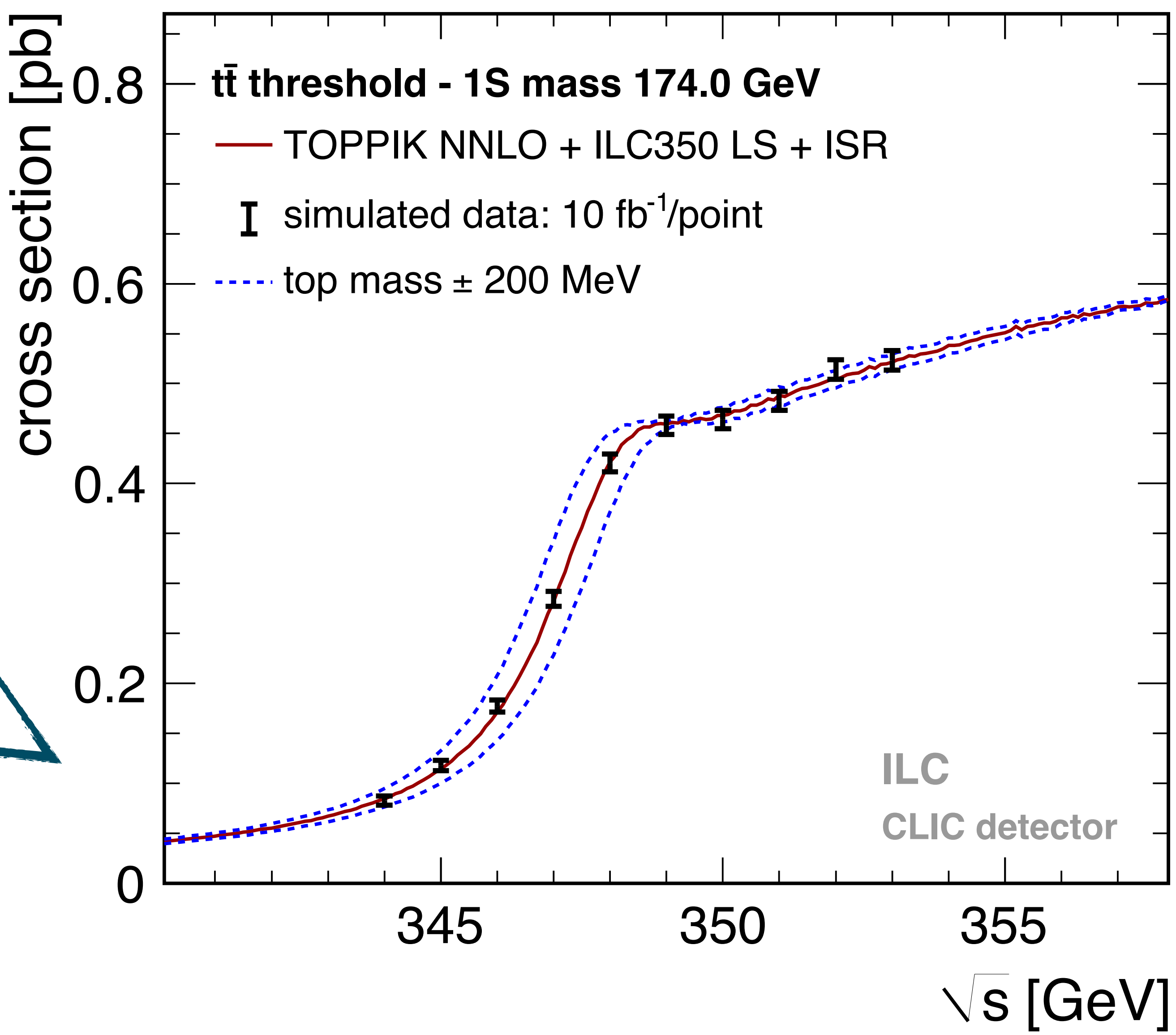


1S top mass and α_s combined 2D fit	
m_t stat. error	34 MeV
m_t theory syst. (1%/3%)	5 MeV / 8 MeV
α_s stat. error	0.0009
α_s theory syst. (1%/3%)	0.0008 / 0.0022

Comparison to ILC

- Same analysis - but with ILC luminosity spectrum (using CLIC efficiencies)

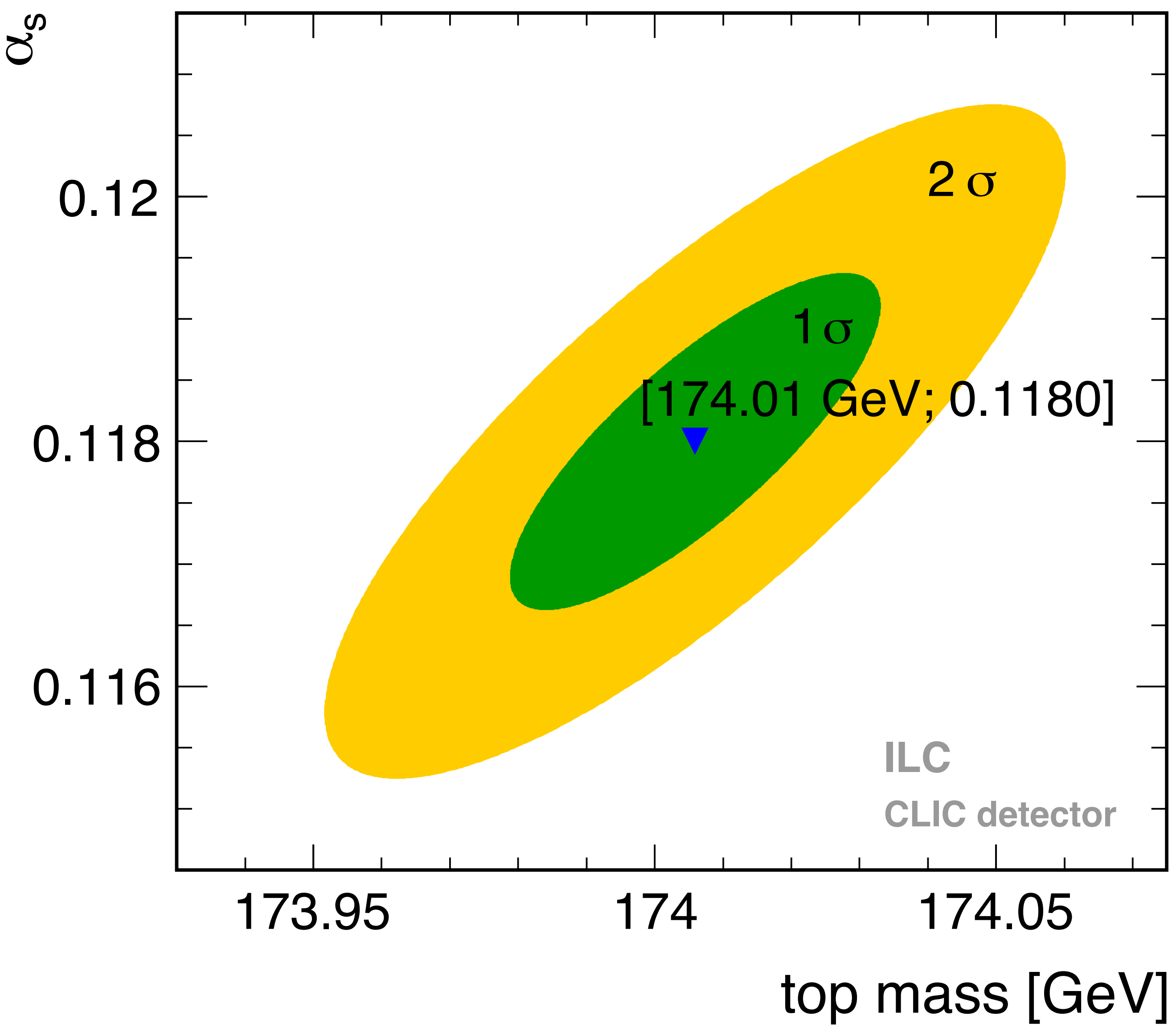




- Narrower main peak: Steeper rise of cross section at threshold

Comparison to ILC

- Identical extraction



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

- Compared to CLIC:
- 20% reduction of stat. mass uncertainty
- 10% reduction of stat. α_s uncertainty
- identical theory uncertainties

Systematics - Invariant Mass above Threshold

- Still incomplete, but some key issues were investigated:
  - Possible bias from top mass and width assumptions in detector resolution: Below statistical error, no indication for bias found
  - Jet Energy Scale: Reconstruction of W bosons can be used to fix this to better than 1% for light jets, assume similar precision for b jets from Z and ZZ events: Systematics below statistical uncertainties of the measurement
  - Color Reconnection: Not studied yet - depends on space-time overlap of final-state partons from t and anti-t decay - Expected to be less than in WW at LEP2: Comparable or smaller systematics on mass - less than 100 MeV

The key issue - and open question:
Above threshold the "PYTHIA mass" is measured - not well defined theoretically
➯ Substantial uncertainties in the interpretation of the measurements, far outweighs statistical uncertainties
➯ Some theory work in this direction already exists, but more is needed (also in in terms of connecting theory and experimental observables)

Systematics - Threshold Scan

- In addition to theory uncertainties directly included in the results, the following aspects were studied:
  - No dependence on precise location of scan energy
  - Non-ttbar background: 5% uncertainty results in 18 MeV uncertainty on mass
  - Beam energy: Expect 10^{-4} precision on CMS energy: ~30 MeV uncertainty on mass (also applies to invariant mass due to kinematic fit)
  - Luminosity spectrum: 20% uncertainty on main peak width results in 75 MeV uncertainty on mass - Achievable precision still under investigation

Understanding the spectrum is more important than the quality of the spectrum - expect similar precision for ILC and CLIC

Summary

- A linear collider operated at and above the ttbar threshold provides two complementary ways of measuring the top quark mass:
  - Direct reconstruction
  - A threshold scan
- For both, total uncertainties on the level of 100 MeV are within reach with 100 fb^{-1}, with the highest precision in a theoretically clean way obtainable with a threshold scan
- The differences between ILC & CLIC are not significant - Understanding of luminosity spectrum and resolutions key to control systematics

- Results extensively documented in arXiv:1303.3758 (submitted to EPJC)