Physics at future linear colliders

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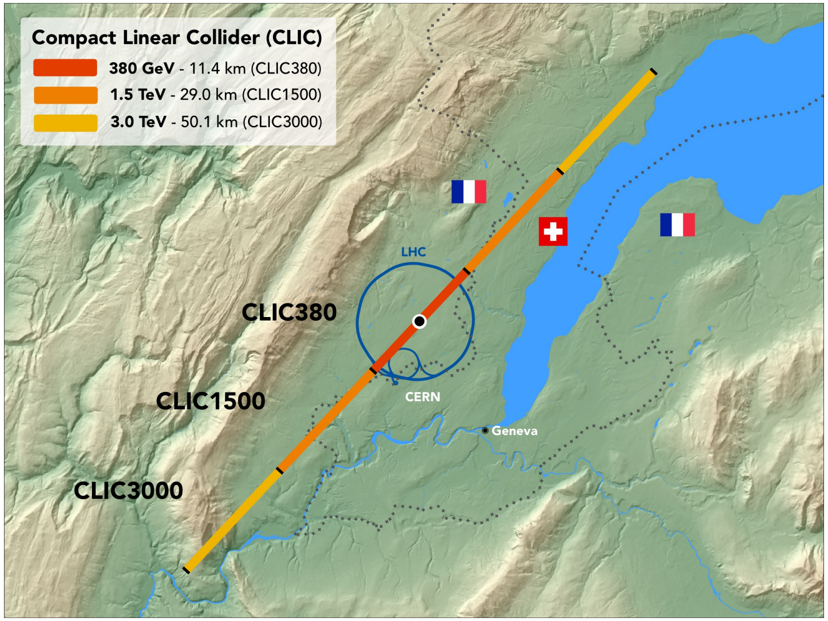
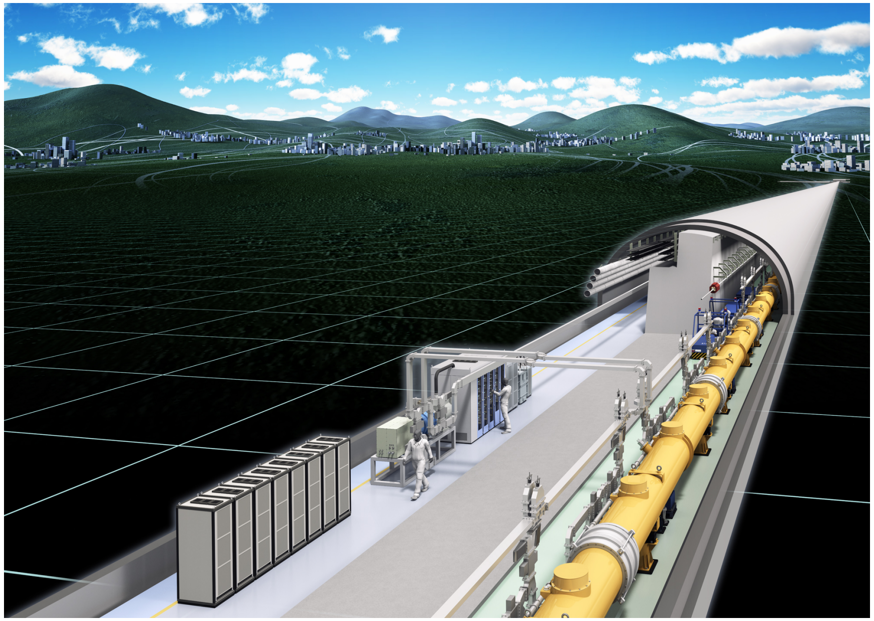
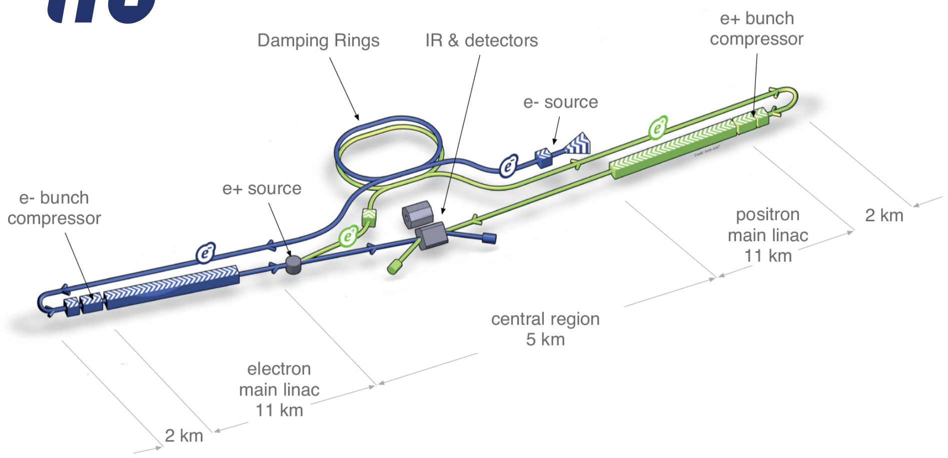
(CERN)

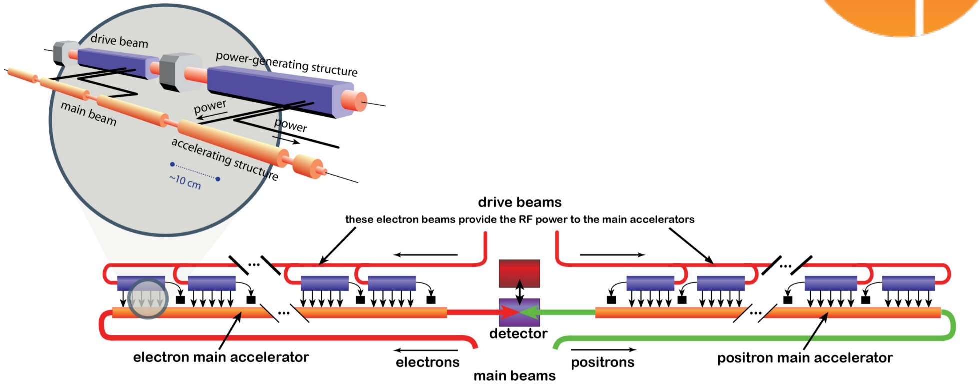
09/09/2018
LFC19: Strong dynamics for physics within and beyond the Standard Model at LHC and future colliders, Trento





Introduction: ILC and CLIC



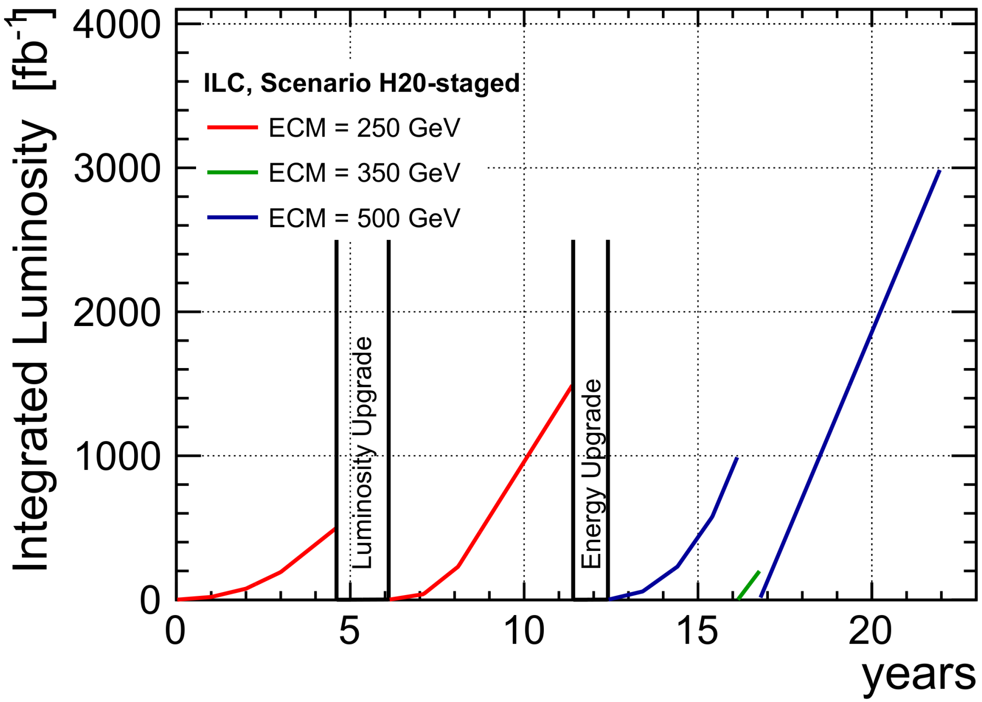


International Linear Collider (ILC):
- Based on superconducting RF cavities
- Gradient: 32 MV/m
- Energy: 250 - 500 GeV (upgradable to 1 TeV)
- $P(e^-) = \pm 80\%$, $P(e^+) = \pm 30\%$
- Length: 20 km (250 GeV), 31 km (500 GeV)

Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV
- $P(e^-) = \pm 80\%$
- Length: 11 km (380 GeV), 50 km (3 TeV)

Linear colliders have the potential to profit from novel accelerator techniques

ILC staged implementation



- The ILC is now proposed with a staged design: first stage at 250 GeV with a luminosity goal of 2 ab^{-1}

- Luminosity upgrade requires machine upgrades (double number of bunches per pulse)

- 1 year = 1.6 x 10^7 seconds

		$\int \mathcal{L}$	fraction with sign($P(e^-), P(e^+)$) =			
	E_{CM} (GeV)	(fb^{-1})	$(-+)$	$(+-)$	$(--)$	$(++)$
ILC250	250	2000	45%	45%	5%	5%
ILC350	350	200	67.5%	22.5%	5%	5%
ILC500	500	4000	40%	40%	10%	10%

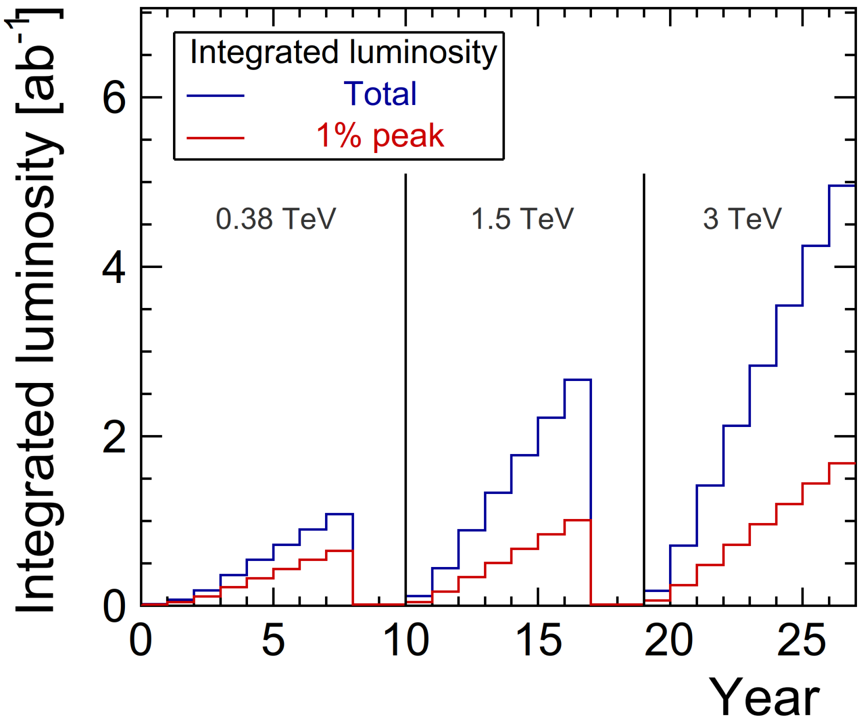
arXiv:1903.01629
arXiv:1908.11299

CLIC staged implementation

CLIC would be implemented
in several energy stages

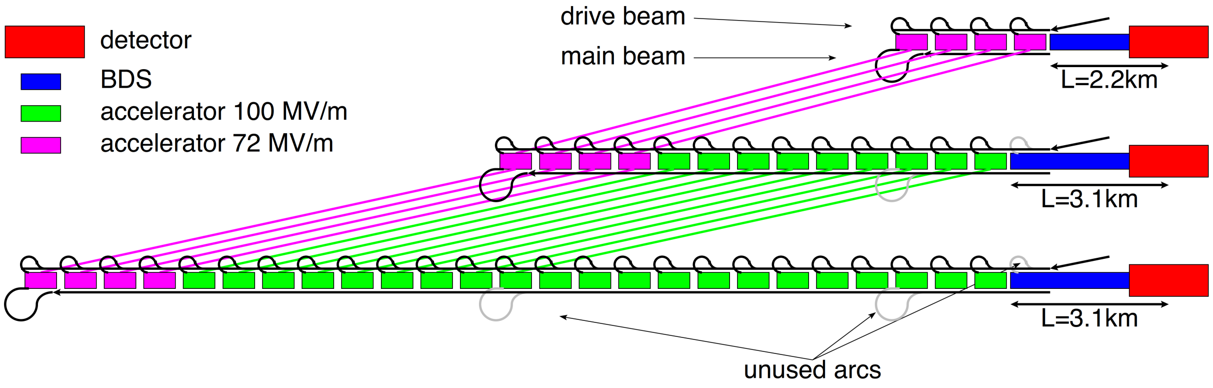
Current baseline scenario:

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	$P(\text{e}^-) = -80\%$ $\mathscr{L}_{\text{int}}$ [ab^{-1}]	$P(\text{e}^-) = +80\%$ $\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0	0.5	0.5
2	1.5	2.5	2.0	0.5
3	3.0	5.0	4.0	1.0



- The strategy can be adapted to possible discoveries at the (HL-)LHC or the initial CLIC stage(s)

- 1 year = 1.2×10^7 seconds (based on CERN experience)

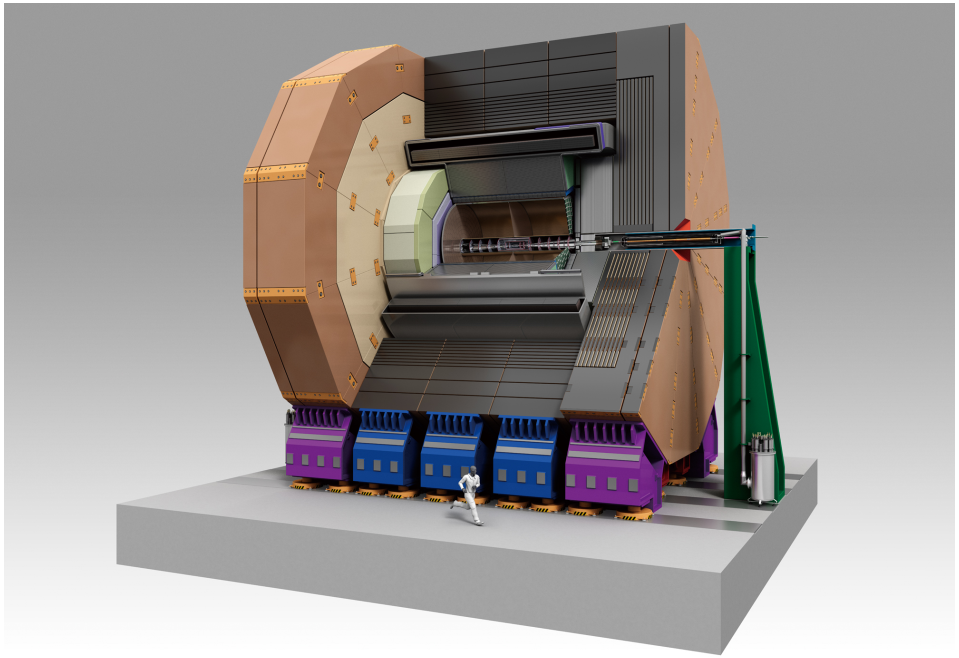


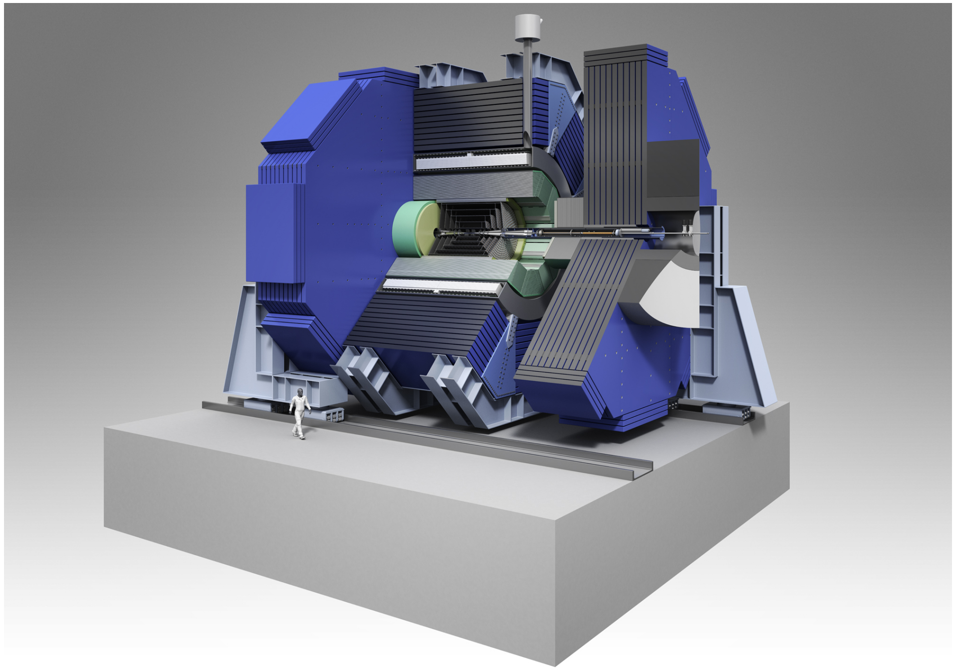
CERN-2018-005-M
arXiv:1812.01644

ILC detector concepts

Designed for Particle Flow Calorimetry:

- High granularity calorimeters (ECAL and HCAL) inside solenoid
- Low mass trackers → reduce interactions / conversions





ILD (International Large Detector):

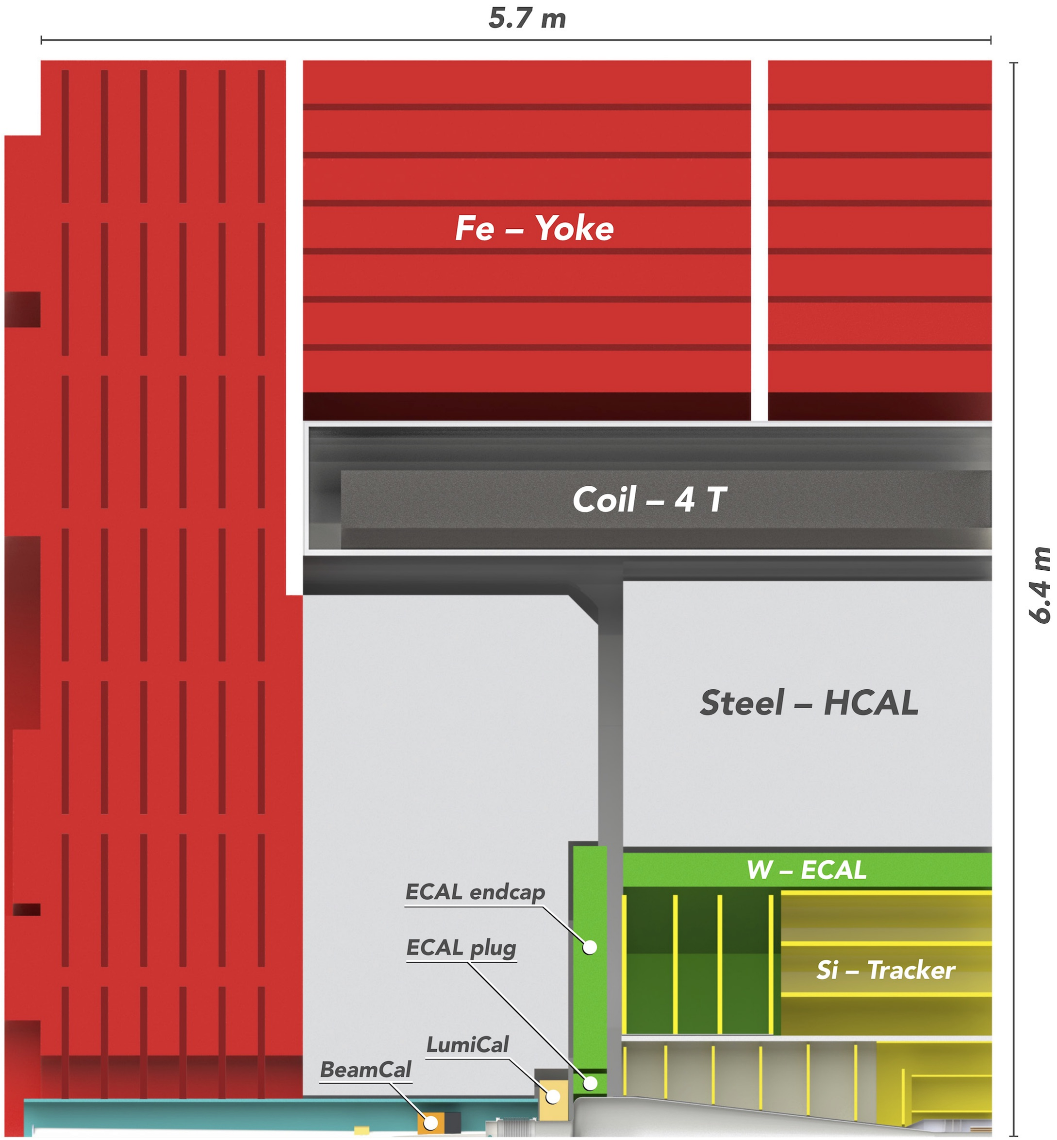
- TPC+silicon envelope, radius: 1.8 m
- B-field: 3.5 T

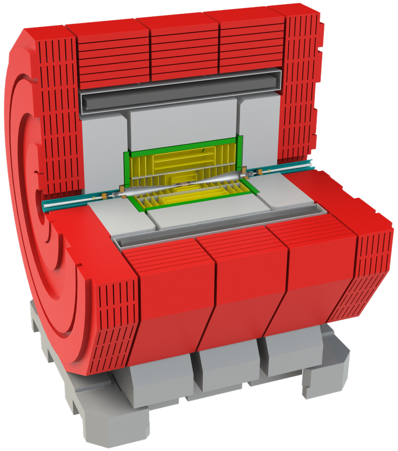
(small option: 1.46 m / 4 T under study)

SiD (Silicon Detector):

- Silicon tracking, radius: 1.2 m
- B-field: 5 T

CLIC detector concept



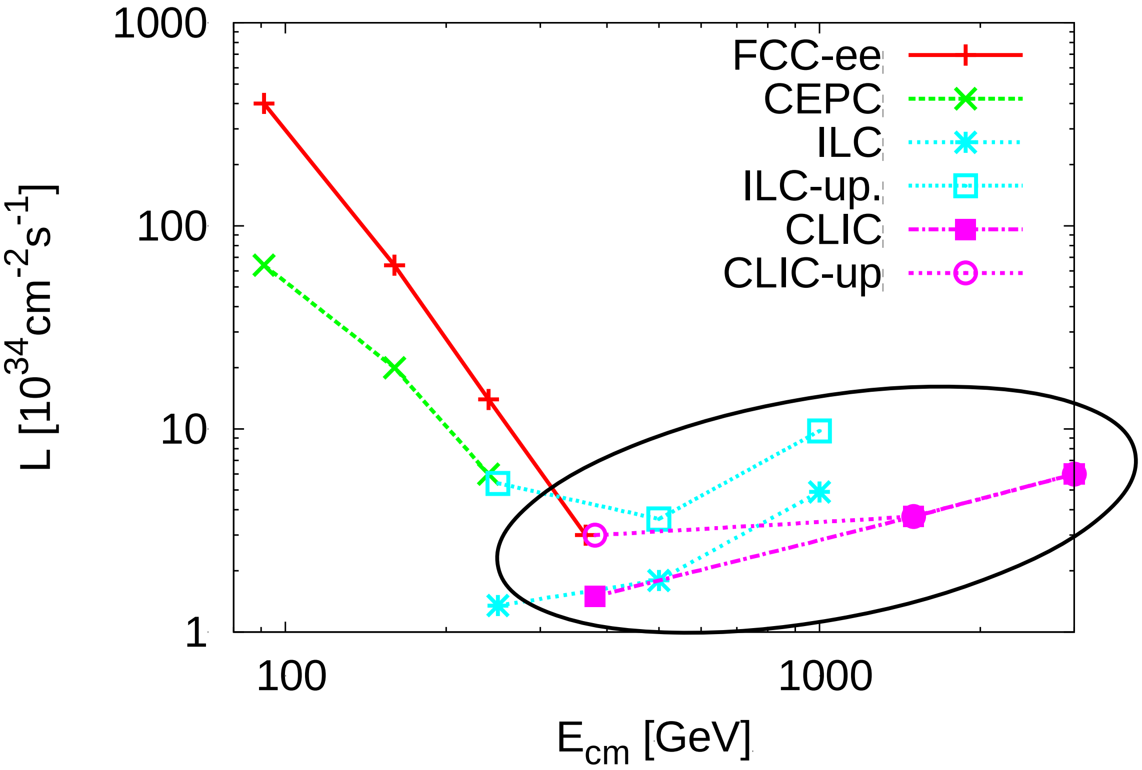


Basic characteristics:
- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (1.5 m radius)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ)

Precise timing for background suppression
(bunch crossings 0.5 ns apart)**:**
- ≈ 10 ns hit time-stamping in tracking
- 1 ns accuracy for calorimeter hits

CLICdp-Note-2017-001
arXiv:1812.07337

Comparison to other e^+e^- collider options



Linear colliders:
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies

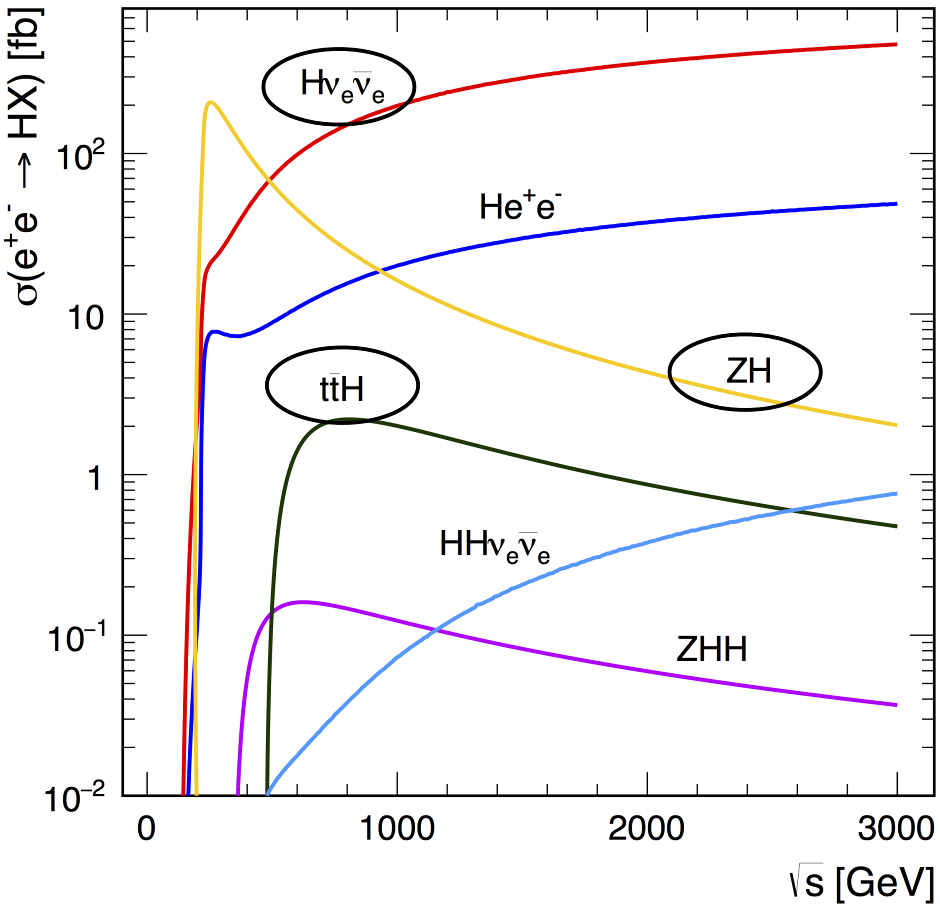
Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

NB: Peak luminosity at LEP2 (209 GeV) was ≈ $10^{32}\ cm^{-2}s^{-1}$

NB: “CLIC-up” is a recent suggestion to double repetition frequency at 380 GeV

Daniel Schulte, Granada Symposium

Single Higgs production



Higgsstrahlung: $e^+e^- \to ZH$

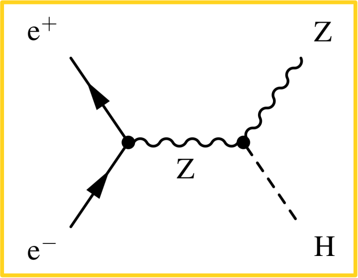
- $\sigma \sim 1/s$, dominant up to ≈ 500 GeV

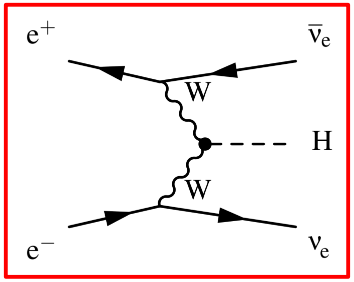
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

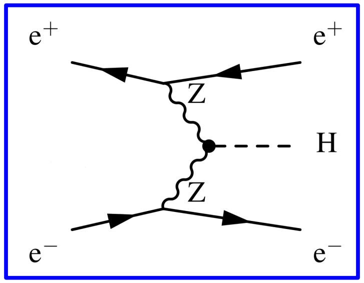
- $\sigma \sim \log(s)$, dominant above 500 GeV
- Large statistics at high energy

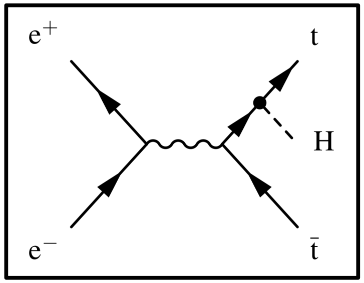
$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$

- Accessible ≥ 500 GeV, maximum ≈ 800 GeV
- Direct extraction of the top-Yukawa coupling

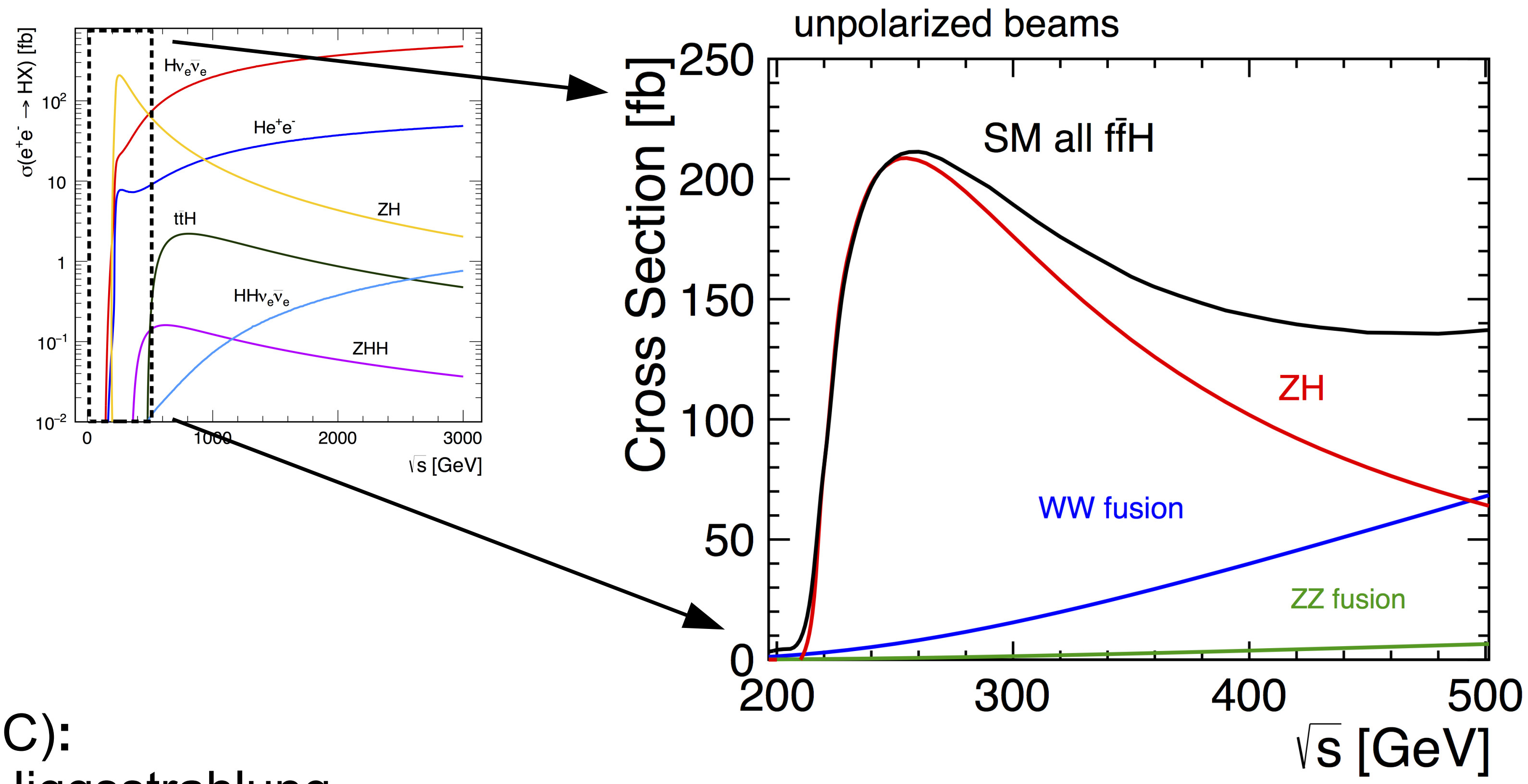






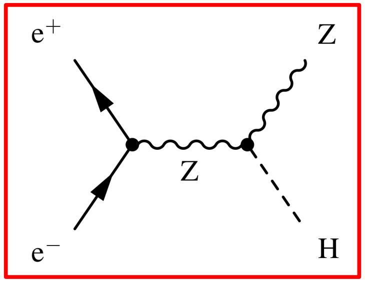


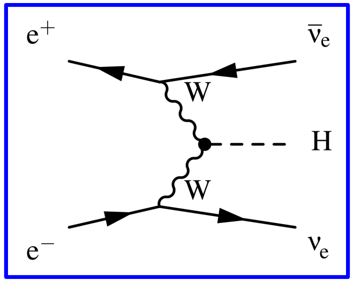
A closer look at $\sqrt{s} < 500$ GeV



$\sqrt{s}$ = 250 GeV (ILC):
Maximum of the Higgsstrahlung cross section

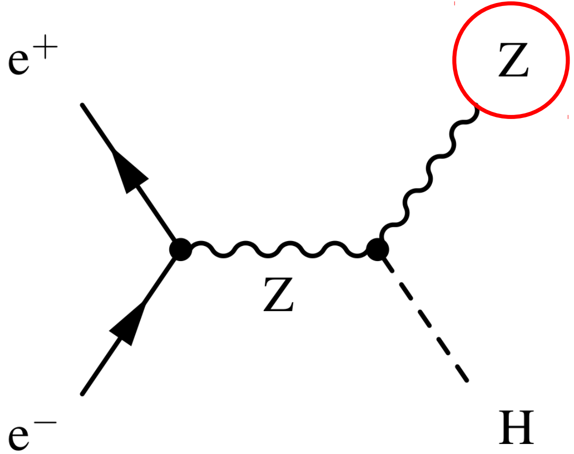
$\sqrt{s}$ = 350/380 GeV (ILC & CLIC):
Also allows to access the WW fusion process
→ Additional information for combined analysis





Recoil method: Z → e^+e^- and $\mu^+\mu^-$

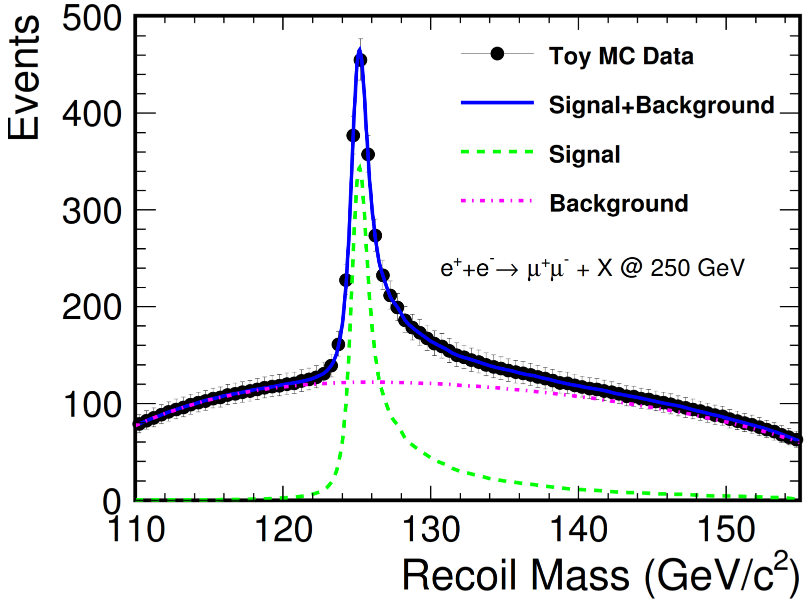
ZH events can be identified from the Z recoil mass
→ Model-independent measurement of σ(ZH) and m_H



$$m^2_{recoil} = \left(\boxed{\sqrt{s}} - \boxed{E_Z}\right)^2 - \left|\boxed{\vec{p}_Z}\right|^2$$

Known at lepton collider

Best precision using
Z → e^+e^-, $\mu^+\mu^-$ at 250 GeV:
- Cross section at maximum
- Tracking resolution
- Impact of beam energy spectrum & ISR smaller

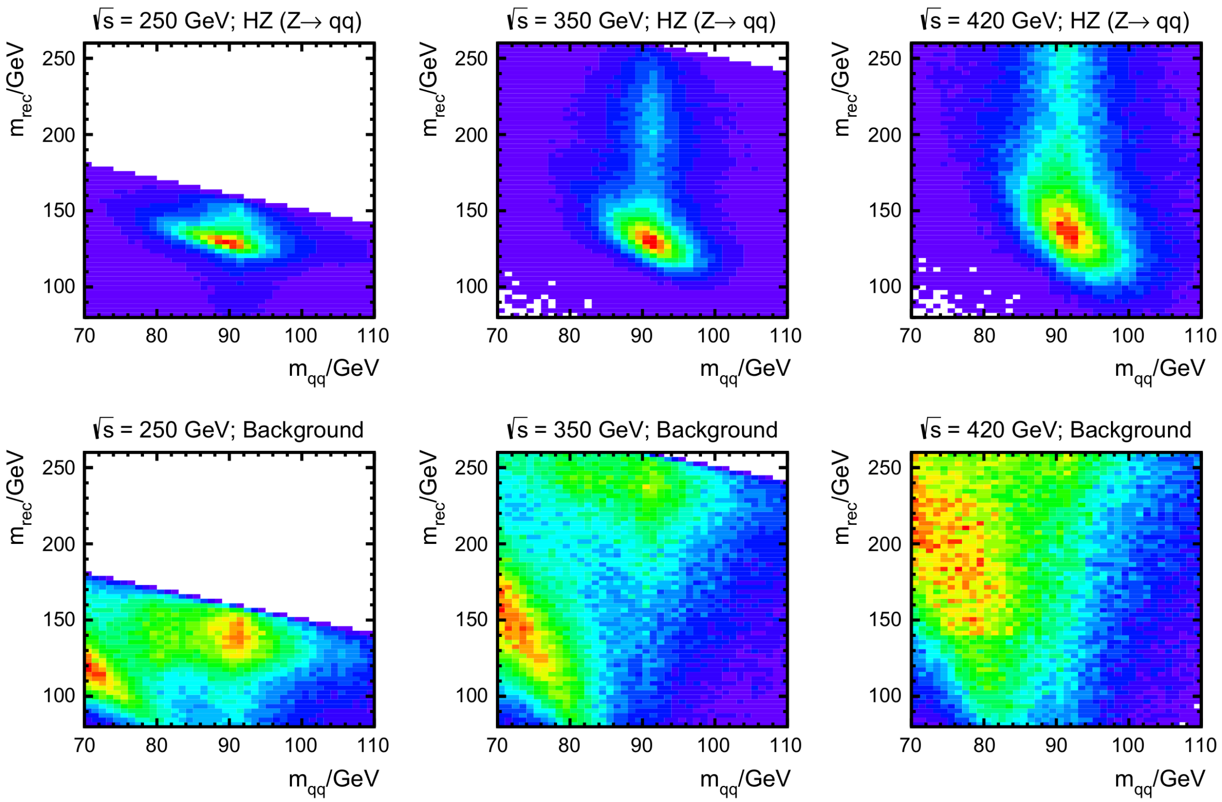


Phys. Rev. D 94, 113002 (2016)

ILC, $\sqrt{s}$ = 250 GeV, L = 2 ab^{-1}
Δσ(HZ) / σ(HZ) = 1.0%
Δm_H = 14 MeV

Recoil method: Z→q$\bar{q}$

$\sqrt{s}$ = 250 GeV: **$\sqrt{s}$ = 350 GeV:** **$\sqrt{s}$ = 420 GeV:**

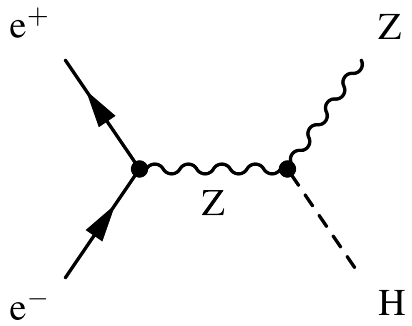


Hadronic Z decays provide the best sensitivity at 350 GeV

Optimisation study for the first CLIC stage (together with top physics):

- At 250 GeV the background is more signal-like
- At 420 GeV the cross section is lower and the jet energy resolution is worse

$\sqrt{s}$ [GeV]:	L_{int} [fb^{-1}]:	σ(ZH) [fb]	Δσ(ZH)
250	1000	136	±2.58%
350	1000	93	±1.27%
420	1000	68	±1.86%



Eur. Phys. J. C 76, 72 (2016)

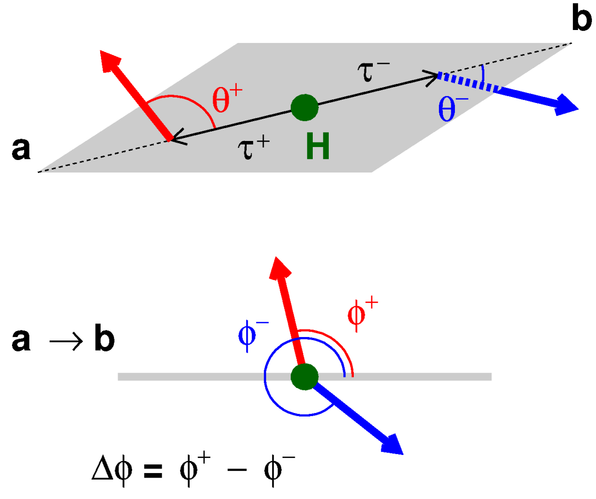
CP state of tau lepton pairs from H → $\tau^+\tau^-$

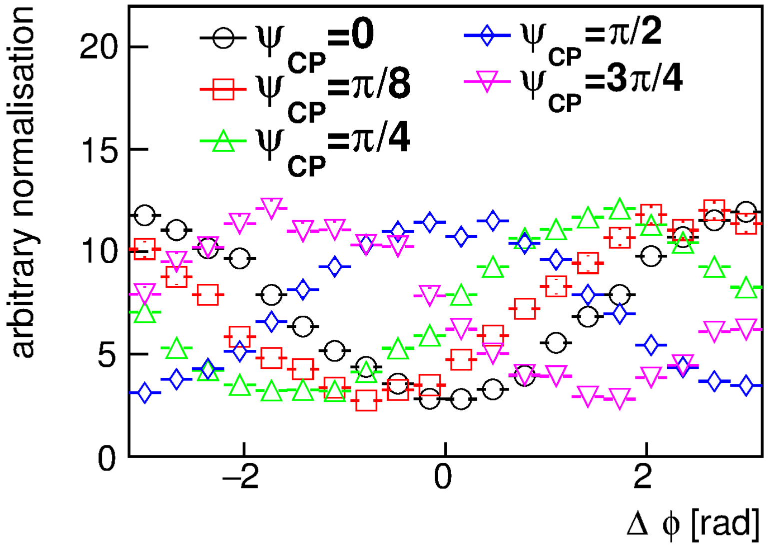
$$\boxed{-ig_{\tau\tau H}\left(\cos\psi_{CP} + i\sin\psi_{CP}\,\gamma_5\right)}$$

ψ_{CP} = 0: Standard Model
ψ_{CP} = π/2: Purely CP-odd coupling

Using $e^+e^- \to ZH$; $H \to \tau^+\tau^-$;
$\tau^\pm \to \pi^\pm\nu$ and $\tau^\pm \to \pi^\pm\pi^0\nu$

ILC, $\sqrt{s}$ = 250 GeV, L = 2 ab^{-1}
$\Delta\psi_{CP} / \psi_{CP}$ = 75 mrad (or 4.3°)

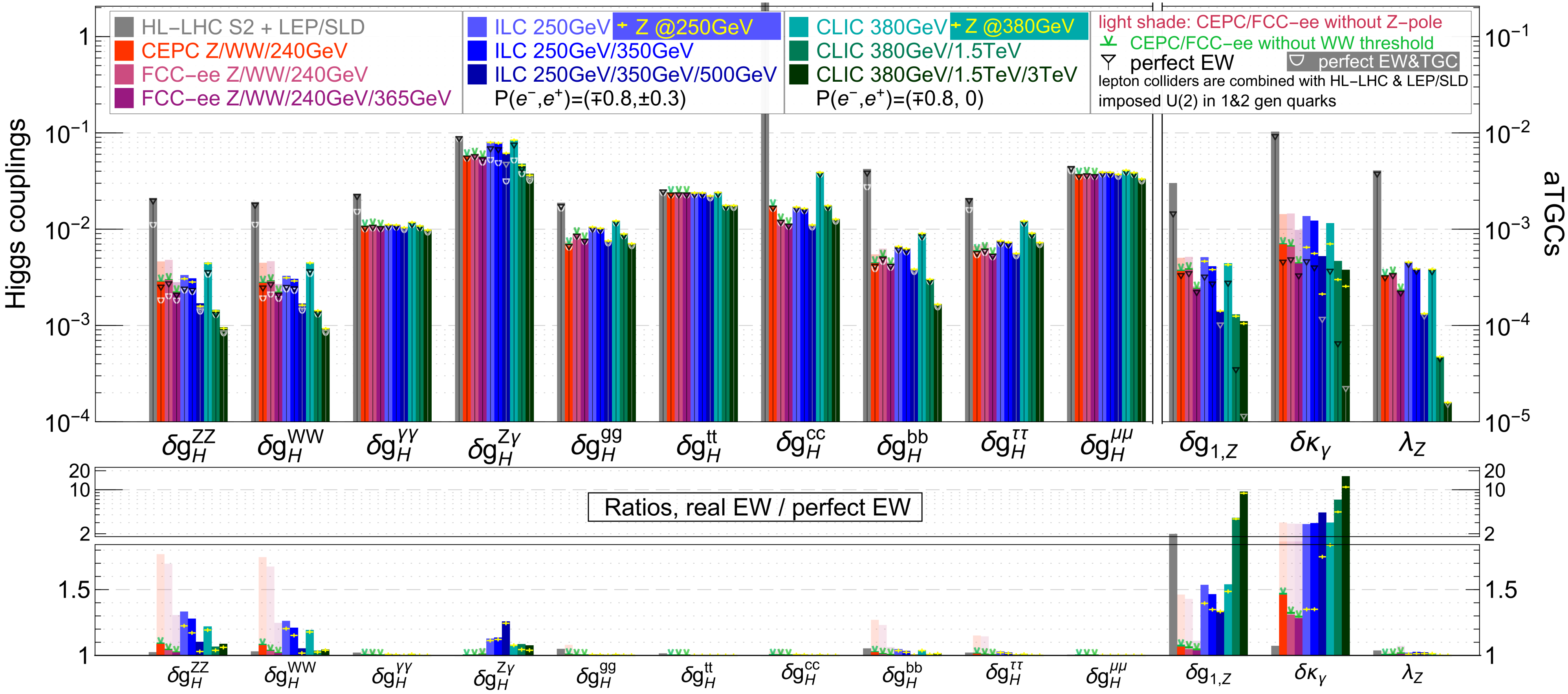




Phys. Rev. D98, 013007 (2018)

Higgs coupling sensitivity

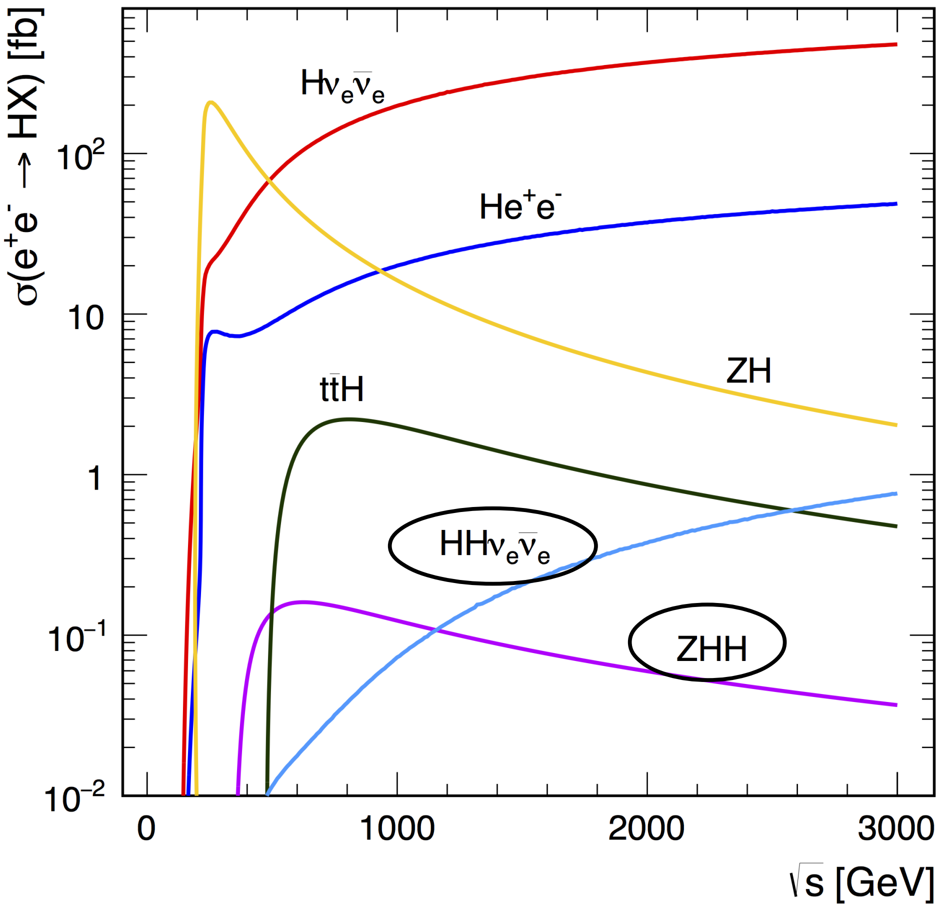
precision reach on effective couplings from full EFT global fit



- Many Higgs couplings can be measured significantly better at ILC and CLIC compared to HL-LHC
- $H \to c\bar{c}$ very challenging at hadron colliders
- Impact of EWPO on the Higgs coupling extraction small

arXiv:1907.04311

Double Higgs production



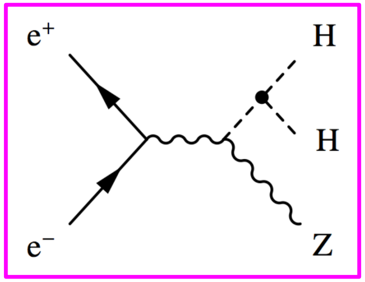
$e^+e^- \rightarrow ZHH$:

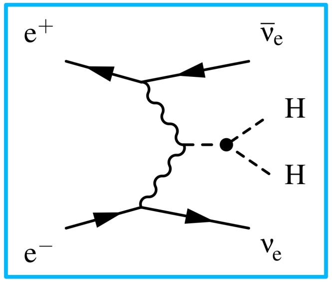
- Cross section maximum ≈ 600 GeV

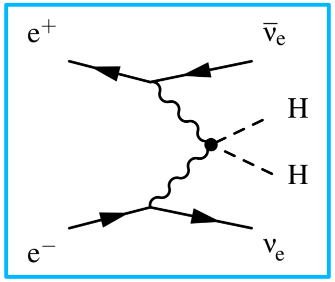
$e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$:

- Benefits from high-energy operation

$HH \rightarrow b\bar{b}b\bar{b}$ is the "golden channel" at lepton colliders, combination with $HH \rightarrow b\bar{b}WW^*$ leads to marginal improvement



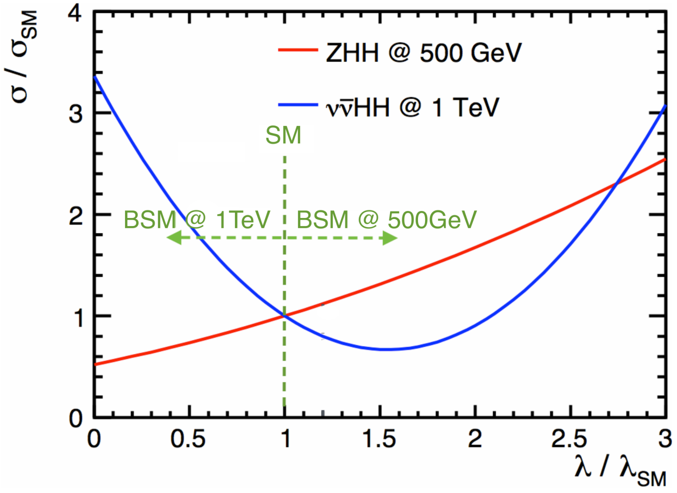




Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

Phys. Rev. D 88, 055024 (2013)

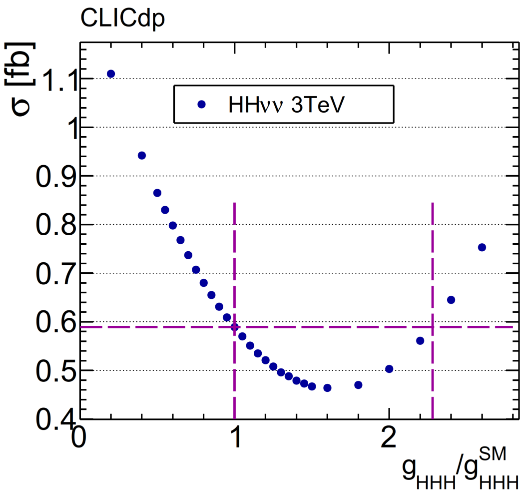
Higgs self-coupling measurements

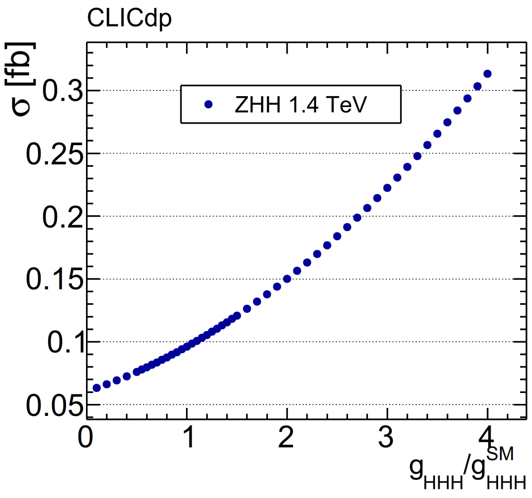


- **ILC**, $\sqrt{s}$ = 500 GeV, L = 4 ab^{-1}**:**
  $\Delta\lambda/\lambda$ = 27% from ZHH cross section

DESY-THESIS-2016-027

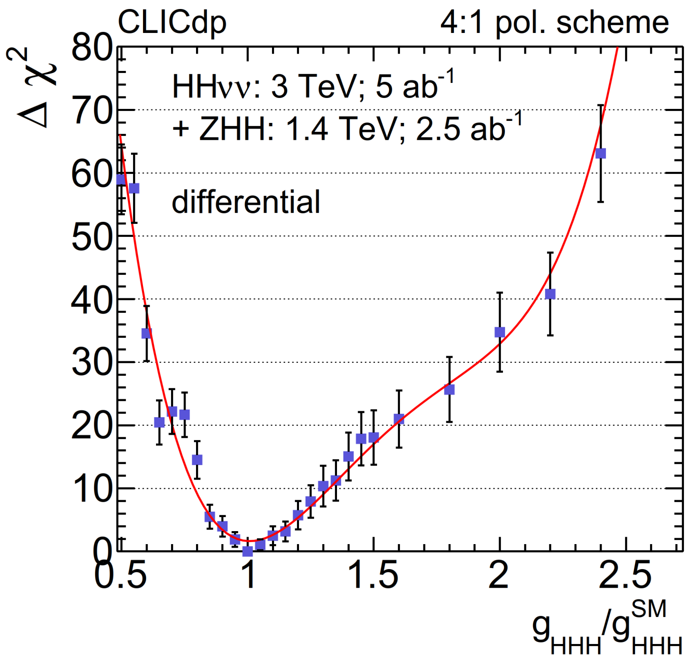
- **Complementarity of the two production processes:**
  $\lambda > \lambda_{SM}$: $\sigma(ZHH)$ at 500 GeV enhanced
  $\lambda < \lambda_{SM}$: $\sigma(HH\nu_e\bar{\nu}_e)$ at high energy enhanced



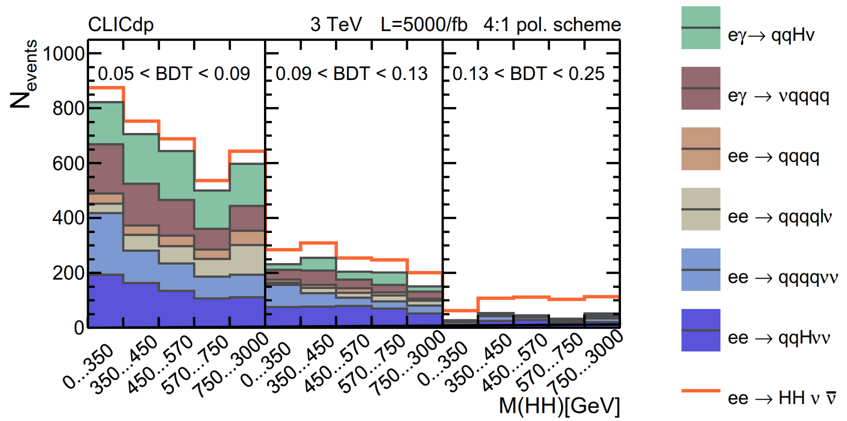


- $HH\nu_e\bar{\nu}_e$ at high energy provides the best sensitivity assuming the SM value of λ, second solution can be excluded using ZHH and/or differential distributions

Higgs self-coupling at CLIC



	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	> 3σ EVIDENCE Δσ/σ = 28%	> 5σ OBSERVATION Δσ/σ = 7.3%
σ(ZHH)	> 5σ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4 TeV: -34% +36% rate only	1.4 & 3 TeV: -7% +11% differential analysis

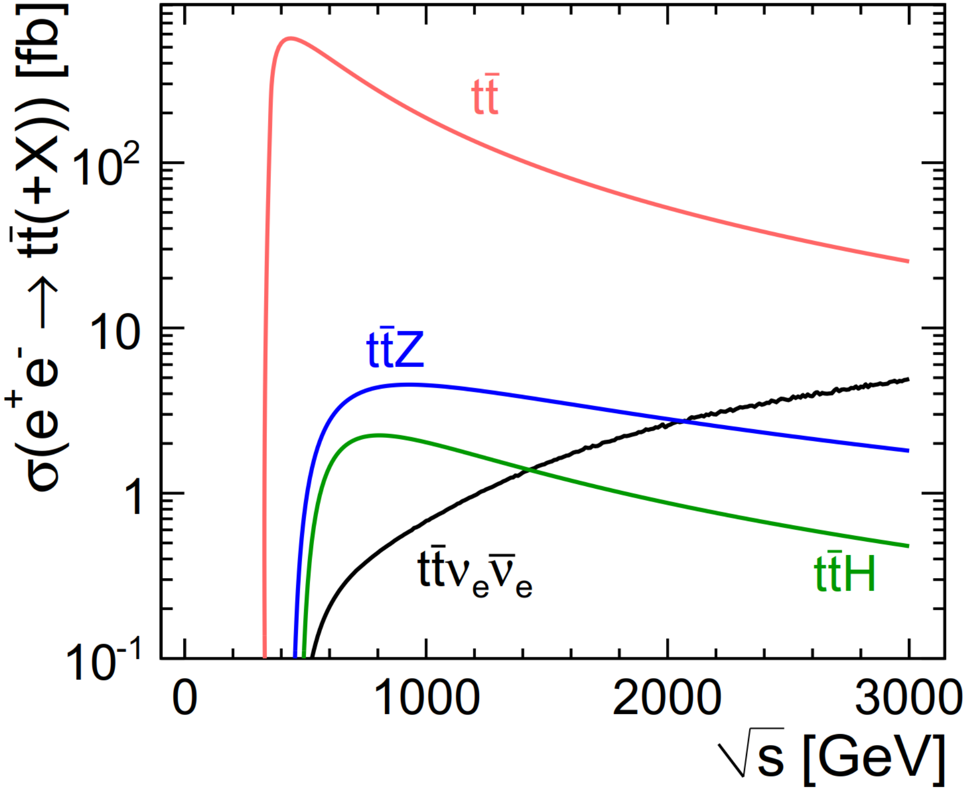


Template fit at 3 TeV
uses two variables: M(HH) and BDT score

NB: ZHH not full simulation yet

arXiv:1901.05897

Top-quark pair production



$e^+e^- \to t\bar{t}$:

- Production threshold at $\sqrt{s} \approx 2m_{top}$
- 380 & 500 GeV is near the maximum

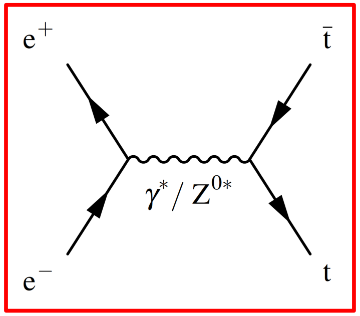
→ large event samples (for rare decays etc.)

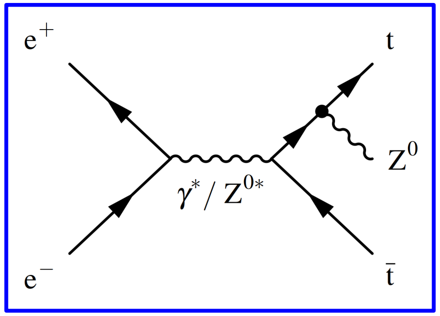
$e^+e^- \to t\bar{t}H$:

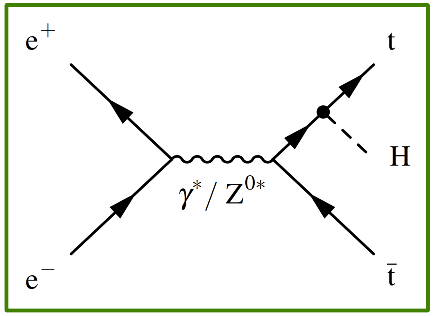
- Maximum near 800 GeV

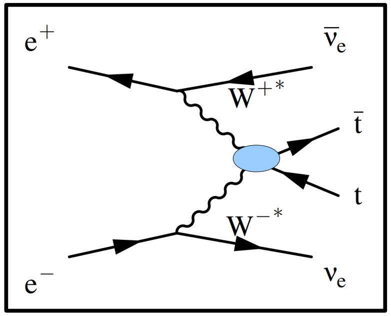
$e^+e^- \to t\bar{t}\nu_e\bar{\nu}_e$ (Vector Boson Fusion):

- Benefits from highest energies



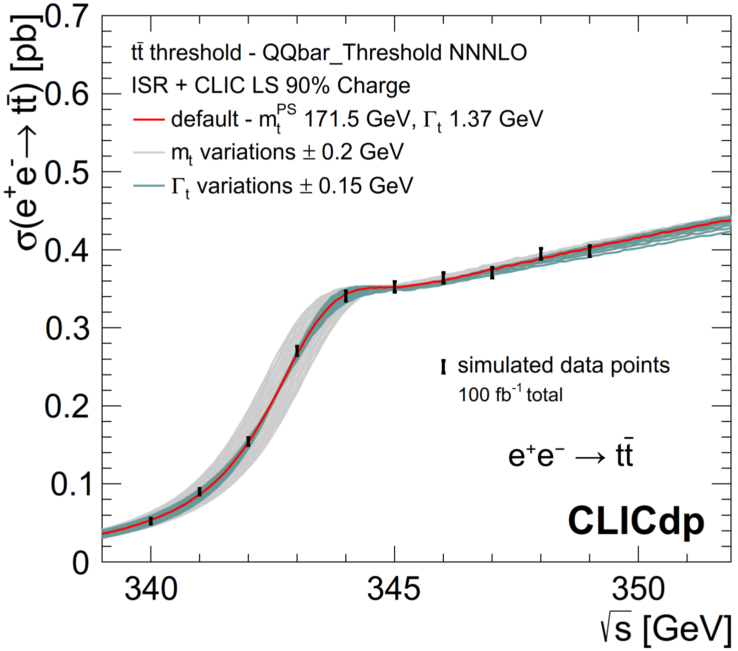






Threshold scan

- Measurement at different centre-of-mass energies in the $t\bar{t}$ production threshold region (data also useful for Higgs physics)



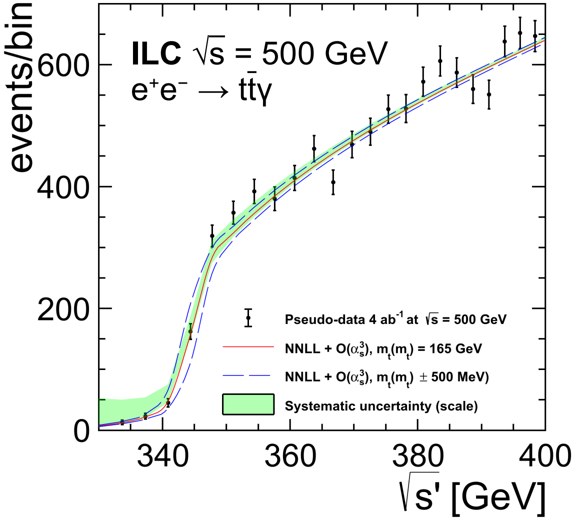
- Statistical uncertainty: ≈ 20 MeV at ILC and CLIC

- Expected precision on 1S mass: ≈ 50 MeV (currently dominated by theory NNNLO scale uncertainty)

- Theoretical uncertainty in the order of 10 MeV when transforming the measured 1S mass to the $\overline{\text{MS}}$ mass scheme

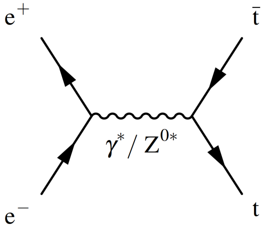
Phys. Rev. Lett. 114, 142002 (2015)

Other methods (less precise)**:**
- ISR photons at higher energies
- Direct reconstruction



arXiv:1807.02441
arXiv:1903.01629

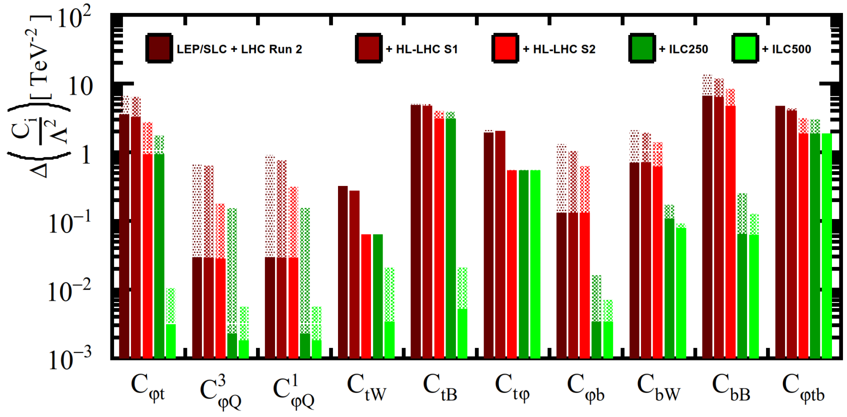
Top-quark EW couplings

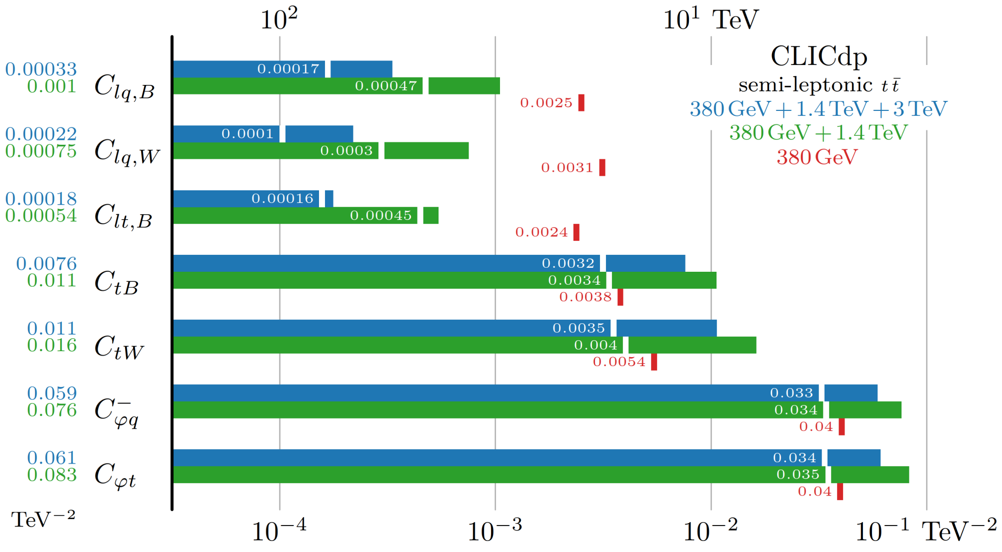


$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \boxed{\frac{c_i}{\Lambda^2}} \mathcal{O}_i$$

CLIC: $t\bar{t}$ production

ILC: $b\bar{b}$ and $t\bar{t}$ production





High-energy operation dramatically improves the sensitivity for certain ("four-fermion") operators

arXiv:1807.02441
arXiv:1907.10619
arXiv:1908.11299

Indirect sensitivity to new physics

Important indirect input at linear colliders:

- Precision electroweak measurements
- Higgs couplings
- SM scattering processes ($e^+e^- \to f\bar{f}$, W^+W^-, ZH, ...): benefit from high energy

Standard Model Effective Field Theory: very useful to compare potential of different collider parameters and options

$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2} \mathcal{O}_H$$

Scaling all Higgs couplings by a common factor

$$+ \frac{1}{g_*^2 m_*^2} \left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B} \right]$$

4-fermion contact ints., W', Z' resonances

$$+ \frac{1}{m_*^2} \left[c_W \mathcal{O}_W + c_B \mathcal{O}_B \right]$$

2 fermion–2 boson contact interactions, S parameter

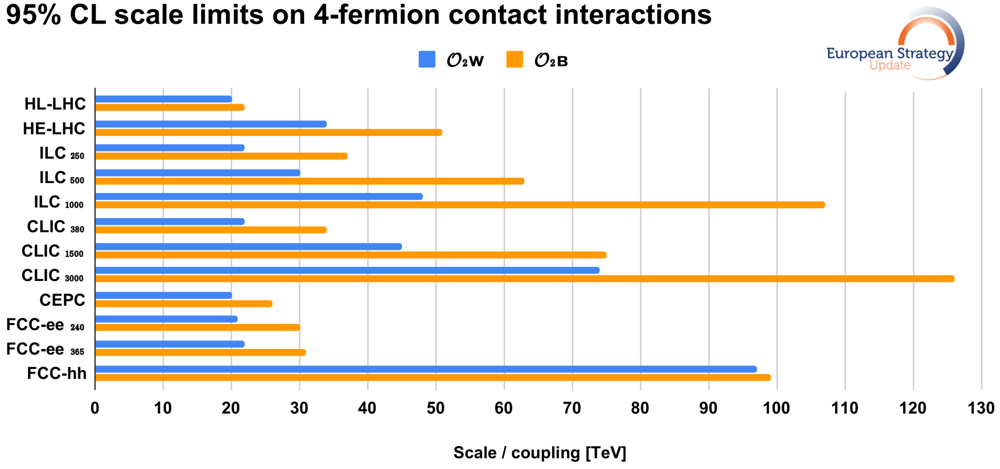
$$+ c_{y_t} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_t} + c_{y_b} \frac{g_*^2}{m_*^2} \mathcal{O}_{y_b}$$

Modify top and bottom Yukawa couplings

$$+ \ldots$$

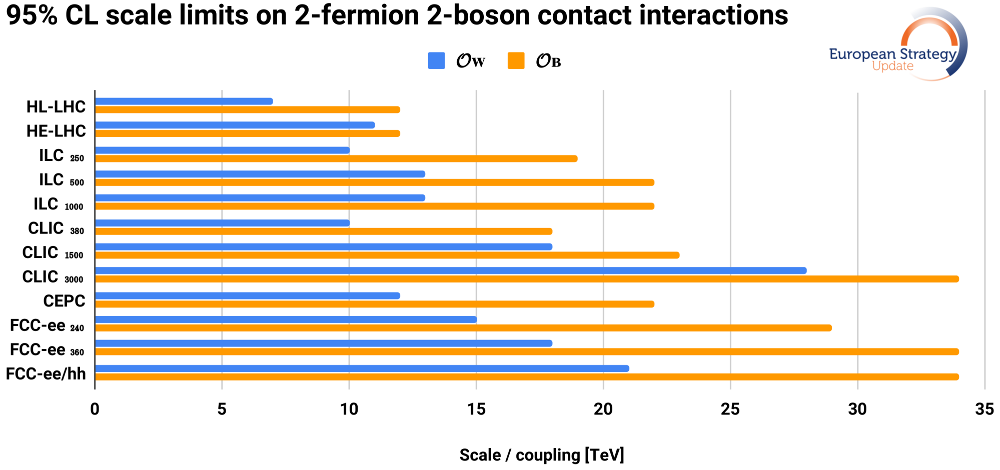
And much, much more…

Example: contact interactions



95% CL scale limits on 4-fermion contact interactions

- Projected limits from di-fermion final states ($e^+e^- \to f\bar{f}$, Drell-Yan with neutral and charged currents)
- Sensitivity increases significantly with $\sqrt{s}$ at ILC and CLIC



95% CL scale limits on 2-fermion 2-boson contact interactions

- New physics effects in the interaction between gauge and Higgs sectors
- O_W dominated by $e^+e^- \to ZH$ at CLIC
- Largest sensitivity in e^+e^- collisions at lower $\sqrt{s}$ (and on O_B in general) from oblique parameter S

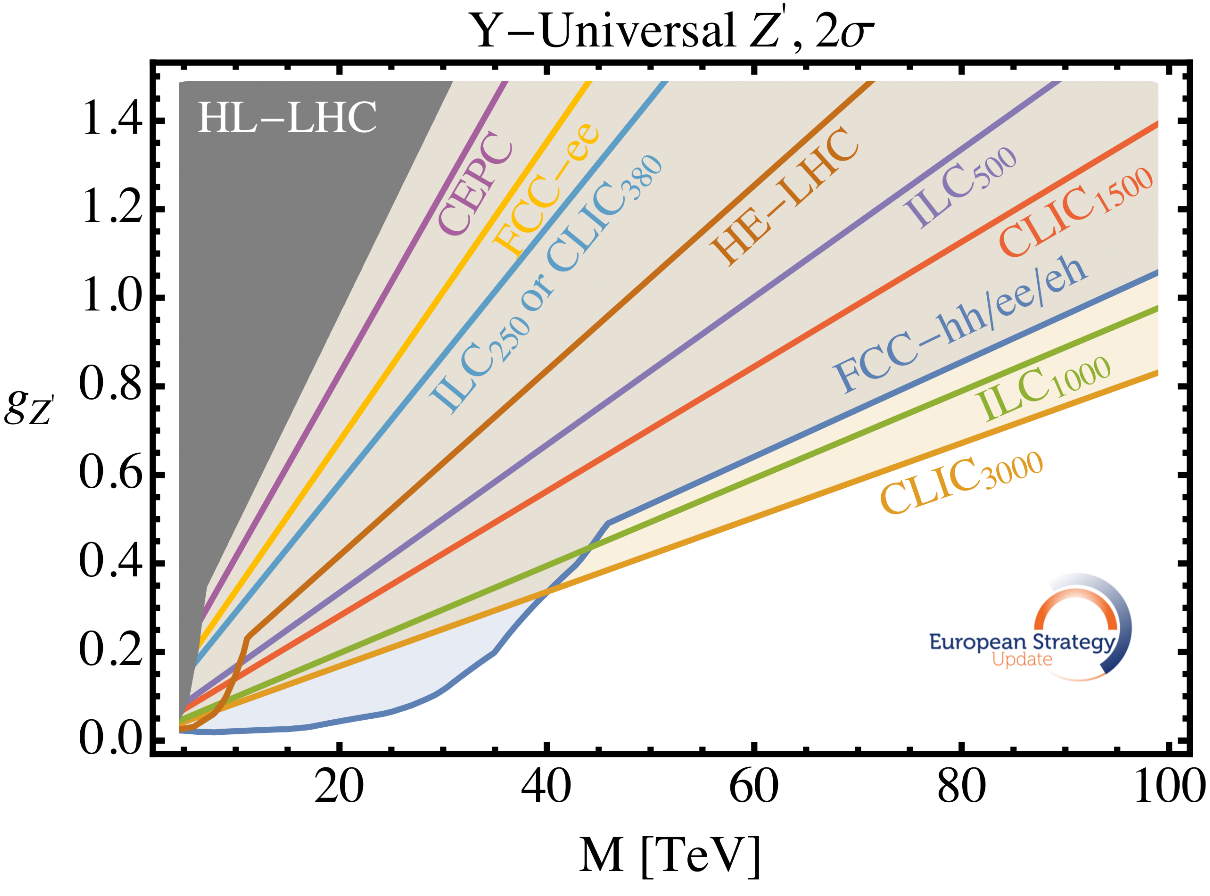
Y-Universal Z'

- New neutral gauge boson Z' with mass M and charges to SM particles equal to hypercharge

$$\boxed{\frac{c_{2B}}{\Lambda^2} = \frac{g_{Z'}^2}{g'^4 M_{Z'}^2}}$$

- Direct reach inferior to the indirect one for high $g_{Z'}$

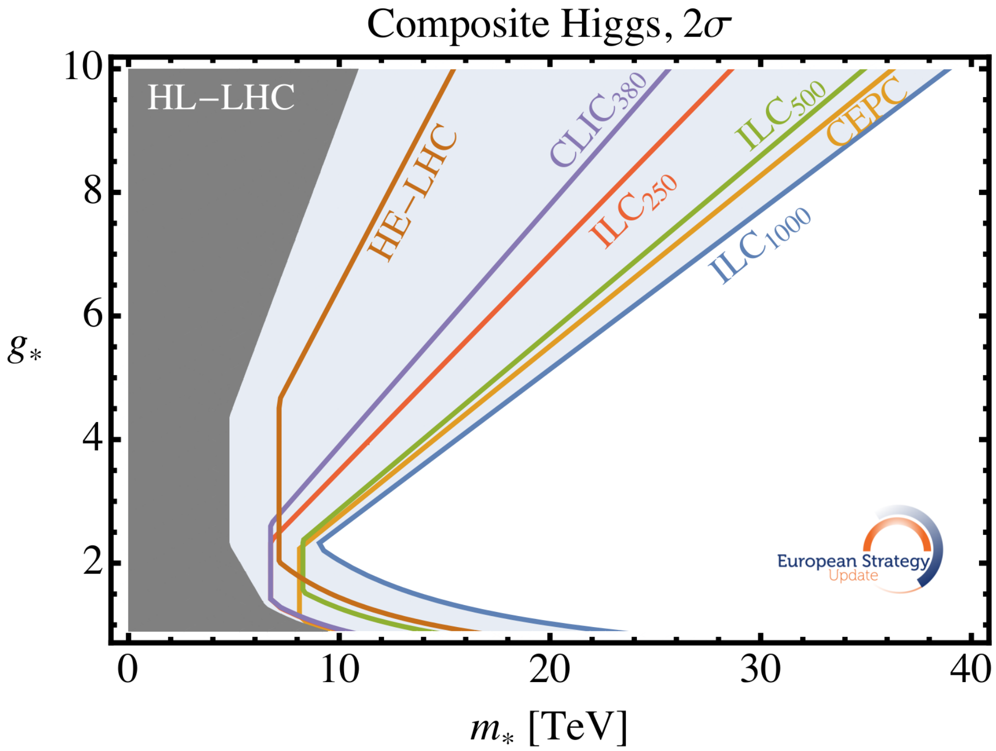
- NB: $g_{Z'} > 1.5 \rightarrow$ width exceeds 0.3 M

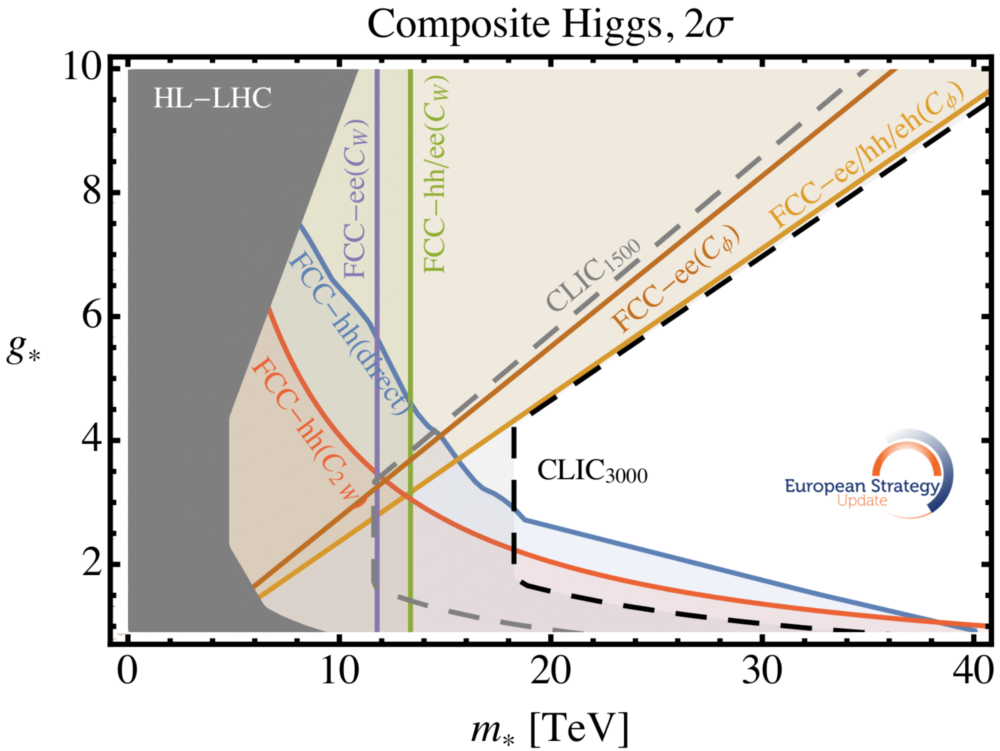


Composite Higgs

m_*: mass scale
g_*: coupling

$$\frac{c_\phi}{\Lambda^2} \sim \frac{g_*^2}{m_*^2}, \qquad \frac{c_W}{\Lambda^2} \sim \frac{1}{m_*^2}, \qquad \frac{c_{2W}}{\Lambda^2} \sim \frac{1}{g_*^2 m_*^2}$$





ILC at 250 GeV and CLIC at 380 GeV already significantly better than HL-LHC

FCC-all and 3 TeV CLIC similar

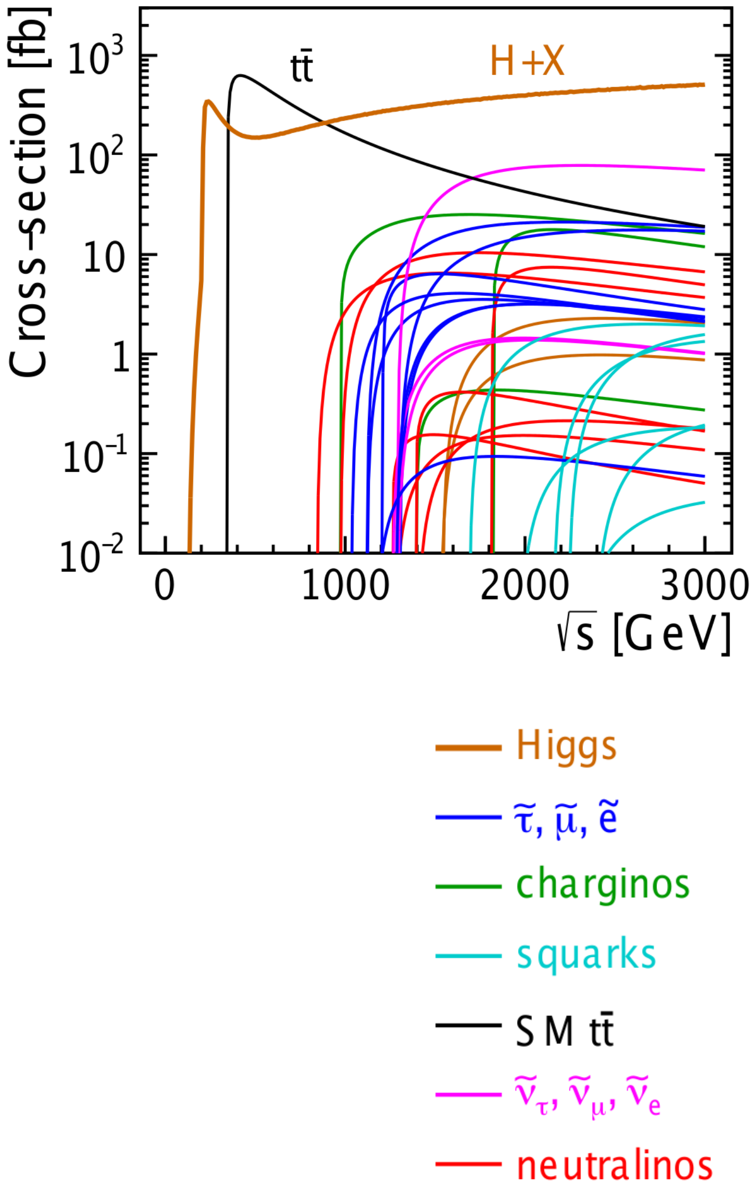
Direct new physics searches

- 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 ≤ $\sqrt{s}$ / 2 for pair production)

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

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



Example: Higgs plus heavy singlet

Heavy singlet mixing with Higgs boson:

$h = h_0 \cos\gamma + S \sin\gamma$

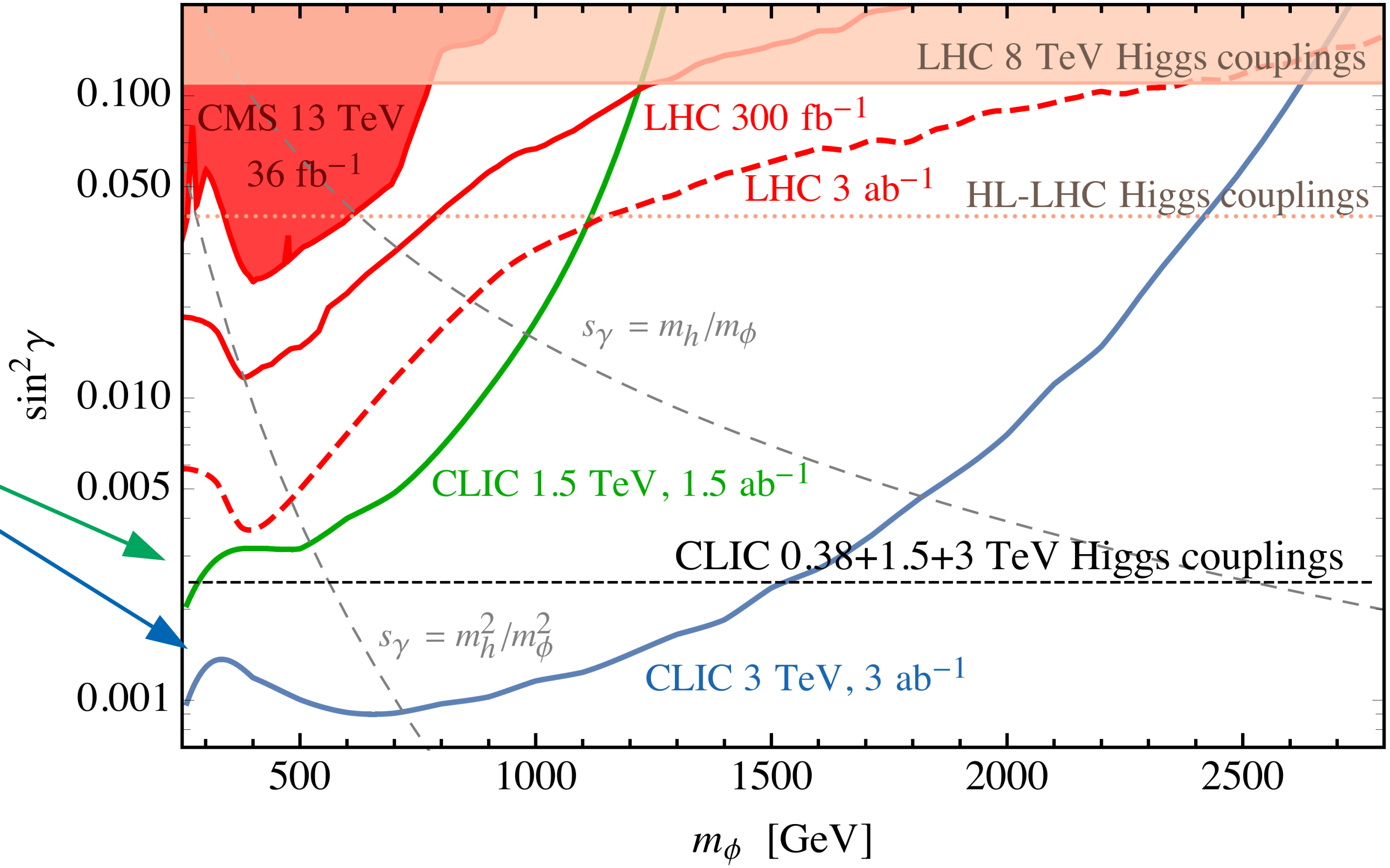
$\phi = S \cos\gamma - h_0 \sin\gamma$

Direct production:

$e^+e^- \rightarrow \nu\bar{\nu}\phi,\ \phi \rightarrow hh$

Indirect sensitivity from Higgs couplings

→ Both approaches are complementary



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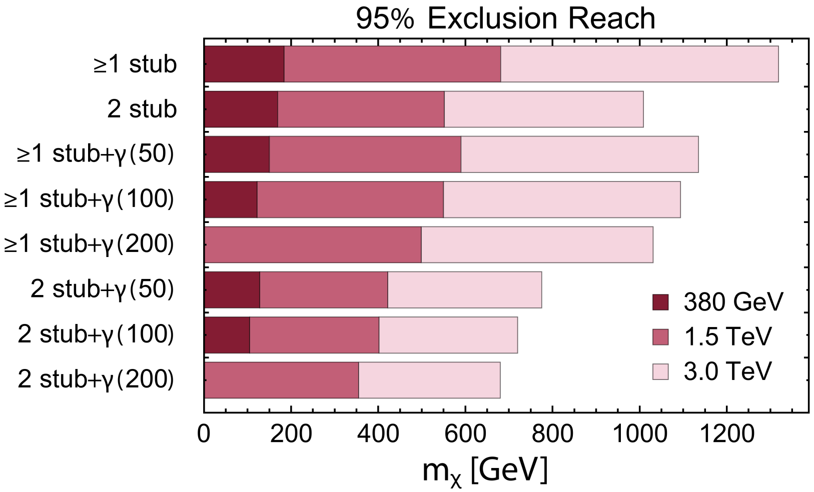
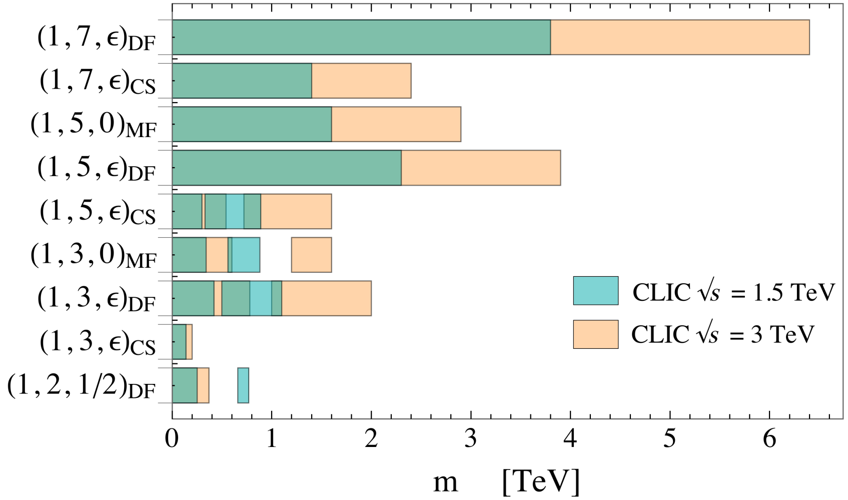
Dark Matter searches...

… using stub tracks:



… in loops:



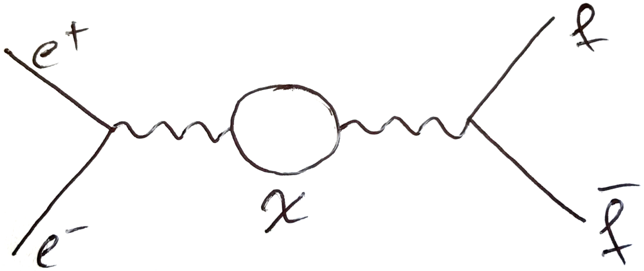
$e^+e^- \rightarrow \chi^+\chi^-(+\gamma)$

Small mass difference: $\chi^\pm \rightarrow \chi^0\pi^\pm$

Long-lifetime: $\chi^\pm$ leaves a short, disappearing (“stub”) track in the detector

- CLIC might discover the thermal Higgsino at 1.1 TeV

Electroweak n-plet states with hypercharge Y: (1,n,Y)



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Summary and conclusions

- Substantial improvement with respect to HL-LHC possible for all discussed physics topics

- The ILC at 250 GeV provides precise measurements of many Higgs couplings and the Higgs mass using the Higgsstrahlung process, CLIC at 380 GeV also gives access to the WW fusion process and top-quark pair production

- An energy of at least 500 GeV gives access to double Higgs production (profits from the highest possible energies)

- Large amount of complementarity between direct and indirect searches for new particles and interactions

Much more information can be found at:
https://clic.cern/european-strategy
https://ilchome.web.cern.ch/content/ilc-european-strategy-document

Thank you!

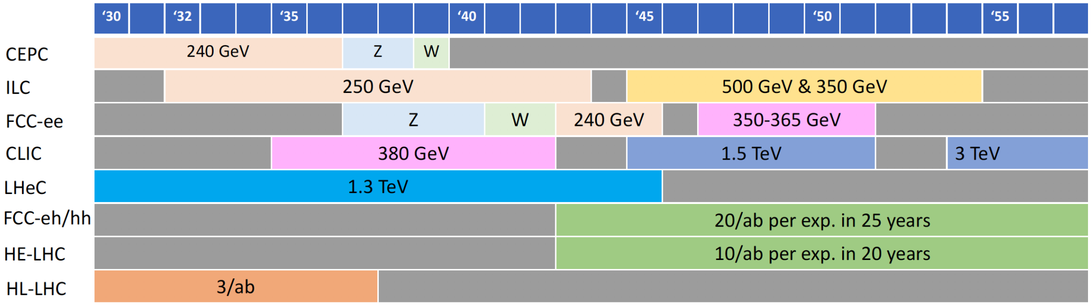
Collider parameters

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] [e^-/e^+]	N(Det.)	$\mathscr{L}_{\text{inst}}$ [10^{34}] cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]
HL-LHC	*pp*	14 TeV	-	2	5	6.0	12
HE-LHC	*pp*	27 TeV	-	2	16	15.0	20
FCC-hh	*pp*	100 TeV	-	2	30	30.0	25
FCC-ee	*ee*	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
							(+1)
ILC	*ee*	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
							(+1)
CEPC	*ee*	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	*ee*	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
							(+4)
LHeC	*ep*	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	*ep*	2.6 TeV	-	1	1.5	2.0	20
FCC-eh	*ep*	3.5 TeV	-	1	1.5	2.0	25

pp colliders

e^+e^- colliders

ep colliders



+ **LE-FCC:** pp, 15 ab^{-1} at $\sqrt{s}$ = 37.5 TeV

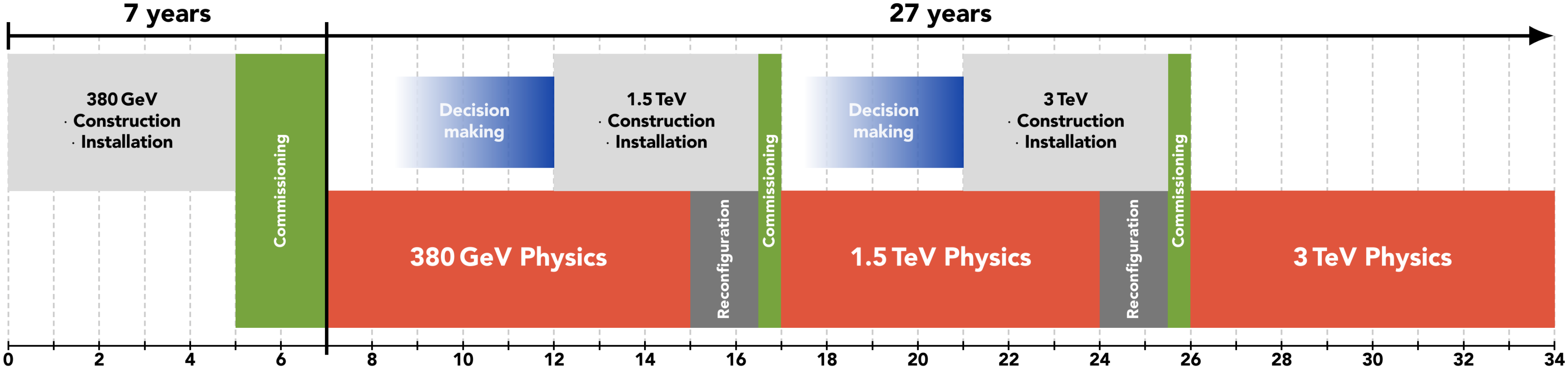
arXiv:1905.03764

Cost and power

Project	Type	Energy [TeV]	Int. Lumi. $[a^{-1}]$	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Daniel Schulte, Granada Symposium

CLIC timeline

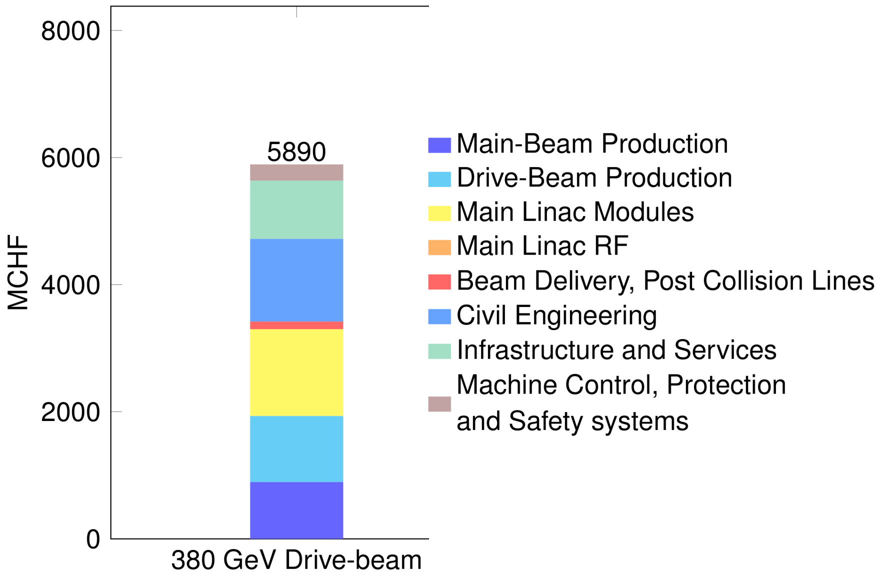


- Technology-driven schedule from start of construction

- After go-ahead, at least 5 years are needed before construction can start
→ first beams could be available by 2035

CERN-2018-005-M

CLIC cost and power



380 GeV: 5890^{+1470}_{-1270} MCHF

Upgrade to 1.5 TeV: add ≈5100 MCHF
Upgrade to 3 TeV: add another ≈7300 MCHF

---

380 GeV: large improvement compared to CDR (2012)

1.5 and 3 TeV: power not yet optimised
→ will be done next

Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17

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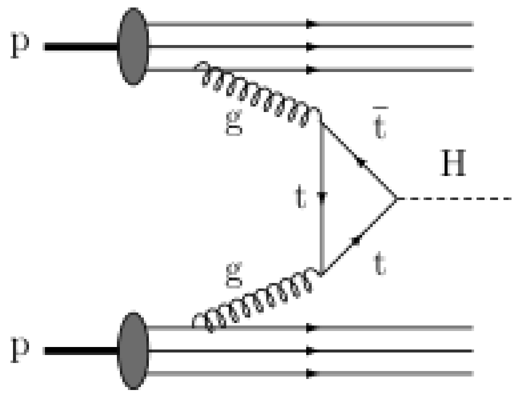
Hadron and e^+e^- colliders

Hadron colliders:

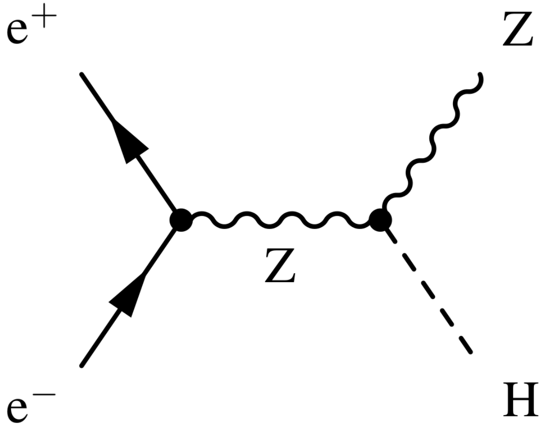


- **Proton is compound object**
→ Initial state unknown
→ Limits achievable precision

- **High-energy circular colliders possible**

- **High rates of QCD backgrounds**
→ Complex triggers
→ High levels of radiation

e^+e^- colliders:

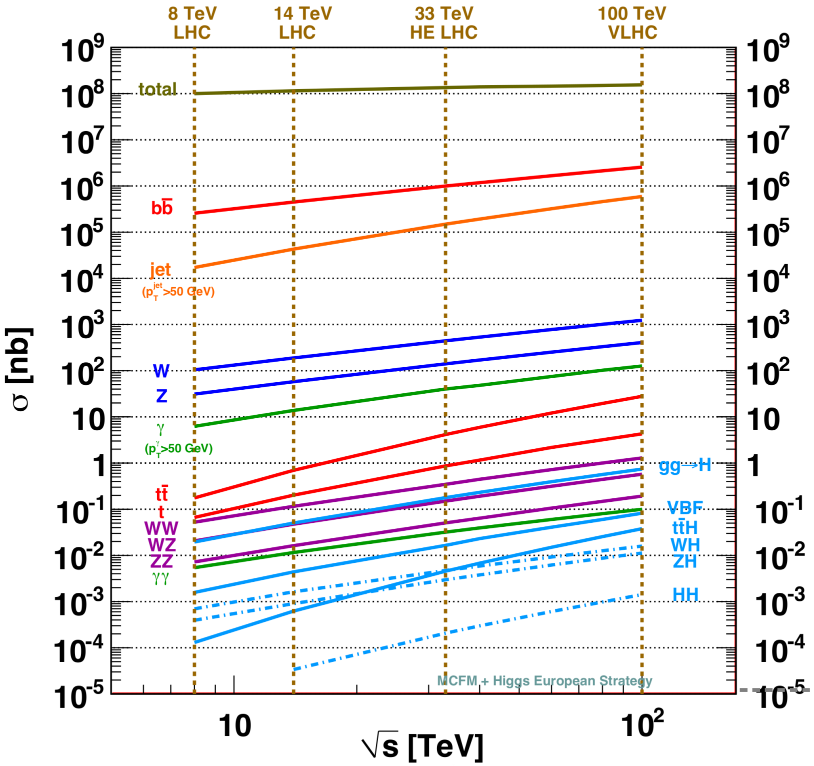


- **e^+e^- are pointlike**
→ Initial state well-defined ($\sqrt{s}$, polarisation)
→ High-precision measurements

- **High energies ($\sqrt{s}$ > 350 GeV) require linear colliders**

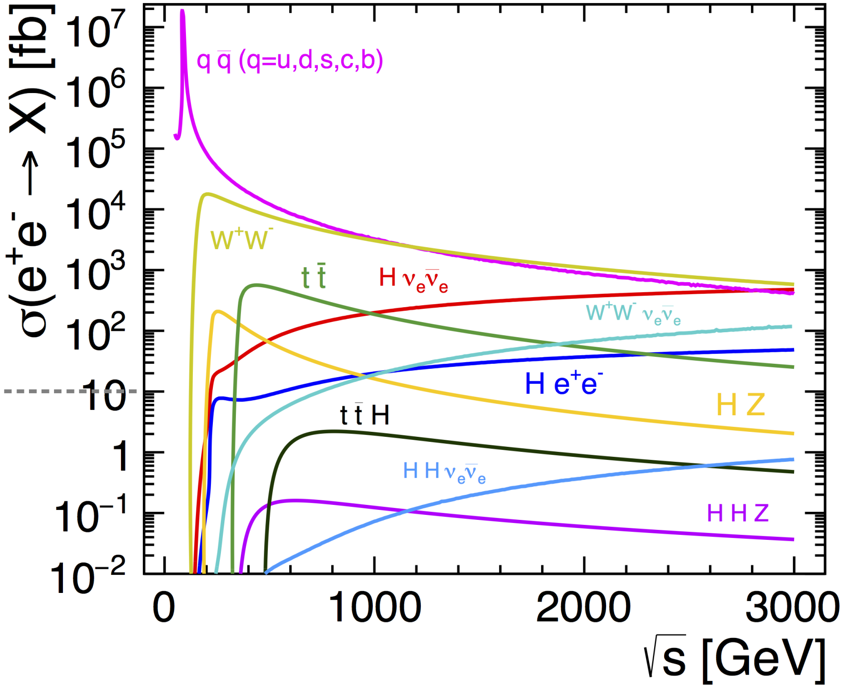
- **Clean experimental environment**
→ Less / no need for triggers
→ Lower radiation levels

pp and e^+e^- collisions



8 orders of Magnitude!

pp collisions:
Interesting events need to be found in huge number of collisions



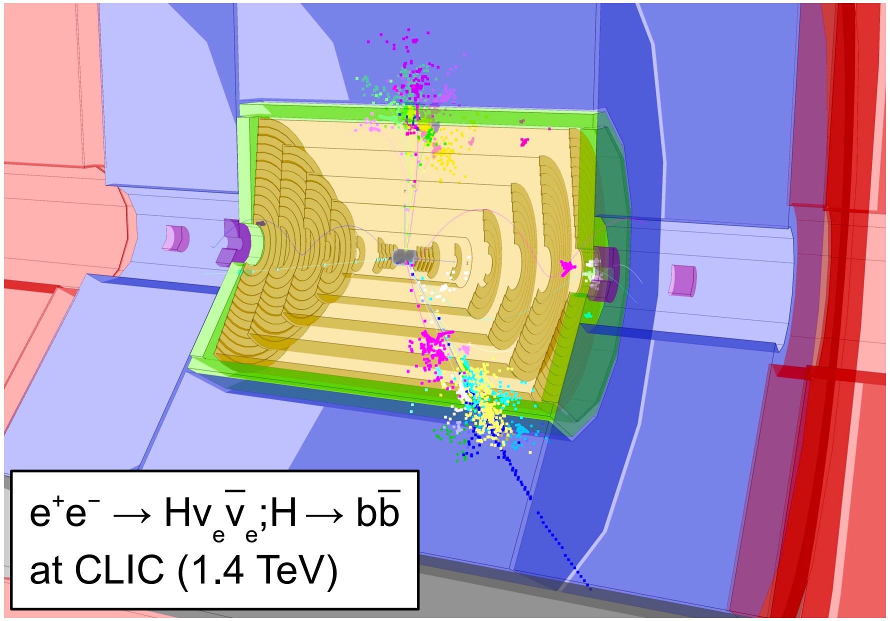
e^+e^- collisions:
More "clean", all events usable

Higgs bosons in e^+e^- collisions

Collider stage:	No. H produced:
ILC 250 GeV, 2 ab^{-1}	500000
CLIC 380 GeV, 1 ab^{-1}	160000
ILC 500 GeV, 4 ab^{-1}	500000
CLIC 1.5 TeV, 2.5 ab^{-1}	1000000
CLIC 3 TeV, 5 ab^{-1}	3300000

- No triggers
→ all Higgs events usable
- Typical overall selection efficiencies: 20 - 60%

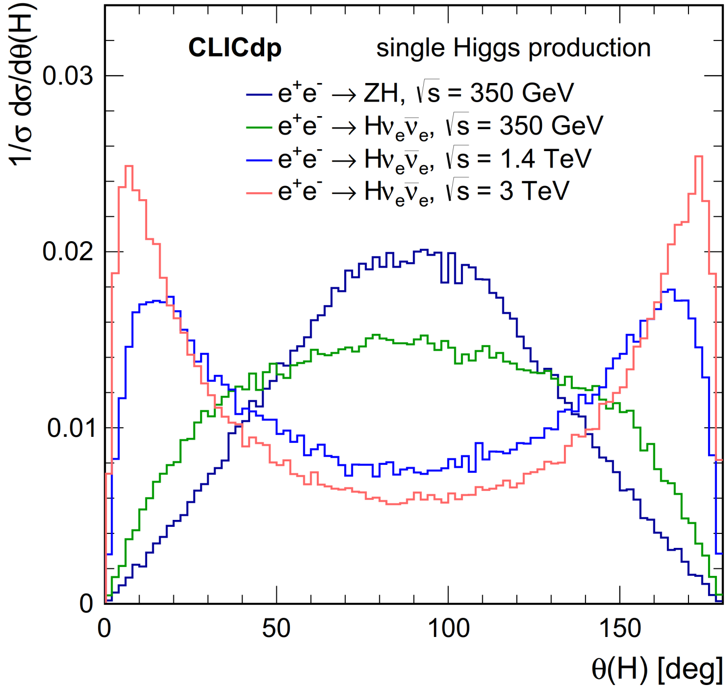
The projections shown in the following are based on realistic full detector simulations and include the impact of beam-beam effects



$e^+e^- \rightarrow H\nu_e\bar{\nu}_e; H \rightarrow b\bar{b}$
at CLIC (1.4 TeV)

Kinematics and polarisation

Higgs polar angle:



At a few hundred GeV:
Higgs bosons produced mostly in the central detector

At high energy:
Good forward detector coverage required

Impact of polarisation:

Polarisation	Scaling factor		
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
−80% : 0%	1.12	1.80	1.12
−80% : +30%	1.40	2.34	1.17
−80% : −30%	0.83	1.26	1.07
+80% : 0%	0.88	0.20	0.88
+80% : +30%	0.69	0.26	0.92
+80% : −30%	1.08	0.14	0.84

Higgsstrahlung:
Polarisation dependence relatively small

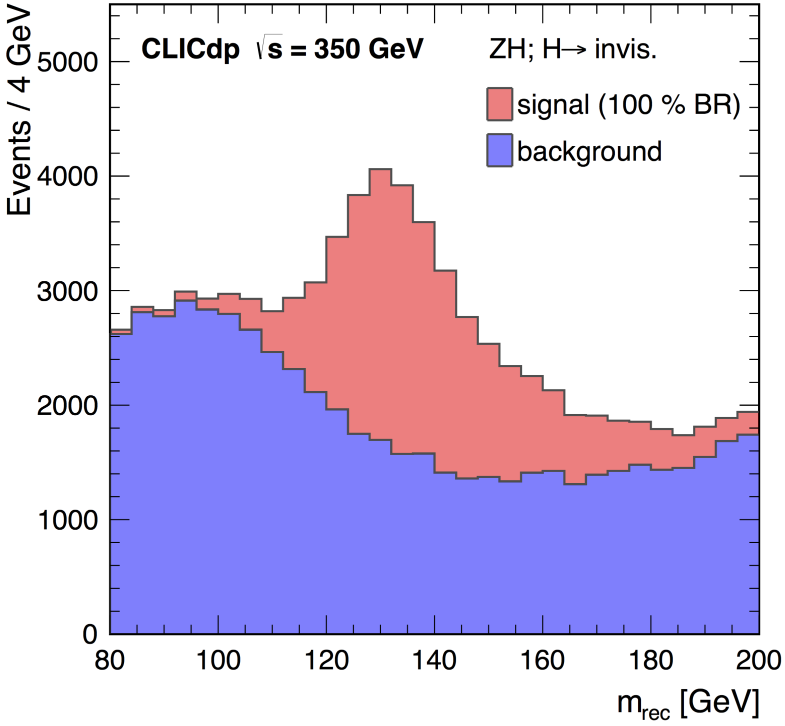
WW fusion:
Large enhancement in the -80% and -80%/+30% configurations

Invisible Higgs decays

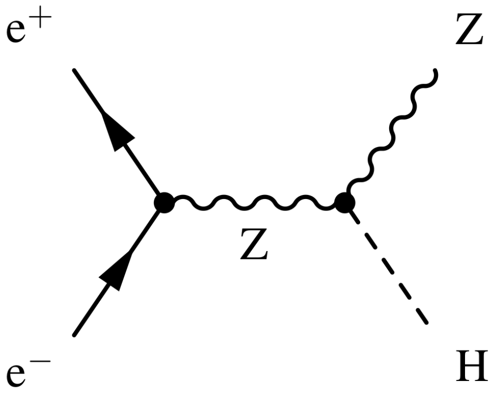
The recoil mass technique also allows to identify invisible Higgs decays in a model-independent manner

CLIC, $\sqrt{s}$ = 350 GeV, L = 1 ab^{-1}
BR(H→inv.) < 0.69% at 90% CL

ILC, $\sqrt{s}$ = 250 GeV, L = 2 ab^{-1}
BR(H→inv.) < 0.32% at 95% CL



Example: Recoil mass from $Z \rightarrow q\bar{q}$ assuming all Higgs bosons decay invisibly (L = 0.5 ab^{-1})



Eur. Phys. J. C 76, 72 (2016)
arXiv:1710.07621

$H \rightarrow b\bar{b}/c\bar{c}/gg$ at $\sqrt{s}$ = 350 GeV

Simultaneous extraction of:

- Three decay modes: $b\bar{b}/c\bar{c}/gg$

→ precise flavour tagging

- Two production modes:

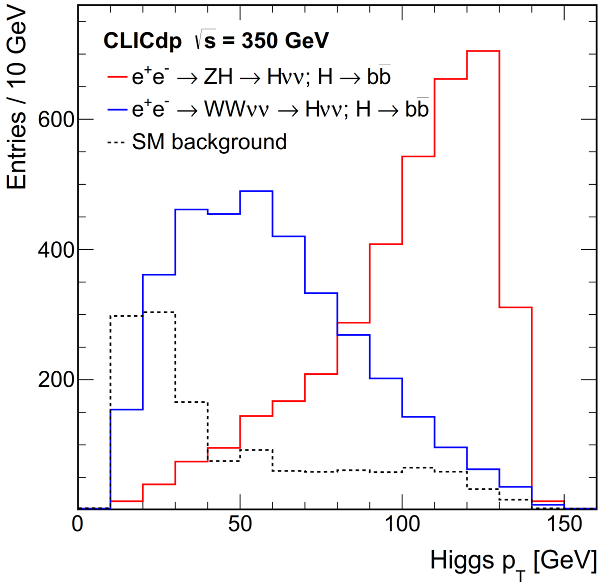
ZH and WW fusion

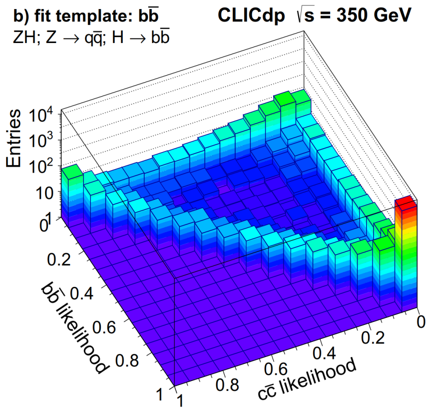
→ Higgs p_T spectrum

Uncertainties on σ x BR

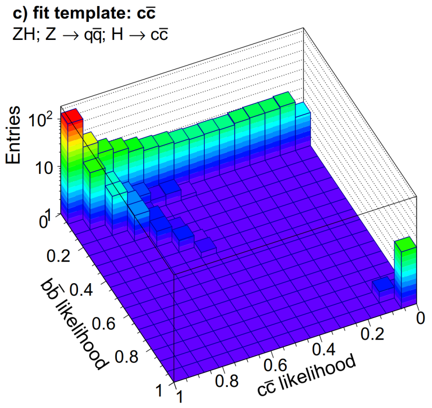
Decay	Statistical uncertainty	
	Higgsstrahlung	WW-fusion
$H \rightarrow b\bar{b}$	0.61 %	1.3 %
$H \rightarrow c\bar{c}$	10 %	18 %
$H \rightarrow gg$	4.3 %	7.2 %

CLIC, $\sqrt{s}$ = 350 GeV, L = 1 ab^{-1}

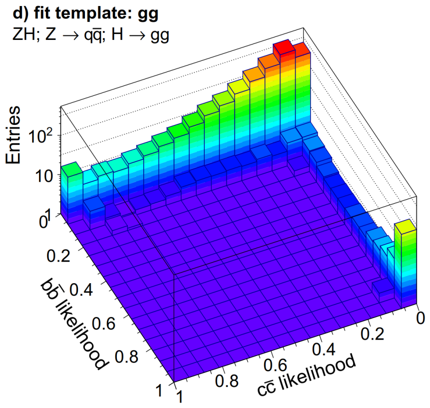




$H \rightarrow b\bar{b}$



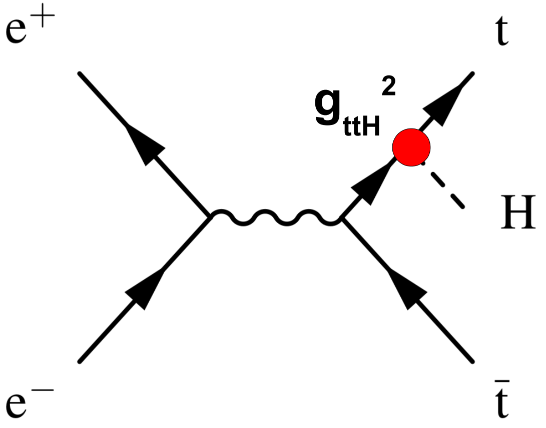
$H \rightarrow c\bar{c}$



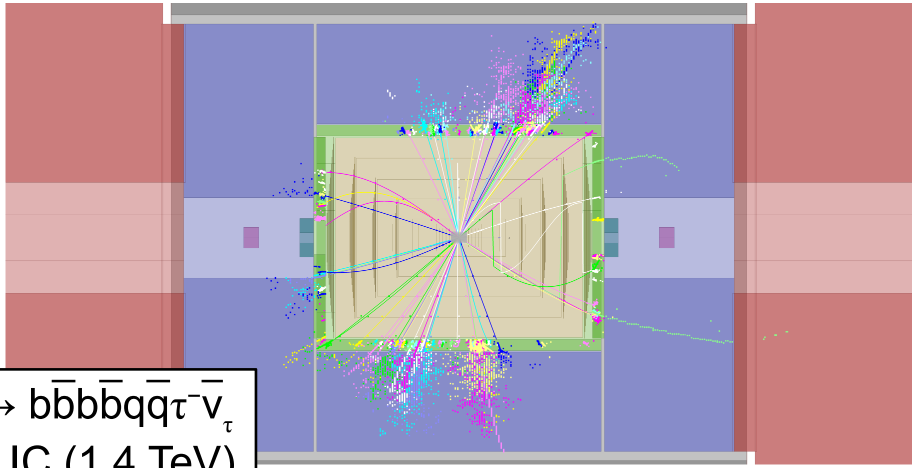
$H \rightarrow gg$

Eur. Phys. J. C 77, 475 (2017)

Top Yukawa coupling



→ $\sigma(t\bar{t}H)$ is directly sensitive to the top Yukawa coupling g_{ttH}



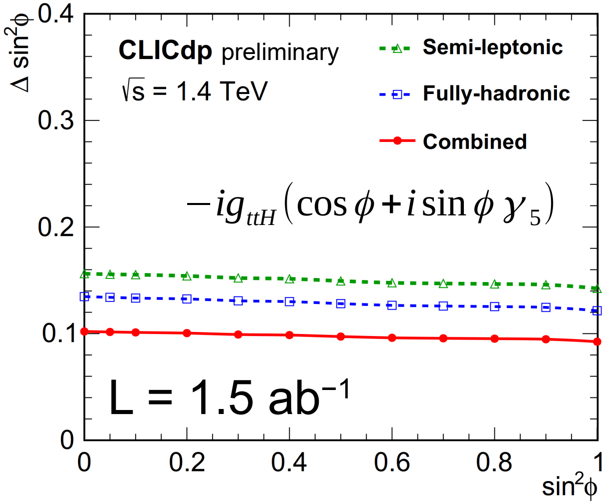
$t\bar{t}H \rightarrow b\bar{b}b\bar{b}q\bar{q}\tau^-\bar{\nu}_\tau$
at CLIC (1.4 TeV)

Most important final states:
$e^+e^- \rightarrow t\bar{t}H \rightarrow q\bar{q}bl\nu\bar{b}b\bar{b}$
$e^+e^- \rightarrow t\bar{t}H \rightarrow q\bar{q}bq\bar{q}\bar{b}b\bar{b}$
→ Roughly similar sensitivity

ILC, $\sqrt{s}$ = 500 GeV, L = 4 ab^{-1}**:**
$\Delta g_{ttH}/g_{ttH}$ = 6.3%
(would be ≈3% for $\sqrt{s}$ = 550 GeV)

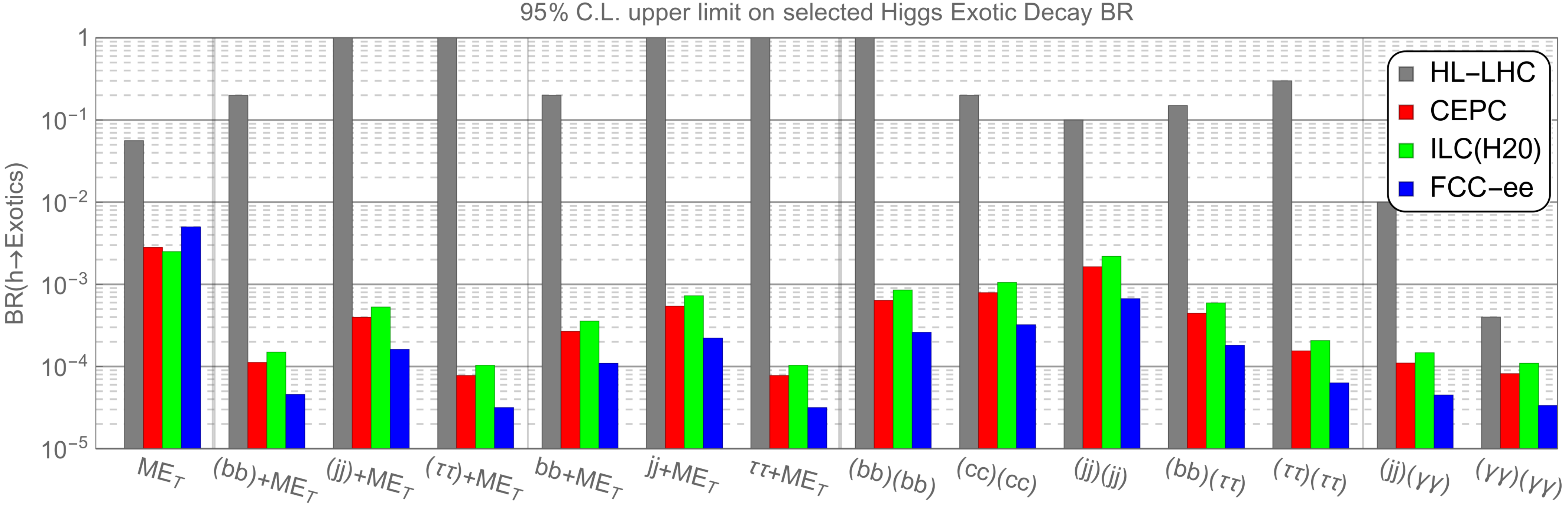
CLIC, $\sqrt{s}$ = 1.4 TeV, L = 2.5 ab^{-1}
$\Delta g_{ttH}/g_{ttH}$ = 2.9%

- Sensitivity to CP mixing in the ttH coupling from $\sigma(t\bar{t}H)$
- Differential distributions under investigation



arXiv:1506.05992
arXiv:1807.02441

Exotic Higgs decays



- An e^+e^- Higgs factory would provide large improvements compared to the HL-LHC
- The ILC projections are for 2 ab^{-1} at 250 GeV
- Potential of WW fusion at higher energies to be explored

(more than 1 million Higgs decays at 3 TeV CLIC)

arXiv:1612.09284

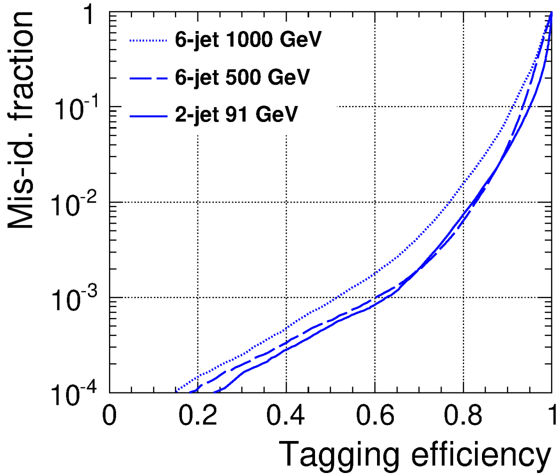
Experimental challenges

HH→$b\bar{b}b\bar{b}$ is the “golden channel” in e^+e^- collisions, combination with HH→$b\bar{b}WW^*$ leads to small improvement

Main experimental challenges:

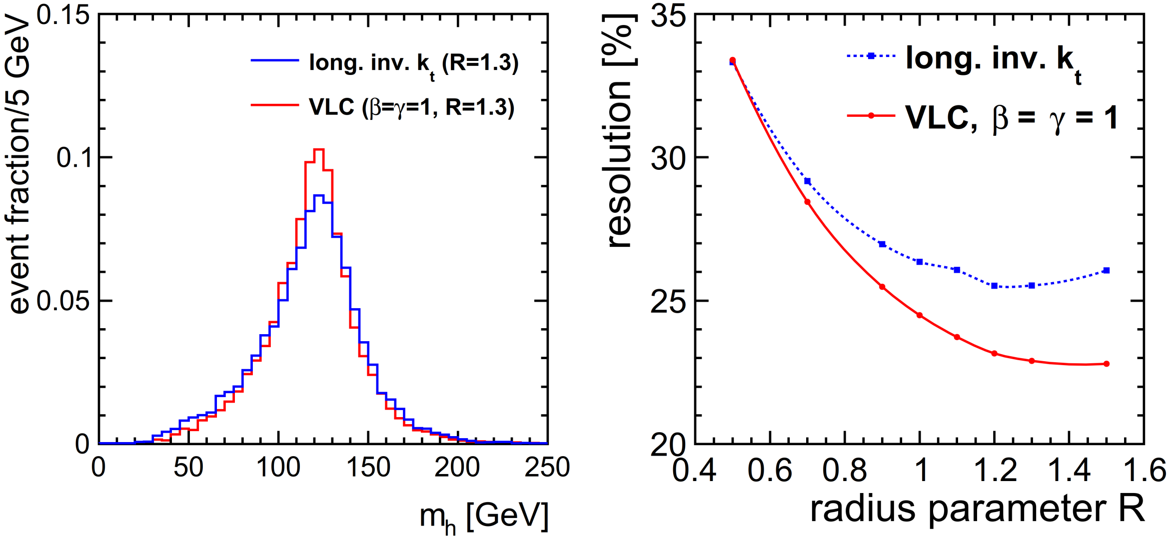
- b-tagging
- Forward detector coverage in case of $e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$
- Jet reconstruction

b-tagging



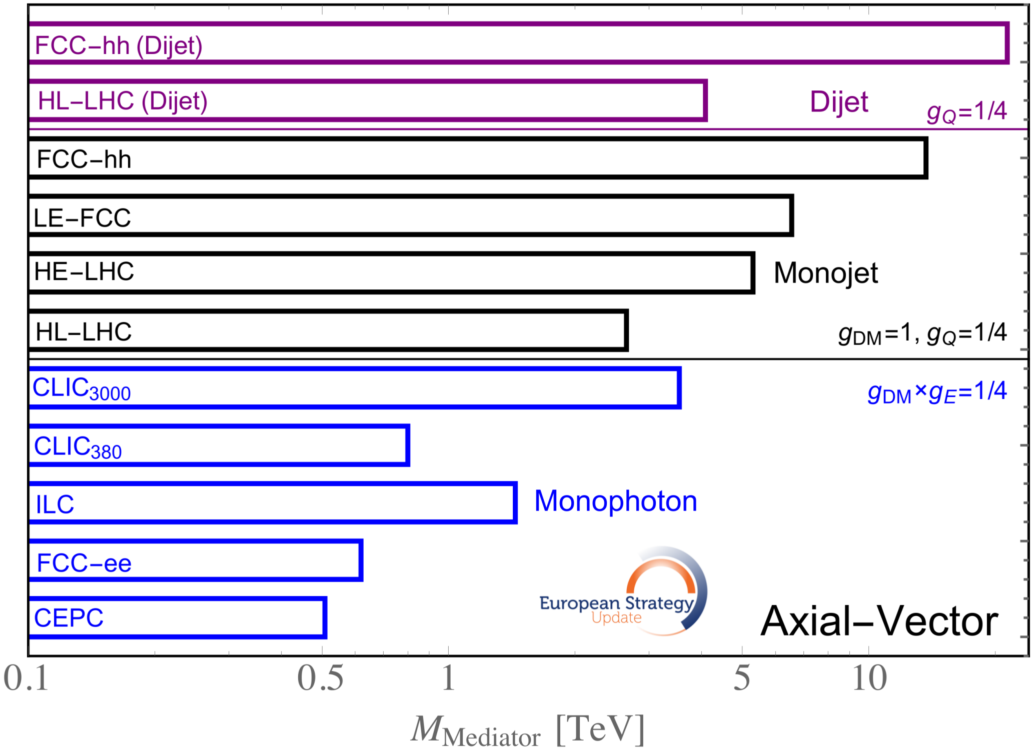
Nucl. Inst. Meth. A808, 109 (2016)

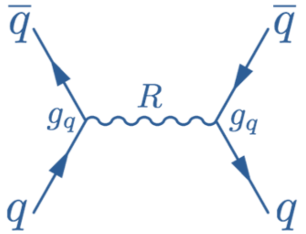
CLIC 3 TeV, HH→$b\bar{b}b\bar{b}$

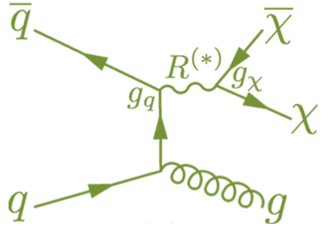


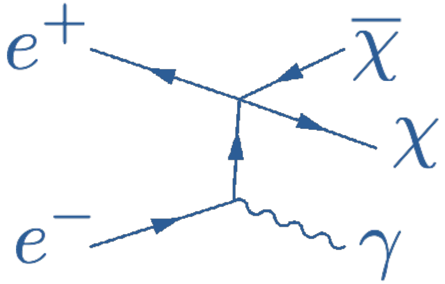
Eur. Phys. J C78, 144 (2018)

Simplified models: axial vector





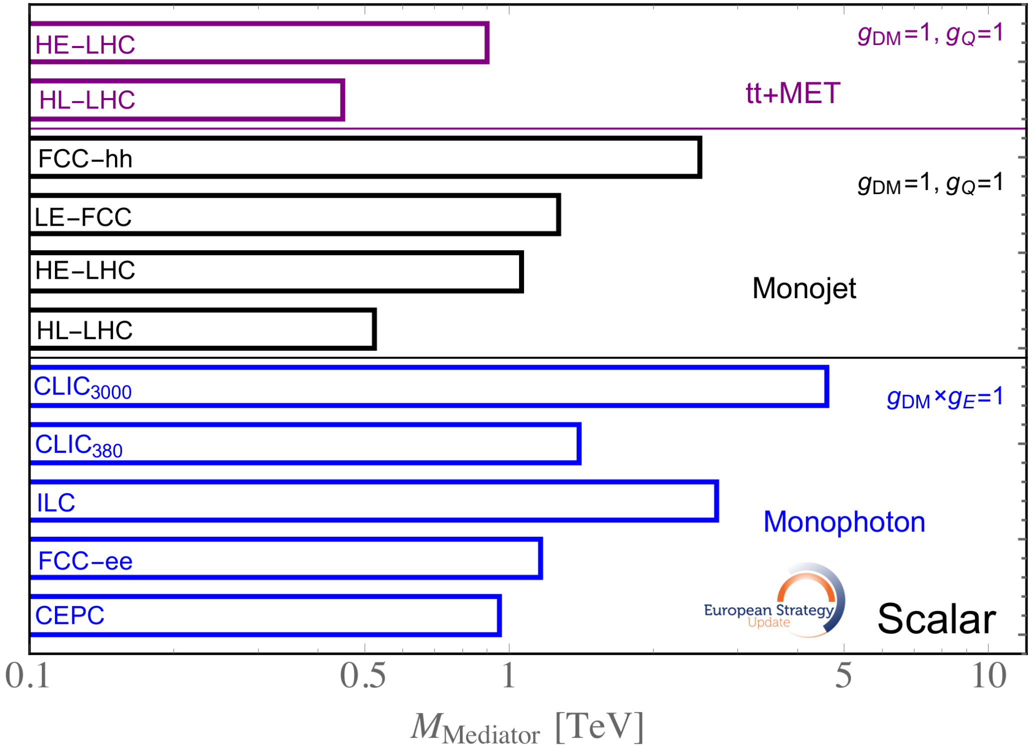


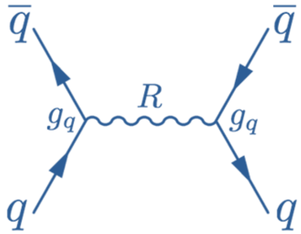


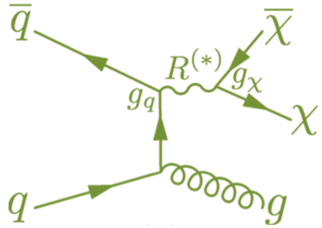
$$-Z'_\mu(g_{\mathrm{DM}}\,\bar{\chi}\gamma^\mu\gamma_5\chi + g_f\sum_f \bar{f}\gamma^\mu\gamma_5 f)$$

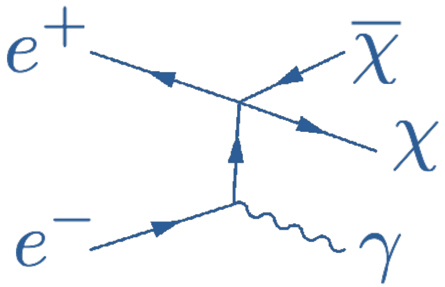
- Mediator is spin-1 particle (Z’) coupled to an axial-vector current
(reach of direct DM searches limited → interesting for colliders)
- pp colliders assume couplings to quarks only, e^+e^- colliders assume couplings to leptons only
→ projections not directly comparable

Simplified models: scalar









$$\phi(g_{\rm DM}\,\bar{\chi}\chi - g_f \sum_f y_f \bar{f} f/\sqrt{2})$$

y_f: Yukawa couplings

- Mediator is spin-0 particle (ϕ)

(reach of direct DM searches limited → interesting for colliders)

- pp colliders assume couplings to quarks only, e^+e^- colliders assume couplings to leptons only

→ projections not directly comparable