Top Mass Precision Measurements at CLIC

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Outline

- What are we measuring - an how?
- Top mass through invariant mass of decay products
- Top mass through threshold scan
  - The influence of the beam energy spectrum: CLIC vs ILC
- Summary / Outlook

What are we measuring?

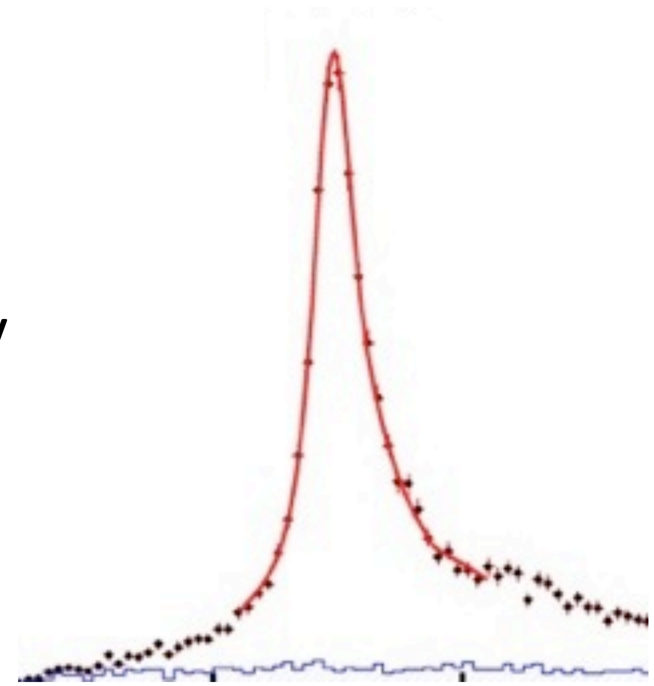
- Experimentally, masses of unstable particles are usually measured through the invariant mass of the decay products
- This is not what is used in theory!

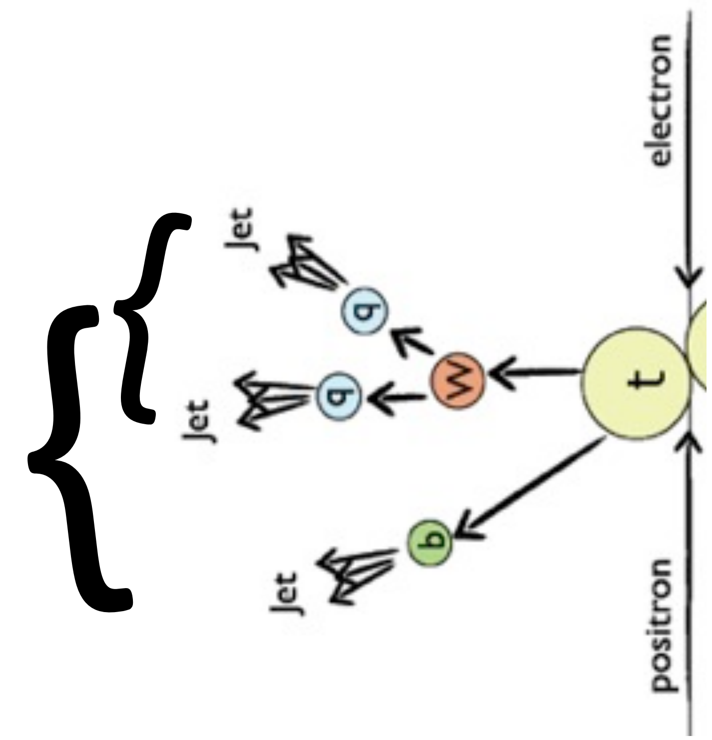
- Several mass definitions exist for the top quark (1s, msbar, pole...) that are theoretically well defined, conversion possible (sometimes with uncertainties on the level of Λ_{QCD})
  - Invariant mass probably closest to pole mass definition, with additional uncertainties

- Ideally: Measure mass in a theoretically well defined observable, or even better, in several ways

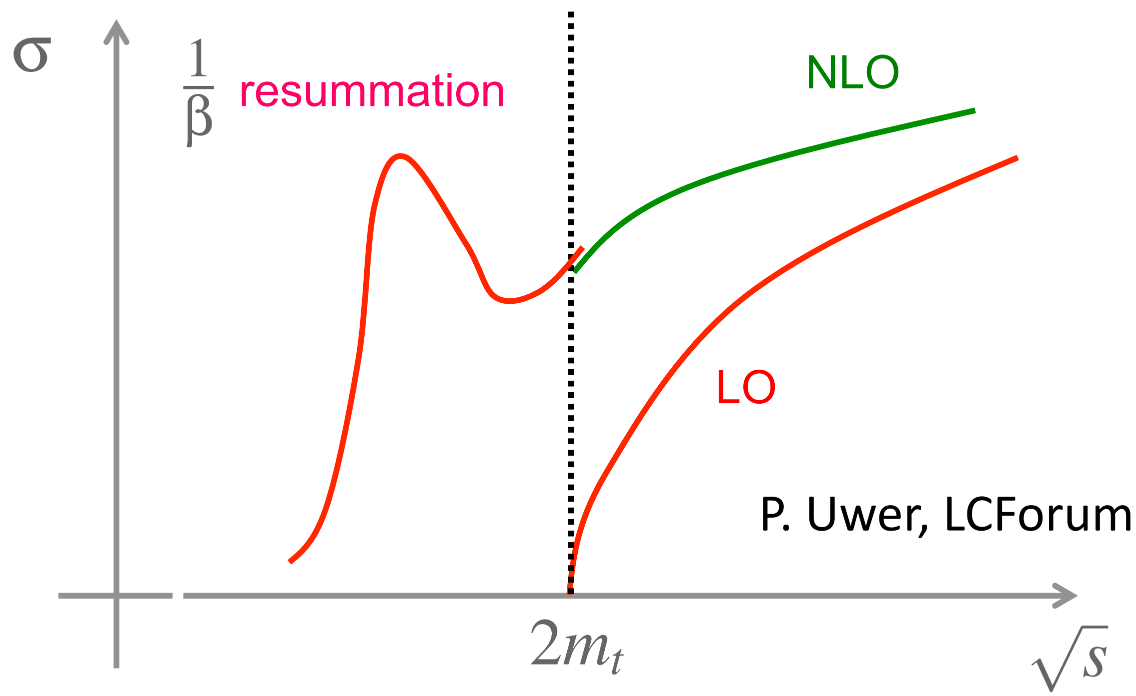
Top Mass at Linear Colliders

- Measurement in top pair production, two possibilities, each with advantages and dis-advantages:
  - Invariant mass
    - experimentally well defined
    - can be performed at arbitrary energy above threshold: high integrated luminosity





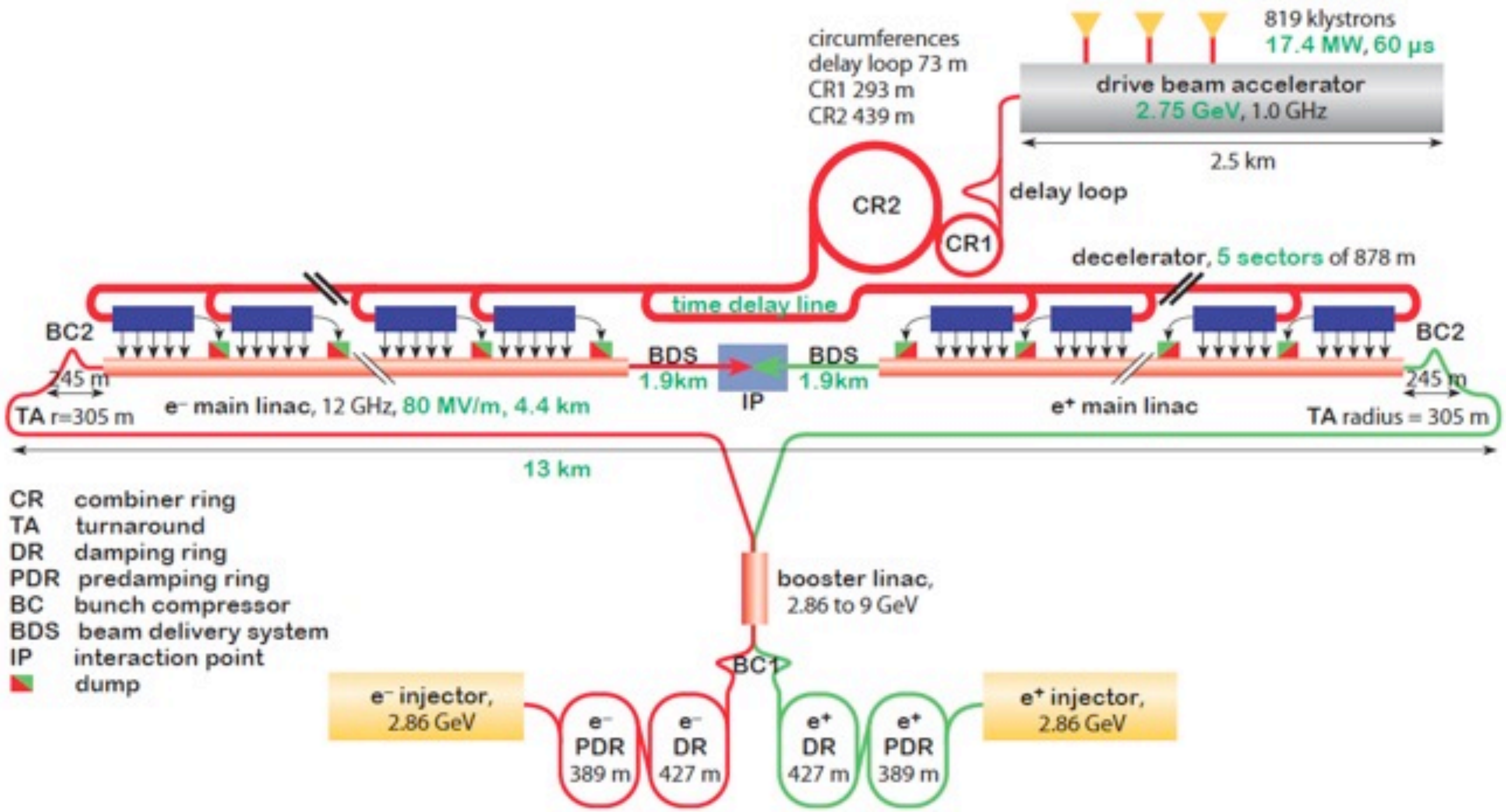
  - Threshold scan
    - theoretically well understood
    - needs dedicated running of the accelerator (but still can also provide other measurements below top threshold - Higgs for example)



P. Uwer, LCForum 02/2012

The Top Program at CLIC

- Top pair production requires a minimum of ~ 350 GeV
  - A threshold scan: Operation of the collider at *O* 10 different energy points around the threshold, spaced by *O* 1 GeV
  - Invariant mass measurements above threshold: Essentially arbitrary energy - Not too high to allow good reconstruction of intermediate particles, high enough to be away from kinematic limits - Here studied at 500 GeV



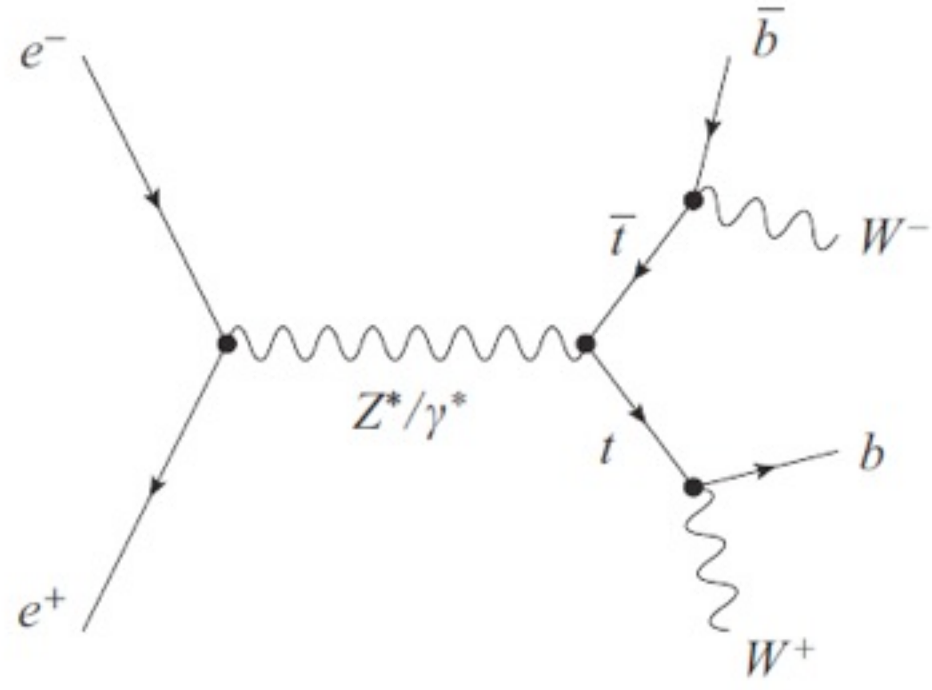
A first stage of CLIC with a maximum energy of 500 GeV

Here: Operated at 350 GeV and 500 GeV

Studied in the CLIC CDR for staged construction of CLIC

Reconstructing Top Quarks at Lepton Colliders

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



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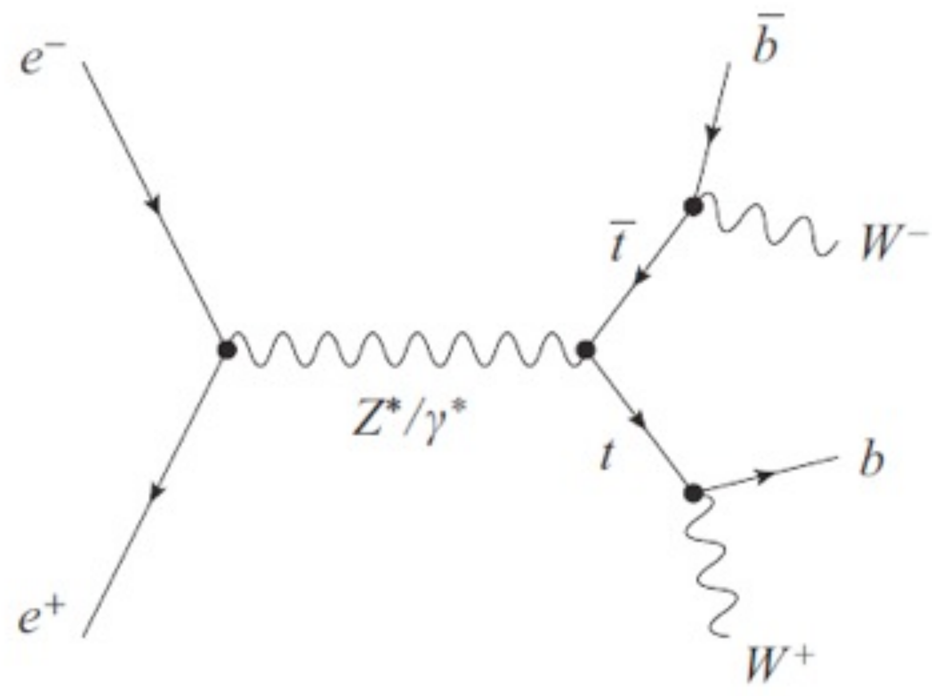
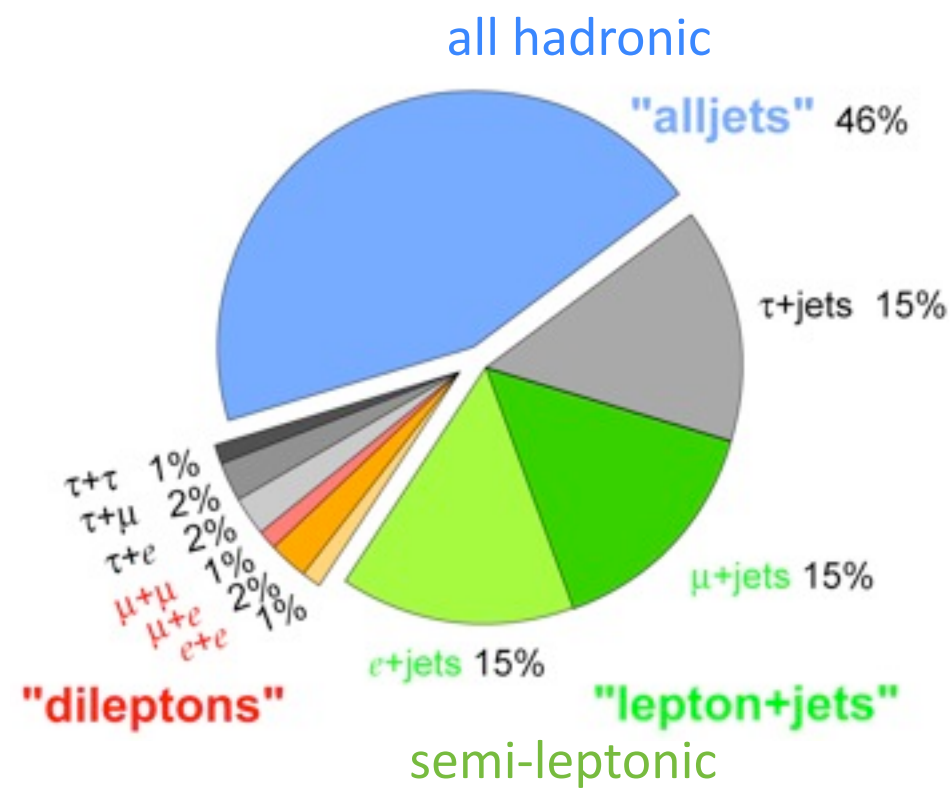


Event signature entirely given by the decay of the W bosons:



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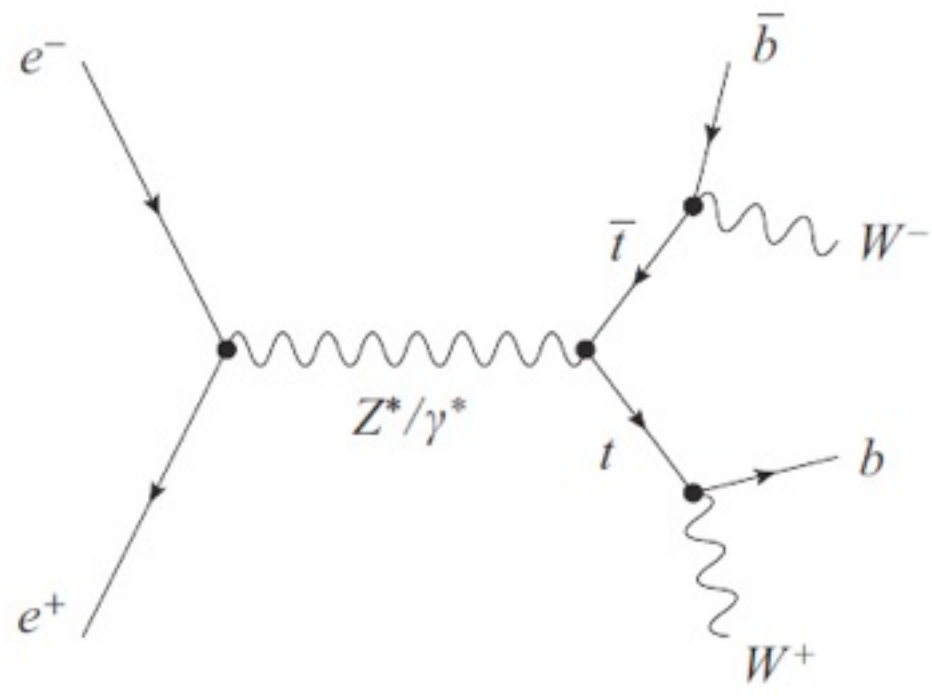

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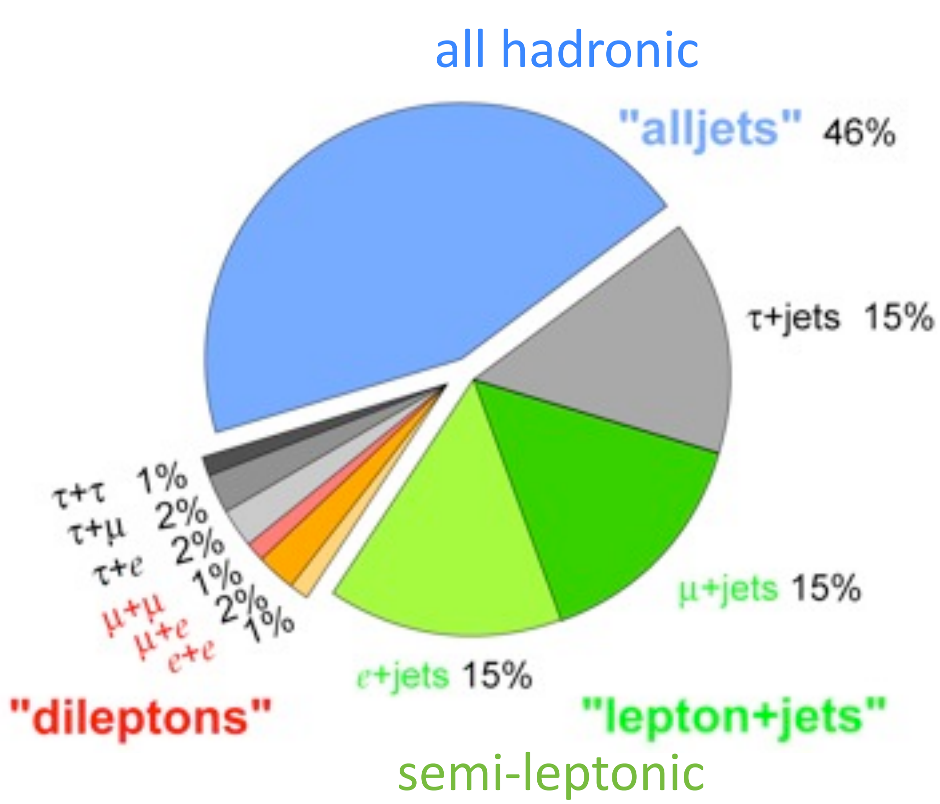
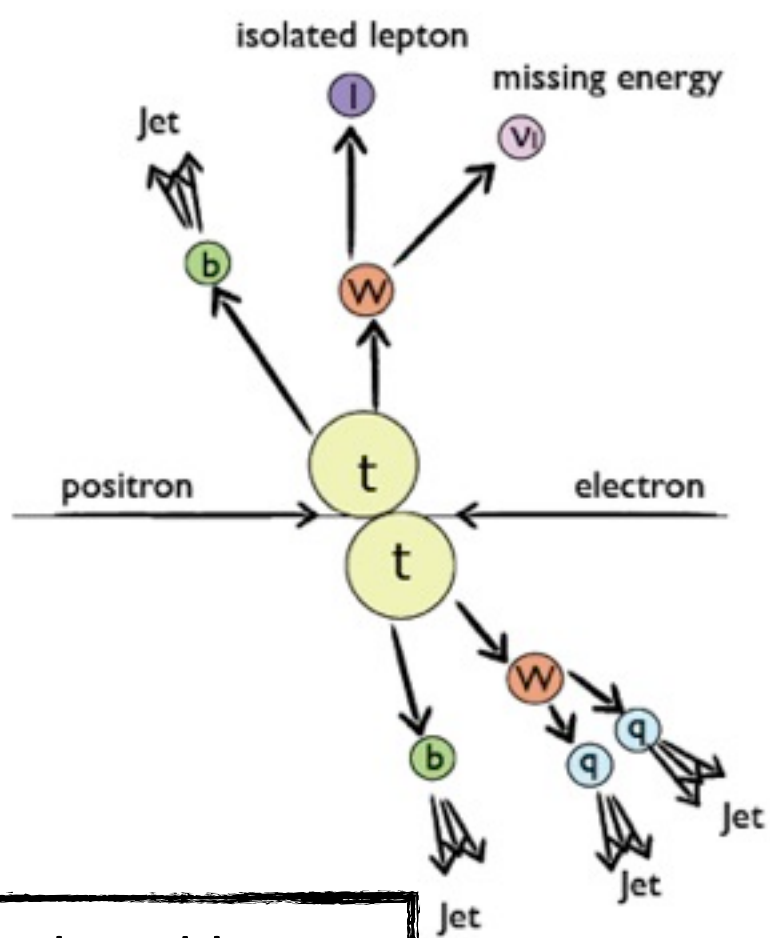


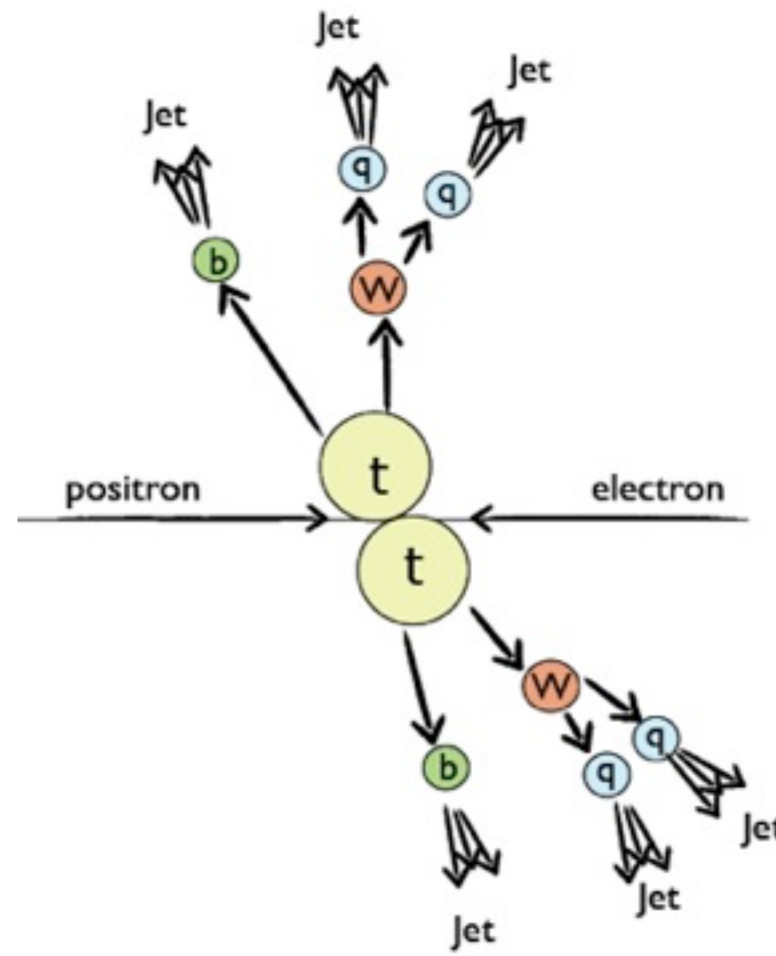
- At hadron colliders: Hard to pick out top pairs from QCD background - Use one and two-lepton final states
- At lepton colliders: Top pairs easy to identify, concentrate on large branching fractions and controllable missing energy (not more than one neutrino!)

Identifying and Reconstructing Top Quarks

- By far dominating decays: All-hadronic (46%), semi-leptonic / lepton+jets (45%, 30% w/o τ)
  - try to avoid decays into τ, increased uncertainties from additional neutrino



4 jets, isolated lepton



6 jets

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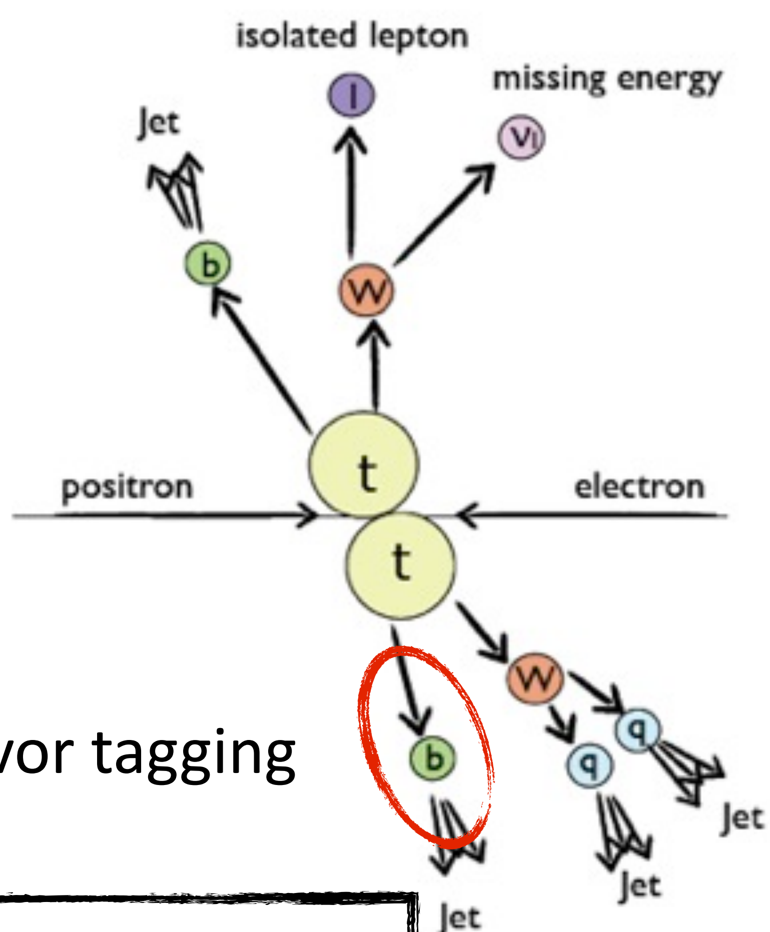

flavor tagging

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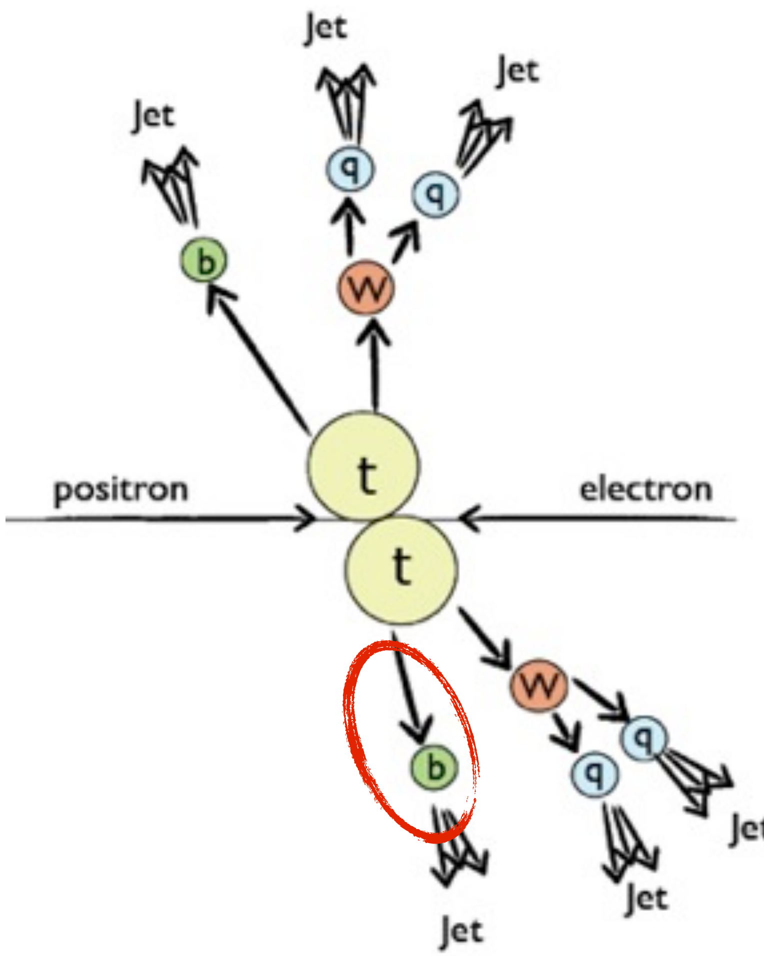

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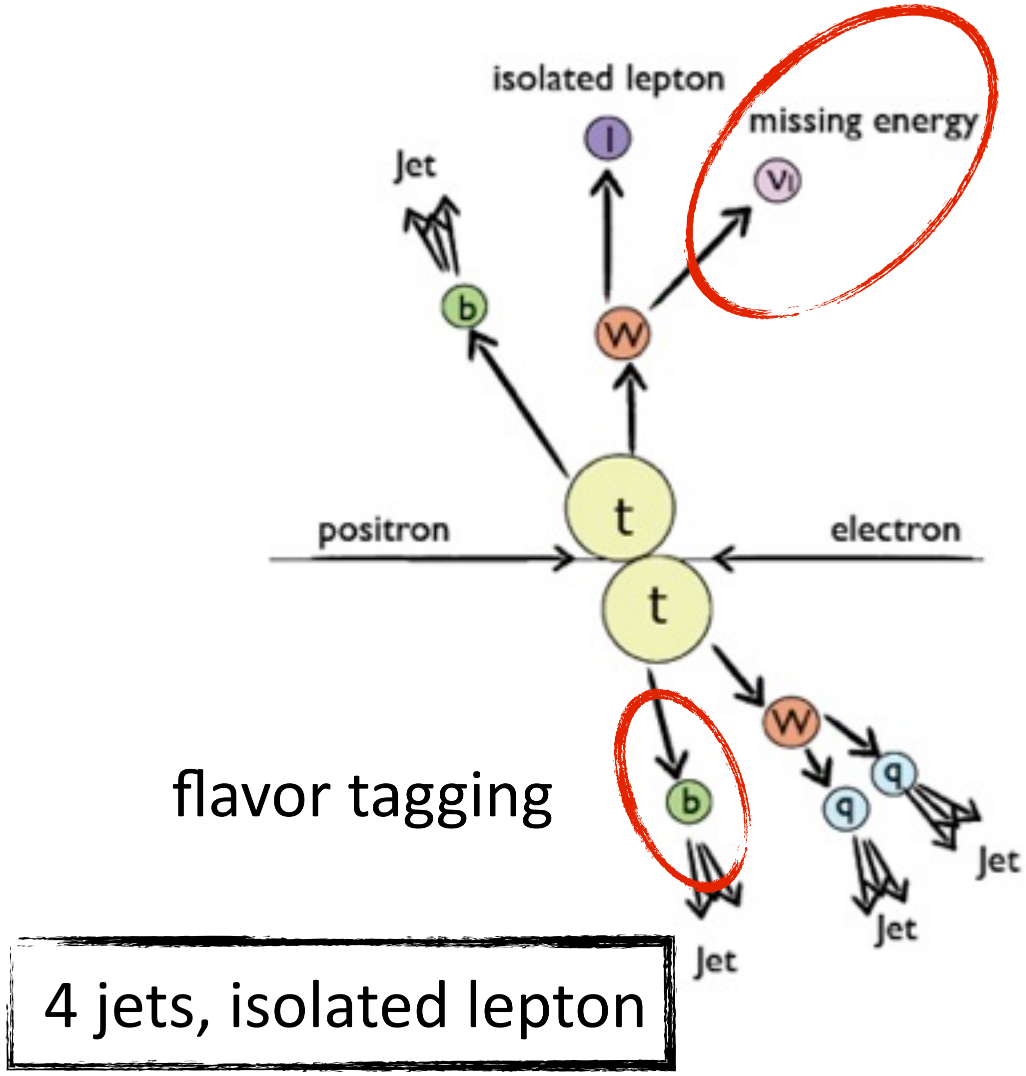

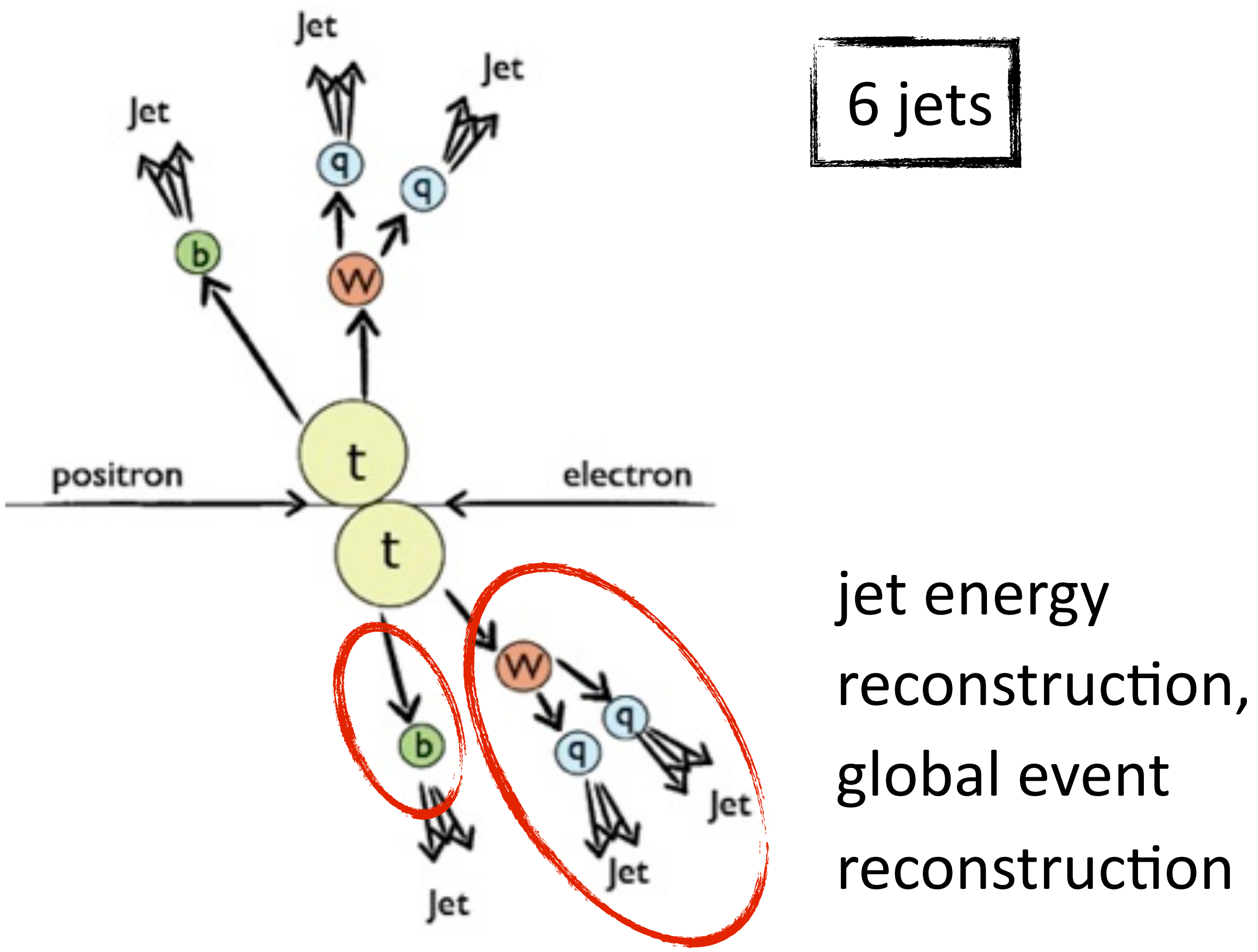

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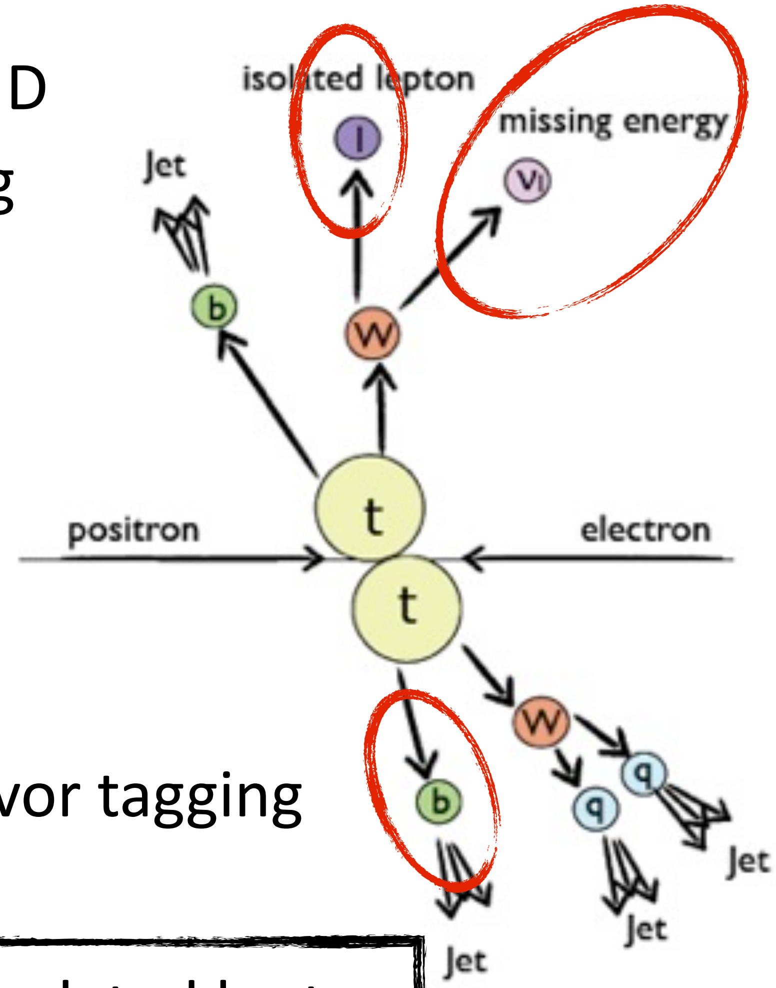
lepton ID
tracking



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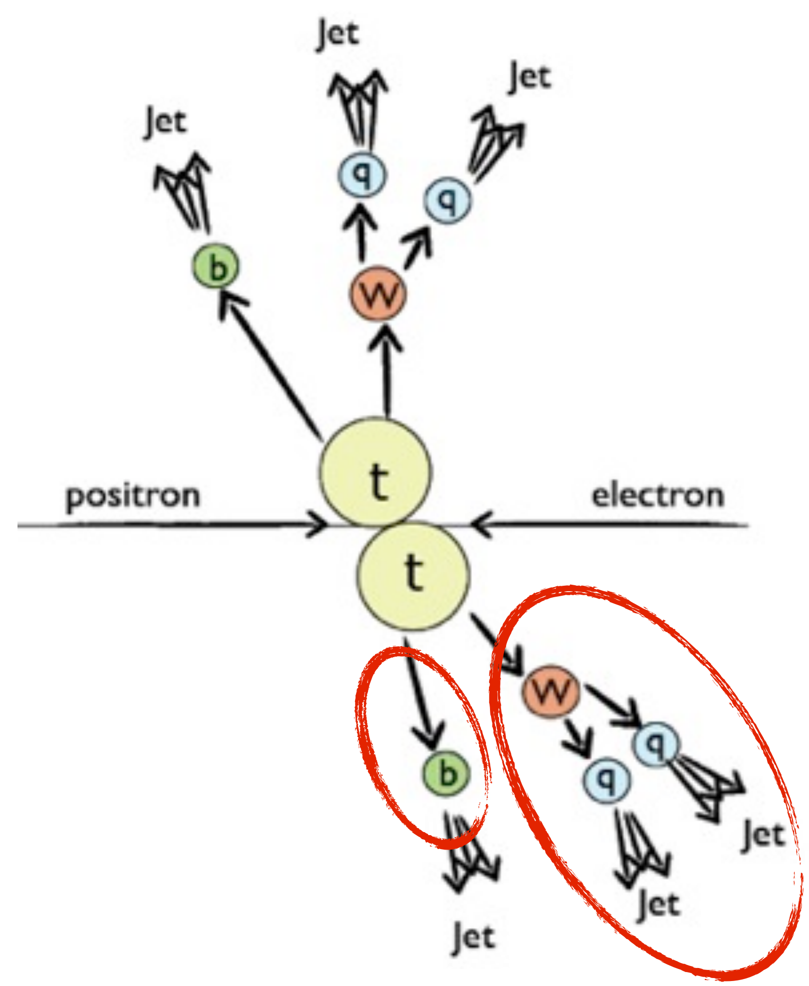

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jet energy reconstruction, global event reconstruction

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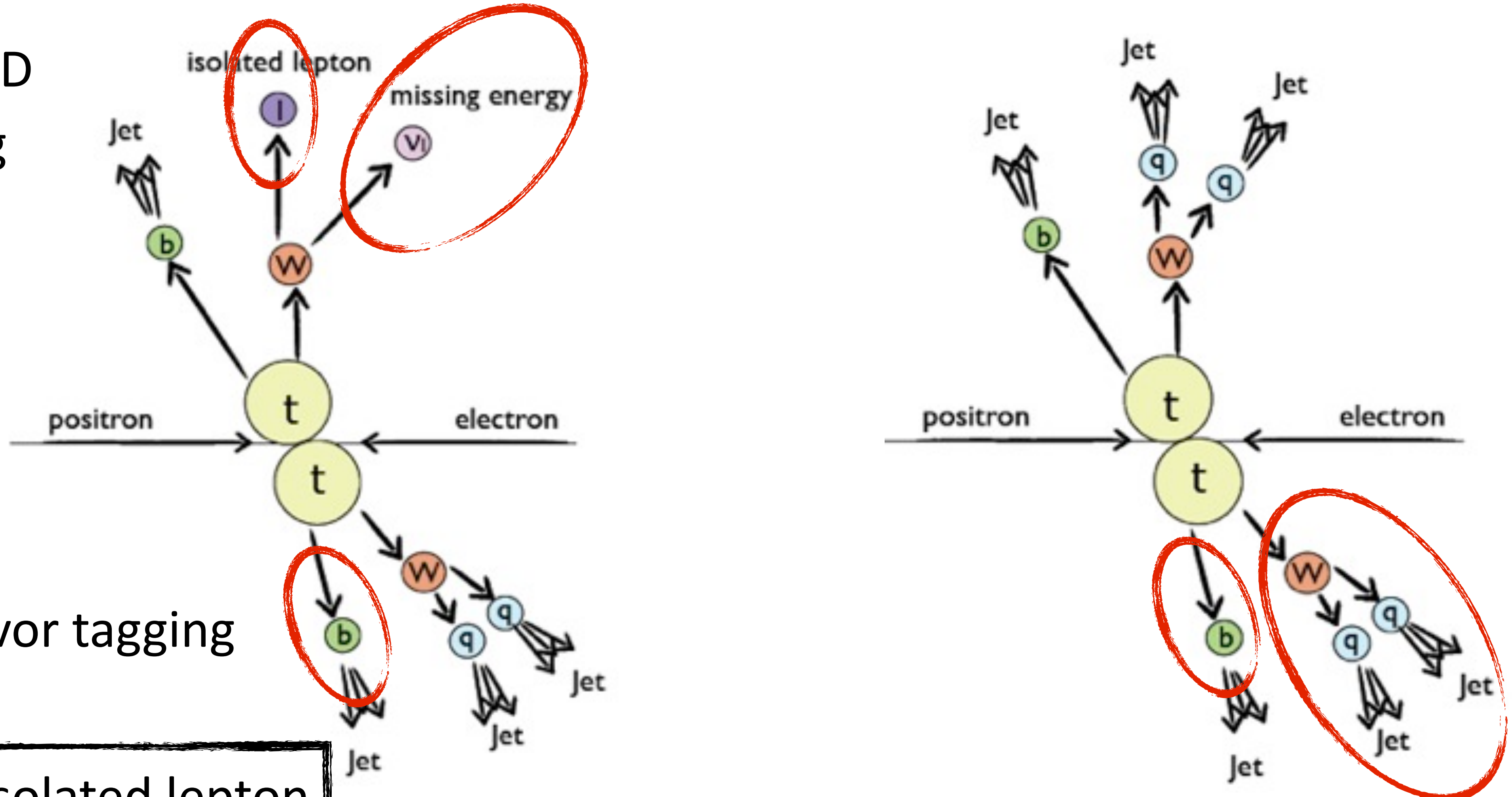
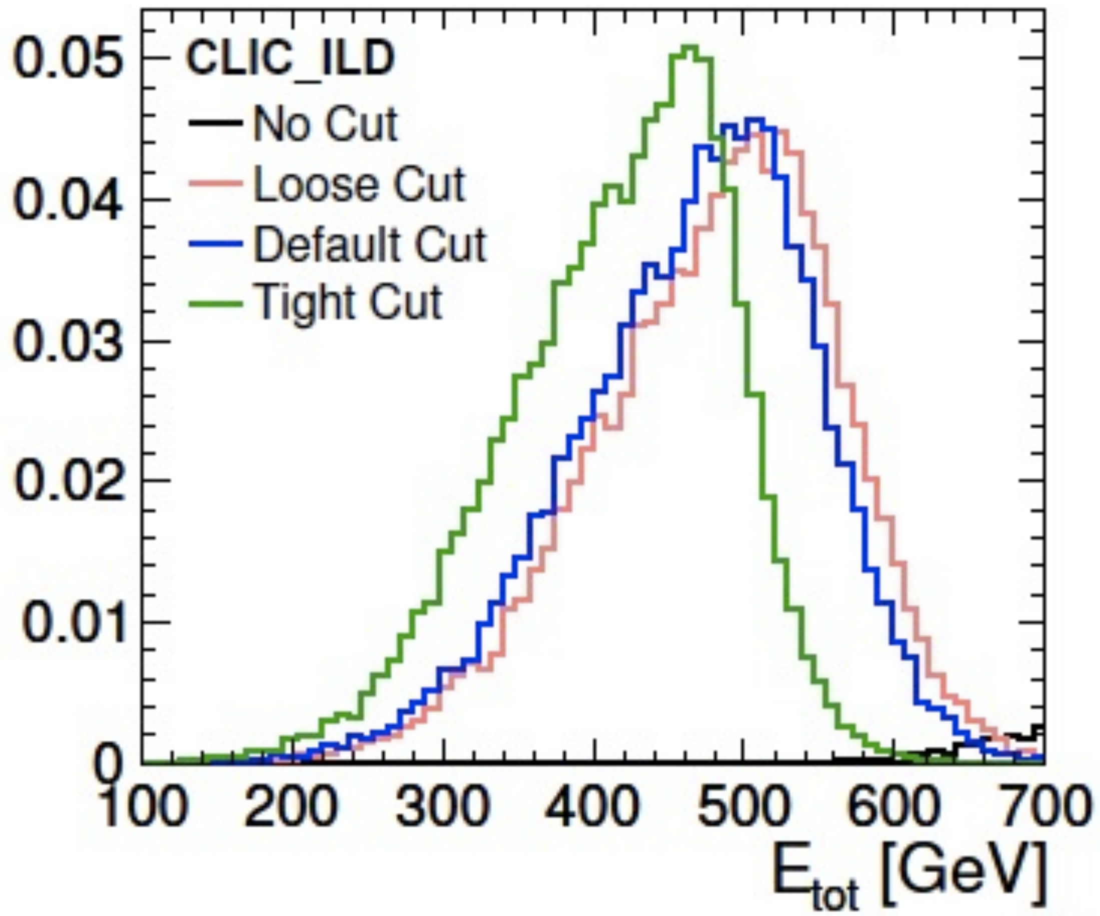


Uses all aspects of CLIC detectors!

The Simulation Studies

- Based on fully simulated & reconstructed events with the CLIC_ILD_CDR500 detector model
  - Overlay of a full bunch-train of γγ -> hadrons events included
- Background influence largely eliminated by
  - Timing and momentum cuts in PandoraPFA



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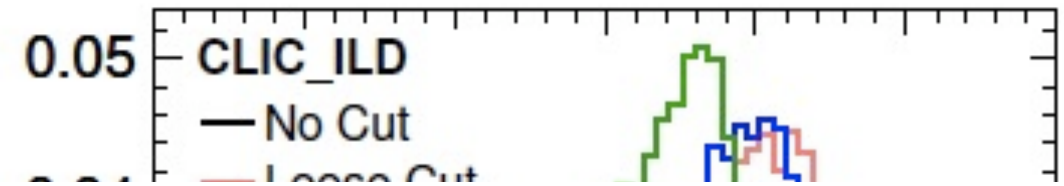

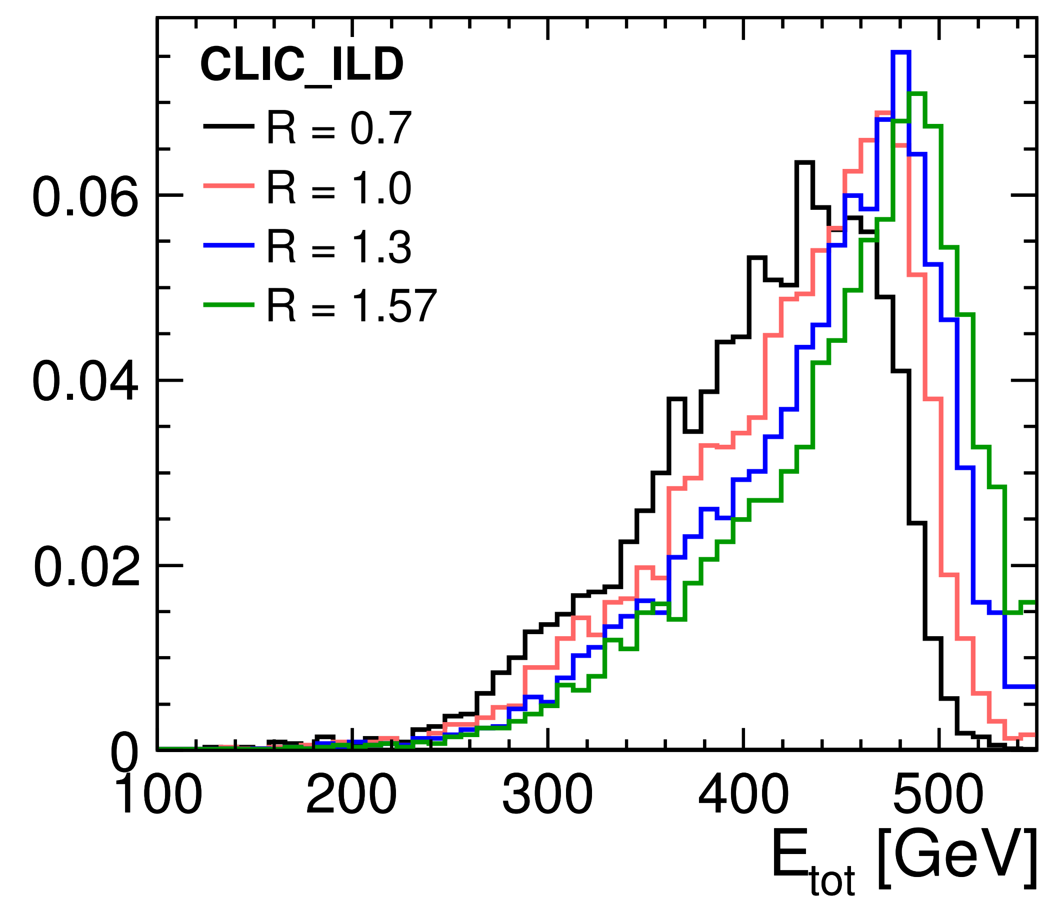

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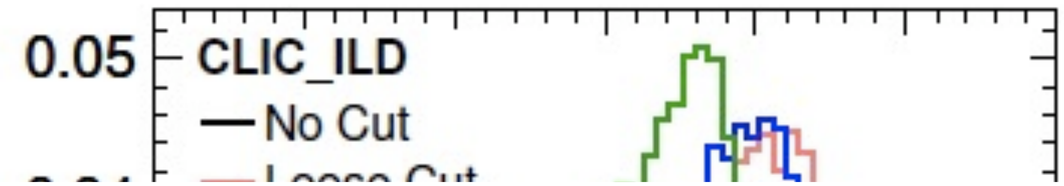
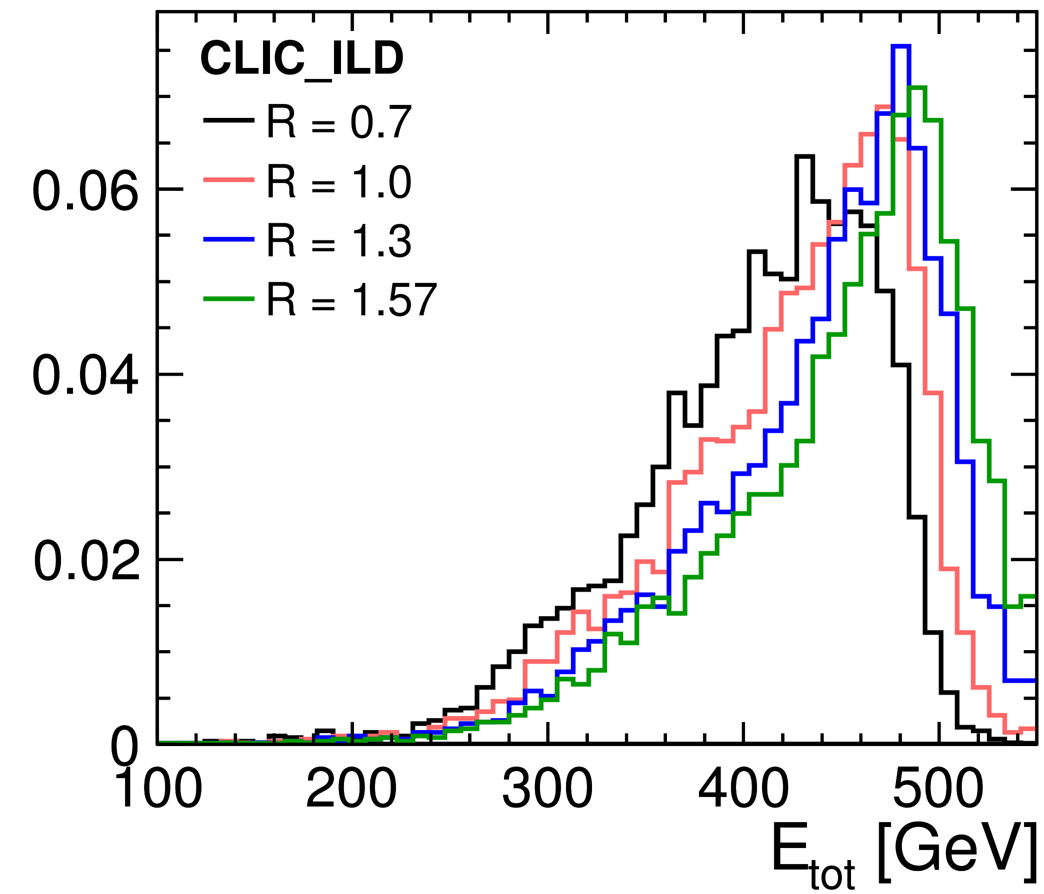
  - Jet finding with the k_t algorithm
- Events (signal & background) generated with PYTHIA or WHIZARD





$\sqrt{s} = 500\,\mathrm{GeV}$, CLIC beam energy spectrum

process type	$e^+e^- \to$	cross section σ	event generator
Signal ($m_t = 174\,\mathrm{GeV}$)	$t\bar{t}$	528 fb	PYTHIA
Background	WW	7.1 pb	PYTHIA
Background	ZZ	410 fb	PYTHIA
Background	$q\bar{q}$	2.6 pb	WHIZARD
Background	WWZ	40 fb	WHIZARD

Top Mass above Threshold: Invariant Mass

Invariant Mass Reconstruction - Exploiting e^+e^-

- Three key advantages at e^+e^- colliders:
  - Well-defined initial state: Can use full 3D energy constraints, not just transverse
  - Clean conditions: More powerful flavor tagging, reduction of background
  - Detectors optimized for precision: Improved jet energy resolution

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- The strategy:
  - Group all events (signal and background) in top candidates:
    - all-hadronic: No isolated lepton, event is clustered into six jets
    - semi-leptonic: One isolated lepton, neutrino from missing energy, event is clustered into four jets (excluding lepton)
    - fully leptonic: Two or more isolated leptons: These events are rejected - large uncertainties in mass reconstruction due to two neutrinos, overall less than 10% of BR
  - Find two b - jets: Flavor-tag all jets in the event, taking the two most probable b-jets as b candidates

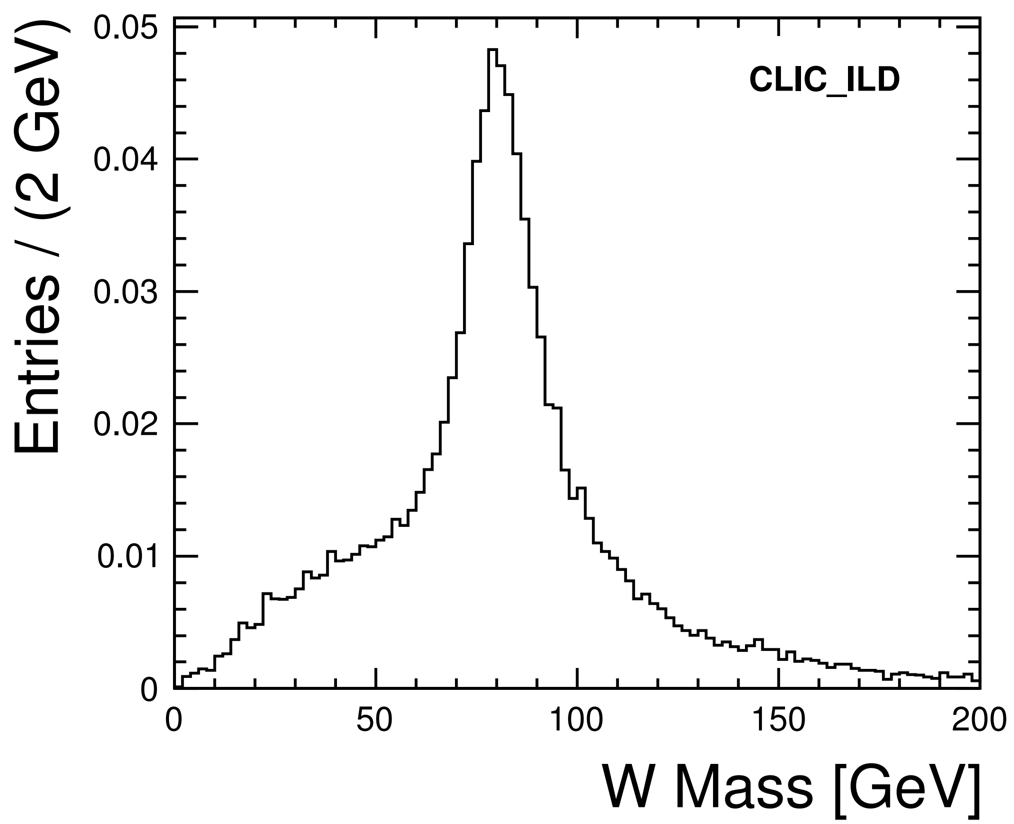
Building the Top: W Bosons

- Reconstruct on-shell W bosons

Semi-leptonic events

- 2 b-jets
- 2 light-jets : first W
- 1 lepton
- missing energy / neutrino

second W

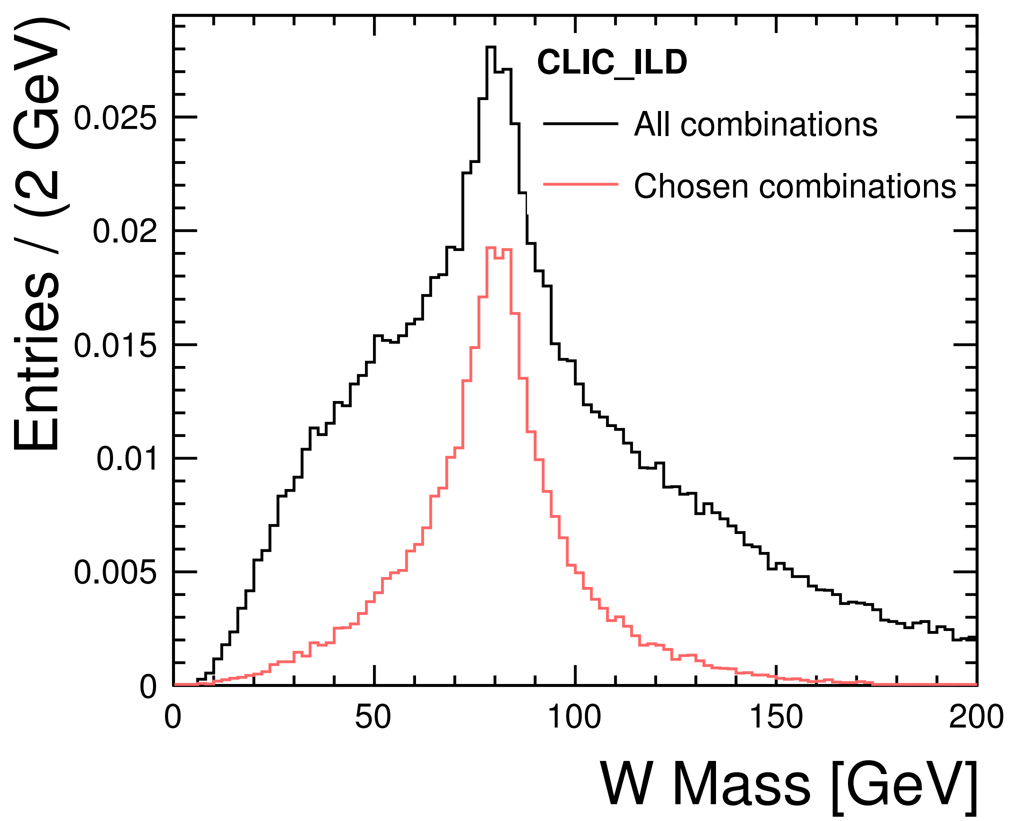


All-hadronic events

- 4 light-jets
- 2 b-jets
- Find two best W candidates:

$$|m_{ij} - m_W| + |m_{kl} - m_W|$$

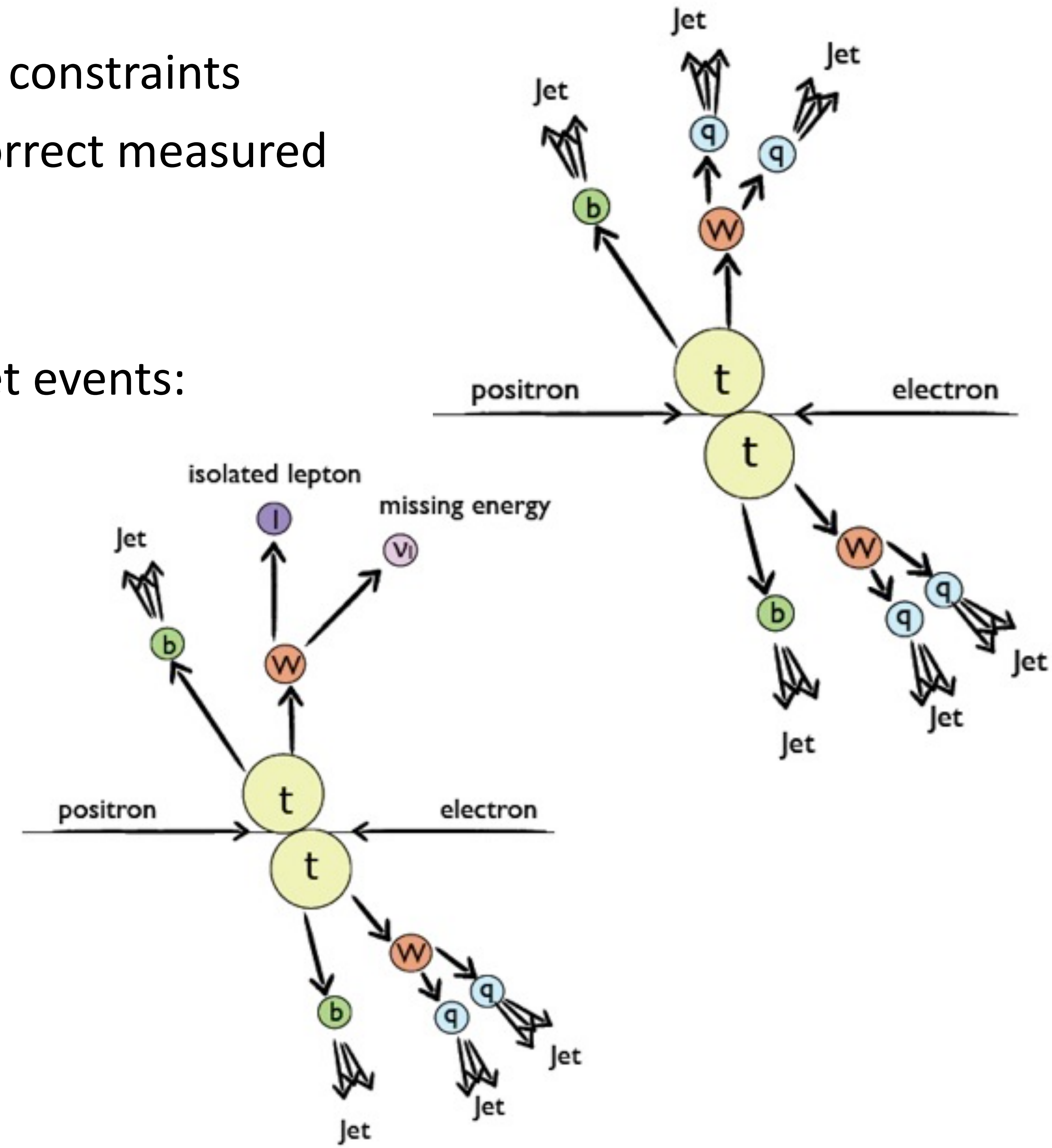
- Minimum value defines best permutation



Building the Top: Combining W and b

Kinematic fit (MarlinKinFit) uses constraints from signal event topology to correct measured properties of decay products

- Constraints for four and six jet events:
  - Energy conservation
  - Momentum conservation
  - W mass equals 80.4 GeV
  - Equal top masses



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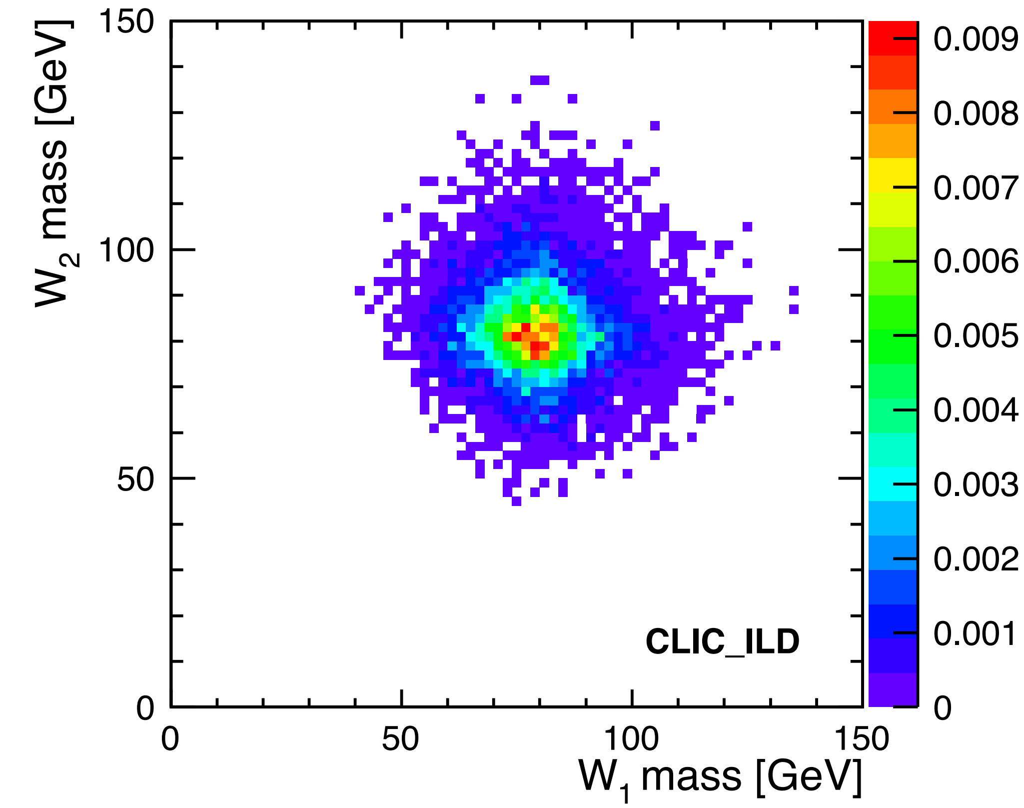
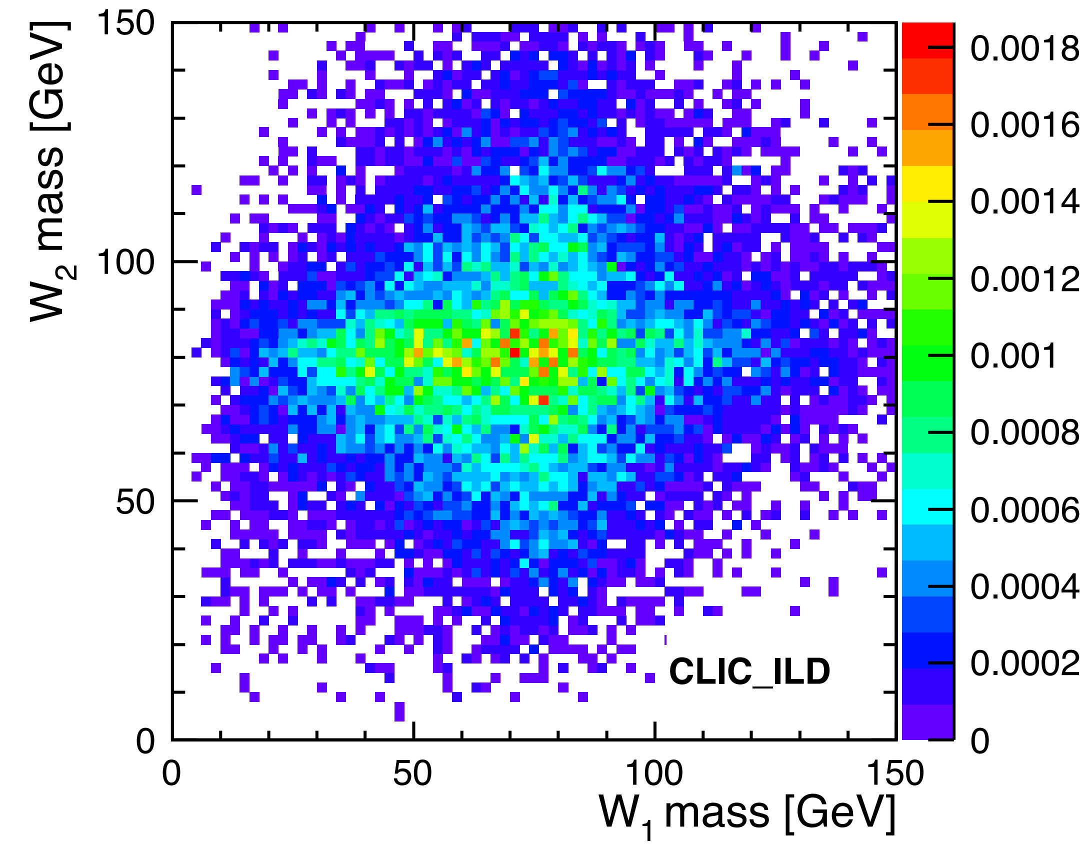
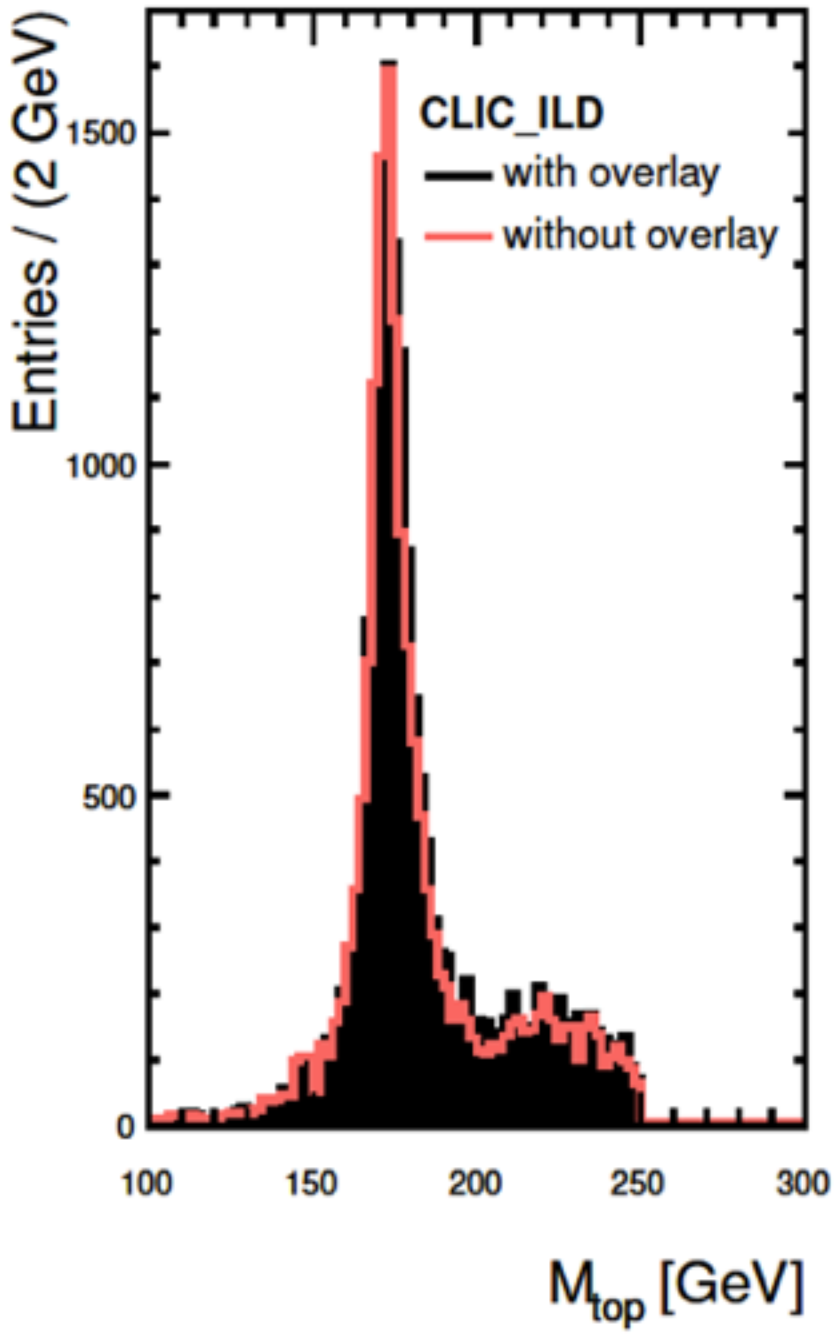
- Constraints for four and six jet events:
  - Energy conservation
  - Momentum conservation
  - W mass equals 80.4 GeV
  - Equal top masses
- Use kinematic fit for final Wb pairing
- Only very clean events pass kinematic fit
  - In case of fit failure: re-examine flavor assignment (recovers W decay into charm) 10% increase in success rate

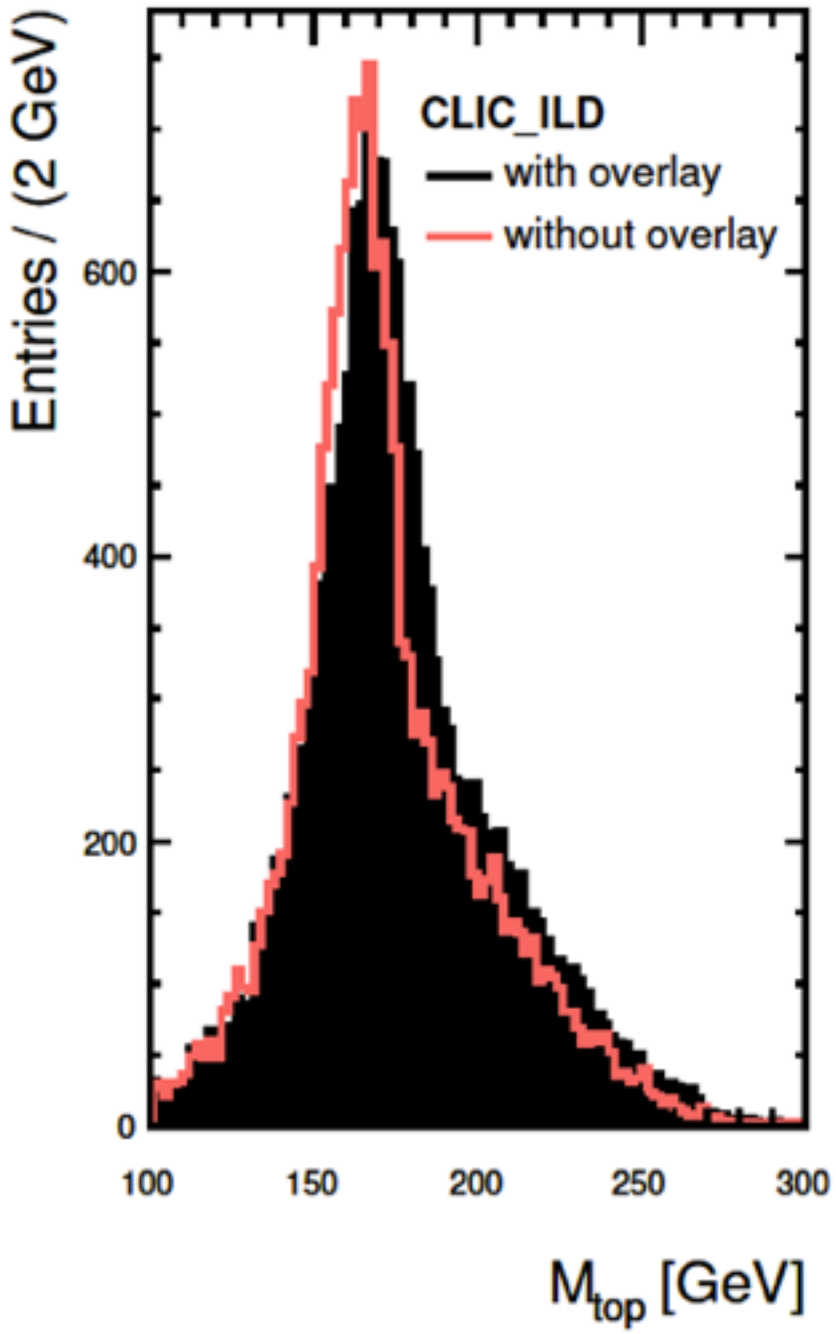




The Power of Kinematic Fitting

- Improved resolution, increased stability towards pile-up of backgrounds at CLIC





all-hadronic top pairs at CLIC

Also reduces JES systematics considerably!

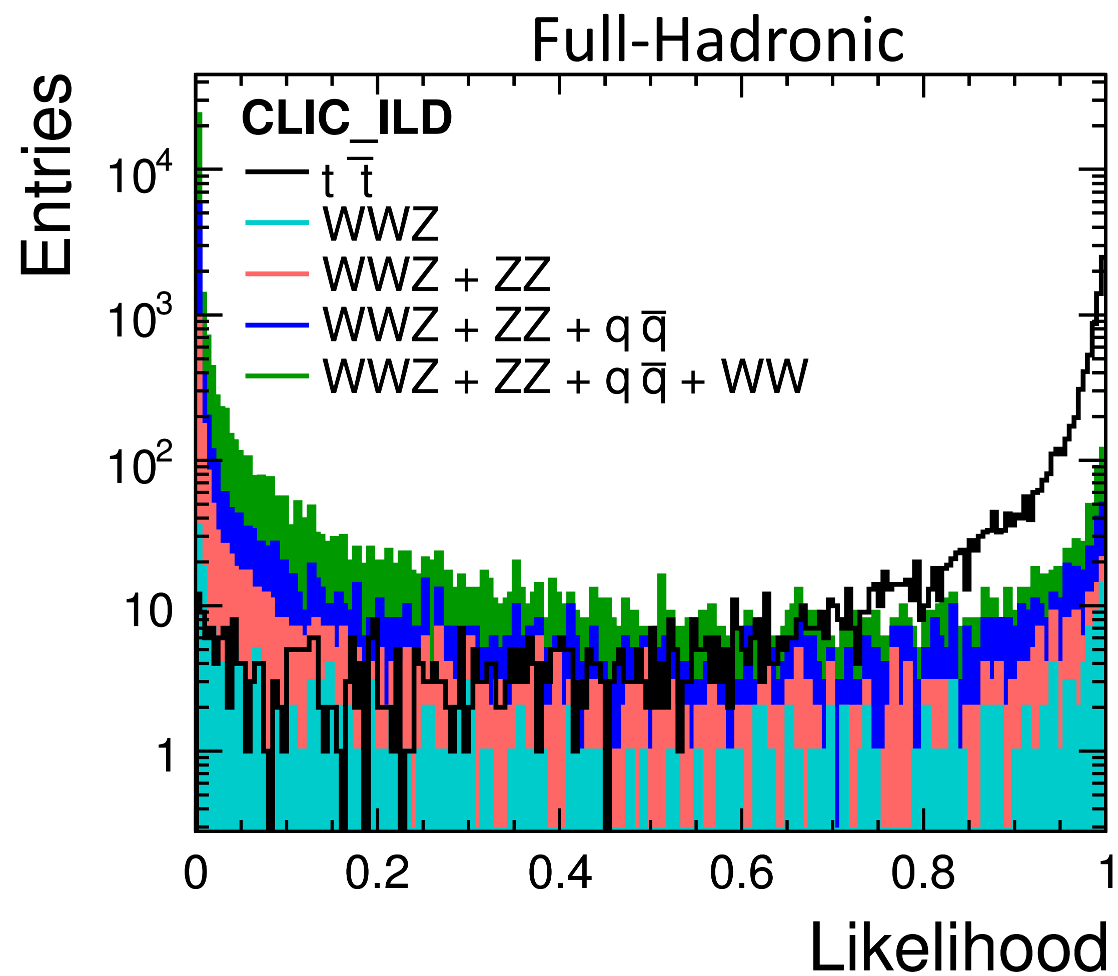
Cleaning the Sample

Kinematic Fit

- Powerful Background Rejection for qq, WW, ZZ
- Rejection of unwanted signal events: full-leptonic events, tau- events

Binned likelihood rejection

- Seven input variables (Number of particles in event, value of b-tags, sphericity, ...)
- Likelihood cut of 0.6 chosen
- Training with independent sample



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Kinematic Fit

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Overall background rejection: 99.8%

Overall signal selection:

Full-Hadronic: 34%

Semi-Leptonic: 43%

- Analysis goal: clean events, not maximized statistics

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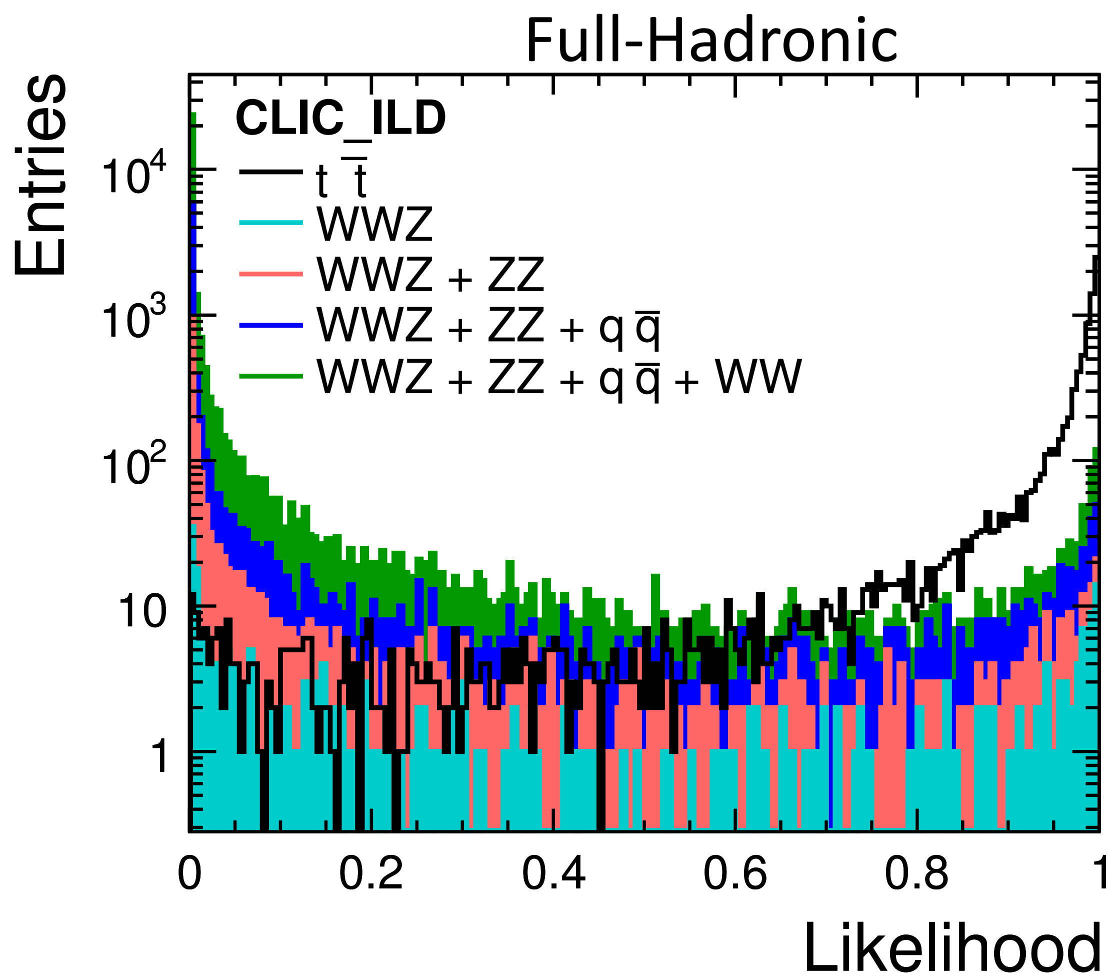

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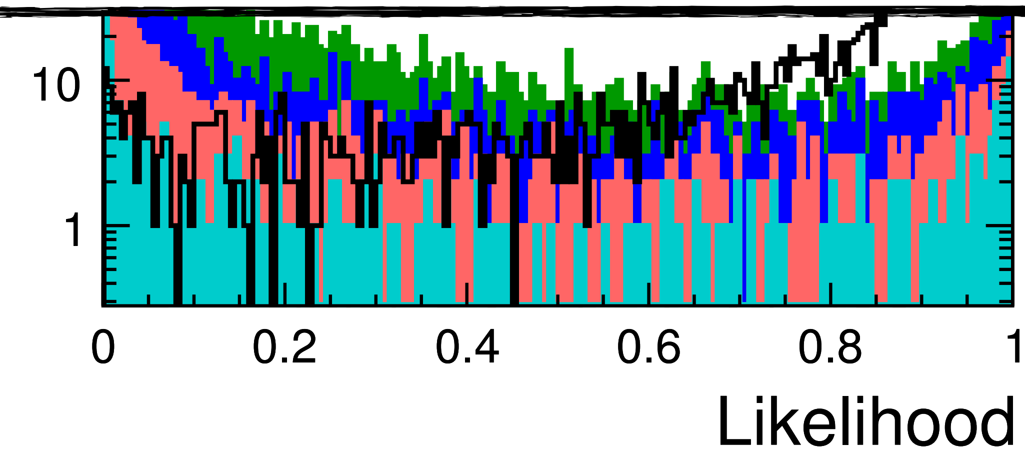
Kinematic fit and background rejection using likelihood (or other multivariate techniques) can also be performed in reverse order (as was done for ILD LOI)

Advantage of doing it this way: Correct assignment of Ws and bs to tops already found before likelihood

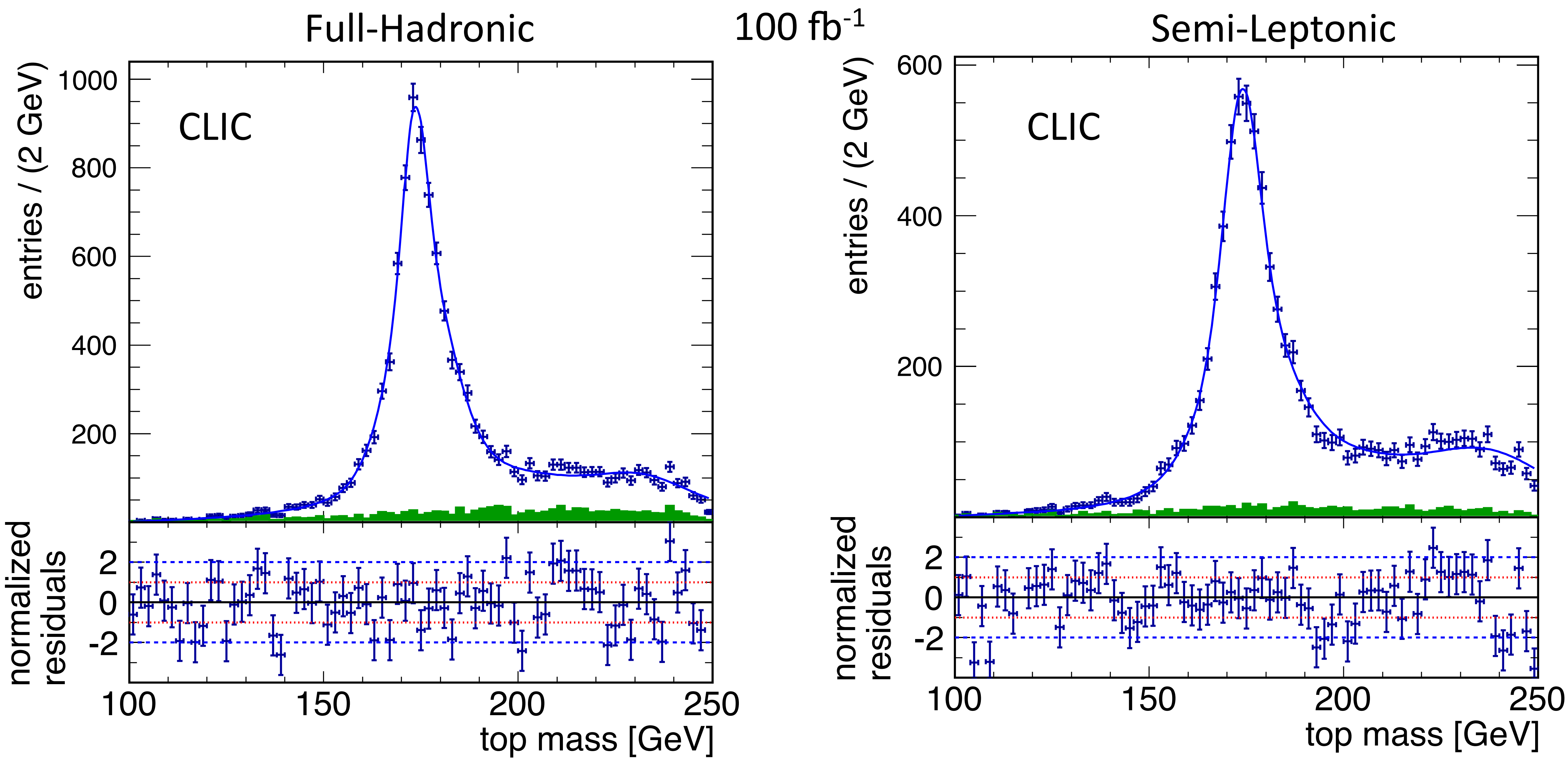
- Analysis goal: clean events, not maximized statistics



Measuring the Mass- CLIC CDR

Un-binned maximum likelihood fit over full range

- Combination of signal and background pdf
- Signal pdf is a convolution of a Breit-Wigner and a detector resolution function



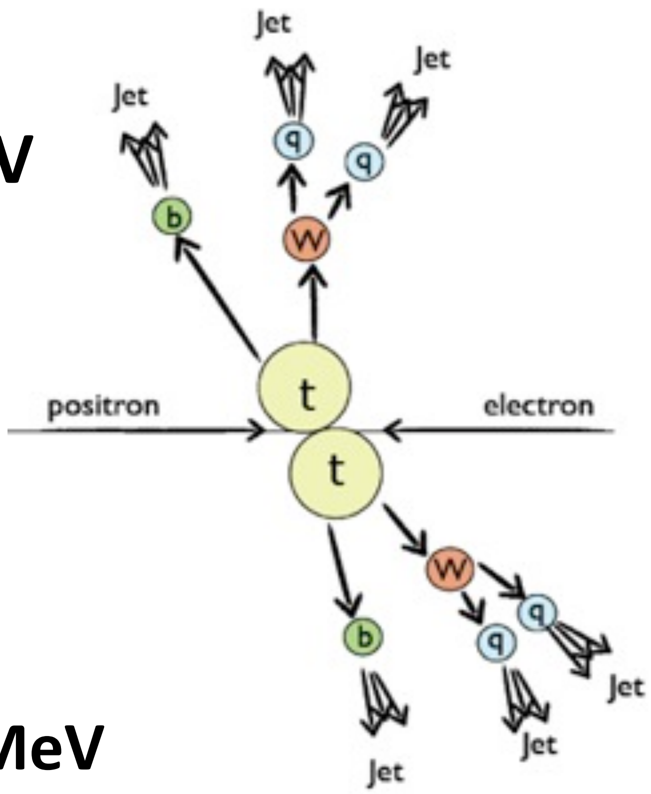
Invariant Mass Results & Systematics

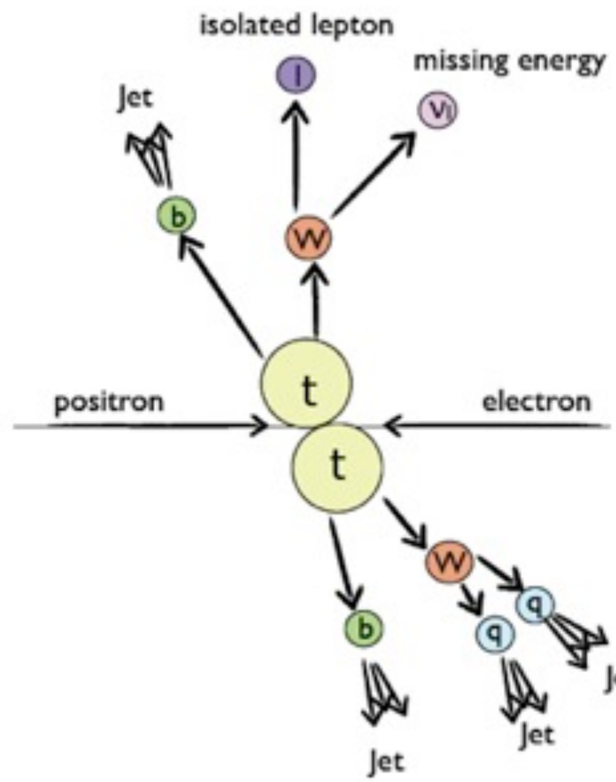
- Top mass results (100 fb^{-1}):

  stat. errors all-hadronic: **100 MeV**, semi-leptonic: **140 MeV**

  combined: **80 MeV**

  (generator values: m_{top} = 174 GeV, width: 1.37 GeV)
- Measurement of width is also possible (statistical uncertainty depends strongly on fit range and technique):
  - Here stat. errors all hadronic **270 MeV**, semi-leptonic: **400 MeV**





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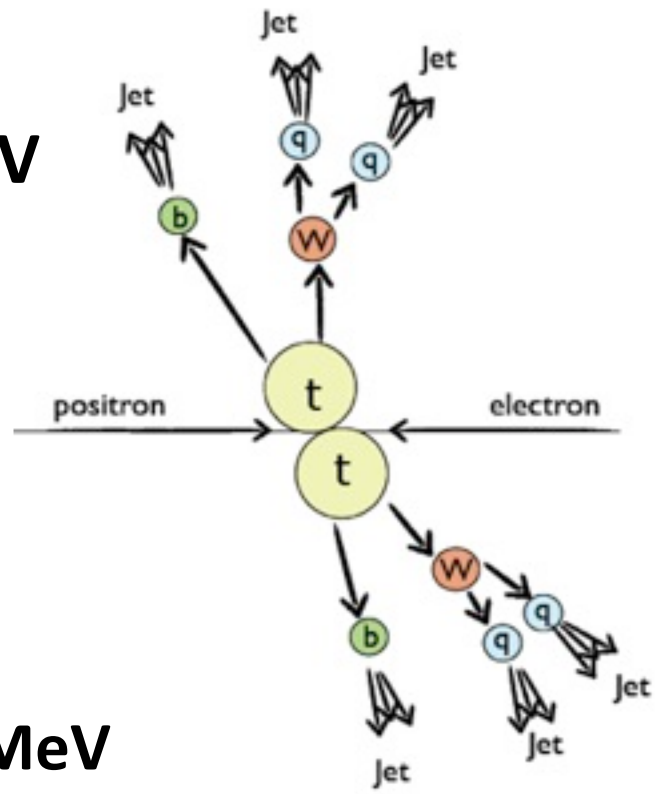
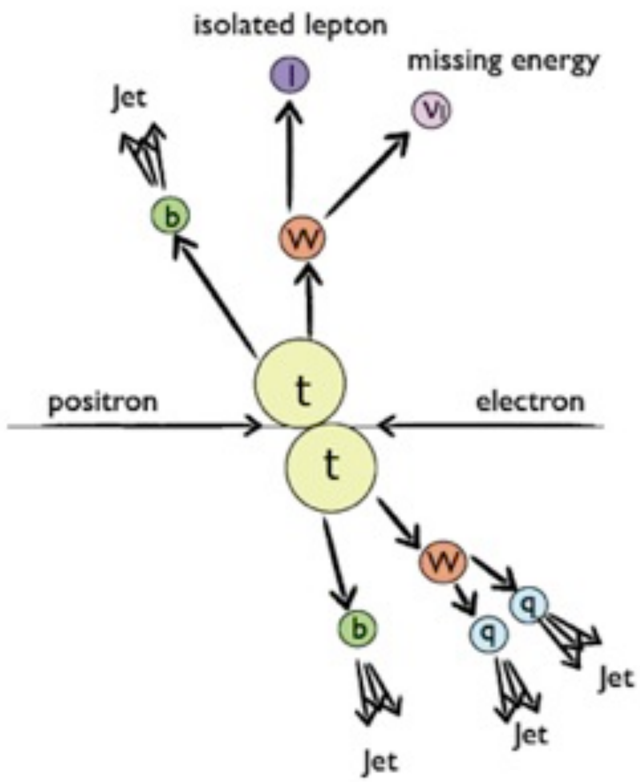


Study of systematic errors due to Jet Energy Scale (all-hadronic):
- Light JES can be well controlled by the mass scale of the reconstructed W bosons -> 0.1% level
- b-JES matters: 1% uncertainty results in 190 MeV on mass and 70 MeV on width -> Can be controlled to higher precision by reconstructed Z -> bb decays, bringing uncertainty below the statistical uncertainties



Top Mass at Threshold: Threshold Scan

The Measurement Strategy - And Simulations

- A simple cross section measurement:
  - Identify top pair events
    - Follows the same strategy as for invariant mass measurement
      - No cut on chi2 of the kinematic fit - maximize significance, not quality of reconstructed mass
    - statistically subtract background

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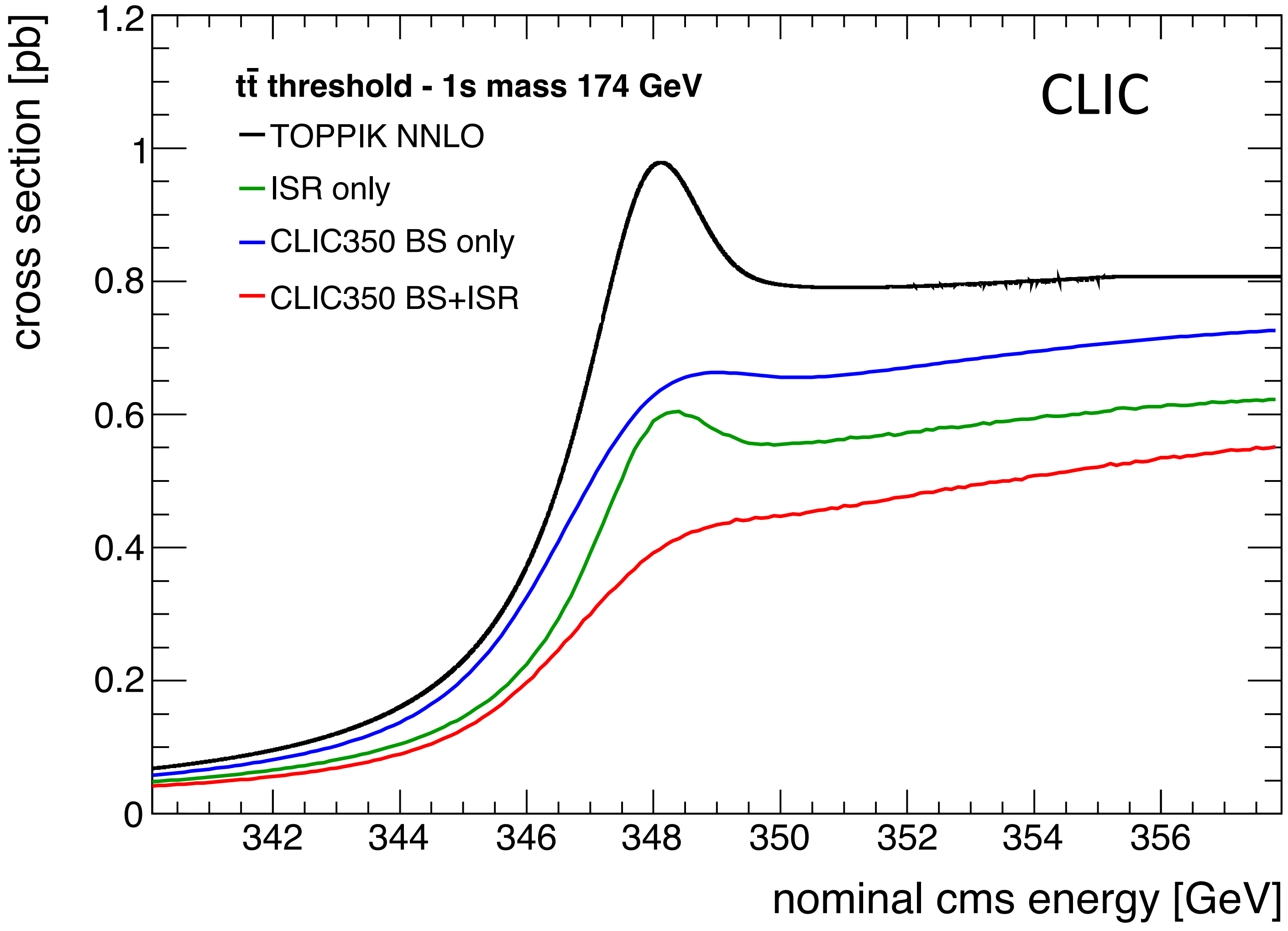
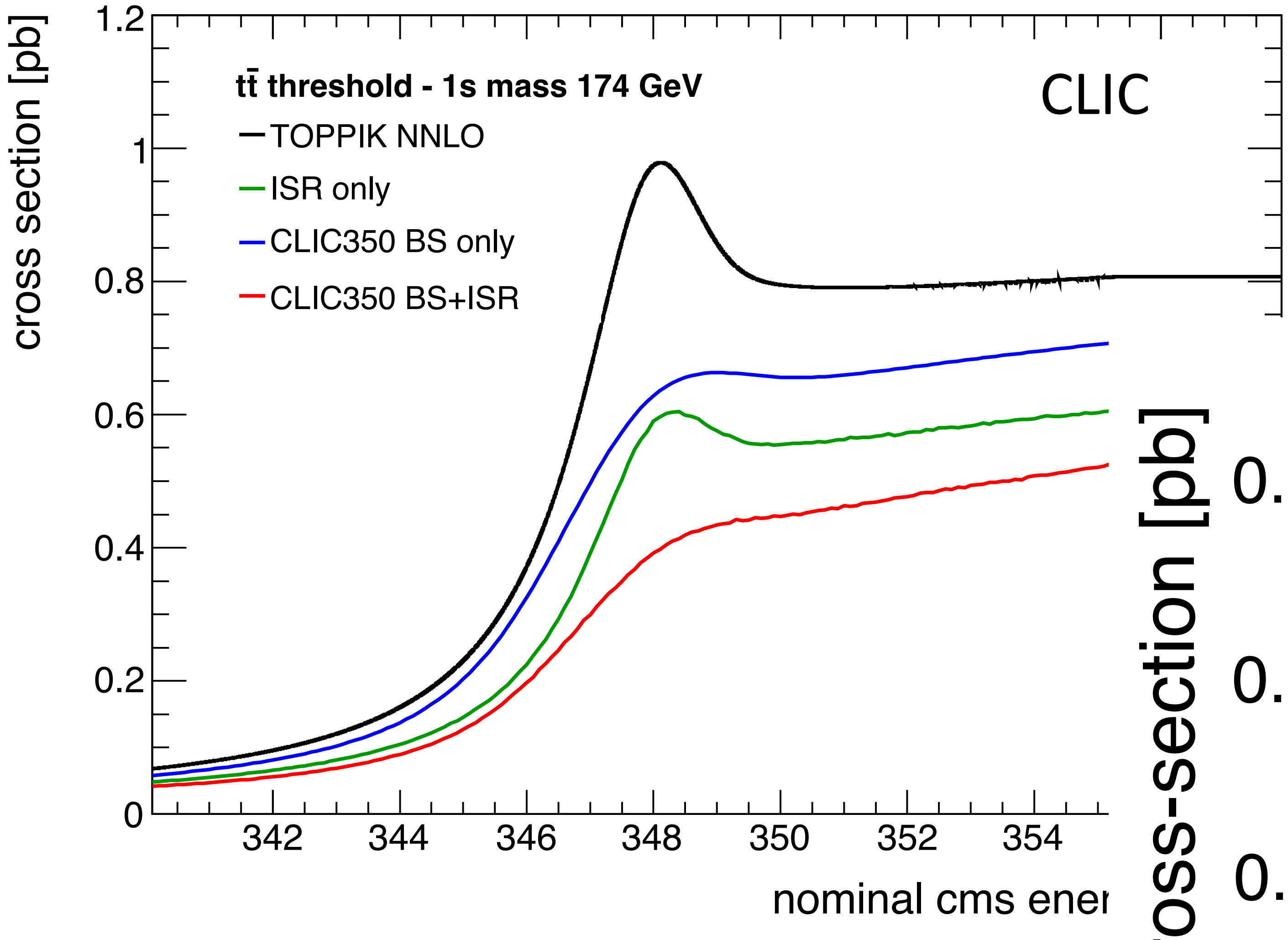
- Simulation Studies: No public event generator for the top threshold exist - PYTHIA for example is LO, with hadronization, does not get threshold right
- Use full NNLO theory calculations to determine cross section as a function of energy (for example TOPPIK, Hoang and Teubner, PRD 60, 114027 (1999))
- Determine signal efficiency and background contamination from full detector simulations above top threshold

The Top Threshold at CLIC



- "Pure"ttbar cross section gets changed by
  - ISR -> Physics
  - Luminosity spectrum -> Machine
    Here: 500 GeV CLIC operated at 350 GeV

The Top Threshold at CLIC



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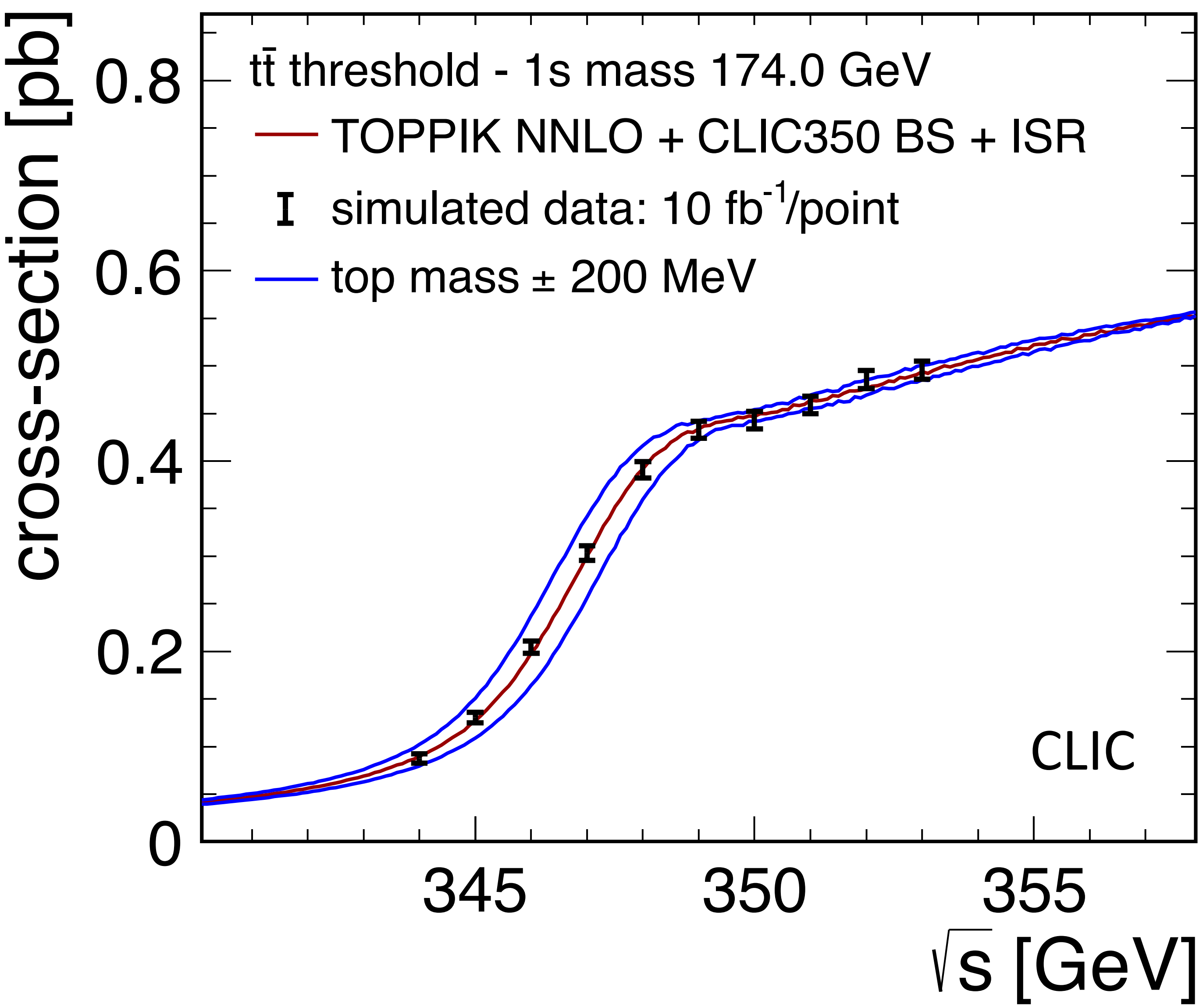
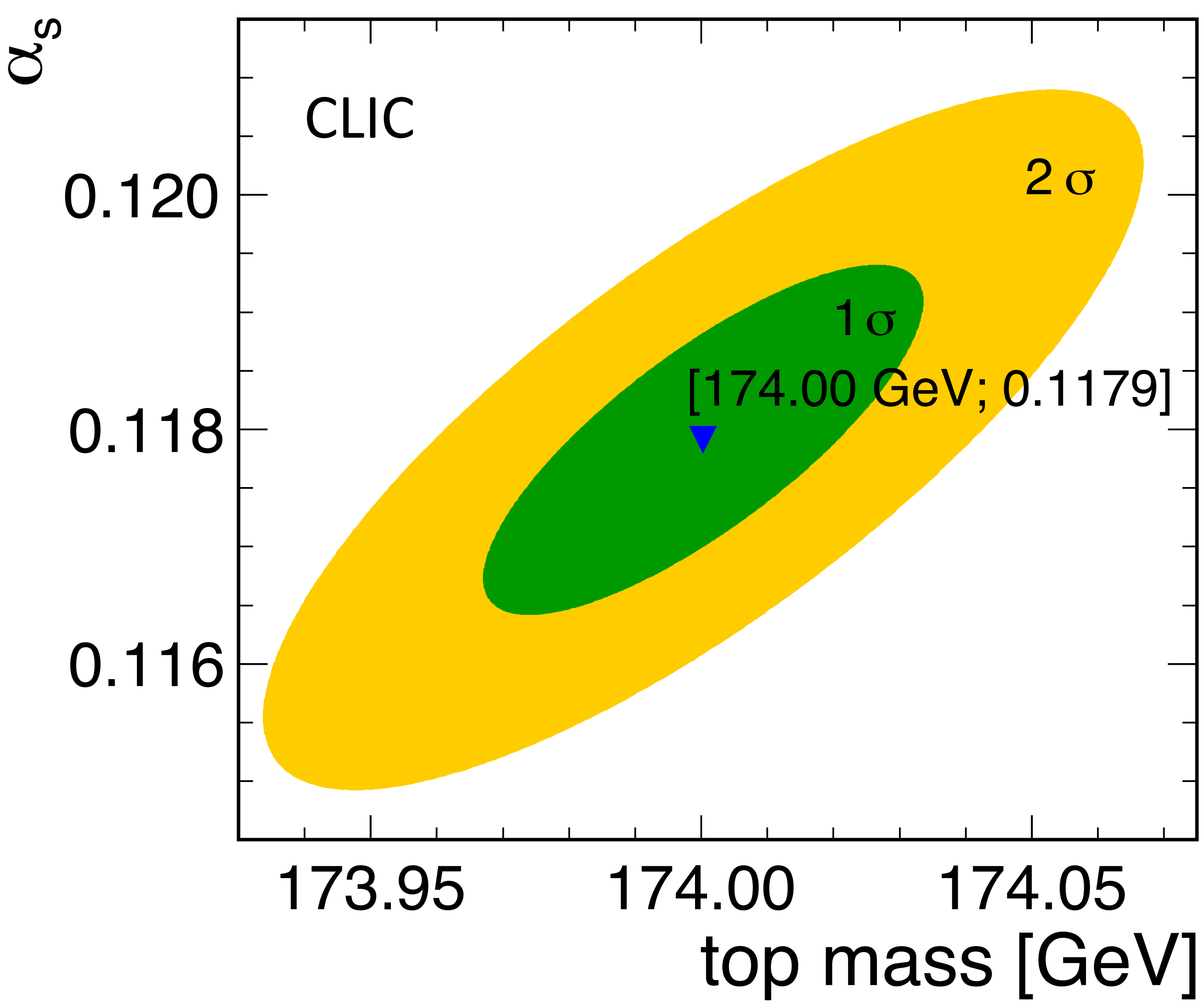


- Data points simulated assuming 10 fb^{-1} per point, 1 GeV spacing between points

Measurement of Mass and Strong Coupling

- Determination of the top quark mass (1S mass scheme) and strong coupling constant with a template fit of the threshold behavior of the cross section



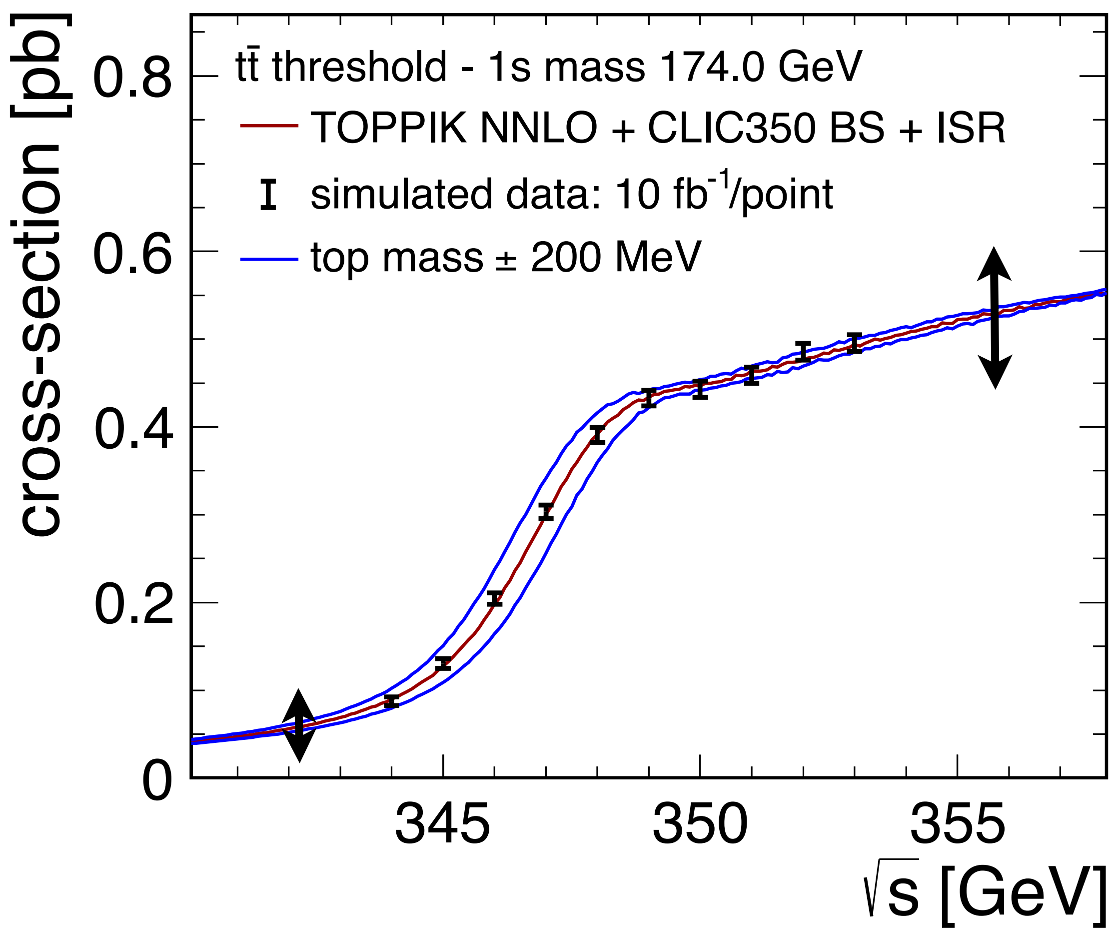
strong correlation of m_t and α_s :
Can be determined simultaneously

with 100 fb^{-1} (10 fb^{-1} per point):
34 MeV stat. error on mass
0.0009 stat. error on α_s

Fit of m_t alone: **21 MeV** stat error, **20 MeV** syst. uncertainty from current WA α_s

Systematic Uncertainties

- Several systematic effects have been studied:



- Several systematic effects have been studied:
  - Theory uncertainty: Overall cross-section normalization (1% & 3% uncertainty)
    5 MeV / 8 MeV on mass
    0.0008 / 0.0022 on α_s

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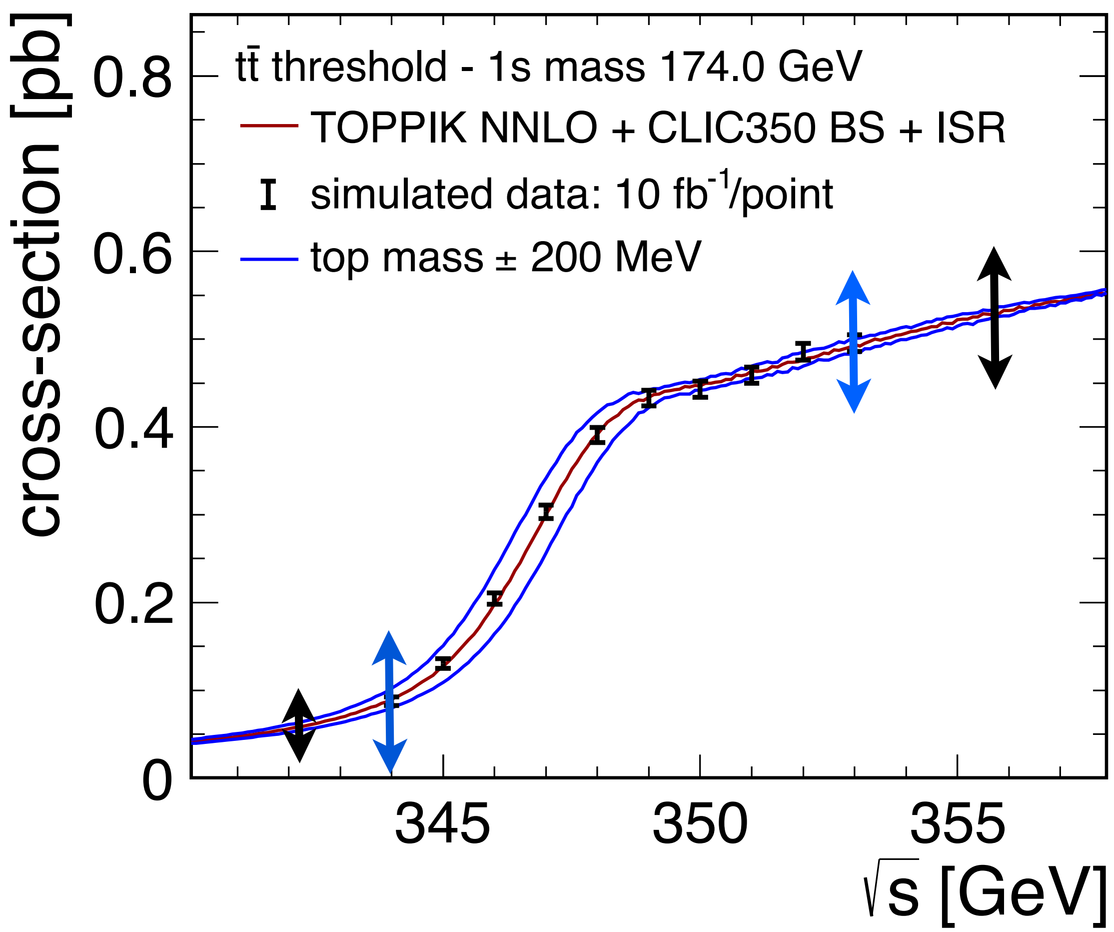
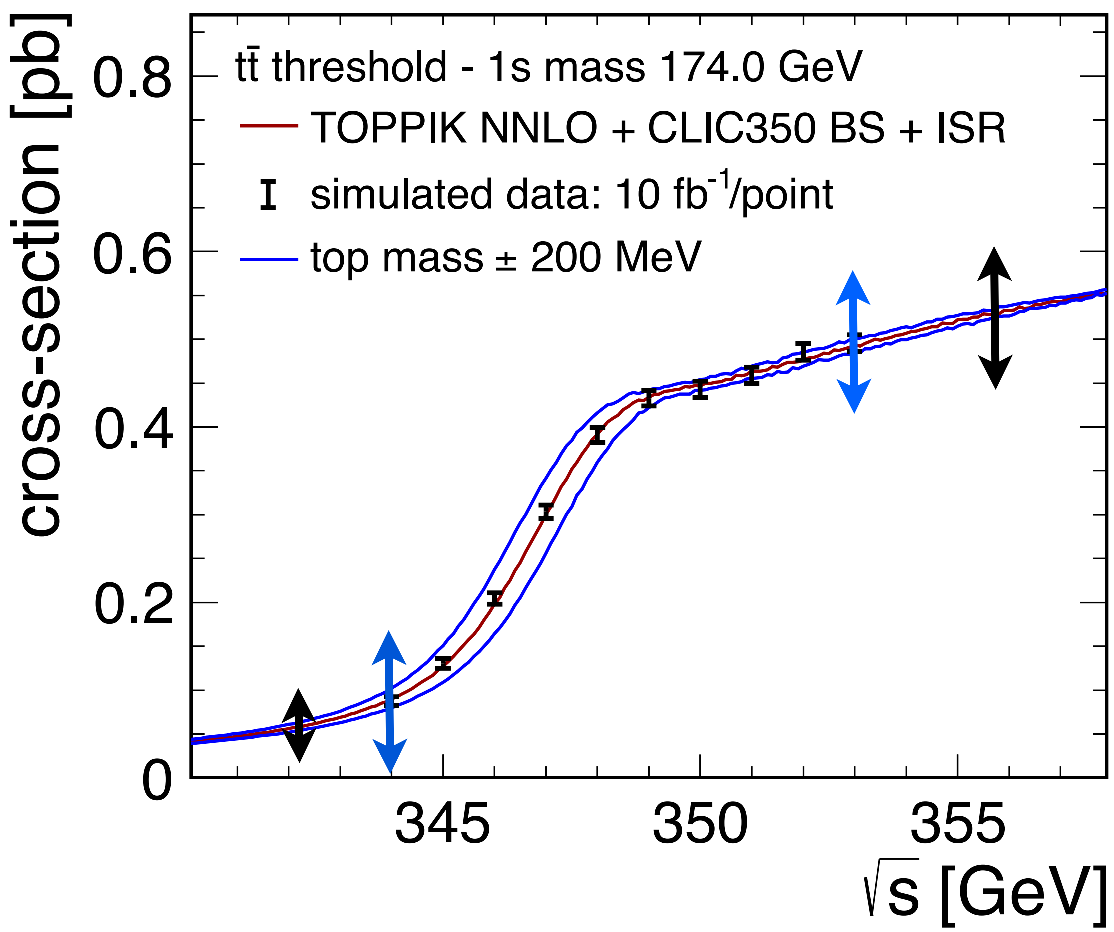


- Several systematic effects have been studied:
  - Theory uncertainty: Overall cross-section normalization (1% & 3% uncertainty)
    5 MeV / 8 MeV on mass
    0.0008 / 0.0022 on α_s
  - Background normalization: Change of subtracted background by +- 5%
    18 MeV on mass
    0.0007 on α_s

Systematic Uncertainties

- Several systematic effects have been studied:



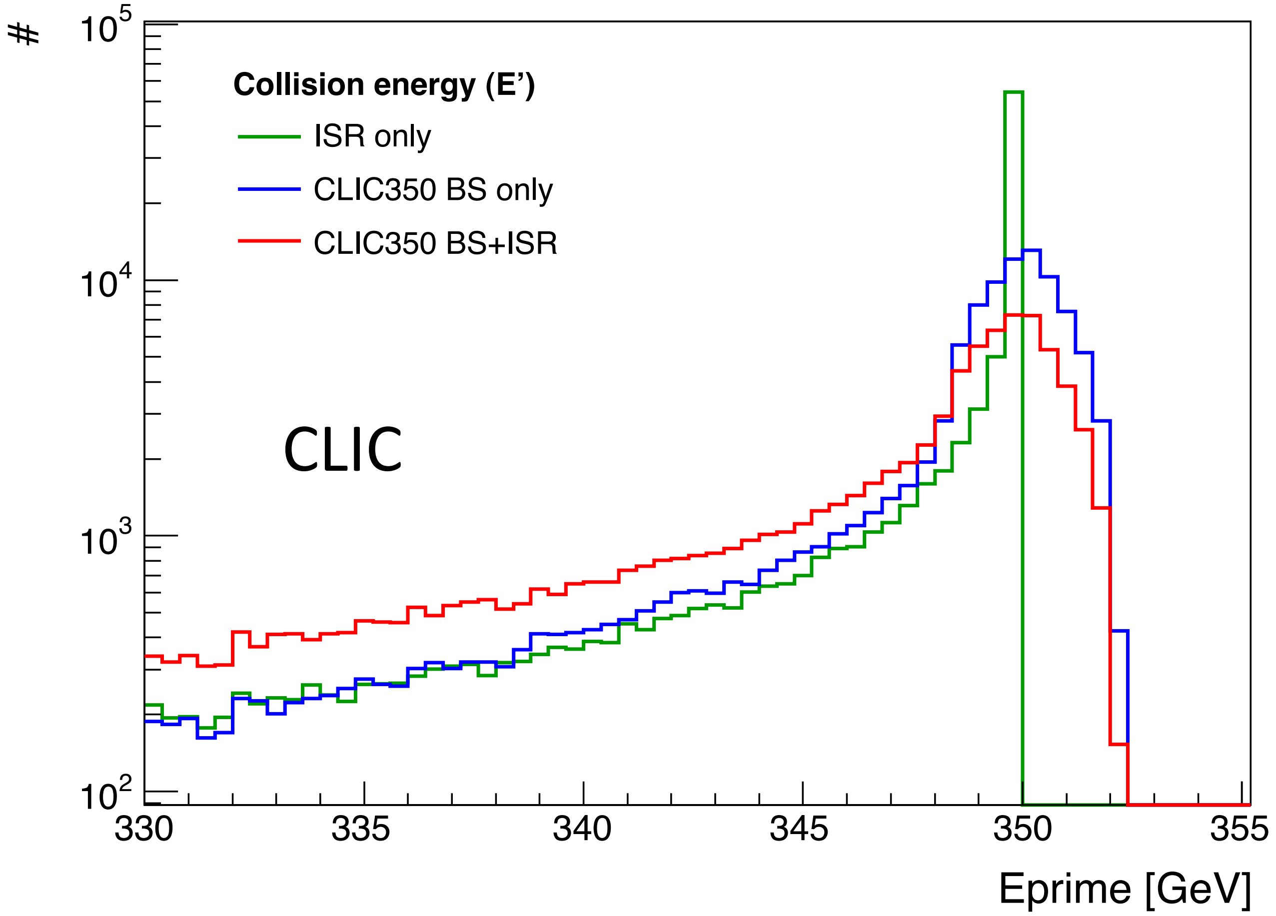
- Several systematic effects have been studied:
  - Theory uncertainty: Overall cross-section normalization (1% & 3% uncertainty)
    5 MeV / 8 MeV on mass
    0.0008 / 0.0022 on α_s
  - Background normalization: Change of subtracted background by +- 5%
    18 MeV on mass
    0.0007 on α_s

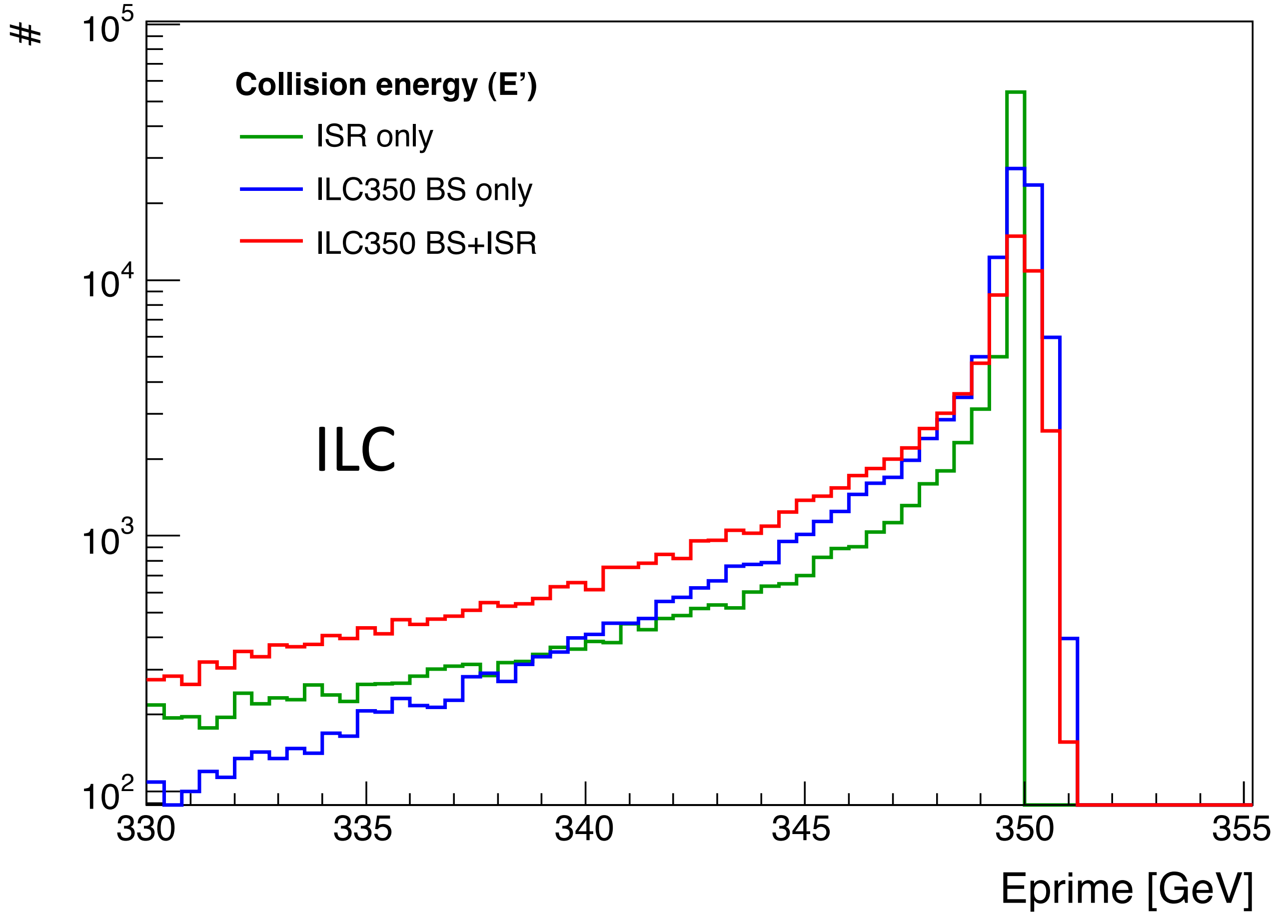
- In addition: Machine center-of-mass energy, expected to be known at the 10^{-4} level from LEP experience and ILC studies: *O* 20 MeV on mass
- Under study: Precision of luminosity spectrum -> width of main peak matters most!

Influence of Luminosity Spectrum: CLIC vs ILC

- Different luminosity spectrum of the two machines:

  Narrower main peak and less pronounced tail in the case of ILC





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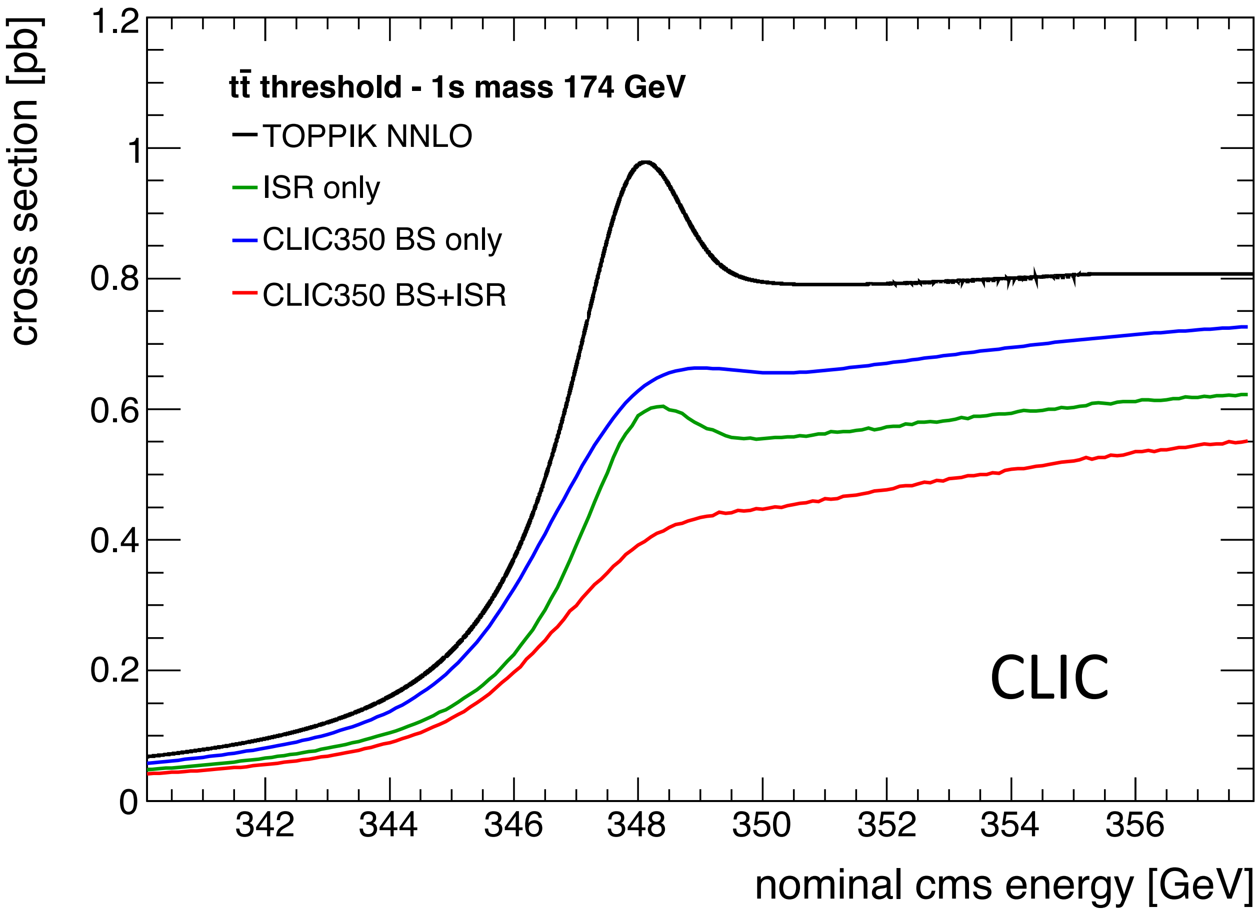
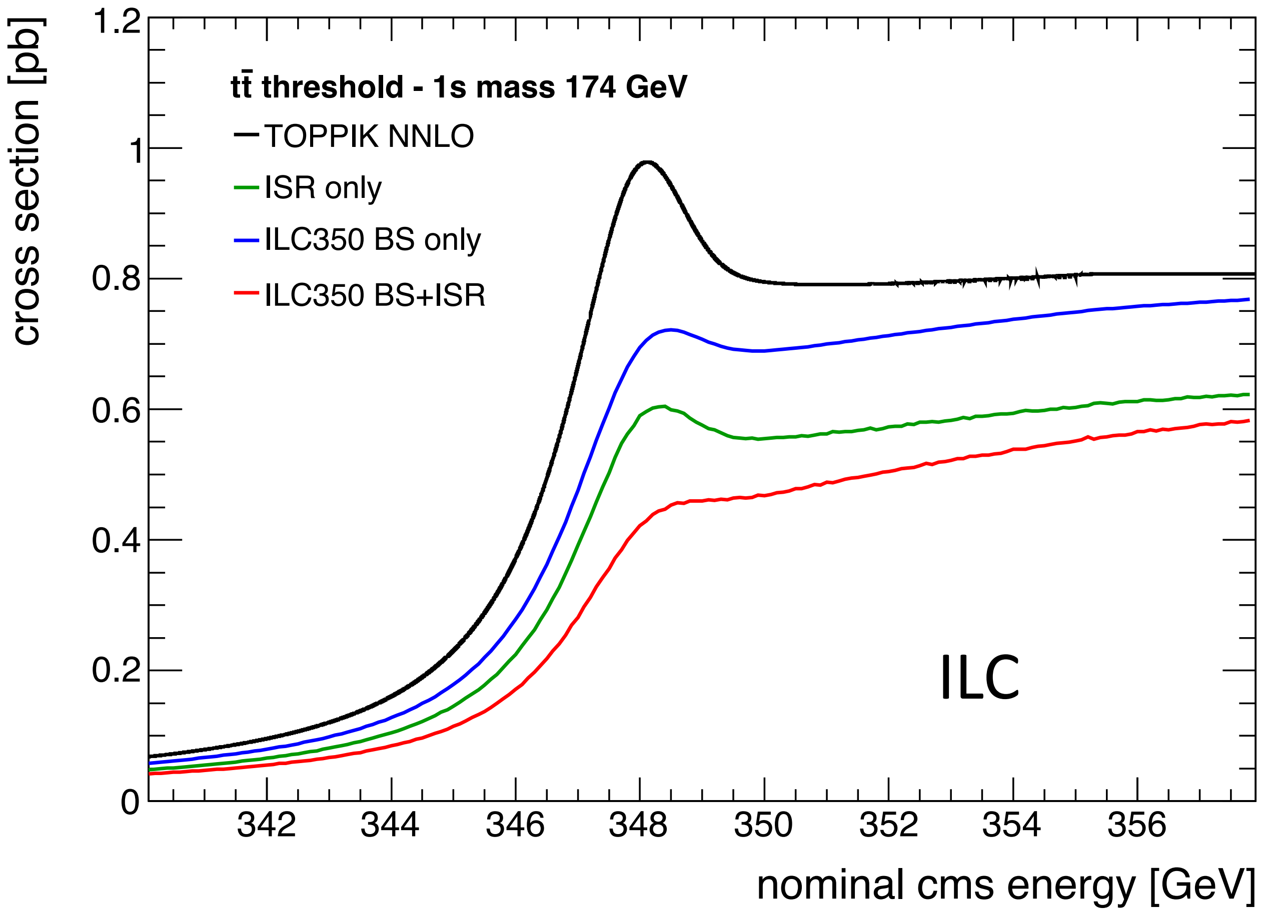
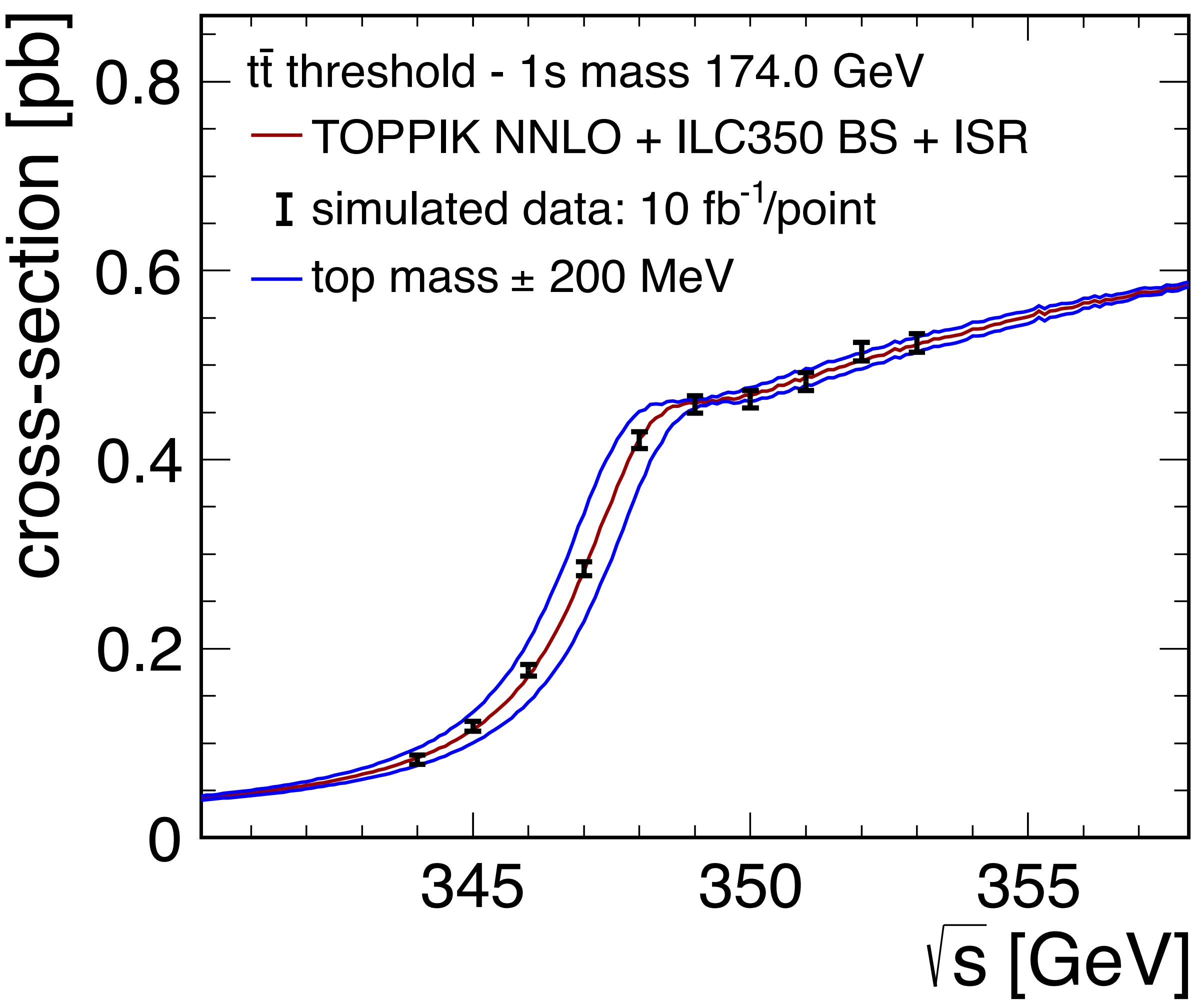


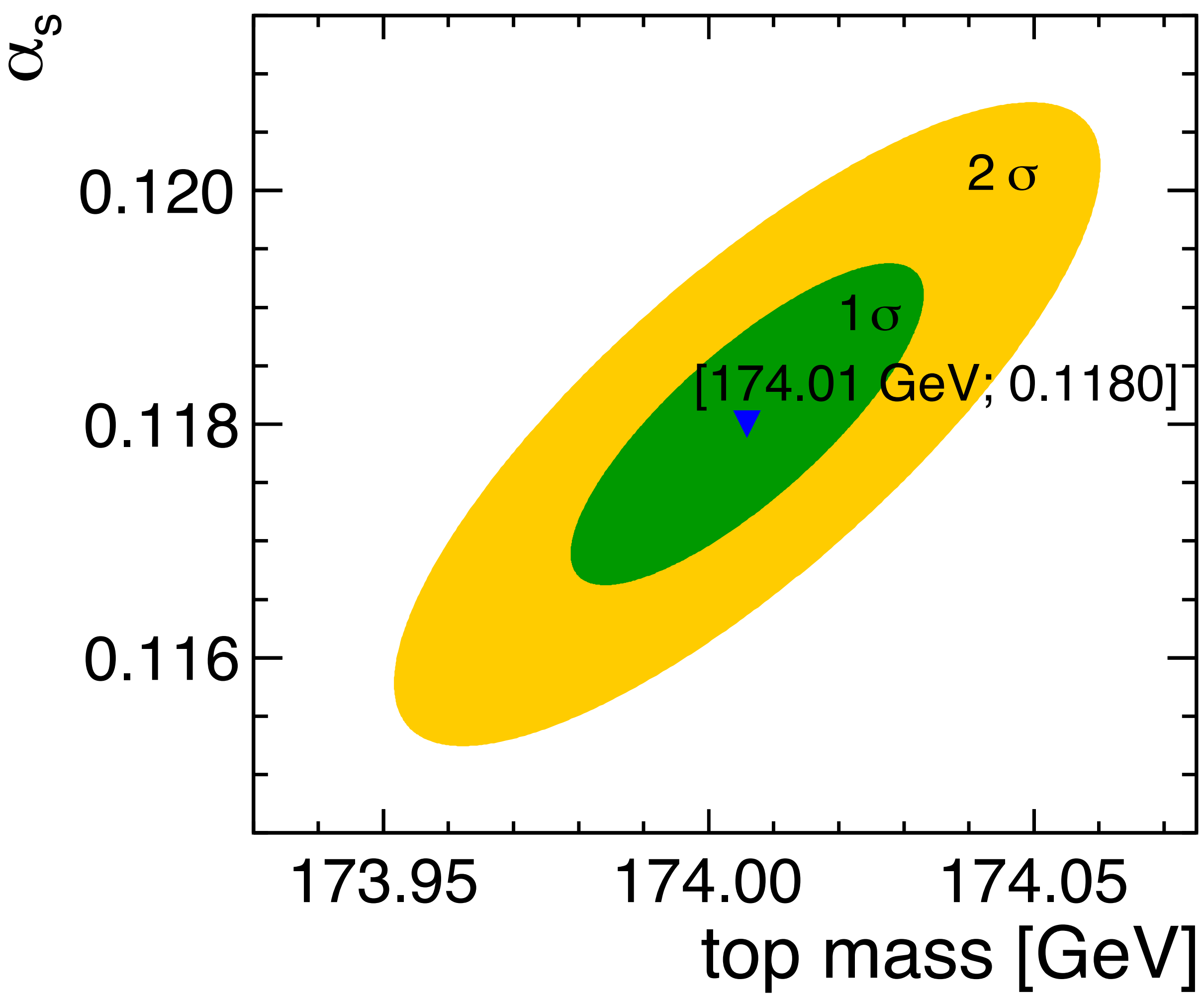


- The difference results in a slightly steeper rise of the cross section at threshold for the case of ILC

Threshold Scan at ILC

- NB: Simulations performed with CLIC_ILD (should not have a substantial effect)





with 100 fb^{-1} (10 fb^{-1} per point): **27 MeV** stat. error on mass, **0.0008** stat. error on α_s
(m_t alone: **18 MeV** stat error, **17 MeV** syst. uncertainty from current WA α_s)

- 15%-20% smaller uncertainties on the mass and 10% smaller uncertainties in α_s compared to CLIC beam conditions-> Negligible compared to systematics

Summary

- A CLIC e^+e^- collider offers excellent possibilities for precise measurements of the top mass:
  - Above threshold (500 GeV) by reconstructing the invariant mass:
    80 MeV statistical precision with 100 fb^{-1}
  - From a threshold scan around 350 GeV fitting the 1S mass and α_s
    34 MeV statistical precision of the mass, **0.0009** statistical precision of α_s with a scan with 100 fb^{-1} split across 10 equally spaced points
  - ▸ Slightly worse resolution than for ILC (on the ~ 15% level) due to different luminosity spectrum (threshold scan, invariant mass) and higher background (invariant mass)
- Expected systematic uncertainties are comparable to statistical errors:
  Top mass measurement on the 100 MeV level possible

Excellent Prospects...

... for precision measurements of the Top mass at CLIC...

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... but it is not quite child's play!