BSM and Higgs simulations for CLIC

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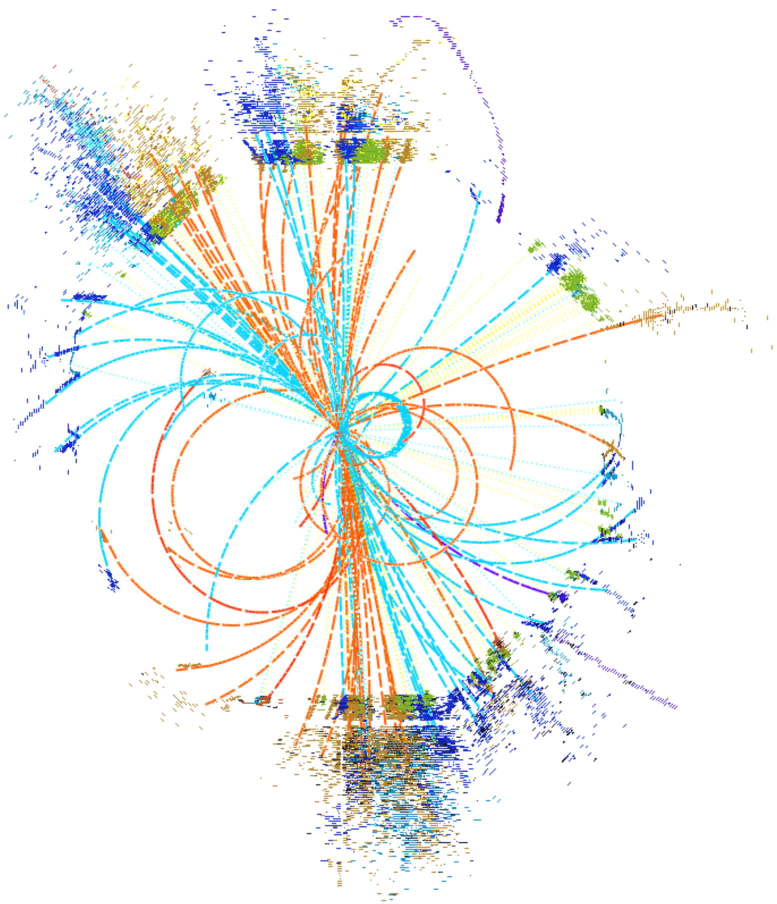
on behalf of the CLICdp collaboration



2nd International WHIZARD Forum
Würzburg, 16-18 March 2015

Overview:

- Precision SM Higgs measurements
- Prospects for BSM physics
- Usage of WHIZARD 2 for CLIC physics benchmark studies

Reminder: 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:

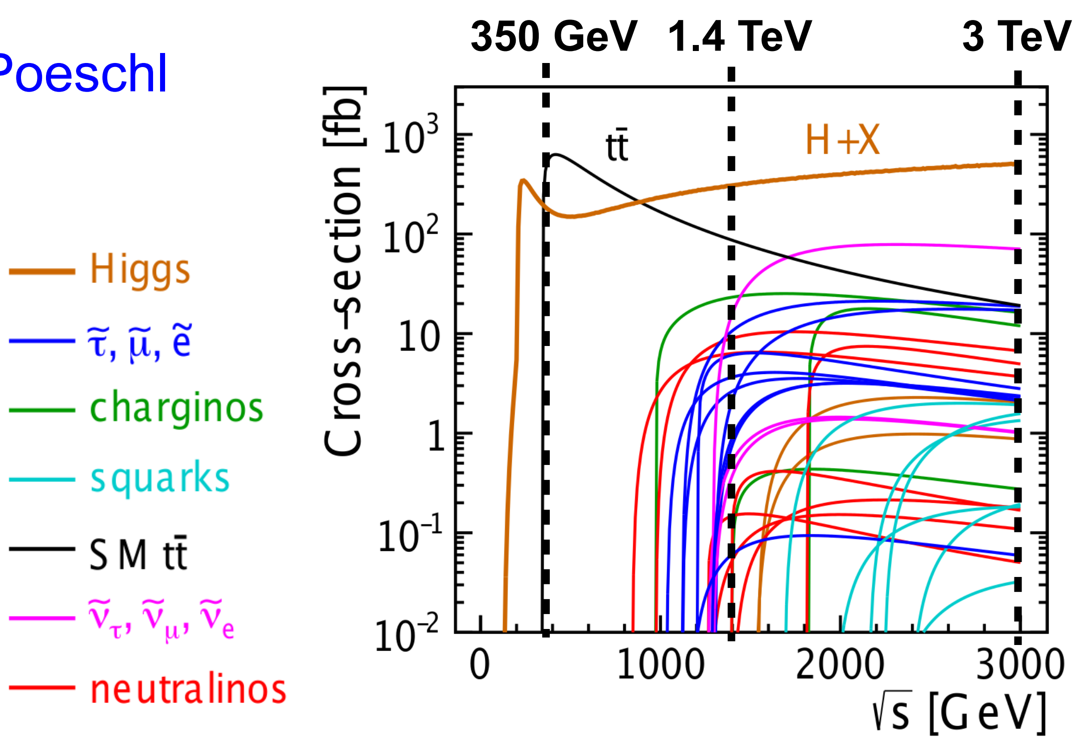
- **<u>Stage 1:</u>** 350 / 380 GeV, 500 fb^{-1}
SM Higgs physics,
$t\bar{t}$ threshold scan → see talk by Roman Poeschl

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

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

(each stage corresponds to 4-5 years)

New CLIC staging baseline
→ see talk by Lucie Linssen

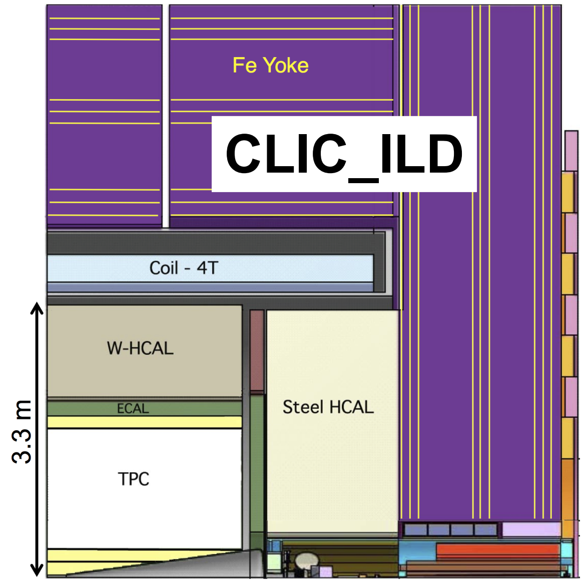


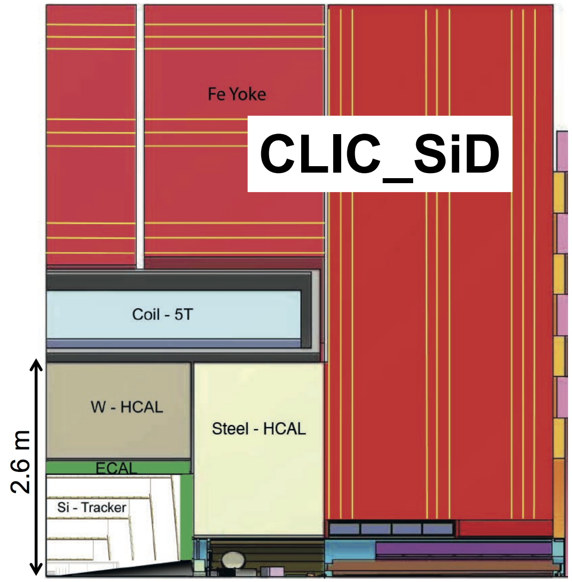
Detector benchmark studies

- Studies in this talk obtained using the CLIC_ILD and CLIC_SiD detector concepts

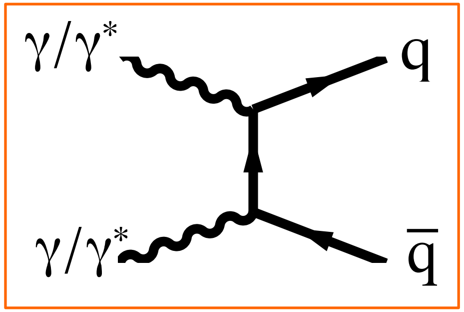
- New CLIC detector concept in preparation

More details → see talk by Lucie Linssen

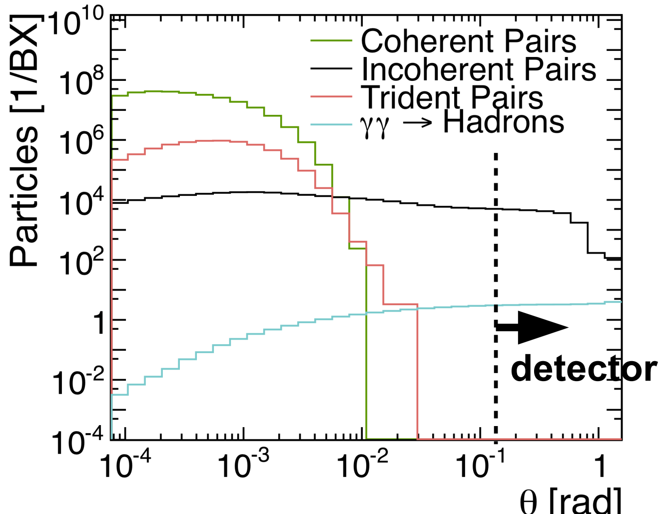




- Pile-up from γγ → hadrons interactions overlaid to the physics events



- 1.3(3.2) events per BX at 1.4(3) TeV
- Suppressed using timing capabilities of the detectors and hadron-collider type jet algorithms



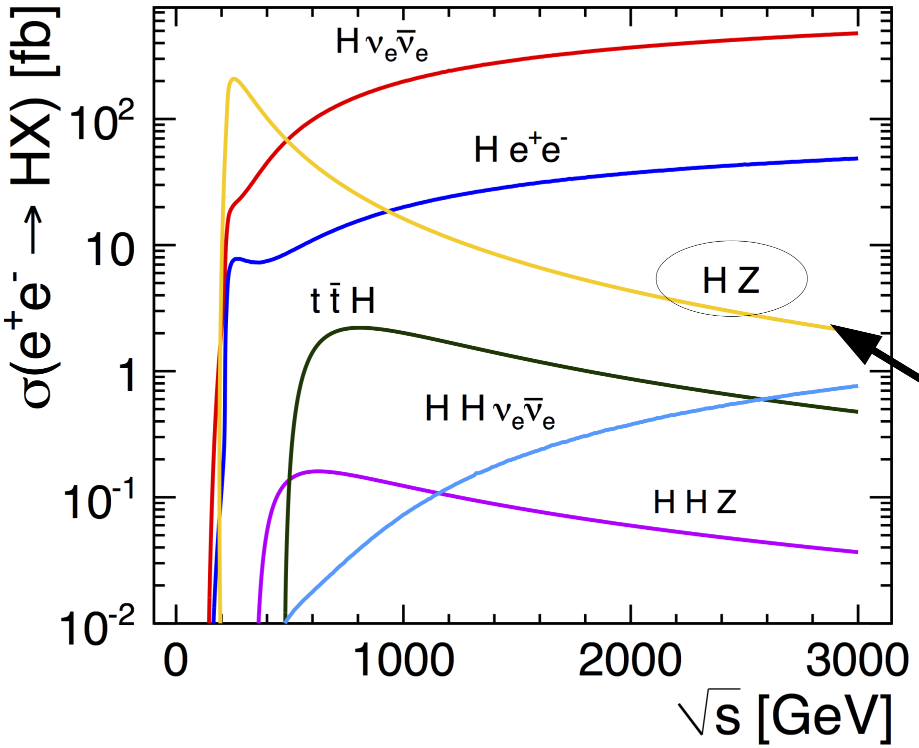
BX = bunch crossing

CLIC Higgs capabilities:

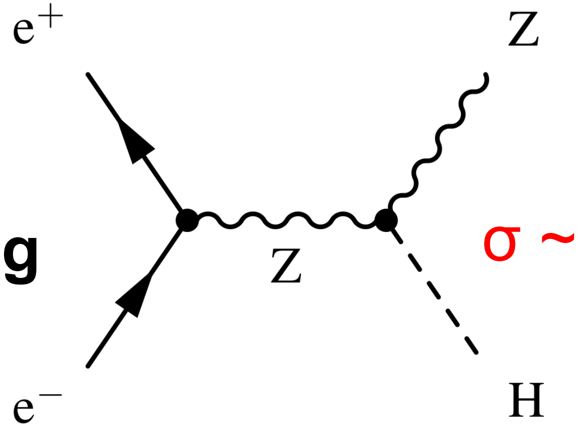
- Single Higgs production
- Processes at high energy
- Combined analysis

[all results as shown at LCWS14, http://lcws14.vinca.rs]

Single Higgs production at CLIC

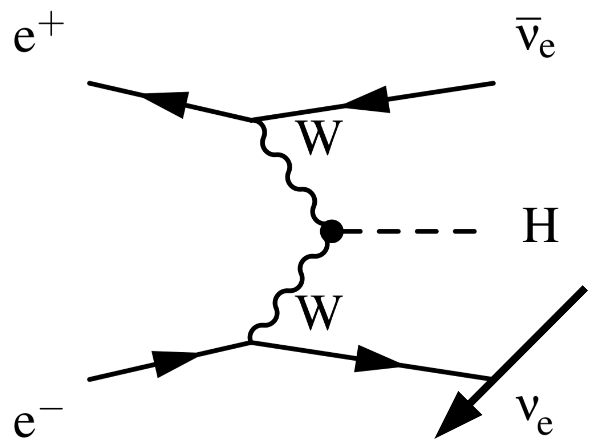


Higgs-strahlung



$\sigma \sim 1/s$

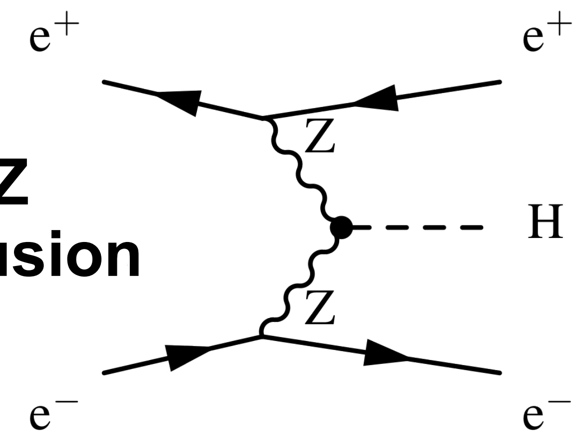
Single Higgs production at CLIC

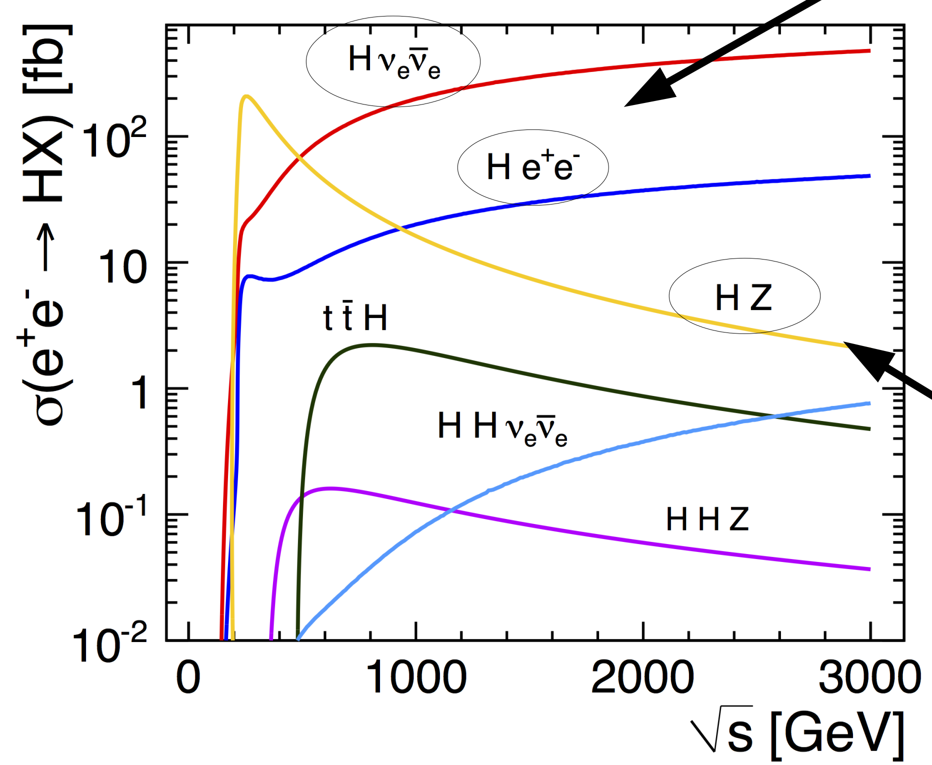


σ ~ log(s)

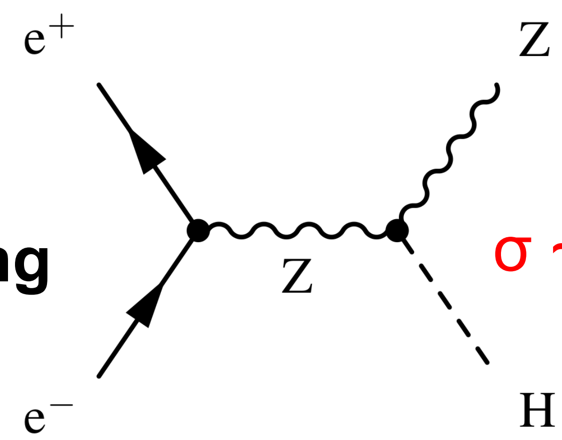
WW fusion

ZZ fusion





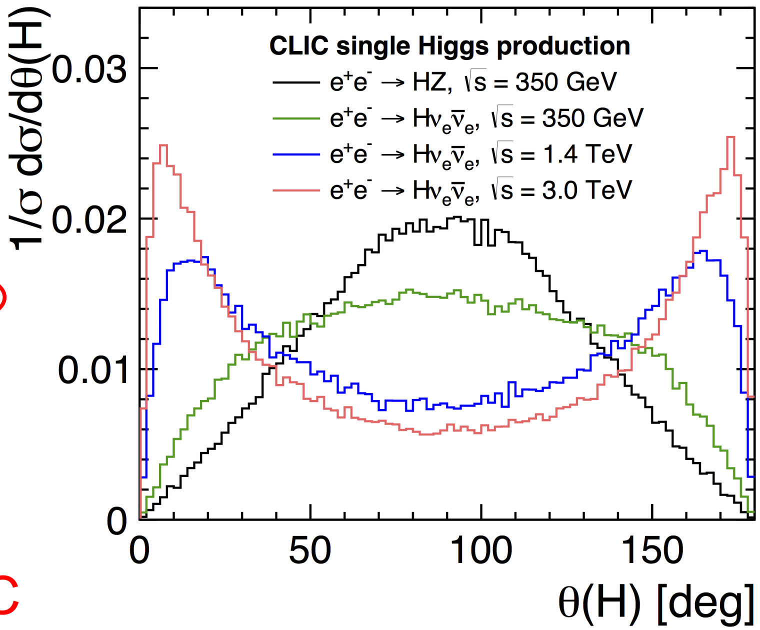
Higgs-strahlung



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



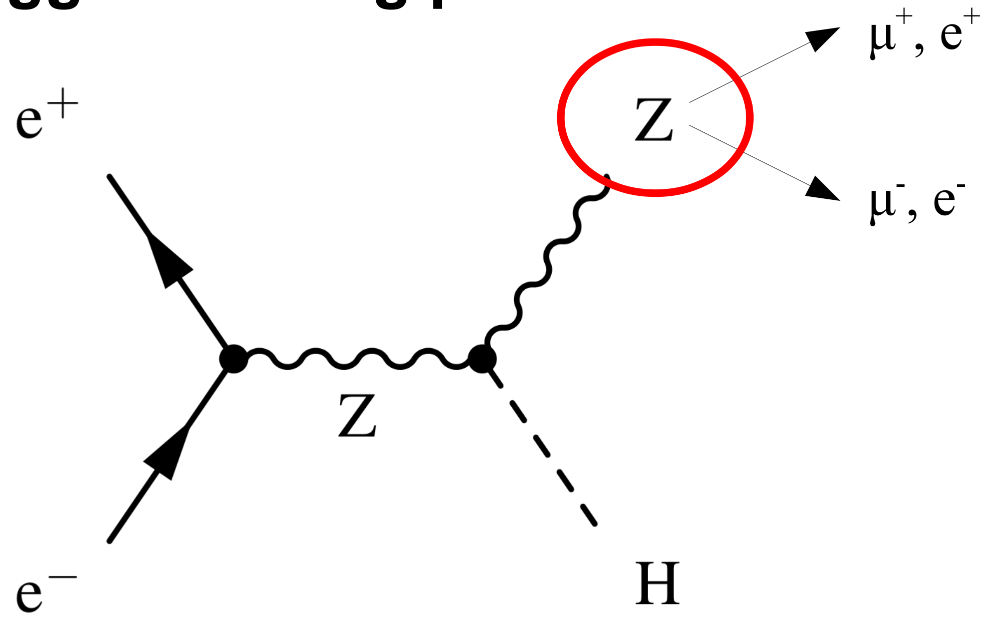
- Large samples of Higgs bosons produced at CLIC
- Measurements at high energy benefit from good detectors in the forward region

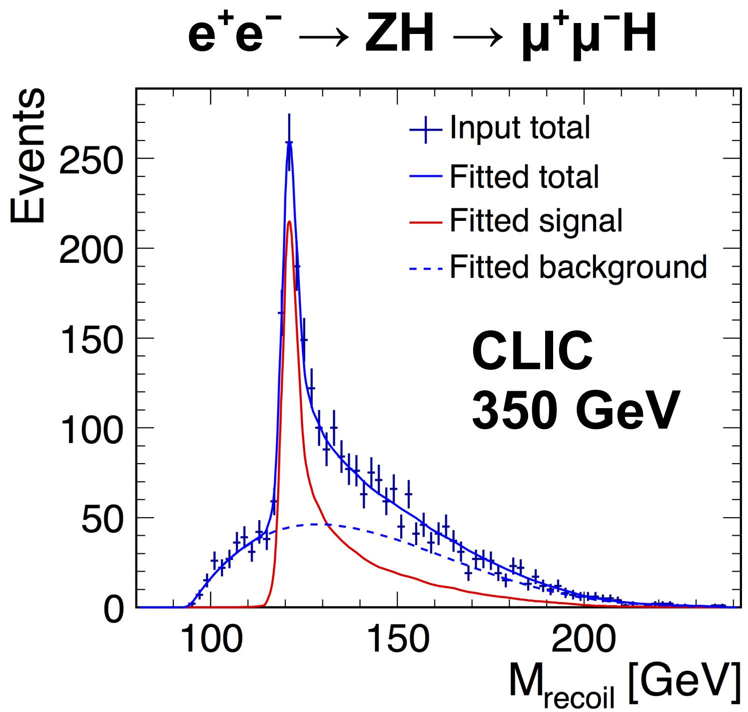
- Benchmark studies assume unpolarised beams

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



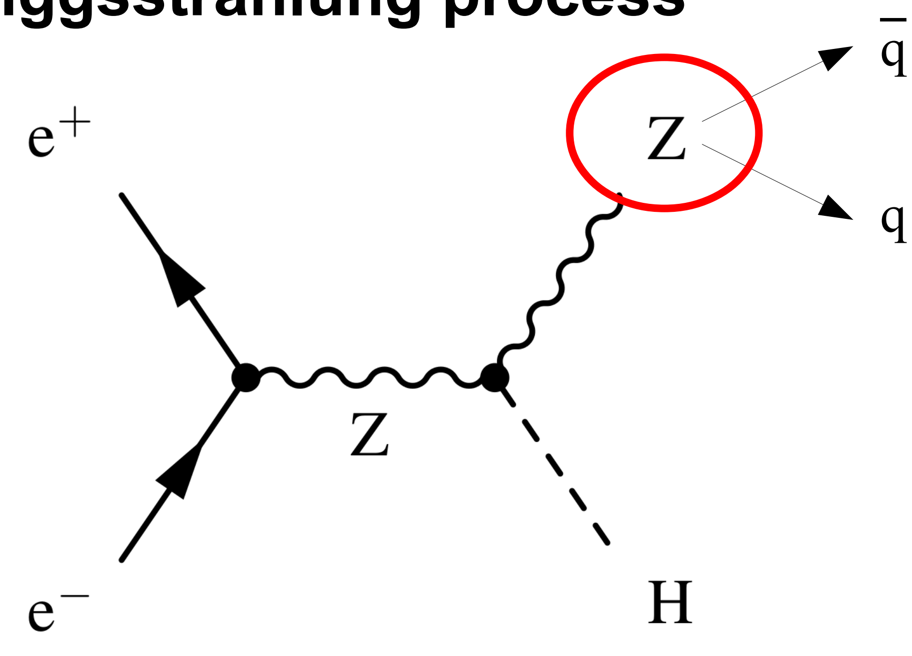


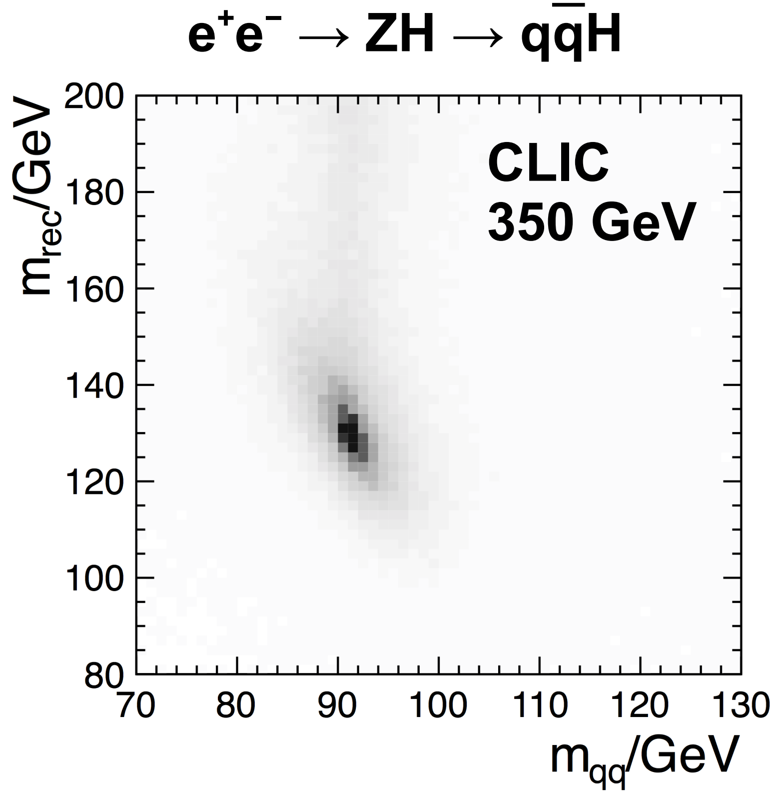
HZ events can be identified from Z recoil mass
→ model independent measurements of the g_{HZZ} coupling

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

Higgsstrahlung at 350 GeV (2)

Higgsstrahlung process

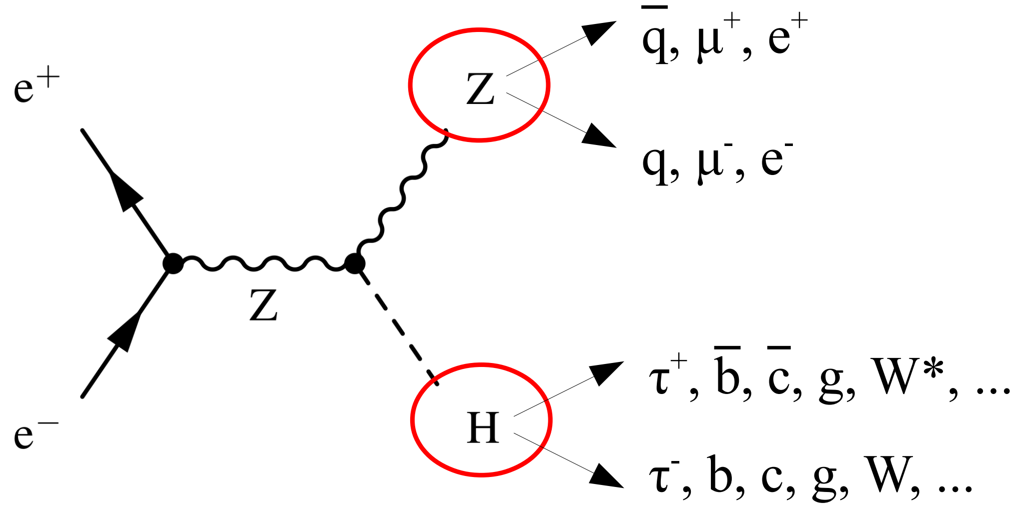




- Substantial improvement using hadronic Z decays
- Challenge: $Z \rightarrow q\bar{q}$ reconstruction may depend on Higgs decay mode
- Even extreme variations of the SM Higgs BRs lead to bias ≤ ½ stat. error

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

σ x BR measurements at 350 GeV



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

Assuming unpolarised beams

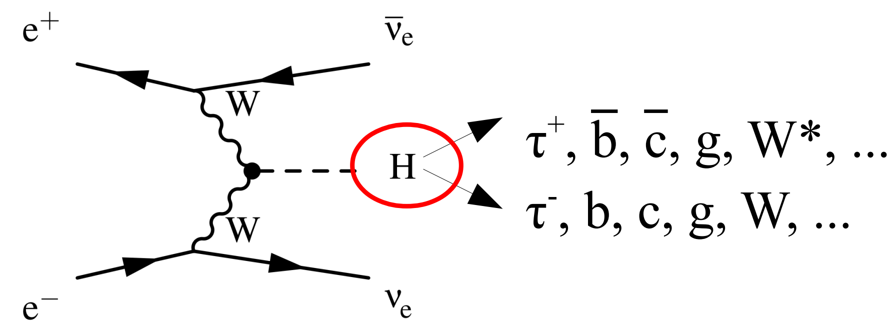
In addition: $BR(H \to inv.) < 0.97\%$ at 90% C.L.

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

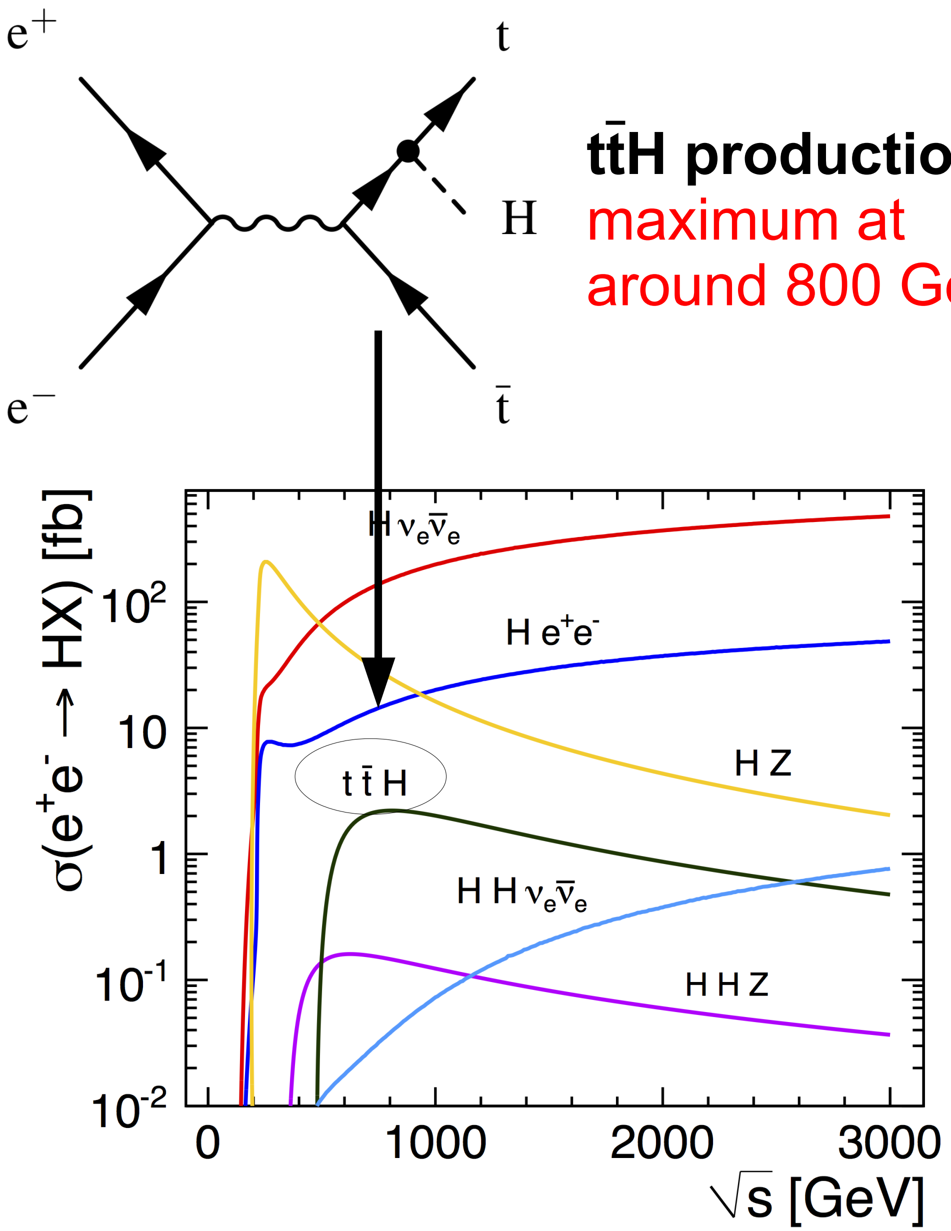
→ Access to rarer decay modes



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

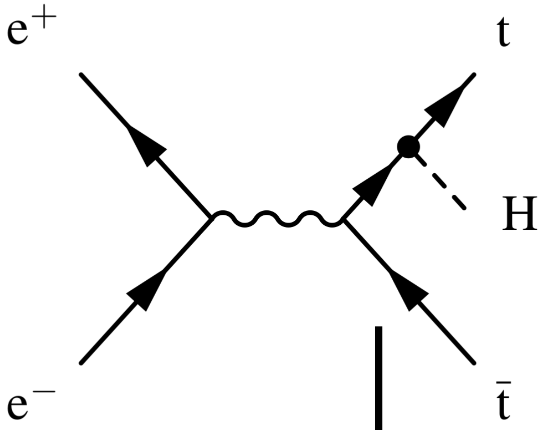
Assuming unpolarised beams

Other processes at higher energy

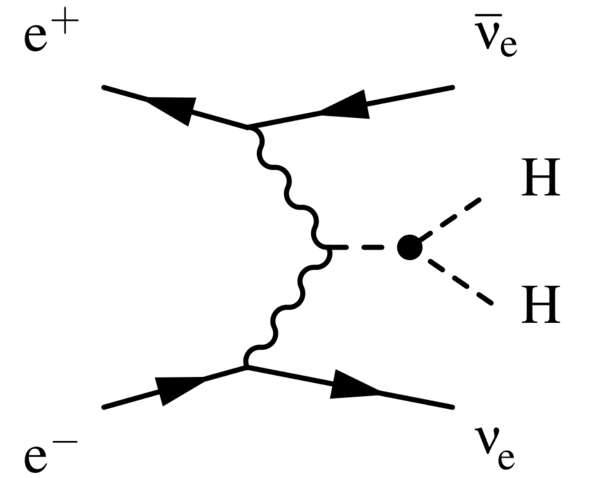


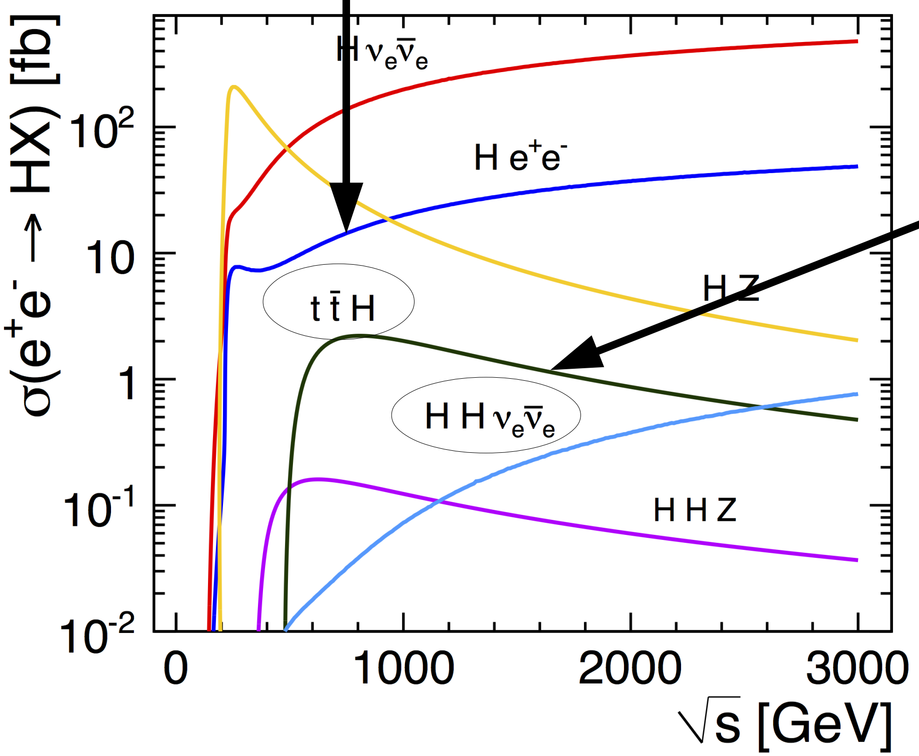
$t\bar{t}$H production:
maximum at around 800 GeV

Other processes at higher energy

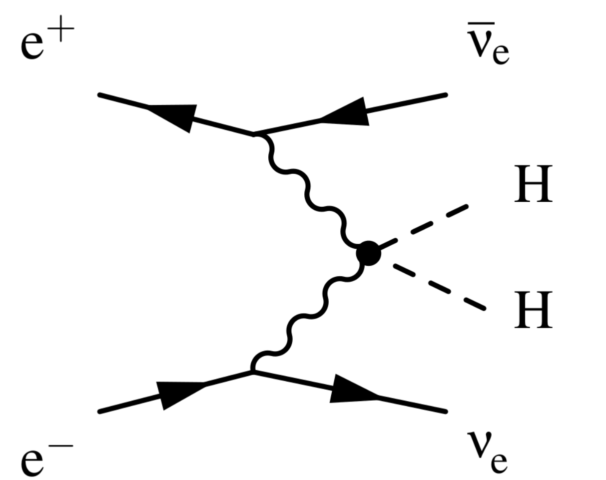


$t\bar{t}H$ production:
maximum at around 800 GeV

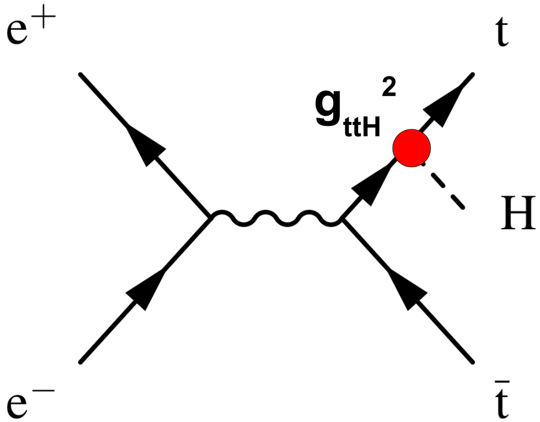




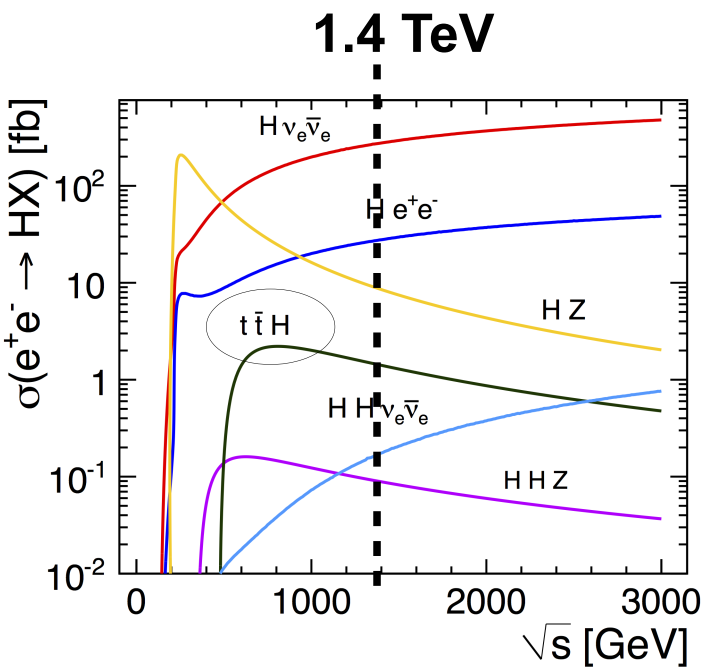
Double Higgs production:
requires high energy



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}

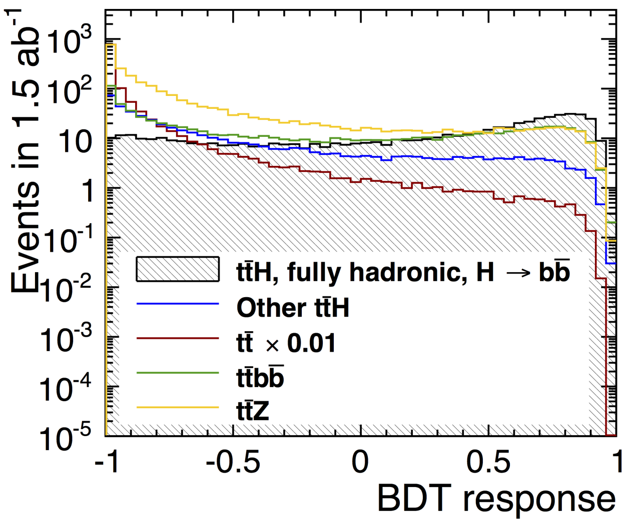


Investigated final states:

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

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

→ Four b-quarks in the final state

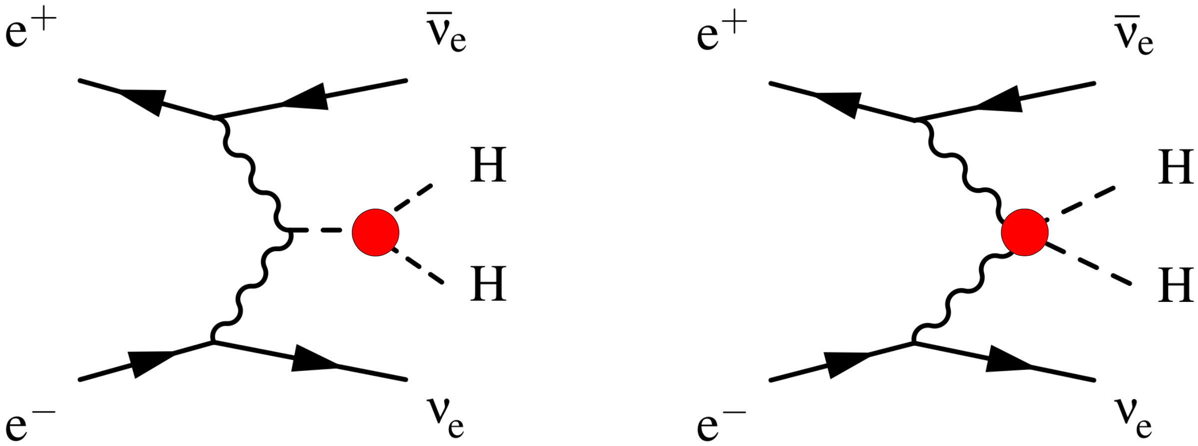


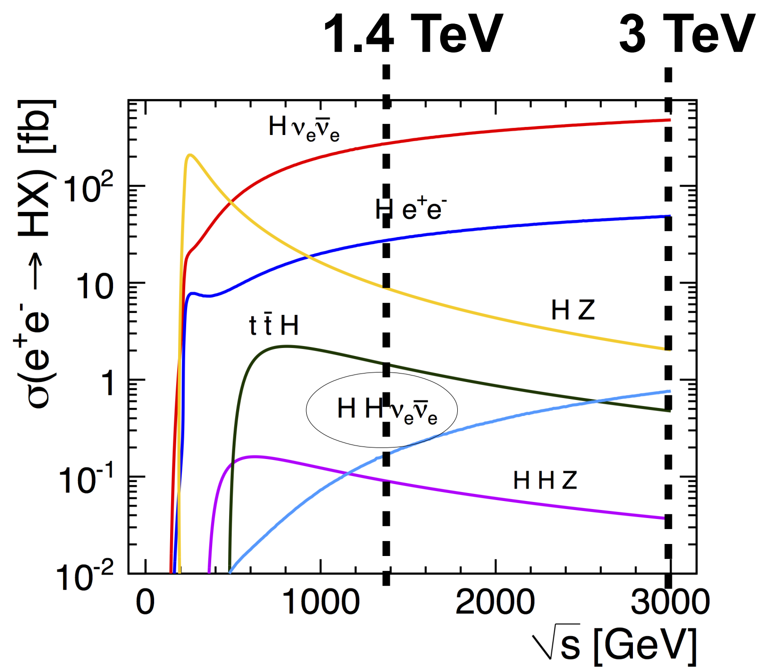
Combination of both final states:

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

→ $\Delta g_{ttH} / g_{ttH} = 4.5\%$

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

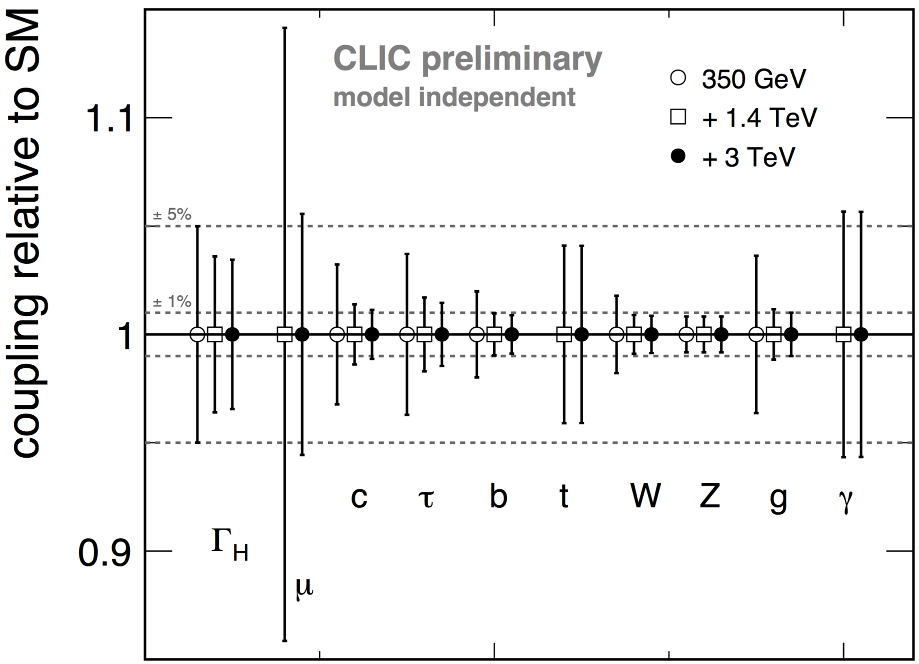
Measurement	1.4 TeV	3 TeV
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
$\Delta(\lambda)$	32%	16%
$\Delta(\lambda)$ for $P(e^-)$ = -80%	24%	12%

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	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$\mathrm{H} \to \mathrm{b\bar{b}}$ mass distribution	m_{H}	tbd	–	–
$\mathrm{H\nu_e\bar{\nu}_e}$	$\mathrm{H} \to \mathrm{b\bar{b}}$ mass distribution	m_{H}	–	40 MeV*	33 MeV*
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{Z} \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{Z} \to \mathrm{q\bar{q}})$	g^2_{HZZ}	1.8%	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	1%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{c\bar{c}})$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hcc}}/\Gamma_{\mathrm{H}}$	5%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{gg})$		6%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \tau^+\tau^-)$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{H\tau\tau}}/\Gamma_{\mathrm{H}}$	6.2%	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{WW}^*)$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{HWW}}/\Gamma_{\mathrm{H}}$	2%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{ZZ}^*)$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{HZZ}}/\Gamma_{\mathrm{H}}$	tbd	–	–
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	3%†	0.3%	0.2%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{c\bar{c}})$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{Hcc}}/\Gamma_{\mathrm{H}}$	–	2.9%	2.7%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{gg})$		–	1.8%	1.8%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \tau^+\tau^-)$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{H\tau\tau}}/\Gamma_{\mathrm{H}}$	–	4.2%	tbd
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mu^+\mu^-)$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{H\mu\mu}}/\Gamma_{\mathrm{H}}$	–	38%	16%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \gamma\gamma)$		–	15%	tbd
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{Z}\gamma)$		–	42%	tbd
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{WW}^*)$	$g^4_{\mathrm{HWW}}/\Gamma_{\mathrm{H}}$	tbd	1.4%	0.9%†
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{ZZ}^*)$	$g^2_{\mathrm{HWW}} g^2_{\mathrm{HZZ}}/\Gamma_{\mathrm{H}}$	–	3%†	2%†
$\mathrm{He^+e^-}$	$\sigma(\mathrm{He^+e^-}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	–	1%†	0.7%†
$\mathrm{t\bar{t}H}$	$\sigma(\mathrm{t\bar{t}H}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_{\mathrm{Htt}} g^2_{\mathrm{Hbb}}/\Gamma_{\mathrm{H}}$	–	8%	tbd
$\mathrm{HH\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{HH\nu_e\bar{\nu}_e})$	g_{HHWW}	–	7%*	3%*
$\mathrm{HH\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{HH\nu_e\bar{\nu}_e})$	λ	–	32%	16%
$\mathrm{HH\nu_e\bar{\nu}_e}$	with -80% e^- polarization	λ	–	24%	12%

*: preliminary
†: estimated

Putting it all together

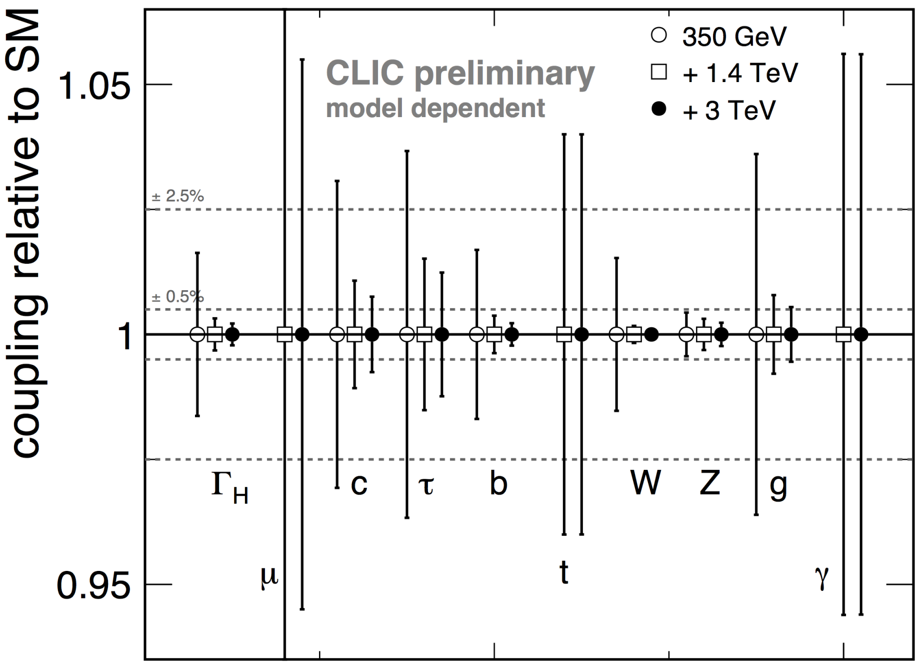


Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.8 %	0.9 %	0.9 %
g_{Hbb}	2.0 %	1.0 %	0.9 %
g_{Hcc}	3.2 %	1.4 %	1.1 %
$g_{H\tau\tau}$	3.7 %	1.7 %	1.5 %
$g_{H\mu\mu}$	–	14.1 %	5.6 %
g_{Htt}	–	4.1 %	$\leq$ 4.1 %
$g^{\dagger}_{Hgg}$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

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

Sub-percent precisions at high energy

→ Results strongly dependent on fit assumptions

What's next for Higgs physics?

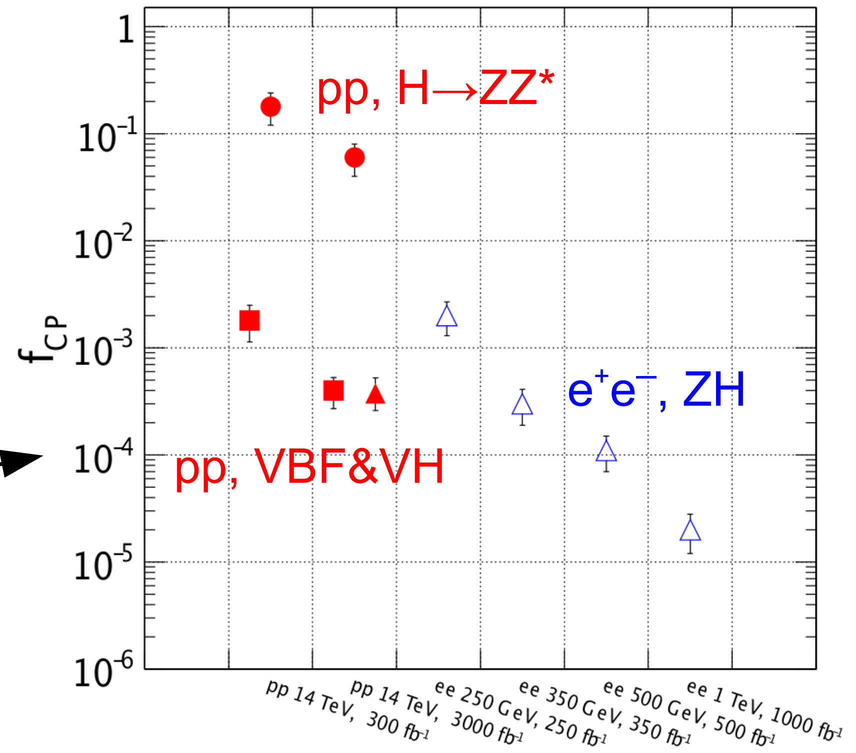
• **Single Higgs production:** addressing a few channels not covered so far ($e^+e^- \rightarrow H\nu_e\bar{\nu}_e \rightarrow WW^*\nu_e\bar{\nu}_e$ at 350 GeV, $H \rightarrow \gamma\gamma$ at 3 TeV, ZZ fusion at 3 TeV)

• **Reanalysis of double Higgs production:** add the $HH \rightarrow b\bar{b}WW^*$ final state (40% more events compared to $HH \rightarrow b\bar{b}b\bar{b}$ alone)

• **Looking at differential distributions:**
example: CP properties of the Higgs boson

- using $t\bar{t}H$ events:
extension of top Yukawa coupling study

- using WW and ZZ fusion events:
large statistics at CLIC promising



Snowmass Higgs WG report, arXiv:1310.8361

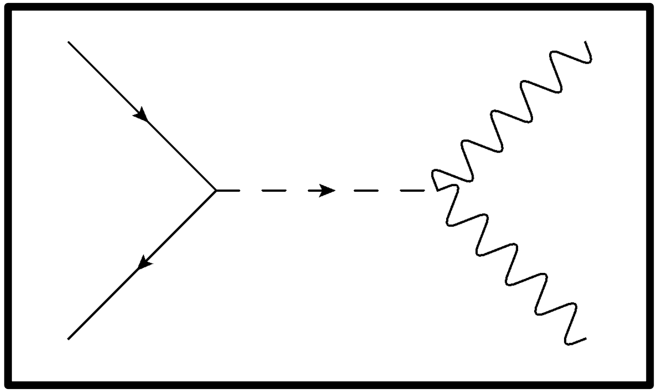
Prospects for BSM physics:

- Direct searches (example: SUSY)
- Sensitivity of precision measurements

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

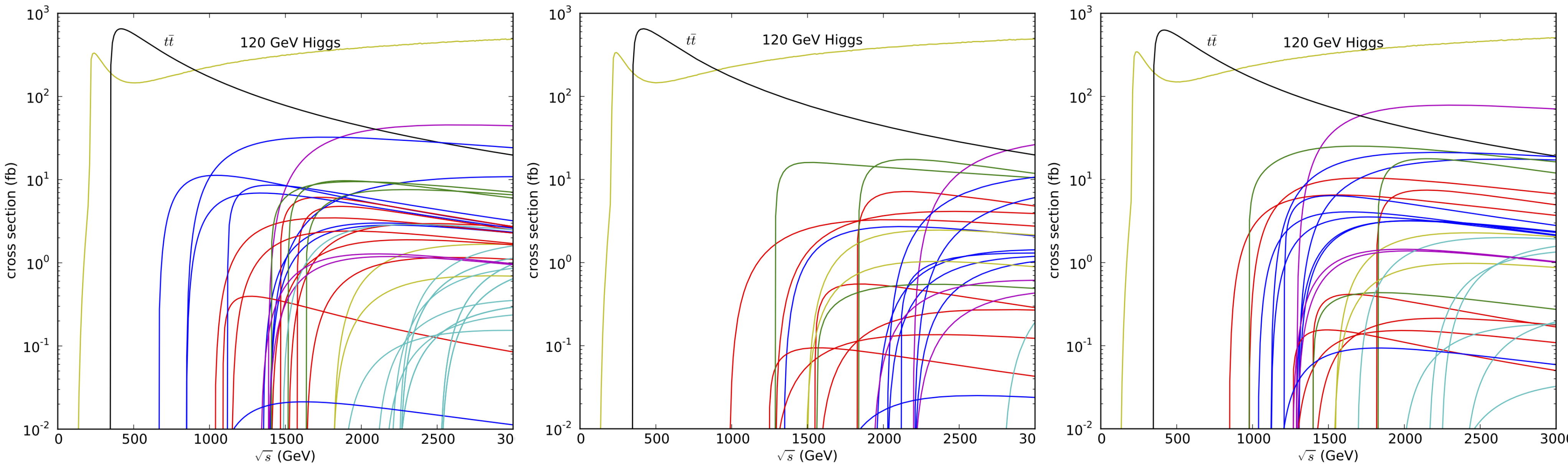


Many examples of SUSY particle production studied for CLIC CDR

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

One of the priorities for future benchmarking studies

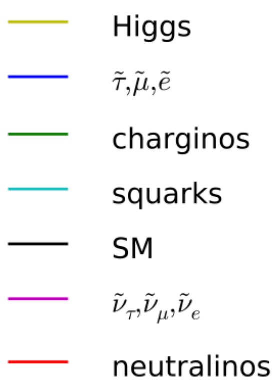
Investigated SUSY models



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

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

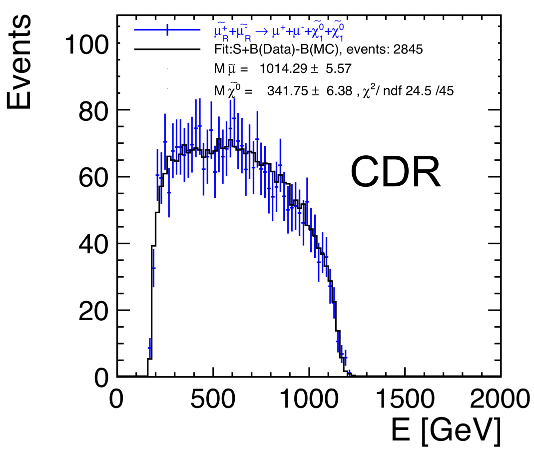
CDR Model III, 1.4 TeV:
- Smuons, selectrons
- Staus
- Gauginos



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

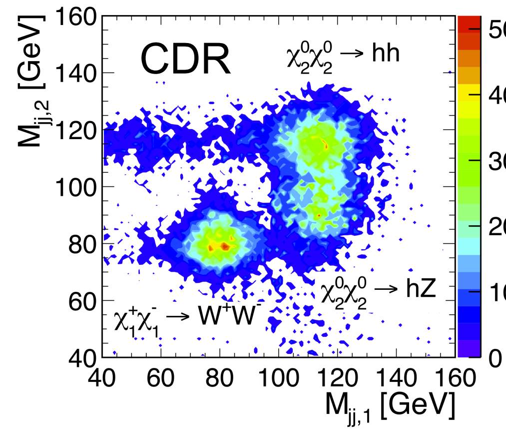
Reconstruction of SUSY particles

Endpoints of energy spectra:



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

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



Jet reconstruction

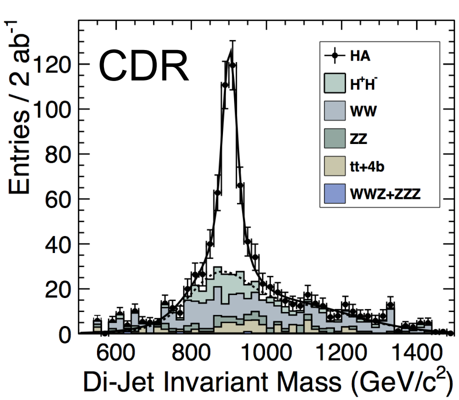
Precision on the measured gaugino masses (few hundred GeV): 1 - 1.5%

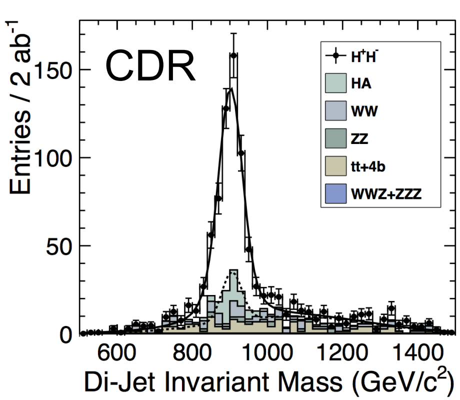
$$e^+e^- \rightarrow \tilde{\chi}_1^+\,\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\,\tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow hh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow Zh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

Complex final states:

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

≈0.3% precision on hevay Higgs masses



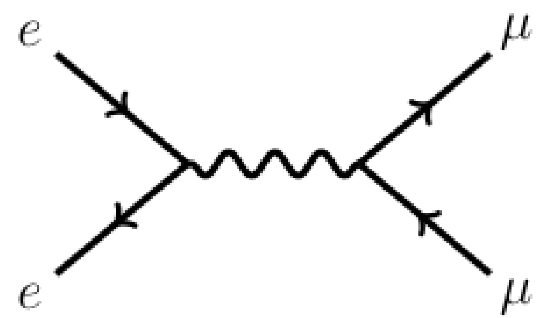


Summary of the SUSY studies

$\sqrt{s}$ (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%

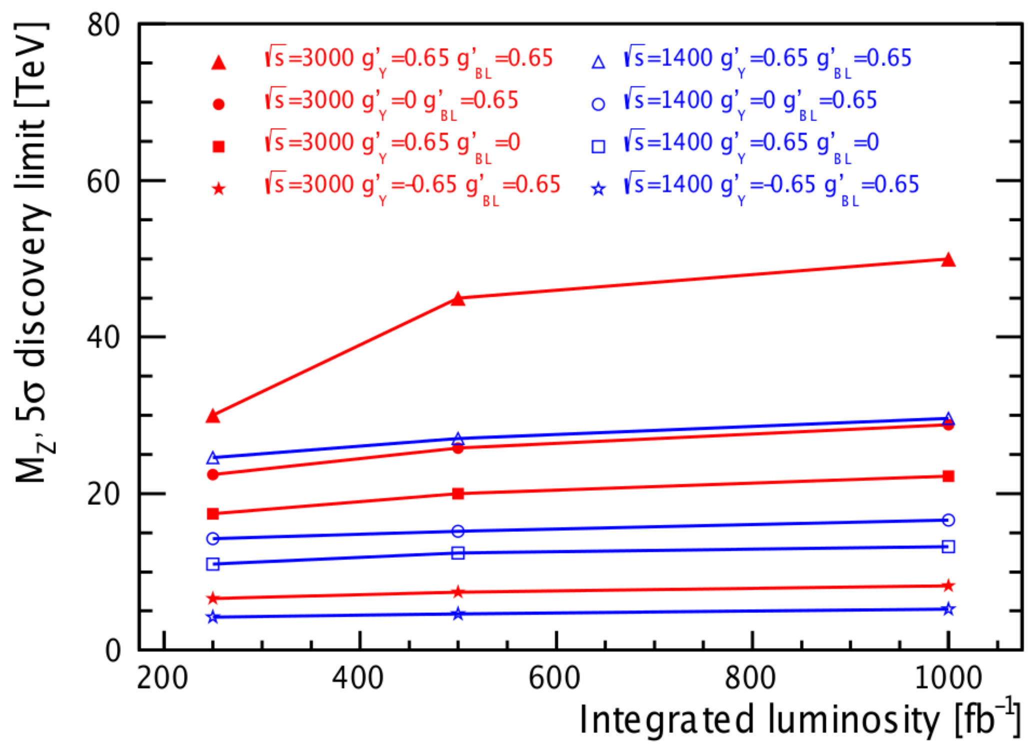
Precision studies of $e^+e^- \rightarrow \mu^+\mu^-$

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



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

($\pm$80% e^- polarisation)



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

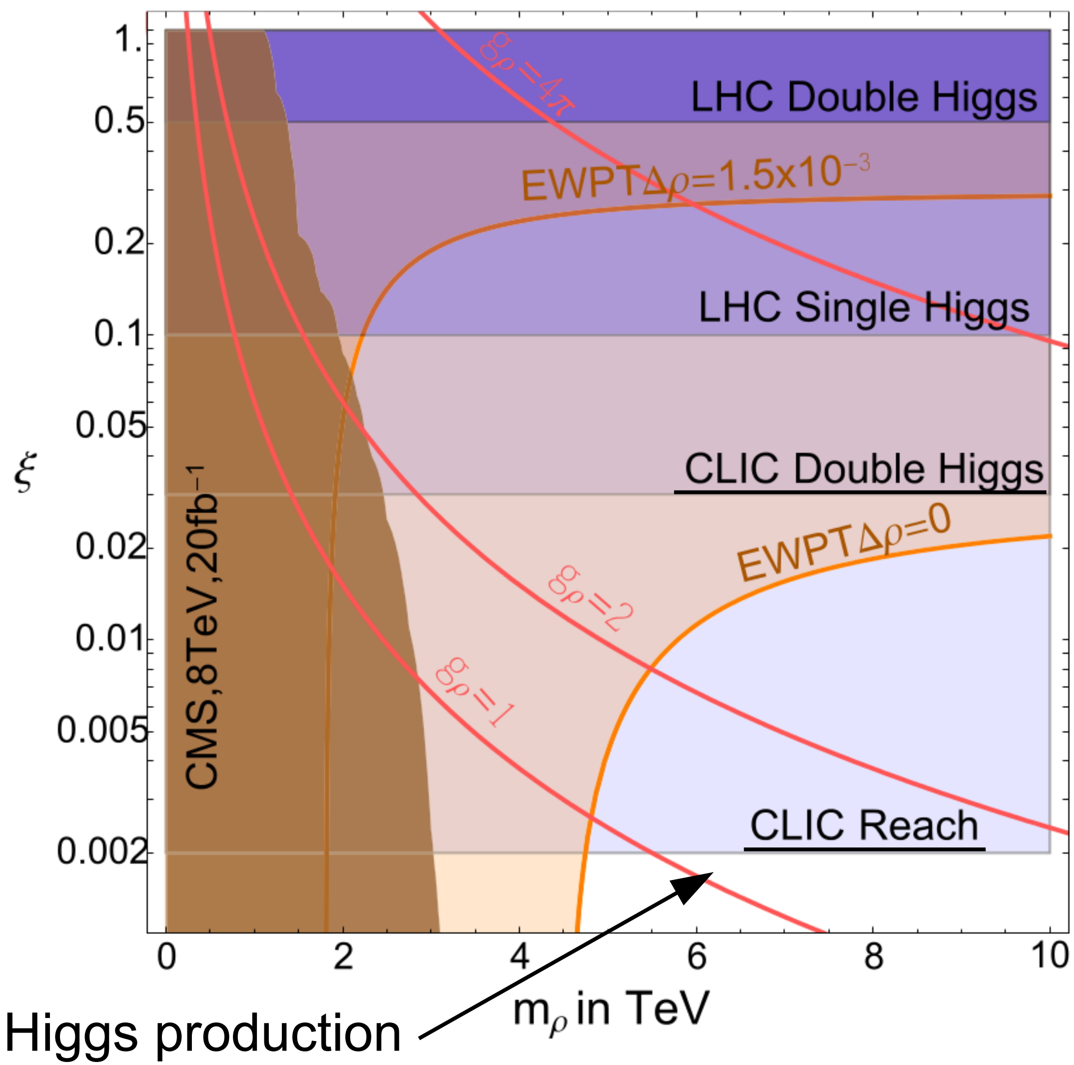
Otherwise:
Discovery reach up to tens of TeV
(depending on the couplings)

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

What's next for BSM?

- **Interesting SUSY signatures not yet studied for CLIC:**

  1.) Gauginos/Higgsinos with small mass splittings
  → Main signal: γ + missing energy + soft particles
  (challenging in the presence of beam-induced backgrounds)
  2.) Top squark production
  e.g. $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ → boosted top quarks

- **Model-independent searches for Dark Matter**
using the γ + missing energy final state

- **Higher-dimensional effective operators**

- **Hidden sector searches, more on compositeness, weakly interacting exotica, …**

Crucial: need to be ready to respond to theoretical interpretation of new LHC data

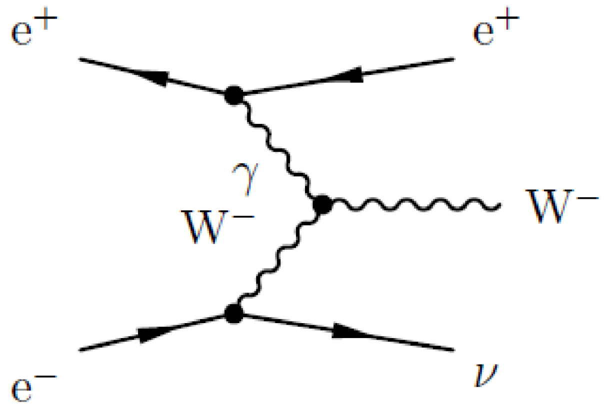
Precision top and EW as tools for BSM

Precision top measurements:

- So far focussed on top mass at lower energies (350 GeV and 500 GeV)
- Explore potential of $t\bar{t}$ events to probe for new physics, examples:
  - A_{FB}^{t} (and A_{FB}^{b})
  - top quark couplings to γ, W and Z
  - Search for FCNC top decays
- V_{tb} from $e\gamma \rightarrow tb\nu_e$ at high energy

Triple and quartic gauge couplings using $e^+e^- \rightarrow W^+W^-$ ($\nu\bar{\nu}$/e^+e^-):
Important to choose parametrisation comparable to other studies/experiments!

W boson mass determination at high energy:
Large samples of single W events produced at high-energy CLIC



Usage of WHIZARD 2 for CLIC physics studies

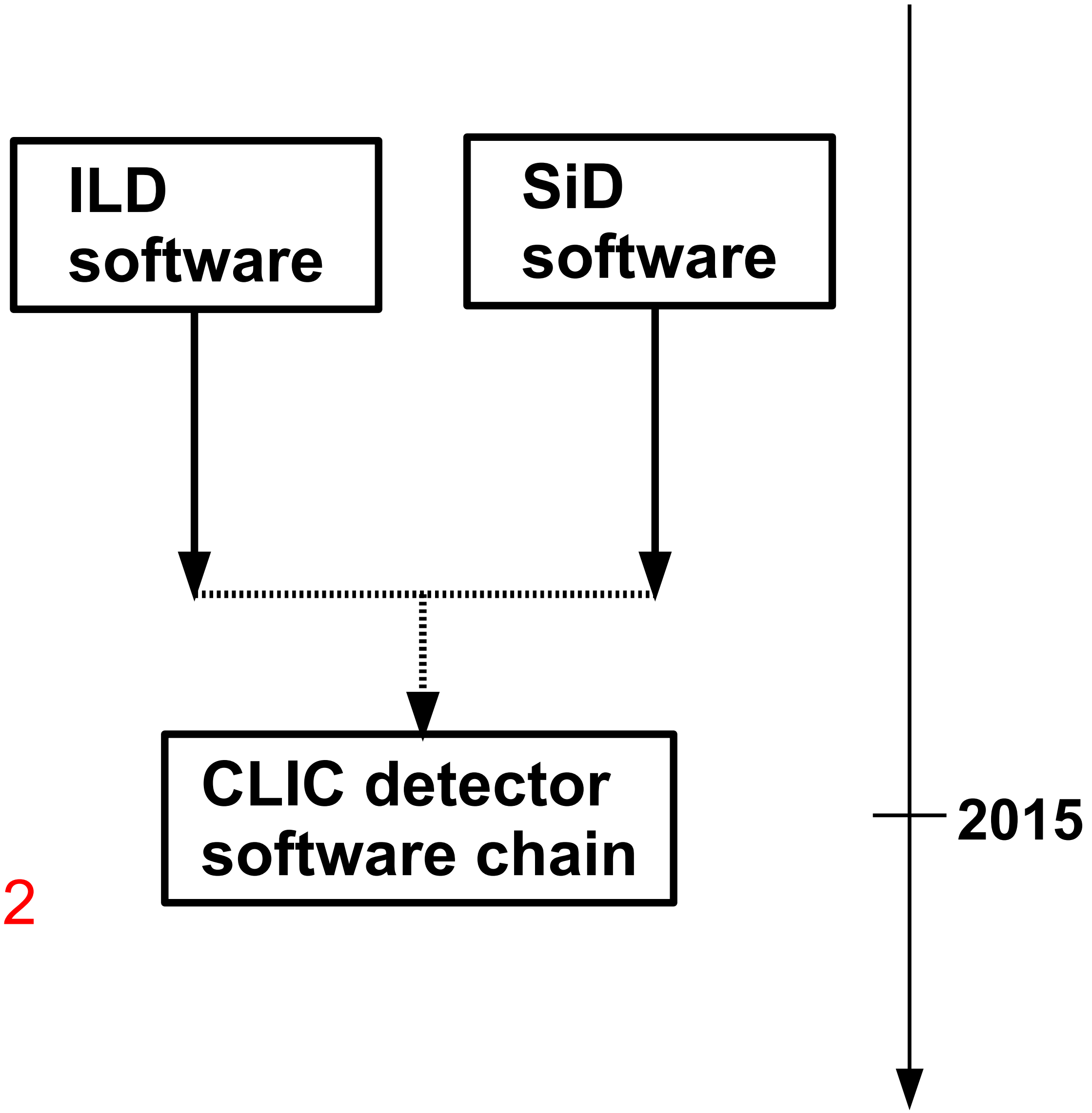
[most of the results shown on the previous slides were obtained using WHIZARD 1.95]

Future detector model and software chain

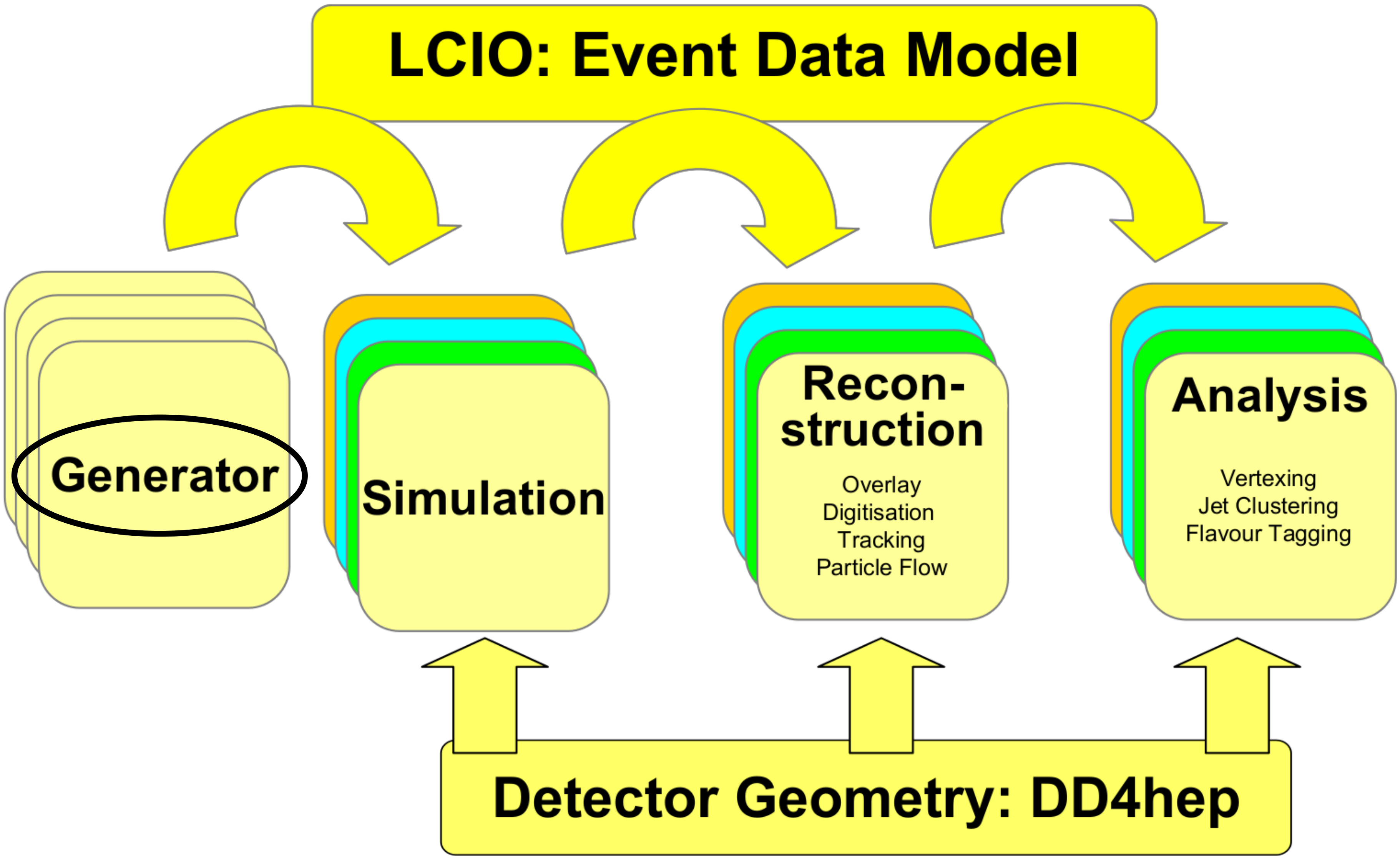
• All current benchmarks are performed either for the CLIC_ILD or the CLIC_SiD detector model

• **New detector concept optimised for CLIC:** move to single software chain in the future

• **On the same time scale:** WHIZARD 1.95 → WHIZARD 2.2



Future software chain



Technical issues

Needed output formats:

- stdhep (for compatibility with CDR software chain)
- LCIO (input for simulation of new detector model)

Hadronisation by PYTHIA 6.4 as integrated in WHIZARD 2

Correlated spectra for lepton and photon beams:

- Reading beam events not convenient for mass production
- The plan is to use parametrisation provided by CIRCE2

Interface WHIZARD 2 to ILCDIRAC production system:

- Will be done in the near future

Summary and conclusions

Summary and conclusions

- 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 production processes and decays

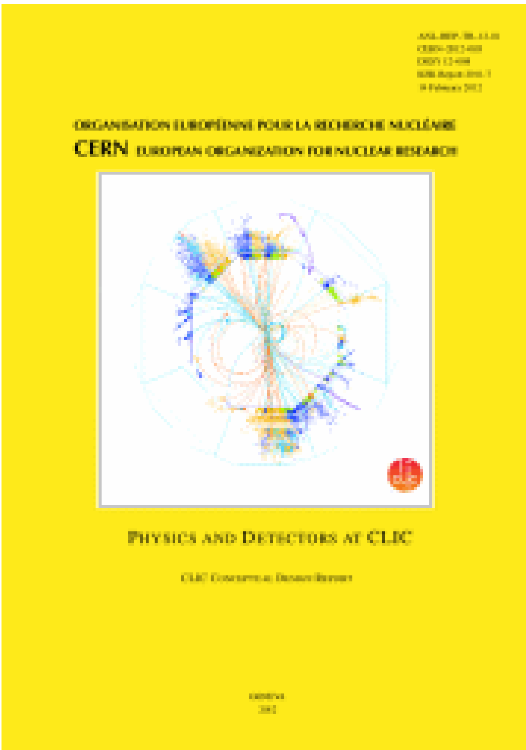
- CLIC operated at high-energy (1.4 and 3 TeV) provides significant discovery potential for BSM phenomena through direct and indirect searches

- Many more studies started / will start soon: also on BSM sensitivity through precision top / SM observables

- WHIZARD 1 is a crucial tool for CLIC physics benchmark studies, we are looking forward to switch to WHIZARD 2 soon

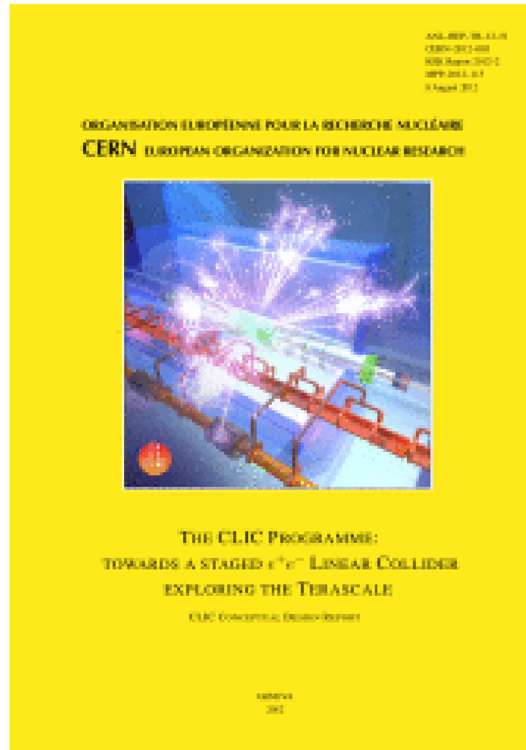
Backup slides

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

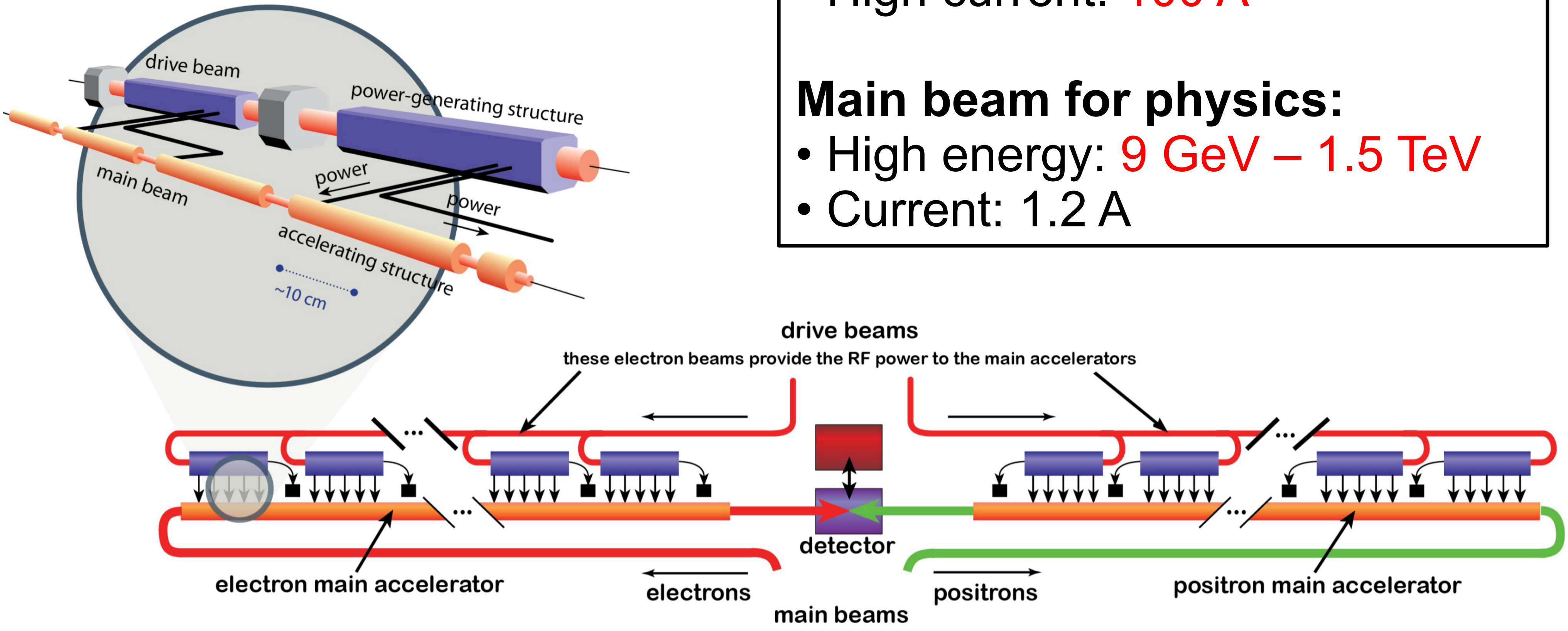
Snowmass white paper:
Most of the Higgs studies

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

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

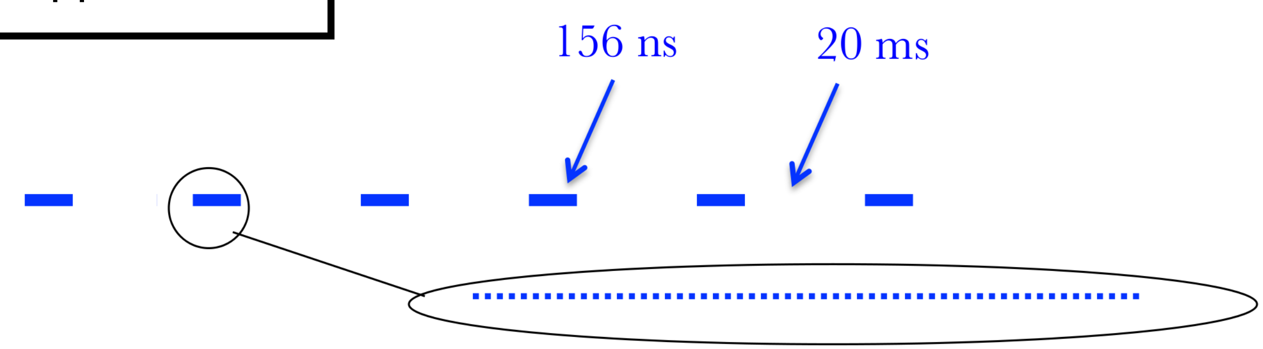


Selected CLIC parameters

	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

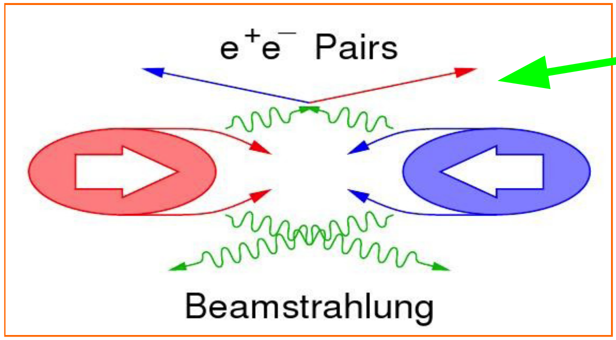
Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

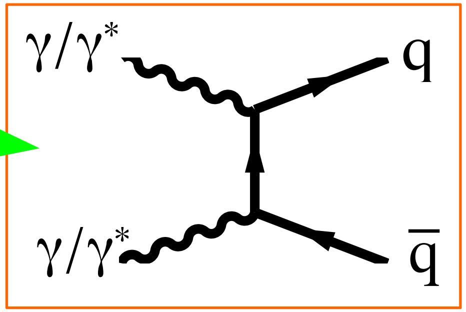


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam related backgrounds

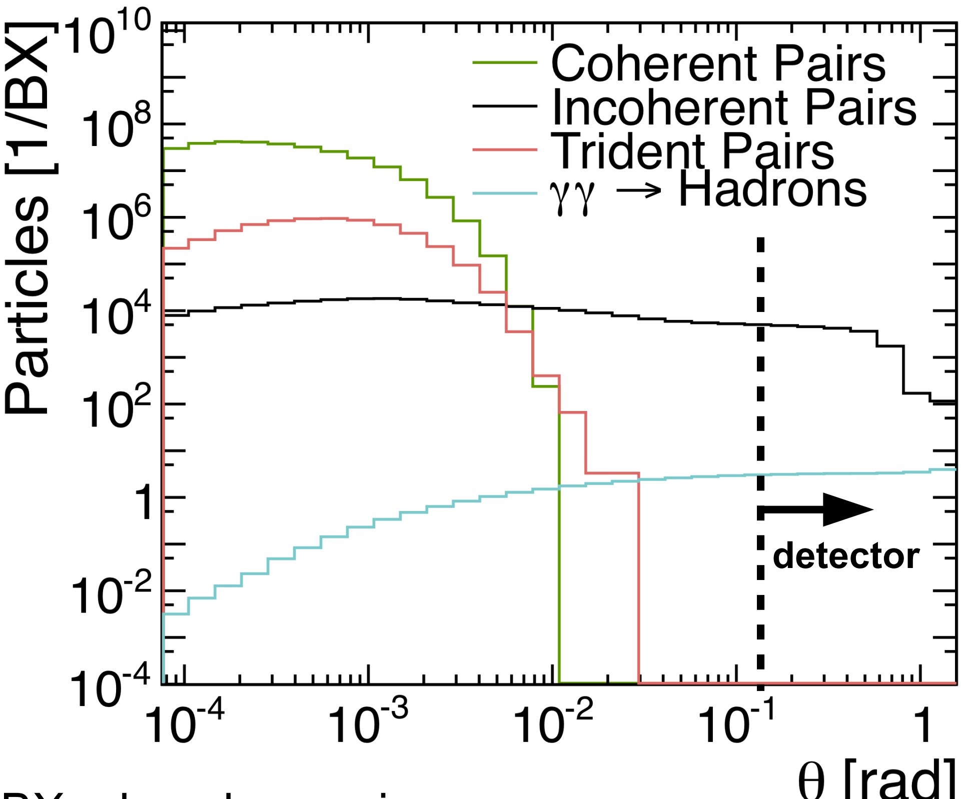


- e^+e^- pairs
- γγ → hadrons



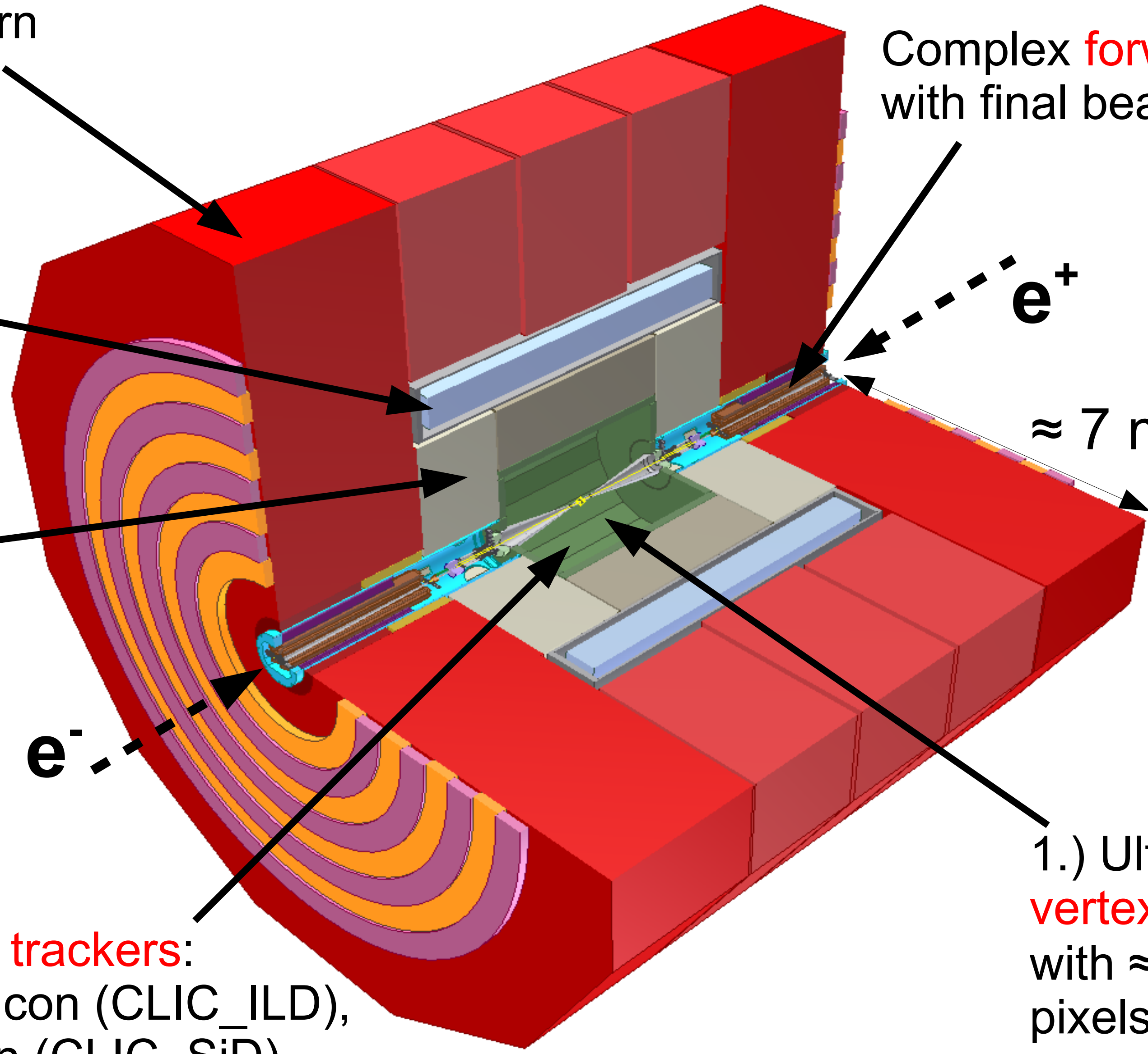
Coherent e^+e^- pairs:
$7 \cdot 10^8$ per BX, very forward
Incoherent e^+e^- pairs:
$3 \cdot 10^5$ per BX, rather forward
→ Detector design issue
(high occupancies)

γγ → hadrons
- "Only" 3.2 events per BX at 3 TeV
- Main background
in calorimeters and trackers
→ Impact on physics



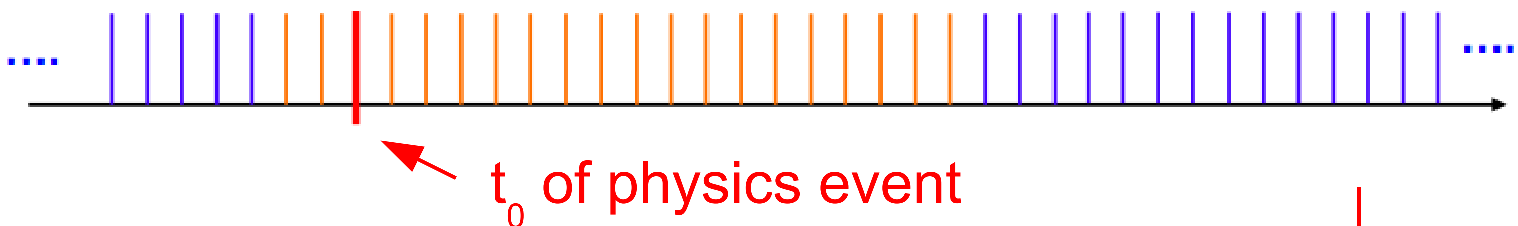
BX = bunch crossing

CLIC detector concepts

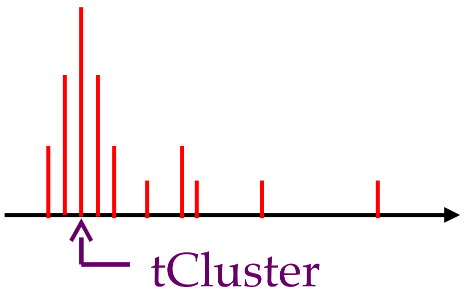


Background suppression

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**

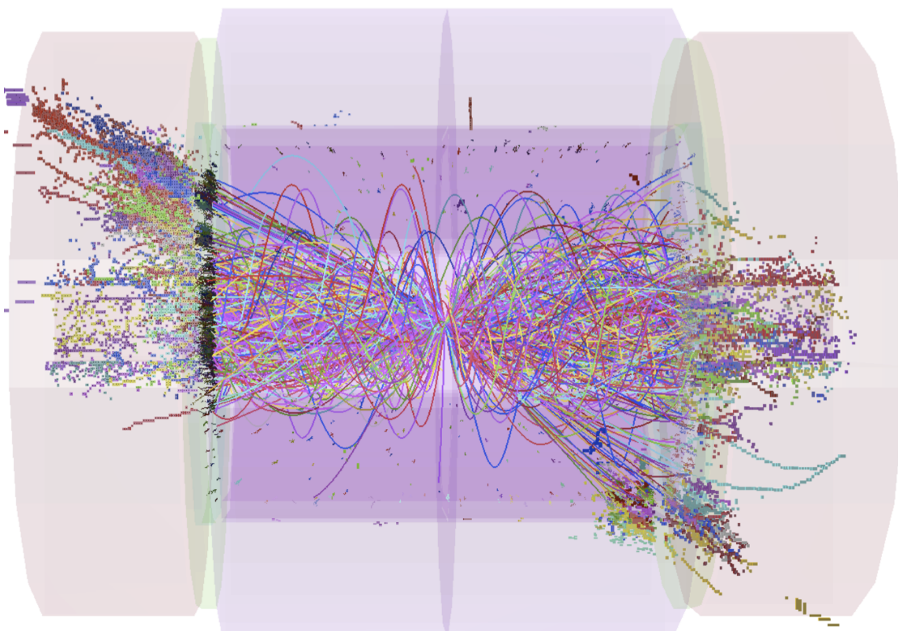
- Cuts depend on particle-type, p_T and detector region

→ Protects physics objects at high p_T

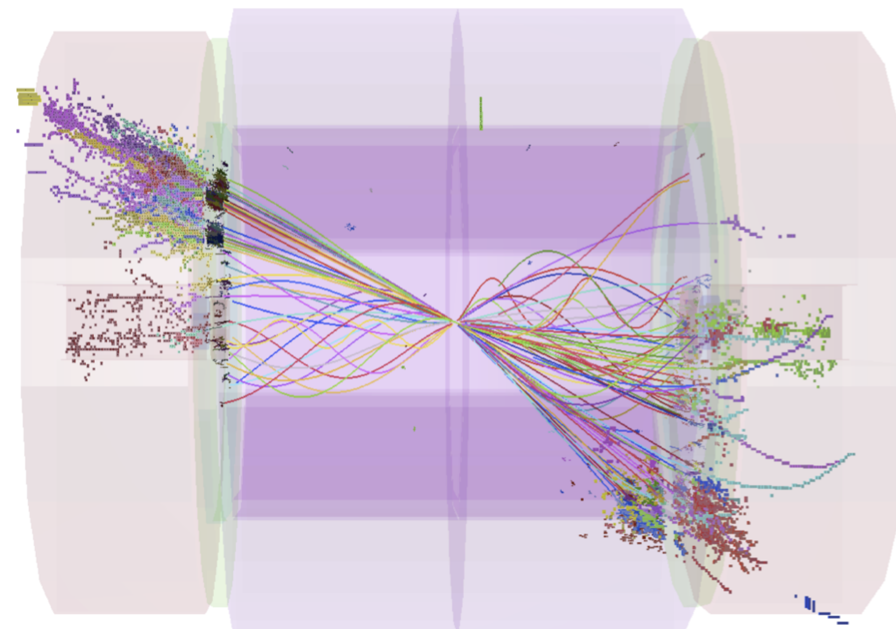
In addition: hadron-collider type jet algorithms (FastJet)

Impact of the timing cuts

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



1.2 TeV background
in the reconstruction window



100 GeV background
after timing cuts

Physics studies are based on Geant4 simulations including pile-up from γγ → hadrons

Precision measurements

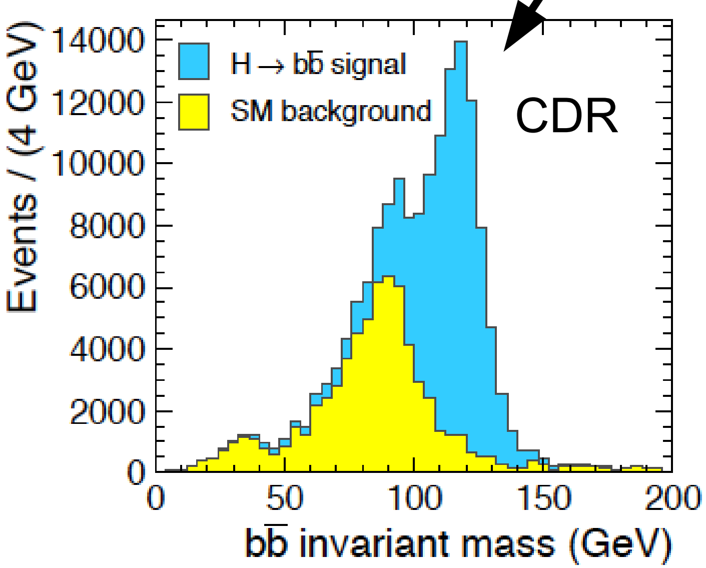
H → $b\bar{b}$/$c\bar{c}$/gg:

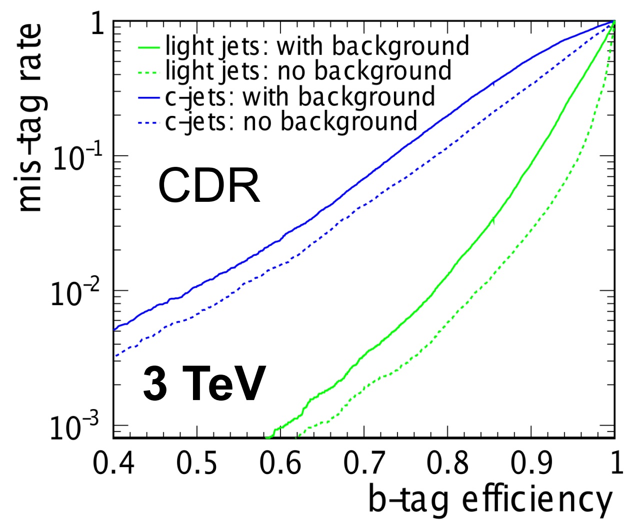
• Separation of the different hadronic final states using precise flavour tagging

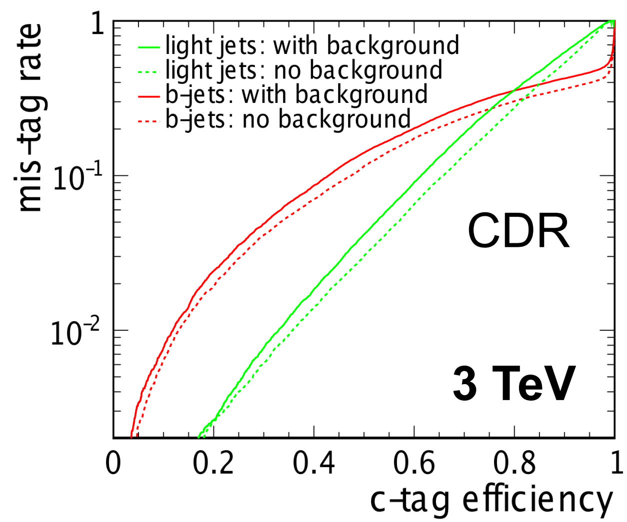
• H → $c\bar{c}$ and gg impossible at hadron colliders

• In addition, the Higgs mass can be extracted from the H → $b\bar{b}$ invariant mass distribution (±40MeV at 1.4 TeV, ±33MeV at 3 TeV)

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



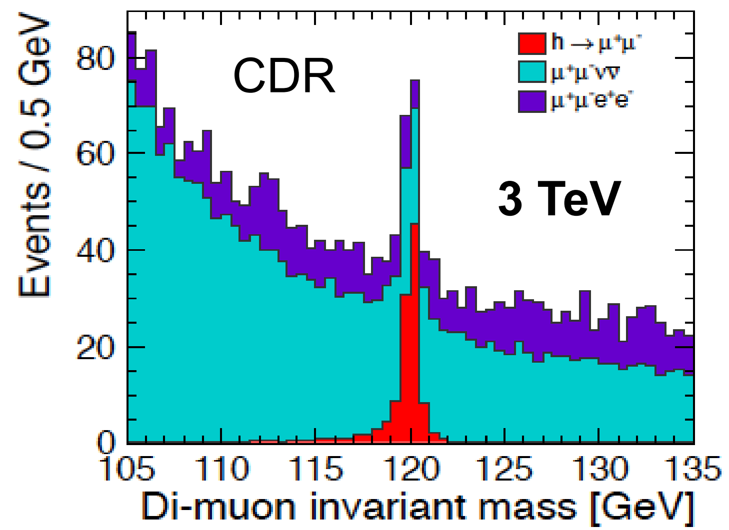




Rare decays

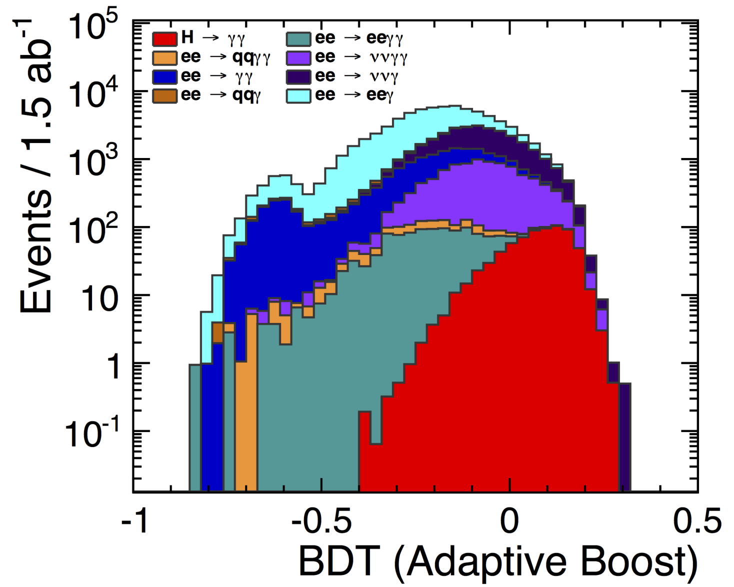
$\sigma(H\nu_e\bar{\nu}_e)$ x BR(H → $\mu^+\mu^-$):

- 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



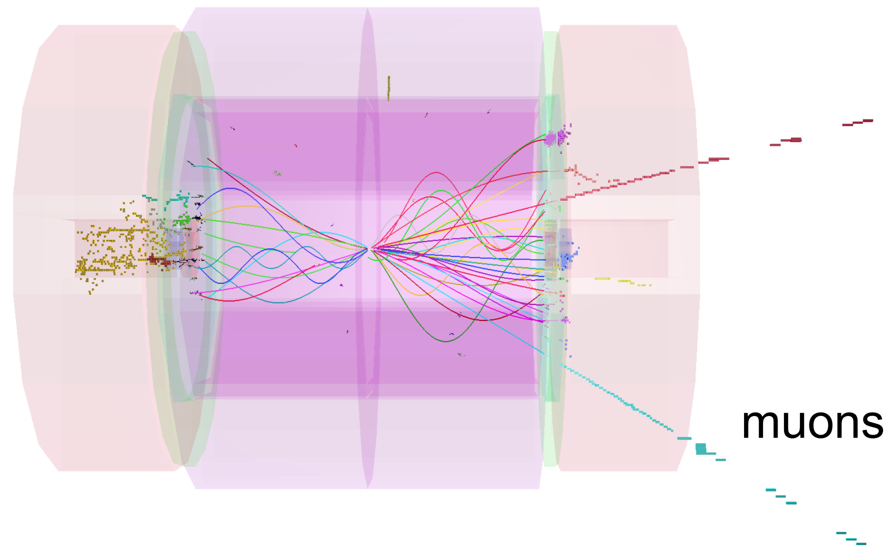
$\sigma(H\nu_e\bar{\nu}_e)$ x BR(H → Zγ):

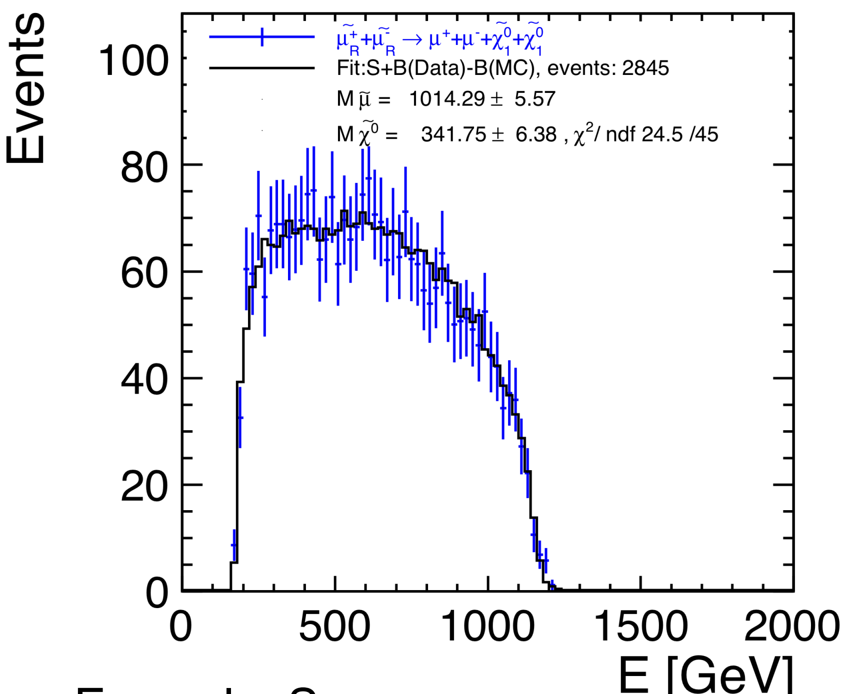
- BR(H→Zγ) ≈ 0.16%
- Hadronic Z decays usable (in contrast to hadron colliders)
- Δ(σ x BR) = 42% at 1.4 TeV

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

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

- Precisions of a few GeV achievable

Hadronic final states: gauginos at 3 TeV

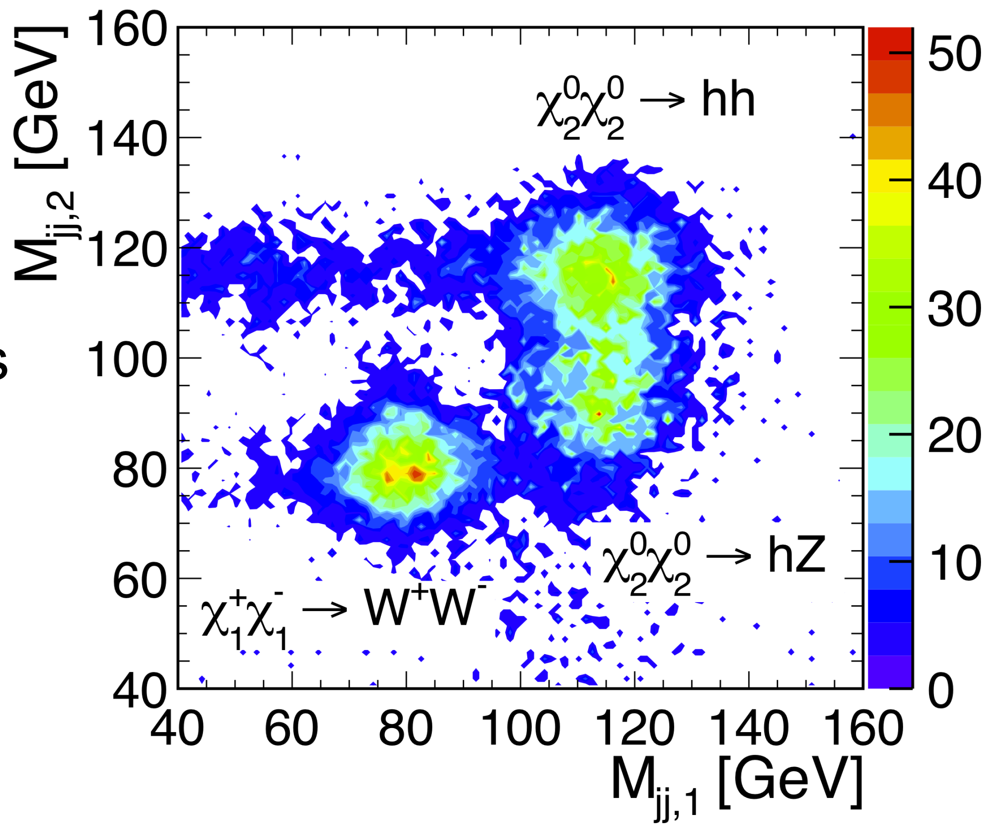
Chargino and neutralino pair production:

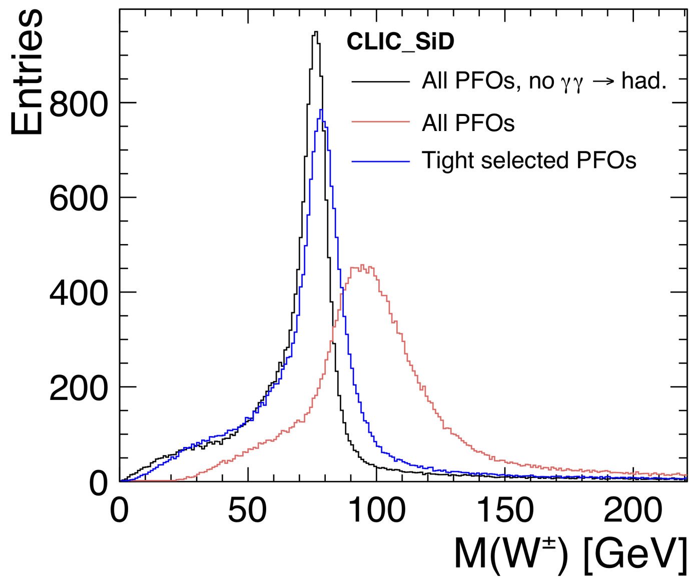
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

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

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

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

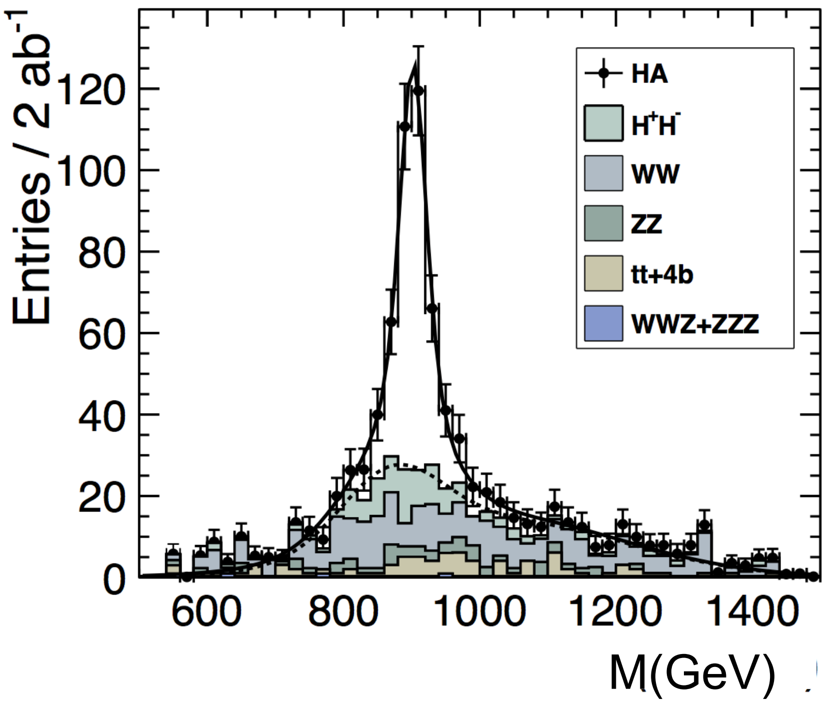
Heavy Higgs bosons:

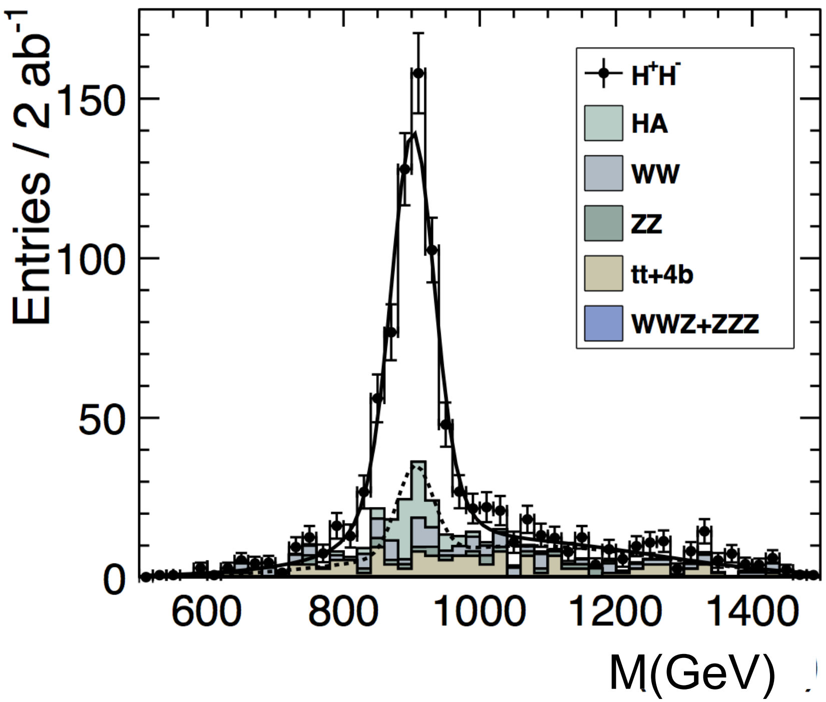
$e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$

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

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

Complex final states





Accuracy of the heavy Higgs mass measurements: ≈0.3%