Top at CLIC

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Excellence Cluster
Universe

Measuring the Top Mass at CLIC

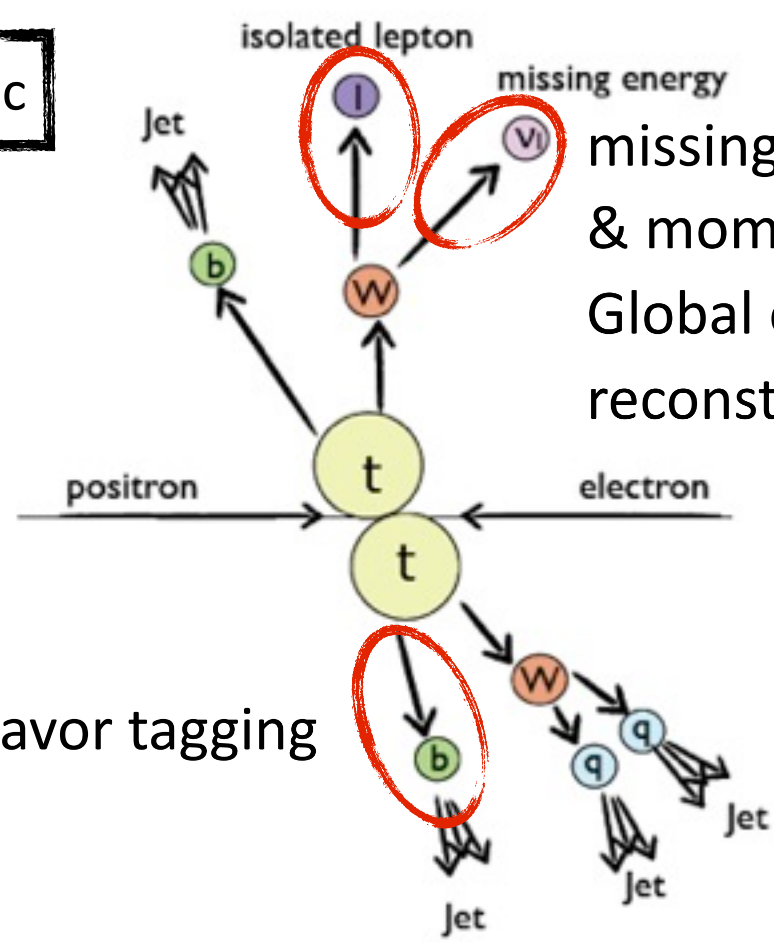
- Two approaches at Linear Colliders:
- Threshold scan:
  - Theoretically well understood
  - Measurement of top pair production cross section at several points around threshold
  - Requires dedicated operation of machine for extended period
- Mass measurement from invariant mass of decay products:
  - Theoretically problematic (experiments measure “event generator top mass”, treatment of QCD corrections ill-defined) - progress is being made
  - Requires excellent jet and lepton reconstruction, helped by kinematic constraints
  - Can be performed at arbitrary energy above threshold - does not compete with other measurements, high integrated luminosity unproblematic

The Top Mass as a Benchmark Process

- Invariant mass reconstruction more challenging from the detector perspective:

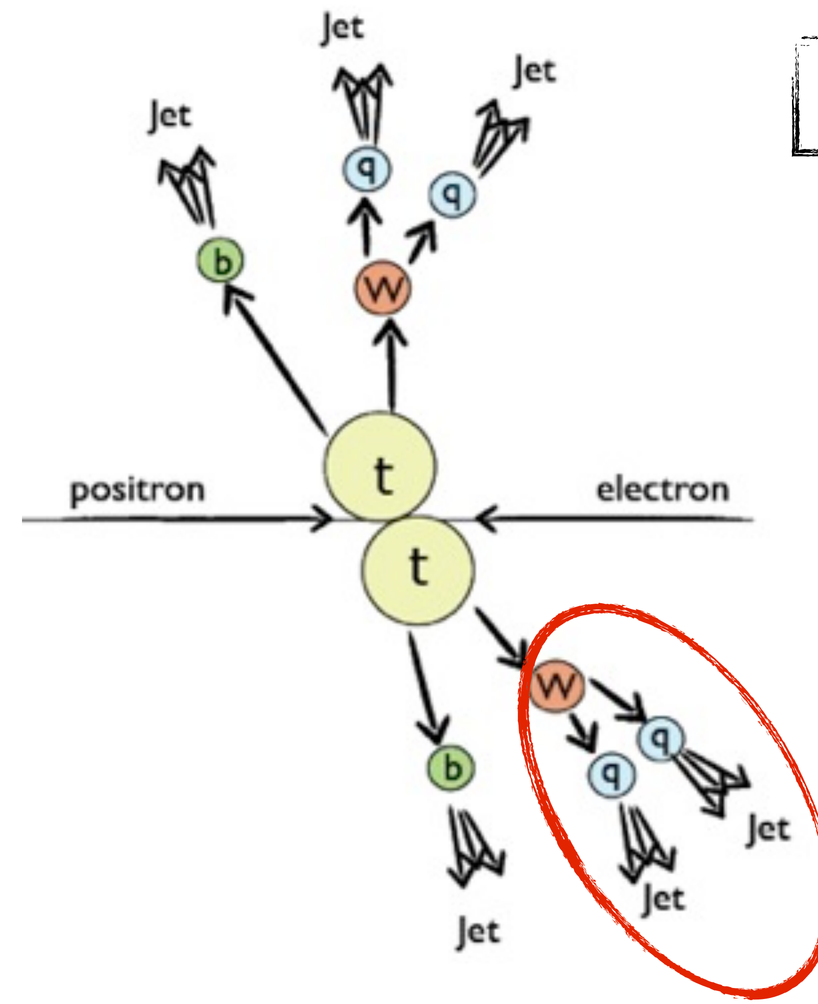
semi-leptonic

lepton-ID
isolation



missing energy
& momentum:
Global event
reconstruction

flavor tagging



all-hadronic

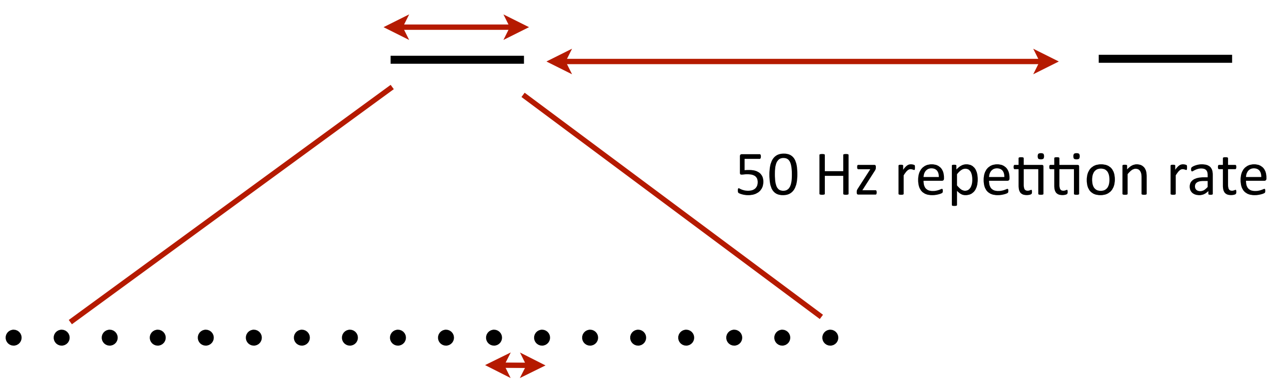
jet energy,
invariant mass

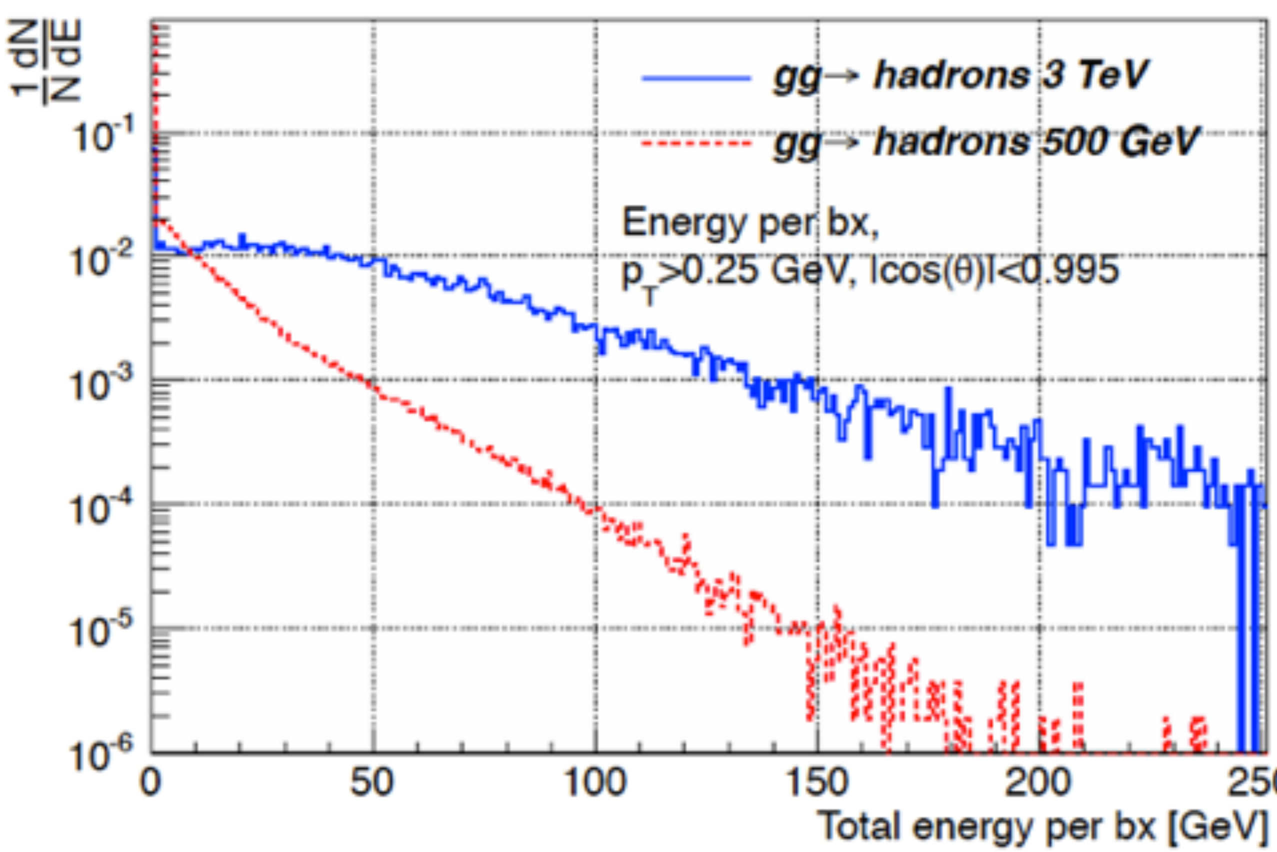
- At 500 GeV: Direct comparison to studies performed for ILC

Experimental Conditions at CLIC

The bunch structure at CLIC

- 0.5 ns bunch spacing
- 312 bunches per train (354 at 500 GeV)

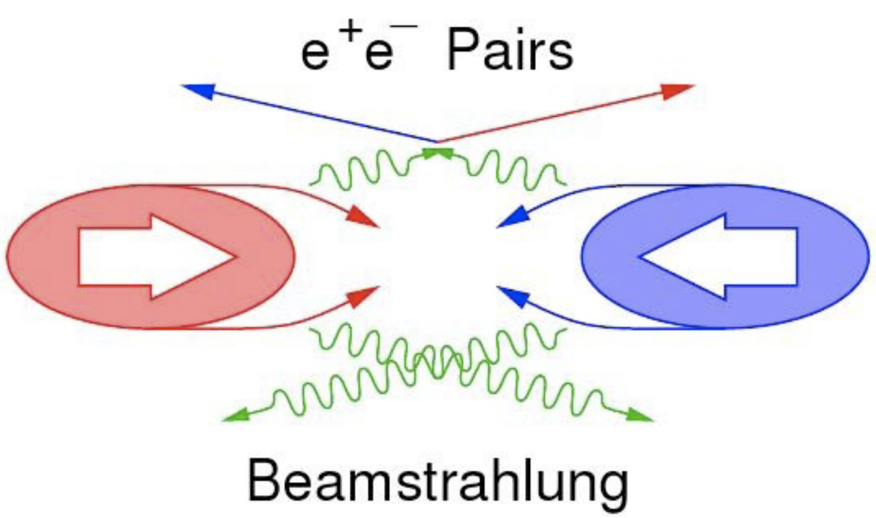




Beamstrahlung driven by energy and focusing

For 500 GeV:

- mean bunch energy loss:
  - $\Delta E/E \sim 7\%$
- coherent e^+e^- pairs:
  - 2.0×10^2 / bunch crossing
- incoherent e^+e^- pairs:
  - 8.0×10^4 / bunch crossing
- $\gamma\gamma \rightarrow$ hadrons interactions:
  - 0.3 / bunch crossing (13.3 GeV, 3.4 GeV in calorimeters)



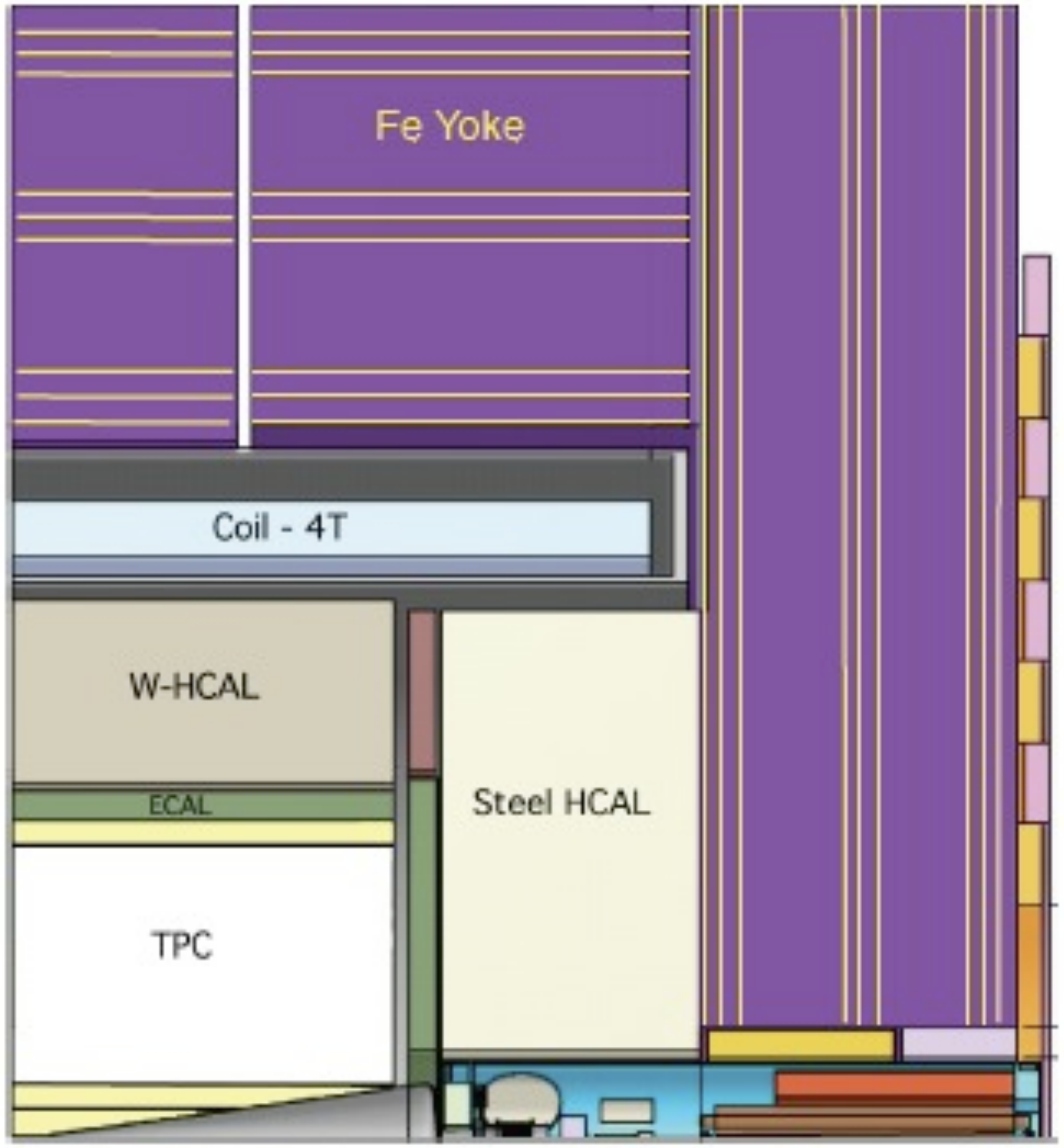
The CLIC_ILD Detector

- Closely following the ILD detector concept, with modifications to account for higher energy and higher backgrounds
  - Relevant modifications:

  Increased magnetic field: 4T

  Increased depth of HCAL: 7.5 λ, achieved with Tungsten absorbers

  Increased inner radius of vertex detector: 25 mm (31 mm @ 3 TeV), compared to 16 mm in ILD



In all detector systems: Time resolution on the few ns level (ns level in calorimeters): Introduce timing in particle flow event reconstruction

CLIC Event Reconstruction

CLIC event (Simulation at 500 GeV):

Integration over a full bunch train

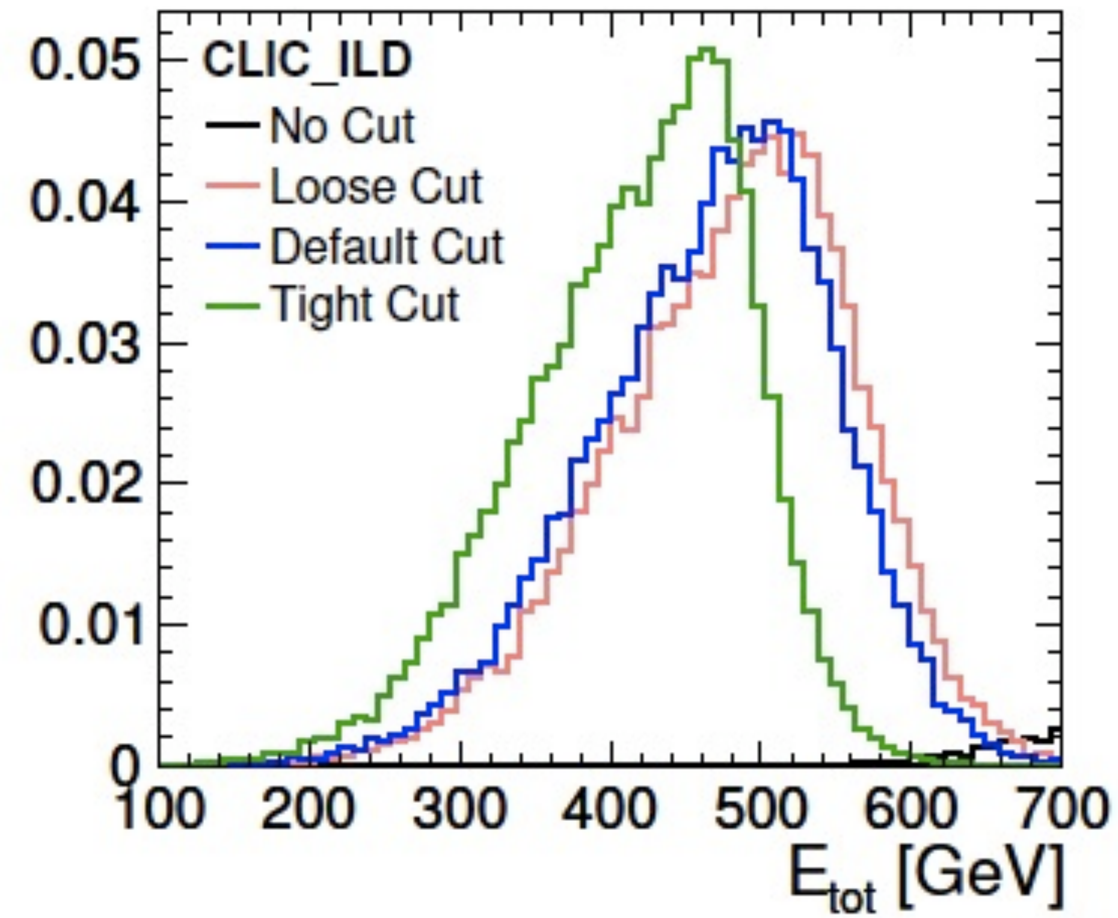
- ~ 312 bunches

Reconstruction challenge:

Suppress pile up from $\gamma\gamma \rightarrow$ hadrons interactions

- adds significant energy to events
- in particular in the forward region
- not in time with the physics event

Effect of timing and p_t cut strengths



Reconstruction Technique: Particle Flow

- Pandora Particle Flow event reconstruction based on geometrical hit assignments
- Application of a combination of timing and pt cuts specially for low p_t particles to reject $\gamma\gamma \rightarrow$ hadron background events
- Different strength of cuts are available for 3 TeV and 500GeV center-of-mass energy

Event Simulation

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

process type	$e^+e^- \rightarrow$	cross section σ	event generator
Signal ($m_t = 174\,\text{GeV}$)	$t\bar{t}$	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

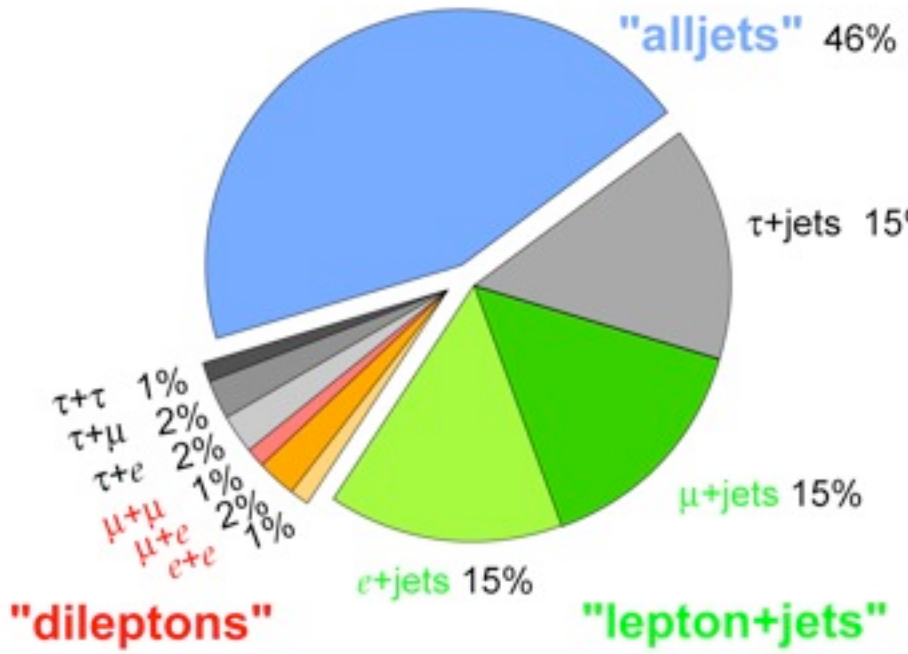
- Always: All possible decay channels simulated, selection of final states of interest as part of the analysis
  - Use of PYTHIA to guarantee correct width of intermediate and final-state bosons

Event Classification

- Classification of top pair events based on W decay

  Identification of isolated leptons:

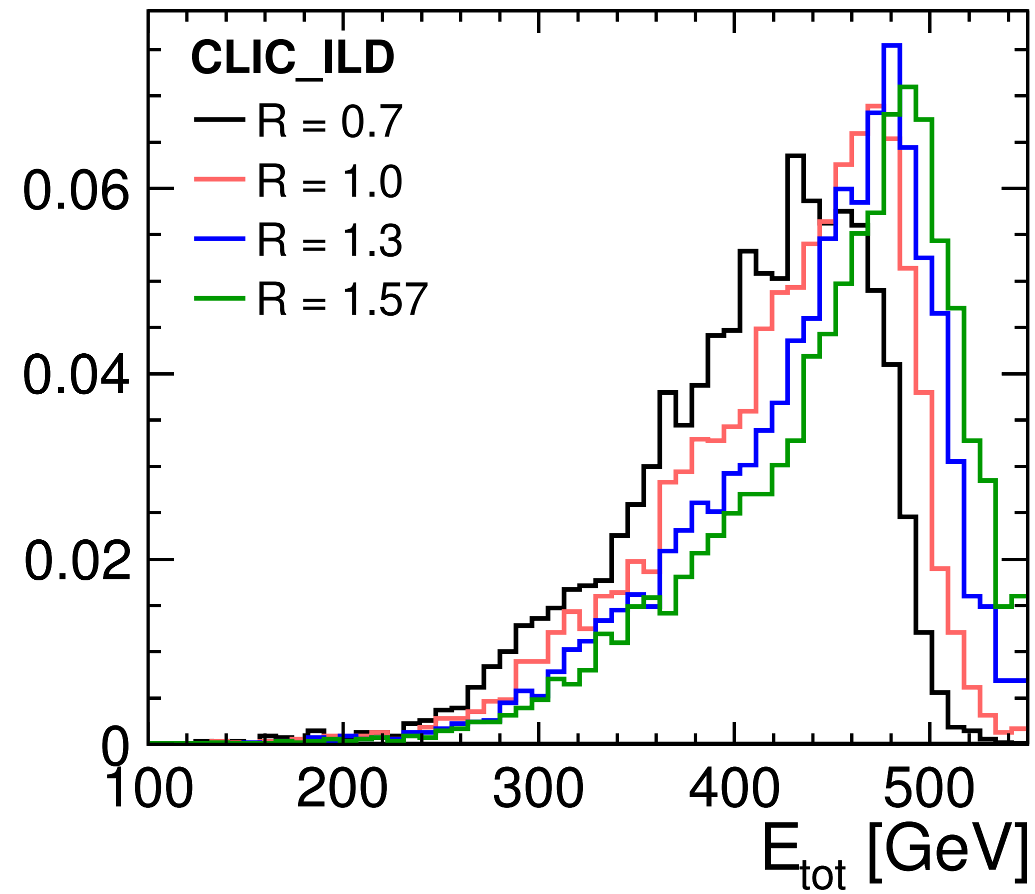
  - No lepton: fully-hadronic
  - One lepton: semi-leptonic
  - two or more leptons: fully-leptonic



- For further analysis: fully-hadronic and semi-leptonic candidates
  - Special case: τ final states - should be rejected, poor mass measurement due to additional neutrino
    - Depending on τ decay, these events end up may end up in the signal samples
    - Rejection later in the analysis based on kinematic constraints

Jet clustering and Flavor Tagging

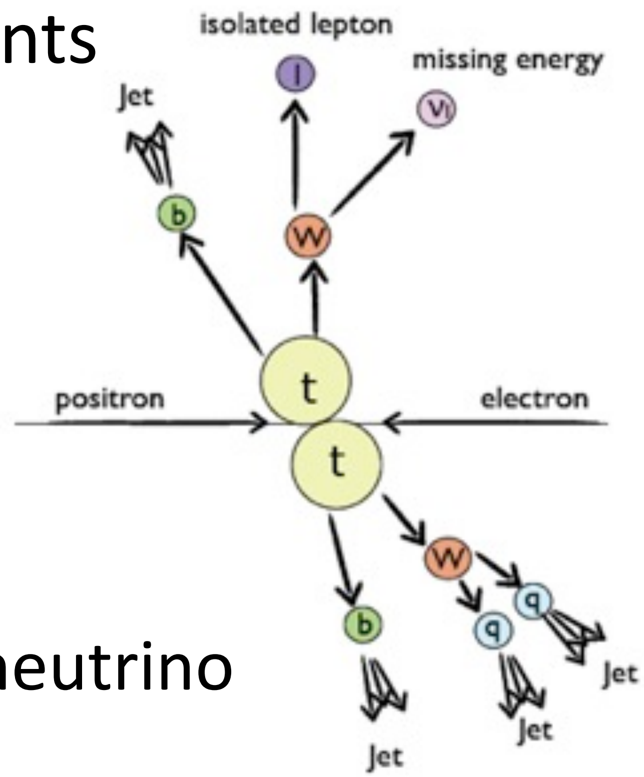
- Jet finding with "hadron k_t" algorithm ($\Delta\eta$, $\Delta\phi$)
  - Exclusive Mode: Force to 4 or 6 jets (lepton excluded)
  - Jet algorithm helps to reject background
  - R value defines size of jet, cross checked with distribution of events without machine background



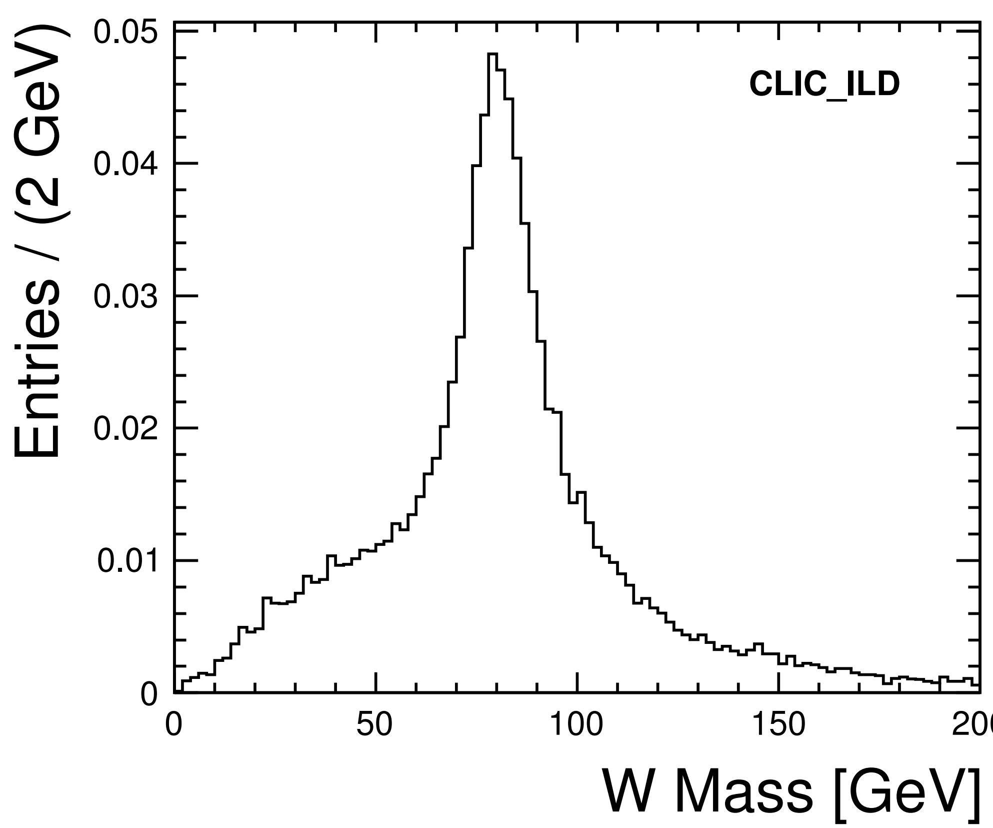
- Flavor tagging based on LCFI Vertex Package
  - Based on a neural net, trained with statistically independent top events
  - Every jet gets assigned with a b-tag value
  - Jets with highest two b-tag values are chosen to be b-jets

Jet combinatorics

Semi-Leptonic events

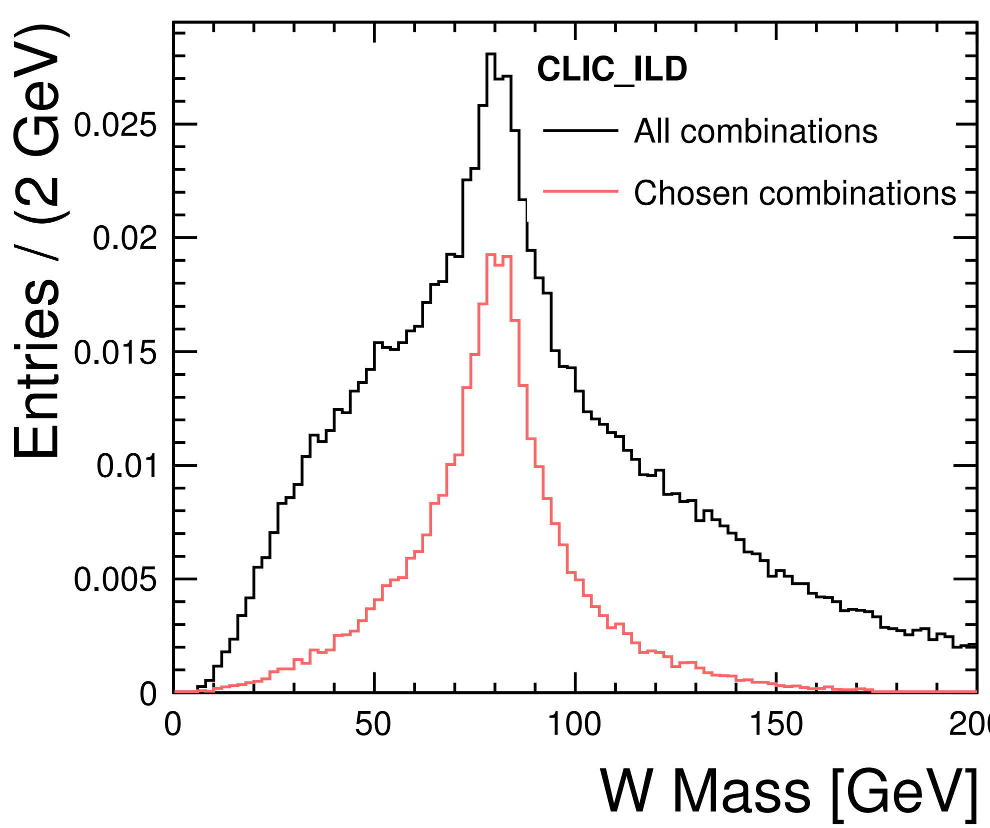


- 2 b-jets
- 2 light-jets
- 1 lepton
- missing energy / neutrino



Full-Hadronic events

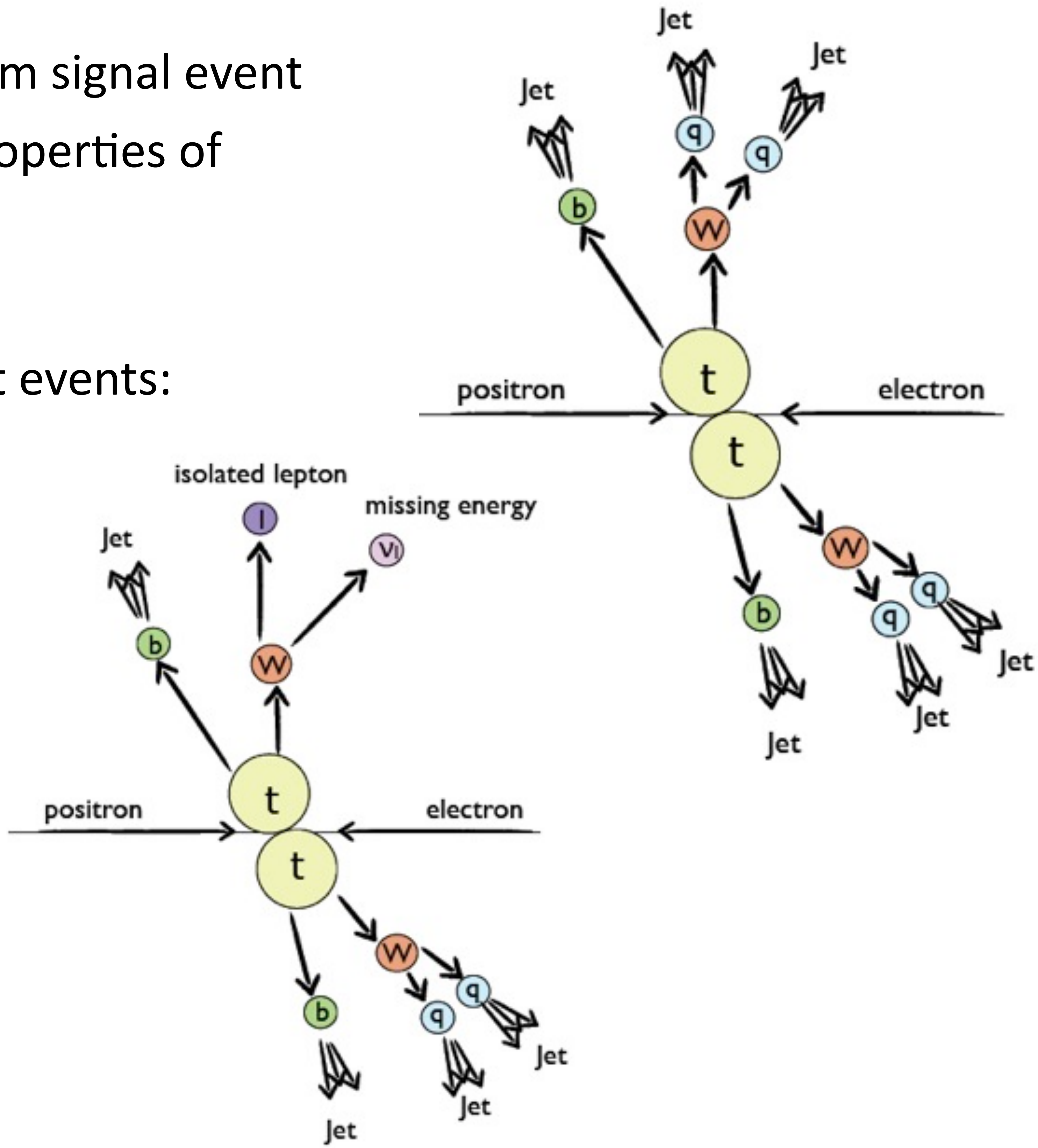
- 4 light-jets
- 2 b-jets
- Calculation: $|m_{ij} - m_W| + |m_{kl} - m_W|$
- Minimum value defines best permutation



Kinematic Fit

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

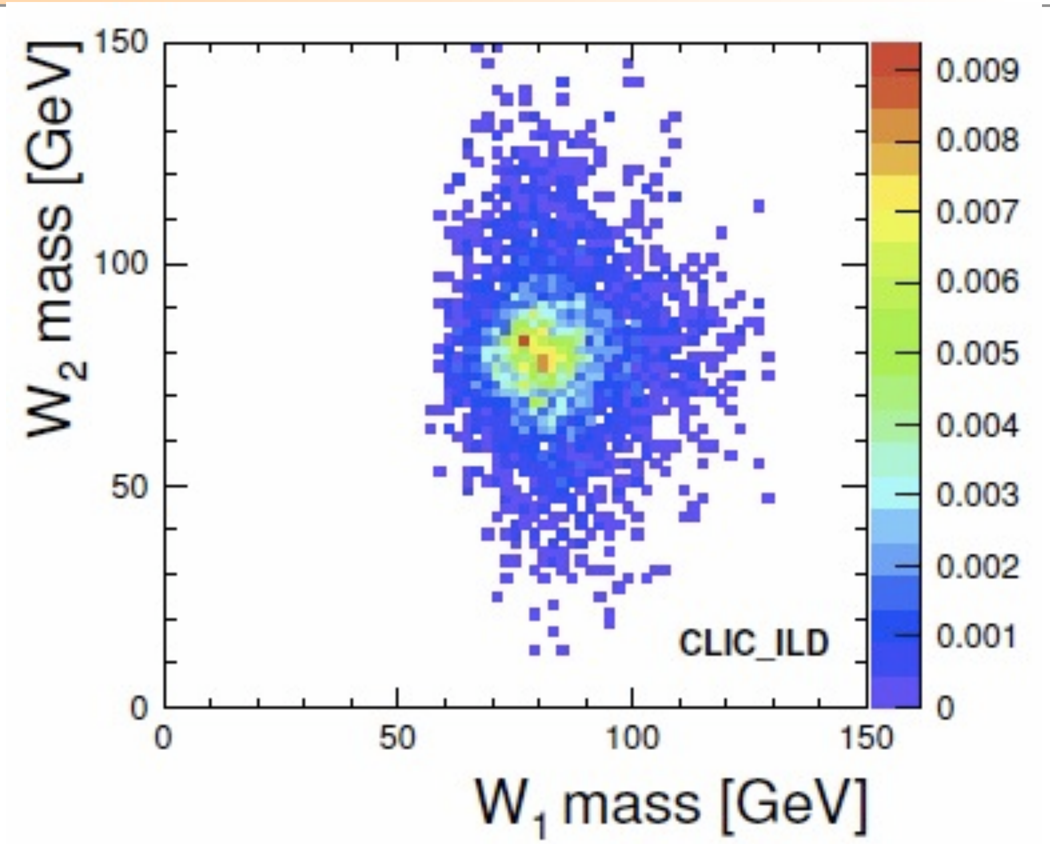
- Constraints for four and six jet events:
  - Energy conservation
  - Momentum conservation
  - W mass equals 80.4 GeV
  - Equal top masses

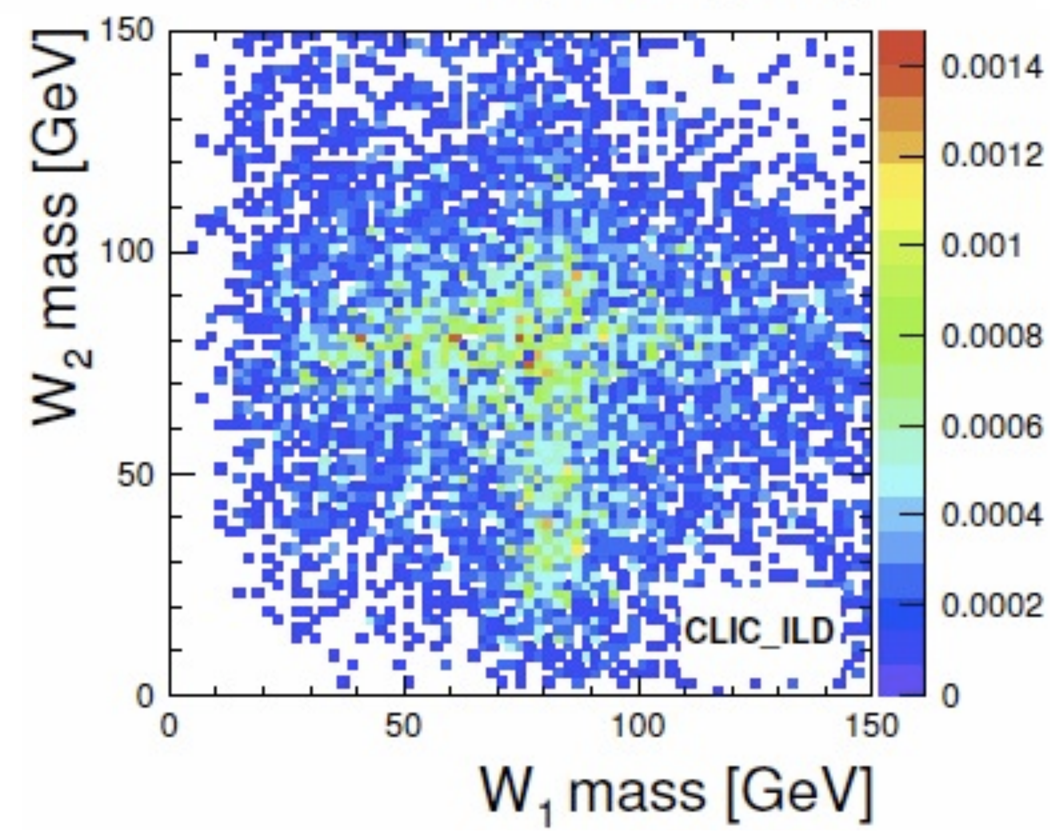


Kinematic Fit

Kinematic fit 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





Kinematic Fit and Background Rejection

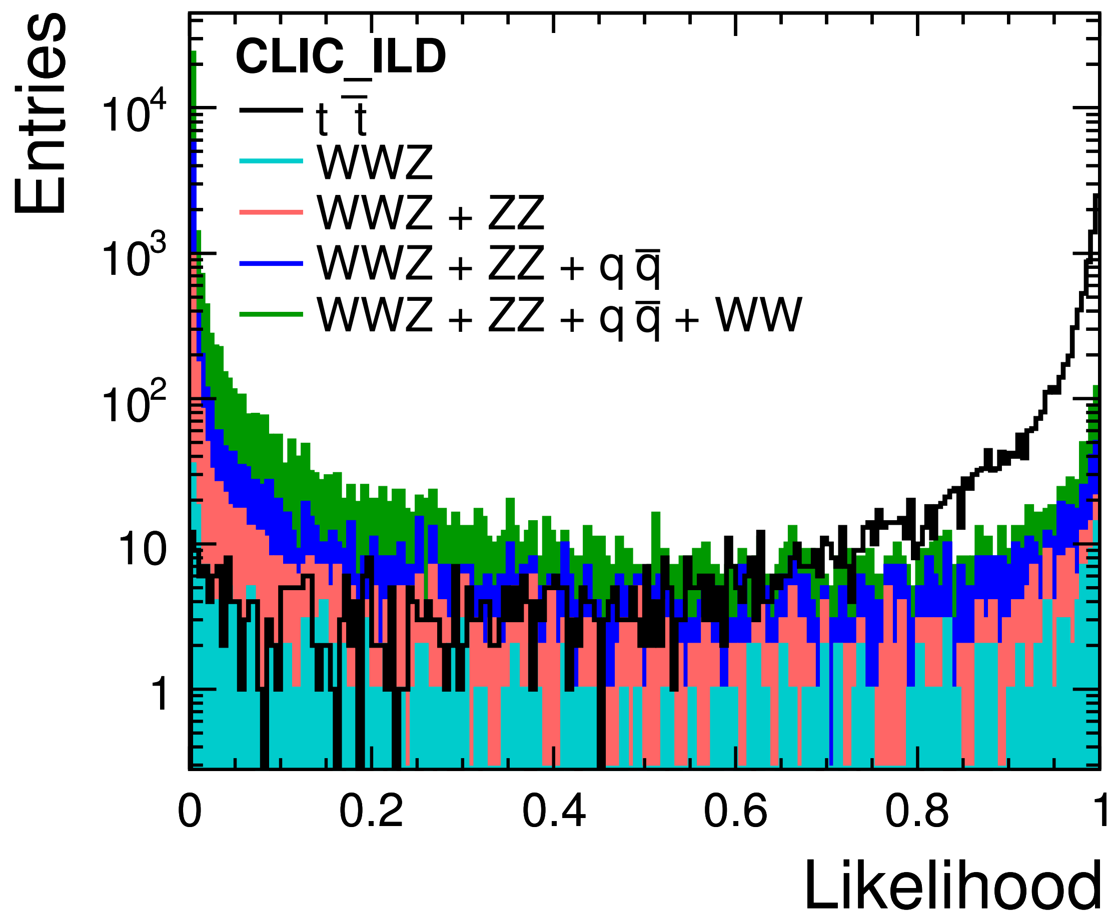
Kinematik Fit

- 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

Full-Hadronic



Kinematic Fit and Background Rejection

Kinematik Fit

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

Overall background rejection: > 99%

Overall signal selection:

Full-Hadronic: 35%

Semi-Leptonic: 56%

- Signal efficiency could be improved
- Analysis goal: clean events, not maximized statistics

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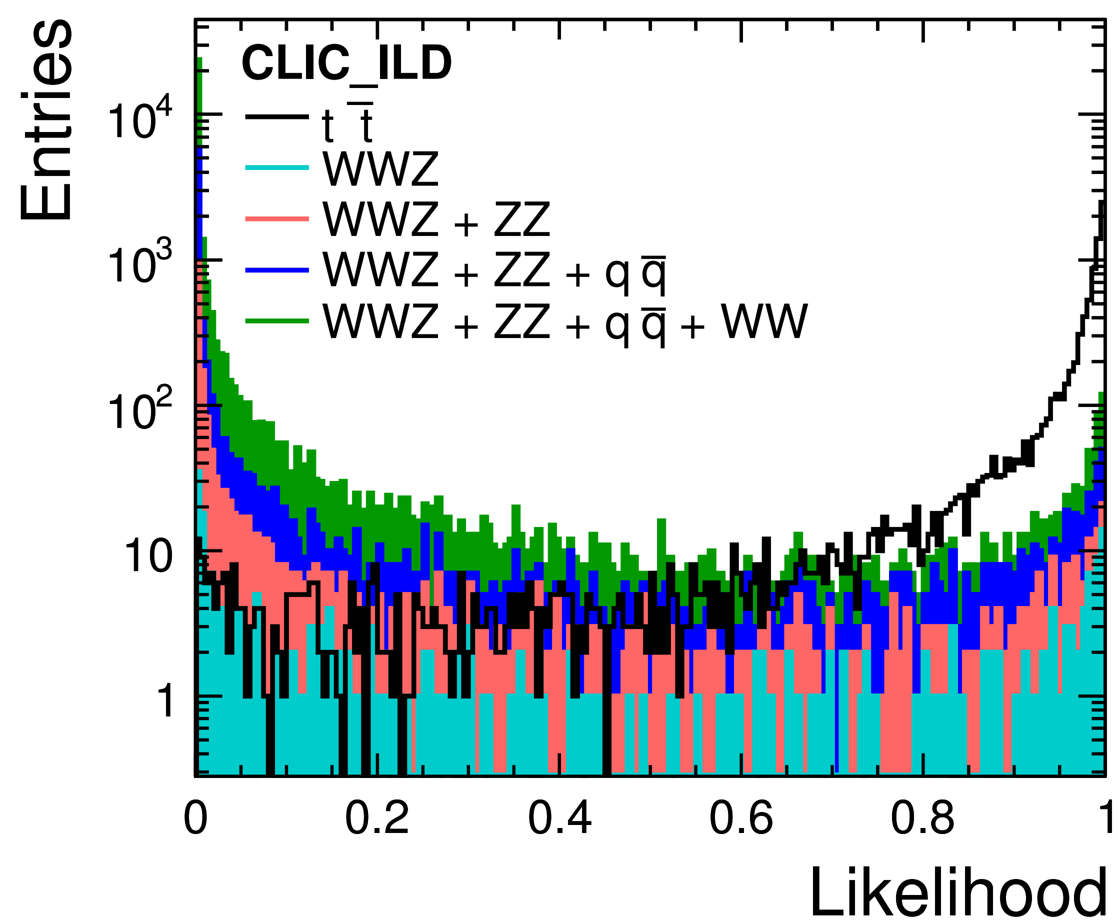
Full-Hadronic

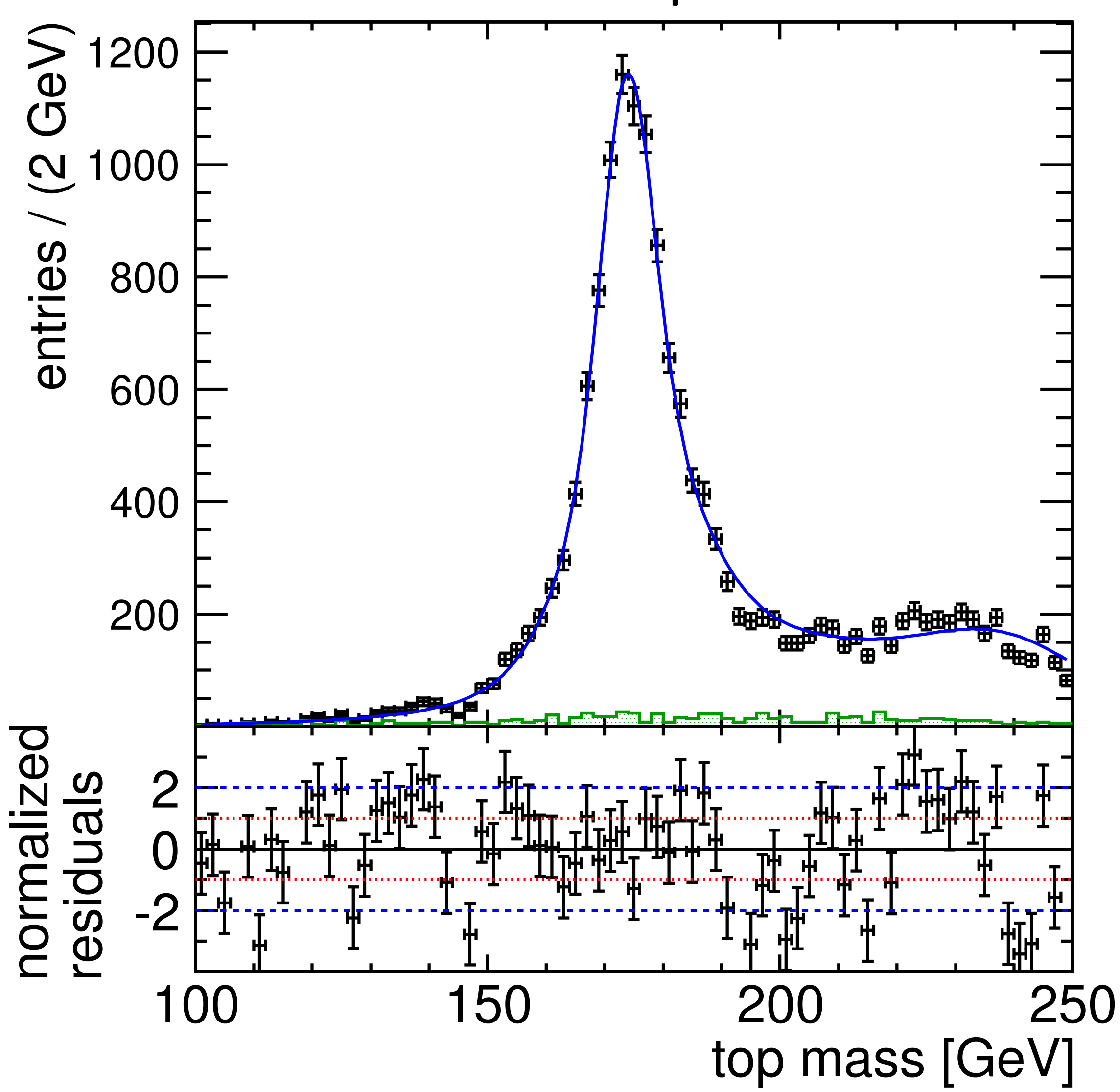


Reconstructed Invariant Mass

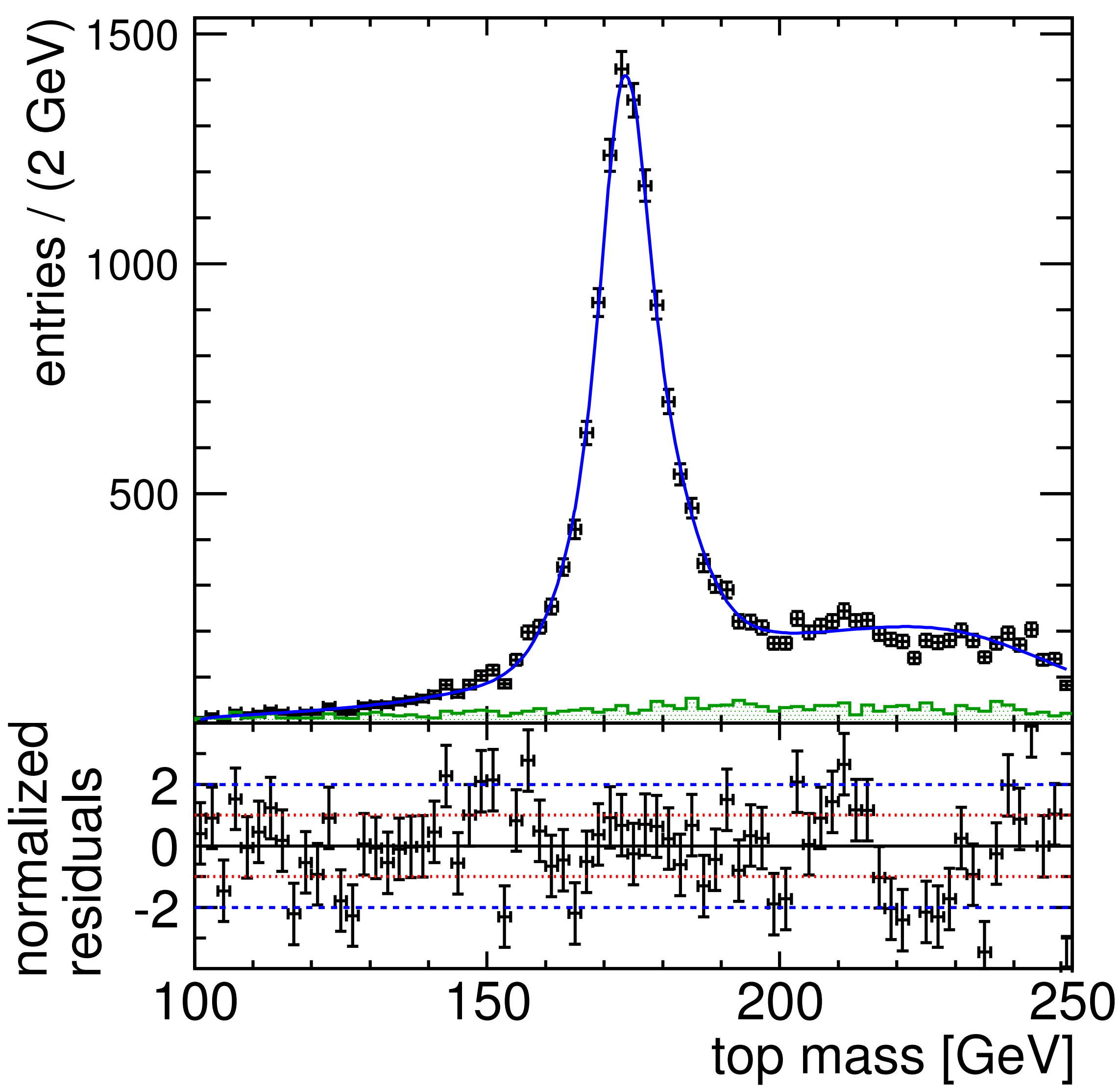
Un-binned maximum likelihood fit over full range

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

Semi-Leptonic



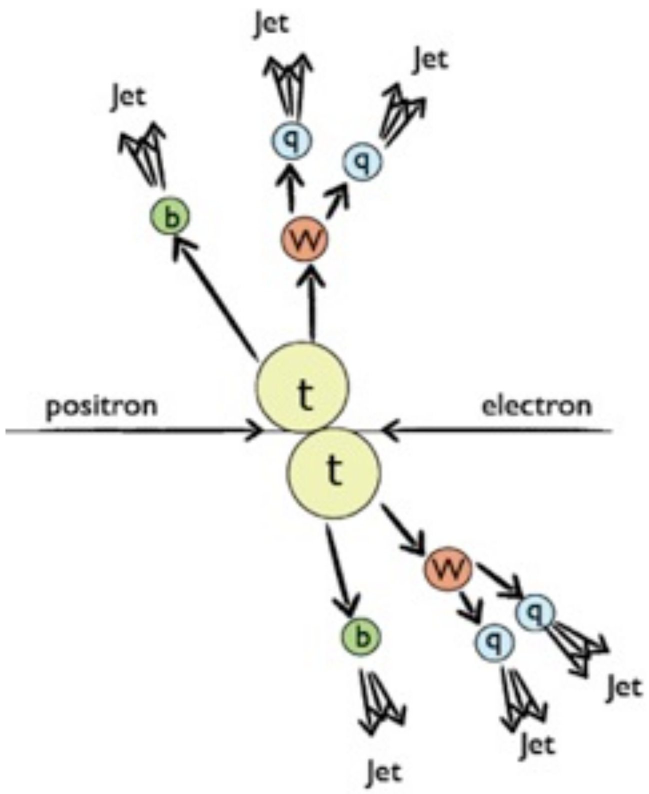
Full-Hadronic



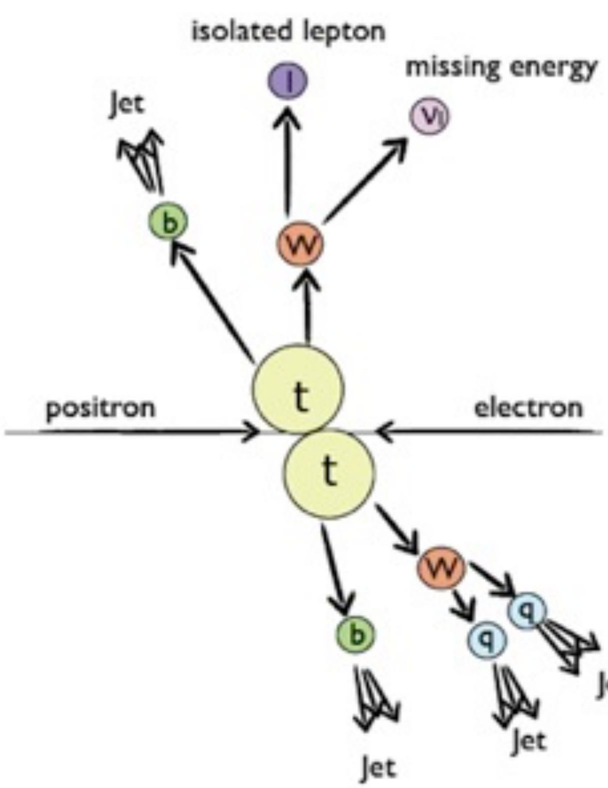
Top Mass for 100 fb^{-1} with CLIC_ILD at 500 GeV

- Results of the overall fit:
  - Full-Hadronic : m_{top} = 174.08 ± 0.08 GeV (stat)
  - Semi-Leptonic: m_{top} = 174.30 ± 0.09 GeV (stat)

  (generator values: m_{top} = 174 GeV, width: 1.37 GeV)
  Fitted width: stat errors of 220 MeV and 260 MeV depends on used fit function, smaller errors with ILD LOI fit



- ILC ILD top mass analysis for 100 fb^{-1}:
  - statistical error:
    - Full-Hadronic: 0.11 GeV
    - SemiLeptonic: 0.14 GeV
  - Full-Hadronic: Similar statistics in final distribution for ILD and CLIC_ILD study
  - Semi-Leptonic: Higher statistics in final distribution in CLIC_ILD study (improved handling of neutrino in MarlinKinFit)



Summary / Outlook

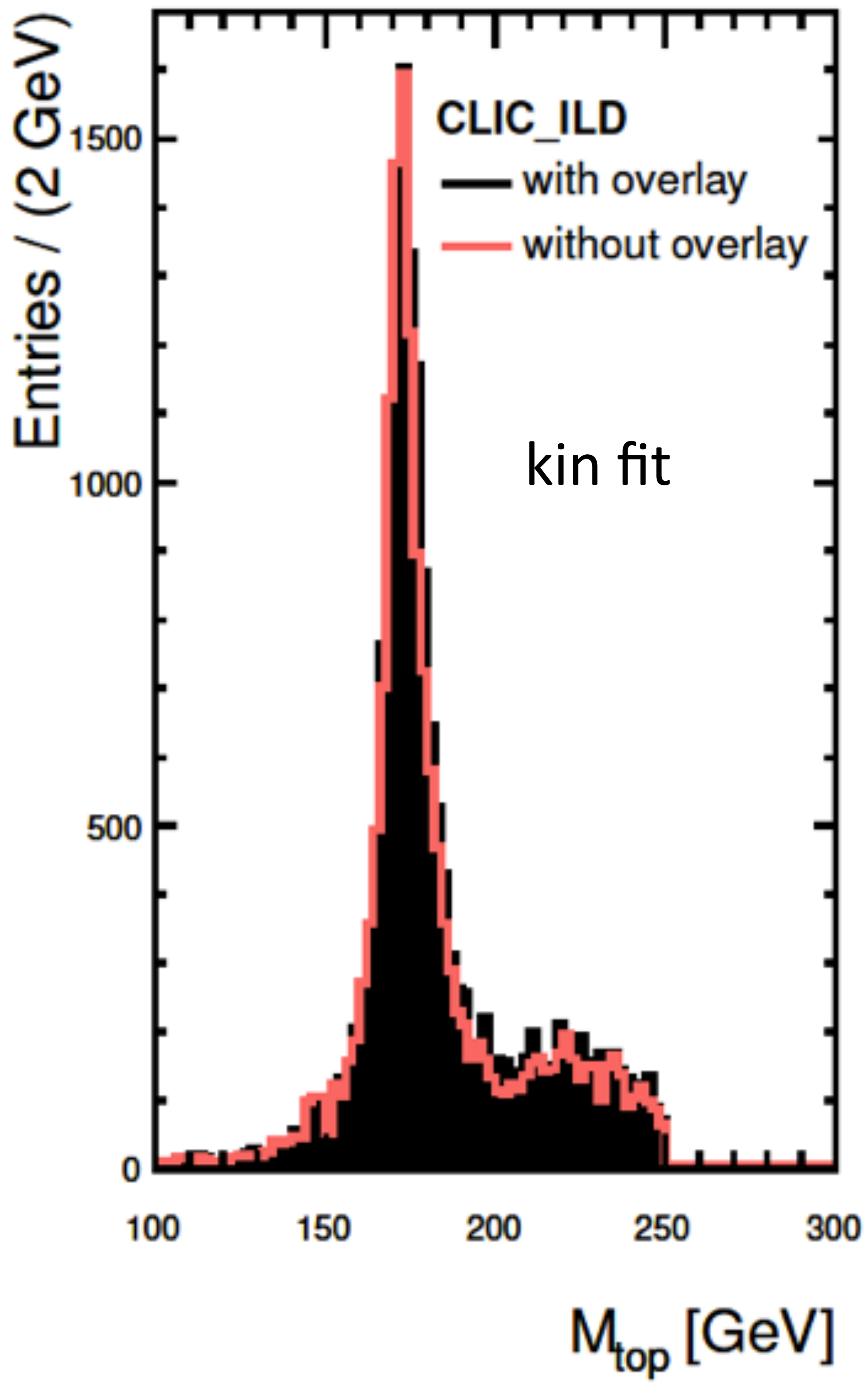
- Low energy version of CLIC also suitable for high precision measurements
    - More details in the CLIC_CDR:
      http://lcd.web.cern.ch/LCD/CDR/CDR.html

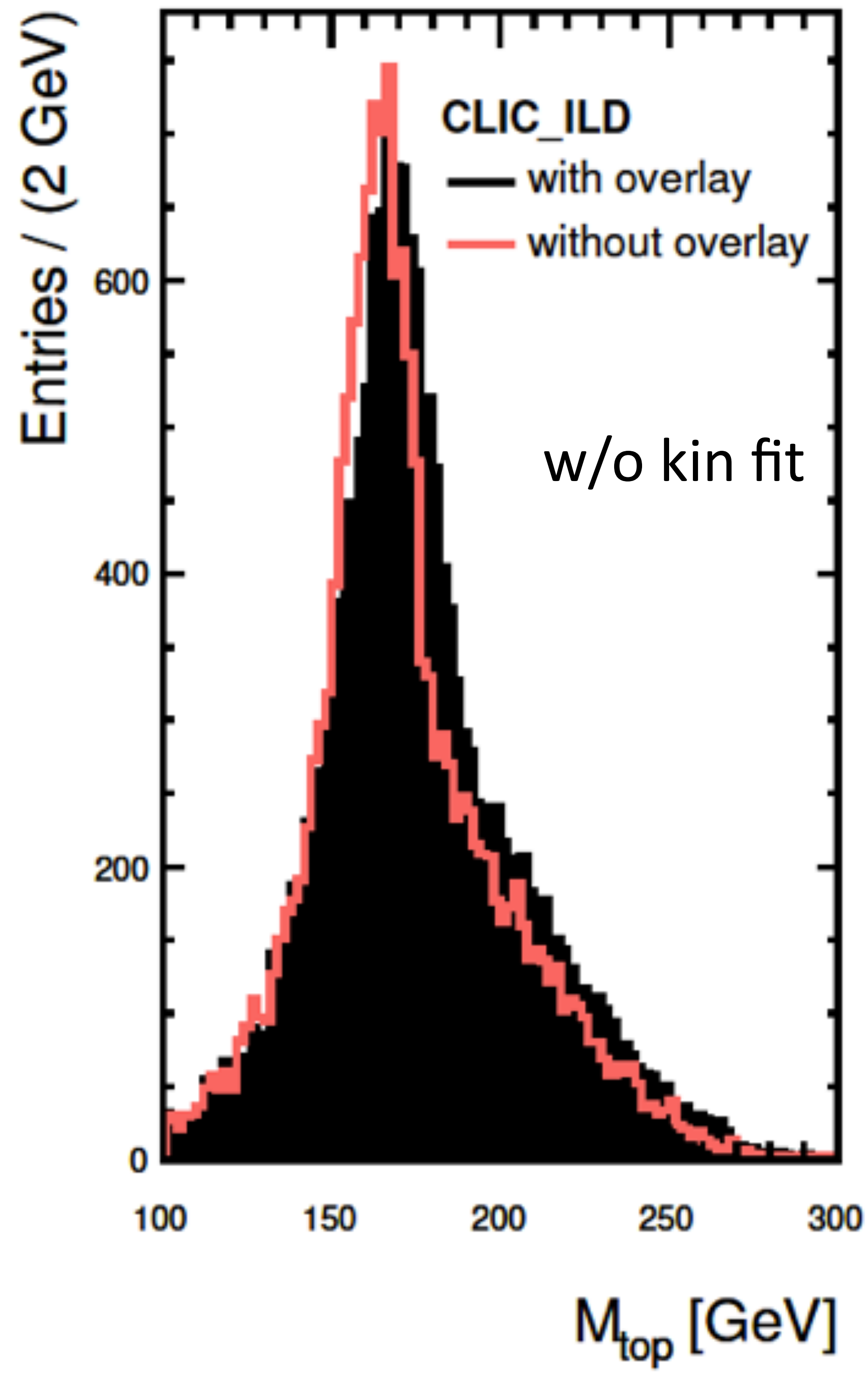
- Machine background conditions and pile up under control
- 100 fb^{-1} with CLIC_ILD at 500 GeV results in a statistical error of 80 (90) MeV on top mass in all-hadronic (semi-leptonic) decays
    - Comparable to ILD & SiD @ ILC

- Next steps: Study a threshold scan - How does CLIC background & beam spectrum affect the precision?
    - Results expected in Summer

Backup

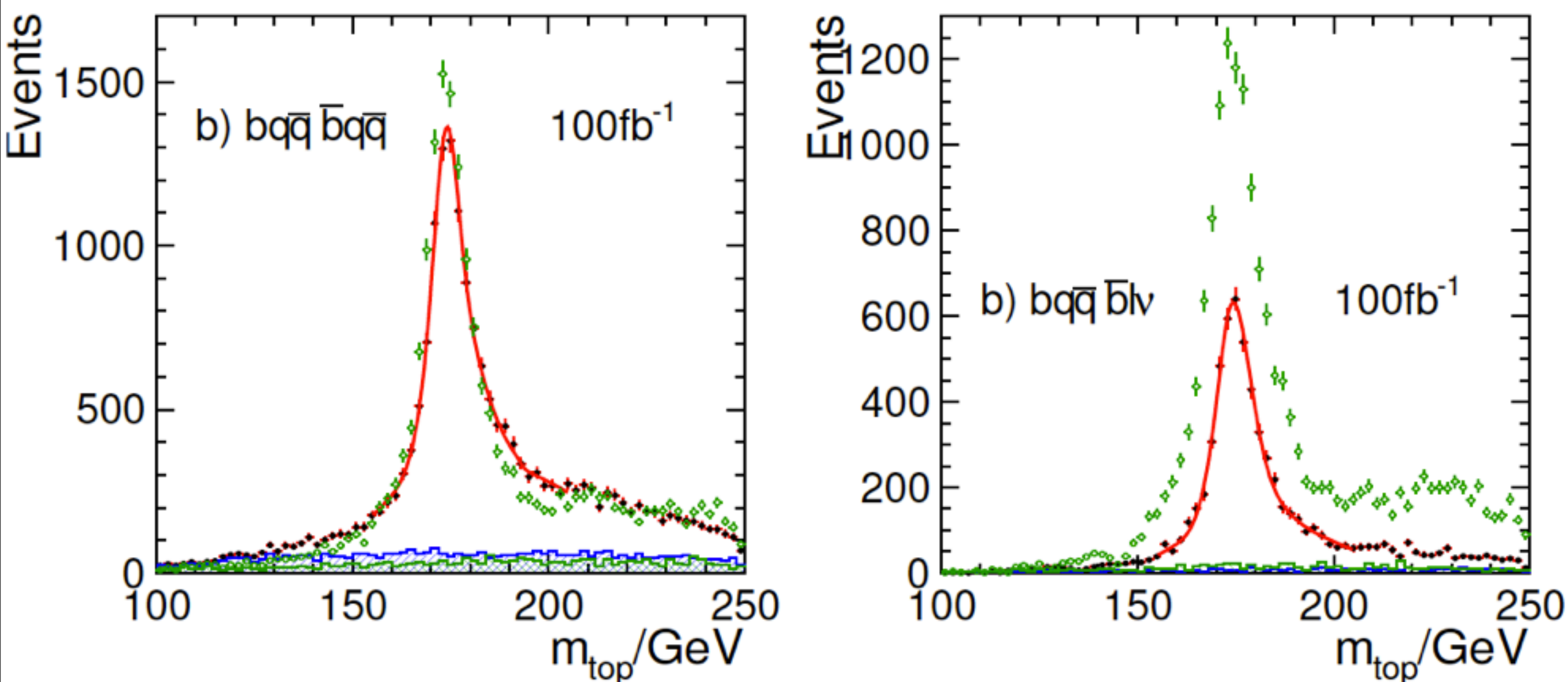
The Power of Kinematic Fitting





fully-hadronic

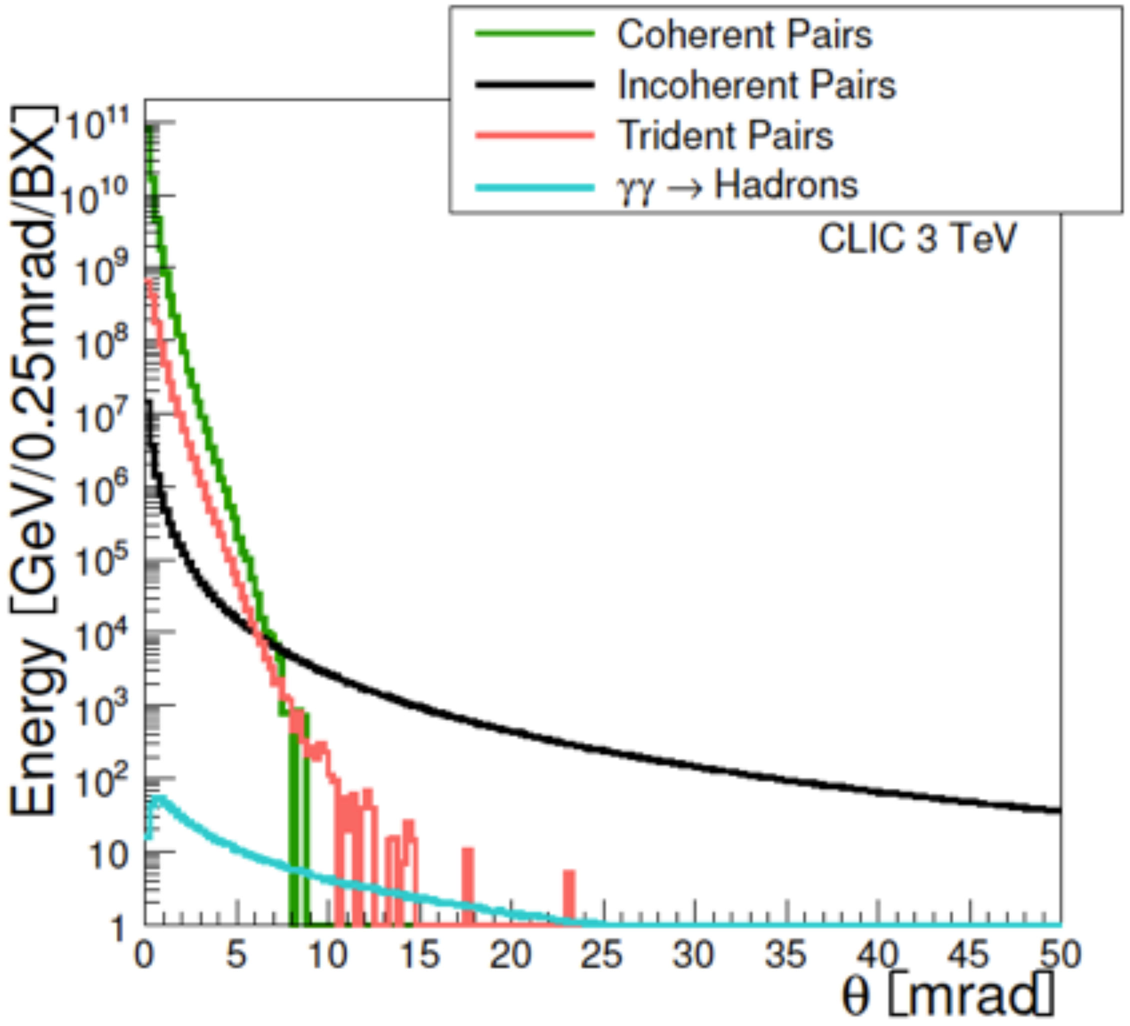
Comparison to ILD LOI Study



green markers / histogram: CLIC_ILD, this study

- Slightly narrower distribution for CLIC study in all-hadronic channel
- Increased statistics in CLIC study in semi-leptonic channel due to “neutrino fit object” as a new feature in MarlinKinFit

Conditions at CLIC: Beamstrahlung Details



- Coherent e^+e^- pairs with angles < 10 mrad
  - Crossing angle and beam pipe opening at CLIC: 20 mrad
  - Outgoing beam: coherent pairs disappear in beampipe
- Incoherent pairs: reduced by solenoidal field, constrain innermost radius of vertex detector

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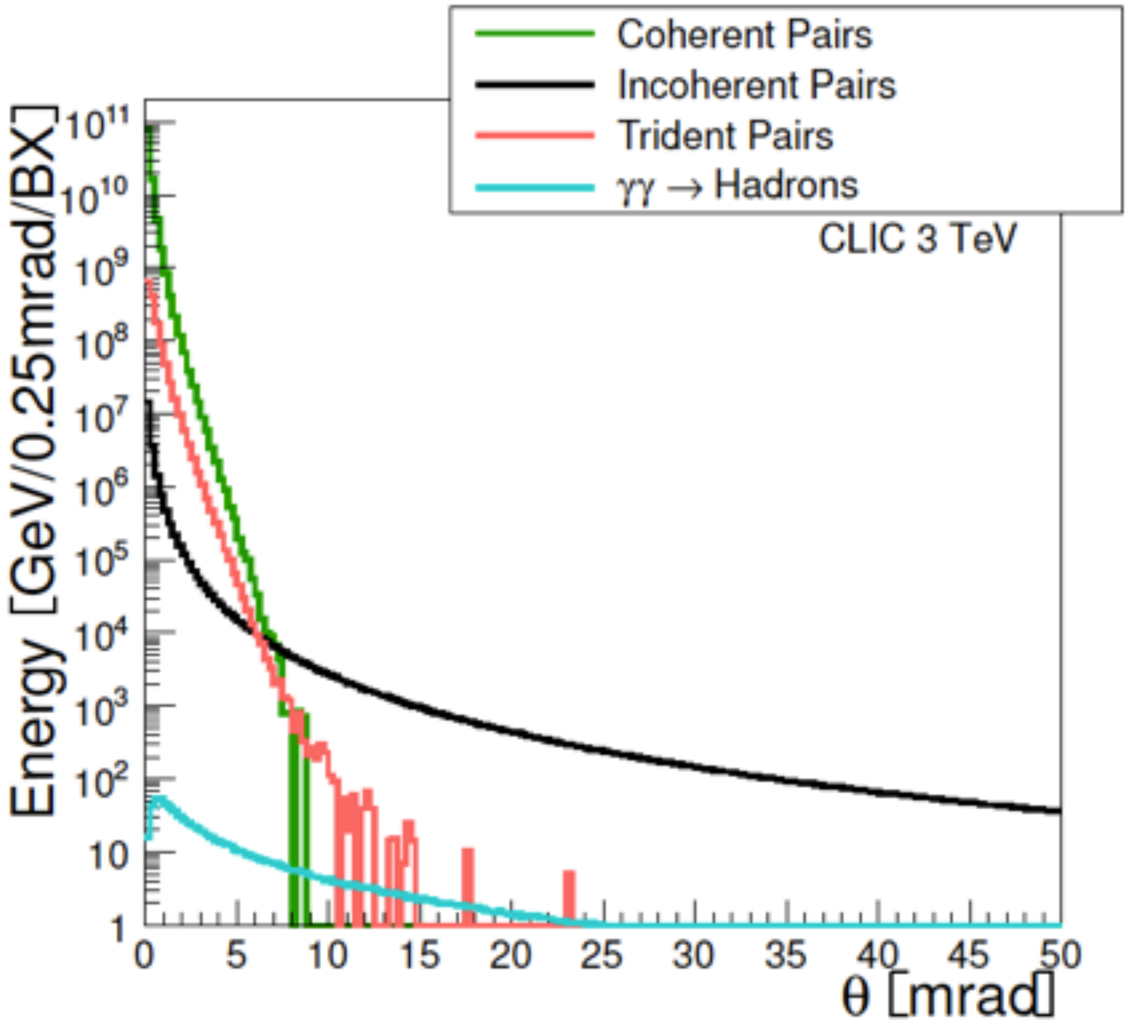

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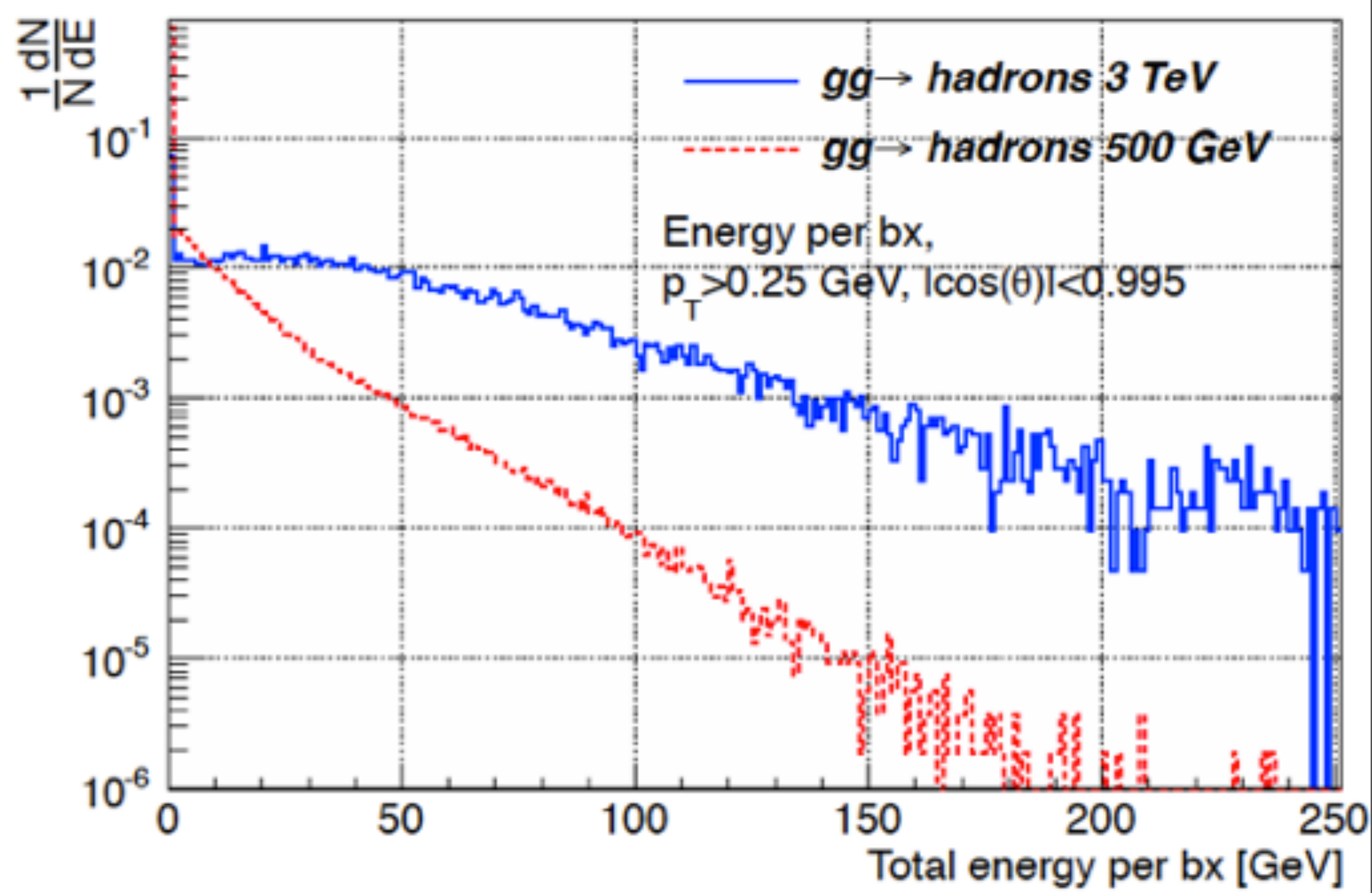
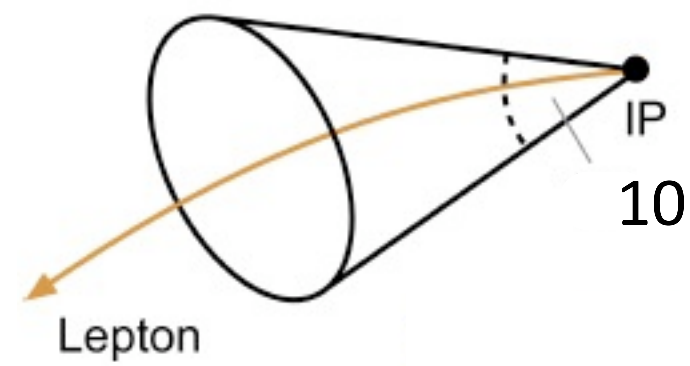


- γγ → hadrons: ~ 3.2 events / bx, ~ 28 ch. particles in detector acceptance
  ➩ 15 TeV in detector during bunch train, forward peaked
  ➩ Requires precise time stamping and clever event reconstruction

Lepton Finder

- Classification of decay branch for each event
- Search for isolated leptons in a cone
  - 10 degree cone opening angle
  - Lepton energy > 10 GeV
  - Particles in cone: charged, energy > 2.5 GeV



Lepton Finder

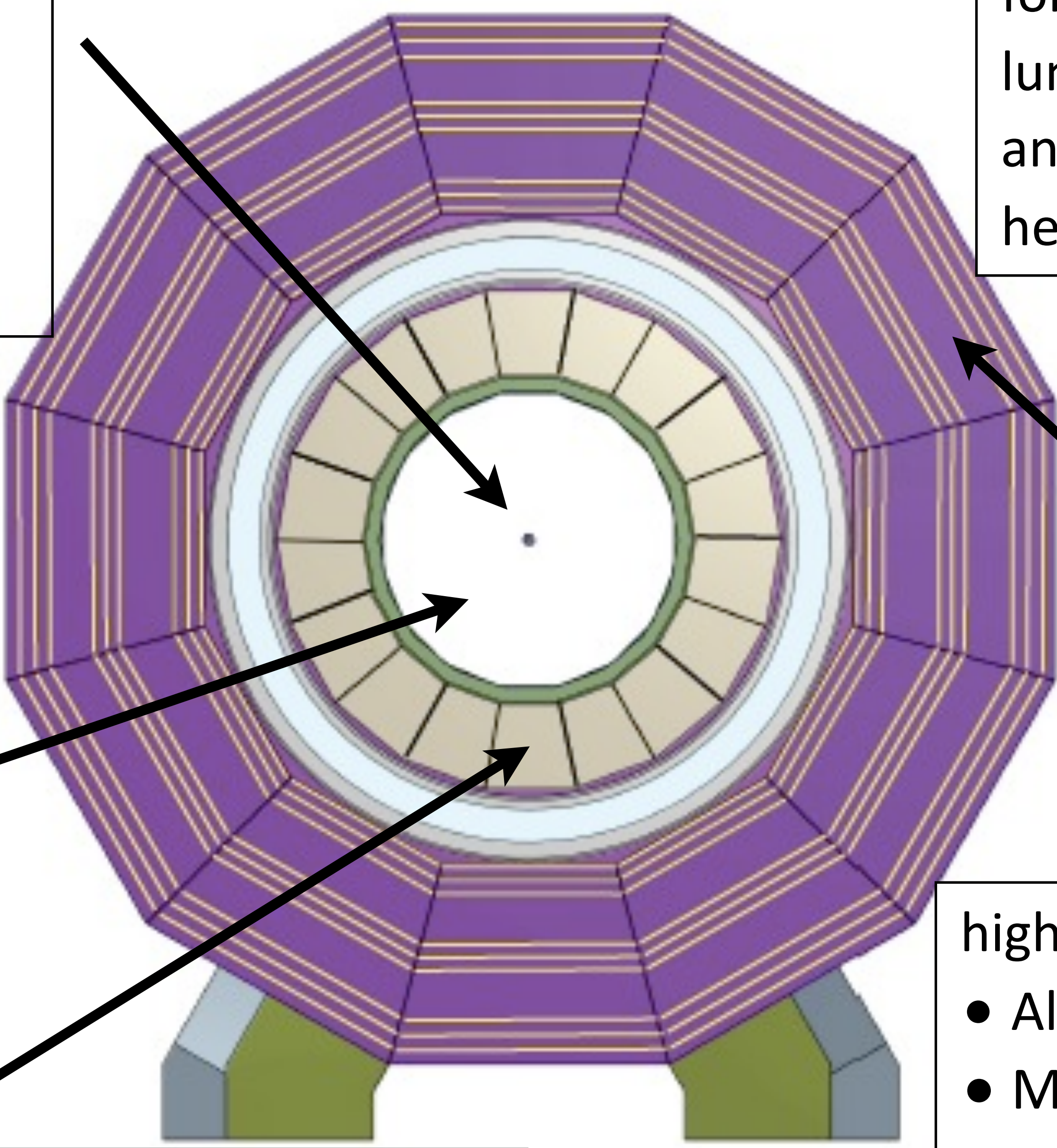
No isolated lepton found	One isolated lepton found	> 1 isolated lepton found
• Full-hadronic decay branch	• Semi-leptonic decay branch	• Full-leptonic decay branch
• 6 jets	• 4 jets, isolated lepton, neutrino	• Events rejected

CLIC_ILD Detector - Main Features

low-mass, high precision vertex detector:
Si pixel detector
Si strip inner tracker
ILD (500GeV): 15mm
CLIC_ILD (500GeV): 25mm
CLIC_ILD (3TeV): 31mm

Detectors concept follows the ILC designs: CLIC_ILD

forward calorimeters for luminosity measurements and overall detector hermeticity



magnet yoke with muon detector / tail catcher

precision tracking:
- SiD: Si strip main tracker
- ILD: TPC main tracker

high-field solenoid
- All detectors inside solenoid
- Magnetic field:
  CLIC_ILD at 4 T

highly granular calorimeters for particle flow
- Hcal: 7.5 λ, steel in endcap, tungsten in barrel