CLIC

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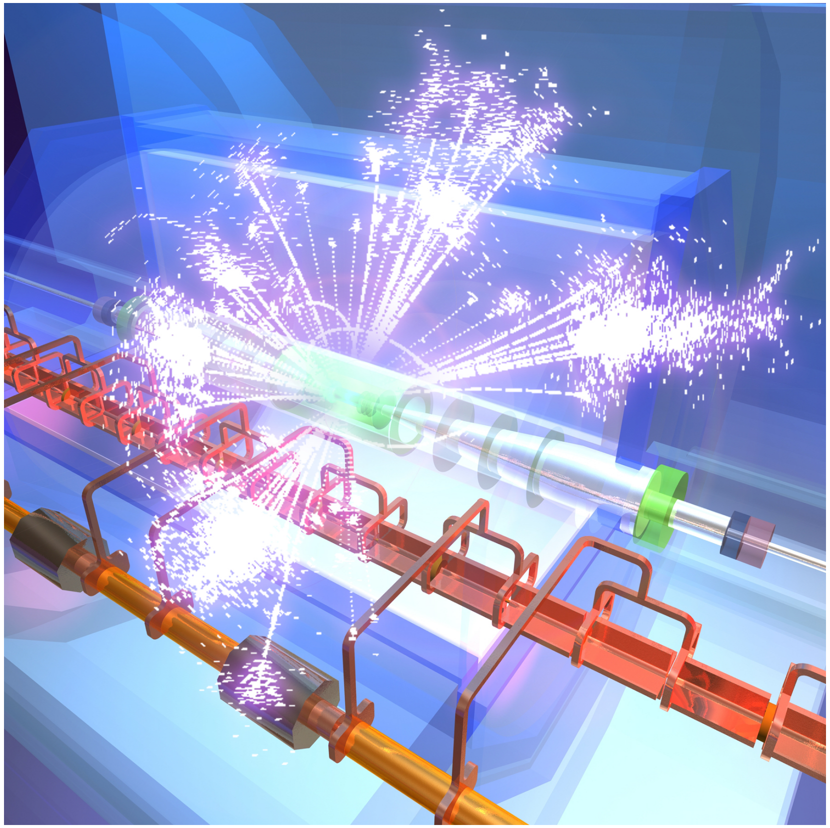

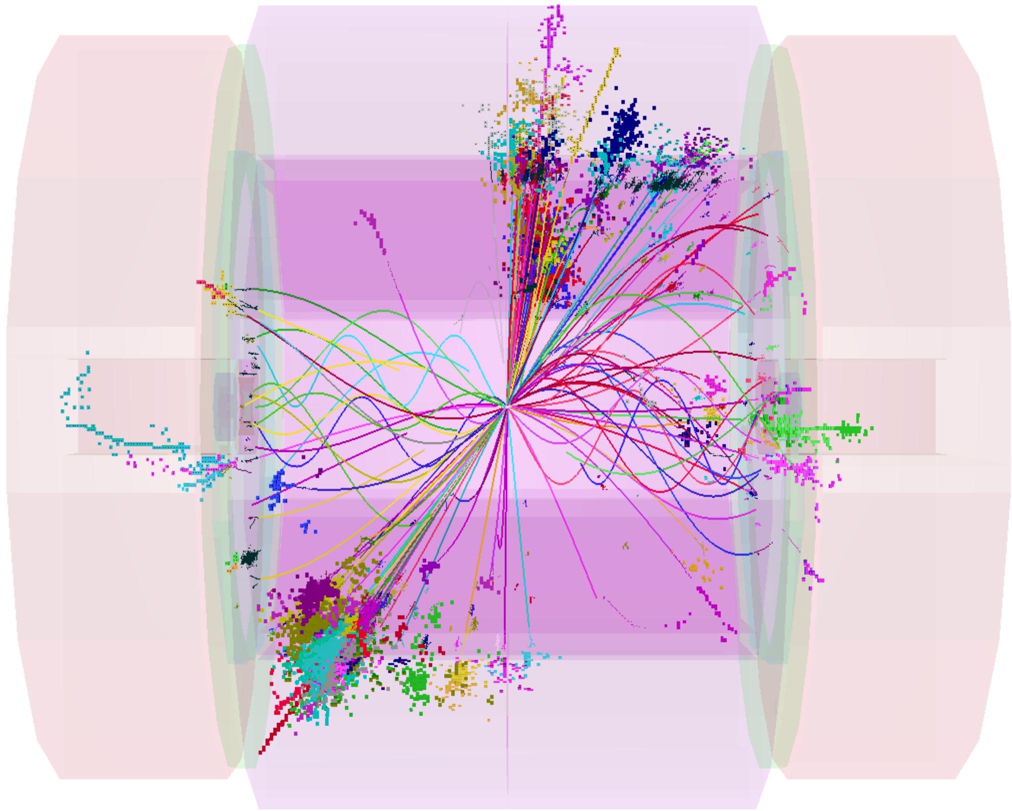

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Context

FCC-ee:ILC:CLIC

★ **The route to high-precision e+e- Higgs physics**
- the Higgs is out there
- scalar field: a completely new form of "matter"
- strong argument to study/exploit the Higgs

★ **The ILC**
- 250 GeV – 500 GeV: upgradeable to 1 TeV
- technologically mature, e.g. XFEL at DESY
- **let's hope it happens!**

★ **CLIC**
- 350 GeV – 3 TeV
- technology still in R&D phase – but much progress
- Does all the ILC physics + sensitivity to higher mass scales
  - e.g. sleptons/gauginos at ~TeV scale
  - run 2 results could make a compelling case for CLIC

★ **FCC-ee**
- 91 GeV – ~350 GeV
- limited energy reach, but potential for v. high lumi at lower $\sqrt{s}$
- machine design needs to be fleshed out + cost of 100 km ring…

Personal perspective/opinion…

!

FCC-ee:ILC:CLIC

- **The route to high-precision e+e- Higgs physics**
  - the Higgs is out there
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- **The ILC**
  - 250 GeV – 500 GeV: upgradeable to 1 TeV
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- **CLIC**
  - 350 GeV – 3 TeV
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  - Does all the I… sensitivity to higher mass scales
    - e.g. …uginos at ~TeV scale
    - …s could make a compelling case for CLIC
- **FCC**
  - 9… ~350 GeV
  - lim…ted energy reach, but potential for v. high lumi at lower √s
  - machine design needs to be fleshed out + cost of 100 km ring…

All would be fantastic machines

Personal perspective/opinion…

!

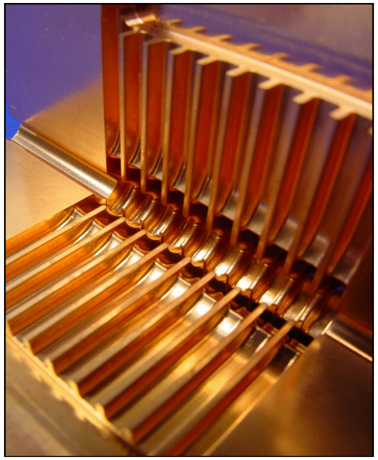
A Brief Introduction to CLIC

CLIC in a Nutshell

CLIC = Compact Linear Collider

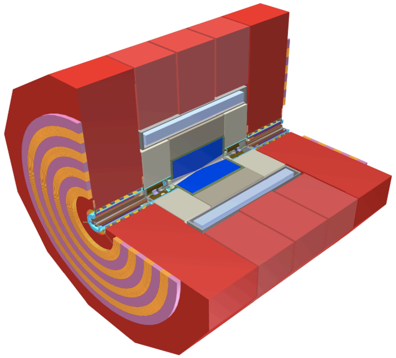
Accelerator:

- ★ High luminosity, high energy e^+e^- linear collider
- ★ Based on 2-beam acceleration scheme
  - Gradient of 100 MV/m (warm technology)
  - Strong accelerator R&D programme at CERN
- ★ Energy:
  - From a few-hundred GeV
  - Upgradable in steps to 3 TeV



Detector:

- ★ Two detector concepts CLIC_ILD and CLIC_SiD
  - based on concepts developed for ILC
- ★ Design driven by 3 TeV requirements



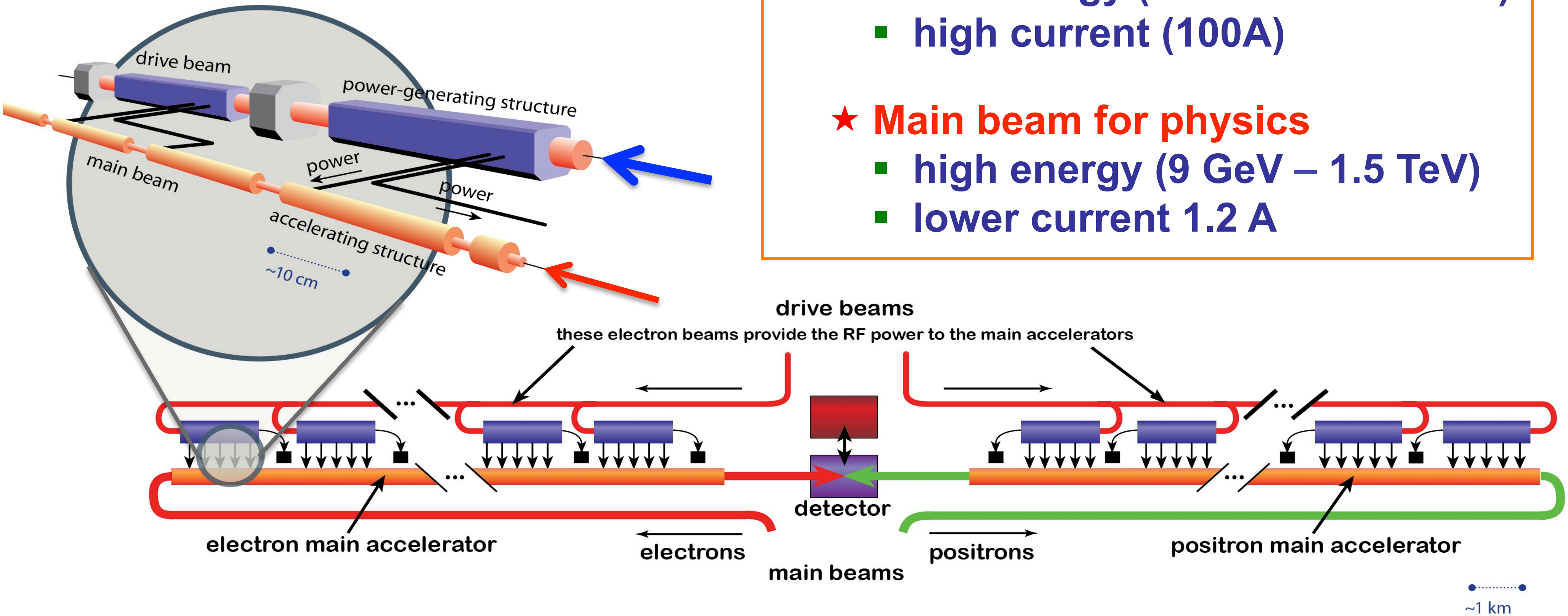
CLIC Two-beam Acceleration Scheme

Accelerating gradient: 100 MV/m
⇨ **"compact"**

Two beam scheme:

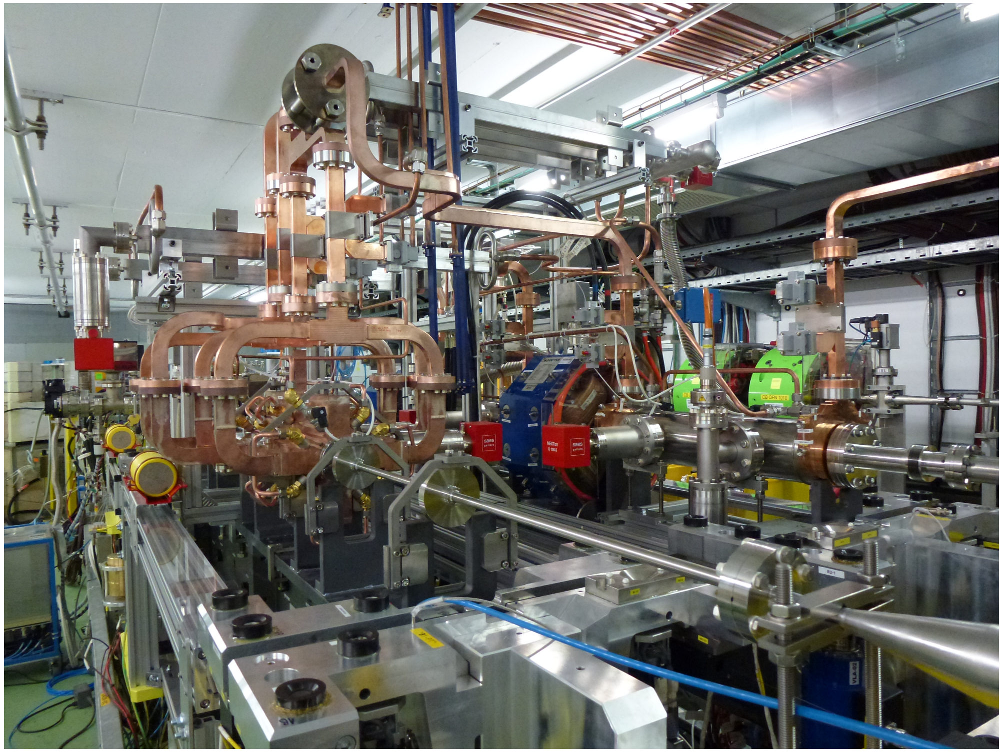
★ **Drive Beam supplies RF power**
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

★ **Main beam for physics**
- high energy (9 GeV – 1.5 TeV)
- lower current 1.2 A



Is it Feasible?

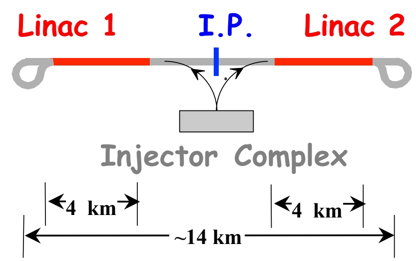
★ **CLIC is a complex machine**
- two beam lines
- a number of technical challenges
- nevertheless, very promising progress on R&D at **CTF3** (CLIC Test Facility)
- CLIC Accelerator CDR (2013): no show-stoppers



CLIC Energy Staging

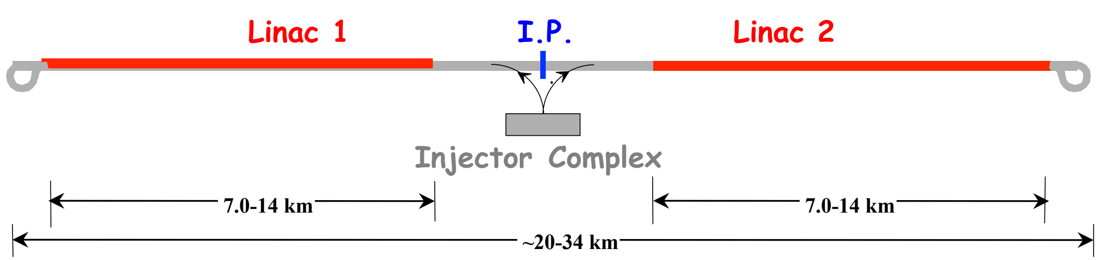
★ **Currently foreseen that CLIC construction would be staged**
- lower energy machine running during most of construction of next stage
- details of staging will depends on LHC physics results and/or CLIC goals.

~350-500 GeV Stage

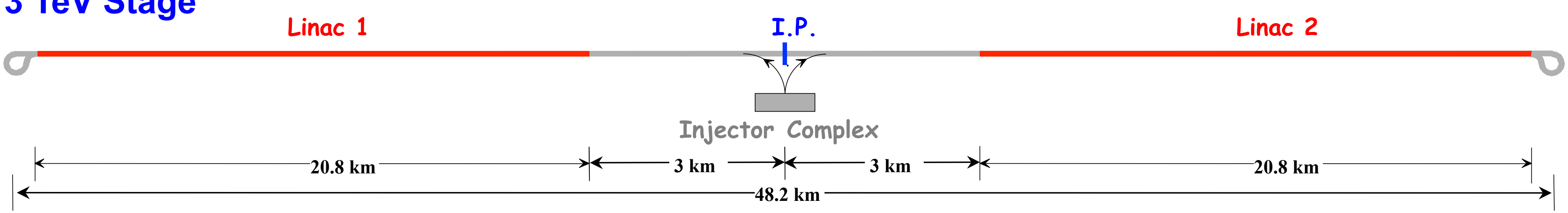


~14 km

1-2 TeV Stage

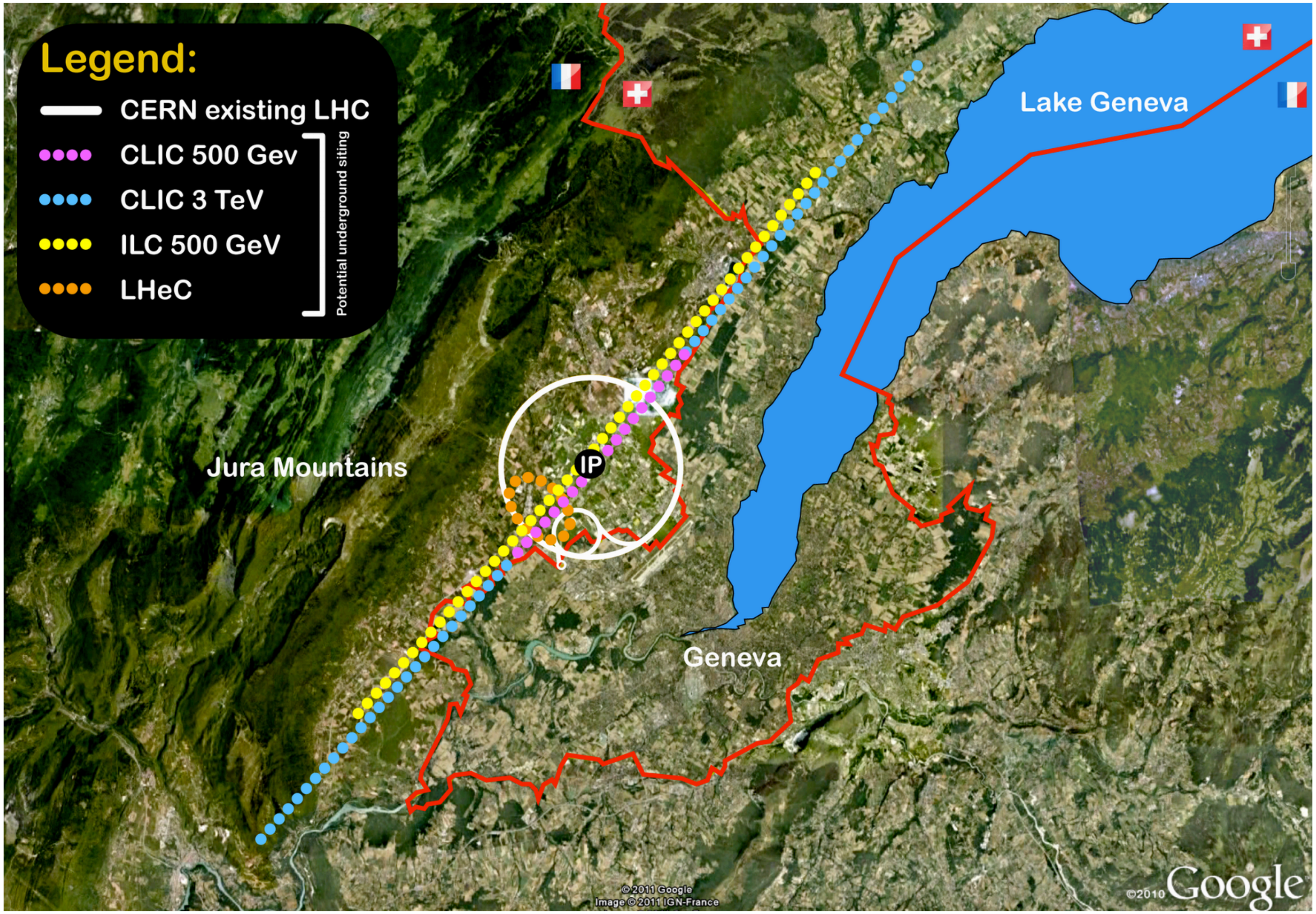


3 TeV Stage



CLIC at CERN

★ **CLIC fits…**



Experimental Conditions at CLIC

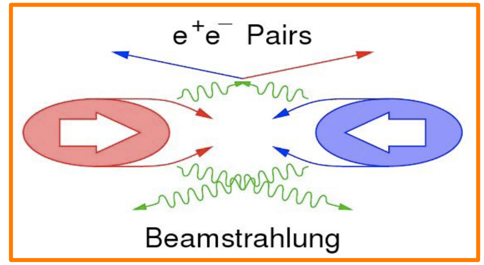
CLIC Machine Environment

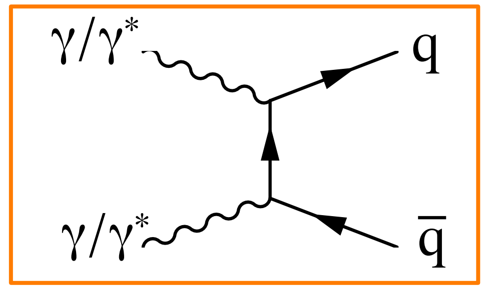
★ CLIC machine environment much more **challenging** than **LEP** or the **ILC**

	LEP 2	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5×10^{31}	5.9×10^{34}
BX separation	247 ns	0.5 ns
#BX / train	4	312
Train duration	1 μs	156 ns
Rep. rate	50 kHz	50 Hz
σ_x / σ_y	240/4 μm	≈ 45 / 1 nm
σ_z		44 μm

Drives timing Requirements for CLIC detector

★ **Beam related background:**
- Small beam profile at IP leads very high E-field:
  - **Beamsstrahlung**
  - **Pair-background**
- Interactions of real and virtual photons:
  - **γγ→ hadrons "mini-jets"**

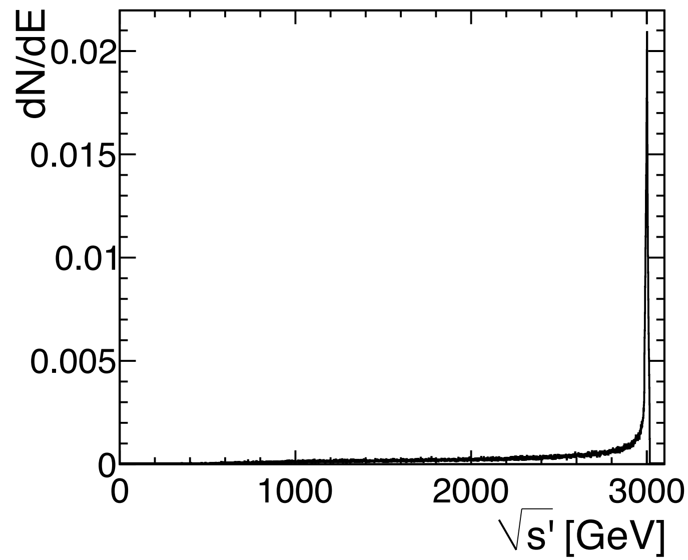




Beamsstrahlung

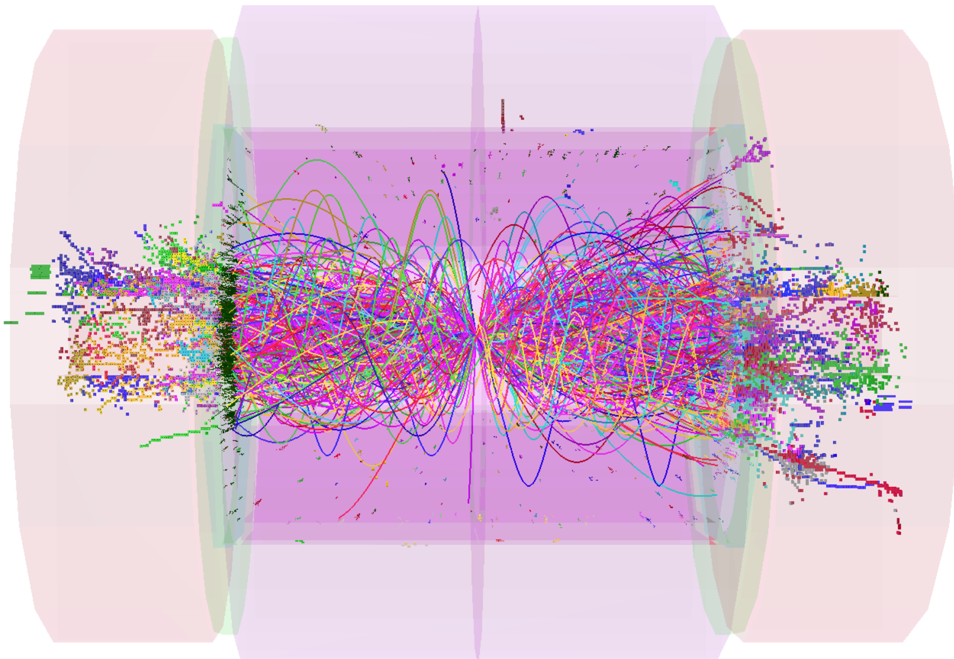
- ★ Beamsstrahlung results in a distribution of centre-of-mass energies
  - Large effect at CLIC due to small beam size, $\sqrt{s'} > 99\,\%\,\sqrt{s}$
    - 77 % at 350 GeV
    - 35 % at 3 TeV

$\sqrt{s'}/\sqrt{s}$	350 GeV	3 TeV
> 99 %	77 %	35 %
> 90 %	98 %	54 %
> 70 %	~100 %	76 %
> 50 %	100 %	88 %

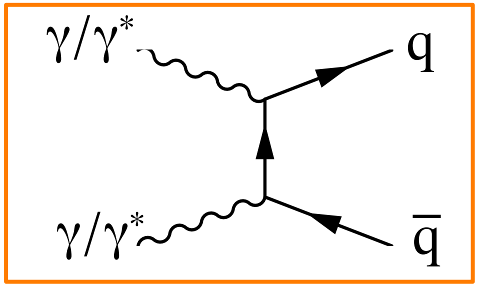


- ★ **Impact on physics** – depends on final state
  - Reduces effective luminosity at nominal centre-of-mass energy
    - not so important for processes well above threshold
  - When well above threshold, boost along beam axis
    - can distort kinematic edges, e.g. in SUSY searches
  - Not a major issue in itself…

Impact of Background



Pile-up of "mini-jets"



20 BXs = 10 ns of γγ→ hadrons

★ **Background must be accounted for in physics studies**

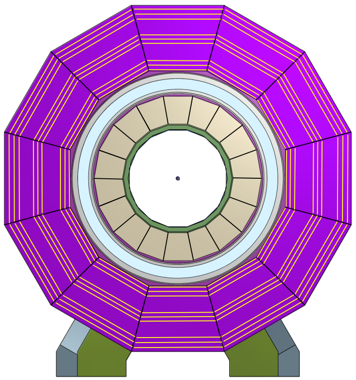
The CLIC Detector Concept(s)

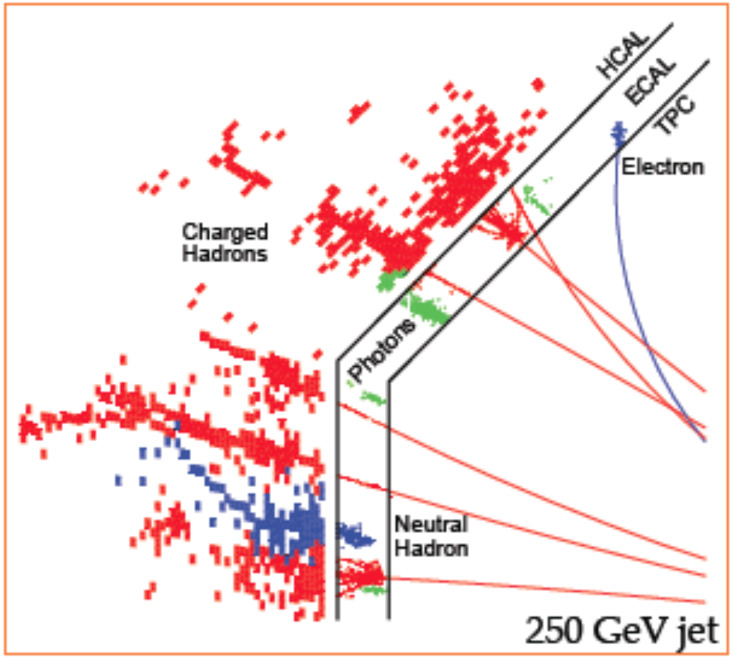
CLIC Detector Concepts

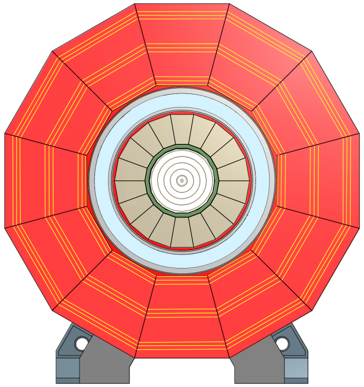
- ★ CLIC Physics studies use detailed GEANT 4 simulation
- ★ Detector models based on ILD and SiD concepts for ILC
- ★ Physics studies use **full reconstruction** with **background**
- ★ Focus on 3 TeV, where backgrounds are worse

★ Detector concepts designed for **high-granularity particle flow** calorimetry

e.g. MT, NIMA 611 (2009) 25-45

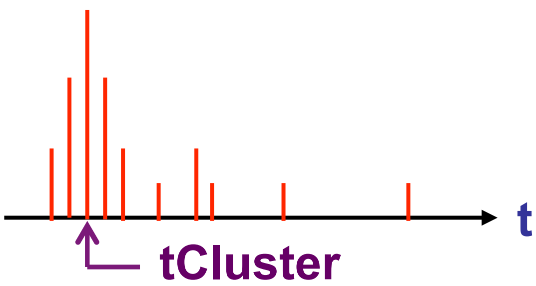






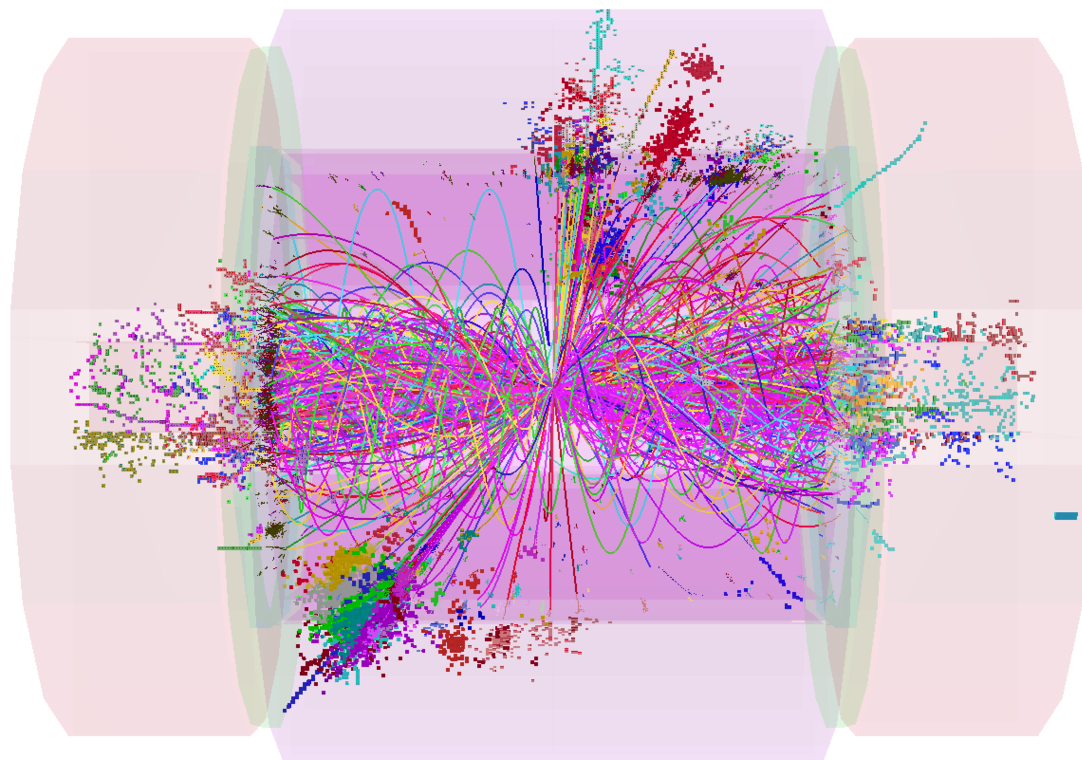
Reconstruction in Time

- ★ High granularity calorimetry allows individual particles to be reconstructed
  - with times assigned to each particle based on individual hit times
- ★ Pile-up from $\gamma\gamma \rightarrow$ hadrons can be effectively rejected using spatial and timing information
- ★ Studied at 3 TeV (the worst case)



e.g. $e^+e^- \rightarrow H^+H^- \rightarrow 8\ \text{jets}$
at $\sqrt{s}$ = 3 TeV

Before **1.2 TeV**



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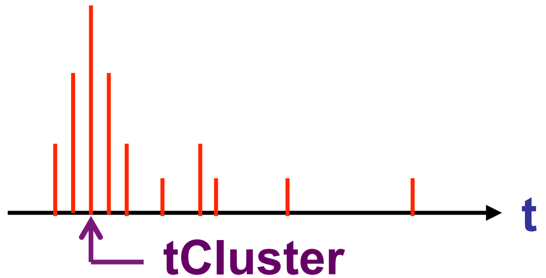
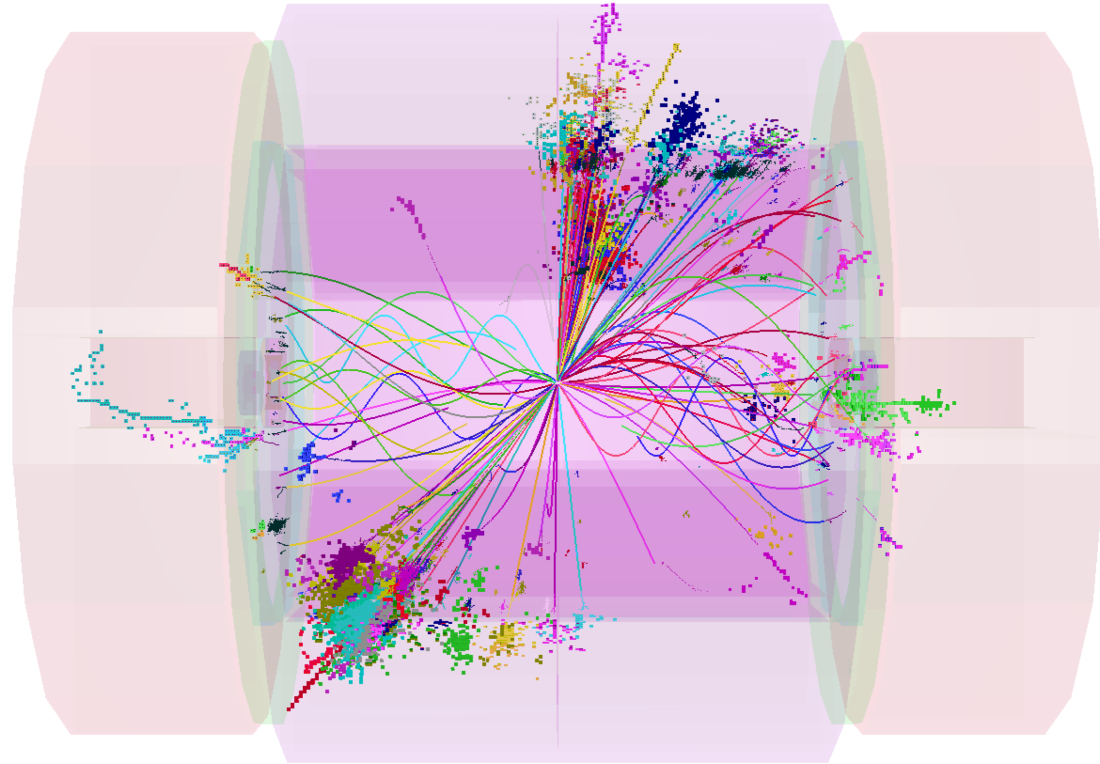


e.g. $e^+e^- \rightarrow H^+H^- \rightarrow 8$ je

at $\sqrt{s}$ = 3 TeV

After **100 GeV**



Background Summary

With a combination of:

- ★ high-granularity calorimetry
- ★ good time resolution
- ★ hadron-collider motivated jet algorithms

➡ **Pile-up: no major impact on physics, even at 3 TeV**

CLIC Physics Studies

- ★ The following CLIC physics studies:
  - **all** use full simulation/full reconstruction
  - **all** include pile-up

  essential to properly assess CLIC physics reach

Physics at CLIC

CLIC Physics Potential

★ CLIC is the most mature option for a multi-TeV future lepton **collider**

★ **In particular,** electron-positron collisions at CLIC bring:
- precision Higgs physics (SM and BSM)
- access to weakly coupled BSM states, e.g. sleptons, gauginos

★ Physics highlights include
- **Higgs**
- Top
- **SUSY**

} Covered in this talk

- Z'
- Contact interactions
- Extra dimensions

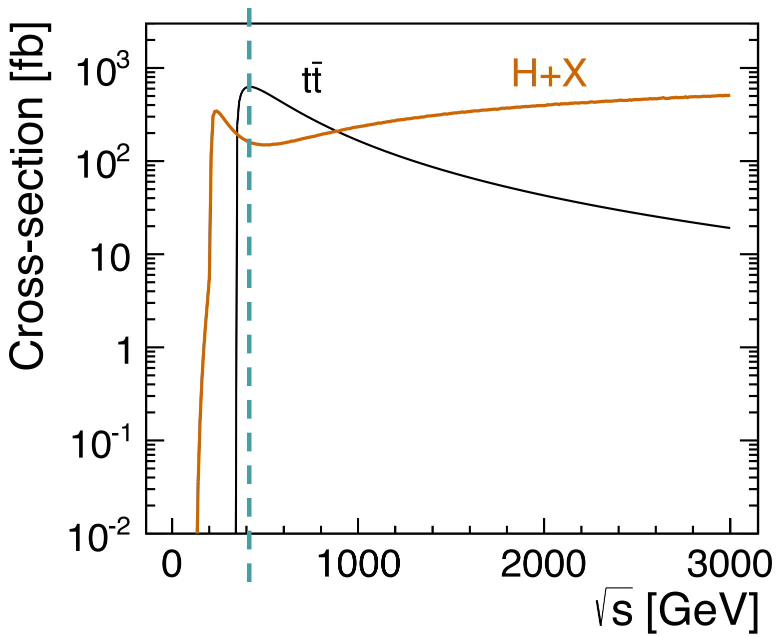
} Only briefest of mentions

- …

The Physics Landscape I

CLIC is foreseen as a staged machine:

- ★ First stage would focus on precision SM physics
  - ~350 GeV* : Higgs and top



- ★ Not at the peak of Higgs cross section
  - But, luminosity scales with √s

	250 GeV	350 GeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}
# ZH events	60,000	45,500
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500

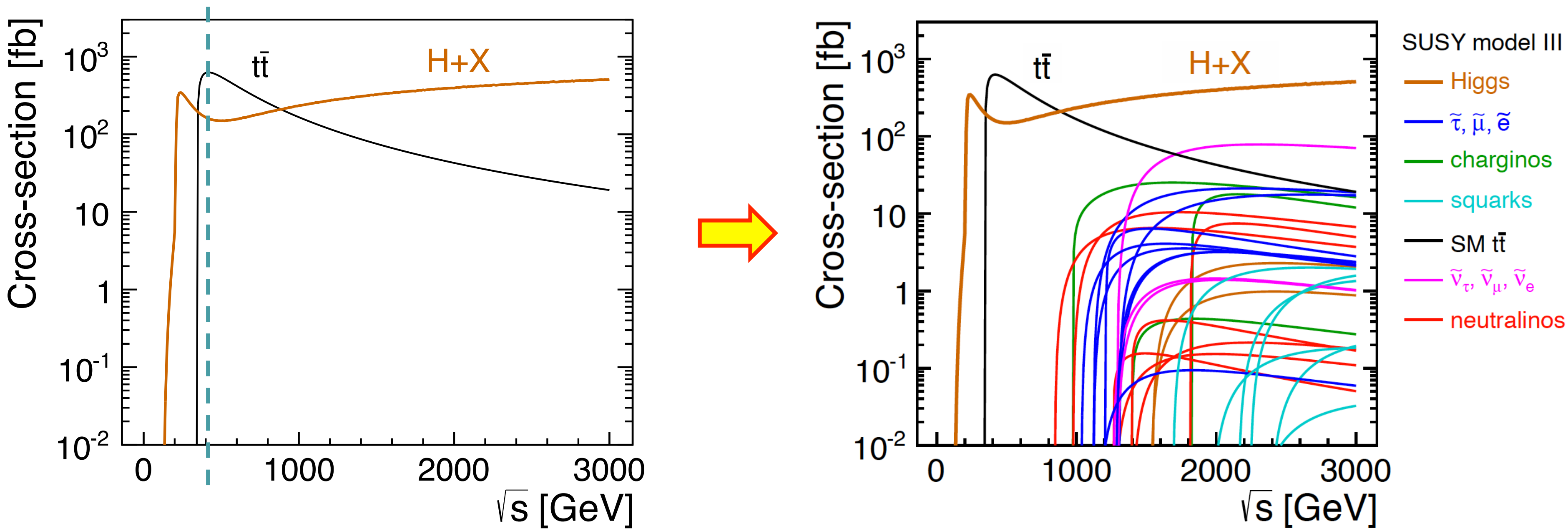
- ★ 250 GeV and 350 GeV give similar precision for coupling measurements

- ★ Energies of subsequent stages motivated by physics
  - results from ~13/14 TeV LHC operation
  - direct dark matter searches,
  - …

The Physics Landscape II

★ **For example, illustrative SUSY "Model III*" of Vol.3 of CLIC CDR**
- **Gauginos and sleptons at $\sqrt{s}$ ~ 1.5 TeV**
- **Squarks at $\sqrt{s}$ ~2.5 TeV**

} **Precision measurements at CLIC**



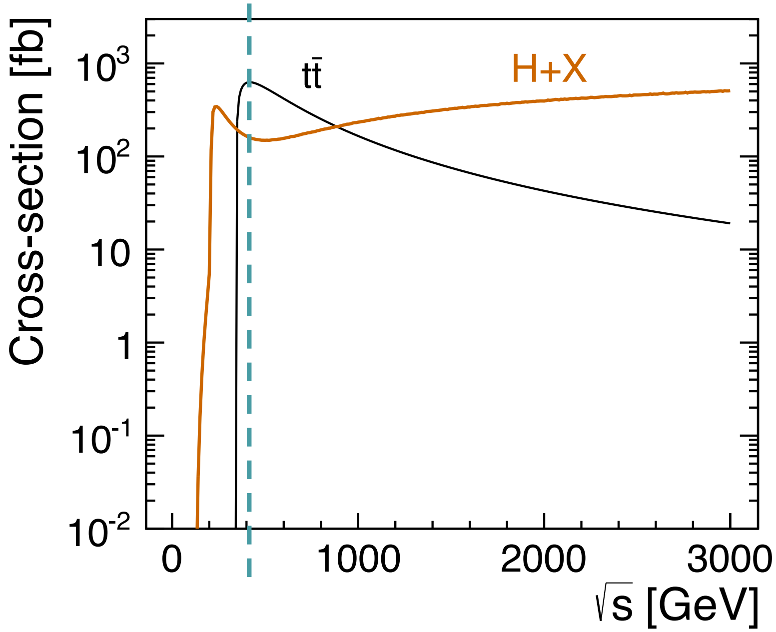
*mSUGRA with non-universal squark masses with tanβ = 10, Allanach *et al.*, CERN LCD-Note 2012-003

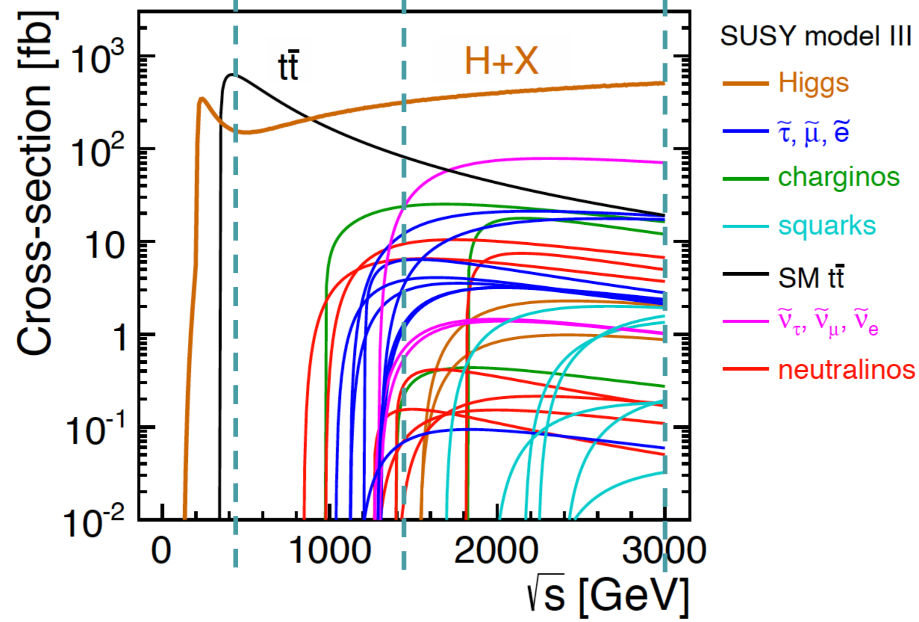
The Physics Landscape II

★ For example, illustrative SUSY "Model III*" of Vol.3 of CLIC CDR
- Gauginos and sleptons at ~1.5 TeV
- Squarks at ~2.5 TeV

} **Precision measurements at CLIC**

Stage I | Stage II | Stage III





For example:

Stage I	~350 GeV	Higgs, Top
Stage II	~1.5 TeV	Higgs, gauginos, sleptons
Stage III	~ 3 TeV	Higgs, squarks, ?

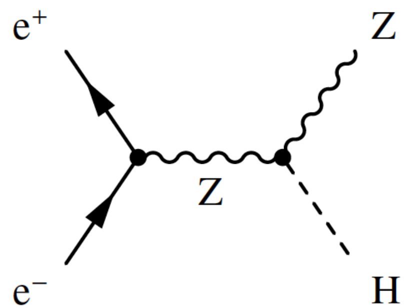
CLIC Physics Studies

- ★ Mature studie: “CLIC Detector & Physics collab.” (CLICdp)
- ★ CLICdp physics studies focussed around 4 documents
  - CLIC CDR Vol. 2: CLIC physics at 3 TeV
  - CLIC CDR Vol. 3: CLIC physics for a staged machine
  - CLIC Physics Snowmass Whitepaper
  - Higgs physics at CLIC: synoptic paper (in progress)

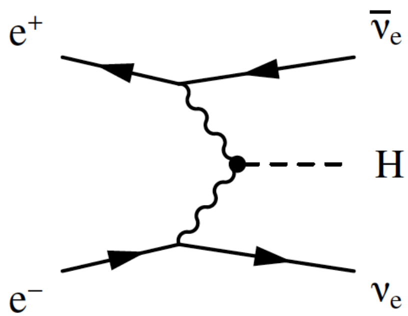
Higgs Physics at CLIC

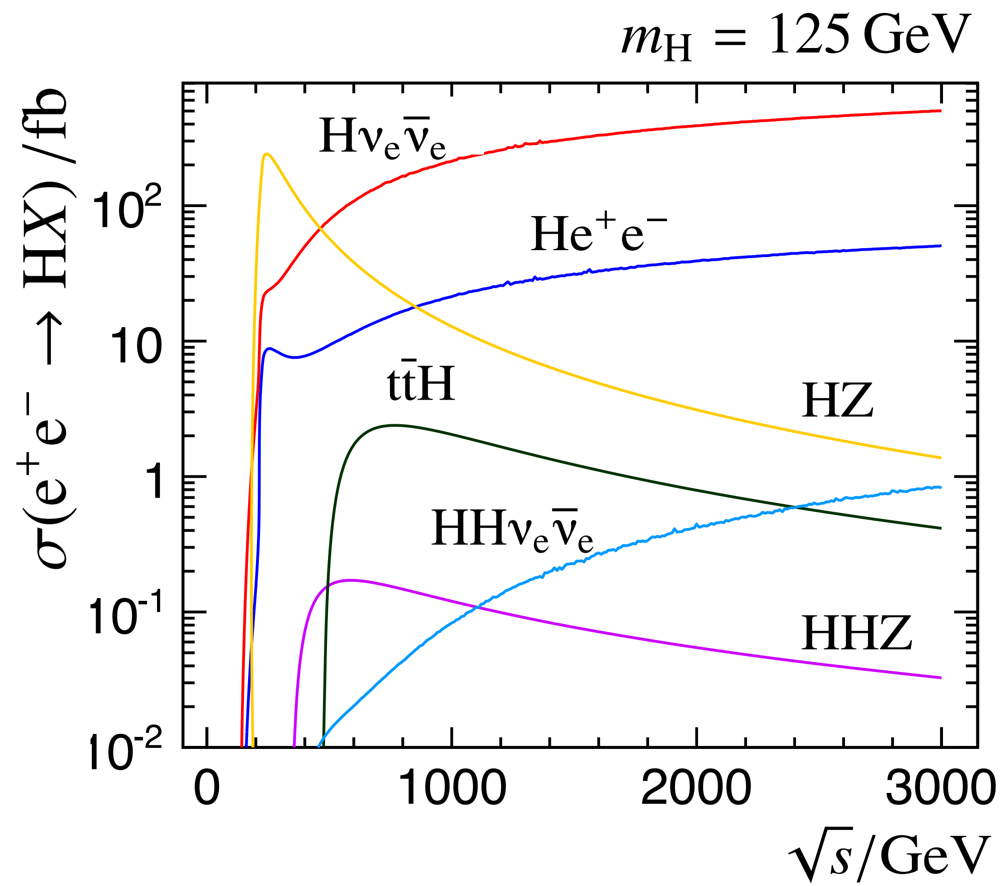
Standard Model Higgs

- ★ A number of SM Higgs processes accessible at CLIC
- ★ Below $\sqrt{s}$ ~ 300 GeV
  Higgs-strahlung dominates



- ★ Above $\sqrt{s}$ ~ 500 GeV
  WW fusion dominates



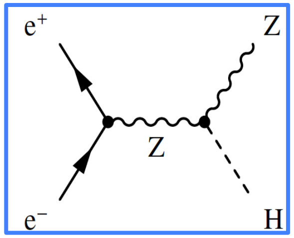


- ★ At $\sqrt{s}$ = 350 GeV both contribute
- ★ CLIC energy stages, provide a rich programme of precision Higgs physics

Model Independence

★ **Higgs-strahlung**

Total HZ cross section
(recoil mass)



$$\sigma(\mathrm{HZ}) \propto \boxed{g^2_{\mathrm{HZZ}}}$$

+exclusive cross sections

$$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \rightarrow XX) \propto \boxed{g^2_{\mathrm{HZZ}} \cdot \frac{g^2_{\mathrm{H}XX}}{\Gamma_{\mathrm{H}}}}$$

Model Independence

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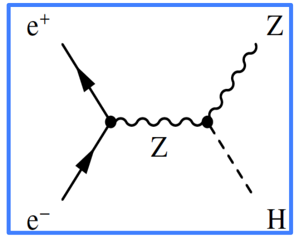
Total HZ cross section (recoil mass)

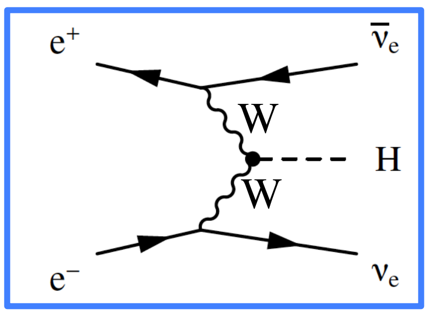


$$\sigma(\mathrm{HZ}) \propto g^2_{\mathrm{HZZ}}$$

+exclusive cross sections

$$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to XX) \propto g^2_{\mathrm{HZZ}} \cdot \frac{g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

★ Total Higgs width determined from WW fusion process



e.g.

$$\frac{\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})}{\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})} \propto \frac{g^2_{\mathrm{HZZ}}}{g^2_{\mathrm{HWW}}}$$

⇒ g_{HWW}

and

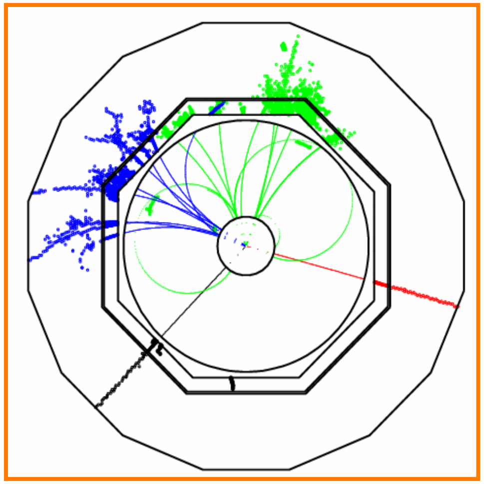
$$\sigma(\mathrm{H}\nu_e\bar{\nu}_e) \times BR(\mathrm{H} \to \mathrm{WW}^*) \propto \frac{g^4_{\mathrm{HWW}}}{\Gamma_{\mathrm{H}}}$$

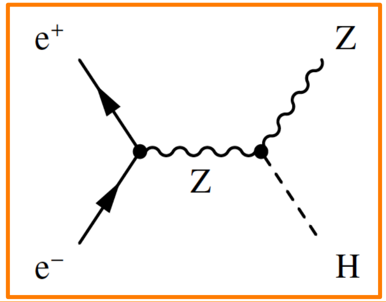
⇒ Γ_{H}

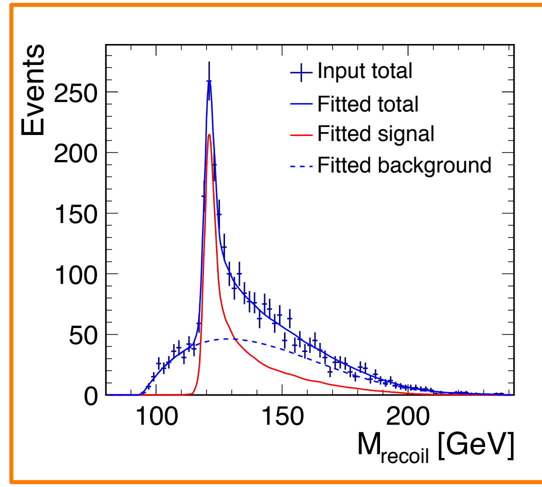
everything else follows…. all fully M.I.

Higgs-strahlung

★ During first stage of CLIC $\sqrt{s}$ = 350 GeV: study the Higgs-strahlung process







★ **Model independent analysis**
- Select Higgs from mass recoiling against leptonically decaying Z
- Measure Higgs BRs

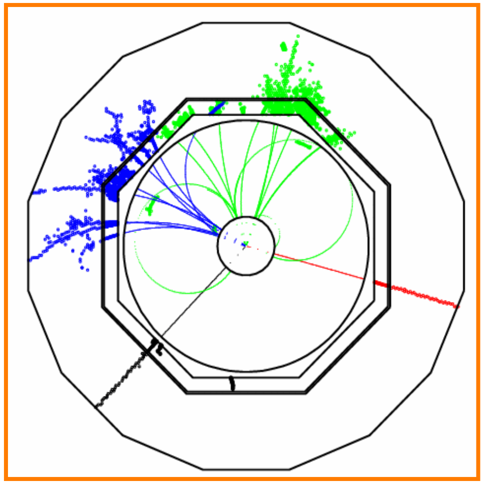
★ Measure Higgs production cross section independent of Higgs decay
- Sensitive to invisible Higgs decay modes
- Absolute measurement of HZ coupling

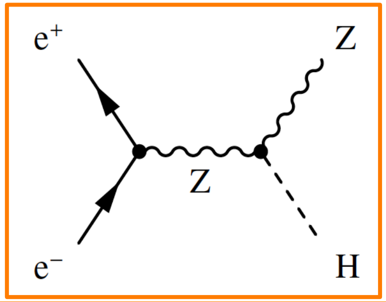
★ Recent studies demonstrate can make MI measurements with $Z \rightarrow q\bar{q}$

500 fb^{-1} at $\sqrt{s}$ = 350 GeV $\quad \frac{\Delta(\sigma)}{\sigma} \sim 1.6\,\%$ ⇨ $\frac{\Delta(g_{HZZ})}{g_{HZZ}} \sim 0.8\,\%$

Higgs-strahlung

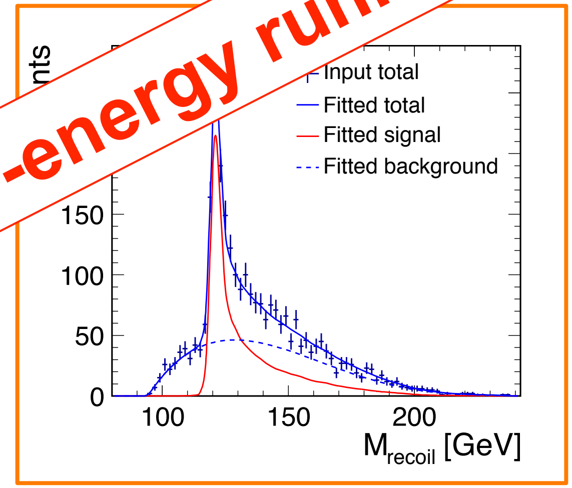
★ During first stage of CLIC √s = 350 GeV: study the Higgs-strahlung proce





★ Model independent anal

- Select Higgs from ... oiling against lepto ... ecaying Z
- Measur ... Ks



★ Measure Higgs produ ... ss section **independent of Higgs decay**

- Sensitive to in ... iggs decay modes
- **Absolute** ... ement of HZ coupling

★ Recen ... s demonstrate can make MI measurements with $Z \to q\bar{q}$

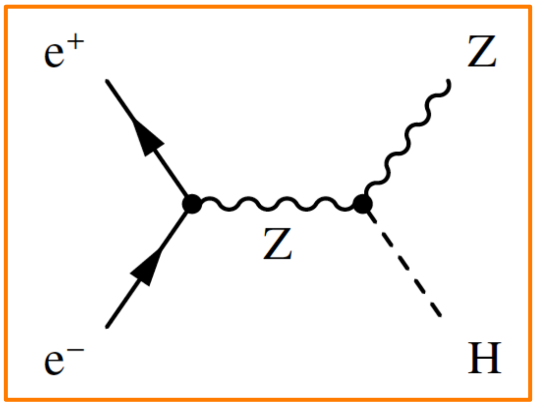
... fb^{-1} at √s = 350 GeV

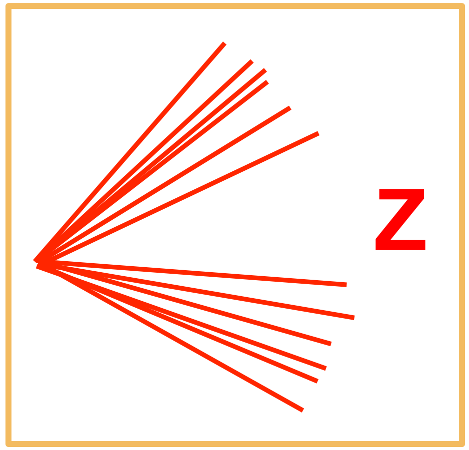
$$\frac{\Delta(\sigma)}{\sigma} \sim 1.6\,\% \Rightarrow \frac{\Delta(g_{HZZ})}{g_{HZZ}} \sim 0.8\,\%$$

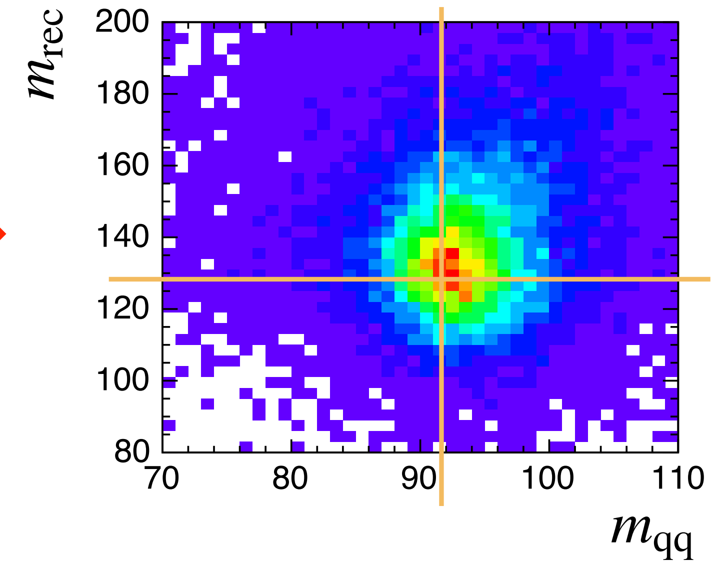
Hadronic recoil removes/reduces need for low-energy running

Invisible Width

- ★ e+ e- gives unique access to invisible Higgs width
  - Take advantage of well-defined initial state
  - Again Higgs-strahlung with $Z \rightarrow q\bar{q}$
  - Recoil: $E_{\rm rec} = \sqrt{s} - E_{\rm qq}$ & $\mathbf{p}_{\rm rec} = -\mathbf{p}_{\rm qq}$





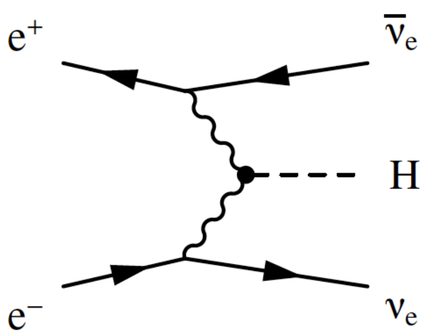


$\Rightarrow$ $Br(\mathrm{H} \rightarrow \mathrm{invis.}) < 1.0\,\%$ @ $90\,\%$ $C.L.$

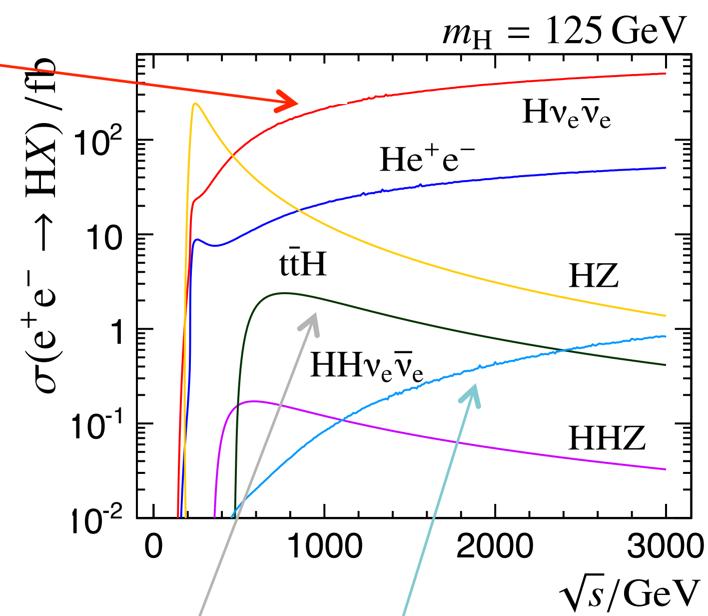
Higgs at Higher Energy

★ **In a higher energy stage of CLIC…**

- **Fusion cross section becomes large**
  - **+ luminosity ~scales with √s**
- **Large numbers of $H\nu_e\bar{\nu}_e$ events**



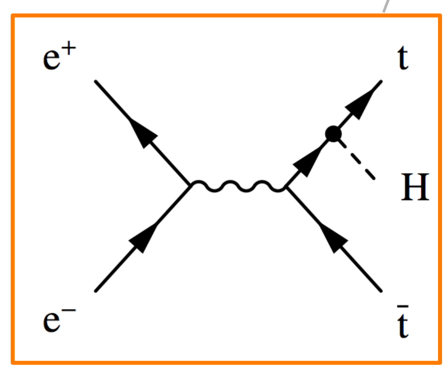
	√s =	
	1.4 TeV	3 TeV
Int Lumi [fb^{-1}]	1500	2000
Cross section	278 fb	479 fb
N(Hνν)	370,000	830,000

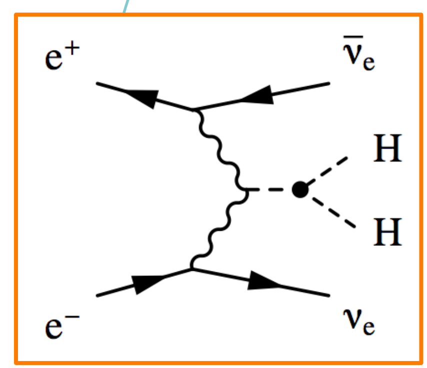


⇨ **Precise BR measurements**

★ **+ Rarer processes give access to**

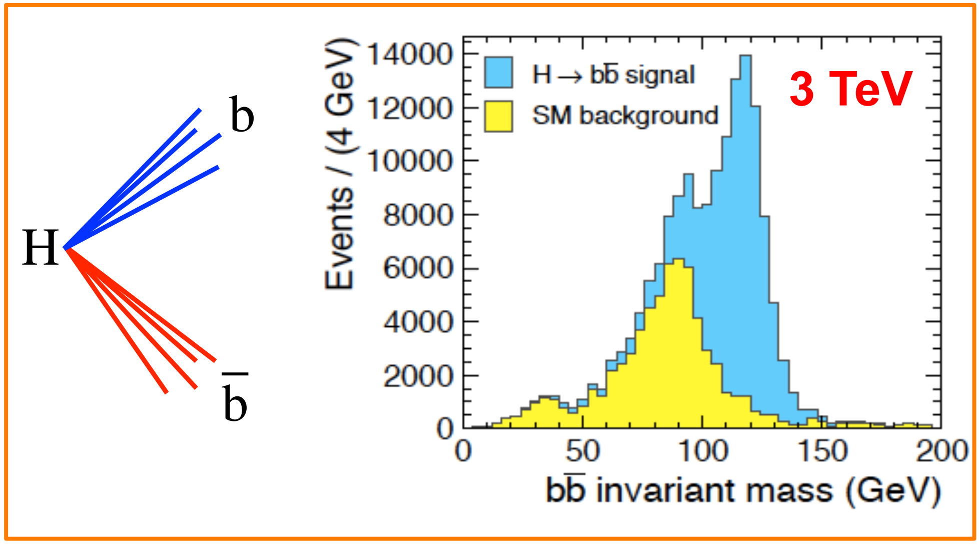
- **top Yukawa coupling**
- **Higgs self-coupling…**

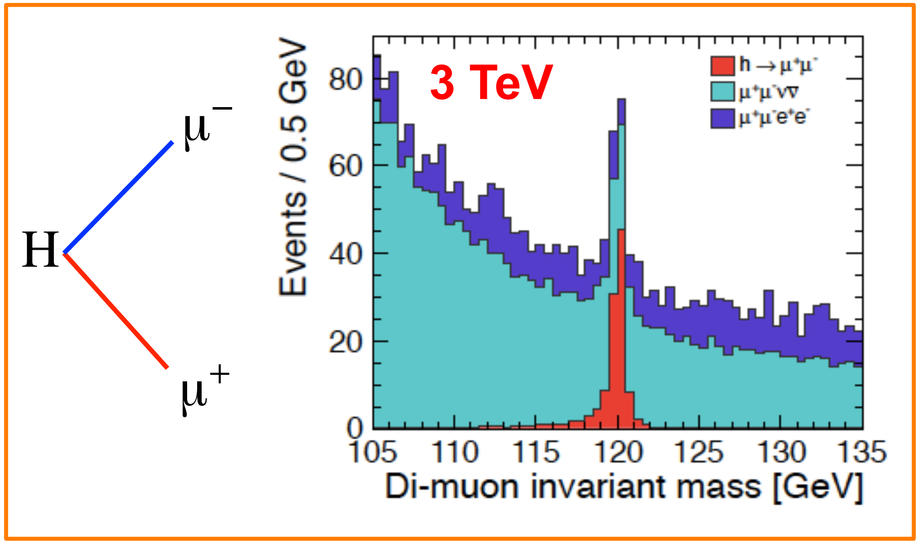




Higgs BRs

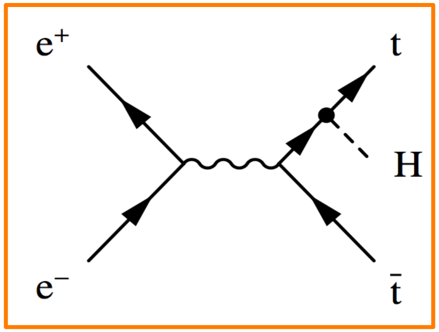
★ **Full detector simulation/reconstruction studies at 3 TeV with pile-up**





⇨ $\sigma(H \to b\bar{b}) \sim \pm 0.2\,\%$ | $\sigma(H \to c\bar{c}) \sim \pm 3\,\%$ | $\sigma(H \to \mu^+\mu^-) \sim \pm 15\,\%$

statistical errors only

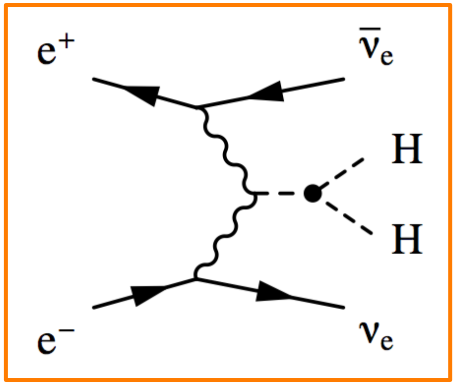


★ **Also sensitive to top Yukawa coupling**

- **studied at √s = 1.4 TeV**

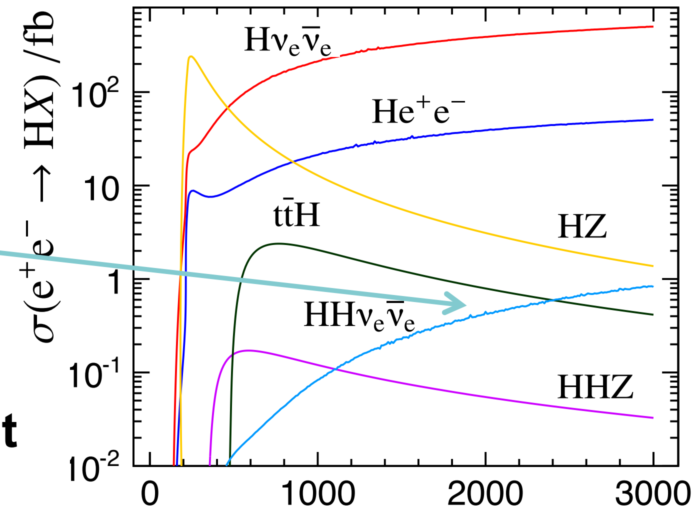
$$\Delta g_{Ht\bar{t}} / g_{Ht\bar{t}} = 4.5\,\%$$

★ Measurement of HH production directly probes Higgs self-coupling λ

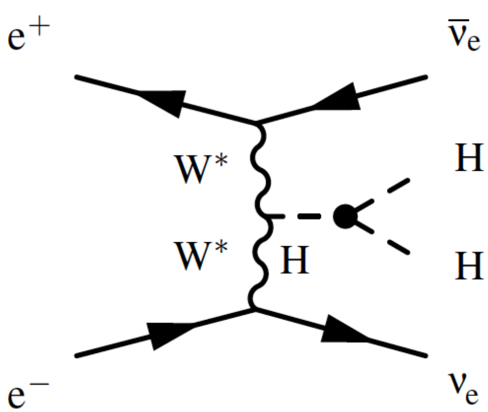


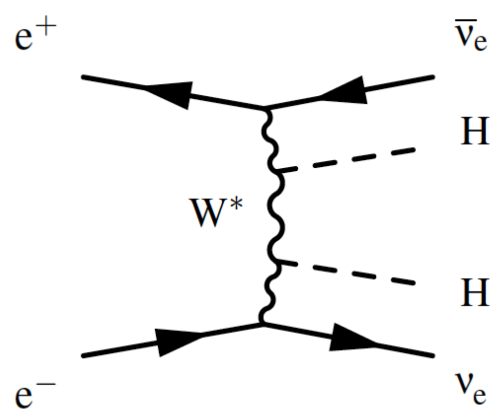
★ Small cross sections:
- increase with √s
- need energy
- need luminosity…

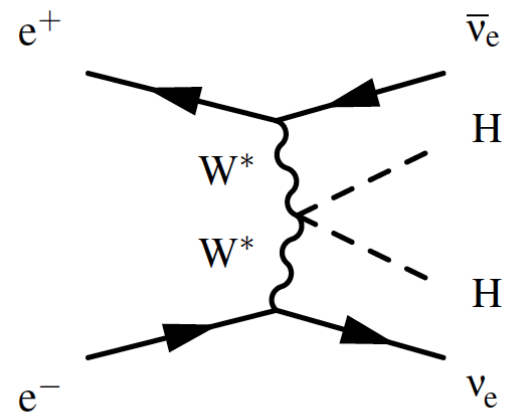
Potentially important measurement at CLIC



★ As for the LHC, in SM trilinear coupling enters through –ve interference

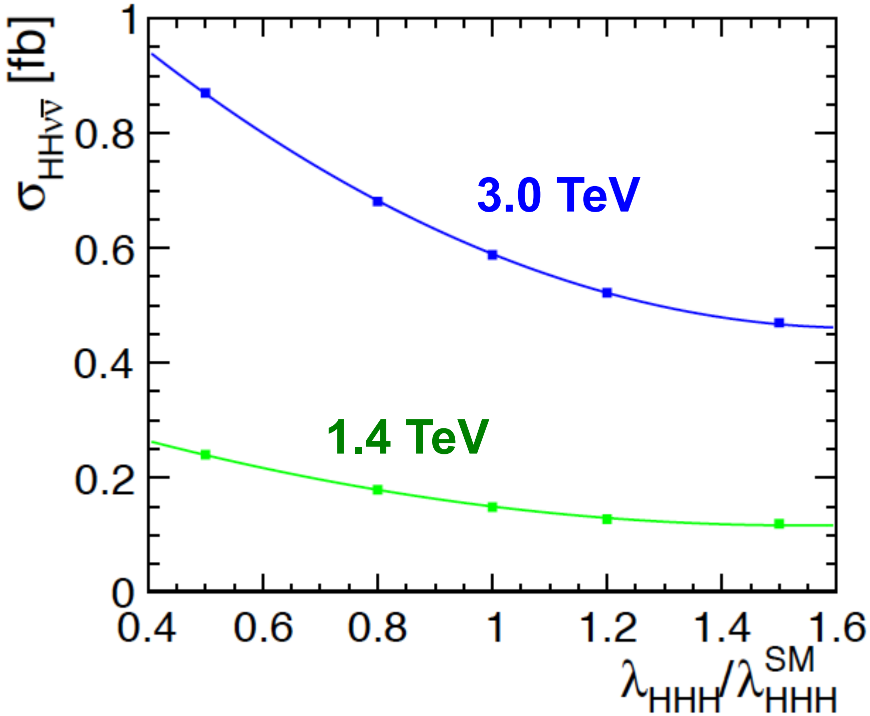






★ **Measure $HH\nu_e\bar{\nu}_e$ cross section**

- **Map back to self-coupling**



★ **CLIC with 80 % electron polarisation:**

$\Delta\lambda/\lambda \sim 24\,\%$ (at 1.4 TeV) $\Delta\lambda/\lambda \sim 12\,\%$ (at 3.0 TeV)

★ **Measure HH cross section**

- **Map back to self-coupling**

Putting it all together

★ **Expected MI precision for CLIC programme**

- **Evaluated using full G4 simulations/full reconstruction ⇨ global fit**

Coupling	350 GeV	+1.4 GeV	+3.0 TeV
HZZ	0.8 %	0.8 %	0.8 %
HWW	1.8 %	0.9 %	0.9 %
Hbb	2.0 %	1.0 %	0.9 %
Hcc	3.2 %	1.4 %	1.1 %
Hgg	3.6 %	1.1 %	1.0 %
$H\tau\tau$	3.5 %	1.5 %	1.4 %
$H\mu\mu$	-	19 %	10 %
Htt	-	4.5 %	4.5 %
HHH	-	24 %	12 %
Γ_H	5.0 %	3.6 %	3.4 %
Γ_{invis}/Γ_H	<1.0 %		

⇨ **CLIC gives O(1%) model independent Coupling determinations** (HZZ to $H\tau\tau$)

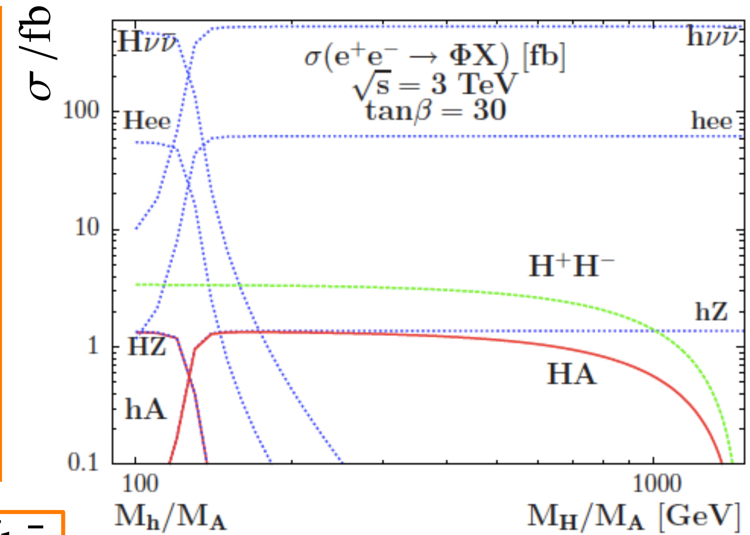
⇨ **Self-coupling** (HHH)

⇨ **Higgs total width** (Γ_H)

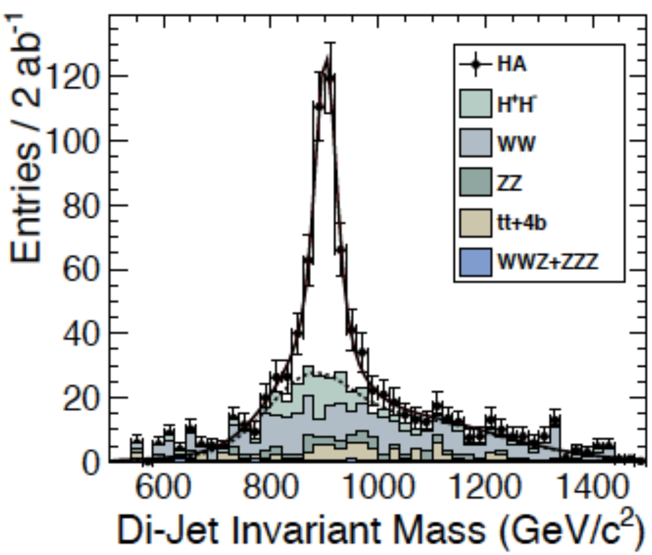
⇨ **Invisible width** (Γ_{invis}/Γ_H)

BSM Higgs

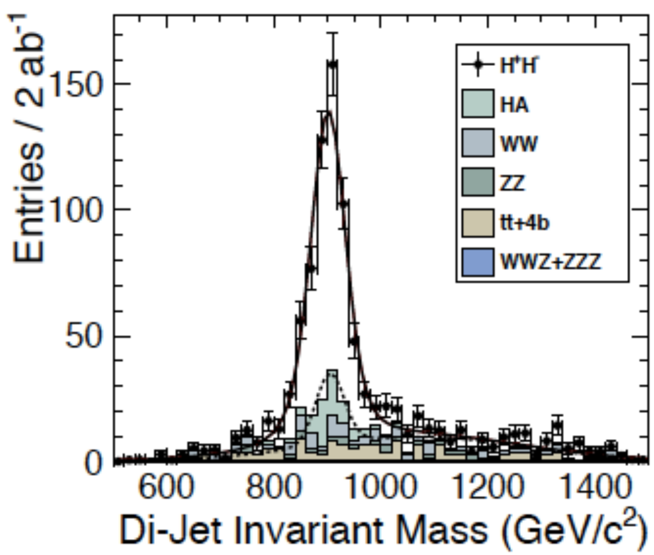
★ In MSSM have extended Higgs sector
- 5 Higgs states from 2 Higgs doublets
- gives rise to heavy states
- in CDR studied models with **750 GeV** and **900 GeV** (near degenerate) heavy Higgs
- cross sections significant at **√s = 3 TeV**
- multi-jet final states



$e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$



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



2 ab^{-1} at 3 TeV

m_{A^0/H^0} : ± 2.8 GeV

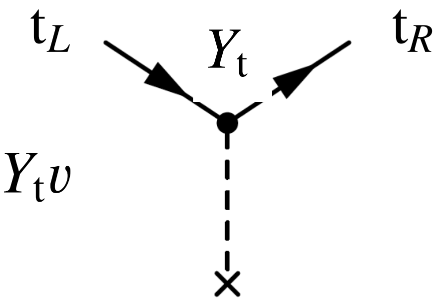
$m_{H^\pm}$: ± 2.4 GeV

Sensitivity up to

$m_A \sim 1.4$ TeV

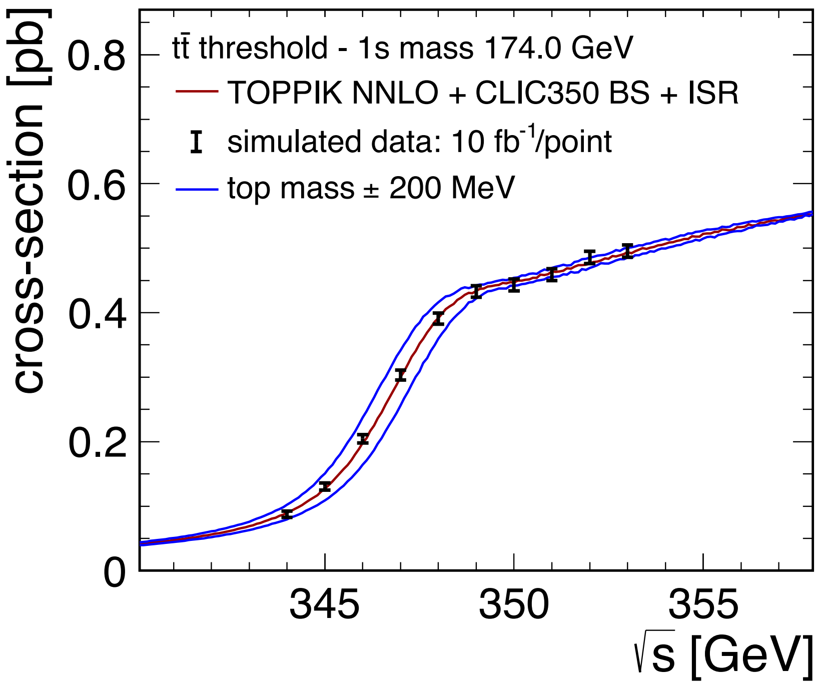
Top Physics

Top quark mass



$$m_t = \frac{1}{\sqrt{2}} Y_t v$$

- **The top quark appears to be special**
  - **fermion mass at the electroweak scale**
  - **Yukawa coupling suspiciously close to 1**
- **CLIC (and ILC @ √s > 350 GeV) ⇨ precision top physics**
  - **e.g. top quark mass from threshold scan**



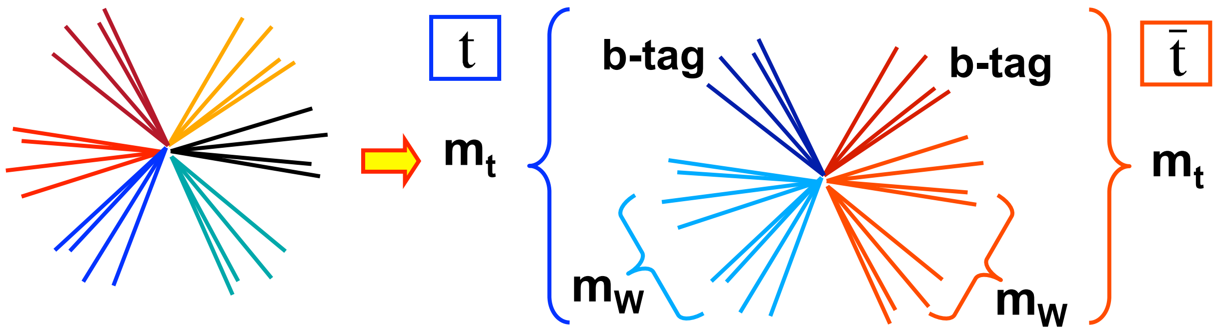
- **Scan with modest lumi (10 fb^{-1}/pt):**

⇨ m_t : ±33 MeV (stat.)

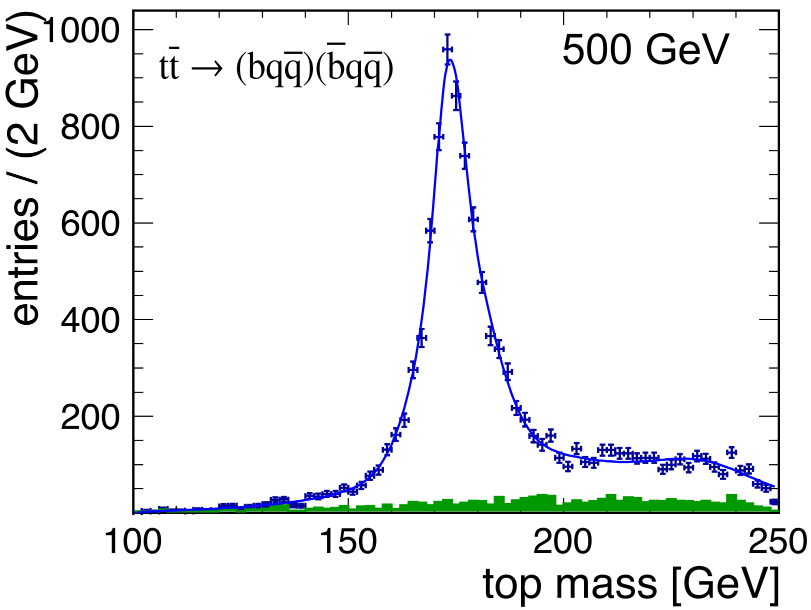
  - **measurement relatively easy to interpret – "know what you are measuring"**
  - **theory uncertainties relatively small**

above threshold

- ★ **Above threshold,** $e^+e^- \to t\bar{t}$ **cross section is large ~100s of fb**
  - **fully hadronic** $t\bar{t} \to (bq\bar{q})(\bar{b}q\bar{q})$ **and semi-leptonic** $t\bar{t} \to (bq\bar{q})(\bar{b}\ell\nu)$ **decays:**



Use:
- b-tagging
- Invariant masses
- Kinematic fits



- ★ **Large cross section & efficient event selection**
  - **high statistics / high purity samples**
  - **precision top physics, e.g.**

$$m_t \ : \ \pm 80\,\text{MeV (stat.)}$$

- ★ **Potential for other precision measurements**
  - A_{FB}
  - **Anomalous couplings – energy helps !**

Beyond the Standard Model

SUSY Benchmarks

- e.g. in the CLIC conceptual design report, three benchmark mSUGRA-motivated models defined:
  - e.g. two high scale models (models I & II)
  - e.g. one lower scale model (model III)
- Main aim – to **benchmark** detector/physics performance
  - CLIC very competitive for **sleptons/gauginos**

***SUSY Model II**

$$m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$$
$$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$$
$$m(\tilde{e}_R) = m(\tilde{\mu}_R) = 1010\,\mathrm{GeV}$$
$$m(\tilde{\nu}_L) = 1097\,\mathrm{GeV}$$
$$m(\tilde{e}_L) = m(\tilde{\mu}_L) = 1100\,\mathrm{GeV}$$
$$m(\tilde{t}_1) = 1393\,\mathrm{GeV}$$

***SUSY Model III**

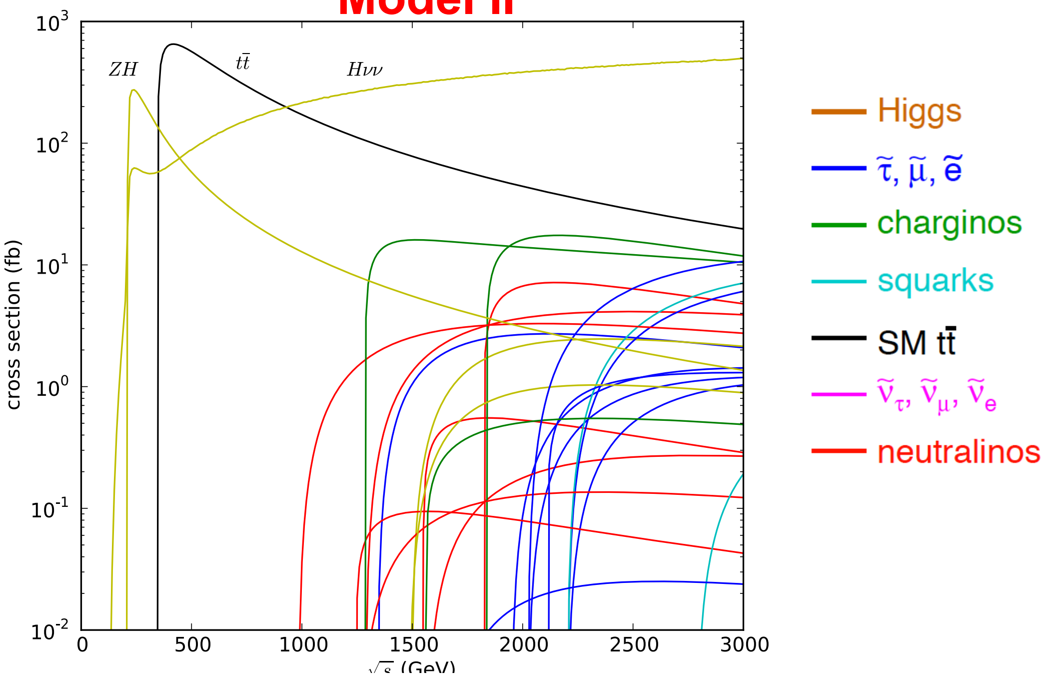
$$m(\tilde{\chi}_1^0) = 357\,\mathrm{GeV}$$
$$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 487\,\mathrm{GeV}$$
$$m(\tilde{e}_R) = m(\tilde{\mu}_R) = 560\,\mathrm{GeV}$$
$$m(\tilde{\nu}_L) = 644\,\mathrm{GeV}$$
$$m(\tilde{e}_L) = m(\tilde{\mu}_L) = 650\,\mathrm{GeV}$$
$$m(\tilde{t}_1) = 844\,\mathrm{GeV}$$

*for details see CDR

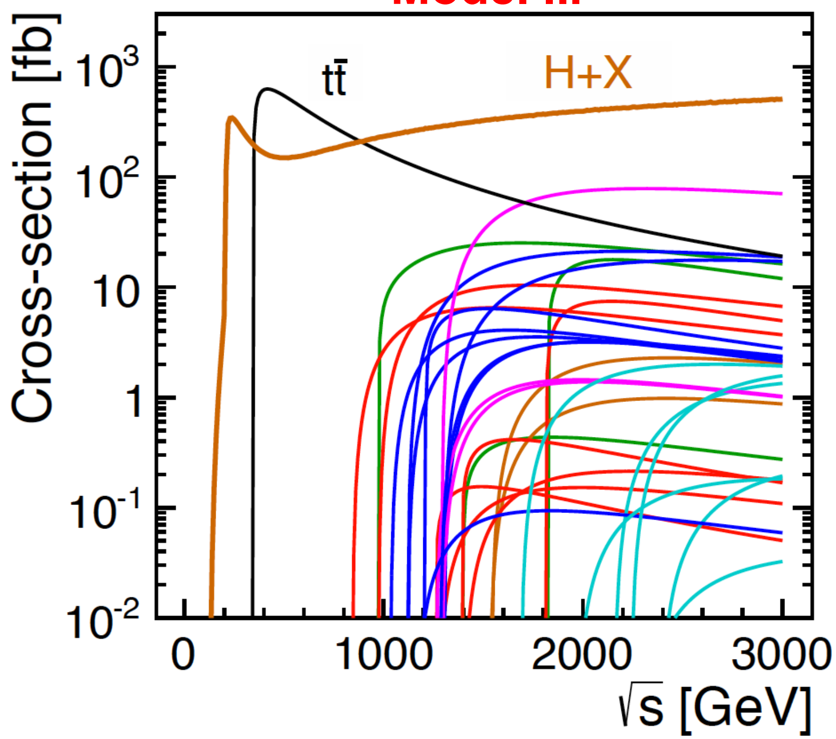
SUSY Benchmarks

- ★ e.g. in the CLIC conceptual design report, three benchmark mSUGRA-motivated models defined:
  - e.g. two high scale models (models I & II)
  - e.g. one lower scale model (model III)
- ★ Main aim – to **benchmark** detector/physics performance

Model II

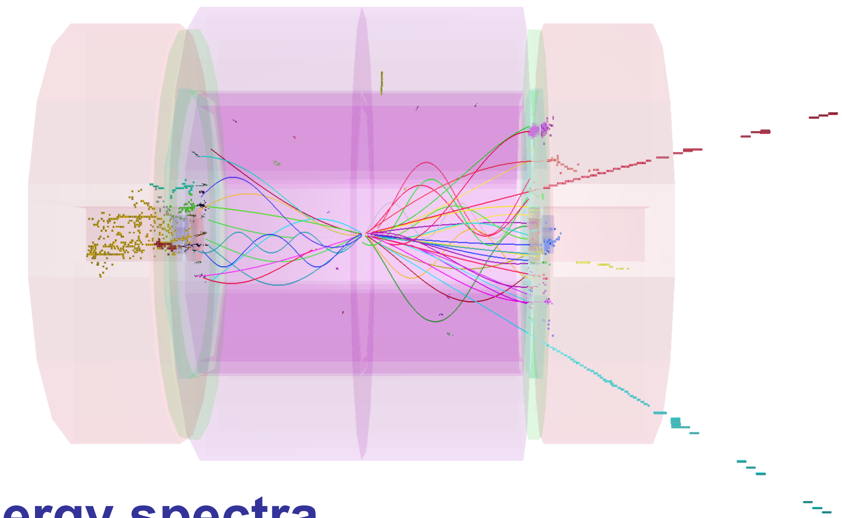


Model III



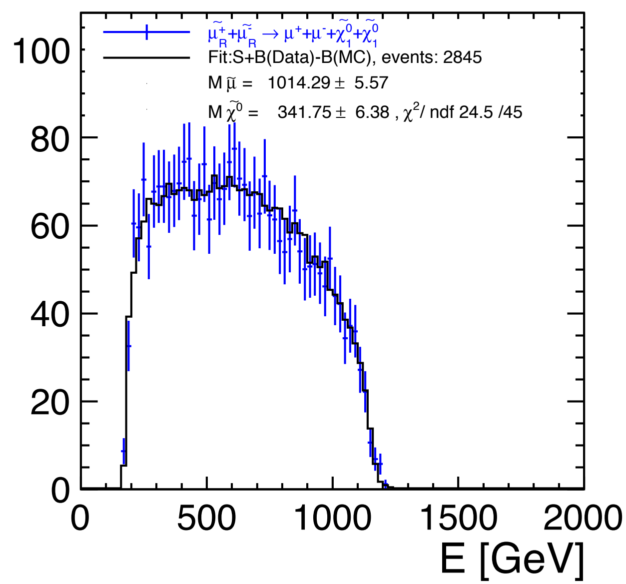
Slepton Production at 3 TeV

- Slepton production at CLIC very clean
- Channels studied include
  - $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^- W^+W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$



- Acoplanar leptons and missing energy
- Masses from analysis of endpoints of energy spectra

e.g. smuon production



All channels combined

$m(\tilde{\mu}_R)$: ± 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

Gaugino Pair Production at 3 TeV

★ **Test of particle flow reconstruction of boosted low mass (EW scale) state**

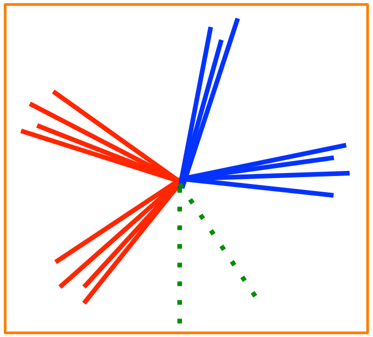
★ **Pair production and decay:**

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

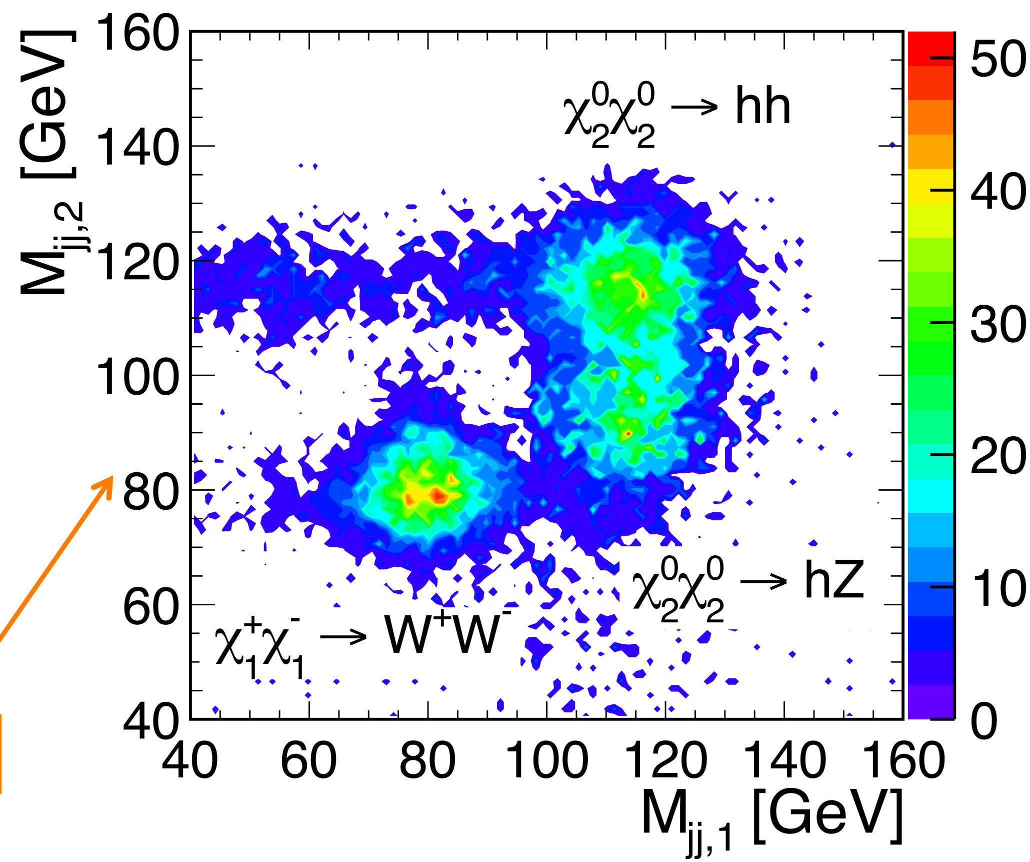
$$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to hh \, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\,\%$$

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

★ **Largest decay BR has same topology for all final states**



Full Simulation with background



★ **Separate using di-jet invariant masses**

$$m(\tilde{\chi}_1^\pm) \; : \; \pm 7\,\text{GeV}$$

$$m(\tilde{\chi}_2^0) \; : \; \pm 10\,\text{GeV}$$

SUSY Summary

★ e.g. CLIC potential* for "Model III" of Vol. 2 of CLIC CDR

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Unit	Generator value	Stat. error
1.4	Sleptons production	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	σ	fb	1.11	2.7%
				$\tilde{\ell}$ mass	GeV	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	GeV	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		σ	fb	5.7	1.1%
				$\tilde{\ell}$ mass	GeV	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	GeV	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		σ	fb	5.6	3.6%
				$\tilde{\ell}$ mass	GeV	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	GeV	487.6	2.7%
1.4	Stau production	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	GeV	517	2.0%
				σ	fb	2.4	7.5%
1.4	Chargino production	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	GeV	487	0.2%
				σ	fb	15.3	1.3%
	Neutralino production	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0 h/Z^0 \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	GeV	487	0.1%
				σ	fb	5.4	1.2%

★ **Large part of SUSY spectrum measured at < 1 % level**

⇨ **Precision to resolve different SUSY breaking models**

★ For model I and model II at √s = 3.0 TeV – see backup slides

SUSY and Beyond…

- Have just scratched the surface of CLIC physics
  - More details given in **Vol. 2 & 3 of CLIC CDR**
- Challenge the Standard Model with **direct** measurements and the **loop level**
  - challenge SM up to the 60 TeV scale

e.g. CLIC at 3 TeV

New particle	CLIC3 $1\ \mathrm{ab}^{-1}$	
squarks [TeV]	1.5	Direct
sleptons [TeV]	1.5	Direct
Z' (SM couplings) [TeV]	20	Loop / Effective operator
2 extra dims M_D [TeV]	20-30	Loop / Effective operator
TGC (95%) (λ_γ coupling)	0.0001	Loop / Effective operator
μ contact scale [TeV]	60	Loop / Effective operator
Higgs compos. scale [TeV]	60	Loop / Effective operator

Summary/Conclusions

Summary/Conclusions

★ **CLIC Physics:**

- **Complementary to the LHC/HL-LHC**
- **Focus on high precision measurements**
  - **physic reach demonstrated (full simulation with pile-up)**
- **Staged approach ⟹ large potential for SM and BSM physics**
  - **~350 – 375 GeV : precision Higgs and top physics**
  - **~1.5 TeV : Higgs (including rarer decays), BSM physics**
  - **> 2 TeV : Higgs, Higgs self-coupling, BSM, …**
  - **Ongoing CLIC study of Higgs properties at 350 GeV and 1.4 TeV**

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  - **> 2 TeV : Higgs, Higgs self-coupling, BSM, …**
  - **Ongoing CLIC study of Higgs properties at 350 GeV and 1.4 TeV**

★ **CLIC is an exciting and realistic option for a future energy frontier machine**

Thank you…

Backup Slides

Background Summary

★ Background conditions much more extreme than LEP

But combination of:

- ★ With high granularity calorimetry,
- ★ good time resolution
- ★ hadron-collider motivated jet algorithms

⇒ No major impact on physics, even at 3 TeV

Demonstrated with Physics Benchmark channels

- ★ All full simulation, full reconstruction
- ★ All with background pile-up
- ★ Mostly focussed on worst case of 3 TeV

CLIC Higgs Studies

Higgs studies for m_H =120 GeV							
$\sqrt{s}$ (GeV)	Process	Decay mode	Measured quantity	Unit	Generator value	Stat. error	Comment
350	SM Higgs production	$ZH \to \mu^+\mu^- X$	σ	fb	4.9	4.9%	Model independent, using Z-recoil
			Mass	GeV	120	0.131	
500		$ZH \to q\bar{q}q\bar{q}$	$\sigma \times$ BR	fb	34.4	1.6%	$ZH \to q\bar{q}q\bar{q}$ mass reconstruction
			Mass	GeV	120	0.100	
500		$ZH, H\nu\bar{\nu} \to \nu\bar{\nu}q\bar{q}$	$\sigma \times$ BR	fb	80.7	1.0%	Inclusive sample
			Mass	GeV	120	0.100	
1400	WW fusion	$H \to \tau^+\tau^-$	$\sigma \times$ BR	fb	19.8	<3.7%	
3000		$H \to b\bar{b}$			285	0.22%	
		$H \to c\bar{c}$			13	3.2%	
		$H \to \mu^+\mu^-$			0.12	15.7%	
1400 3000	WW fusion		Higgs tri-linear coupling g_{HHH}			$\sim 30\,\%$ $\sim 16\,\%$	

Model I & II Studies

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Unit	Generator value	Stat. error
3.0	Sleptons production	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	σ	fb	0.72	2.8%
				$\tilde{\ell}$ mass	GeV	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	GeV	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		σ	fb	6.05	0.8%
				$\tilde{\ell}$ mass	GeV	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	GeV	340.3	1.0%
		$\tilde{e}_L^+\tilde{e}_L^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- hh$ $\tilde{e}_L^+\tilde{e}_L^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- Z^0Z^0$		σ	fb	3.07	7.2%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^- W^+W^-$		σ	fb	13.74	2.4%
				$\tilde{\ell}$ mass	GeV	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	GeV	643.2	0.6%
3.0	Chargino production	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	GeV	643.2	1.1%
				σ	fb	10.6	2.4%
	Neutralino production	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0 h/Z^0 \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	GeV	643.1	1.5%
				σ	fb	3.3	3.2%
3.0	Production of right-handed squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	Mass	GeV	1123.7	0.52%
				σ	fb	1.47	4.6%
3.0	Heavy Higgs production	$H^0A^0 \to b\bar{b}b\bar{b}$	I	Mass	GeV	902.4	0.3%
				Width	GeV		31%
		$H^+H^- \to t\bar{b}b\bar{t}$		Mass	GeV	906.3	0.3%
				Width	GeV		27%

Model III Studies

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Unit	Generator value	Stat. error
1.4	Sleptons production	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	σ	fb	1.11	2.7%
				$\tilde{\ell}$ mass	GeV	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	GeV	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		σ	fb	5.7	1.1%
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				$\tilde{\ell}$ mass	GeV	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	GeV	487.6	2.7%
1.4	Stau production	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	GeV	517	2.0%
				σ	fb	2.4	7.5%
1.4	Chargino production	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	GeV	487	0.2%
				σ	fb	15.3	1.3%
	Neutralino production	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0 h/Z^0 \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	GeV	487	0.1%
				σ	fb	5.4	1.2%

Possible Staging Scenario

★ **A number of possible staging scenarios**

- **details, currently being worked out, e.g.**

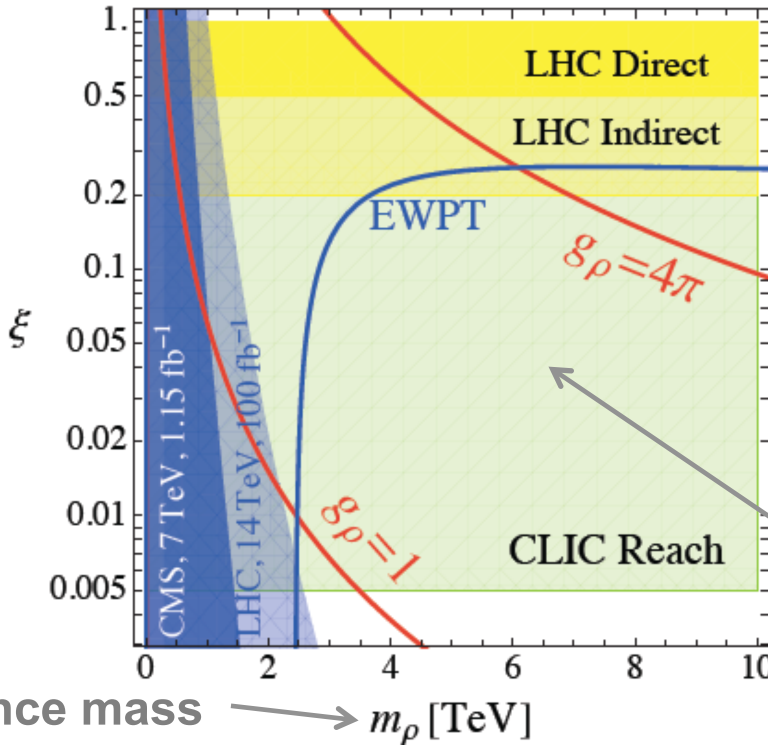
parameter	symbol			
centre of mass energy	E_{cm} [GeV]	500	1400	3000
luminosity	$\mathcal{L}$ [10^{34} $cm^{-2}s^{-1}$]	2.3	3.2	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} $cm^{-2}s^{-1}$]	1.4	1.3	2
gradient	G [MV/m]	80	80/100	100
site length	[km]	13	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	72	44	44
IP beam size	σ_x/σ_y [nm]	200/2.26	$\approx$ 60/1.5	$\approx$ 40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	271	361	582

Composite Higgs

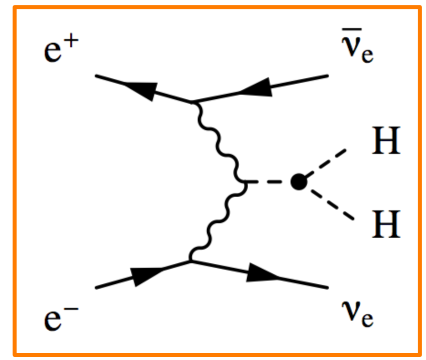
★ In some scenarios, a light Higgs is a bound state of new strongly interacting dynamics at the TeV scale   e.g. Giudice et al., JHEP 06 (2007) 045

- sensitivity from double Higgs production via WW fusion at CLIC

Dimensionless Scale parameter →



Vector resonance mass →



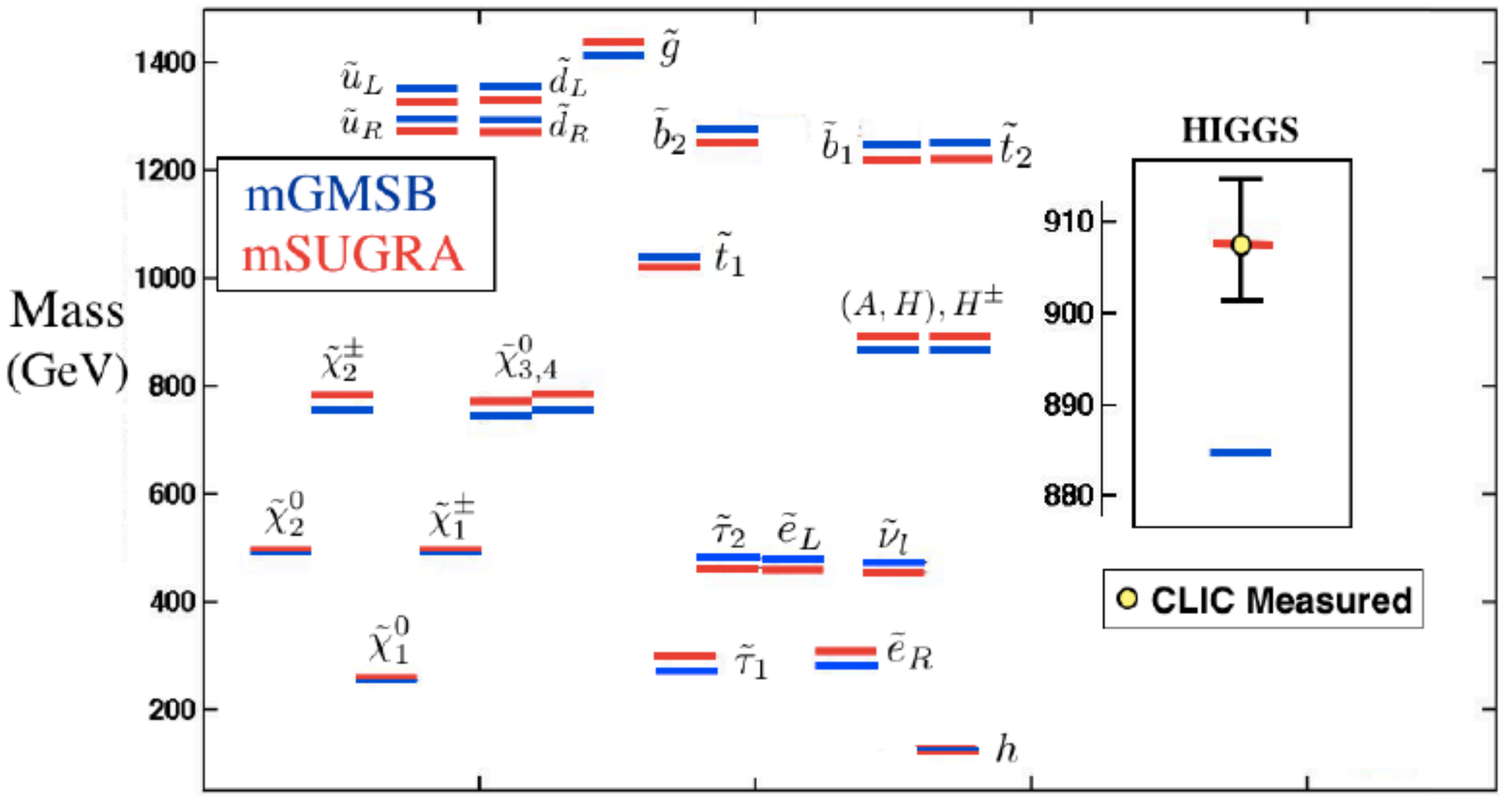
Region favoured by EW precision tests

★ Probe Higgs compositeness at the 30 TeV scale for 1 ab^{-1} at 3 TeV
(60 TeV scale if combined with precise measurements from single Higgs production)

Power of precision

Precision measurements at CLIC allow one to distinguish between models of new physics, e.g. following first observations at LHC

e.g. CLIC resolving power for SUSY breaking models

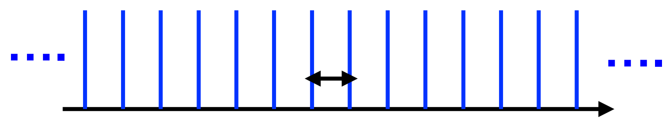


Higgs Production Rates

	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\overline{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\overline{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

Backgrounds in the Calorimeters

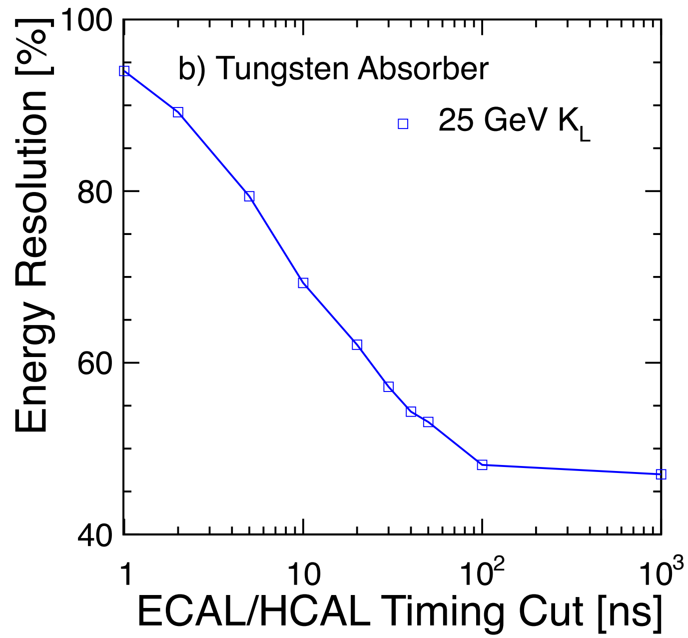
- ★ Calorimeter backgrounds per bunch-crossing are manageable, ~ 60 GeV
- ★ Want to integrate over as few as possible BXs
- ★ Tight timing requirements !



- ★ But can't make calorimeter time window arbitrarily short…
- ★ Time needed to accumulate all calorimetric energy (due to low energy particles, nuclear break-up etc.) significant compared to 0.5 ns Bx
- ★ HCAL resolution depends on time window

Tungsten (Barrel): ~100 ns

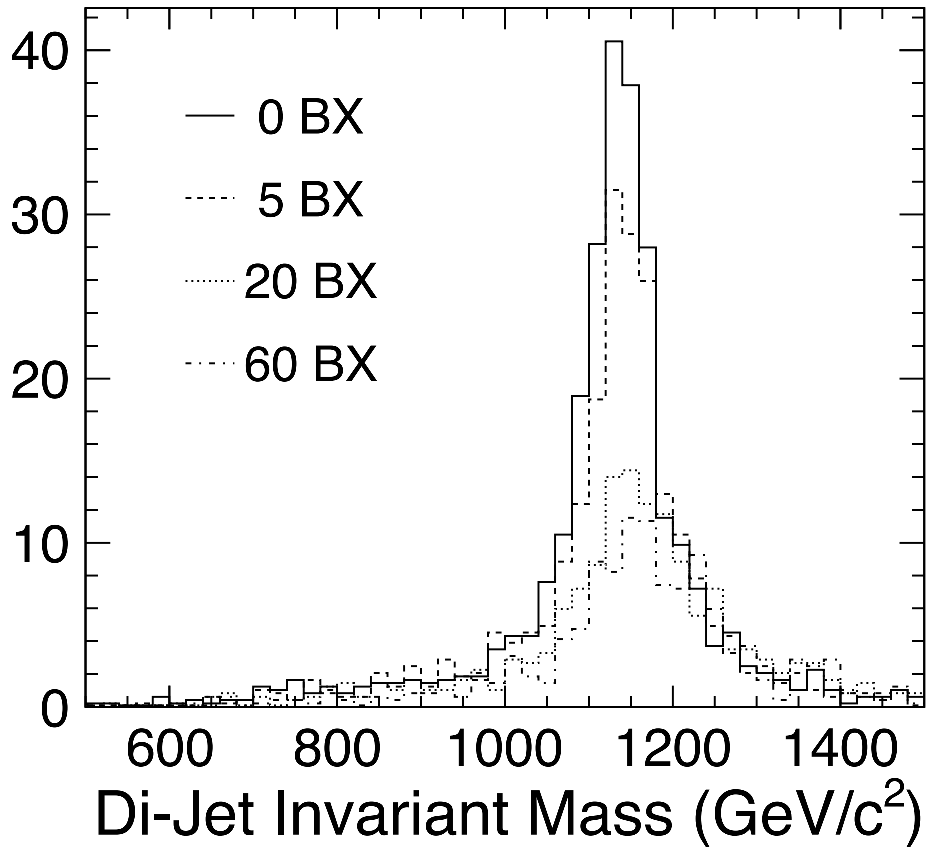
Steel (Endcap): ~10 ns



CLIC Timing cont.

★ **Tension between maximising calorimeter integration time and minimizing number of BXs of $\gamma\gamma \rightarrow$ hadrons background**

- **e.g. reconstructed di-jet mass in $e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$**



⇒ **< 5 BX**

But < 2.5 ns not long enough for calorimetry

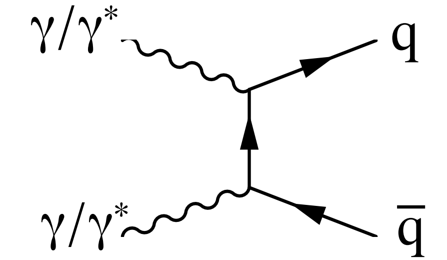
Impact of Background

★ Large backgrounds from interactions of real (Beamsstrahlung) and virtual photons

- Coherent e^+e^- pairs (real)
  - 7×10^8 per bunch crossing (BX) at 3 TeV
  - but mainly collinear with beams – impacts design of forward region
- Incoherent e^+e^- pairs
  - 3×10^5 per BX (low p_T)
  - mostly low angle, impact design of low angle tracking/beam pipe
- $\gamma\gamma \rightarrow$ hadrons (real and virtual) - "pile-up of mini-jet events"
  - 3.2 events per bunch crossing at 3 TeV
  - main background in central tracker/calorimeters

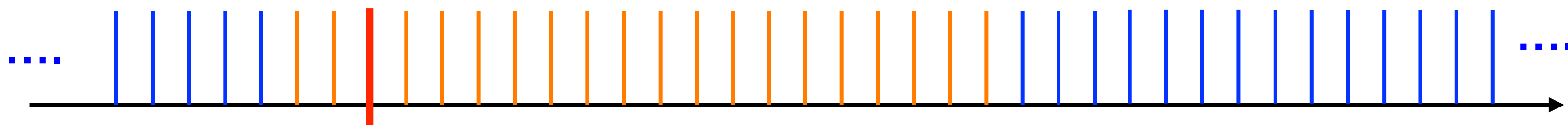
★ Bunch train structure ⇨ pile-up of "mini-jets"

- CLIC: BX separation 0.5 ns
  - Integrate over multiple BXs of $\gamma\gamma \rightarrow$ hadrons
  - 19 TeV visible energy per 156 ns bunch train



A CLIC Detector in Time

- ★ Based on trigger-free readout of detector hits all with time-stamps
  - assume multi-hit capability of 5 hits per bunch train
- ★ Assume can identify t0 of physics event in offline trigger/event filter
  - define "reconstruction" window around t0



- ★ Hits within window passed to track and particle flow reconstruction

Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
HCAL Endcap	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	10/√12
TPC (CLIC_ILD)	Entire train	n/a

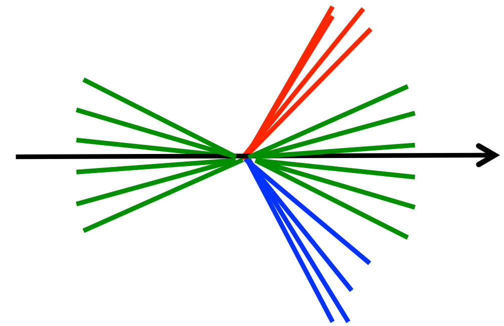
Sufficient calorimeter integration window

CLIC hardware requirements

- ★ Still 1.2 TeV reconstructed background per event

Jet Finding at CLIC

★ At LEP, preferred jet-finding algorithm: Durham k_T
- all particles in event clustered into the jets
- not appropriate for CLIC



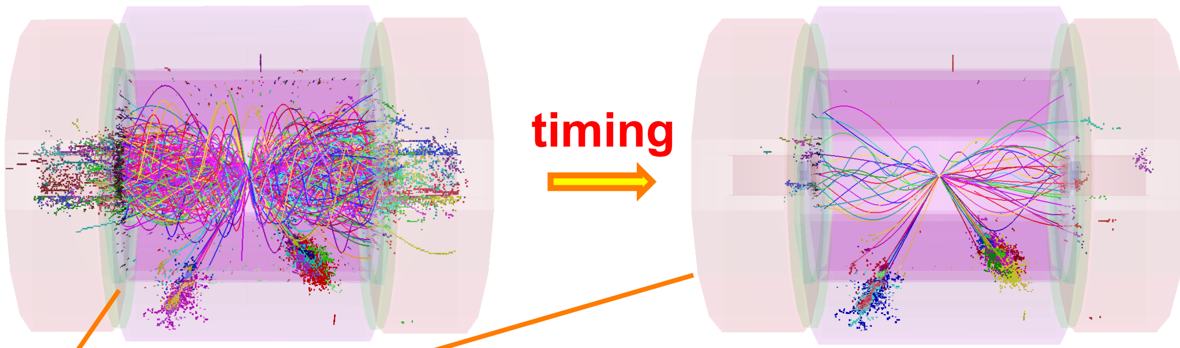
★ Events at CLIC
- significant background from forward-peaked $\gamma\gamma \rightarrow$ hadrons
- are often boosted along beam axis (beamsstrahlung)
- “hadron collider” type algorithms more appropriate

★ Jet finding at CLIC
- studied for benchmark physics analyses (FASTJET package)
- preferred option “k_T” with distance measure $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$
  - invariant under longitudinal boosts
- particles either combined with existing jet or beam axis
  - reduces sensitivity to $\gamma\gamma \rightarrow$ hadrons

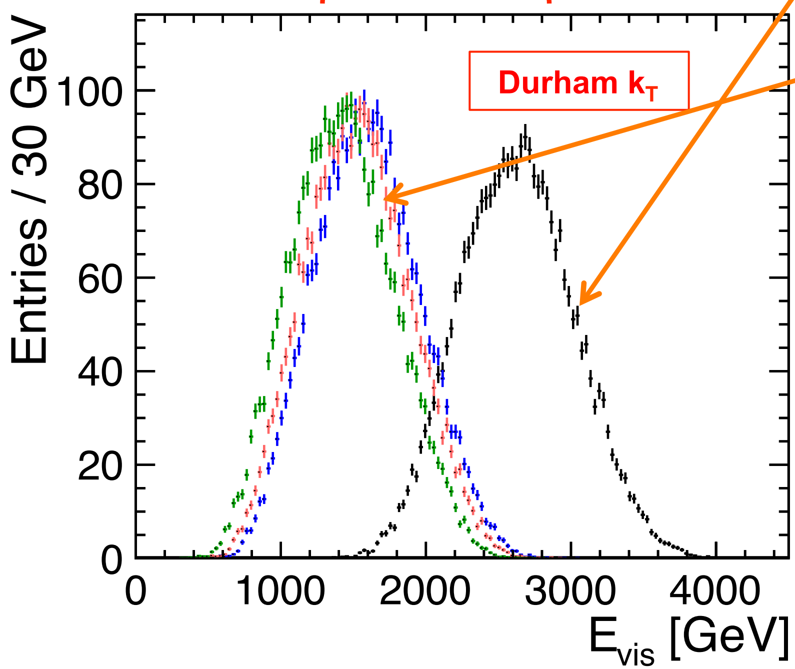
Jet Finding at CLIC

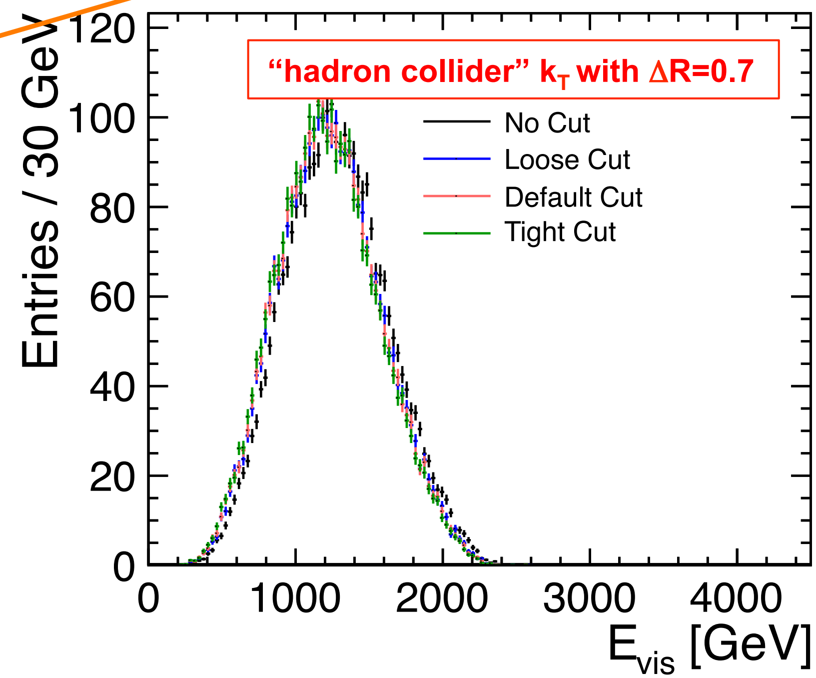
★ e.g. $e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$

- two jets + missing energy



All particles clustered





★ Two "weapons" against background: timing cuts + jet finding