Higgs and BSM physics at CLIC

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on behalf of the CLICdp collaboration

The Compact Linear Collider

Future linear electron-positron collider providing high luminosity: few x 10^{34} $cm^{-2}s^{-1}$

CLIC would be implemented in energy stages, defined by physics and technical considerations

Staged construction gives access to three centre of mass energies:

- **Stage 1: 500 fb^{-1} at $\sqrt{s}$ = 350 GeV**
  - **SM Higgs and top physics, top threshold scan**

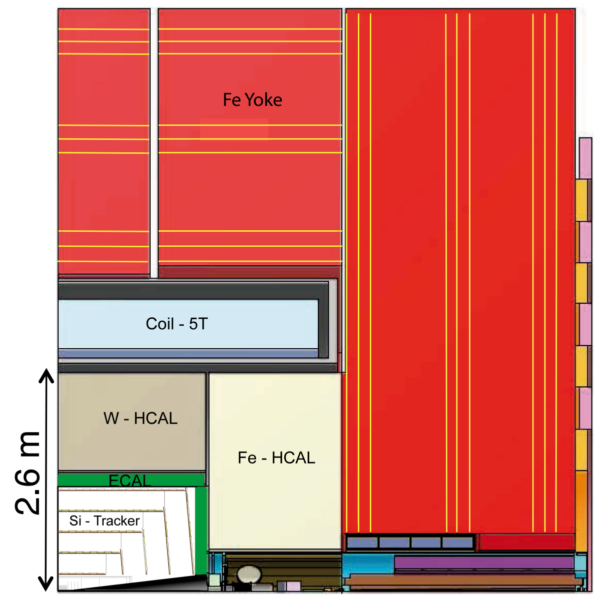
see "Top quark physics at a future linear collider" R. Poeschl

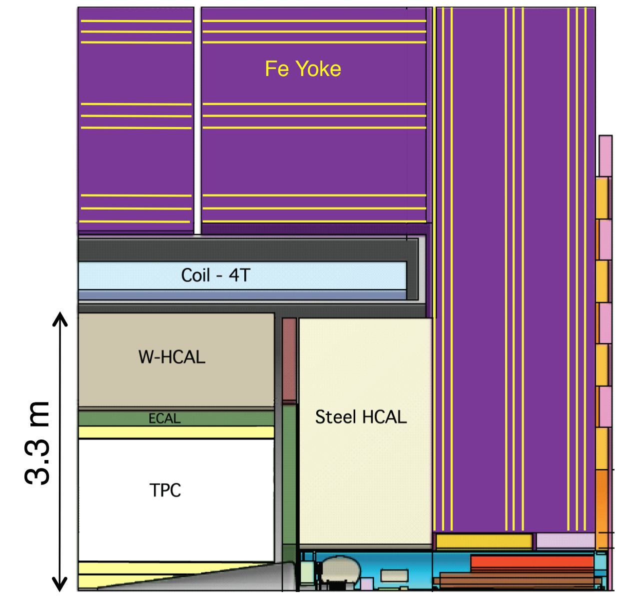
- **Stage 2: 1.5 ab^{-1} at $\sqrt{s}$ = 1.4 TeV**
  - **Improved Higgs precision, top Yukawa coupling, first BSM searches**
- **Stage 3: 2 ab^{-1} at $\sqrt{s}$ = 3 TeV**
  - **Rarest Higgs processes, double Higgs production, best BSM sensitivity**

Each stage corresponds to 4-5 years data taking

Detectors, beam conditions and backgrounds

Physics studies in this talk use the CLIC_SiD and CLIC_ILD detector concepts

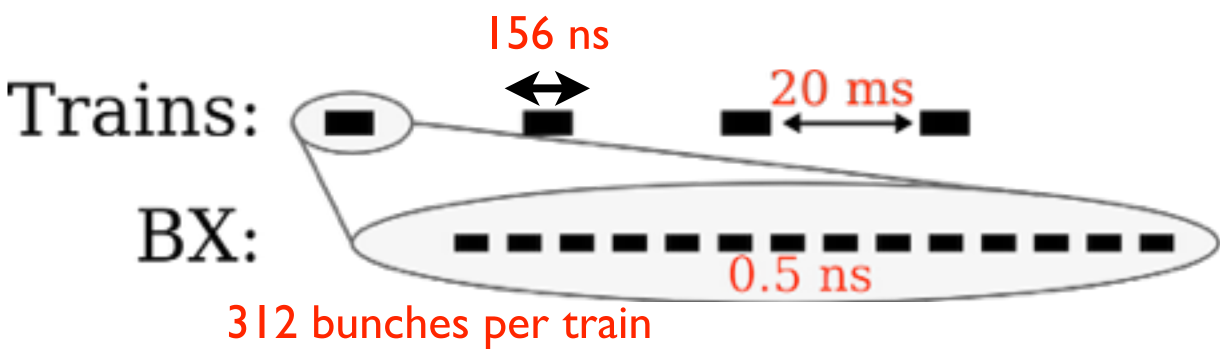




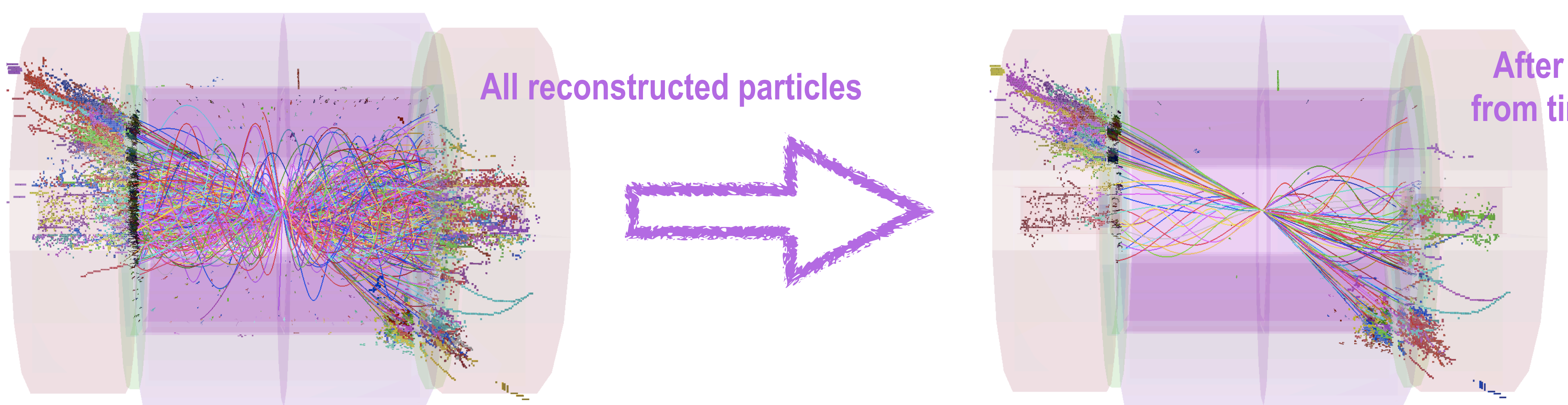
All studies use full physics and detector simulation

CLIC beams consist of short dense bunch trains

- **enables power-pulsing, triggerless readout**
- **results in pile-up of beam-induced backgrounds**

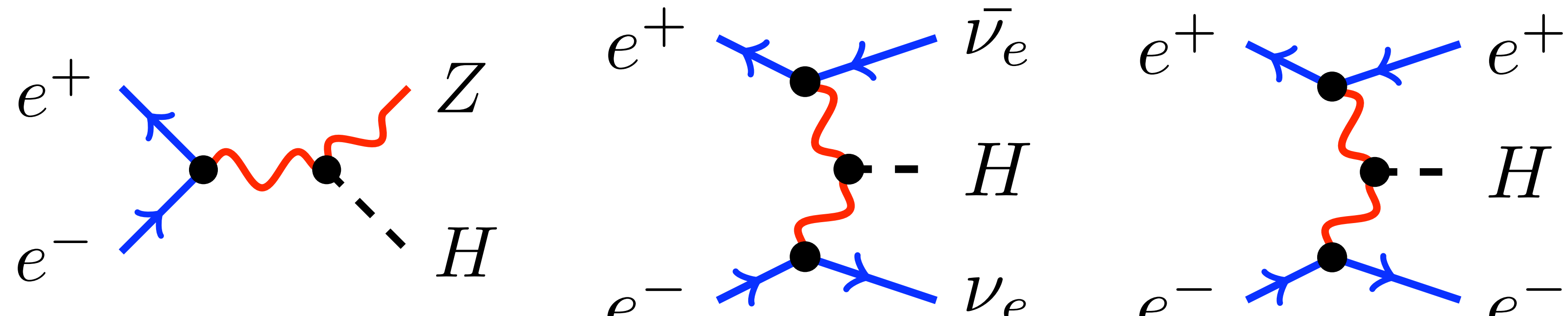


tt event plus 60 bunch crossings of beam-induced background

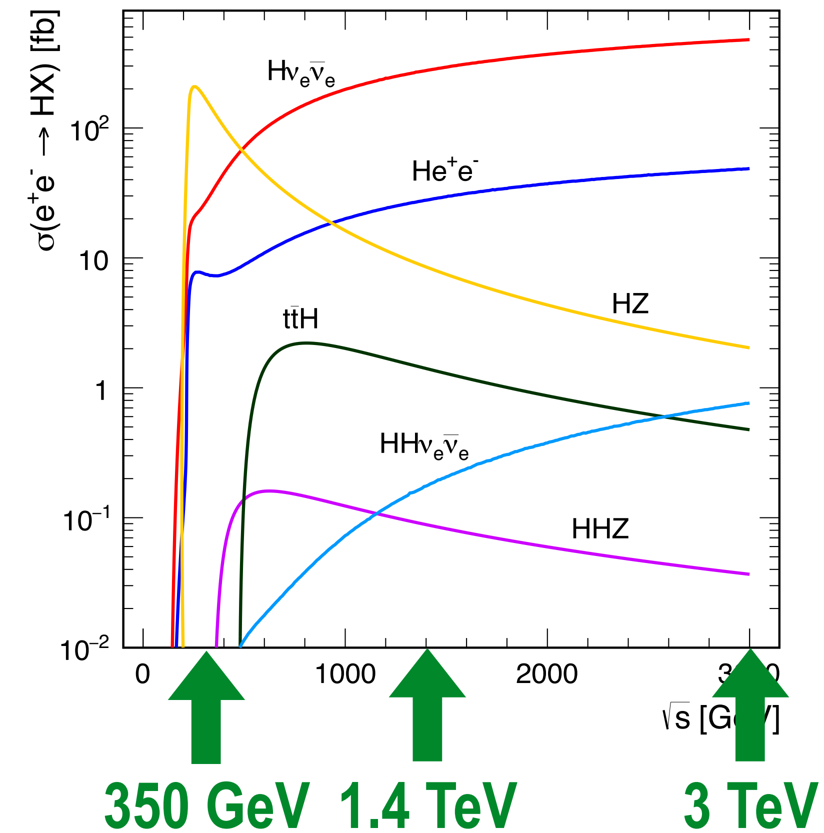


Single Higgs production at CLIC

Large samples of Higgs bosons will be produced at CLIC

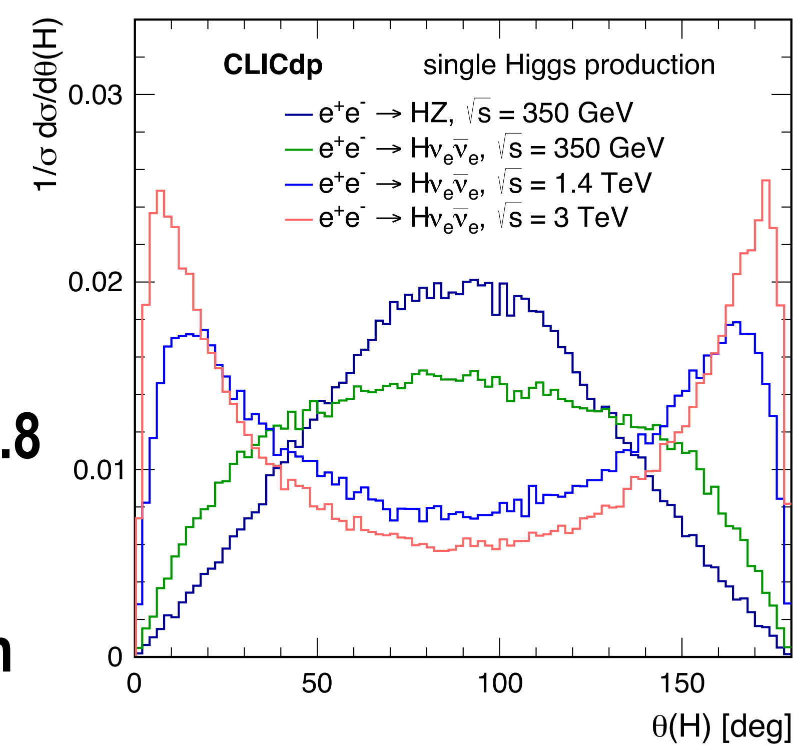


Higgsstrahlung WW-fusion ZZ-fusion



	350 GeV 500 fb-1	1.4 TeV 1.5 ab-1	3 TeV 2 ab-1
ZH	68,000	20,000	11,000
Hνν	17,000	370,000	830,000
Hee	3,700	37,000	84,000

unpolarised beams

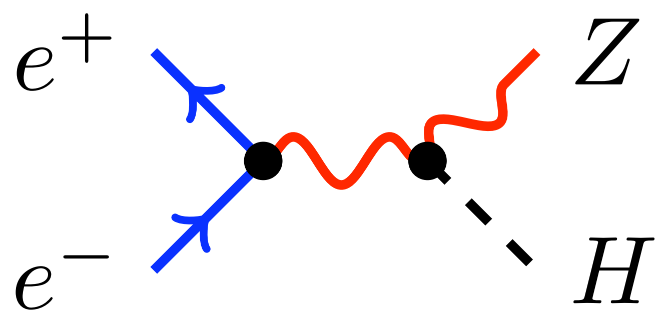


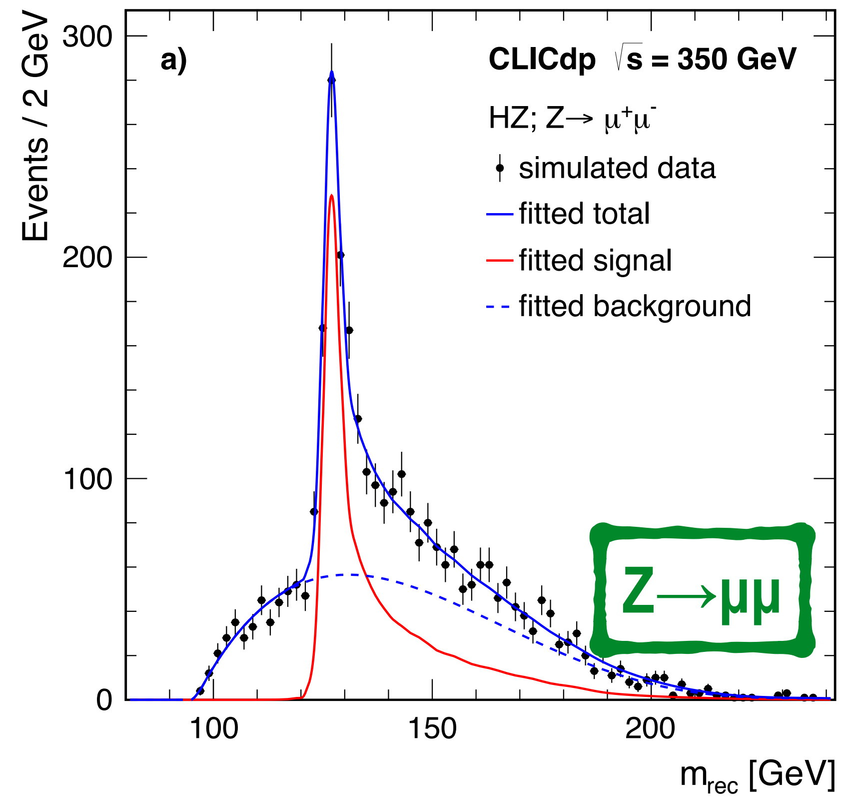
Polarising the electron beam (80%) enhances WW-fusion by a factor 1.8

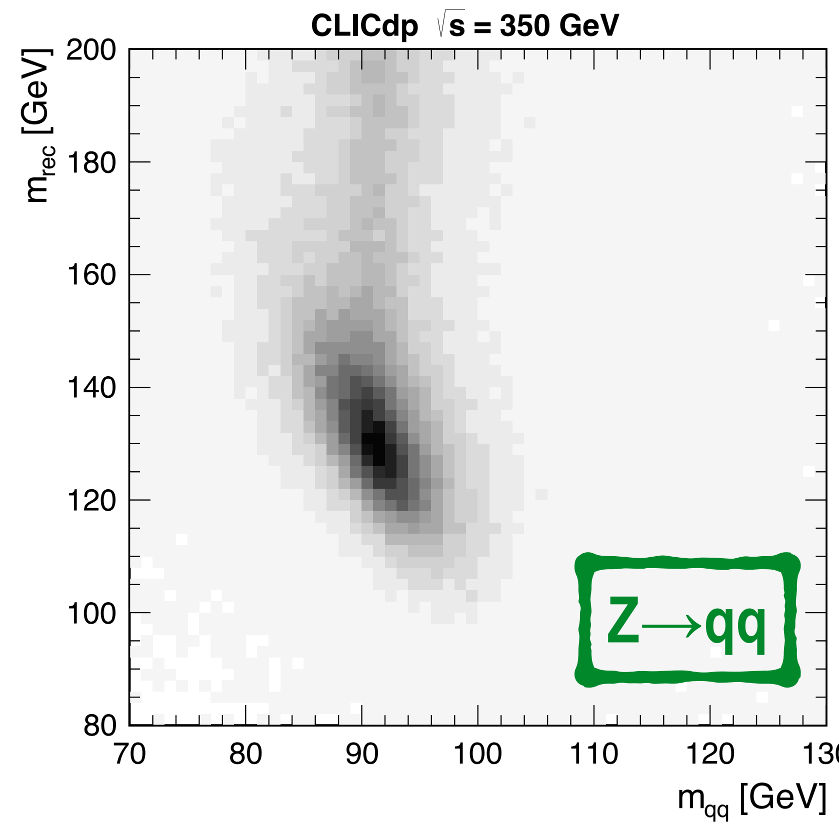
- but benchmark studies assume unpolarised beams

Measurements at high √s require good detectors in the forward region

Higgsstrahlung at √s = 350 GeV







Identify HZ events from only the Z recoil mass: model independent measurement of g_{HZZ}

- very clean for Z→μμ, ee decays: 2% uncertainty on g_{HZZ}
- also possible for hadronic Z decays with minimal bias: 0.9% uncertainty on g_{HZZ}

Combined uncertainty 0.8% on model independent measurement of g_{HZZ}

Cross section x branching ratio measurements:

- precision at few % level

Constrain the invisible Higgs decay < 1% at 90% CL

	Stat precision
σ(ZH)xBR(H→ττ)	6.2%
σ(ZH)xBR(H→bb)	1%
σ(ZH)xBR(H→cc)	5%
σ(ZH)xBR(H→gg)	6%
σ(ZH)xBR(H→WW*)	2%
σ(Hνν)xBR(H→bb)	3%

unpolarised beams

Precision Higgs measurements at √s > 1 TeV

H→bb, cc, gg

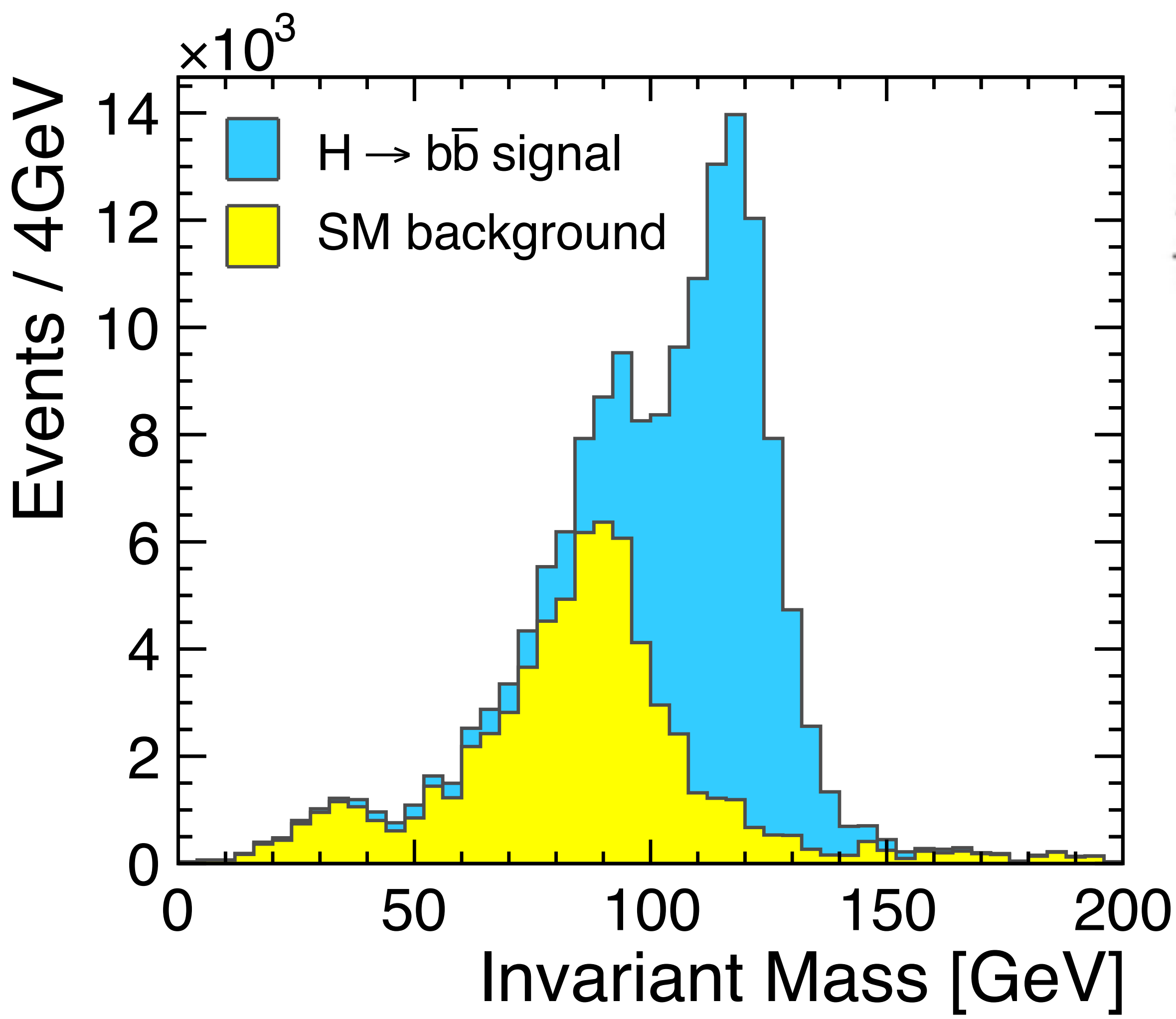
Separation of the different hadronic final states uses precise flavour tagging

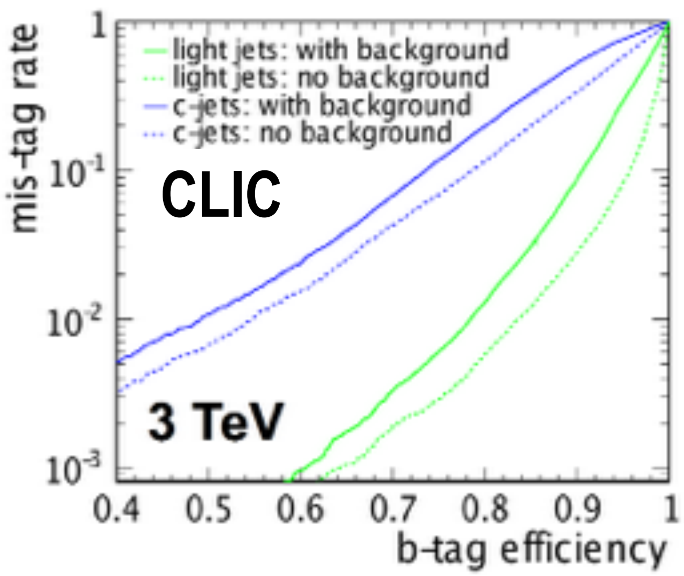
- very challenging at the LHC

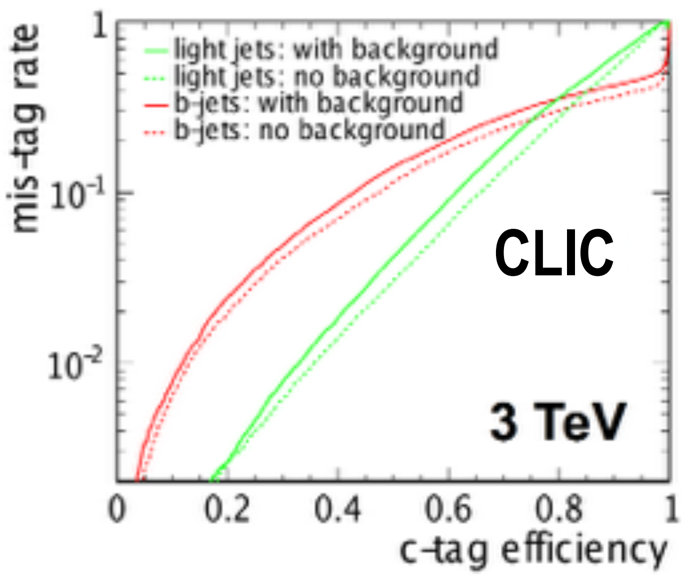
Higgs mass can be extracted from the H→bb invariant mass distribution: ±33 MeV at 3 TeV

	3 TeV
σ(Hνν)xBR(H→bb)	0.2%
σ(Hνν)xBR(H→cc)	2.7%
σ(Hνν)xBR(H→gg)	1.8%

unpolarised beams





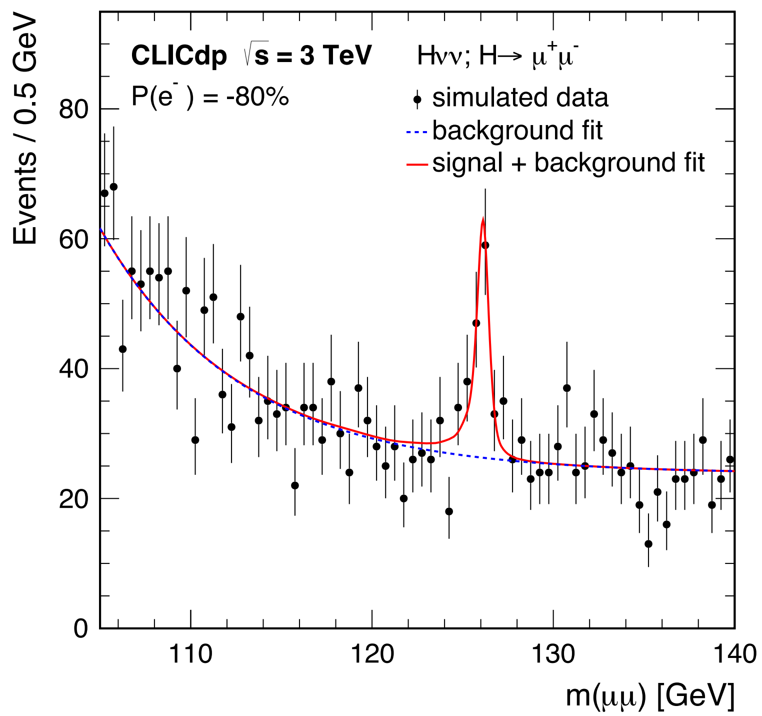


Rare Higgs decays at $\sqrt{s}$ > 1 TeV

σ(Hνν) x BR(H→μμ)

- **BR ~ 0.022%**
- **requires precise tracking**
- **38% at 1.4 TeV, 16% at 3 TeV**

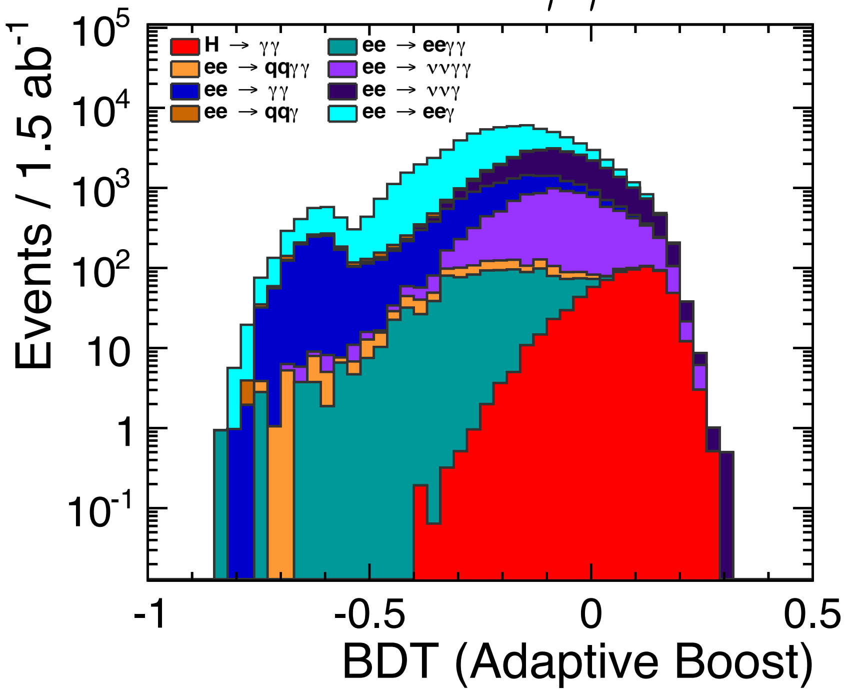
$H \to \mu^+\mu^-$



σ(Hνν) x BR(H→γγ)

- **BR ~ 0.23%**
- **reconstructed γγ mass resolution 3.3 GeV**
- **15% at 1.4 TeV**

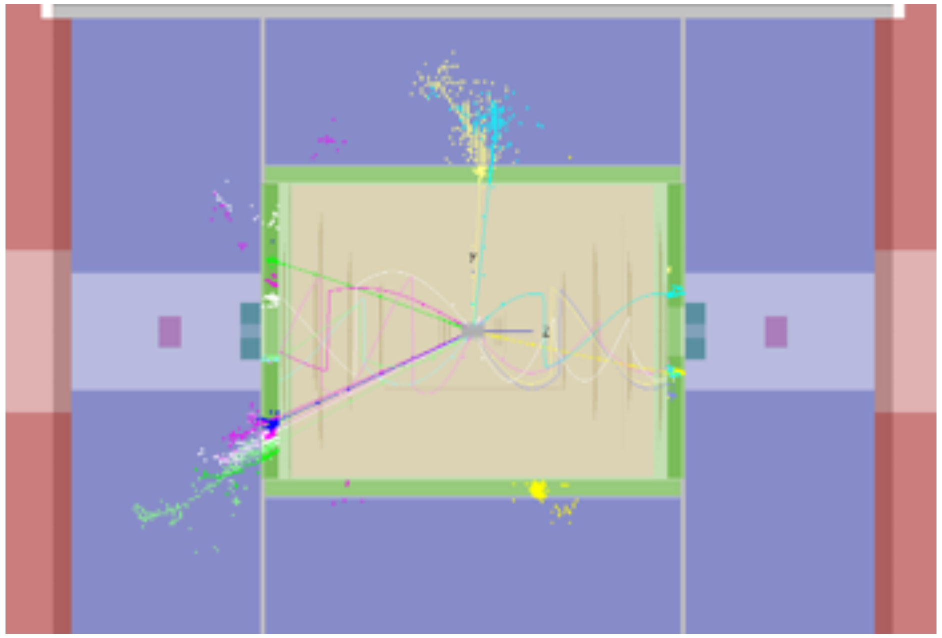
$H \to \gamma\gamma$



σ(Hνν) x BR(H→Zγ)

- **BR ~ 0.16%**
- **hadronic Z decays used**
- **42% at 1.4 TeV**

$H \to Z\gamma$



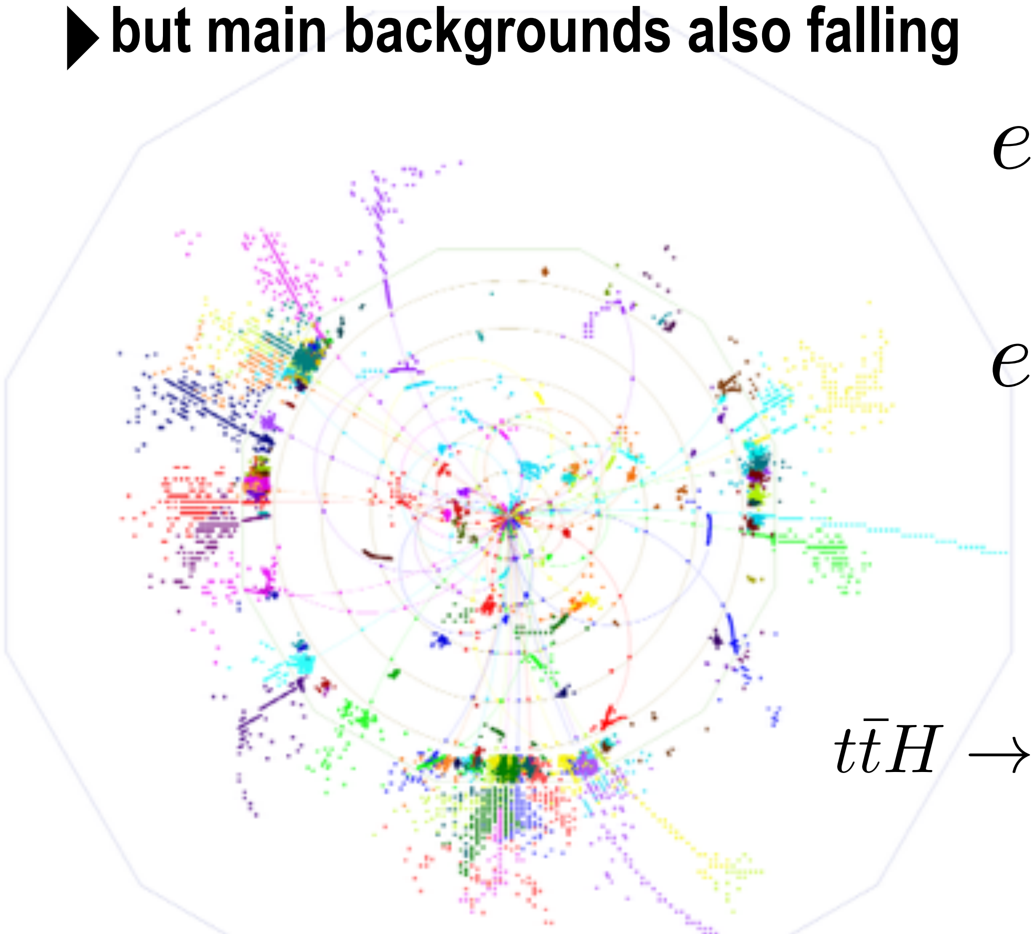
unpolarised beams

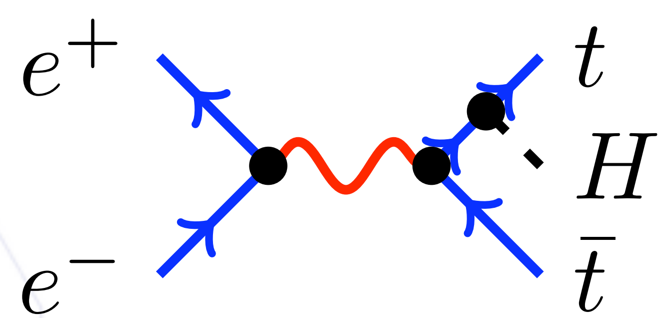
Top Yukawa coupling at √s = 1.4 TeV

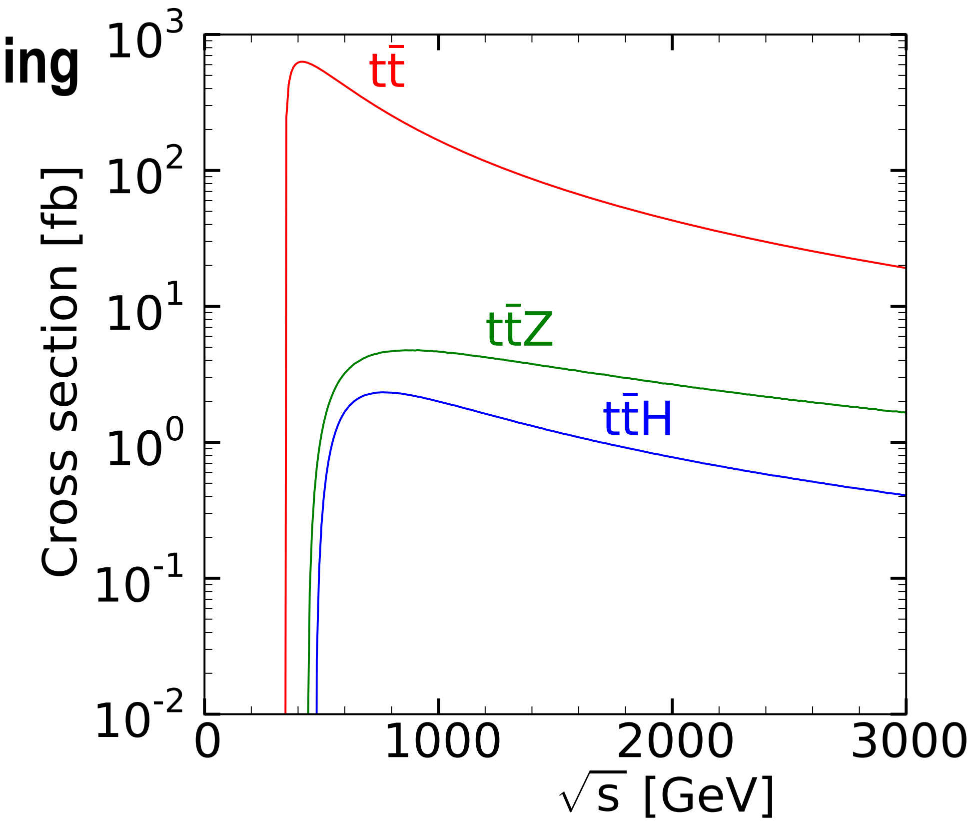
The ttH cross section is directly sensitive to the top Yukawa coupling

ttH production peaks at ~800 GeV, measured at 1.4 TeV

- but main backgrounds also falling







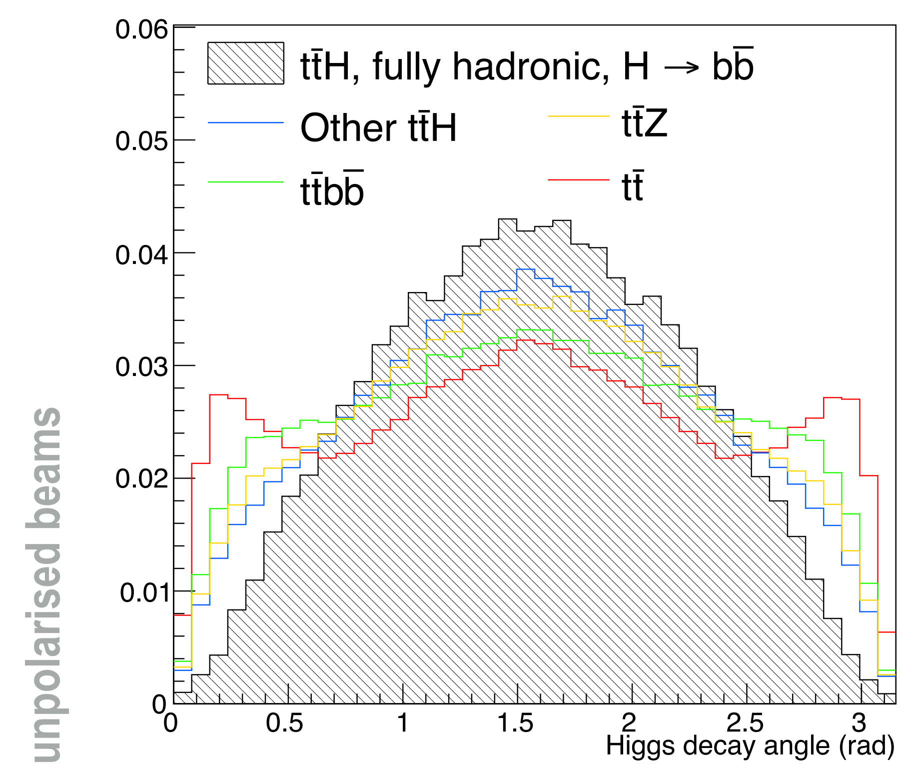
$$t\bar{t}H \rightarrow b\bar{b}b\bar{b}q\bar{q}\tau^-\bar{\nu}_\tau$$

Complex reconstruction: 8 fermions inc. 4 b-quarks

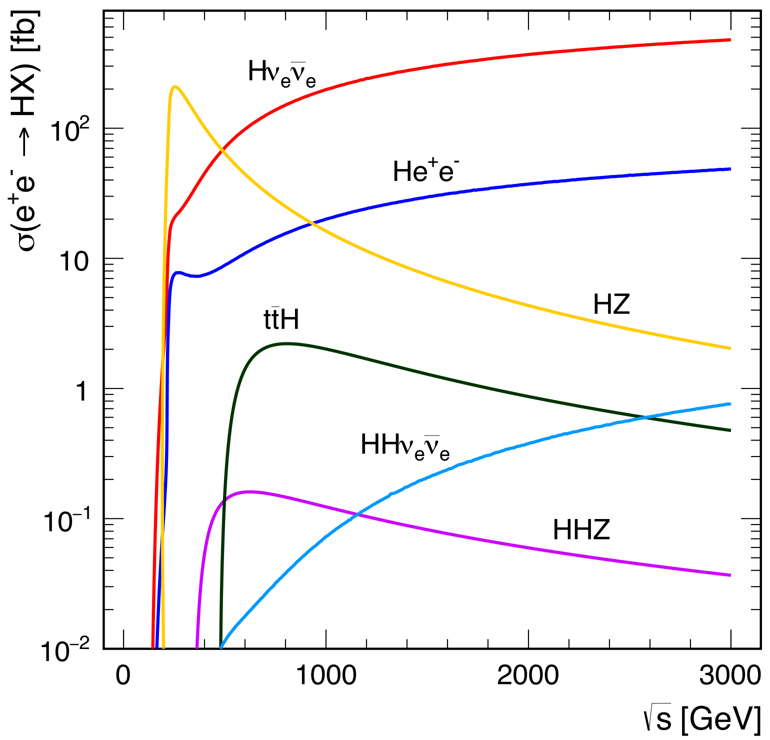
- 6 jet + lepton + missing energy final state (semi-leptonic)
- 8 jet final state (fully hadronic)

Combined uncertainty on the top Yukawa coupling 4.5%

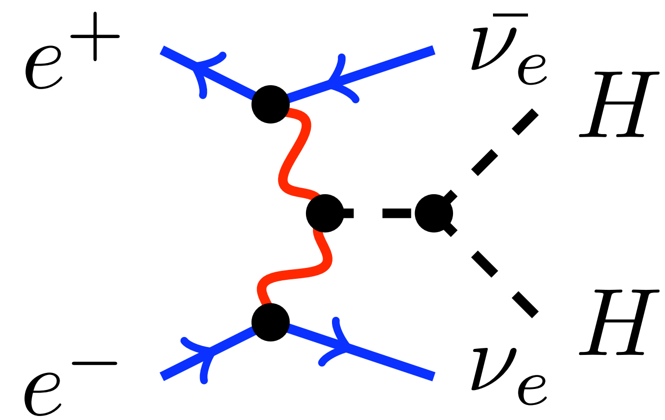
Comparable to other measurements at 1 TeV



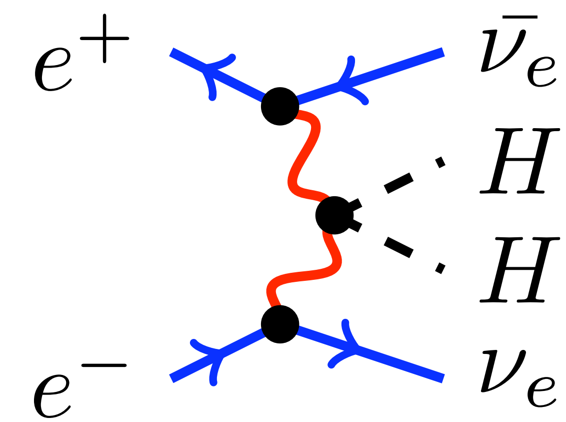
Double Higgs production at √s > 1 TeV



HHvv



Trilinear self-coupling λ



Quartic coupling g_{HHWW}

The HHvv cross section is sensitive to the Higgs self-coupling and the quartic coupling

Only 225 (1200) HHvv events at √s = 1.4 (3) TeV

▸ high luminosity and high energy crucial

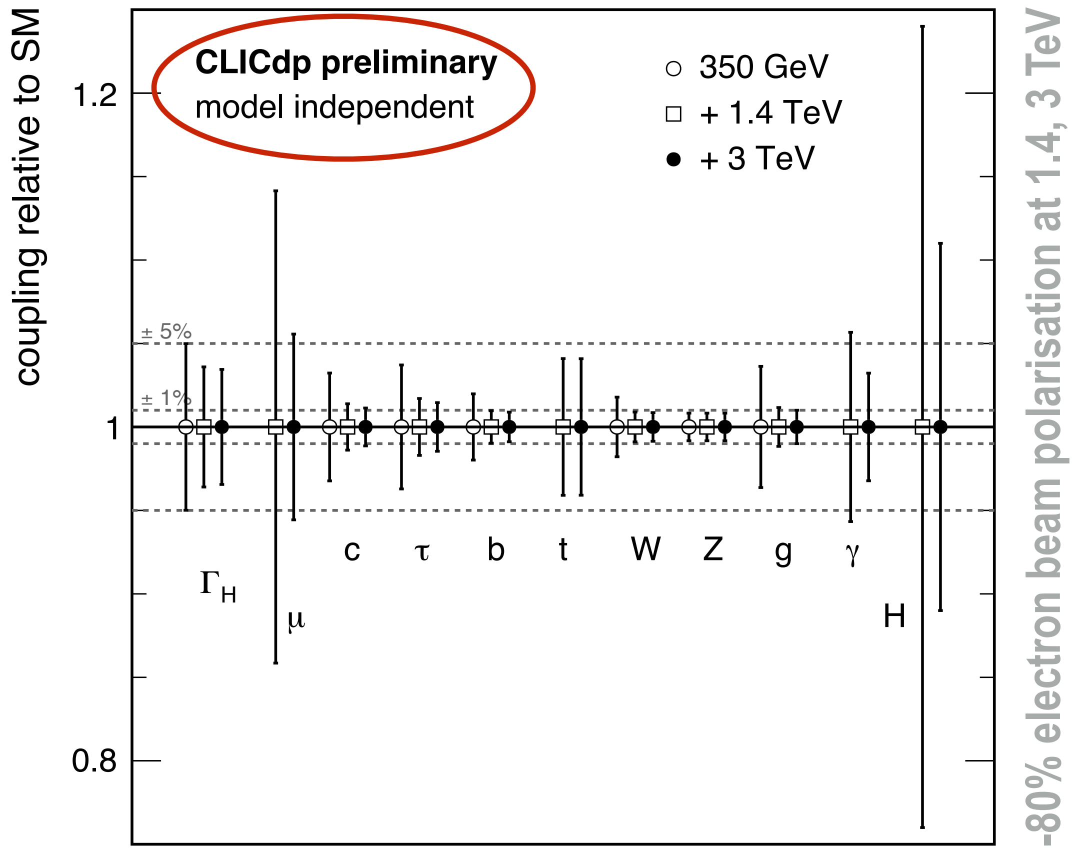
Events forced to 4-jet topology

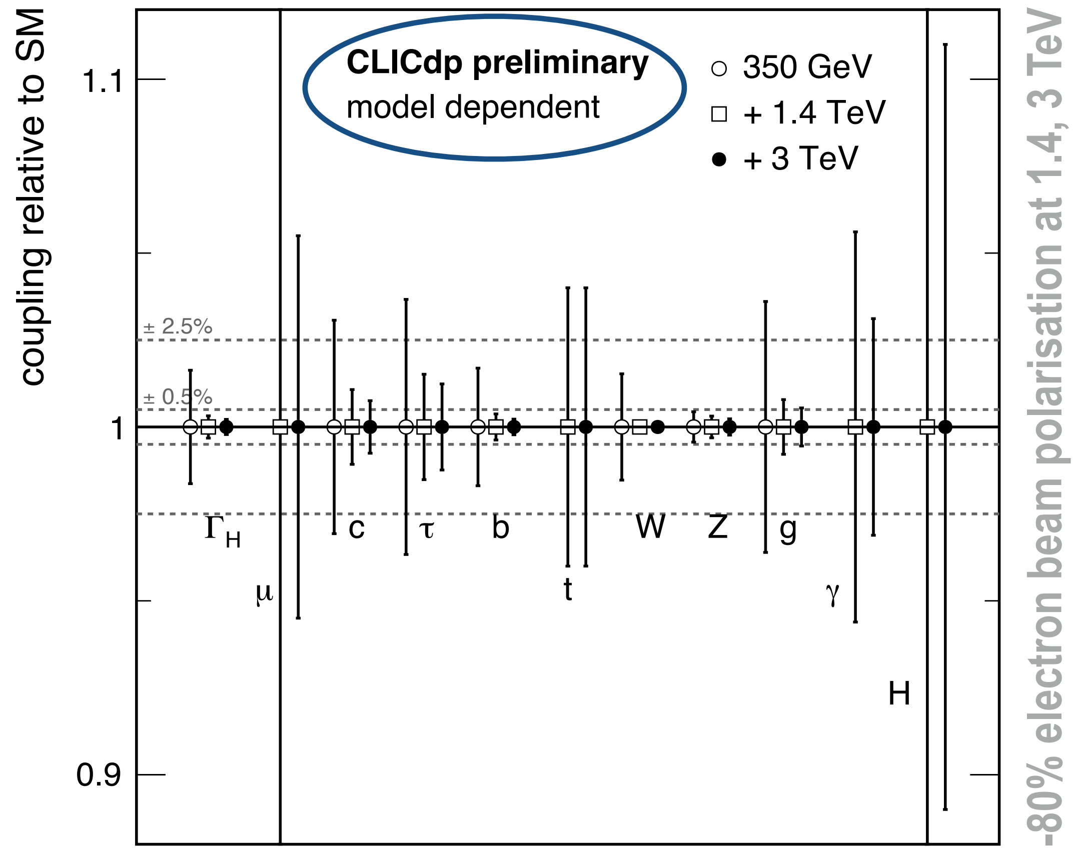
Jets paired by hemisphere/to minimise mass χ^2

Template fit to extract sensitivity

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

Model-independent fit to Higgs properties





Fully model independent fit

- only possible at lepton colliders
- stems from model independent measurement of g_{HZZ}
- Higgs width extracted with 5-3.5% precision

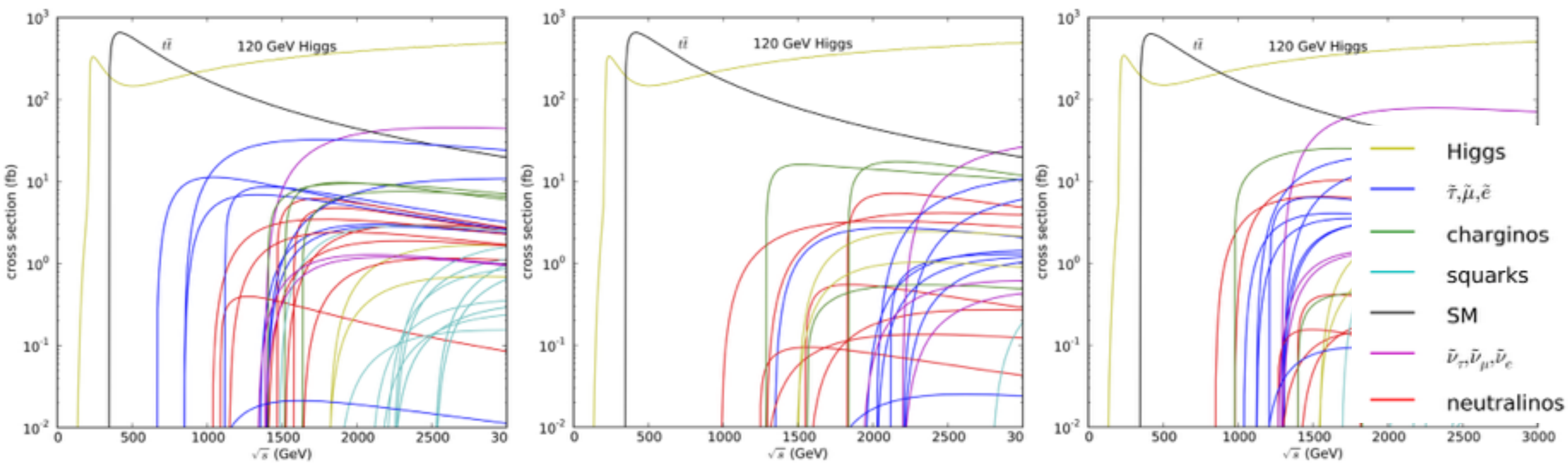
Model dependent fit

- as at LHC (no invisible H decays)
- sub-% precision at high energy
- Higgs width extracted with <1% precision
- but results depend strongly on fit assumptions

Prospects for BSM physics at CLIC

Direct searches via pair-production of new particles up to the kinematic limit M < $\sqrt{s}$ / 2

- three SUSY models used to benchmark performance:



CDR model 1, $\sqrt{s}$ = 3 TeV
- squarks
- heavy Higgs

CDR model 2, $\sqrt{s}$ = 3 TeV
- smuons, selectrons
- gauginos

CDR model 3, $\sqrt{s}$ = 1.4 TeV
- smuons, selectrons, staus
- gauginos

Indirect searches via precision measurements of known variables, comparison with SM

- sensitive to, for example, Z' bosons and composite Higgs

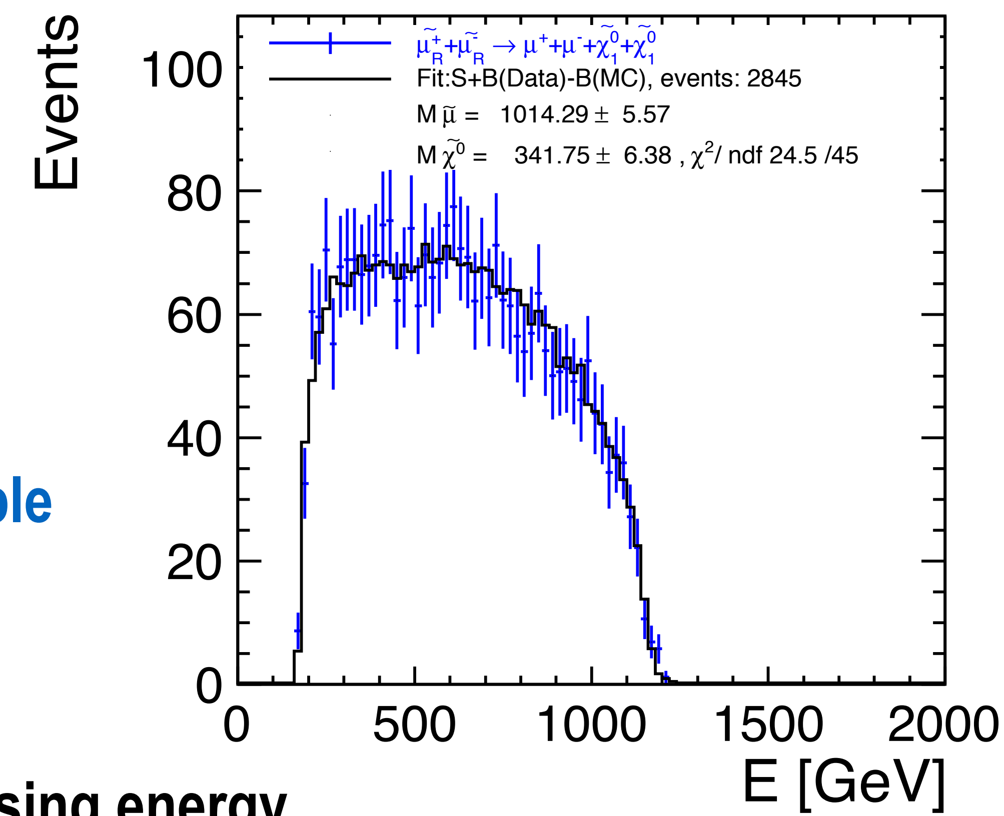
Sleptons and gauginos at $\sqrt{s}$ = 3 TeV

Slepton signature very clean: leptons and missing energy

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

Masses from end-points of energy spectra

- **for slepton masses ~ 1 TeV, precisions of < 1% achievable**

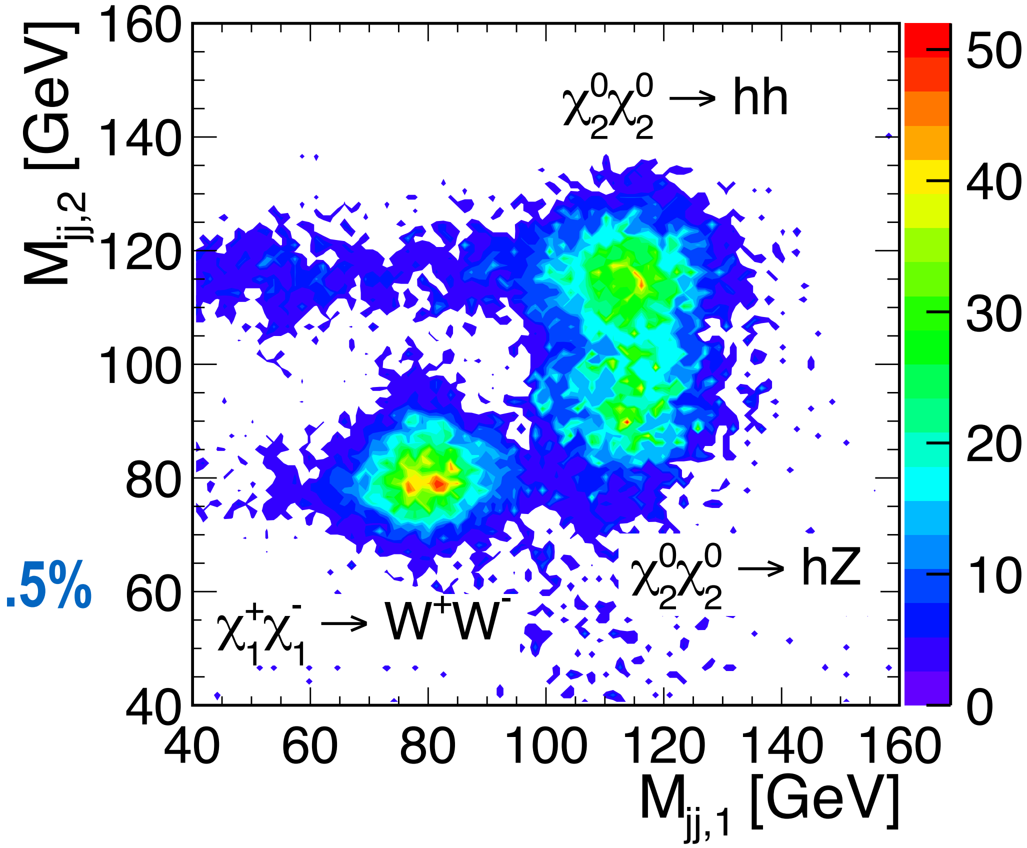


Chargino and neutralino pair production: four jets and missing energy

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

Masses from end-points of energy spectra

- **for gaugino masses of few hundred GeV, precisions of 1-1.5%**



Heavy Higgs bosons at √s = 3 TeV

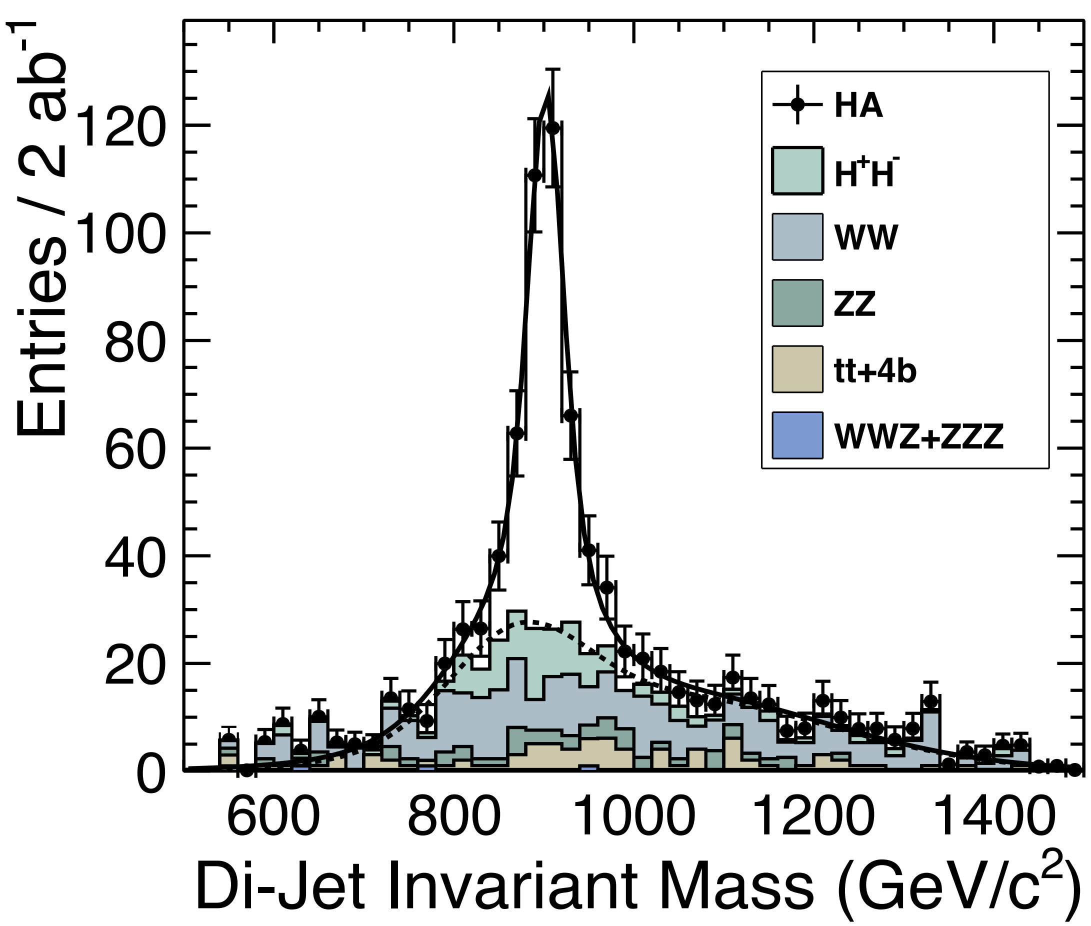
Heavy Higgs bosons (~degenerate in mass) would produce complex final states of heavy-flavour jets

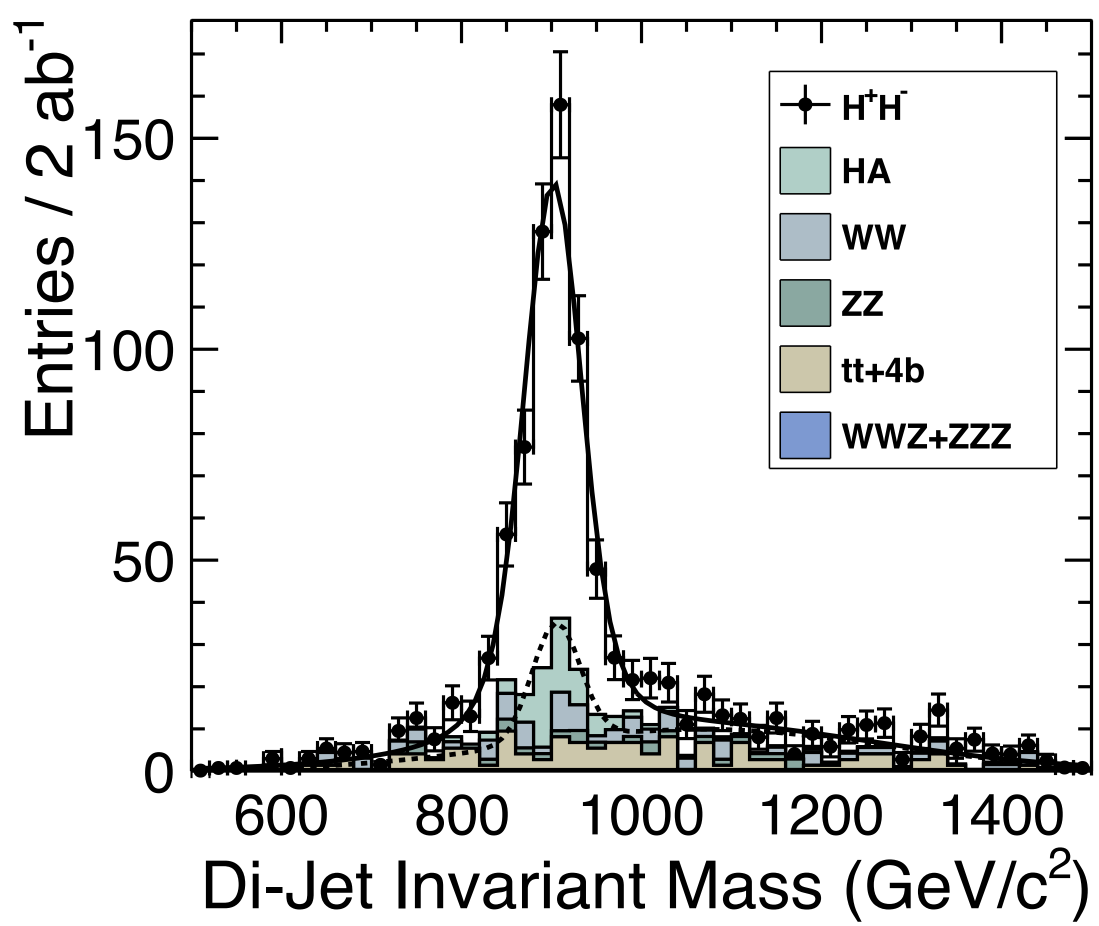
$$e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$$

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

Separation requires heavy-flavour tagging

- accuracy of Higgs mass measurements ~0.3%



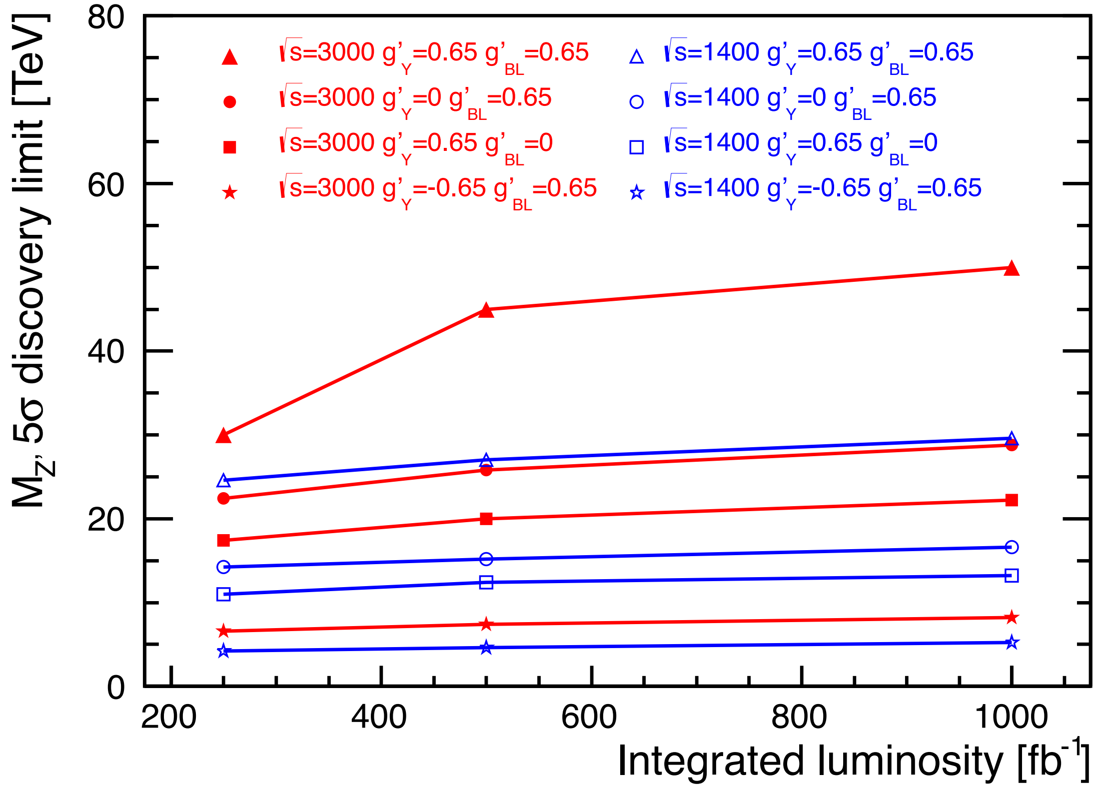


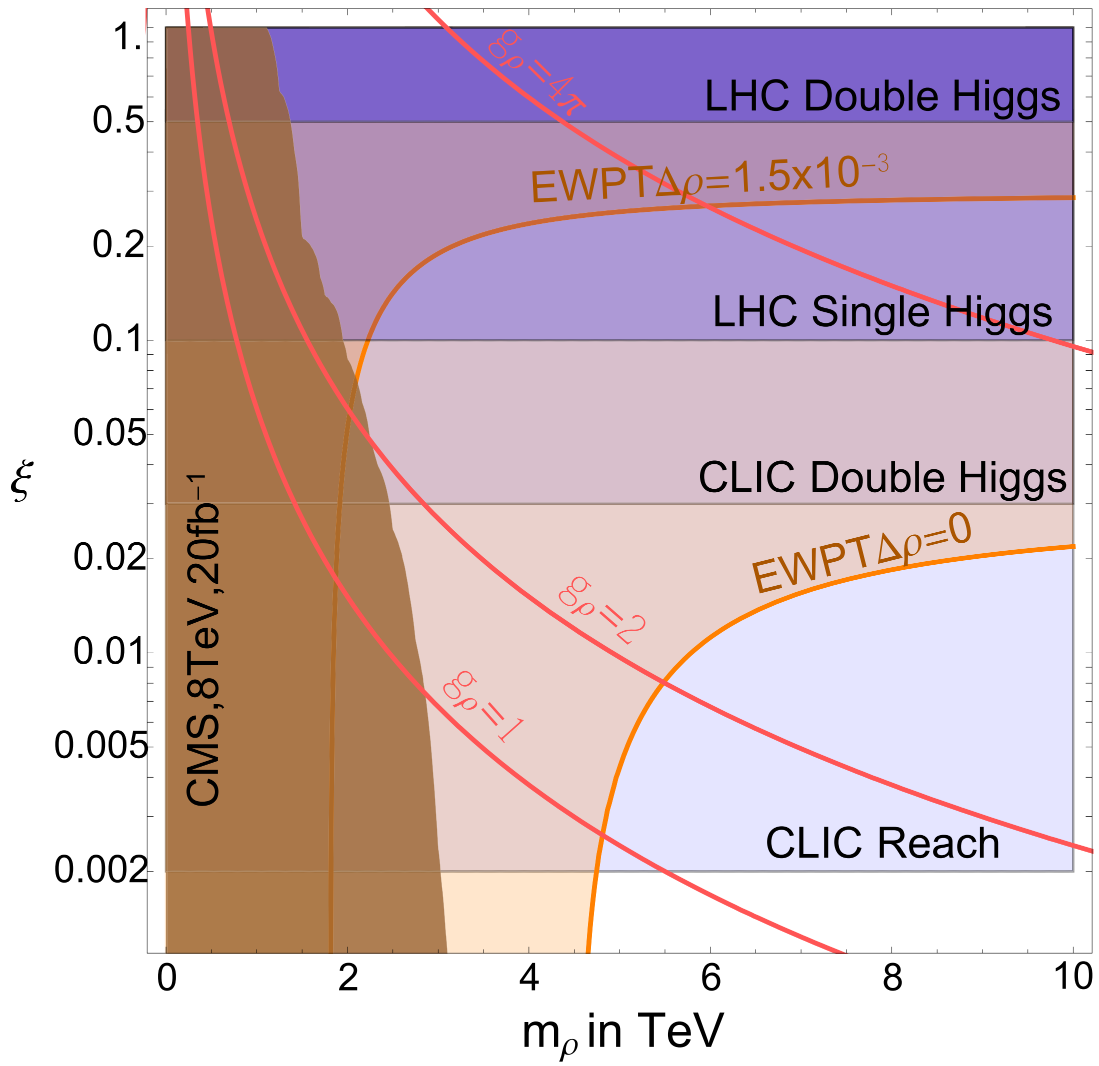
Indirect searches

Precision studies of di-muon pair production

- **total cross section**
- **forward-backward asymmetry**
- **left-right asymmetry (requires beam polarisation)**

Sensitive to Z' bosons, reach up to 10s of TeV





Composite Higgs theories (bound state of fermions)

- **m_ρ: mass of the vector resonance**
- **ξ: strength of Higgs interactions**

CLIC reach from single Higgs production provides an indirect probe of Higgs composite scale up to 70 TeV

Summary

CLIC offers a strong physics programme throughout its three energy stages

Higgs physics at CLIC

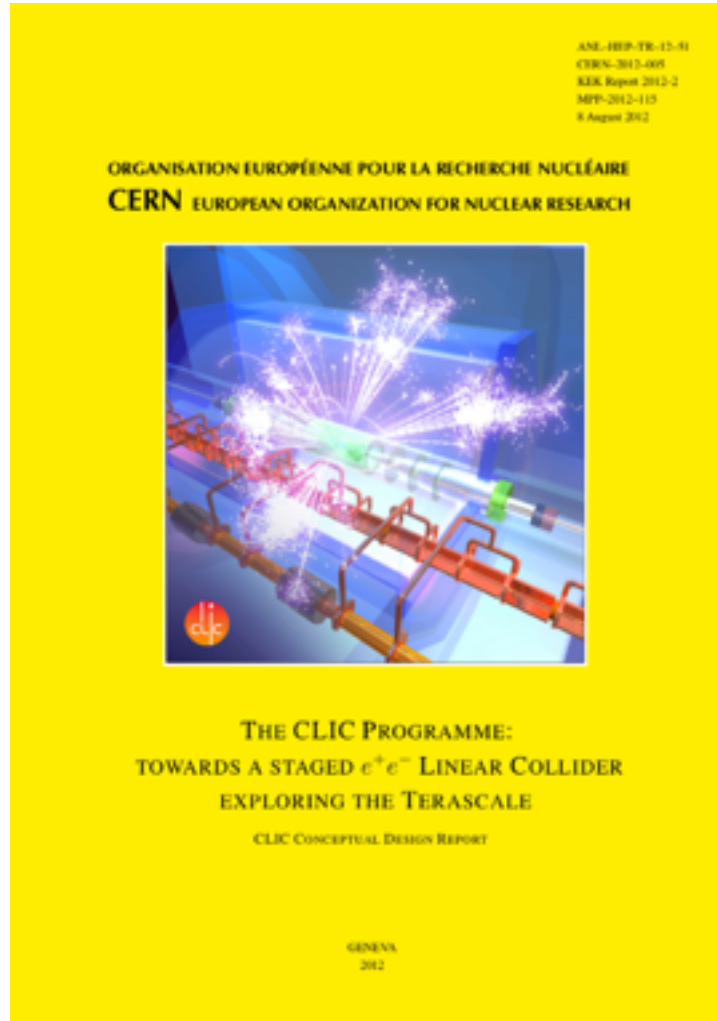
- model independent measurement of g_{HZZ}
- high statistics: precision measurements and rare decays
- top Yukawa coupling and Higgs self-coupling
- combined, model independent fit of Higgs parameters

BSM physics at CLIC

- direct searches possible up to the kinematic limit
- mass measurements of SUSY particles with %-level precision
- indirect searches increase reach to tens of TeV

Thanks for your attention!

If you want to know more

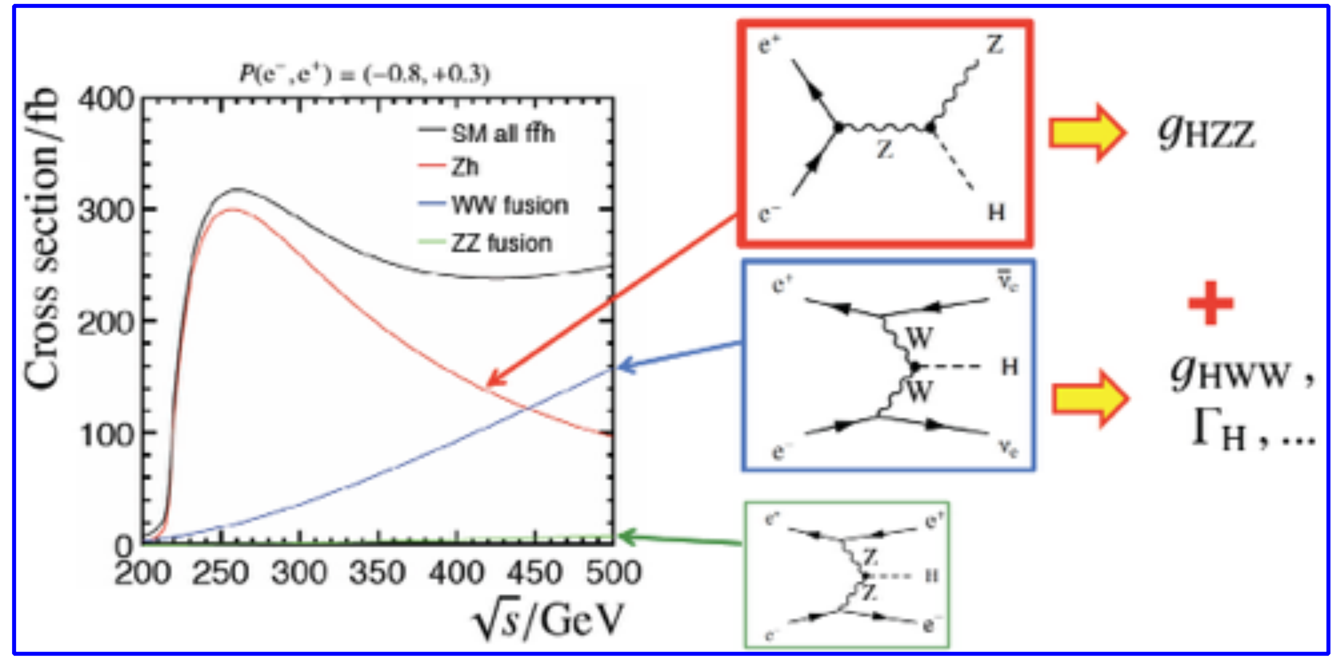


CLIC CDR vol 2
Physics and Detectors
CERN-2012-003
arxiv: 1202.5940

CLIC CDR vol 3
The CLIC Programme
CERN-2012-005
arxiv: 1209.2543

CLIC Snowmass White Paper
Physics at CLIC
arxiv: 1307.5288

Optimising the first energy stage



Higgs mass measurement (Higgsstrahlung):

- $\sqrt{s}$ = 250 GeV: Δm_H ~ 30 MeV
- $\sqrt{s}$ = 350 GeV: Δm_H ~ 120 MeV

Alternatively: WW-fusion + H →bb:

- $\sqrt{s}$ = 350 GeV: Δm_H ~ 50 MeV (tbc)

Higgs couplings:

- Requires access to Higgsstrahlung and WW-fusion: g_{HZZ}, g_{HWW}, Γ_H, couplings to fermions…
- $\sqrt{s}$ = 350 GeV a good compromise

$$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^* \propto \frac{g^4_{HWW}}{\Gamma_H})$$

- But results may profit from higher energy&luminosity

Top physics:

- Threshold scan requires $\sqrt{s}$ = 360 GeV

CLIC with $\sqrt{s}$ > 1 TeV will give best perspectives. But in some areas the first energy stage can already improve significantly on HL-LHC:

- Top A_{fb} and top couplings to Z, γ, W need $\sqrt{s}$ > 400 GeV
- It might be worth adapting the first stage to enable these studies