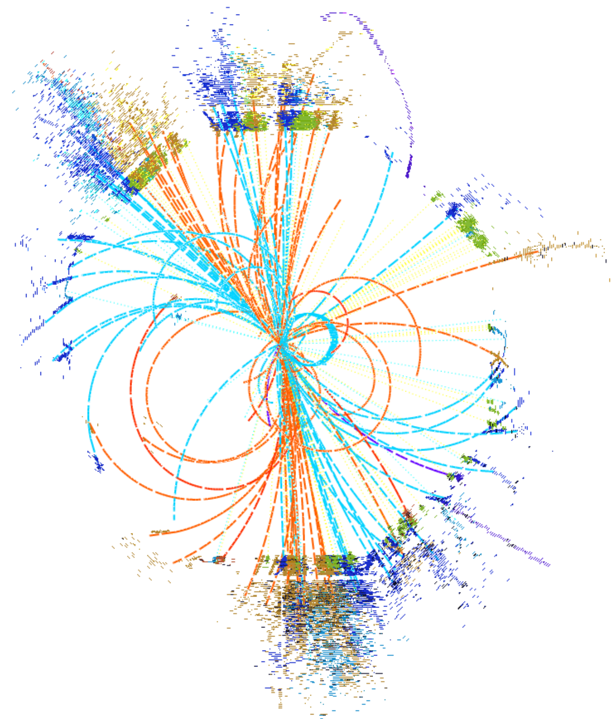
BSM physics at CLIC

Philipp Roloff (CERN)

on behalf of the
CLICdp collaboration



08/12/2016,
Morioka, Japan

International Workshop on
Future Linear Colliders (LCWS2016)

International Workshop on Future Linear Colliders
LCWS2016
5-9 DECEMBER, 2016
Aiina Center & MALIOS,
MORIOKA CITY, IWATE, JAPAN

Reminder: CLIC energy stages

CLIC would be implemented in several energy stages

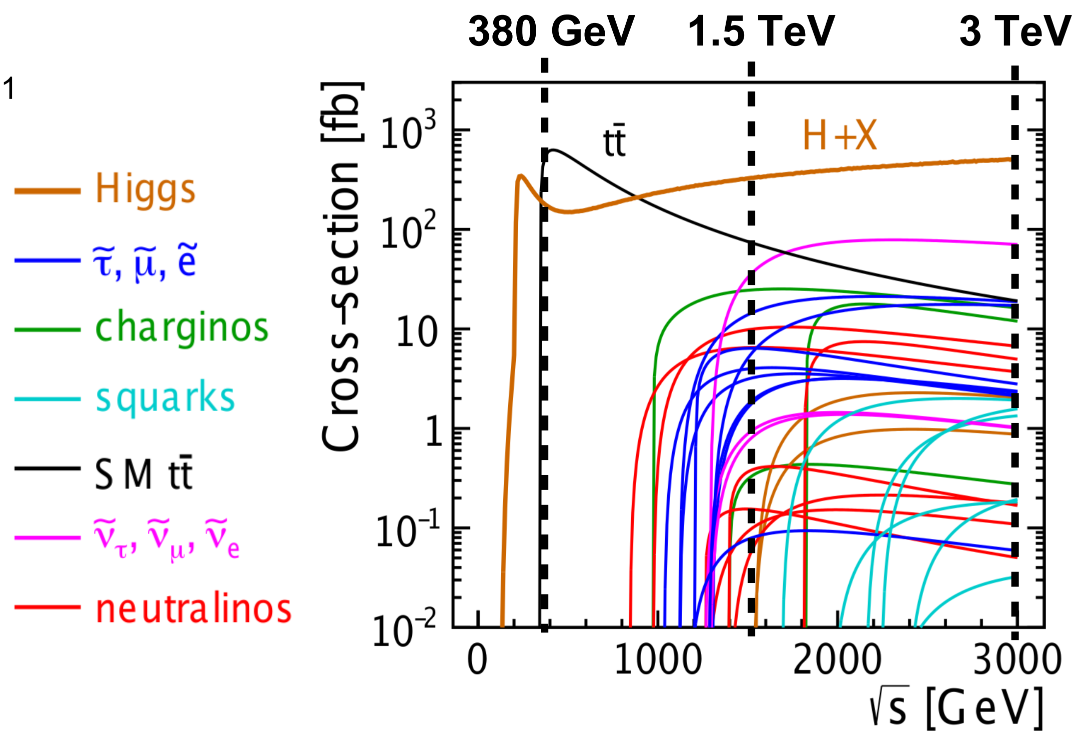
arXiv:1608.07537

Current baseline scenario:

- **Stage 1:** 380 + 350 GeV, 500 + 100 fb^{-1}
  Precision SM Higgs and top physics

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

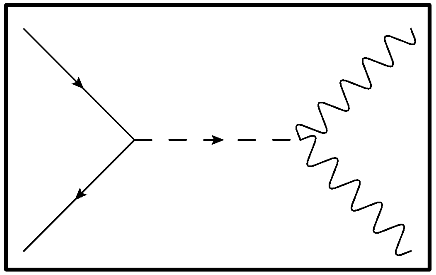
- **Stage 3:** 3 TeV, 3 ab^{-1}
  Targeted at BSM physics,
  rare Higgs processes and decays



(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

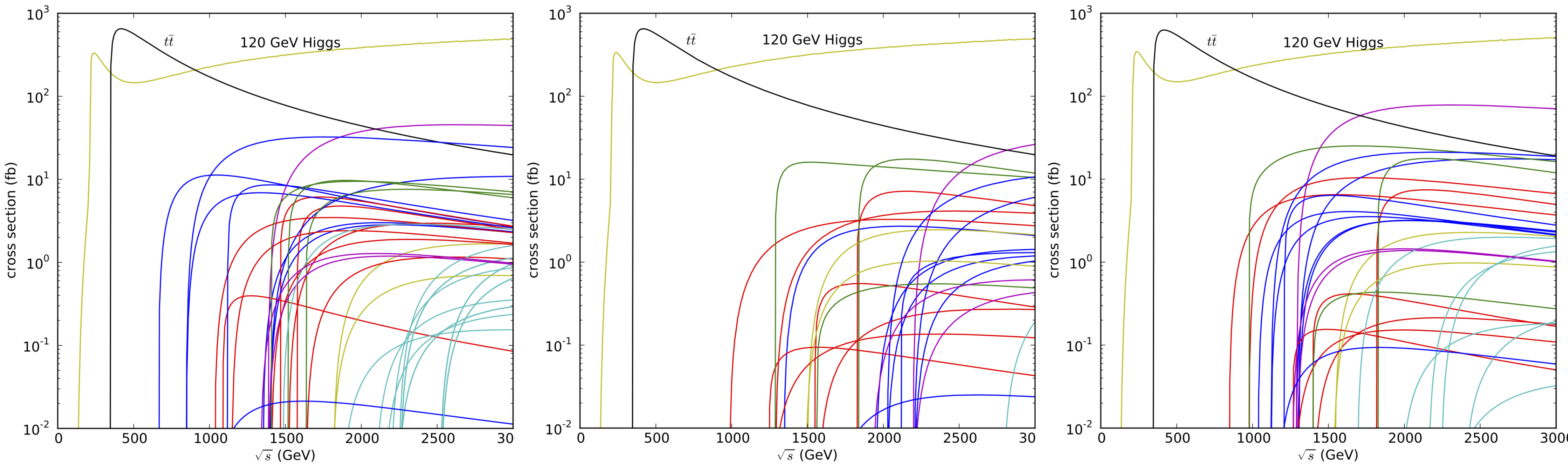
Best discovery reach for highest energy in both cases

- 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

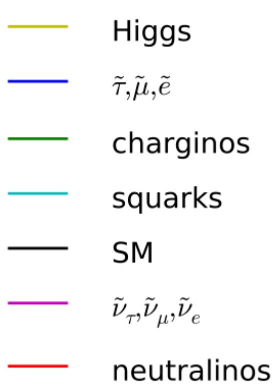
SUSY studies at CLIC



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

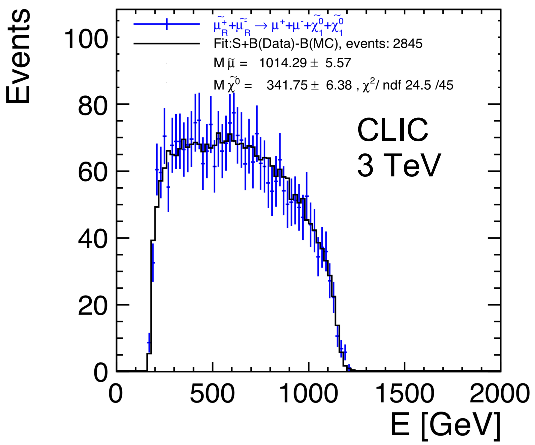


In general, O(1%) precision on masses and pair production cross sections found

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

Reconstruction of SUSY particles

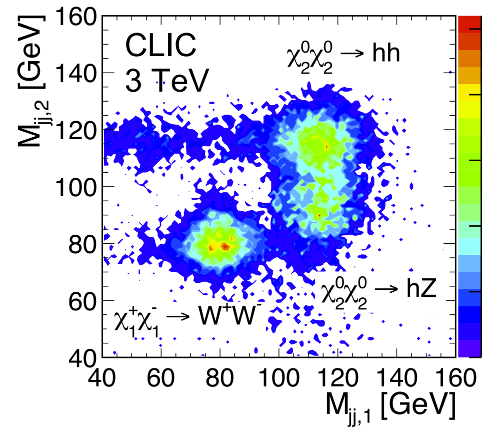
Endpoints of energy spectra:



$m(\tilde{\mu}_R)$	± 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

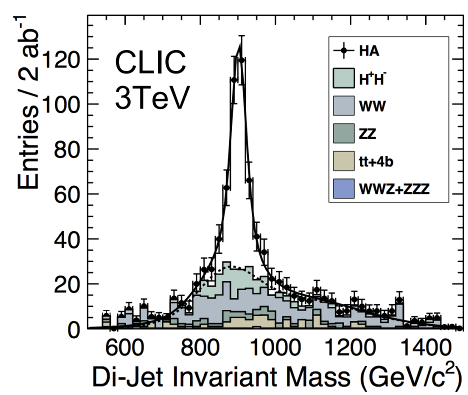
Precision on the measured gaugino masses (few hundred GeV): 1 - 1.5%

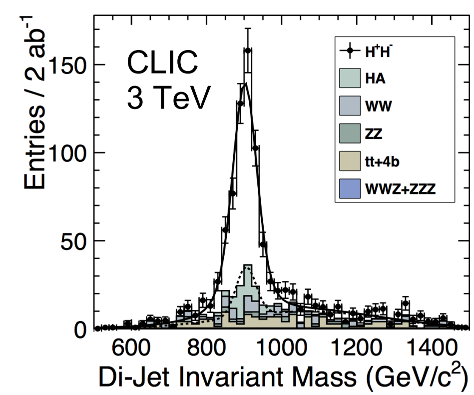
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh\, \tilde{\chi}_1^0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

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



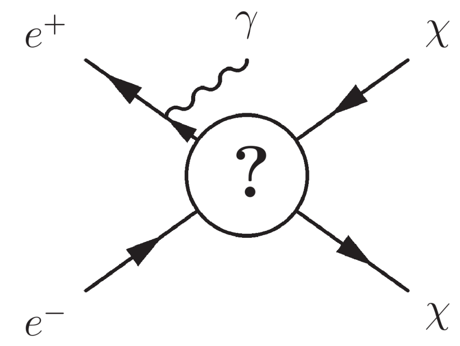


Summary of the SUSY studies

$\sqrt{s}$ (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%

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

- Aim to study the potential of single photon events with missing energy at high energy

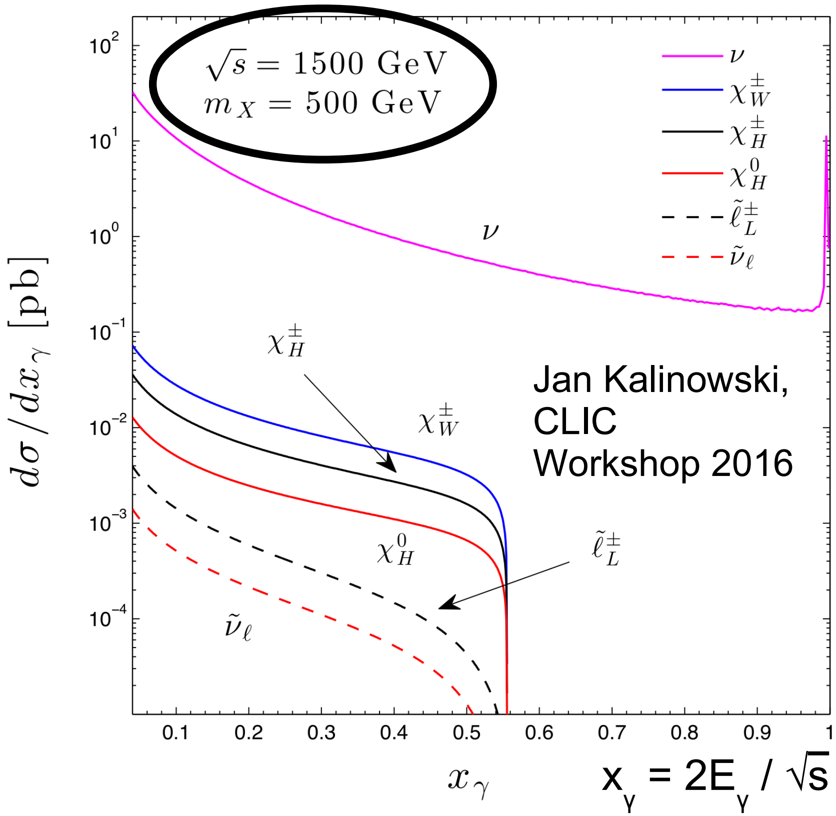


- Recent improvements in PandoraPFA photon reconstruction important for this study

- If a signal is confirmed over the $e^+e^- \to \nu\bar{\nu}\gamma$ background, try to extract mass from E_γ distribution, spin from threshold shape

- Polarisation might help with model discrimination

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



Indirect searches

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

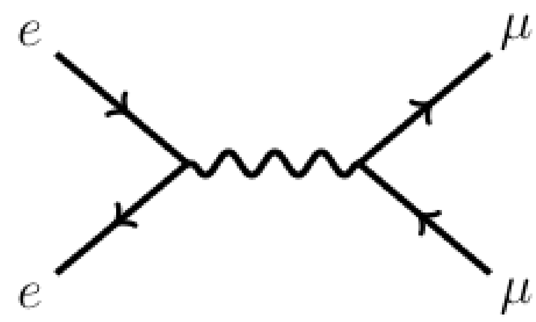
Minimal anomaly-free Z' model:
Charge of the SM fermions under U(1)' symmetry:
$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$

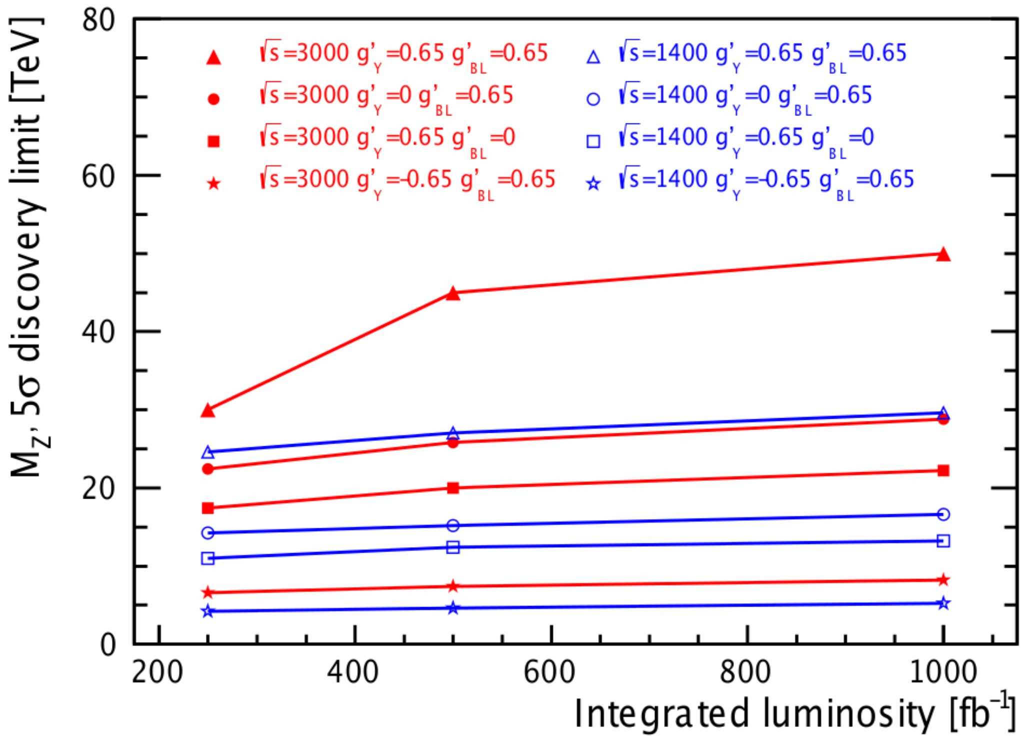
Observables:
- total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- forward-backward-asymmetry
- left-right asymmetry

(±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)

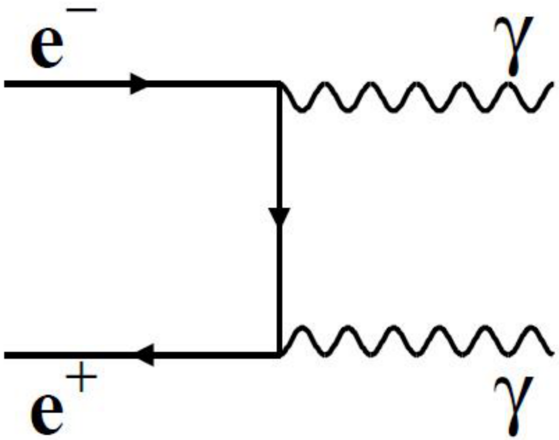




Precision study of $e^+e^- \to \gamma\gamma$ (1)

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

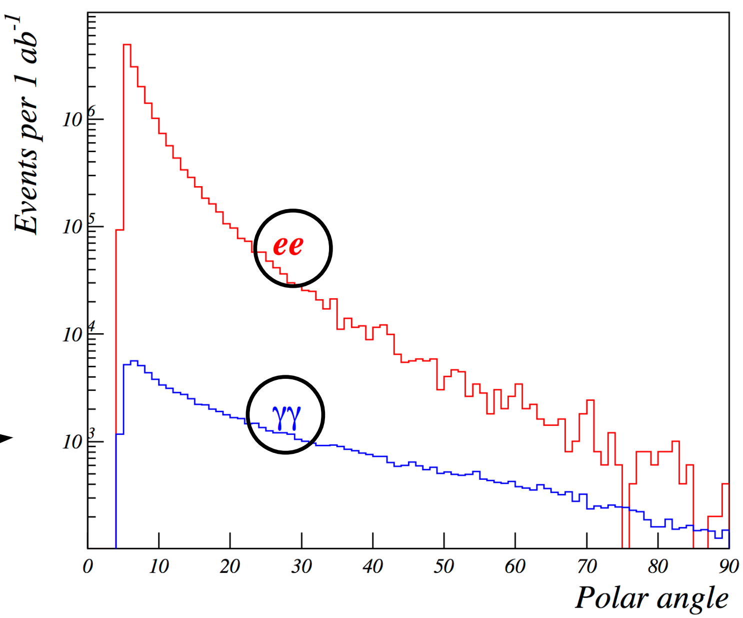
$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+\cos^2\theta)$$



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

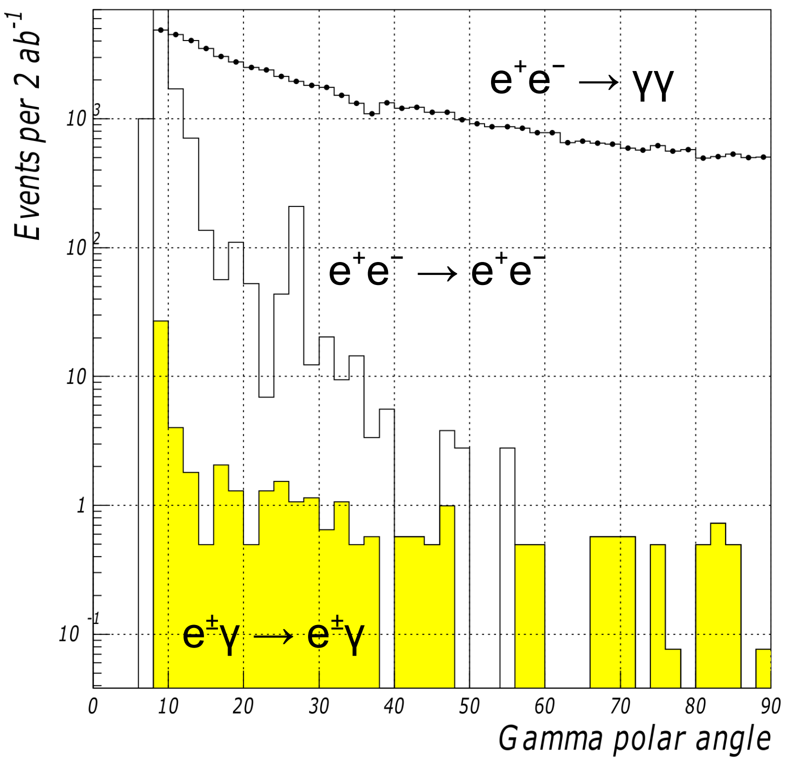
Events with small energy loss due to Beamstrahlung and ISR are selected
→ two back-to-back photons

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

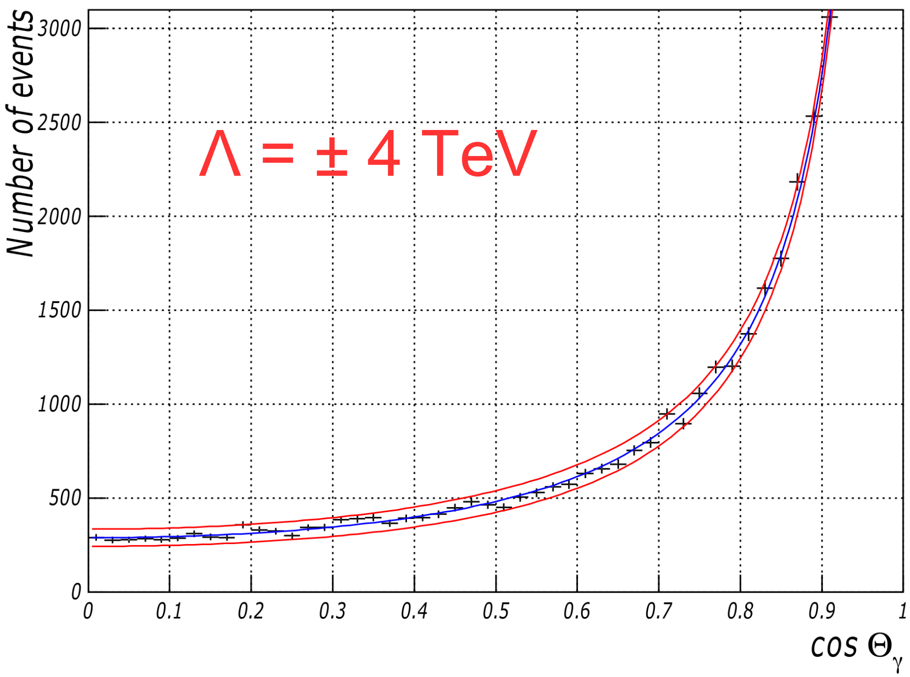


Precision study of $e^+e^- \to \gamma\gamma$ (2)

Selected events:



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



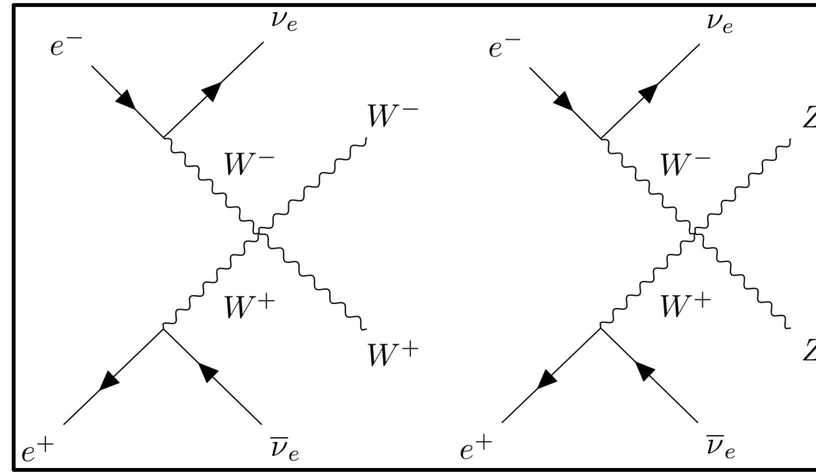
Fit result: Λ > 6.33 TeV
(or electron size < 3.1 x 10^{-18} cm)

Combined LEP data: Λ > 431 GeV

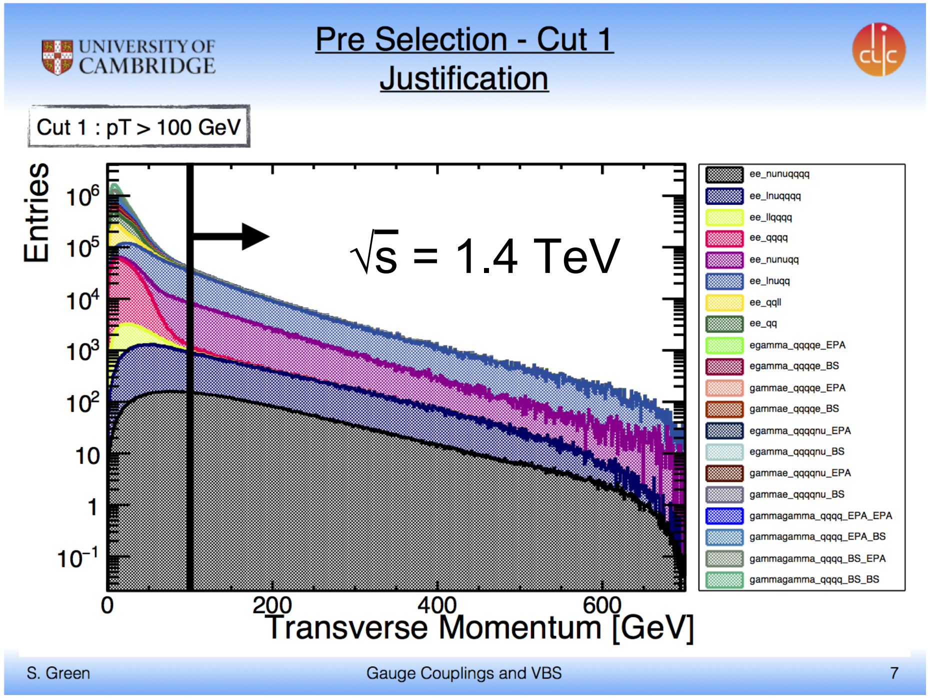
Vector boson scattering

• Vector boson scattering is sensitive to new physics in the Higgs sector
• Search for additional resonances or anomalous couplings

→ see talk by Wolfgang Kilian



Study based on full detector simulation in advanced stage
→ 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



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, $e^+e^- \rightarrow \gamma\gamma$,
vector boson scattering)

- Many interesting topics not covered yet!

Backup slides

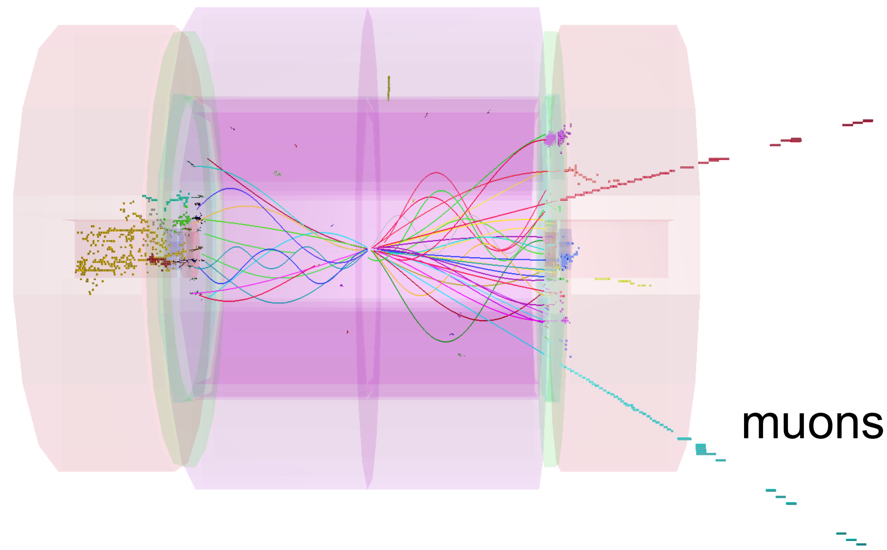
The simplest case: sleptons at 3 TeV

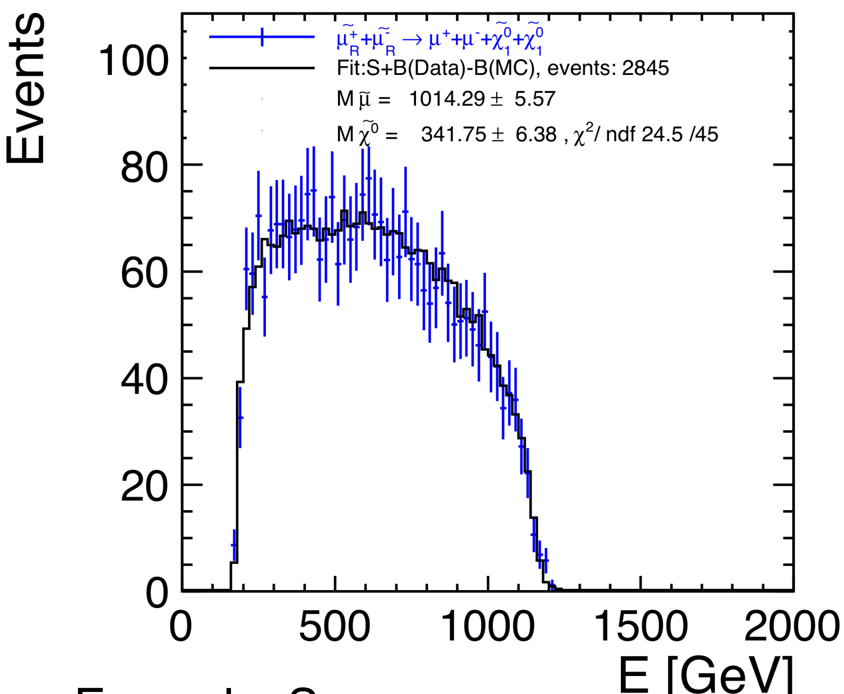
- Slepton production very clean at CLIC
- Slepton masses ≈ 1 TeV
- Investigated channels include:

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

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

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





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

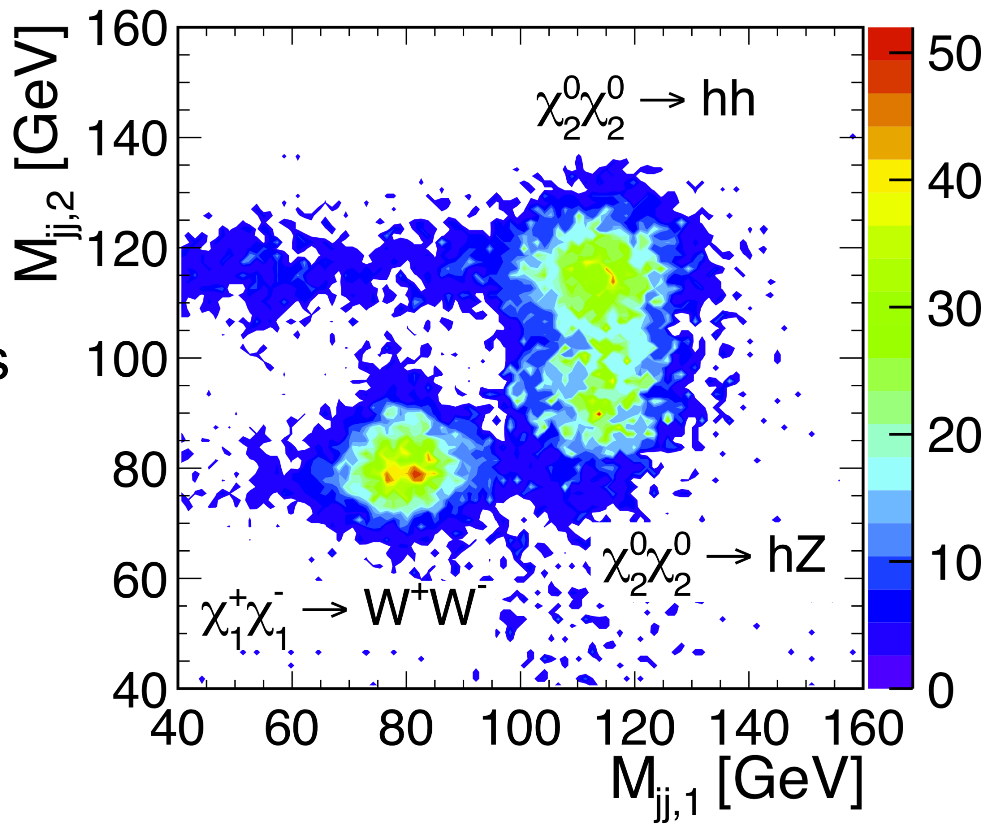
Hadronic final states: gauginos at 3 TeV

Chargino and neutralino pair production:

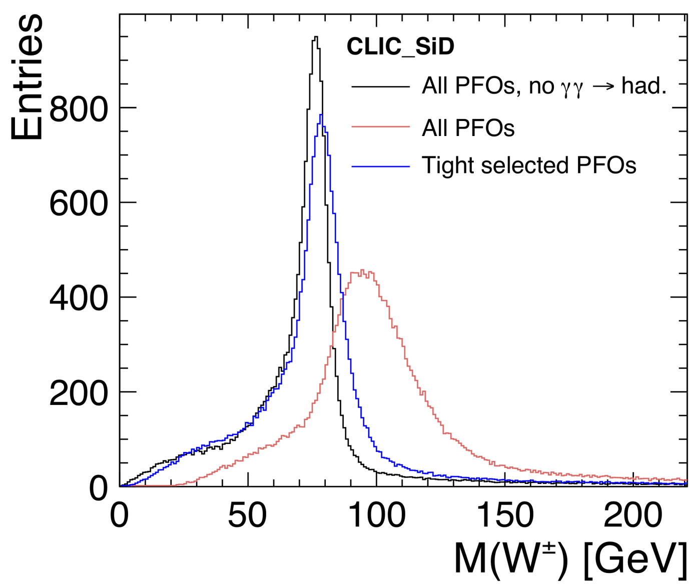
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

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

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



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

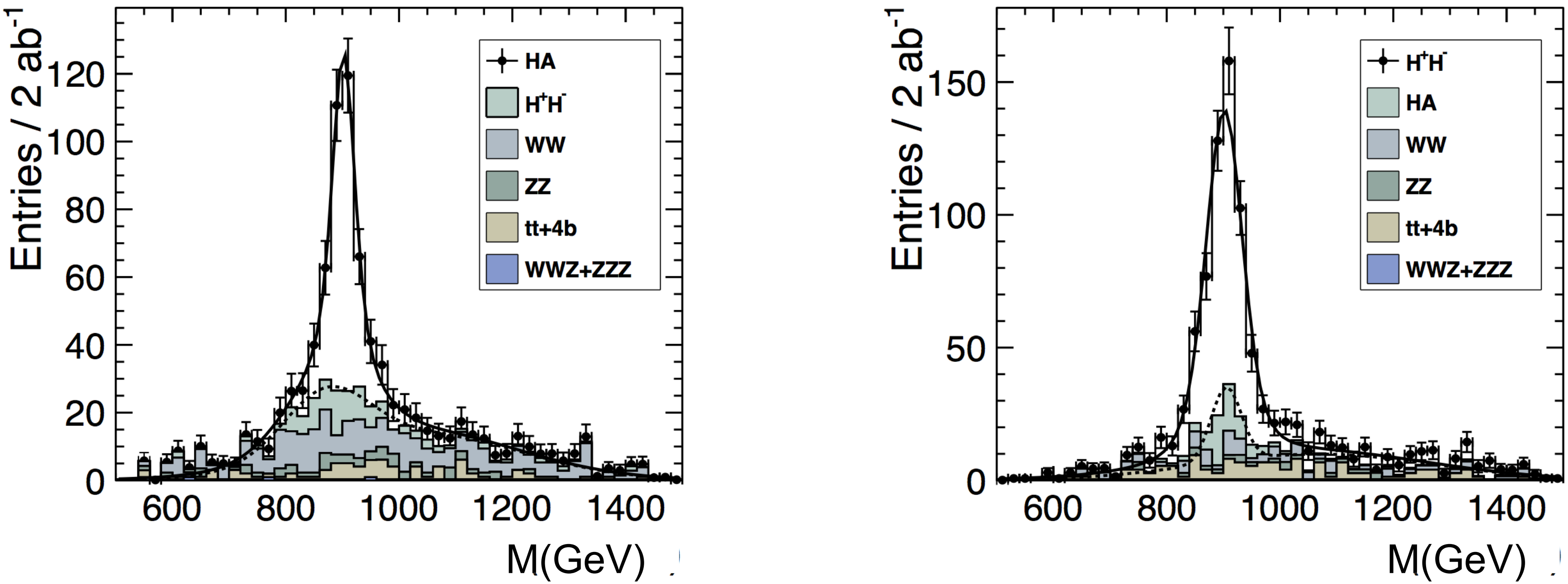
Heavy Higgs bosons:

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

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

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

Complex final states



Accuracy of the heavy Higgs mass measurements: ≈0.3%