Top Mass and Future Top Studies at CLIC

Frank Simon,
Max-Planck-Institut für Physik
Munich, Germany

on behalf of the CLICdp Collaboration

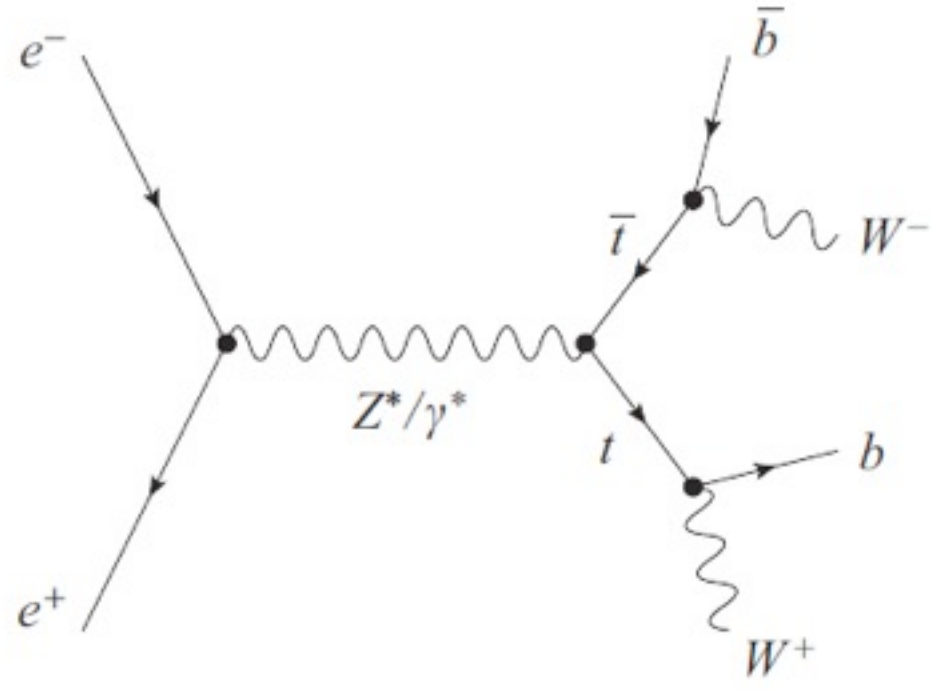
LCWS2013, Tokyo, November 2013

Outline

- Reconstructing Top quarks at Linear Colliders - TeV energies and below
- Mass measurement
  - Above threshold
  - At threshold
- Systematic uncertainties
  - Luminosity Spectrum
- Possibilities in the Multi-TeV regime
- Conclusions

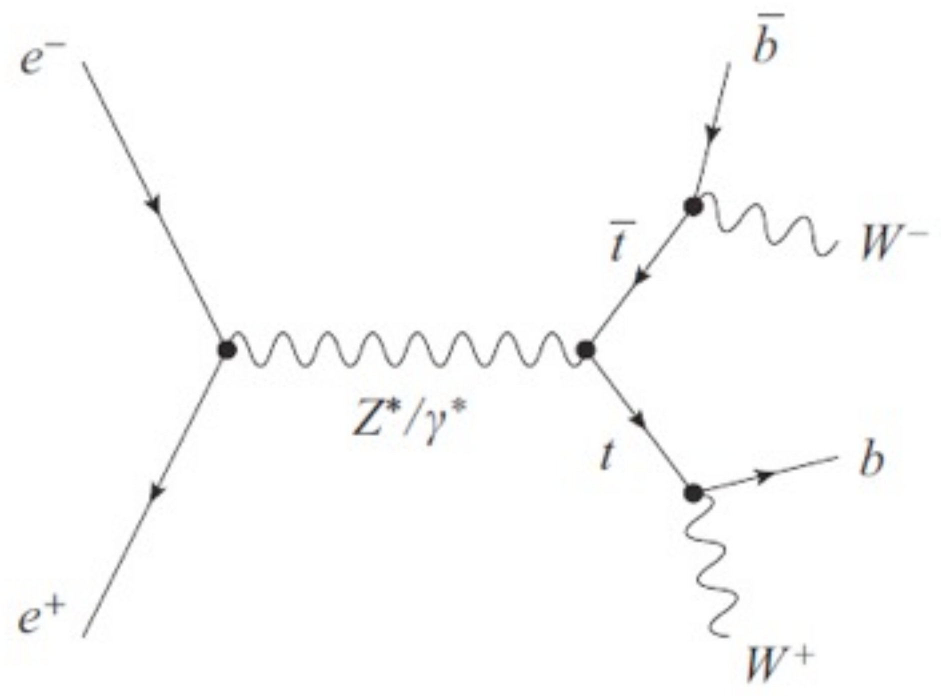
Reconstructing Top Quarks at Lepton Colliders

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

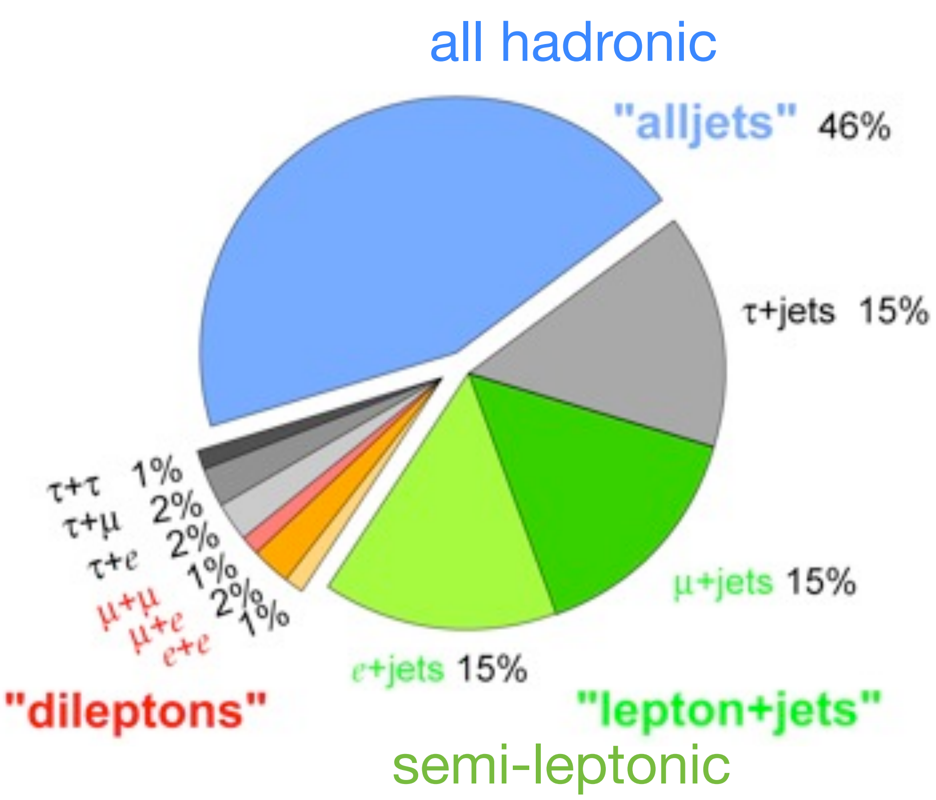


Reconstructing Top Quarks at Lepton Colliders

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

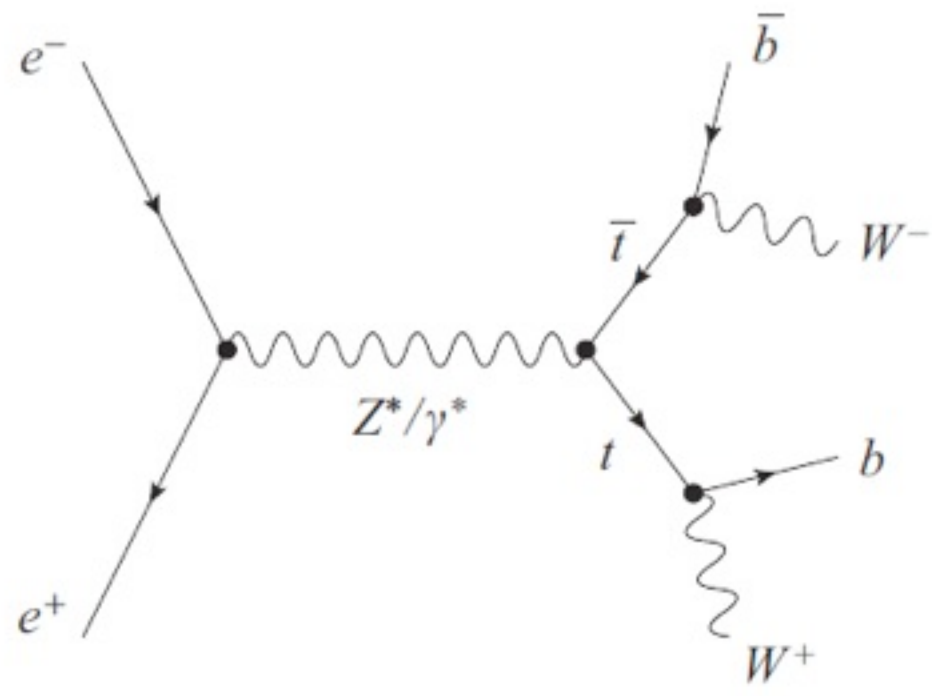


Event signature entirely given by the decay of the W bosons:

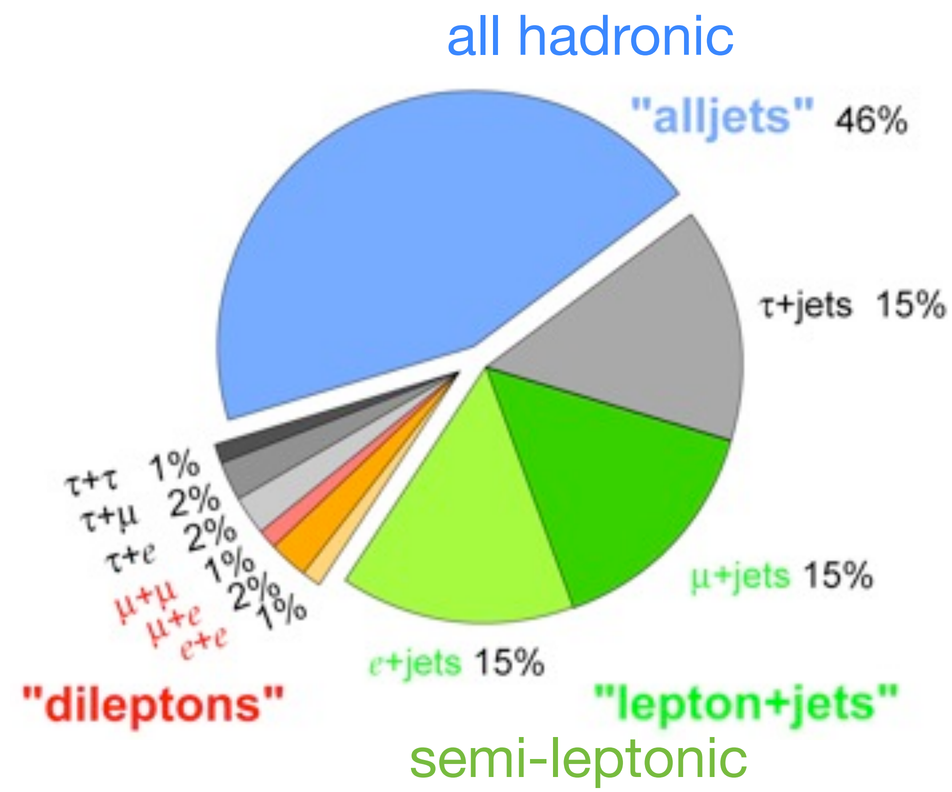


Reconstructing Top Quarks at Lepton Colliders

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



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



- 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

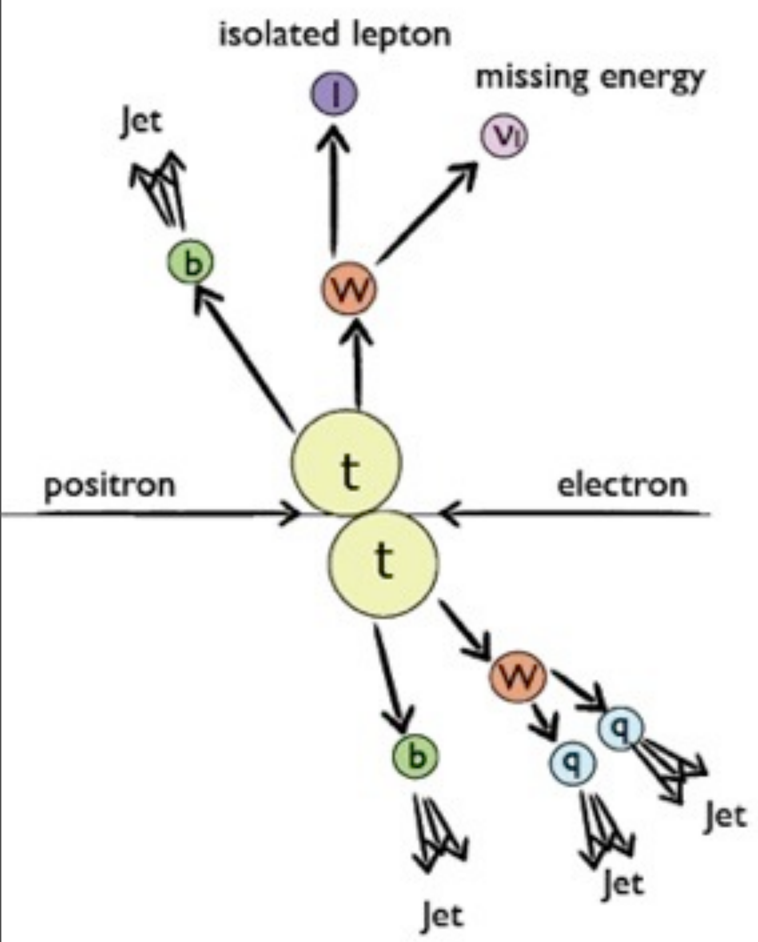
no direct simulation of threshold - using NNLO cross sections

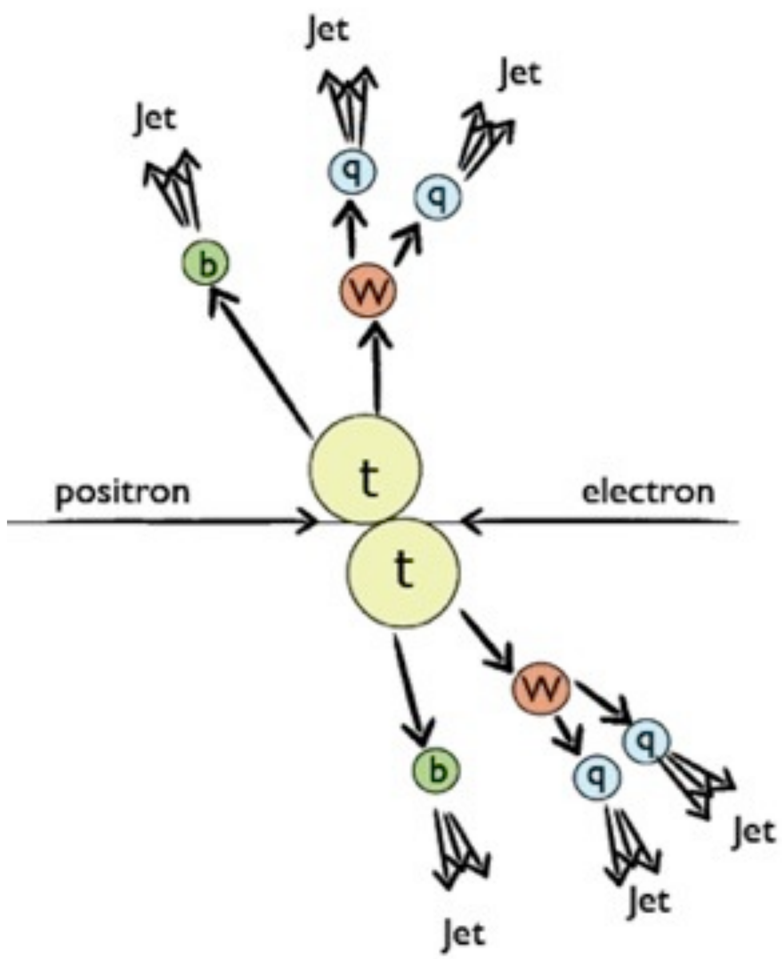
type	final state	σ 500 GeV	σ 352 GeV
Signal (m_{top} = 174 GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

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

Identifying & Reconstructing Top Quarks

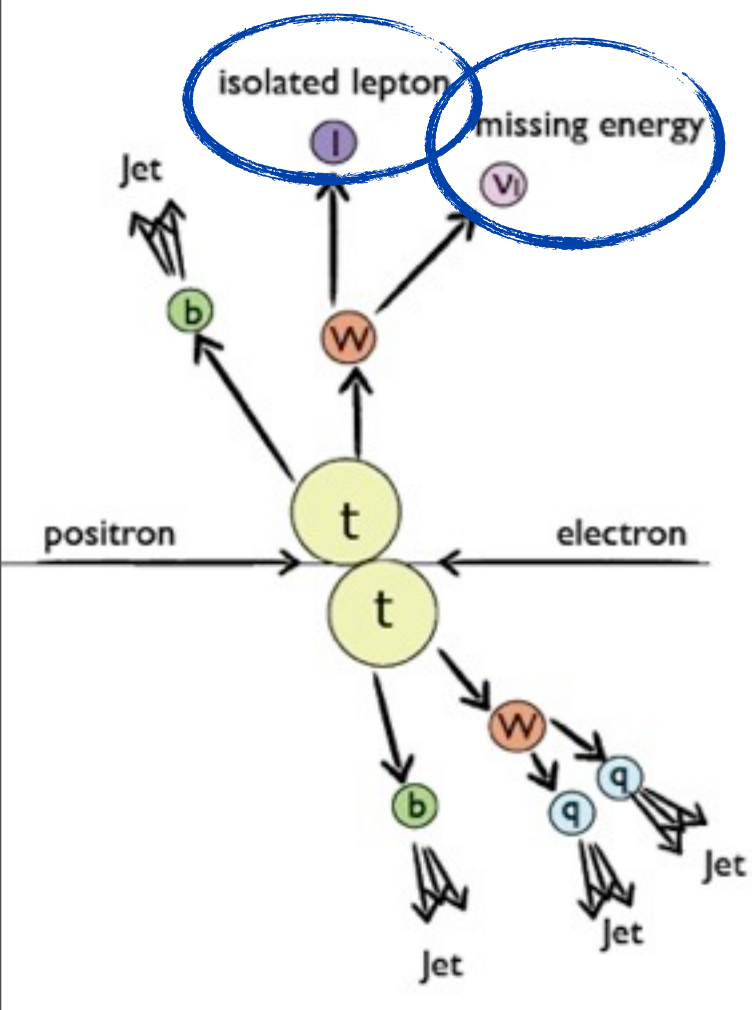
- Strategy depends on targeted ttbar final state



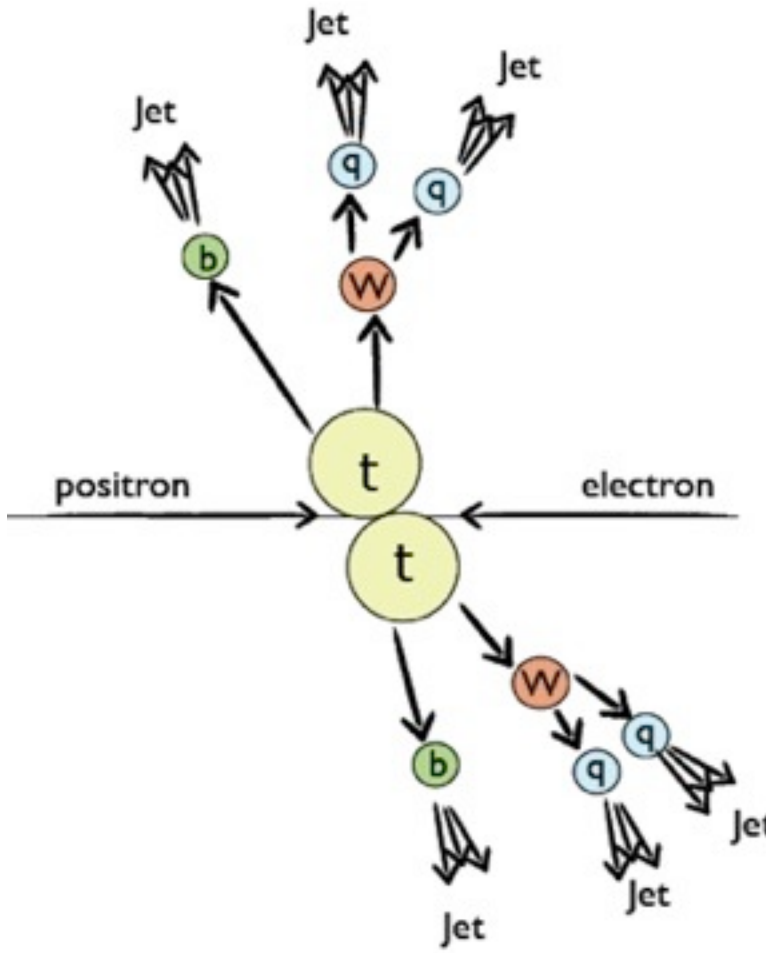


Identifying & Reconstructing Top Quarks

- Strategy depends on targeted ttbar final state

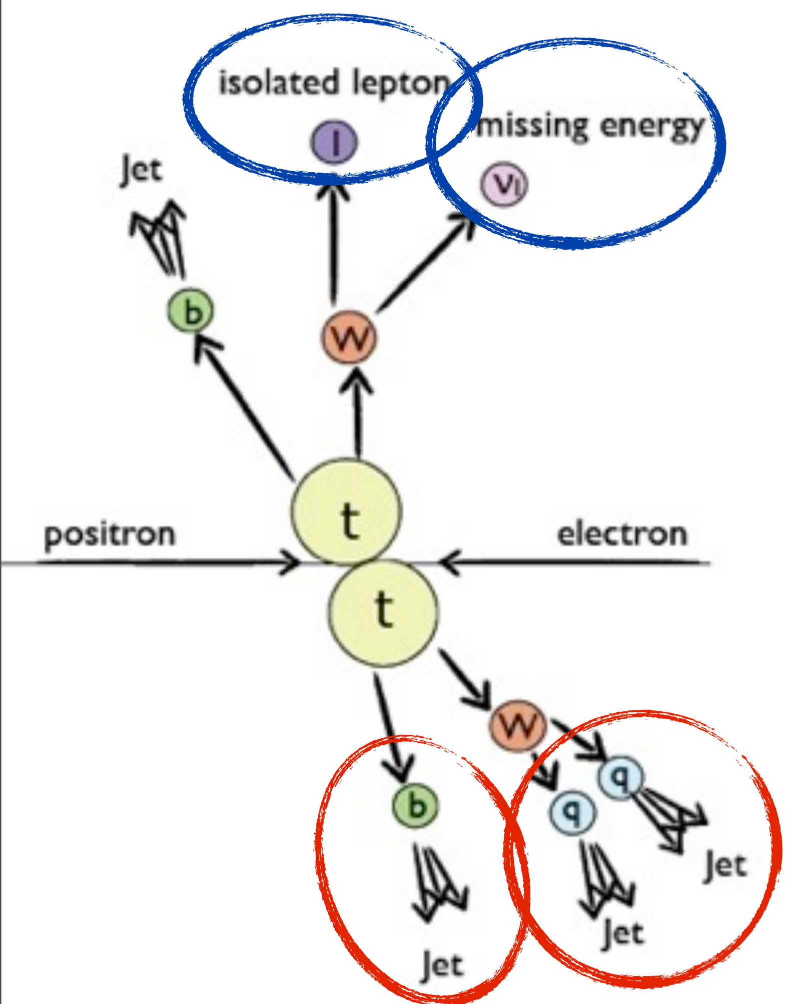


Semi-leptonic:
- isolated lepton ID, momentum measurement
- missing energy measurement



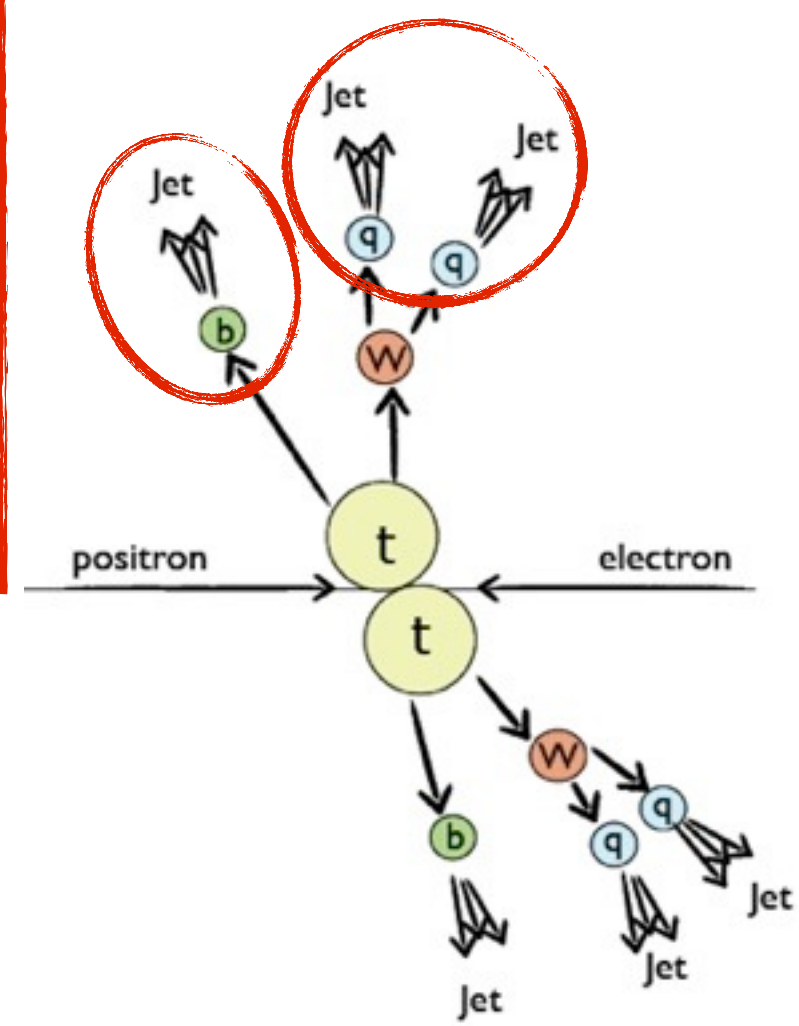
Identifying & Reconstructing Top Quarks

- Strategy depends on targeted ttbar final state



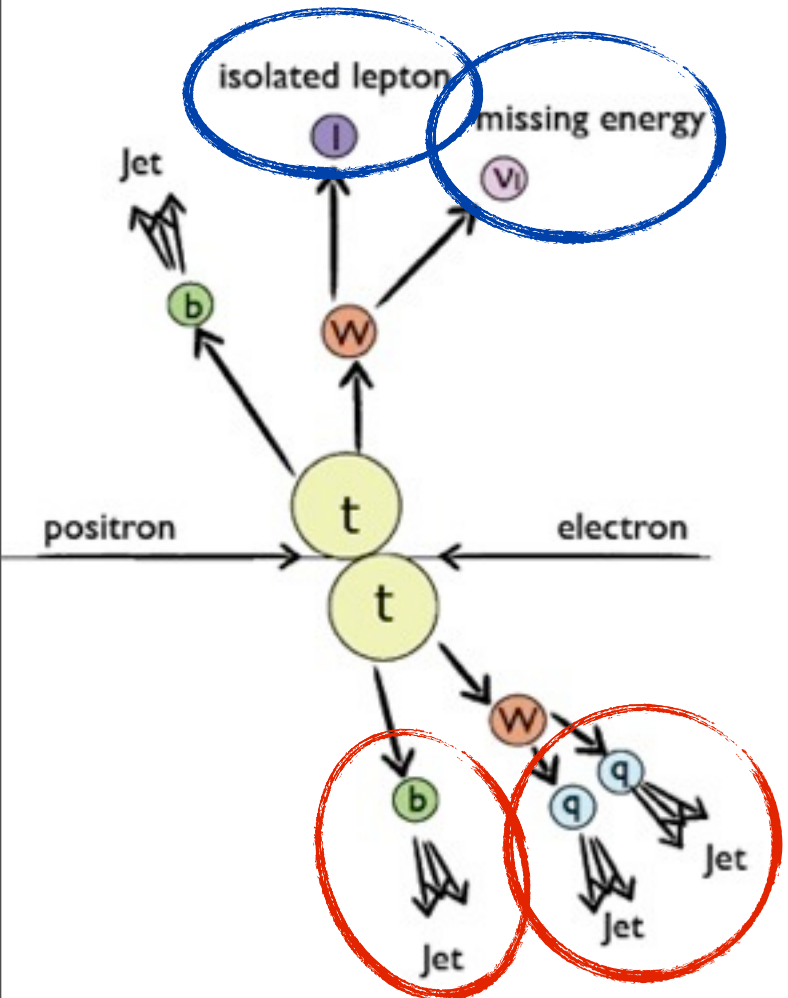
Semi-leptonic:
- isolated lepton ID, momentum measurement
- missing energy measurement

Universal
- Flavor tagging:
  - b - identification
  - b/c separation
- b-Jet energy measurement
- light Jet reconstruction & energy measurement



Identifying & Reconstructing Top Quarks

- Strategy depends on targeted ttbar final state



Semi-leptonic:

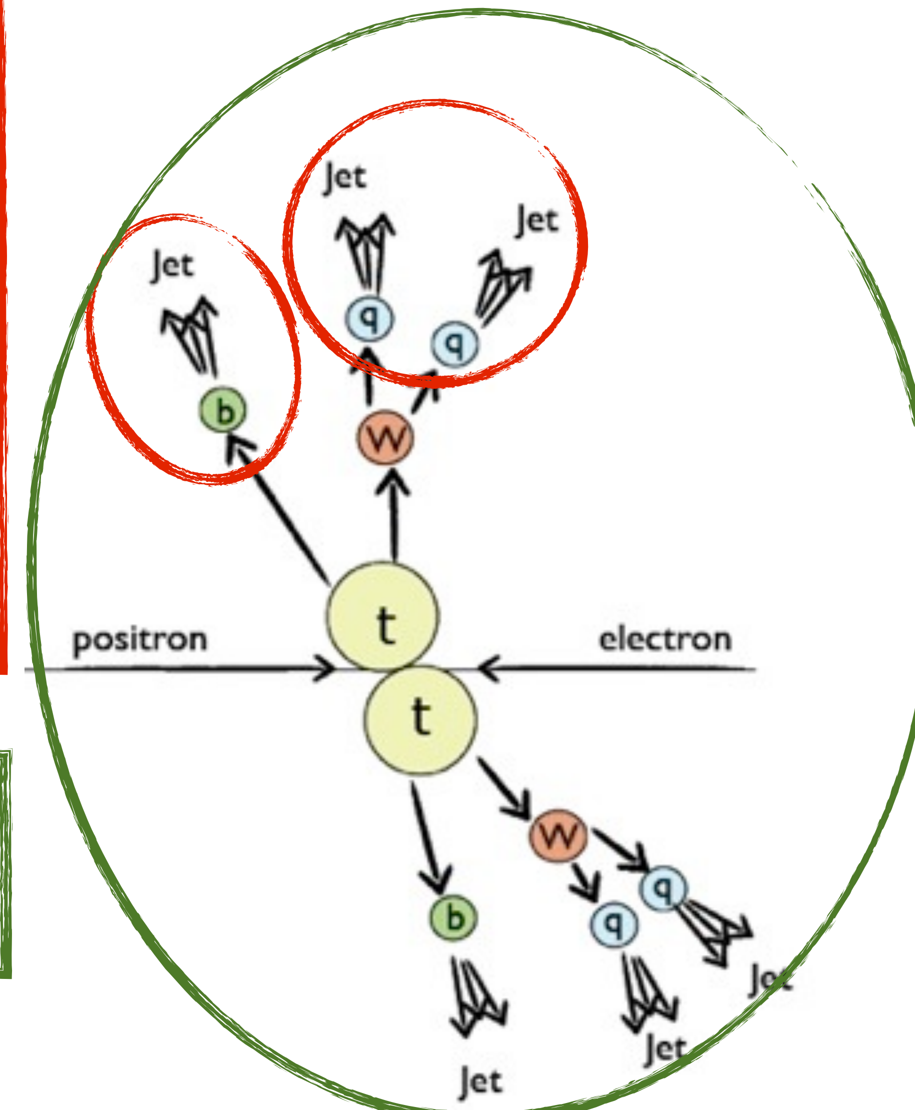
- isolated lepton ID, momentum measurement
- missing energy measurement

Universal

- Flavor tagging:
  - b - identification
  - b/c separation
- b-Jet energy measurement
- light Jet reconstruction & energy measurement

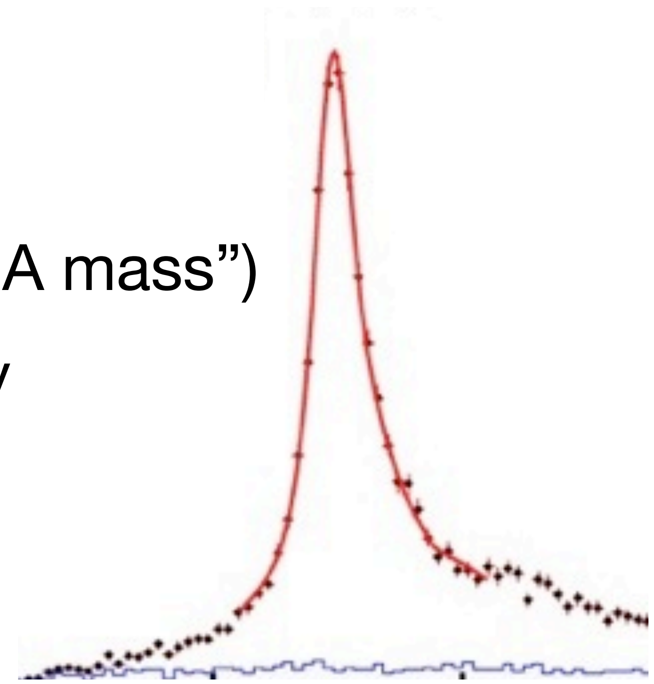
All-hadronic

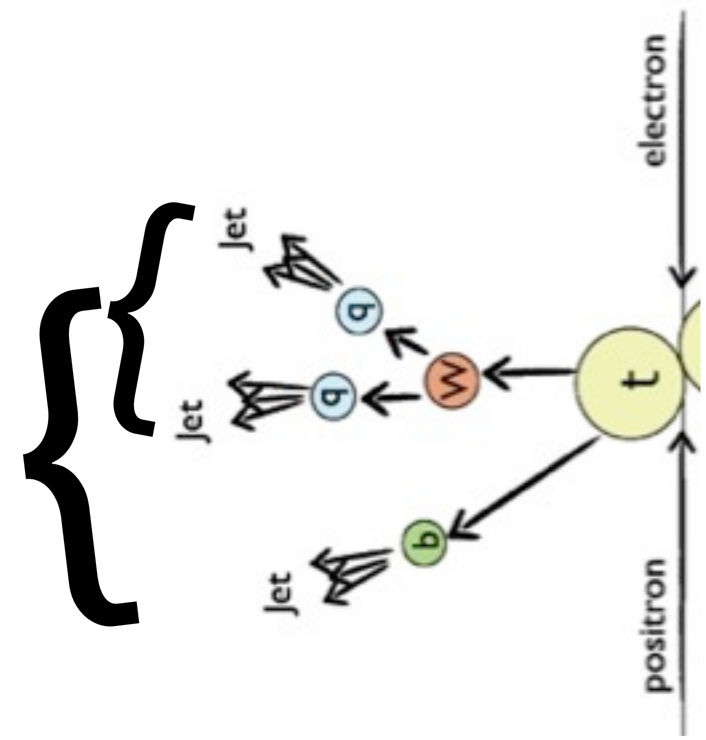
- global hadronic energy reconstruction



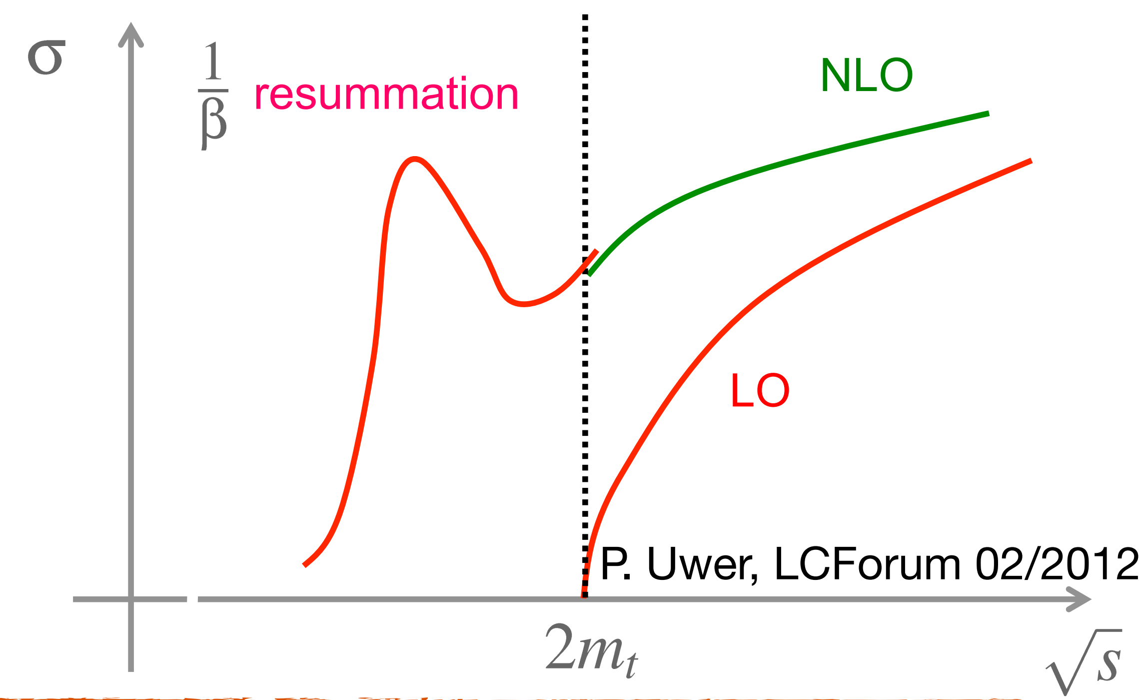
Top Mass at Linear Colliders

- 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





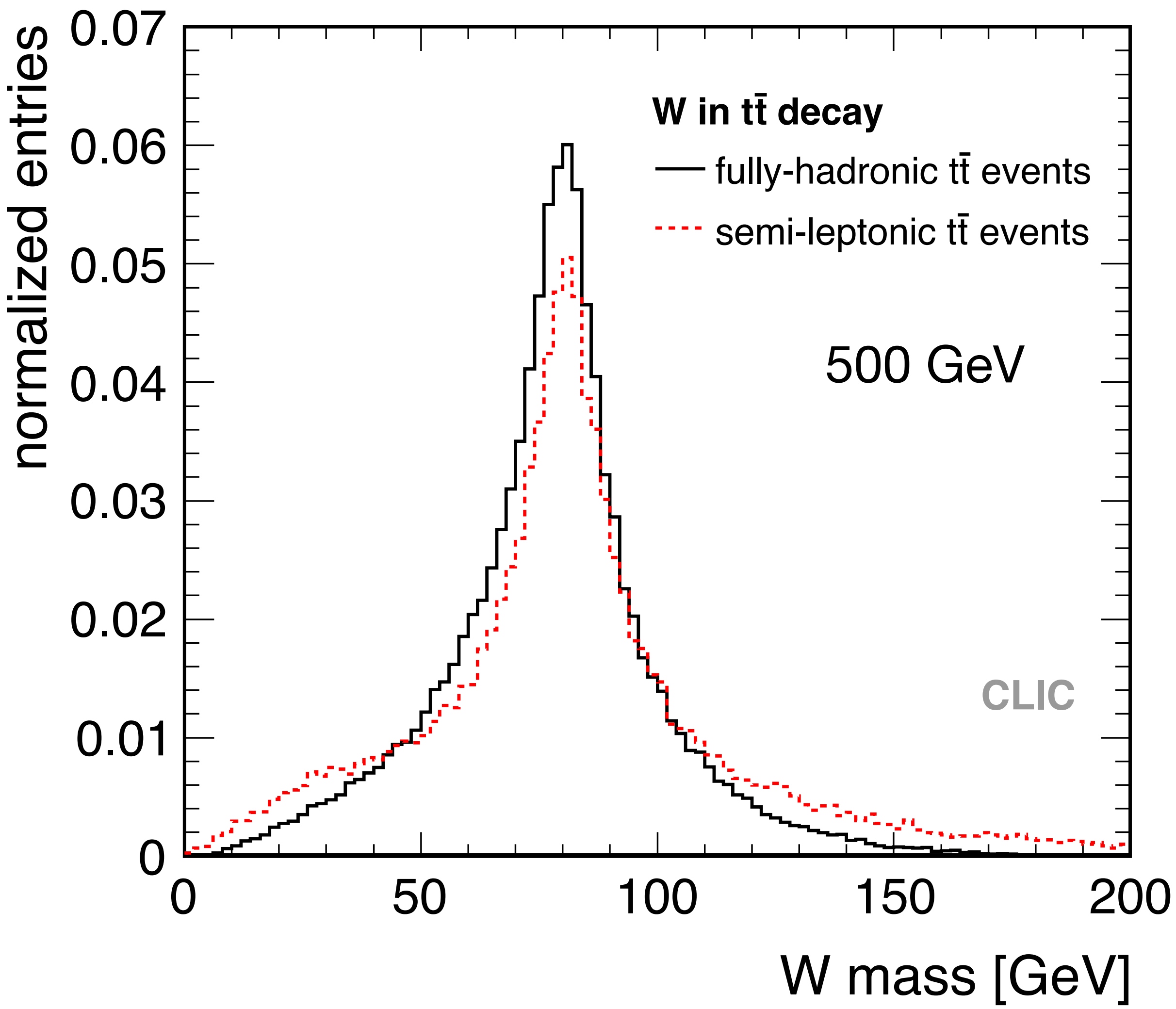
  - Threshold scan
    - theoretically well understood, can be calculated to higher orders
    - needs dedicated running of the accelerator (but is also in a sweet spot for Higgs physics)
    - ‣ The “ultimate” mass measurement at a LC!



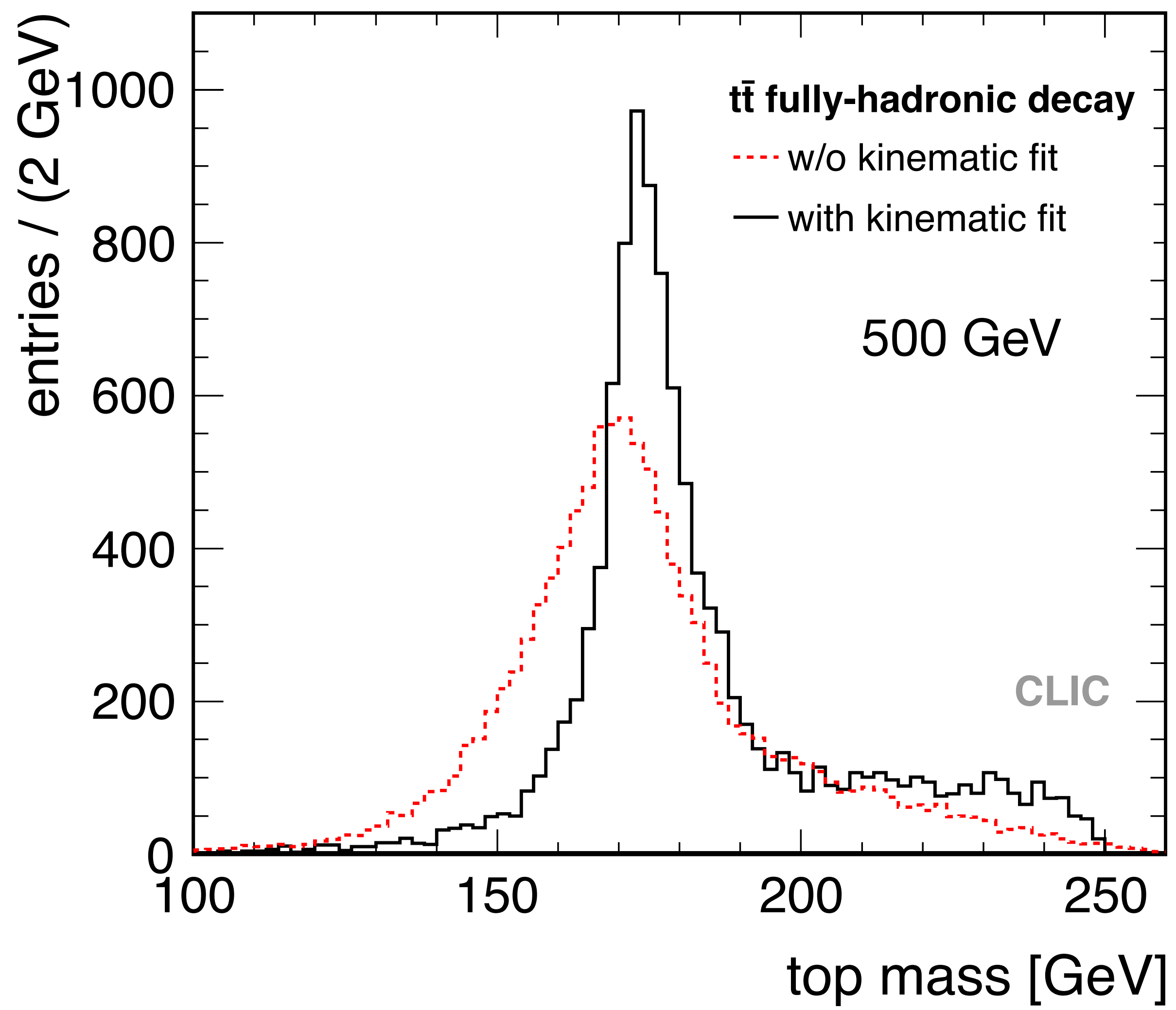
Analysis Strategy

- 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

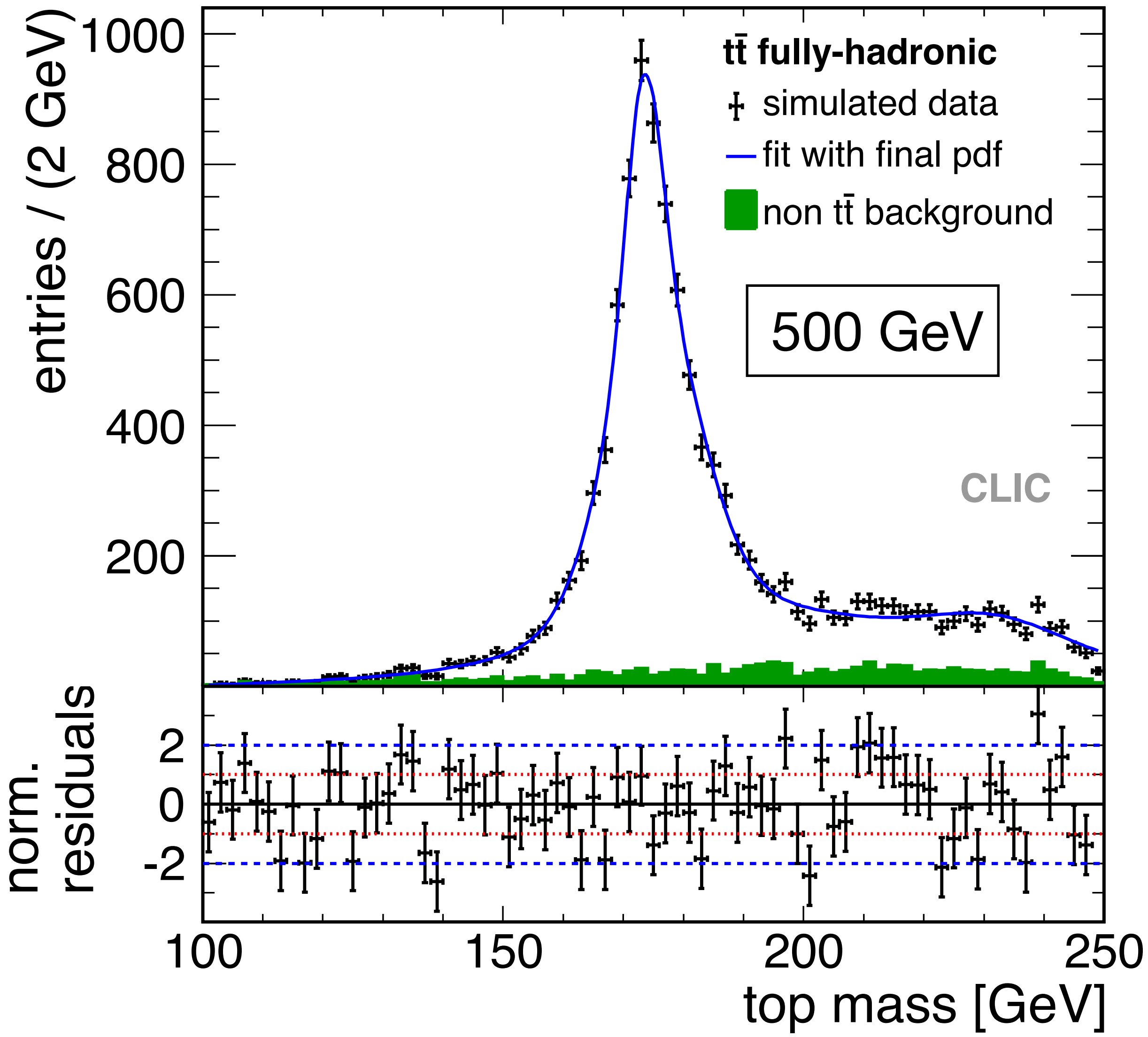


- Direct W reconstruction: sub-100 MeV precision on reconstructed mass: < 1 % uncertainty on JES



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

Top Reconstruction - Performance

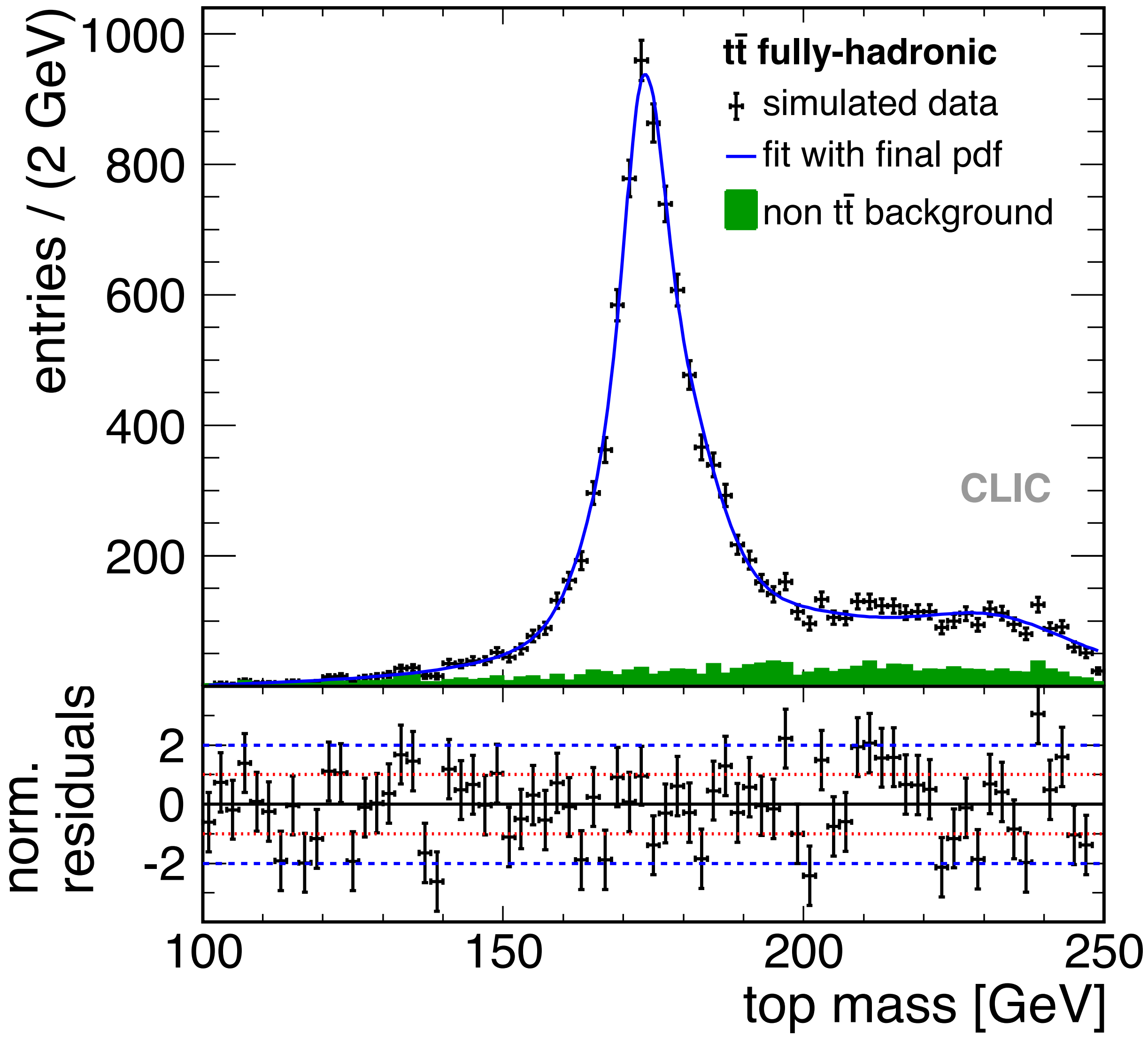


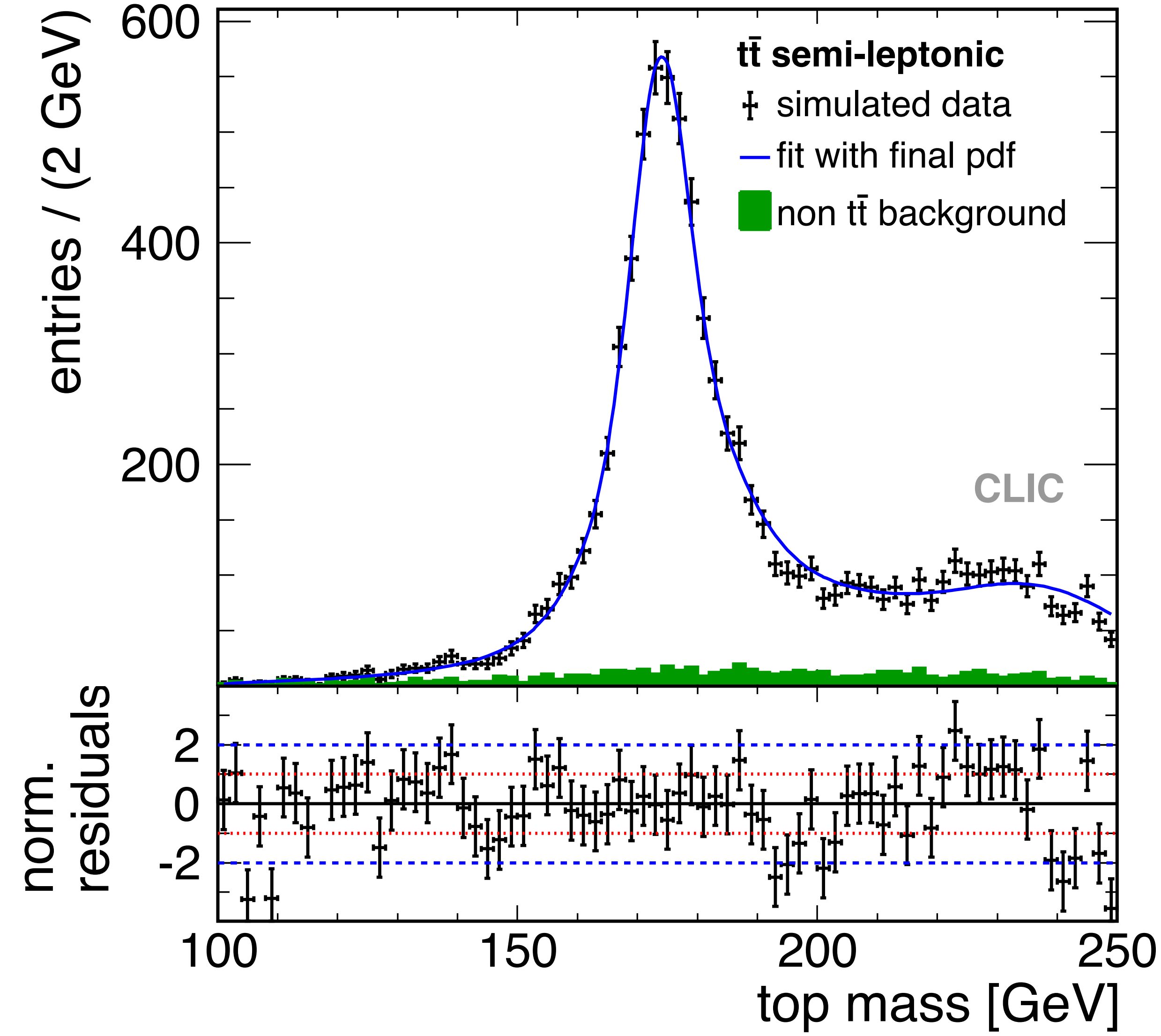
- Very low non-ttbar background
  - S/B ~8.5 (12) for FH (SL) at 500 GeV
  - S/B ~4.5 directly above threshold
- High reconstruction efficiency
  - 34% (44%) for FH (SL) at 500 GeV
  - 92% for selected decay modes at threshold

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

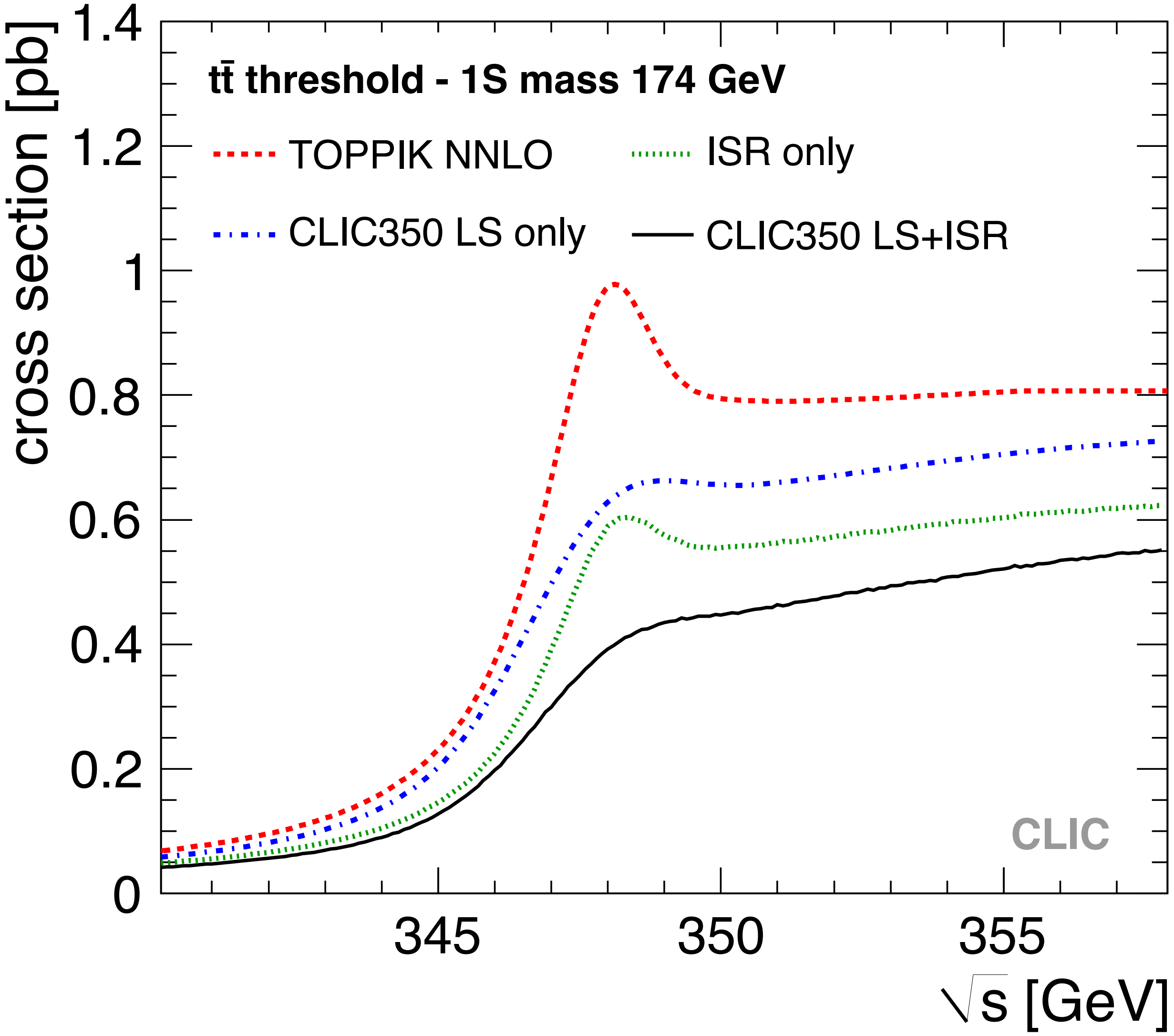




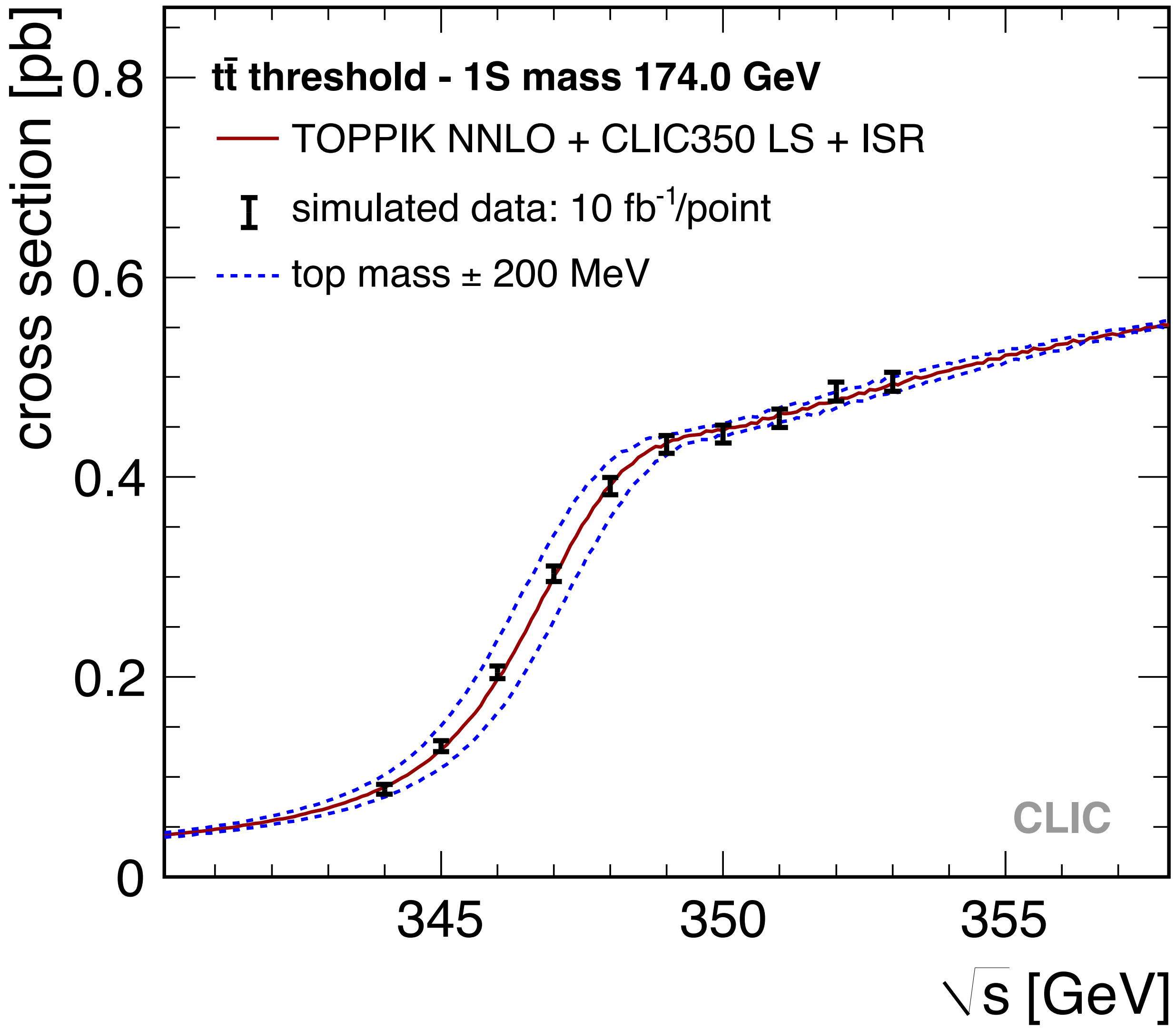
- Width less constrained than mass: substantial detector effects (peak width ~ 5 GeV compared to 1.4 GeV top width)

channel	m_{top}	Δm_{top}	Γ_{top}	$\Delta\Gamma_{\text{top}}$
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

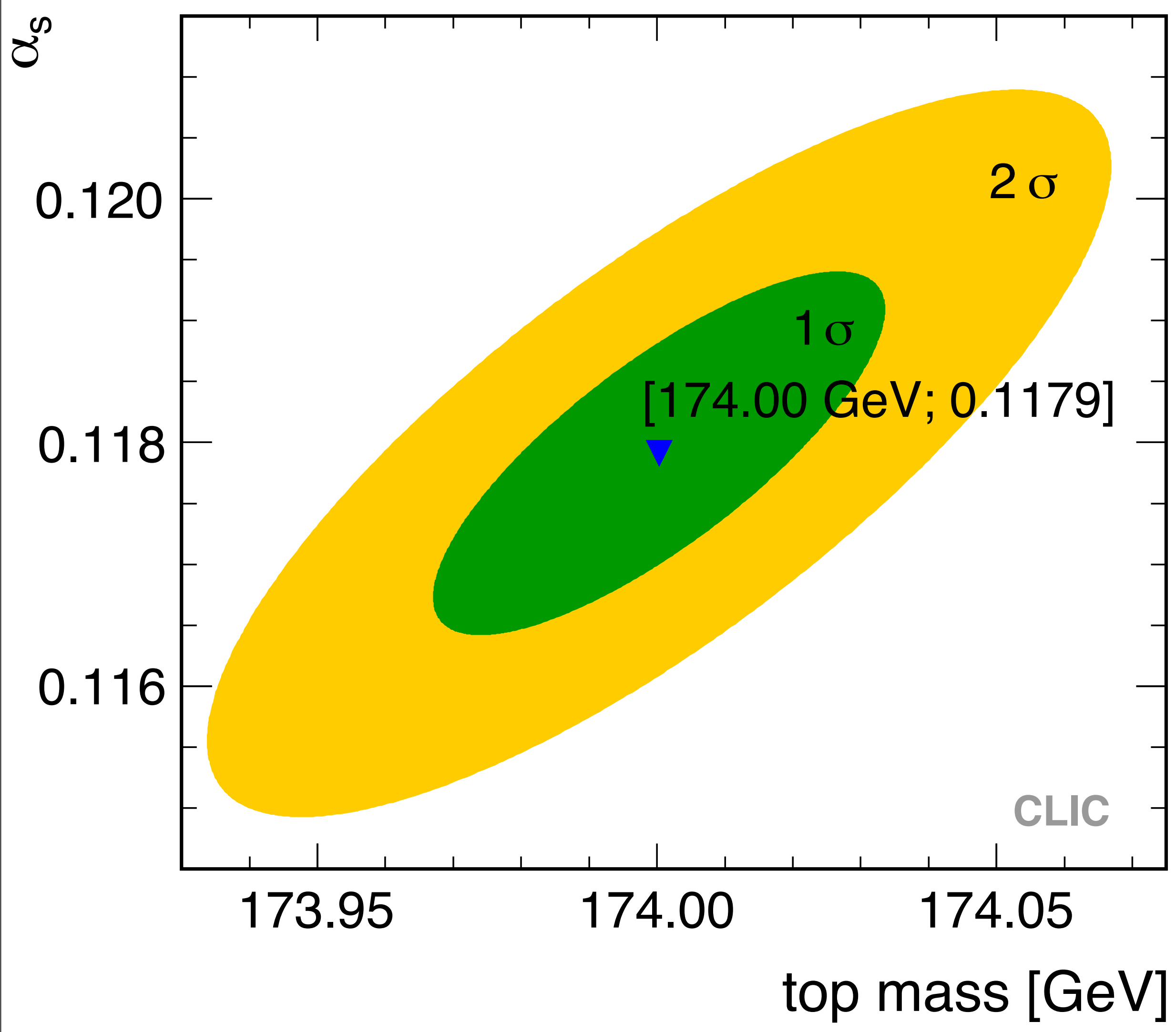


- Pure NNLO cross section (calculated with TOPPIK [Hoang & Teubner]) distorted by ISR and luminosity spectrum



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

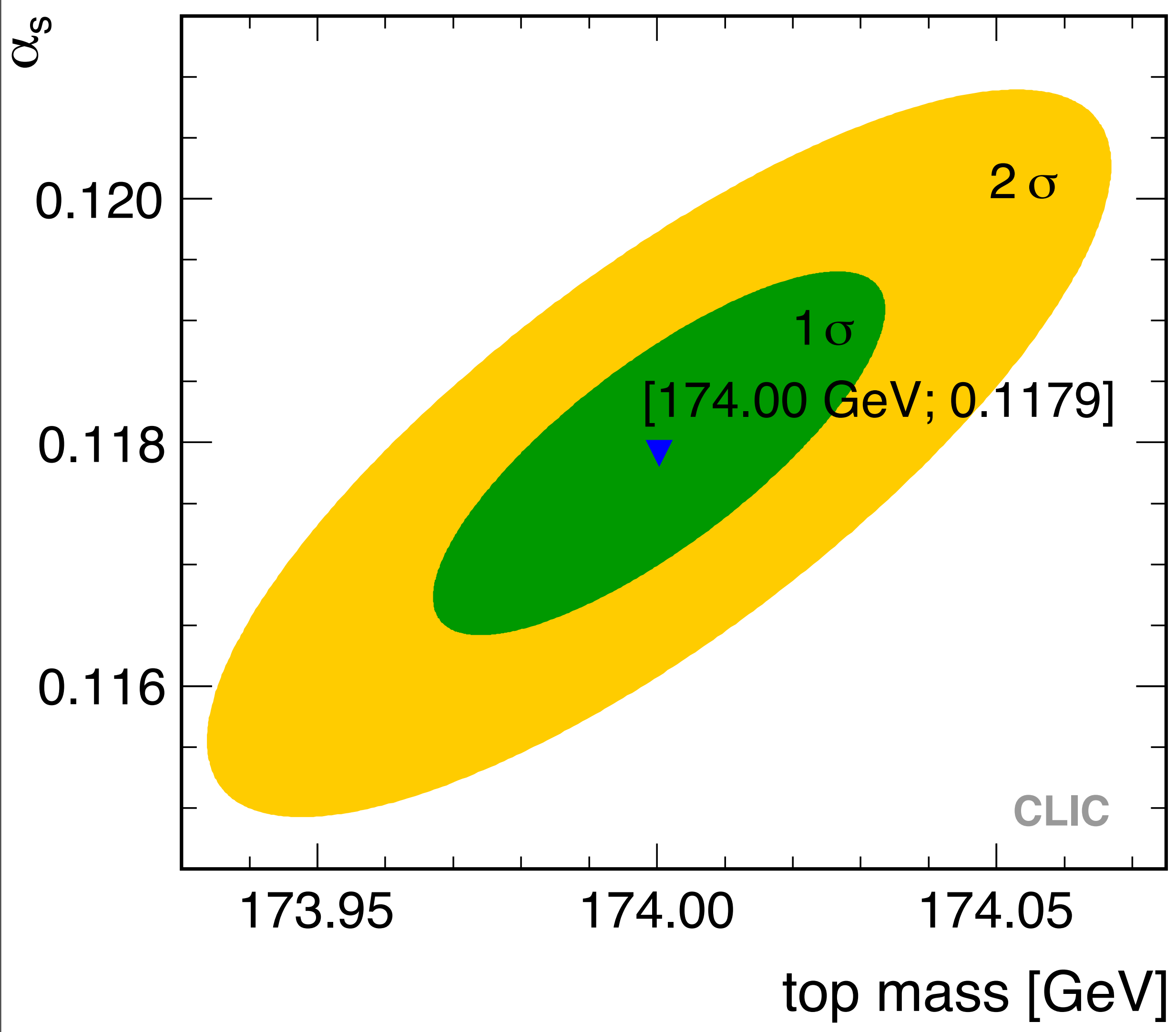
Measuring Top Mass and Strong Coupling



- 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

Measuring Top Mass and Strong Coupling



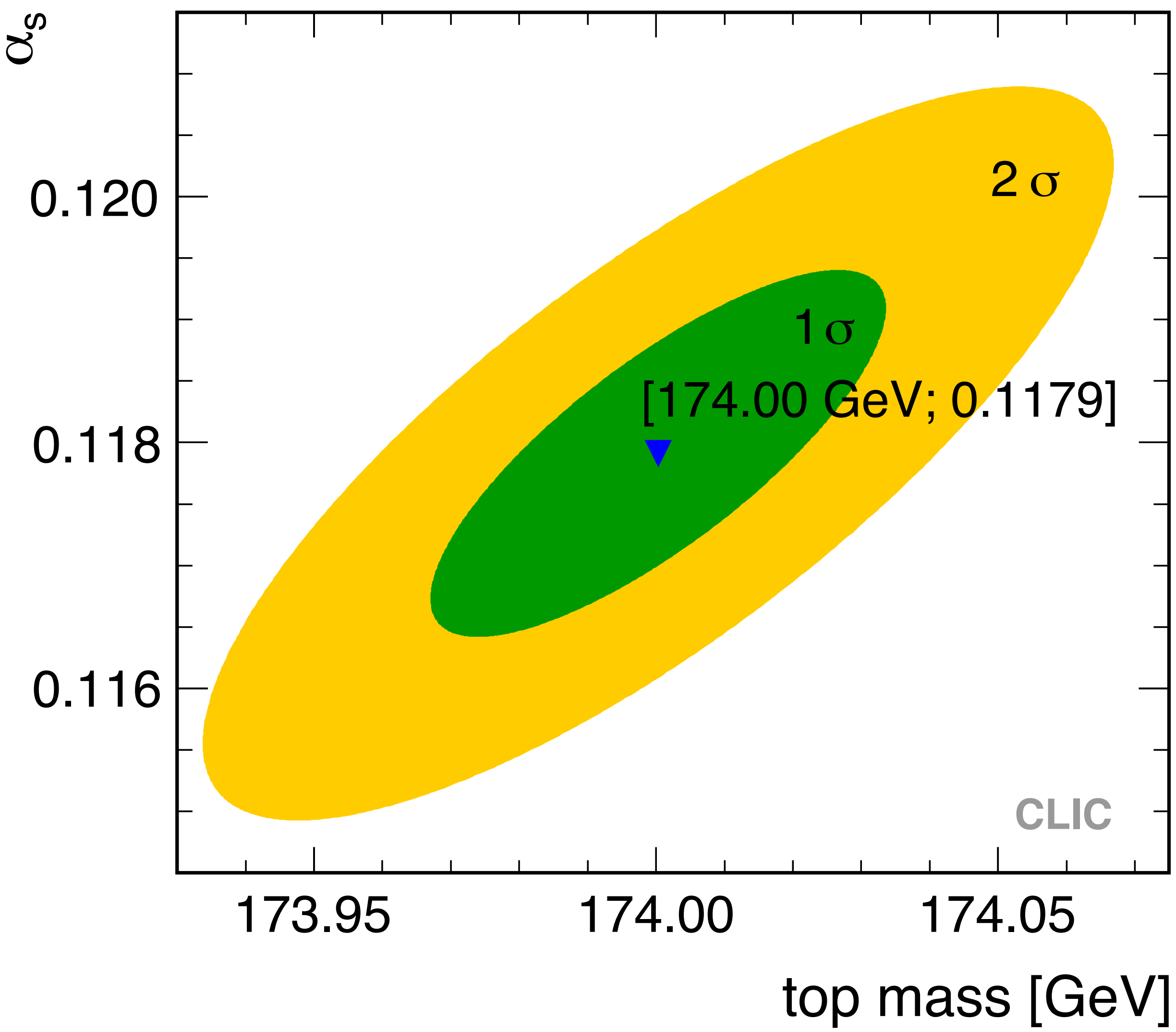
- 2D template fit to cross section

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

- Alternative: 1D fit - Taking α_s as input with current WA uncertainties

$$\Delta m_t = (\pm 22 \text{ (stat)} \pm 20 \ (\alpha_s) \ \pm 18 / 56 \text{ (theory 1\%/3\%)}) \text{ MeV}$$

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

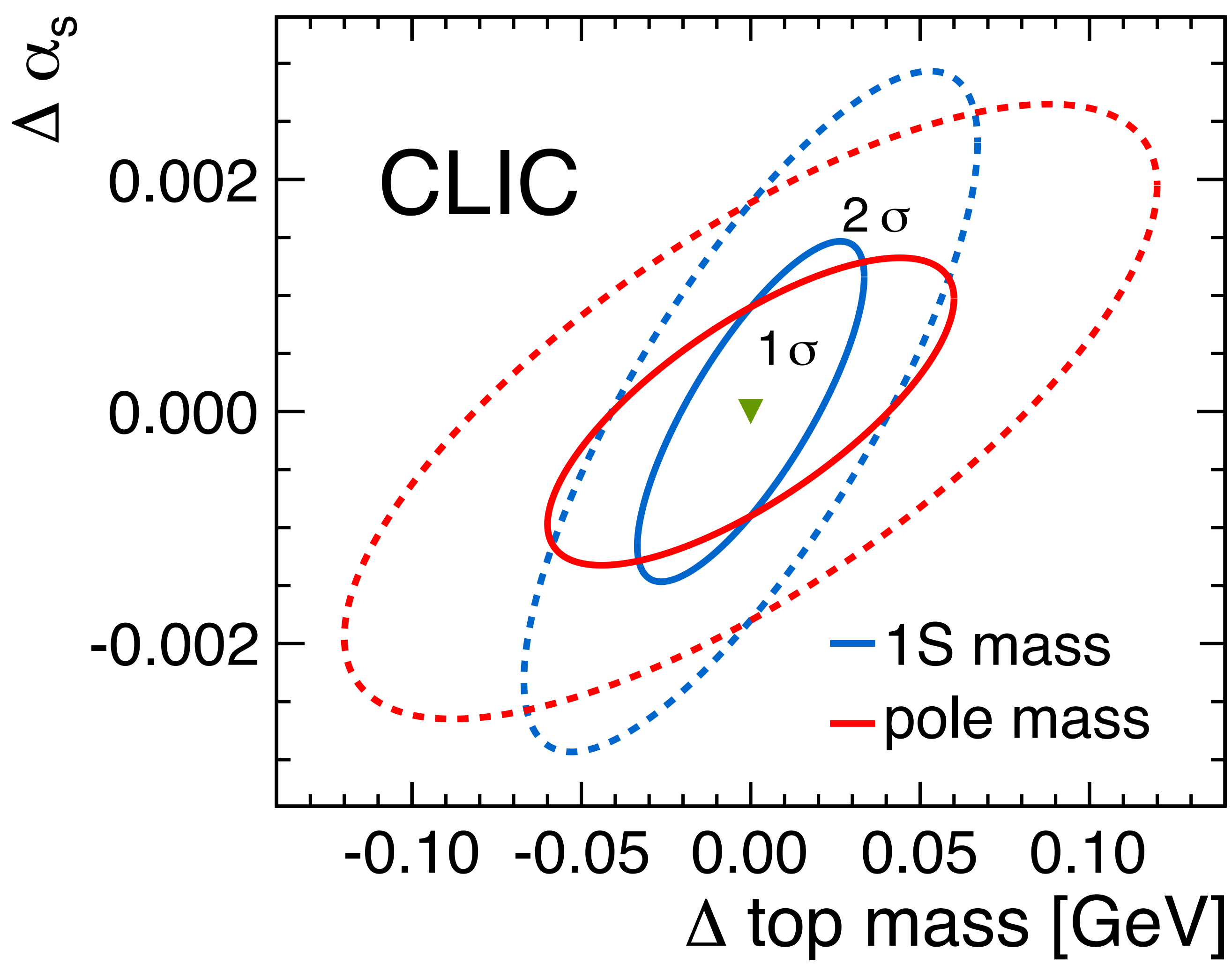
- Alternative: 1D fit - Taking α_s as input with current WA uncertainties

$$\Delta m_t = (\pm 22 \text{ (stat)} \pm 20 \ (\alpha_s) \ \pm 18 / 56 \text{ (theory 1\%/3\%)}) \text{ MeV}$$

Differences to ILC due to different luminosity spectrum small: 10% to 20% reduction of statistical uncertainties

1S Mass vs Pole Mass

- Several theoretically well-founded definitions for the top quark mass exist - For a threshold scan the 1S mass is particularly well suited
- Illustrated by repeating the same analysis using the pole mass definition



Increasing statistical uncertainties:

m_t from 34 MeV (1S) to 60 MeV (pole)

Unchanged uncertainties on α_s, stronger dependence of m_{pole} on α_s results in deterioration of m_t precision

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

- Measurement likely limited by systematics, given the statistical power of a high-luminosity threshold scan at a LC
- Incomplete - but looked at several key aspects:
  - Theory uncertainties currently based on simple scaling (order 10 MeV to a few 10 MeV, depending on fit strategy -> uncertainty mostly absorbed in α_s uncertainty for combined fits) - More sophisticated studies planned
  - Non-ttbar background: 5% uncertainty results in 18 MeV uncertainty on mass (After selection, the non-ttbar background cross section is ~ 70 fb, so 5% uncertainty can be reached with ~ 6 fb^{-1} below threshold)
  - Beam energy: Expect 10^{-4} precision on CMS energy: ~30 MeV uncertainty on mass

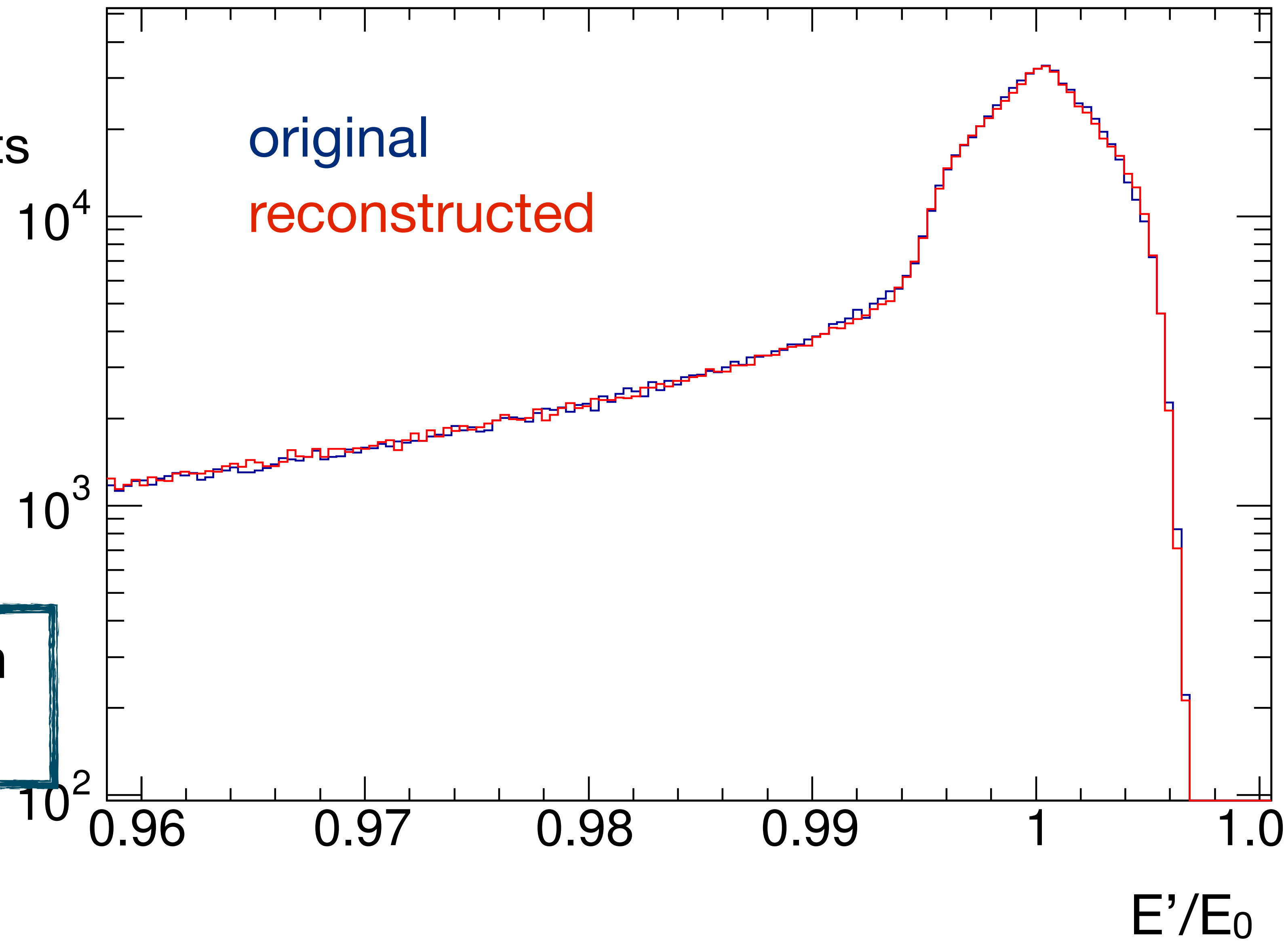
Systematics - Threshold Scan

- Measurement likely limited by systematics, given the statistical power of a high-luminosity threshold scan at a LC
- Incomplete - but looked at several key aspects:
  - Theory uncertainties currently based on simple scaling (order 10 MeV to a few 10 MeV, depending on fit strategy -> uncertainty mostly absorbed in α_s uncertainty for combined fits) - More sophisticated studies planned
  - Non-ttbar background: 5% uncertainty results in 18 MeV uncertainty on mass (After selection, the non-ttbar background cross section is ~ 70 fb, so 5% uncertainty can be reached with ~ 6 fb^{-1} below threshold)
  - Beam energy: Expect 10^{-4} precision on CMS energy: ~30 MeV uncertainty on mass

“Interpretation” uncertainty:
Theory uncertainties are incurred when transforming the 1S mass used to describe the threshold to the MSbar mass - O ~ 100 MeV, depending on α_s precision (here, the deal of shifting uncertainties from m_t to α_s would strike back)

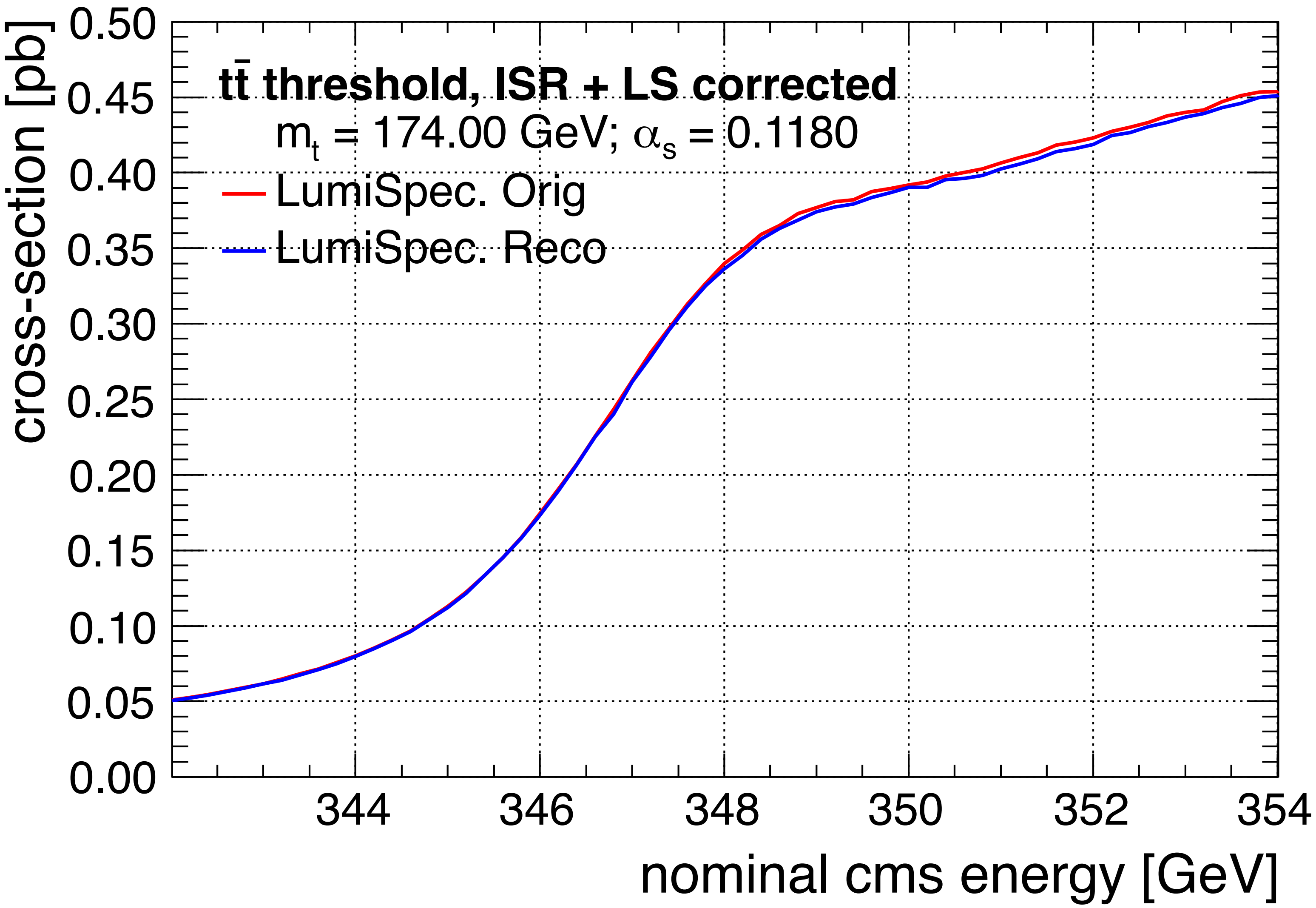
Systematics - Luminosity Spectrum

- Initial back-of-the envelope studies indicated possible systematics of 10s of MeV - mainly related to the shape of the main luminosity peak
- The challenge: Determining the shape (and normalization) of the luminosity spectrum from data
  - Accessible via energy and angle of $e^{\pm}$ from Bhabha events
  - Parametrized by a complex 19 parameter function, parameters determined from fits to Bhabha events (details: arXiv:1309.0372)



Hot off the press: First application of 3 TeV model to 350 GeV

Systematics - Luminosity Spectrum



- Impact of reconstructed luminosity spectrum on threshold behavior
  - Currently still a small bias: slightly reduced peak luminosity in model (0.7% too low)
  - Expect to improve with different fitting approach

Global Results Summary - Luminosity Spectrum uncertainty:

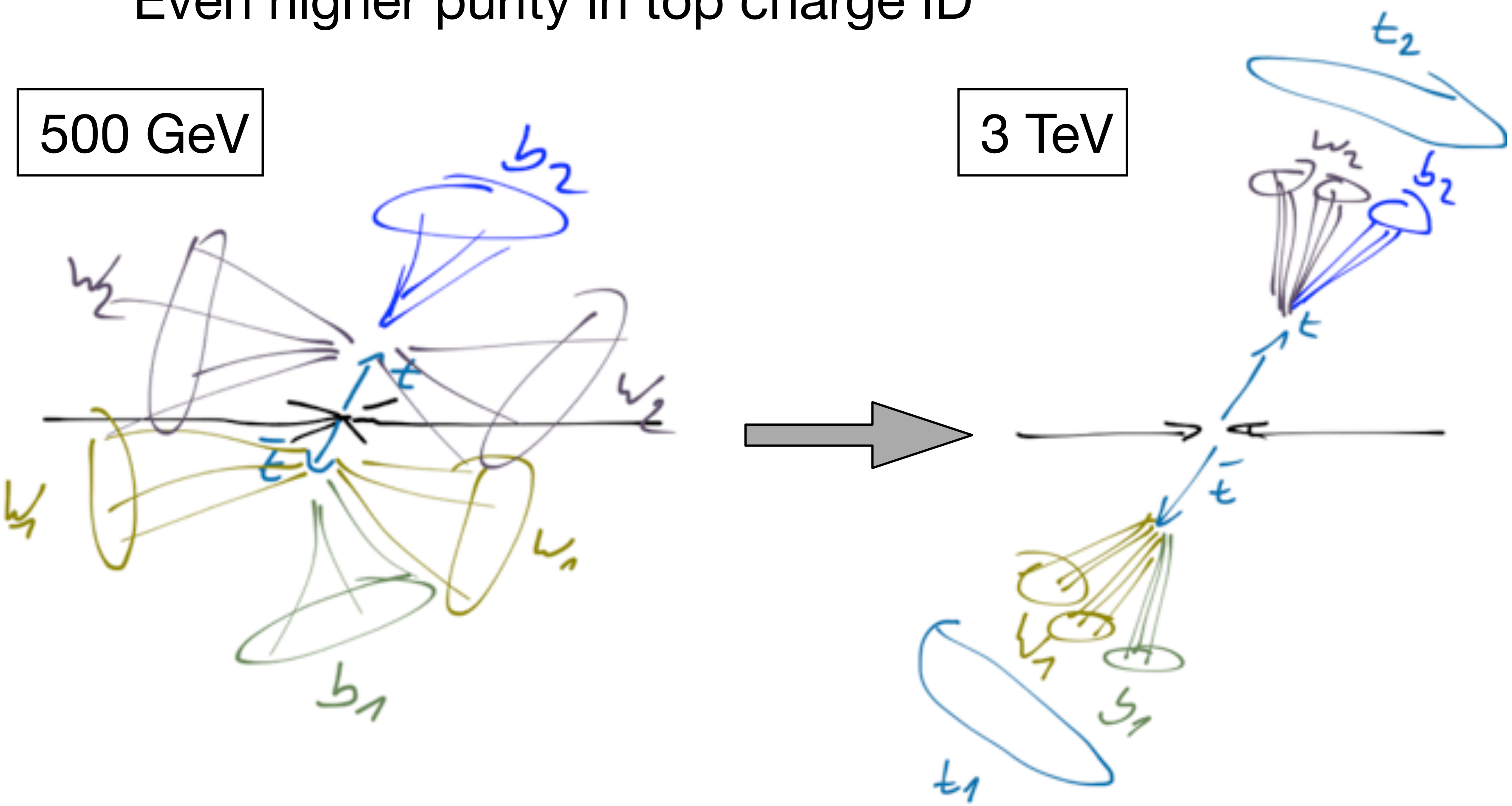
1D fit: Δm_t = (± 22 (stat) ± **5.3** (lumi parameters) - **22** (lumi reco)) MeV

2D fit: Δm_t = (± 34 (stat) ± **6.0** (lumi parameters) + **5.5** (lumi reco)) MeV

$\Delta \alpha_s$ = (± 9 (stat) ± **2.5** (lumi parameters) + **10** (lumi reco)) x 10^{-4}

Top as a Tool at High Energy

- The unique feature of CLIC: Collisions up to 3 TeV
  - Excellent sensitivity to New Physics: Effects in indirect searches often scale as E^2/Λ^2 => Benefit of high energy!
    - Well-demonstrated physics potential for ILC at 500 GeV: Measurement of ttbar asymmetries (forward-backward, left-right)
    - Higher energy improves unique assignment of final-state particles to top, anti-top: Even higher purity in top charge ID



Requires reconstruction of top quarks as highly boosted objects: Techniques well established at LHC, Potential benefits from PFA

Top as a Tool at High Energy

- CLIC studies still at the beginning - Collecting possibilities:
  - Asymmetries to measure couplings to γ, Z
  - Measurement of couplings to W (and H - included in Higgs studies already)
  - Sensitivity to CP violation
  - Flavor-changing top decays
  - ...

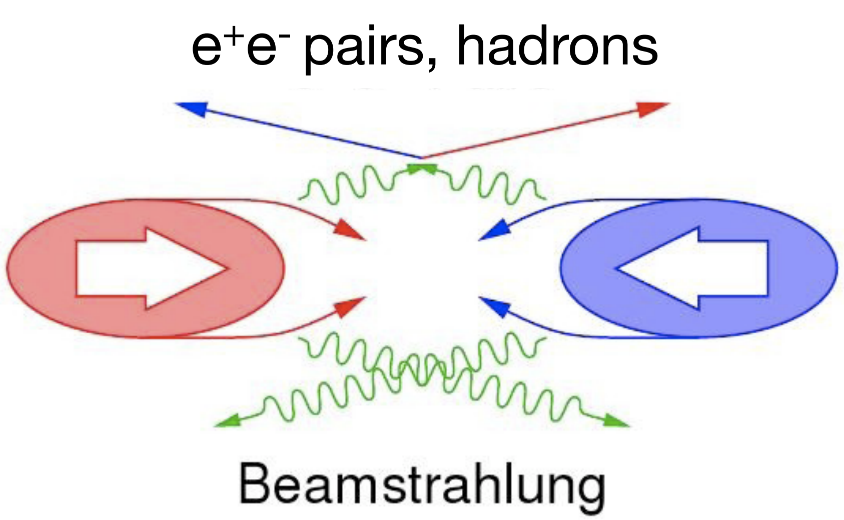
Summary

- Top physics is an integral part of the physics program of CLIC
  - The study of top properties - up to now focusing primarily on the mass
  - Using top as tool to explore New Physics
- The top mass can be measured both at and above threshold
  - A threshold scan provides the ultimate precision, with a theoretically well-understood interpretation of the result - Total uncertainties of 100 MeV or below within reach
  - Experimental systematics, including those from the knowledge of the luminosity spectrum, can be controlled with sufficient precision
- The high energy available at CLIC provides access to very high scales through precision measurements using top quarks
  - Boosted tops offer unique identification of top / anti-top and high purity in asymmetry measurements
  - ‣ Experimental studies planned for the near future

Backup

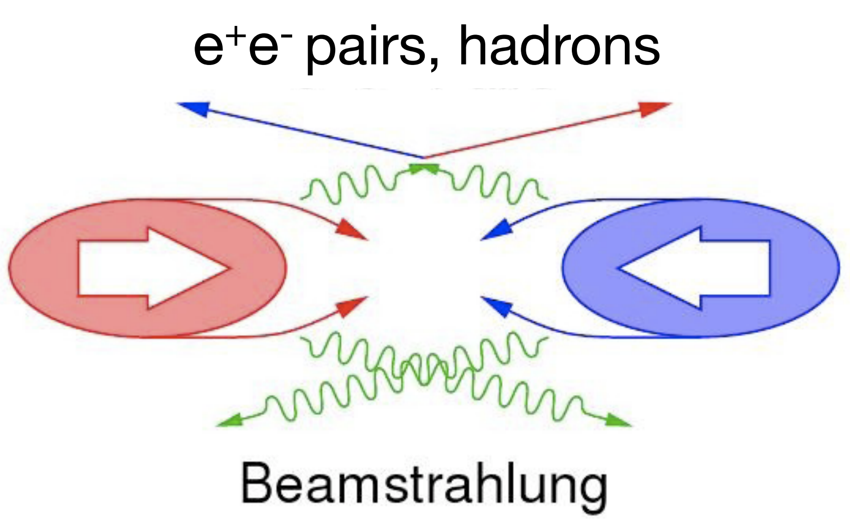
Extras on top: Machine-Induced Backgrounds

- High energy, high luminosity and strong focusing means lots of beamstrahlung photons
  - Production of secondary particles
  - Energy sufficient to produce quark pairs: Results in “mini-jet” events



Extras on top: Machine-Induced Backgrounds

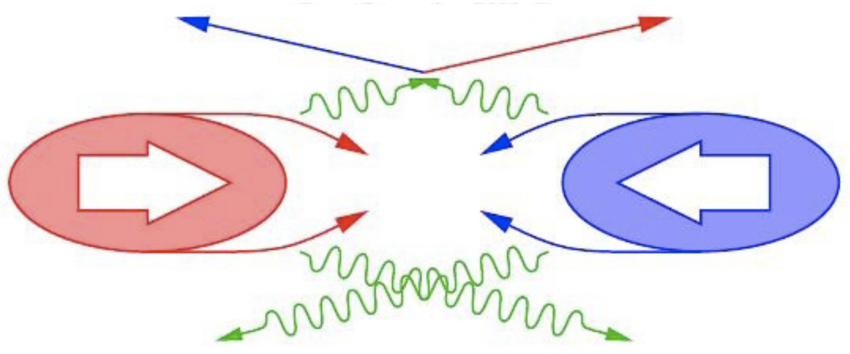
- High energy, high luminosity and strong focusing means lots of beamstrahlung photons
  - Production of secondary particles
  - Energy sufficient to produce quark pairs: Results in “mini-jet” events



These hadrons are a particular reconstruction challenge: “Pile-up” on the physics event, additional particles affect jet reconstruction

Extras on top: Machine-Induced Backgrounds

- High energy, high luminosity and strong focusing means lots of beamstrahlung photons
  - Production of secondary particles
  - Energy sufficient to produce quark pairs: Results in “mini-jet” events



These hadrons are a particular reconstruction challenge: “Pile-up” on the physics event, additional particles affect jet reconstruction

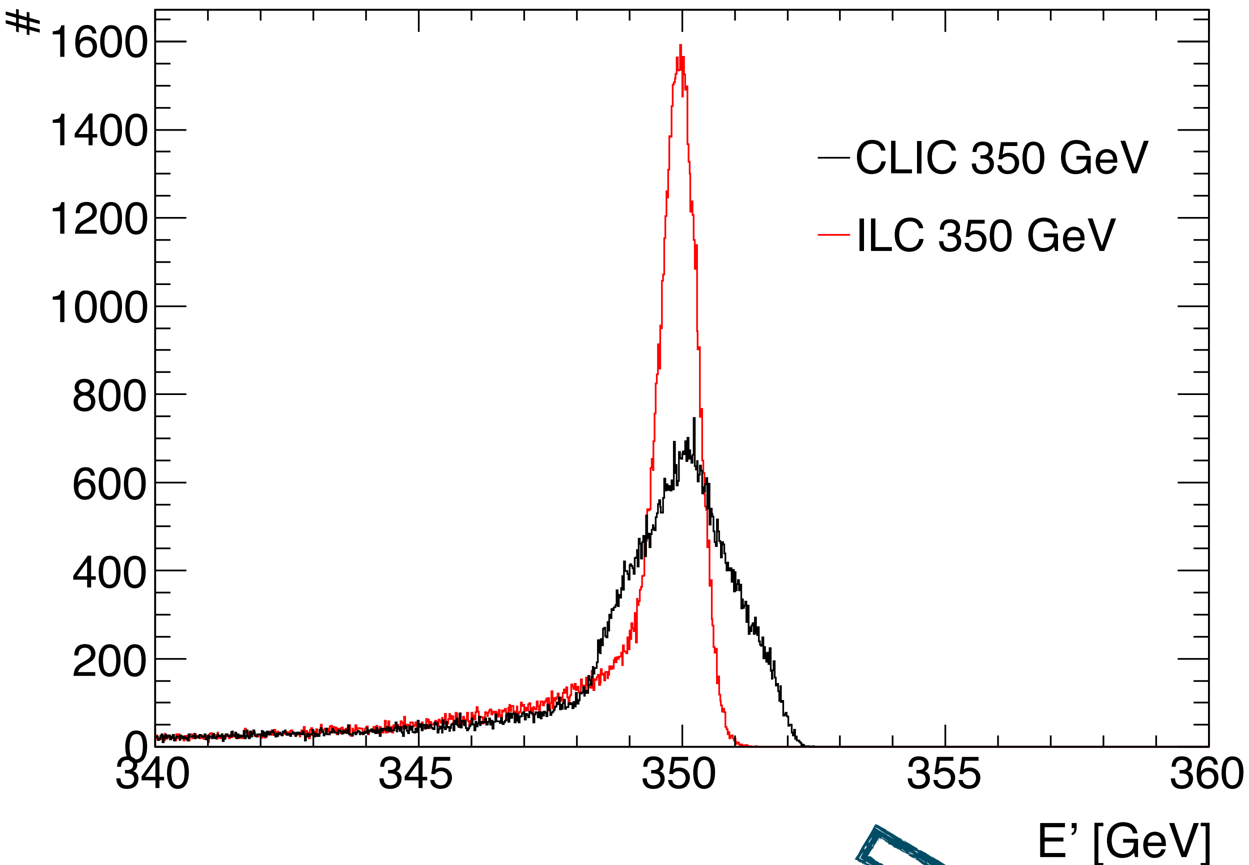
Impact and strategies for mitigation depend on machine:

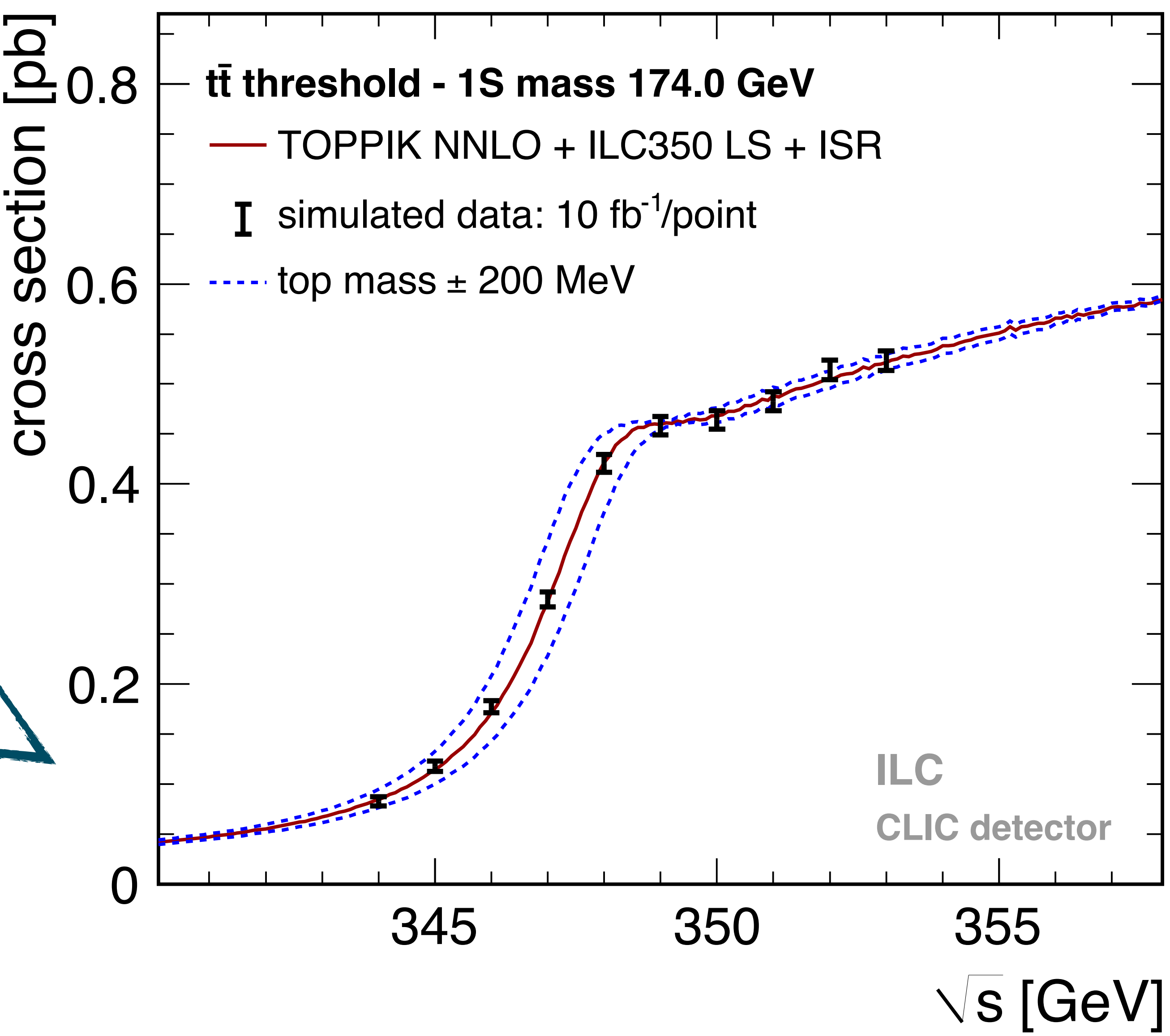
- At ILC the BXs are far appart in time (100s of ns): Only background from one BX piles up - Rejection based on jet finding
- At CLIC the BXs are separated by 0.5 ns: Pile-up from multiple BX - Rejection based on timing cuts and jet finding

N.B.: Hadrons / BX lower at CLIC than at ILC at the same energy

Comparison to ILC

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

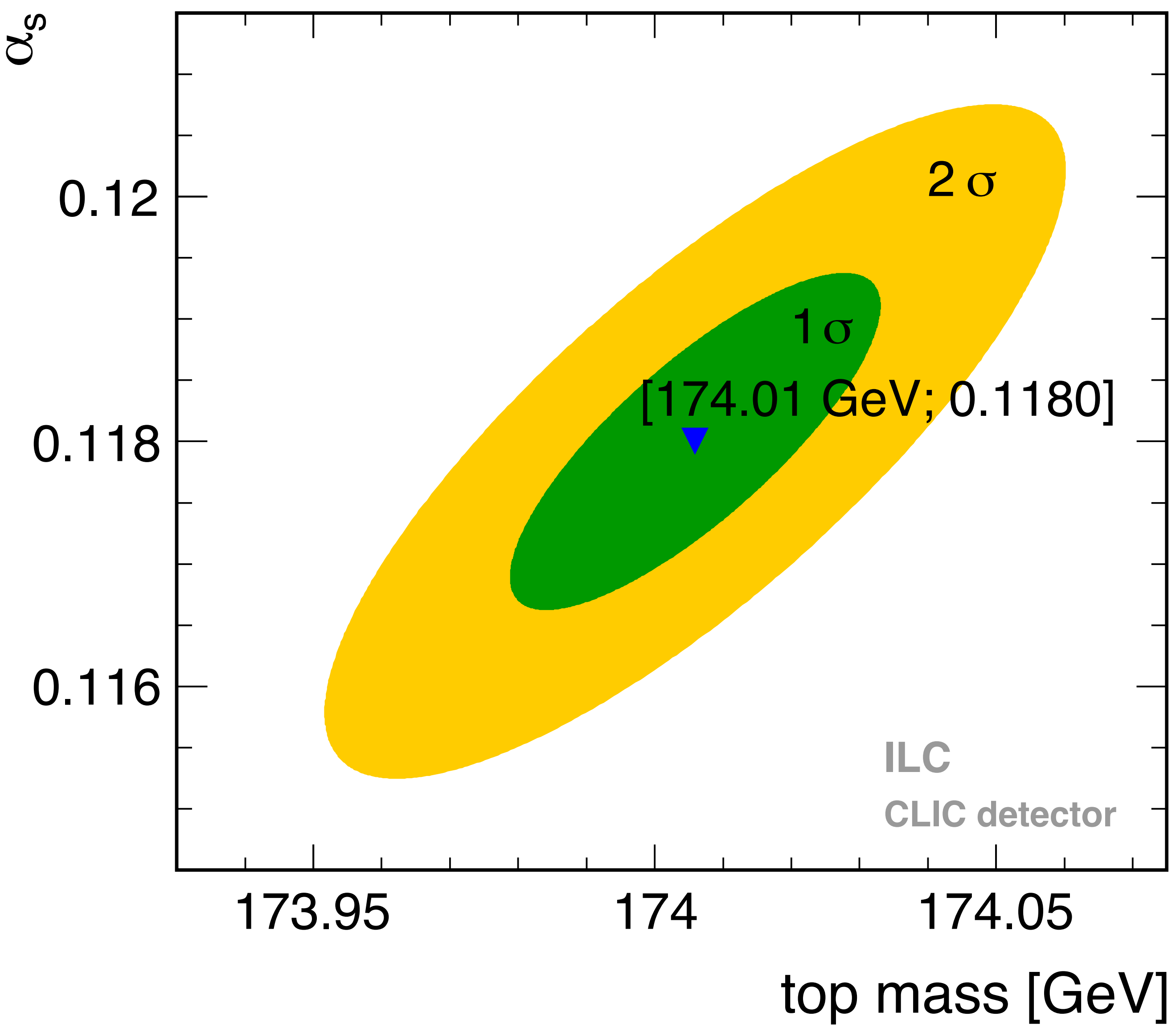




- Narrower main peak: Steeper rise of cross section at threshold

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