Top Mass Precision Measurements at Lepton Colliders

LCForum @ Terascale
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Frank Simon
MPI for Physics

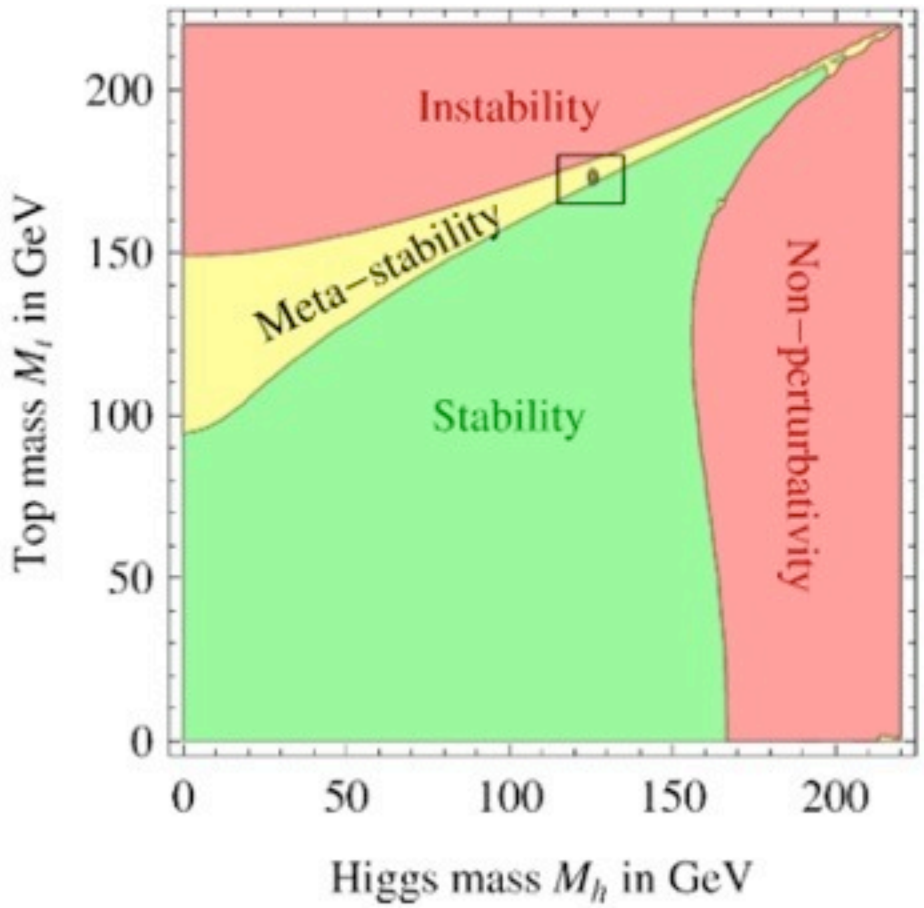
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

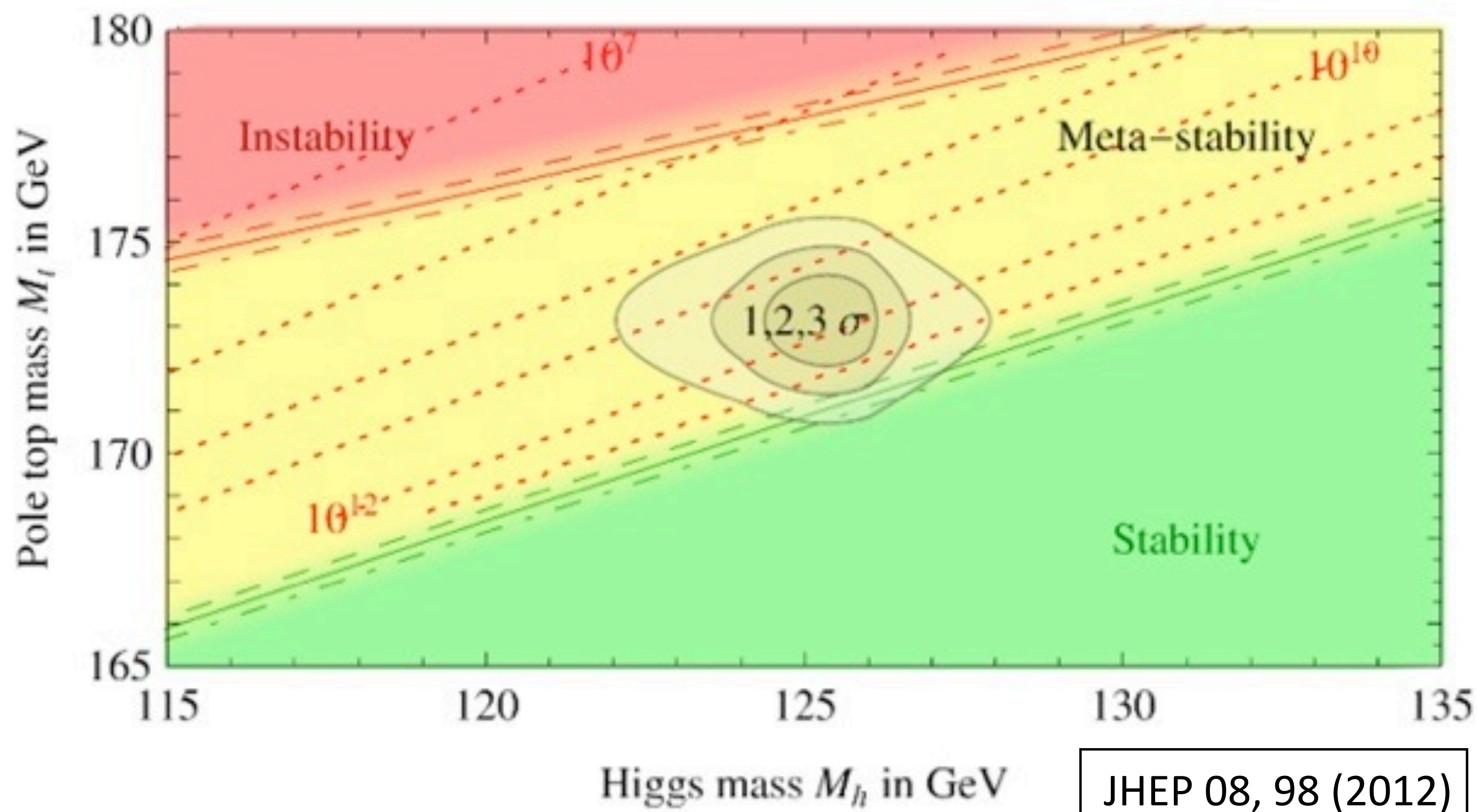
Outline

- Why should we care?
- 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

Based on work done for the **CLIC CDR** - Also valid for **ILC**
(with small, but overall insignificant modifications to the results)

Why should we care?





JHEP 08, 98 (2012)

- Top mass, together with Higgs mass and strong coupling, provides key information on the stability of the SM vacuum at higher scales
  - Possible validity of the SM up to the Planck scale?
  - Impact on evolution of the early universe (Higgs inflation models, ...) & physics beyond the SM

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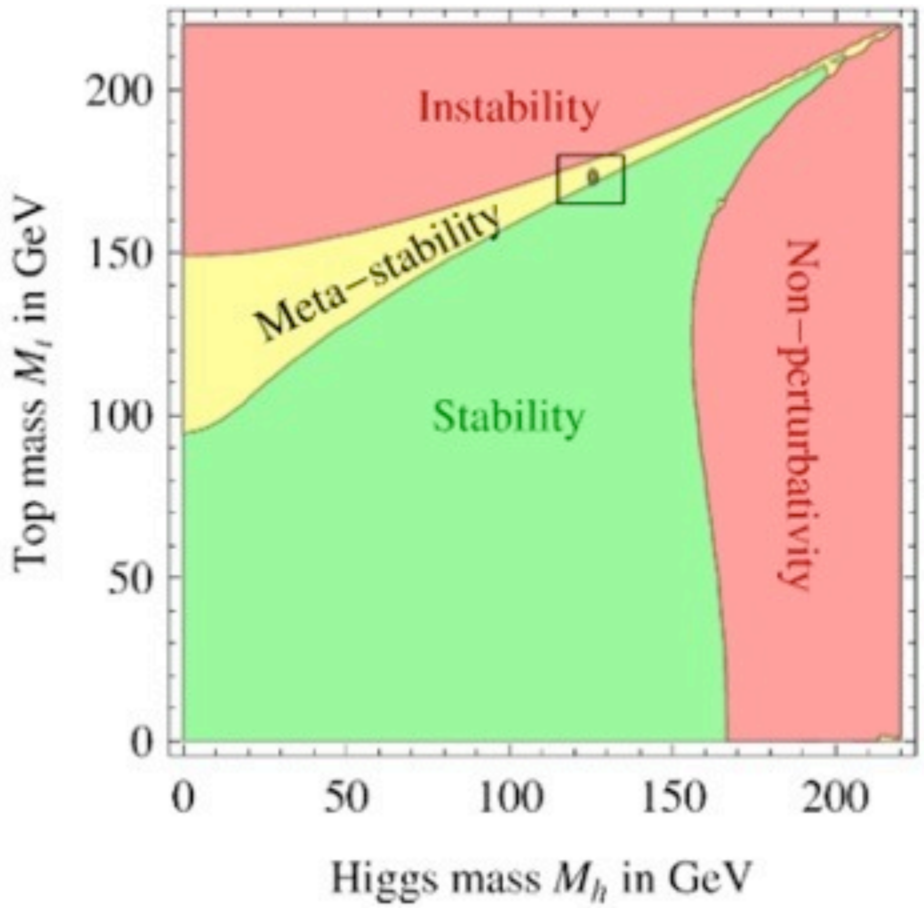

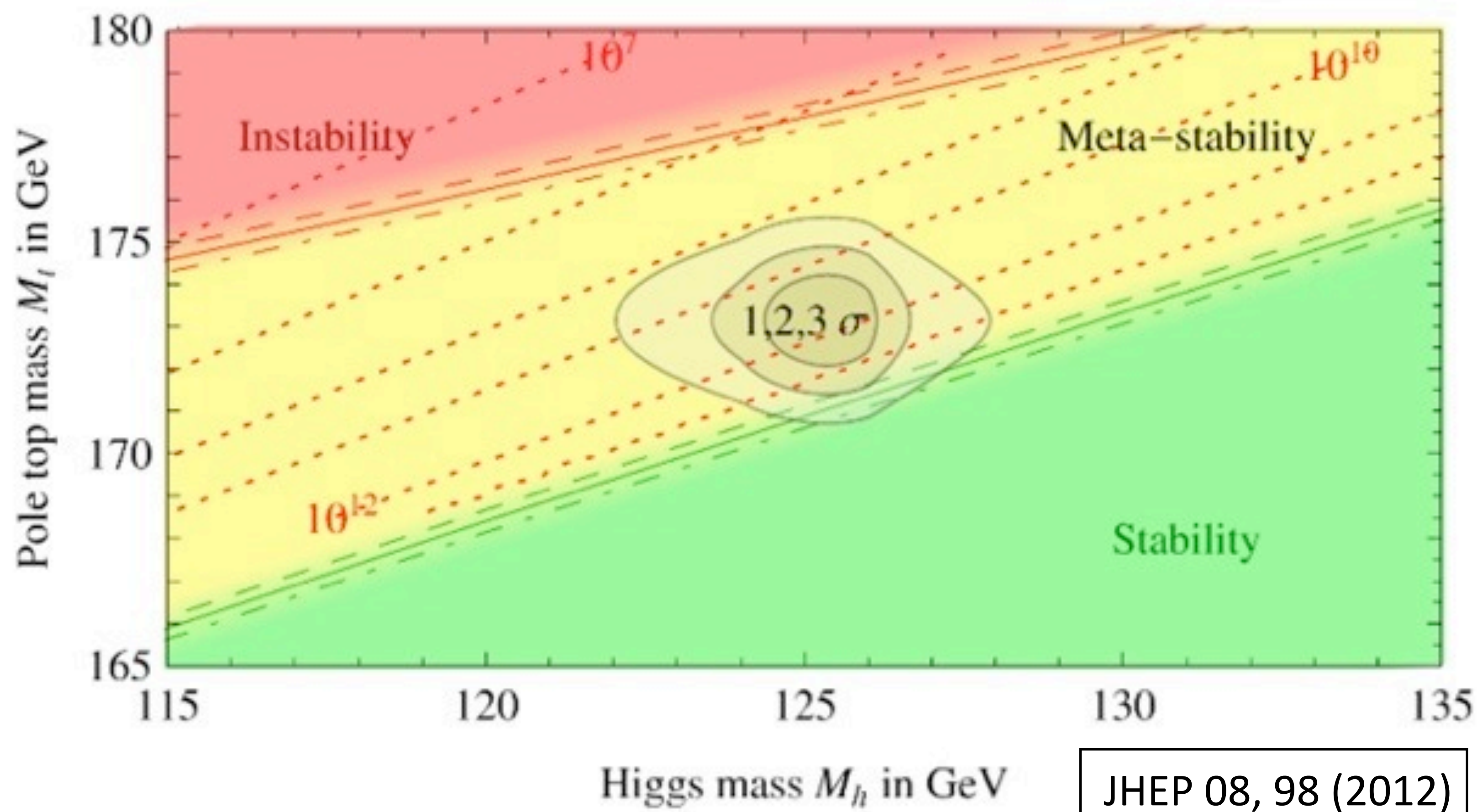

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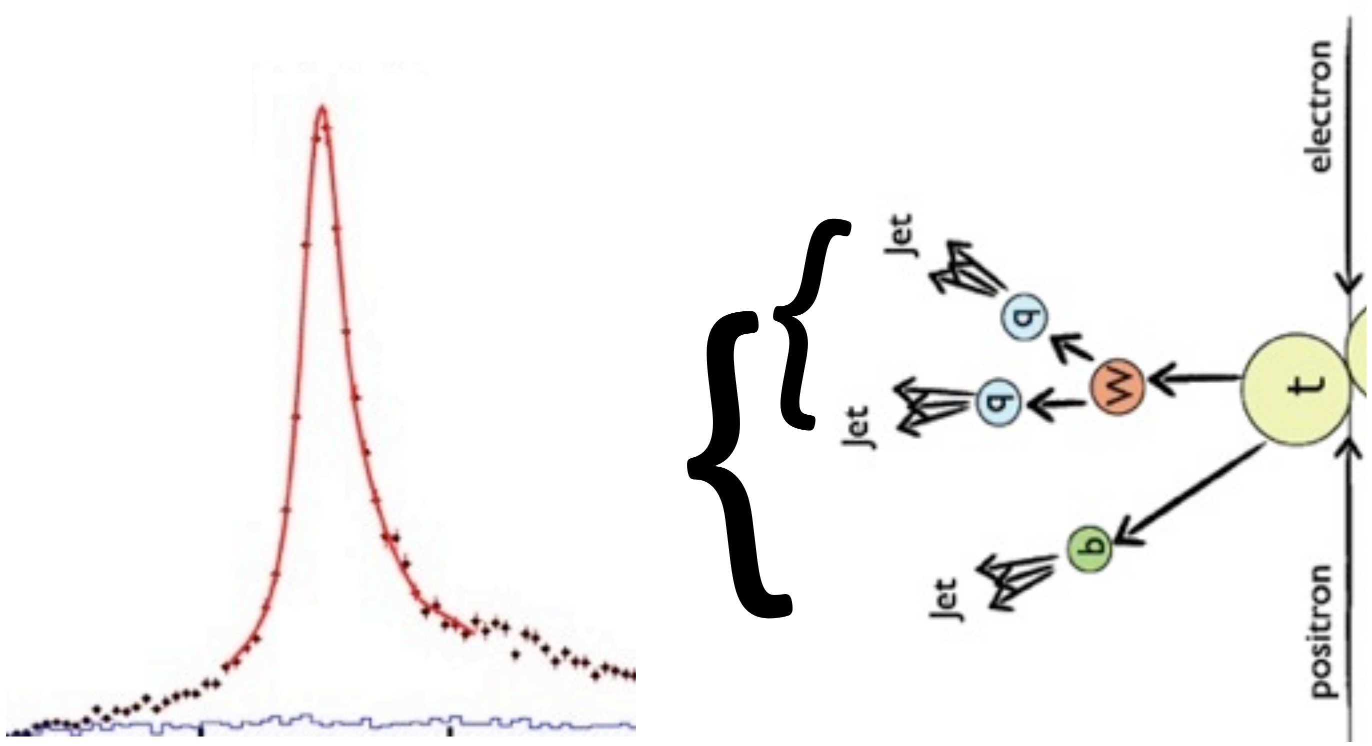
Leading uncertainty: Top Mass! ➩ A case for beyond-LHC precision

What are we measuring?

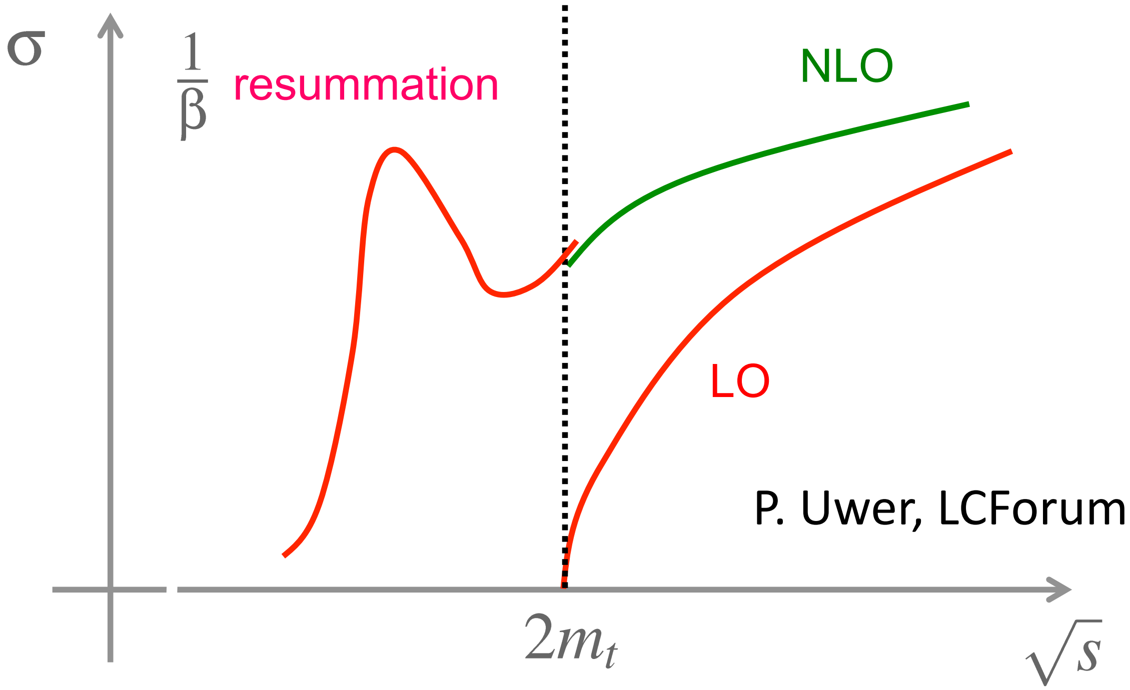
- Experimentally, masses of unstable particles are usually measured through the invariant mass of the decay products
- This is not what is used in theory!
- Several mass definitions exist for the top quark (1s, msbar, pole...) that are theoretically well defined, conversion possible (sometimes with uncertainties 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

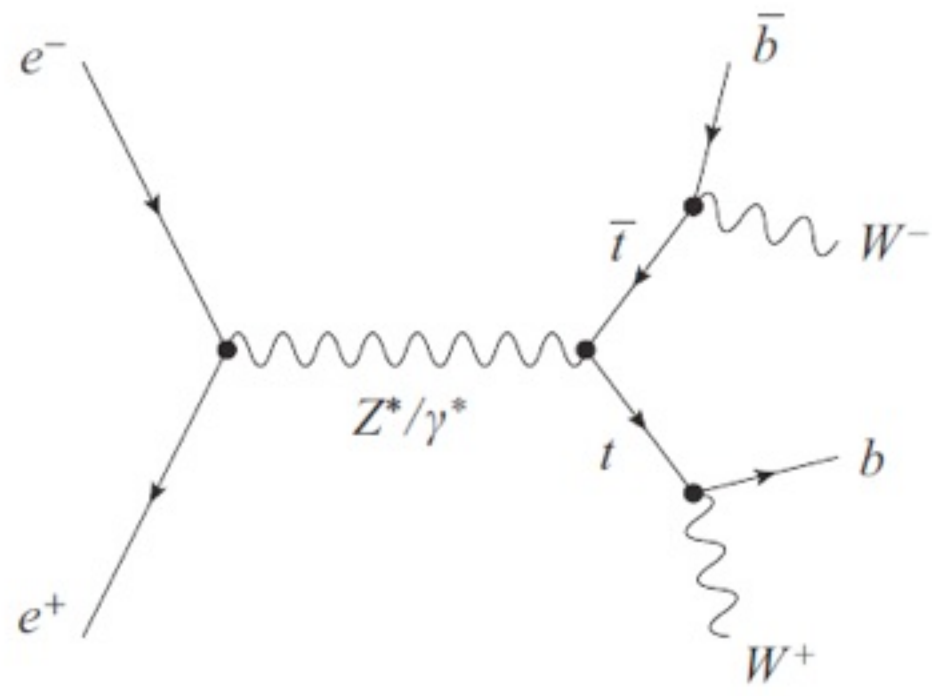
The Top Program at a Linear Collier

- 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

Can be done at a 500 GeV machine (which can be operated also at 350 GeV), or in an early ILC / CLIC stage with 350 GeV (flexibility down to 250 GeV for Higgs studies)

Reconstructing Top Quarks at Lepton Colliders

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



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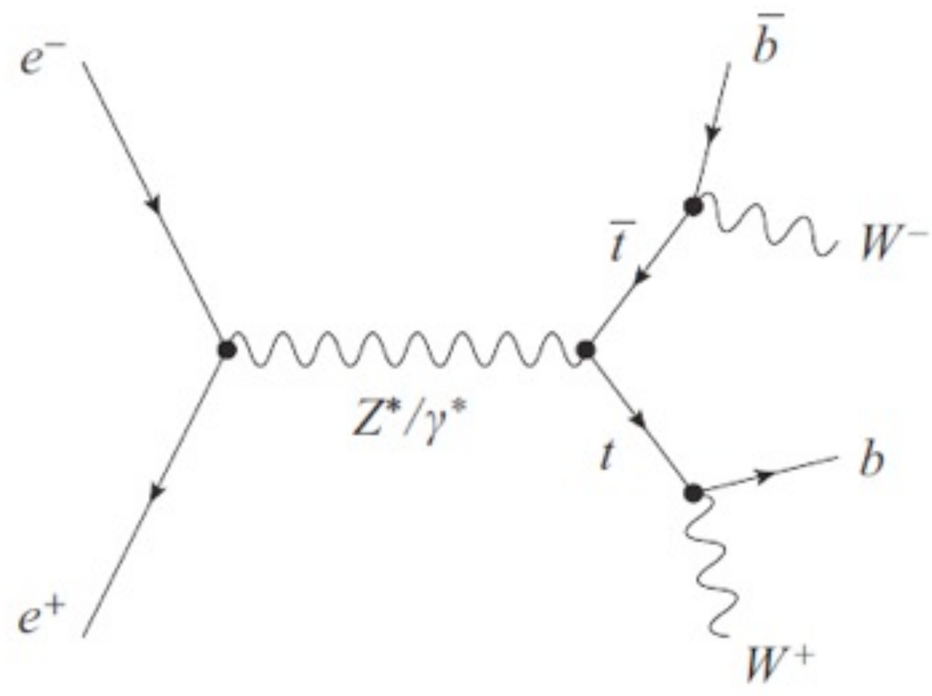
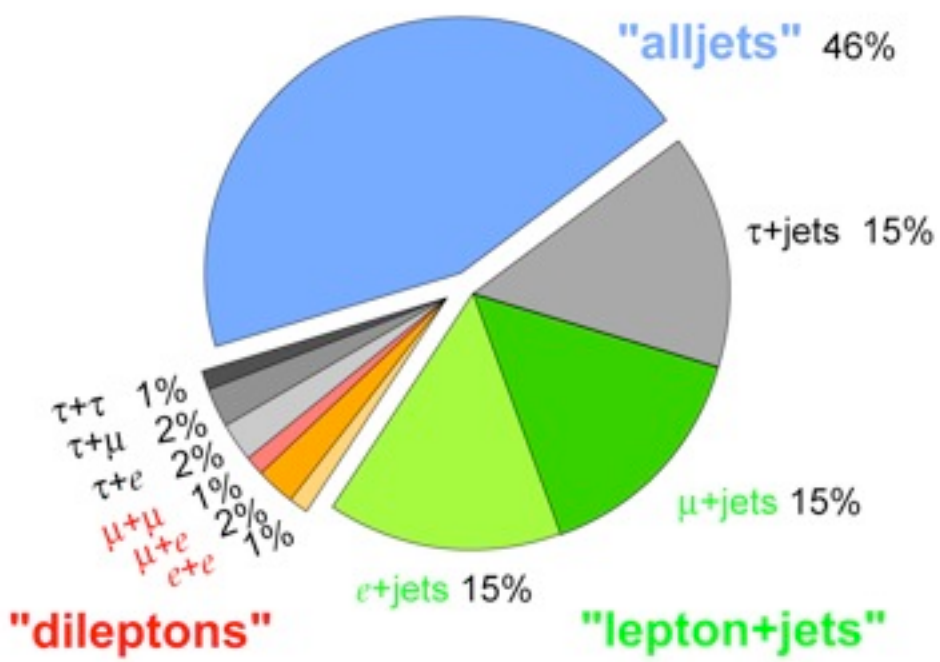


Event signature entirely given by the decay of the W bosons:



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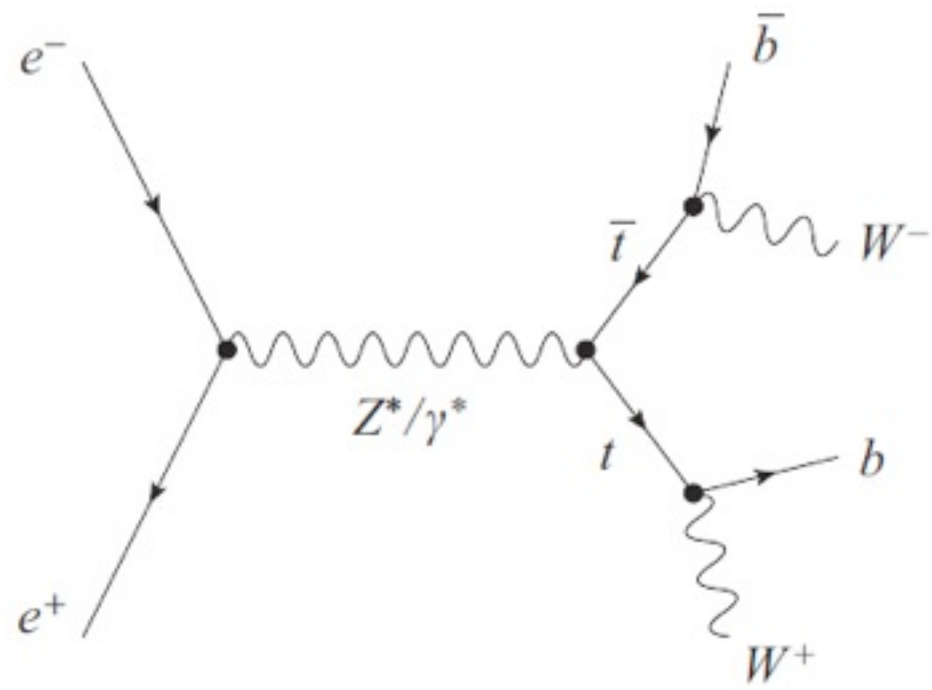

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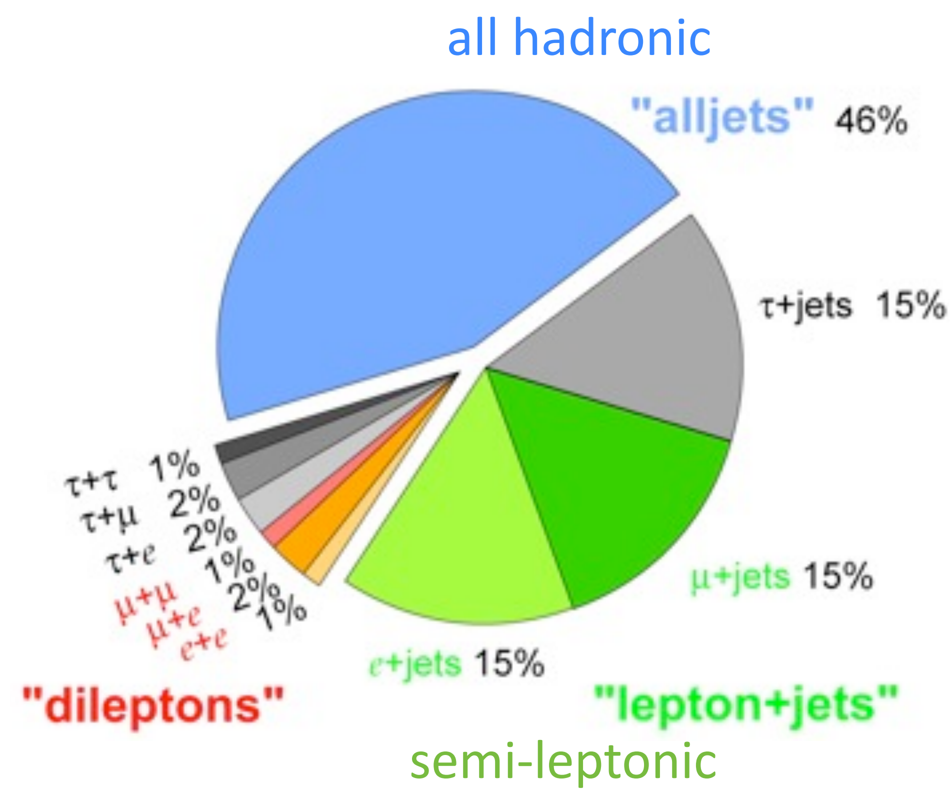
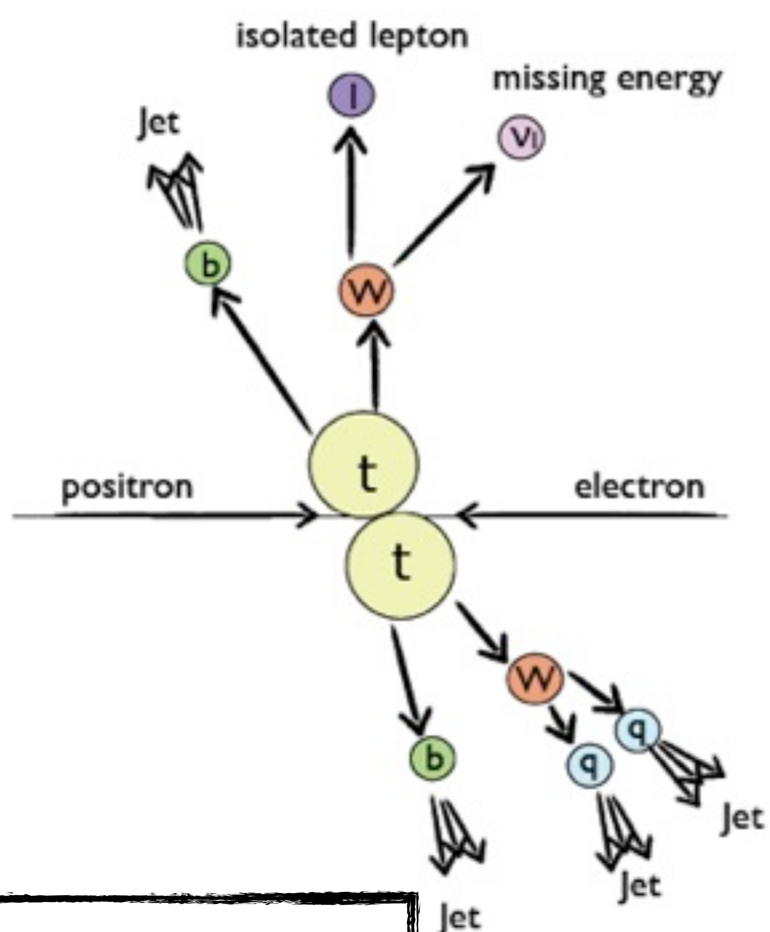


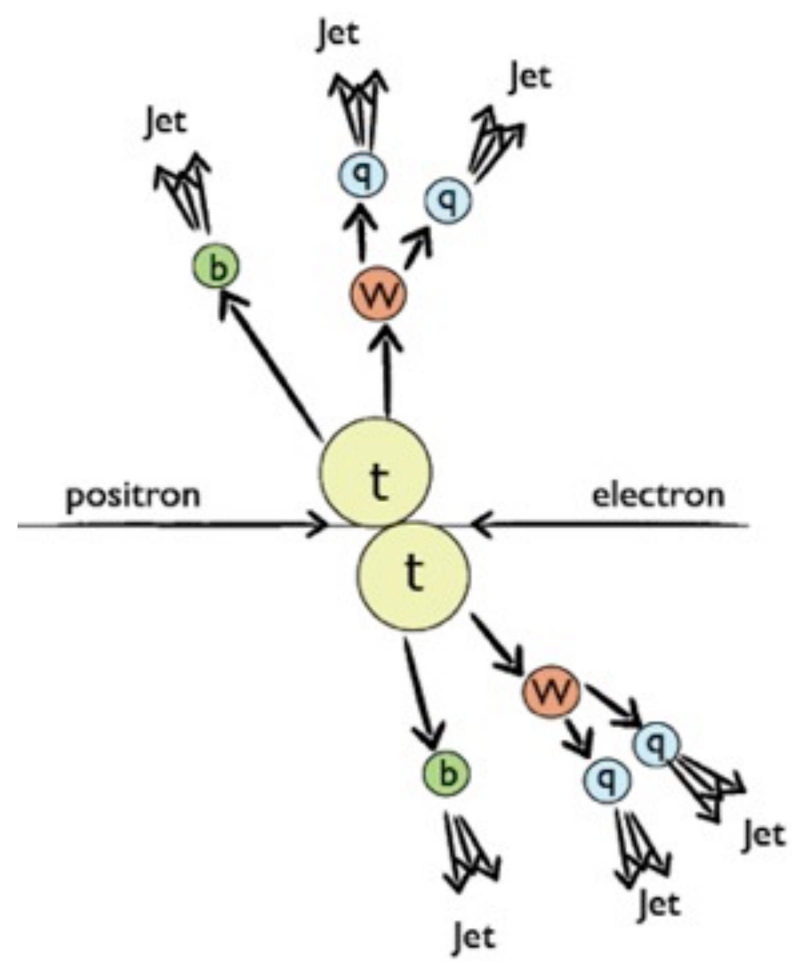
- At hadron colliders: Hard to pick out top pairs from QCD background - Use one and two-lepton final states
- At lepton colliders: Top pairs easy to identify, concentrate on large branching fractions and controllable missing energy (not more than one neutrino!)

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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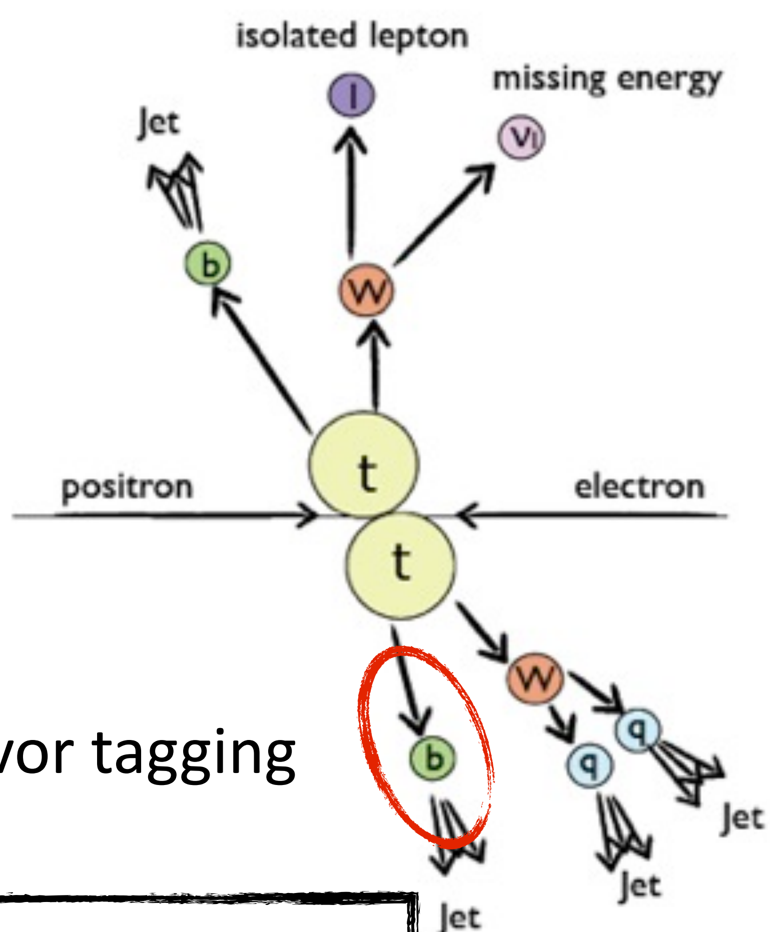

flavor tagging

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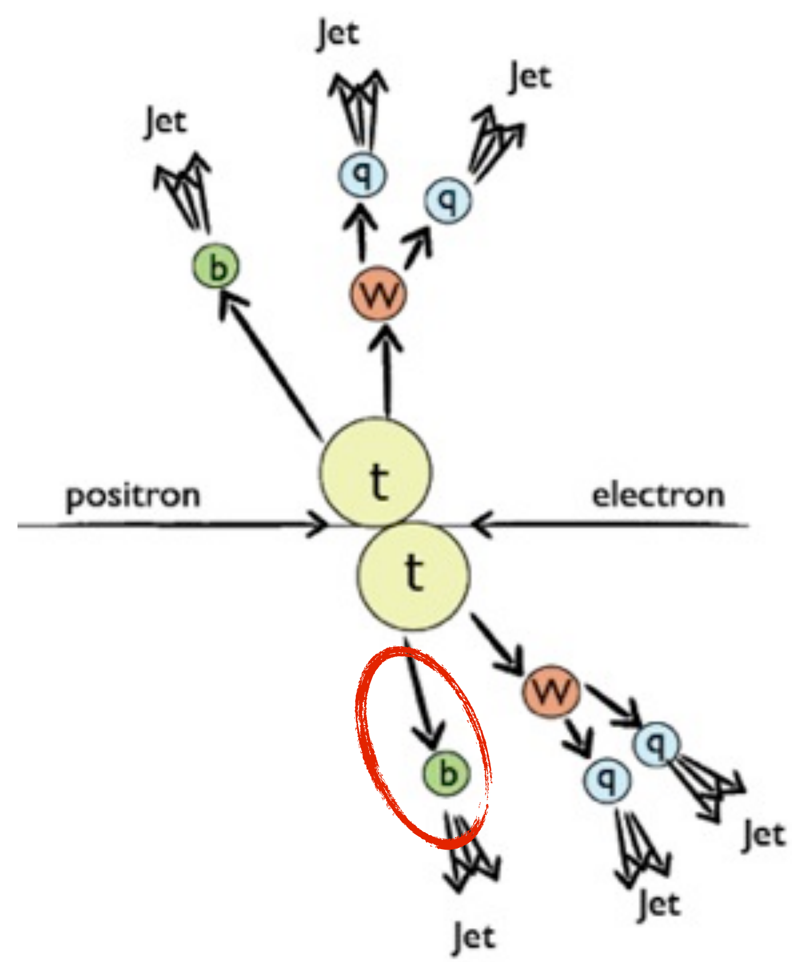

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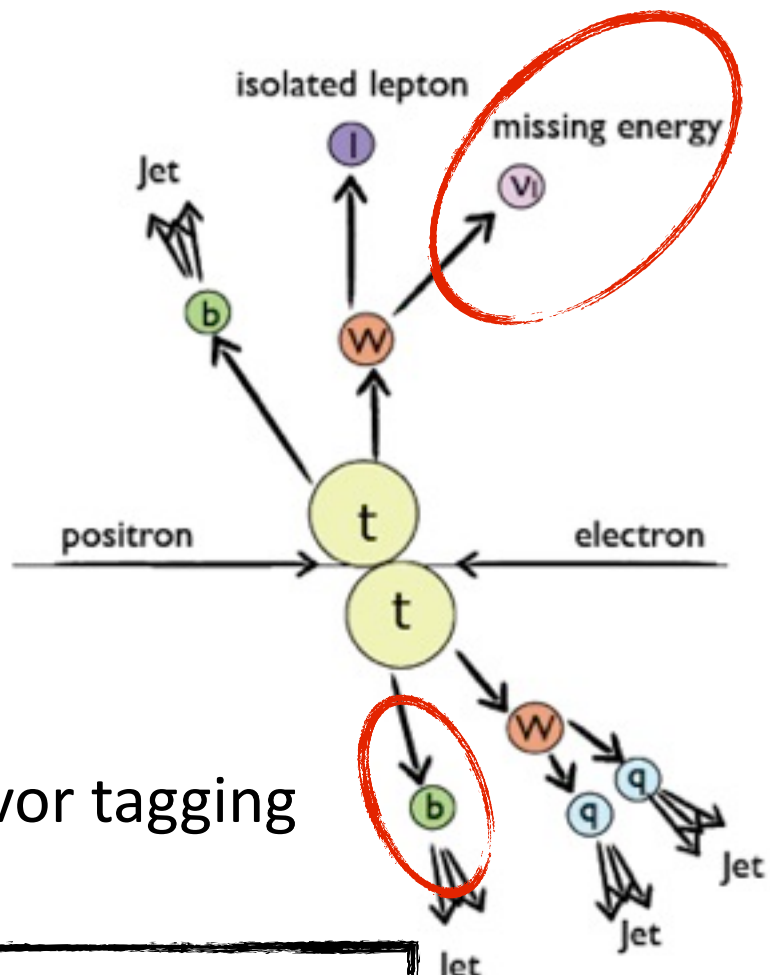

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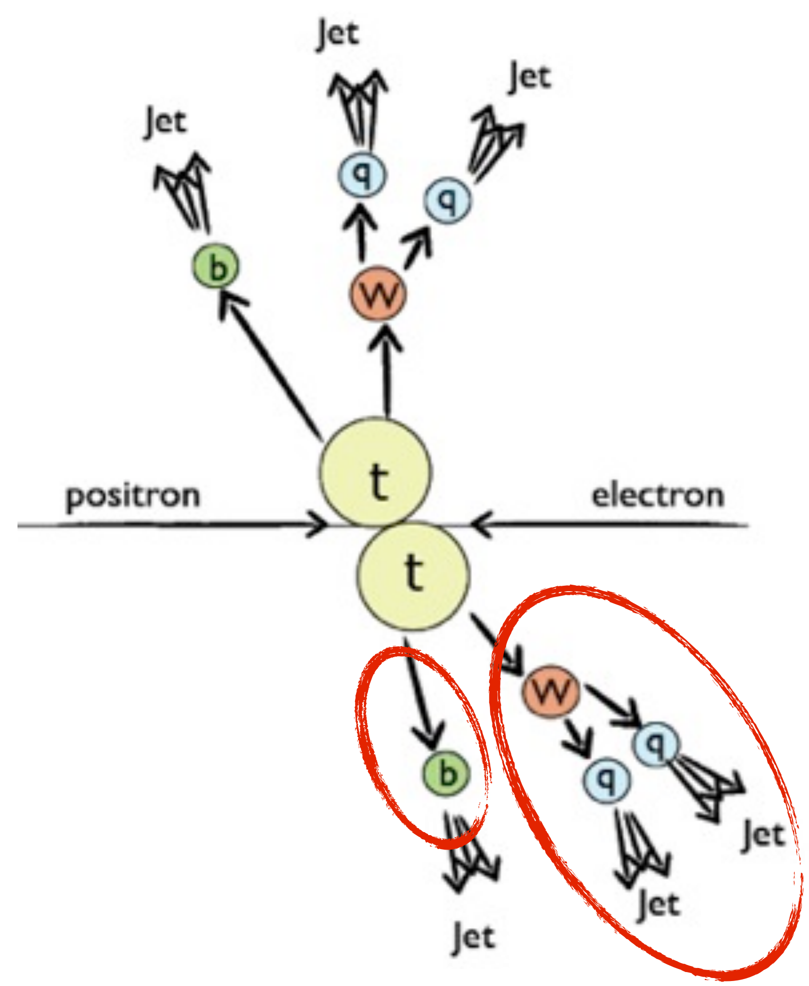

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jet energy reconstruction, global event reconstruction

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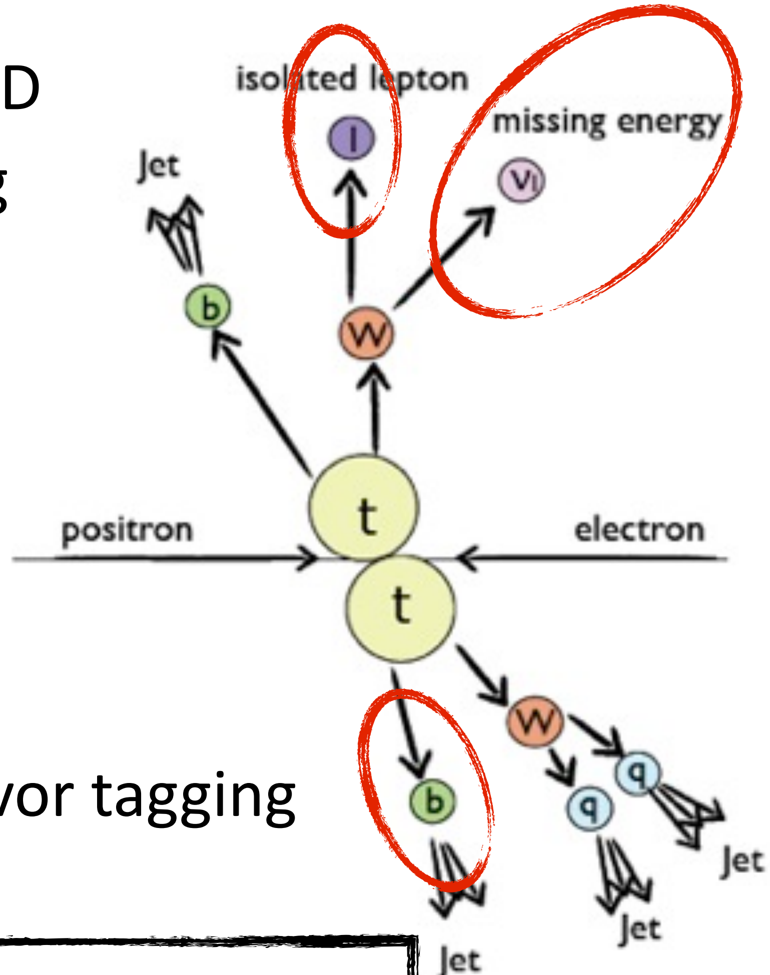
tracking



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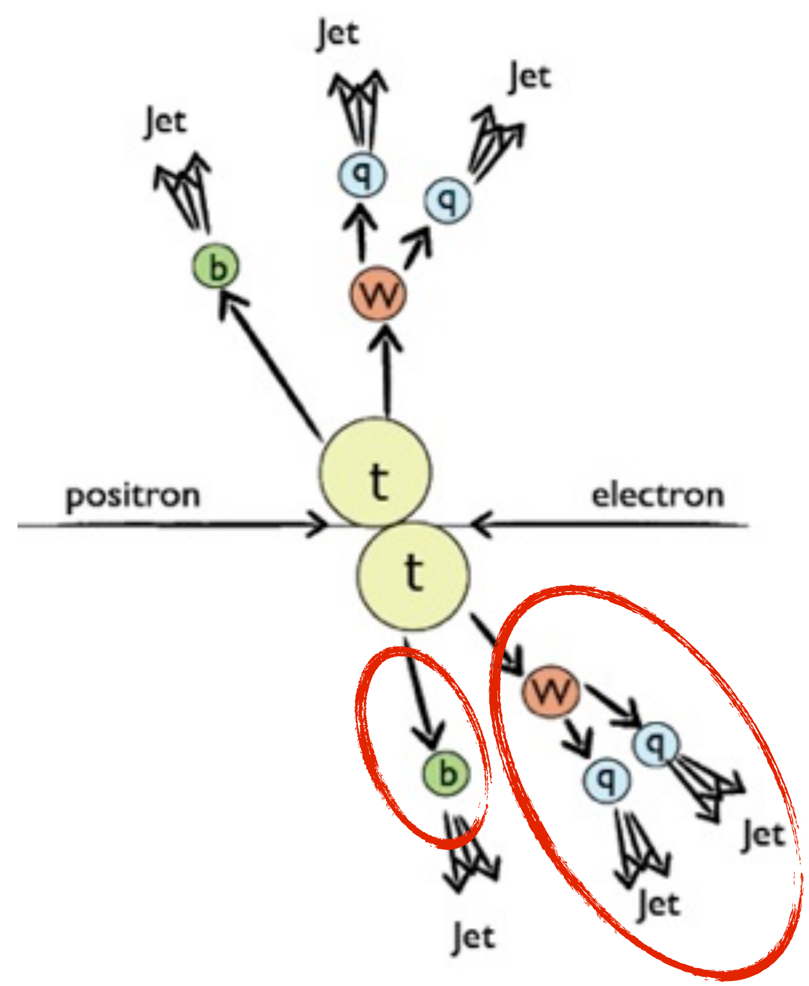

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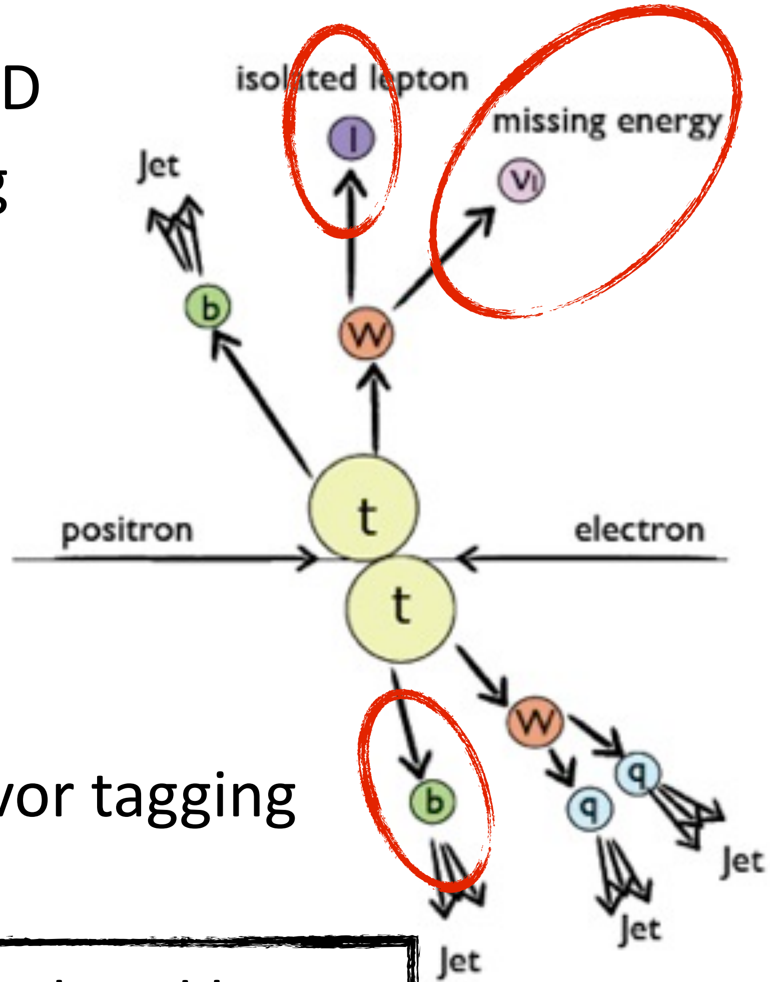

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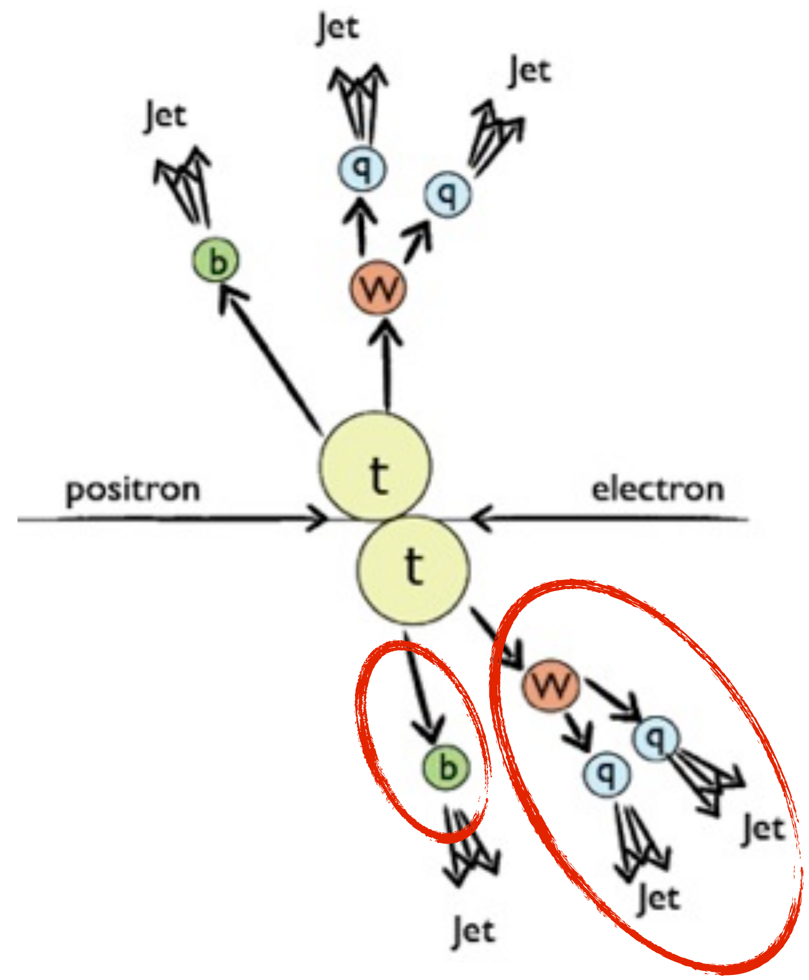

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jet energy reconstruction, global event reconstruction

Uses all aspects of Linear Collider detectors!

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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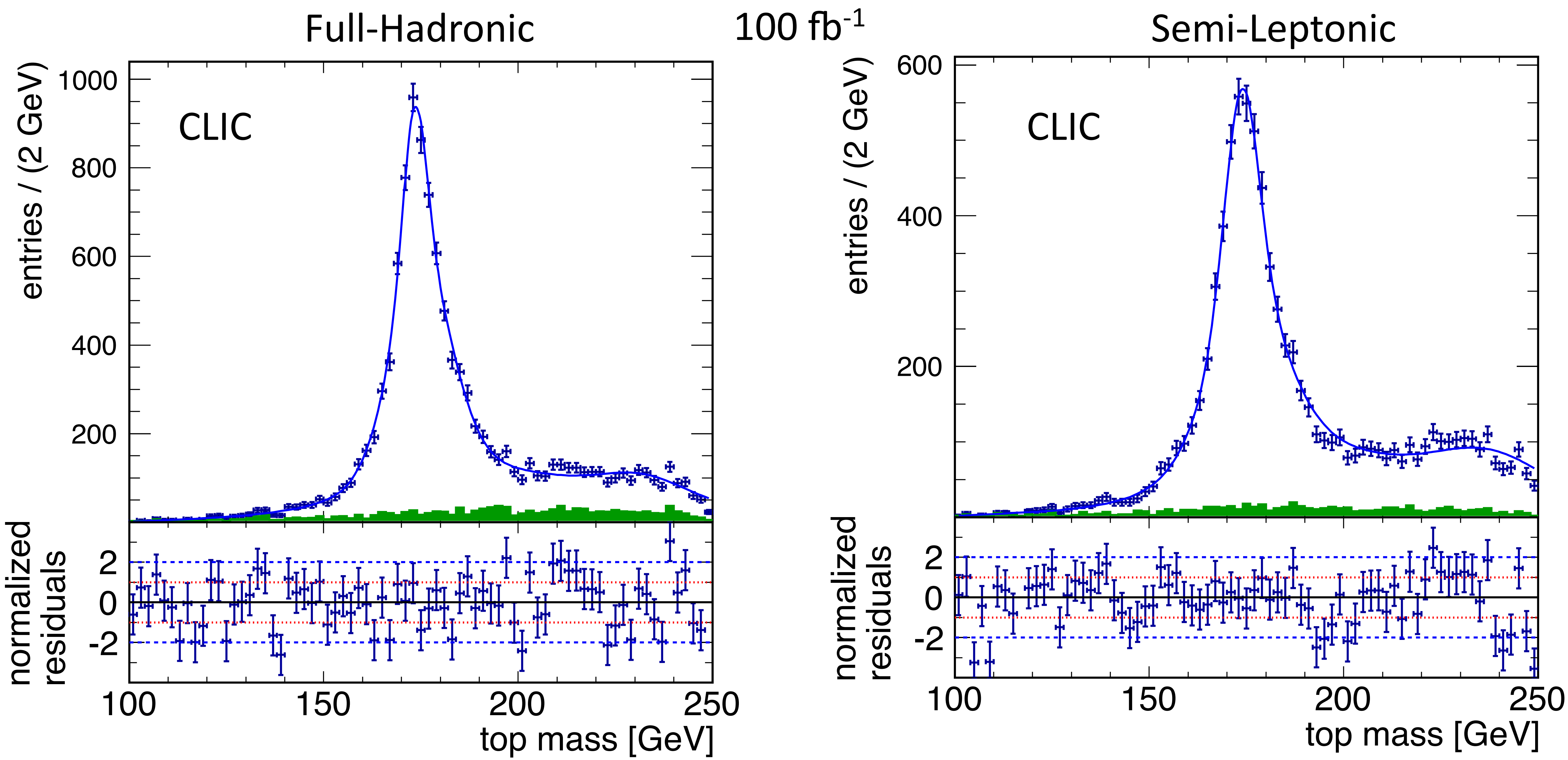
  - Detectors optimized for precision: Improved jet energy resolution
- The strategy:
  - Group all events (signal and background) in top candidates:
    - all-hadronic: No isolated lepton, event is clustered into six jets
    - semi-leptonic: One isolated lepton, neutrino from missing energy, event is 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

Measuring the Mass- CLIC CDR

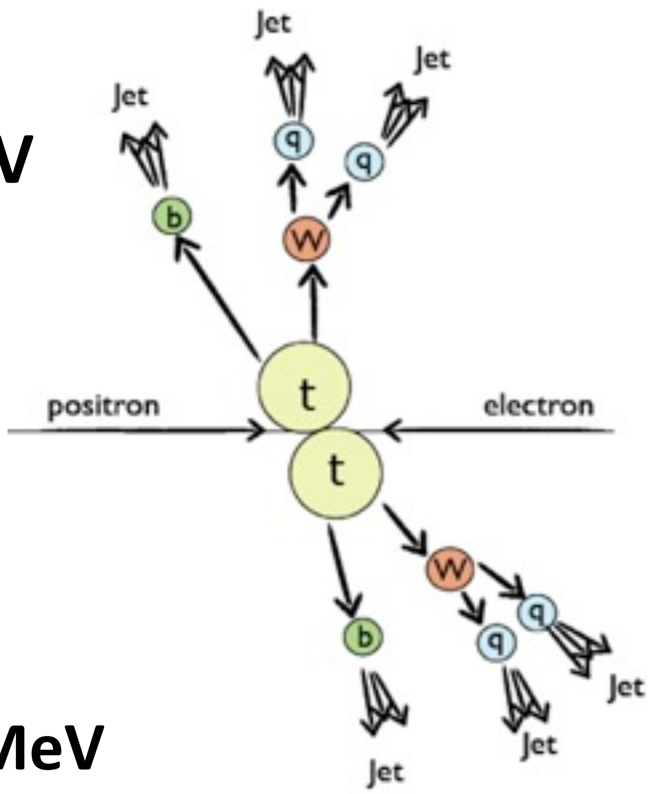
Un-binned maximum likelihood fit over full range

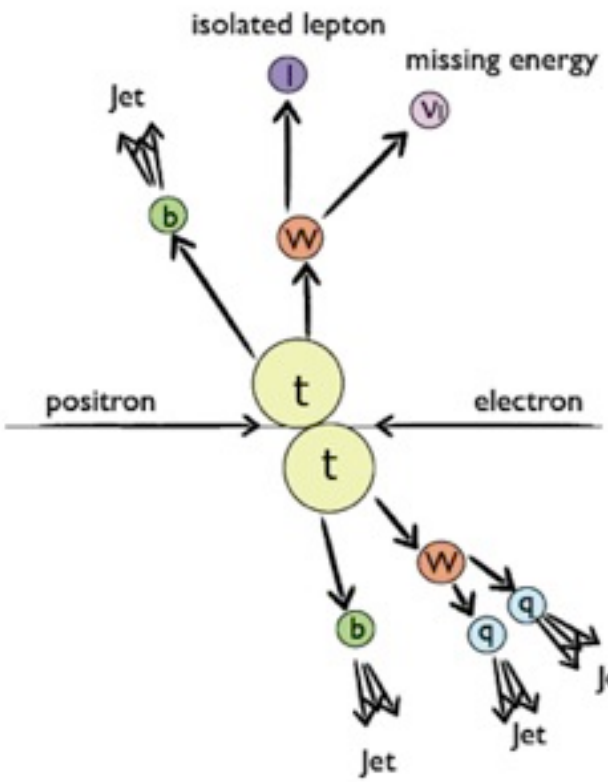
- Combination of signal and background pdf
- Signal pdf is a convolution of a Breit-Wigner and a detector resolution function



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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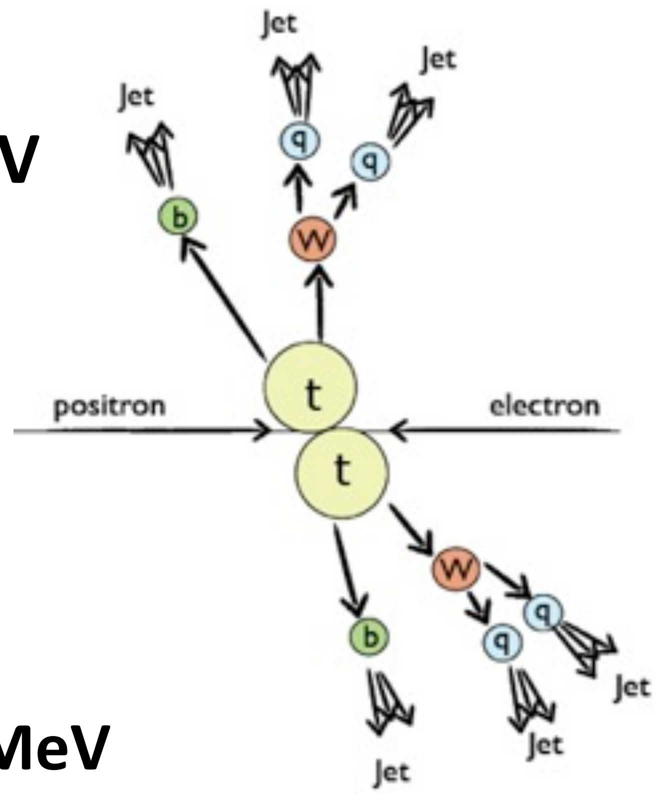

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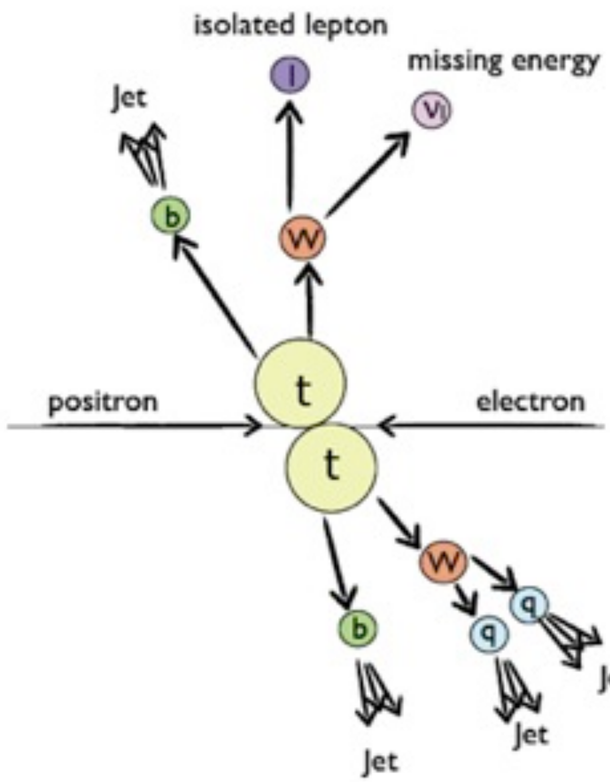
Study of systematic errors due to Jet Energy Scale (all-hadronic):

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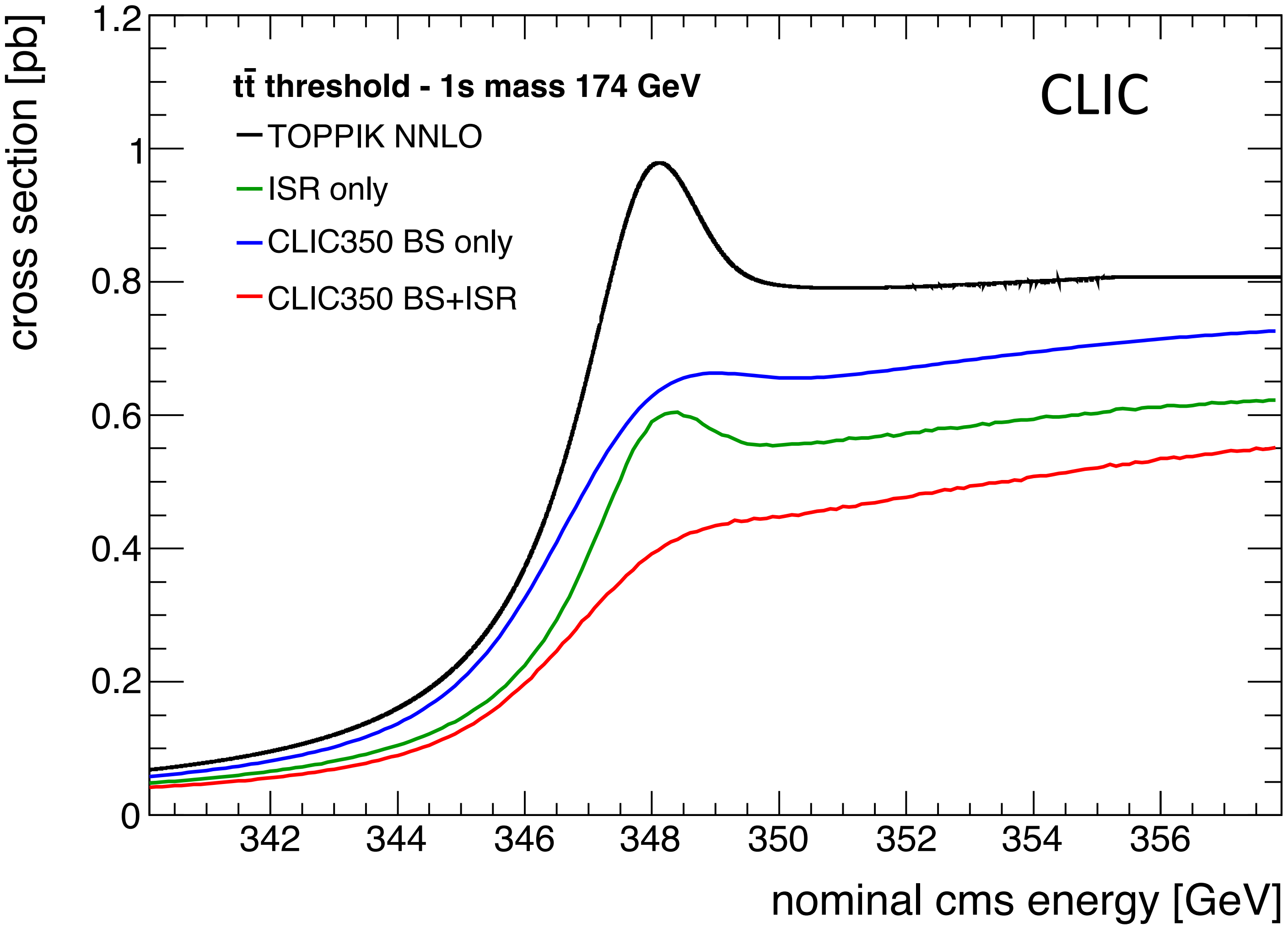
- Simulation Studies: No public event generator for the top threshold exist - PYTHIA for example is LO, with hadronization, does not get threshold right
- Use full NNLO theory calculations to determine cross section as a function of energy (for example TOPPIK, Hoang and Teubner, PRD 60, 114027 (1999))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

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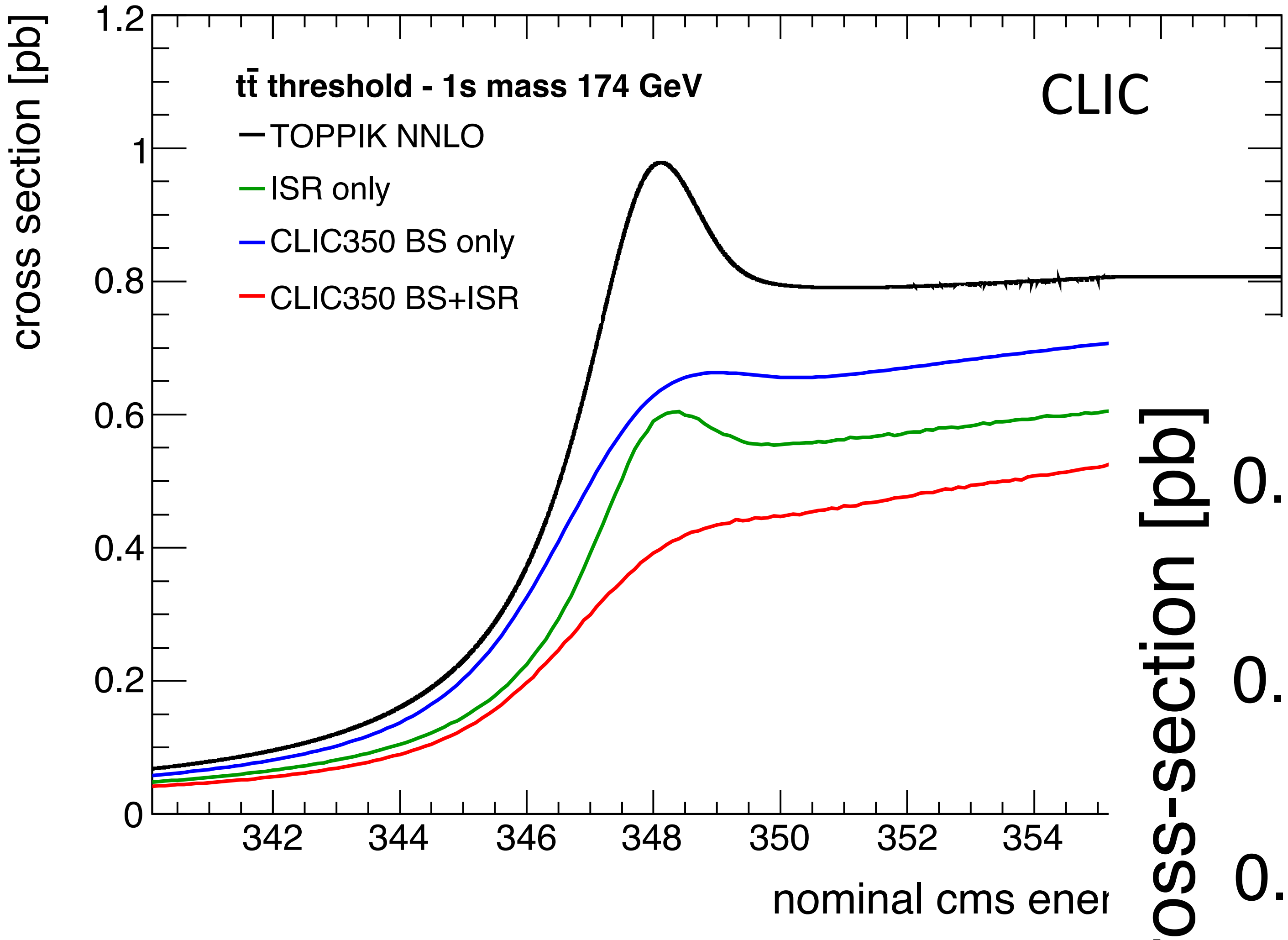

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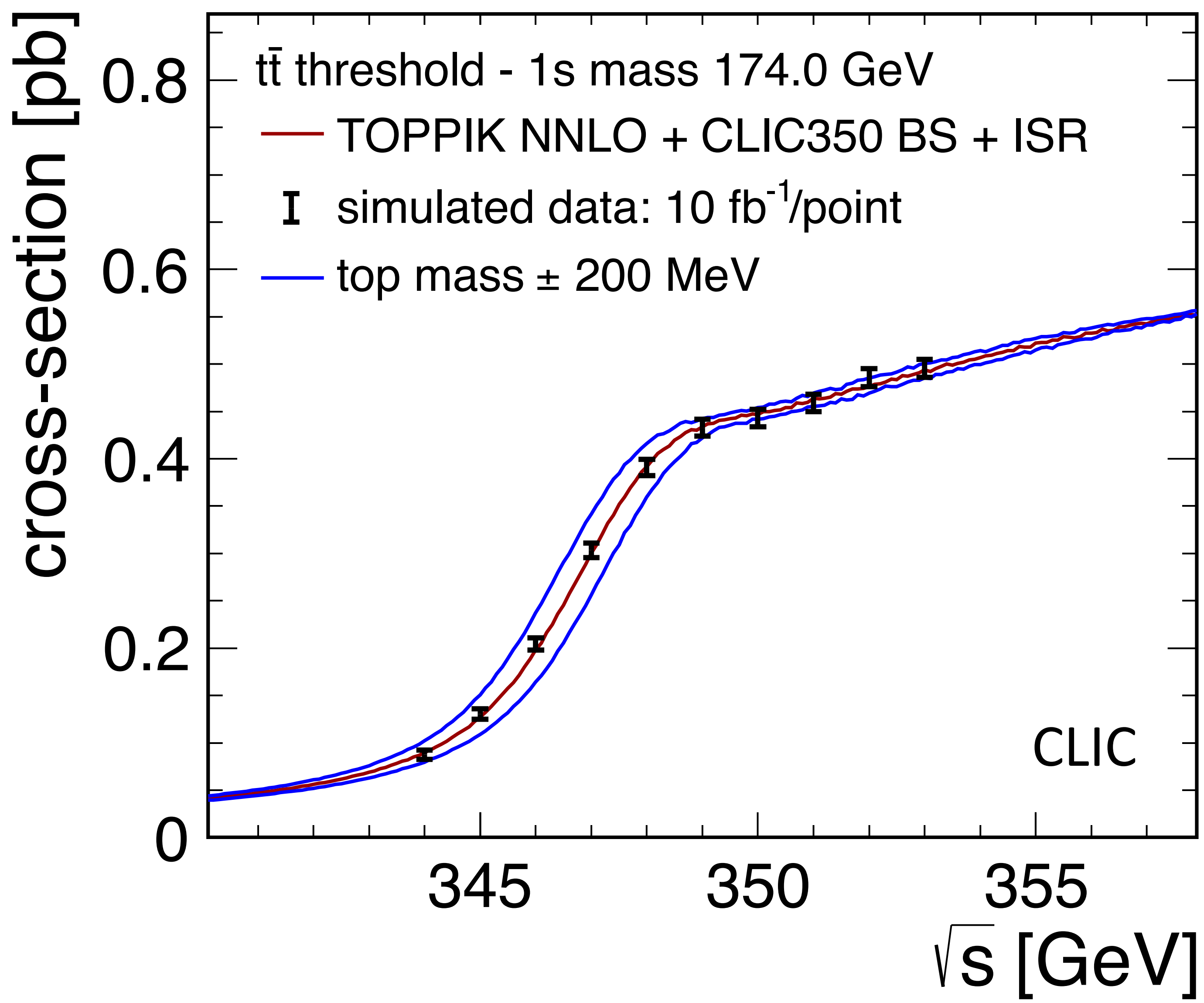
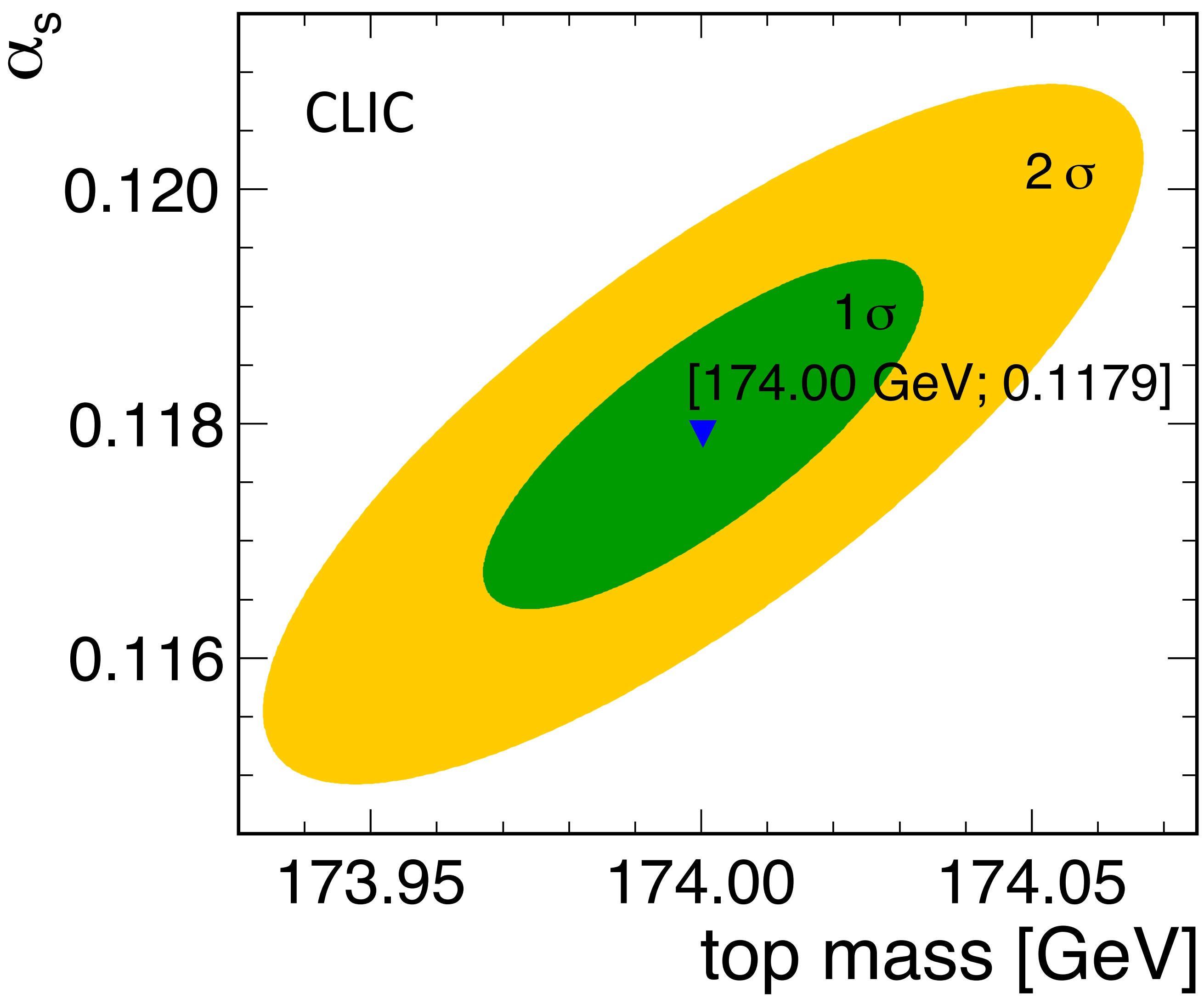


- Data points simulated assuming 10 fb^{-1} per point, 1 GeV spacing between points

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



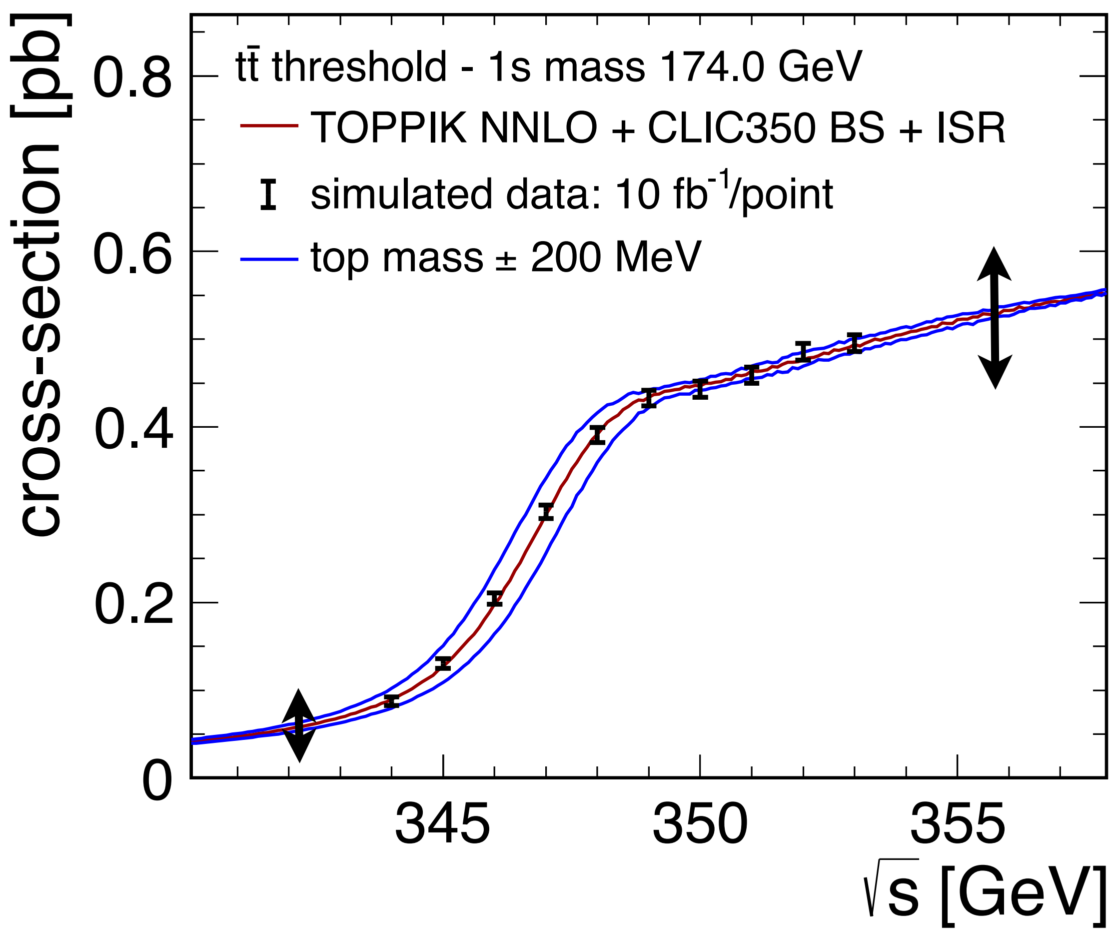
strong correlation of m_t and α_s :
Can be determined simultaneously

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:



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    5 MeV / 8 MeV on mass

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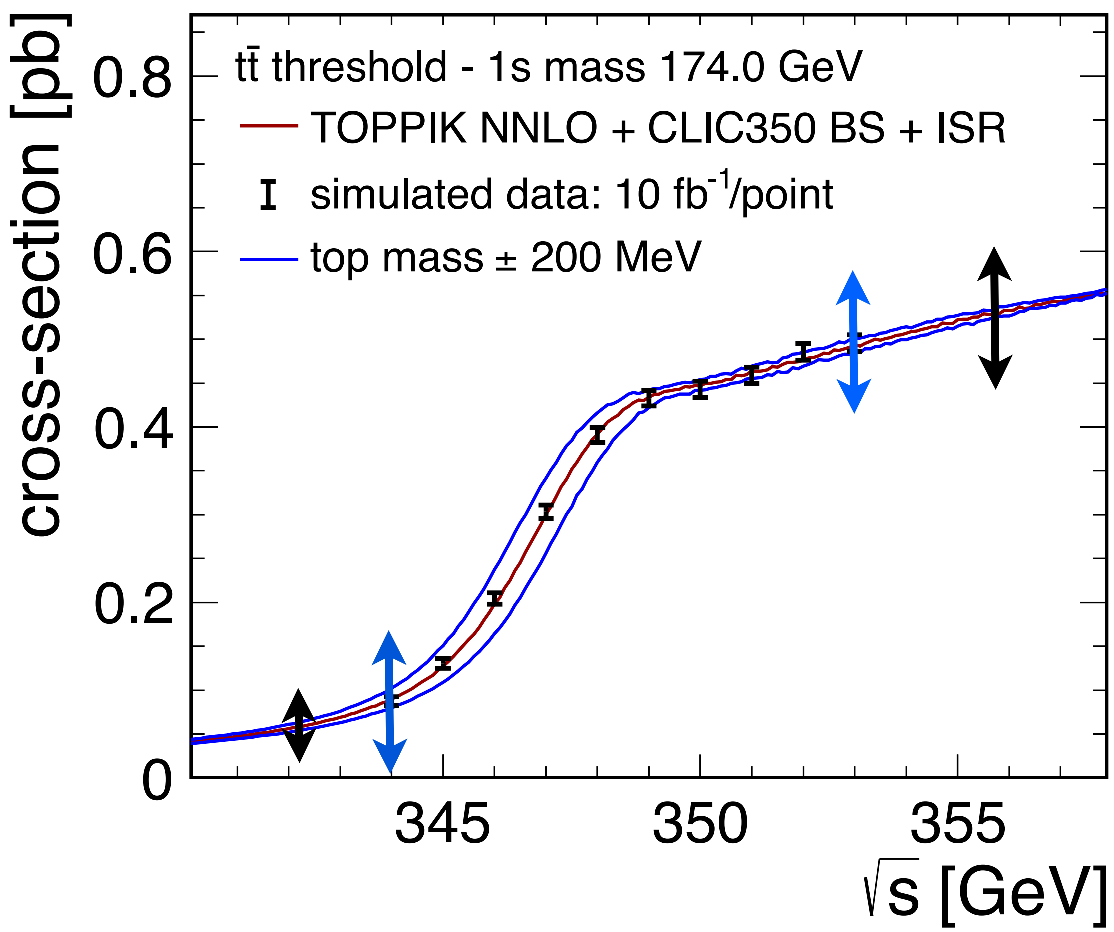

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  - Background normalization: Change of subtracted background by +- 5%
    18 MeV on mass
    0.0007 on α_s

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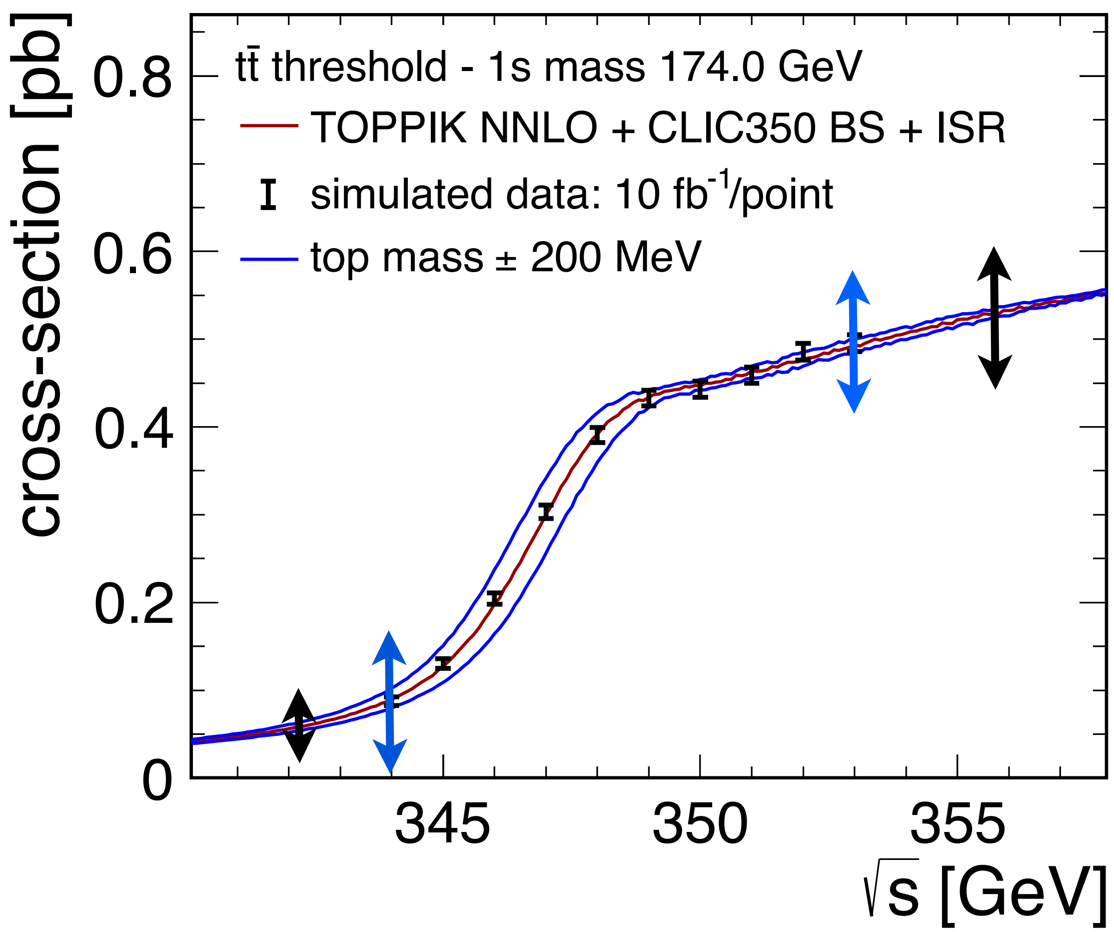

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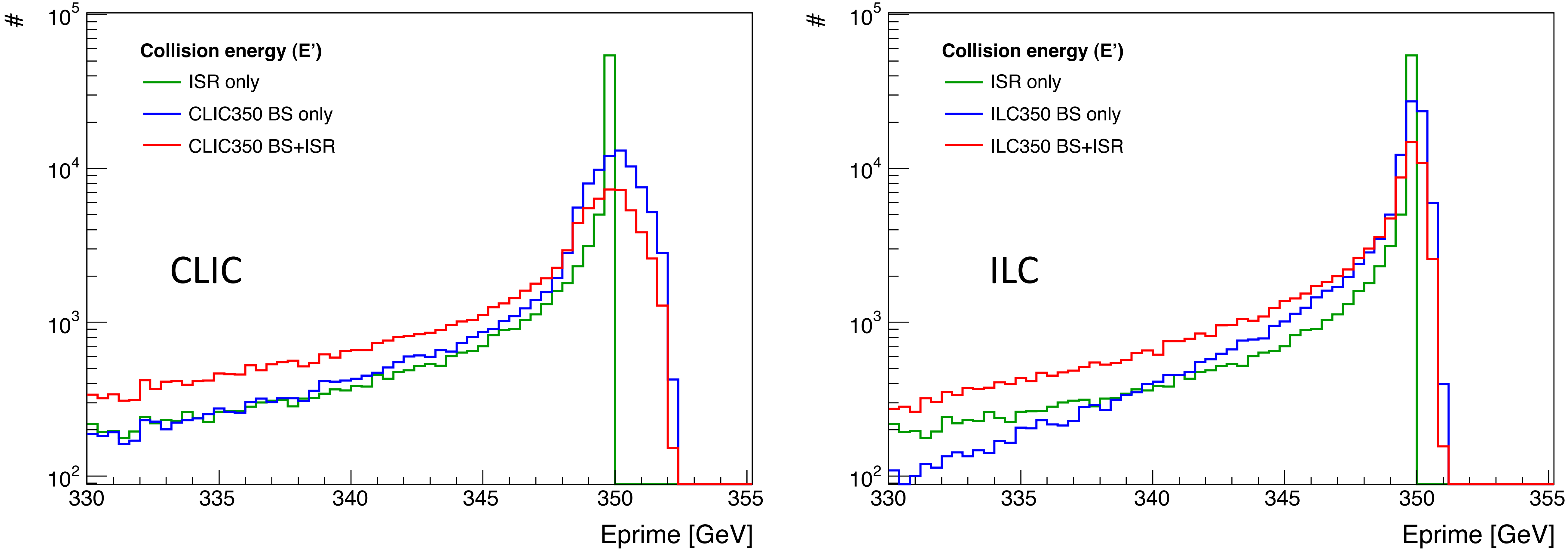
    18 MeV on mass
    0.0007 on α_s

- 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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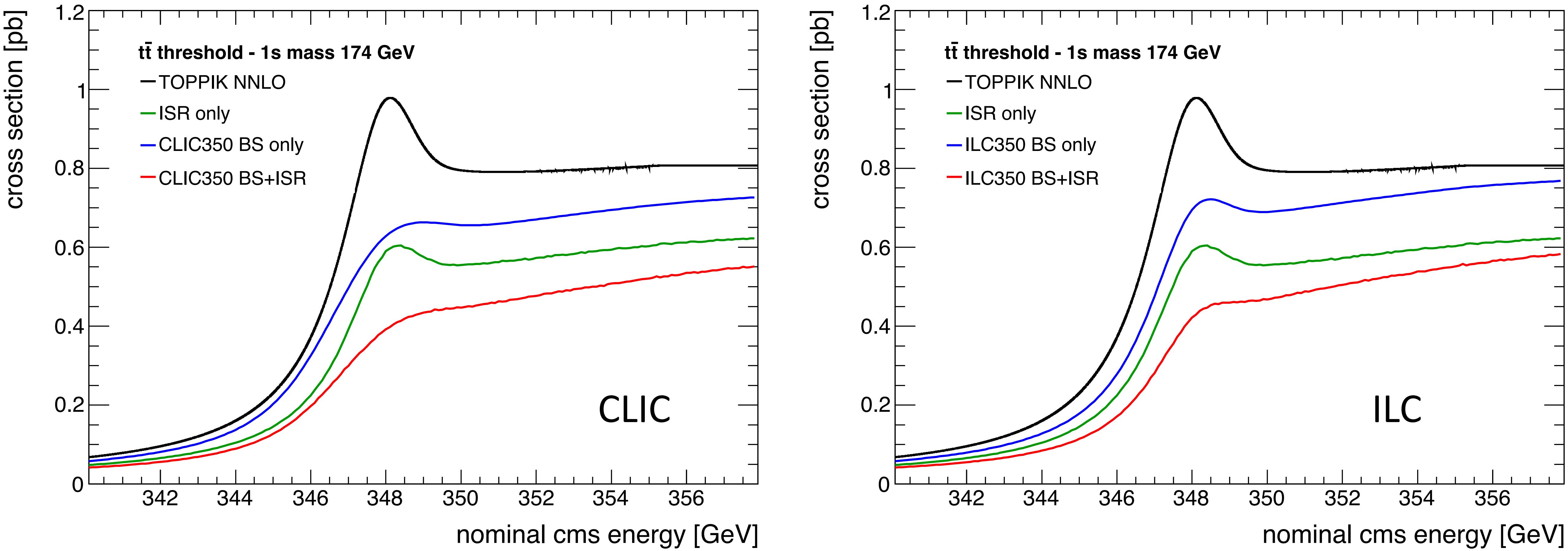
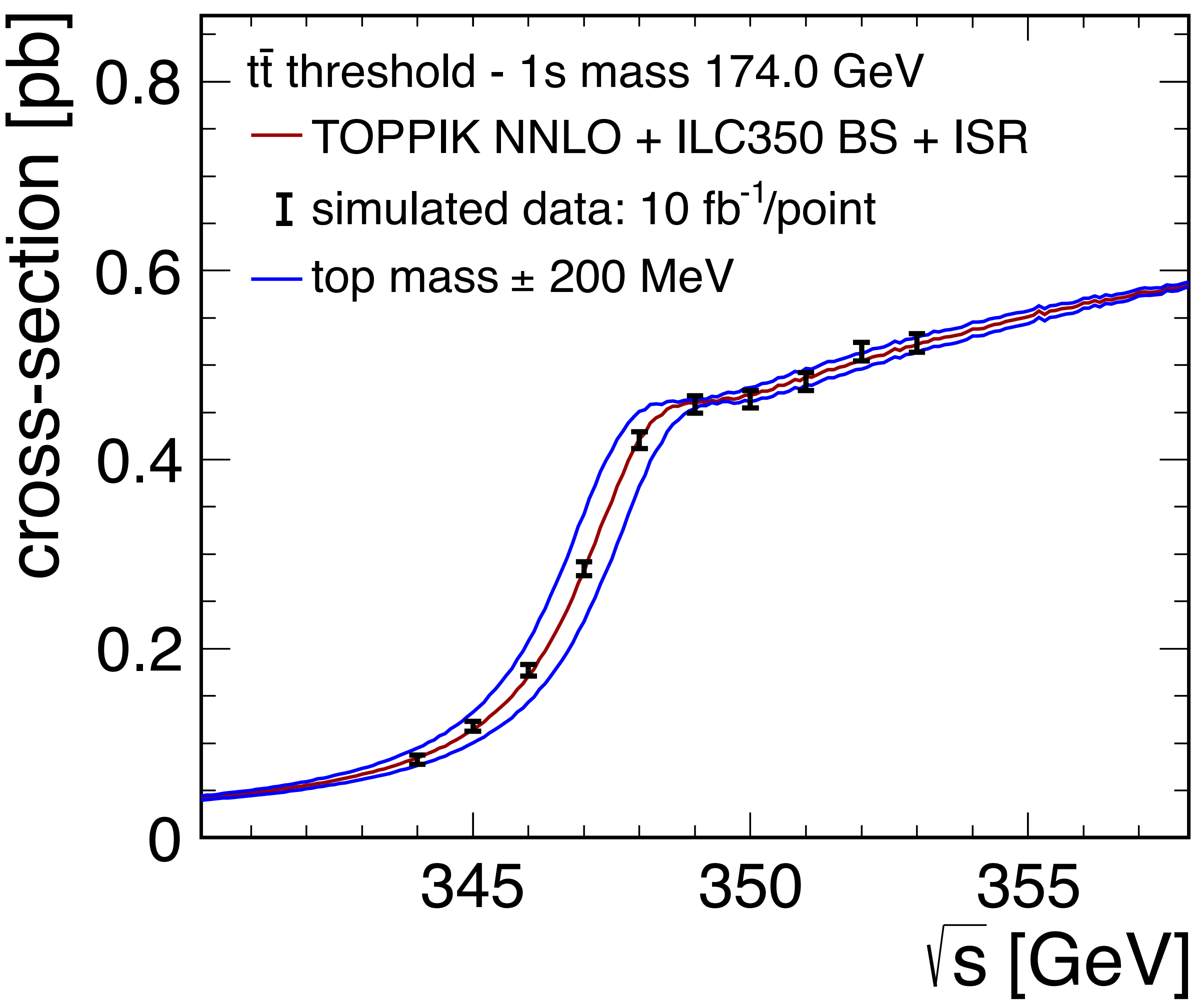
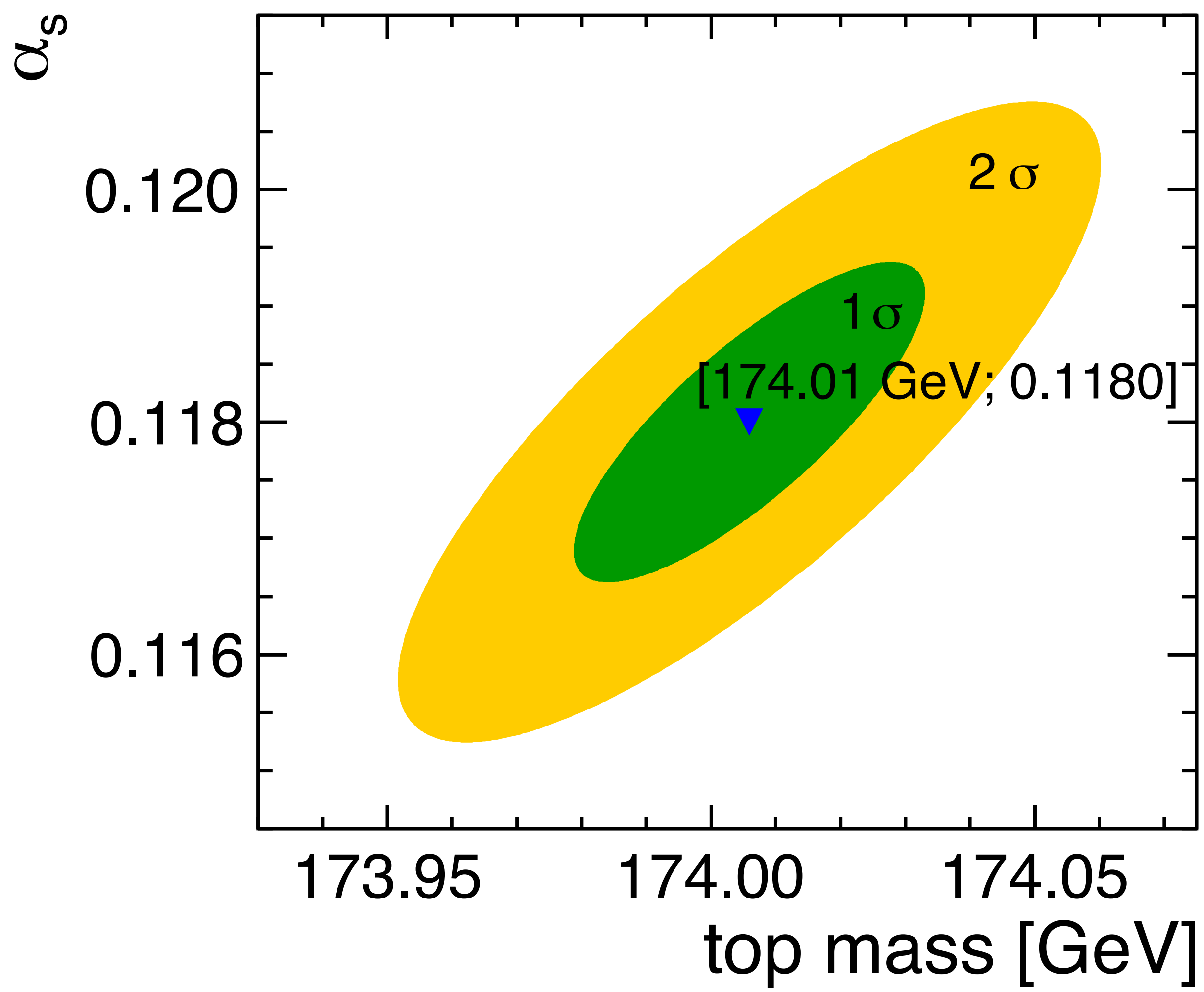


- The difference results in a slightly steeper rise of the cross section at threshold for the case of ILC

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 statistical resolution for CLIC than for ILC (on the ~ 15% level) due to different luminosity spectrum (threshold scan, invariant mass) and higher background (invariant mass)
    - Negligible compared to systematics - Precision independent of machine choice!
- 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 Linear Colliders...

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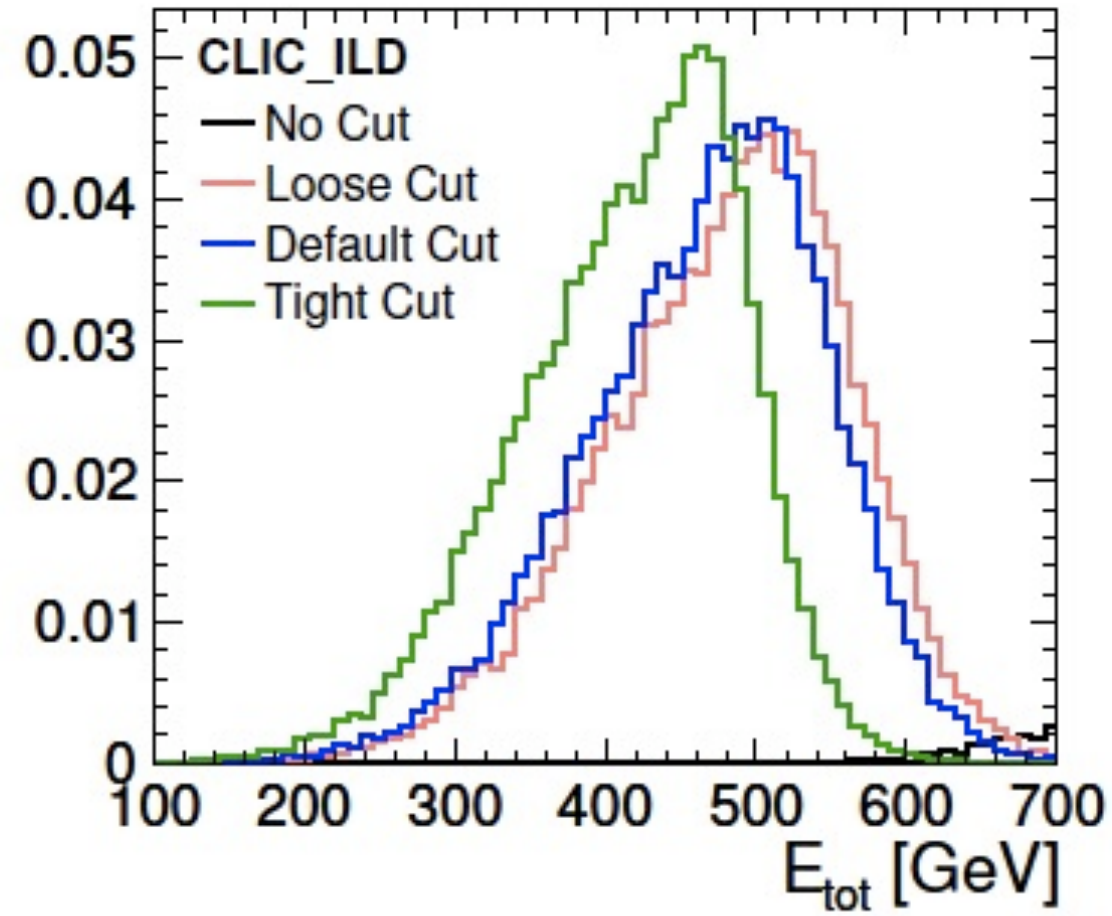
of the Top mass at Linear Colliders...

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

Backup

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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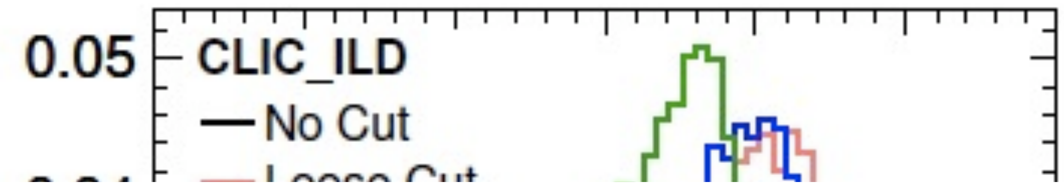

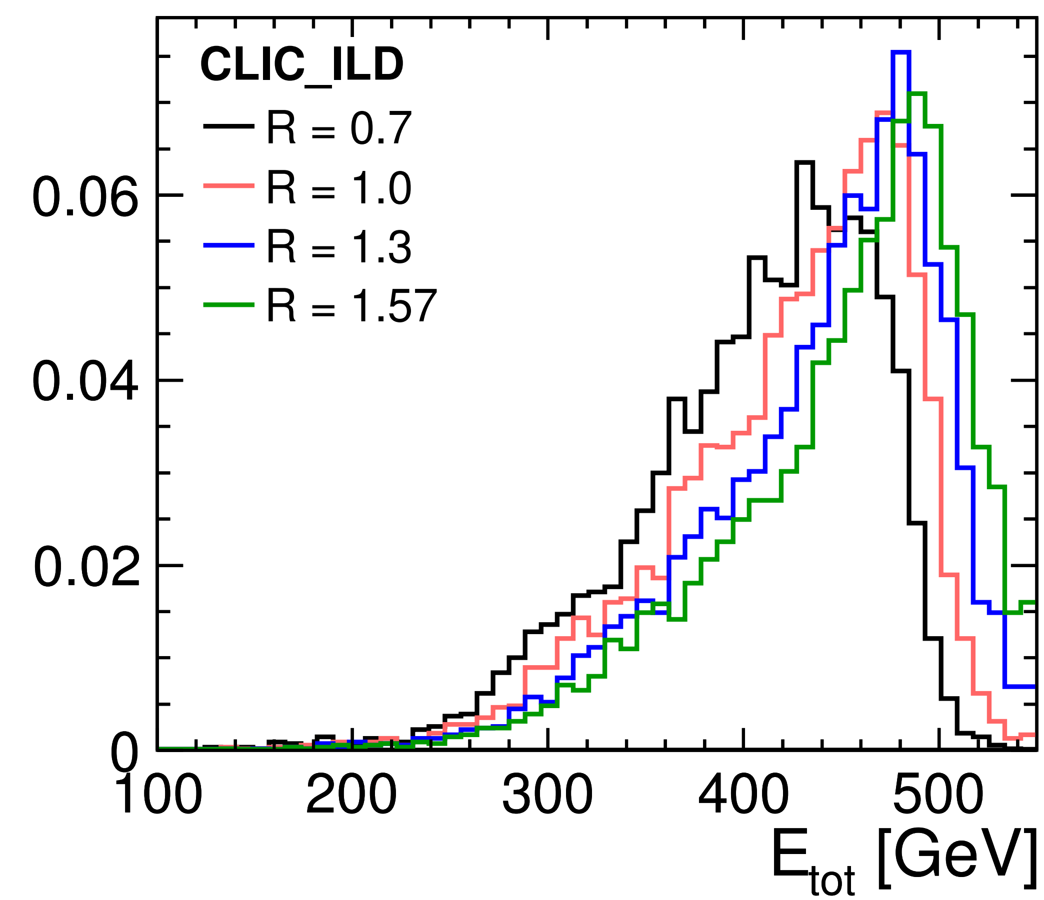

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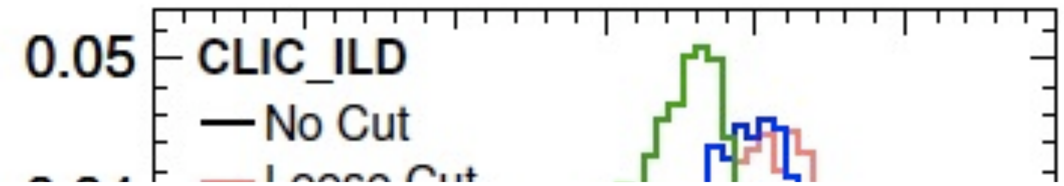
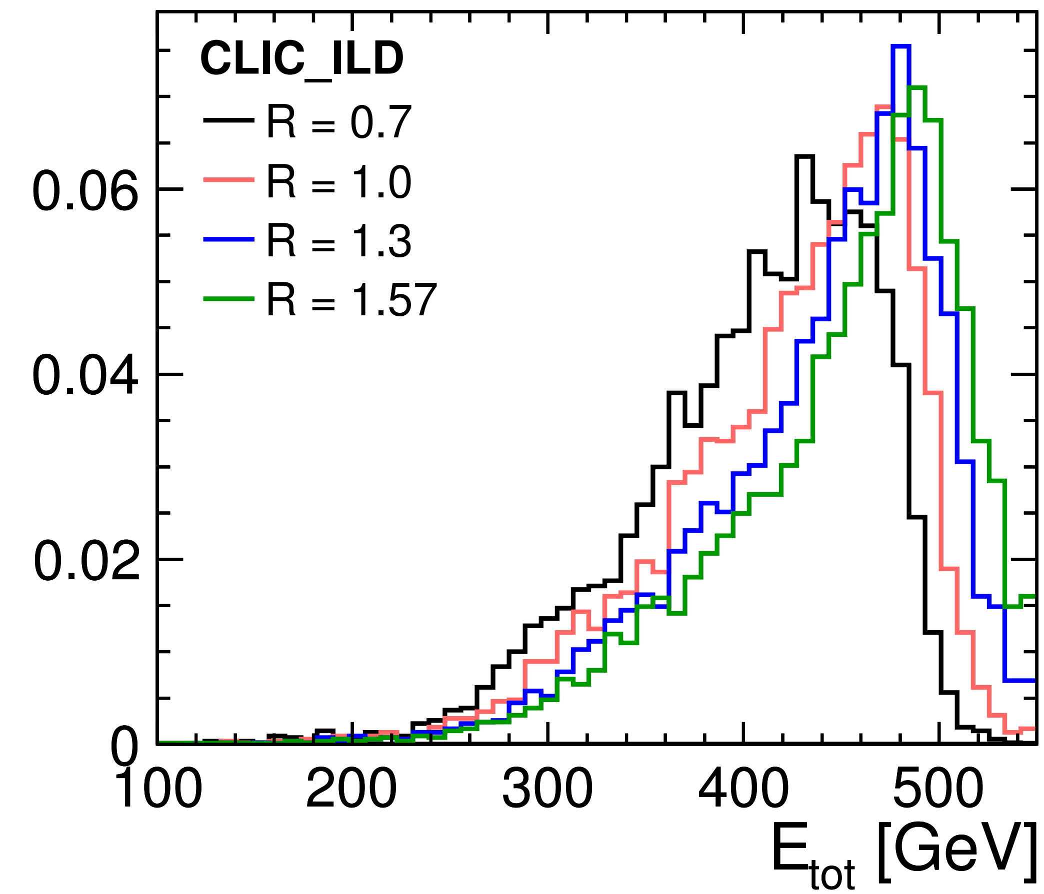


- Events (signal & background) generated with PYTHIA or WHIZARD

$\sqrt{s} = 500\,\mathrm{GeV}$, 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



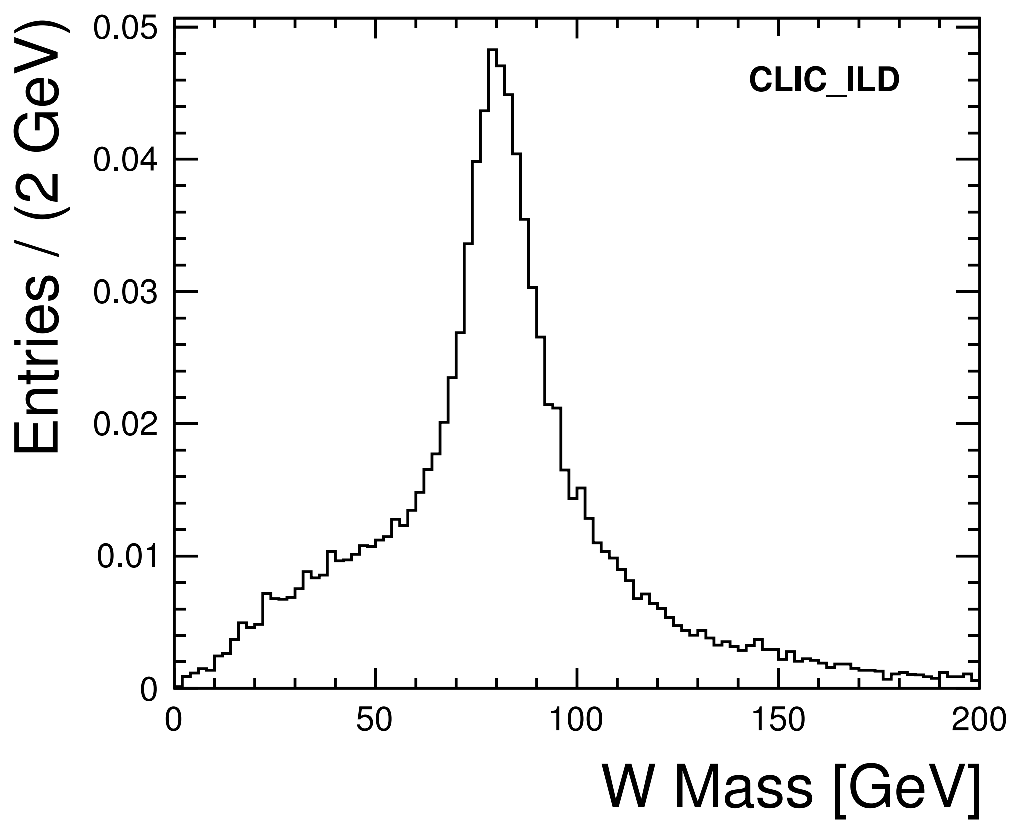
Building the Top: W Bosons

- Reconstruct on-shell W bosons

Semi-leptonic events

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

second W

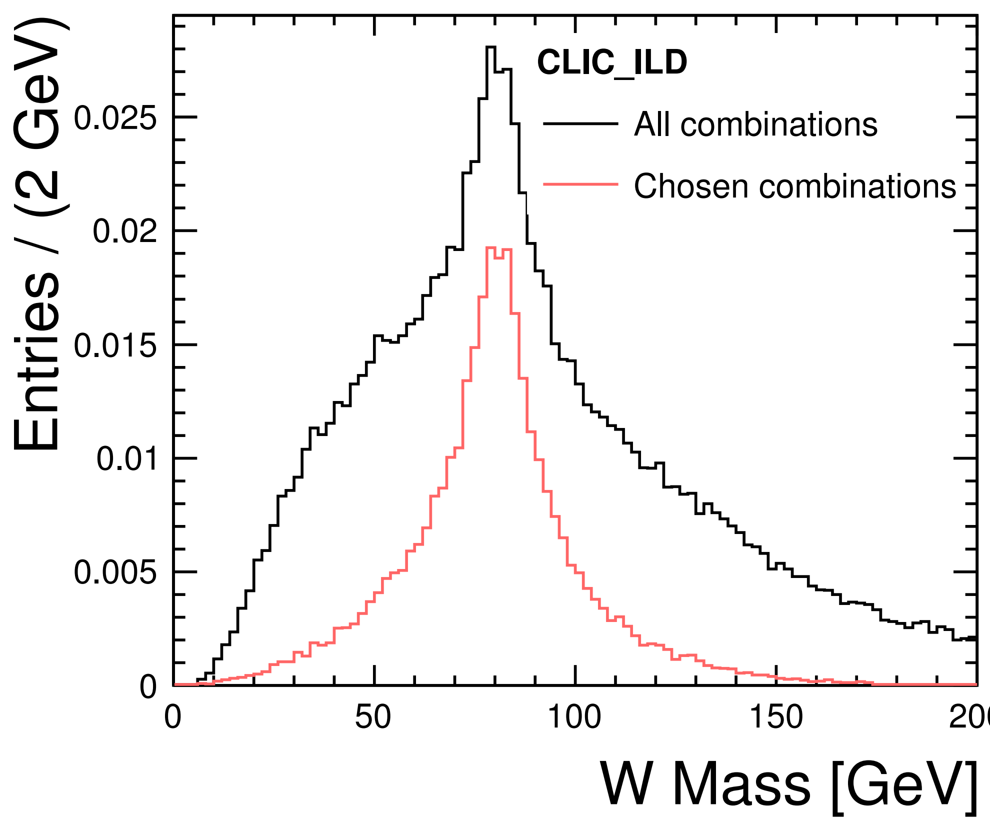


All-hadronic events

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

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

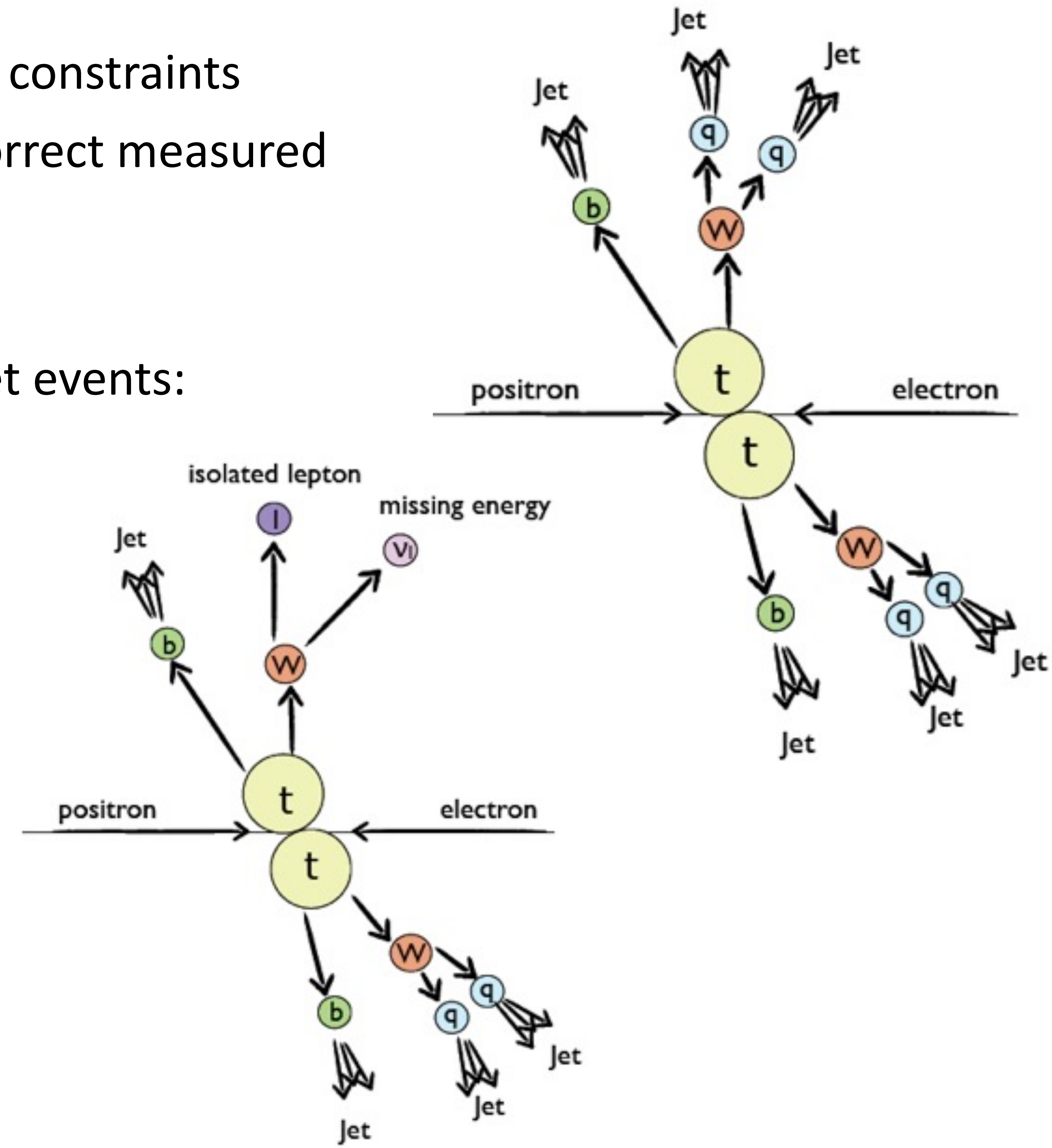
- Minimum value defines best permutation



Building the Top: Combining W and b

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

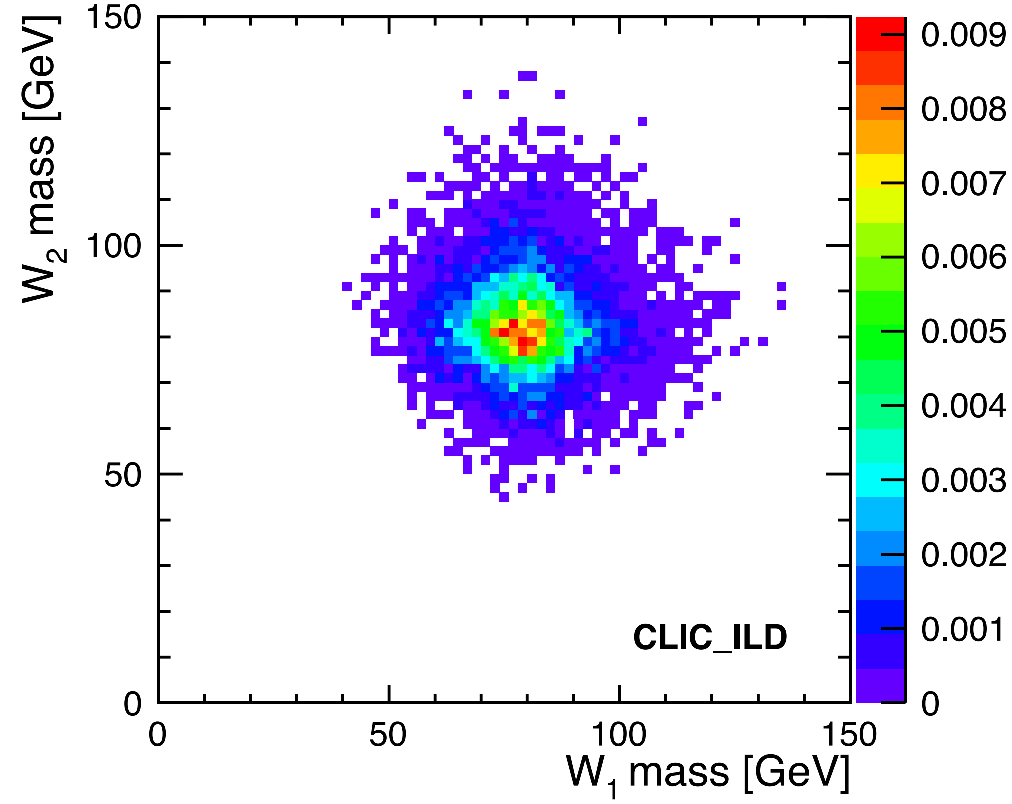
- Constraints for four and six jet events:
  - Energy conservation
  - Momentum conservation
  - W mass equals 80.4 GeV
  - Equal top masses

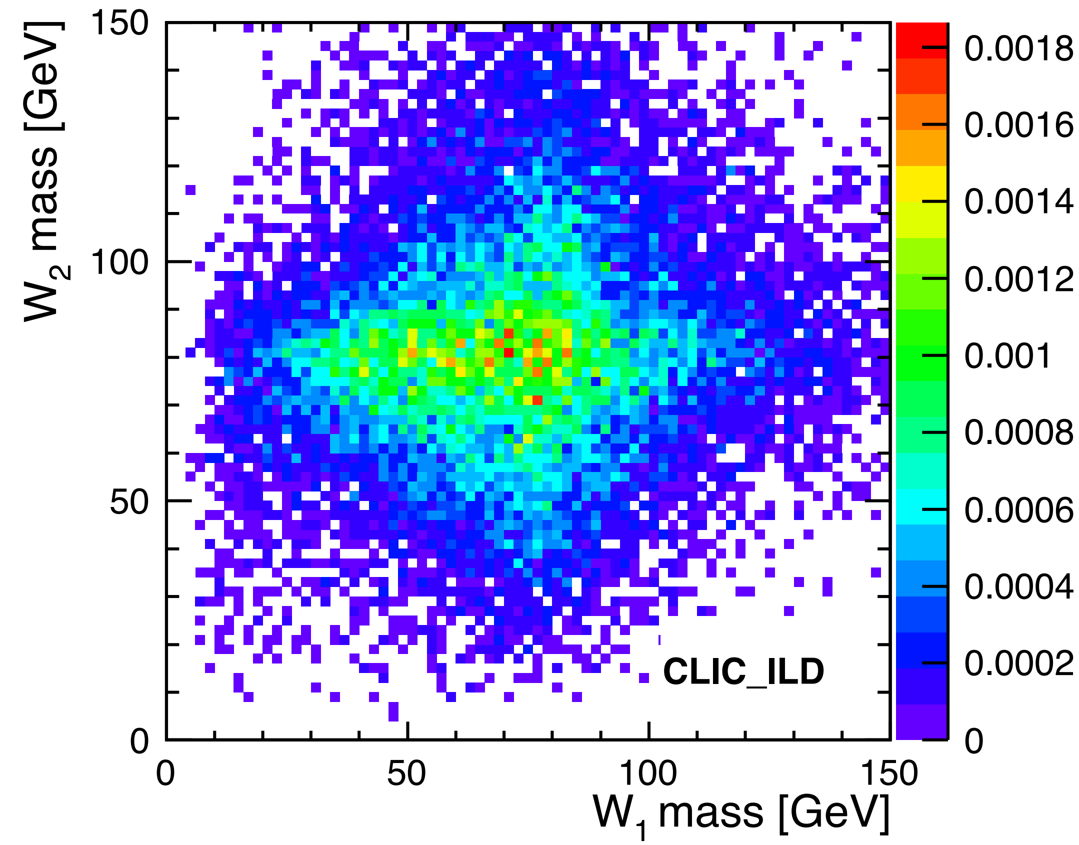


Building the Top: Combining W and b

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

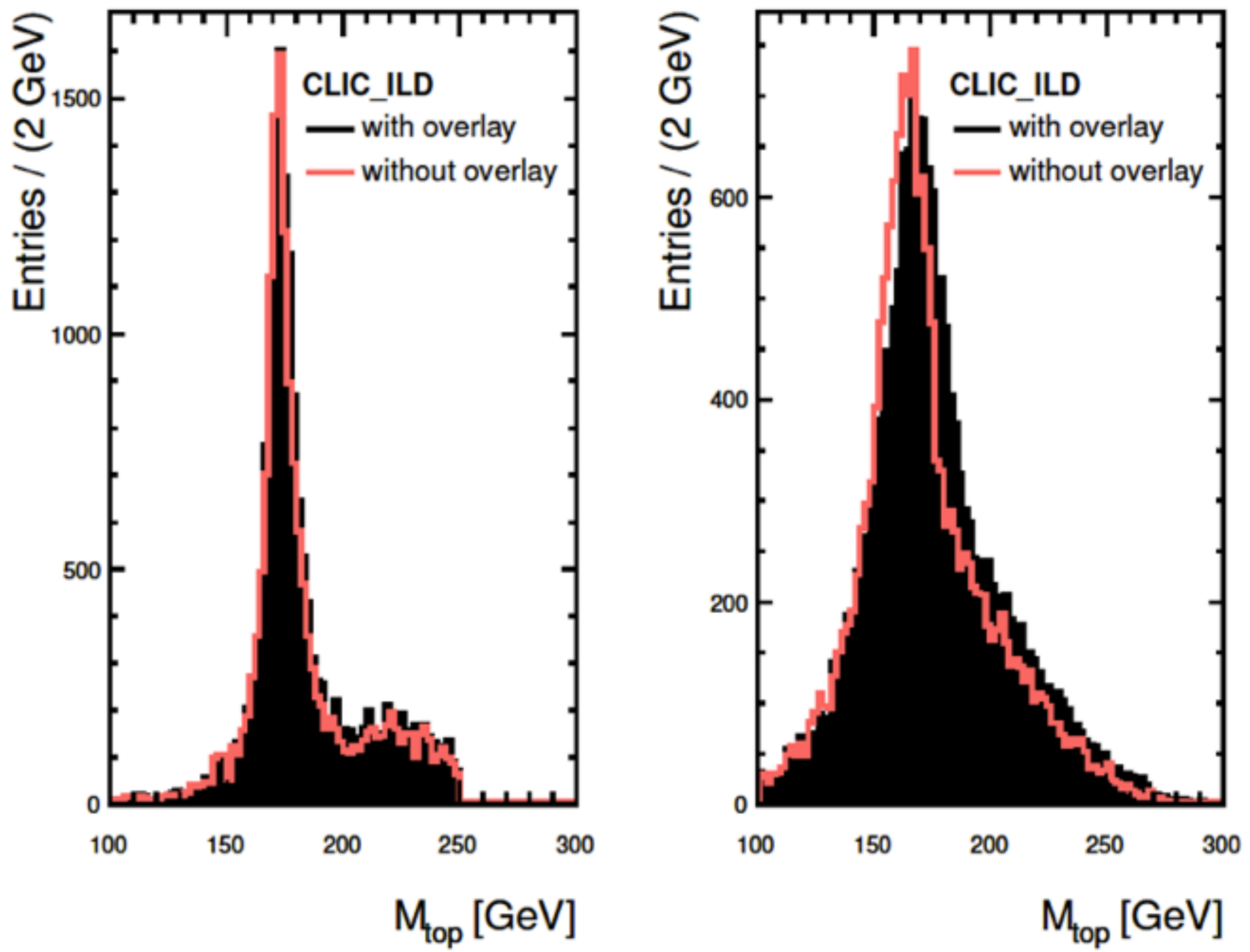
- Constraints for four and six jet events:
  - Energy conservation
  - Momentum conservation
  - W mass equals 80.4 GeV
  - Equal top masses
- Use kinematic fit for final Wb pairing
- Only very clean events pass kinematic fit
  - In case of fit failure: re-examine flavor assignment (recovers W decay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

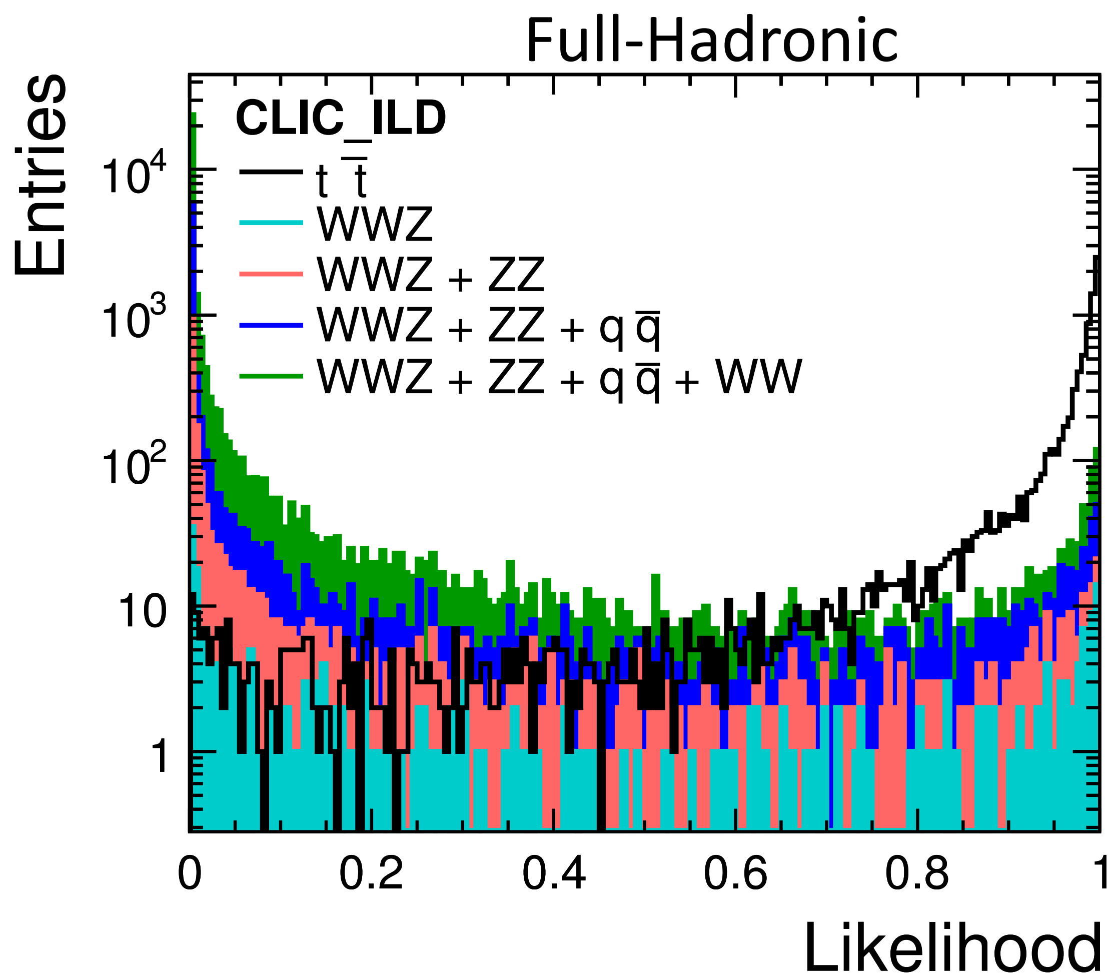
Cleaning the Sample

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



Cleaning the Sample

Kinematic Fit

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

Overall background rejection: 99.8%

Overall signal selection:

Full-Hadronic: 34%

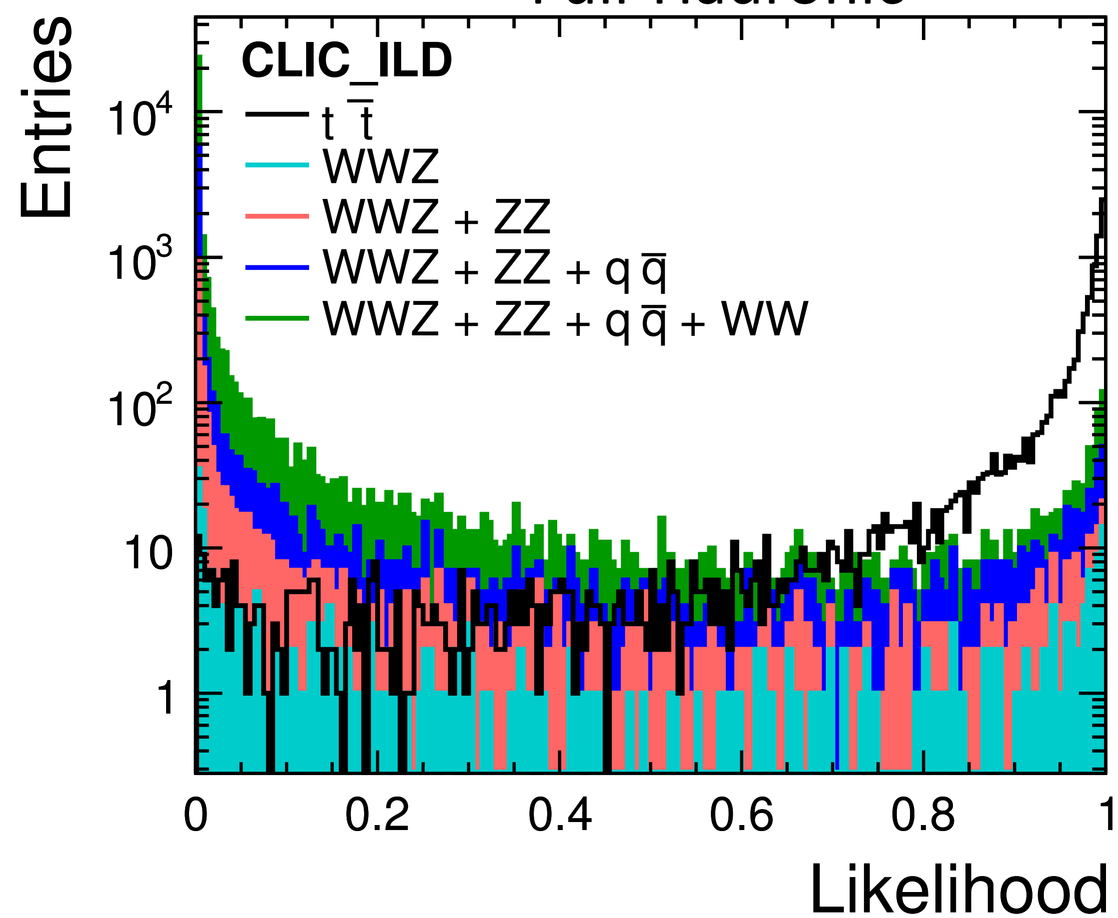
Semi-Leptonic: 43%

- Analysis goal: clean events, not maximized statistics

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

Full-Hadronic



Cleaning the Sample

Kinematic Fit

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

Binned likelihood rejection

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

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