Experimental Top Physics at Linear Colliders

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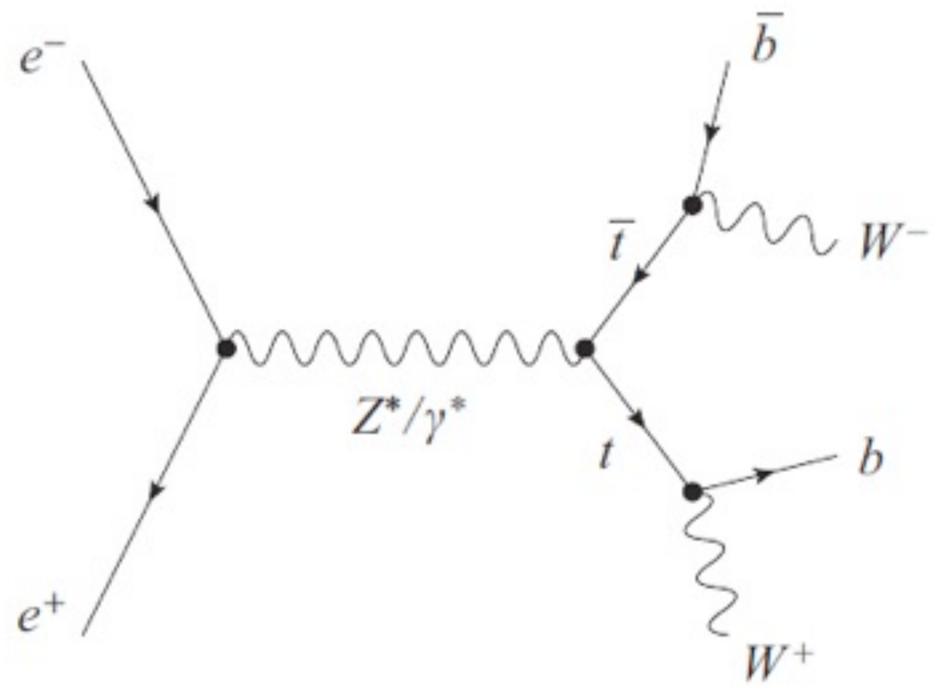
Outline

- Identifying and reconstructing Top
- Measuring Top Properties: Focus on Mass
- Top as a Tool: BSM probes through Asymmetries

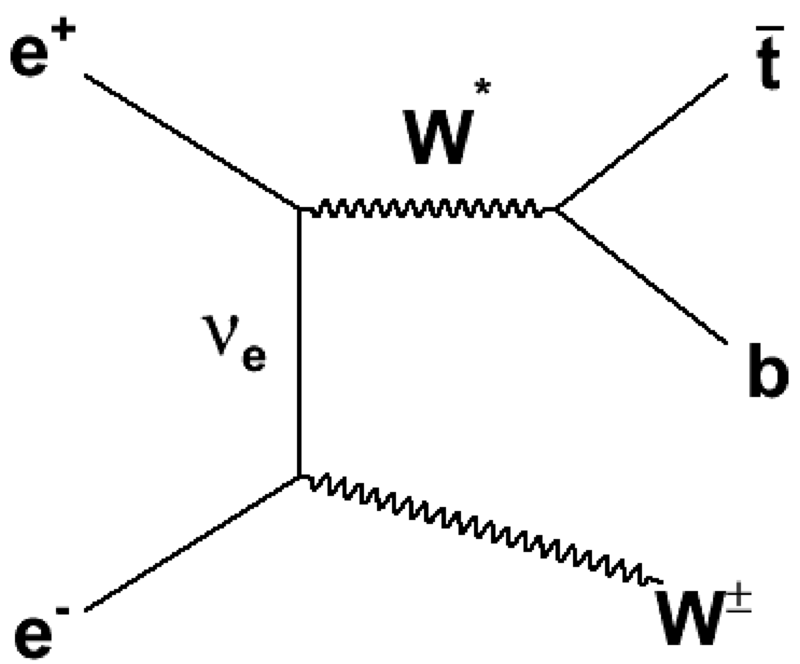
Based mainly on two papers:

- K. Seidel, F. Simon, M. Tesar, S. Poss, *“Top quark mass measurements at and above threshold at CLIC”*, EPJ C73, 2530 (2013)
- M.S. Amjad *et al.*, *“A precise determination of top quark electro-weak couplings at the ILC operating at $\sqrt{s}$ = 500 GeV”*, arXiv:1307.8102 [hep-ex]

Top Production at LC



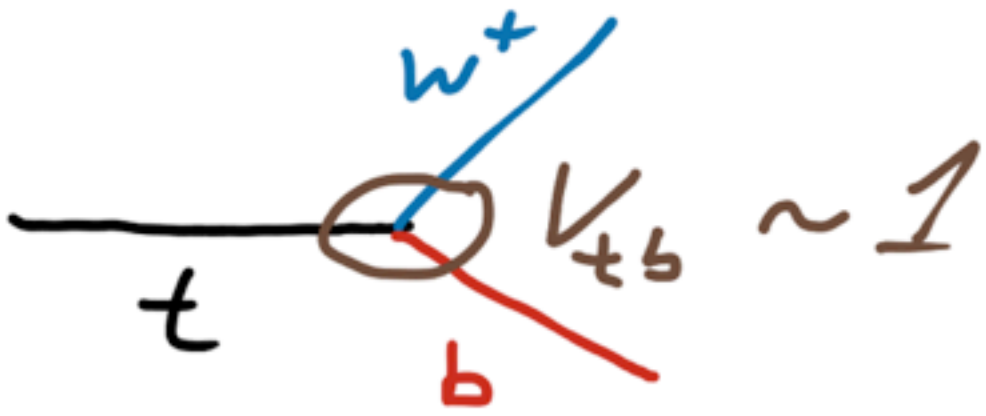
- Typically the process of interest - and the dominating process: top pair production
  - s-channel process



- Subdominant process (~ 15% at 500 GeV): Single top production
  - t-channel process

(not always considered yet in studies - particularly important for asymmetry measurements: Tough to separate from ttbar, leads to a dilution of asymmetries - and interference)

Top Decay



- Due to the 3rd family elements in the CKM matrix: Basically 100% decay by Wb transition
- Top mass: Substantially above W + b masses: Decay into a **real W** and a **b**-Quark
- Short lifetime: ~ 5 x 10^{-25} (about a factor of 10 shorter than hadronization time): Decays as an (almost) free quark: A unique opportunity!

➾ the decay of a top quark is characterized through the decay of the W boson!

$$W^+ \rightarrow e^+\nu_e : \mu^+\nu_\mu : \tau^+\nu_\tau : u\bar{d}' : c\bar{s}'$$

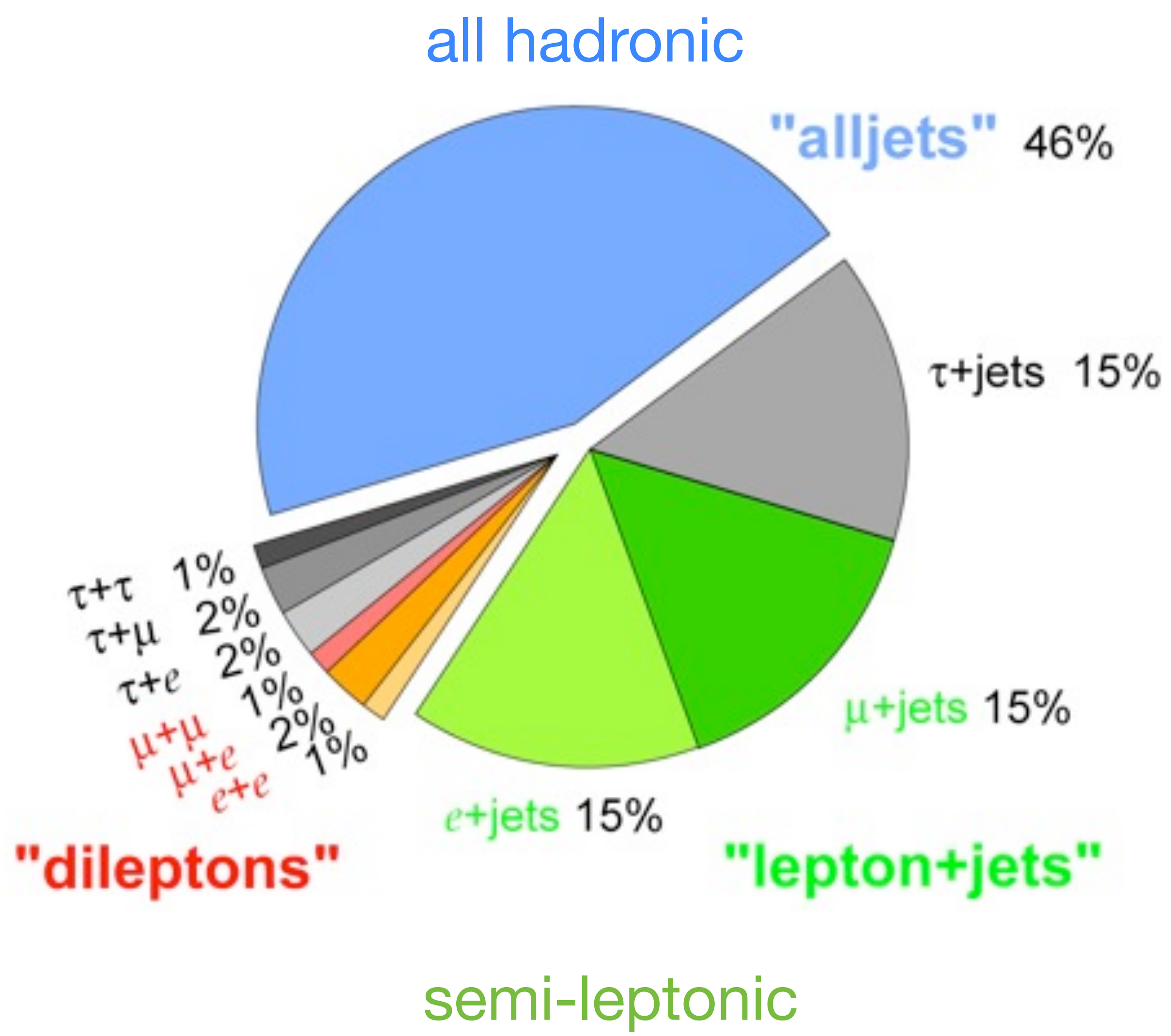
1 : 1 : 1 : 3 : 3

(quarks count 3x due to color charge)

Top Decay

- We typically study top pair production: The decay of both W bosons matter - 3 “types” of decays:

- all hadronic: both W bosons decay into quarks
- semi-leptonic: one W boson decays into quarks, one into leptons
- all-leptonic / dileptons: Both Ws decay into lepton + neutrino



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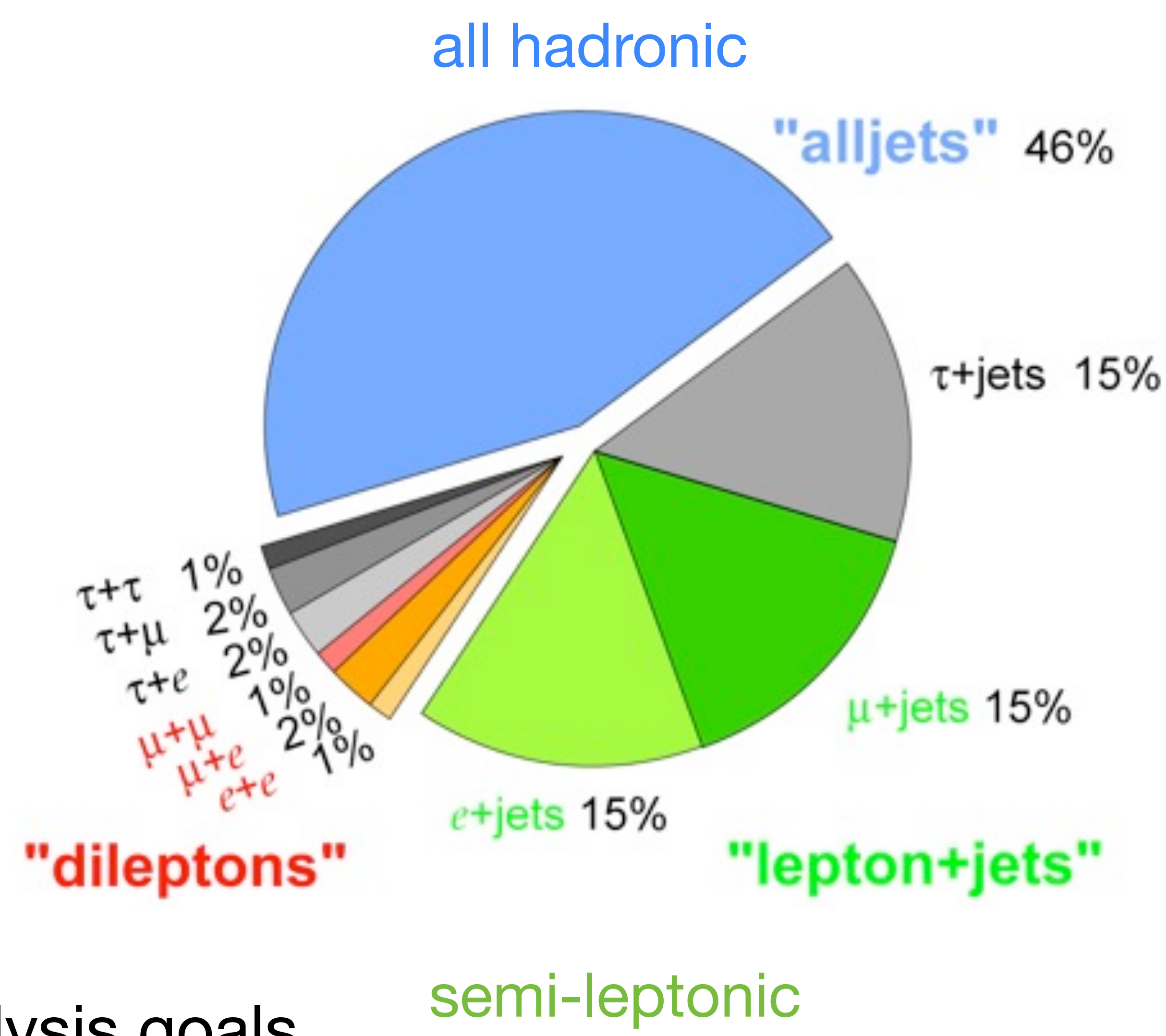


Which one(s) to go for depends on the analysis goals

In general:

- Leptonic final states good for asymmetries: Charge provides simple top / anti-top ID
- Taus are tough: Additional neutrino in final state
- All hadronic: Highest BR, no missing energy - Interesting for measurement of properties

It's not all Top - Backgrounds

- Other processes contribute provide similar final states (sometimes after reconstruction errors)
- Main backgrounds typically considered:

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

(numbers for CLIC luminosity spectrum, ILC very similar)

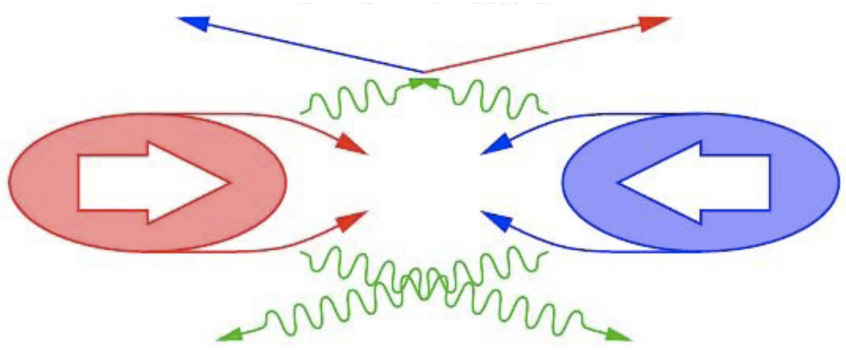
high cross-sections

can mimic ttbar final state: WWbb

Even at lepton colliders: Need strategies to reject non-ttbar background!

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



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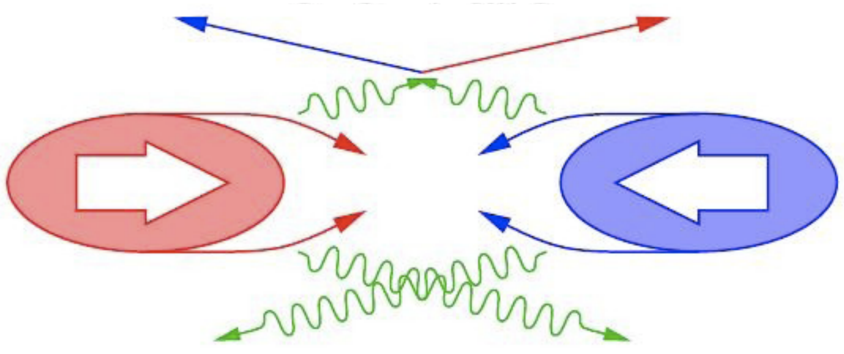

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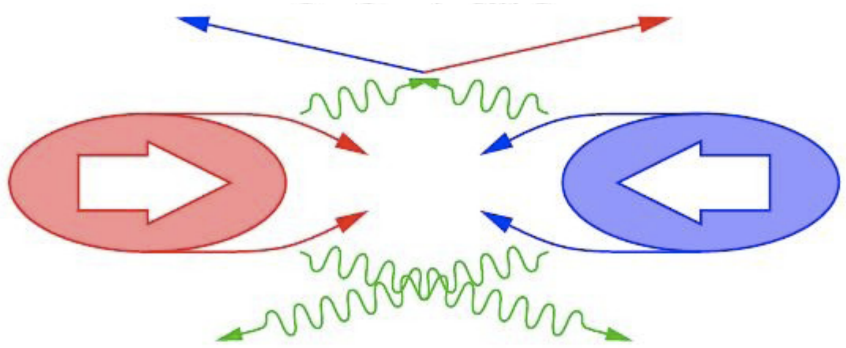


These hadrons are a particular reconstruction challenge: “Pile-up” on the physics event, additional particles affect jet reconstruction

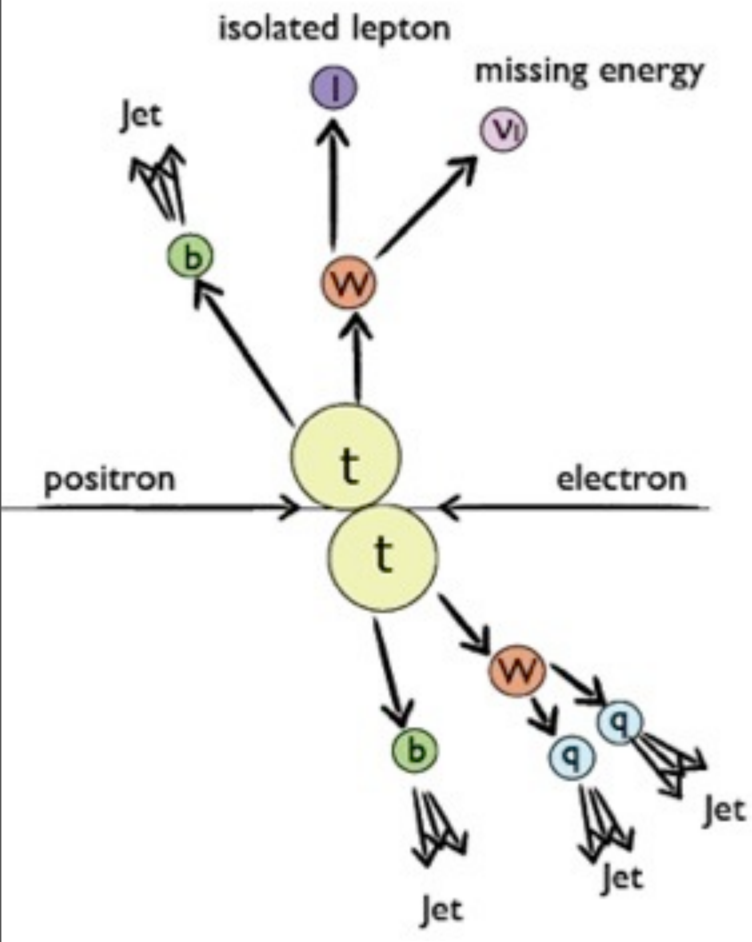
Impact and strategies for mitigation depend on machine:

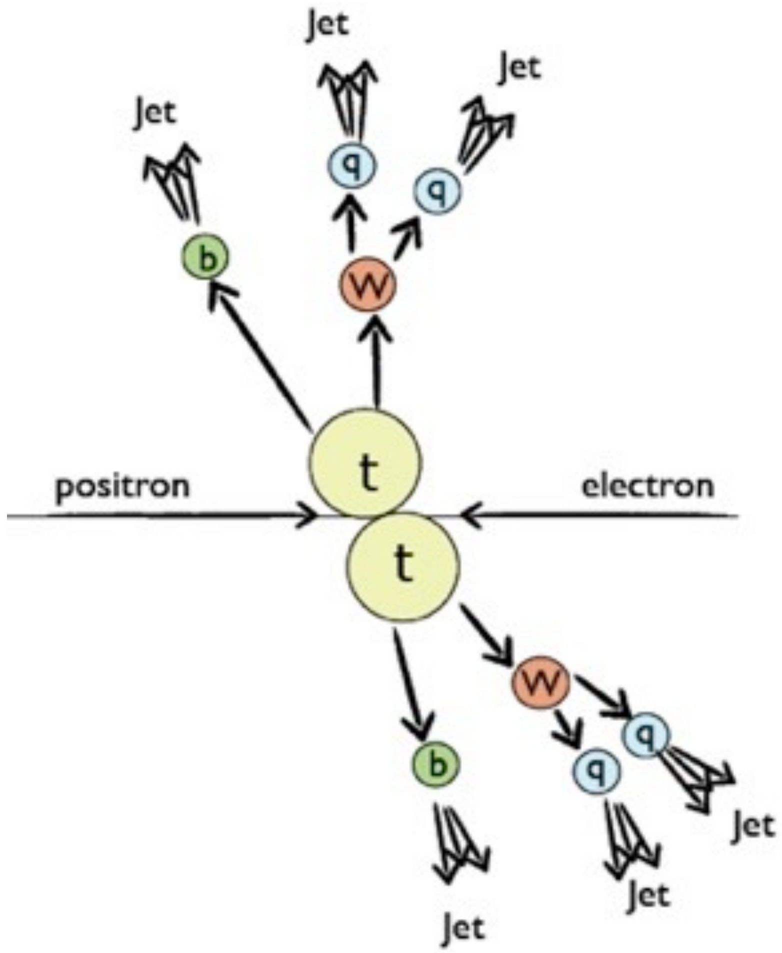
- At ILC the BXs are far appart in time (100s of ns):
  Only background from one BX piles up - Rejection based on jet finding
- At CLIC the BXs are separated by 0.5 ns: Pile-up from multiple BX - Rejection based on timing cuts and jet finding

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

Identifying & Reconstructing Top Quarks

- Strategy depends on targeted ttbar final state





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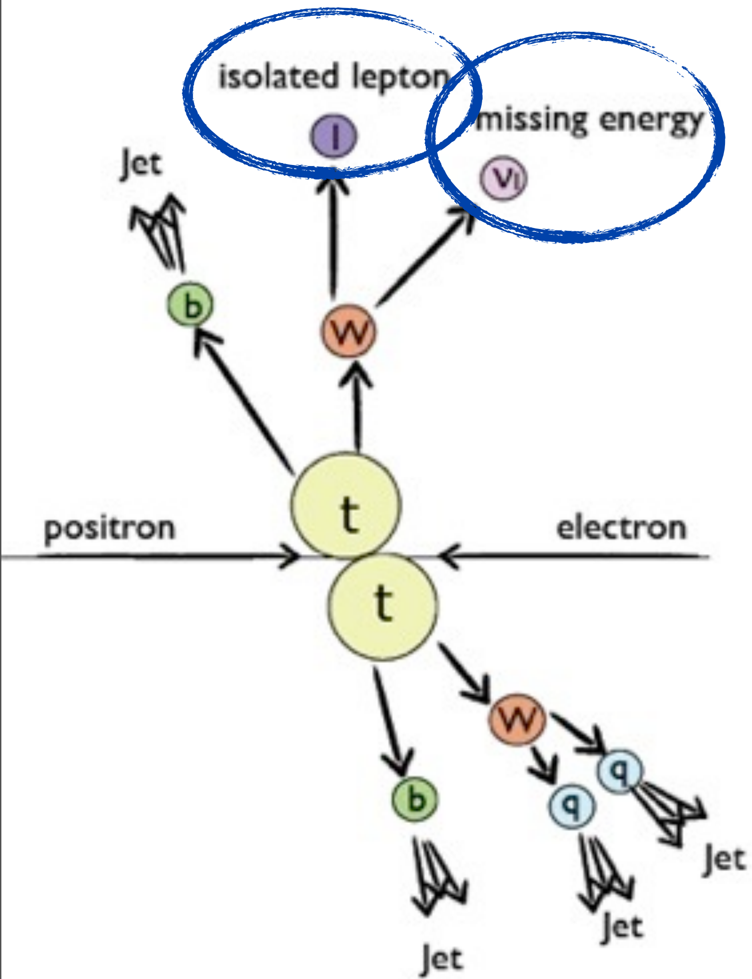
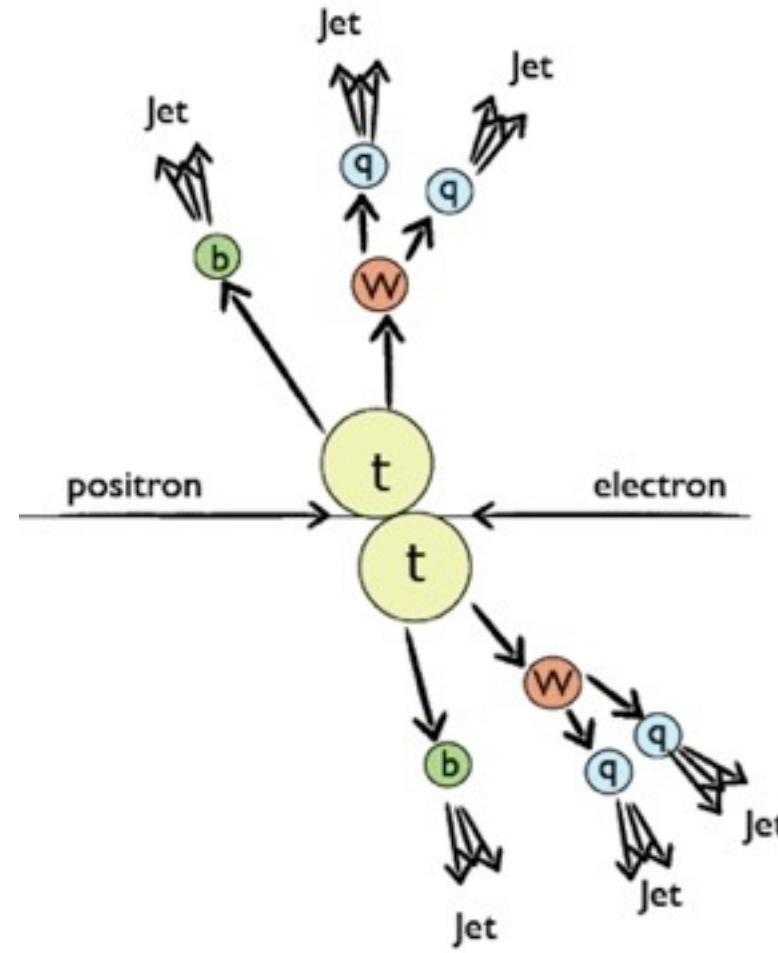


Semi-leptonic:
- isolated lepton ID, momentum measurement
- missing energy measurement



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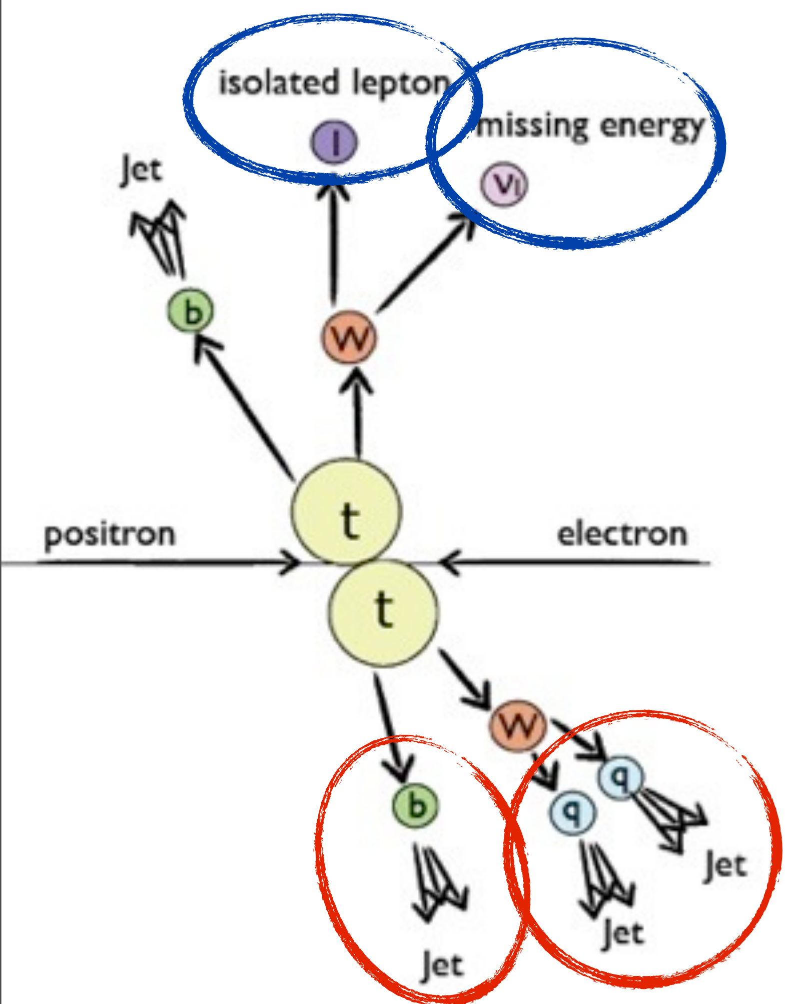

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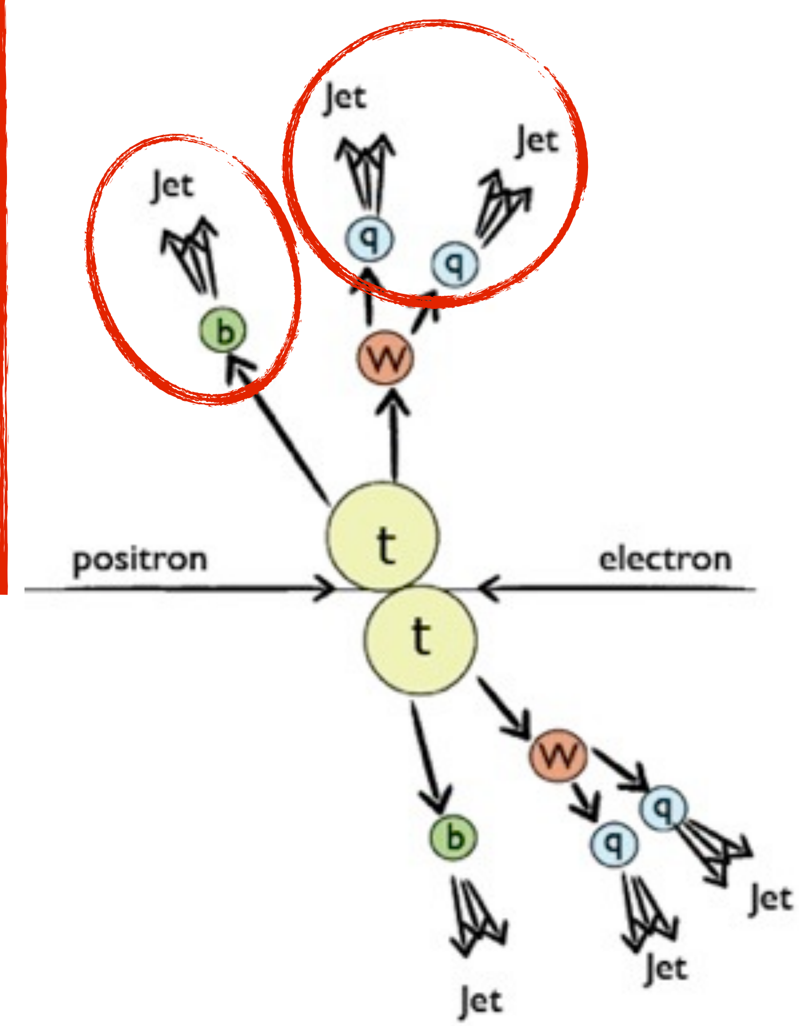
Universal

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



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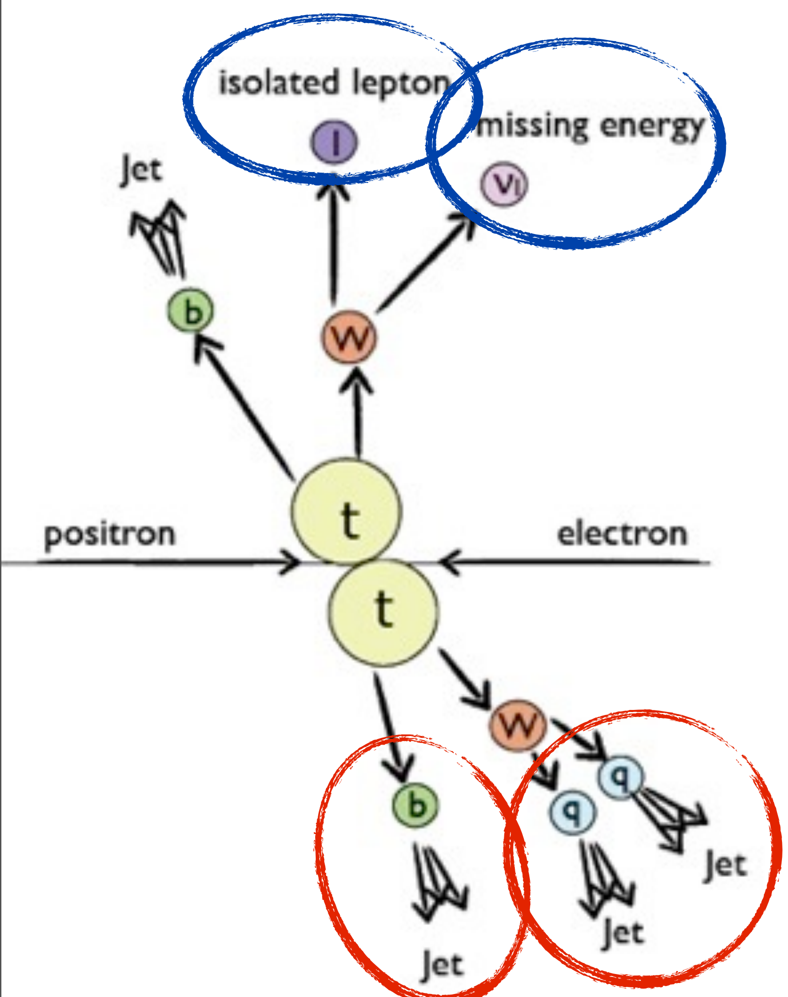

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Universal
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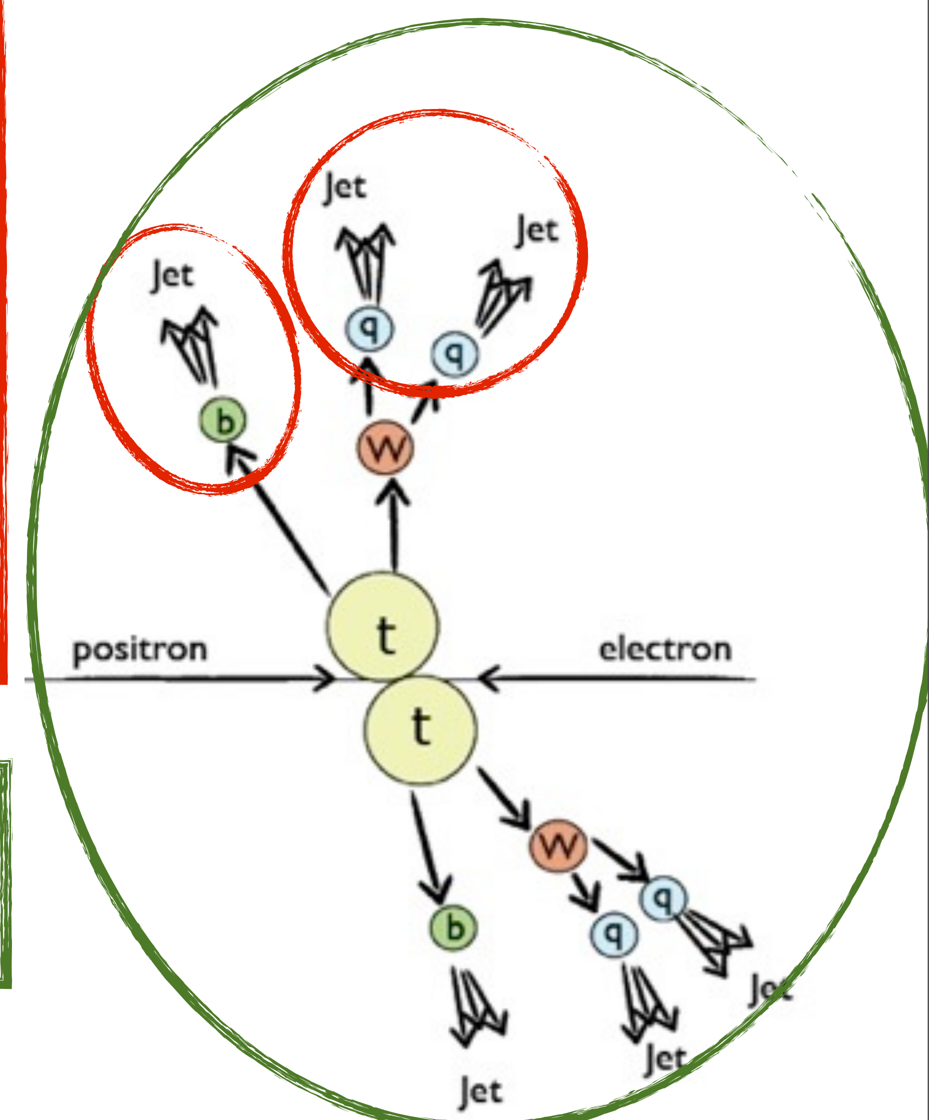
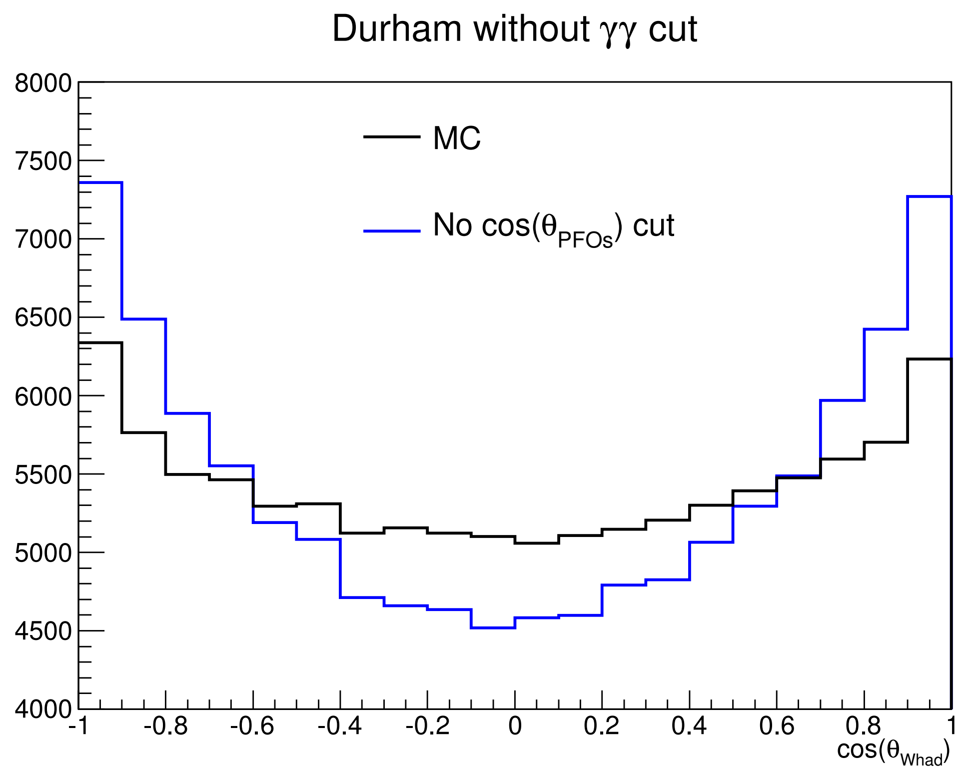
All-hadronic
- global hadronic energy reconstruction

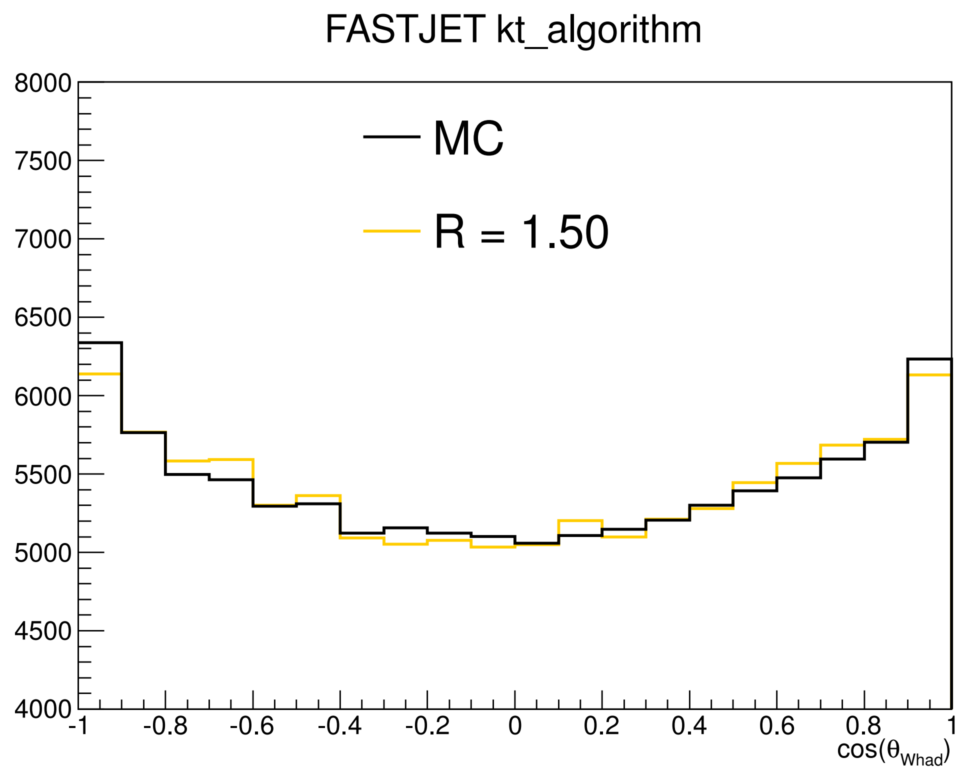


Coping with Backgrounds: Jet Finding

- $\gamma\gamma \rightarrow$ hadrons events lead to additional particles, predominantly forward
- With the standard e^+e^- jet finding algorithm, the Durham algorithm, these particles get added almost completely to the signal jets
- Can be solved by using the k_t algorithm optimized for hadron collisions: Two-particle distance defined by $\Delta\eta$, $\Delta\phi$, not by the angle between the particles
  - First studied for CLIC, successful in controlling very large backgrounds at 3 TeV
  - Also ideal at ILC, now the default for all analyses (basically since $\gamma\gamma \rightarrow$ hadrons background has been included in the simulations)

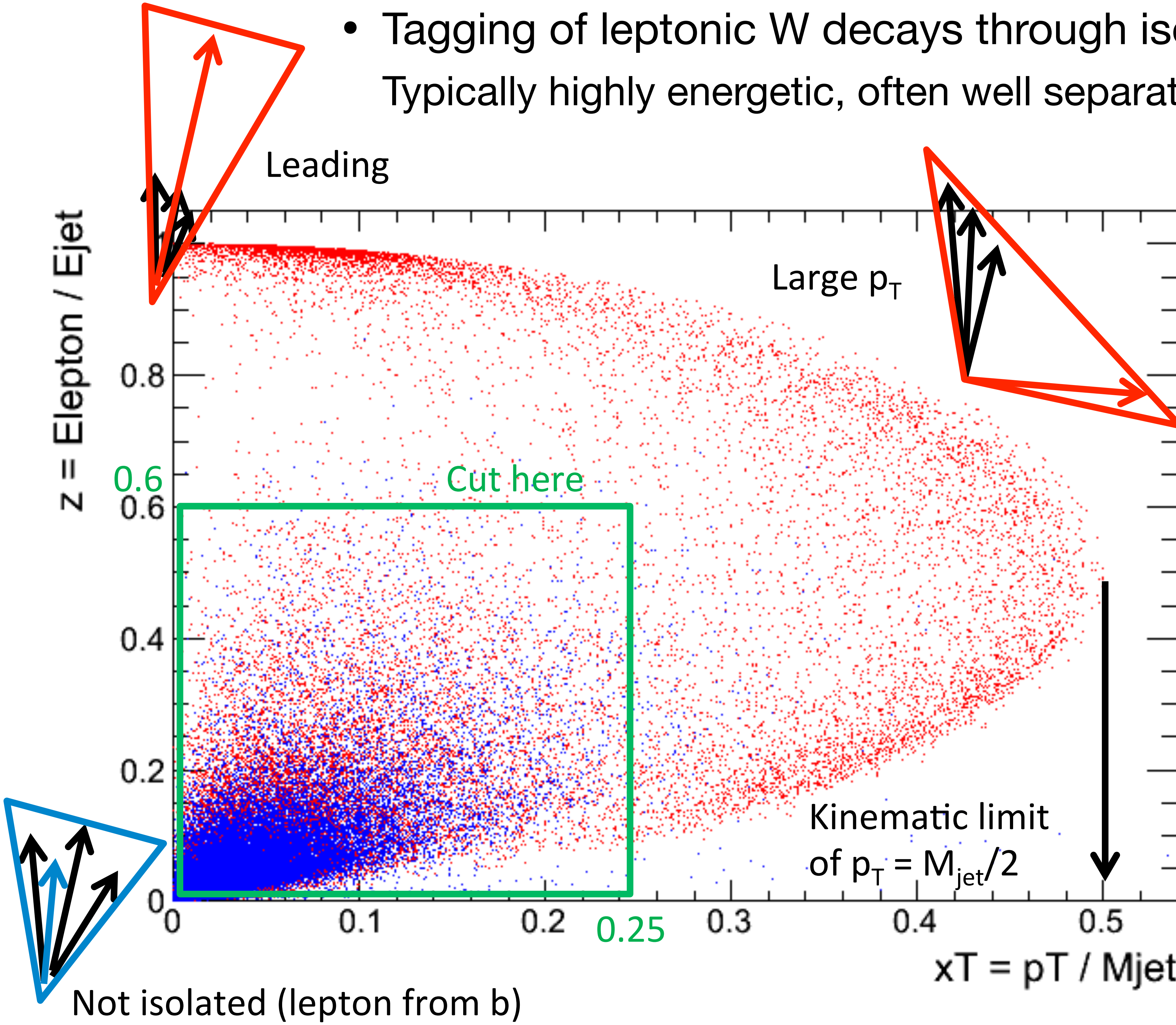
- Polar angle for hadronic W in ILC @ 500 GeV





Identifying Semi-Leptonic Events

- Tagging of leptonic W decays through isolated leptons: Typically highly energetic, often well separated from hadronic activity

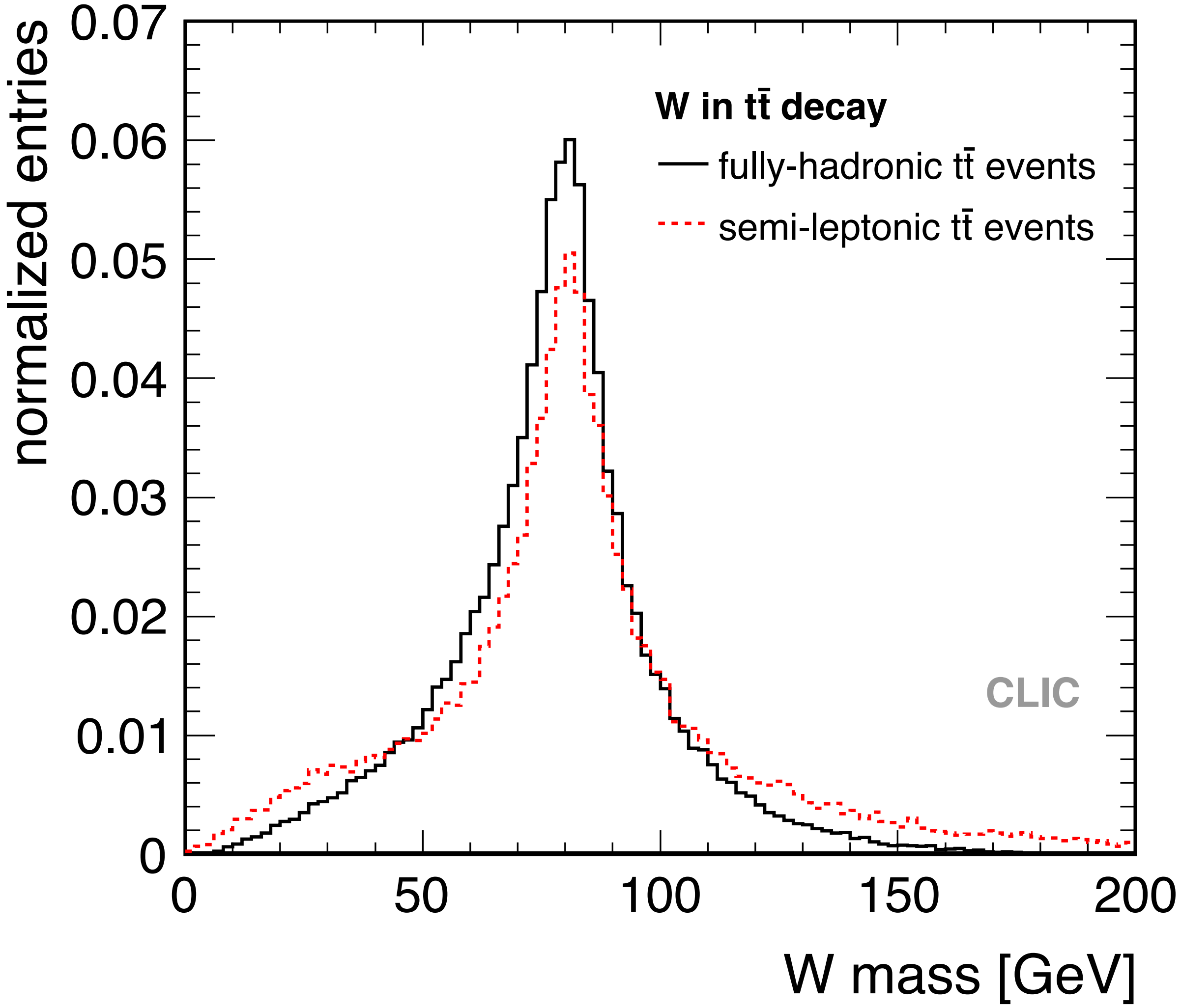


Red = leptons in semileptonic top events

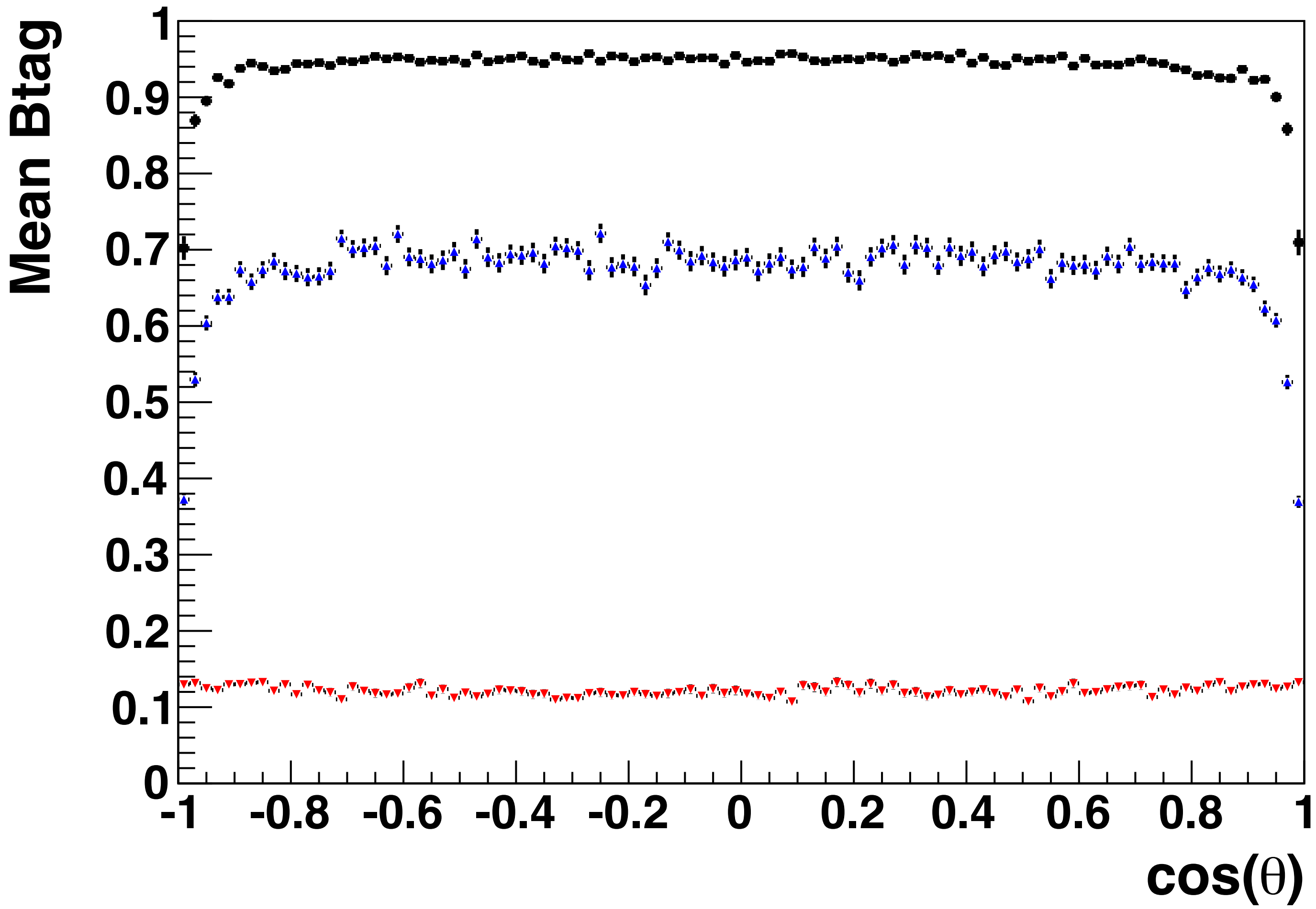
Blue = leptons in full hadronic top events = leptons from b

main experimental challenge: Distinguish leptons from W decays and from B decays

Reconstructing Top Quarks



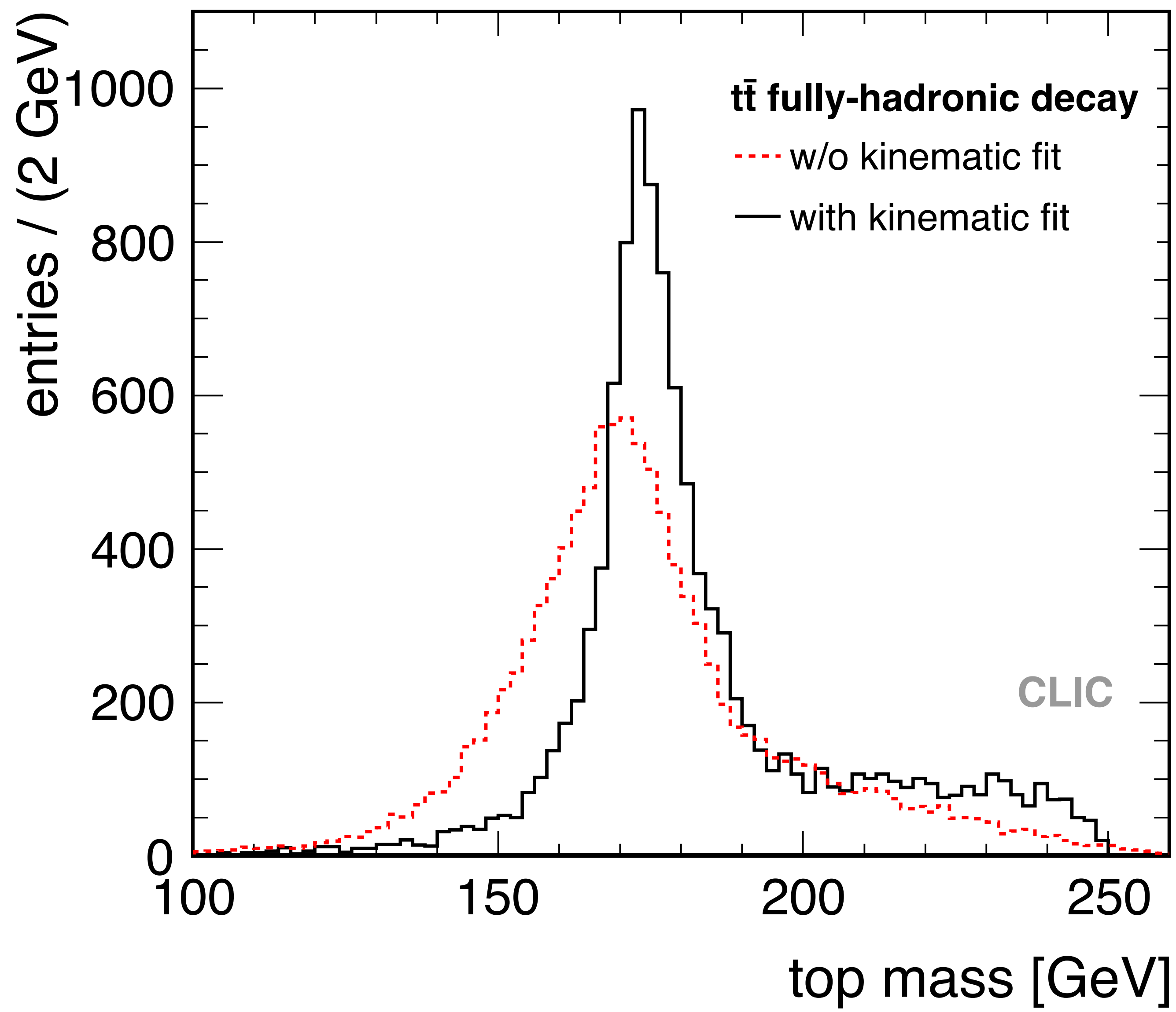
- Reconstruction of W bosons: Mass used to identify true ttbar events



- Flavor-tagging absolutely crucial to assign the right jets to the right particles - Good separation of b-jets (best, second) from light jets (here ILD, semileptonic ttbar)

Exploiting Prior Knowledge: Kinematic Fits

- Particularly relevant for invariant mass reconstruction - but also serves as a powerful background rejection tool!
- Use known constraints (total energy, momentum, masses of W, equal mass of t and tbar, ...) to improve event reconstruction assuming a ttbar event
    - Will very often fail to satisfy constraints for non-ttbar events: Efficiently rejects background



Separating Signal and Background

- Typically using multivariate analysis tools - Exploiting specific ttbar properties, such as high multiplicity, rather spherical events compared to background
  - Typical variables: sphericity, b-tags, multiplicity, W masses, dcut, top mass w/o kin fit

Top reconstruction: The bottom line

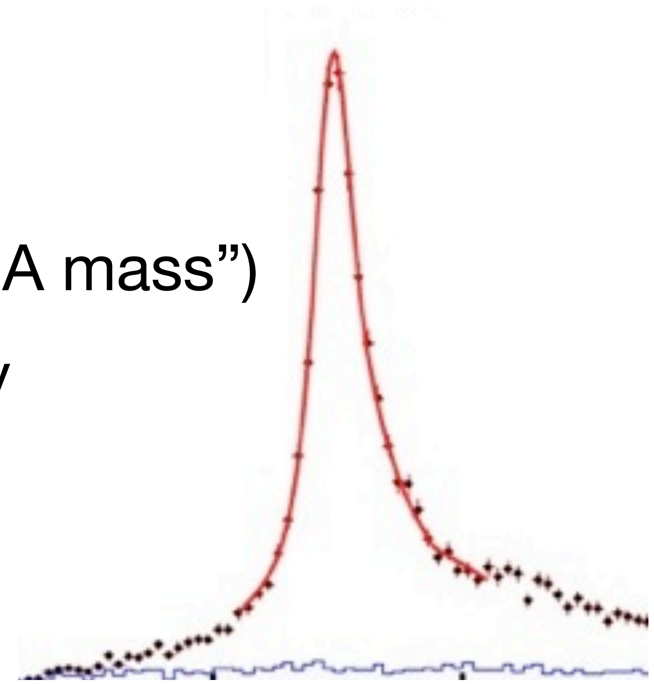
- Excellent signal / background separation - Almost background-free ttbar events, irrespective of collider type (ILC, CLIC) - Details depend on analysis optimization / goals
  - S/B ~8.5 (12) for FH (SL) at 500 GeV
  - S/B ~4.5 directly above threshold
- High reconstruction efficiency
  - 34% (44%) for FH (SL) at 500 GeV
  - 92% for selected decay modes at threshold

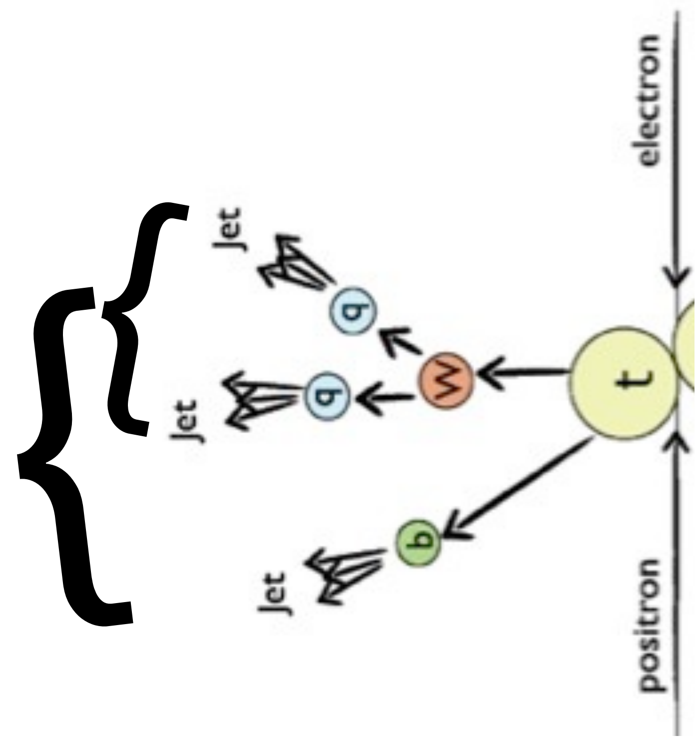
Numbers for CLIC mass study

Measuring Top Properties - Focus on Mass

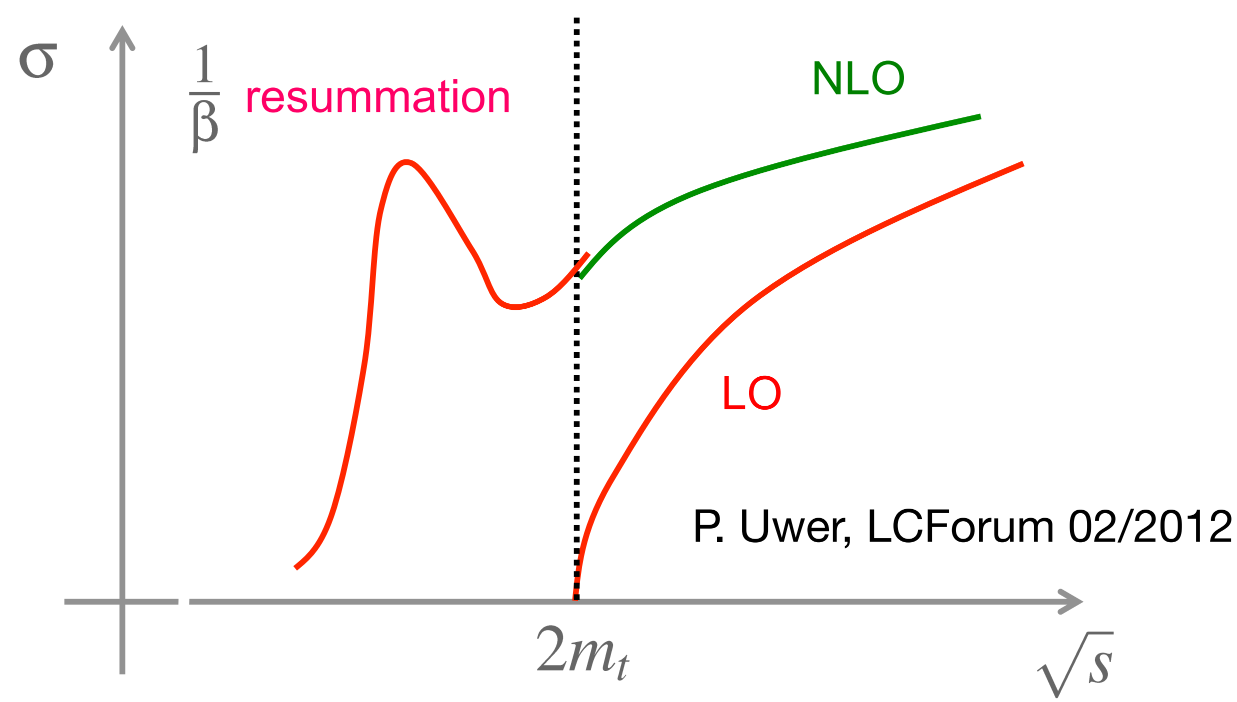
Measuring the Mass: Two Approaches

- 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)



Top Mass in a Threshold Scan

- The ultimate measurement at a lepton collider: Theoretically well under control
- Experimentally: Measure the total cross-section of ttbar production at several energies around the threshold
  - Requires: Clean identification of ttbar events, well-understood background levels
  - Not required: Perfect kinematic reconstruction of final state (but it helps to control / understand efficiencies!)

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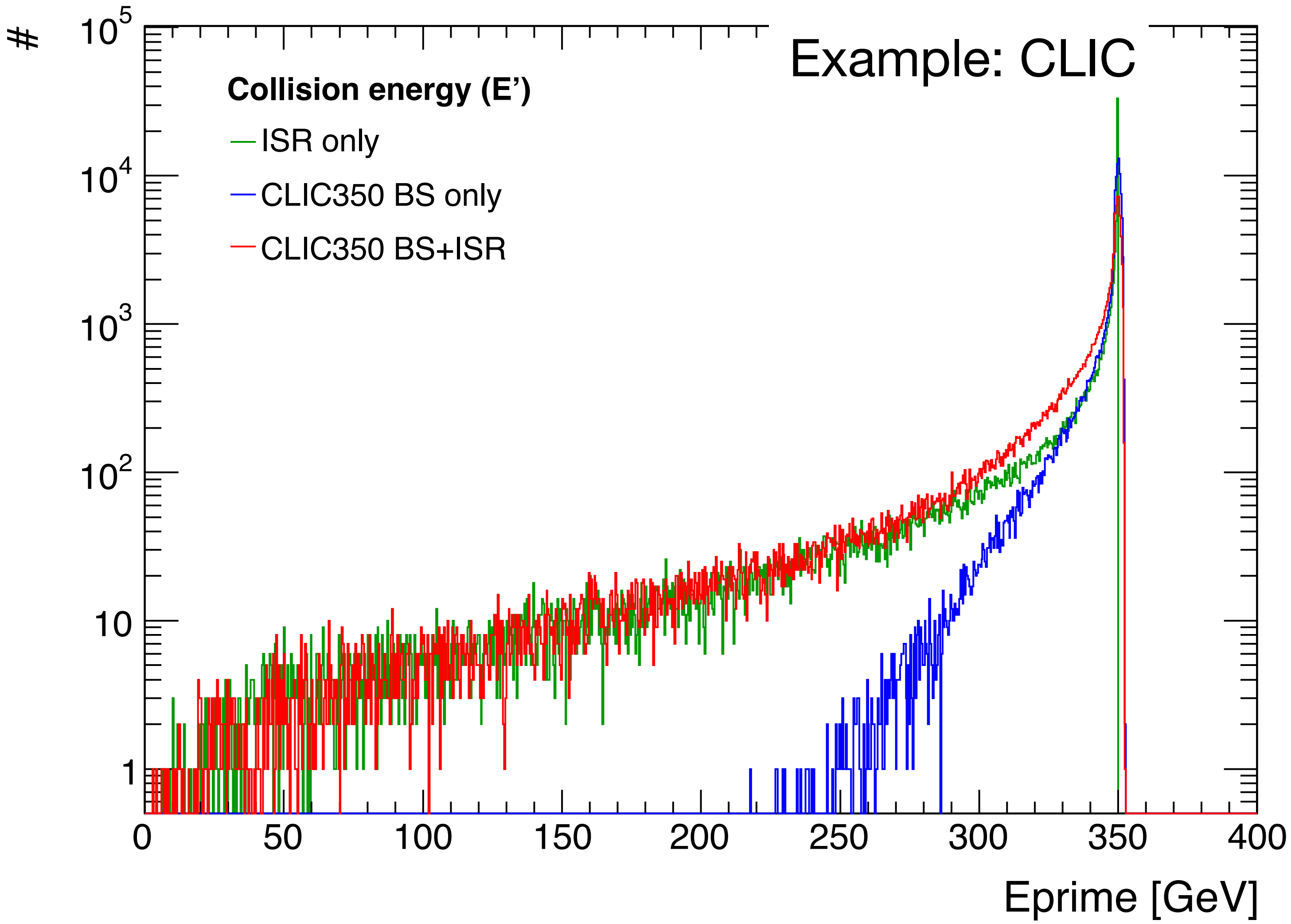
Side remark: Simulating Threshold scans

- Most event generators (for example PYTHIA (LO), WHIZARD, ...) do not simulate the ttbar threshold correctly - And we need ways of taking the latest theory developments into account (NNNLO, EW corrections, ...)
- At least for the total cross section: Factorize the problem!
  - Determine efficiencies and background contamination on fully simulated samples close to threshold
  - Scale signal according to theory prediction for each energy

Threshold Scan: From Theory to Observable



- The pure ttbar cross-section receives modifications from two effects:
  - **I**nitial **S**tate **R**adiation - Physics, due to radiation of electrons prior to collision (“structure functions of electrons”)
  - **L**uminosity **S**pectrum - depends on the machine - Affected by focusing, phase space, ...

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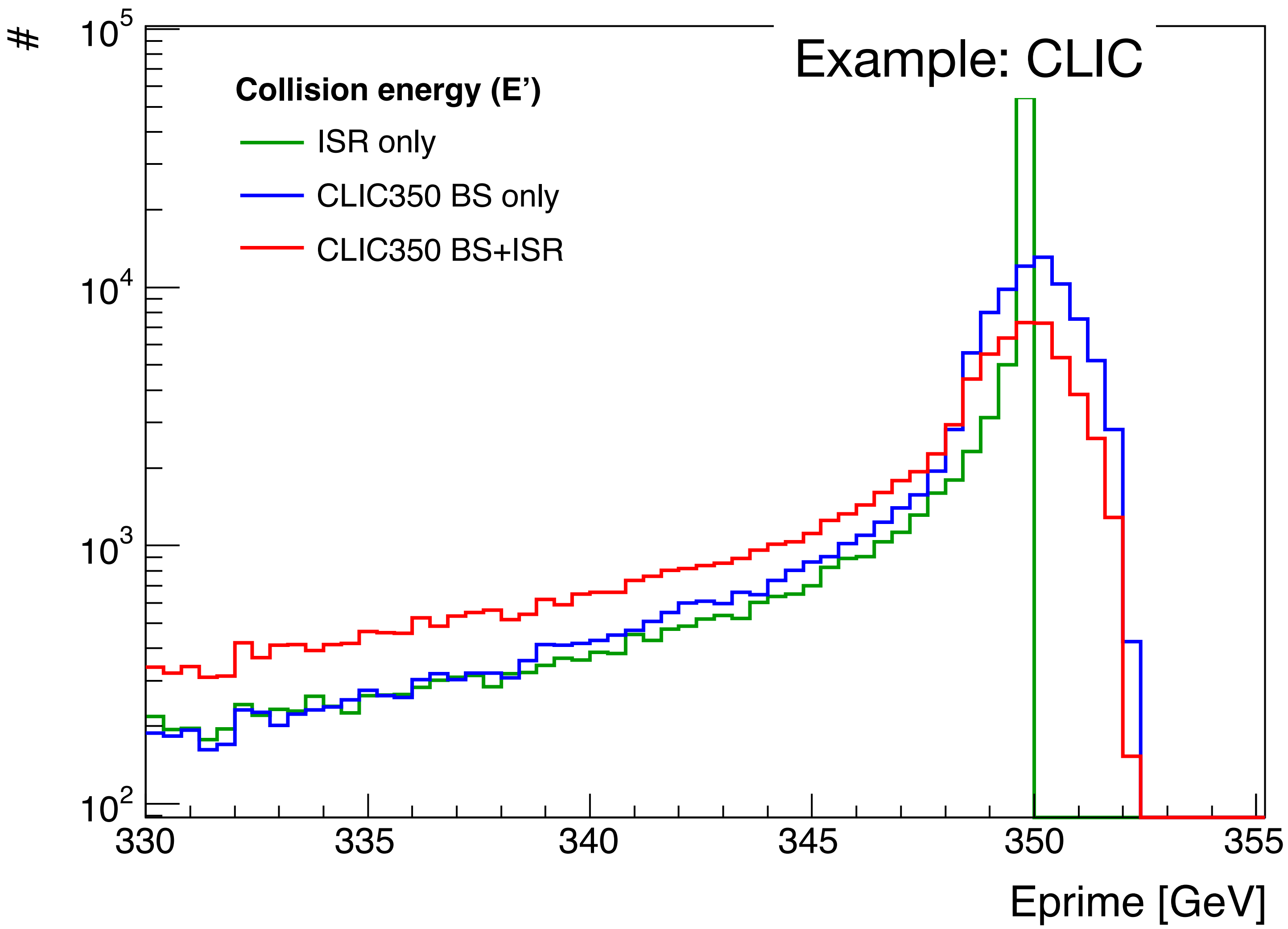

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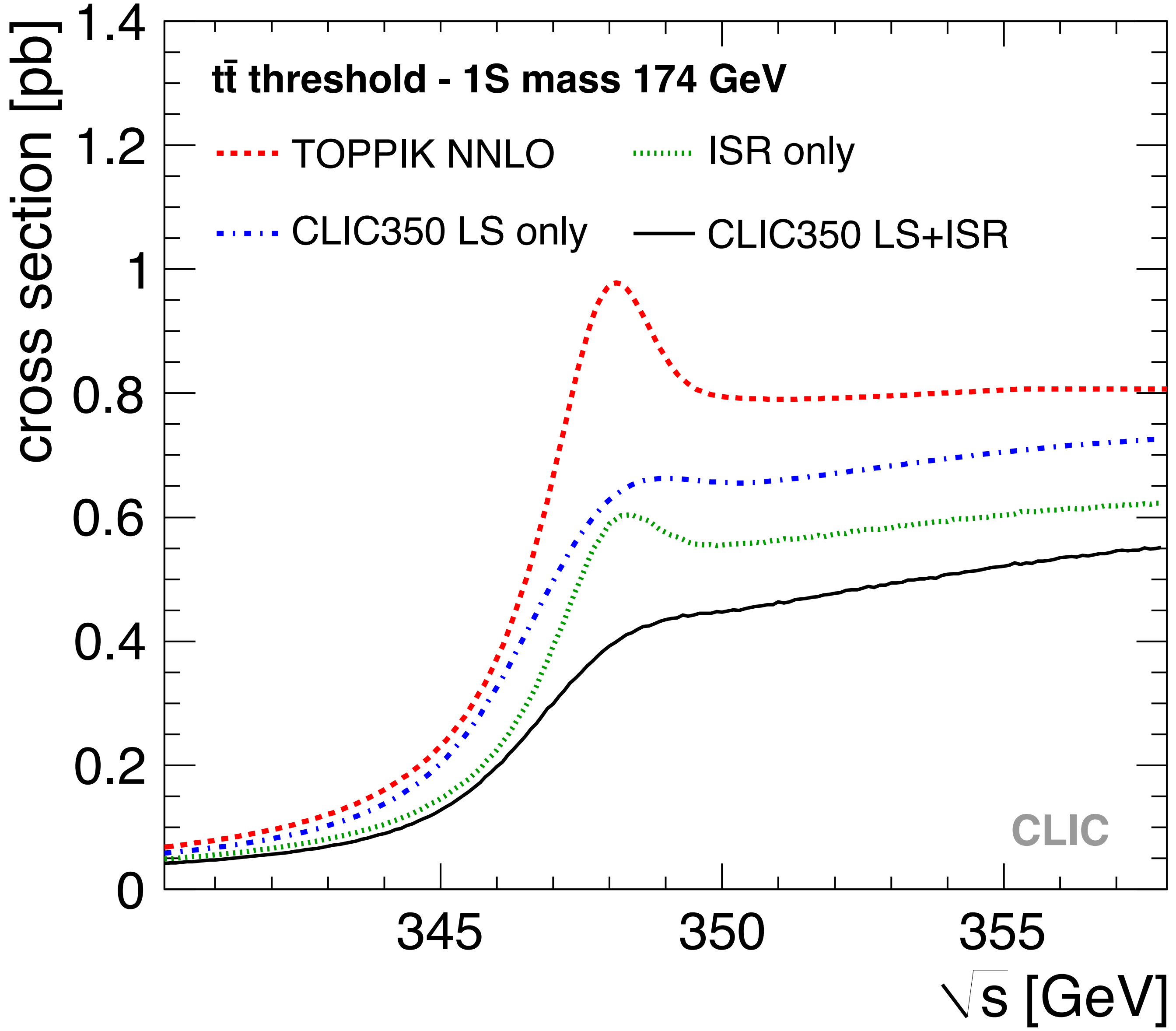

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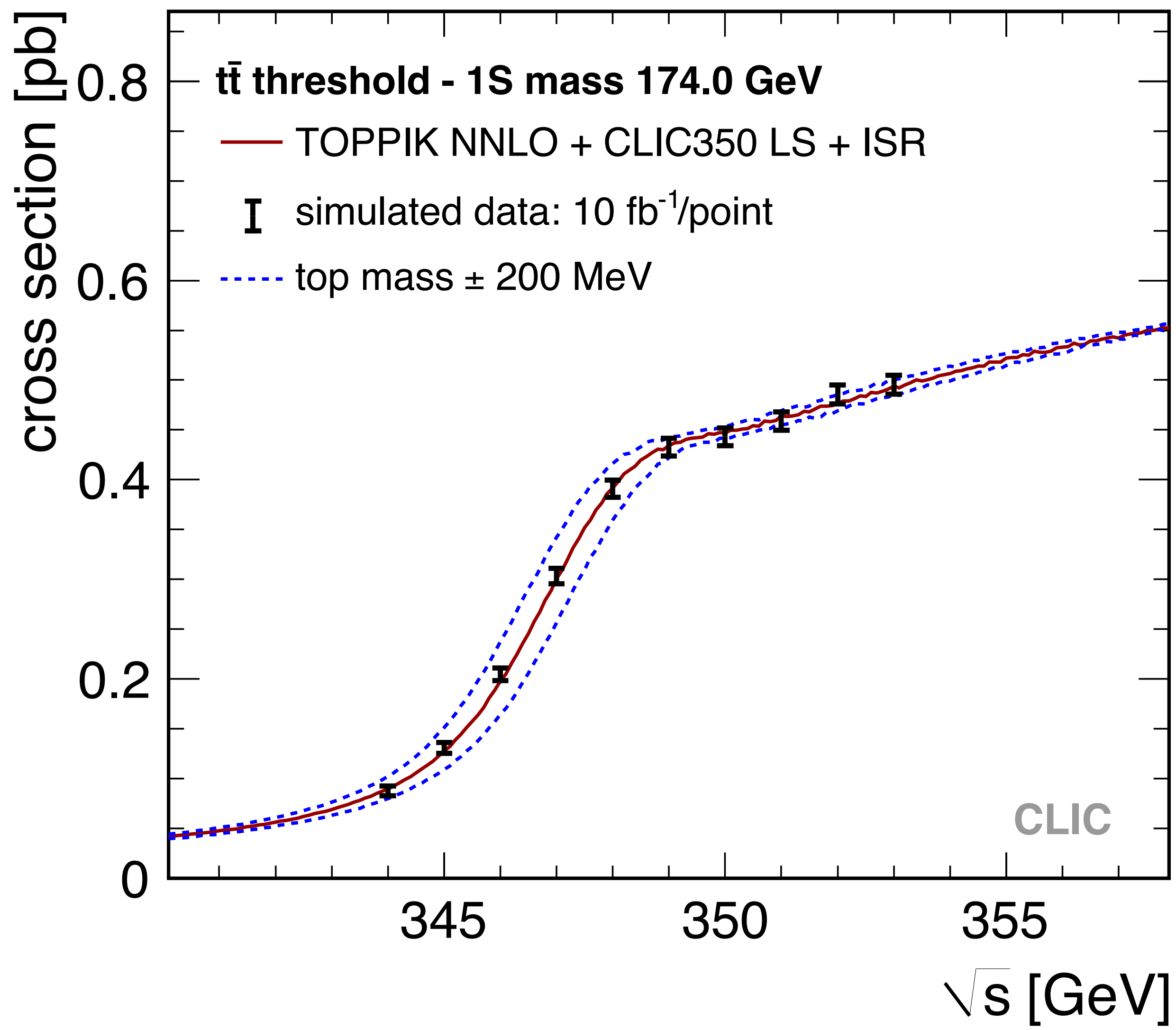
- ISR reduces the overall cross-section due to long tail to low energy, slightly broadens main peak and changes slope of cross-section "edge"
- Luminosity spectrum substantially washes out peak: Beam energy spread in addition to steeply falling spectrum towards lower energy

Threshold Scan: The Influence of the Machine



- Simulated threshold scan: 10 data points, 10 fb^{-1} each (~ 1 year of running for a fully commissioned machine)

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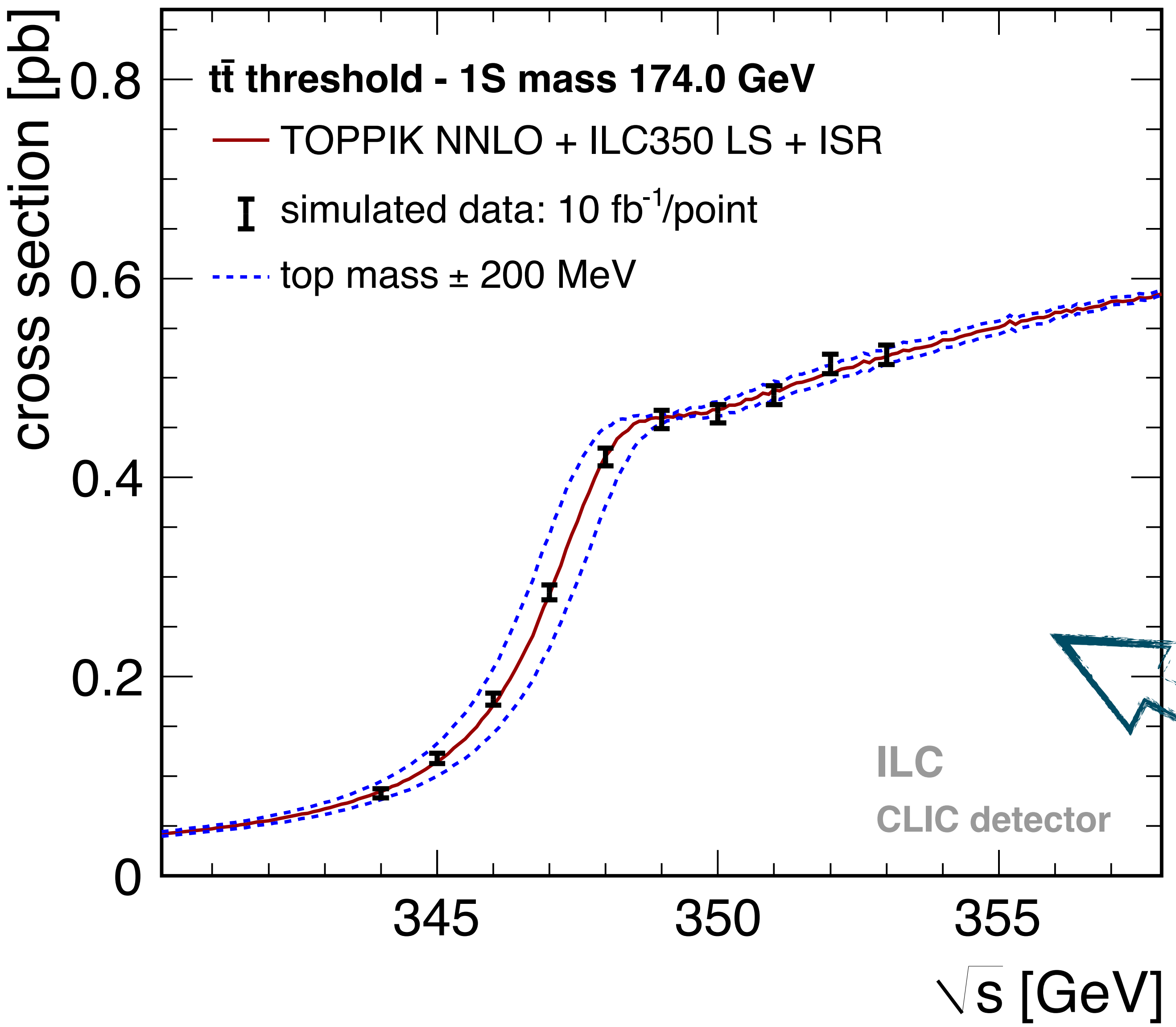

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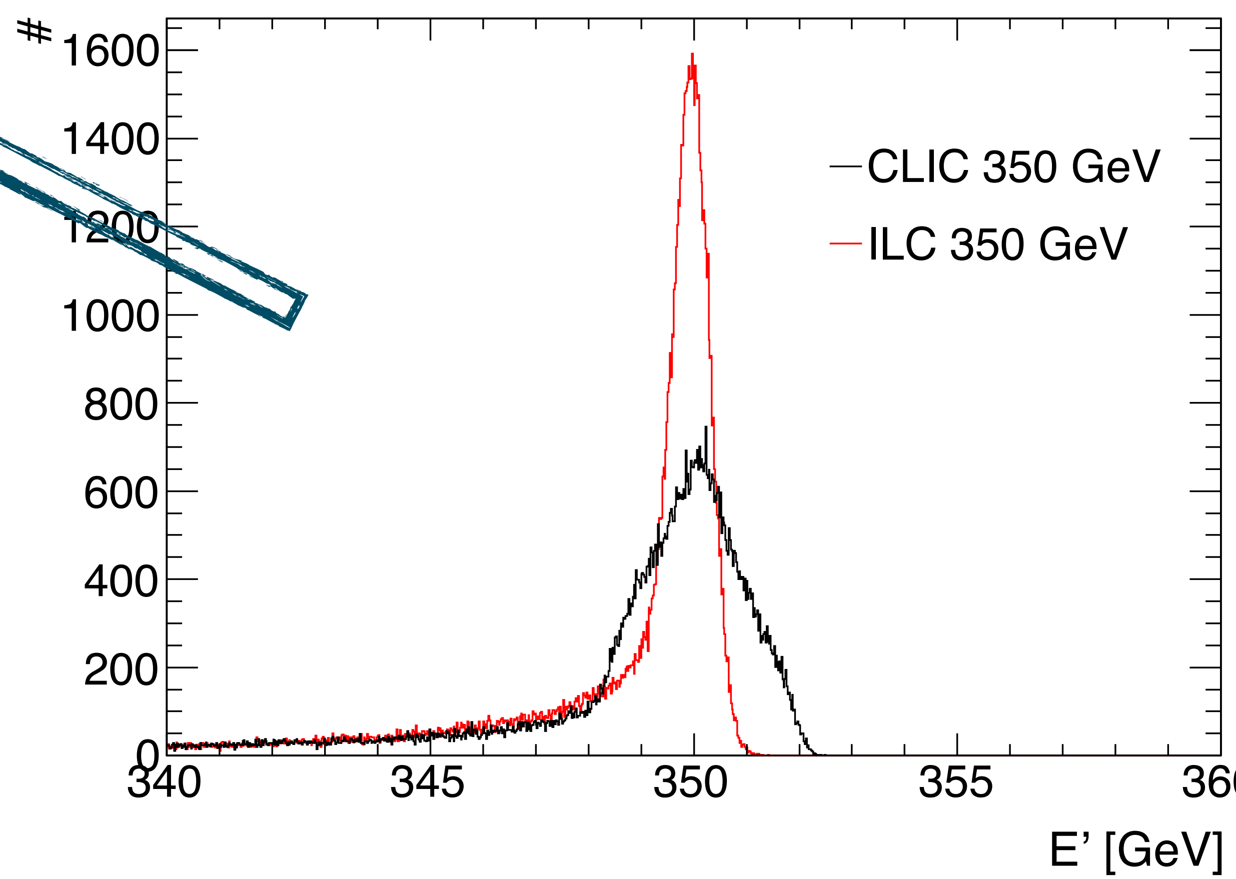
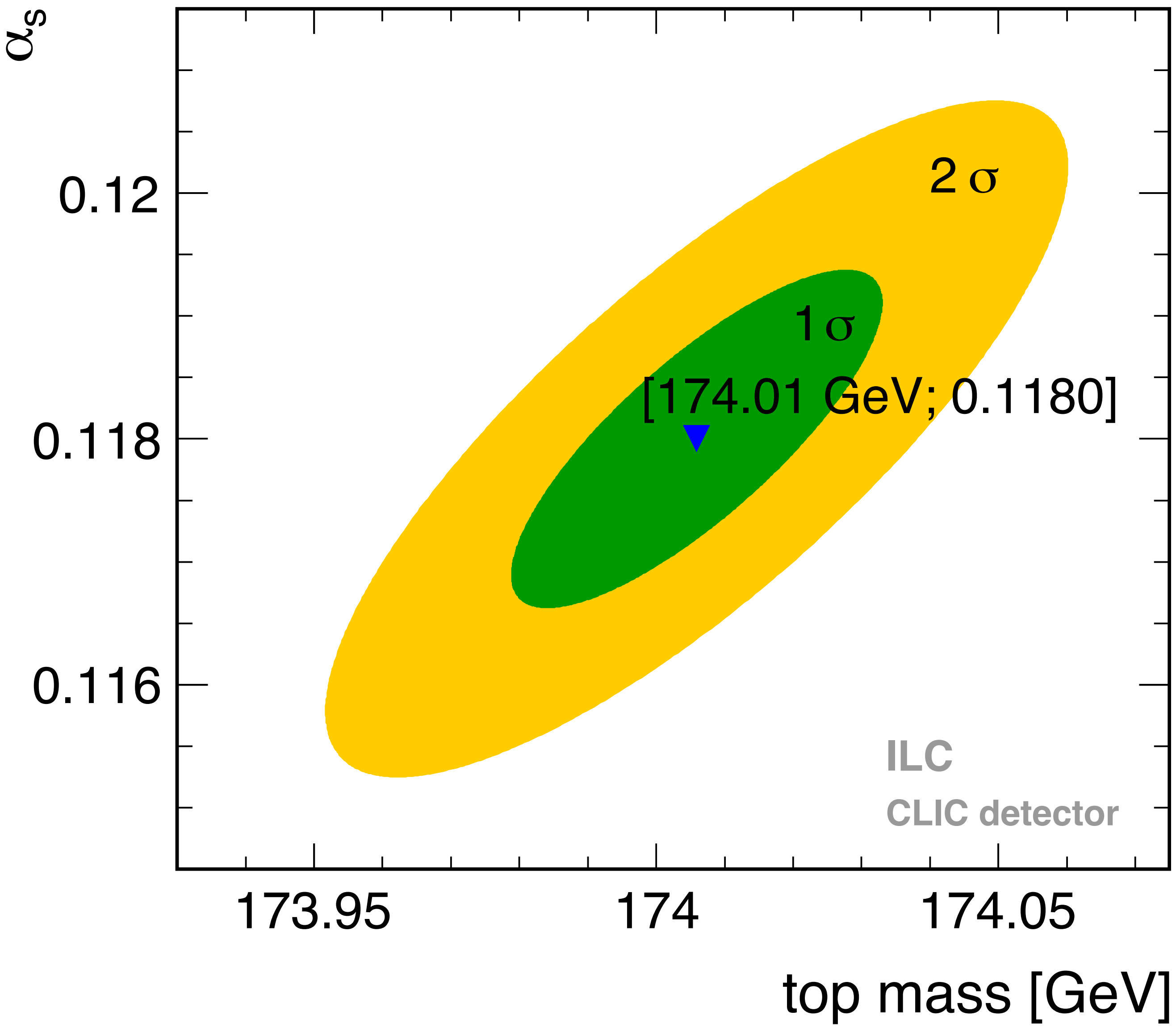


Results: Expected Precision



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

For CLIC luminosity spectrum:
~ 20% larger stat. uncertainty in m_t
~ 10% larger stat. uncertainty in α_s

differences (much) smaller than theory uncertainties

- The threshold behavior depends on m_t and strong coupling - Best robustness for further interpretation by combined extraction of both parameters

Mass at Threshold: Systematics

- Measurement likely limited by systematics, given the statistical power of a high-luminosity threshold scan at a LC
- Not a full study yet, but several key aspects have been looked at:
    - 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
    - Luminosity spectrum: 20% uncertainty on main peak width results in 75 MeV uncertainty on mass - Achievable precision still under investigation, current indications are that this uncertainty is considerably smaller

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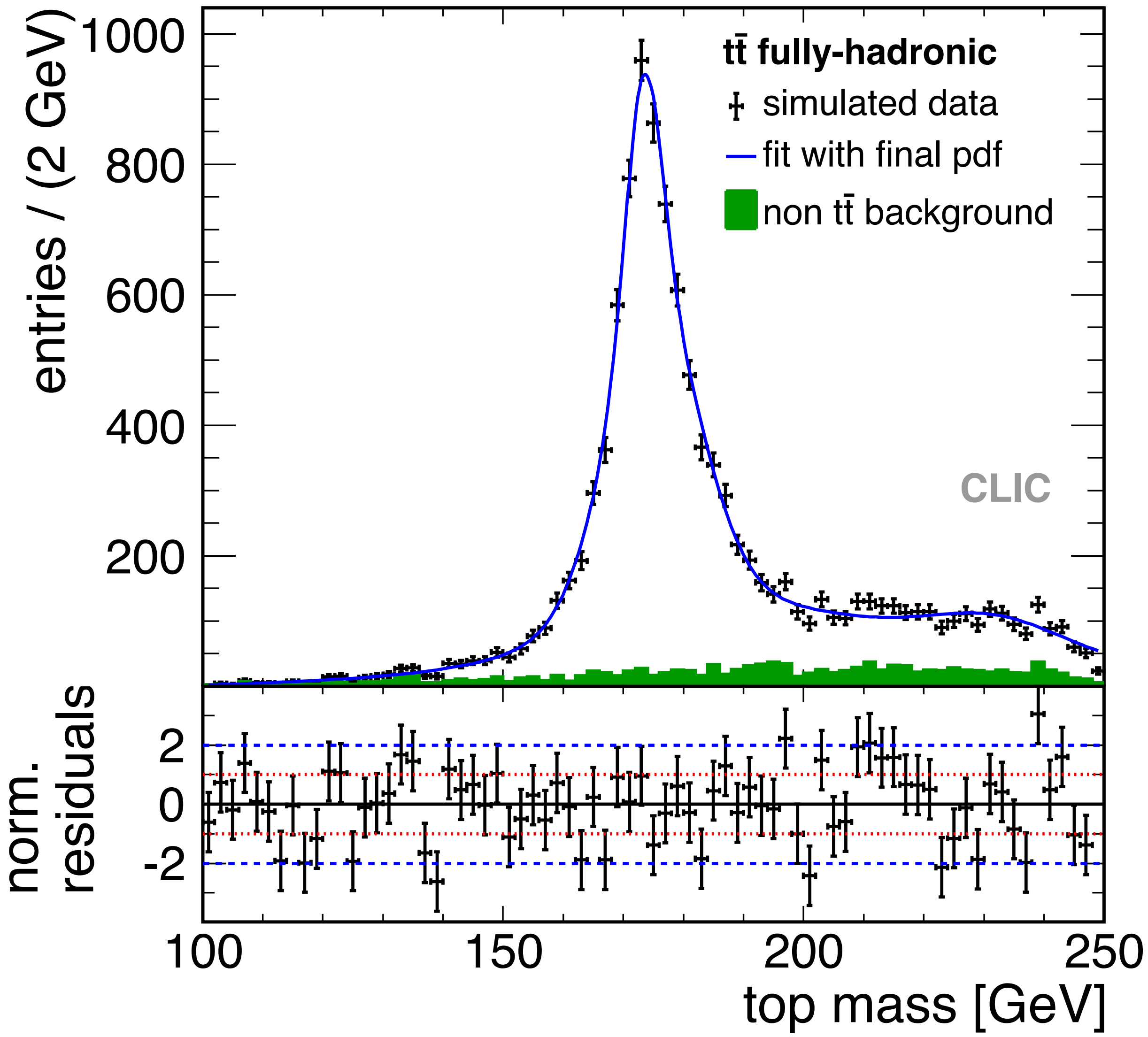
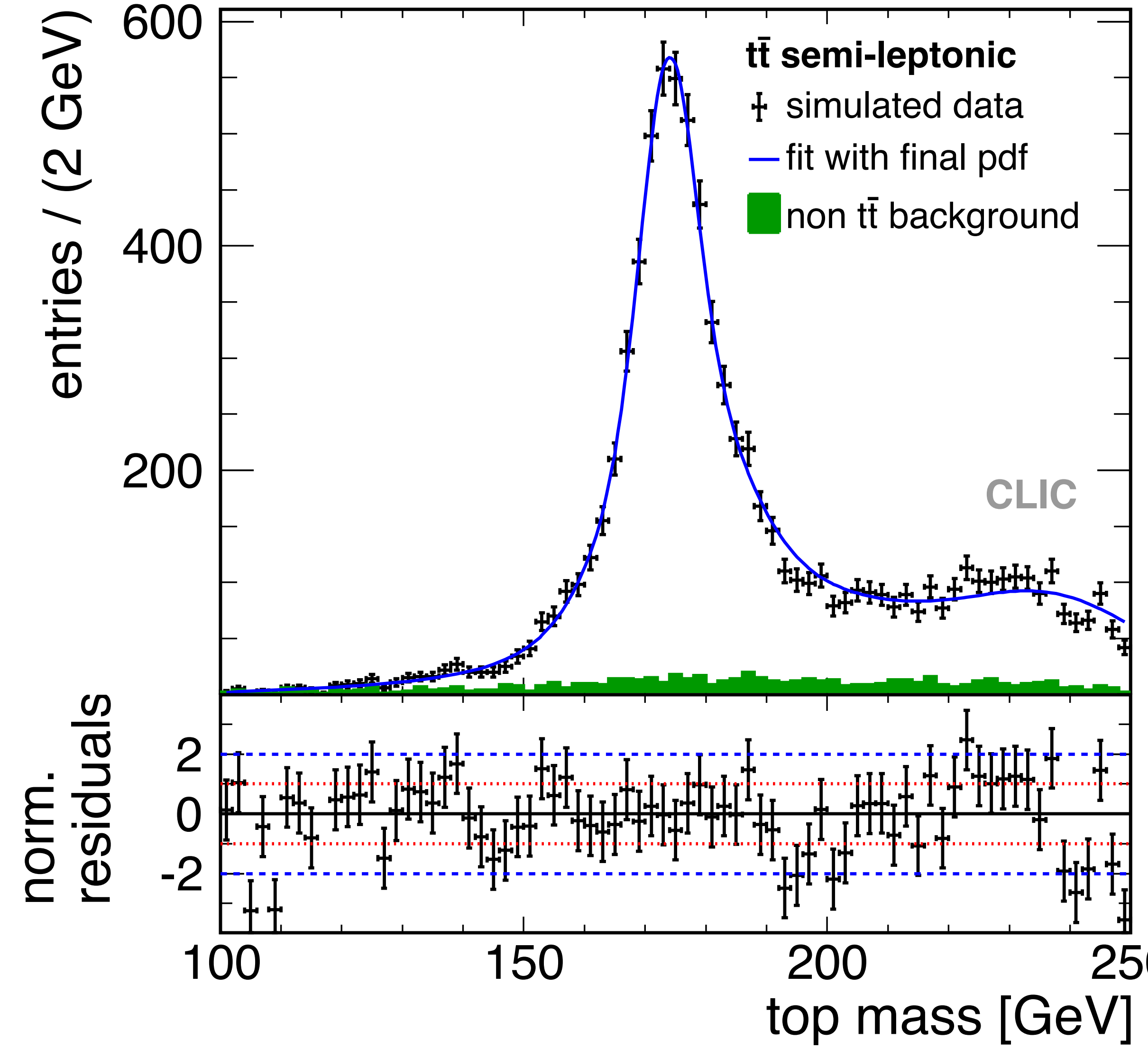
In addition: Theory uncertainties are incurred when transforming the 1S mass used to describe the threshold to the MSbar mass - O ~ 100 MeV, depending on α_s precision (here, the deal of shifting uncertainties from m_t to α_s would strike back)

Mass above Threshold - Invariant Mass

- Reconstruction of the invariant mass
  - Highest precision when requiring equal mass for both tops in the event, can be used in the kinematic fit - Measure only one mass per event
  - A key challenge: Correct pairing of jets to particles - b and W to tops, jets to W
    - Based on flavor tagging and invariant mass of W candidates: Highest b-tags as b jets, pick the best Ws out of the remaining possible combinations
      (NB: One can make mistakes in the b -identification: Decays of W to cs, tagging of c as b candidate -> Fix iteratively)

Invariant Mass - Results





- 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

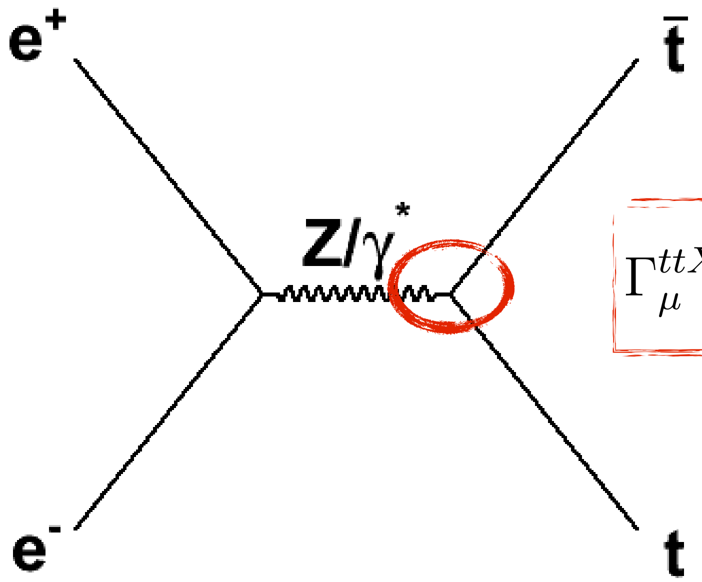
Systematics - Invariant Mass above Threshold

- 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 on the 50 MeV level
  - 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)

Tops as Tools - Asymmetries to search for New Physics

Probing EW Top Couplings



The coupling is described several coupling form-factors

$$\Gamma_\mu^{ttX}(k^2, q, \overline{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\overline{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$

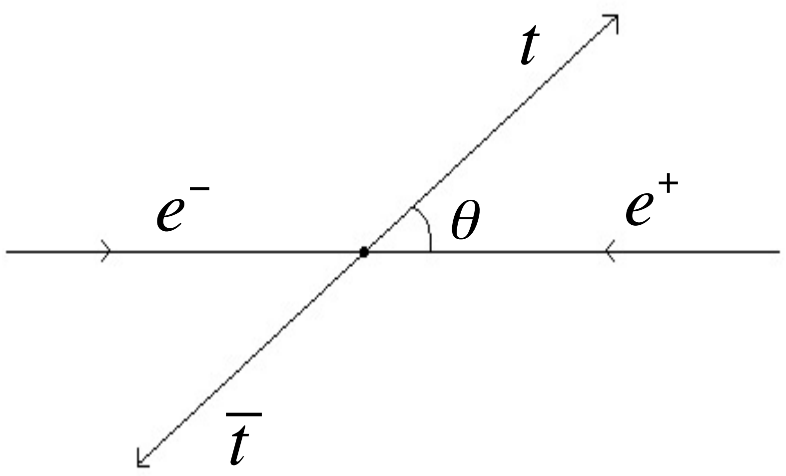
X: Z, γ, *A*: axial coupling *V*: vector coupling

- Most of these couplings can be accessed through measurements of
  - ***Total cross-section***
  - ***Forward-backward Asymmetry*** $\boldsymbol{A_{FB}}$
  - ***Helicity Angle λ*** distribution (related to fraction of left- and right-handed tops)
- For each: Two polarizations e^-_L - e^+_R, e^-_R - e^+_L
- Gives access to the five CP-conserving non-trivial form-factors

➯ Capability for polarized beams at LCs crucial for these measurements!

One Example: Measuring A_{FB}

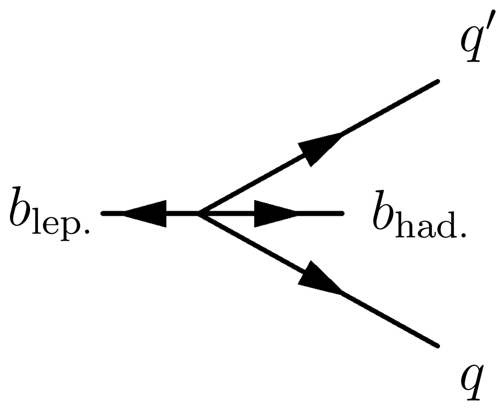
$$A_{FB} = \frac{N_{top}(\cos\theta > 0) - N_{top}(\cos\theta < 0)}{N_{top}(\cos\theta > 0) + N_{top}(\cos\theta < 0)}$$



- The key ingredient: Uniquely identifying the top (or anti-top)!
- The standard approach: In a leptonic W decay, the charge of the lepton tags the charge of the W, and with that the charge of the top quark:
  - positive lepton = top
  - negative lepton = anti-top
- Analysis typically based on semi-leptonic ttbar events: High BR, good tagging
- Increasing statistics: Using fully hadronic decays by tagging the charge of the b quark
  - Sum up the charge of all tracks associated to an identified b-jet - Take jets with a positive sum as belonging to a tbar, jets with a negative sum as belonging to t (still work in progress - Need to optimize flavor-tagging algorithm for charge ID)

Challenges in the Asymmetry Measurement

- Maximum parity violation in the weak interaction:
  - For right-handed top quarks (dominate for right-handed electrons in the collision):
    The W boson is emitted preferentially in the flight direction of the top - direction of hadronic W (and with that of the top) well reconstructed - in addition a very soft b quark



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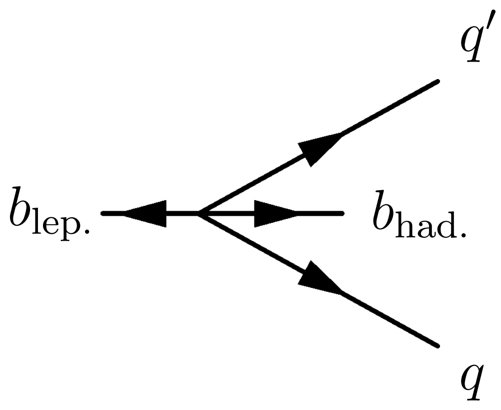

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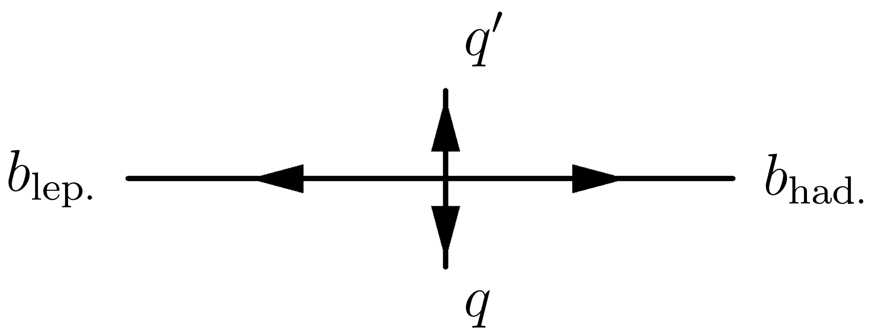

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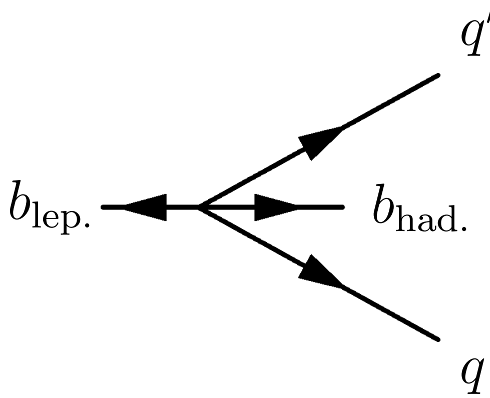

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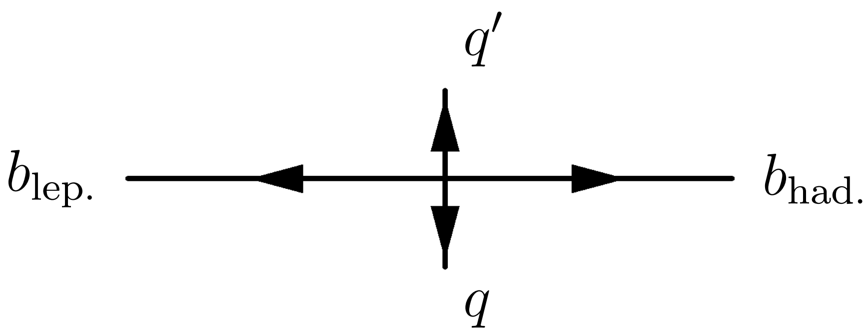
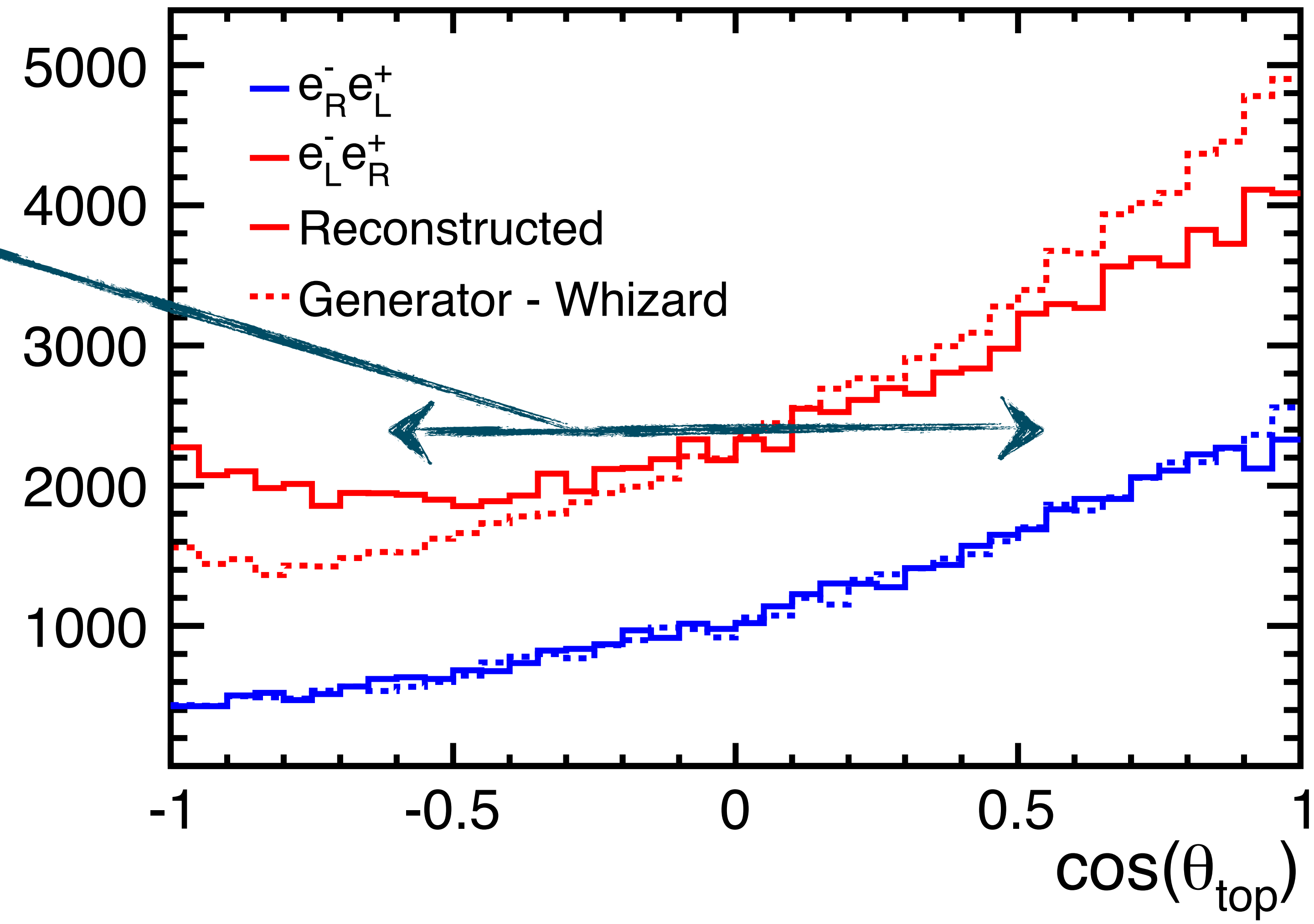


➯ Mistakes in top angle reconstruction when assigning the wrong b-jet to the W (has no consequence for t_R)

Challenges in the Asymmetry Measurement

- Illustrating the issue:

Migration effects:
mix-up in top reconstruction
tends to reduce asymmetry



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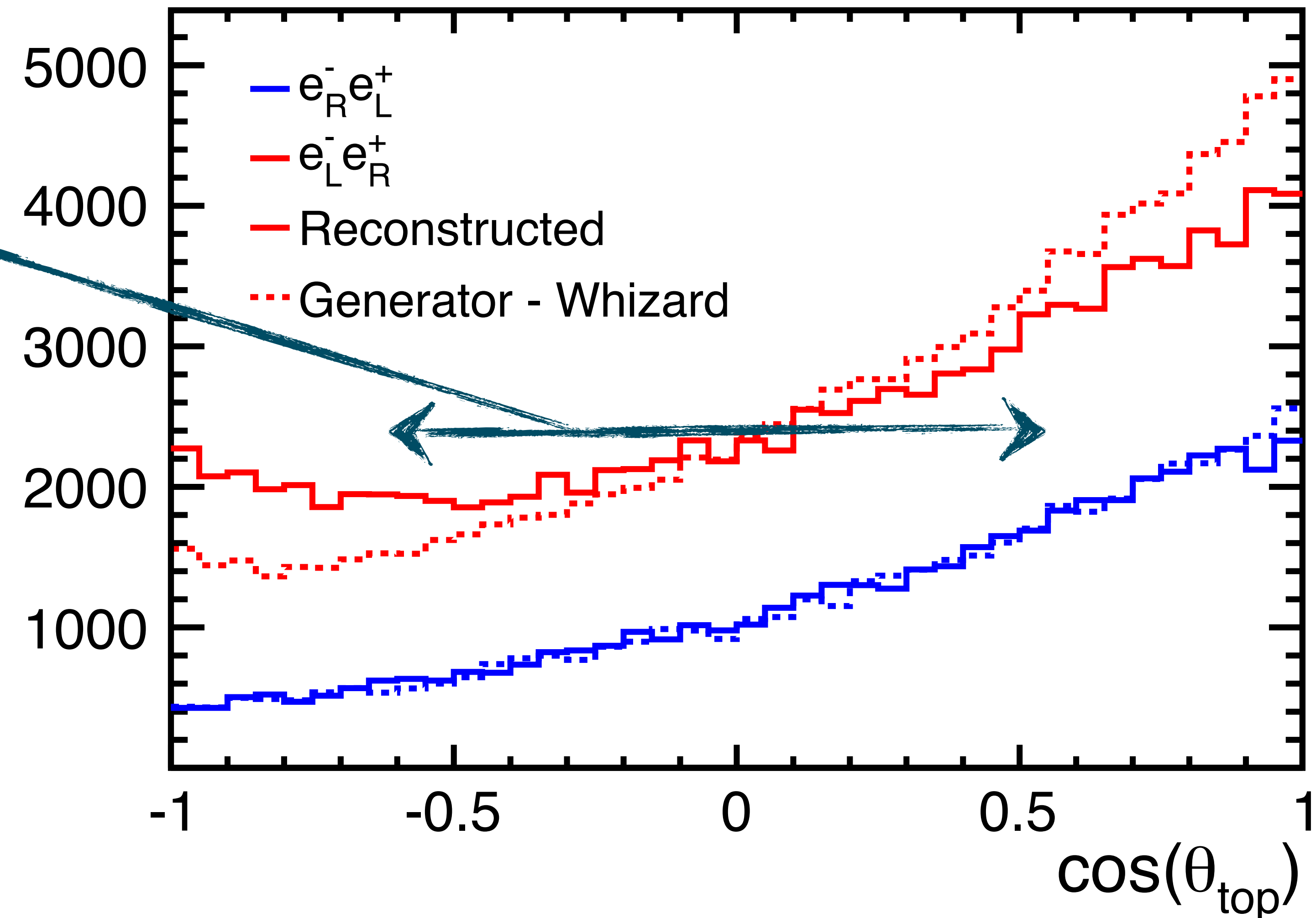


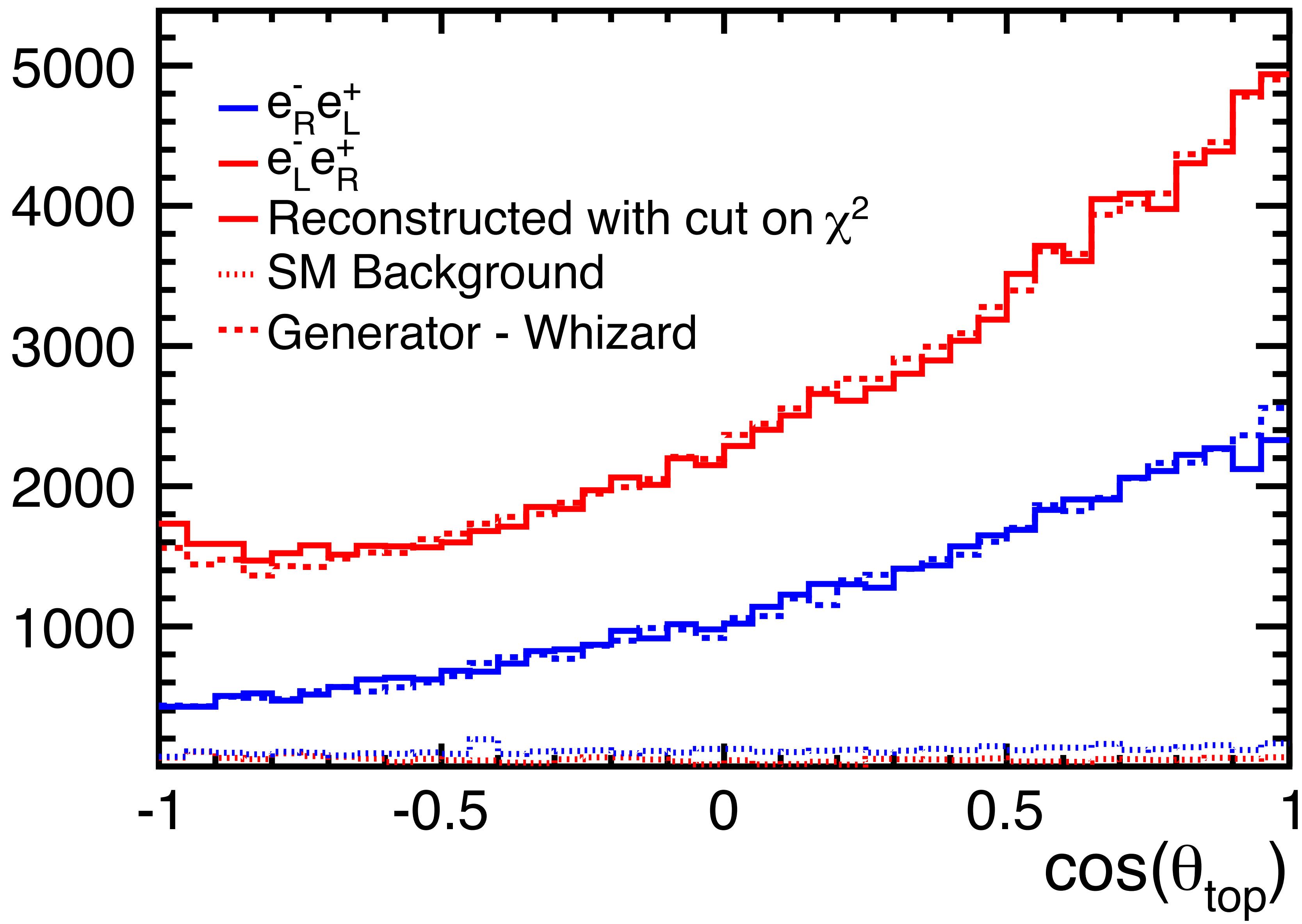
- The cure: Impose strict requirements on the quality of reconstructed events: Correct b momentum in t restframe, correct t boost, correct angle between b and W:

$$\chi^2 = \left(\frac{\gamma_t - 1.435}{\sigma_{\gamma_t}}\right)^2 + \left(\frac{E_b^* - 68}{\sigma_{E_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} - 0.26}{\sigma_{cos\theta_{bW}}}\right)^2$$

Taking a Hard Line: Fixing Event Migrations

- Cut on top event χ^2:
  Clean top reconstruction out of b and W fixes the issue

  The price to pay:
  Reduced efficiency
  (by about a factor of 2)



The results:

A statistical precision on A_{FB} for 500 fb^{-1} equally shared between two polarization configurations of:
1.8% for polarizations (-0.8, +0.3 - predominantly e^-_L e^+_R)
1.3% for polarizations (0.8, -0.3 - predominantly e^-_R e^+_L)

Systematics

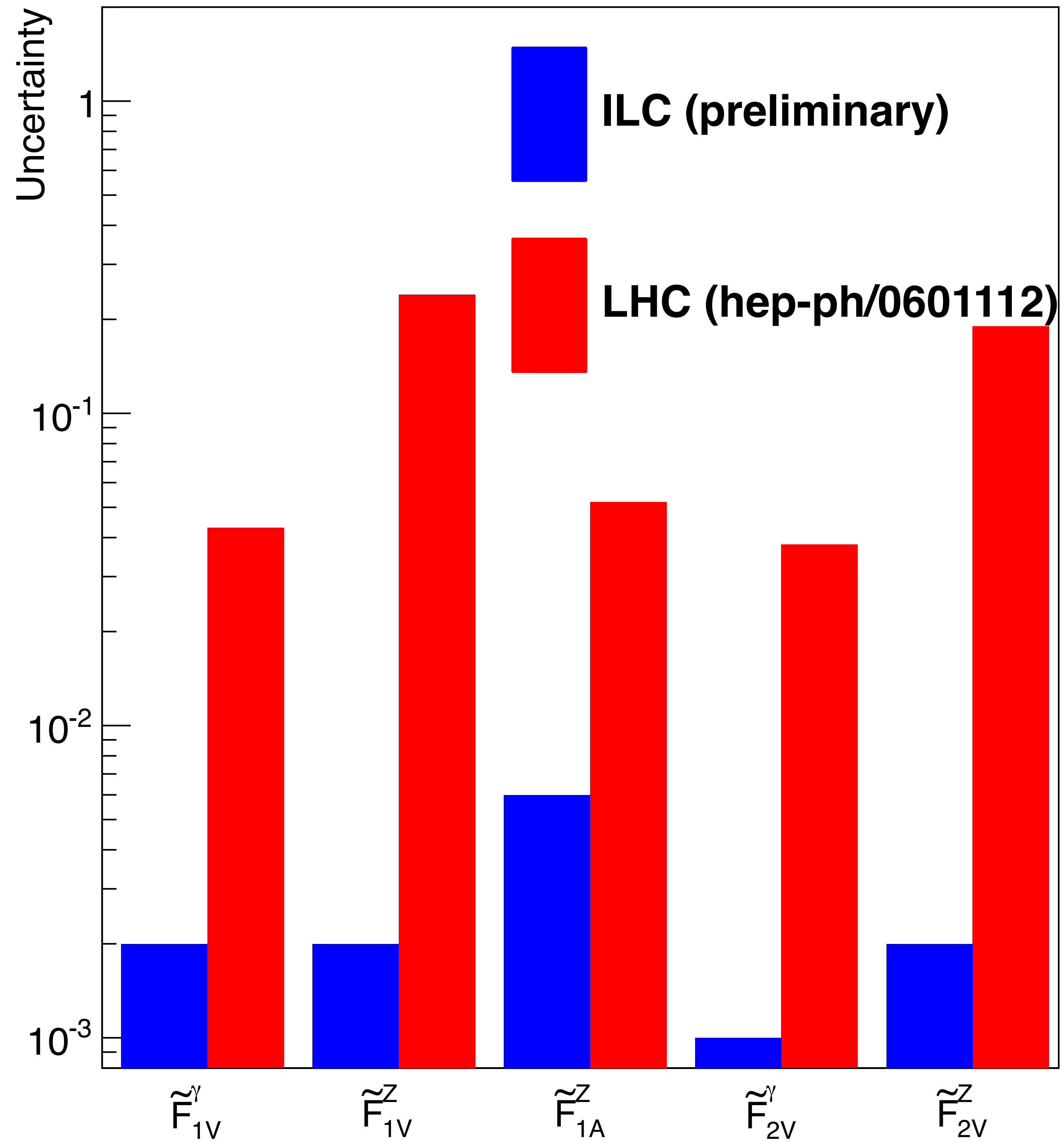
- As for the mass, the studies are not complete yet, but quite a few effects have been looked at
  - Overall luminosity - key for cross sections, cancels for asymmetries - expected to be known at the 0.1% level
  - Polarization: Expect 0.1% uncertainty for electrons, 0.35% for positrons - Uncertainties on asymmetries on the 0.25% level - smaller than statistical uncertainties
  - Selection efficiencies: Need to be understood, systematics can be reduced with less "complicated" selection - Replacement of χ^2 cut by b-charge might to suppress event migrations desirable
  - Other experimental uncertainties (acceptance, b-tagging, material, ...) - LEP used an uncertainty on R_b of 0.2%
  - Theory uncertainties: - Comparable to experimental uncertainties at present

In general: Expect systematics not exceeding statistical precision - if required control of experimental quantities is achieved

The global Picture: Top Couplings at a LC

- More than an order of magnitude improvement over LHC expectations across the board- in some cases as much as two orders

Additional potential may exist at higher energies - with further improved BSM sensitivities
Not studied yet...



Summary

- Linear colliders offer excellent conditions for precision top physics: Good reconstruction of events, almost background-free identification
  - Profits from
    - Knowledge of initial state in e^+e^- collisions
    - Excellent detectors: Flavor tagging, jet reconstruction, hermeticity
    - Cross-sections of physics backgrounds not very much larger than signal

- A qualitatively new level of precision in the measurement of top properties: Mass with a to 100 MeV (or better?)
  - Requires theory uncertainties at the same or smaller level - Possible for a threshold scan - Much more is needed to achieve the same above threshold

- Use tops to probe New Physics: EW couplings 1 order of magnitude+ better than LHC - Exploit sensitivity of high-mass top quark to possible BSM physics