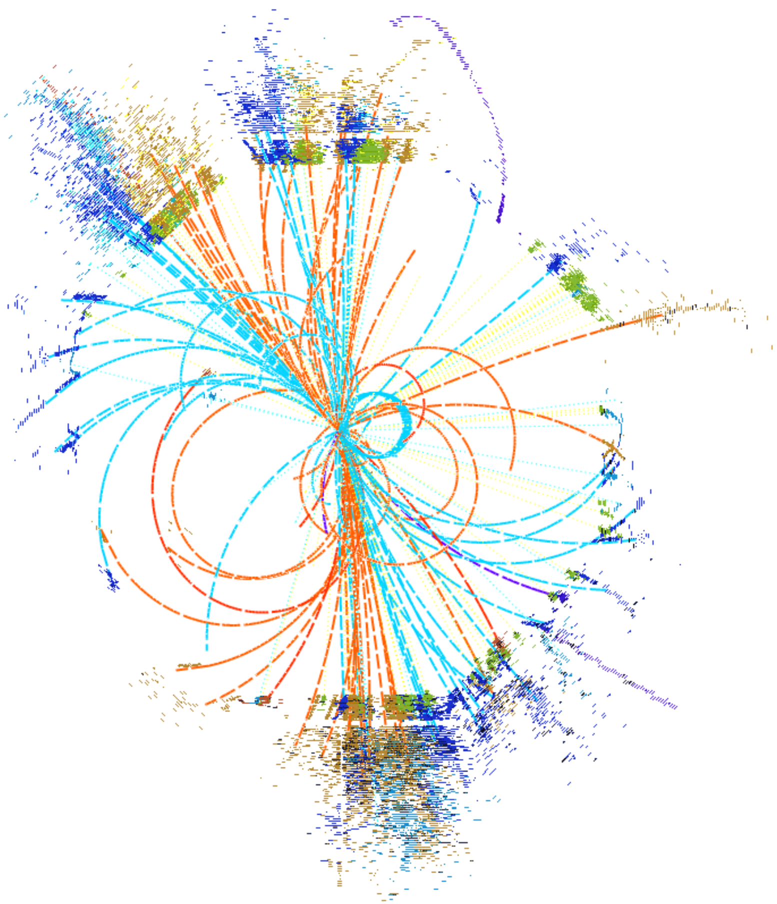
Physics and detectors at CLIC

Philipp Roloff (CERN)
on behalf of the CLICdp collaboration



University of Edinburgh
11/11/2014

Overview

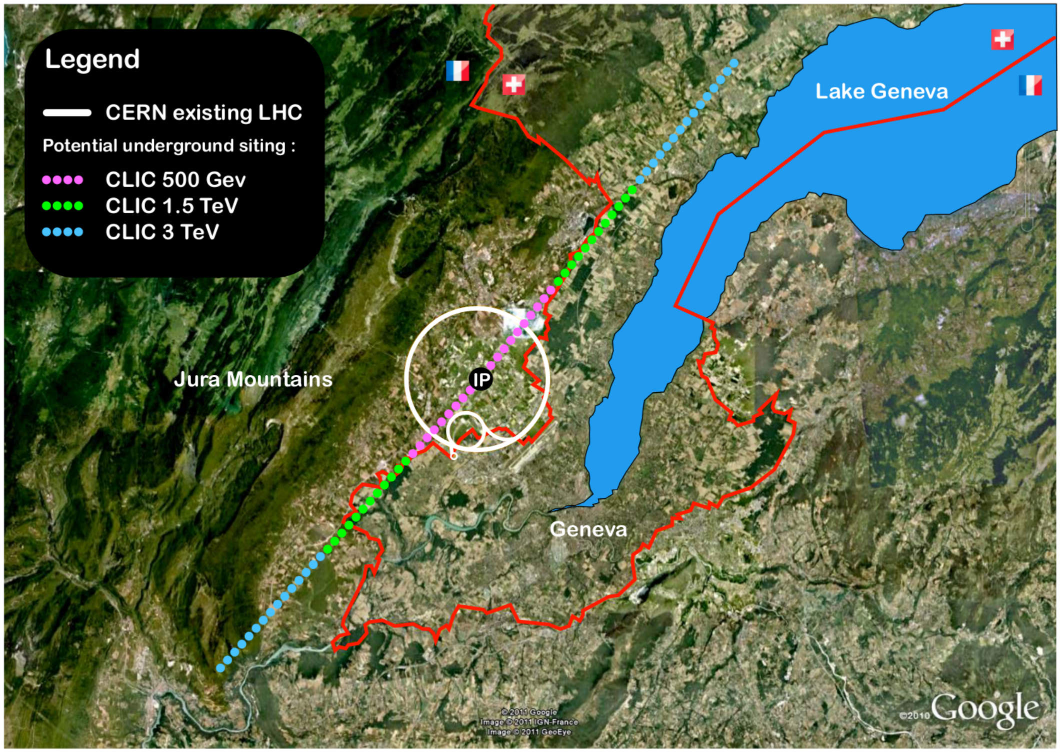
- **Introduction:**
  - The CLIC accelerator
- **Physics at CLIC:**
  - Standard Model physics
  - Beyond Standard Model searches
- **Implications for the detectors**
- **R&D for the CLIC vertex detector**
- **Summary and conclusions**

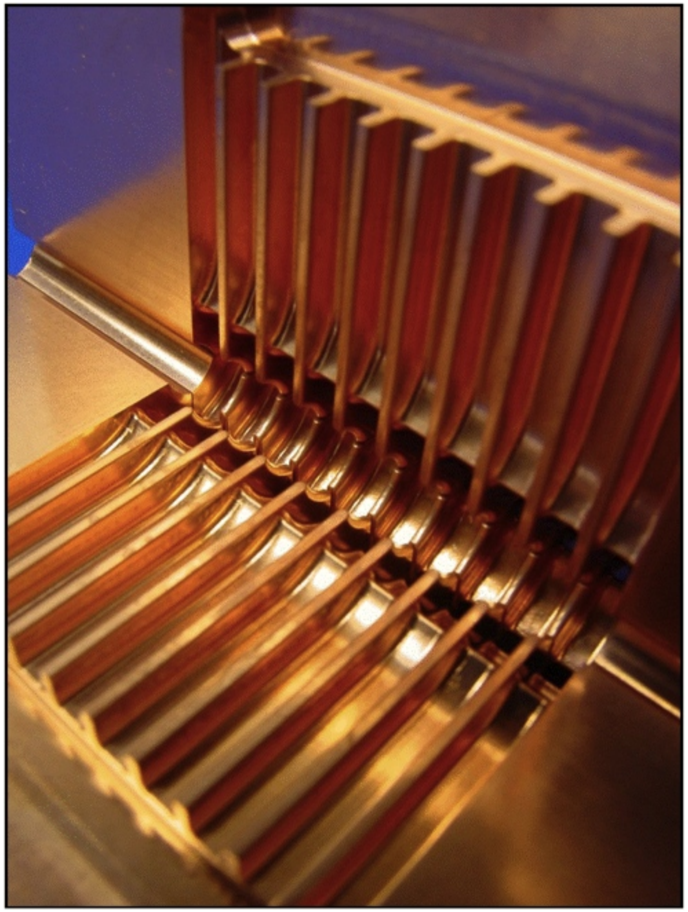
Introduction

The CLIC accelerator

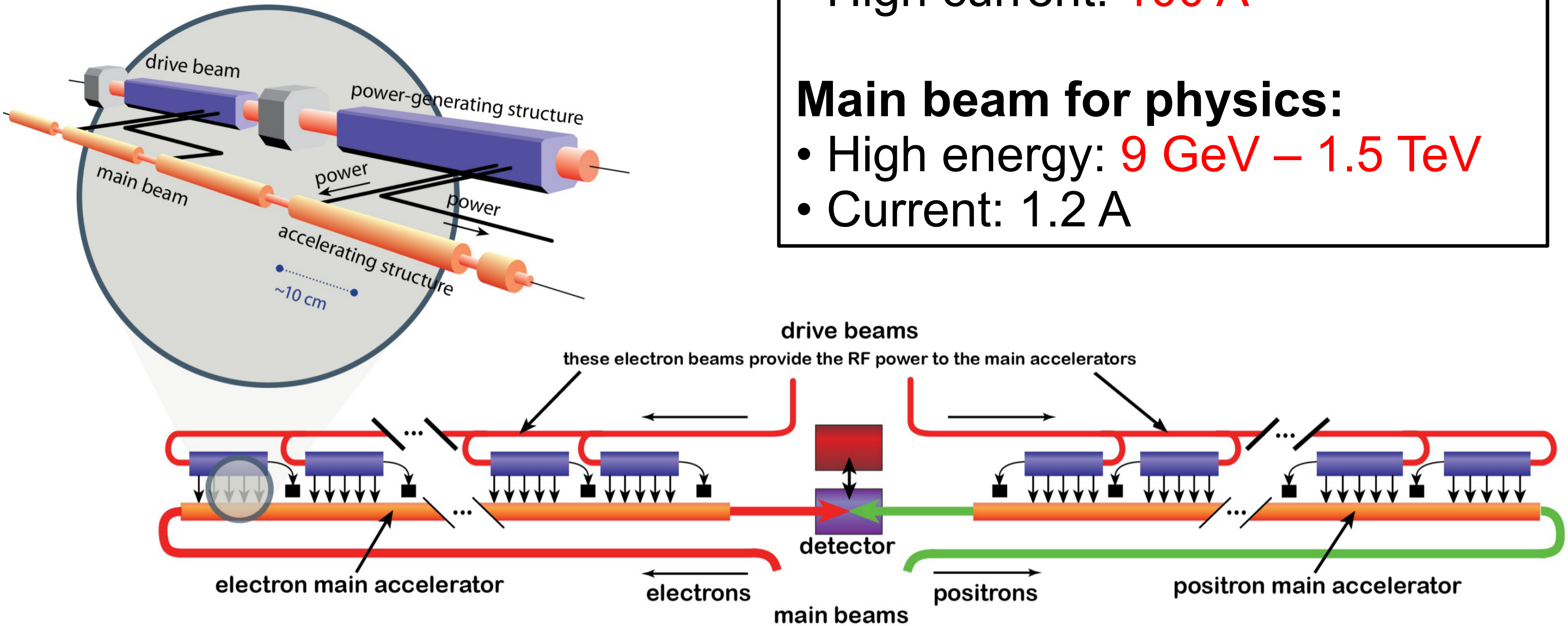
CLIC is the only mature option for a future multi-TeV e^+e^- collider

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





2-beam acceleration scheme

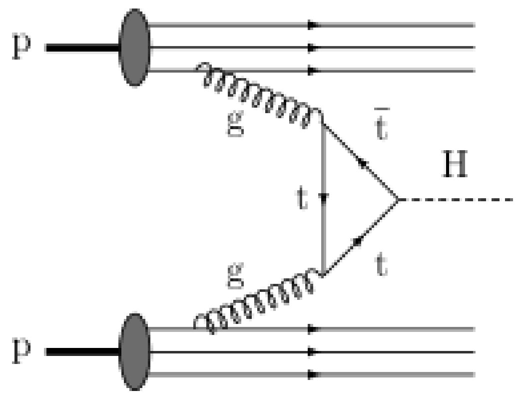


Drive beam supplies RF power:
- 12 GHz bunch structure
- Low energy:
2.4 GeV – 240 MeV
- High current: 100 A

Main beam for physics:
- High energy: 9 GeV – 1.5 TeV
- Current: 1.2 A

Comparison to hadron colliders

Hadron colliders:



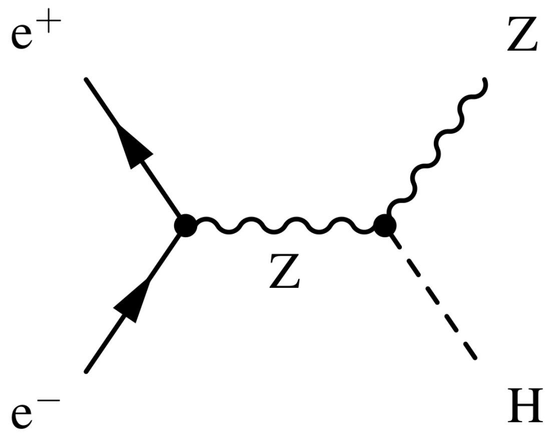
- **Proton is compound object**
  → Initial state unknown
  → Limits achievable precision

- **High-energy circular colliders possible**

- **High rates of QCD backgrounds**
  → Complex triggers
  → High levels of radiation

- **High cross sections for coloured states**

e^+e^- colliders:



- **e^+e^- are pointlike**
  → Initial state well-defined
  (energy, polarisation)
  → High-precision measurements

- **High energies require linear colliders**

- **Clean experimental environment**
  → Trigger-less readout
  → Low radiation levels

- **Well suited for electroweak states**

CLIC strategy and objectives

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

4-5 year Preparation Phase

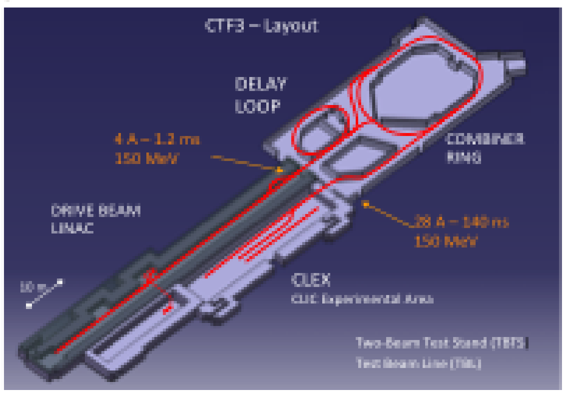
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

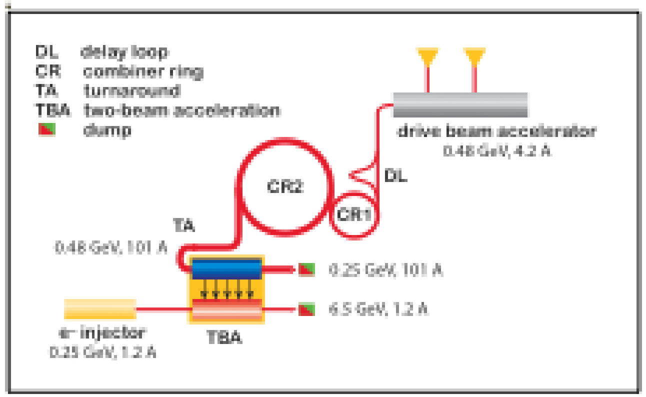
Prepare detailed Technical Proposals for the detector-systems.

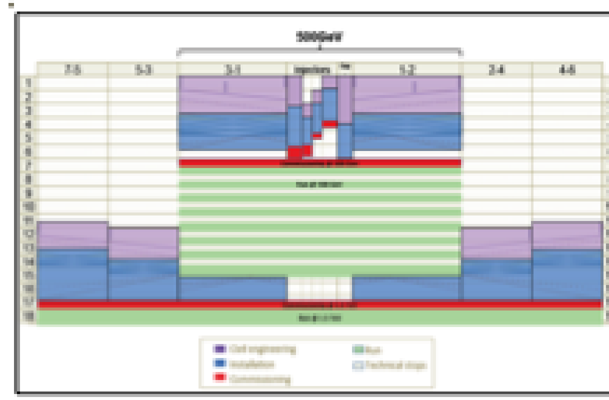
Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.







2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

CLIC energy stages

CLIC would be implemented in stages:
• Optimised running conditions over a wide energy range
• The energy stages are defined by physics (with additional technical considerations)
→ The strategy can be adapted to discoveries at the LHC at 13/14 TeV

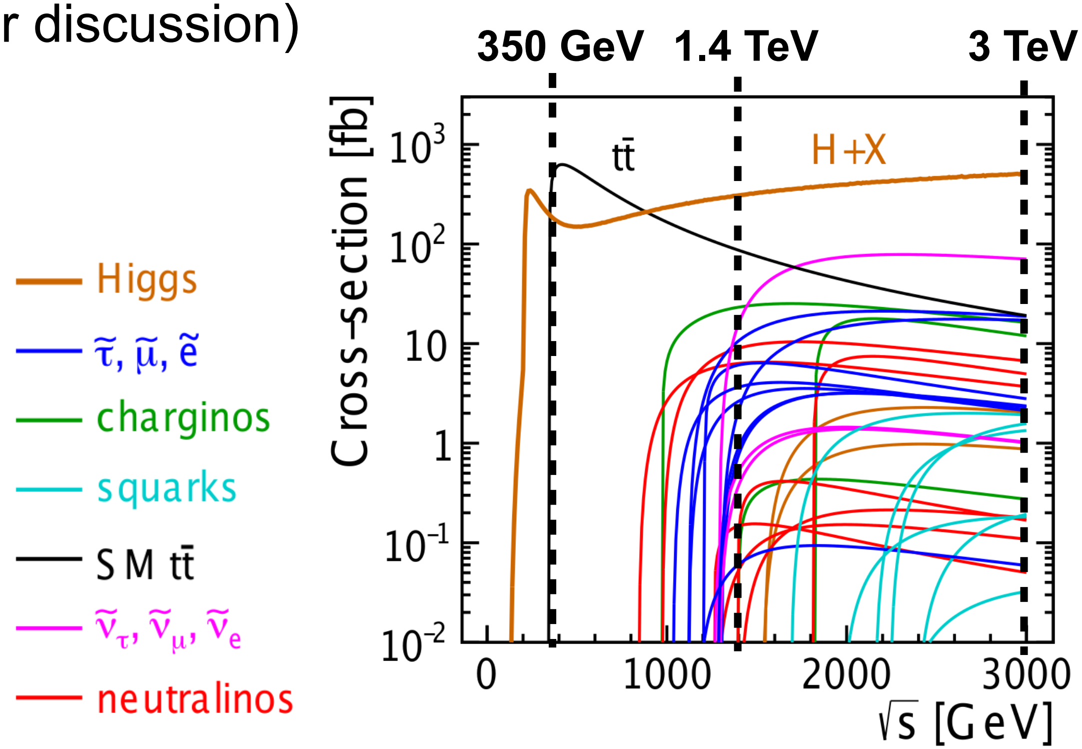
Example scenario assumed for this talk:

• **Stage 1:** 350 / 375 GeV, 500 fb^{-1} (under discussion)
SM Higgs physics, $t\bar{t}$ threshold scan

• **Stage 2:** 1.4 TeV, 1.5 ab^{-1}
Targeted at BSM physics,
rare Higgs processes and decays

• **Stage 3:** 3 TeV, 2 ab^{-1}
Targeted at BSM physics,
rare Higgs processes and decays

(each stage corresponds to 4-5 years)

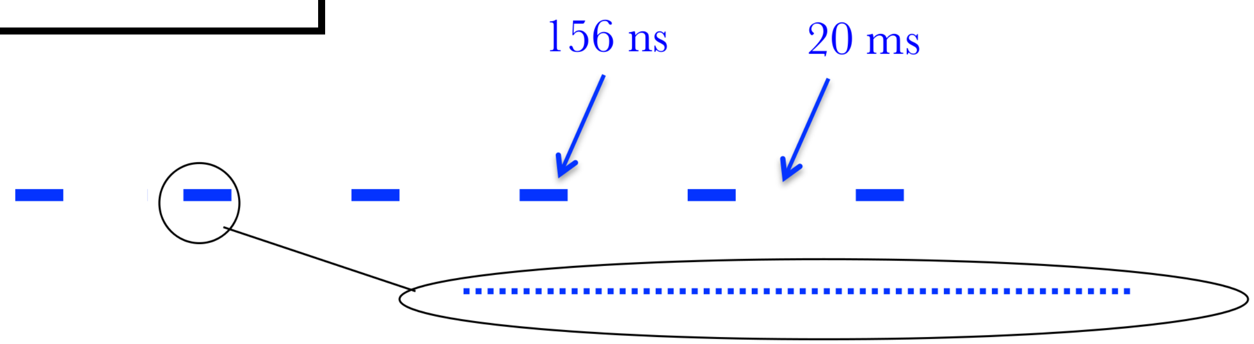


Selected CLIC parameters

	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

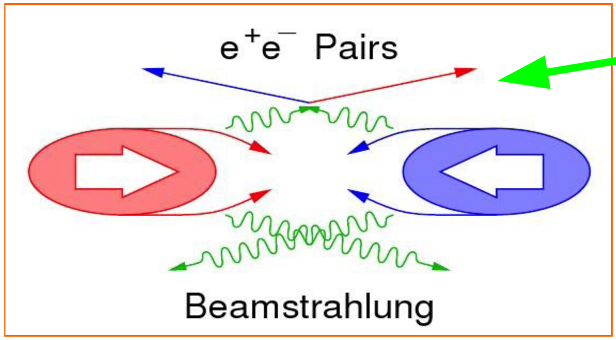
Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

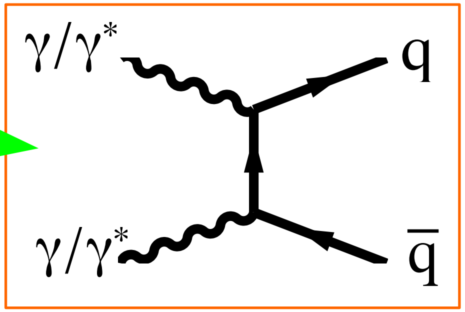


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam-related backgrounds

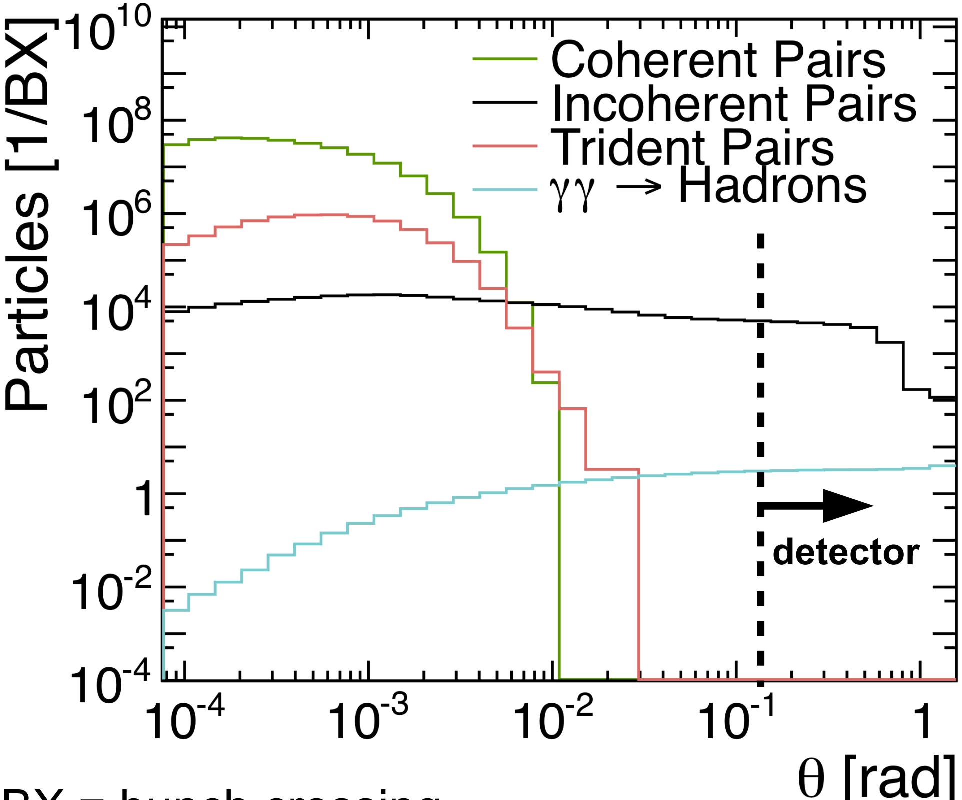


- e^+e^- pairs
- $\gamma\gamma \rightarrow$ hadrons



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 events per BX at 3 TeV
- Main background
in calorimeters and trackers
→ Impact on physics



BX = bunch crossing

Physics at CLIC

Standard Model physics:

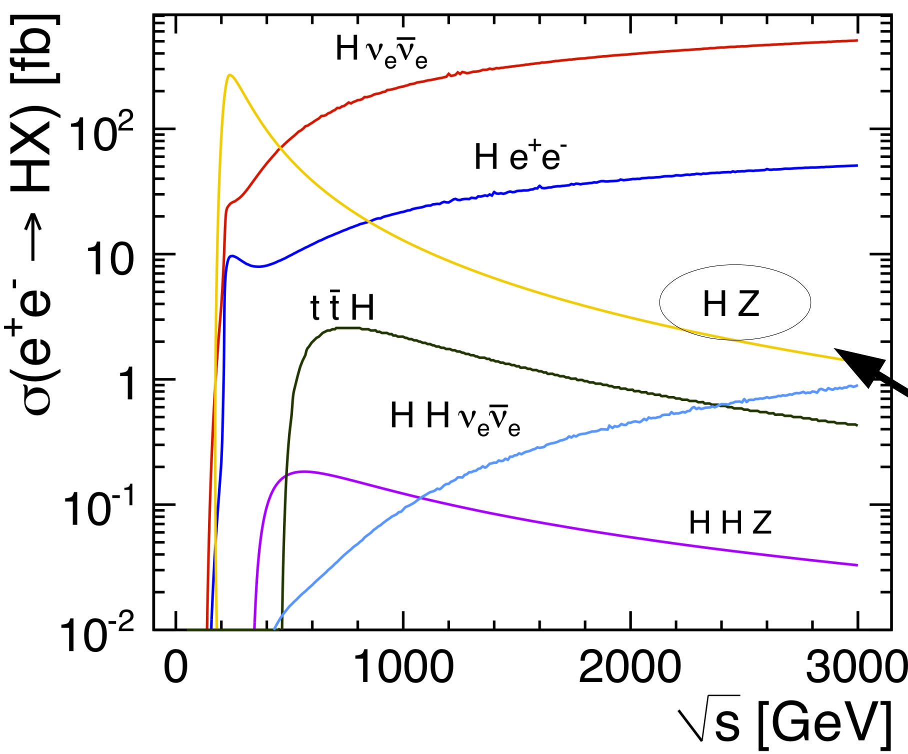
- Higgs boson:
  - Single Higgs production
  - Other processes at higher energy
  - Combined analysis
- top quark mass

Beyond Standard Model searches:

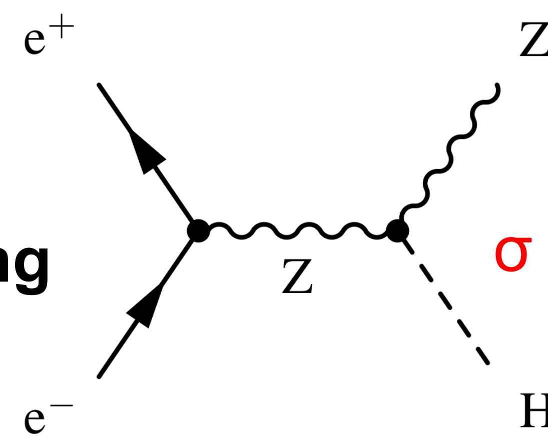
- Supersymmetry
- Indirect measurements

Benchmark studies are based on full detector simulations (Geant4) and include the pile-up from $\gamma\gamma \rightarrow$ hadrons interactions!

Single Higgs production at CLIC

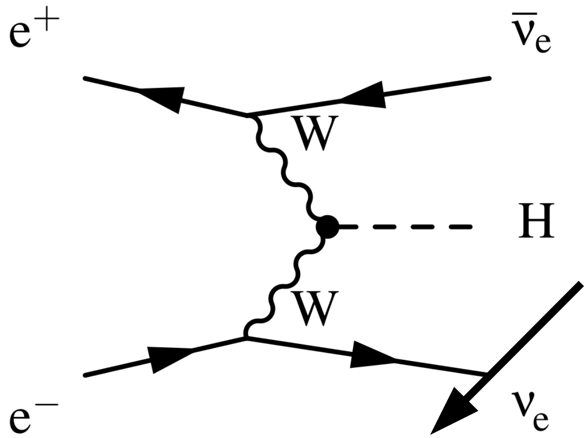


Higgs-strahlung



$\sigma \sim 1/s$

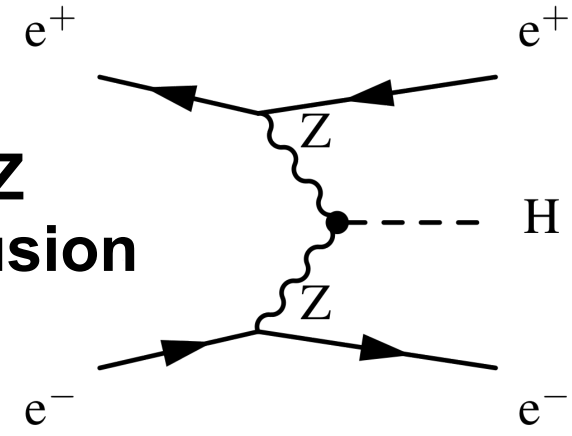
Single Higgs production at CLIC

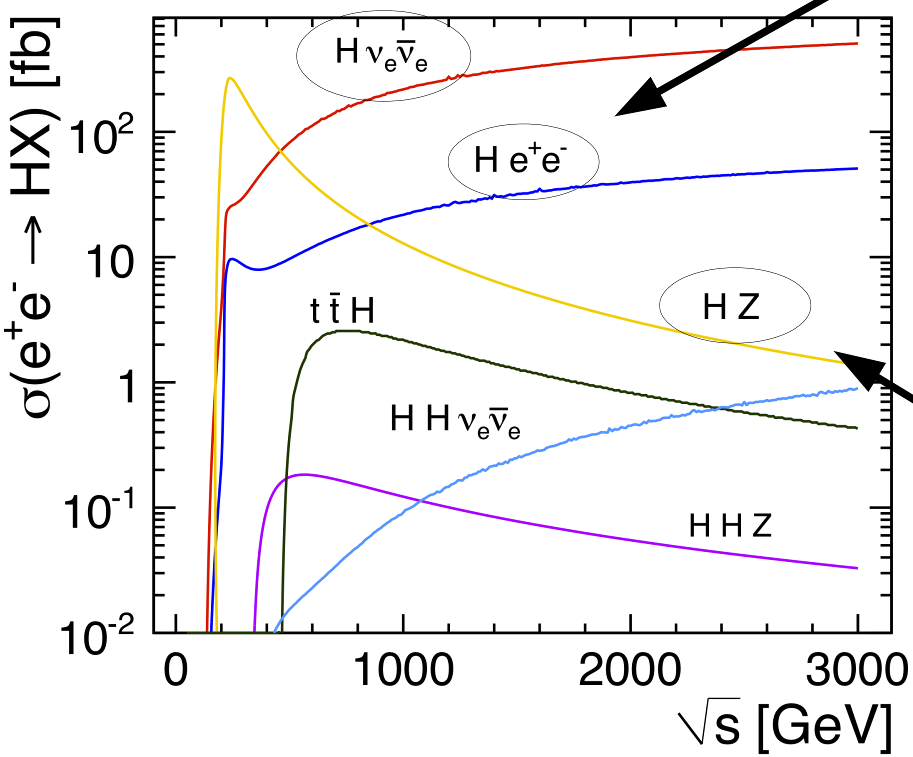


WW fusion

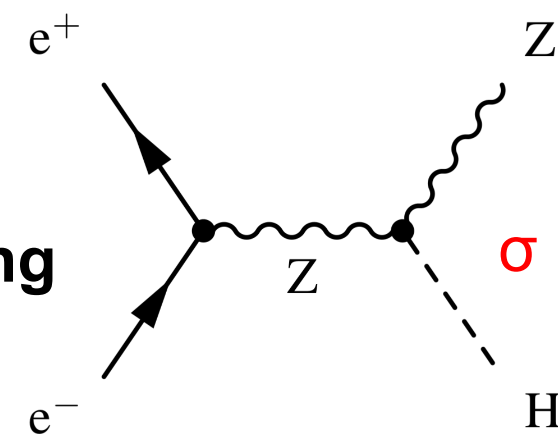
σ ~ log(s)

ZZ fusion





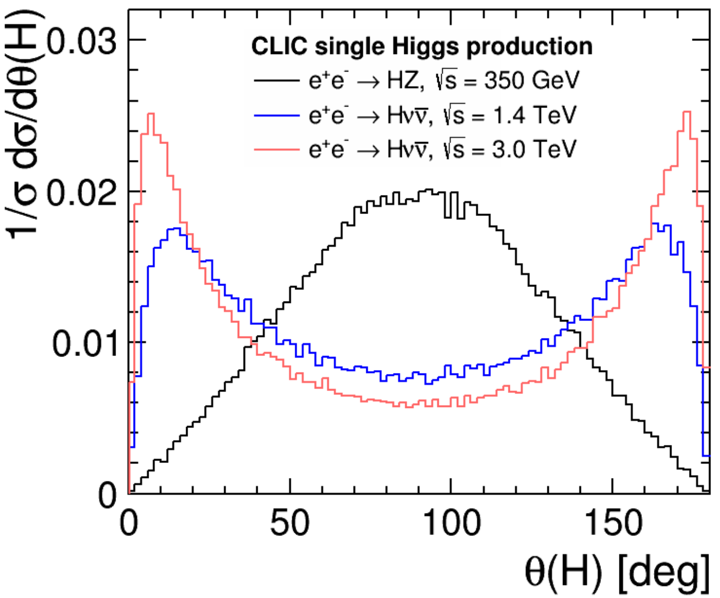
Higgs-strahlung



σ ~ 1/s

Some numbers

	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000



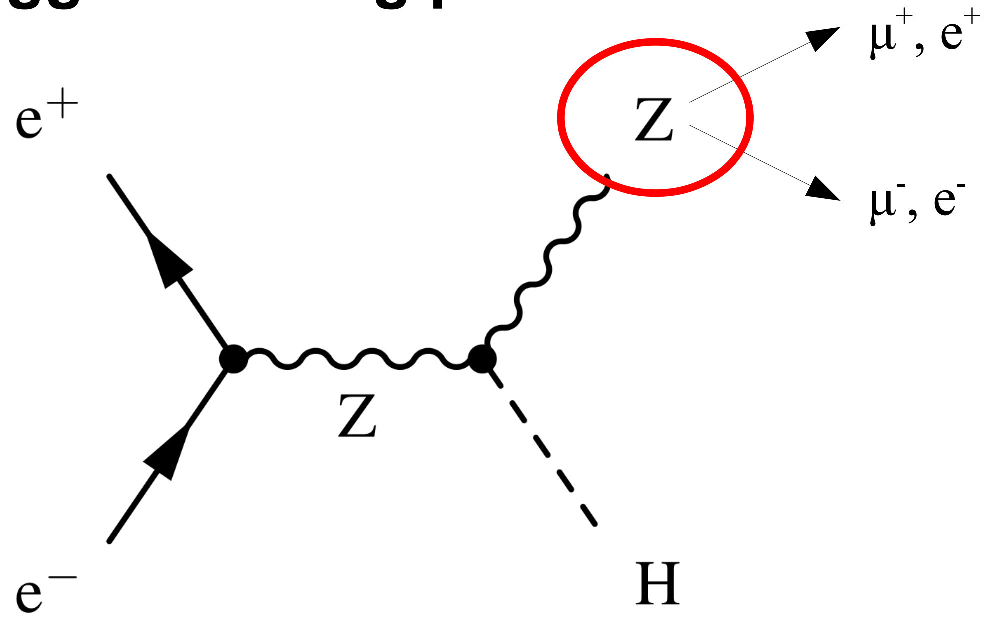
- Large samples of Higgs bosons produced at CLIC
- Measurements at high energy benefit from good detectors in the forward region

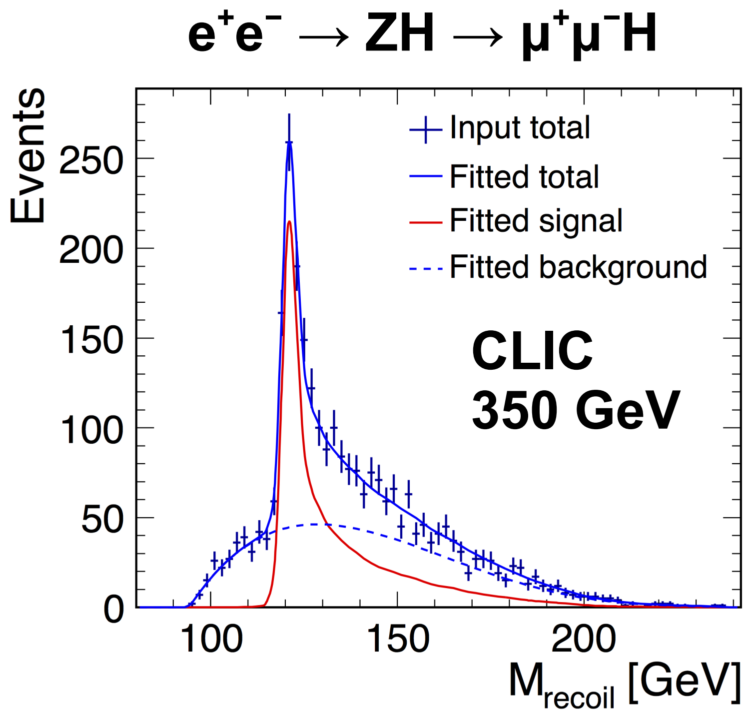
- Benchmark studies assume unpolarised beams

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%	1.18	1.80

Higgsstrahlung at 350 GeV (1)

Higgsstrahlung process



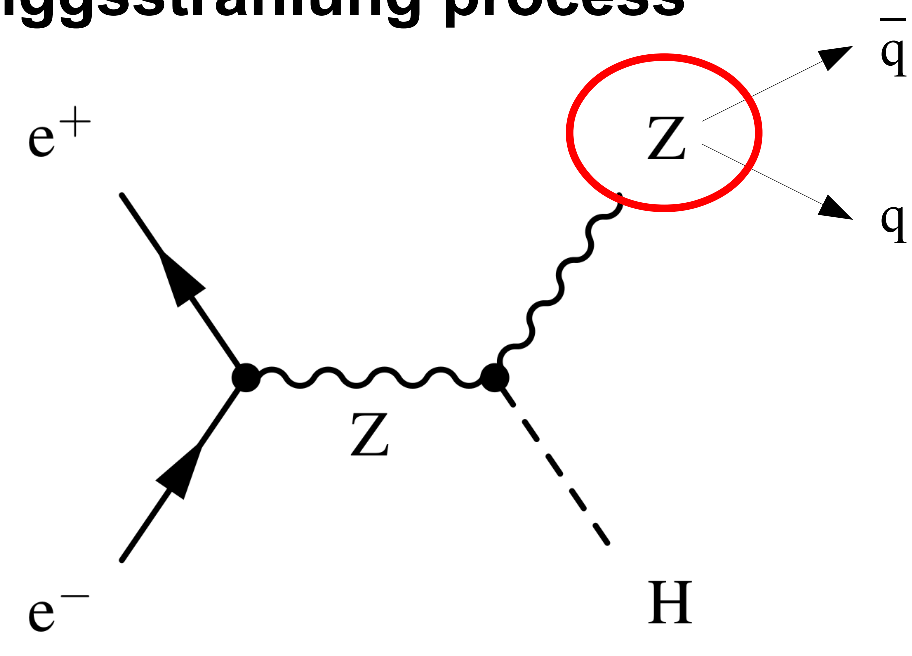


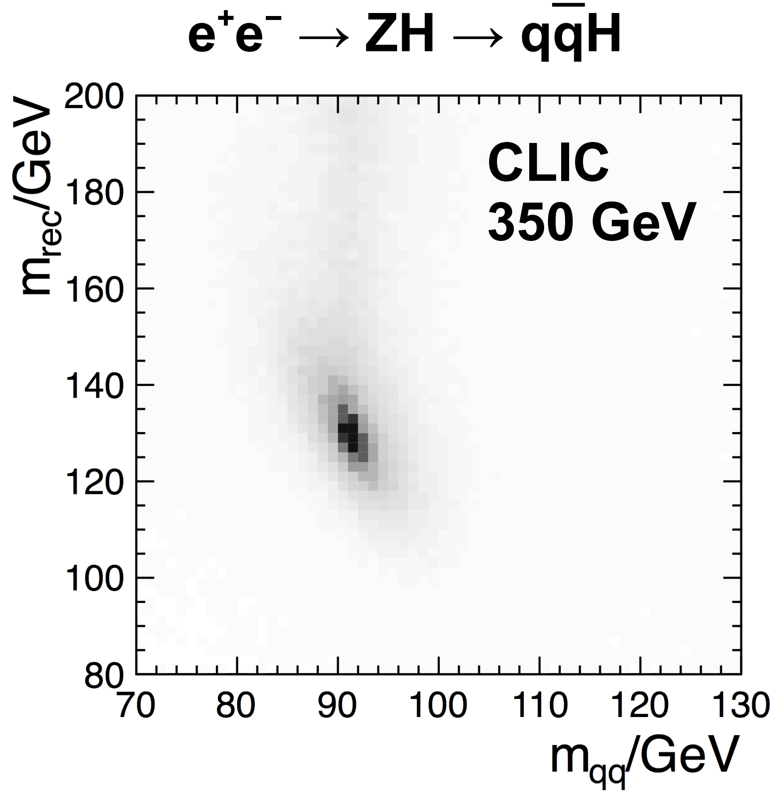
HZ events can be identified from Z recoil mass
→ model independent measurements of the g_{HZZ} coupling

$\Delta(\sigma_{HZ}) / \sigma_{HZ} \approx 4\% \rightarrow \Delta(g_{HZZ}) / g_{HZZ} \approx 2\%$ from $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$

Higgsstrahlung at 350 GeV (2)

Higgsstrahlung process

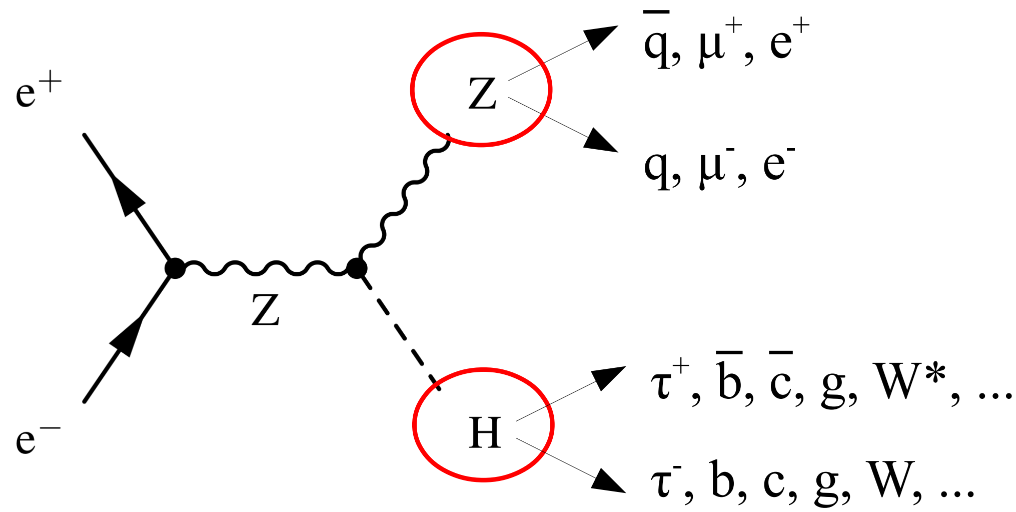




- Substantial improvement using hadronic Z decays
- Challenge: $Z \rightarrow q\bar{q}$ reconstruction may depend on Higgs decay mode
- Even extreme variations of the SM Higgs BRs lead to bias ≤ ½ stat. error

$\Delta(\sigma_{HZ}) / \sigma_{HZ} \approx 1.8\% \rightarrow \Delta(g_{HZZ}) / g_{HZZ} \approx 0.9\%$ from hadronic Z decays

σ x BR measurements at 350 GeV



Measurement	Observable	Stat. precision
σ(HZ) x BR(H → $\tau^+\tau^-$)	$g^2_{HZZ} g^2_{H\tau\tau} / \Gamma_H$	6.2%
σ(HZ) x BR(H → $b\bar{b}$)	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	1% (estimated)
σ(HZ) x BR(H → $c\bar{c}$)	$g^2_{HZZ} g^2_{Hcc} / \Gamma_H$	5% (estimated)
σ(HZ) x BR(H → gg)		6% (estimated)
σ(HZ) x BR(H → WW*)	$g^2_{HZZ} g^2_{HWW} / \Gamma_H$	2% (estimated)
σ($H\nu_e\bar{\nu}_e$) x BR(H → $b\bar{b}$)	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	3% (estimated)

Assuming unpolarised beams

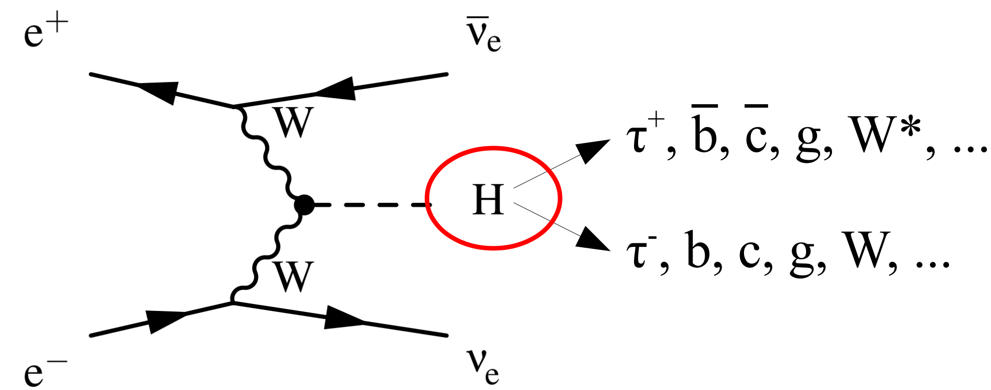
In addition: BR(H → inv.) < 0.97% at 90% C.L.

Measurements using $H\nu_e\bar{\nu}_e$ events

Large Higgs samples produced in WW fusion at high energy:

→ Precision measurements of σ x BR

→ Access to rarer decay modes



Measurement	Observable	Stat. precision (1.4 TeV)	Stat. precision (3 TeV)
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to \tau^+\tau^-$)	$g^2_{HWW}g^2_{H\tau\tau} / \Gamma_H$	4.2%	tbd
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to b\bar{b}$)	$g^2_{HWW}g^2_{Hbb} / \Gamma_H$	0.3%	0.2%
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to c\bar{c}$)	$g^2_{HWW}g^2_{Hcc} / \Gamma_H$	2.9%	2.7%
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to gg$)		1.8%	1.8%
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to \mu^+\mu^-$)	$g^2_{HWW}g^2_{H\mu\mu} / \Gamma_H$	38%	16%
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to \gamma\gamma$)		15%	tbd
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to Z\gamma$)		42%	tbd
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to ZZ^*$)	$g^2_{HWW}g^2_{HZZ} / \Gamma_H$	3% (estimated)	2% (estimated)
$\sigma(H\nu_e\bar{\nu}_e)$ x BR($H \to WW^*$)	g^4_{HWW} / Γ_H	1.4%	0.9% (estimated)

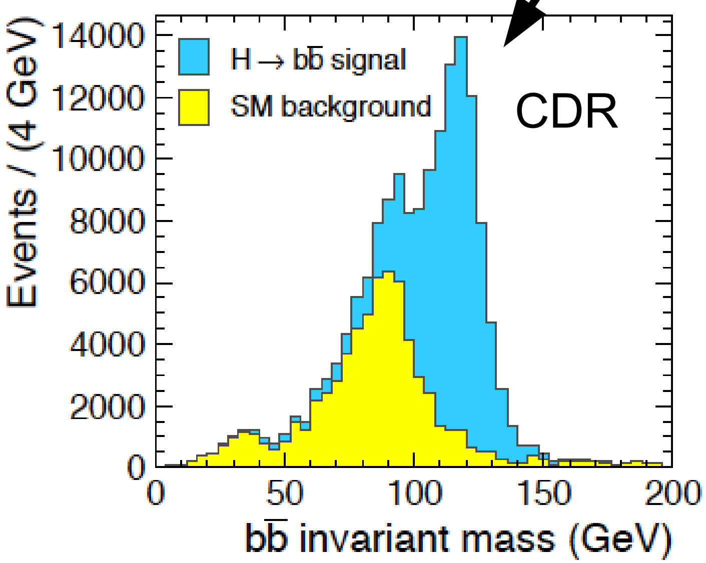
Assuming unpolarised beams

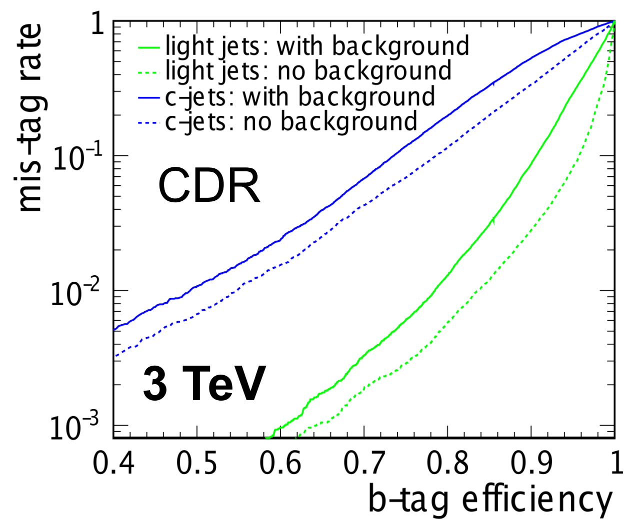
Precision measurements

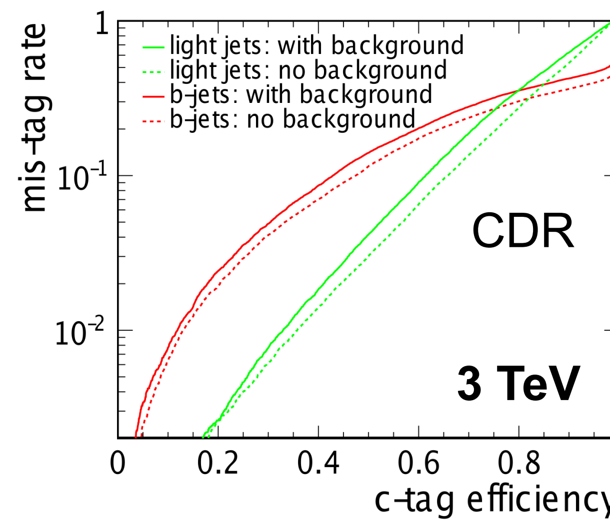
$H \rightarrow b\bar{b}/c\bar{c}/gg$:

- Separation of the different hadronic final states using precise flavour tagging
- $H \rightarrow c\bar{c}$ and gg impossible at hadron colliders
- In addition, the Higgs mass can be extracted from the $H \rightarrow b\bar{b}$ invariant mass distribution (±40MeV at 1.4 TeV, ±33MeV at 3 TeV)

Measurement	1.4 TeV	3 TeV
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow b\bar{b})$	±0.3%	±0.2%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow c\bar{c})$	±2.9%	±2.7%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \rightarrow gg^{-})$	±1.8%	±1.8%



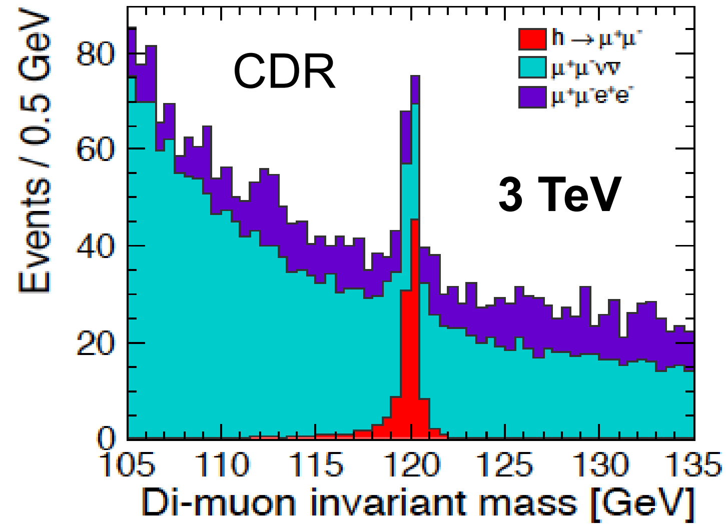




Rare decays

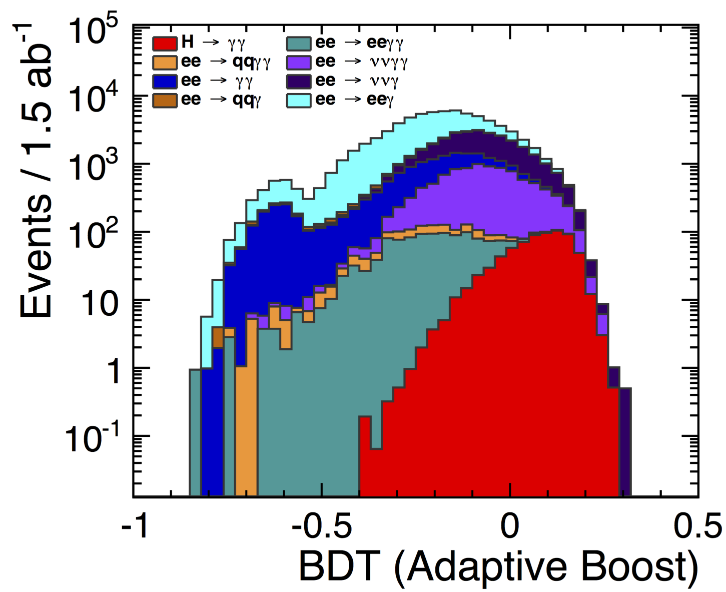
$\sigma(H\nu_e\bar{\nu}_e)$ x BR(H → $\mu^+\mu^-$):

- Very small BR (≈ 0.022%)
- Requires precision tracking
- Δ(σ x BR) = 38%(16%) at 1.4(3) TeV



$\sigma(H\nu_e\bar{\nu}_e)$ x BR(H → γγ):

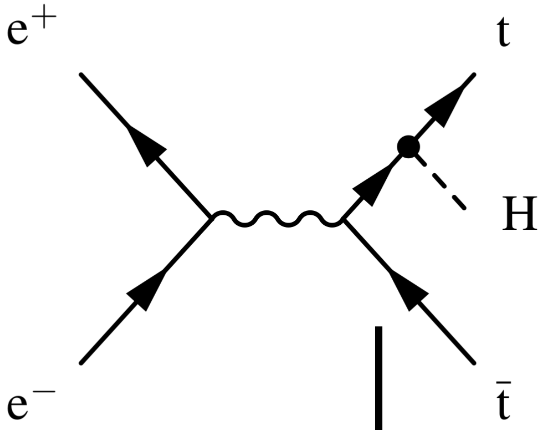
- BR(H→γγ) ≈ 0.23%
- Δ(σ x BR) = 15% at 1.4 TeV



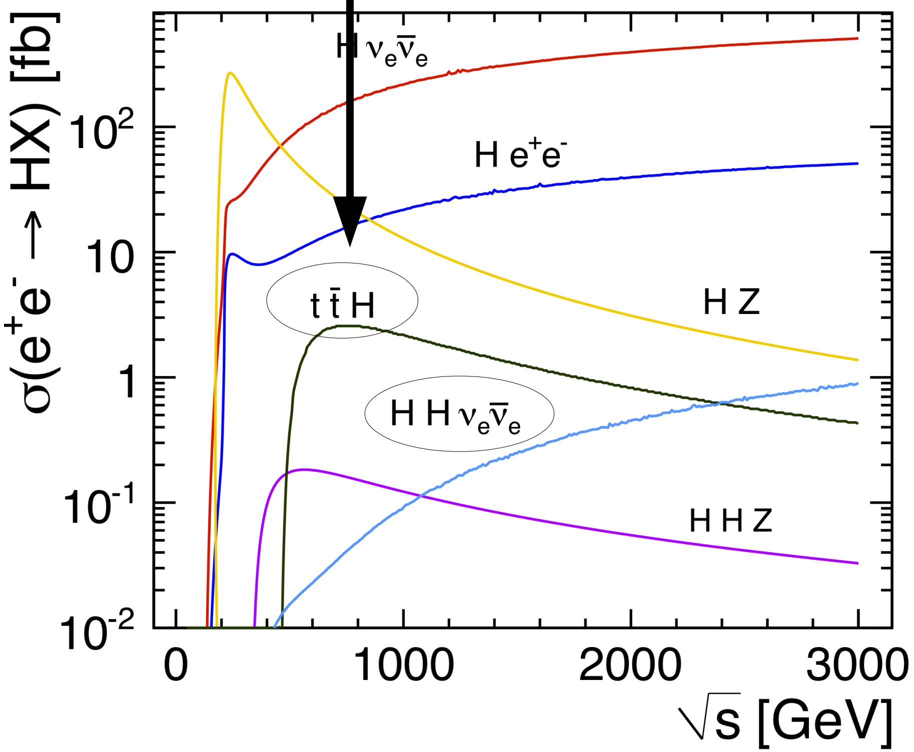
$\sigma(H\nu_e\bar{\nu}_e)$ x BR(H → Zγ):

- BR(H→Zγ) ≈ 0.16%
- Hadronic Z decays usable
(in contrast to hadron colliders)
- Δ(σ x BR) = 42% at 1.4 TeV

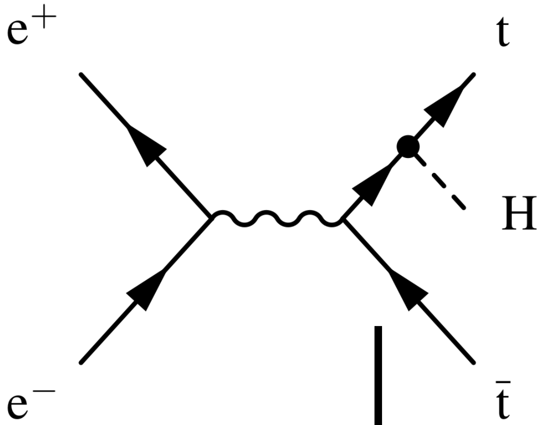
Other processes at higher energy



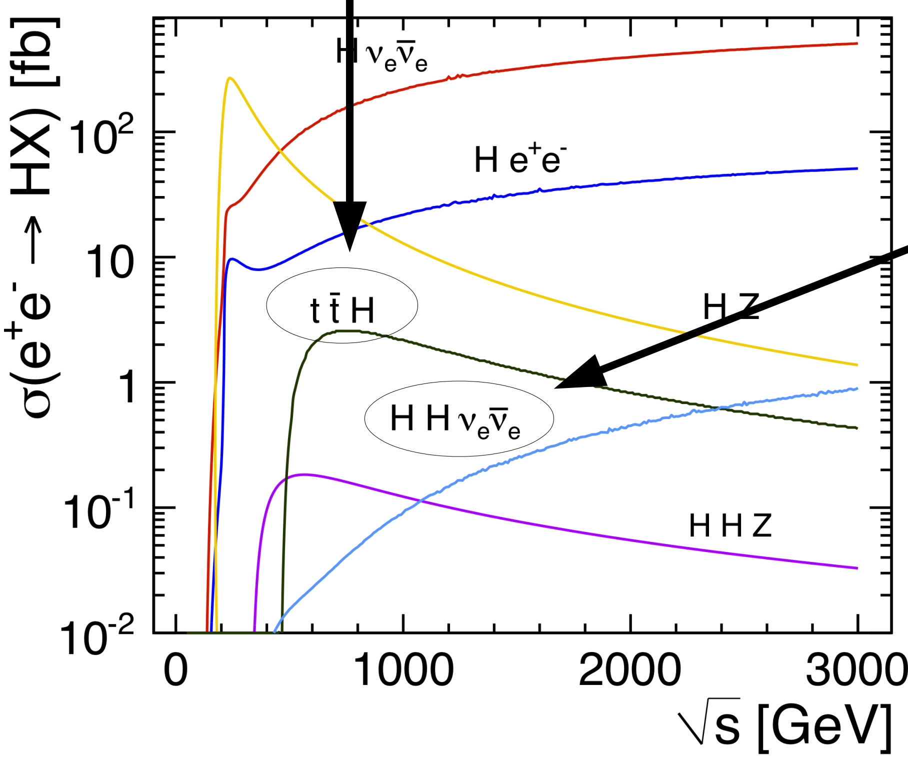
$t\bar{t}H$ production:
maximum at around 800 GeV

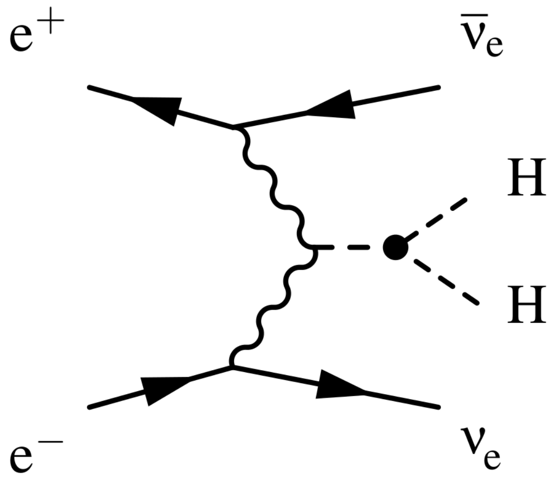


Other processes at higher energy

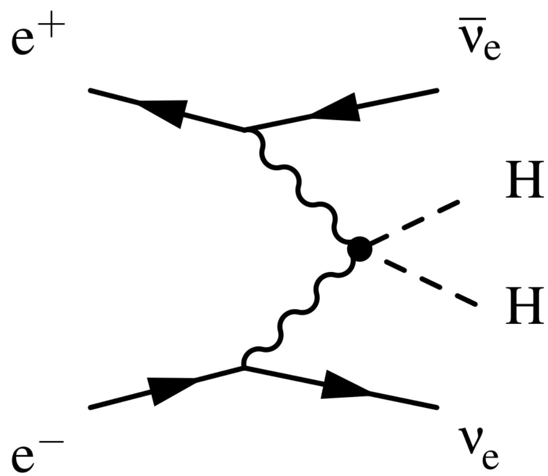


$t\bar{t}H$ production:
maximum at around 800 GeV

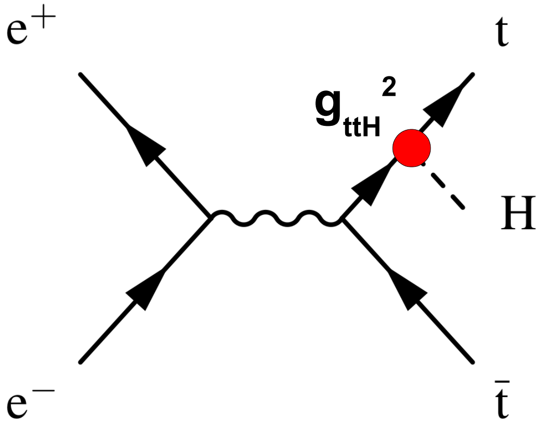




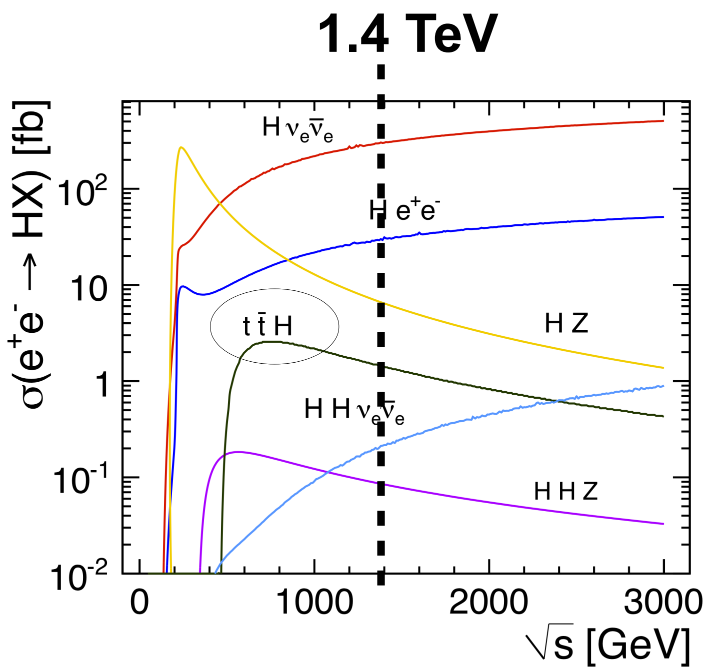
Double Higgs production:
requires high energy



The $t\bar{t}H$ final state at 1.4 TeV



→ The $t\bar{t}H$ cross section is directly sensitive to the top Yukawa coupling g_{ttH}

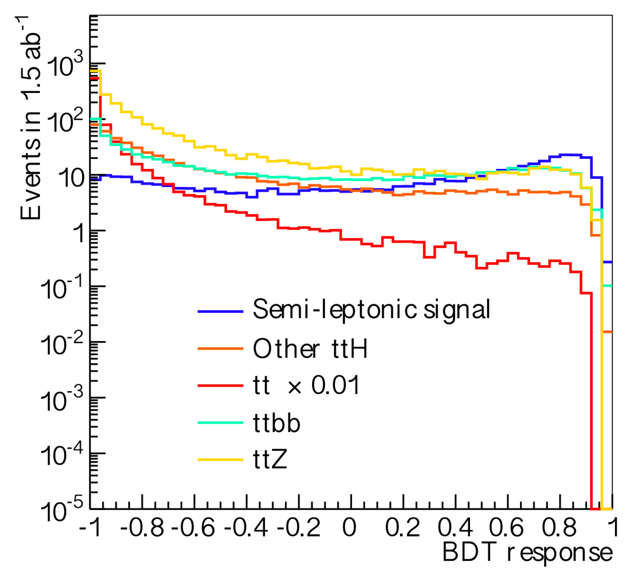


Investigated final states:

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

"*8 jets*": $t(\rightarrow q\bar{q}b)\bar{t}(\rightarrow q\bar{q}\bar{b})H(\rightarrow b\bar{b})$

→ Four b-quarks in the final state

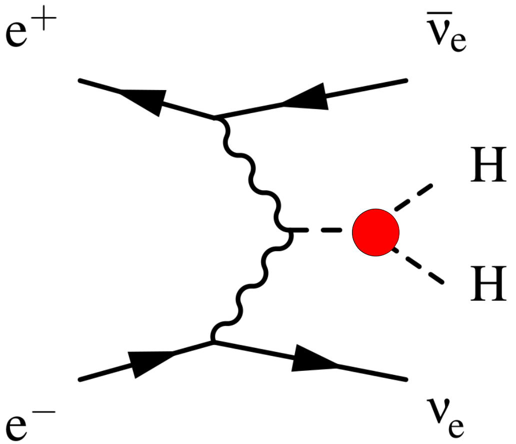


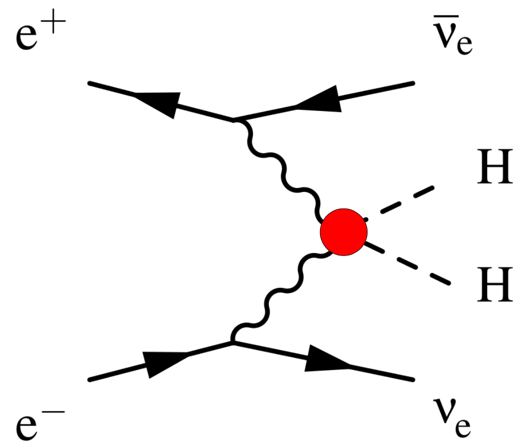
Combination of both final states:

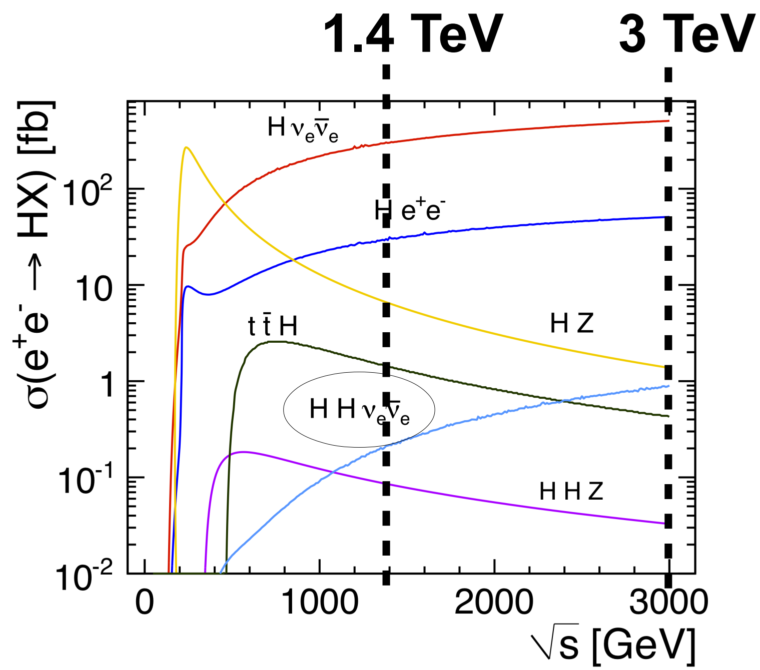
$\Delta\sigma(t\bar{t}H) / \sigma(t\bar{t}H) = 8.4\%$

→ $\Delta g_{ttH} / g_{ttH} = 4.5\%$

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 HHWW coupling

- Only 225 (1200) $e^+e^- \to HH\nu_e\bar{\nu}_e$ events at 1.4 (3) TeV

→ high energy and luminosity crucial

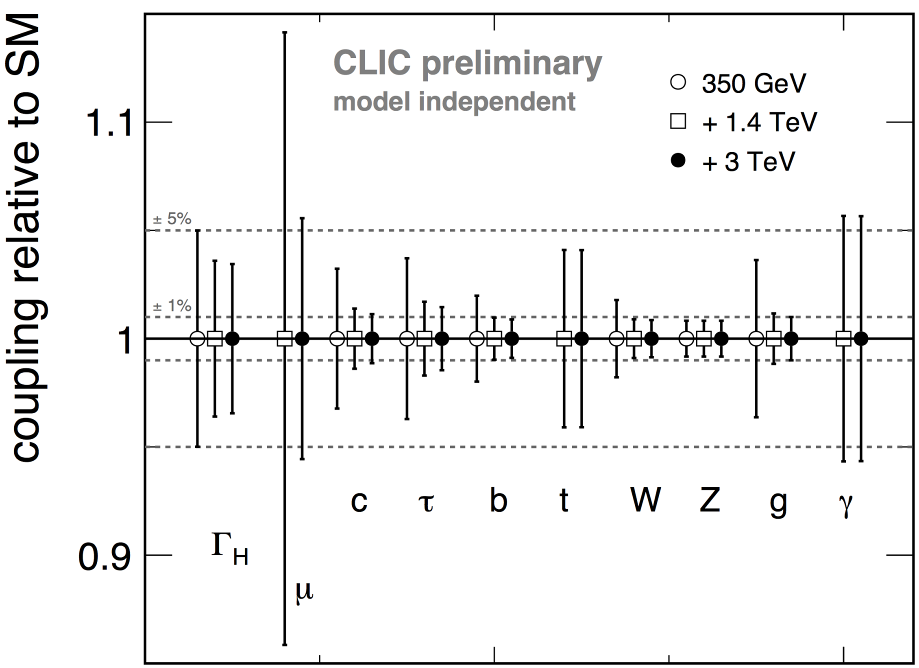
Measurement	**1.4 TeV**	**3 TeV**
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
$\Delta(\lambda)$	32%	16%
$\Delta(\lambda)$ for $P(e^-) = -80\%$	24%	12%

CLIC Higgs studies

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8%	–	–
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	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau} / \Gamma_H$	6.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW} / \Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ} g^2_{HZZ} / \Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	3%†	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%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau} / \Gamma_H$	–	4.2%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	–	38%	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	42%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW} / Γ_H	tbd	1.4%	0.9%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ} / \Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt} g^2_{Hbb} / \Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	32%	16%
$HH\nu_e\bar{\nu}_e$	with −80% e^- polarization	λ	–	24%	12%

*: preliminary
†: estimated

Putting it all together

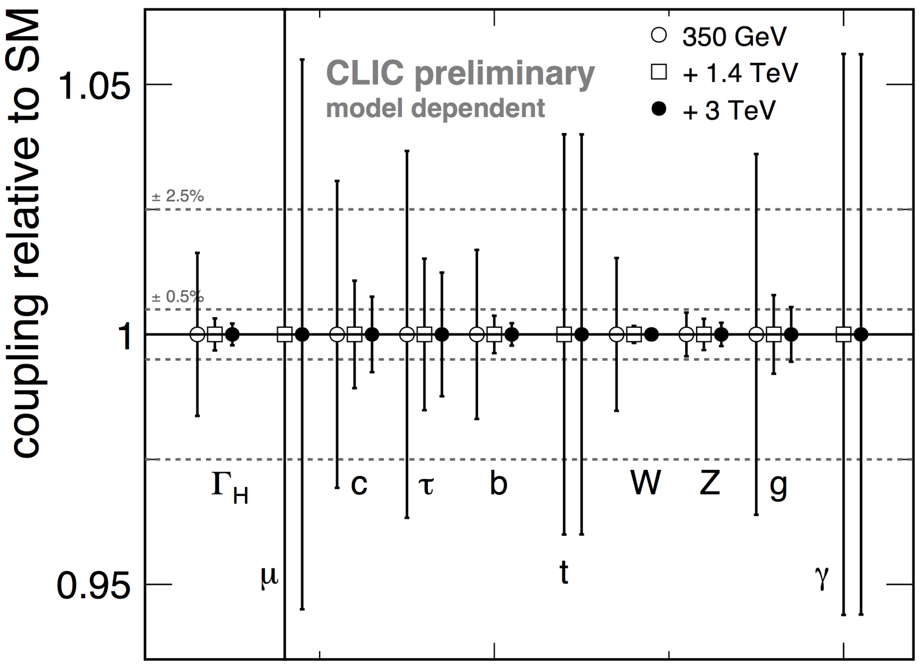


Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.8 %	0.9 %	0.9 %
g_{Hbb}	2.0 %	1.0 %	0.9 %
g_{Hcc}	3.2 %	1.4 %	1.1 %
$g_{H\tau\tau}$	3.7 %	1.7 %	1.5 %
$g_{H\mu\mu}$	–	14.1 %	5.6 %
g_{Htt}	–	4.1 %	$\leq$ 4.1 %
$g^{\dagger}_{Hgg}$	3.6 %	1.2 %	1.0 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	< 5.7 %
Γ_H	5.0 %	3.6 %	3.4 %

-80% electron polarisation at 1.4 and 3 TeV

- Fully model-independent, only possible at a lepton collider
- All results limited by 0.8% from σ(HZ) measurement
- The Higgs width is extracted with 5 – 3.5% precision

Analysis similar to LHC experiments



Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
κ_{HZZ}	0.44 %	0.31 %	0.23 %
κ_{HWW}	1.5 %	0.17 %	0.11 %
κ_{Hbb}	1.7 %	0.37 %	0.22 %
κ_{Hcc}	3.1 %	1.1 %	0.75 %
$\kappa_{H\tau\tau}$	3.7 %	1.5 %	1.2 %
$\kappa_{H\mu\mu}$	–	14.1 %	5.5 %
κ_{Htt}	–	4.0 %	$\leq$ 4.0 %
κ_{Hgg}	3.6 %	0.79 %	0.55 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	< 5.6 %
$\Gamma_{H,md,derived}$	1.6 %	0.32 %	0.22 %

-80% electron polarisation at 1.4 and 3 TeV

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

No invisible decays:

$$\Gamma_{H,\text{model}} = \sum_i \kappa_i^2 \cdot BR_i^{SM}$$

Sub-percent precisions at high energy
→ Results strongly dependent on fit assumptions

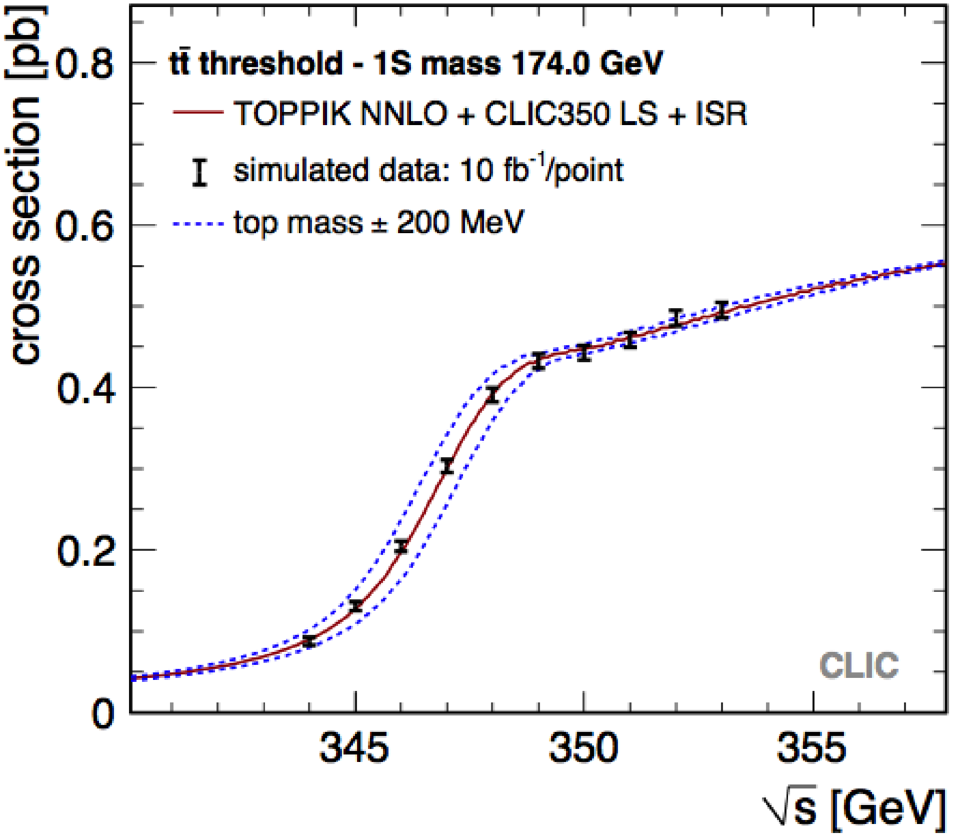
Top mass

$t\bar{t}$ threshold scan:

• Measurements at 10 different centre-of-mass energies (10 fb^{-1} each), data also useful for Higgs physics

• Theoretical uncertainty on the order of 100 MeV when transforming the measured 1S mass to the $\overline{MS}$ mass scheme

• Precision at the LHC limited to about 500 MeV

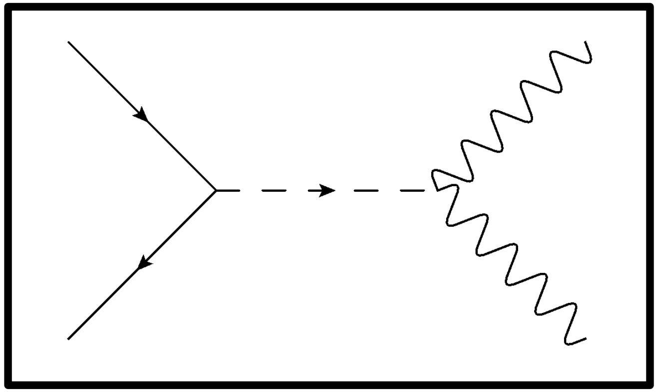


$\Delta_{stat}(m_t)$	34 MeV
$\Delta_{stat}(\alpha_s)$	0.0009

Prospects for BSM physics

- **Two approaches:**

1.) Pair production of new particles if $M \leq \sqrt{s} / 2$
→ CLIC especially attractive for electroweak states
→ Precision measurement of new particle masses and couplings

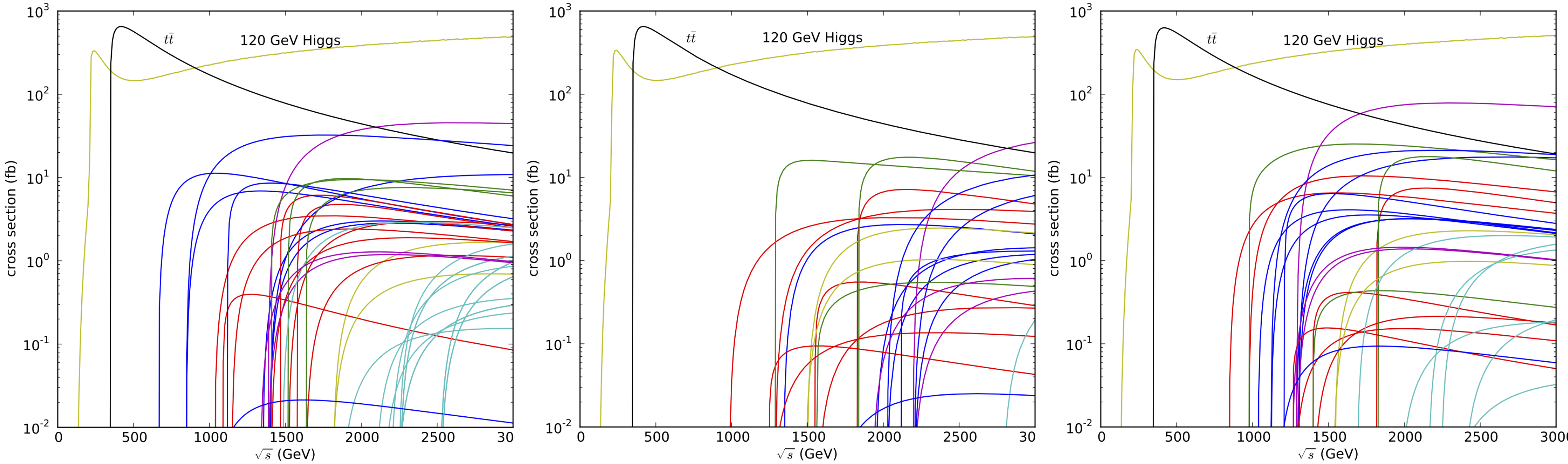


Many examples of SUSY particle production studied for CLIC CDR

2.) Indirect searches through precision observables
→ possibility to reach much higher mass scales (tens of TeV)

One of the priorities for future benchmarking studies

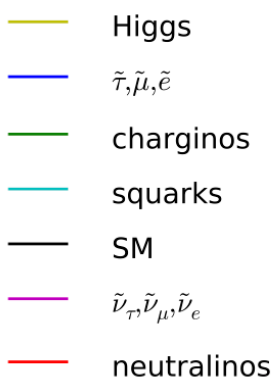
Investigated SUSY models



CDR Model I, 3 TeV:
- Squarks
- Heavy Higgs

CDR Model II, 3 TeV:
- Smuons, selectrons
- Gauginos

CDR Model III, 1.4 TeV:
- Smuons, selectrons
- Staus
- Gauginos



Top squarks → Edinburgh

Wider applicability than only SUSY: Reconstructed particles can be classified simply as states of given mass, spin and quantum numbers

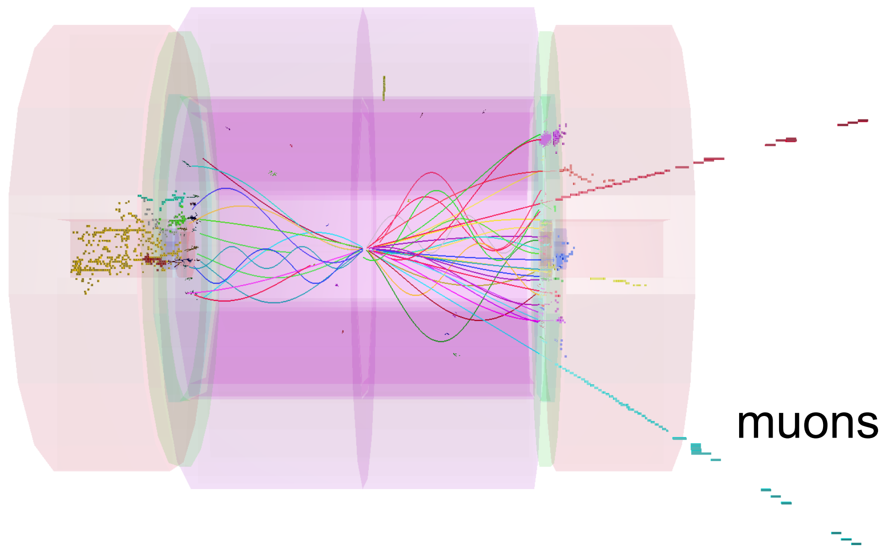
The simplest case: sleptons at 3 TeV

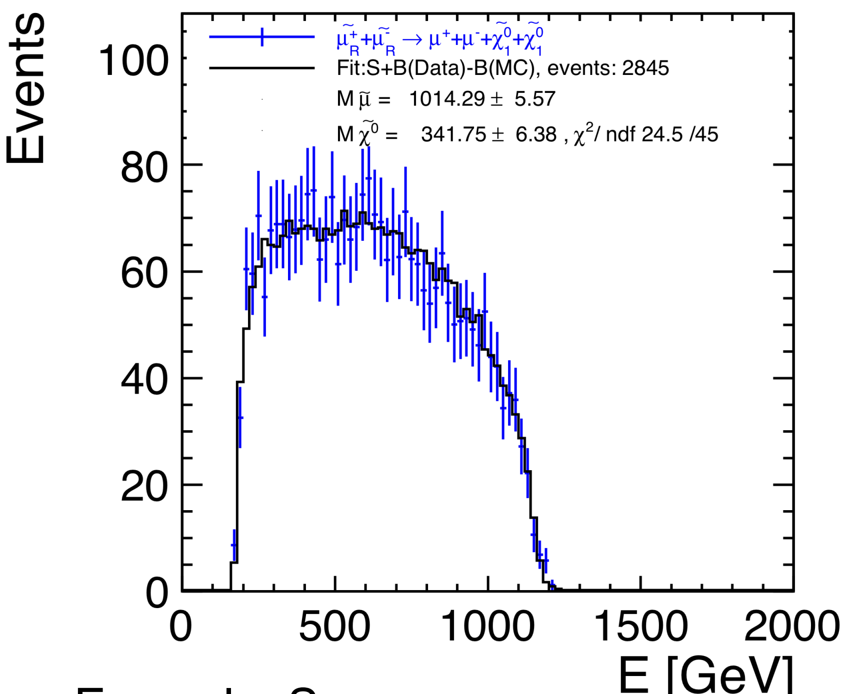
- Slepton production very clean at CLIC
- Slepton masses ≈ 1 TeV
- Investigated channels include:

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

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

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





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

- Precisions of a few GeV achievable

Hadronic final states: gauginos at 3 TeV

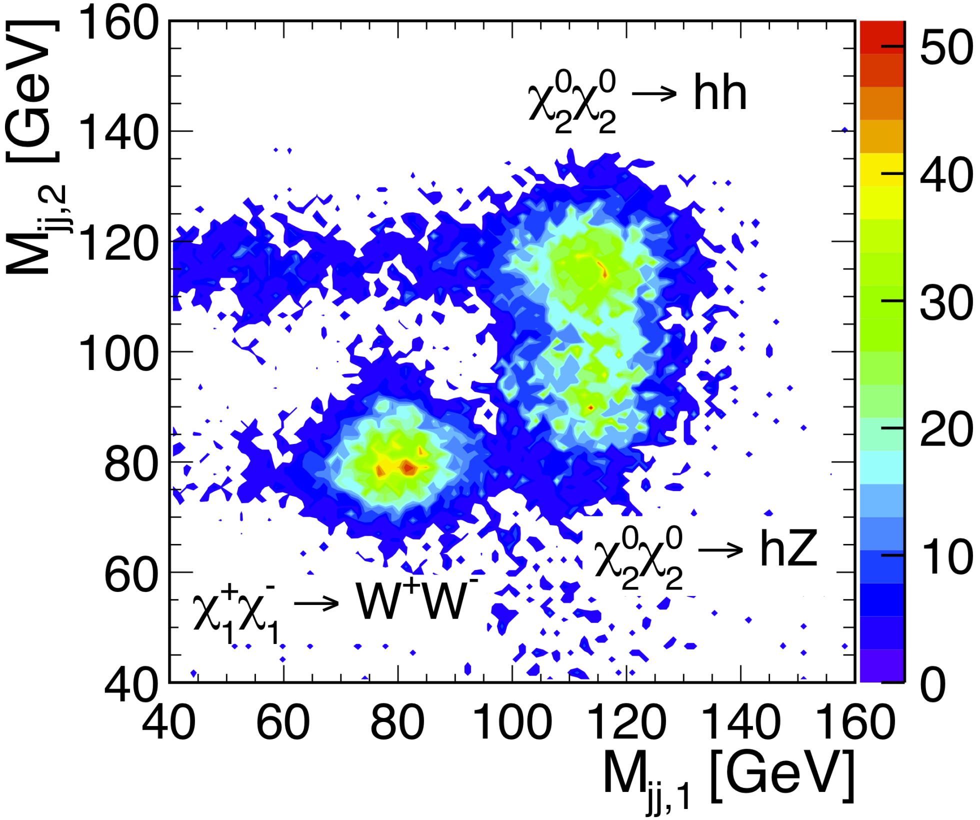
Chargino and neutralino pair production:

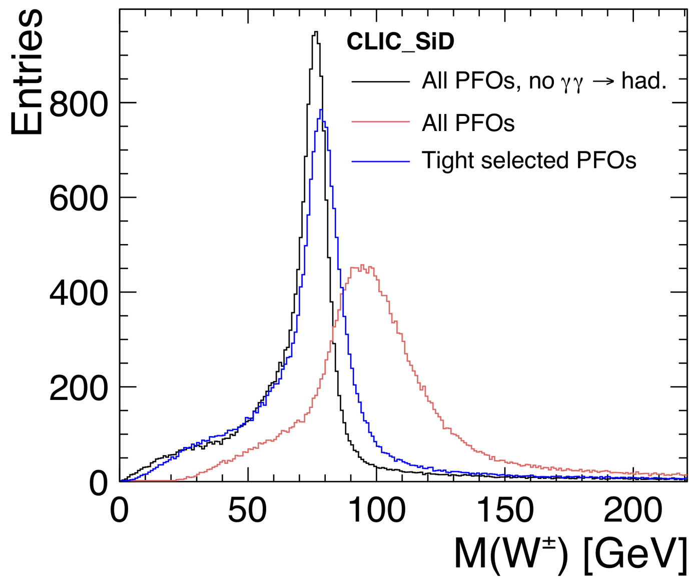
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$

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

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

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%

Heavy Higgs bosons at 3 TeV

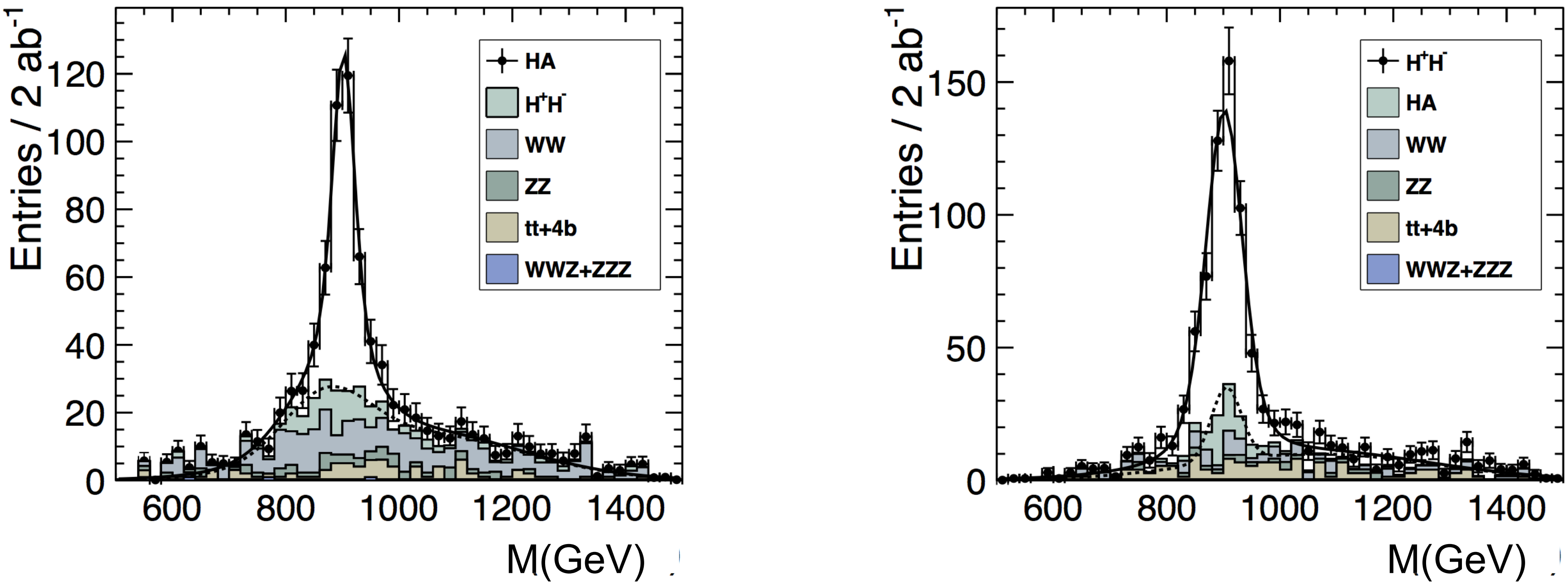
Heavy Higgs bosons:

$e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$

$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$

(H, A and $H^\pm$ almost degenerate in mass)

Complex final states



Accuracy of the heavy Higgs mass measurements: ≈0.3%

Summary of the SUSY studies

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

Precision studies of $e^+e^- \to \mu^+\mu^-$

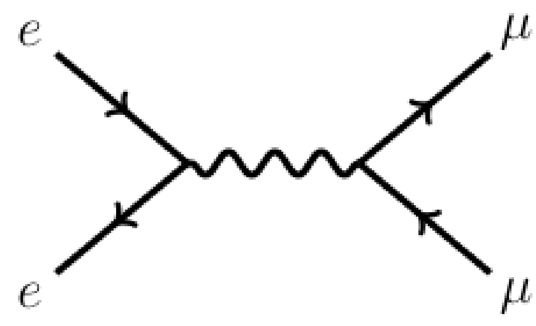
Minimal anomaly-free Z' model:
Charge of the SM fermions under U(1)' symmetry:
$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$

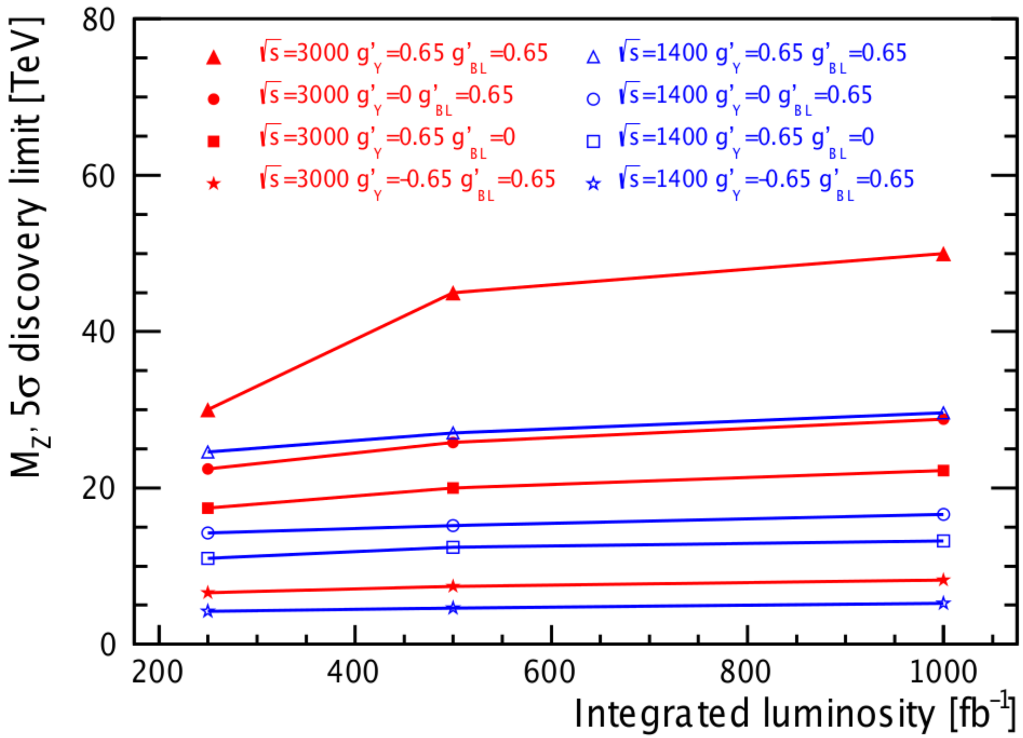
Observables:
- total $e^+e^- \to \mu^+\mu^-$ cross section
- forward-backward-asymmetry
- left-right asymmetry

(±80% e^- polarisation)

If LHC discovers Z' (e.g. for M = 5 TeV):
Precise measurement of the effective couplings

Otherwise:
Discovery reach up to tens of TeV
(depending on the couplings)



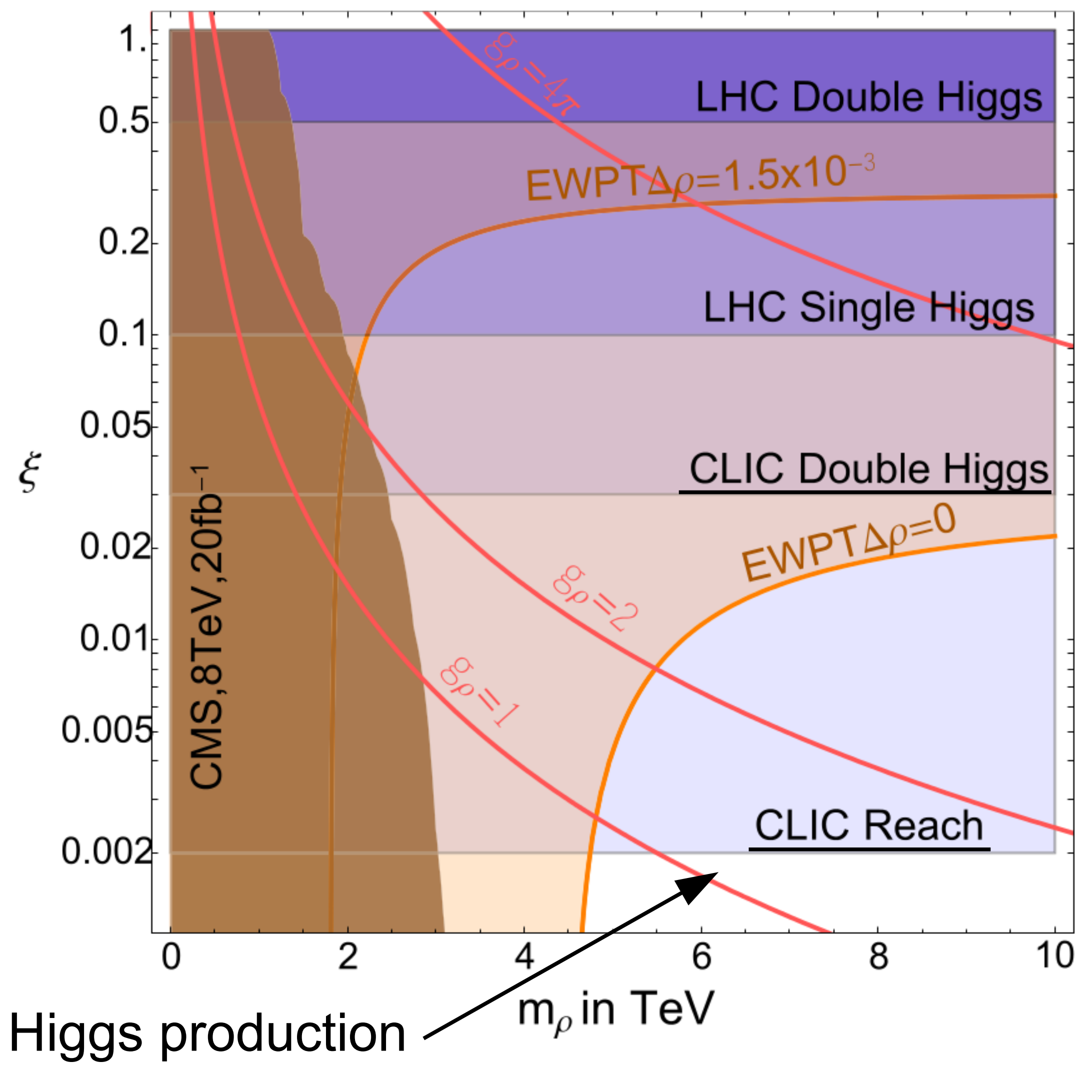


Composite Higgs bosons

- Higgs as composite bound state of fermions

- m_ρ: mass of the vector resonance of the composite theory

- $\xi = (v / f)^2$ measures the strengths of the Higgs interactions



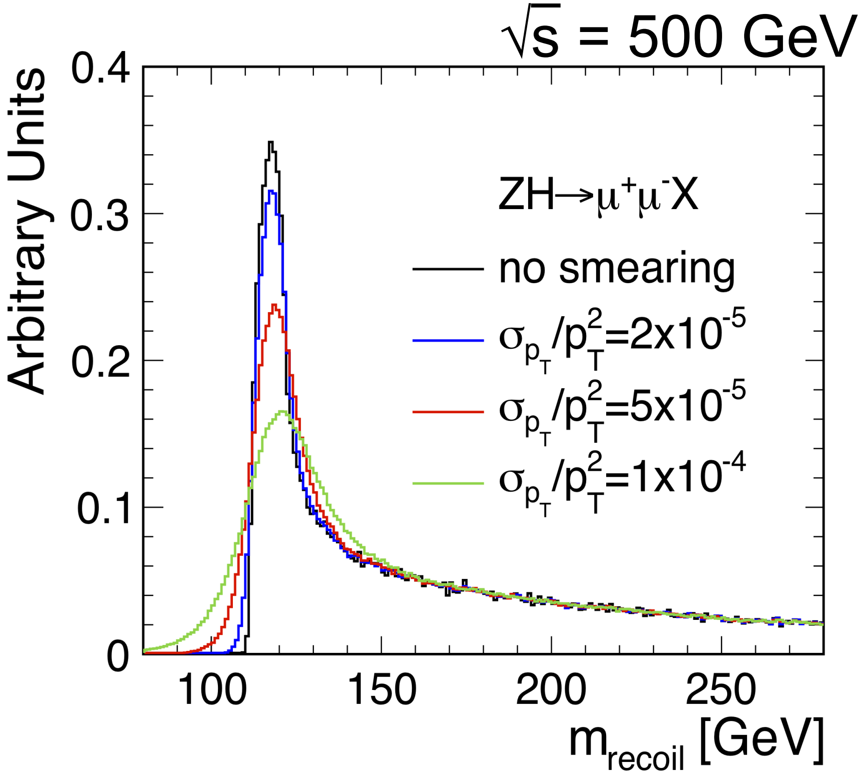
CLIC provides an indirect probe of a Higgs composite scale of 70 TeV

Implications for the detectors

Physics aims → detector needs

- **Momentum resolution**
(e.g. Higgs recoil mass, $H \to \mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times10^{-5}\,GeV^{-1}$$



- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E = 1000-50\,GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

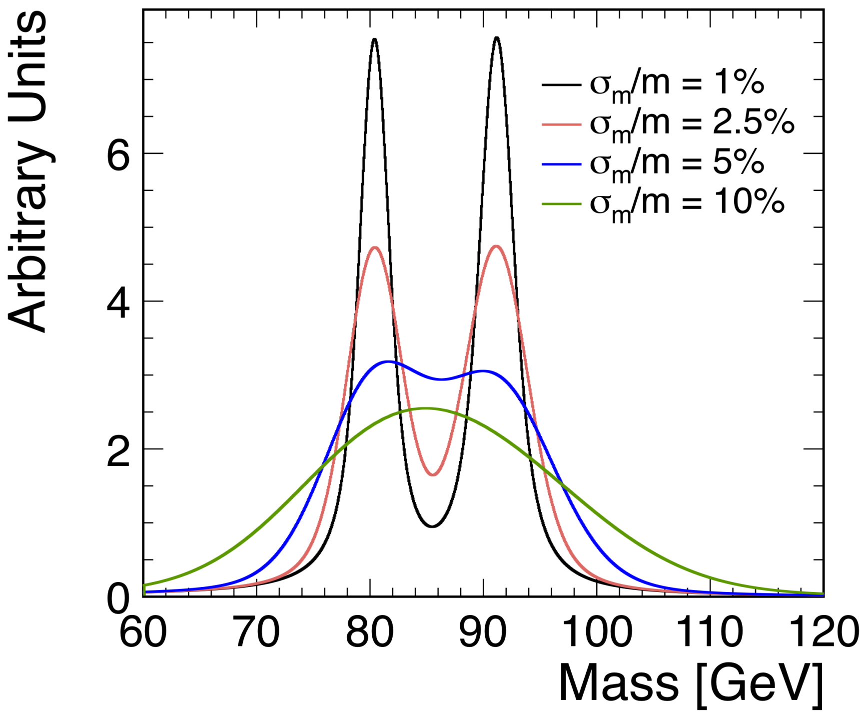
$$\sigma(d_0) = \sqrt{a^2 + b^2\cdot GeV^2/(p^2\sin^3\theta)},\ a\approx5\,\mu m,\ b\approx15\,\mu m$$

- **Lepton identification, very forward electron tagging**

Physics aims → detector needs

- **Momentum resolution**
(e.g. Higgs recoil mass, H → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times10^{-5}\,GeV^{-1}$$



- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E = 1000-50\,GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

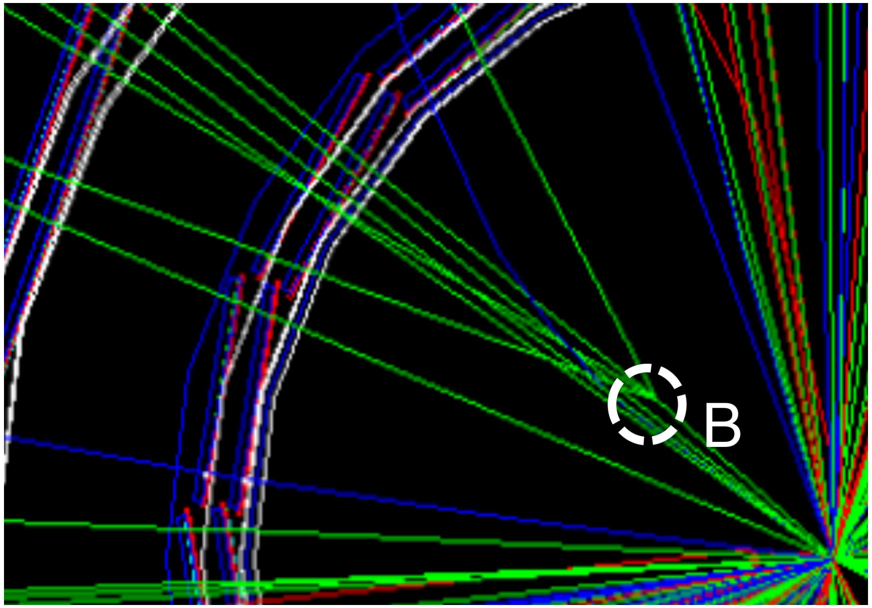
$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2/(p^2\sin^3\theta)},\ a \approx 5\,\mu m,\ b \approx 15\,\mu m$$

- **Lepton identification, very forward electron tagging**

Physics aims → detector needs

- **Momentum resolution**
(e.g. Higgs recoil mass, H → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times10^{-5}\,GeV^{-1}$$



- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E = 1000-50\,GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3\theta)},\ a \approx 5\,\mu m,\ b \approx 15\,\mu m$$

- **Lepton identification, very forward electron tagging**

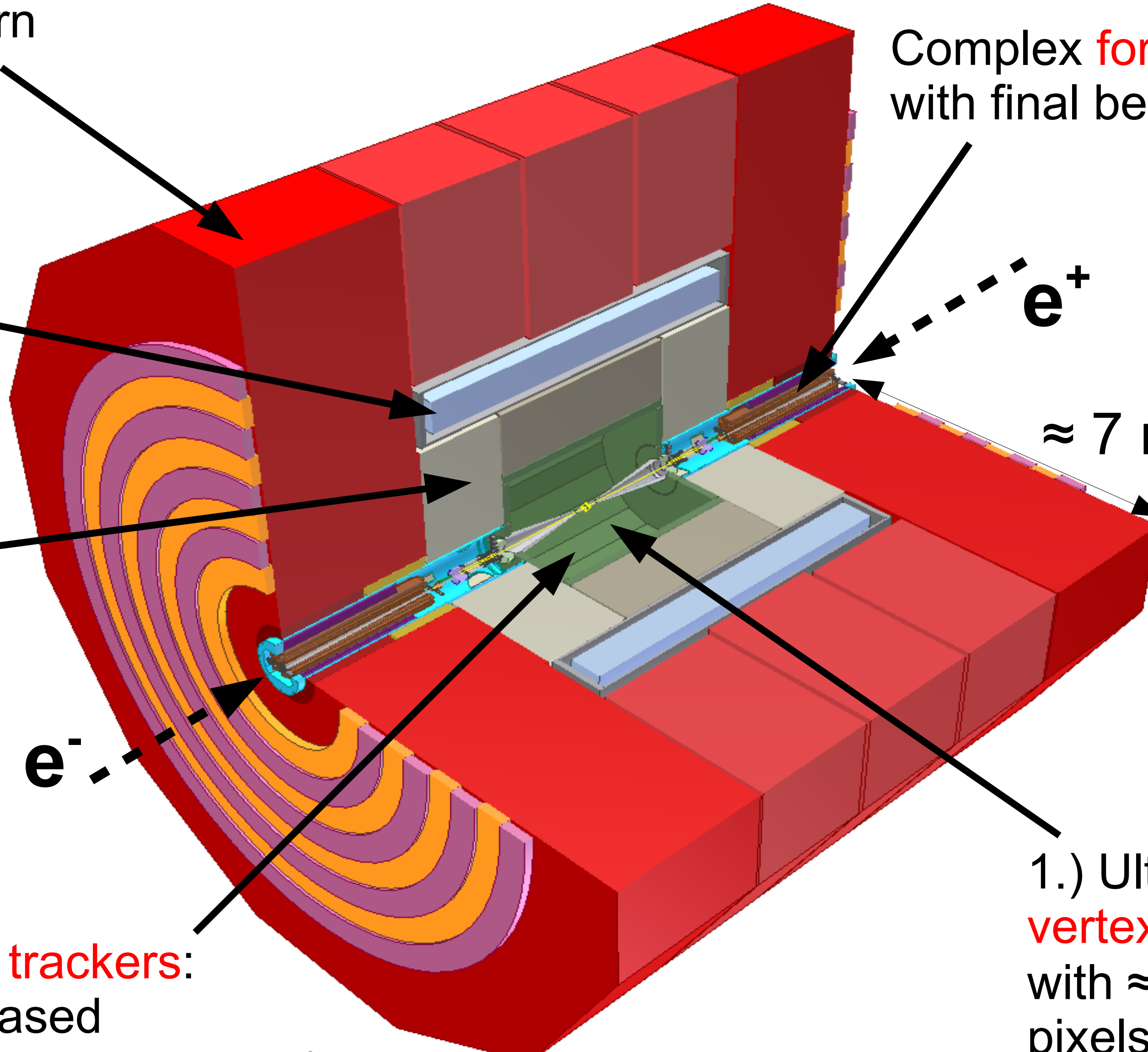
CLIC detector concepts

Instrumented return yoke for muon ID

Strong solenoids (4-5 T)

3.) Fine grained (PFA) calorimetry, 1+7.5 λ

Complex forward region with final beam focusing

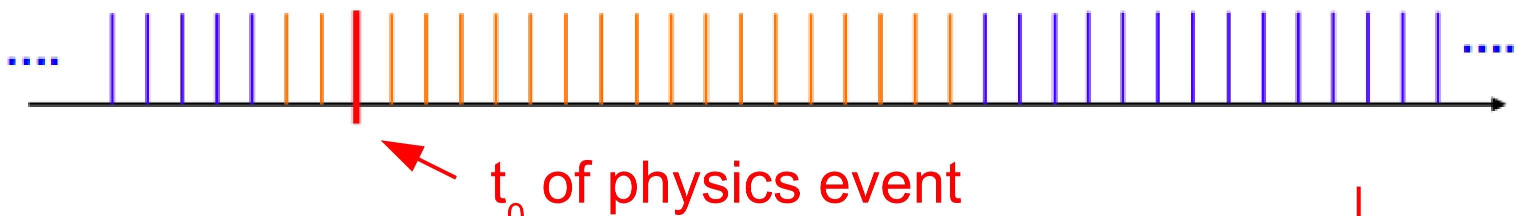


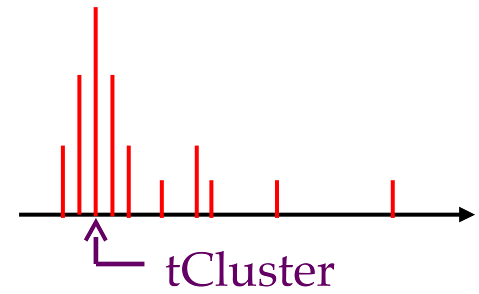
1.) Ultra low-mass vertex detector with ≈ 25 x 25 μm² pixels → more later

2.) Main trackers: silicon-based (large pixels and strips)

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

In addition: hadron-collider type jet algorithms (FastJet)

Time windows and hit resolutions

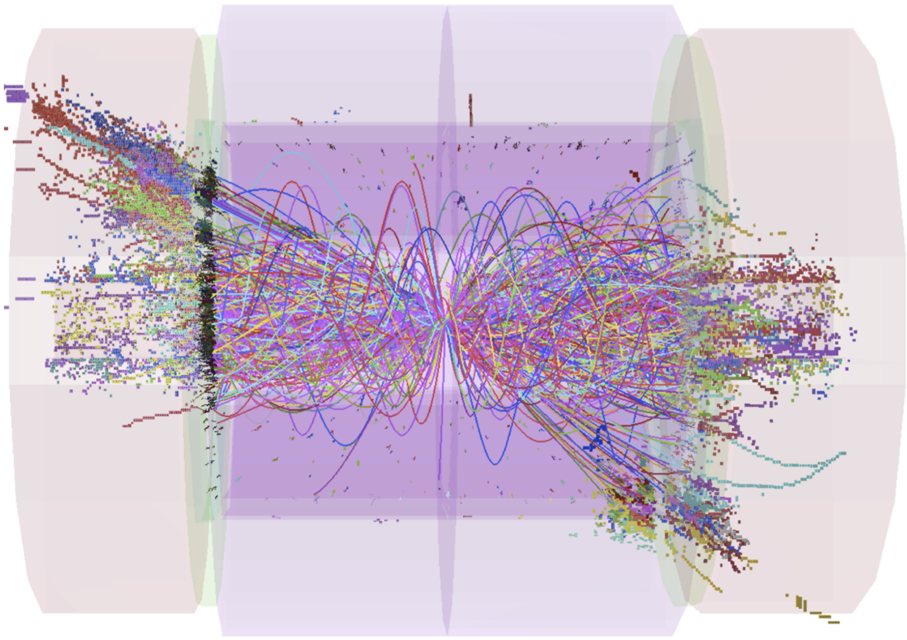
Used in the reconstruction software for CDR simulations:

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

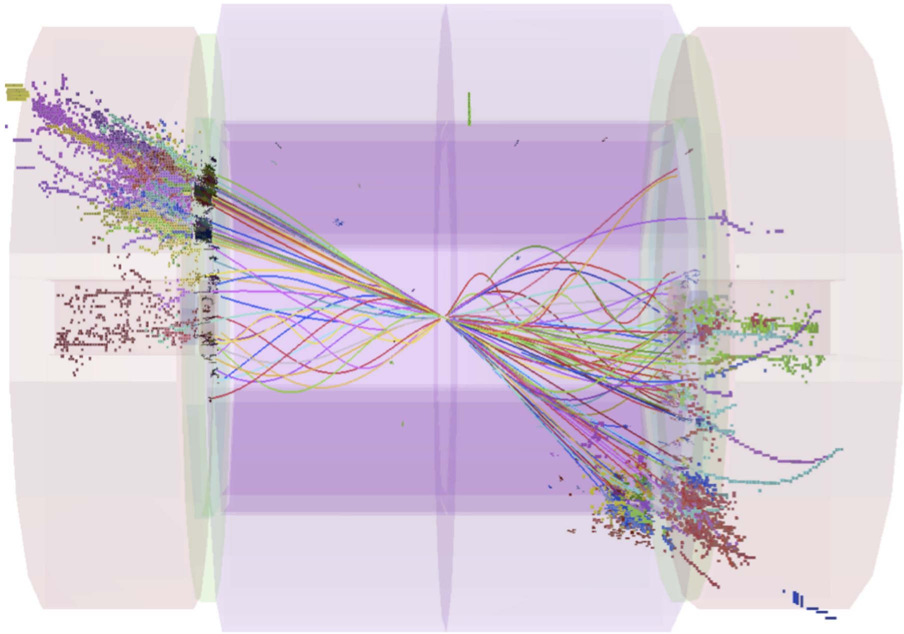
- CLIC hardware requirements
- Achievable in the calorimeters with a sampling every ≈ 25 ns

Impact of the timing cuts

$e^+e^- \rightarrow t\bar{t}$ at 3 TeV with background from $\gamma\gamma \rightarrow$ hadrons overlaid



1.2 TeV background
in the reconstruction window



100 GeV background
after timing cuts

R&D for the CLIC vertex detector

Vertex detector requirements

Requirements:

- 3 μm single point resolution

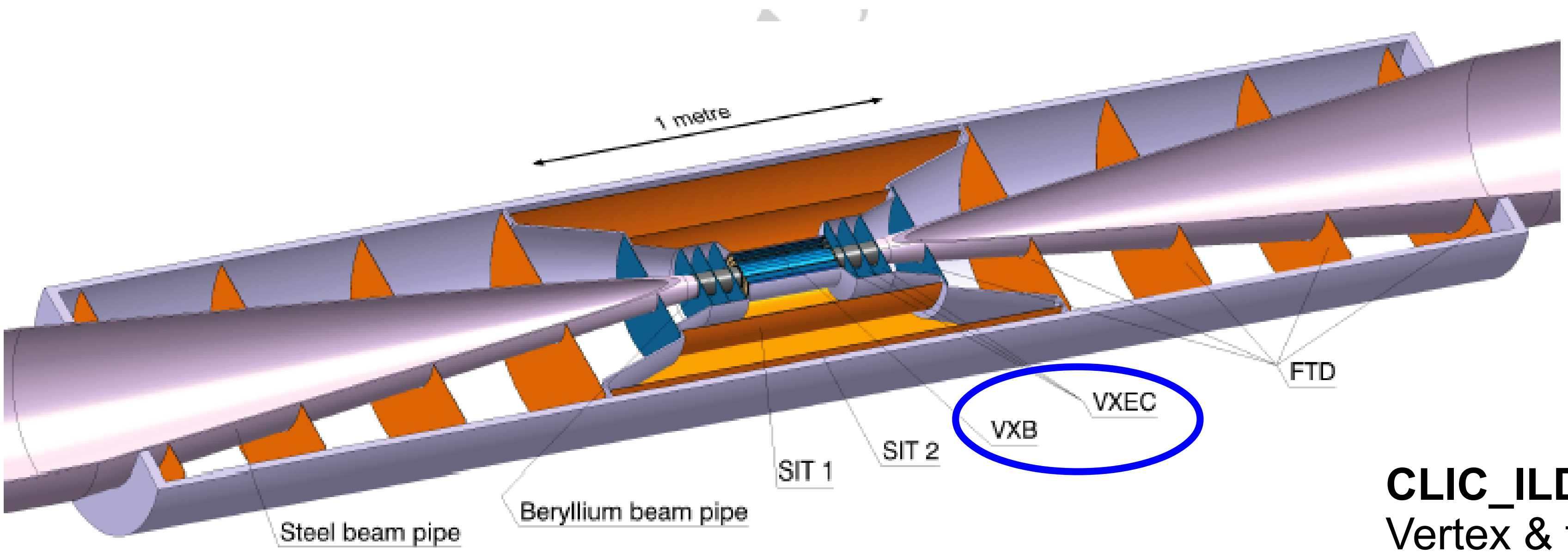
→ 25 x 25 μm^2 pixel size with analog readout → ≈ 2×10^9 pixels

- Material: 0.2% X_0 per layer:

→ Very thin materials / sensors

→ Low-power design, power pulsing, low-mass cooling, aim: 50 mW / cm^2

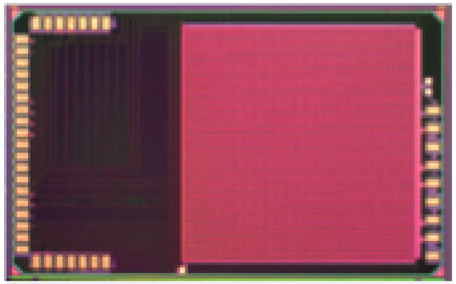
- Time stamping precision: ≈10 ns (to reject backgrounds)
- Radiation level: ≈10^{10} n_{eq} /cm^2 /yr (10^{-4} of LHC)



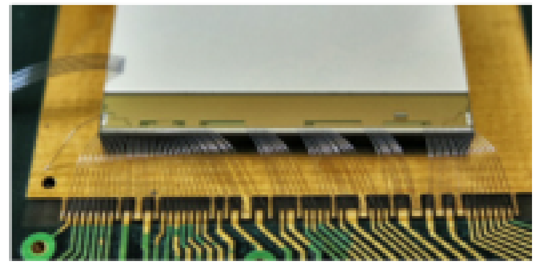
CLIC_ILD
Vertex & forward tracking

Vertex-detector technology R&D

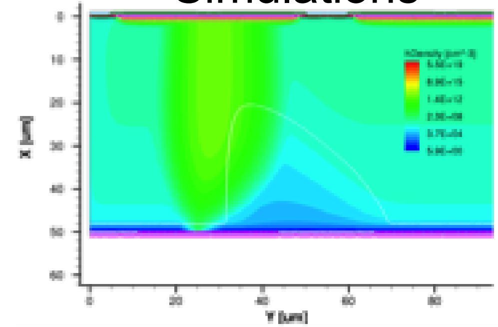
Readout ASICs



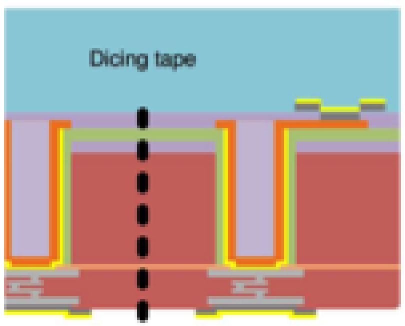
Sensors



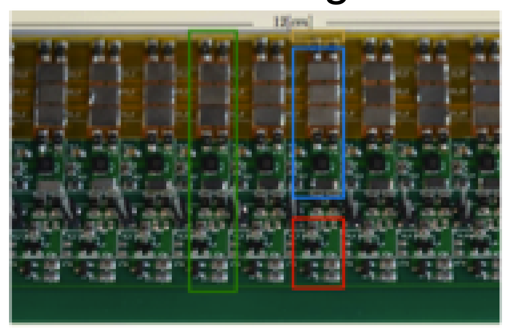
Simulations



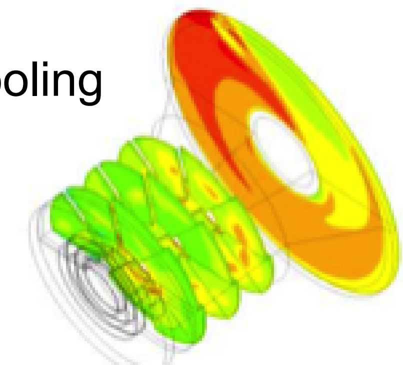
Interconnects



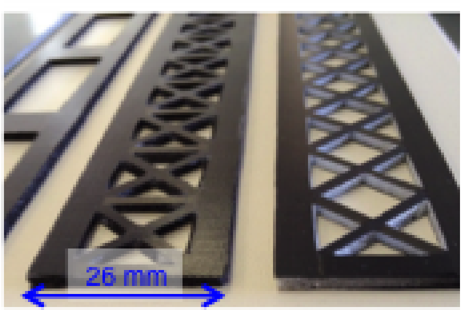
Powering



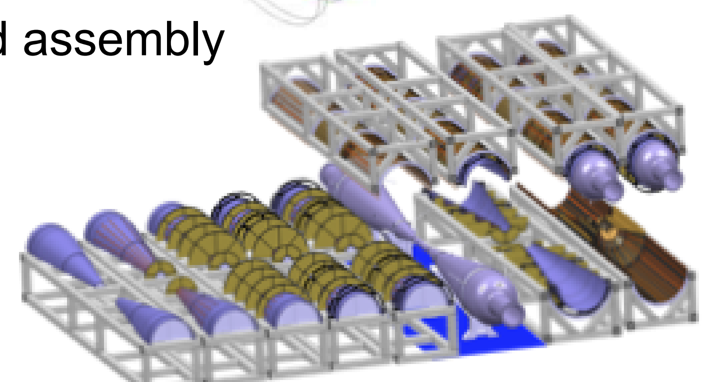
Cooling



Light-weight supports

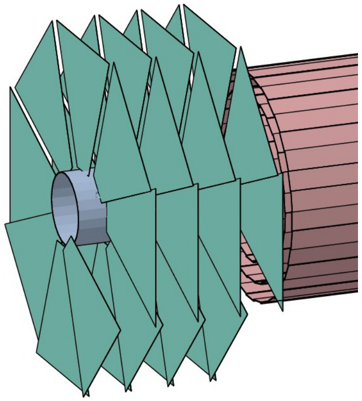


Detector integration and assembly



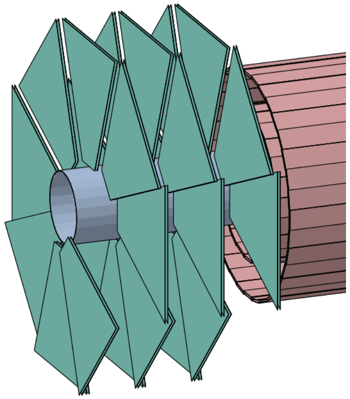
Examples for recent developments → following slides

Detector optimisation: flavour tagging

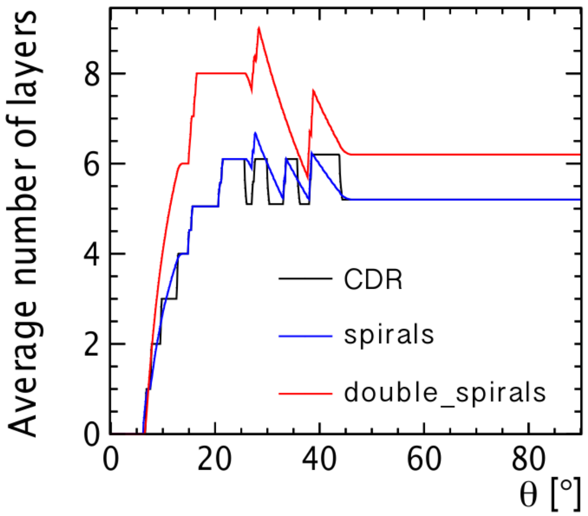


Example: comparison of vertex detector designs based single- or double-sided layers

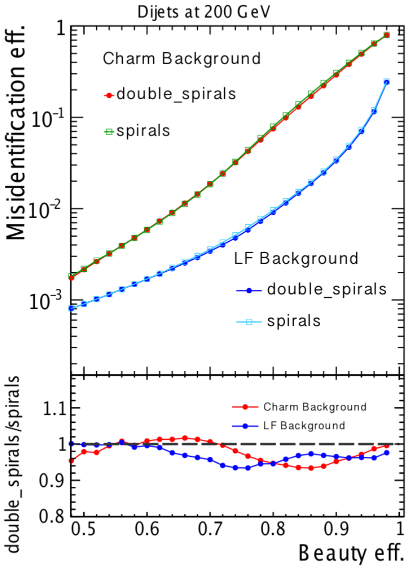
Double-sided layers
(3 in barred and forward)



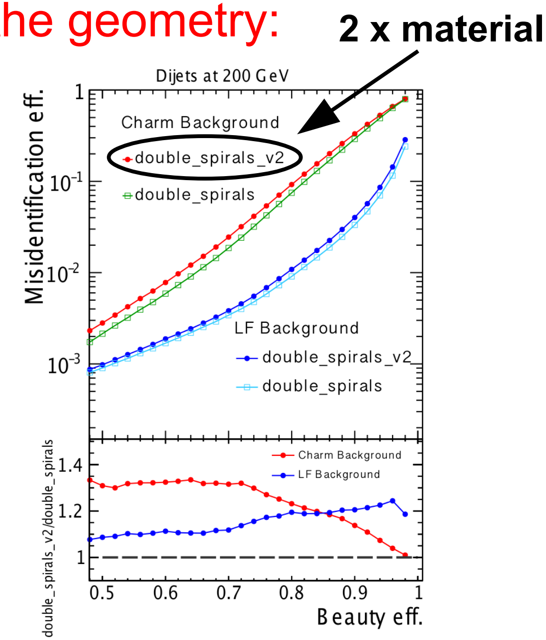
Single-sided layers
(5 in barred, 4 forward)



1.) Similar performance for both layouts:

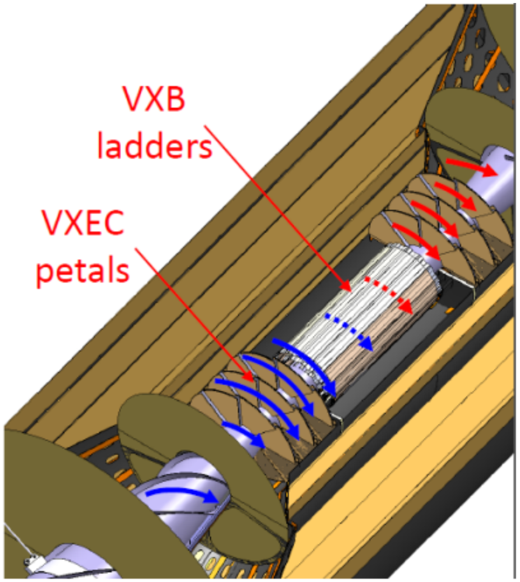


2.) The material budget has a larger impact than the geometry:



Cooling concept

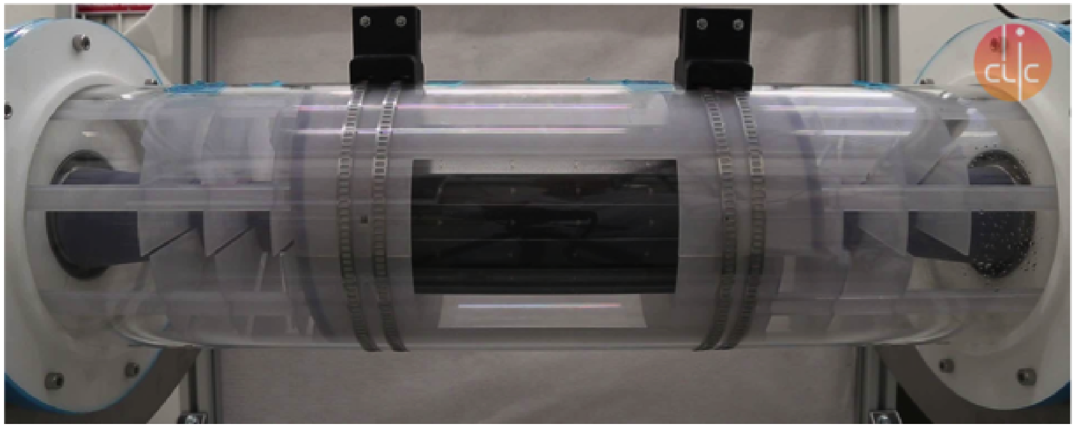
- P ≈ 500 W in vertex detectors
- **Spiral end-cap geometry:**



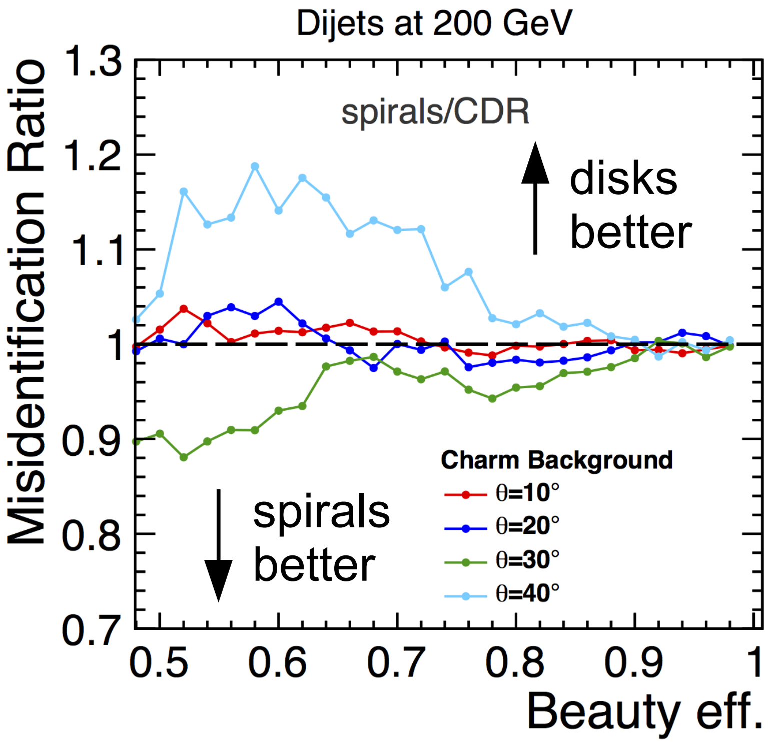
- ANSYS finite element simulation of air-flow cooling → seems feasible

T_{in} = 0º C,
m_{flow} = 20 g/s

- **Mock-up to verify simulations:**



Flavour-tagging performance for spiral and disk geometries: mostly similar

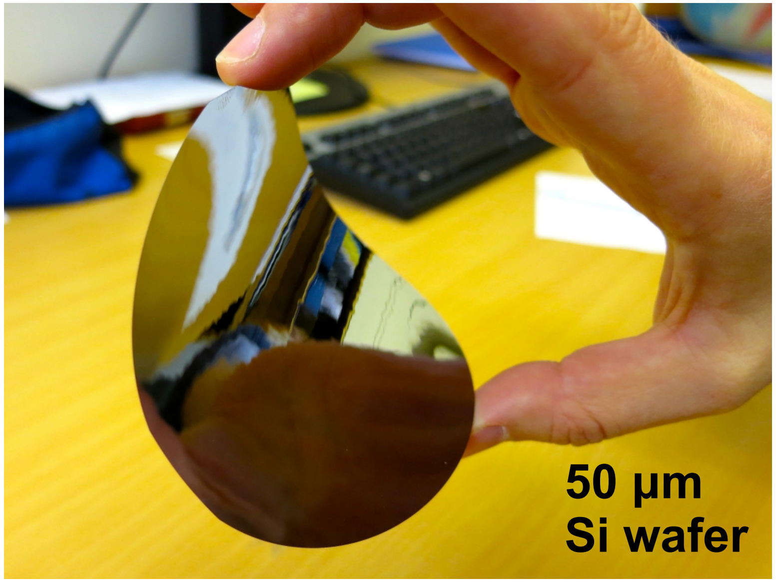


Thin sensor assemblies

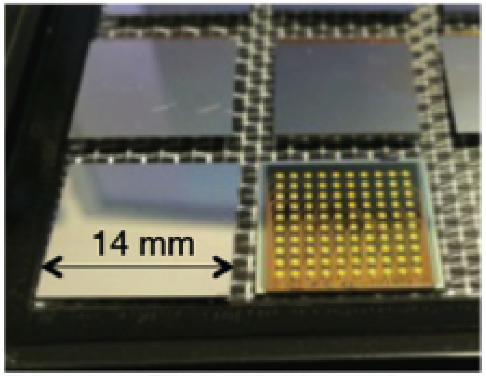
• Focus on hybrid concept: thin depleted sensor + separate readout ASIC

• Ultimate goal: 50 μm sensor on 50 μm ASIC with 25 μm pitch

Through-Silicon-Vias (TSV):
• Vertical electrical connection → no wire bonds
• Chip/sensor assemblies buttable on all sides
• Large active surfaces → less material



Using the Medipix/Timepix readout chip family:
• Timepix: DESY test beam 2013, lab tests CERN, LNLS
• Timepix3: CERN PS test beam 2014
• CLICpix: CCPDv3 (capacitive coupling) in CERN PS & SPS test beams 2014, future bump-bonding trials at SLAC

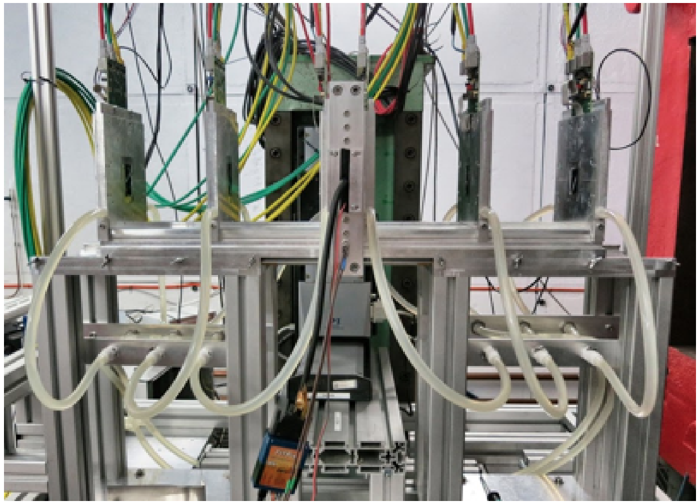


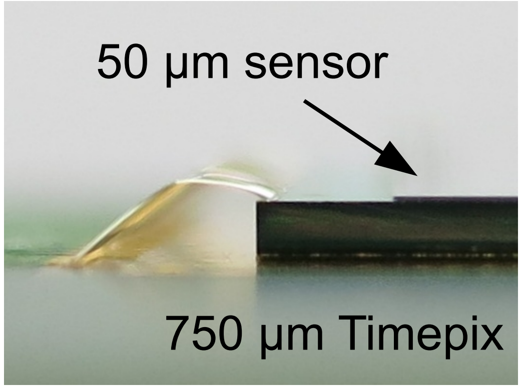
Medipix3RX with TSV (CEA-LETI)

Timepix test beam

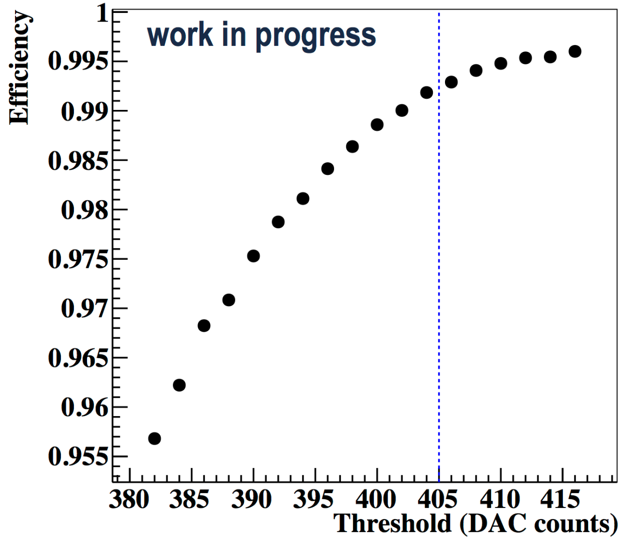
- Thin sensors (50 – 300 µm) bump-bonded to Timepix chips (55 x 55 µm^2 pixel size)

- **Data recorded at DESY:**
  - 5.6 GeV electron beam
  - EUDET telescope

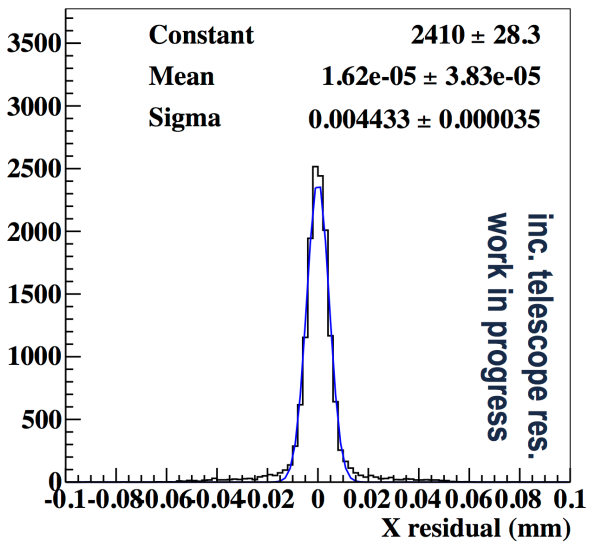




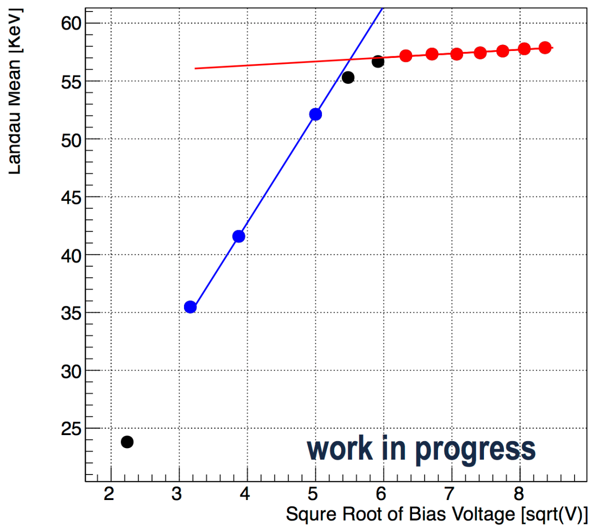
50 µm sensor efficiency: 99.2% at operating threshold



100 µm sensor two-hit cluster resolution: ≈4.5 µm



200 µm sensor depletion voltage: ≈30 V



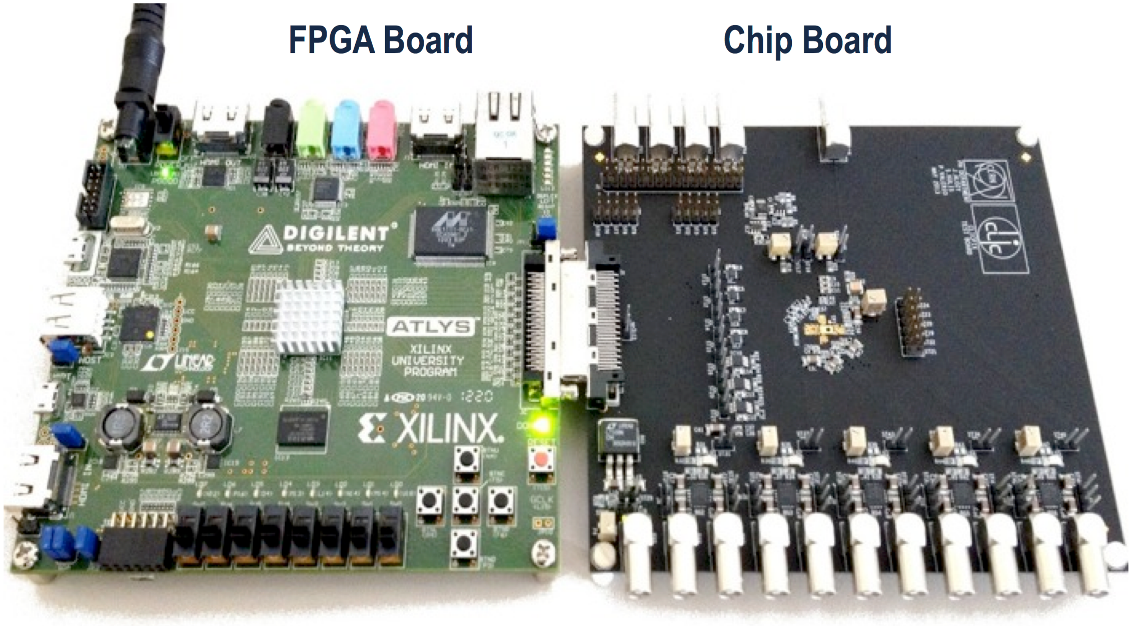
CLICpix ASIC

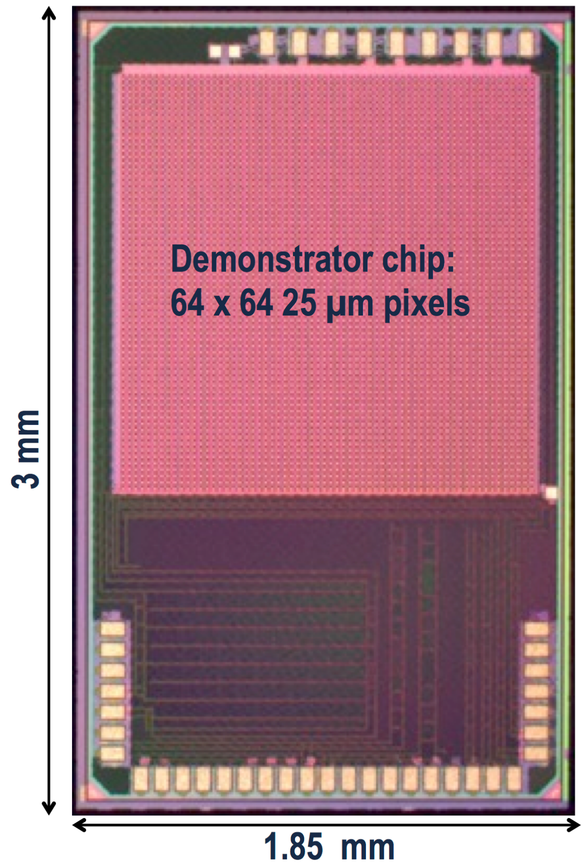
- Commerical 65 nm CMOS technology
- Demonstrator chip with 64 x 64 pixel matrix
- 25 µm pixel pitch
- Simultaneous 4-bit time (TOA)

and 4-bit energy (TOT) measurement per pixel

→ front-end time slicing < 10 ns

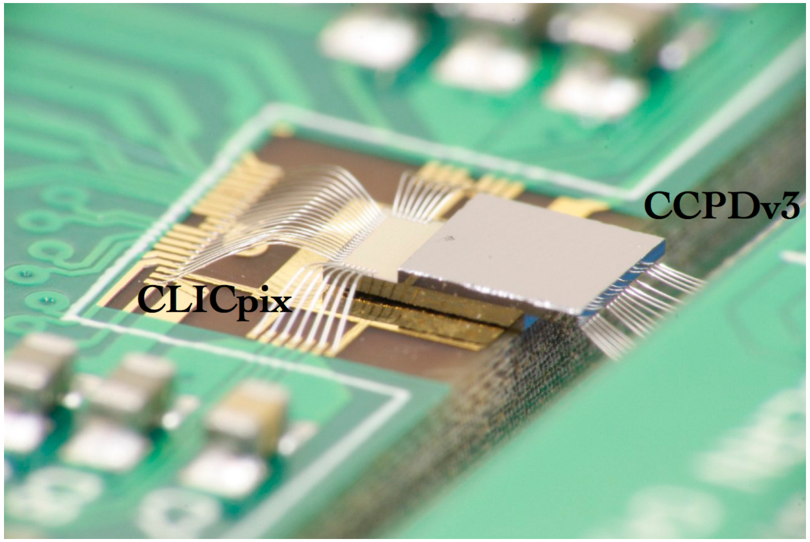
- Allows for power pulsing: $P_{avg} < 50\ mW/cm^2$



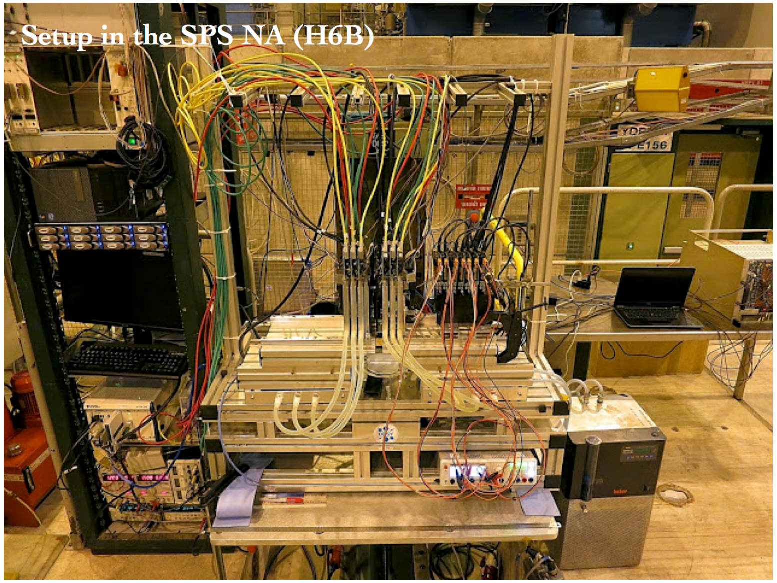


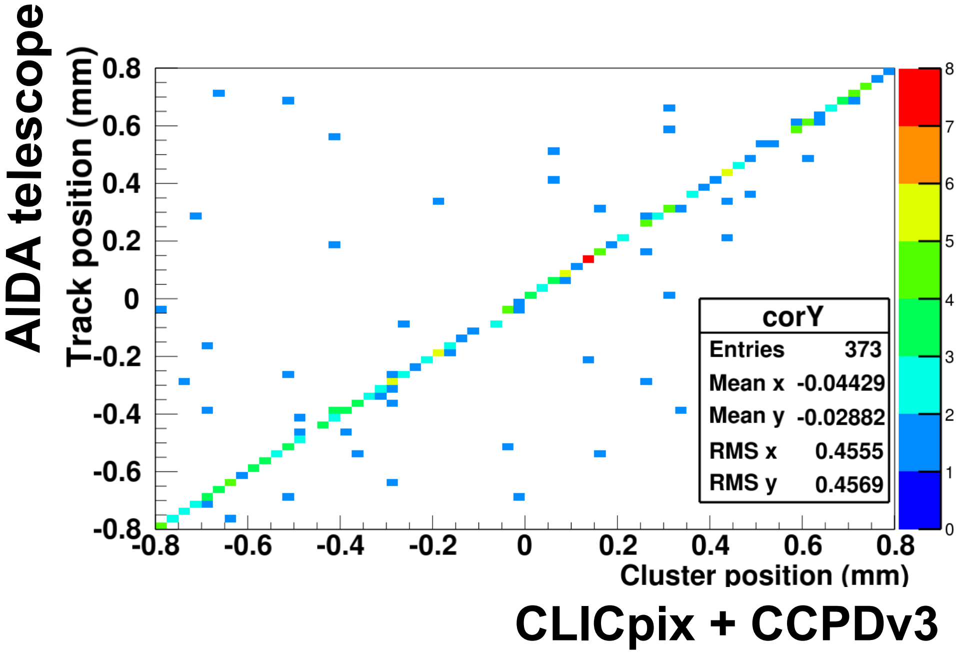
CLICpix test beam

Capacitive coupled pixel detector (CCPv3):
• Active sensor with two-stage aplifier in each pixel
• Implemented in AMS H18 180 nm HV-CMOS process
• Capacitive coupling to CLICpix bond pads through layer of glue



Data taking:
• In October at PS and SPS
• This week again at SPS



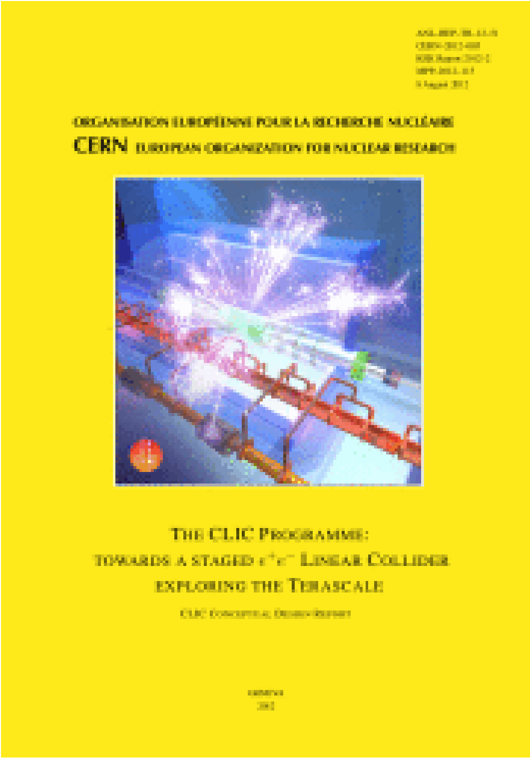


Summary and conclusions

If you want to know more...

CLIC Conceptual Design Report (CDR) Vol. 2:
Physics and Detectors
(mostly at 3 TeV)

arXiv:1202.5940



CLIC CDR Vol. 3:
Staged construction,
SUSY at 1.4 TeV, Z'

arXiv:1209.2543

Snowmass white paper:
Most of the Higgs studies

arXiv:1307.5288
(last update: 01/10/2013)

The CLIC detector and physics study

- Collaboration of 23 institutes from 16 countries
- CERN acts as host laboratory
- More information: http://clicdp.web.cern.ch/

Summary and conclusions

- CLIC is the only mature option for a multi-TeV electron-positron collider

- Very active R&D projects for accelerator and physics/detector

- Energy-staging → optimal for physics:

350 – 375 GeV: precision SM Higgs and top physics
1.4 TeV, 3 TeV: targeted at BSM physics (through direct and indirect measurements), rare Higgs processes

- The energies of the TeV stages will depend on the LHC results

THANK YOU!