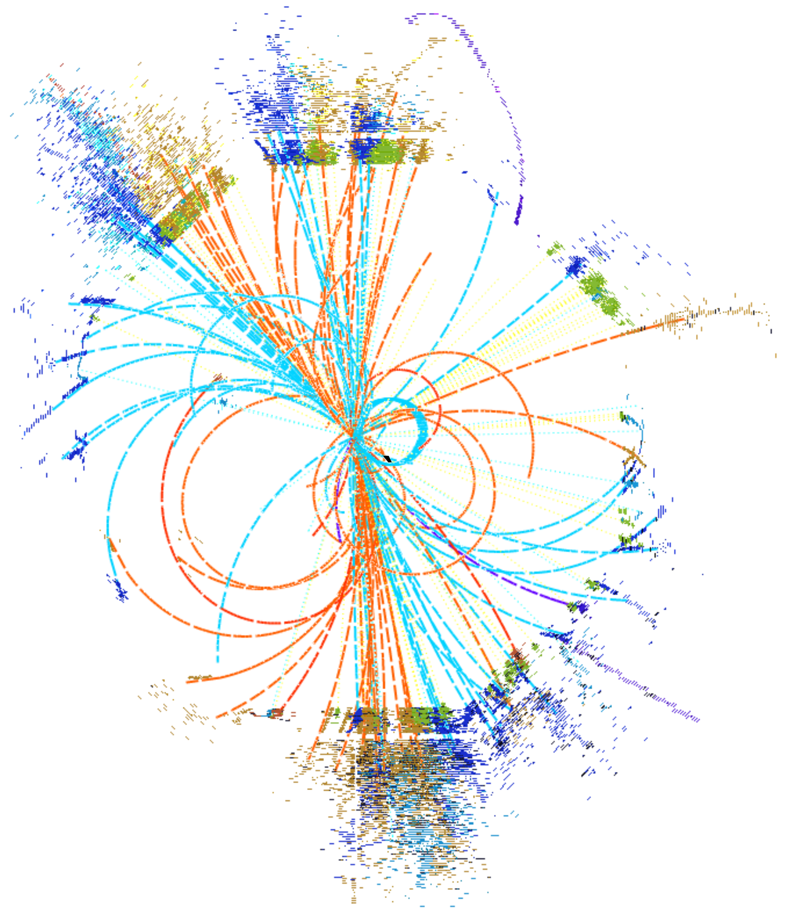
Precision electroweak physics in e^+e^- collisions at CLIC

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



Snowmass Energy Frontier workshop,
University of Washington, Seattle, 30/06/2013

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} $cm^{-2}s^{-1}$)

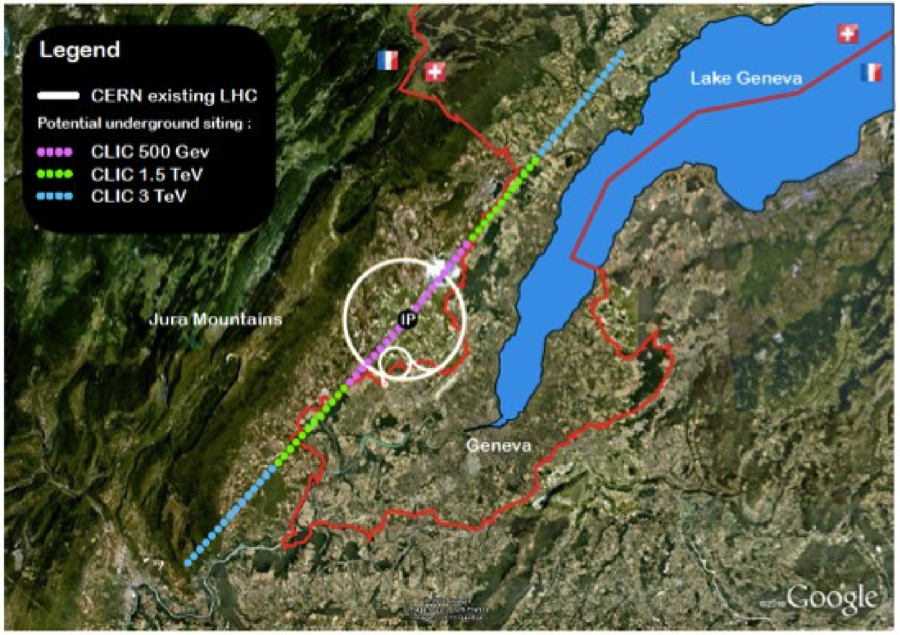
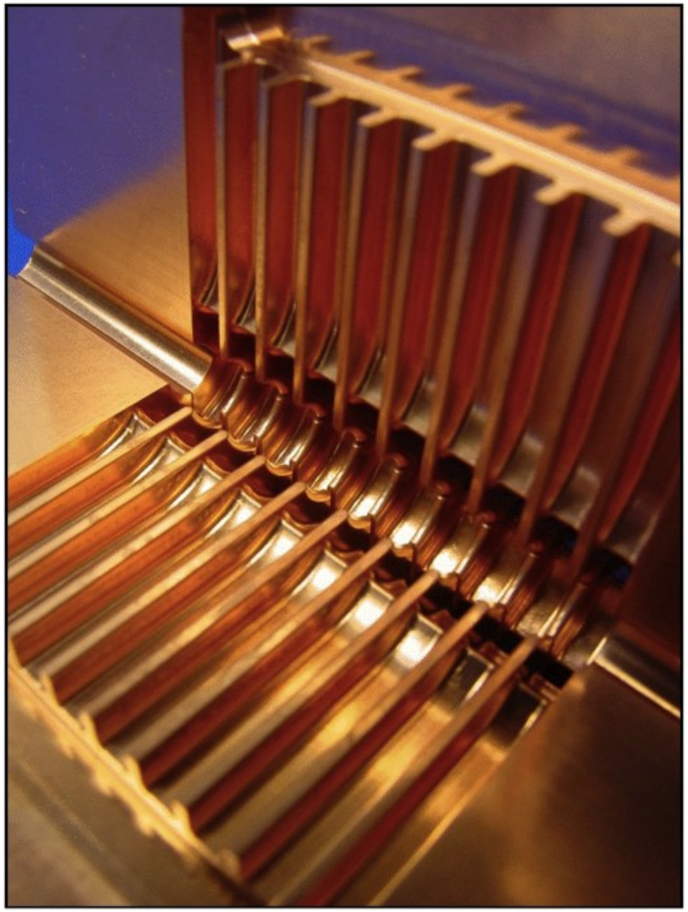


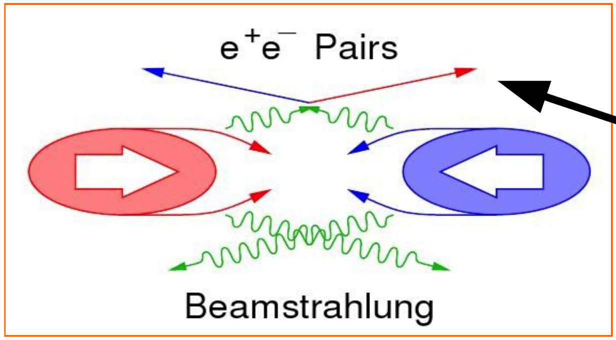
Fig. 7.2: CLIC footprints near CERN, showing various implementation stages [5].



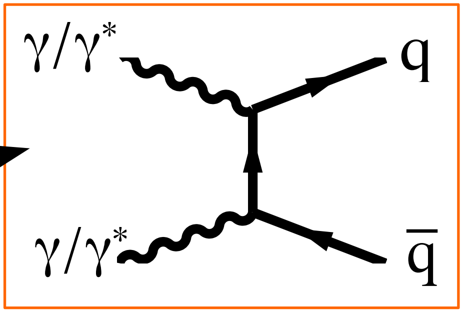
The CLIC detector and physics study

- 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!

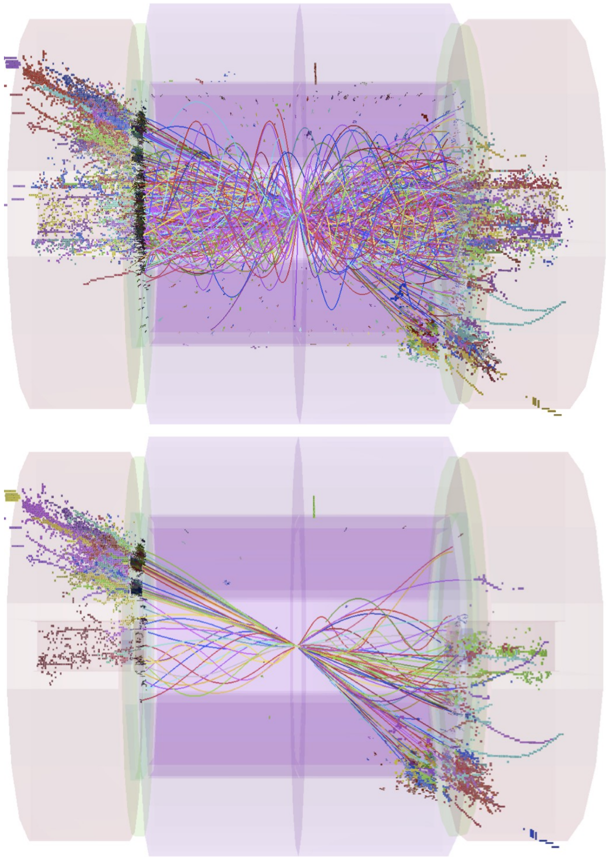
Experimental conditions



Beam-related backgrounds
- e^+e^- pairs
- $\gamma\gamma \rightarrow$ hadrons



e^+e^- pairs:
Detector design issue
(mostly very forward, high occupancies)
$\gamma\gamma \rightarrow$ hadrons:
- Main background in calorimeters and trackers $\rightarrow$ impact on physics
- Overlay of physics events with pileup from $\gamma\gamma \rightarrow$ hadr. interactions in benchmark studies

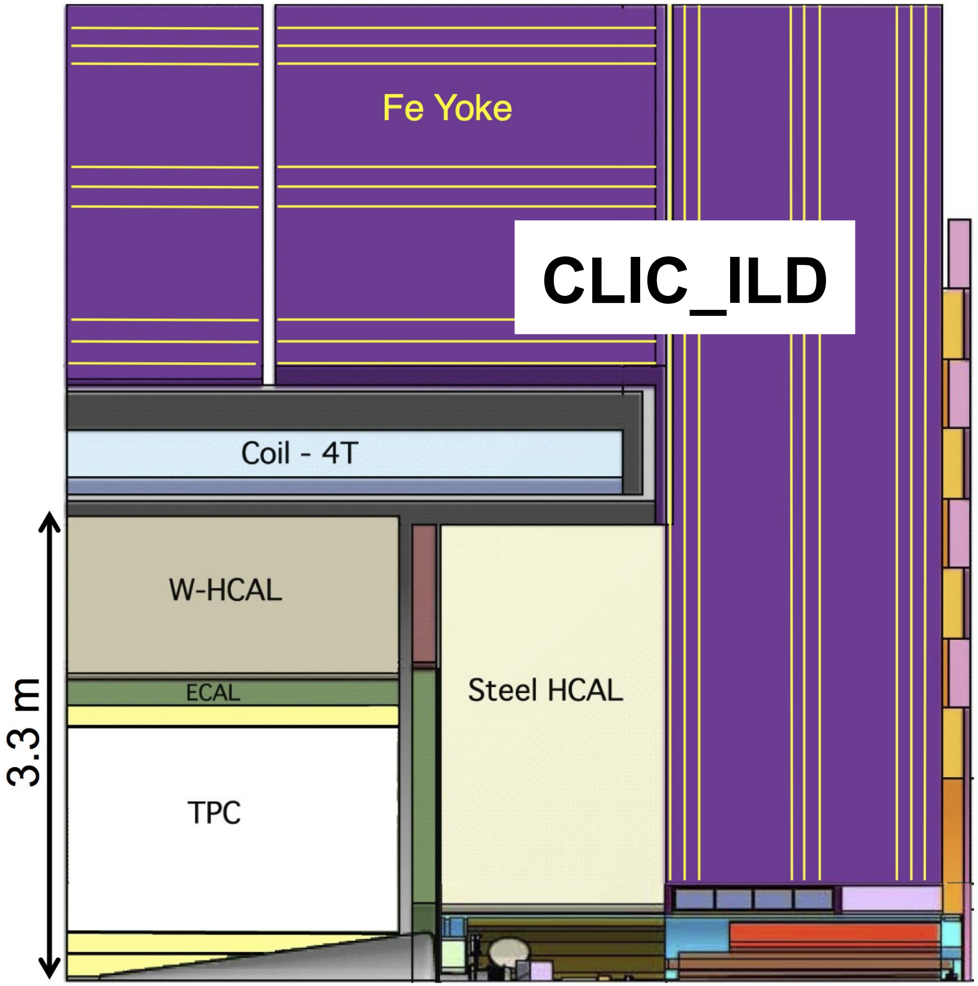


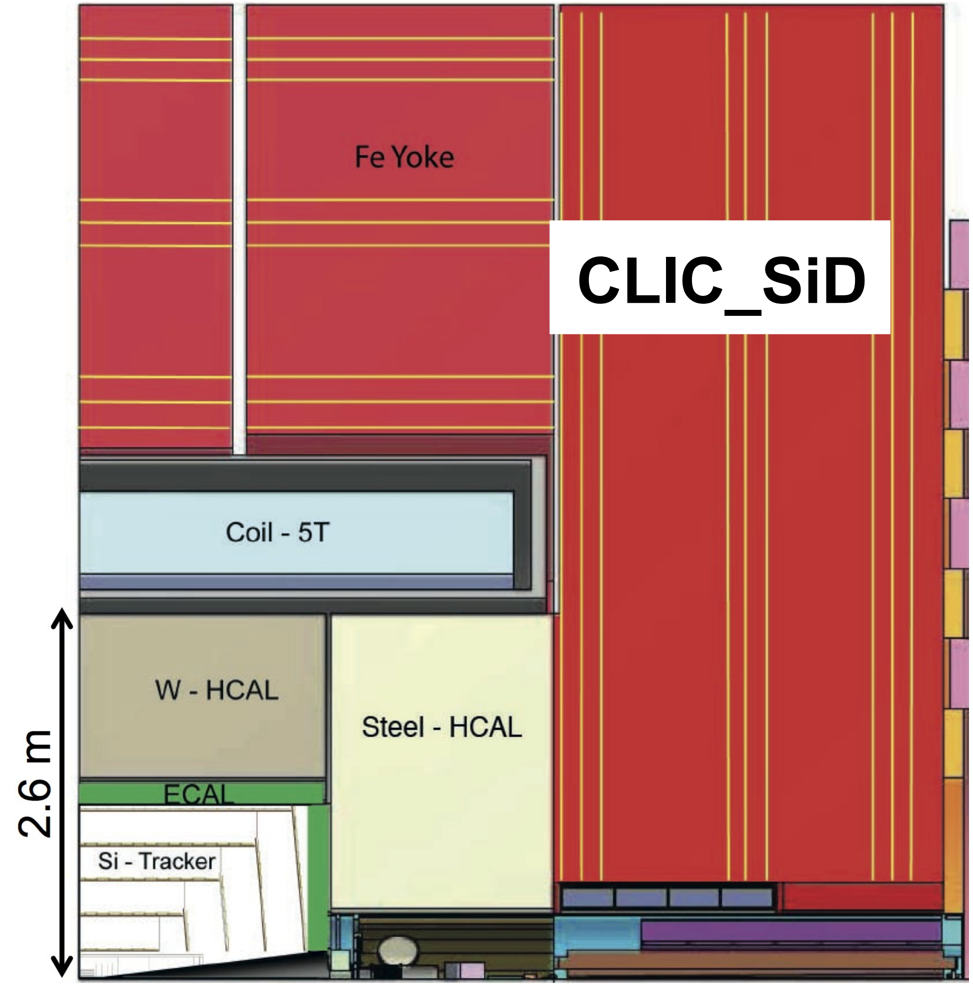
Backgrounds suppressed using combined cuts on cluster times and p_T

$e^+e^- \rightarrow t\bar{t}$ at 3 TeV

CLIC detector concepts

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





Benchmark studies are based on full detector simulations (Geant4)

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

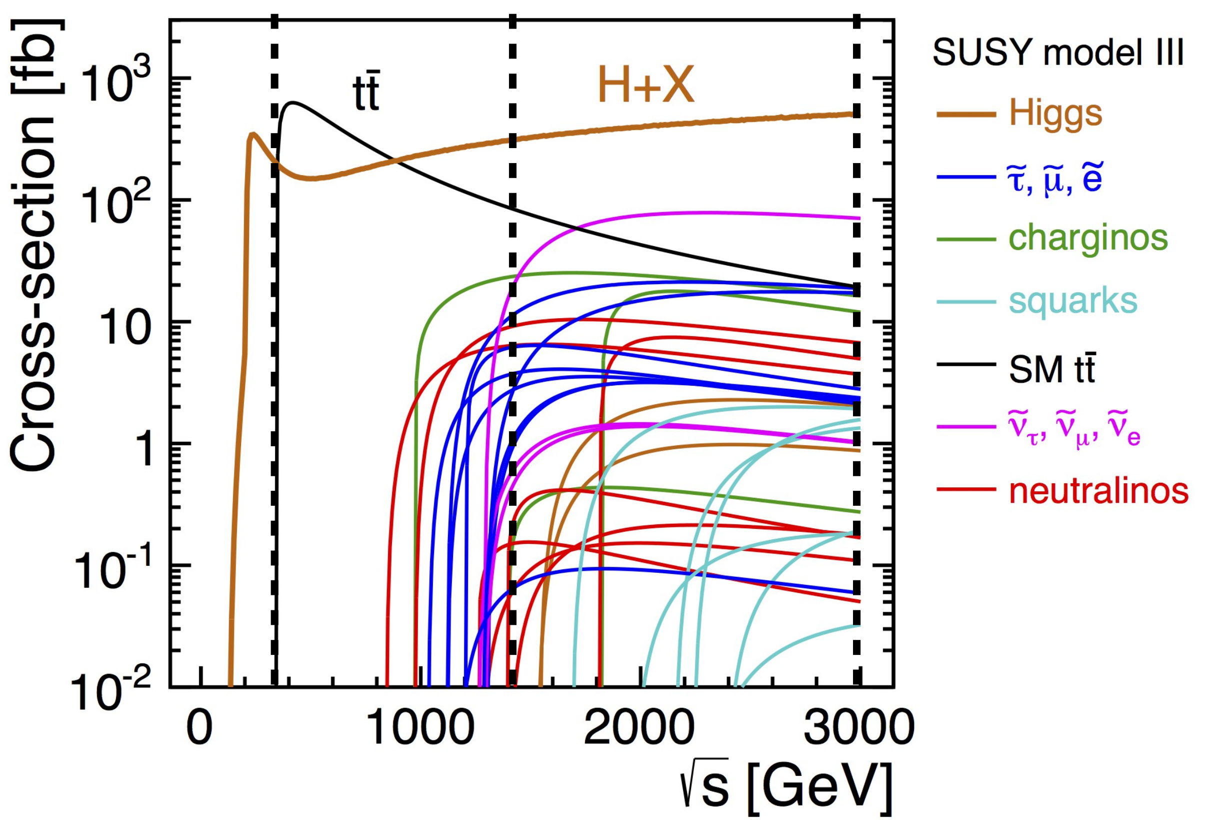
→ strategy can be adapted to discoveries at the LHC

Currently studied example scenario:

- **Stage 1:** 350/375 GeV, 500 fb^{-1}
SM Higgs & top threshold scan

- **Stage 2:** 1.4 TeV, 1.5 ab^{-1}
BSM physics, precision Higgs measurements

- **Stage 3:** 3 TeV, 2 ab^{-1}
BSM physics, precision Higgs measurements



CLIC benchmark studies

Benchmark studies so far focus on SM Higgs measurements and BSM searches

Top quark mass:

$\sqrt{s}$ (GeV)	Technique	Measured quantity	Integrated luminosity (fb^{-1})	Unit	Generator value	Stat. error
350	Threshold scan	Mass α_S	10×10	GeV	174 0.118	0.033 0.0009
500	Invariant mass	Mass	100	GeV	174	0.080

→ see talk by Sophie Redford in top quark session

SM Higgs mass:

350 GeV: $\Delta(m_H)$ = 120 MeV, model independent from Z recoil

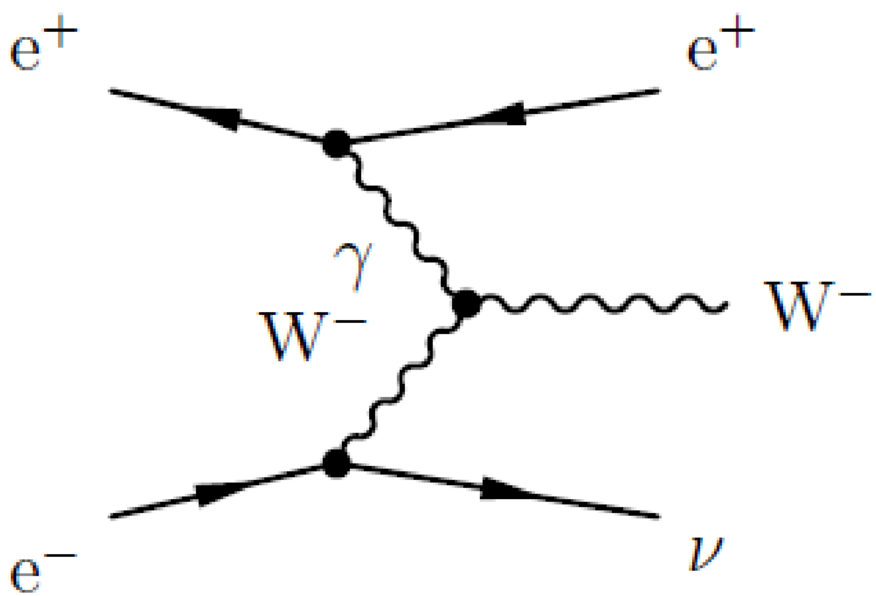
1.4 TeV: $\Delta(m_H) \approx$ 40 MeV (estimated) from $H \rightarrow b\bar{b}$

3 TeV: $\Delta(m_H) \approx$ 33 MeV (estimated) from $H \rightarrow b\bar{b}$

→ see talk by Ph. R. in Higgs session

M_W from single W events

- Large samples of single W events produced at high-energy CLIC
- Potential for competitive measurement of M_W using $W^\pm \rightarrow q\bar{q}$
- Need full simulation study to understand the impact of systematic effects, i.e. the jet energy scale



$e^+e^- \rightarrow e^+W^-\nu$

	1.4 TeV	3 TeV
L_{int}	1500 fb^{-1}	2000 fb^{-1}
# eWv events	$22.3 \cdot 10^6$	$44.9 \cdot 10^6$

Numbers of events including ISR and Beamstrahlung assuming unpolarised beams

Anomalous triple gauge boson vertices

Triple gauge couplings have beed studied in the past using $e^+e^- \rightarrow W^+W^-$ events (hep-ph/0412251):

Table 10: Sensitivity of the real parts of CP-even couplings in units of 10^{-3}, defined and expounded upon in [30]. The integrated luminosities for the 500 GeV, 800 GeV and 3000 GeV stages are assumed here to be 500 fb^{-1}, 1 ab^{-1} and 3 ab^{-1} respectively.

$\sqrt{s}$ [GeV]	$\mathrm{Re}(\Delta g_1^L)$	$\mathrm{Re}(\Delta\kappa_L)$	$\mathrm{Re}(\lambda_L)$	$\mathrm{Re}(g_5^L)$	$\mathrm{Re}(g_1^R)$	$\mathrm{Re}(\Delta\kappa_R)$	$\mathrm{Re}(\lambda_R)$	$\mathrm{Re}(g_5^R)$
500	2.6	0.85	0.59	2.0	10	2.4	3.6	6.7
800	1.6	0.35	0.24	1.4	6.2	0.92	1.8	4.8
3000	0.93	0.051	0.036	0.88	3.1	0.12	0.36	3.2

→ Improved precision at high-energy

New analysis based on current full detector simulation desirable

Outlook

Planned future studies based on full detector simulation:

- Triple and quartic gauge boson vertex corrections to $e^+e^- \rightarrow W^+W^-(\nu\bar{\nu}/e^+e^-)$

- Forward-backward and left-right asymmetries of fermion production to achieve precision measurements of $\sin^2\theta_f^{eff}$ at various energies

- W boson mass determination at high energy and high luminosity

- Total $e^+e^- \rightarrow f\bar{f}$ cross sections at high energy with various electron-positron polarisations in search of form-factor suppressions or enhancements

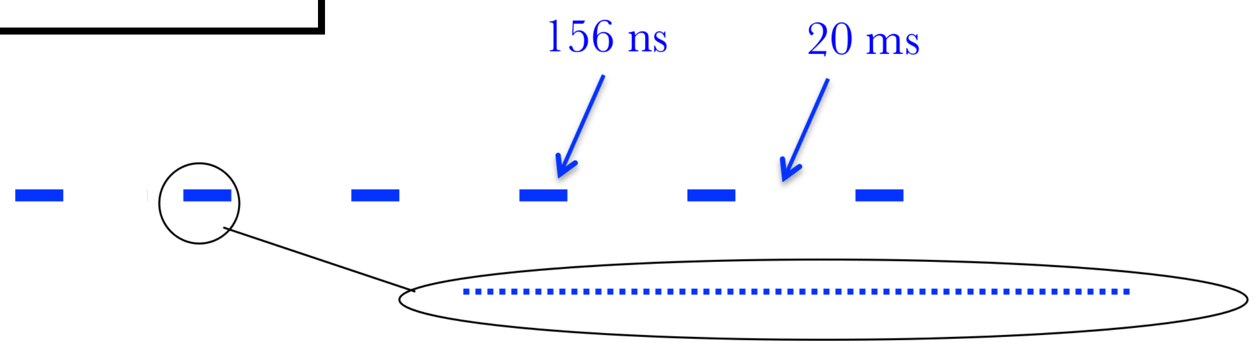
Backup slides

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

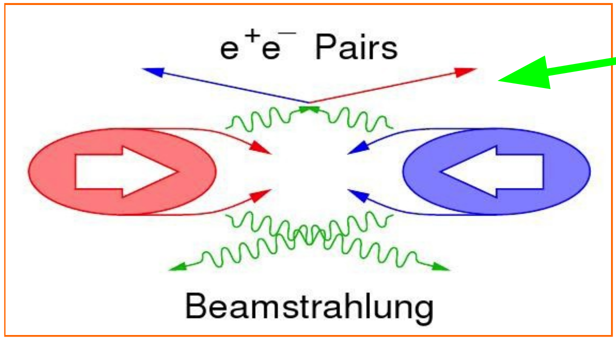
Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

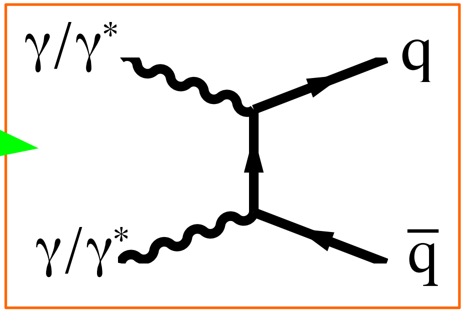


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam related backgrounds



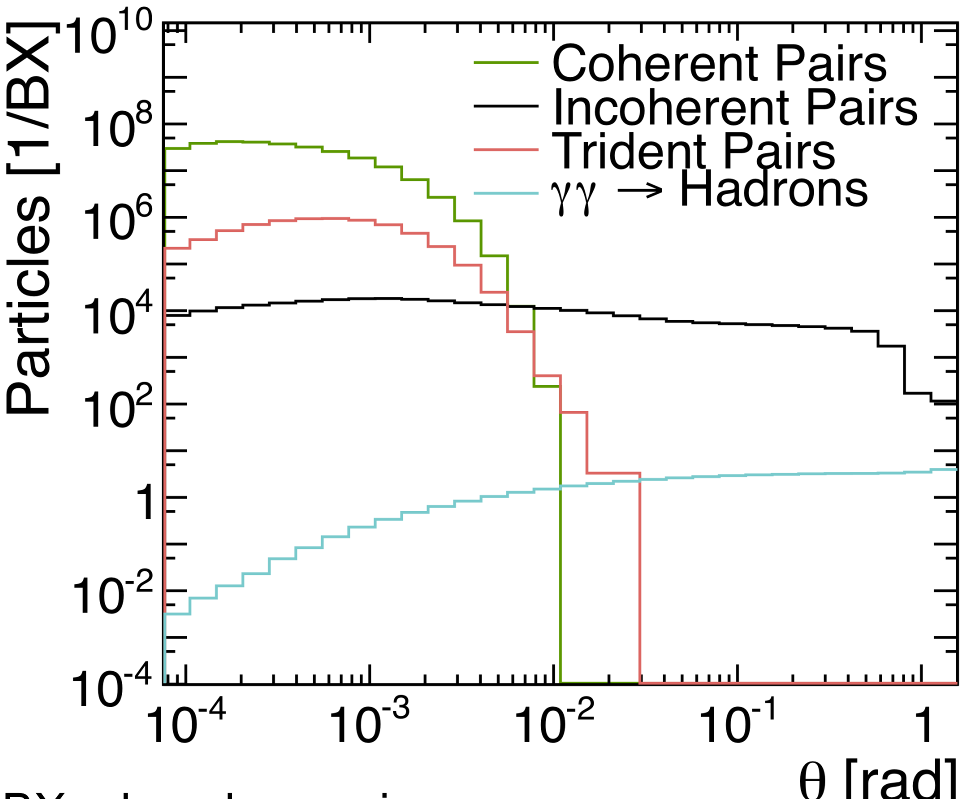
- e^+e^- pairs
- $\gamma\gamma \rightarrow$ hadrons
- Beam halo muons



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)

$\gamma\gamma \rightarrow$ hadrons
- "Only" 3.2 per BX at 3 TeV
- Main background

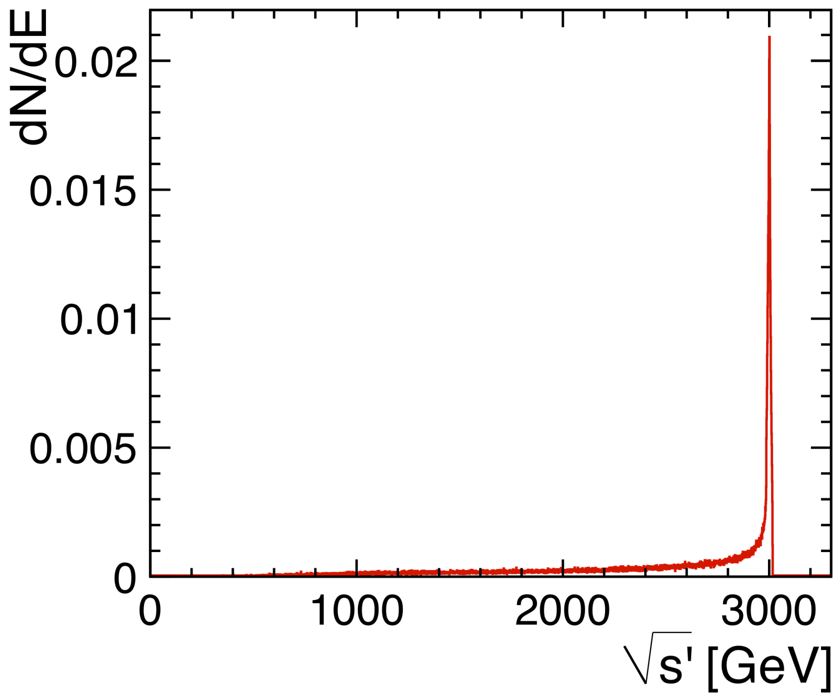
in calorimeters and trackers
→ Impact on physics



BX = bunch crossing

Luminosity spectrum

Significant energy loss at the interaction point due to Beamstrahlung



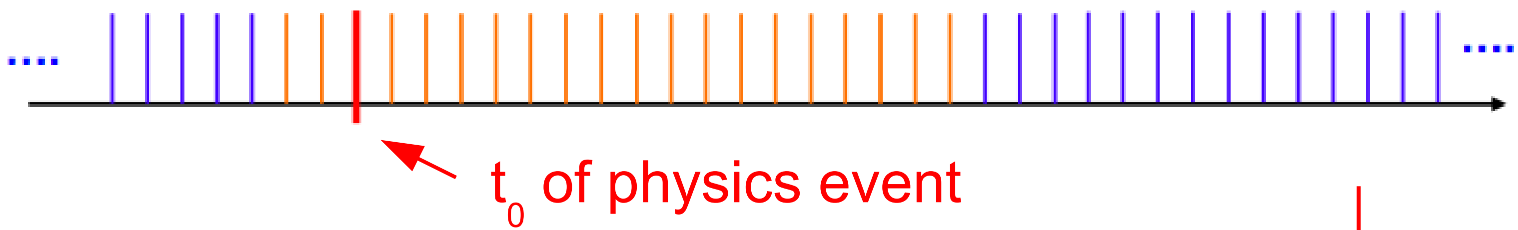
$$\sqrt{s'} = \sqrt{4 \cdot E_1 \cdot E_2}$$

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

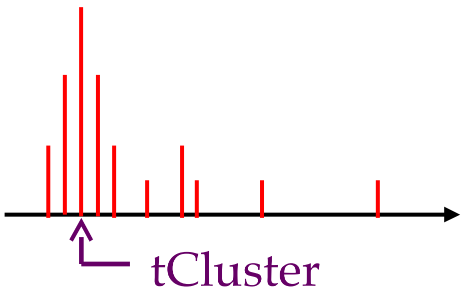
Most physics processes are studies well above the production threshold
→ Profit from (almost) full luminosity

Background suppression

Triggerless readout of full bunch train:



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

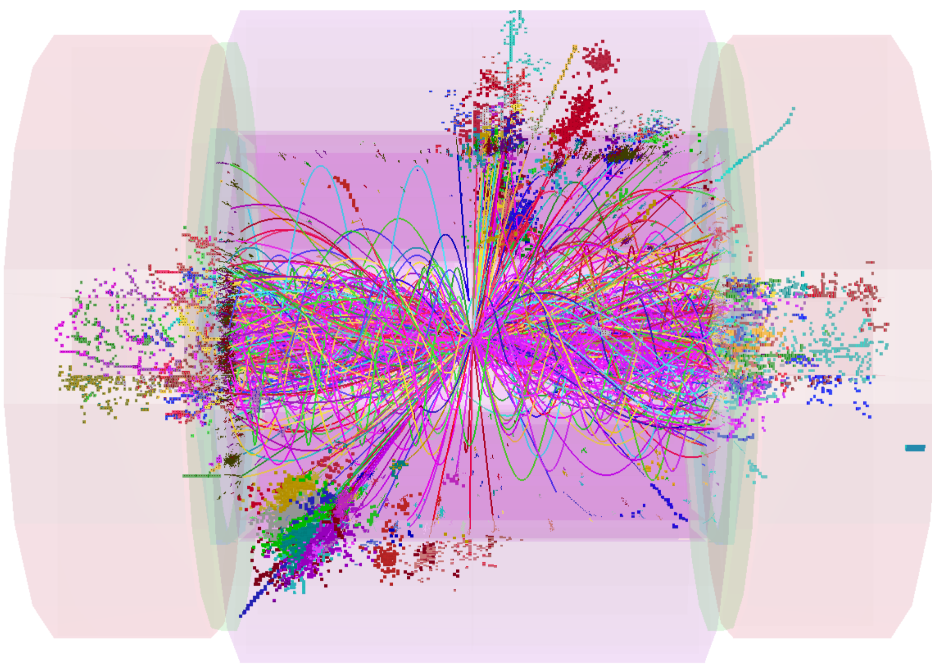
Used in the reconstruction software for CDR simulations:

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

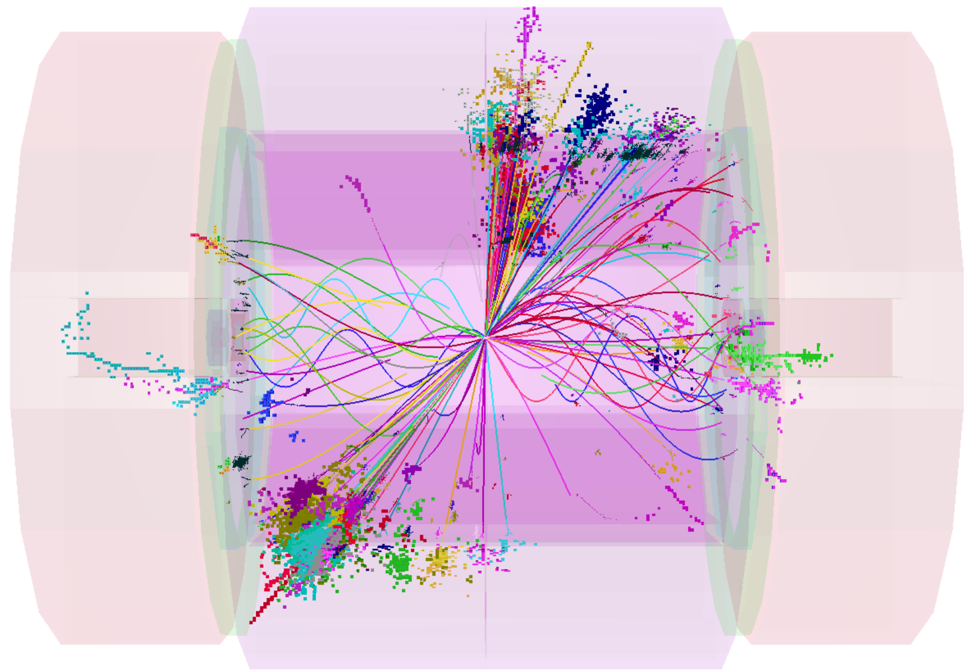
- CLIC hardware requirements
- Achievable in the calorimeters with a sampling every ≈ 25 ns

Impact of the timing cuts

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

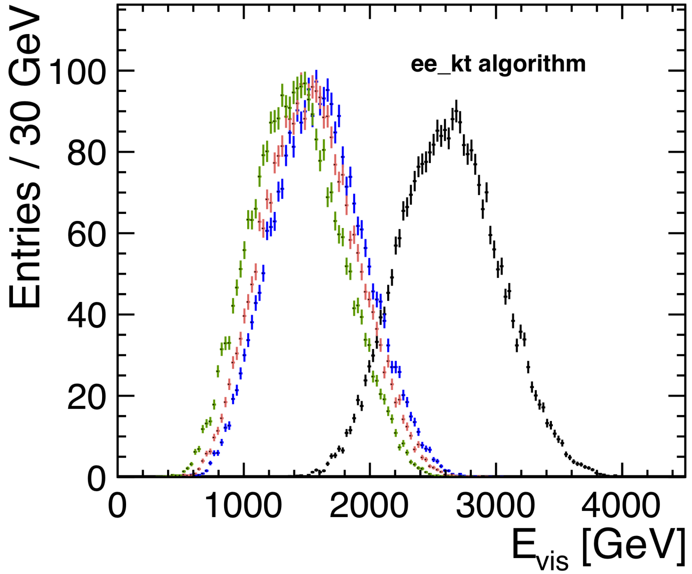


1.2 TeV background
in the reconstruction window



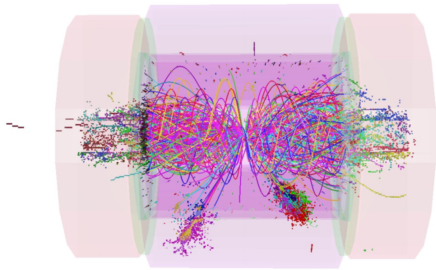
100 GeV background
after (tight) timing cuts

Jet reconstruction at CLIC I

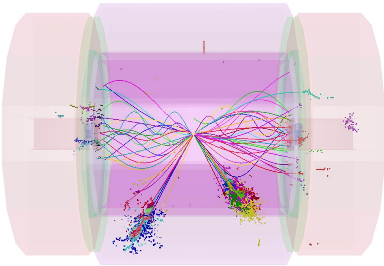


$$e^+e^- \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

Two jets + missing energy



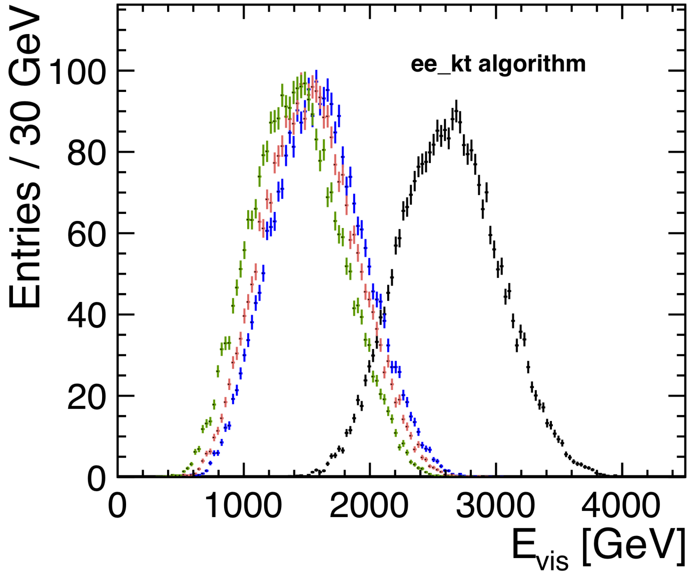
Timing cuts

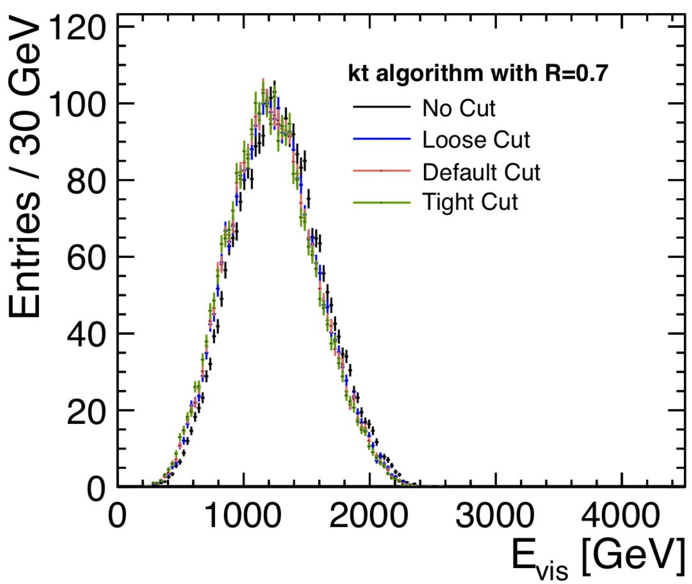


- Using Durham k_T à la LEP

→ Timing cuts are effective, but not sufficient

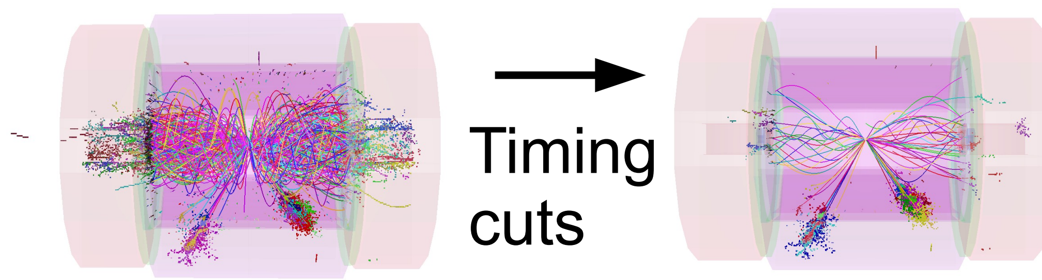
Jet reconstruction at CLIC II





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

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

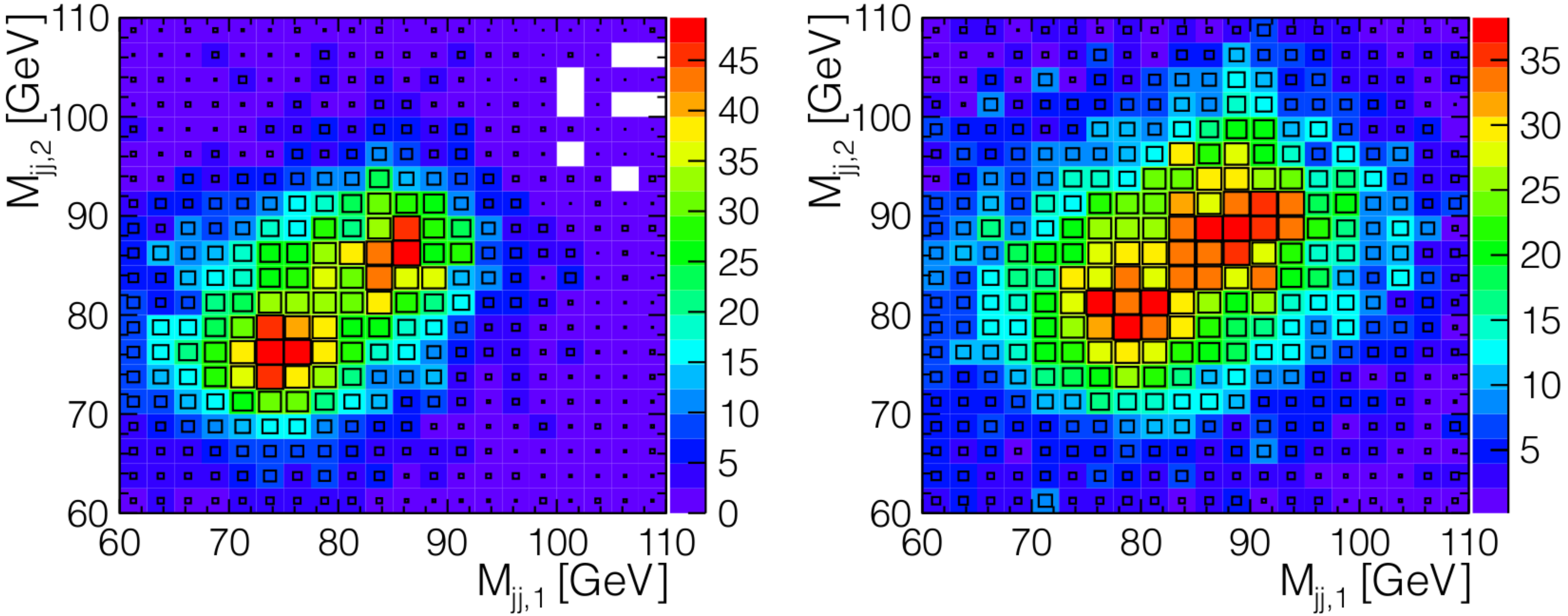


Figure 19: Separation of W and Z from the chargino decay without overlay (left) and with 60 BX of background (right) for CLIC_SiD.

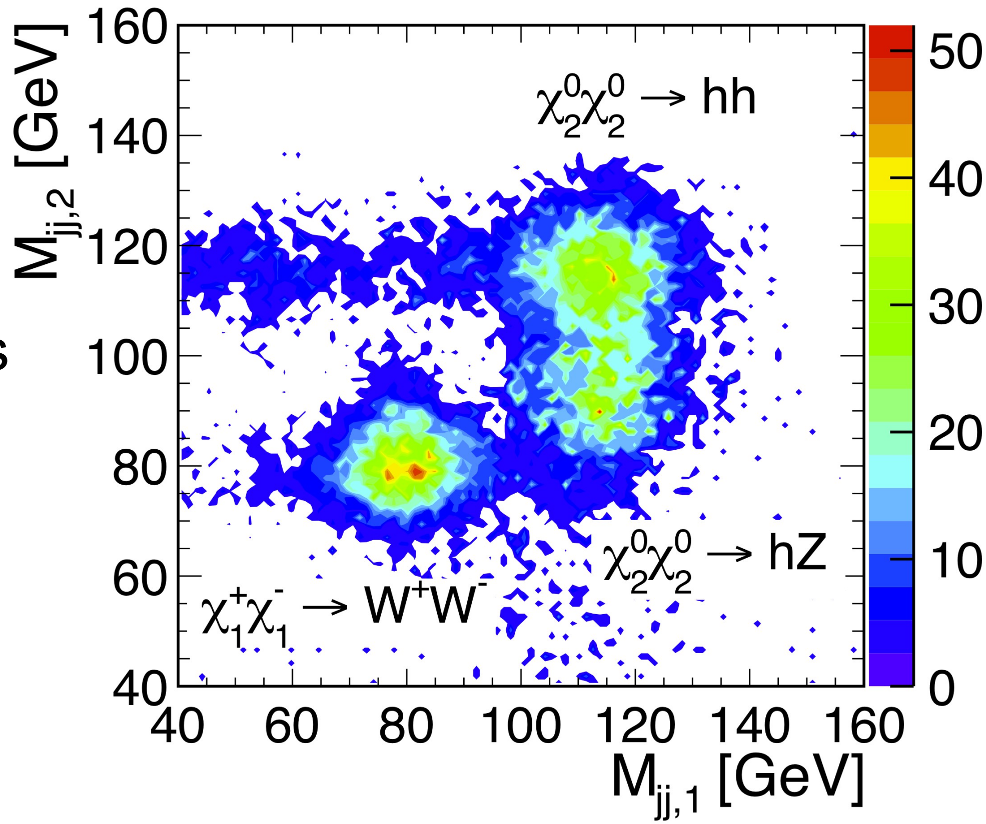
Test of the di-jet mass reconstruction

Chargino and neutralino pair production:

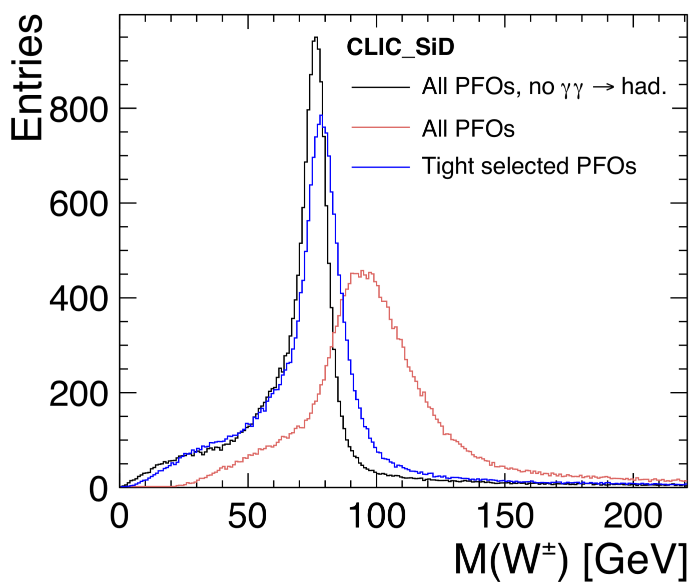
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$

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

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



Reconstruct $W^{\pm}$/Z/h in hadronic decays
→ four jets and missing energy

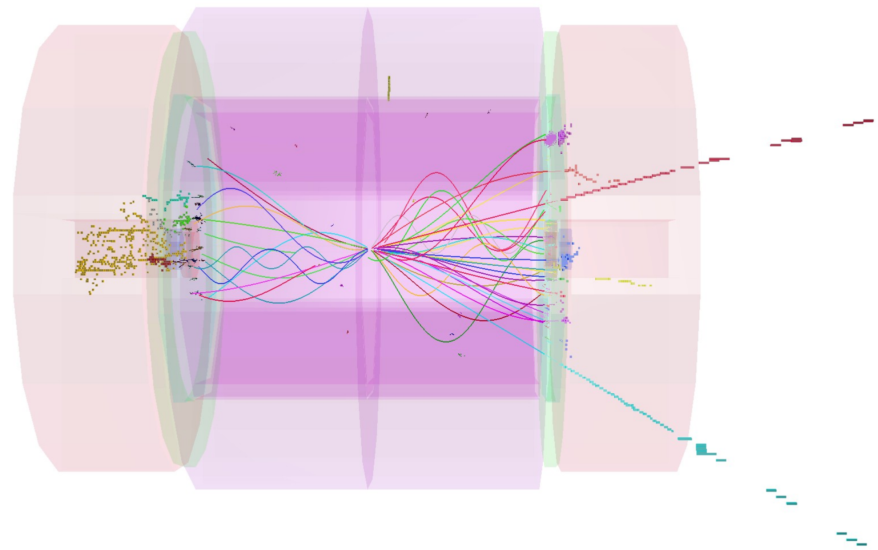


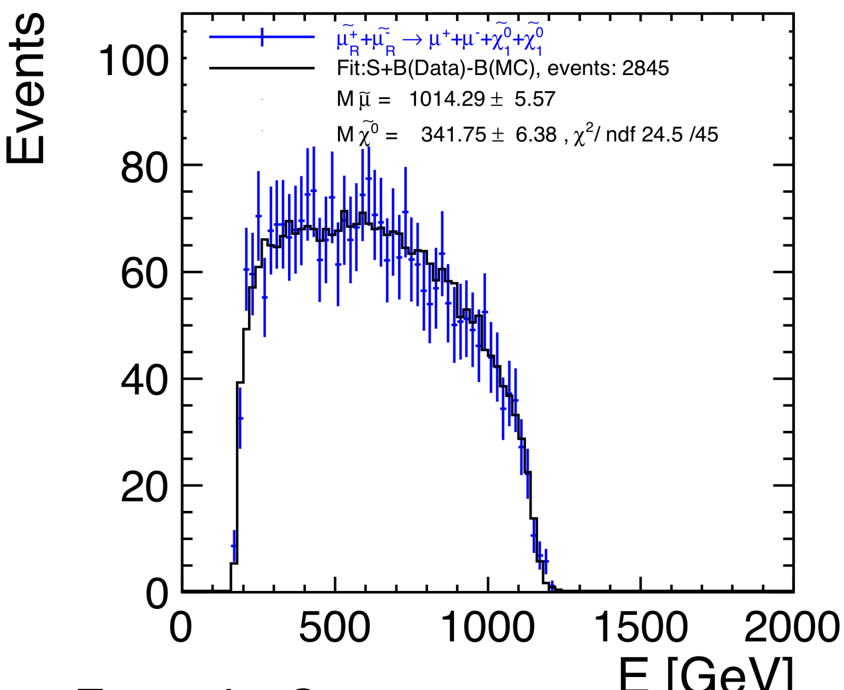
Precision on the measured gaugino masses (few hundred GeV): 1 - 1.5%

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

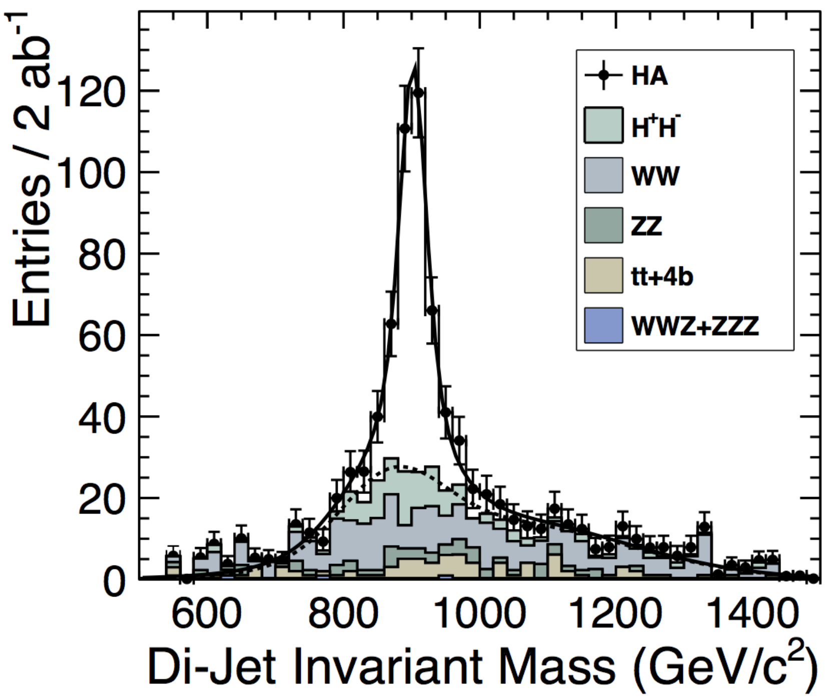
- Leptons and missing energy
- Masses from endpoints of energy spectra

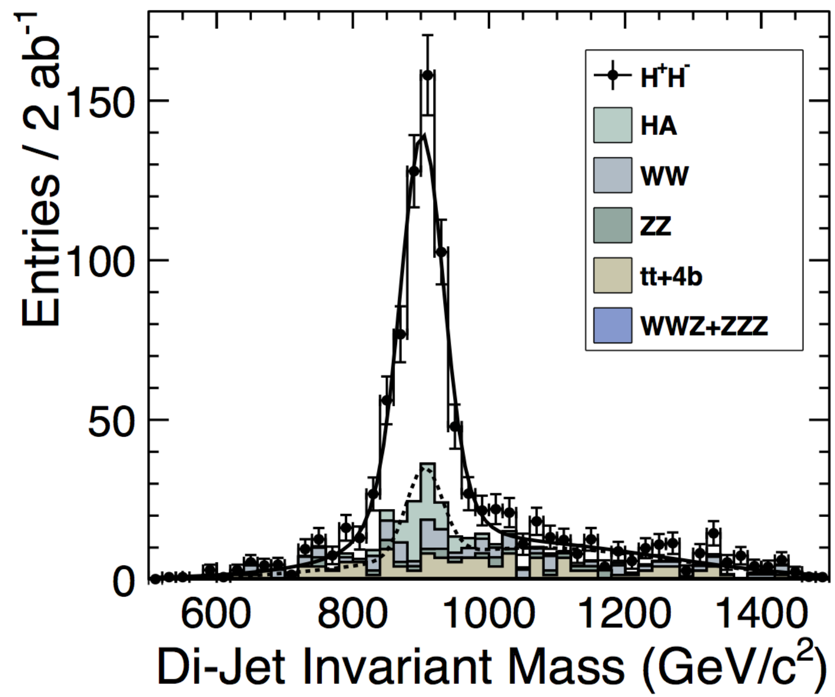
$$m(\tilde{\mu}_R)\ :\ \pm 5.6\,\mathrm{GeV}$$
$$m(\tilde{e}_R)\ :\ \pm 2.8\,\mathrm{GeV}$$
$$m(\tilde{\nu}_e)\ :\ \pm 3.9\,\mathrm{GeV}$$
$$m(\tilde{\chi}_1^0)\ :\ \pm 3.0\,\mathrm{GeV}$$
$$m(\tilde{\chi}_1^\pm)\ :\ \pm 3.7\,\mathrm{GeV}$$

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%