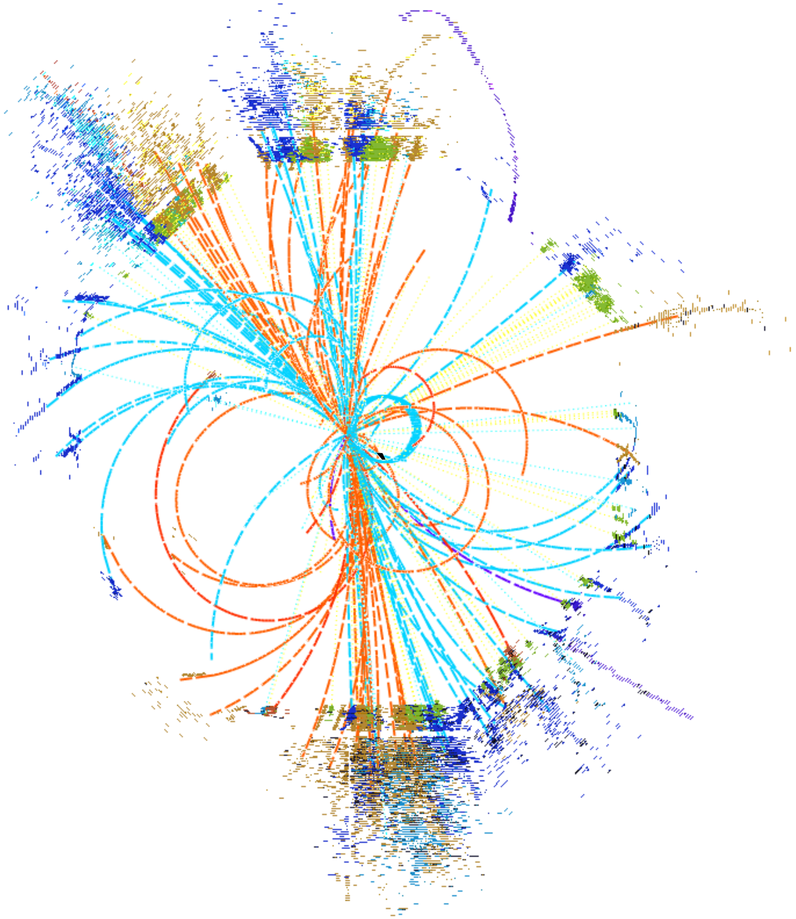
Top quark mass measurements at and above threshold in e^+e^- collisions at Linear Colliders

Philipp Roloff (CERN)
on behalf of the CLIC detector and physics study



EPS HEP 2013, Stockholm
19/07/2013

The CLIC detector and physics study

- Pre-collaboration structure based on “Memorandum of Cooperation” (MoC): http://lcd.web.cern.ch/lcd/Home/MoC.html
- CERN acts as host laboratory
- At the moment 17 institutes from 14 countries, more contributors most welcome!

CLIC in one slide

CLIC is the most mature option for a multi-TeV future e^+e^- collider

- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Staged construction: ≈350 GeV up to 3 TeV
- High luminosity (a few 10^{34} $cm^{-2}s^{-1}$)

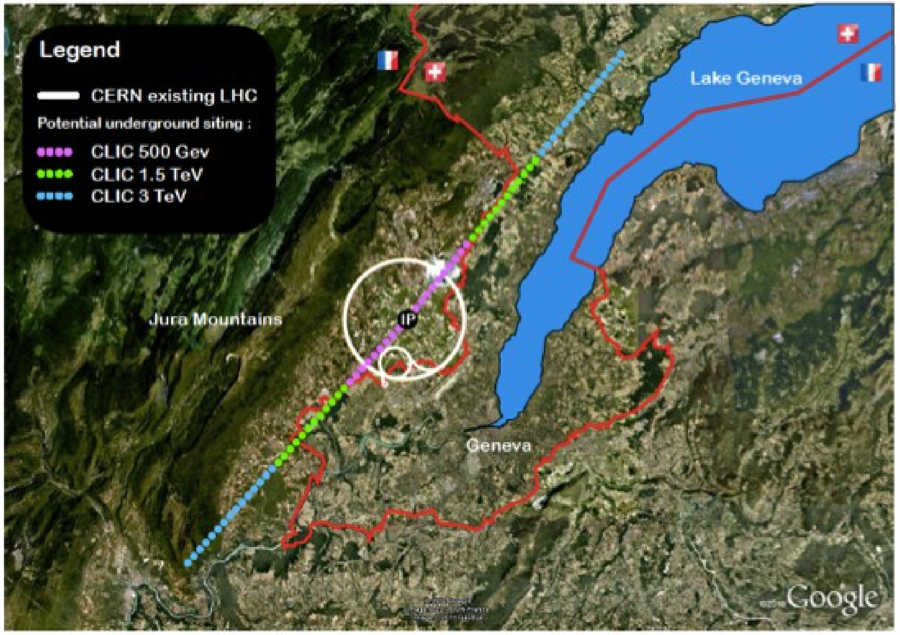
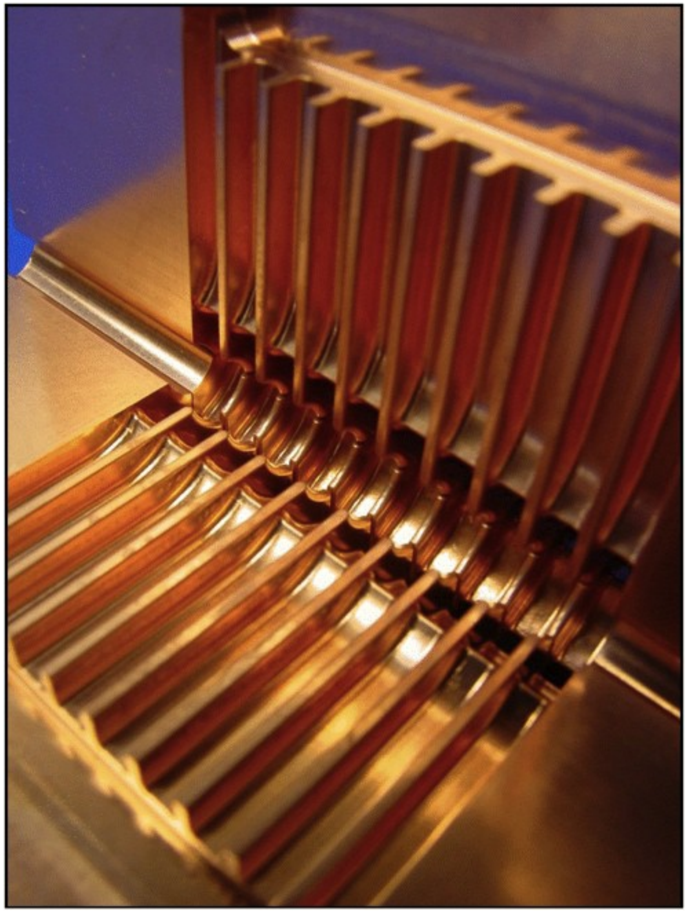


Fig. 7.2: CLIC footprints near CERN, showing various implementation stages [5].



CLIC energy stages

- CLIC will be implemented in stages: optimised running conditions over a wide energy range
- The energy stages are defined by physics with additional technical considerations

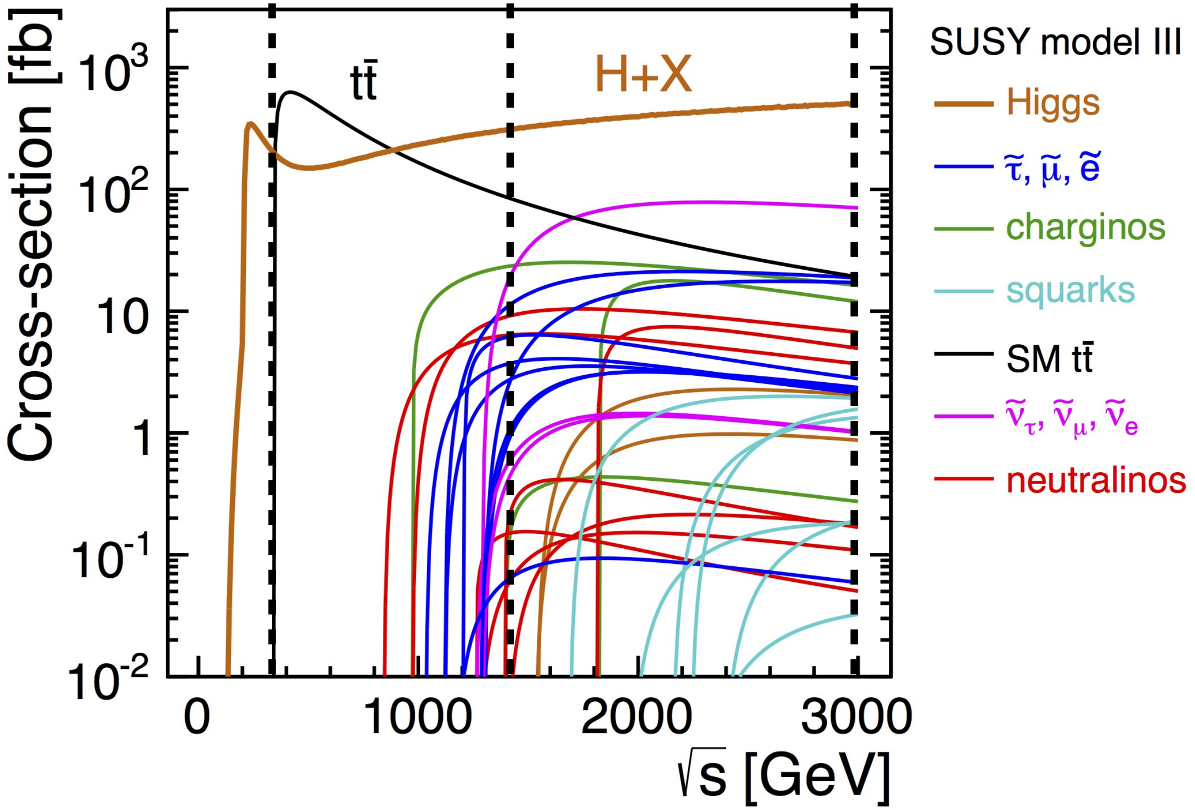
→ strategy can be adapted to discoveries at the LHC

Example scenario:

- **Stage 1:** 350 / 375 GeV
  Higgs & top mass measurement

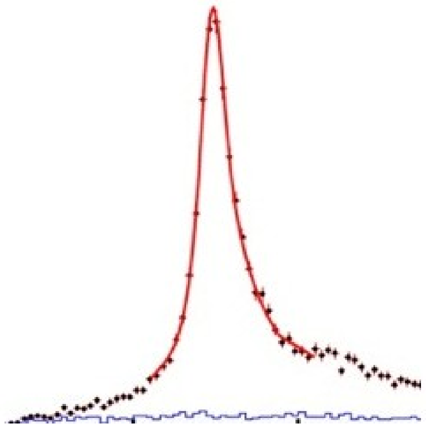
- **Stage 2:** 1.4 TeV
  BSM physics, precision Higgs measurements

- **Stage 3:** 3 TeV
  BSM physics, precision Higgs measurements



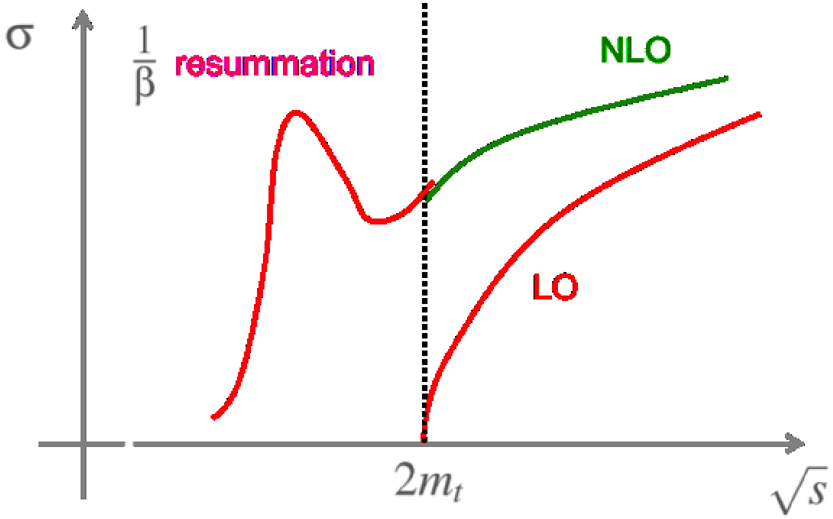
Top mass at Linear Colliders

1.) From reconstructed invariant mass
(500 GeV, L_{int} = 100 fb^{-1})



+ Experimentally well defined
+ Can be performed at any energy above threshold → large statistics
- Difficult to translate the result into a theoretically well-defined quantity

2.) From threshold scan
(350 GeV, L_{int} = 10 $\times$ 10 fb^{-1})



+ Theoretically well understood, can be calculated to higher orders
- Needs dedicated running of the accelerator (but ≈ 350 GeV also very important for Higgs physics)

Top reconstruction at lepton colldiers

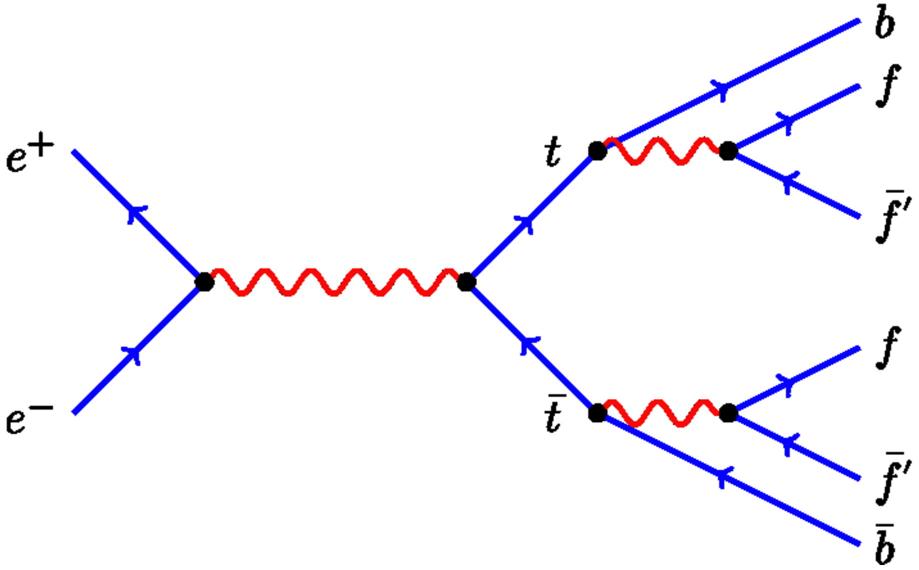
- Top quarks produced in pairs in electron-positron annihilation

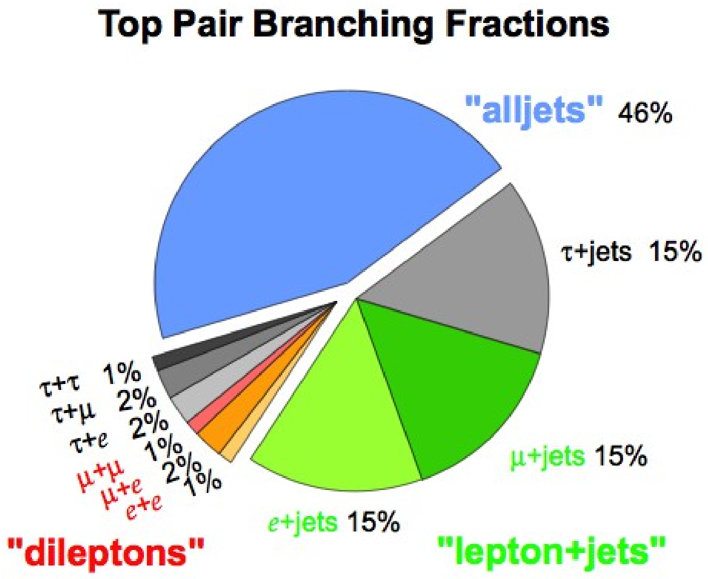
- Top quark pairs (relatively) easy to identify

→ Focus on fully hadronic and semi-leptonic final states:

  - large available statistics

  - the four vectors of both top quarks can be reconstructed (neutrino = missing momentum for semi-leptonic events)

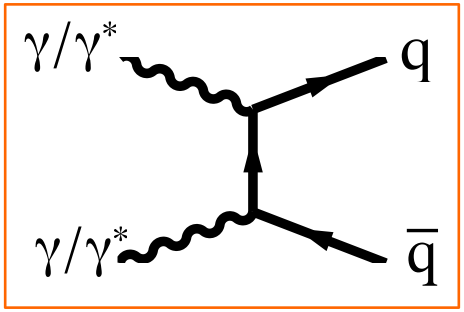


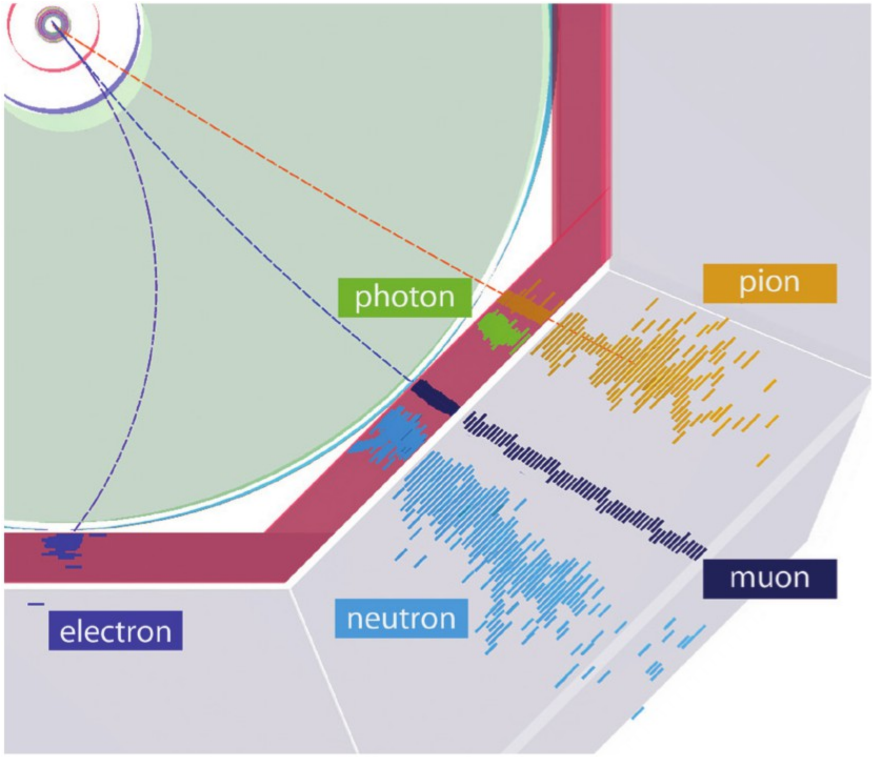


MC samples and event reconstruction

- PYTHIA and WHIZARD for event generation
- Full detector simulation using Geant4
- Event reconstruction using particle flow analysis (Pandora PFA)
- **Key challenge at CLIC:** pileup from γγ → hadrons interactions → rejected by combined timing & p_T cuts for reconstructed particles and using hadron-collider type jet reconstruction algorithms

type	final state	σ (500 GeV)	σ (352 GeV)
Signal ($m_{\text{top}} = 174$ 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





Analysis strategy (1)

1.) Group events using the number of isolated leptons (electrons or muons):
- fully-hadronic: no leptons
- semi-leptonic: 1 lepton
- 2 leptons → rejected here

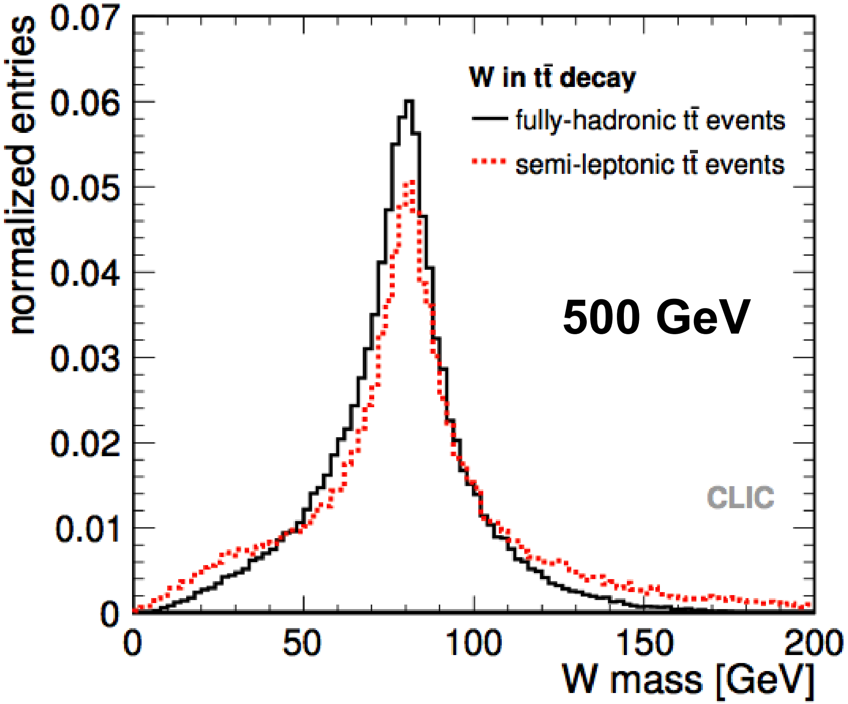
2.) Jet reconstruction using the exclusive k_T algorithm:

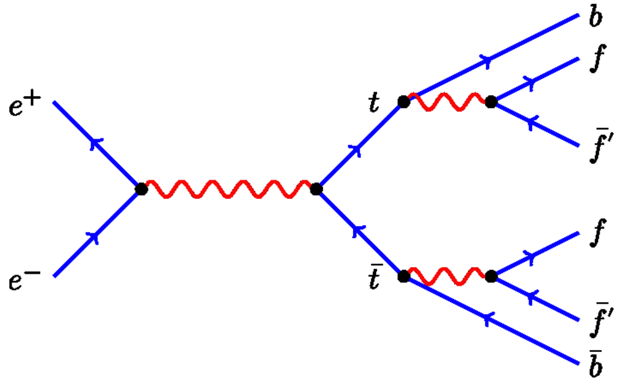
→ 4 jets for semi-leptonic events,
6 jets for fully-hadronic events

3.) Flavour tagging: the two most likely b-jet candidates are identified

4.) W pairing: grouping jets and leptons into W candidates

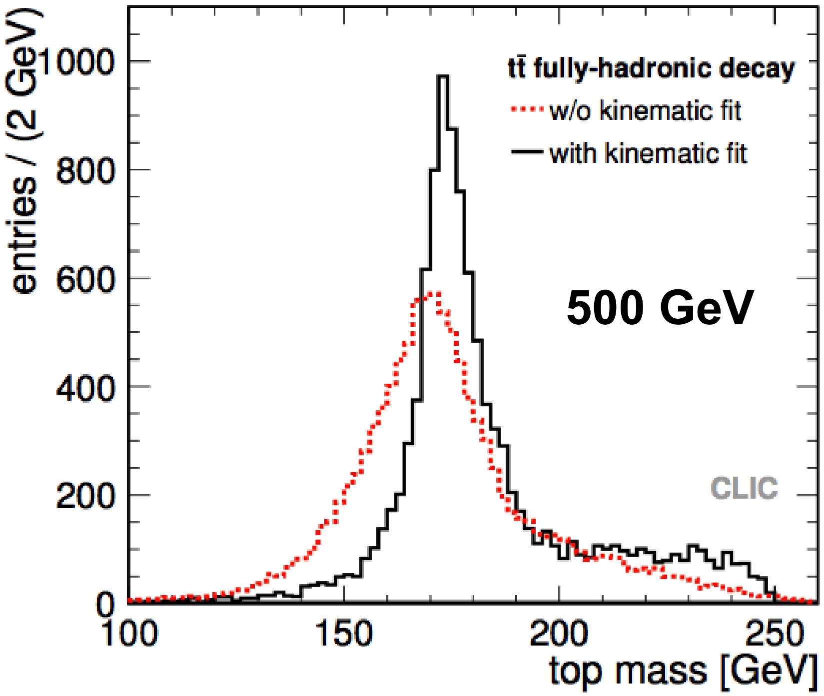
→ unique for the semi-leptonic case,
use combination with
minimal deviations from nominal
W mass for all-hadronic final state





Analysis strategy (2)

5.) Kinematic fit → use energy & momentum conservation to constrain the event



- Association of W candidates and b-jets to top candidates performed in this step
- Enforces equal t and $\bar{t}$ mass

→ only one mass measurement per event

- Already good rejection of non-$t\bar{t}$ background

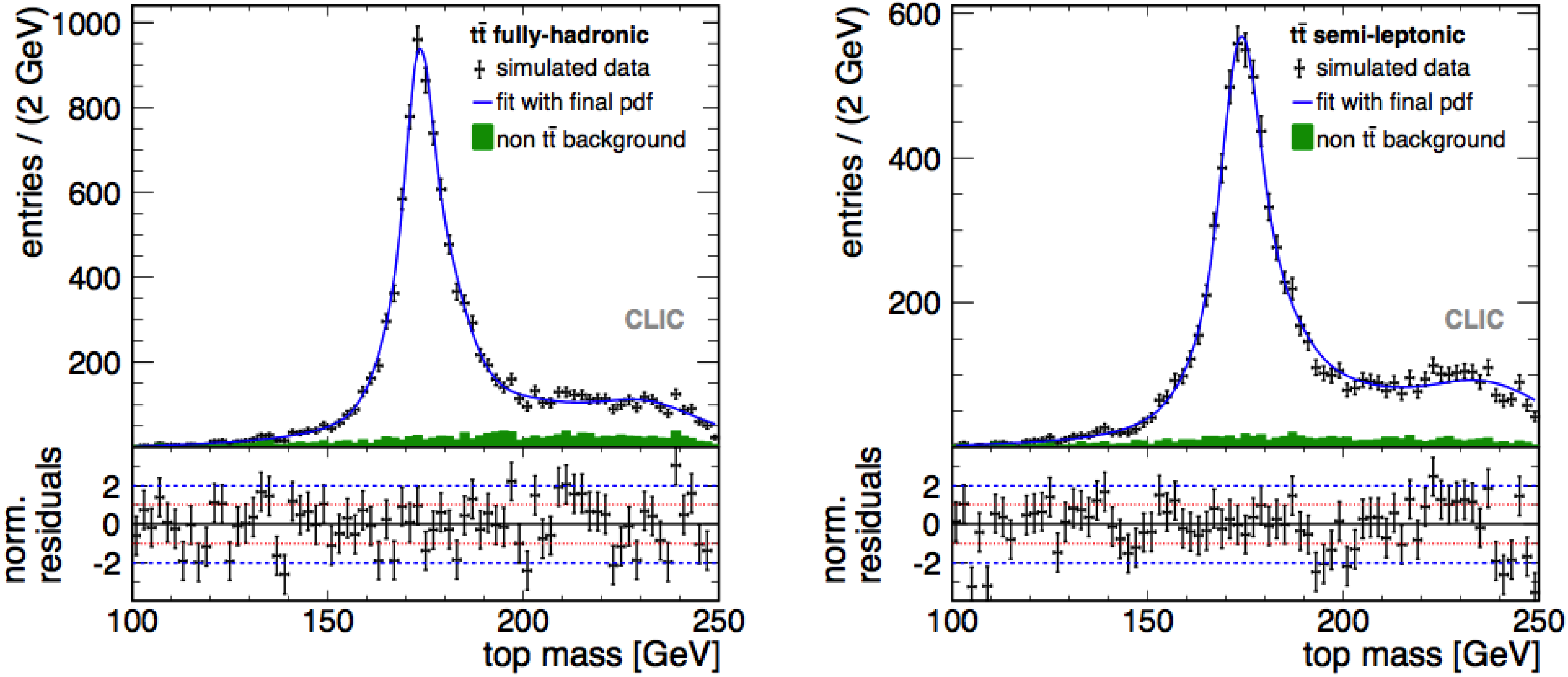
6.) Further background rejection using likelihood

based on event variables (sphericity, b-tags, multiplicity, W masses, max. distance for which 4 or 6 jets are found, difference of the two top masses without kinematic fit)

High selection efficiencies:

- 34% (44%) for fully-hadronic (semi-leptonic) events at 500 GeV
- 92% at threshold

Results from invariant mass



500 GeV, L_{int} = 100 fb^{-1}

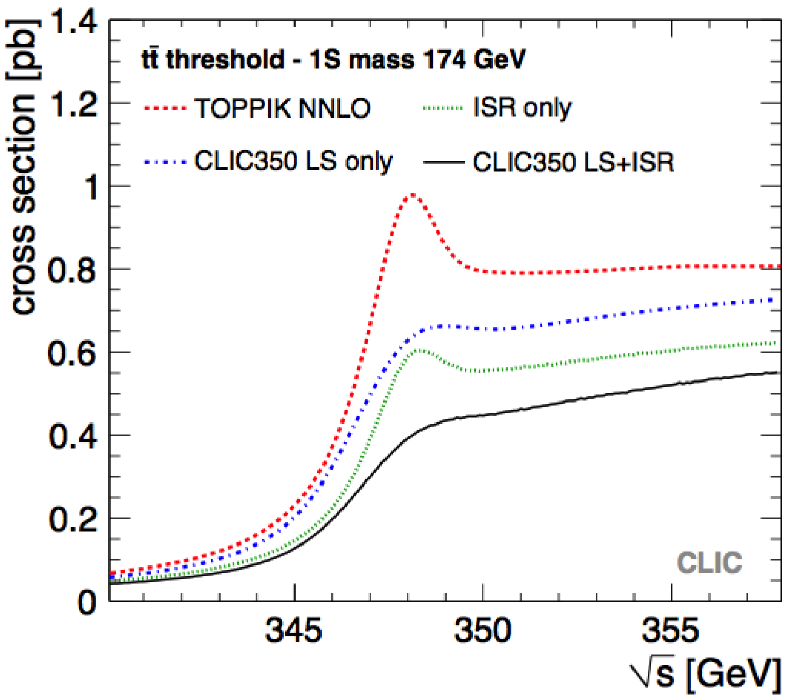
channel	m_{top}	Δm_{top}	Γ_{top}	$\Delta\Gamma_{top}$
fully-hadronic	174.049	0.099	1.47	0.27
semi-leptonic	174.293	0.137	1.70	0.40
combined	174.133	0.080	1.55	0.22

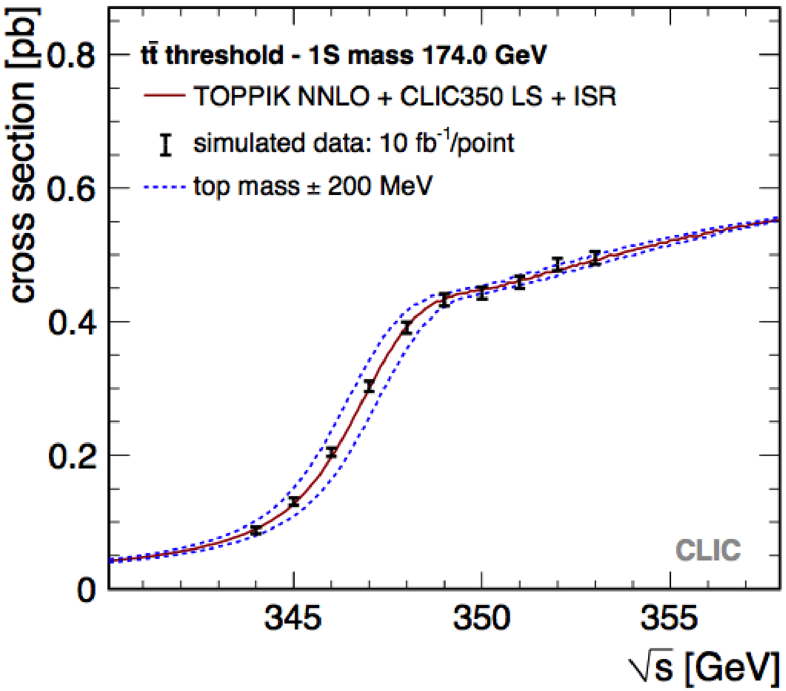
- Non-tt̄ background very small
- Width less well constrained than mass (peak width ≈5 GeV larger than top width of 1.4 GeV)

Threshold scan

- NNLO cross section from TOPPIK (Hoang & Teubner)

- Initial-state radiation (ISR) and luminosity spectrum (LS) affect the cross section as a function of the centre-of-mass energy

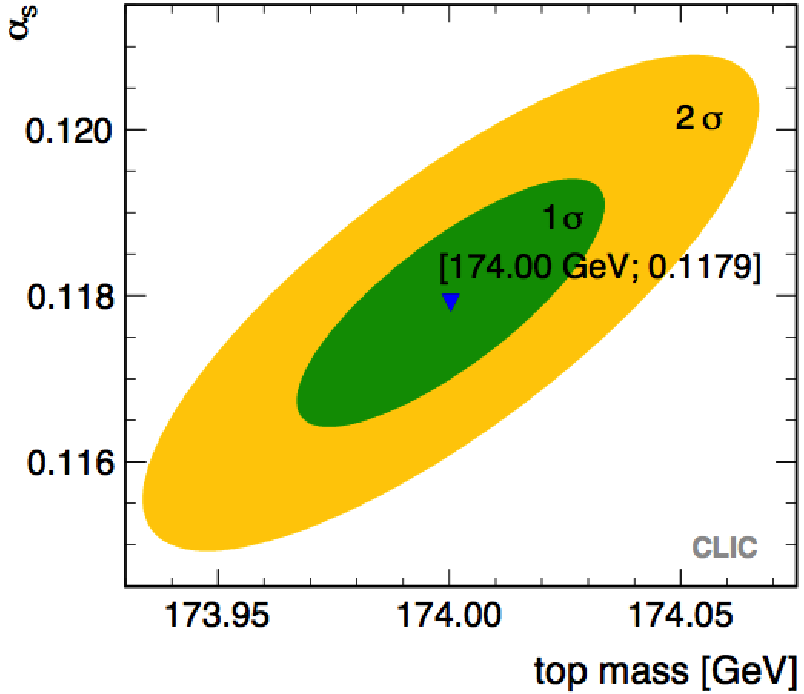




- Selection efficiency and background levels from full detector simulation → expected precision for measured data points

Results from threshold scan

- The cross section in the threshold region depends on the strong coupling constant α_s
- The 1S top mass and α_s are simultaneously extracted in a 2D fit



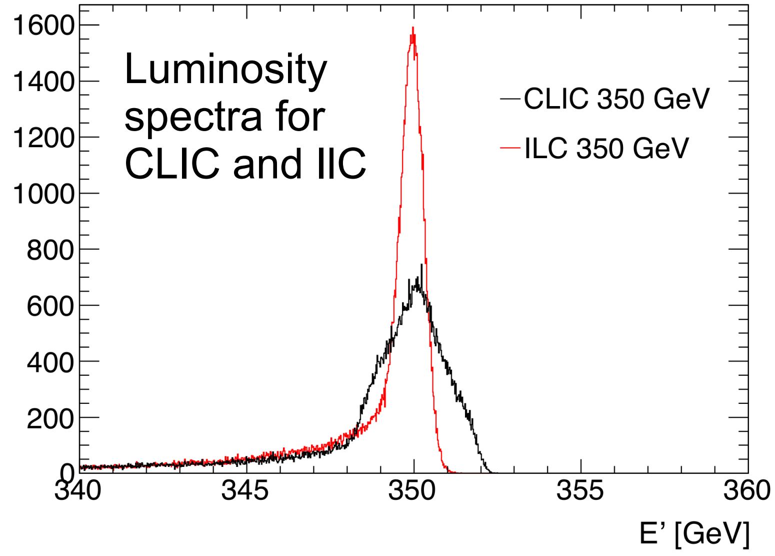
$\Delta_{stat}(m_t)$	34 MeV
$\Delta_{stat}(\alpha_s)$	0.0009

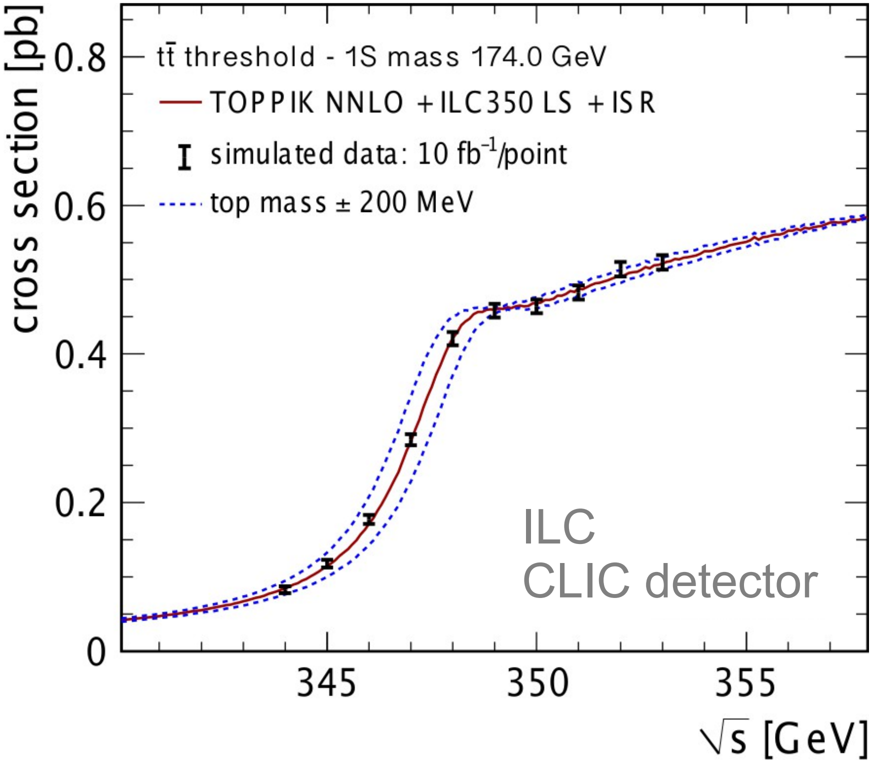
- Impact of 3% and 1% uncertainties on the normalisation of the theory calculation:

	1% norm. uncert.	3% norm. uncert.
$\Delta_{theo}(m_t)$	5 MeV	8 MeV
$\Delta_{theo}(\alpha_s)$	0.0008	0.0022

Comparison to the ILC

Same analysis, but using the ILC luminosity spectrum with narrower main peak
→ Steeper rise of the cross section at the threshold





Compared to CLIC:
≈20% smaller uncertainty on m_t
≈10% smaller uncertainty on α_s
Theoretical uncert. unchanged

$\Delta_{stat}(m_t)$	27 MeV
$\Delta_{stat}(\alpha_s)$	0.0008

Systematic uncertainties: invariant mass

No full study of systematic uncertainties yet, but key issues were investigated:

- **Possible bias from top mass and width assumptions in detector resolutions:** below statistical uncertainty if varied → no bias found

- **Jet energy scale:** can be constrained in-situ to better than 1% for light quark jets using the reconstructed W mass, similar performance expected for b-jets using Z and ZZ events
→ resulting uncertainties smaller than statistical precision of the measurement

The interpretation of the measurement currently leads to theoretical uncertainties large compared to the experimental error

Systematic uncertainties: threshold scan

In addition to the theory normalisation uncertainty other sources of systematic uncertainty were studied:

- **Shift of measurement points to higher energies by 0.5 GeV:** results unchanged → precision of LHC sufficient to define range

- **Normalisation of non-$t\bar{t}$ background**: 5% variation leads to 18 MeV shift in top mass

- **Beam energy:** 10^{-4} uncertainty on the centre-of-mass energy leads to a 30 MeV uncertainty on the mass

- **Luminosity spectrum:** 20% uncertainty of the RMS width of the main luminosity peak leads to 75 MeV uncertainty on top mass, realistic studies of the uncertainties on the CLIC luminosity spectrum ongoing

Summary

- A linear collider operated at and above the $t\bar{t}$ threshold allows to perform two complementary measurements of the top mass:

  - Direct reconstruction using the invariant mass distribution
  - Threshold scan

- For both techniques total experimental uncertainties on the level of 100 MeV are within reach for 100 fb^{-1} of data

- Only small differences in precision found between CLIC and ILC

More information:

- K. Seidel et al., *Top quark mass measurements at and above threshold at CLIC*, arXiv:1303.3758
- CLIC CDR Vol. 3, *The CLIC programme: towards a staged e^+e^- Linear Collider exploring the Terascale*, arXiv:1209.2543
- CLIC CDR Vol. 2, *Physics and Detectors at CLIC*, arXiv:1202.5904

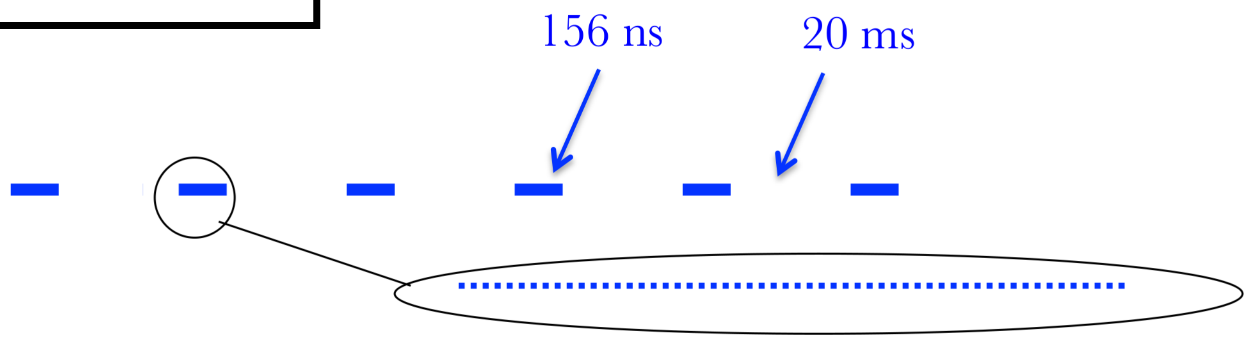
Backup slides

Selected CLIC parameters

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	$5.9 \cdot 10^{34}$
Bunch separation	0.5 ns
#Bunches / train	312
Train duration	156 ns
Train rep. rate	50 Hz
Crossing angle	20 mrad
Particles / bunch	$3.72 \cdot 10^9$
σ_x/σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

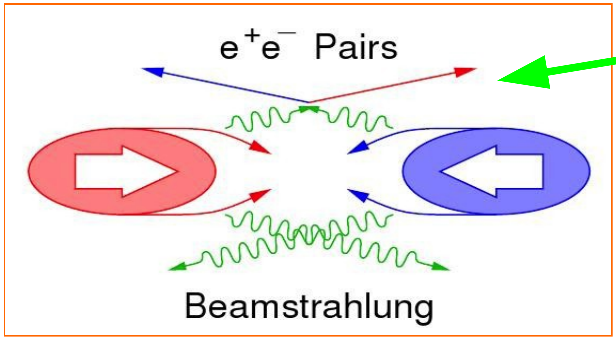
Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

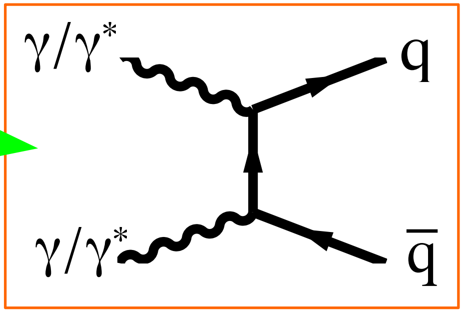


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam related backgrounds



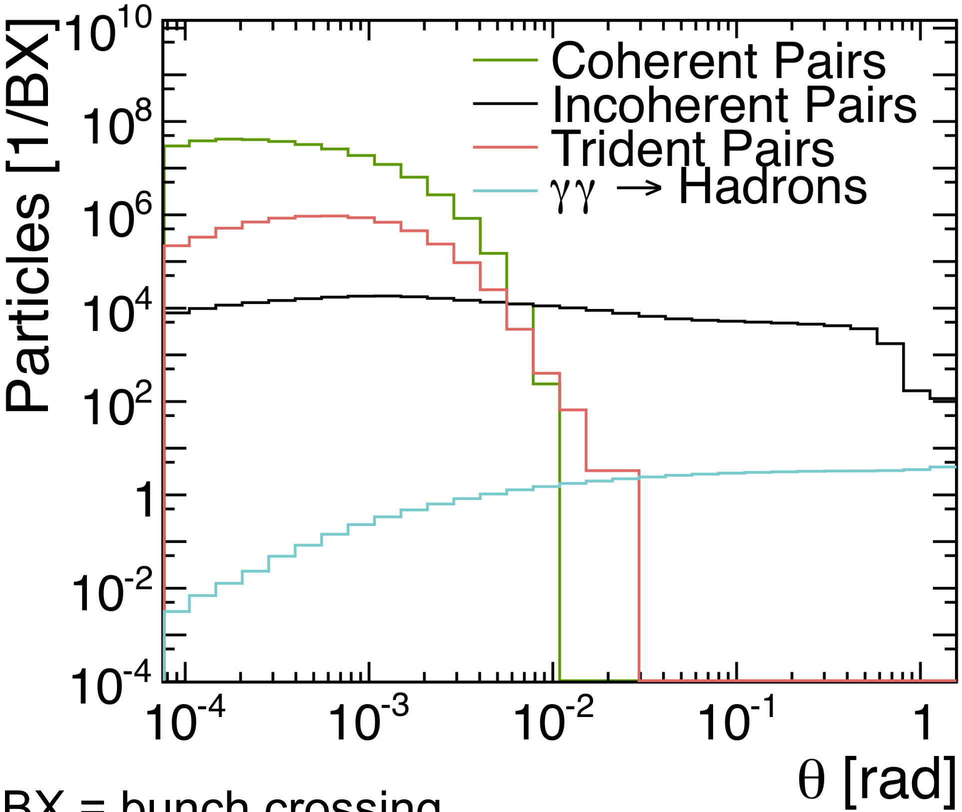
- e^+e^- pairs
- γγ → hadrons
- Beam halo muons



Coherent e^+e^- pairs:
$7 \cdot 10^8$ per BX, very forward
Incoherent e^+e^- pairs:
$3 \cdot 10^5$ per BX, rather forward
→ Detector design issue
(high occupancies)

γγ → hadrons
- "Only" 3.2 per BX at 3 TeV
- Main background

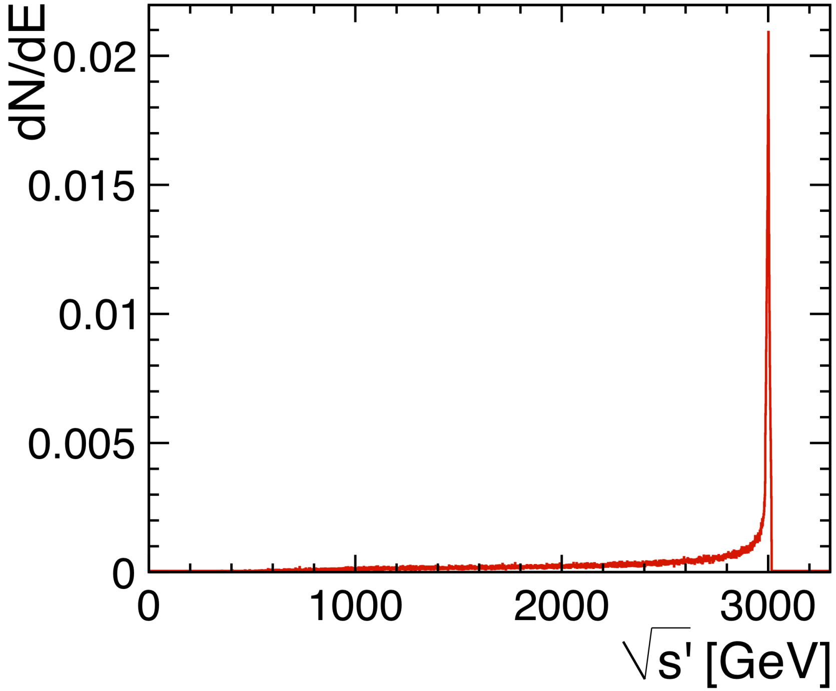
in calorimeters and trackers
→ Impact on physics



BX = bunch crossing

Luminosity spectrum

Significant energy loss at the interaction point due to Beamstrahlung



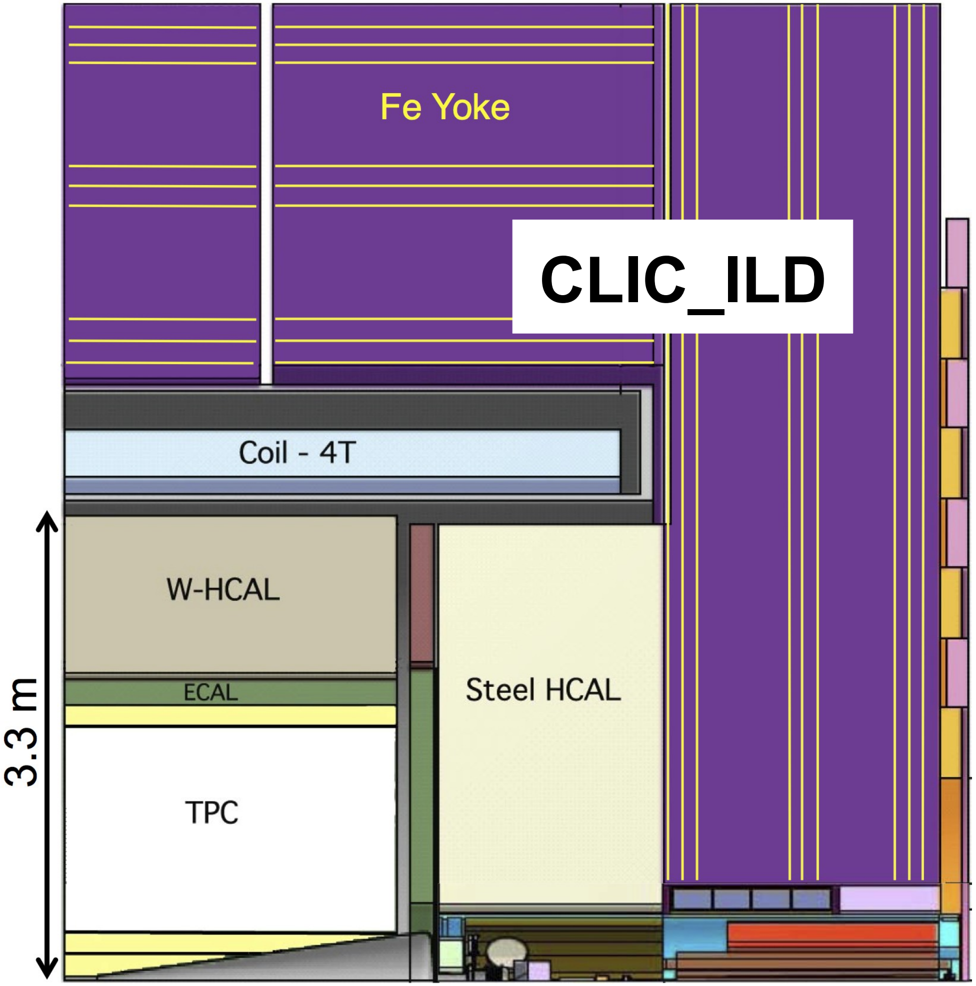
Full luminosity: $L = 5.9 \cdot 10^{34}$ cm^{-2}s^{-1}
In the most energetic 1%:
("peak luminosity") $L_{0.01} = 2.0 \cdot 10^{34}$ cm^{-2}s^{-1}

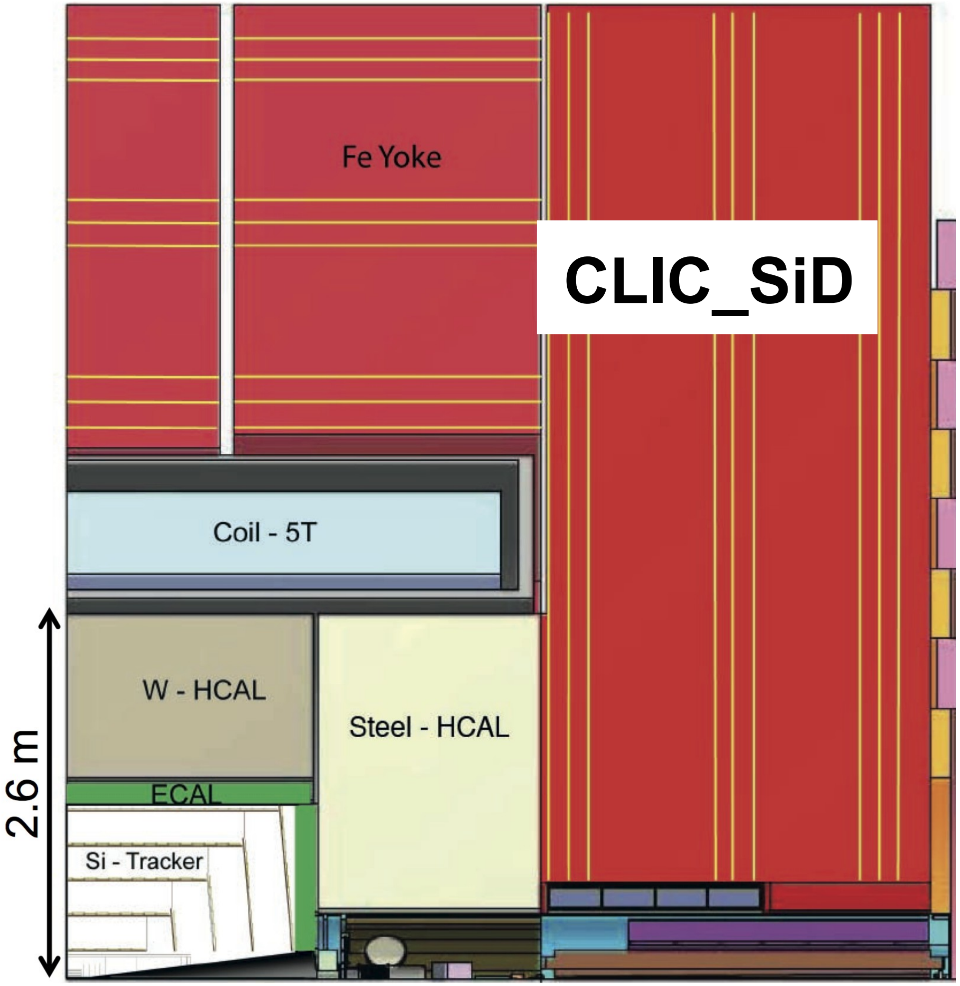
Most physics processes are studies well above the production threshold
→ Profit from (almost) full luminosity

$$\sqrt{s'} = \sqrt{4 \cdot E_1 \cdot E_2}$$

CLIC detector concepts

Based on ILC concepts (ILD and SiD), adapted to CLIC conditions

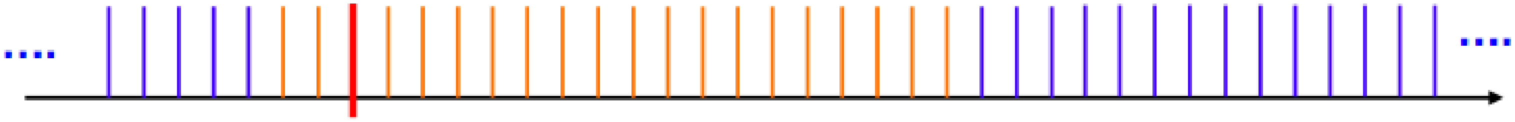




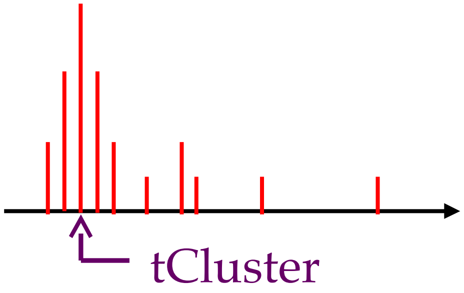
All benchmark studies are based on full detector simulations (Geant4)

Background suppression

Triggerless readout of full bunch train:



t_0 of physics event



1.) **Identify t_0 of physics event in offline event filter**

- Define reconstruction window around t_0
- All hits and tracks in this window are passed to the reconstruction

→ Physics objects with precise p_T and cluster time information

2.) **Apply cluster-based timing cuts**

- Cuts depend on particle-type, p_T and detector region

→ Protects physics objects at high p_T

Time windows and hit resolutions

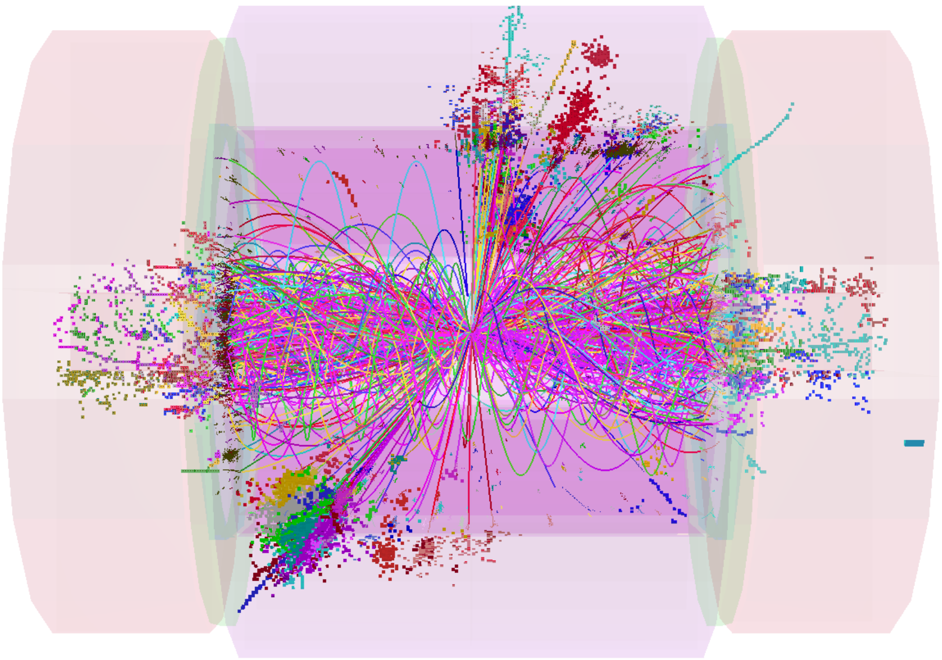
Used in the reconstruction software for CDR simulations:

Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a

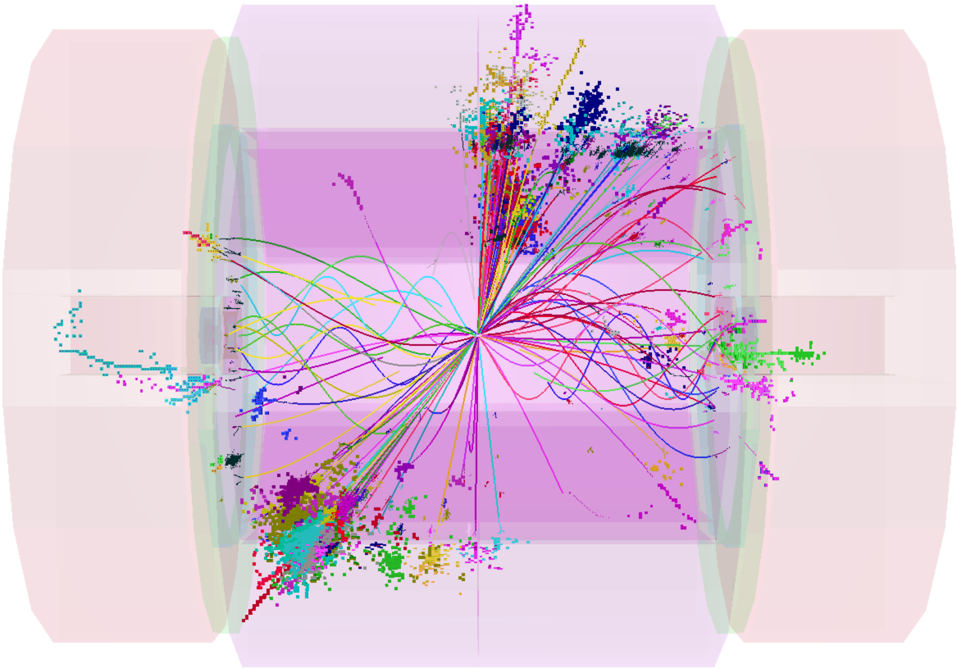
- CLIC hardware requirements
- Achievable in the calorimeters with a sampling every ≈ 25 ns

Impact of the timing cuts

$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$ (8 jet final state)

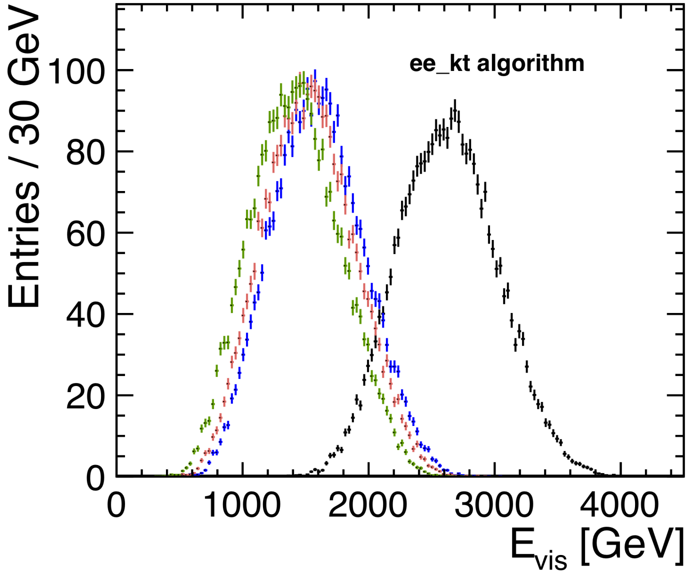


1.2 TeV background
in the reconstruction window



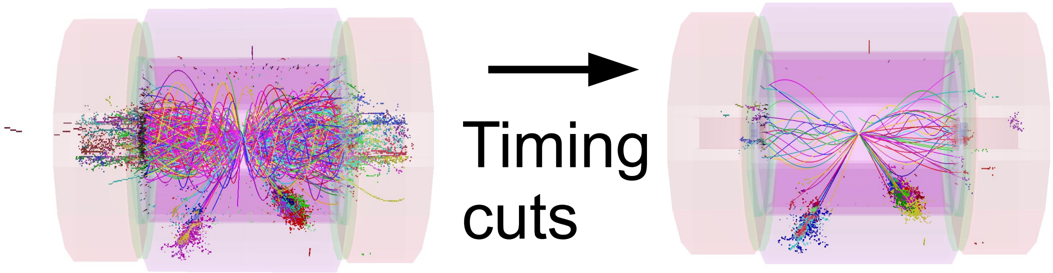
100 GeV background
after (tight) timing cuts

Jet reconstruction at CLIC I



$$e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

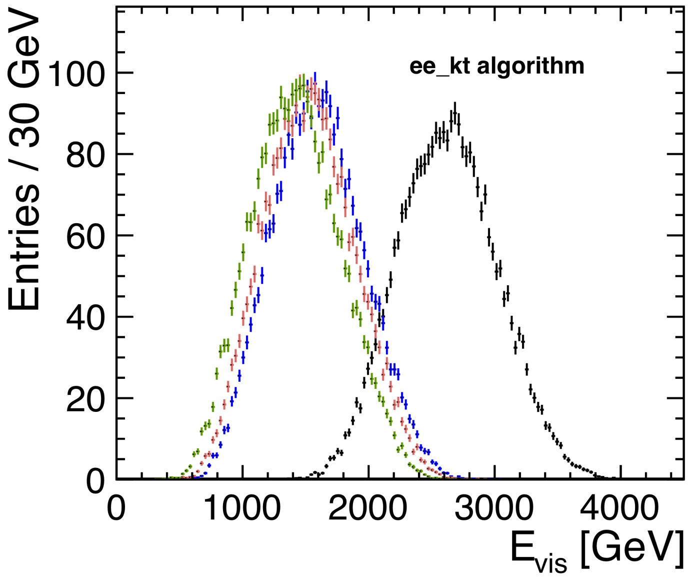
Two jets + missing energy

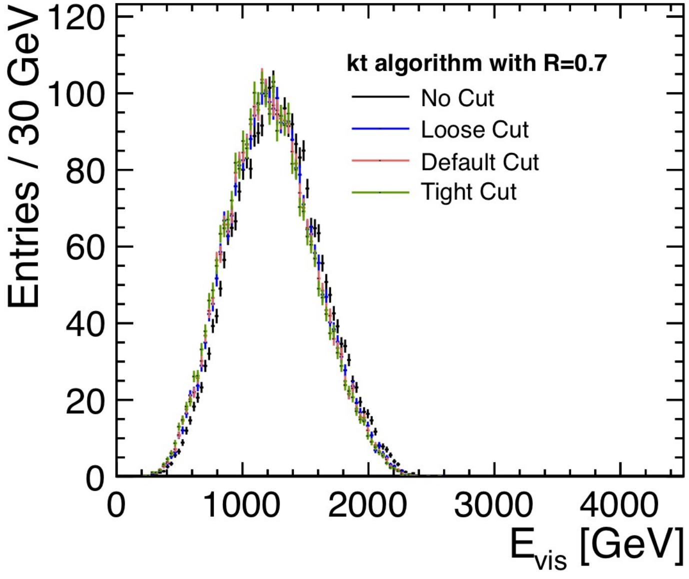


- Using Durham k_T à la LEP

→ Timing cuts are effective, but not sufficient

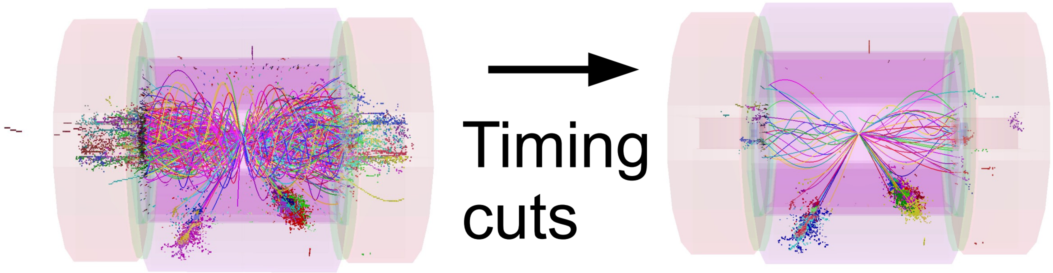
Jet reconstruction at CLIC II





$$e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

Two jets + missing energy



- Using Durham k_T à la LEP

→ Timing cuts are effective, but not sufficient

- "hadron collider" k_T, R = 0.7

→ Background significantly reduced further

→ Need timing cut + jet finding for background reduction

W^+W^- and ZZ

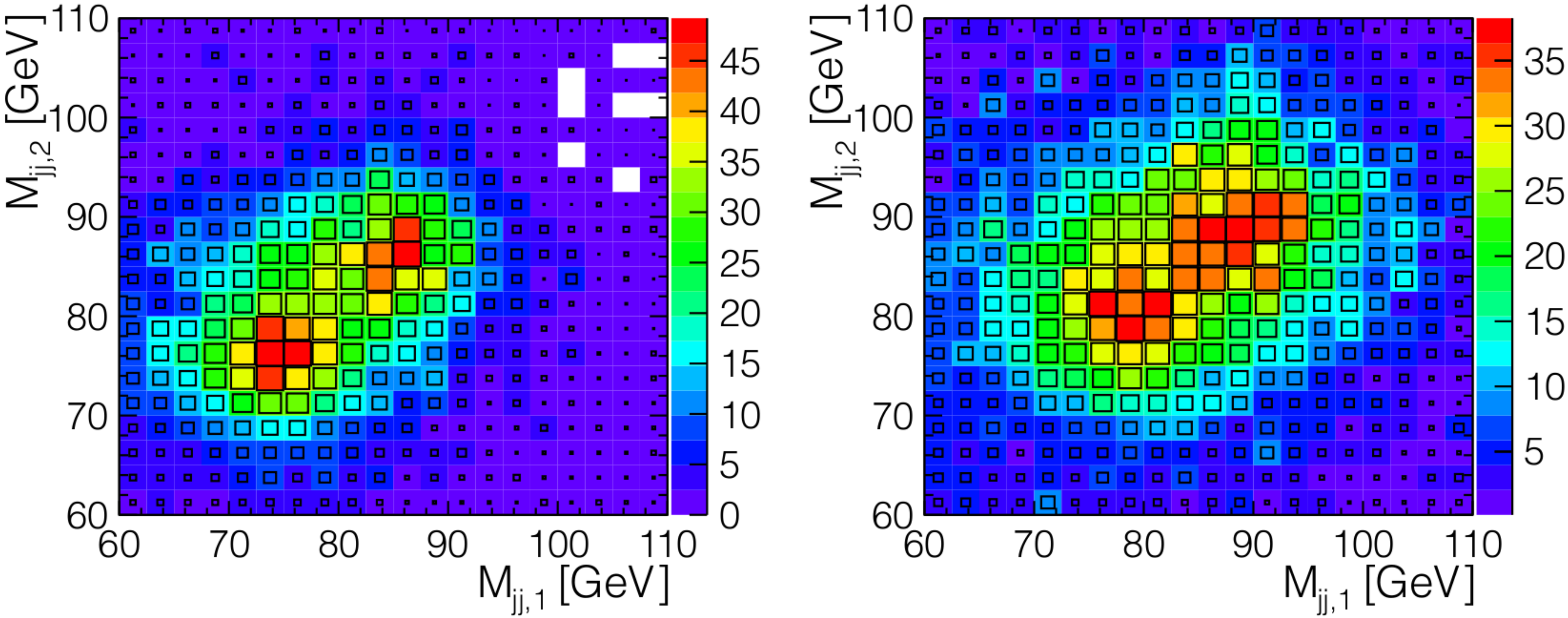


Figure 19: Separation of W and Z from the chargino decay without overlay (left) and with 60 BX of background (right) for CLIC_SiD.

Test of the di-jet mass reconstruction

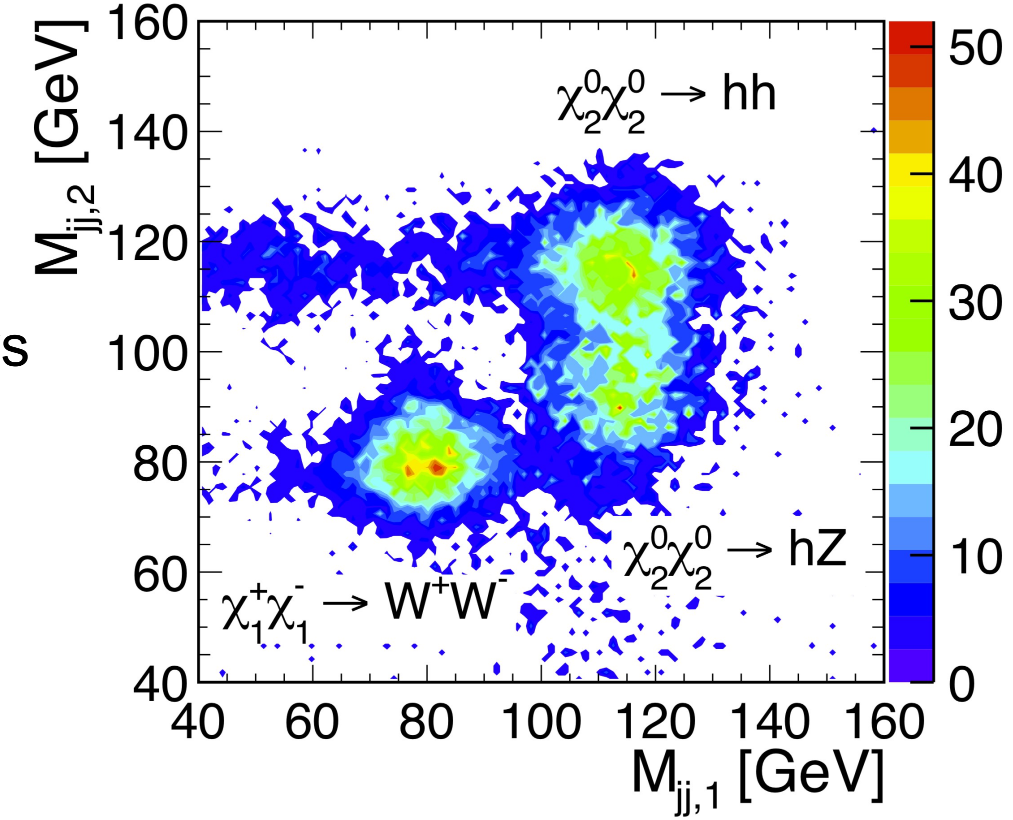
Chargino and neutralino pair production:

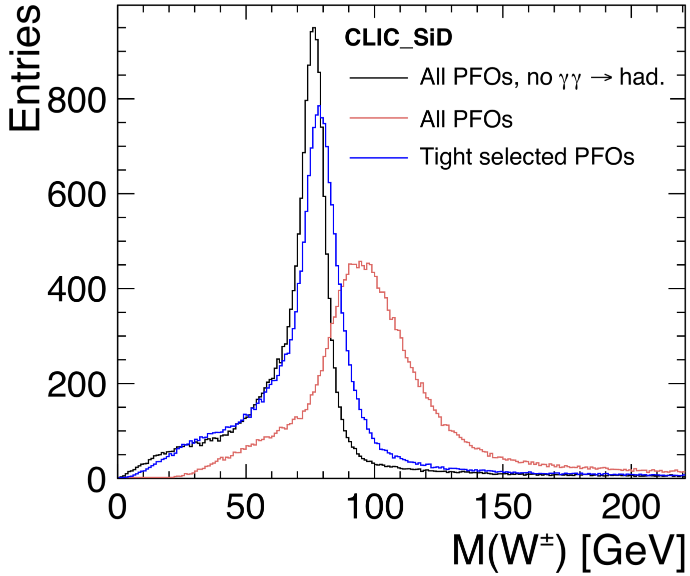
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\%$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 17\%$$

Reconstruct W±/Z/h in hadronic decays
→ four jets and missing energy





Precision on the measured gaugino masses (few hundred GeV): 1 - 1.5%

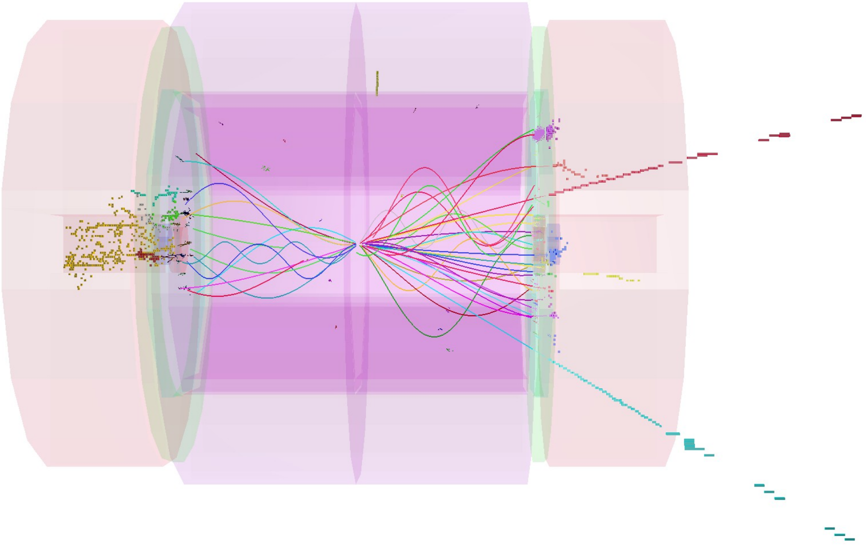
Test of the lepton reconstruction

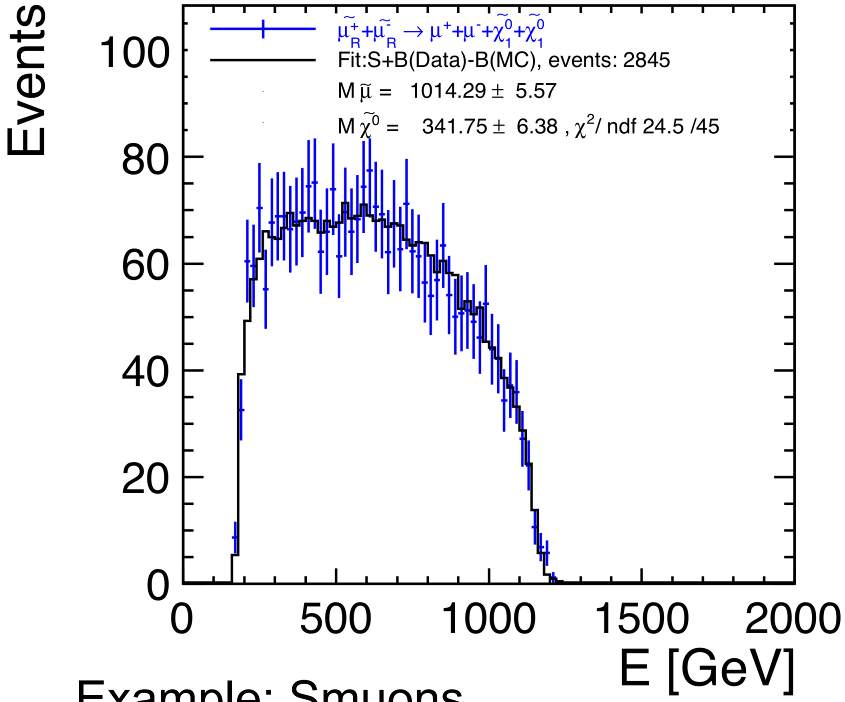
- Slepton production very clean at CLIC
- SUSY "model II": slepton masses ≈ 1 TeV
- Investigated channels include:

$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^-W^+W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$





Example: Smuons

- Leptons and missing energy
- Masses from endpoints of energy spectra

$m(\tilde{\mu}_R)$: ± 5.6 GeV

$m(\tilde{e}_R)$: ± 2.8 GeV

$m(\tilde{\nu}_e)$: ± 3.9 GeV

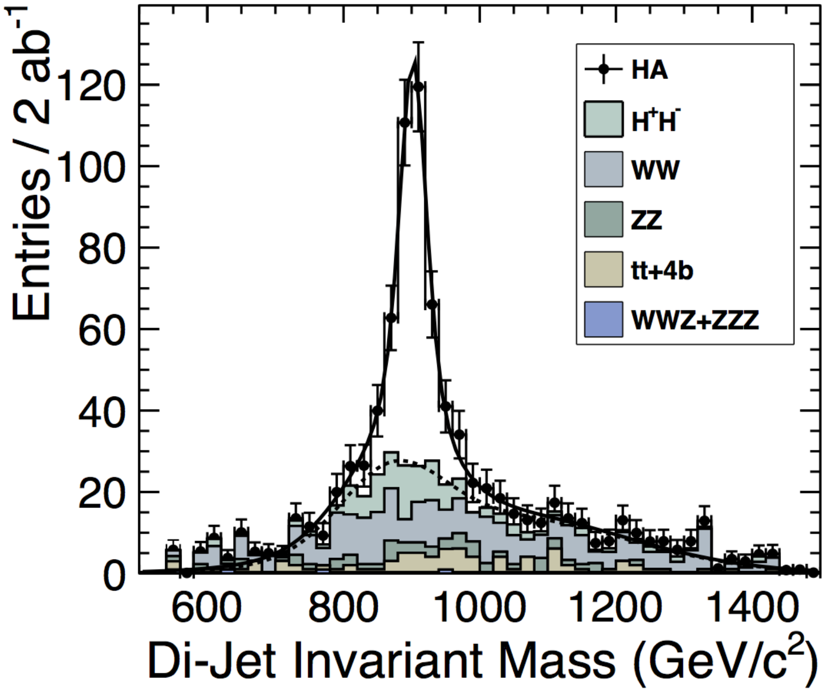
$m(\tilde{\chi}_1^0)$: ± 3.0 GeV

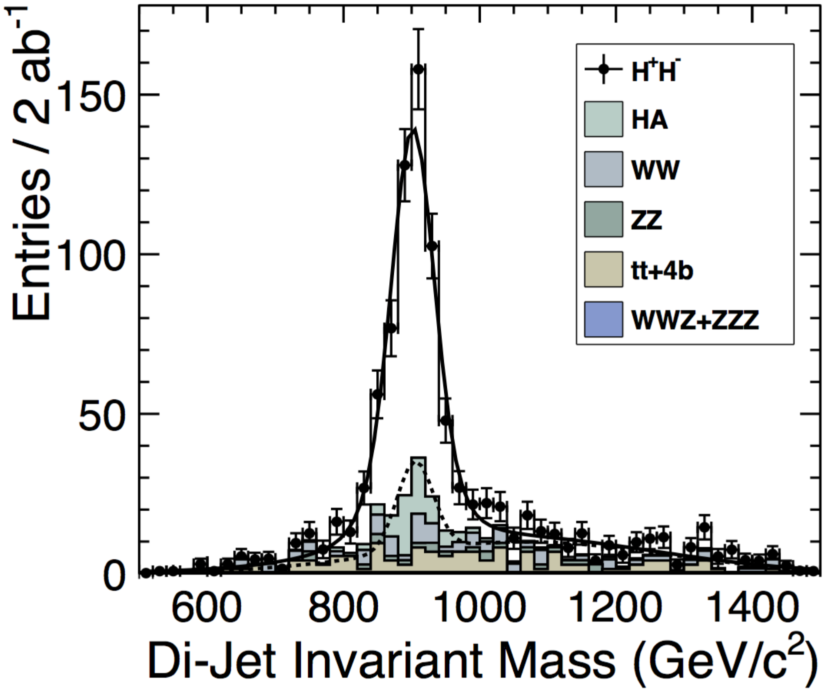
$m(\tilde{\chi}_1^\pm)$: ± 3.7 GeV

Complex final states

Heavy Higgs bosons:
$e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$
$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$

Flavour tagging crucial!





Accuracy of the heavy Higgs mass measurements: ≈ 0.3%