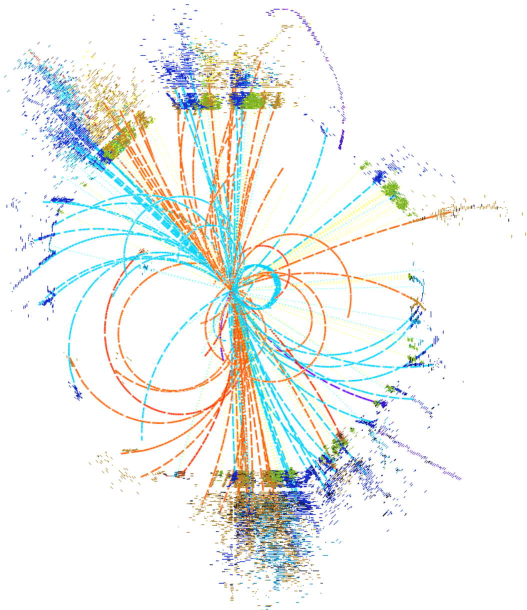
Direct and indirect BSM searches at $\sqrt{s}$ > 500 GeV



Philipp Roloff (CERN)

ECFA Linear Collider Workshop 2016,
Joint ILD/SiD/CLICdp session on
physics benchmark analyses

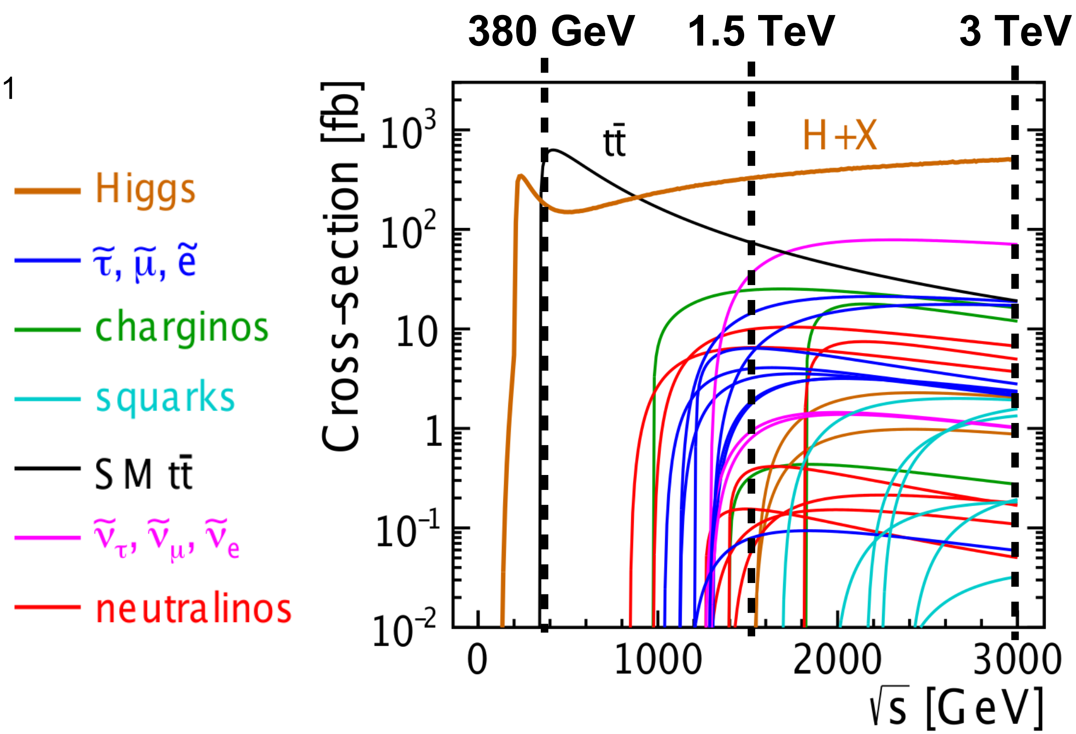
Santander (Spain),
03/06/2016

Reminder: CLIC energy stages

CLIC would be implemented in several energy stages

Current baseline scenario:

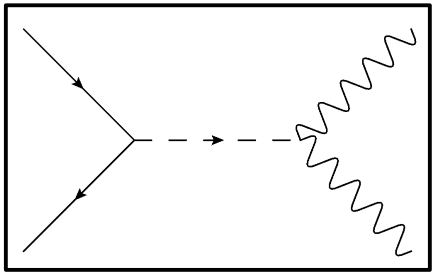
- **<u>Stage 1:</u>** 380 + 350 GeV, 500 + 100 fb^{-1}
  Precision SM Higgs and top physics
- **<u>Stage 2:</u>** 1.5 TeV, 1.5 ab^{-1}
  Targeted at BSM physics,
  rare Higgs processes and decays
- **<u>Stage 3:</u>** 3 TeV, 3 ab^{-1}
  Targeted at BSM physics,
  rare Higgs processes and decays



(each stage corresponds to 5 - 7 years incl. luminosity ramp-up)

→ The strategy can be adapted to possible LHC discoveries at 13 TeV!

Beyond Standard Model searches



1.) Direct observation of new particles (e.g. pair production if $M \leq \sqrt{s} / 2$):
→ Precision measurement of new particle masses and couplings

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

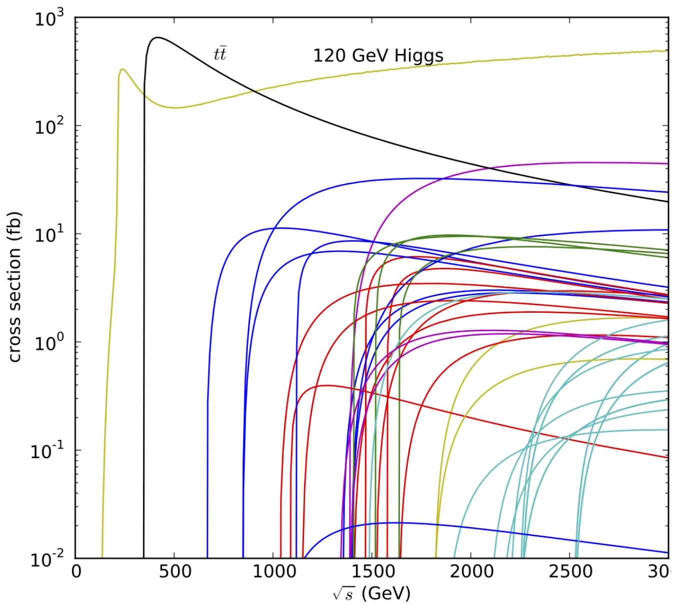
Best discovery reach for highest energy in both cases

- Very rare processes accessible due to low backgrounds
→ linear colliders especially suitable for electroweak states

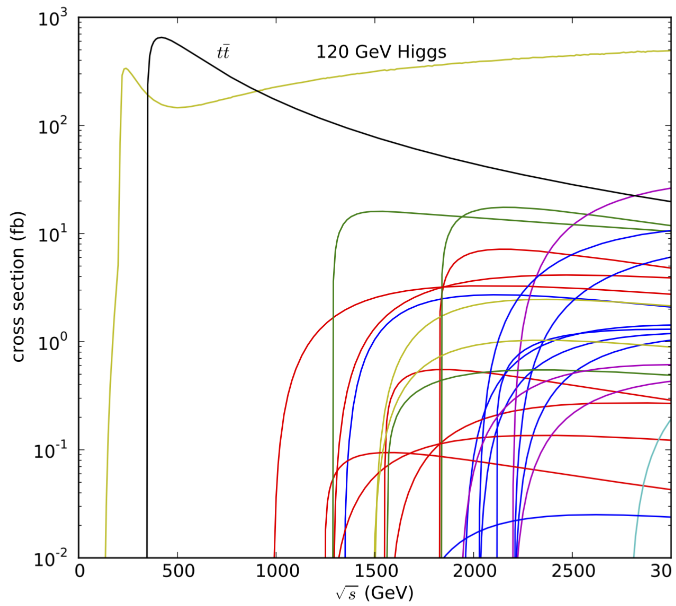
- Polarised beams might be useful to constrain the underlying theory

Direct searches

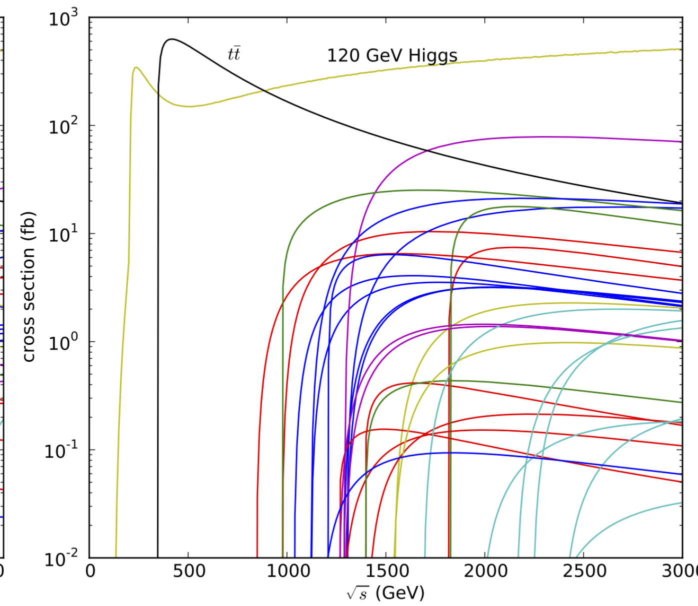
SUSY studies at CLIC



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

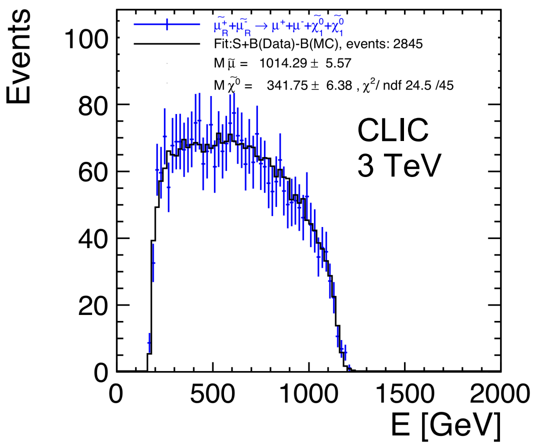
- Higgs
- $\tilde{\tau}$,$\tilde{\mu}$,$\tilde{e}$
- charginos
- squarks
- SM
- $\tilde{\nu}_{\tau}$,$\tilde{\nu}_{\mu}$,$\tilde{\nu}_{e}$
- neutralinos

In general, O(1%) precision on masses and pair production cross sections found

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

Reconstruction of SUSY particles

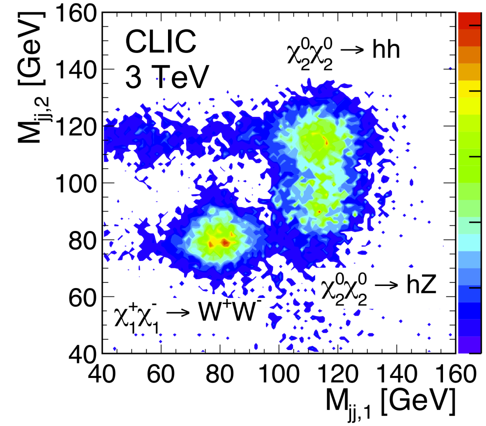
Endpoints of energy spectra:



$m(\tilde{\mu}_R)$	:	± 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

slepton masses:
1.0 - 1.1 TeV

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



Jet reconstruction

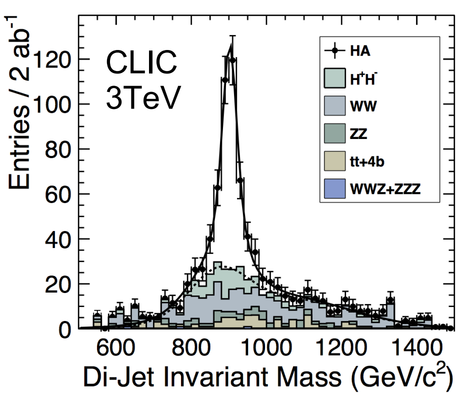
Precision on the measured gaugino masses (few hundred GeV): 1 - 1.5%

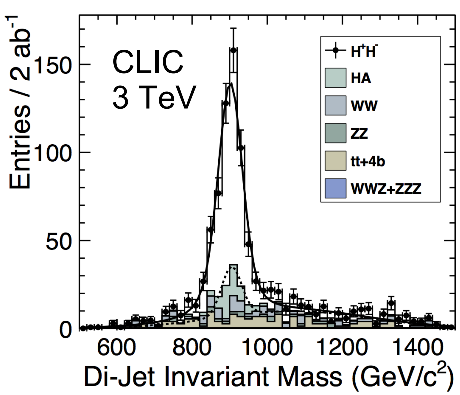
$$e^+e^- \rightarrow \tilde{\chi}_1^+\,\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\,\tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow hh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow Zh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

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 heavy Higgs masses



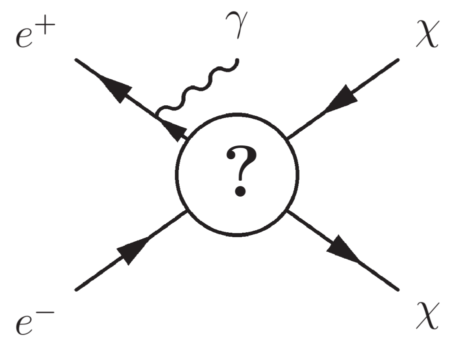


Summary of the SUSY studies

$\sqrt{s}$ (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	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
	Neutralino	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ 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	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
	Neutralino	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

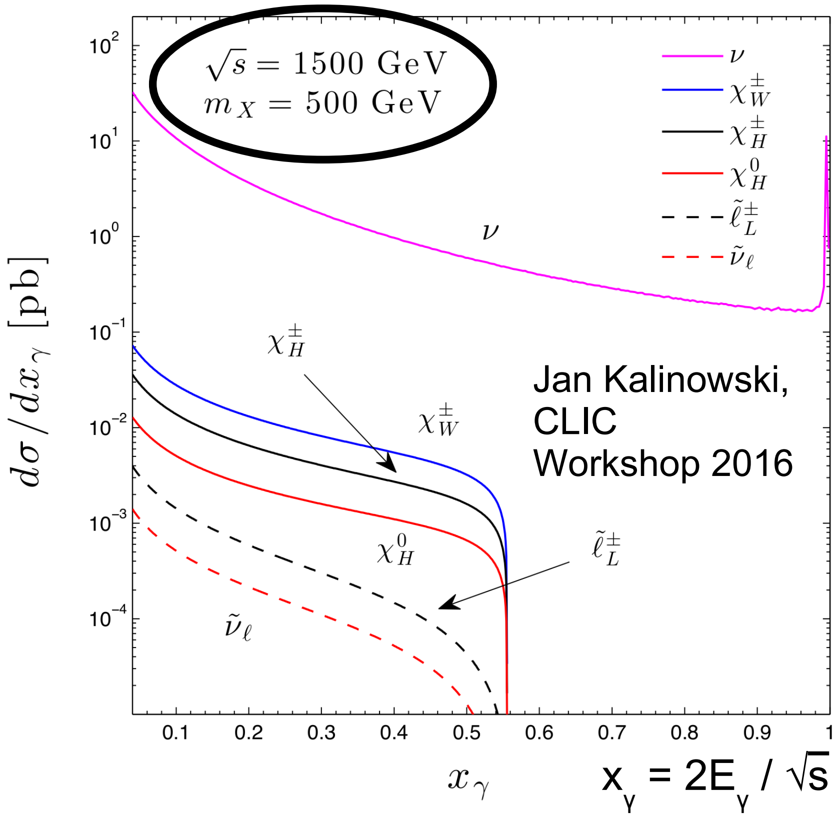
$e^+e^- \rightarrow \gamma + E^{miss}$ at high energy

• Need to study the potential of single photon events with missing energy also at high energy



• Recent improvements in PandoraPFA photon reconstruction will help
→ see talk by Boruo Xu

• If a signal is confirmed over the $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ background, try to extract mass, spin and coupling structure

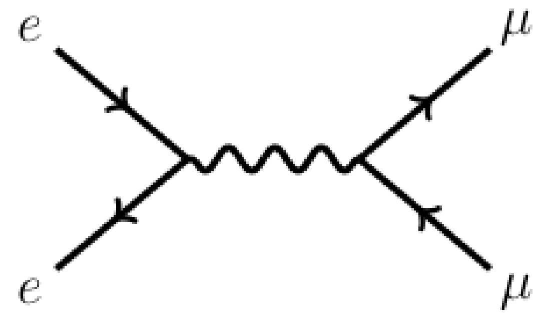


• Control of systematics crucial: luminosity spectrum, polarisation measurement, background calculations, ...

Indirect searches

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

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

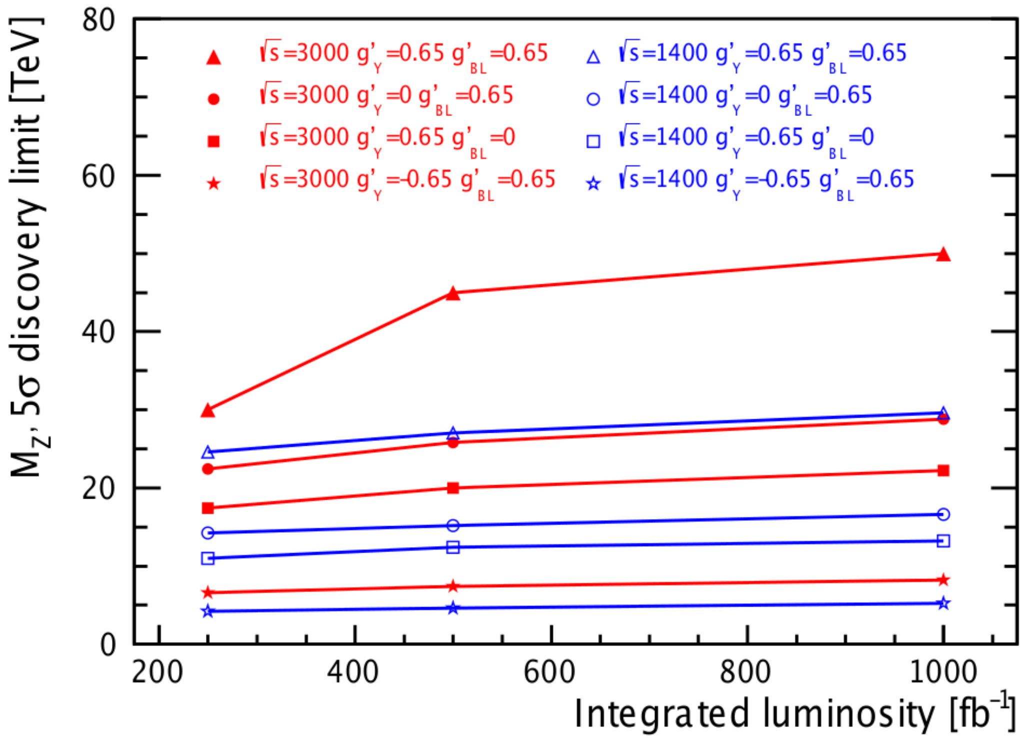


Observables:
- total $e^+e^- \to \mu^+\mu^-$ cross section
- forward-backward-asymmetry
- left-right asymmetry

(±80% e^- polarisation)

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

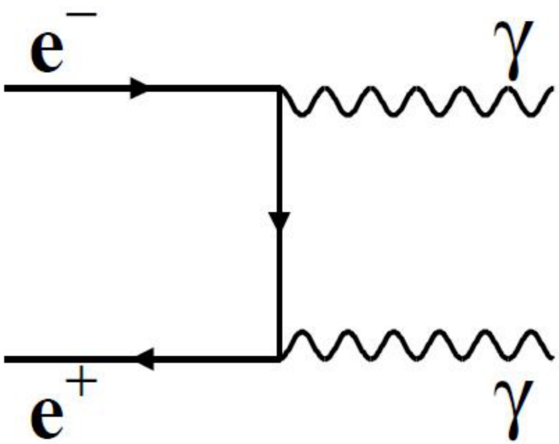
Otherwise:
Discovery reach up to tens of TeV
(depending on the couplings)



Precision study of $e^+e^- \to \gamma\gamma$ (1)

New physics searches with ee → γγ:
deviation from QED expectation

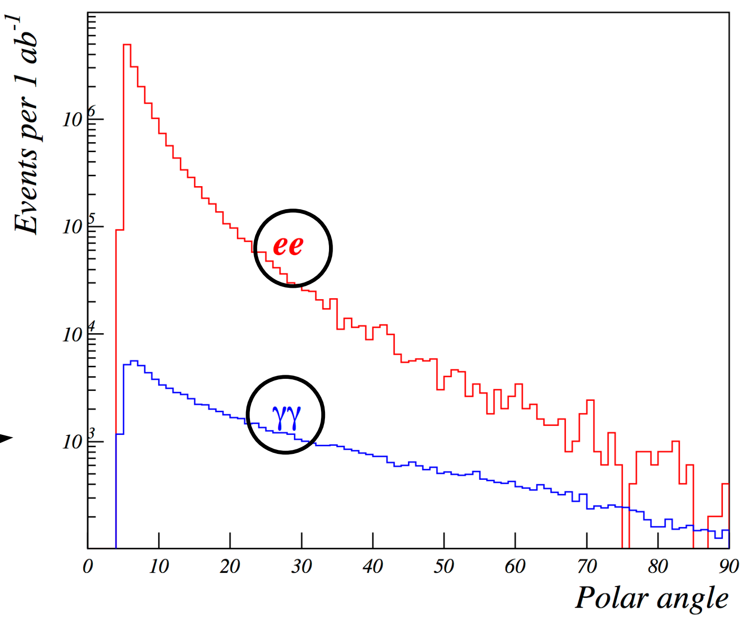
$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+\cos^2\theta)$$



Simplest Ansatz: QED cutoff parameter Λ
(other interpretations possible:
excited electrons, ...)

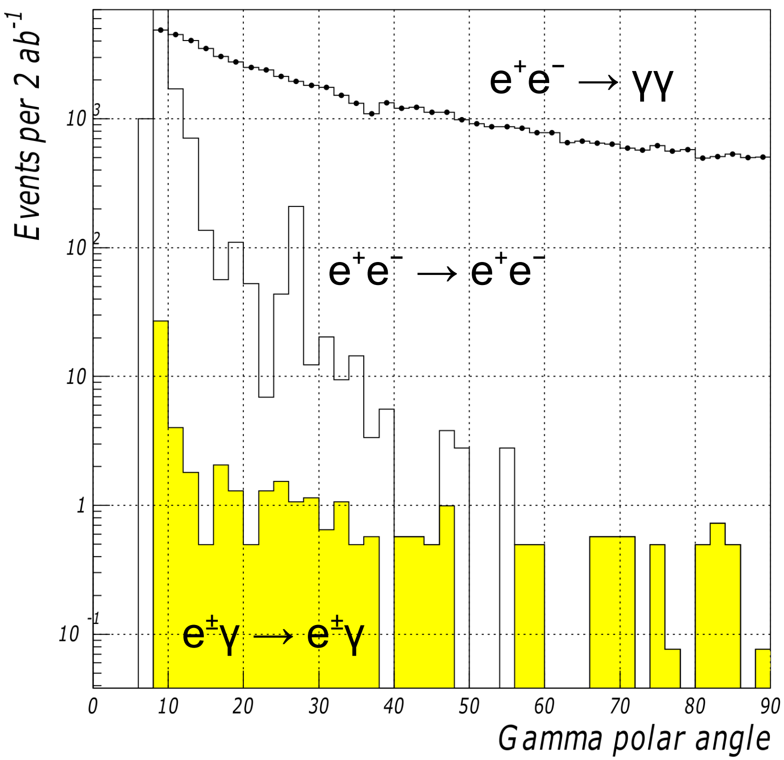
Events with small energy loss
due to Beamstrahlung and ISR
are selected
→ two back-to-back photons

Most critical background:
$e^+e^- \to e^+e^-$

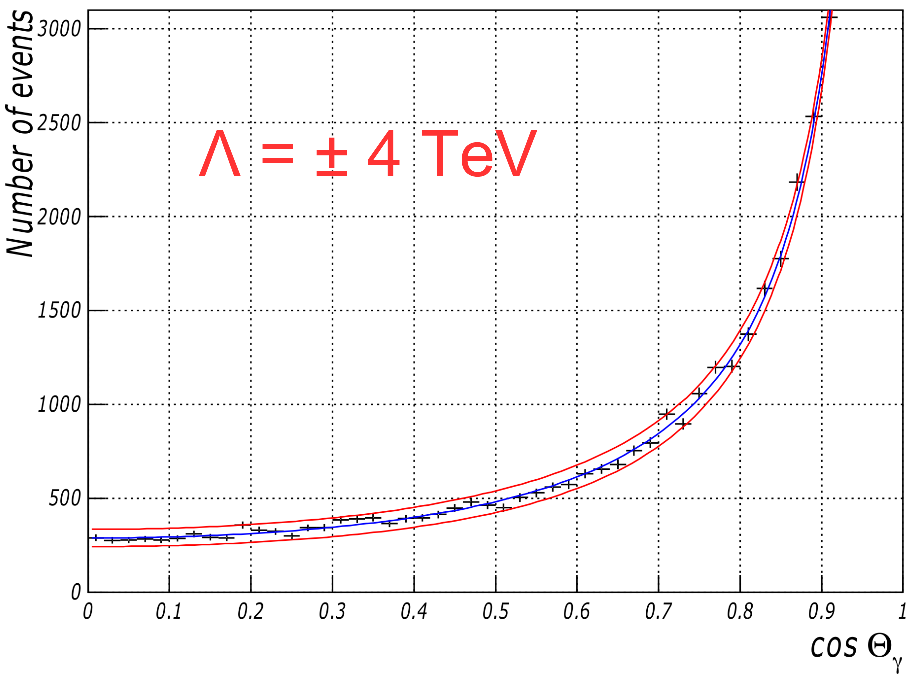


Precision study of $e^+e^- \to \gamma\gamma$ (2)

Selected events:



$\sqrt{s}$ = 3 TeV, L = 2 ab^{-1},
CLIC_SiD detector

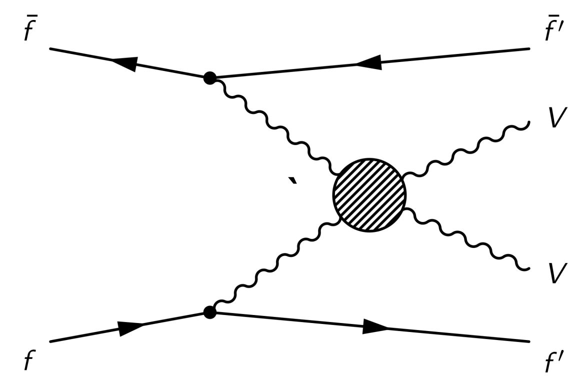


Fit result: Λ > 6.33 TeV
(or electron size < 3.1 x 10^{-18} m)

Combined LEP data: Λ > 431 GeV

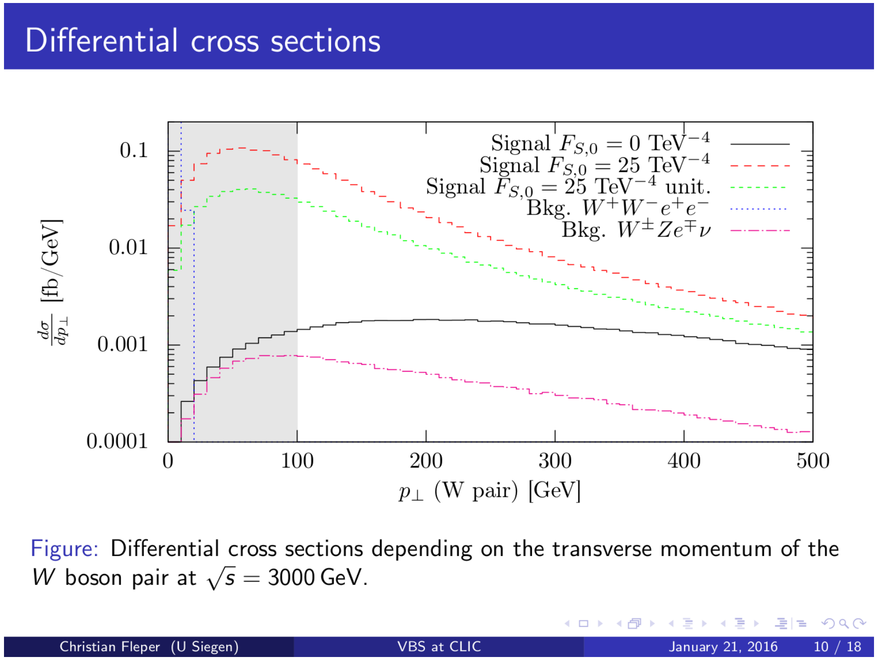
Vector boson scattering (1)

- Vector boson scattering is sensitive to new physics in the Higgs sector



- Search for additional resonances or anomalous couplings

- Study on generator level (WHIZARD 2.2.8)
- Assuming performance for separation of hadronic W and Z decays predicted by full simulation
- Backgrounds with electrons in fiducial regions of BeamCal and LumiCal rejected
- Cuts used to suppress background processes



Christian Fleper, CLIC Workshop 2016

Vector boson scattering (2)

Theoretical CLIC values

$-40\,\text{TeV}^{-4} < F_{S,0,1} < 40\,\text{TeV}^{-4}$ (1400 GeV)
$-7\,\text{TeV}^{-4} < F_{S,0,1} < 7\,\text{TeV}^{-4}$ (3000 GeV)

Latest ATLAS analysis G. Aad et al.: arXiv:1405.6241

$-461\,\text{TeV}^{-4} < F_{S,0} < 527\,\text{TeV}^{-4}$
$-758\,\text{TeV}^{-4} < F_{S,1} < 791\,\text{TeV}^{-4}$

CLIC at 3 (1.4) TeV roughly two (one) orders of magnitude more precise than LHC at 8 TeV

Study based on full detector simulation starting
→ Several interesting experimental challenges including**:**
- Reconstruction and separation of hadronic W and Z boson decays
- Missing momentum reconstruction in the presence of beam-induced backgrounds
- Forward electron tagging to reject backgrounds

Summary and conclusions

• A linear collider operated at high-energy provides significant discovery potential for BSM phenomena

• Measurement of the gaugino, slepton and heavy Higgs masses with O(1%) precision up to the kinematic limit (M ≈ 1.5 TeV)

• Single photon + missing energy events allow model-independent searches for dark matter candidates (complementary to LHC)

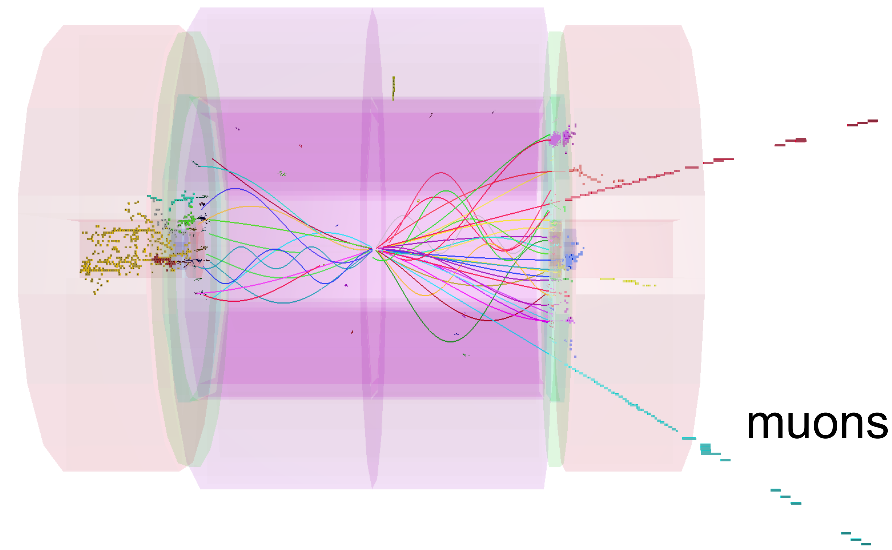
• Sensitivity to New Physics at large scales (tens of TeV) through precision measurements
(examples: Z' from fermion pair production, $e^+e^- \to \gamma\gamma$,
vector boson scattering)

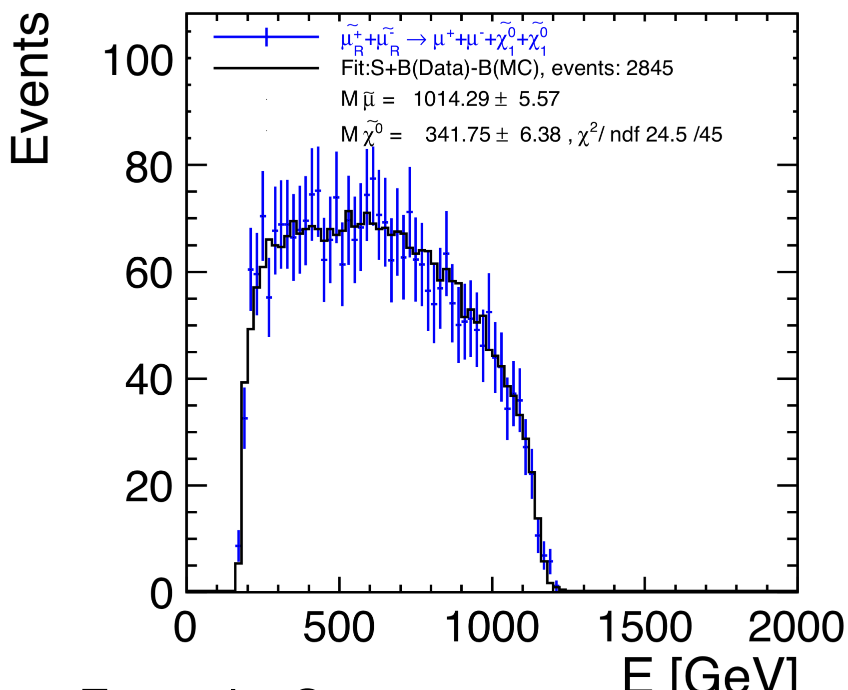
Backup slides

The simplest case: sleptons at 3 TeV

- Slepton production very clean at CLIC
- 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

- Precisions of a few GeV achievable

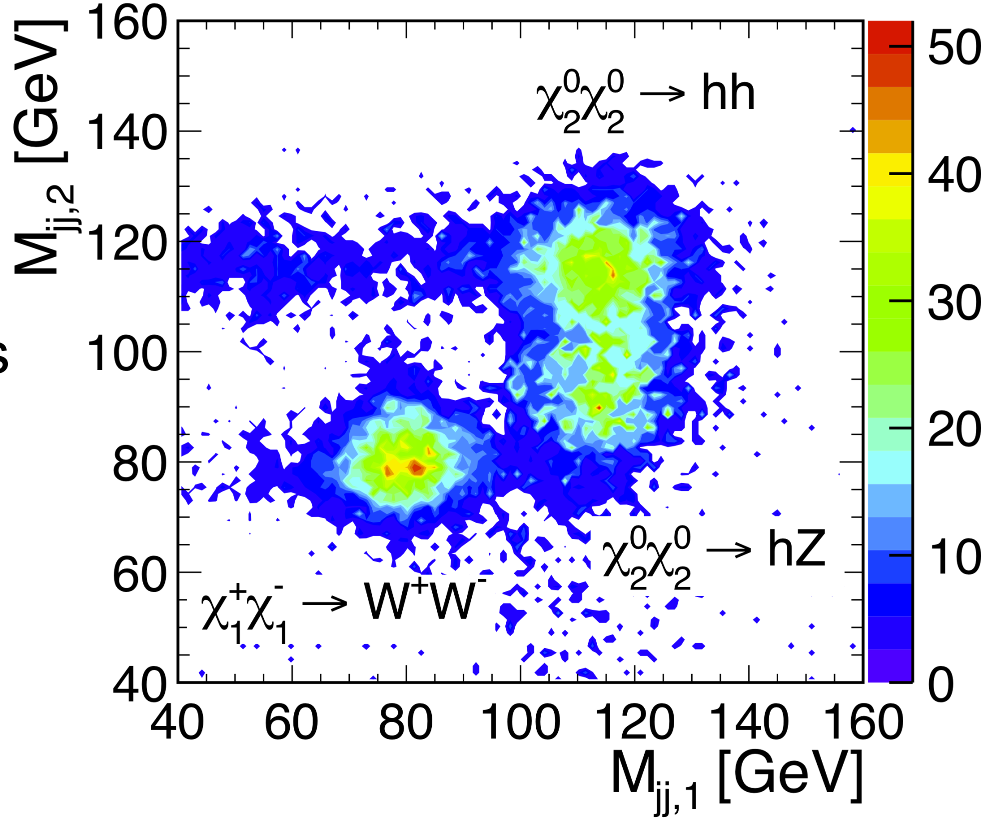
Hadronic final states: gauginos at 3 TeV

Chargino and neutralino pair production:

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

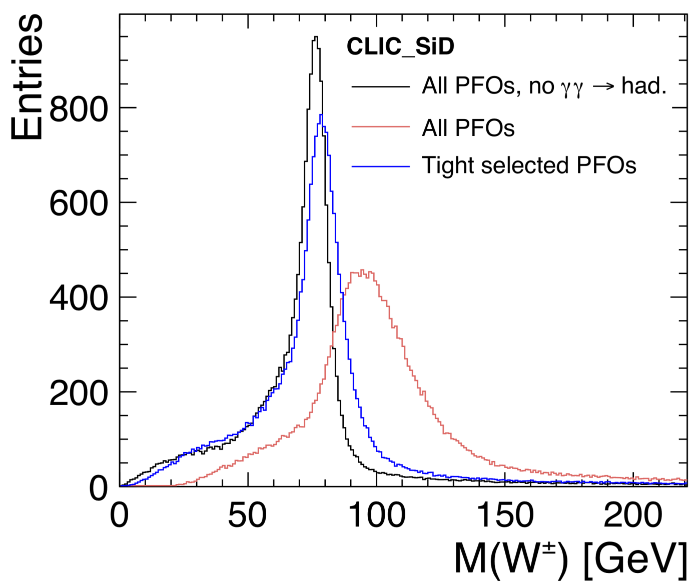
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\%$$

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



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

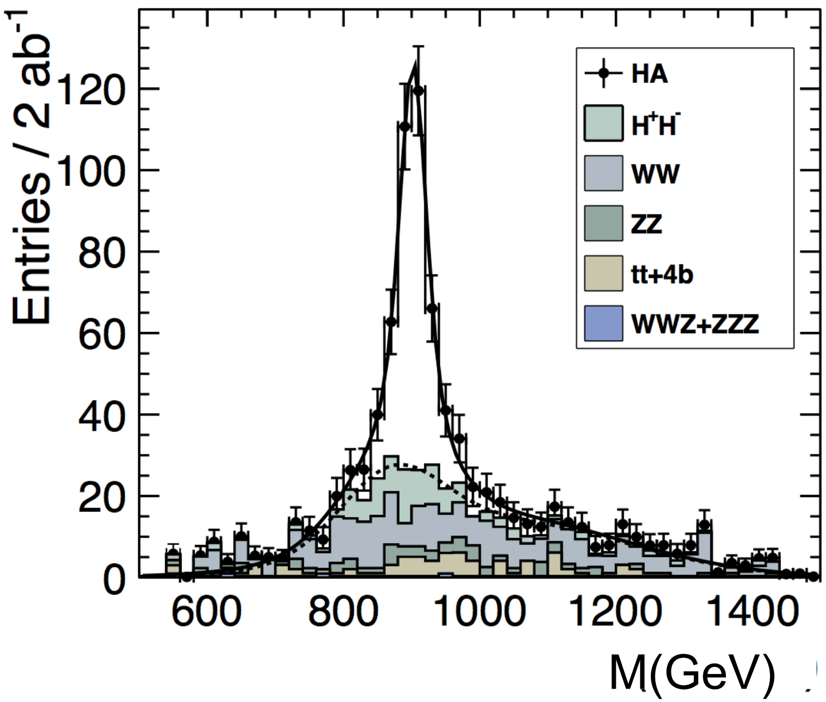
Heavy Higgs bosons:

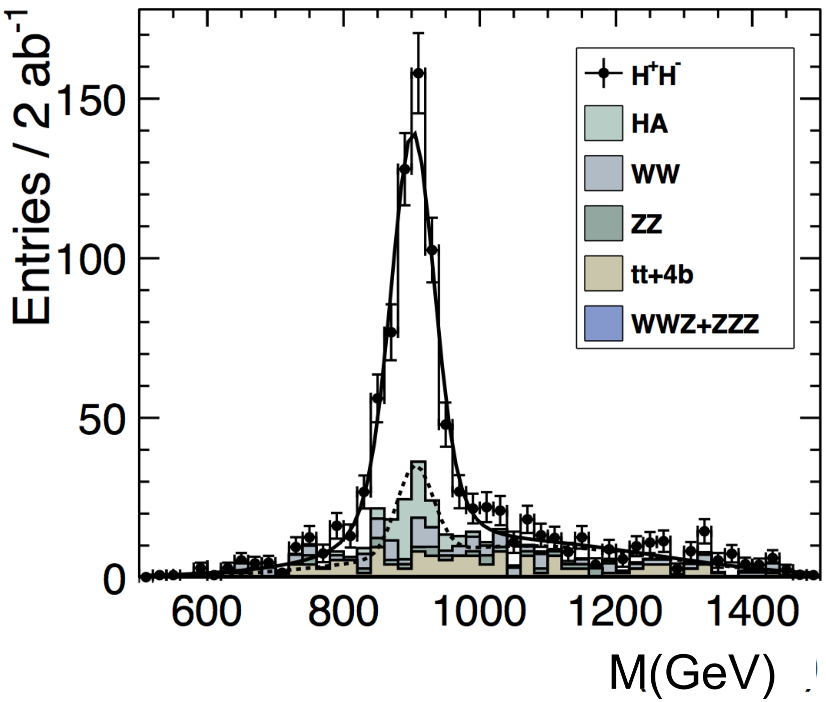
$e^+e^- \to HA \to b\bar{b}b\bar{b}$

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

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

Complex final states





Accuracy of the heavy Higgs mass measurements: ≈0.3%