Direct and indirect BSM searches at CLIC

CLICdp Advisory Board meeting, 17 April 2018

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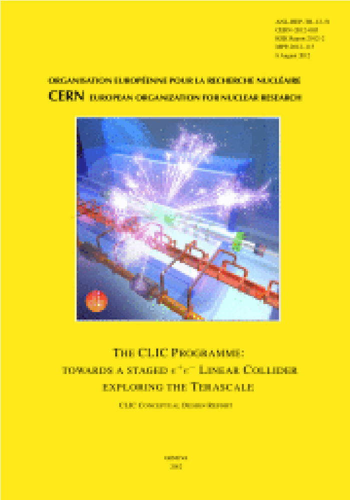
on behalf of the CLICdp collaboration

Overview

Direct searches:

• Many studies of SUSY particle production performed in 2010-2012 for the CDR

• Selection of channels also driven by the aim to benchmark the detector concepts



Indirect sensitivity of precision measurements:

• Main focus of the full simulation studies in CLICdp since 2013: top and Higgs physics (discussion of BSM potential included in this talk)
→ see the previous two presentations

• Other electroweak processes investigated recently:
$e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \gamma\gamma$, vector boson scattering and $e^+e^- \to W^+W^-$

Direct searches for new particles

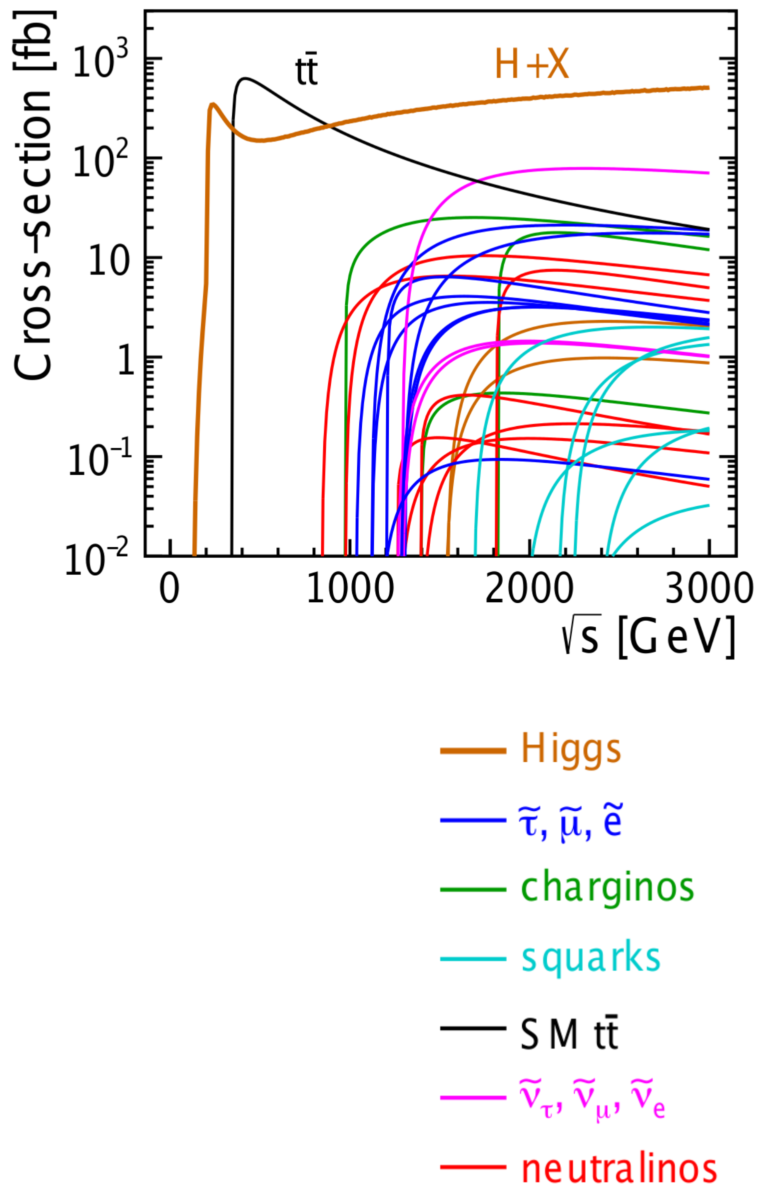
Direct searches

- Direct observation of new particles coupling to γ*/Z/W
→ precision measurement of new particle masses and couplings

- The sensitivity often extends up to the kinematic limit
(e.g. $M \leq \sqrt{s} / 2$ for pair production)

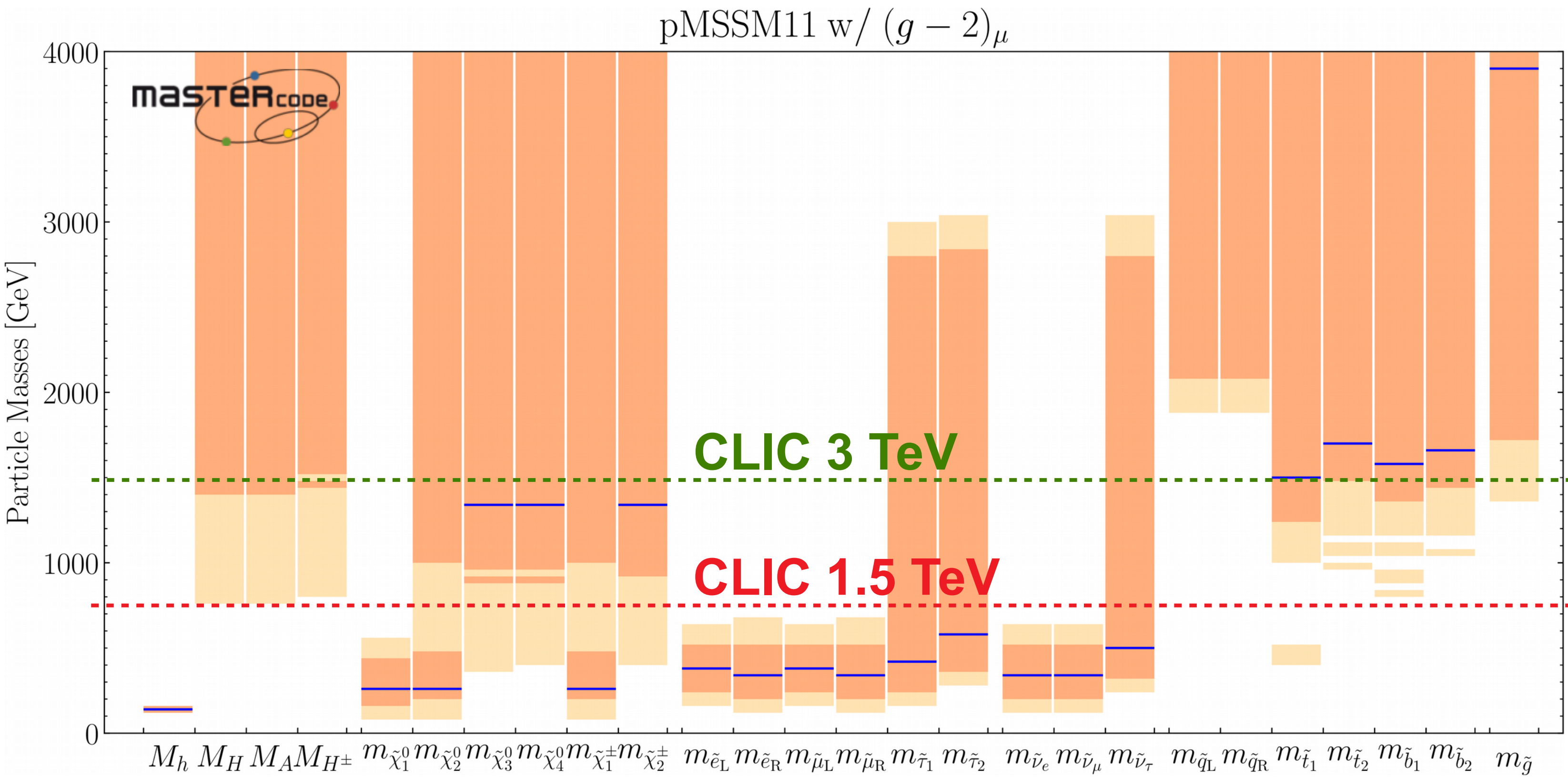
- Very rare processes accessible due to low backgrounds (no QCD)
→ CLIC especially suitable for electroweak states

- Polarised electron beam and threshold scans might be useful to constrain the underlying theory



Direct observation of sparticles

Example: Phenomenological MSSM with 11 parameters



Blue lines: best fit values

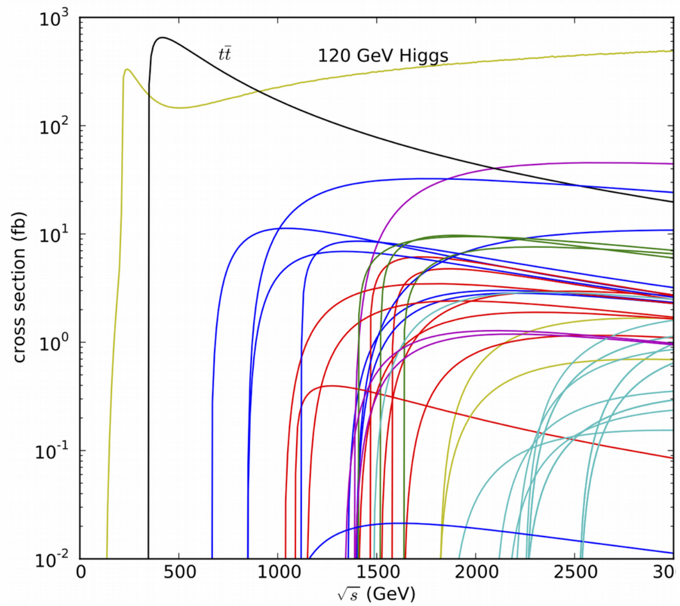
Orange bands: 68% & 95% CL ranges

arXiv:1710.11091

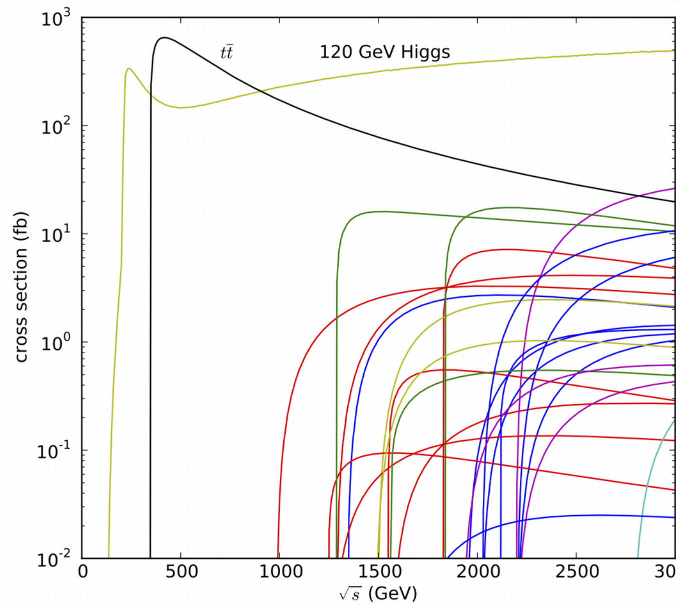
- Global fit to current experimental data (LHC results, low-energy and flavour experiments, CDM measurements)
- In this model, many gaugions and sleptons are accessible at CLIC, stop and sbottom are possible

→ Direct discoveries are (still) a main motivation for high-energy CLIC operation

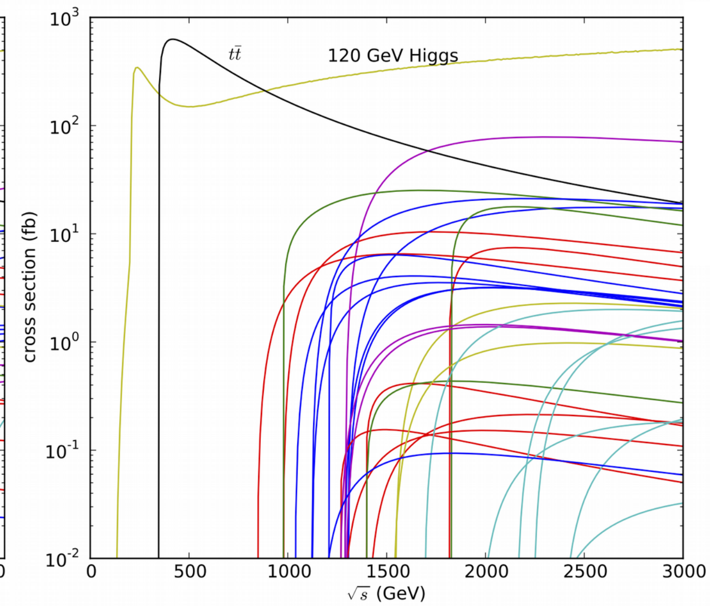
Investigated SUSY models



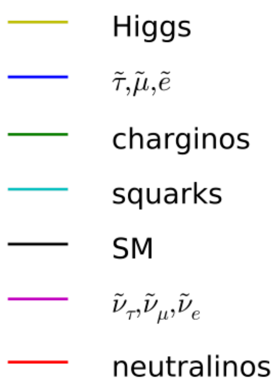
CDR Model I, 3 TeV:
- Squarks
- Heavy Higgs



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



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



- Typical pair production cross sections for EW SUSY particles: 1 - 10 fb^{-1} → thousands to tens of thousands of events
- **Wider applicability than only SUSY:** Reconstructed particles can be classified simply as states of given mass, spin and quantum numbers

CERN-2012-003
CERN-2012-005

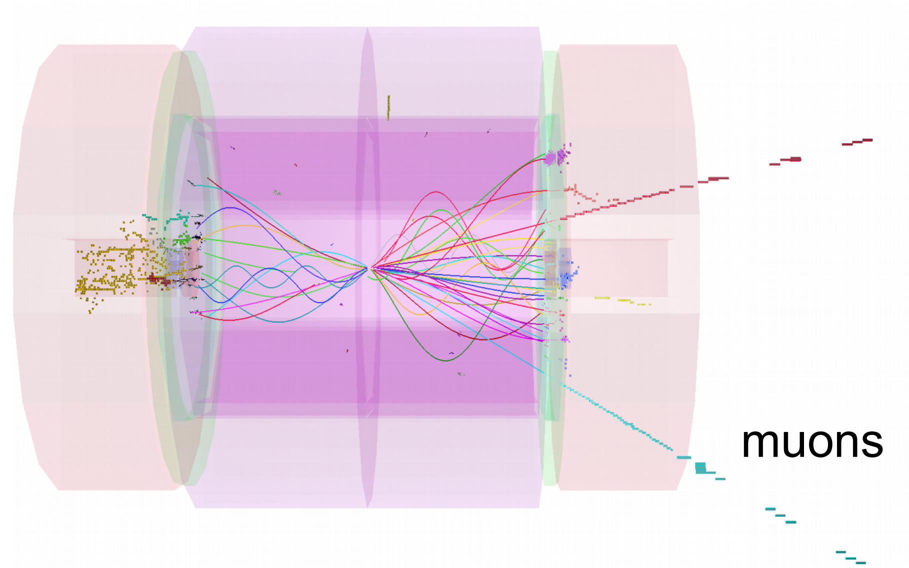
The simplest case: sleptons at 3 TeV

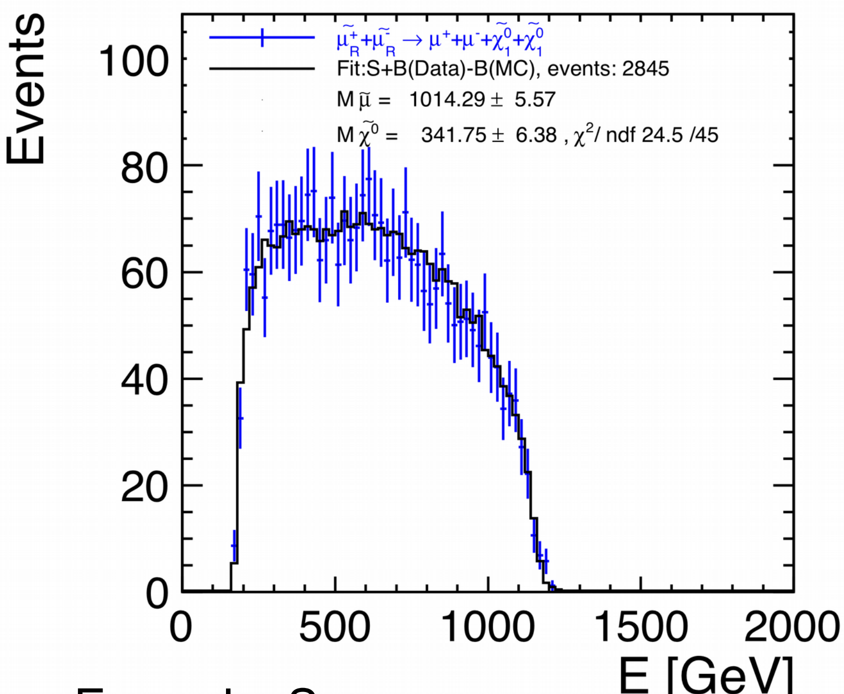
- Slepton production very clean at CLIC
- Slepton masses ≈ 1 TeV
- Investigated channels include:

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

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

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





Example: Smuons

- Leptons and missing energy
- Masses from endpoints of energy spectra
- Precisions of a few GeV achievable

$m(\tilde{\mu}_R)$	:	± 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

JHEP 09, 001 (2013)

Hadronic final states: gauginos at 3 TeV

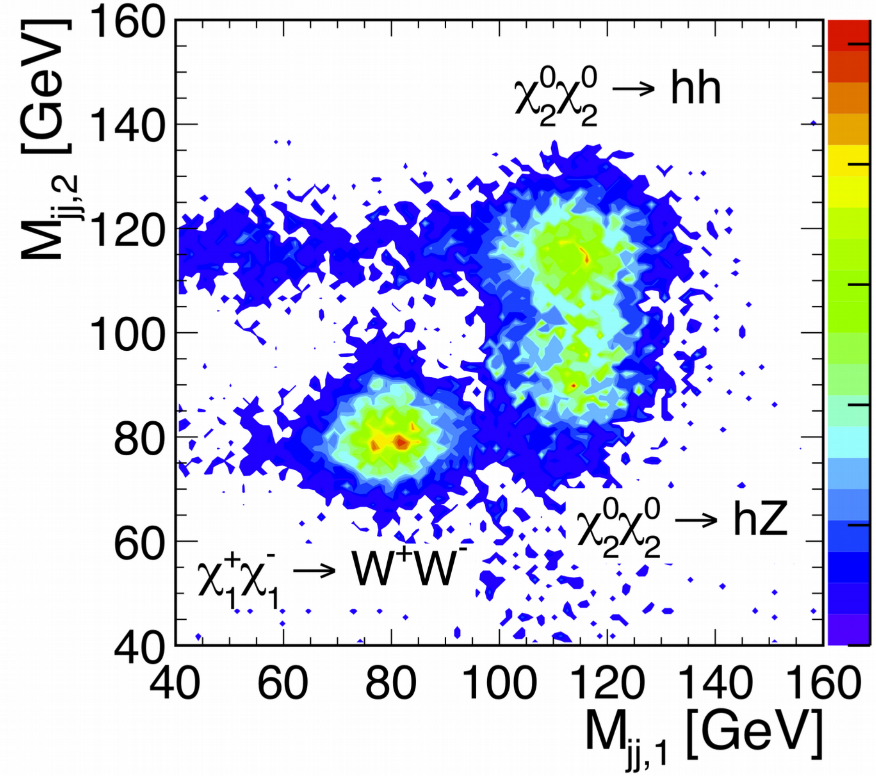
Chargino and neutralino pair production:

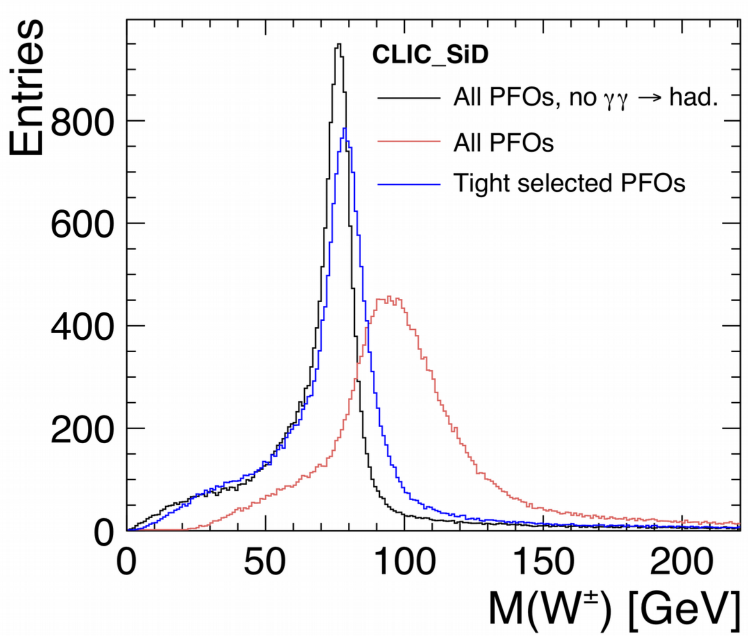
$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$

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

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

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





$M(\tilde{\chi}_1^0)$ = 340.3 GeV

$M(\tilde{\chi}_2^0)$ = 643.1 GeV

$M(\tilde{\chi}_1^+)$ = 643.2 GeV

Achieved precisions on these masses: 1-1.5%

LCD-Note-2011-037

Heavy Higgs bosons at 3 TeV

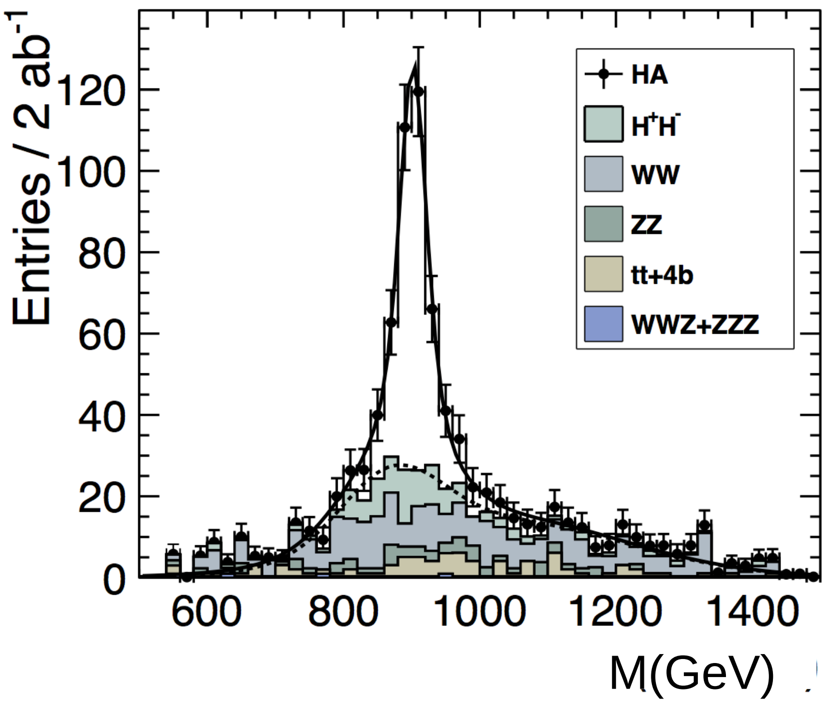
Heavy Higgs bosons:

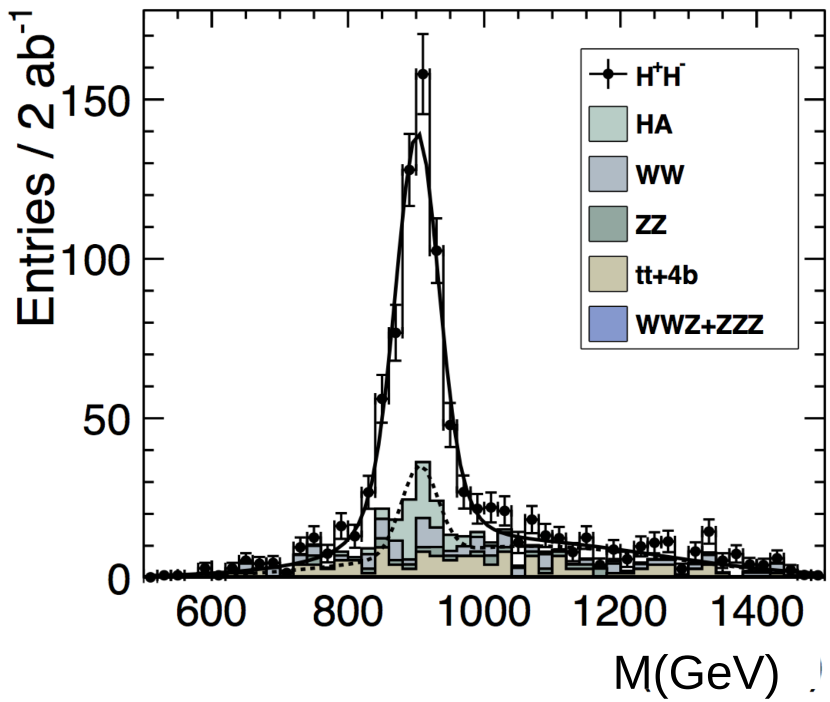
$e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$

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

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

Complex final states





Accuracy of the heavy Higgs mass measurements: ≈0.3%

CERN-2012-003

Summary of CDR SUSY studies

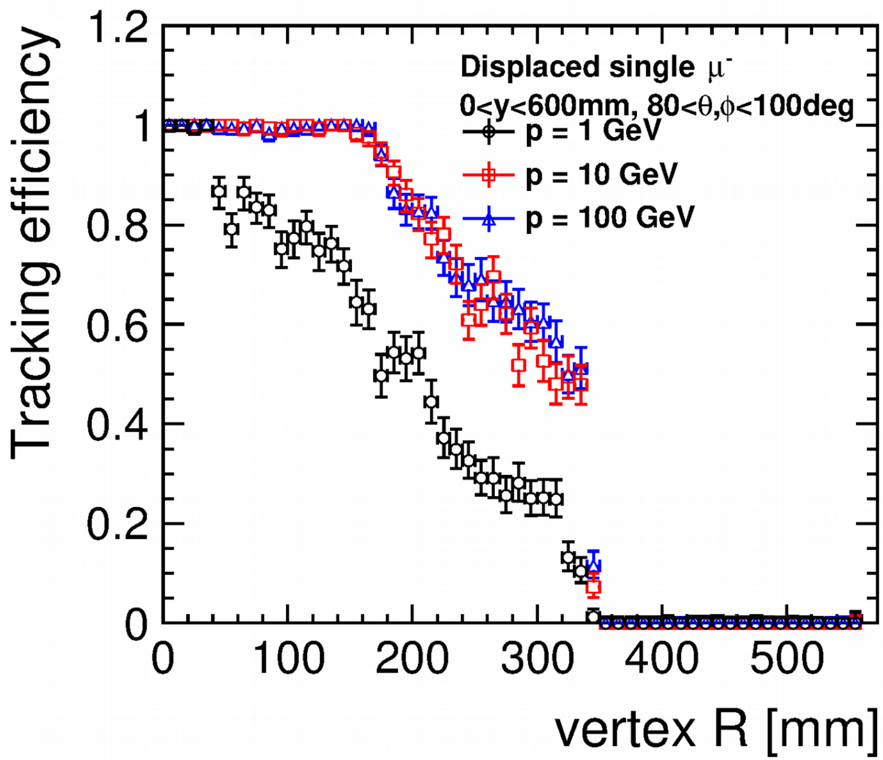
$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ 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%

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

CERN-2012-003
CERN-2012-005

What about displaced signatures?

Tracking efficiencies for displaced central tracks

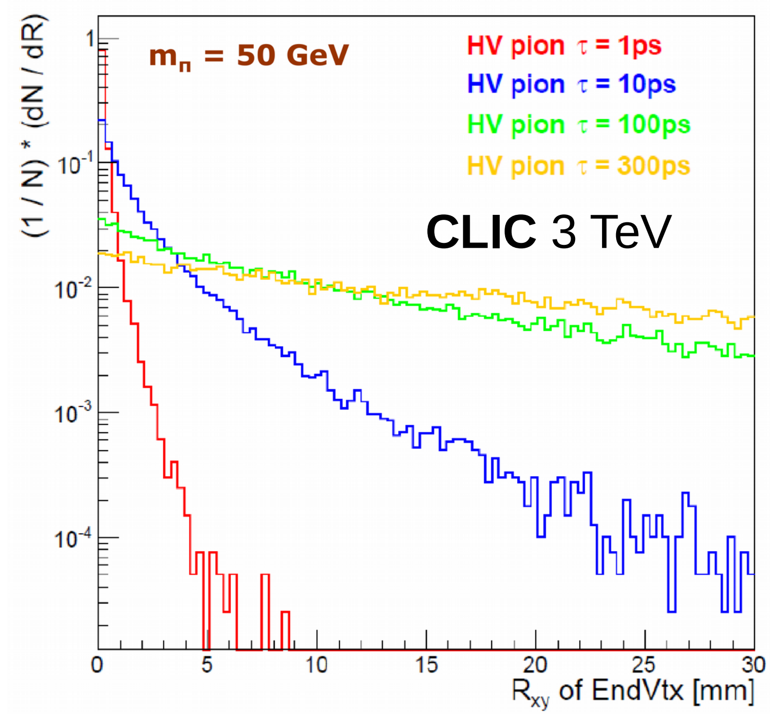


- The efficiencies decrease towards larger R as 5 hits are required
- Longer lifetimes accessible in the forward region

→ see the detector overview talk

Example application: hidden valley searches using Higgs decays

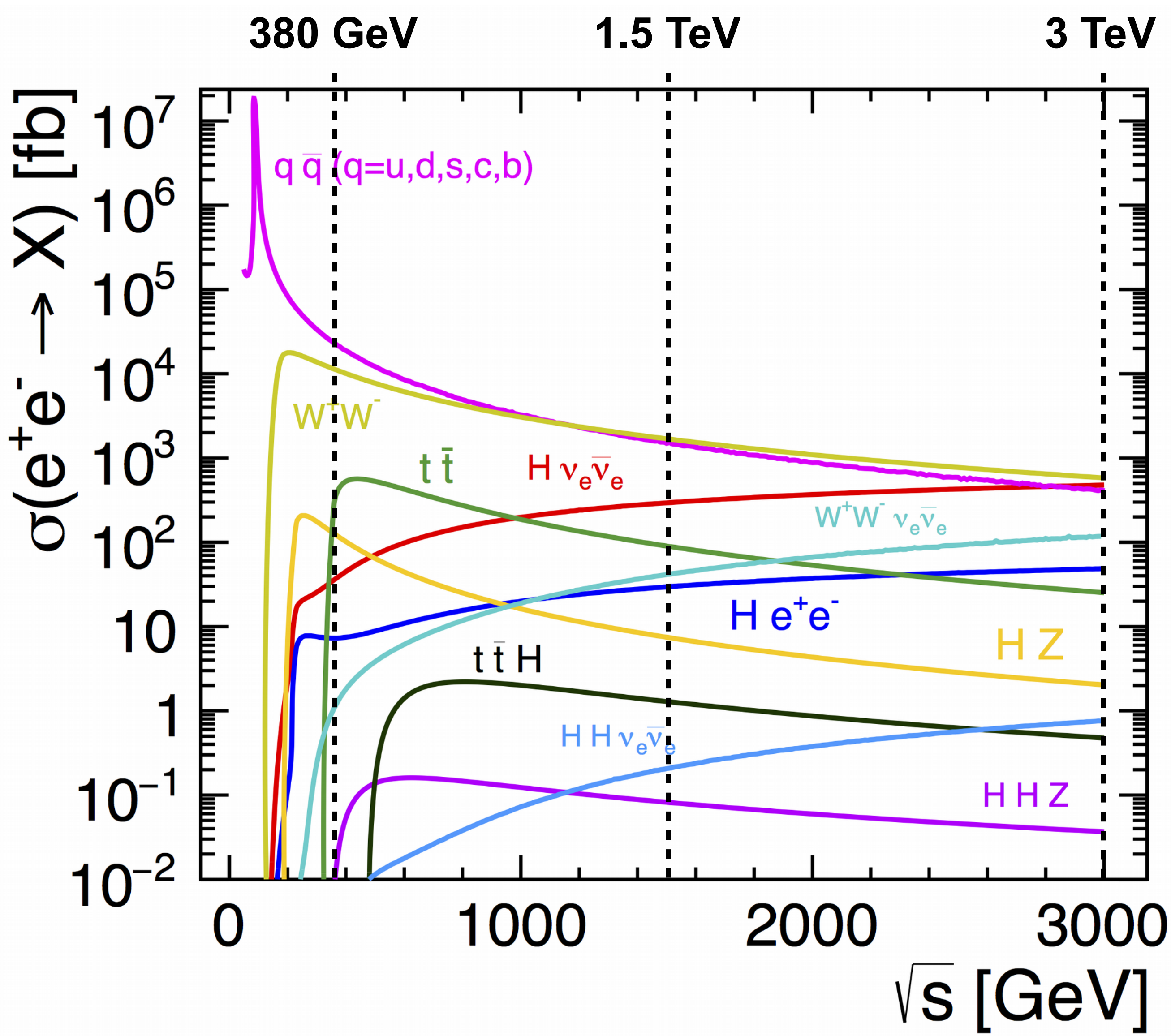
$e^+e^- \to H\nu_e\bar{\nu}_e$; $H \to \pi_V\pi_V \to b\bar{b}b\bar{b}$



Many other interesting possibilities to be explored...

BSM potential of Higgs production & $e^+e^- \to W^+W^-$

Standard Model processes at CLIC



$e^+e^- \rightarrow$ 2 particles:
σ decreases with $\sqrt{s}$

Vector boson fusion & scattering:
σ increases with $\sqrt{s}$

Effective Field Theory

Standard Model

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Dimension-6 operators

Scale of new decoupled physics

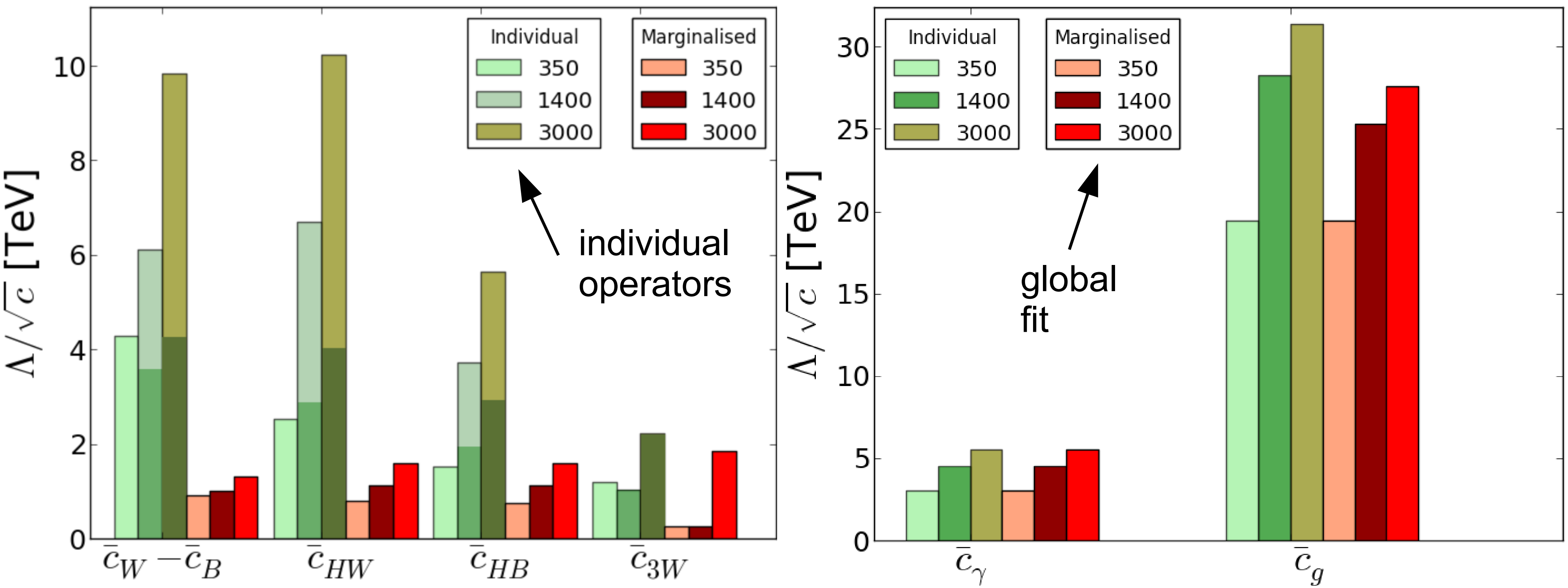
- Model-independent framework for probing indirect signs of new physics
→ very useful for comparison of future collider options / parameters

- **Input to fits:** Higgs production in Higgsstrahlung and WW fusion,
$e^+e^- \rightarrow t\bar{t}H$, weak boson pair production: $e^+e^- \rightarrow W^+W^-$

→ see the previous talk for a similar interpretation of top pair production

CLIC sensitivities to dimension-6 operators

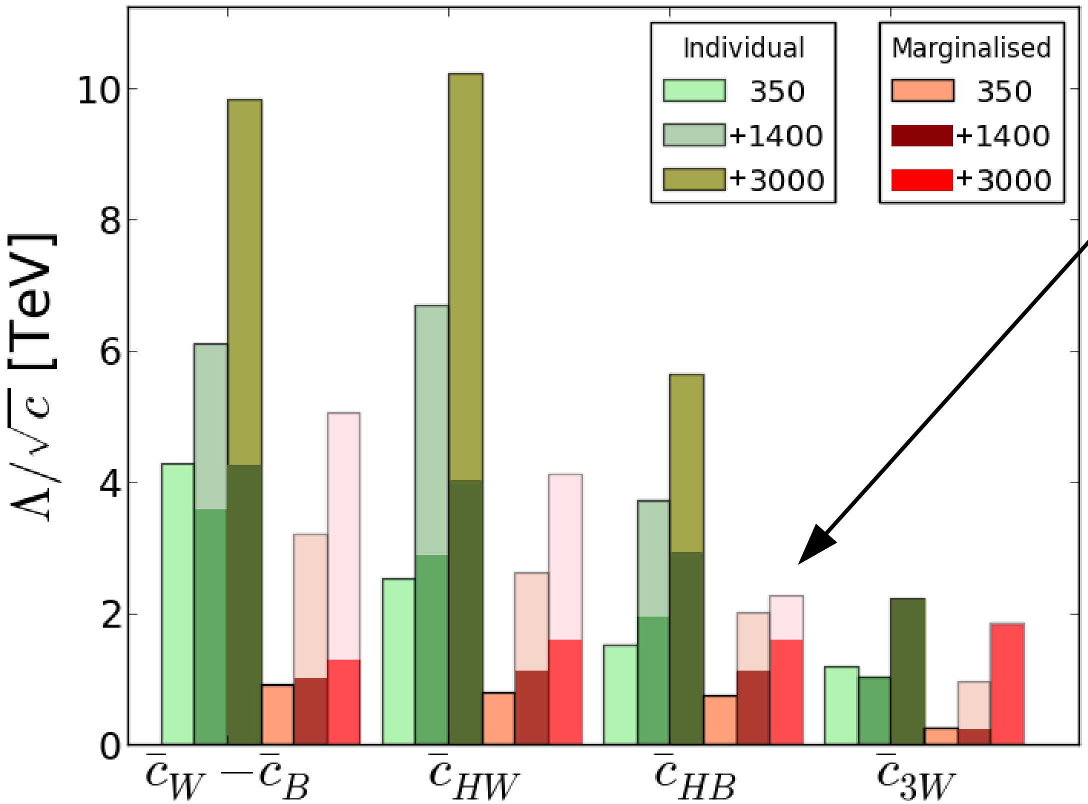
Individual energy stages



- EFT analysis of Higgs and W^+W^- production
- Lighter (darker) green bars include (omit) Higgsstrahlung at high energy
- Precision enhanced by higher centre-of-mass energy
- Sensitivity to new physics scales Λ=O(10) TeV for individual operators, reduces to O(1) TeV for global fit

JHEP 05, 096 (2017)

Full CLIC programme



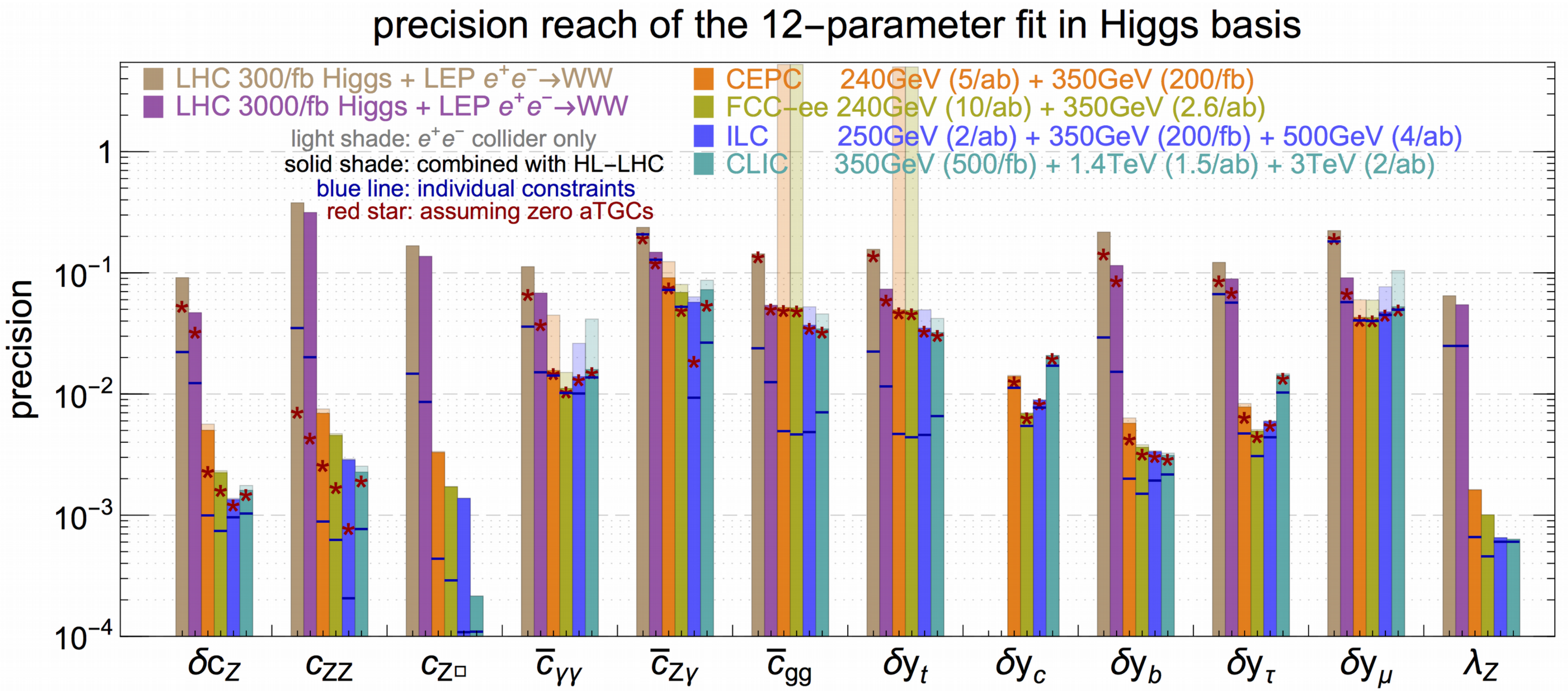
Combination of successive energy stages

→ The global fit benefits from the inclusion of earlier energy stages

- EFT analysis of Higgs and W^+W^- production

JHEP 05, 096 (2017)

Comparison of different collider options



- Many EFT parameters can be measured significantly better at CLIC compared to the HL-LHC
- $H \rightarrow c\bar{c}$ is difficult at hadron colliders

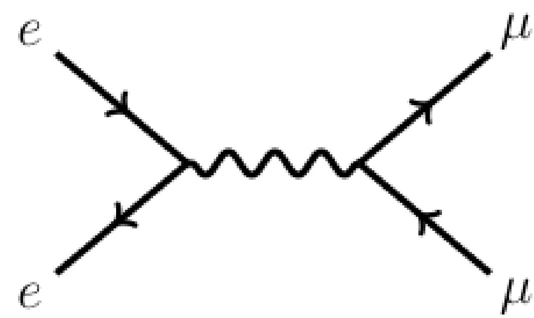
JHEP 09, 014 (2017)

NB: The luminosity projections assume different levels of optimism for the compared future collider options

Other precision EW measurements at high energy

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

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

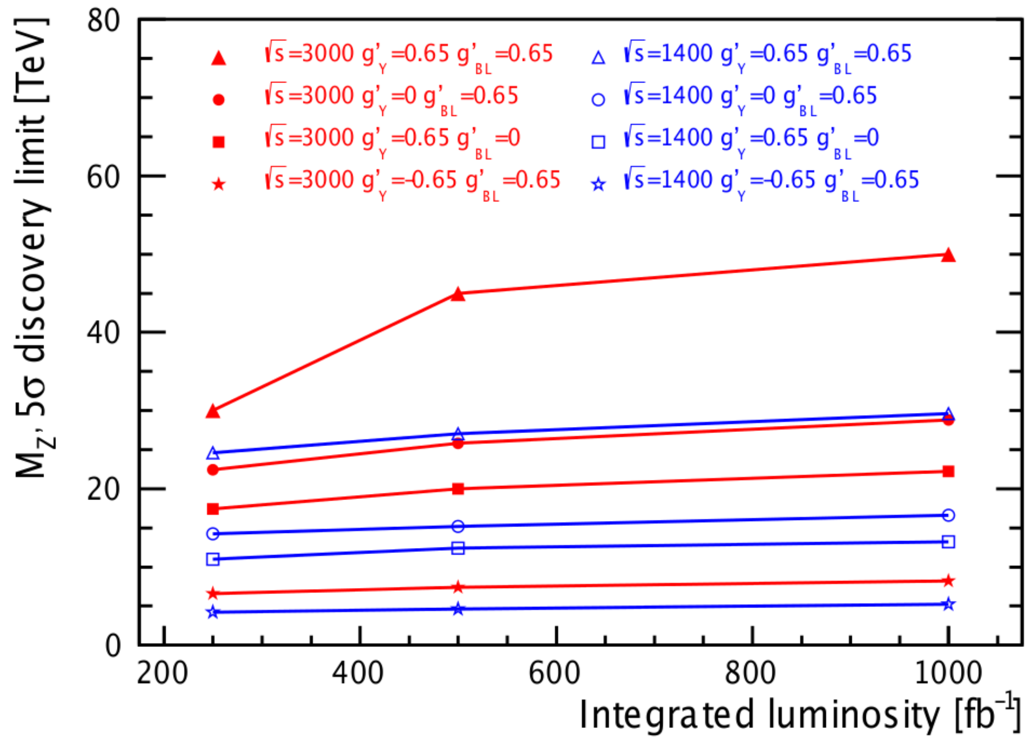


Observables:
- total $e^+e^- \to \mu^+\mu^-$ cross section
- forward-backward-asymmetry
- left-right asymmetry

(±80% e^- polarisation)

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

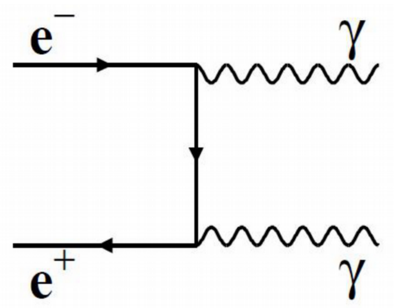
Otherwise:
Discovery reach up to tens of TeV
(depending on the couplings)



arXiv:1208.1148

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

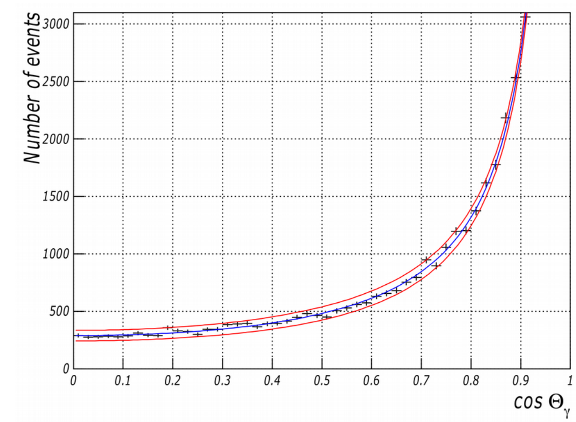
New physics searches with $e^+e^- \rightarrow \gamma\gamma$:
deviation from QED expectation



CLIC: $\sqrt{s}$ = 3 TeV, L = 2 ab^{-1}, ΔL/L = 0.5%

Example: QED cutoff parameter Λ

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



Scenario:	CLIC reach (95% CL):	LEP limit (95% CL):
QED cutoff parameter Λ (electron size)	6.33 TeV ($3.1 \cdot 10^{-18}$ cm)	≈390 GeV
Contact interactions: Λ'	20.1 TeV	≈830 GeV
Extra dimensions: $M_s/\Lambda^{1/4}$	15.9 TeV	≈1 TeV
Excited electron: M(e*)	4.87 TeV	≈250 GeV

Unique to lepton colliders, CLIC at 3 TeV factor 15 - 25 better than the LEP limits

Vector boson scattering (1)

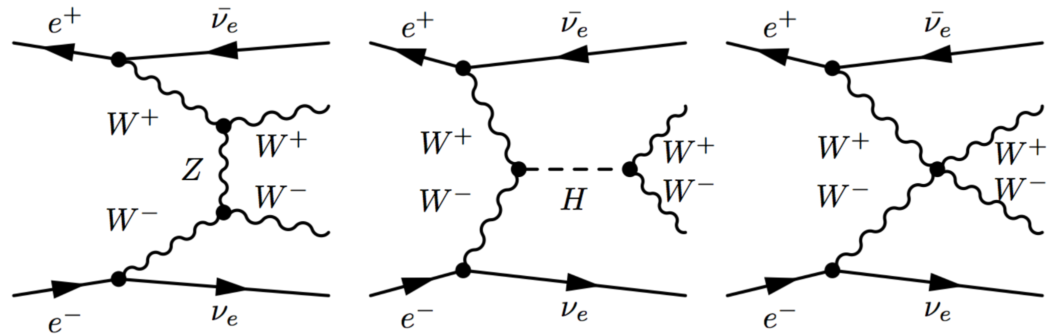
- Vector boson scattering (VBS) gives insight into the mechanism of electroweak symmetry breaking

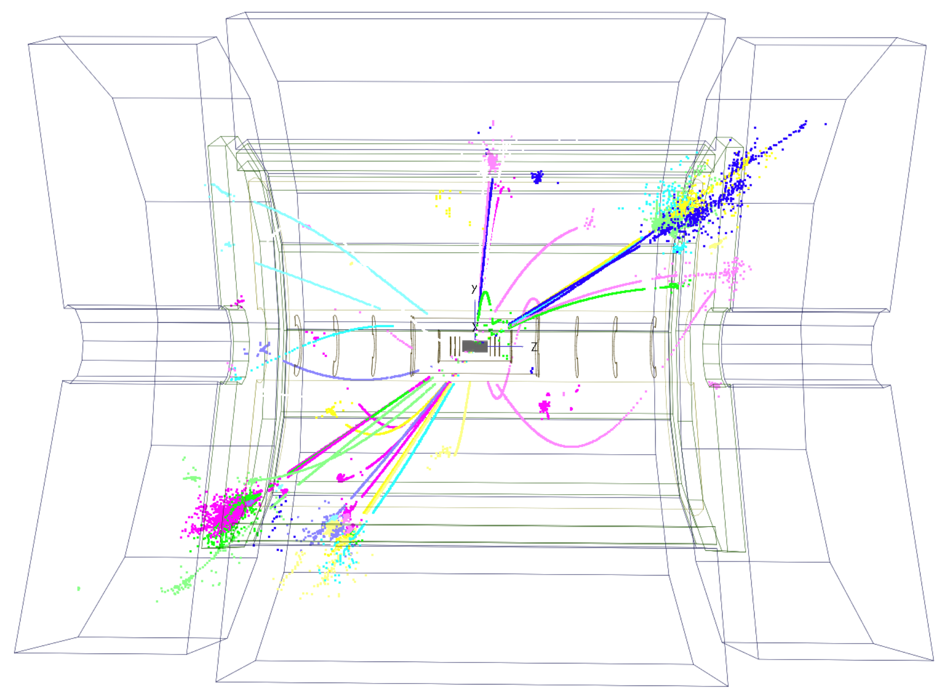
- Example processes investigated for high-energy CLIC operation:

$$e^+e^- \to W^+W^-\nu\bar{\nu}$$
$$e^+e^- \to ZZ\nu\bar{\nu}$$

- Search for additional resonances or anomalous couplings

- At CLIC fully hadronic events can be used (in contrast to hadron colliders): $W^+W^-\nu\bar{\nu}/ZZ\nu\bar{\nu} \to q\bar{q}q\bar{q}\nu\bar{\nu}$





$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$ at 1.4 TeV

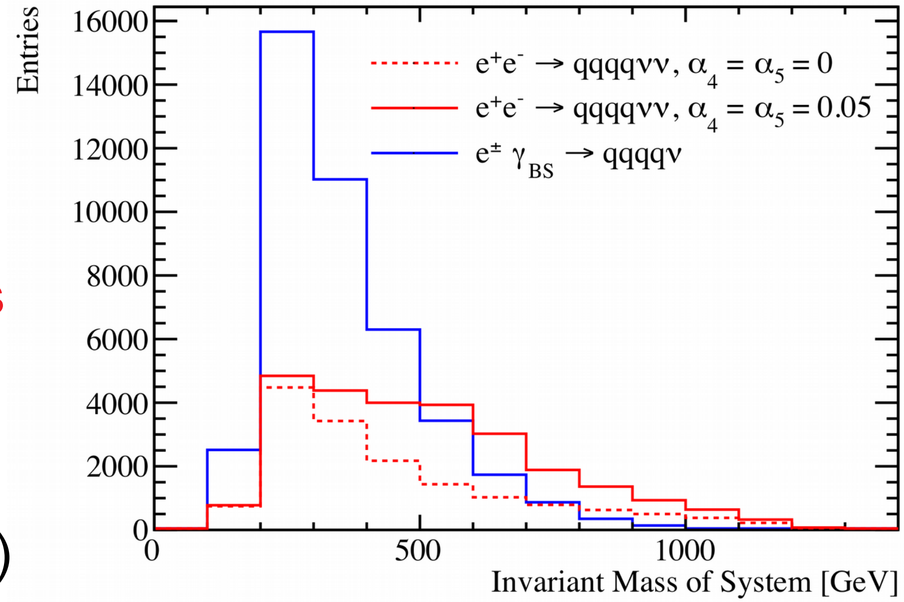
Vector boson scattering (2)

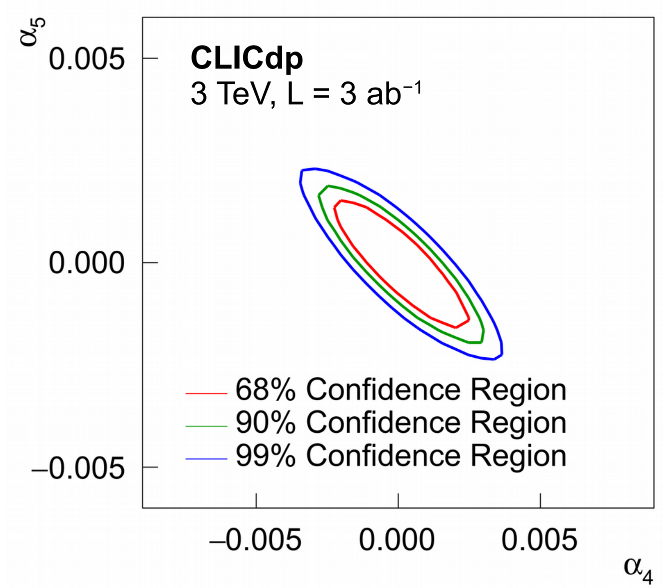
- Extract the operator coefficients α_4 and α_5 from invariant mass of the final-state bosons

- Most important background after event selection: $e^{\pm}\gamma_{BS} \rightarrow qqqq\nu$ (γ_{BS}: photon originating from Beamstrahlung)

- The sensitivities to α_4 and α_5 improve by about one order of magnitude from 1.5 to 3 TeV

- Precision expected for CLIC at 3 TeV similar to HL-LHC





Steven Green, CERN-THESIS-2017-237

Outlook and conclusions

Important future work

Example studies where full detector simulations are important for realistic estimates of the CLIC physics potential

Direct searches:

• SUSY with compressed spectra: missing energy + soft particles / leptons in the presence of beam-induced backgrounds
• Very long-lived signatures: e.g. using the imaging calorimeters → reconstruction challenge
• Mono-photon + missing energy events (ongoing work)

Precision EW measurements:

• m_W with precision of a few MeV? → systematic uncertainties
• More on multi-boson production, e.g. differential distributions for $e^+e^- \to W^+W^-$ (ongoing work), $e^+e^- \to W^+W^-Z$, ... → challenge for PFA
• 2-fermion production other than $e^+e^- \to \mu^+\mu^-/t\bar{t}$

NB: QCD measurements (e.g. α_s) also not yet investigated

Summary and conclusions

- A high-energy e^+e^- collider has excellent discovery potential for new physics through:

  - direct detection of new particles up to the kinematic limit
  - precision EW measurements, which can provide indirect sensitivity to scales of up to tens of TeV

- In many cases the sensitivity rises steeply with the centre-of-mass energy

- The flexibility of an e^+e^- linear collider (extendable energy, threshold scans, beam polarisation) might be crucial to understand possible hints for new physics seen at the HL-LHC and elsewhere

Backup slides