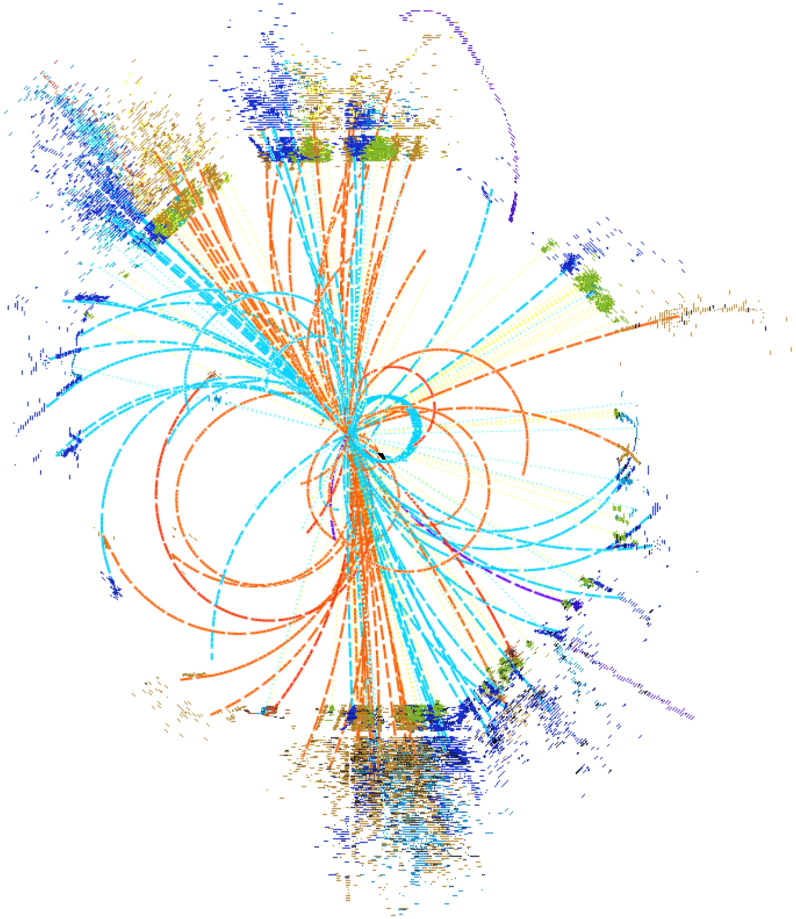
Measurement of Higgs couplings and mass in e^+e^- collisions at CLIC

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



Snowmass Energy Frontier workshop,
University of Washington, Seattle, 02/07/2013

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

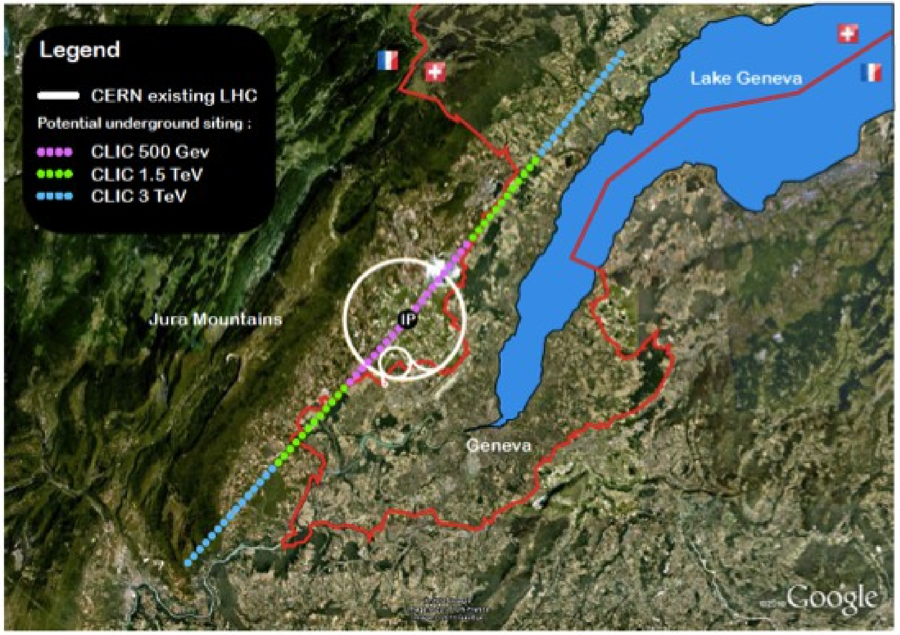
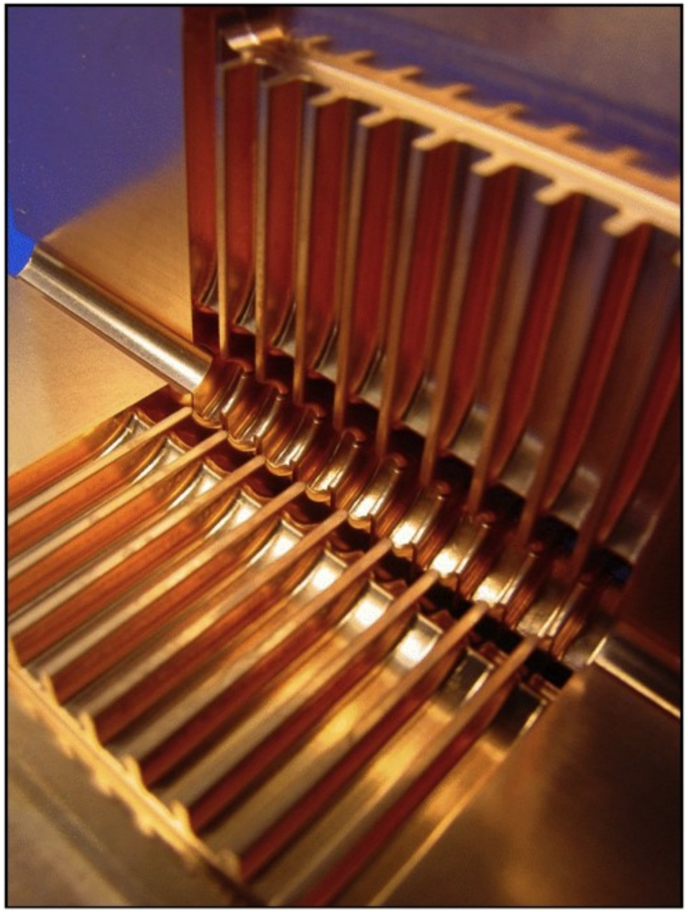


Fig. 7.2: CLIC footprints near CERN, showing various implementation stages [5].

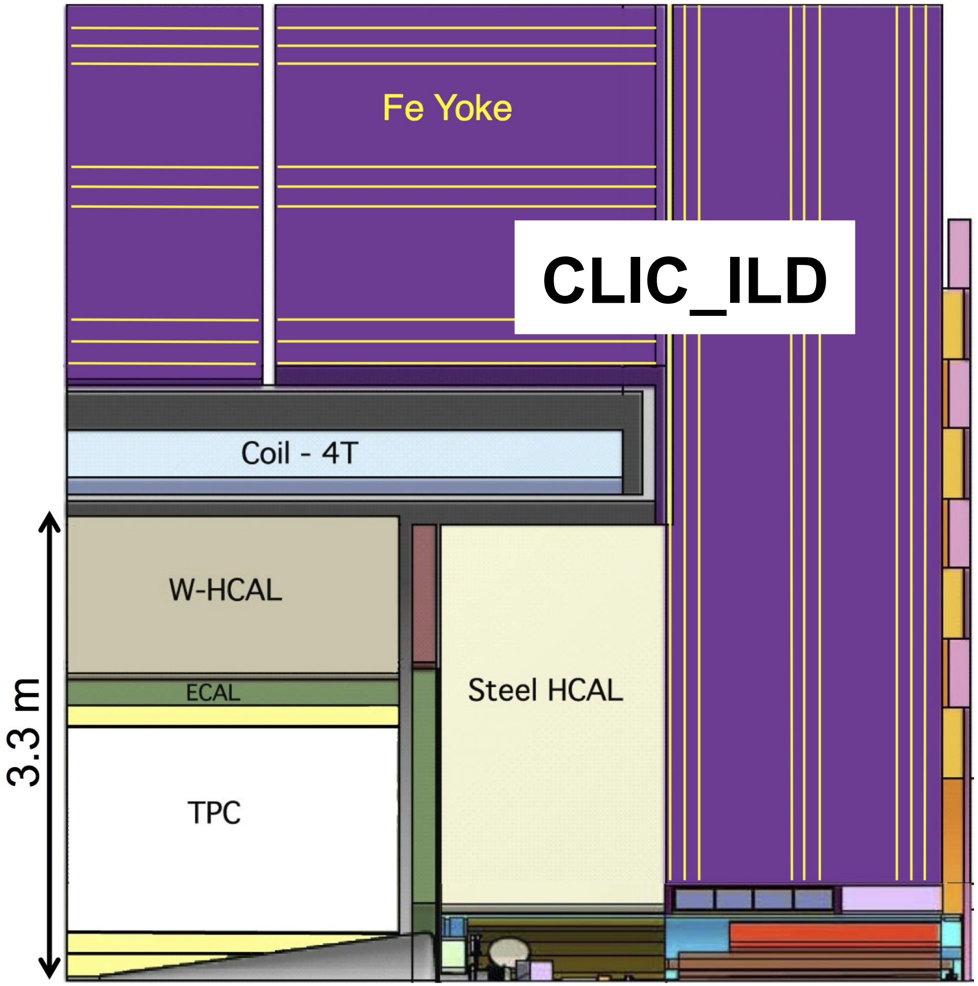


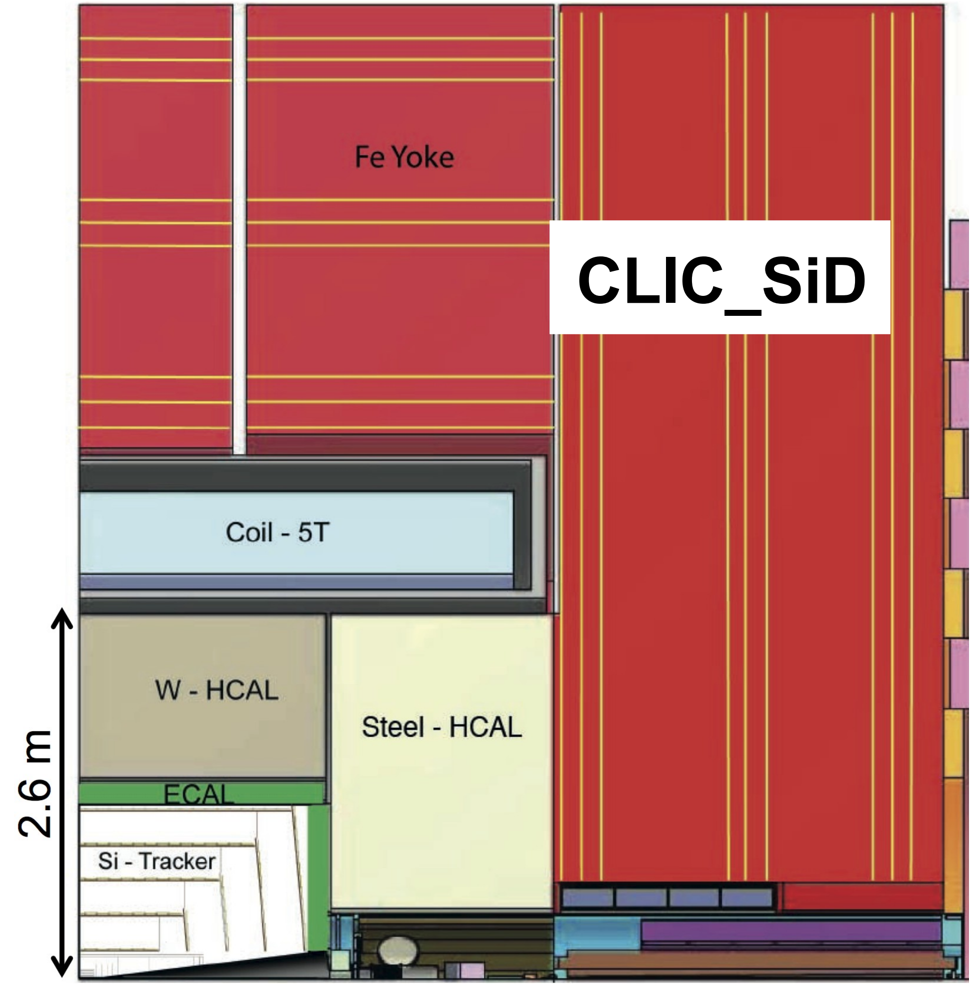
The CLIC detector and physics study

- 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!

CLIC detector concepts

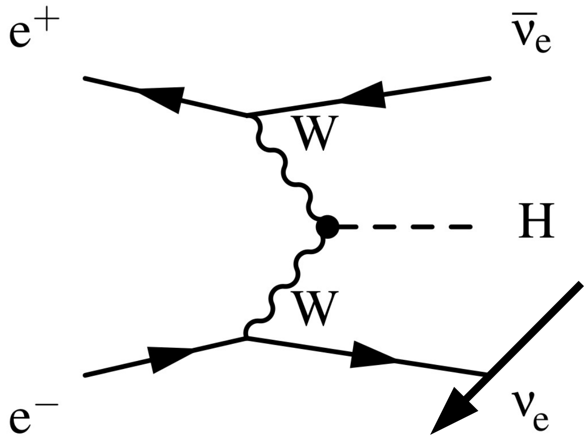
Based on ILC concepts (ILD and SiD), adapted to CLIC conditions





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

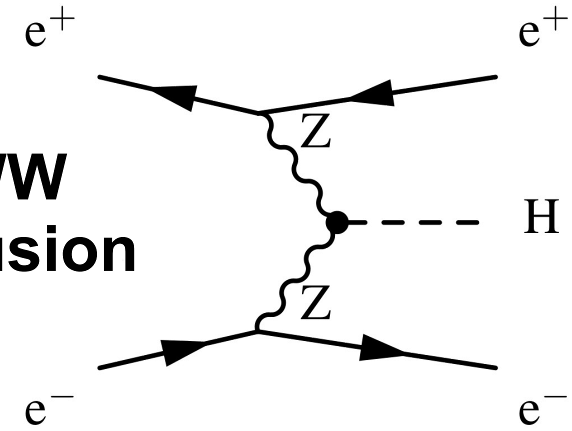
Higgs production at CLIC

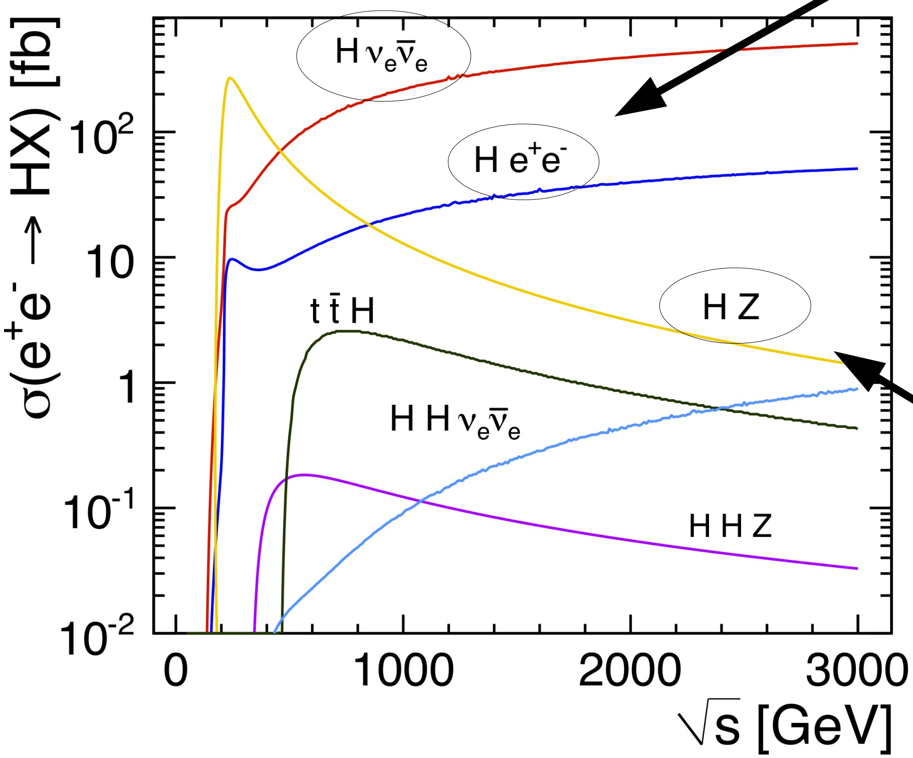


ZZ fusion

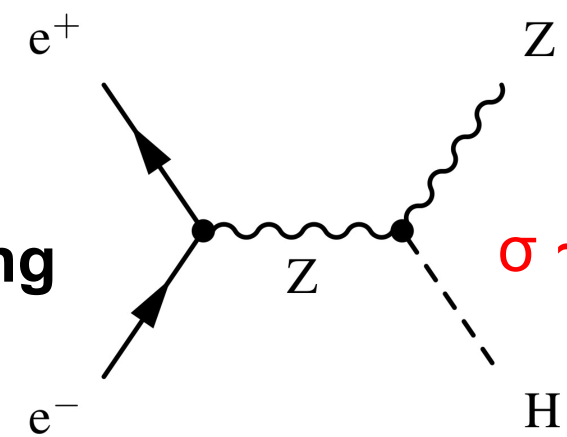
σ ~ log(s)

WW fusion

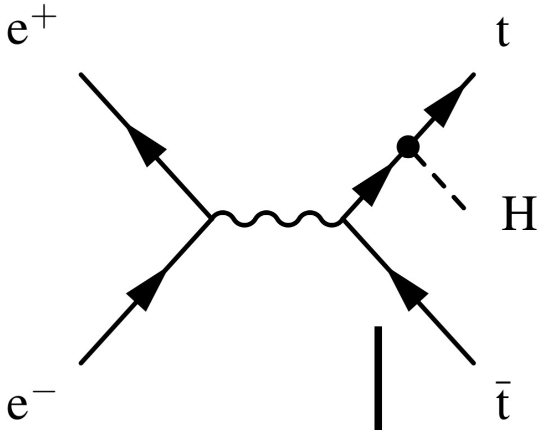




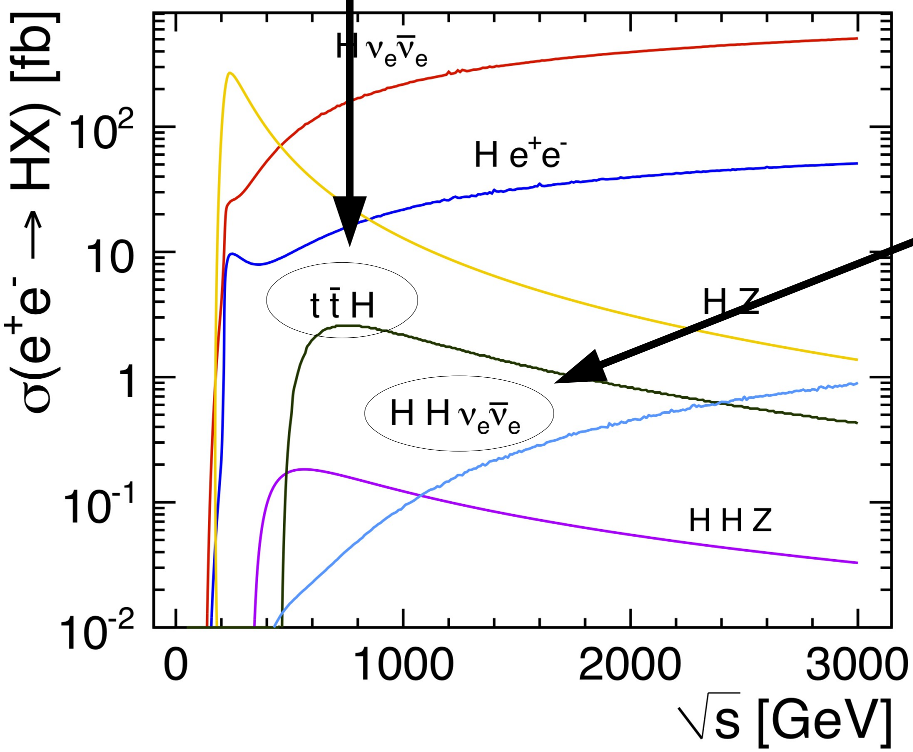
Higgs - strahlung

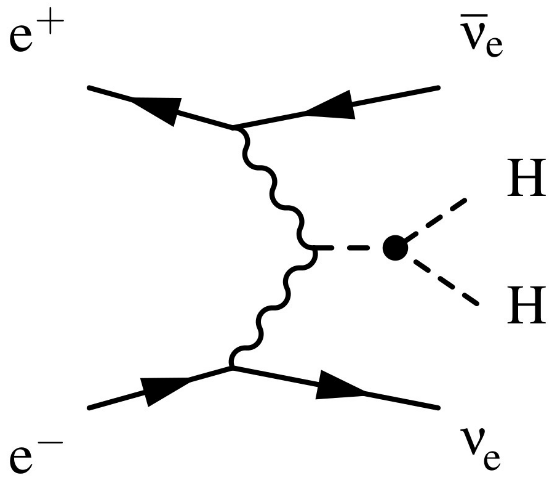


σ ~ 1/s

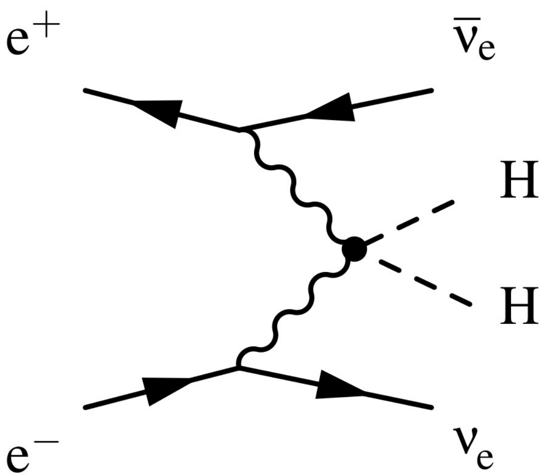


$t\bar{t}H$ production:
maximum at
around 800 GeV





Double Higgs production:
requires high energy



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

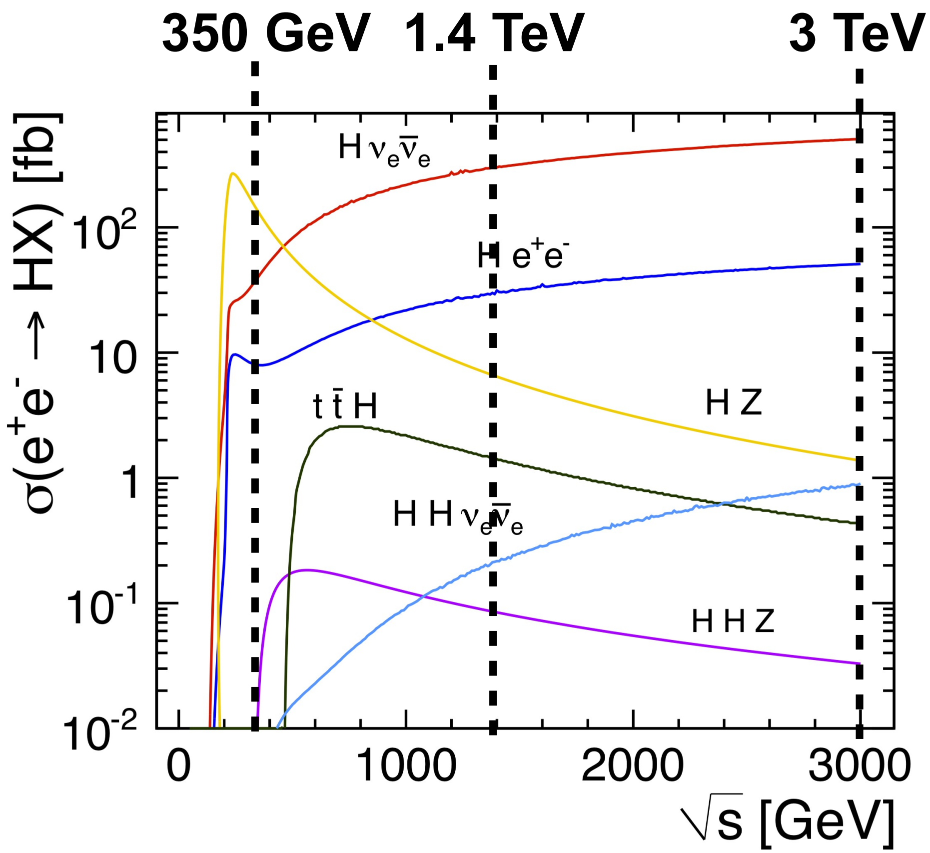
→ strategy can be adapted to discoveries at the LHC

Currently studied example scenario:

- **Stage 1:** 350/375 GeV, 500 fb^{-1}
HZ cross section, mass, $H\nu_e\bar{\nu}_e$ contribution sizeable, various branching rations, *top threshold scan*

- **Stage 2:** 1.4 TeV, 1.5 ab^{-1}
BSM physics, $t\bar{t}H$, Higgs self-coupling, rare Higgs decays

- **Stage 3:** 3 TeV, 2 ab^{-1}
BSM physics, $t\bar{t}H$, Higgs self-coupling, rare Higgs decays



Some numbers

Unpolarised cross sections for m_H = 125 GeV including ISR:

	350 GeV	1.4 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	134 fb	9 fb	2 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	52 fb	279 fb	479 fb
$\sigma(e^+e^- \to He^+e^-)$	7 fb	28 fb	49 fb

Numbers of events including ISR & Beam-strahlung:

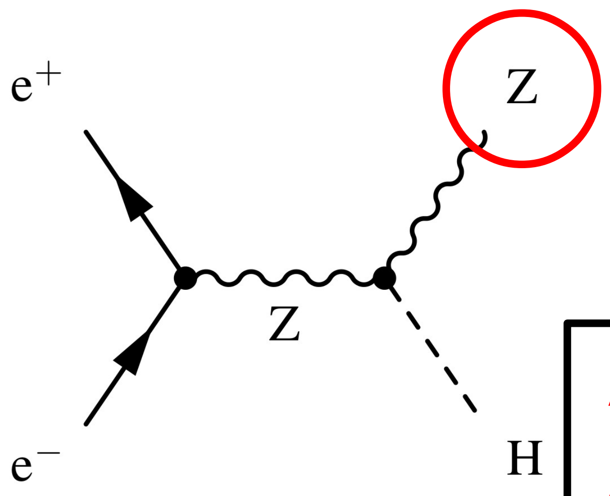
	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	68'000	20'000	11'000
# $H\nu_e\bar{\nu}_e$ events	26'000	370'000	830'000
# He^+e^- events	3'700	37'000	84'000

The electron polarisation for the CLIC baseline is ±80%, possibility for positron polarisation at lower level

polarization	Enhancement Factor	
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$
unpolarized	1.00	1.00
$-80\% : 0\%$	1.13	1.80
$-80\% : +30\%$	1.41	2.34

Measurements at 350 GeV (1)

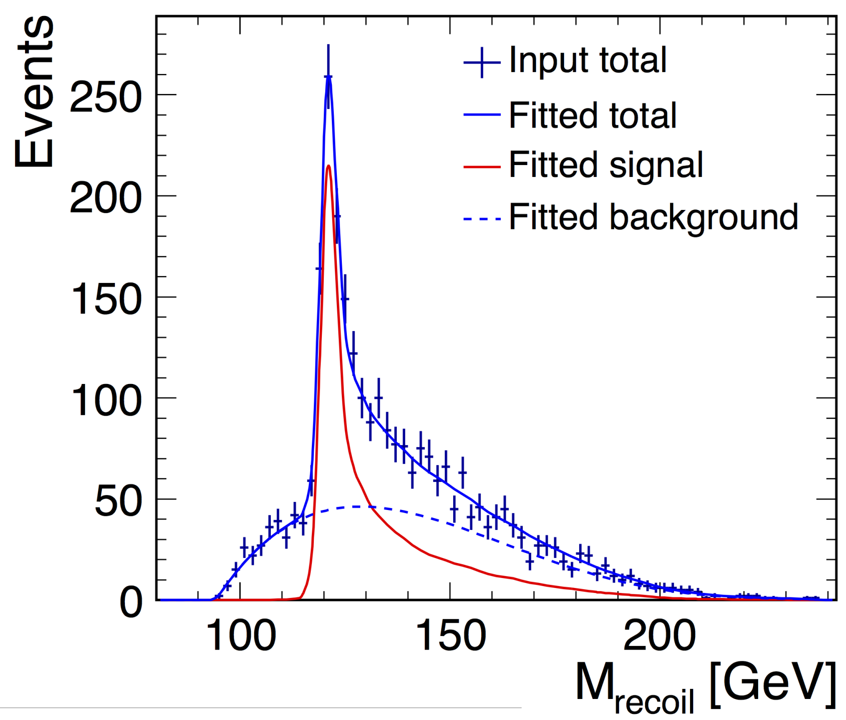
Higgsstrahlung process:



- HZ events can be identified from Z recoil mass
→ model independent measurements of m_H and the g_{HZZ} coupling

$\Delta(m_H) \approx 120$ MeV
$\Delta(\sigma_{HZ}) / \sigma_{HZ} \approx 4\%$

$e^+e^+ \rightarrow ZH \rightarrow \mu^+\mu^-H$



$\sqrt{s}$	250 GeV	350 GeV	350 GeV
$\mathscr{L}_{int}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}
$\Delta(\sigma)/\sigma$	3%	3.7%	3.1%
$\Delta(g_{HZZ})/g_{HZZ}$	1.5%	1.9%	1.6%

ILC with $P(e^-) = -80\%$, $P(e^+) = +30\%$
→ lower cross section at 250 GeV compensated by higher luminosity at 350 GeV

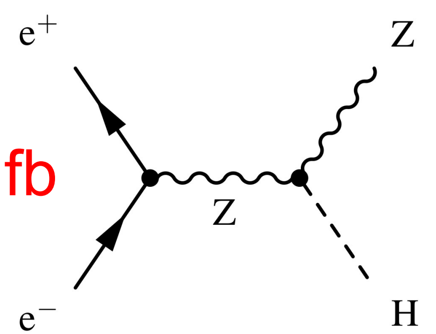
Measurements at 350 GeV (2)

Measurement	Observable	Stat. precision
$\sigma(HZ)$ x $BR(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau} / \Gamma_H$	5.7%
$\sigma(HZ)$ x $BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	ongoing
$\sigma(HZ)$ x $BR(H \to c\bar{c})$	$g^2_{HZZ} g^2_{Hcc} / \Gamma_H$	ongoing
$\sigma(HZ)$ x $BR(H \to gg)$		ongoing
$\sigma(HZ)$ x $BR(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW} / \Gamma_H$	ongoing

Assuming unpolarised beams

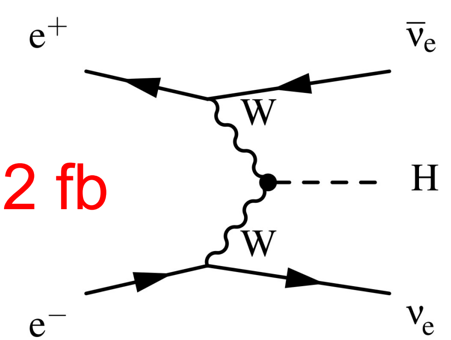
Sensitivity to the total Higgs decay width due to sizeable cross section for WW fusion:

$\sigma \approx 134$ fb



$$\frac{\sigma(e^+e^- \to ZH) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to \nu_e\bar{\nu}_e H) \times BR(H \to b\bar{b})} \propto \left(\frac{g_{HZZ}}{g_{HWW}}\right)^2$$

$\sigma \approx 52$ fb



$$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

Measurements in $H\nu_e\bar{\nu}_e$ events at 1.4 TeV

Measurement	Observable	Stat. precision
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau} / \Gamma_H$	< 3.7%
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	0.3% (preliminary)
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	2.9% (preliminary)
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to gg)$		1.8% (preliminary)
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	20% (preliminary)
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to \gamma\gamma)$		15% (preliminary)
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to Z\gamma)$		ongoing
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to ZZ^*)$	g^4_{HZZ} / Γ_H	ongoing
$\sigma(H\nu_e\bar{\nu}_e)$ x $BR(H \to WW^*)$	g^4_{HWW} / Γ_H	ongoing
$\sigma(He^+e^-)$ x $BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	ongoing

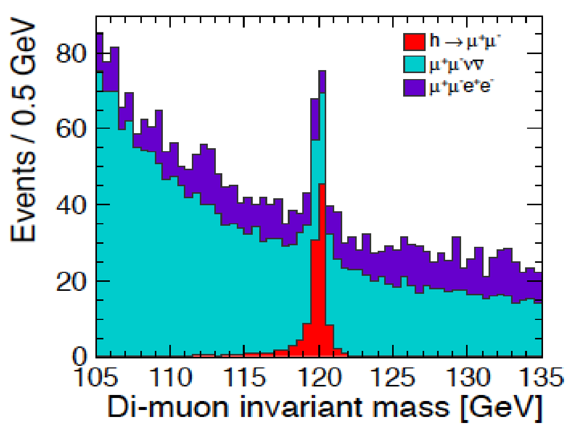
Assuming unpolarised beams

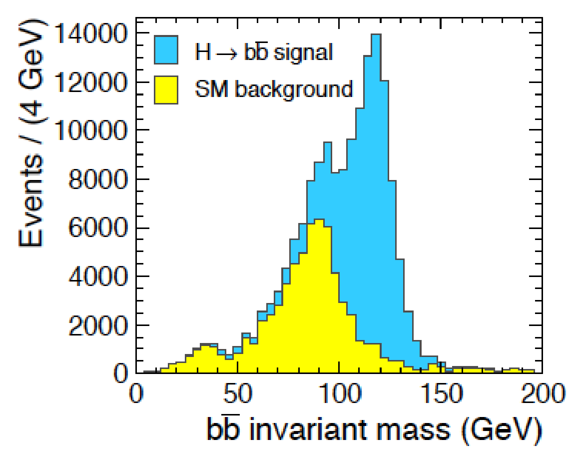
Higgs mass from $H \to b\bar{b}$ mass distribution: $\Delta(m_H) \approx 40$ MeV (estimated)

Measurements in $H\nu_e\bar{\nu}_e$ events at 3 TeV

Measurement	Observable	Stat. precision
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	0.2%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	2.7%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow gg)$		1.8%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	16%

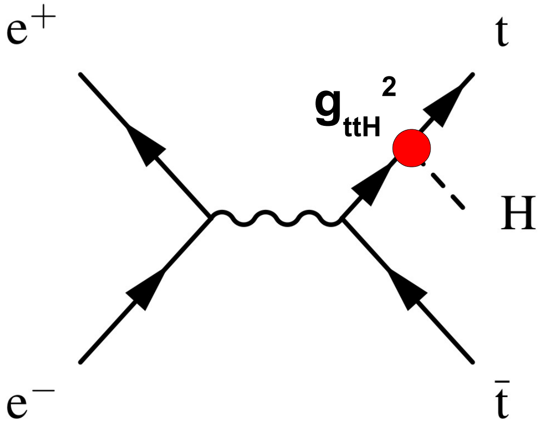
Assuming unpolarised beams



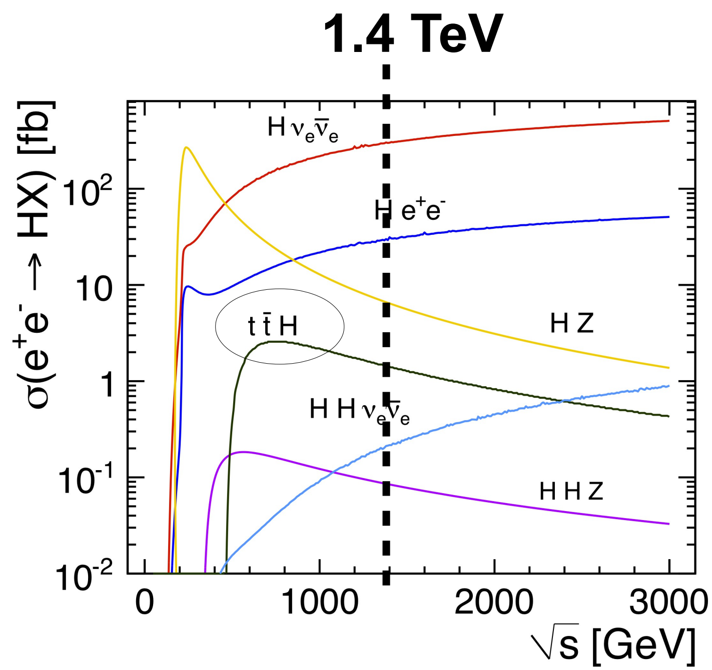


Higgs mass from $H \rightarrow b\bar{b}$ mass distribution: $\Delta(m_H) \approx 33$ MeV (estimated)

The $t\bar{t}H$ and Ze^+e^- final states at 1.4 TeV



→ The tth cross section is directly sensitive to the top Yukawa coupling g_{ttH}



Investigated final states:

"*6 jets*": $t(\to qqb)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$

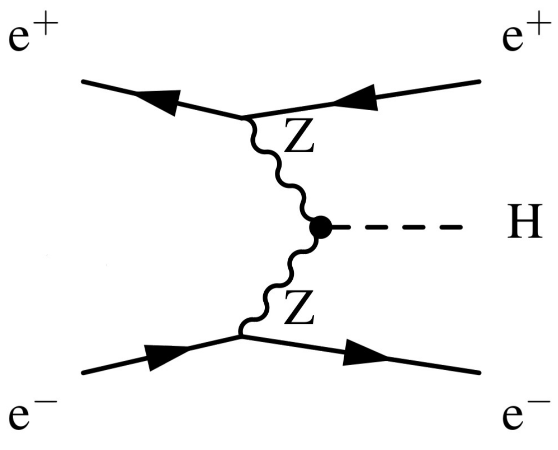
$\Delta(\sigma(t\bar{t}H)) \approx 16\%$ (preliminary) assuming unpolarised beams

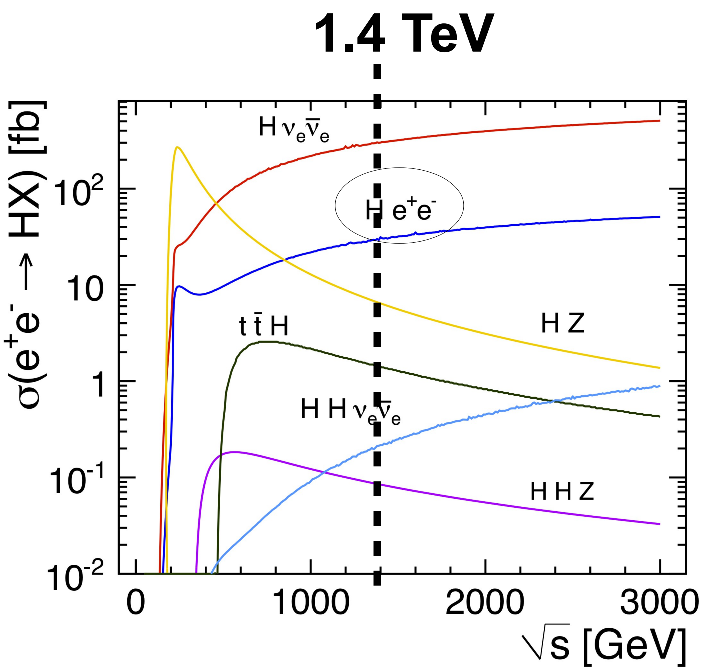
"*8 jets*": $t(\to qqb)\bar{t}(\to qq\bar{b})H(\to b\bar{b})$

expected to be more precise (as for the ILC at 1 TeV)

Aim to extract the top Yukawa coupling from combined cross section for both decay channels

Higgs production in ZZ fusion





At high energy large samples of ZZ and WW fusion events available:

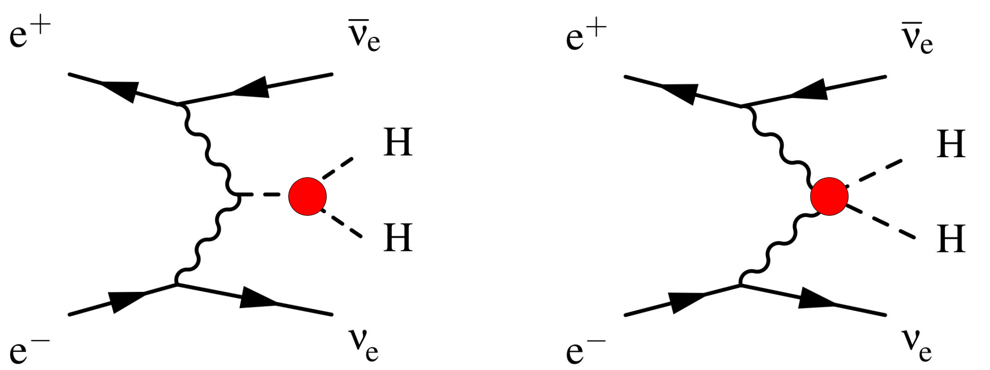
$$\frac{\sigma(He^+e^-) \times BR(H \to b\bar{b})}{\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})}$$

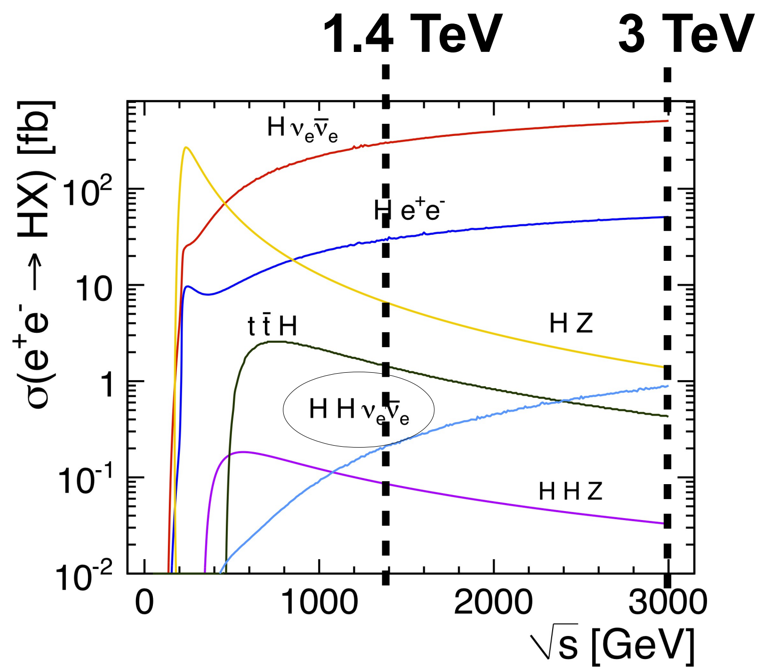
ongoing study

→ Precise determination of the ratio g_{HZZ} / g_{HWW}

(many systematic effects cancel in the ratio)

Double Higgs production at high energy





- The $HH\nu_e\bar{\nu}_e$ cross section is sensitive to the Higgs self coupling, λ, and the quartic g_{HHWW} coupling
- $\sigma(HH\nu_e\bar{\nu}_e)$ = 0.15 (0.59) fb at 1.4 (3) TeV

→ high energy and luminosity crucial

NB: The results on this slide were obtained for m_H = 120 GeV

Measurement	1.4 TeV	3 TeV
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
$\Delta(\lambda)$	28%	16%
$\Delta(\lambda)$ for $P(e^-)$ = -80%	21%	12%

Overview of Higgs measurements at CLIC

Channel	Measurement	Observable	Statistical precision		
			350 GeV $500\ \mathrm{fb}^{-1}$	1.4 TeV $1.5\ \mathrm{ab}^{-1}$	3.0 TeV $2.0\ \mathrm{ab}^{-1}$
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	?	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV†	33 MeV†
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \to gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	5.7%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	?	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	?	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	3.7%	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	20%†	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%†	
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–		
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	–	?	
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–		
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–		
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%†	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%†	3%†
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	28%	16%
$HH\nu_e\bar{\nu}_e$	with 80% e^- polarization	λ	–	21%	12%

Summary and outlook

• The first stage of a CLIC collider at 350 GeV provides precise determinations of the absolute values of many Higgs boson couplings

• Subsequent high-energy running, here assumed at 1.4 and 3 TeV, improves the precision of many observables significantly and gives access to rare Higgs decays

• High-energy CLIC operation provides the potential to measure the trilinear Higgs self-coupling at the 10% level

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For the meeting in Minneapolis we expect to have:

• Additional results from currently ongoing studies

• A combined fit to all measurements at 350 GeV, 350 GeV + 1.4 TeV and 350 GeV + 1.4 TeV + 3 TeV to extract the Higgs couplings and width

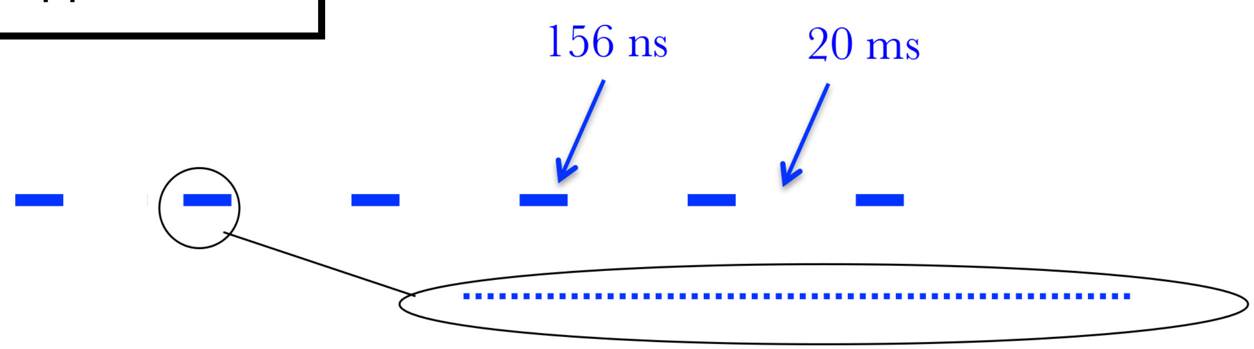
Backup slides

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

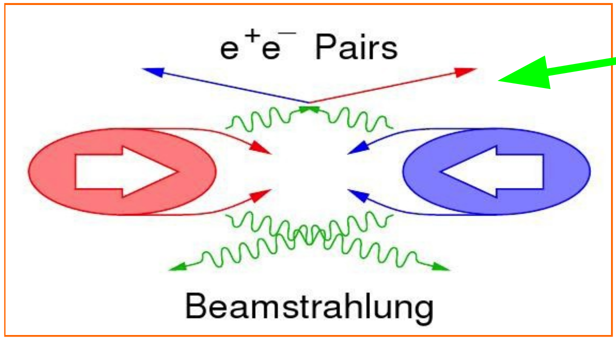
Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

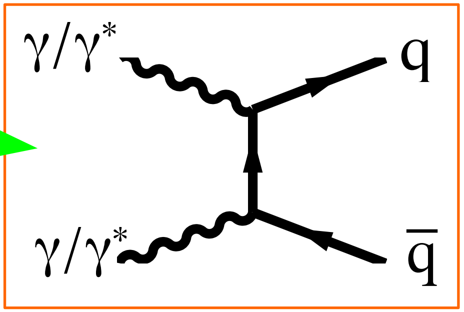


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam related backgrounds

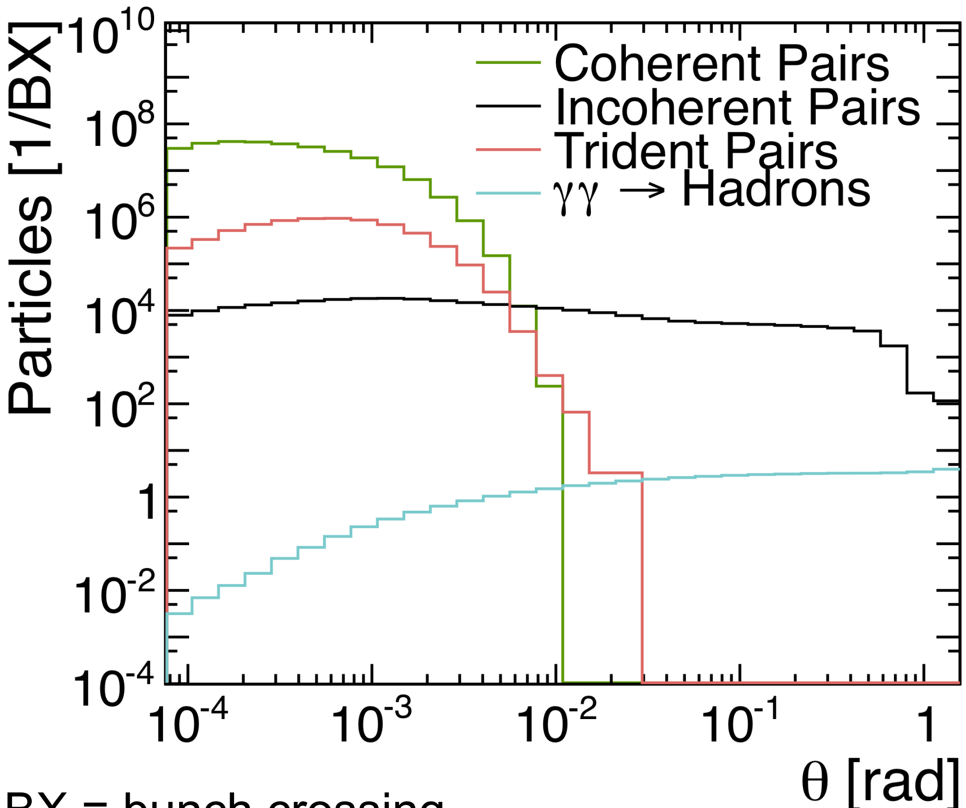


- e^+e^- pairs
- $\gamma\gamma \rightarrow$ hadrons
- Beam halo muons



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)

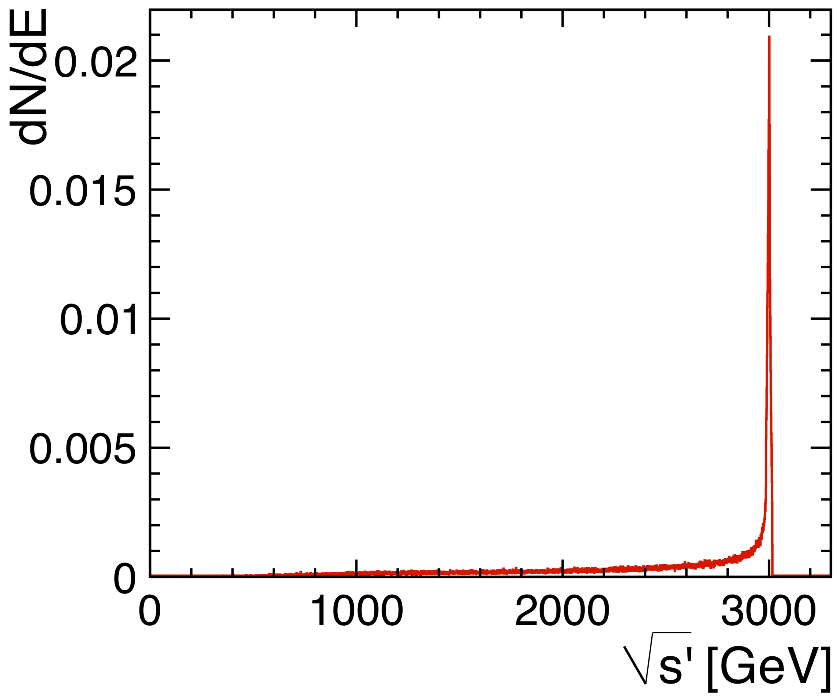
$\gamma\gamma \rightarrow$ hadrons
- "Only" 3.2 per BX at 3 TeV
- Main background
in calorimeters and trackers
→ Impact on physics



BX = bunch crossing

Luminosity spectrum

Significant energy loss at the interaction point due to Beamstrahlung



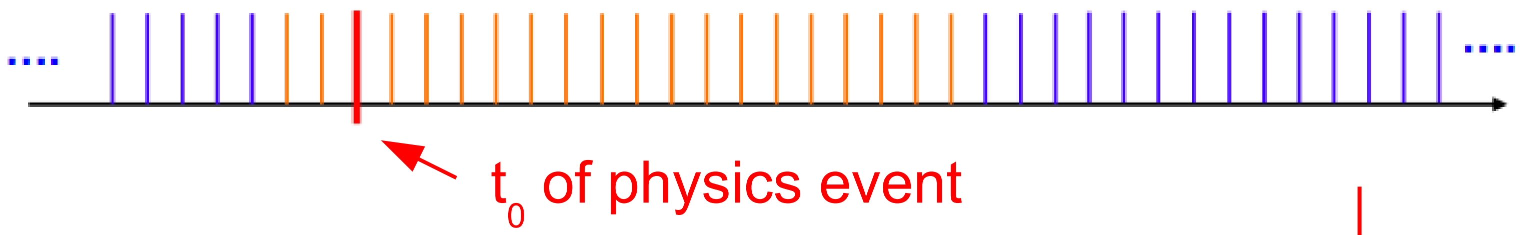
$$\sqrt{s'} = \sqrt{4 \cdot E_1 \cdot E_2}$$

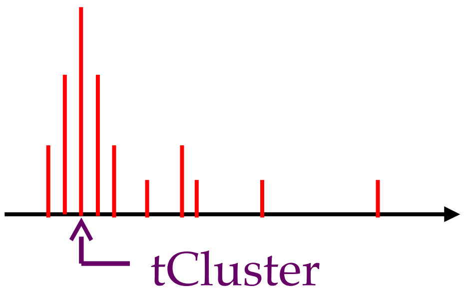
Full luminosity: L = 5.9 · 10^{34} $cm^{-2}s^{-1}$
In the most energetic 1%:
("peak luminosity") $L_{0.01}$ = 2.0 · 10^{34} $cm^{-2}s^{-1}$

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

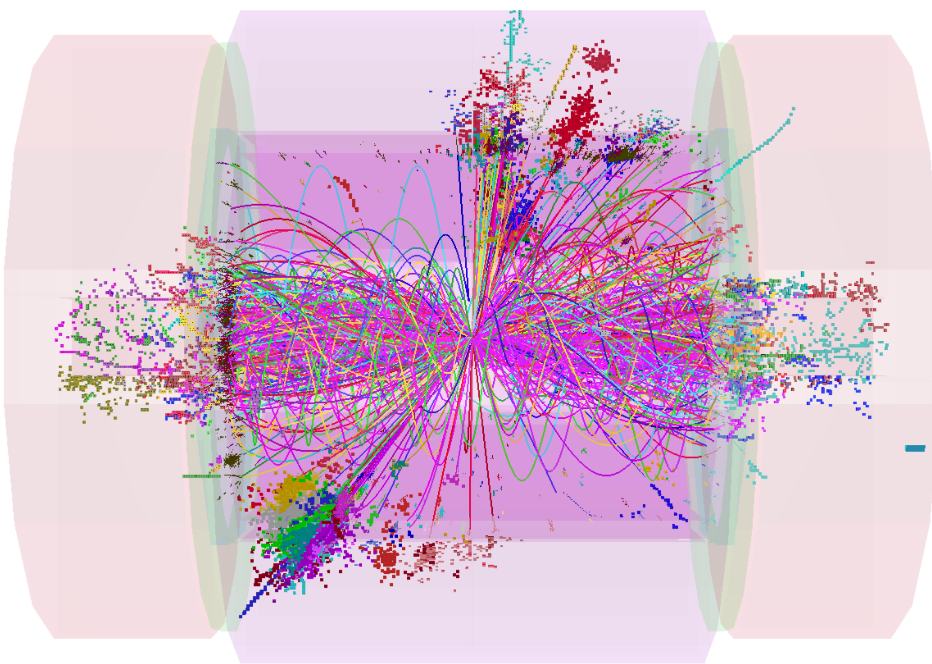
Used in the reconstruction software for CDR simulations:

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

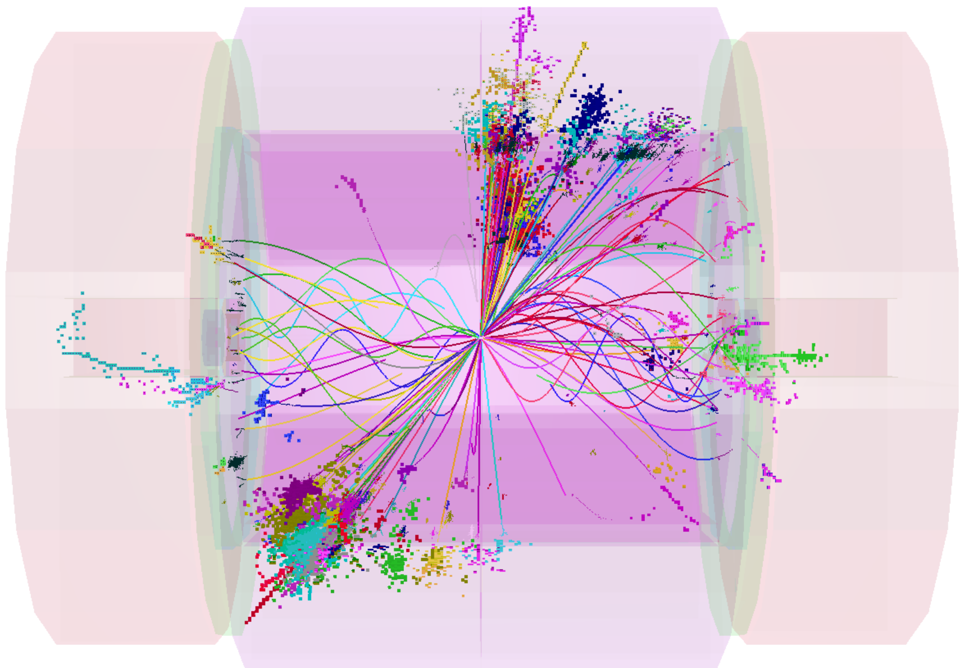
- CLIC hardware requirements
- Achievable in the calorimeters with a sampling every ≈ 25 ns

Impact of the timing cuts

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

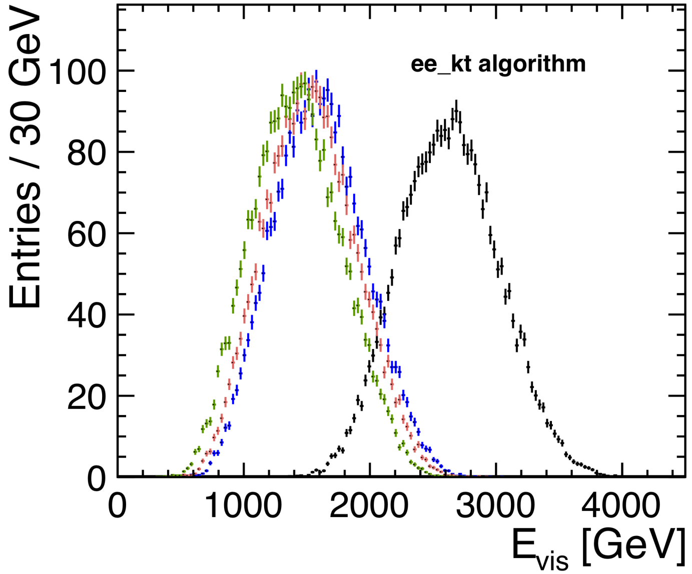


1.2 TeV background
in the reconstruction window



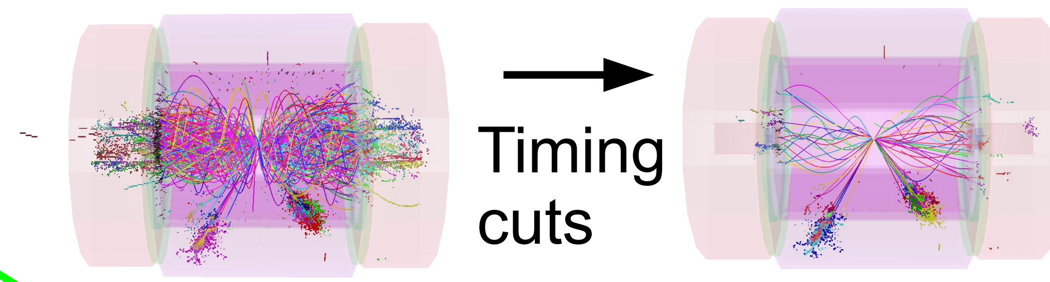
100 GeV background
after (tight) timing cuts

Jet reconstruction at CLIC I



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

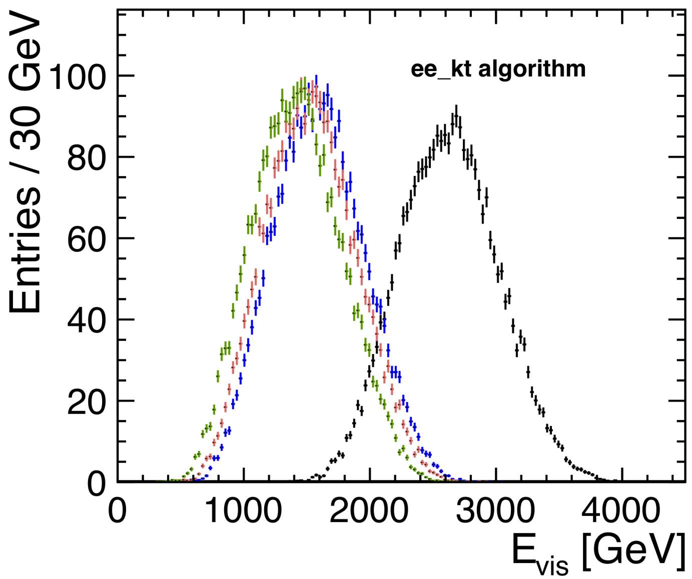
Two jets + missing energy

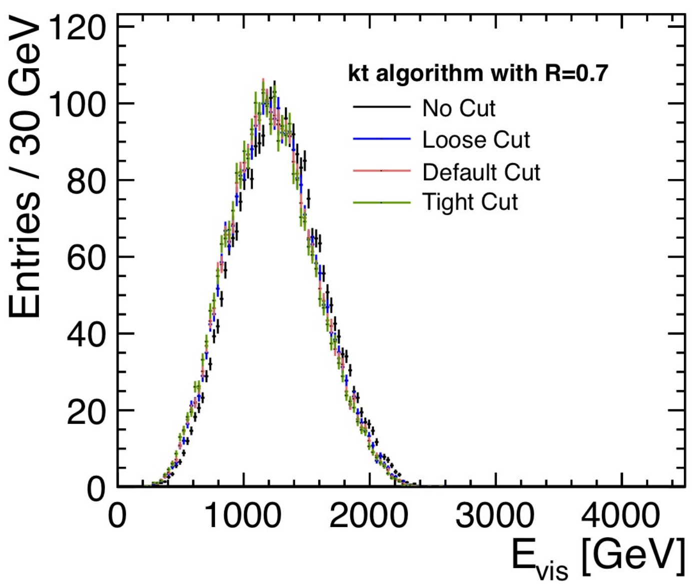


- Using Durham k_T à la LEP

→ Timing cuts are effective, but not sufficient

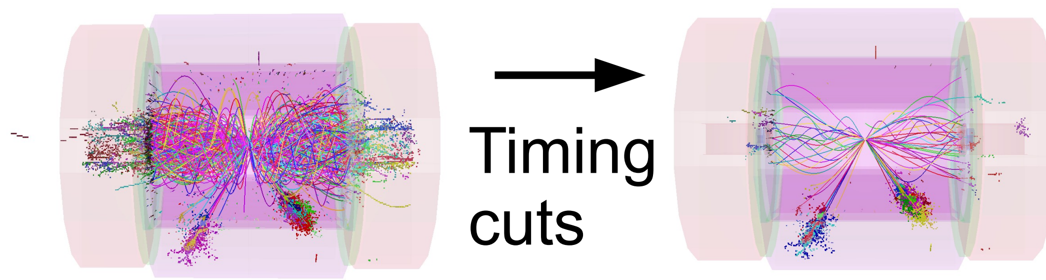
Jet reconstruction at CLIC II





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

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

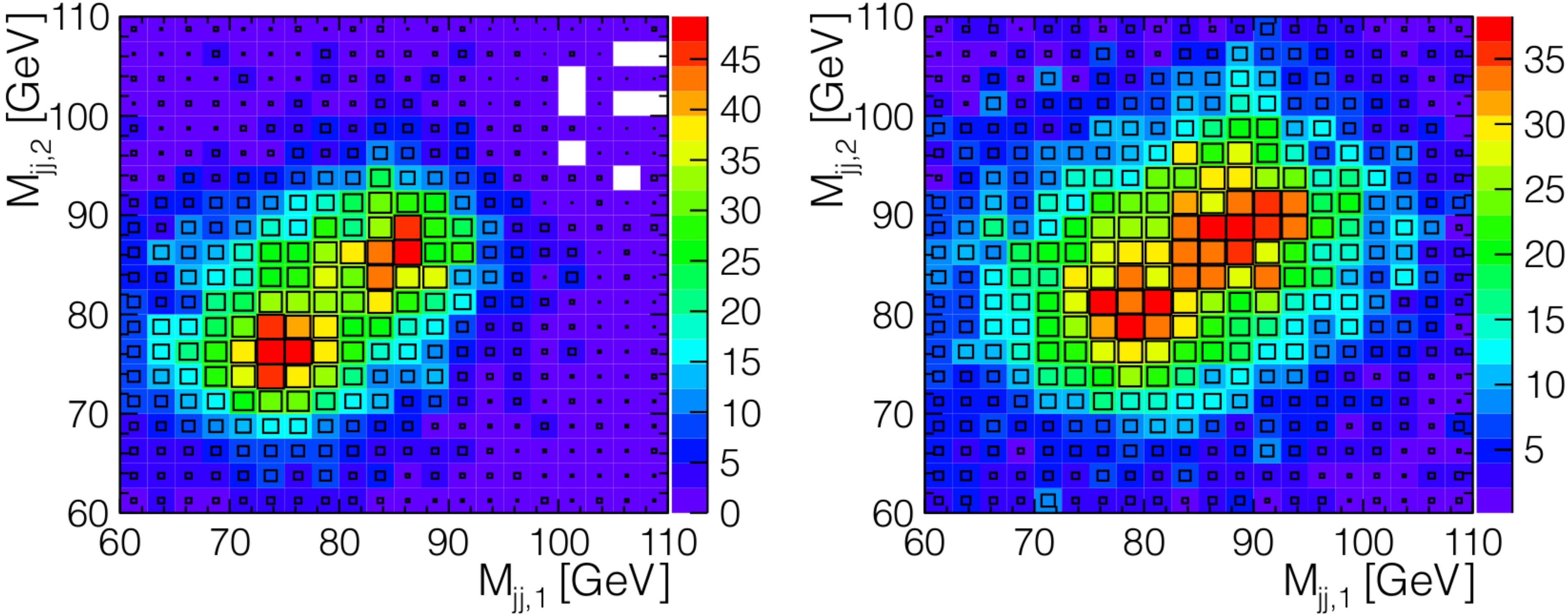


Figure 19: Separation of W and Z from the chargino decay without overlay (left) and with 60 BX of background (right) for CLIC_SiD.

Test of the di-jet mass reconstruction

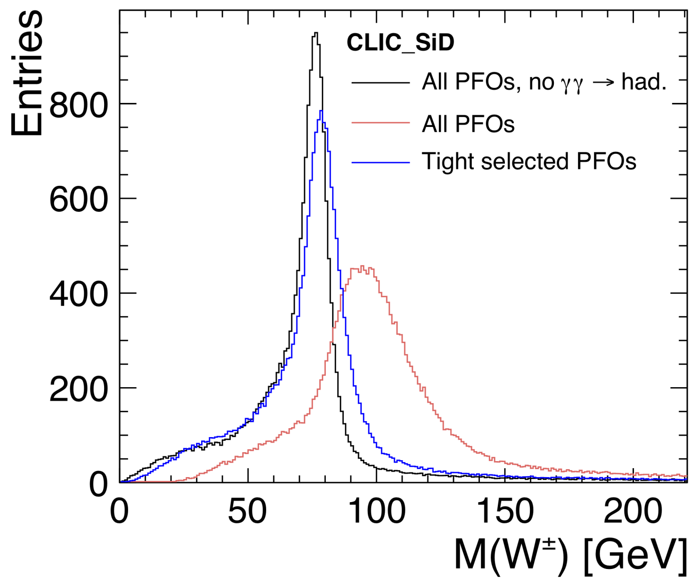
Chargino and neutralino pair production:

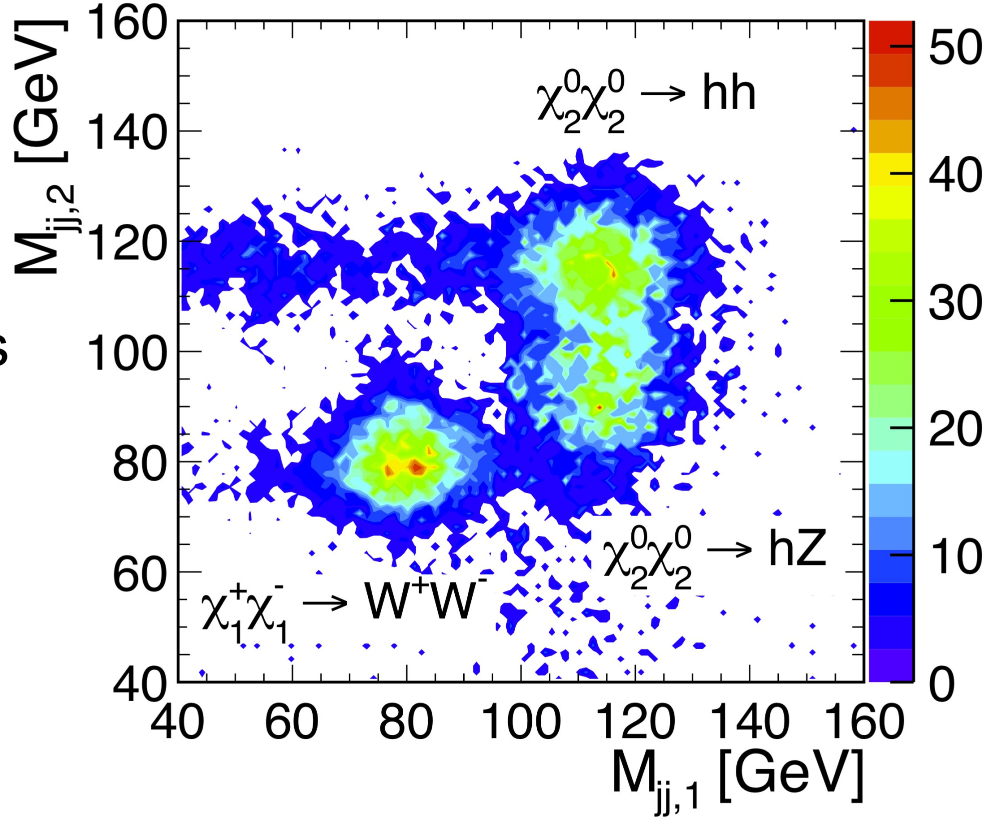
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

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

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

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



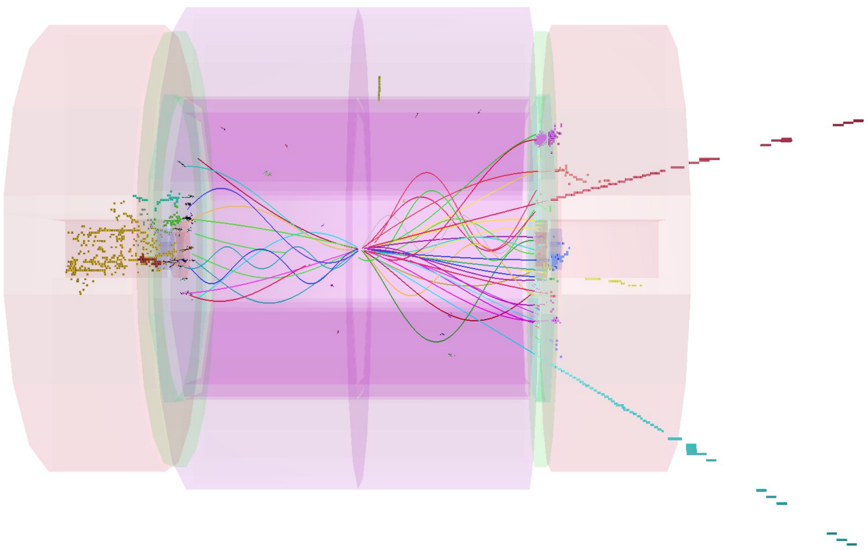


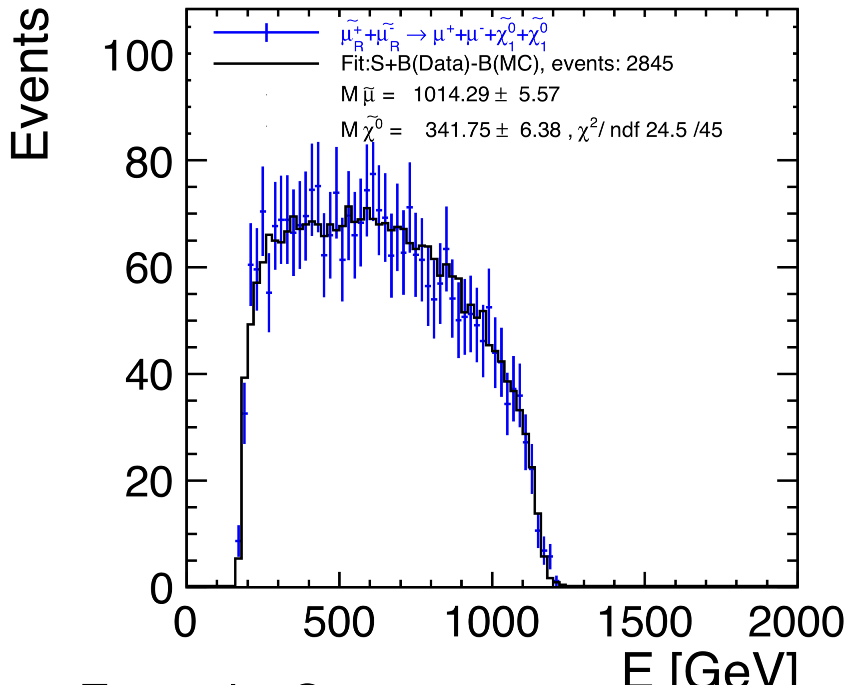
Precision on the measured gaugino masses (few hundred GeV): 1 - 1.5%

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

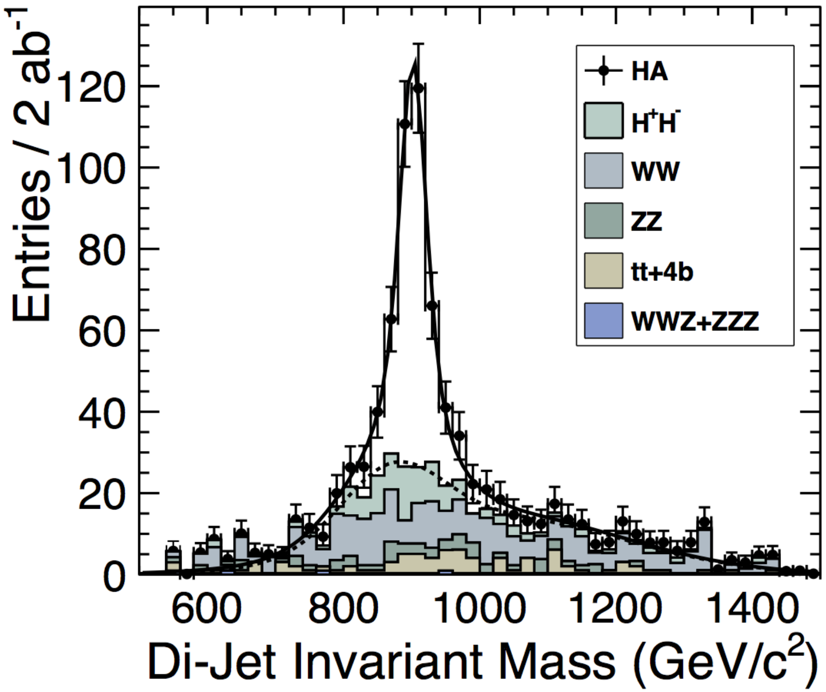
- Leptons and missing energy
- Masses from endpoints of energy spectra

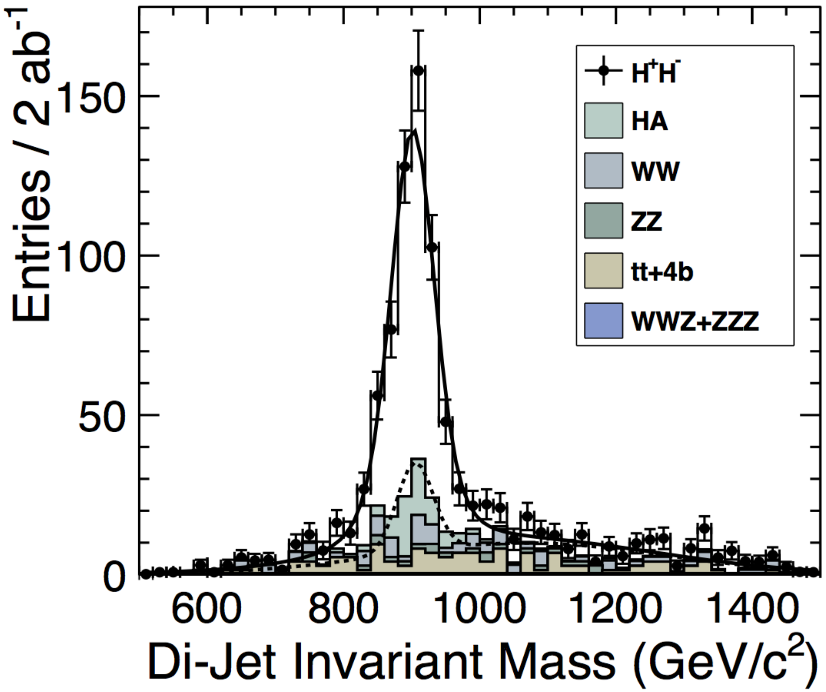
$m(\tilde{\mu}_R)$	± 5.6 GeV
$m(\tilde{e}_R)$	± 2.8 GeV
$m(\tilde{\nu}_e)$	± 3.9 GeV
$m(\tilde{\chi}_1^0)$	± 3.0 GeV
$m(\tilde{\chi}_1^\pm)$	± 3.7 GeV

Complex final states

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

Flavour tagging crucial!





Accuracy of the heavy Higgs mass measurements: ≈ 0.3%