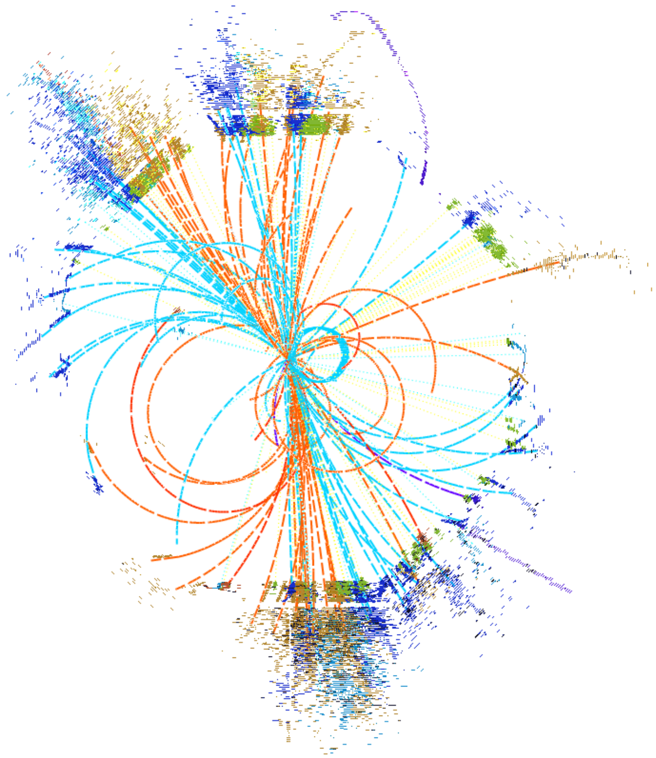
Future colliders

Philipp Roloff (CERN)

28/08/2017
Multi-Boson Interactions 2017
KIT, Karlsruhe



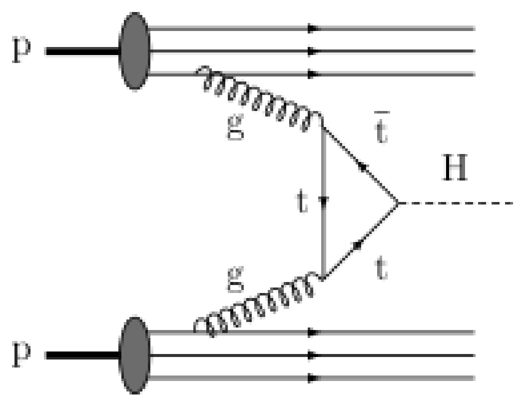
Overview:

- Introduction
- Electron-positron colliders
- Proton-proton colliders

Other options not covered in the following:
muon colliders, electron-proton colliders, photon colliders

Hadron and e^+e^- colliders

Hadron colliders:

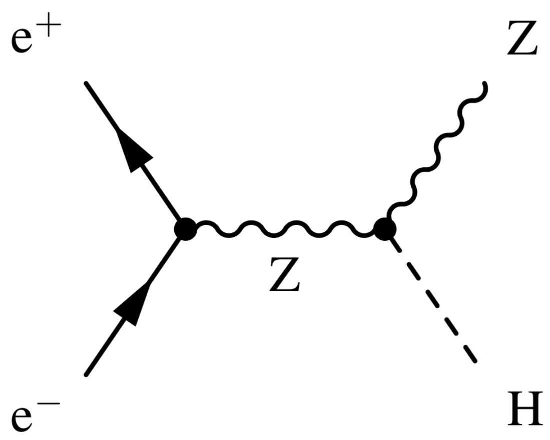


- **Proton is compound object**
→ Initial state unknown
→ Limits achievable precision

- **High-energy circular colliders possible**

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

e^+e^- colliders:

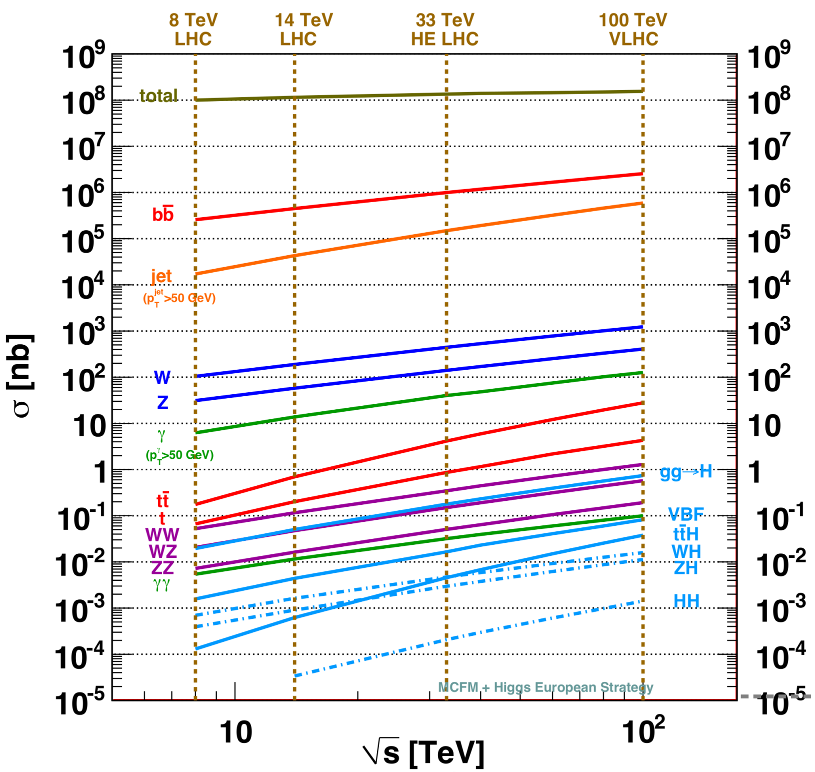


- **e^+e^- are pointlike**
→ Initial state well-defined ($\sqrt{s}$, polarisation)
→ High-precision measurements

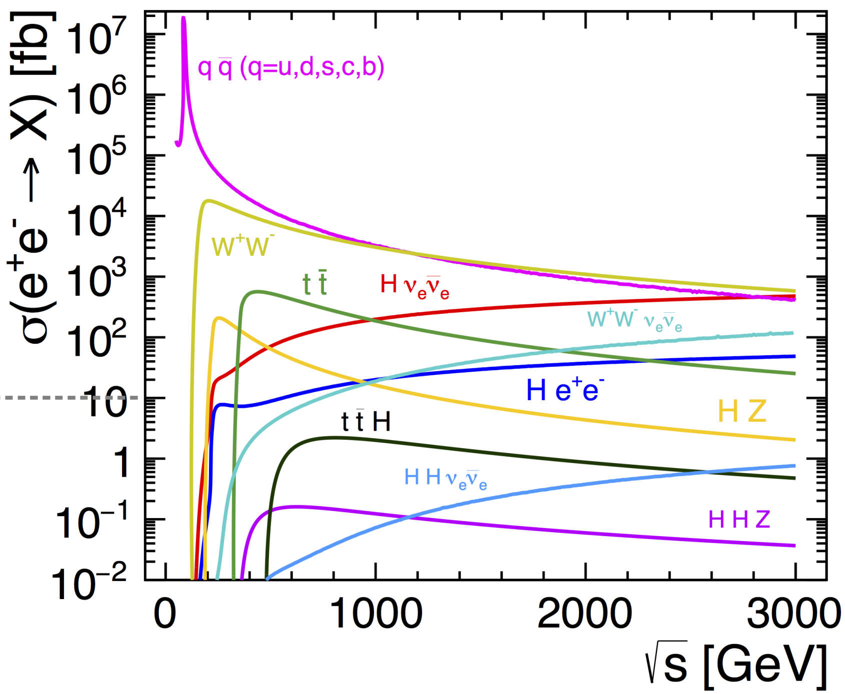
- **High energies ($\sqrt{s}$ > 350 GeV) require linear colliders**

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

pp and e$^+$e$^-$ collisions



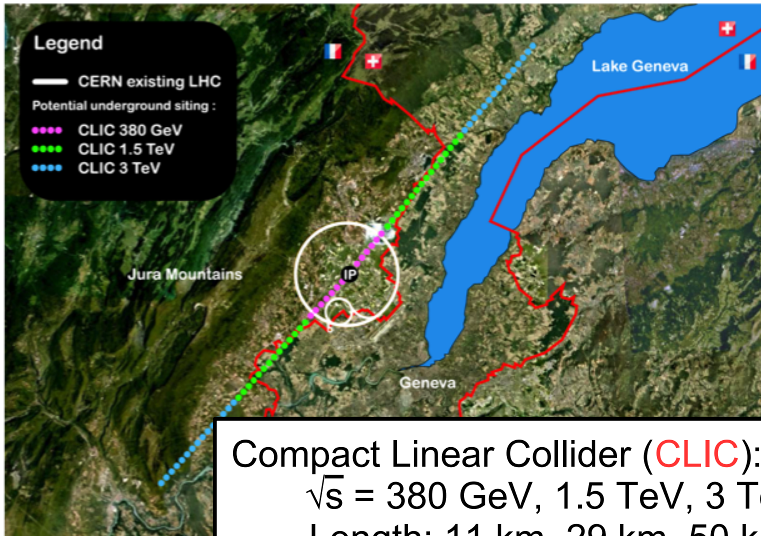
8 orders of Magnitude!



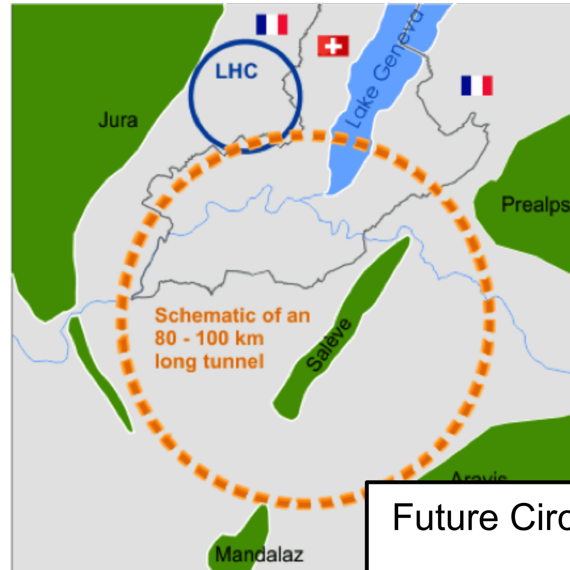
pp collisions:
Interesting events need to be found in huge number of collisions

e$^+$e$^-$ collisions:
More “clean”, all events usable

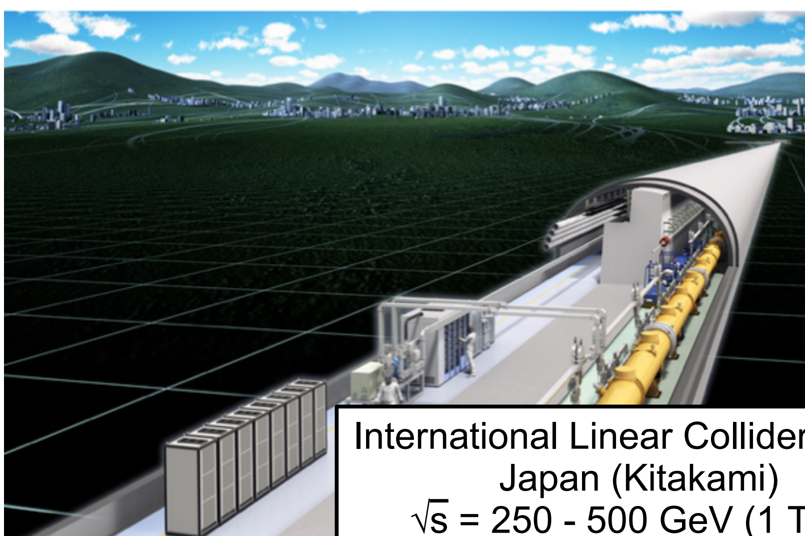
Studies of high-energy e^+e^- colliders



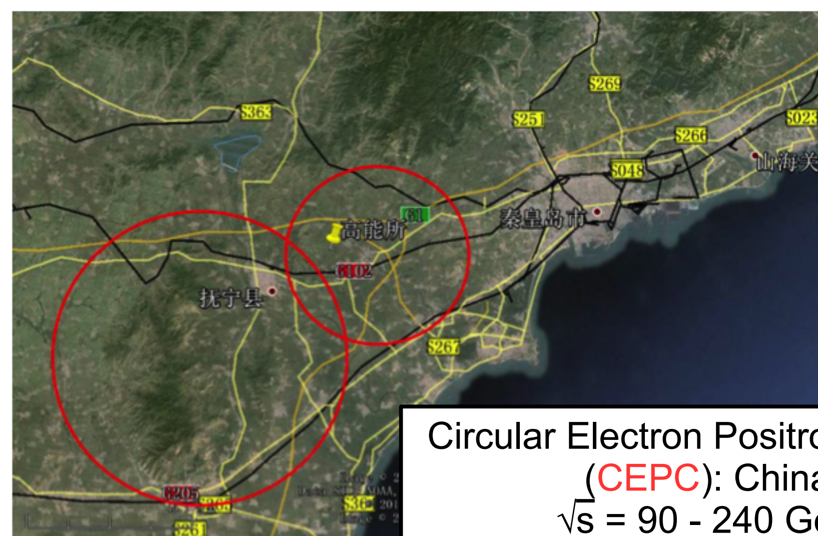
Compact Linear Collider (CLIC): CERN
$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km



Future Circular Collider (FCC-ee): CERN
$\sqrt{s}$ = 90 - 350 GeV
Circumference: 97.75 km

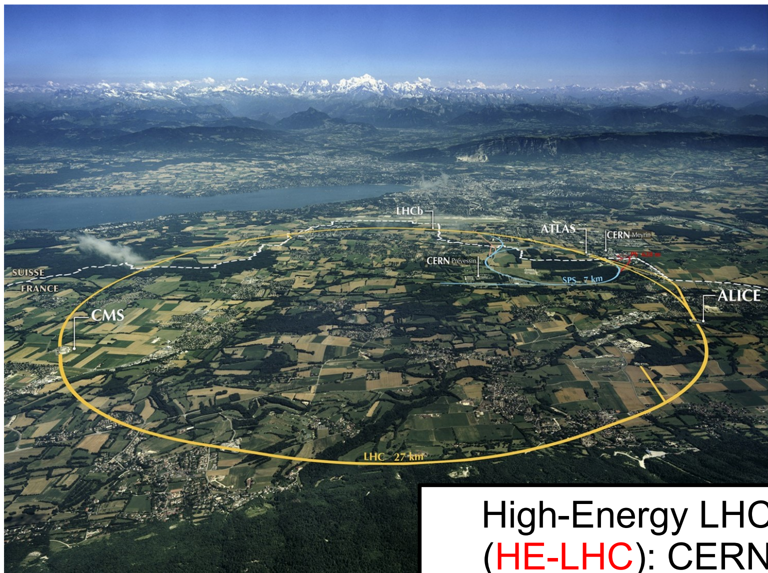


International Linear Collider (ILC): Japan (Kitakami)
$\sqrt{s}$ = 250 - 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)

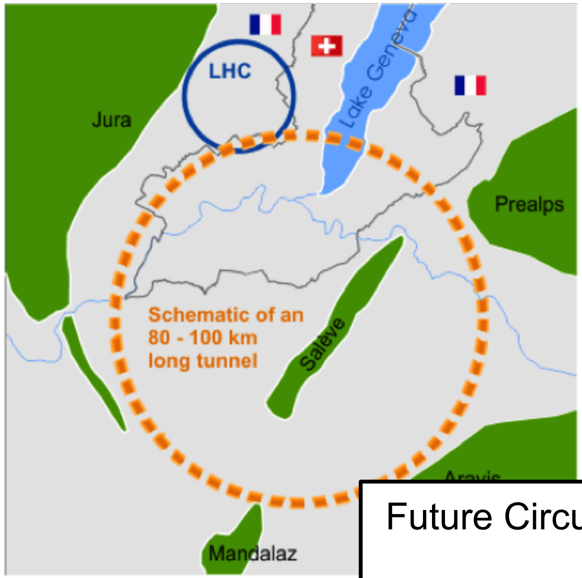


Circular Electron Positron Collider (CEPC): China
$\sqrt{s}$ = 90 - 240 GeV
Circumference: 100 km

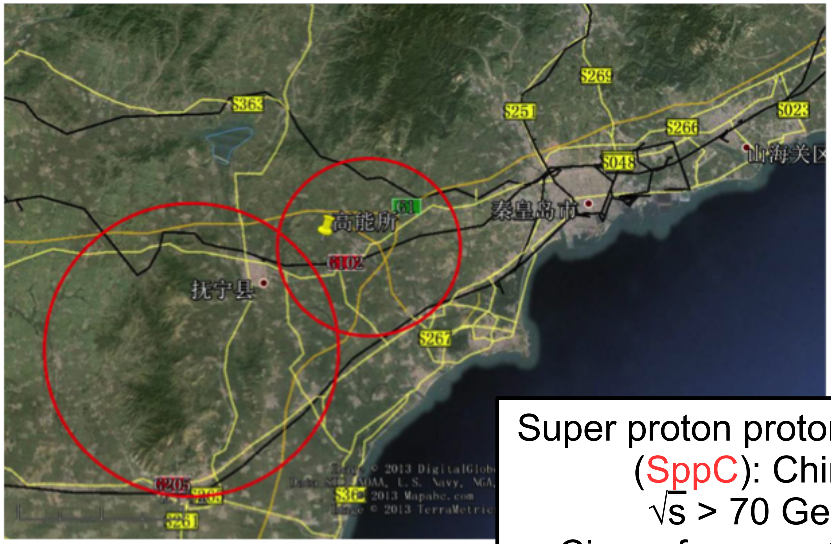
Studies of high-energy pp colliders



High-Energy LHC
(HE-LHC): CERN
$\sqrt{s} \approx 27$ TeV
Circumference: 27 km



Future Circular Collider (FCC-hh): CERN
$\sqrt{s} \approx 100$ TeV
Circumference: 97.75 km

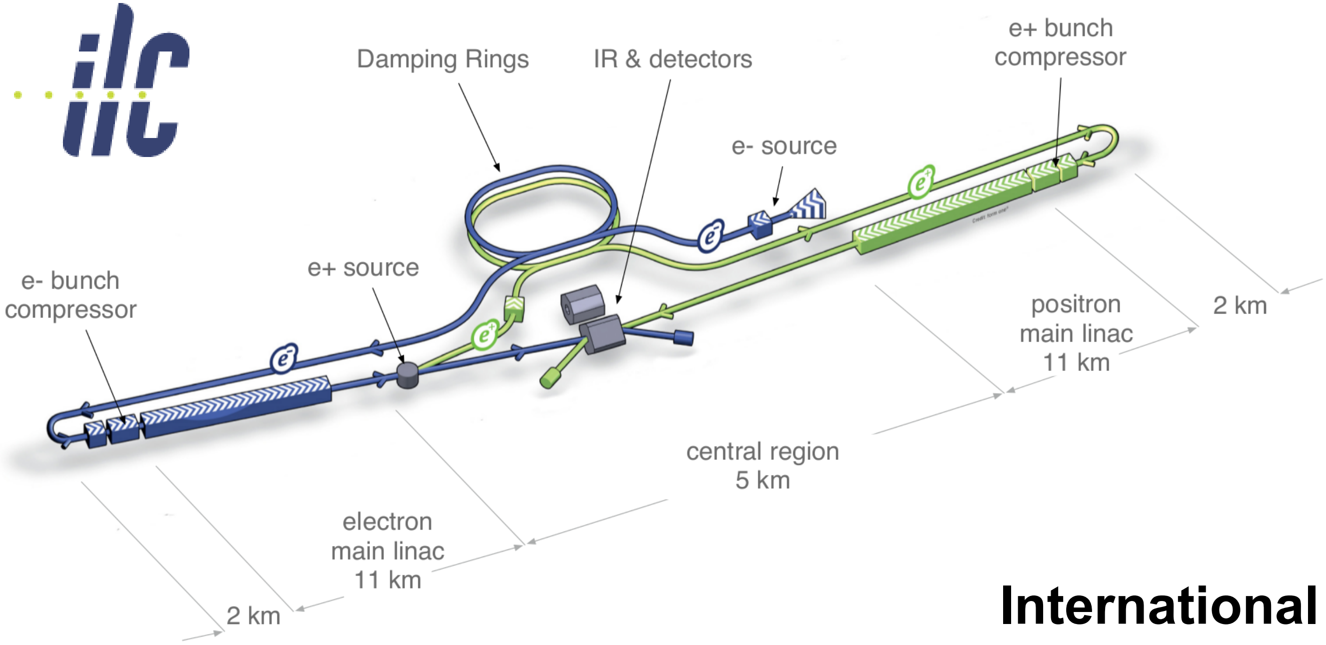


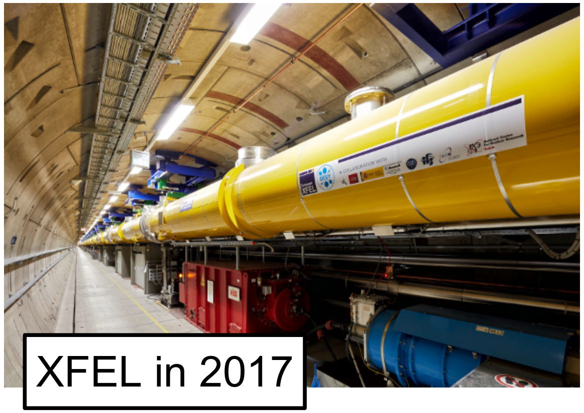
Super proton proton Collider
(SppC): China
$\sqrt{s} > 70$ GeV
Circumference: 100 km

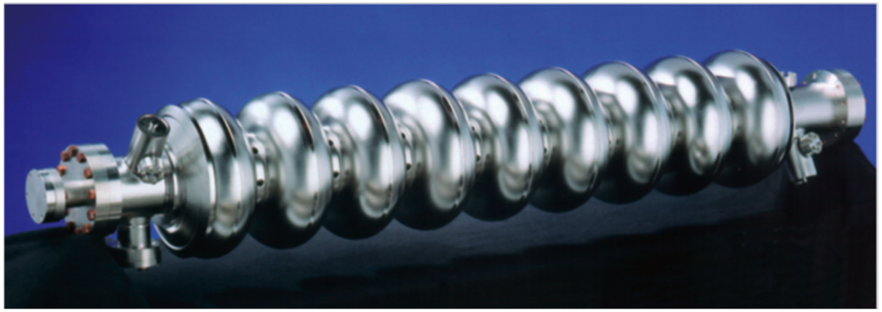
Electron-positron colliders:

- ILC, CLIC, FCC-ee, CEPC
- Detector concepts
- Physics highlights

ILC



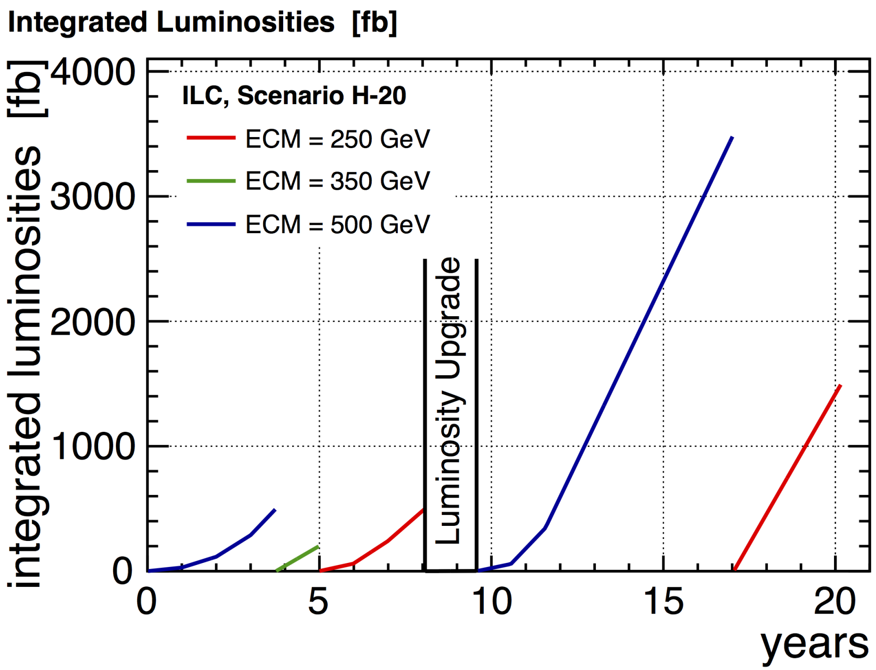




International Linear Collider (ILC):
- Based on superconducting RF cavities
- Gradient: 32 MV/m
- Energy: 250-500 GeV (upgradable to 1 TeV)
- Length: 31 km (for 500 GeV)
- $P(e^-) = \pm 80\%$, $P(e^+) = \pm 30\%$
- European XFL using similar technology

ILC staging scenarios

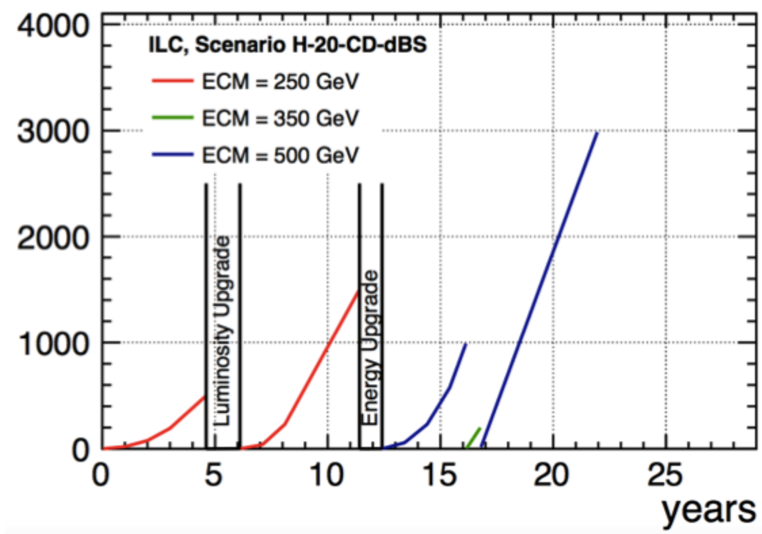
Baseline running scenario with 500 GeV machine:



arXiv:1506.07830

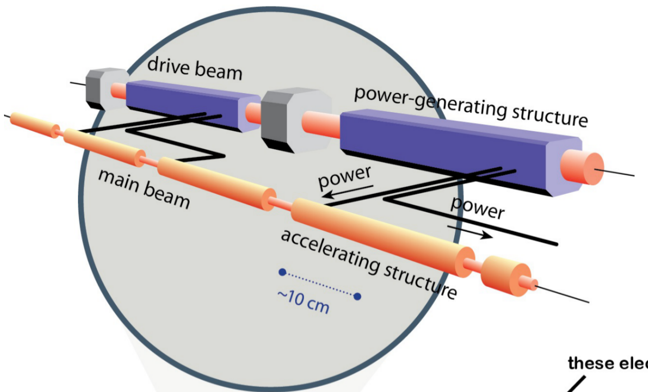
Energy staging currently under consideration:

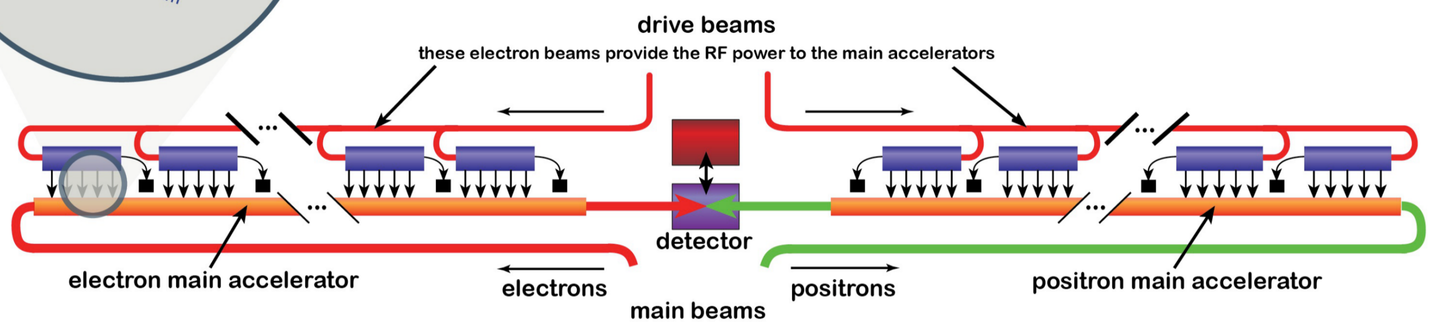
Example: 250 GeV and with energy upgrade

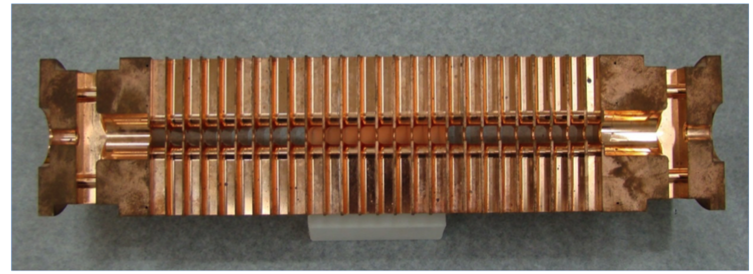


D. Schulte, EPS-HEP 2017

CLIC

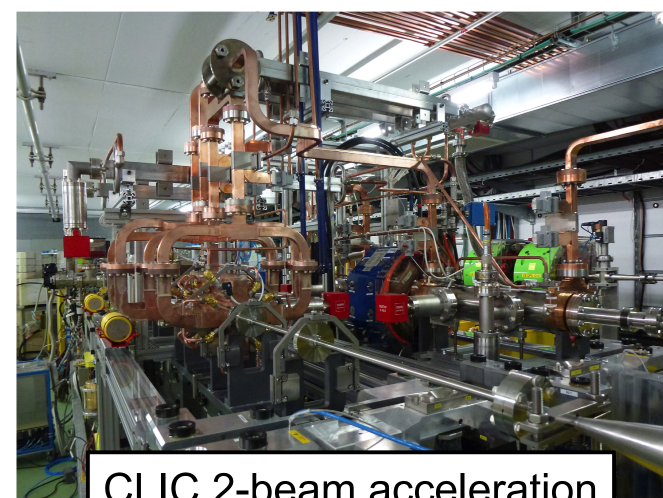






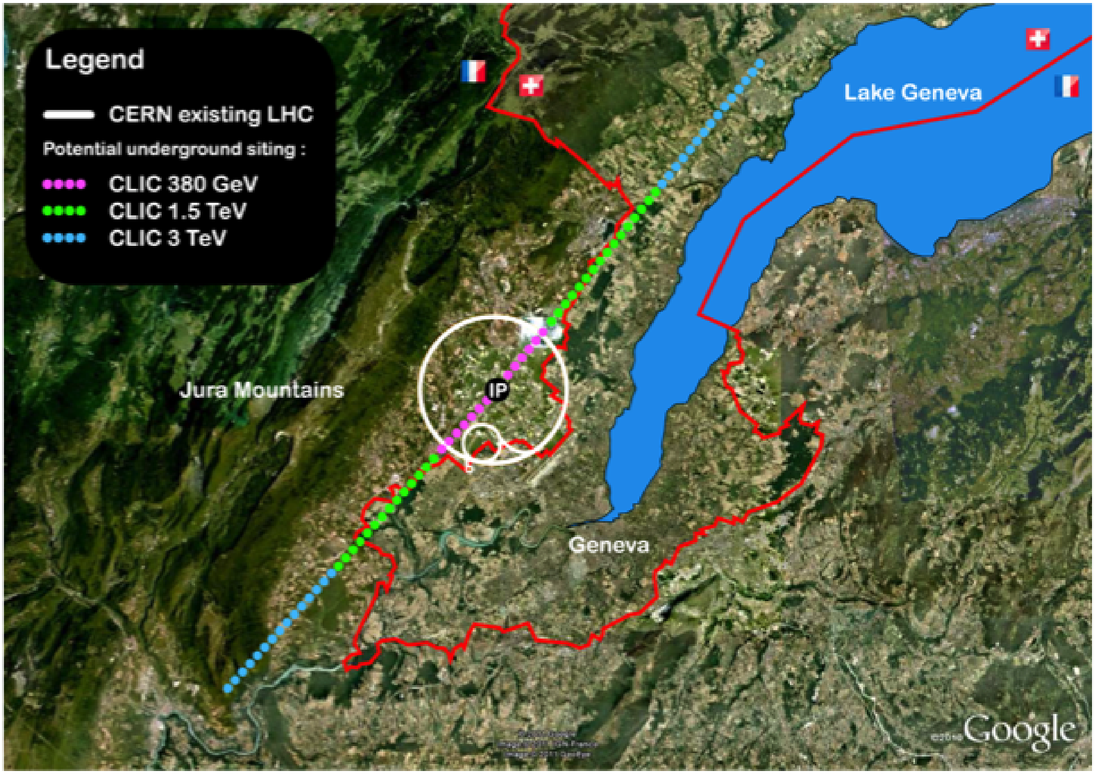
Compact Linear Collider (CLIC):

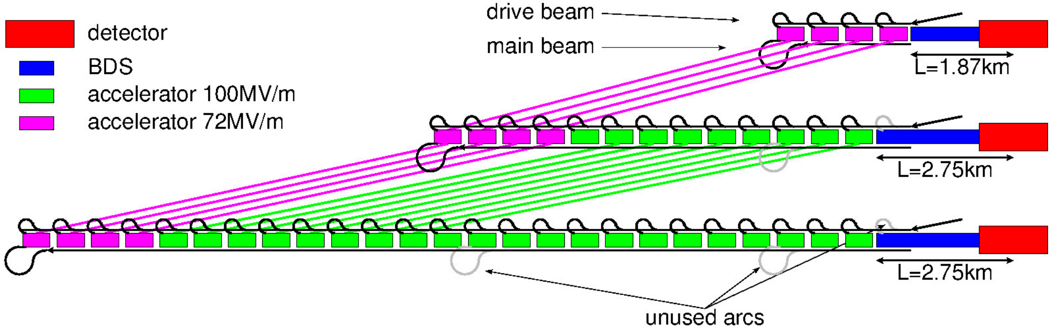
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV
(in several stages)
- Length: 50 km (for 3 TeV)
- $P(e^-) = \pm 80\%$



CLIC 2-beam acceleration

CLIC staged implementation





CERN-2016-004

CLIC would be implemented in several energy stages

Baseline scenario:

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{int}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

→ The strategy can be adapted to possible LHC discoveries at 13/14 TeV!

FCC-ee (1)

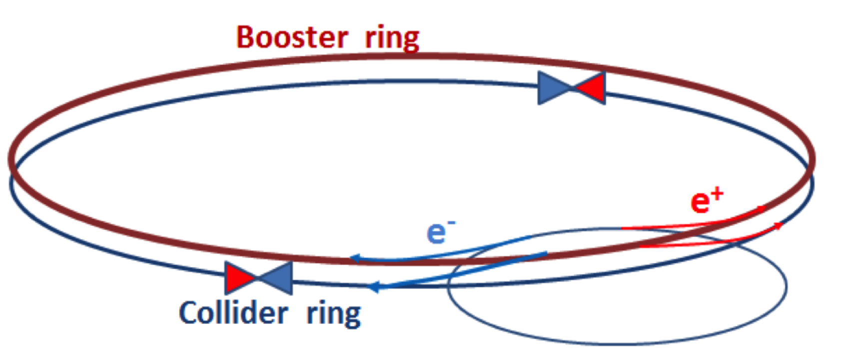
Several interesting physics working points:

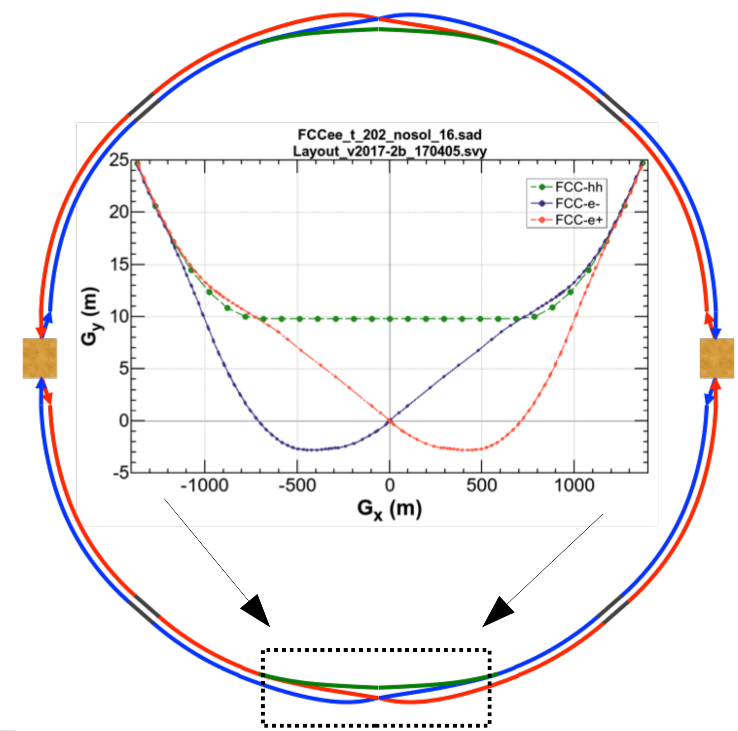
Main process:	$\sqrt{s}$ [GeV]:	L [10^{34} cm^{-2}s^{-1}]
$e^+e^- \to Z$	91.2	130
$e^+e^- \to W^+W^-$	160	16
$e^+e^- \to ZH$	240	5
$e^+e^- \to t\bar{t}$	350	1.4

Luminosities presented at FCC Week 2017

- Short beam lifetime at high energy requires top-up scheme

- FCC-ee fits FCC-hh layout, large crossing angle requires some additional tunnel





FCC-ee (2)

Several interesting physics working points:

Main process:	$\sqrt{s}$ [GeV]:	L [10^{34} $cm^{-2}s^{-1}$]
$e^+e^- \rightarrow Z$	91.2	130
$e^+e^- \rightarrow W^+W^-$	160	16
$e^+e^- \rightarrow ZH$	240	5
$e^+e^- \rightarrow t\bar{t}$	350	1.4

Luminosities presented at FCC Week 2017

Operation model assumed for the CDR:

√s (GeV)	Z	WW	HZ	top
Lumi (ab^{-1}/year)	15, then 30	4	1	0.3
Events/year	1.2×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}
Physics goal	150 ab^{-1}	10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}
Runtime (years)	6	2	5	5

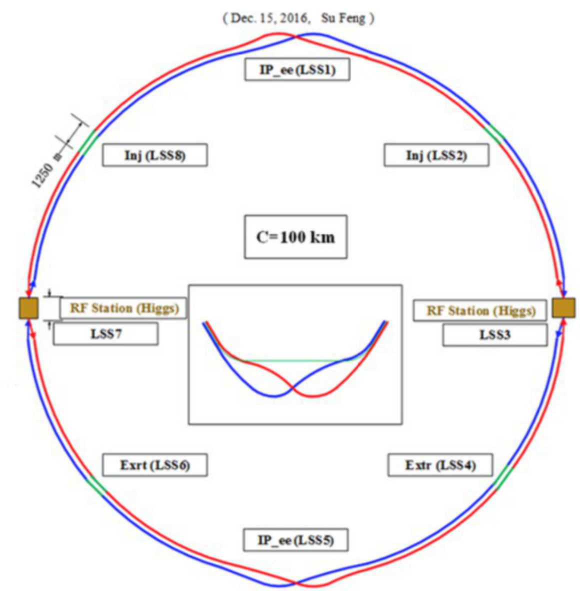
CEPC

- pre-CDR (2015): 54 km ring
- CDR (expected in 2017): 100 km ring

→ parameters for 240, 160 and 91 GeV under study

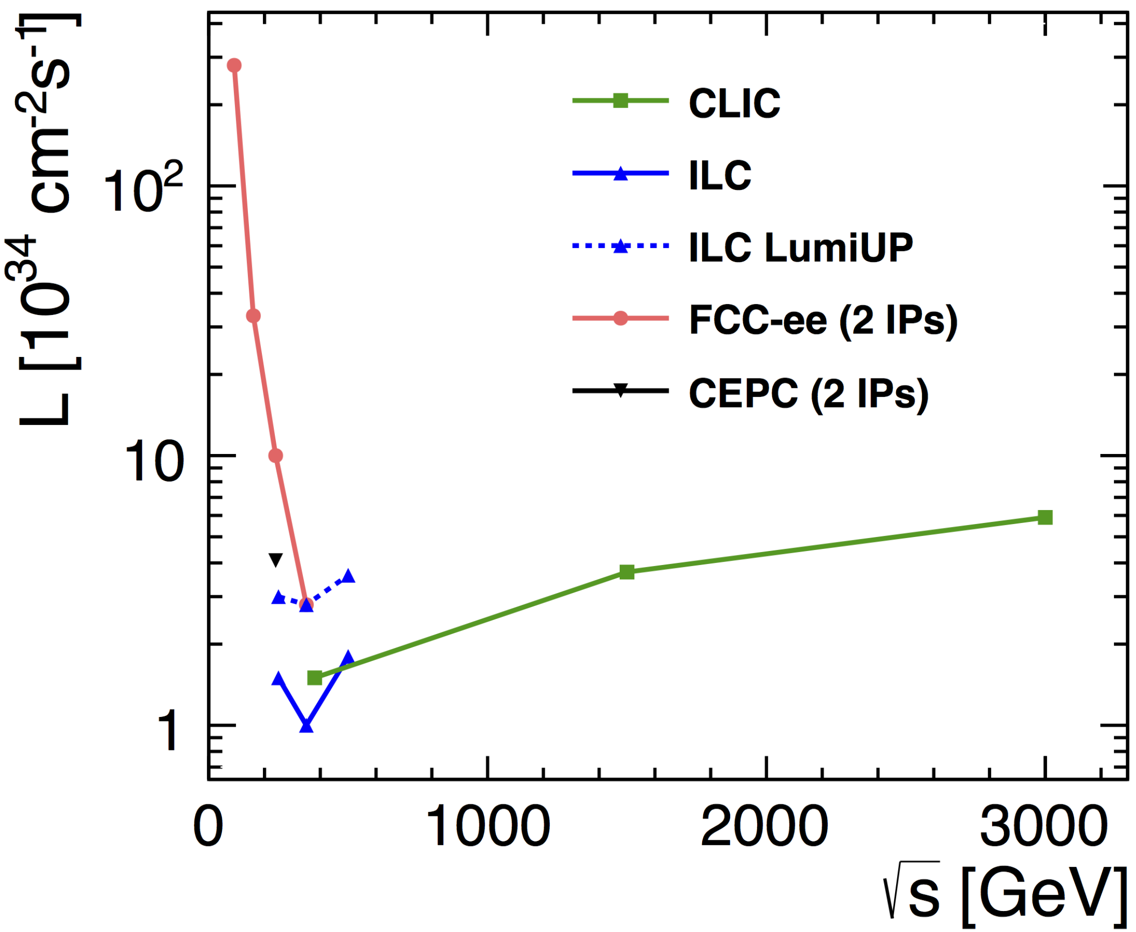
Parameters of CEPC Double ring

	Higgs	*W*	*Z*
Number of IPs	2	2	2
Energy (GeV)	120	80	45.5
SR loss/turn (GeV)	1.67	0.33	0.034
Half crossing angle (mrad)	16.5	16.5	16.5
Piwinski angle	3.19	5.69	4.29
N_e/bunch (10^{11})	0.968	0.365	0.455
Bunch number	**412**	**5534**	**21300**
Beam current (mA)	19.2	97.1	465.8
SR power /beam (MW)	**32**	**32**	**16.1**
Bending radius (km)	11	11	11
Momentum compaction (10^{-5})	1.14	1.14	4.49
β_{IP} x/y (m)	0.171/0.002	0.171 /0.002	0.16/0.002
Emittance x/y (nm)	1.31/0.004	0.57/0.0017	1.48/0.0078
Transverse σ_{IP} (um)	15.0/0.089	9.9/0.059	15.4/0.125
ξ_x/ξ_y/IP	0.013/0.083	0.0055/0.062	0.008/0.054
RF Phase (degree)	128	126.9	165.3
V_{RF} (GV)	2.1	0.41	0.14
f_{RF} (MHz) (harmonic)	650	650 (217800)	650 (217800)
Nature σ_z (mm)	2.72	3.37	3.97
Total σ_z (mm)	2.9	3.4	4.0
HOM power/cavity (kw)	0.41(2cell)	0.36(2cell)	1.99(2cell)
Energy spread (%)	0.098	0.065	0.037
Energy acceptance (%)	1.5		
Energy acceptance by RF (%)	2.1	1.1	1.1
n_γ	0.26	0.15	0.12
Life time due to beamstrahlung (min)	52		
F (hour glass)	0.96	0.98	0.96
L_{max}/IP (10^{34}cm^{-2}s^{-1})	**2.0**	**5.15**	**11.9**



M. Ruan, LHCP 2017

Comparison of the e^+e^- collider options



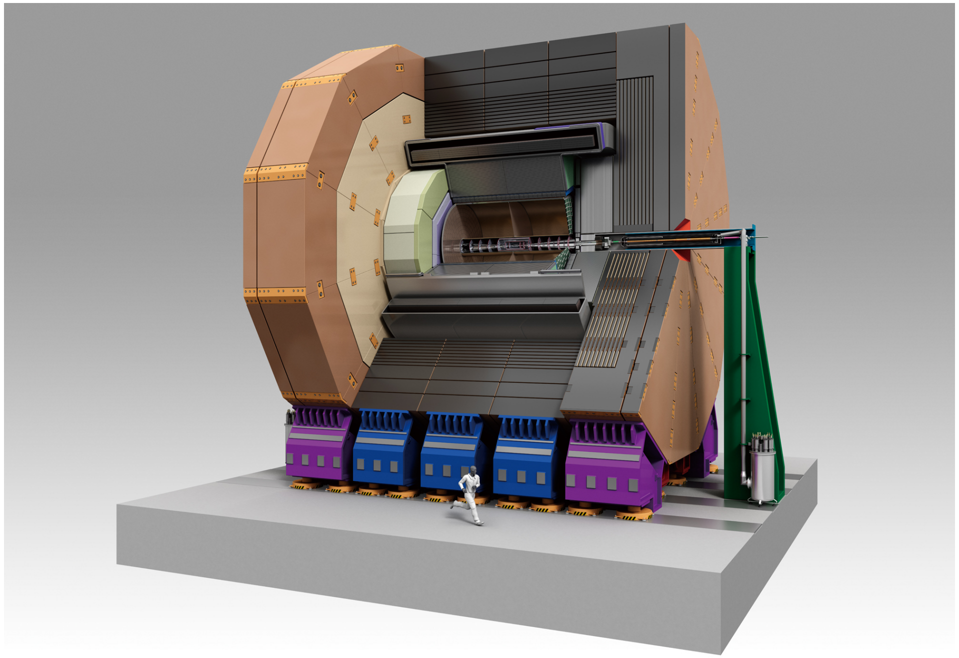
Linear colliders:
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies

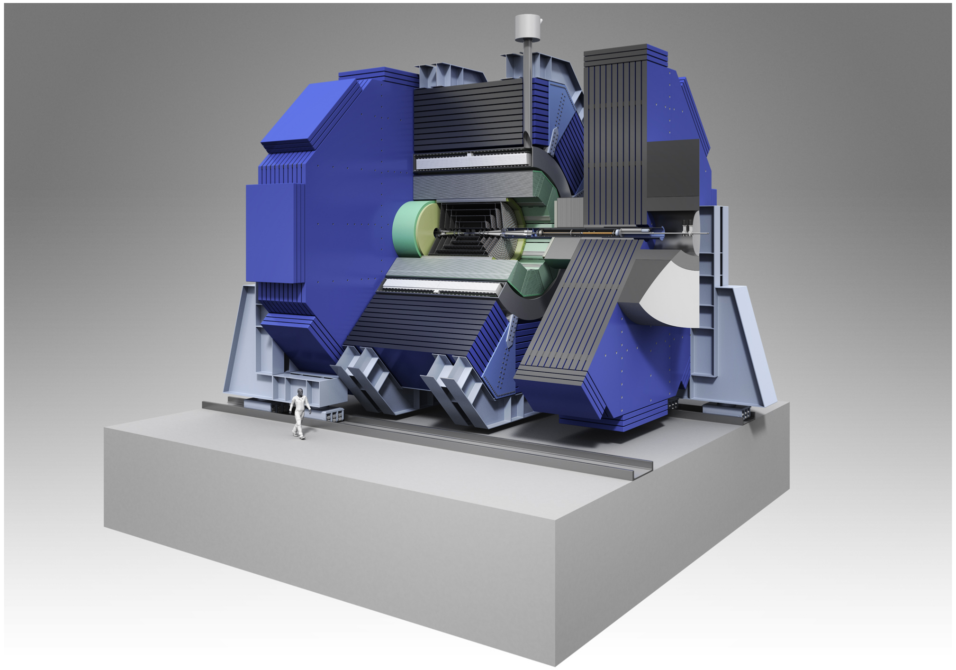
Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

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

ILC detector concepts

Designed for Particle Flow Calorimetry:
- High granularity calorimeters (ECAL and HCAL) inside solenoid
- Low mass trackers → reduce interactions / conversions



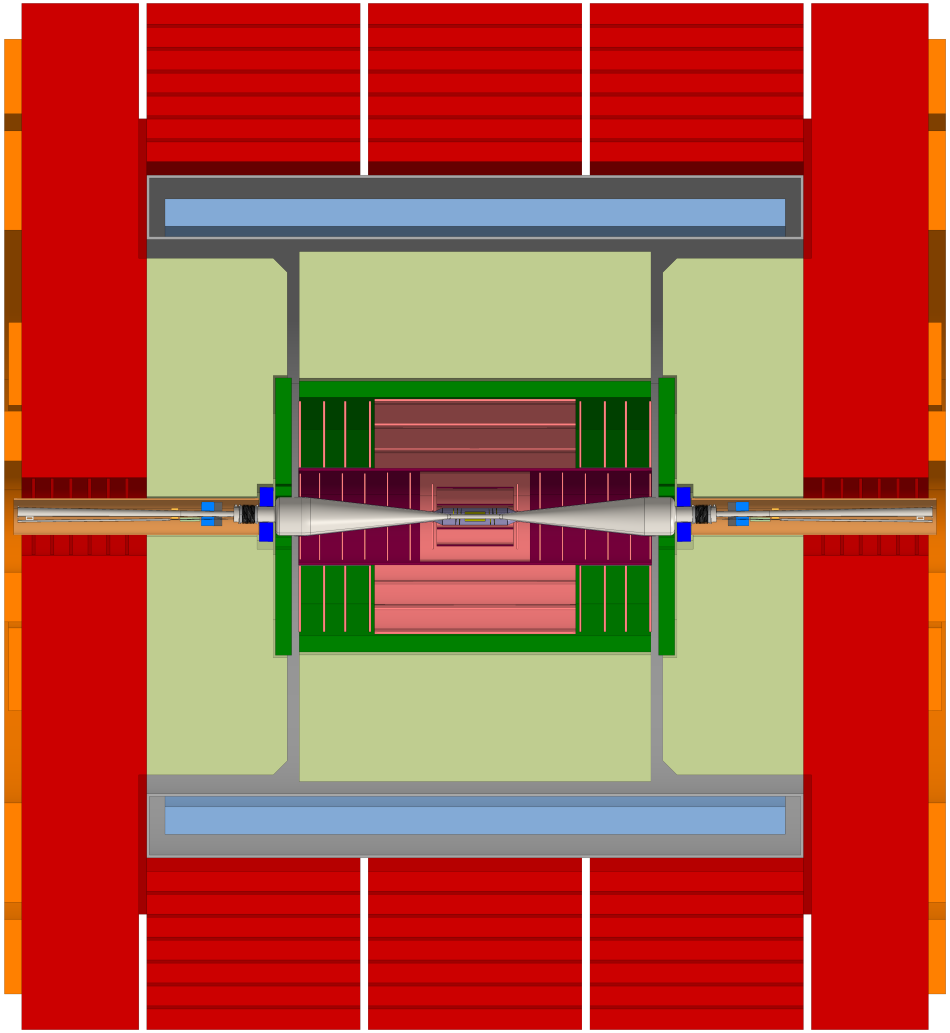


ILD (International Large Detector):
- TPC+silicon envelope, radius: 1.8 m
- B-field: 3.5 T

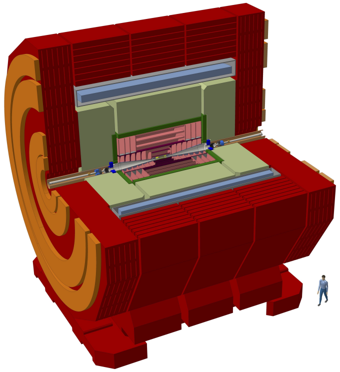
(small option: 1.46 m / 4 T under study)

SiD (Silicon Detector):
- Silicon tracking, radius: 1.2 m
- B-field: 5 T

CLIC detector concept



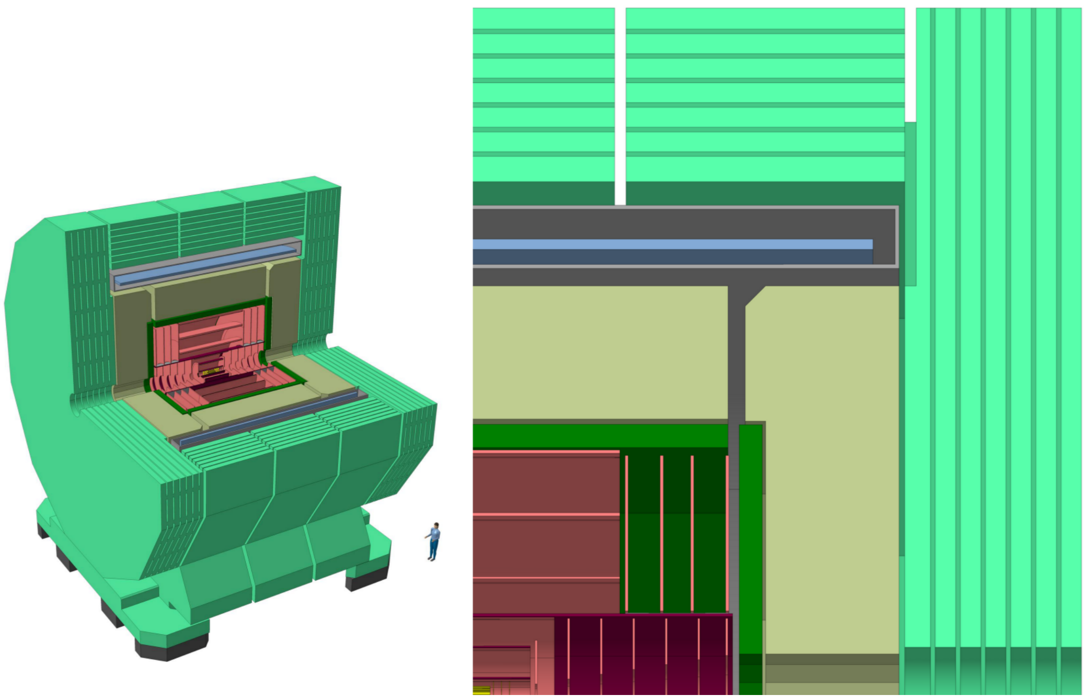
CLICdp-Note-2017-001

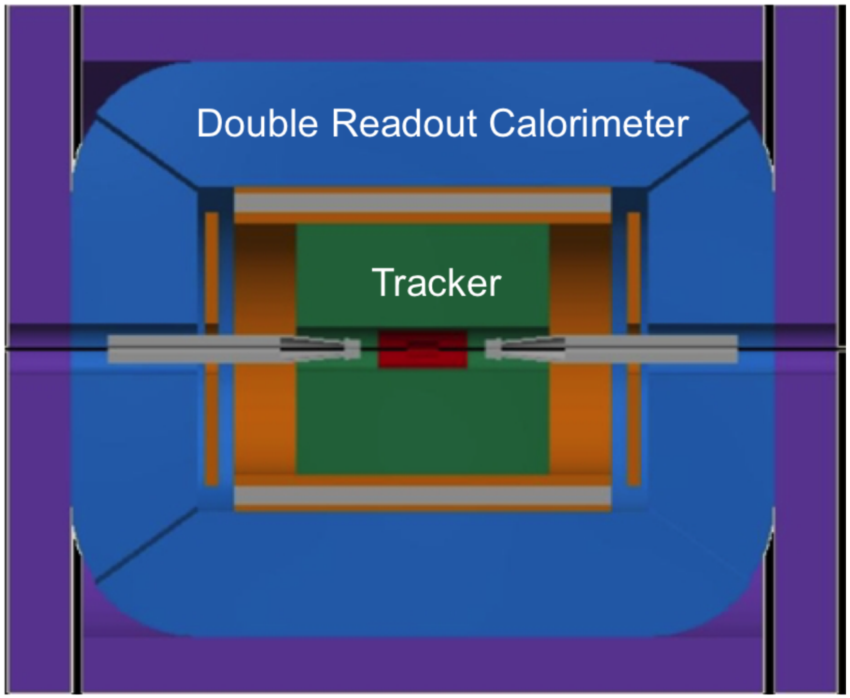


Basic characteristics:
- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (1.5 m radius)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ)

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

FCC-ee detector options

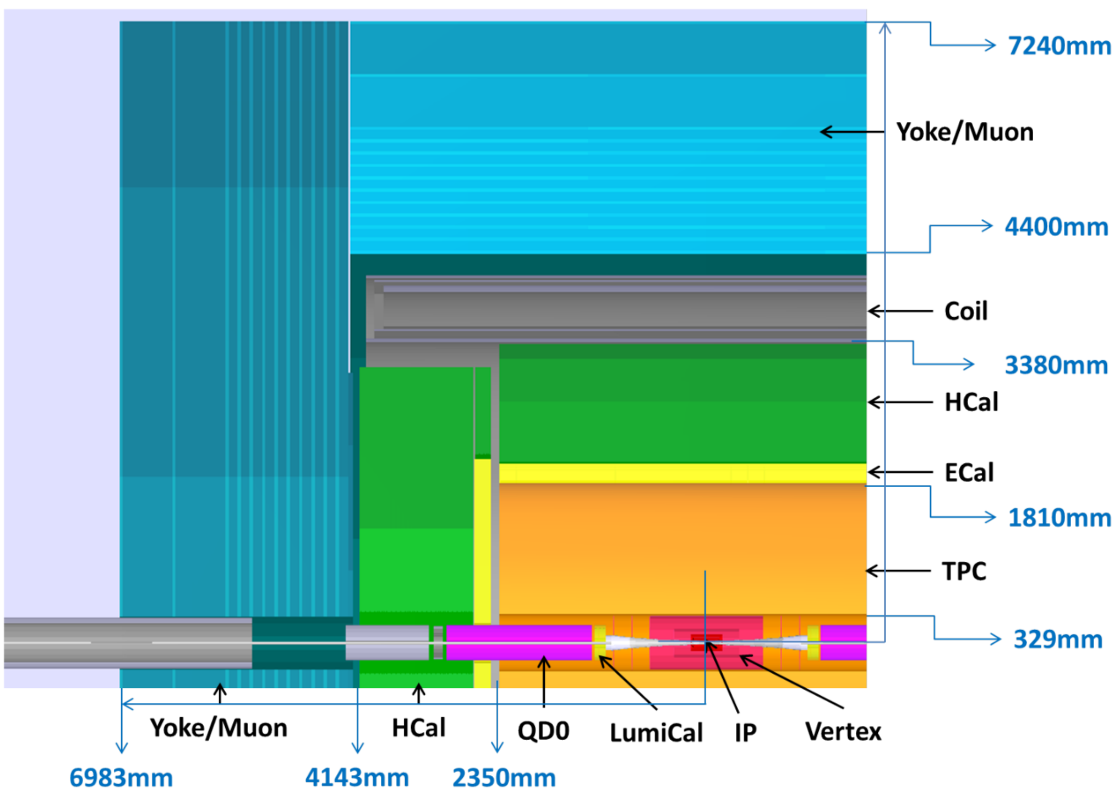




CLICdet-inspired detector concept:
- Smaller magnetic field: 2 T
- Larger tracker radius to keep similar momentum resolution
- Lower $\sqrt{s}$ → HCAL less deep

IDEA detector concept (also for CEPC):
- B-field: 2 T
- Drift chamber with PID
- Double read-out calorimetry
- Possibly instrumented return yoke
- Or: possibly surrounded by large tracking volume for long-lived particles (R≈8 m)

CEPC detector



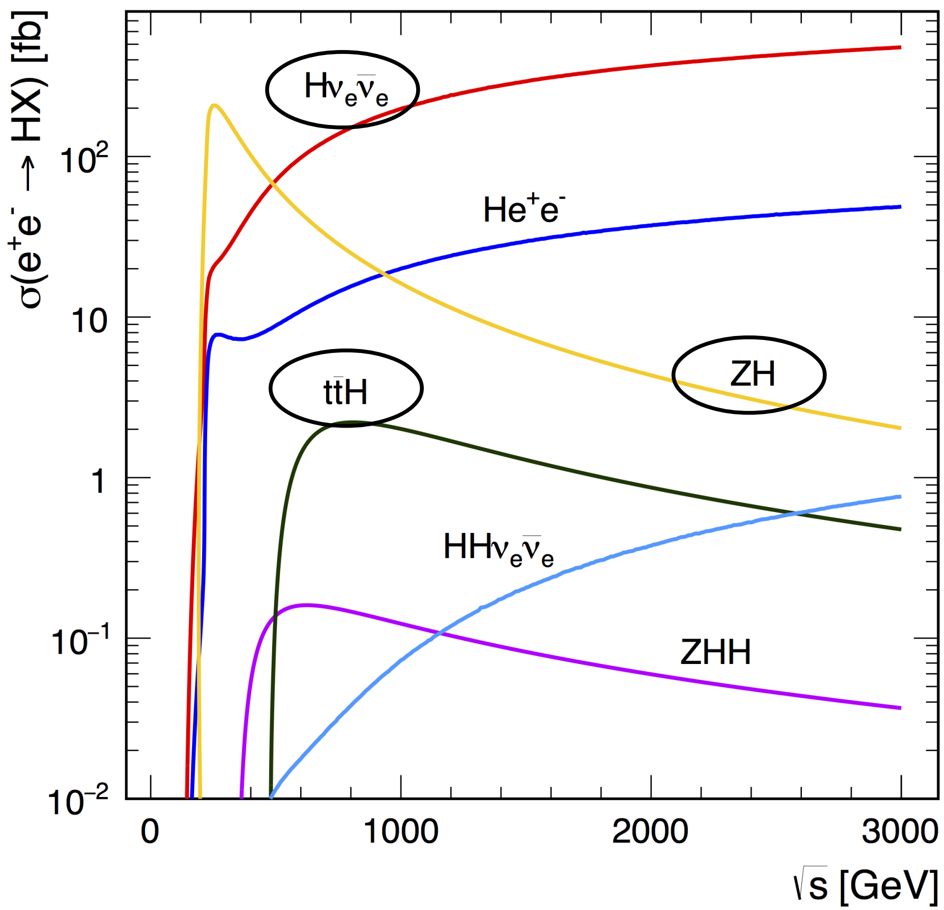
ILD-inspired detector studied for the preCDR:

- Increased cooling due to continuous operation
- Thickness of return yoke reduced

Towards CDR:

- Study 2+ detector concepts: ILD-/SiD-like and IDEA

Single Higgs production



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

- $\sigma \sim 1/s$, dominant up to ≈ 450 GeV
- Higgs identification from Z recoil

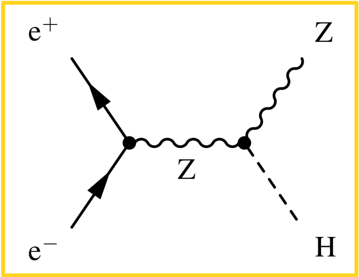
→ model-independent measurement of g_{HZZ}

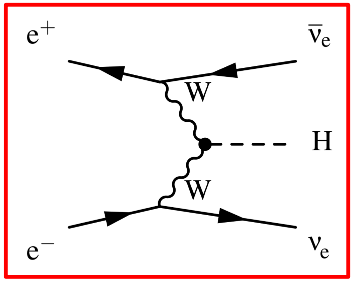
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

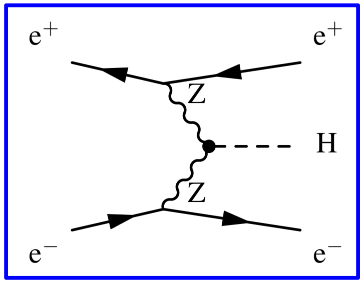
- $\sigma \sim \log(s)$, dominant above 450 GeV
- Large statistics at high energy

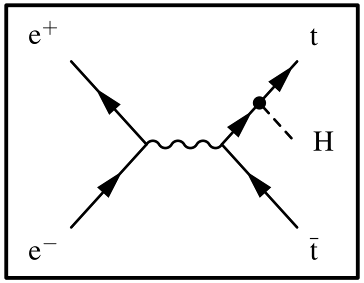
$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$

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

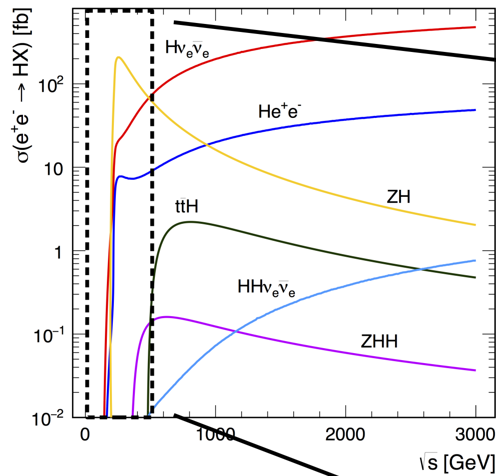


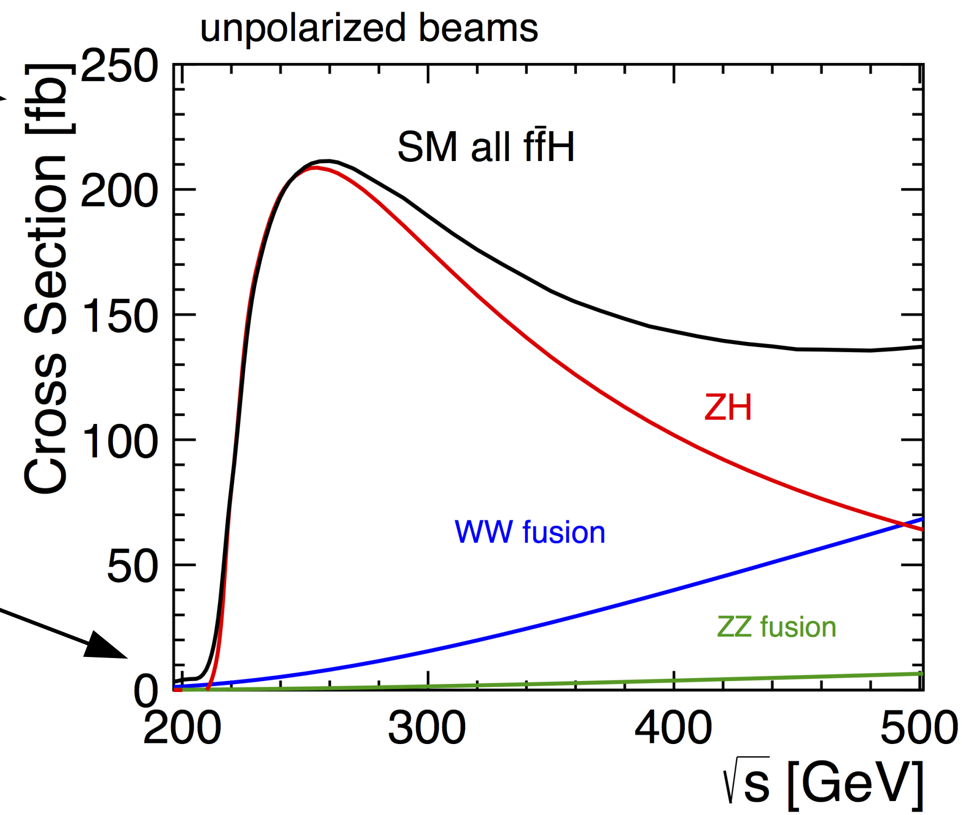






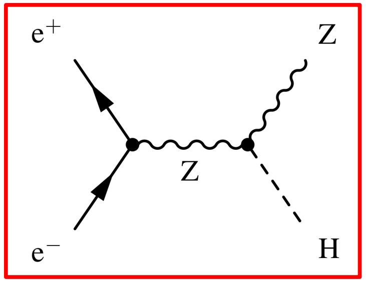
Closer look at $\sqrt{s}$ < 500 GeV

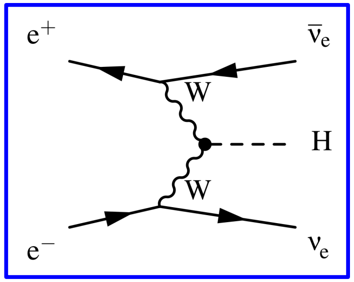




$\sqrt{s}$ = 240/250 GeV:
(CEPC, FCC-ee, ILC)
Maximum of the Higgsstrahlung cross section

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





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

Effective Field Theory:

Standard Model

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

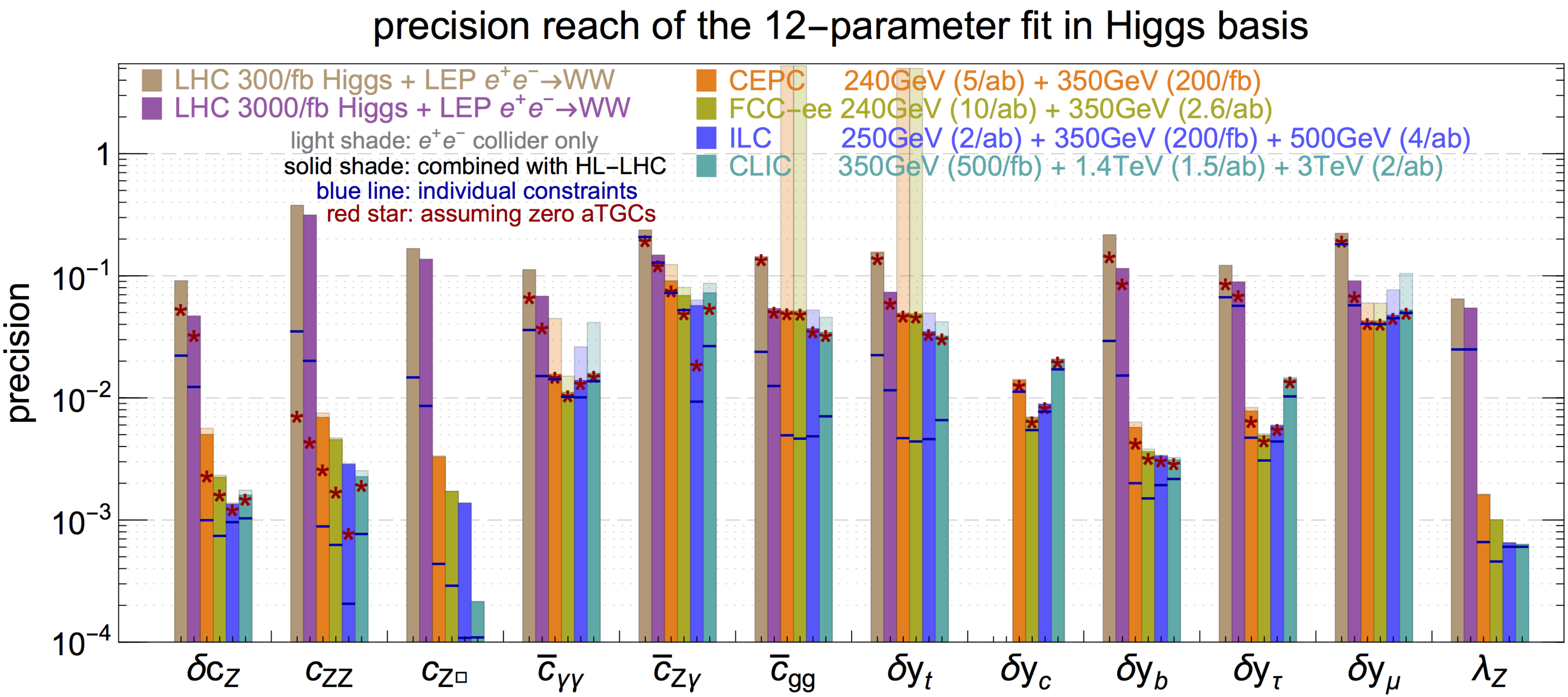
Dimension-6 operators

Scale of new decoupled physics

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

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

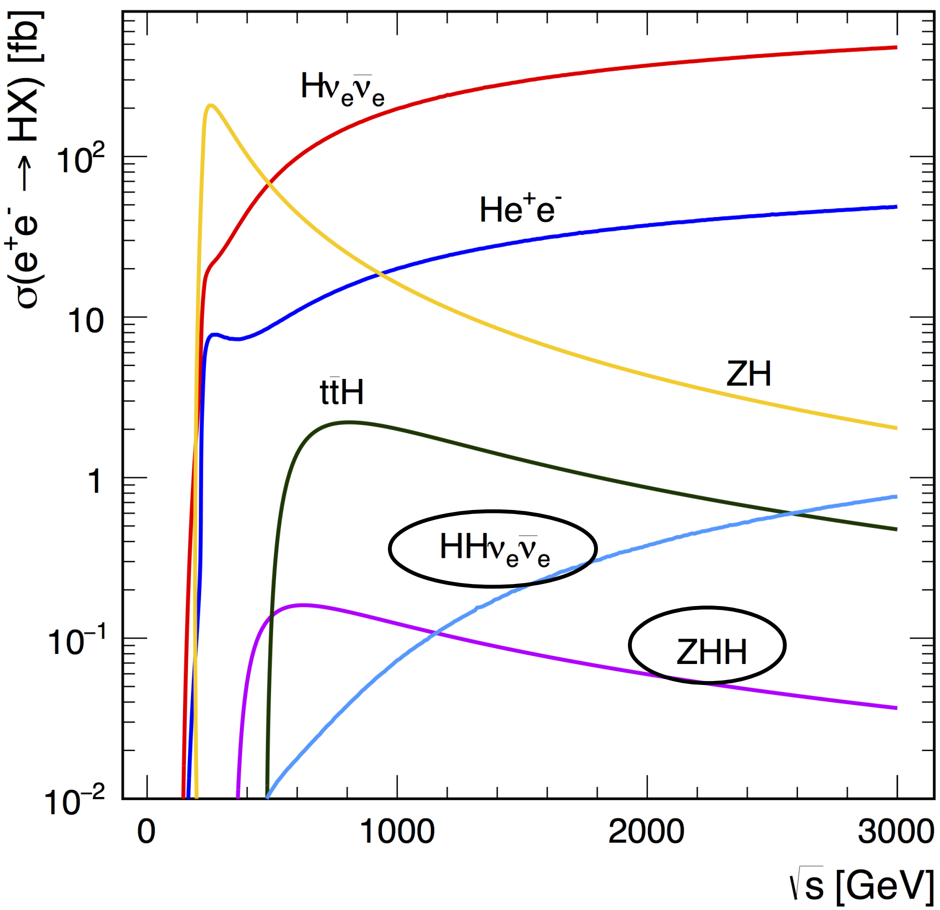
Comparison of different collider options



- Many EFT parameters can be measured significantly better at an electron-positron collider compared to the HL-LHC
- $H\rightarrow c\bar{c}$ only accessible in at lepton colliders

arXiv:1704.02333
see also JHEP 05, 096 (2017)

Double Higgs production



$e^+e^- \rightarrow$ ZHH:
- Cross section maximum ≈ 600 GeV, but very small number of events (σ ≤ 0.2 fb)

$e^+e^- \rightarrow HH\nu_e\bar{\nu}_e$:
- Allows simultaneous extraction of triple Higgs coupling, λ, and quartic HHWW coupling
- Benefits from high-energy operation

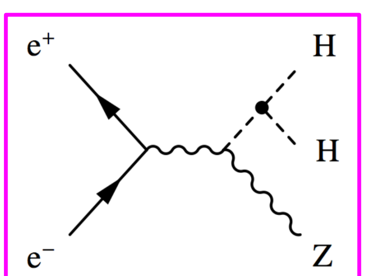
Projected precisions:
- Δ(λ) = 27% for ILC including luminosity upgrade
- Δ(λ) = 16% for CLIC from total cross section

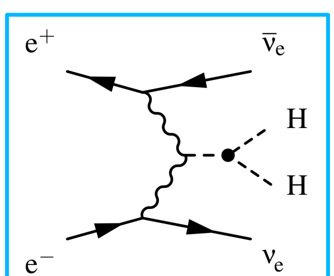
(→ Δ(λ) ≈ 10% from differential distributions)

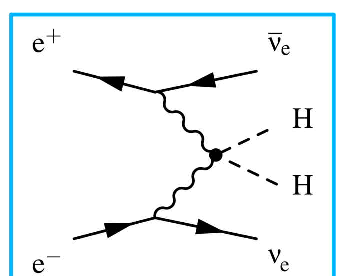
arXiv:1506.05992
Eur. Phys. J. C 77, 475 (2017)

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)







Top quark mass

$t\bar{t}$ threshold scan:

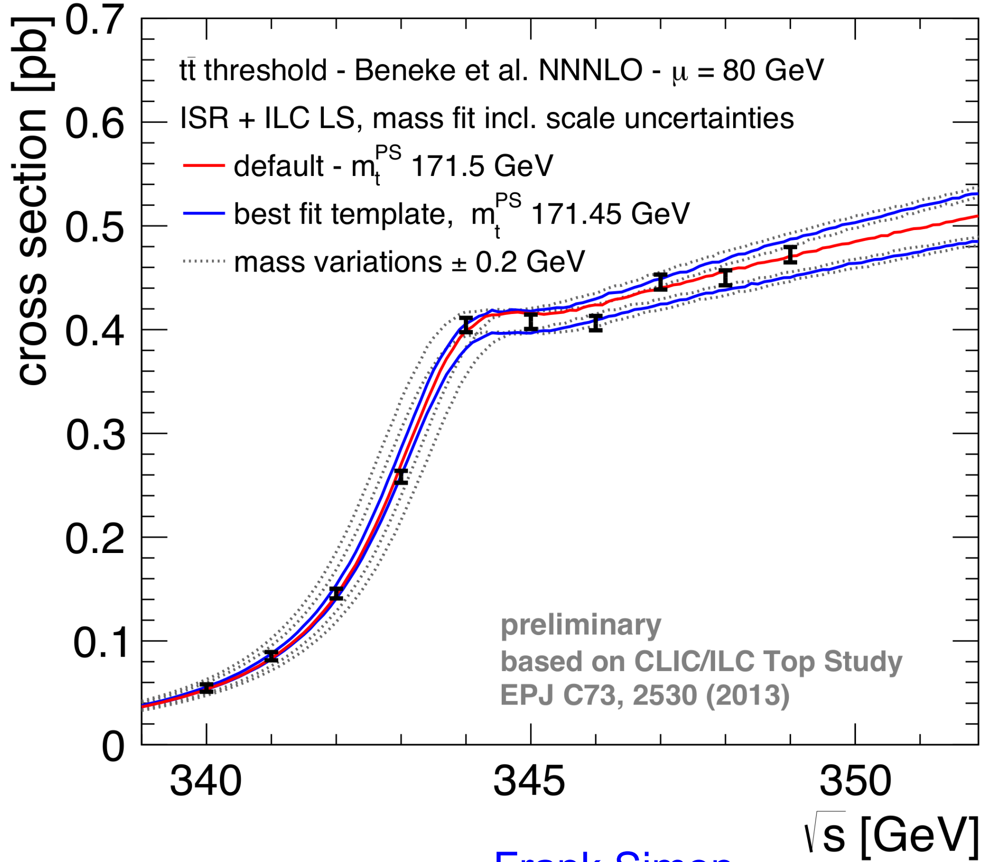
• Measurement at different centre-of-mass energies in the $t\bar{t}$ production threshold region (data also useful for Higgs physics)

• Expected precision on 1S mass: ≈50 MeV, independent of accelerator (ILC, CLIC, FCC-ee) currently dominated by theory NNNLO scale uncertainty

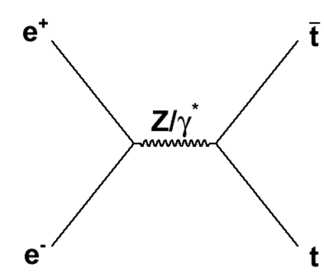
• Theoretical uncertainty in the order of 10 MeV when transforming the measured 1S mass to the $\overline{MS}$ mass scheme

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

• Precision at the LHC limited to several hundred MeV



Frank Simon, topLC 2017



Top electroweak couplings

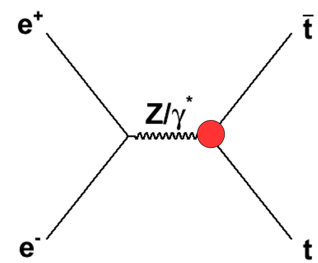
- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

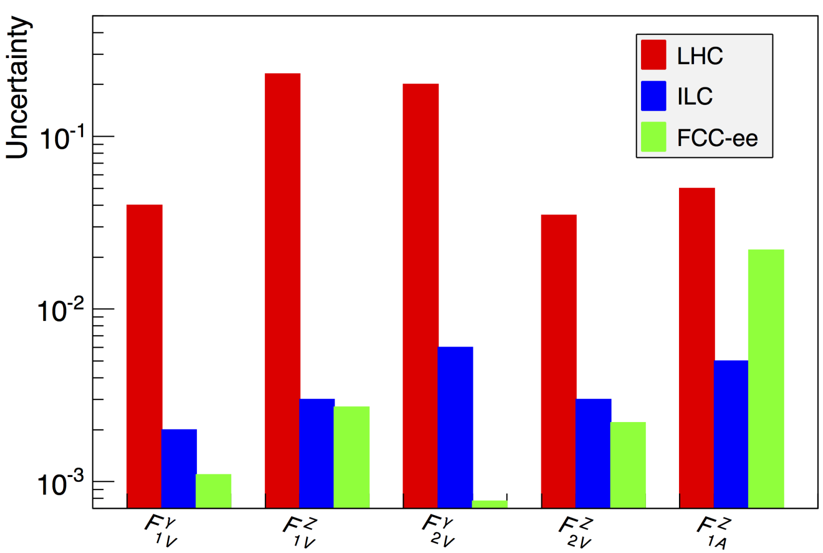
arXiv:hep-ph/0601112

CP conserving — CPV

$$\Gamma_{\mu}^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

- New physics would modify the $t\bar{t}V$ vertex

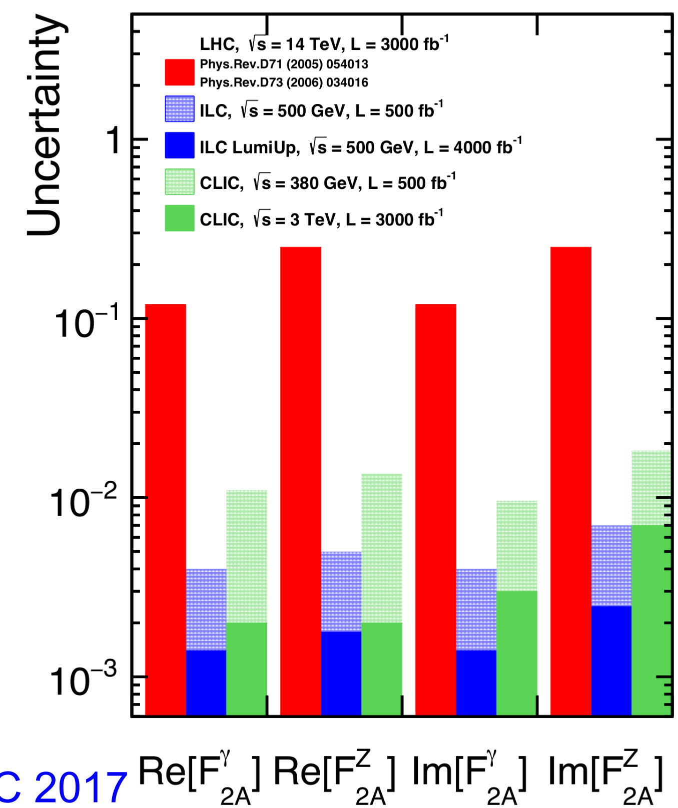




JHEP04(2015)182

- e^+e^- colliders 1-2 orders of magnitude better than HL-LHC

- EFT analyses are also being performed

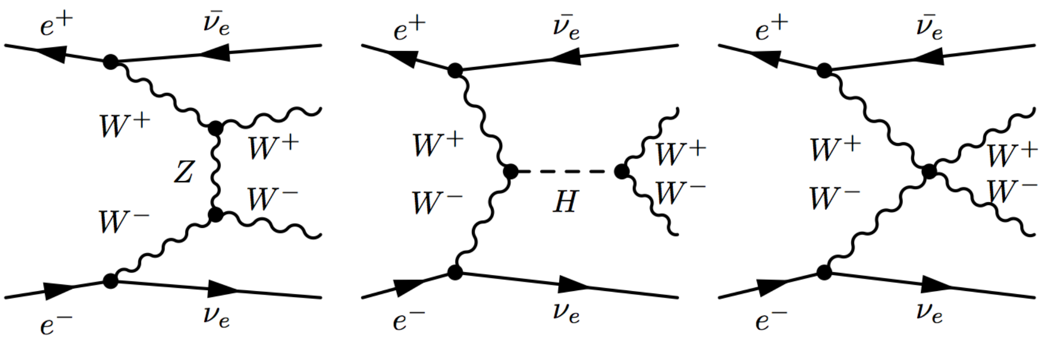


Martín Perelló, topLC 2017

Vector boson scattering

- Example processes recently investigated using a full detector simulation for CLIC:

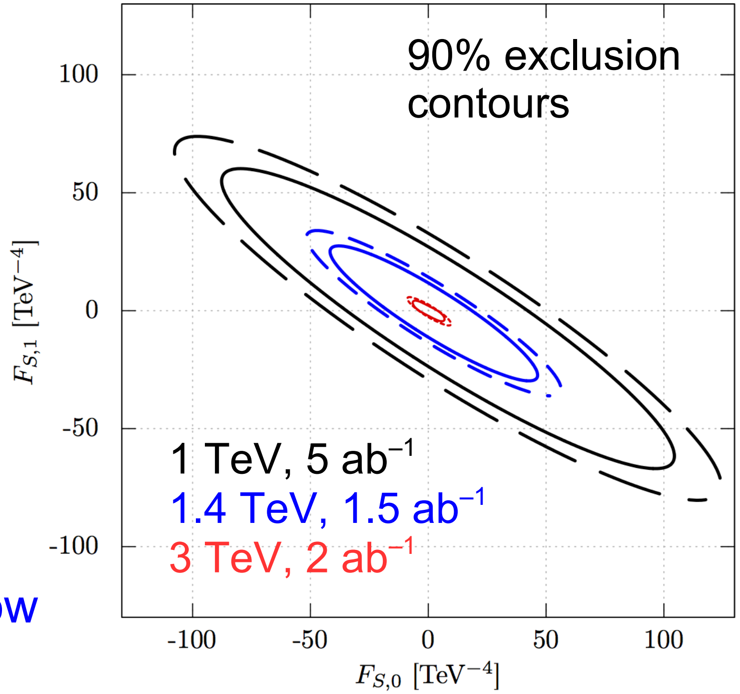
$e^+e^- \rightarrow W^+W^-\nu\bar{\nu}$
$e^+e^- \rightarrow ZZ\nu\bar{\nu}$



- Search for additional resonances or anomalous couplings

- The sensitivity rises steeply with the centre-of-mass energy

$$\mathcal{L}_{S,0} = F_{S,0} \ \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{D}_\nu \mathbf{H}\right] \mathrm{tr}\left[(\mathbf{D}^\mu \mathbf{H})^\dagger \mathbf{D}^\nu \mathbf{H}\right]$$
$$\mathcal{L}_{S,1} = F_{S,1} \ \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{D}^\mu \mathbf{H}\right] \mathrm{tr}\left[(\mathbf{D}_\nu \mathbf{H})^\dagger \mathbf{D}^\nu \mathbf{H}\right]$$



→ see talk by Wolfgang Kilian tomorrow

VBS: experimental aspects

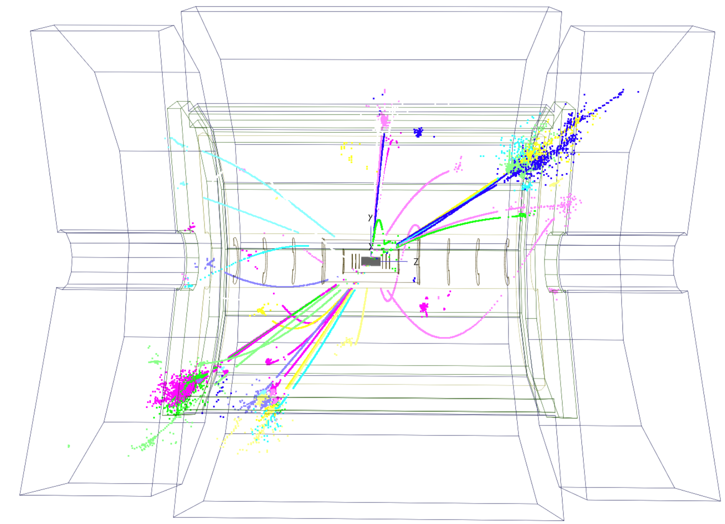
- At an e^+e^- collider, fully hadronic events can be used (in contrast to hadron colliders): $W^+W^-\nu\bar{\nu}/ZZ\nu\bar{\nu} \rightarrow q\bar{q}q\bar{q}\nu\bar{\nu}$
  $\rightarrow$ largest event samples and full kinematic information

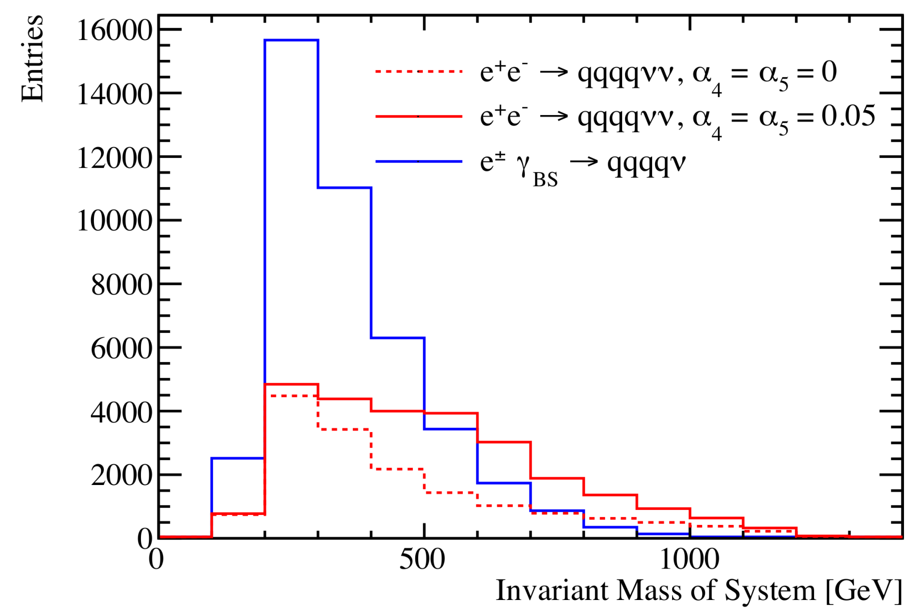
- Extract the operator coefficients α_4 and α_5 from invariant mass of the final-state bosons

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

$$\alpha_4 = F_{S,0}\, v^4/16$$
$$\alpha_5 = F_{S,1}\, v^4/16$$

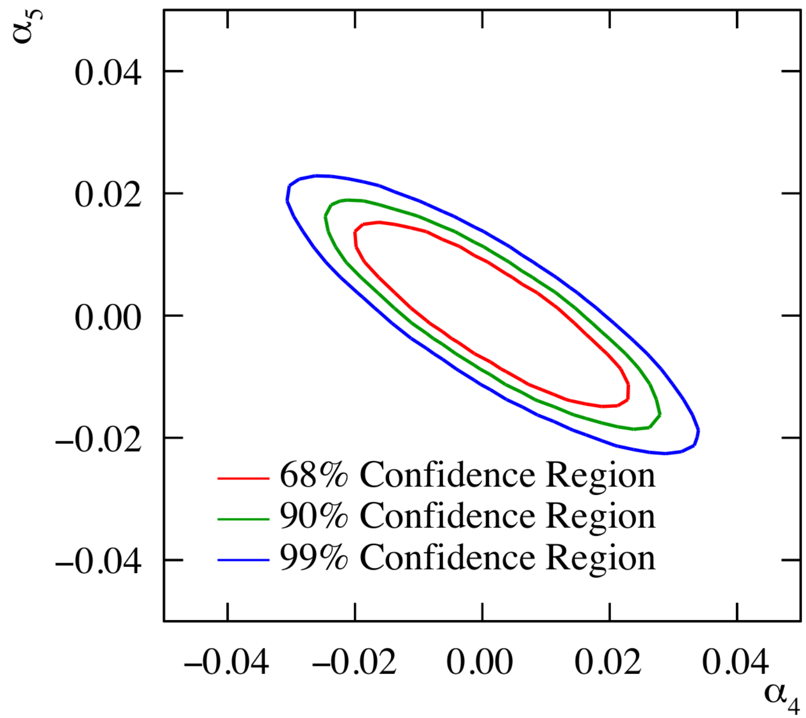
CLIC, $\sqrt{s}$ = 1.4 TeV





VBS: results

CLIC, $\sqrt{s}$ = 1.4 TeV

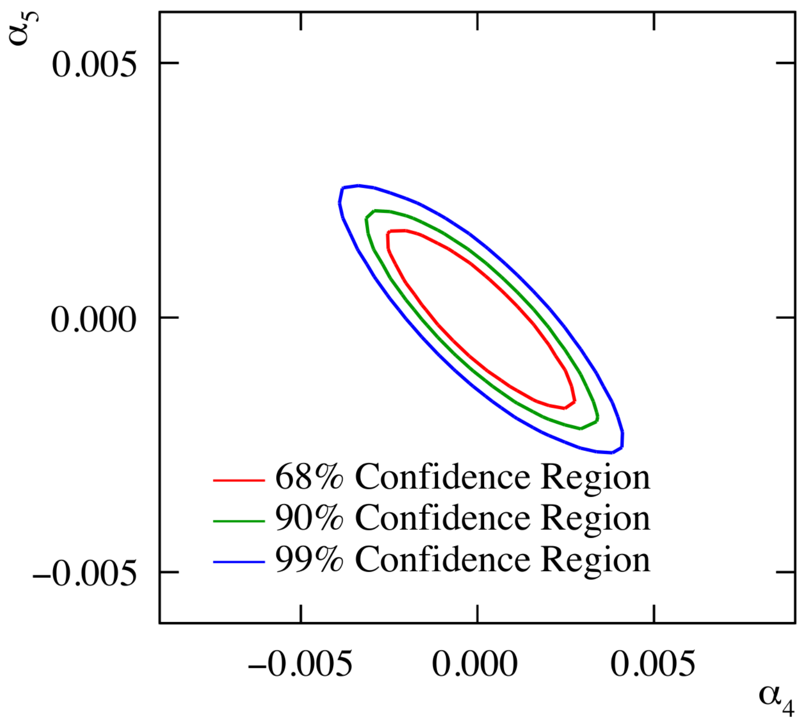


1D fit (68% CL):

$-0.0082 < \alpha_4 < 0.0116$

$-0.0055 < \alpha_5 < 0.0078$

CLIC, $\sqrt{s}$ = 3 TeV



1D fit (68% CL):

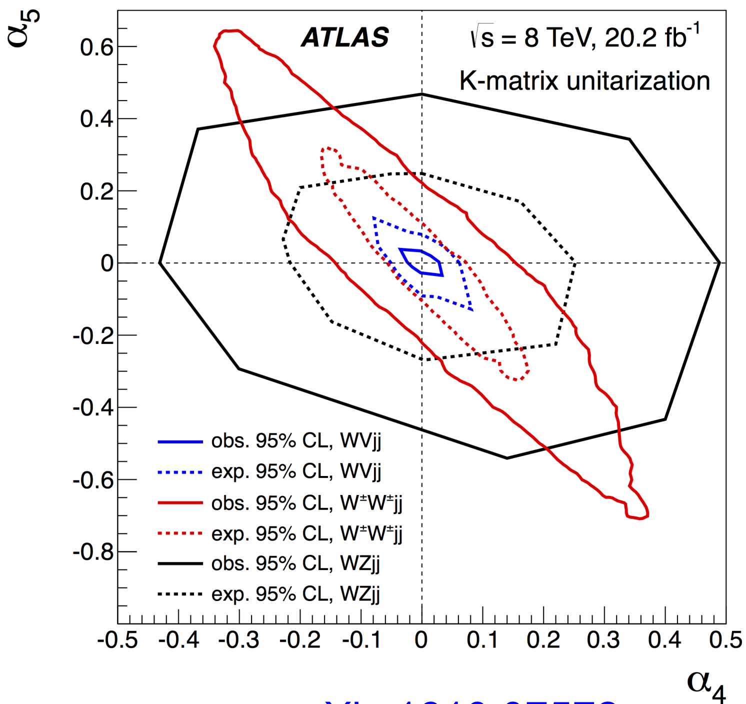
$-0.00102 < \alpha_4 < 0.00112$

$-0.00070 < \alpha_5 < 0.00074$

→ Sensitivity almost one order of magnitude better at 3 TeV

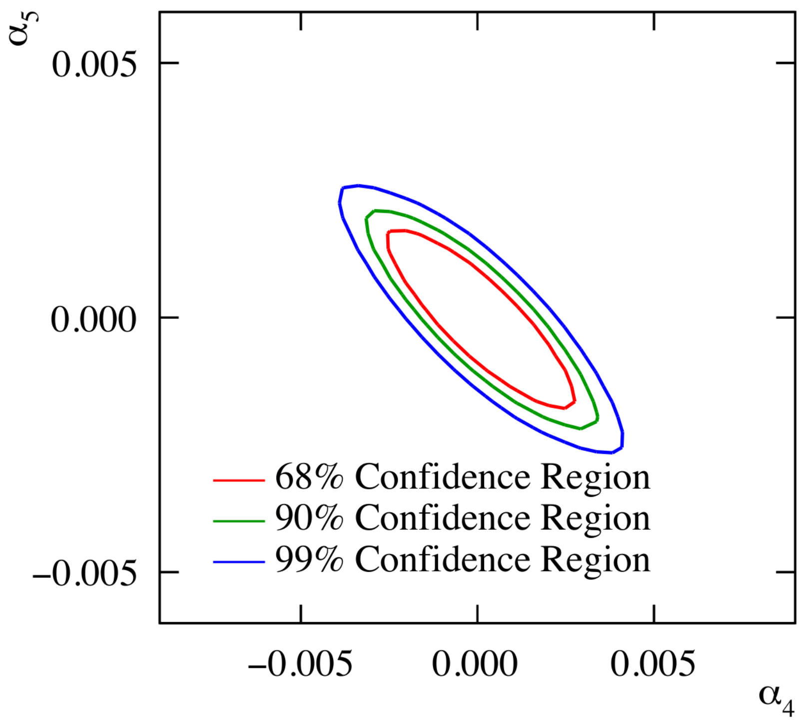
VBS: comparison to LHC

ATLAS, $\sqrt{s}$ = 8 TeV



arXiv:1610.07572

CLIC, $\sqrt{s}$ = 3 TeV



1D fit (68% CL):

$-0.00102 < \alpha_4 < 0.00112$

$-0.00070 < \alpha_5 < 0.00074$

→ Sensitivity significantly better than 8 TeV LHC

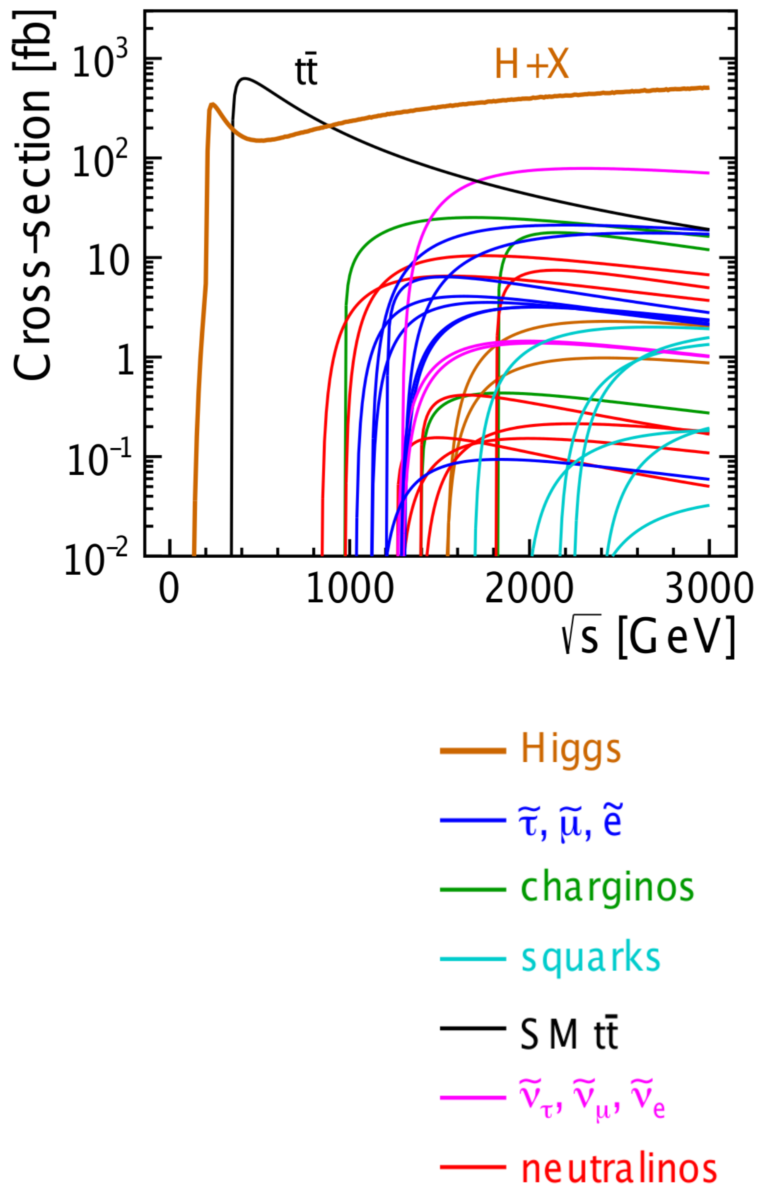
Direct BSM searches

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

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

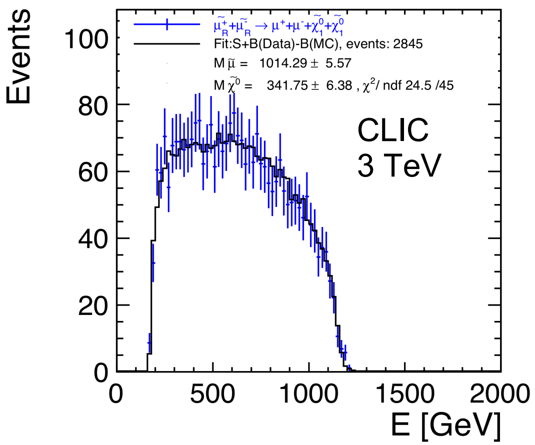
- Very rare processes accessible due to low backgrounds (no QCD)
→ e^+e^- colliders especially suitable for electroweak states

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



Reconstruction of SUSY particles

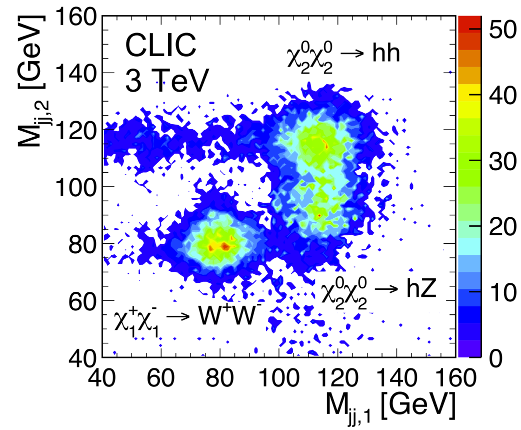
Endpoints of energy spectra:



$m(\tilde{\mu}_R)$:	± 5.6 GeV
$m(\tilde{e}_R)$:	± 2.8 GeV
$m(\tilde{\nu}_e)$:	± 3.9 GeV
$m(\tilde{\chi}_1^0)$:	± 3.0 GeV
$m(\tilde{\chi}_1^\pm)$:	± 3.7 GeV

slepton masses:
1.0 - 1.1 TeV

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



Jet reconstruction

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

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

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

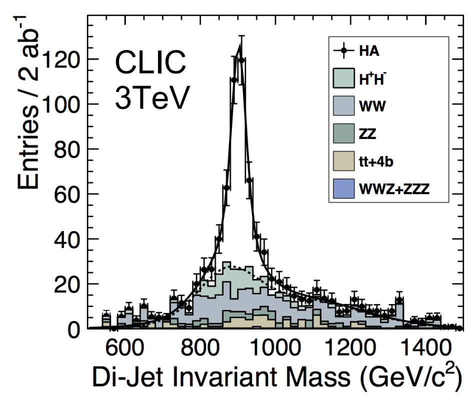
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow Zh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

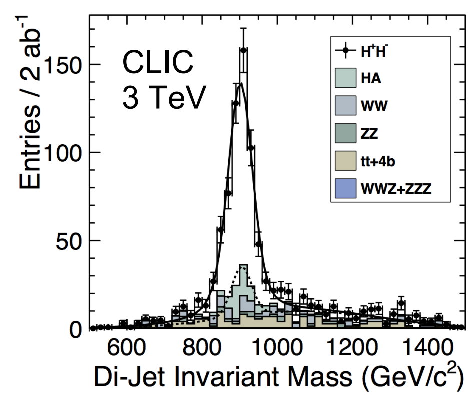
Complex final states:

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

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

≈ 0.3% precision on heavy Higgs masses



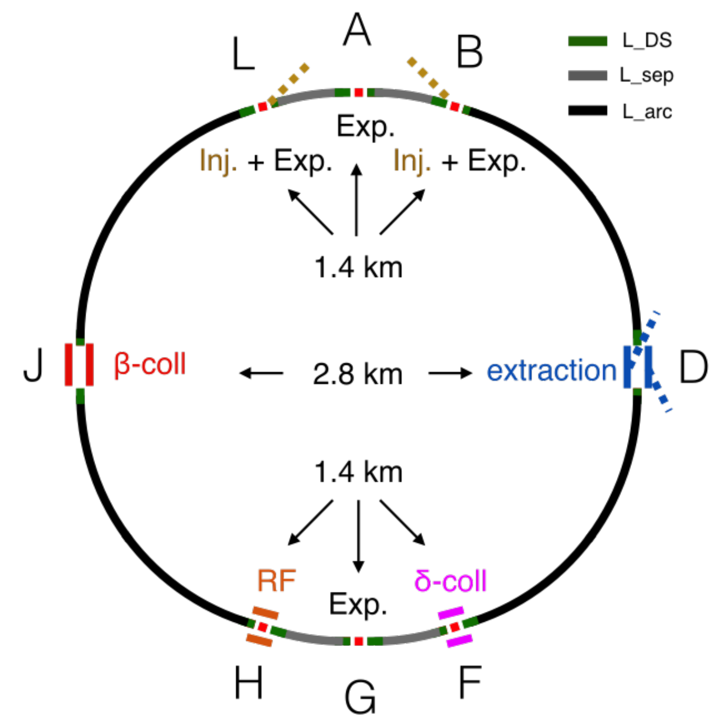


Proton-proton colliders:

- FCC-hh, HE-LHC, CEPC
- Detector concept for FCC-hh
- Physics highlights at 100 TeV

FCC-hh

- Proton-proton collider with $\sqrt{s}$=100 TeV, ion option
- FCC layout optimised for Geneva site, (circumference: 97.75 km) can use LHC or SPS as injector
- FCC-ee is potential first stage, FCC-eh is an additional option
- The goal is 16 T operating filed → requires Nb_3Sn technology



FCC-hh magnet development

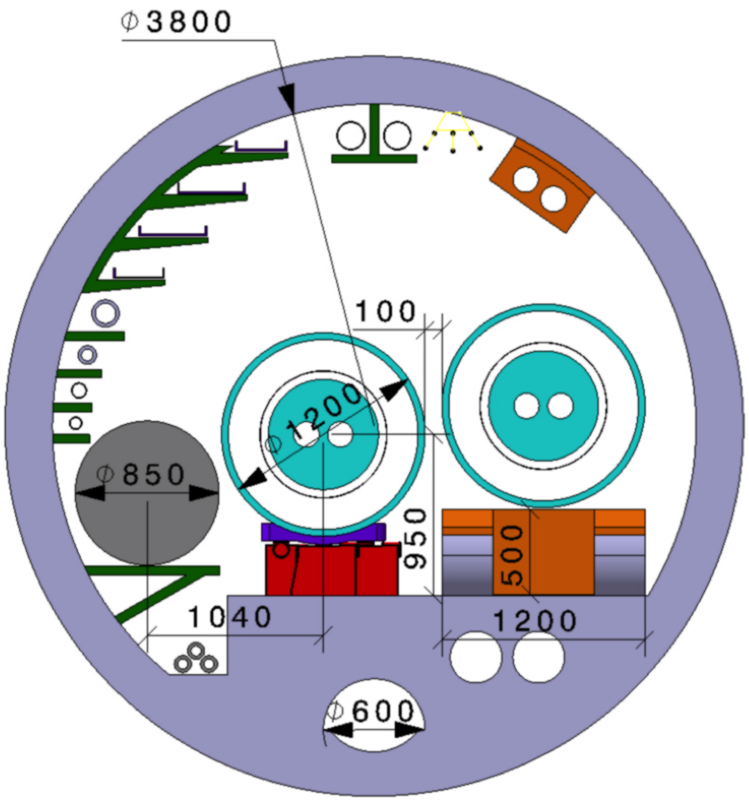
HE-LHC

Use the FCC-hh magnet technology for a proton-proton collider in the LHC tunnel:

- $\sqrt{s}$ = 27 TeV (= 14 TeV · 16 T / 8.33 T)
- Luminosity 4 times higher than HL-LHC ($\sim 1/E^2$)
- Constraint on external diameter of magnet cryostat (1.2 m) for LHC tunnel compatibility

Key ingredients:
- FCC-hh magnet technology
- FCC-hh vacuum system
- HL-LHC crab waist scheme
- HL-LHC electron lens
- HL-LHC/LIU beam parameters

(25 ns bunch structure, 5 ns operation)



FCC-hh and HE-LHC parameters

	New tunnel		LHC tunnel		
parameter	**FCC-hh**		**HE-LHC**	**HL-LHC**	**LHC**
$\sqrt{s}$ [TeV]	**100**		**27**	**14**	**14**
Dipole field [T]	16		16	8.33	8.33
Circumference [km]	**97.75**		26.7	26.7	26.7
Beam current [A]	0.5		1.12	1.12	0.58
Bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
Bunch spacing [ns]	25	25 (5)	25 (5)	25	25
Synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
Long. emit. damping time [h]	0.54		1.8	12.9	12.9
Peak luminosity [10^{34} cm^{-2}s^{-1}]	**5**	30	25	**5**	1
events/bunch crossing	170	**~1000** (200)	~800 (160)	135	27

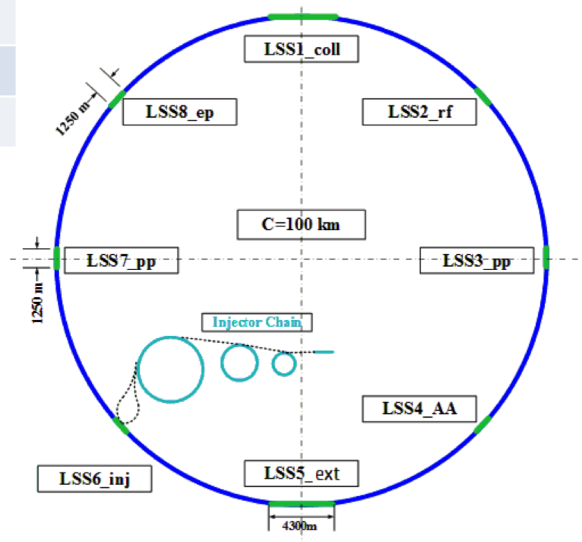
SppC

The SppC layout recently adapted to 100 km circumference

Parameter	Unit	Value		
		PreCDR	CDR	Ultimate
Circumference	km	54.4	**100**	100
C.M. energy	TeV	70.6	**75**	125-150
Dipole field	T	20	12	20-24
Injection energy	TeV	2.1	2.1	4.2
Number of IPs		2	2	2
Nominal luminosity per IP	$cm^{-2}s^{-1}$	1.2e35	**1.0e35**	-
Circulating beam current	A	1.0	0.7	-
Bunch separation	ns	25	25	-
Bunch population		2.0e11	1.5e11	-
SR power per beam	MW	2.1	1.1	-
SR heat load per aperture @arc	W/m	45	13	-

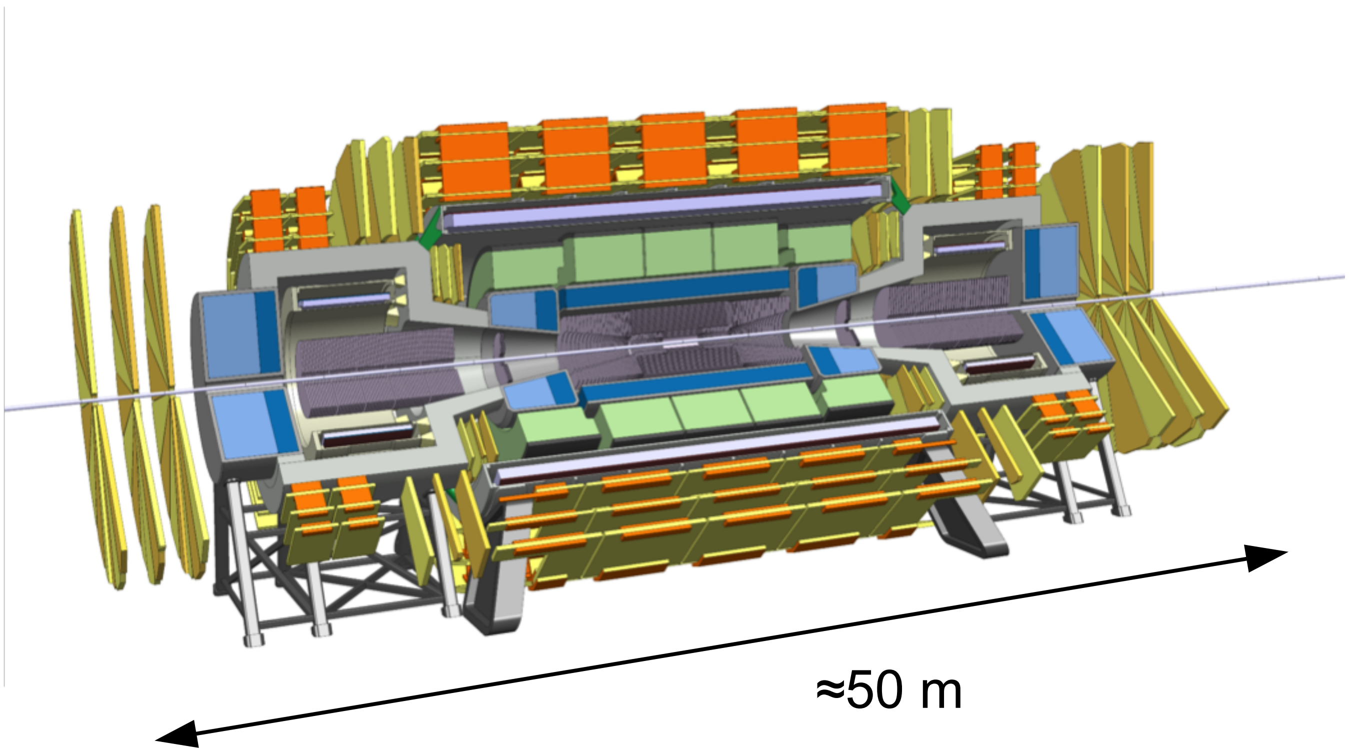
Iron-based HTS dipole technology considered
(12 T baseline, 20-24 T upgrade)

SPPC Layout



J. Tang, FCC Week 2017

FCC-hh detector concept

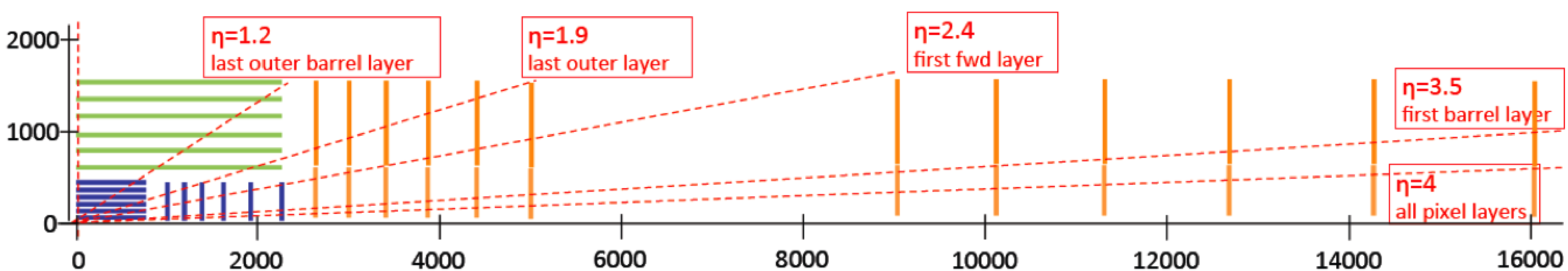


Reference detector for CDR:
- 4 T solenoid, 10 m diameter
- Forward solenoids
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

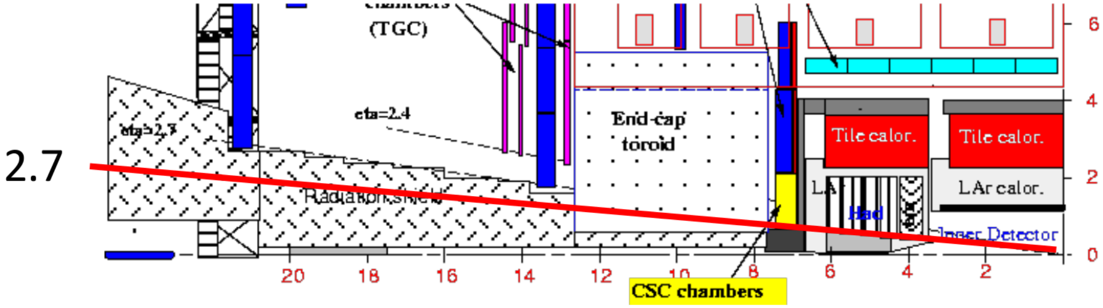
W. Riegler,
FCC Week 2017

Forward coverage up to |η| ≈ 6

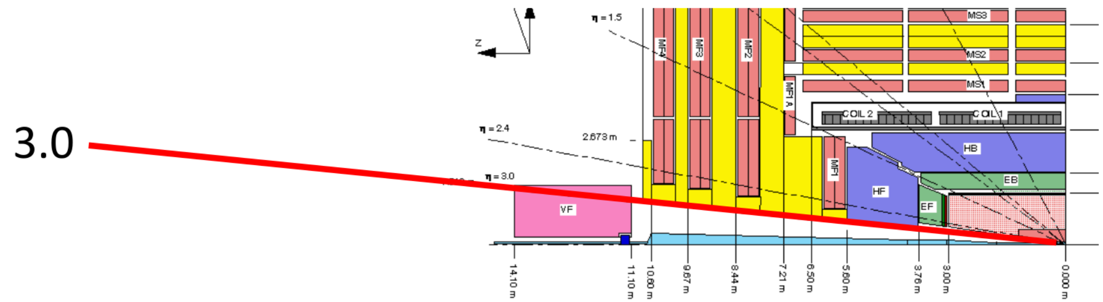
FCC-hh tracker layout



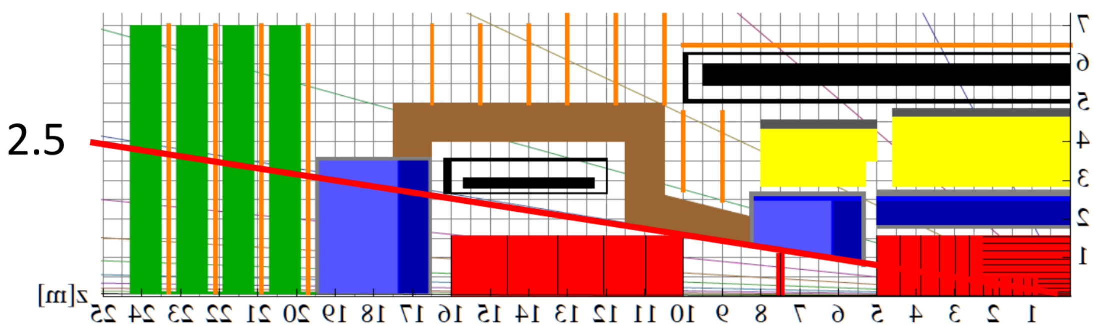
Comparison to ATLAS and CMS



ATLAS



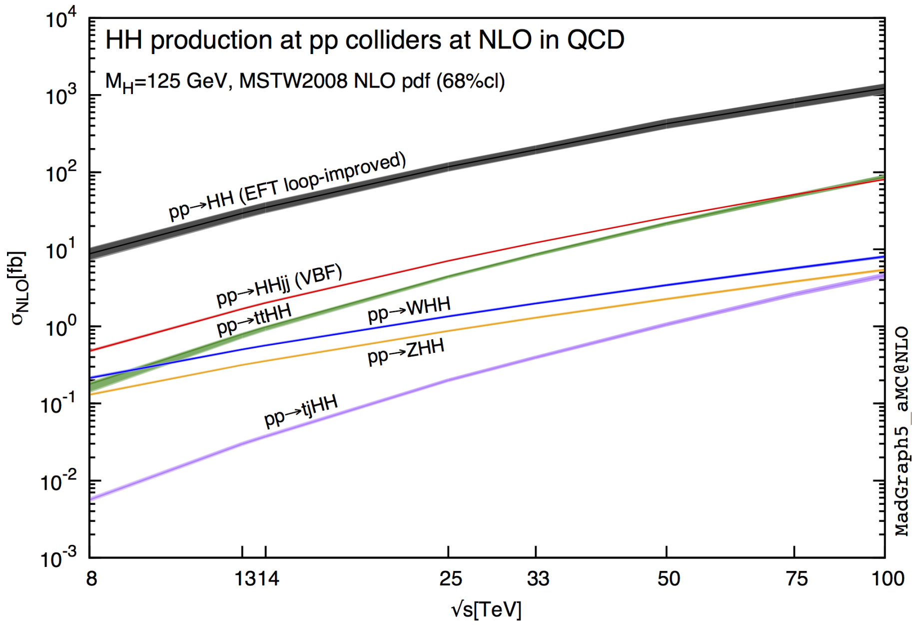
CMS



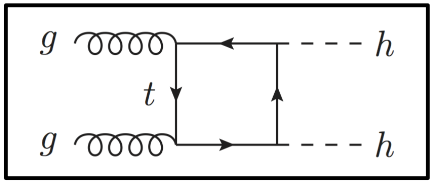
FCC-hh
(requires cavern length of 70 m)

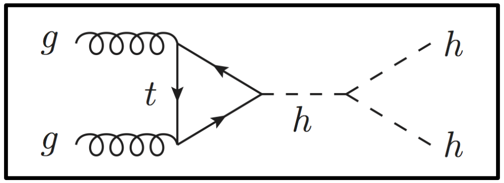
- Compared to ATLAS & CMS, the forward calorimeters are moved far out to reduce radiation load and increase the granularity
- A shield (brown) is needed to stop neutrons escaping to the cavern and muon system

Double Higgs production at 100 TeV



The double Higgs production cross section is a factor 40 larger at 100 TeV compared to 14 TeV





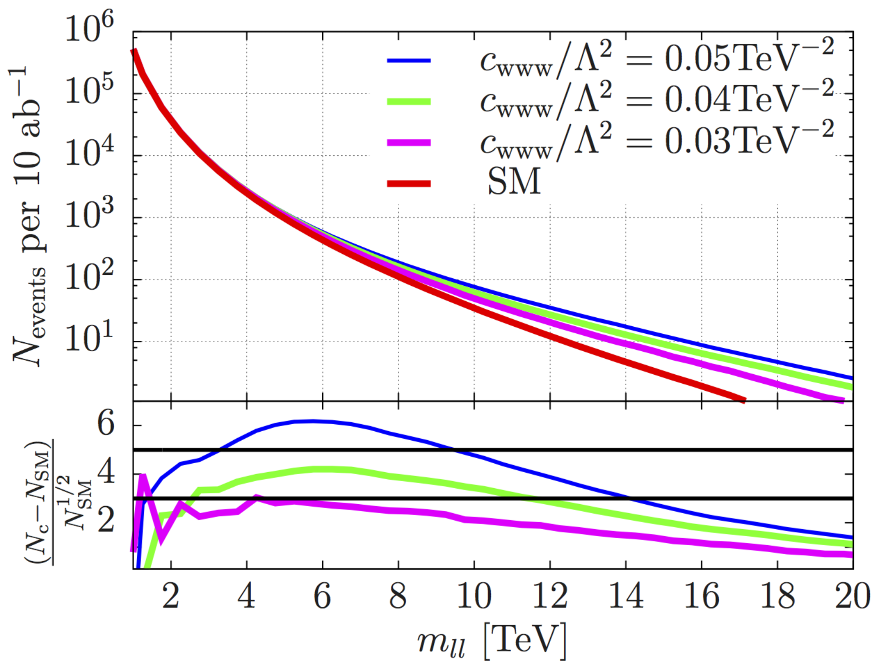
- Most promising channel: HH → $b\bar{b}\gamma\gamma$
- A precision of a few % on λ might be possible

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

arXiv:1606.09408

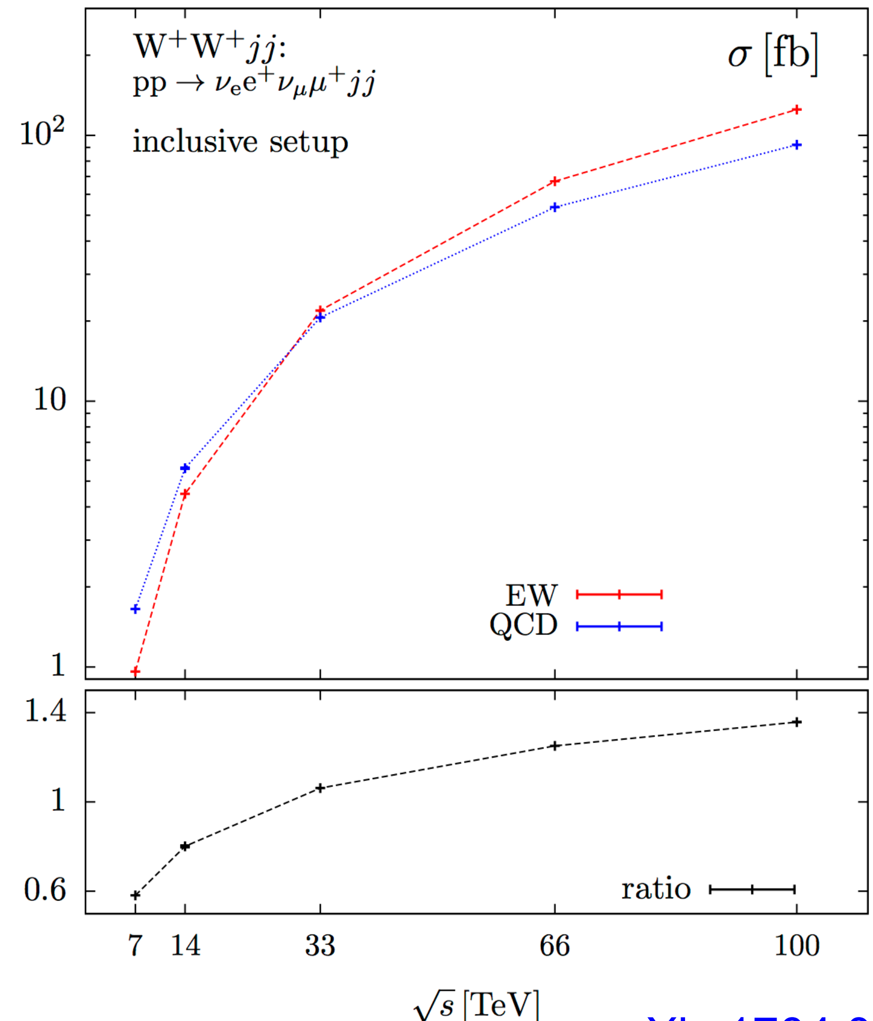
Di-boson production and VBS

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



$$\mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$

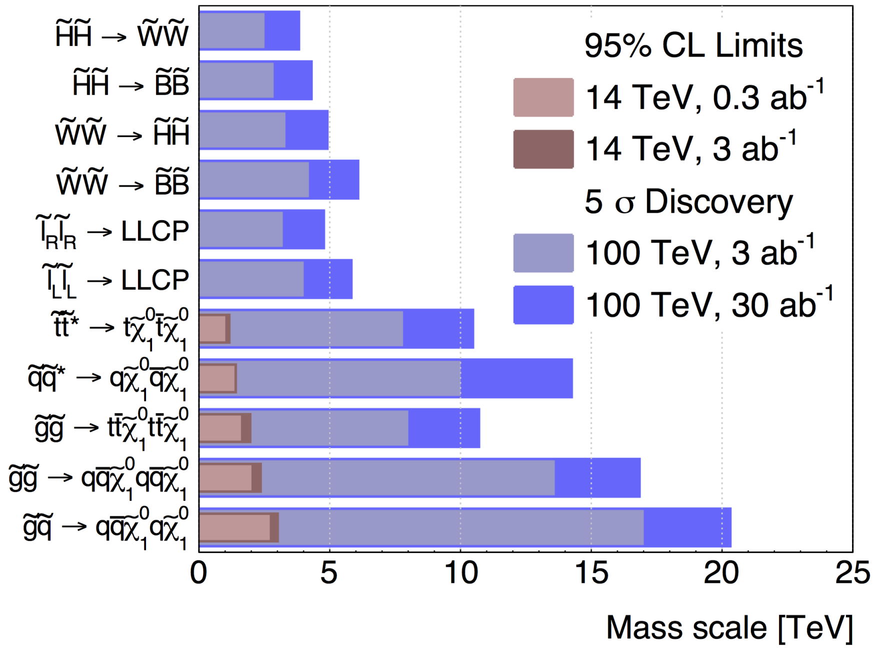
arXiv:1607.01831

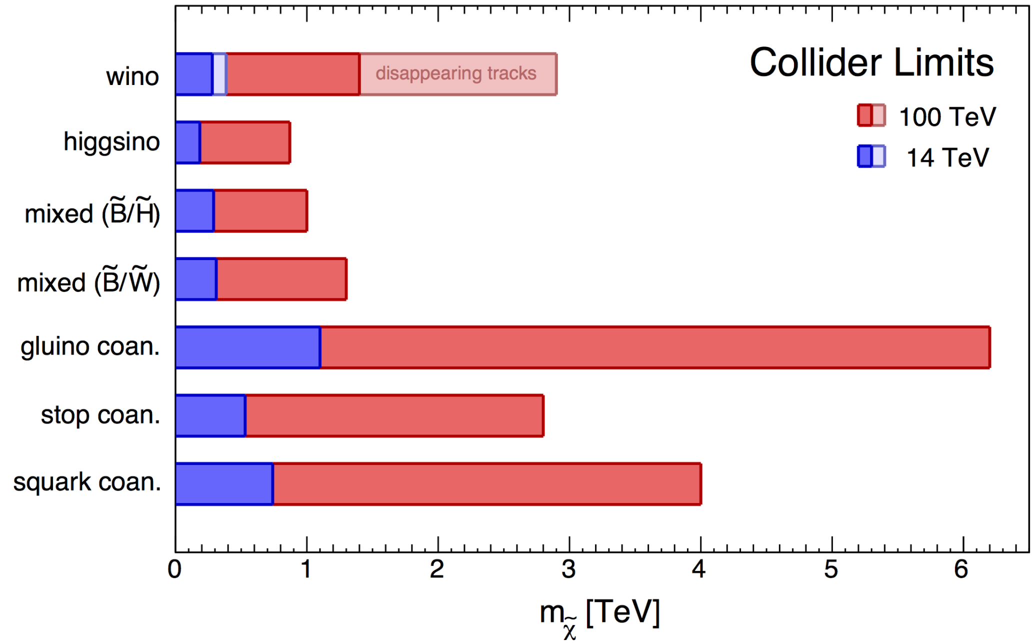


arXiv:1704.04911

Comparison to (multi-TeV) electron-positron collisions would be very interesting

Direct SUSY and DM searches at 100 TeV





Mass reach typically increased by 5-7 compared to HL-LHC

arXiv:1606.00947

Current status and outlook

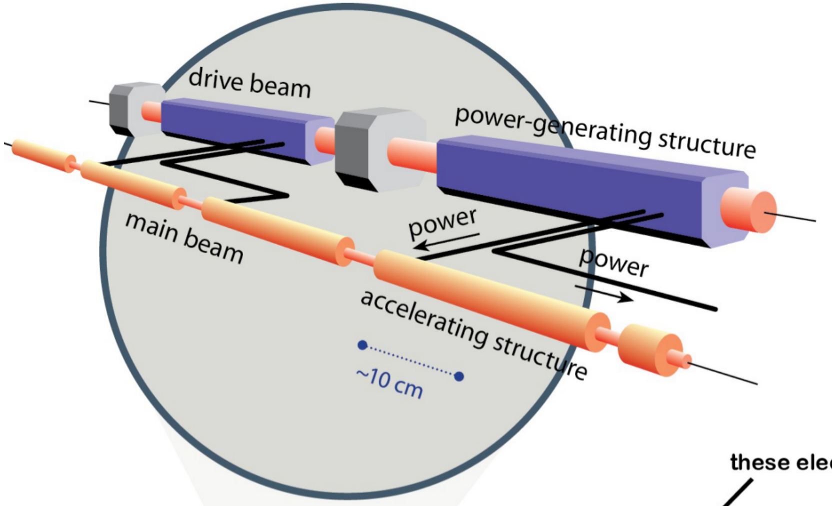
Project:	Status:
ILC	• TDR/DBD in 2013 • European XFL in operation using similar acceleration technology
CLIC	• CDR in 2012 • Staging baseline document in 2016 • Project Implementation Plan foreseen for 2018
CEPC & SppC	• Pre-CDR in 2015 • CDR planned for 2017
FCC-ee/hh & HE-LHC	• CDR planned for 2018
HE-LHC	• Existing LHC tunnel • Prospect to use FCC-hh magnet technology

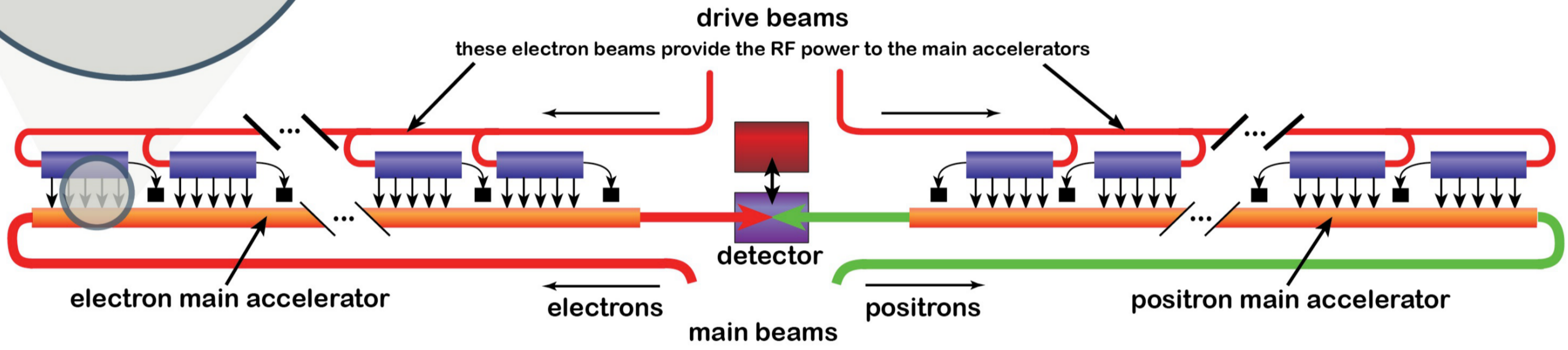
Backup slides

CLIC acceleration scheme

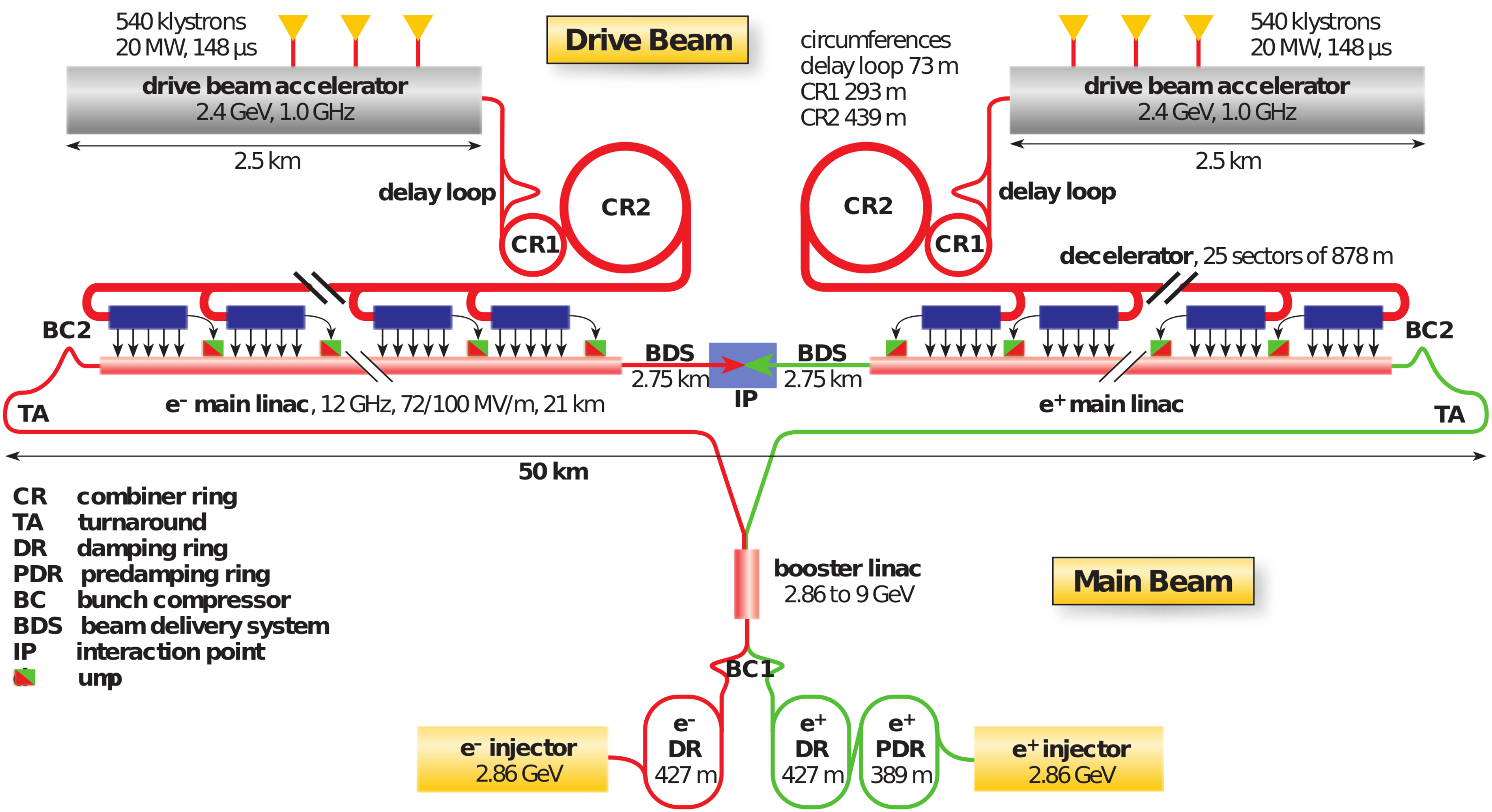
Drive beam supplies RF power:
• 12 GHz bunch structure
• Low energy:
2.4 GeV - 240 MeV
• High current: 100 A

Main beam for physics:
• High energy: 9 GeV - 1.5 TeV
• Current: 1.2 A



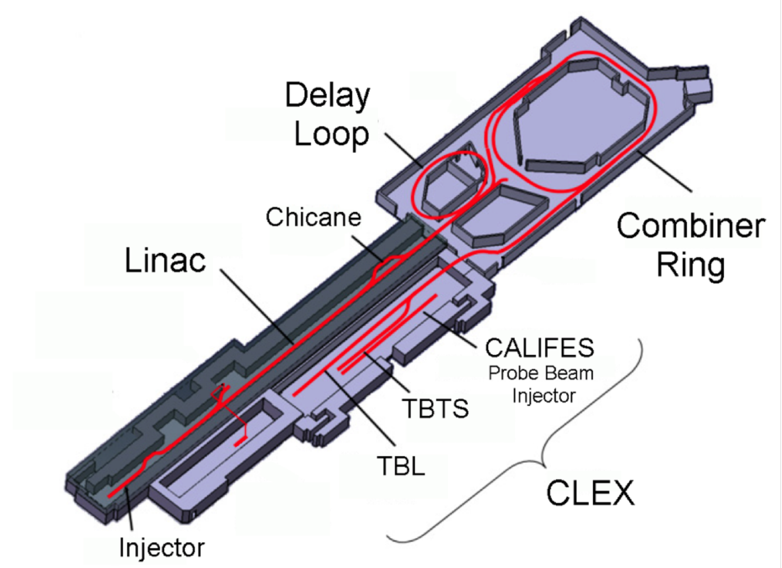


CLIC layout at 3 TeV



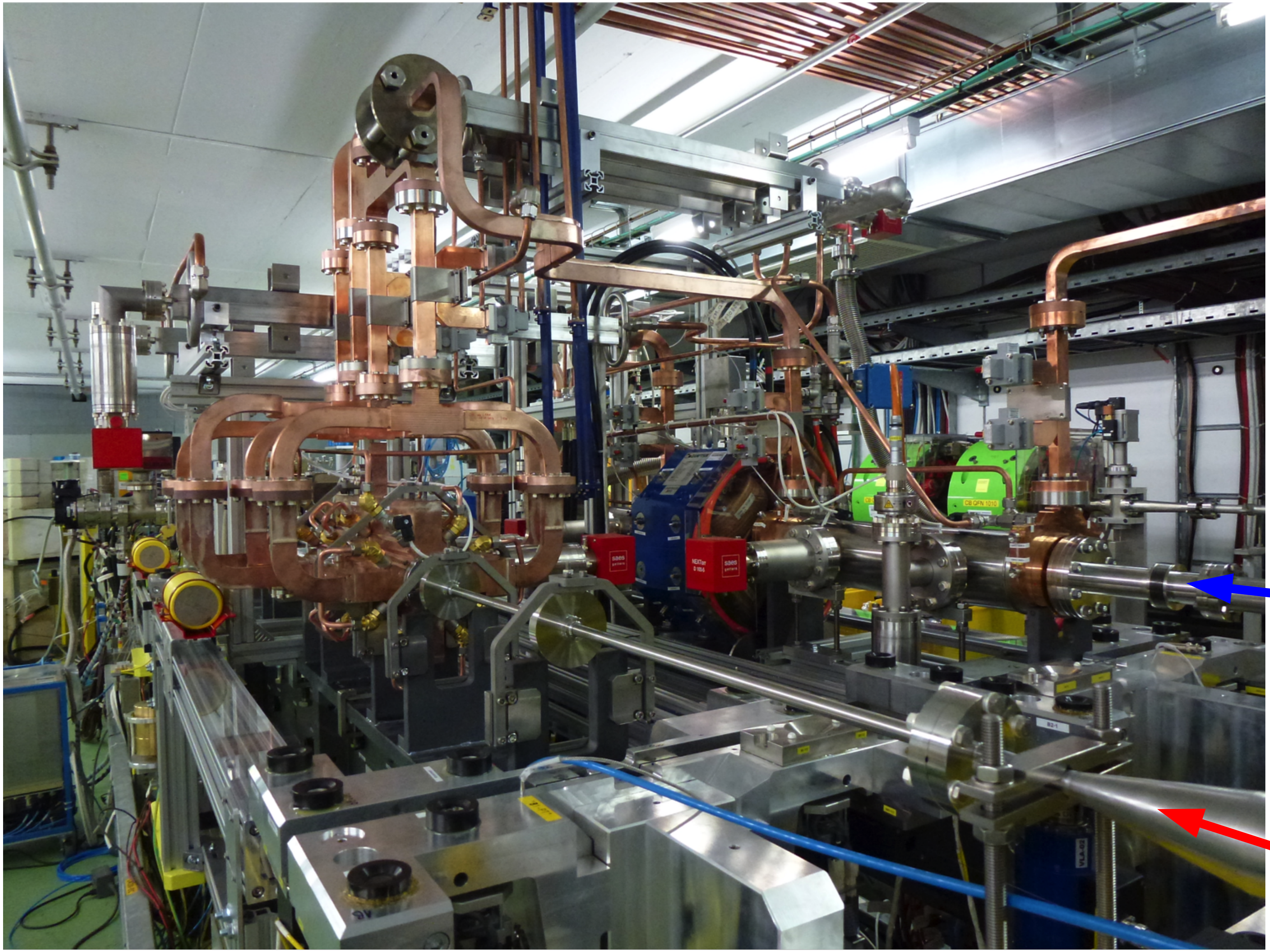
The CLIC Test Facility (CTF3)

CTF3 successfully demonstrated:
- Drive beam generation
- RF power extraction
- Two-beam acceleration up to a gradient of 145 MeV/m



- CTF3 completed its mission in 2016
- A new facility since 2017 (based on the CTF3 probe beam): **CERN Linear Electron Accelerator for Research (CLEAR)**

2-beam acceleration module in CTF3

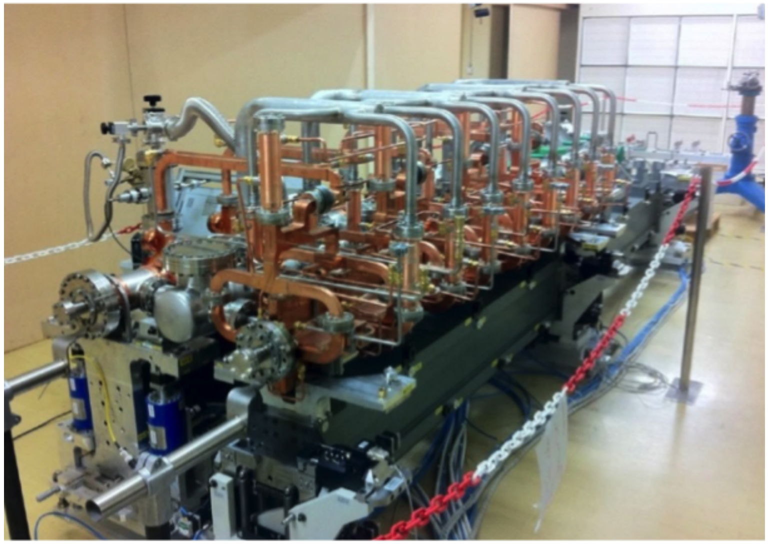


drive beam

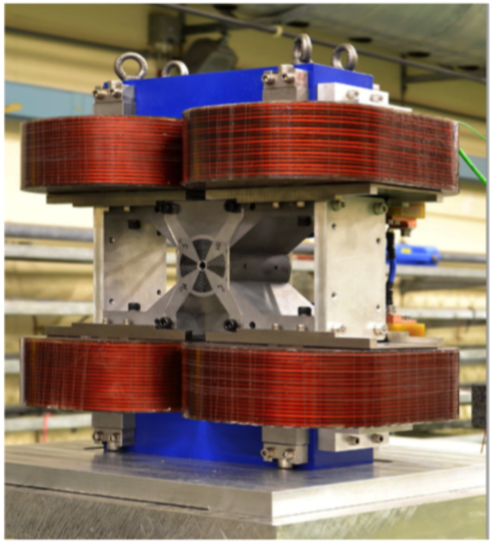
main beam

CLIC accelerator R&D

Mechanical tests of 2-beam module



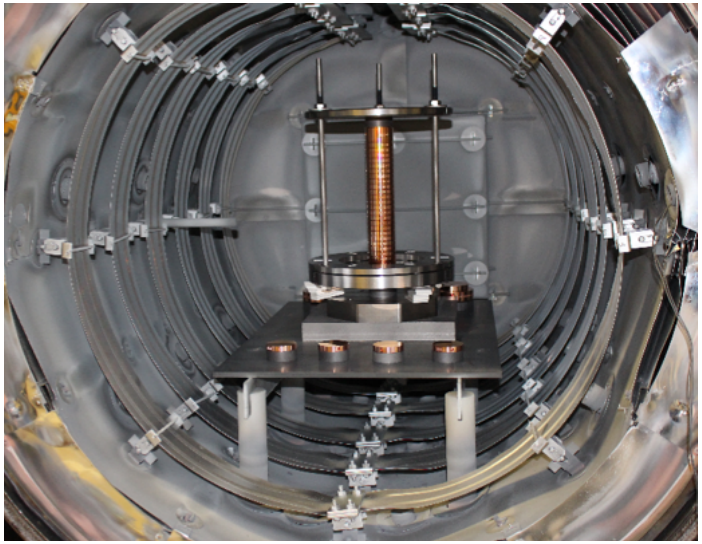
Prototype final focus quadrupole



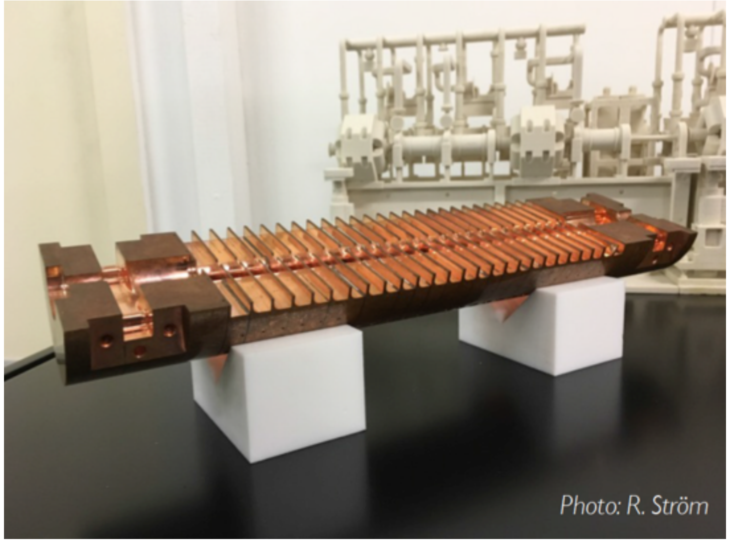
Tunable permanent magnet

Accelerator structure, 1 disk

Brazing of a CLIC structure



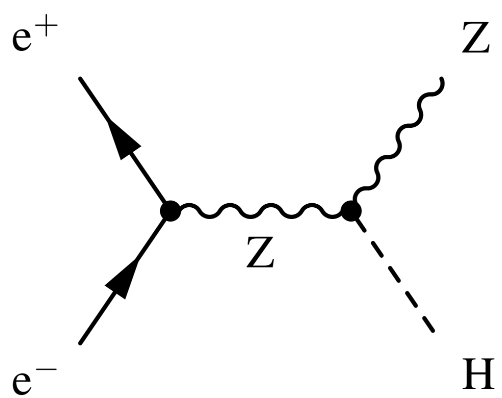
Cut through a CLIC acceleration structure

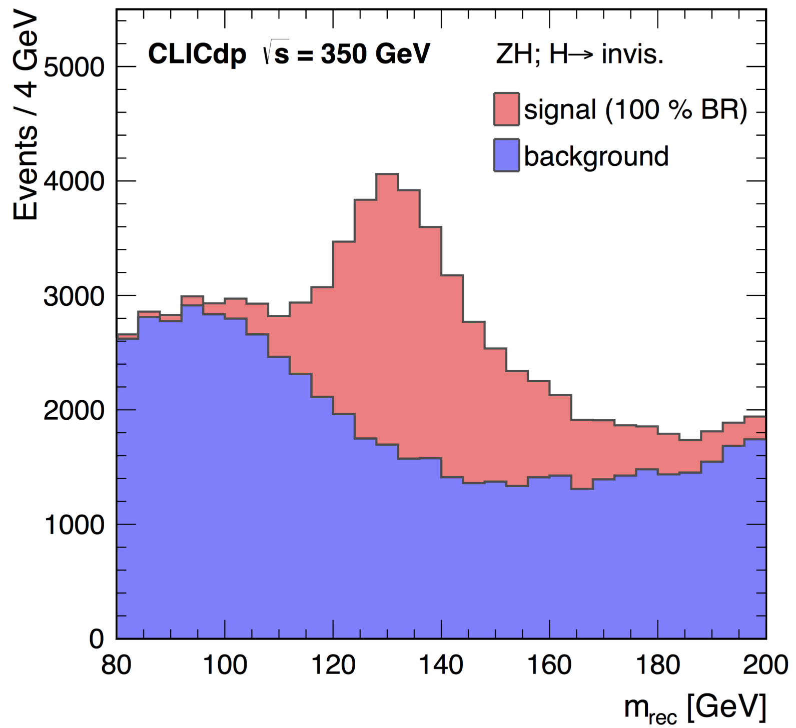


Invisible Higgs decays

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

Example:
BR(H→inv.) < 0.97% at 90% CL for CLIC at 350 GeV





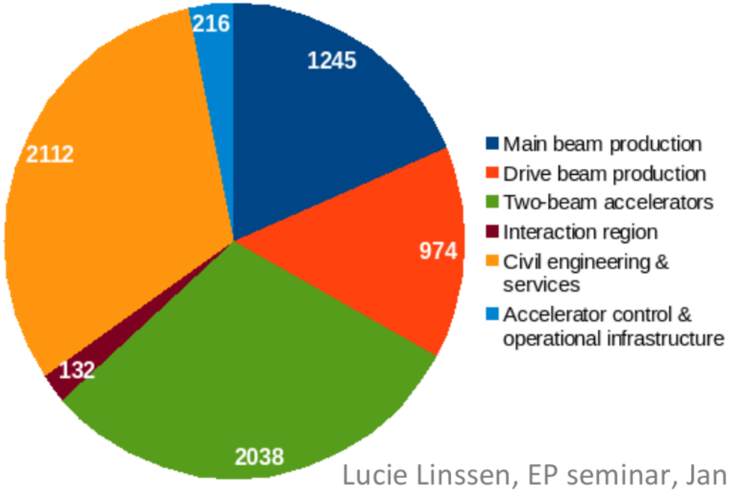
Recoil mass from Z→$q\bar{q}$ assuming all Higgs bosons decay invisibly

CLIC cost estimate

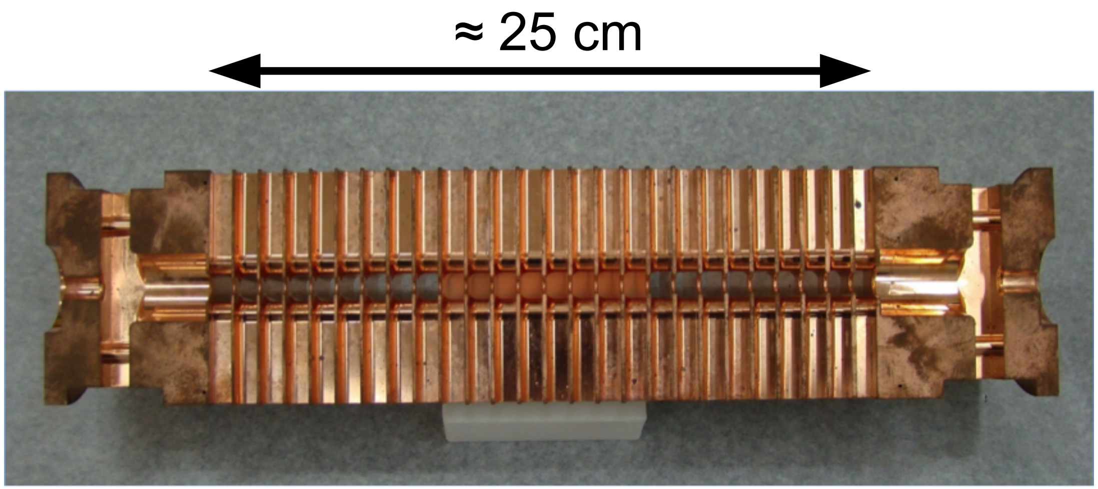
Preliminary estimate (scaled from CDR) with room for improvement.
New estimate will be provided for European Strategy Update.

System	**Value for 380 GeV** (MCHF of Dec 2010)
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operation infrastructure	216
TOTAL	**6690**

Value for the CLIC accelerator at $\sqrt{s}$ = 380 GeV (11.4 km site length)



CLIC accelerating structures



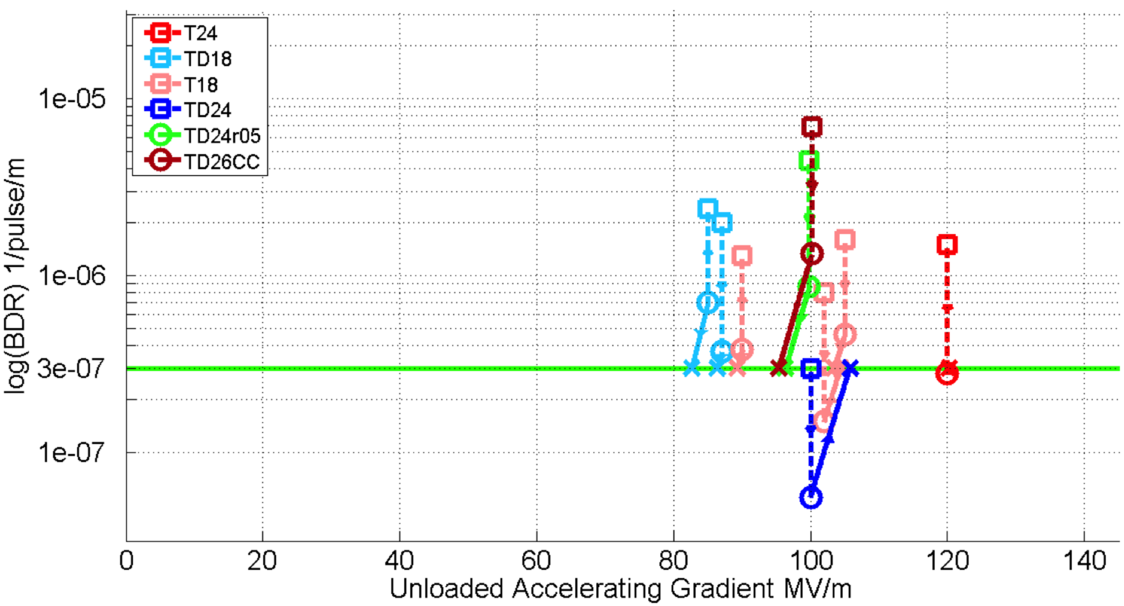
- 12 GHz (X-band)
- Break down rate (BDR):

$p \leq 3 \cdot 10^{-7}$ $m^{-1}pulse^{-1}$

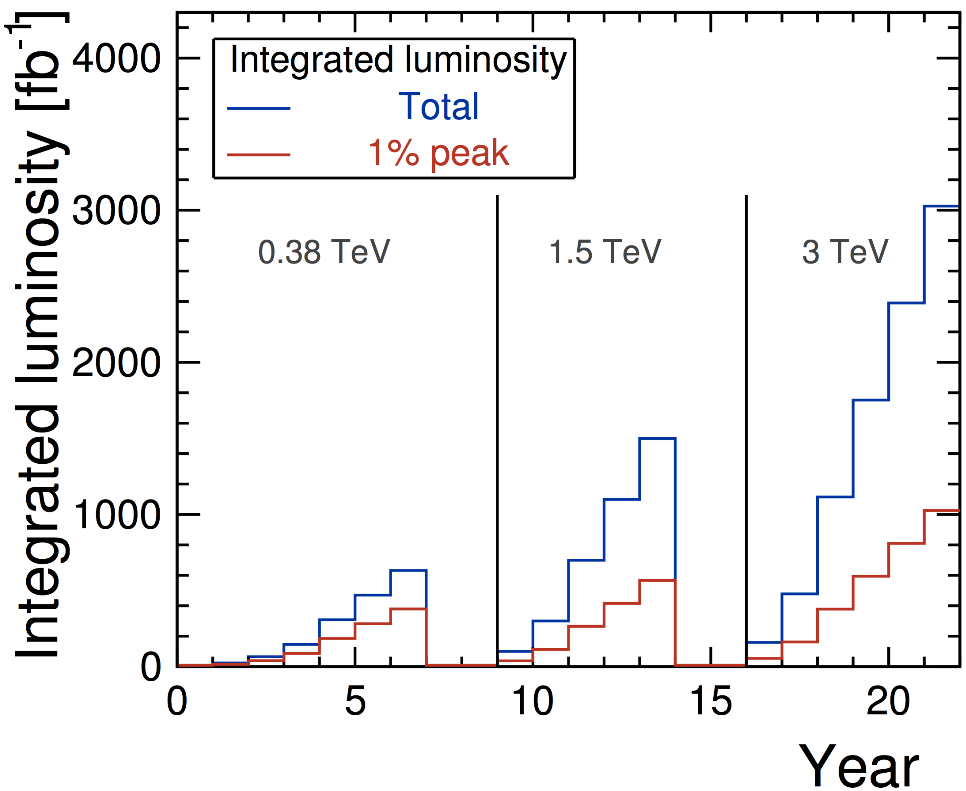
R&D programme established gradient O(100MV/m)

Shorter pulses have less breakdowns

Now focussing on:
- Further improvements
- Preparation for mass production
- Cost reduction

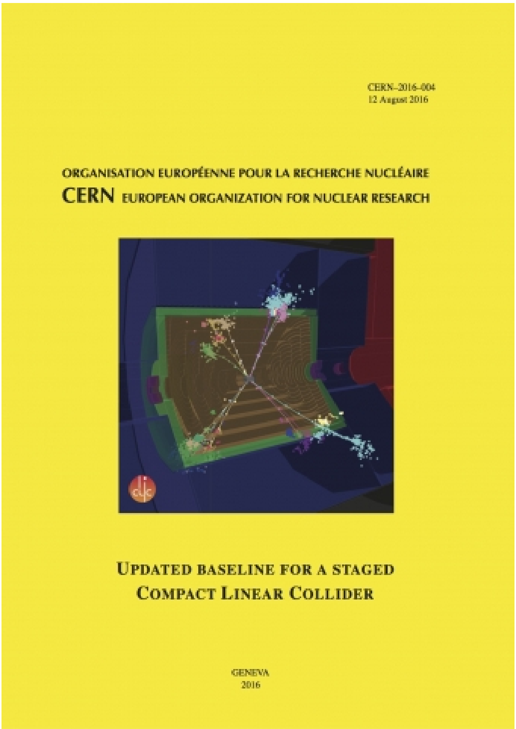


New baseline scenario



NB: Many physics studies in the following assume a slightly different scenario

- Initial stage at 380 GeV optimised for Higgs and top measurements (including $t\bar{t}$ threshold scan)
- Baseline scenario of 22 years presented in CERN-2016-004

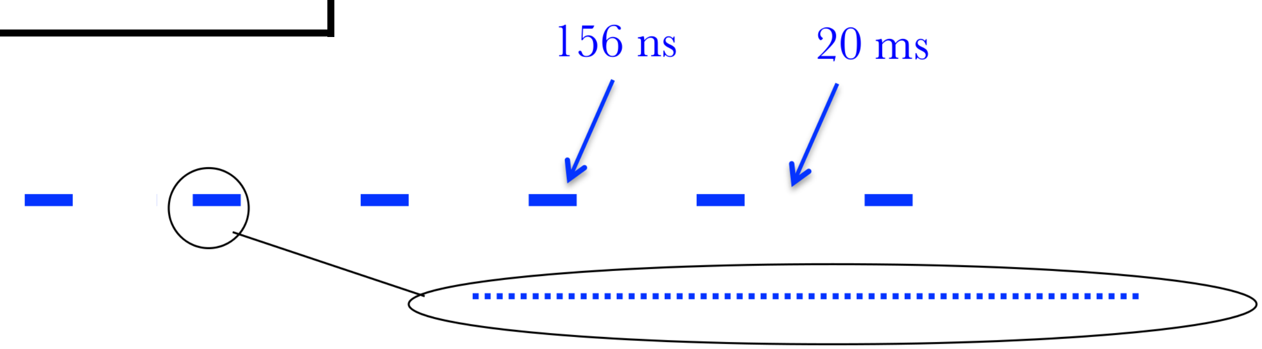


CLIC experimental conditions

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	$5.9 \cdot 10^{34}$
Bunch separation	0.5 ns
#Bunches / train	312
Train duration	156 ns
Train rep. rate	50 Hz
Crossing angle	20 mrad
Particles / bunch	$3.72 \cdot 10^{9}$
σ_x/σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

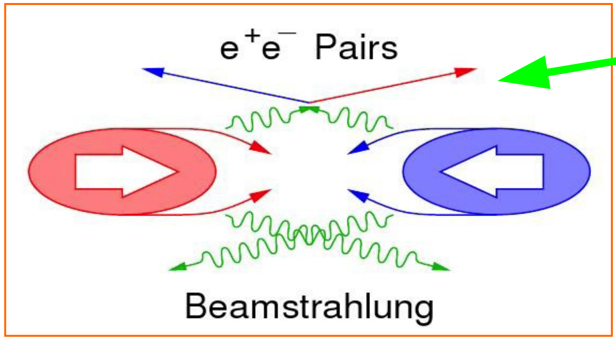
Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

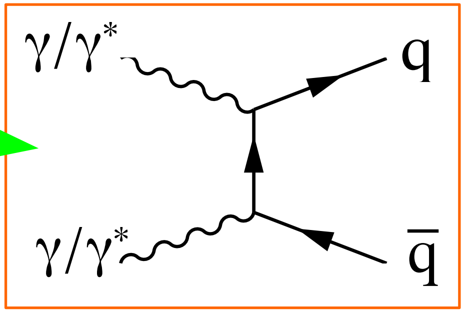


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam-induced backgrounds

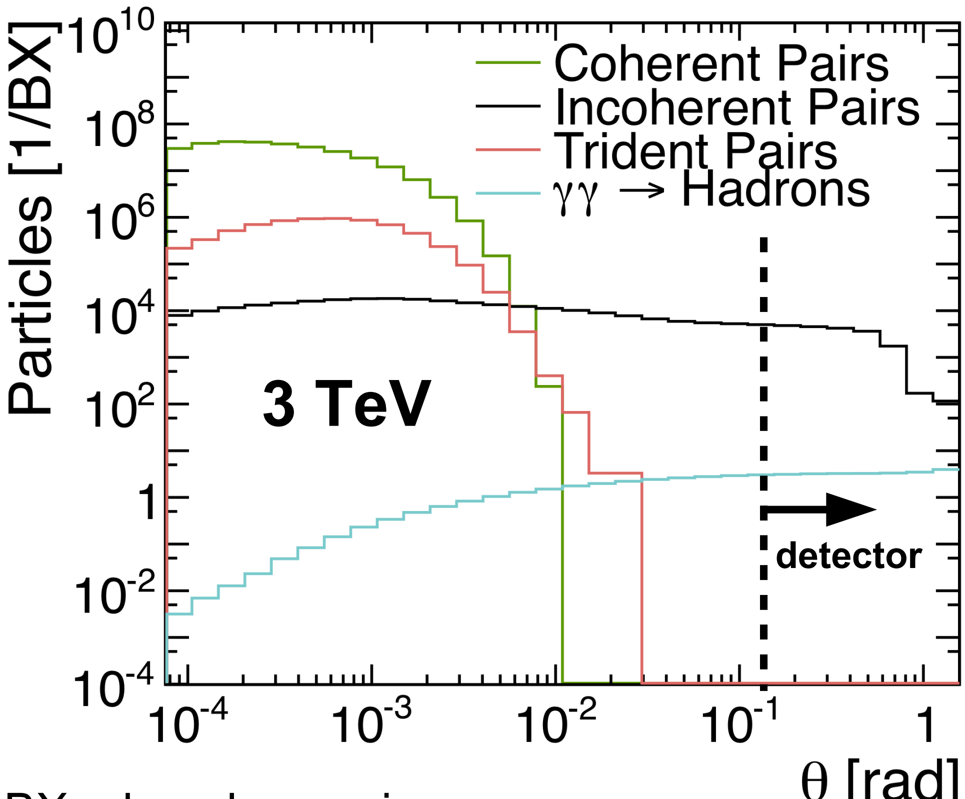


- e^+e^- pairs
- γγ → hadrons



Coherent e^+e^- pairs:
$7 \cdot 10^8$ per BX, very forward
Incoherent e^+e^- pairs:
$3 \cdot 10^5$ per BX, rather forward
→ Detector design issue
(high occupancies)

γγ → hadrons
- "Only" 3.2 events per BX at 3 TeV
- Main background
in calorimeters and trackers
→ Impact on physics



BX = bunch crossing

Detector requirements

- **Momentum resolution**
(e.g. Higgs recoil mass, H → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times 10^{-5}\, GeV^{-1}$$

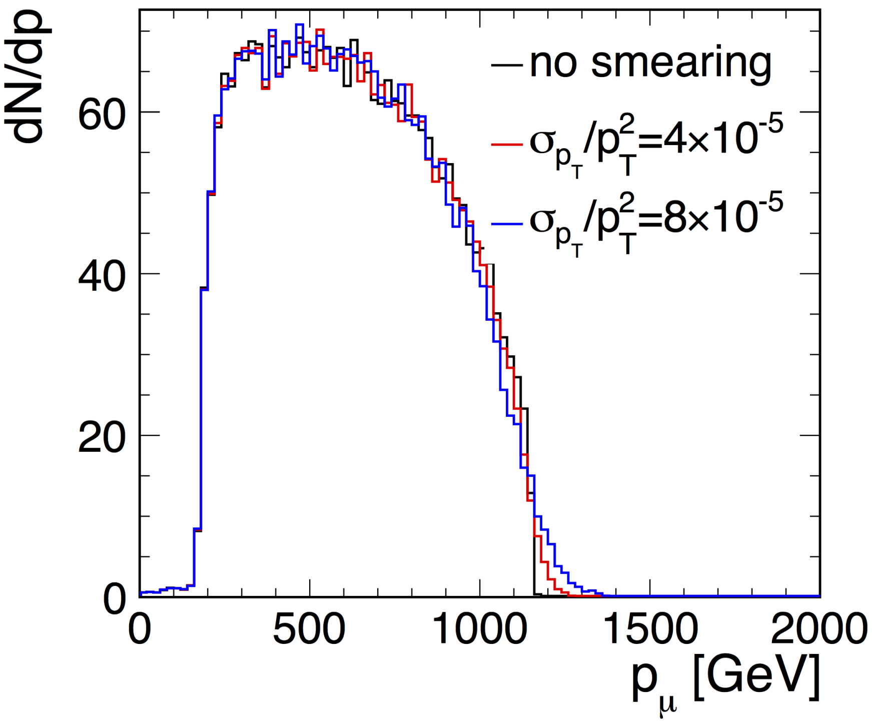
- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E=1000-50\, GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0)=\sqrt{a^2+b^2\cdot GeV^2/(p^2\sin^3\theta)},\ a\approx 5\,\mu m,\ b\approx 15\,\mu m$$

- **Lepton identification, very forward electron tagging**



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

Detector requirements

- **Momentum resolution**

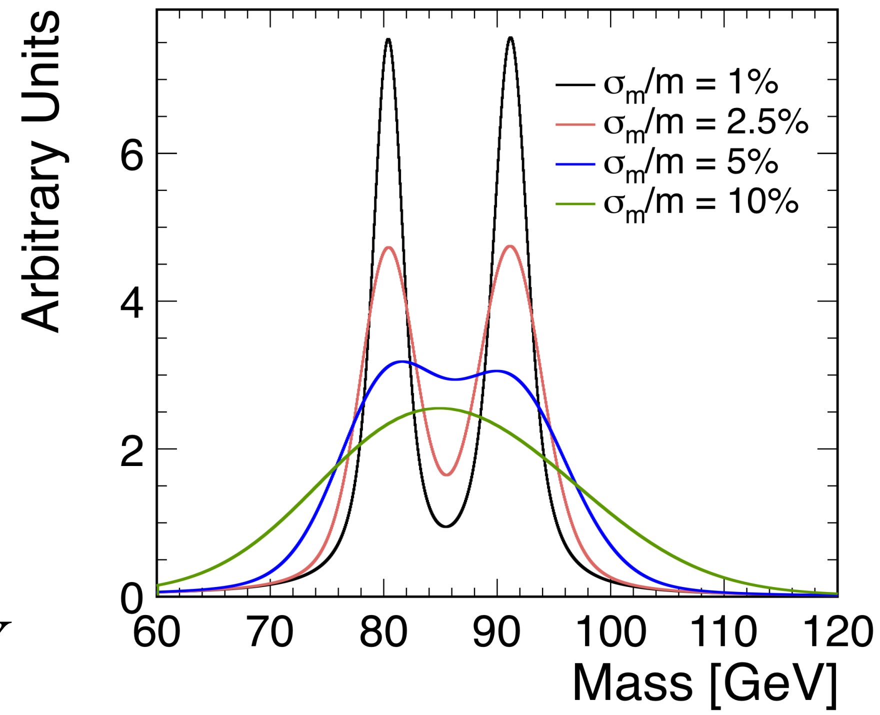
(e.g. Higgs recoil mass, H → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times 10^{-5}\, GeV^{-1}$$

- **Jet energy resolution**

(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E = 1000-50\, GeV$$



- **Impact parameter resolution**

(b/c tagging, e.g. Higgs couplings)

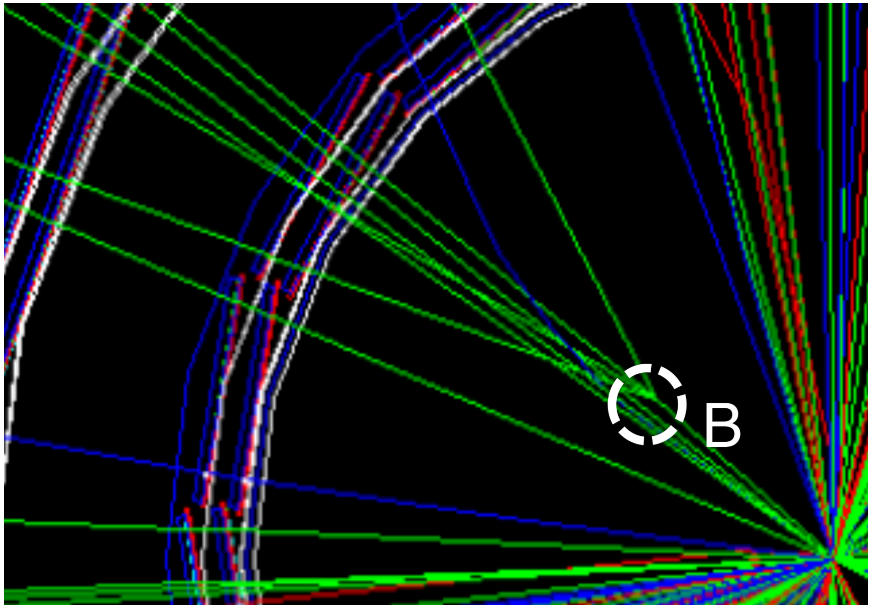
$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2/(p^2 \sin^3\theta)},\ a \approx 5\,\mu m,\ b \approx 15\,\mu m$$

- **Lepton identification, very forward electron tagging**

Detector requirements

- **Momentum resolution**
(e.g. Higgs recoil mass, H → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times10^{-5}\,GeV^{-1}$$



- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E=1000-50\,GeV$$

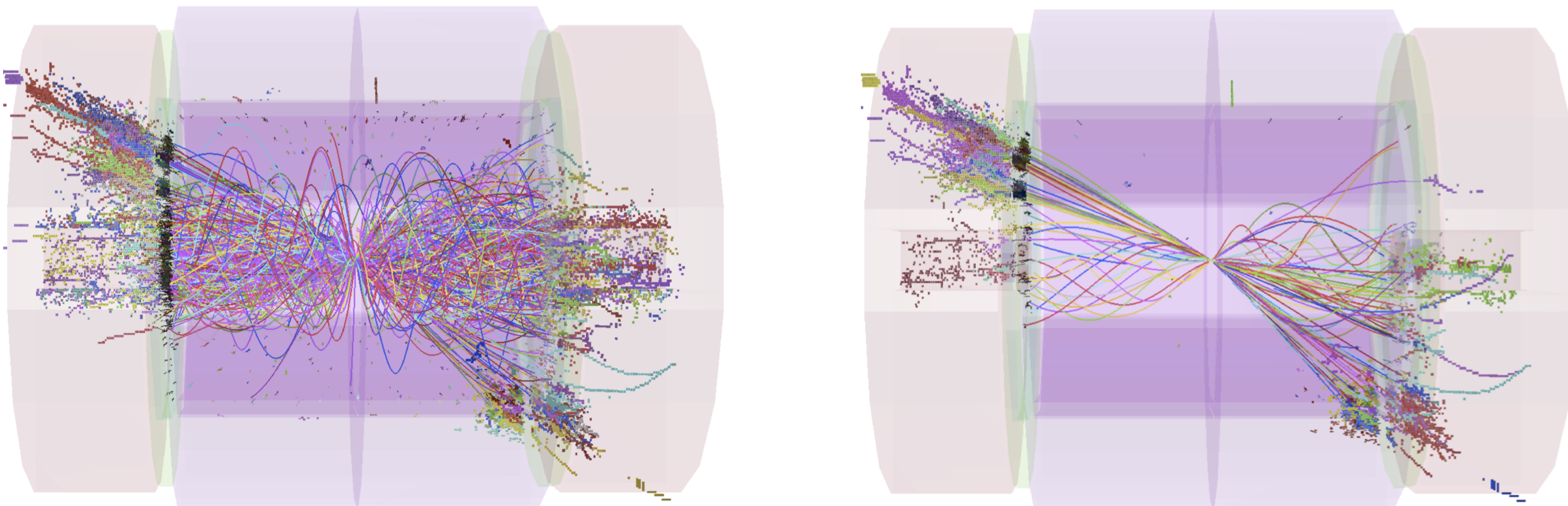
- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0)=\sqrt{a^2+b^2\cdot GeV^2/(p^2\sin^3\theta)},\ a\approx5\,\mu m,\ b\approx15\,\mu m$$

- **Lepton identification, very forward electron tagging**

Background suppression

Beam-induced background from γγ → hadrons can be efficiently suppressed by applying p_T-dependent timing cuts on individual reconstructed particles (= particle flow objects)



$e^+e^- \rightarrow t\bar{t}$ at 3 TeV with background from γγ → hadrons overlaid

1.2 TeV background
in the reconstruction window
(≥ 10 ns) around physics event

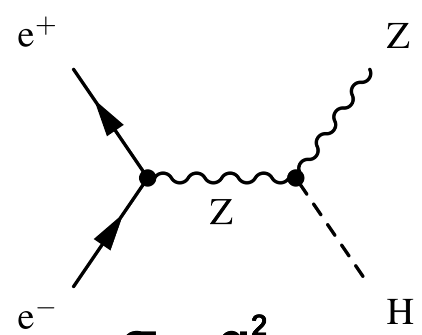
100 GeV background
after timing cuts

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

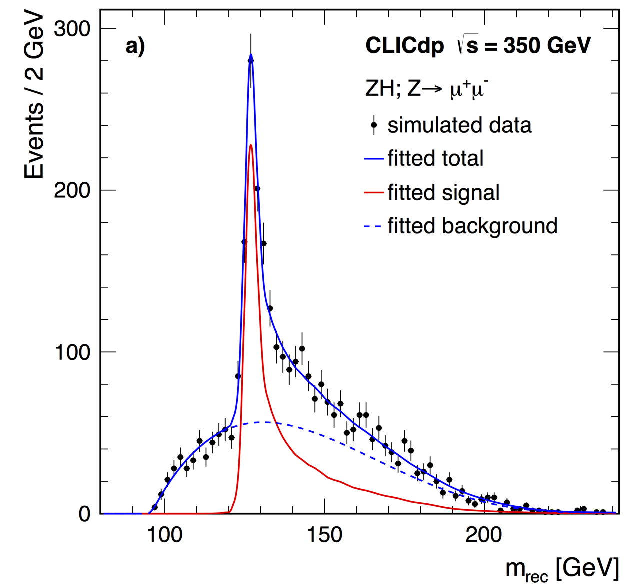
Using $Z \rightarrow e^+e^-, \mu^+\mu^-$:

• HZ events can be identified from the Z recoil mass
→ Model-independent measurement of the g_{HZZ} coupling

• Best precision at 240/250 GeV (tracking resolution, beam energy spectra)



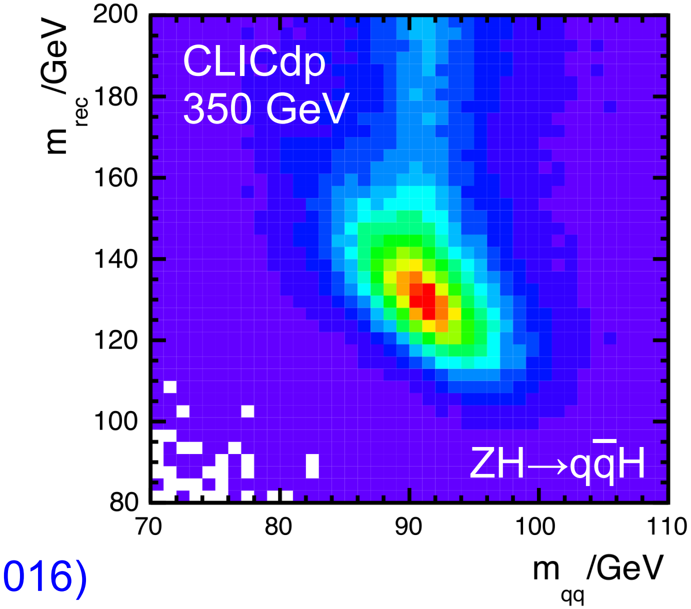
$\sigma \sim g^2_{HZZ}$



Using $Z \rightarrow q\bar{q}$:

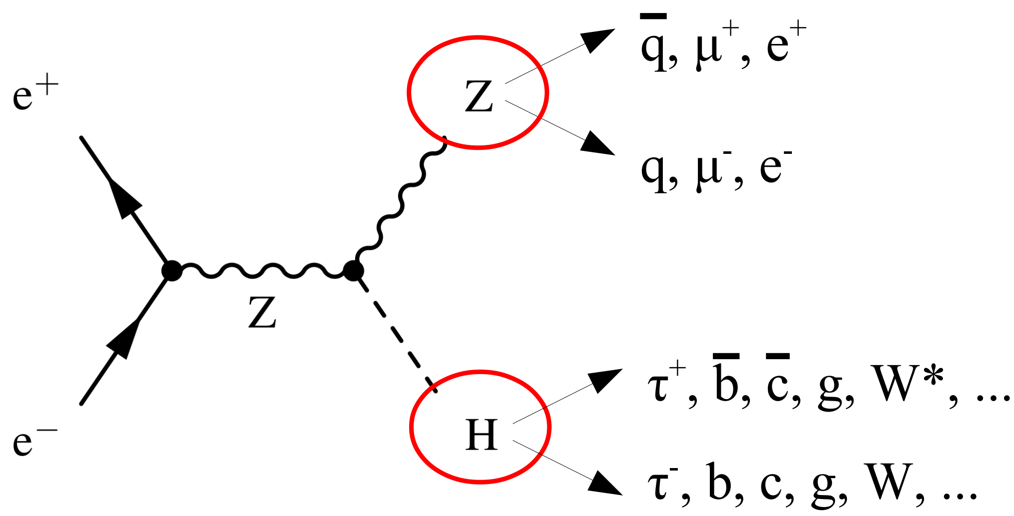
• Almost model-independent measurement of g_{HZZ} possible using hadronic Z decays
→ Substantial improvement in precision possible

• Better precision at 350 GeV found than at 250 GeV or 420 GeV



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

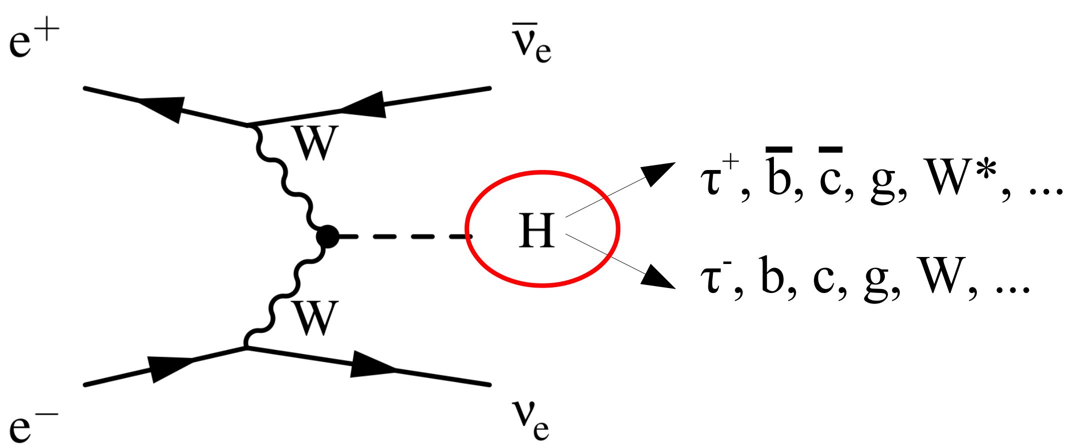
σ x BR measurements



At 350 GeV:
Higgsstrahlung

$\sigma \sim g^2_{HZZ} g^2_{HVV/Hff} / \Gamma_H$

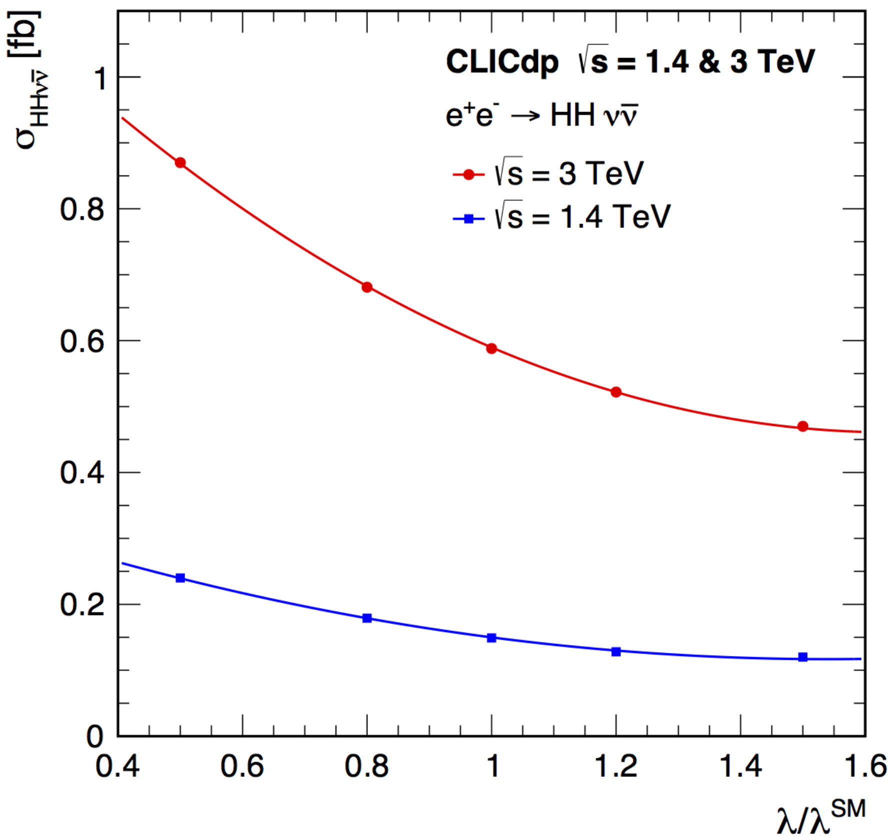
+ BR(H→inv.) < 0.97% at 90% CL



At 350 GeV and higher:
WW fusion

$\sigma \sim g^2_{HWW} g^2_{HVV/Hff} / \Gamma_H$

Double Higgs production at CLIC

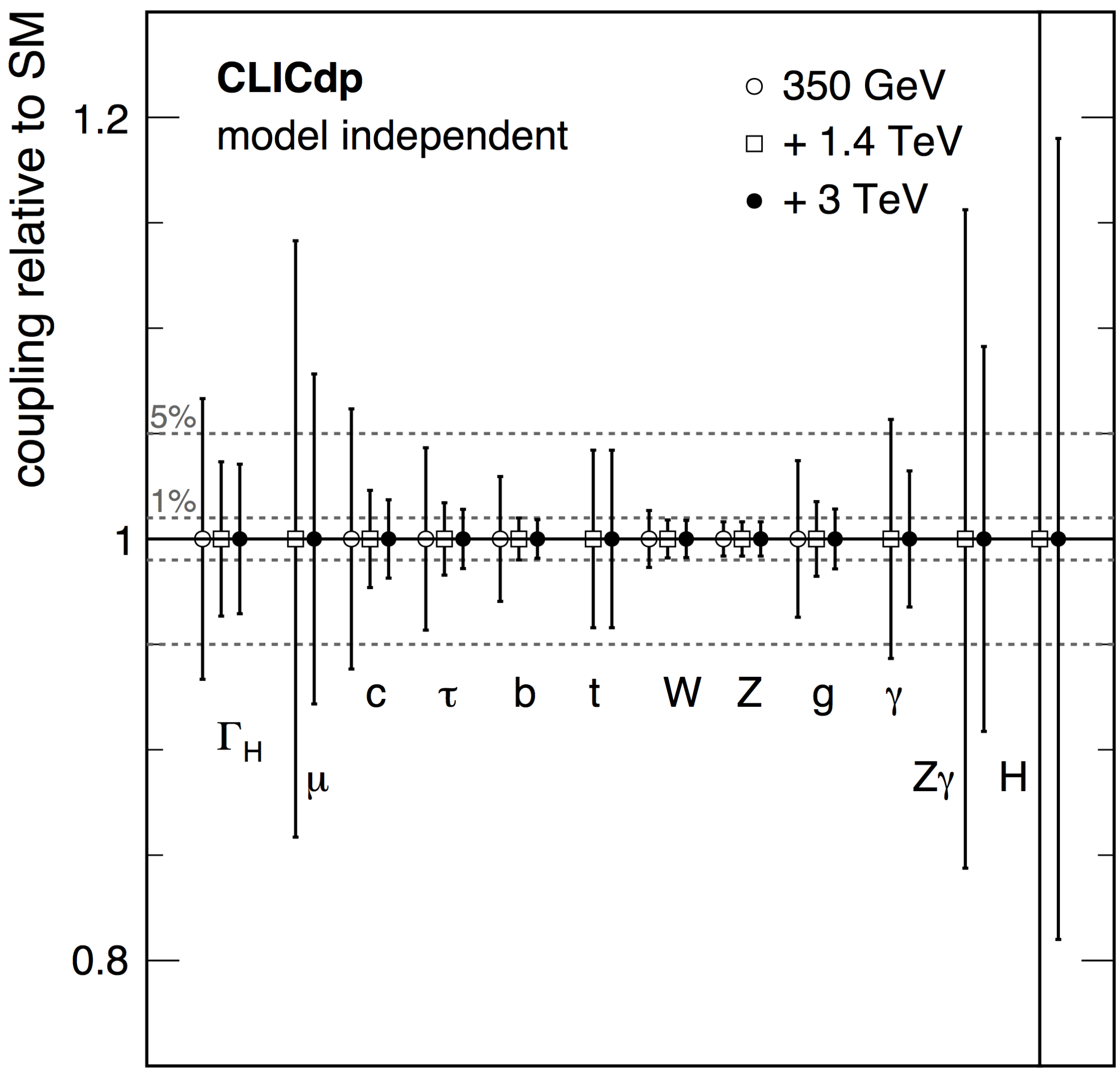


From cross section with P(e^-) = -80%:
$\Delta\lambda/\lambda$ = 16%
with 1.5 ab^{-1} at 1.4 TeV and 3 ab^{-1} at 3 TeV

Currently in progress: template fit to differential distributions
→ Improved precision on λ
→ Simultaneous extraction of λ and g_{HHWW}

1.4 TeV: $\Delta\lambda/\lambda = 1.22 \cdot \Delta\sigma(HH\nu_e\bar{\nu}_e) / \sigma(HH\nu_e\bar{\nu}_e)$
3 TeV: $\Delta\lambda/\lambda = 1.47 \cdot \Delta\sigma(HH\nu_e\bar{\nu}_e) / \sigma(HH\nu_e\bar{\nu}_e)$

Higgs properties at CLIC (1)



- Fully model-independent analysis only possible at lepton colliders
- All results limited by 0.8% from σ(HZ) measurement
- The Higgs width is extracted with 6.7-3.5% precision

CLICdp Collab.
arXiv:1608.07538
accepted by EPJC

Higgs properties at CLIC (2)

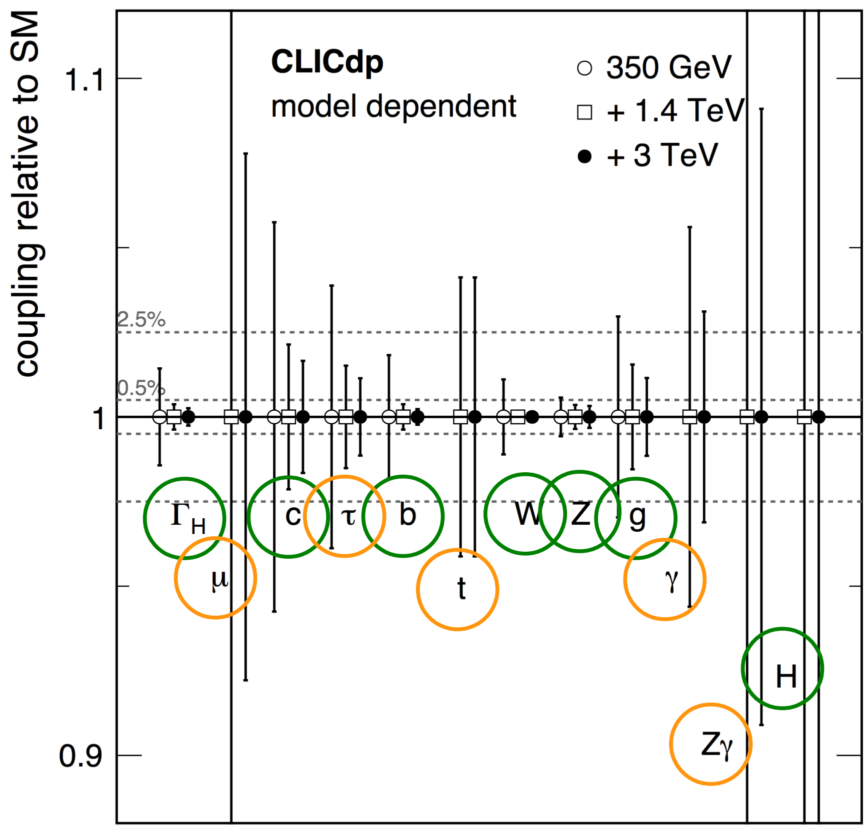
Model dependent fit:

$$\kappa_i^2 = \Gamma_i / \Gamma_i^{SM}$$

BR$_i$: SM branching fractions (prediction)

Only SM Higgs decays:

$$\frac{\Gamma_{H,md}}{\Gamma_H^{SM}} = \sum_i \kappa_i^2 \, BR_i$$

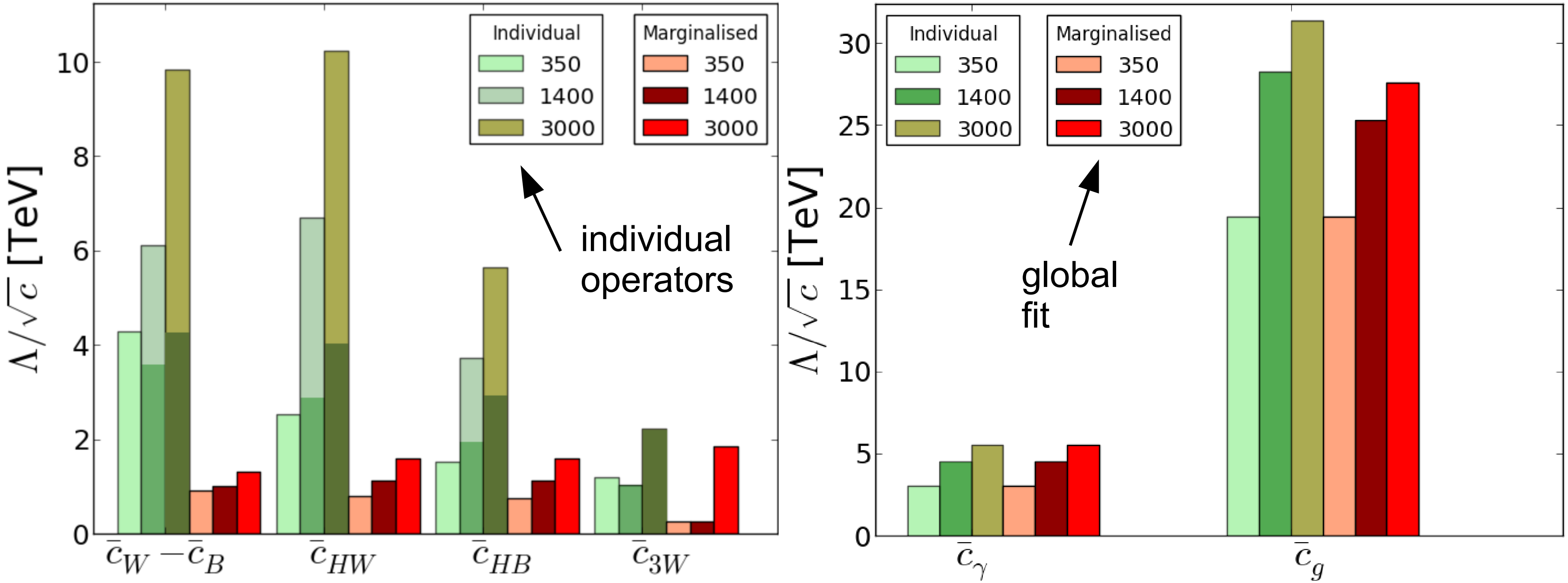


significantly better than HL-LHC or not possible at hadron colliders (green circle)

similar to HL-LHC (orange circle)

CLIC sensitivities to dimension-6 operators

Individual CLIC energy stages

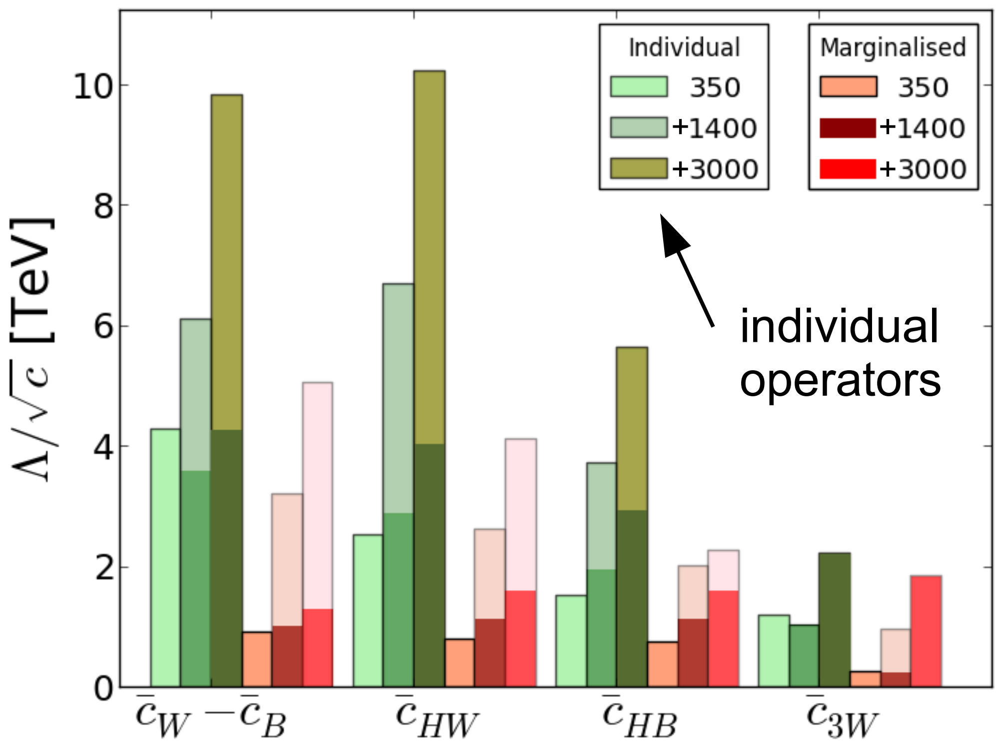


Sensitivity enhanced by higher centre-of-mass energy

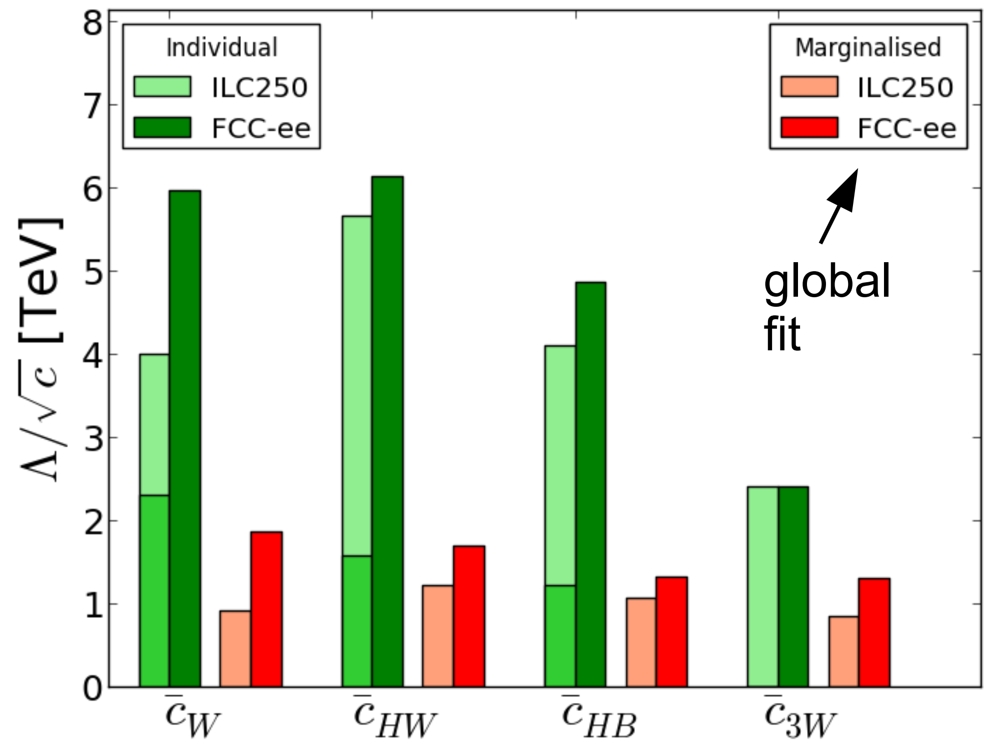
Ellis, PR, Sanz, You, JHEP 1705, 096 (2017)

Comparison to other options

CLIC



FCC-ee / ILC



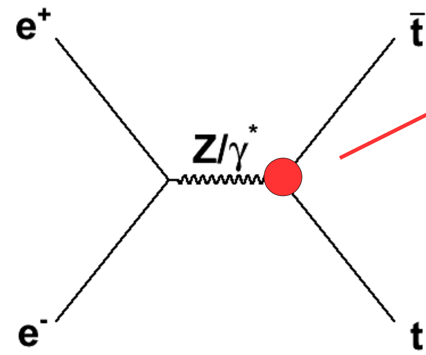
CLIC has better sensitivity for several operator coefficients

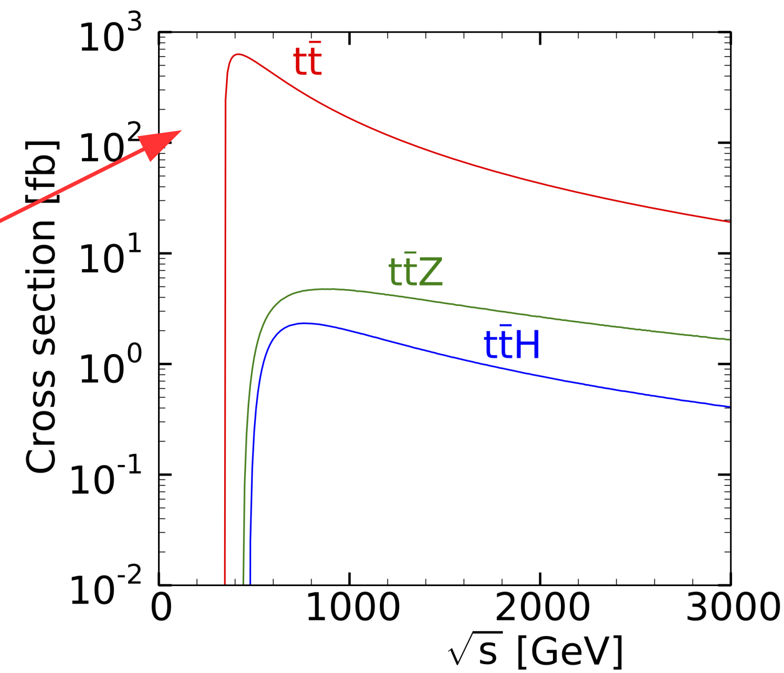
NB: FCC-ee / ILC includes EWPT observables

Ellis, You, JHEP 1603, 089 (2016)
Ellis, PR, Sanz, You, JHEP 1705, 096 (2017)

Top electroweak couplings

- Top quark pairs are produced via Z/γ* in electron-positron collisions





- The general form of the coupling can be described as:

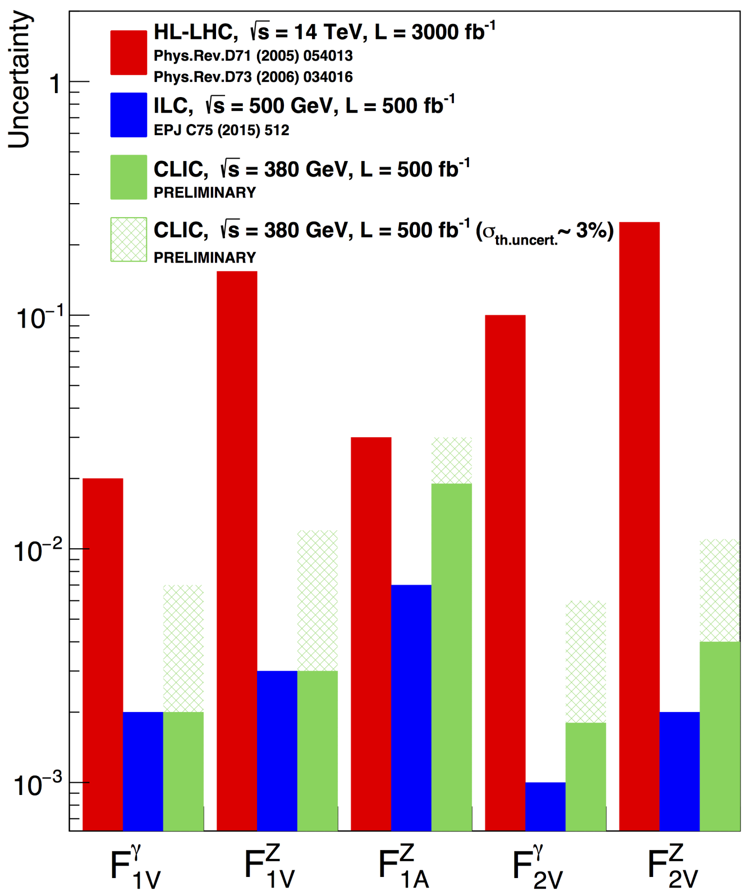
CP conserving **CPV**

$$\Gamma_{\mu}^{ttV}(k^2,\, q,\, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}\,(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

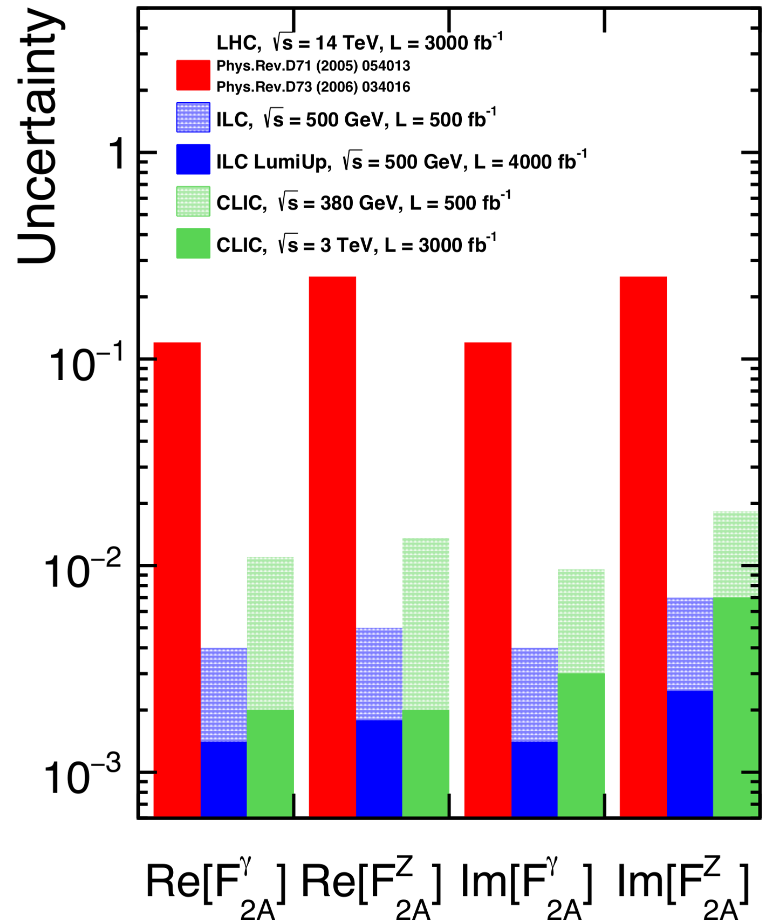
- New physics would modify the tt̄V vertex

arXiv:hep-ph/0601112

Results: form factors



CERN-2016-004

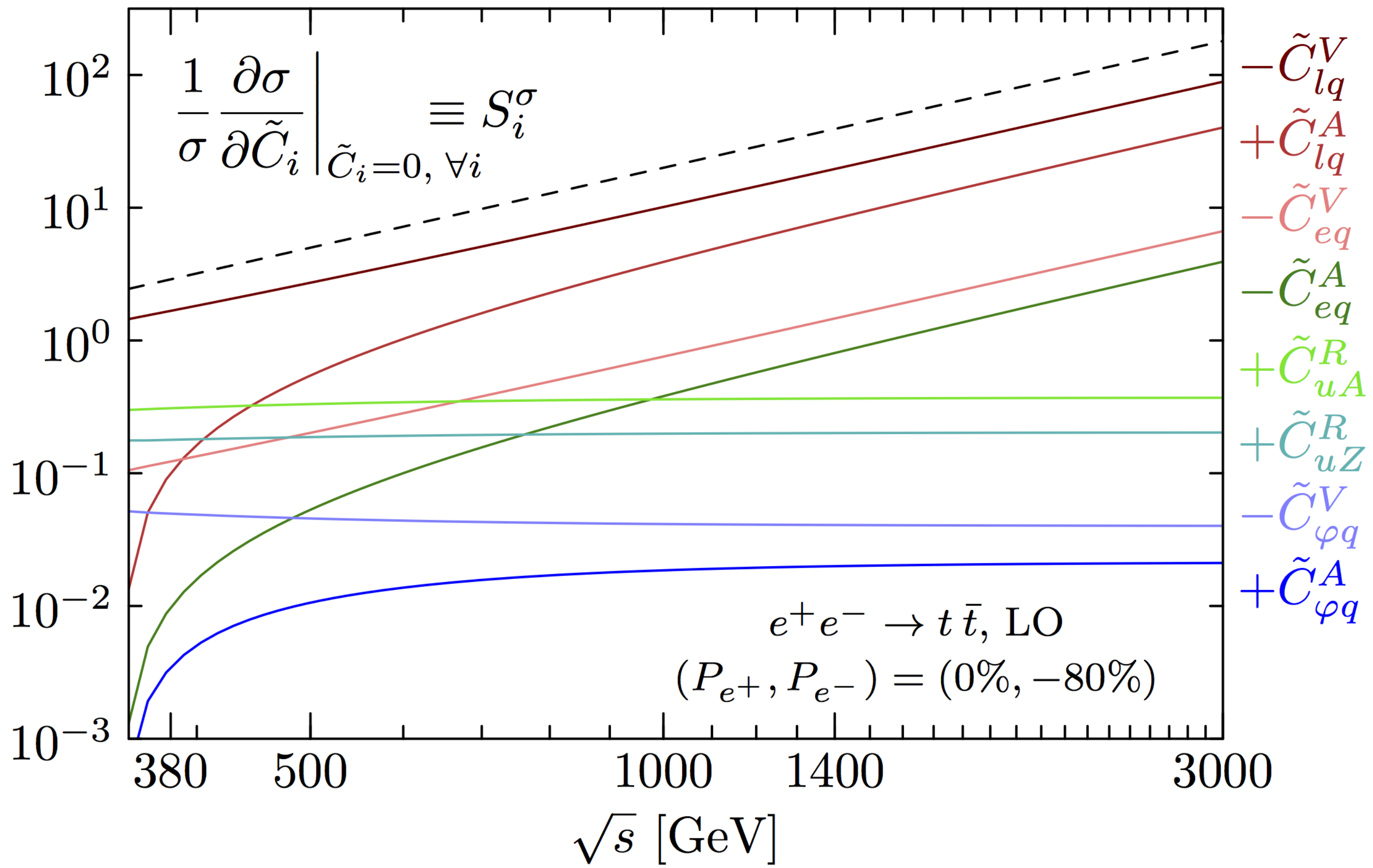


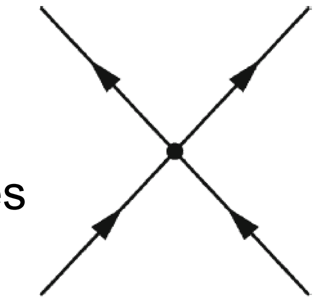
Martín Perelló, topLC 2017

- The expected precisions for CLIC are 1-2 orders of magnitude better than for HL-LHC
- Interesting top physics program at the first CLIC stage at 380 GeV!

What about $t\bar{t}$ at high energy?

Dependence of $\sigma(e^+e^- \to t\bar{t})$ on dimension-6 operators:





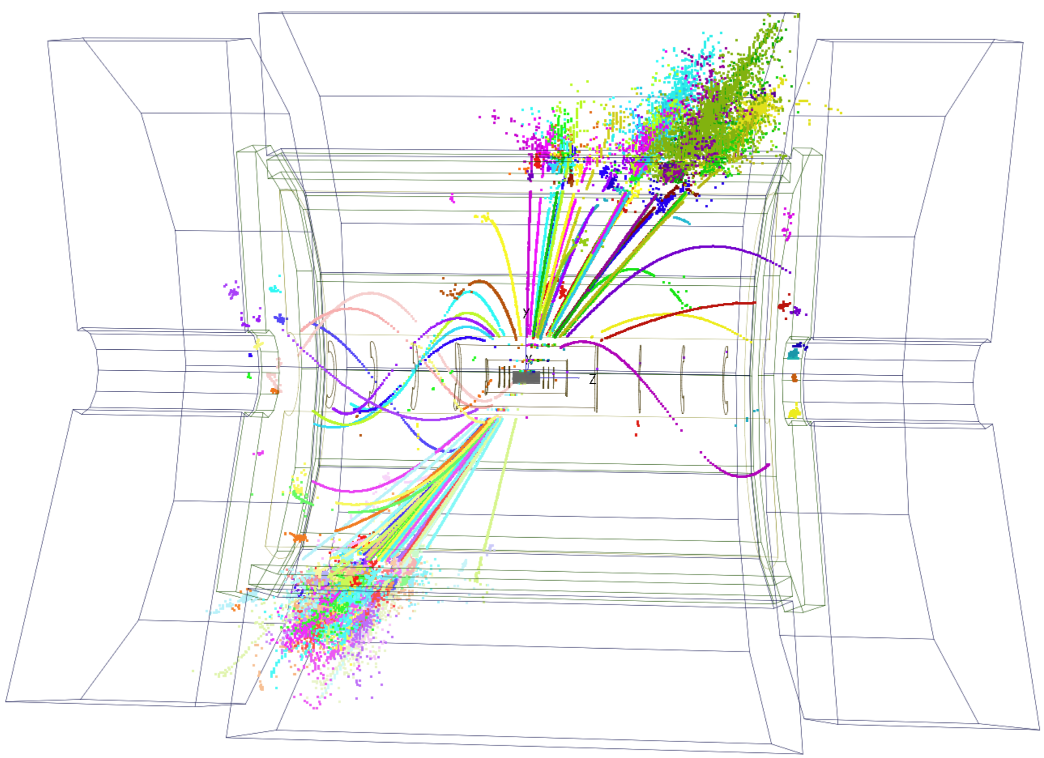
Four-fermion operators:
Sensitivity rises steeply with energy
→ best measured at high energy

Vertex operators:
Sensitivity flat in energy for several operators
→ best measured at 380 GeV (most $t\bar{t}$ events)

Durieux, Perelló, Vos, Zhang, to be published

The top pair production measurements at 380 GeV and at high energy provide complementary information

Boosted top reconstruction at CLIC

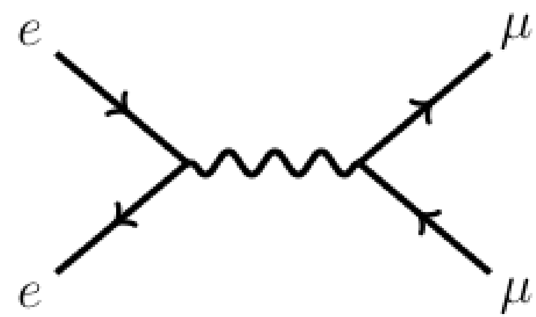


$e^+e^- \rightarrow t\bar{t} \rightarrow q\bar{q}q\bar{q}b\bar{b}$ at $\sqrt{s}$ = 3 TeV

- Hadronic decays of high-energy top quarks do not lead to three separated jets
- Instead, reconstruction of the top in a “large” jet and identification of substructure compatible with $t \rightarrow Wb \rightarrow q\bar{q}b$
- Studied ≈10 years for the LHC, new and active effort for CLIC including different approaches
- Also useful for $t\bar{t}H$, top squarks, ...

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

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

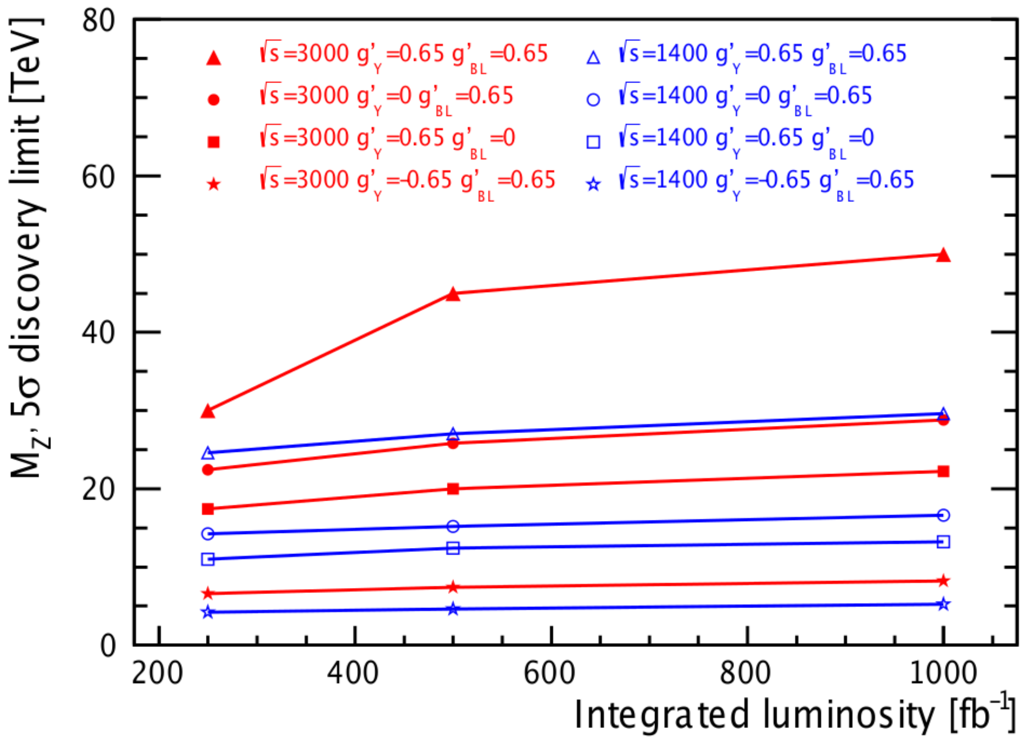


Observables:
- total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- forward-backward-asymmetry
- left-right asymmetry

(±80% e^- polarisation)

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

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

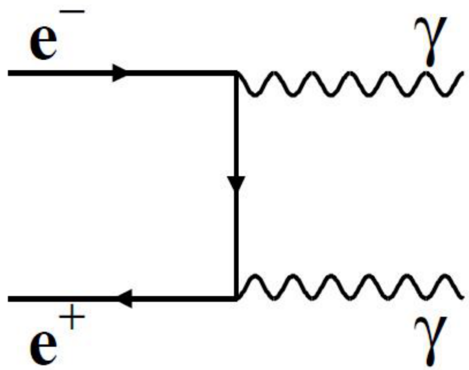


Blaising, Wells, arXiv:1208.1148

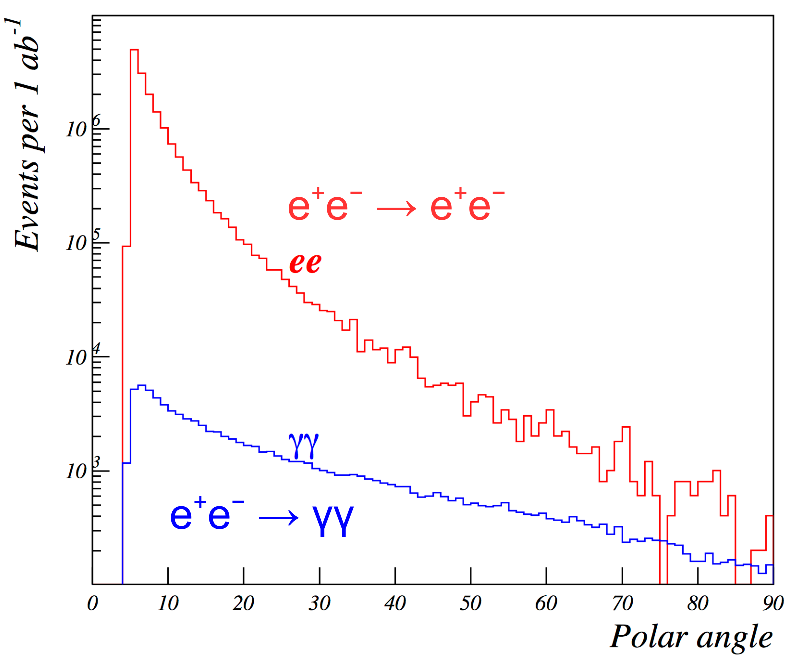
Precision study of $e^+e^- \rightarrow \gamma\gamma$

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

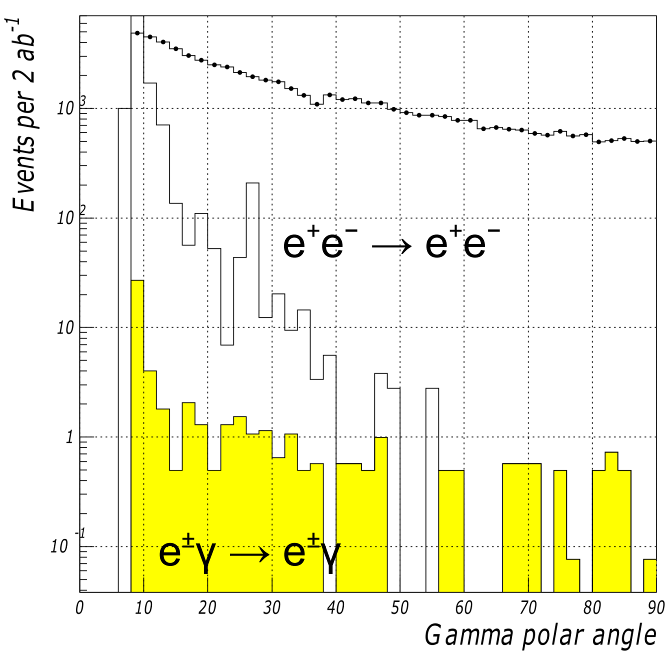
Events with small energy loss
due to Beamstrahlung and ISR are selected
→ two back-to-back photons
(track veto crucial)



Signal and main background

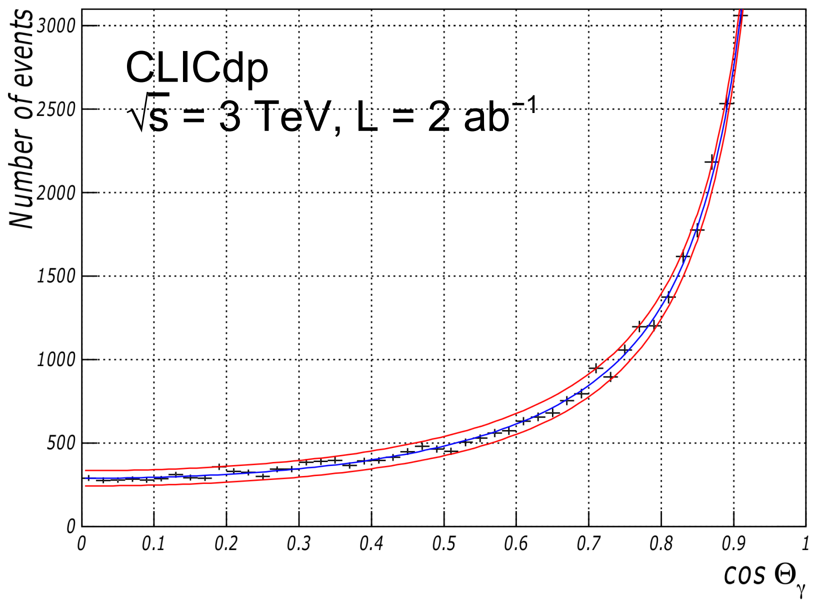


After selection:



$e^+e^- \rightarrow \gamma\gamma$: results and interpretation

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



Example: QED cutoff parameter Λ (simplest Ansatz)

CLIC: L = 2 ab^{-1}, ΔL/L = 0.5%

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

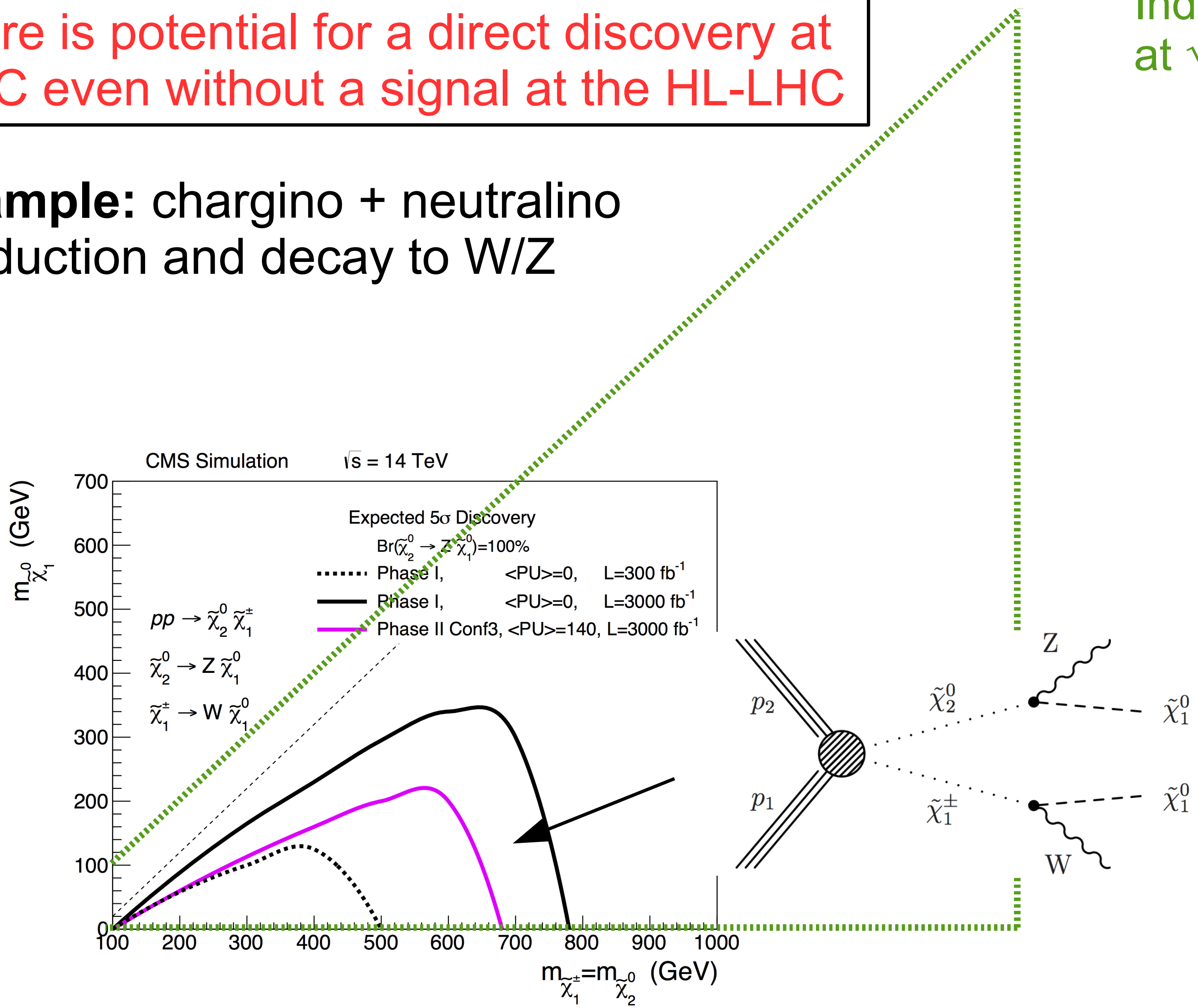
→ CLIC at 3 TeV factor 15 - 30 better than the LEP limits

Heavy electroweak states (1)

There is potential for a direct discovery at CLIC even without a signal at the HL-LHC

Indicative CLIC reach at $\sqrt{s}$ = 3 TeV

Example: chargino + neutralino production and decay to W/Z



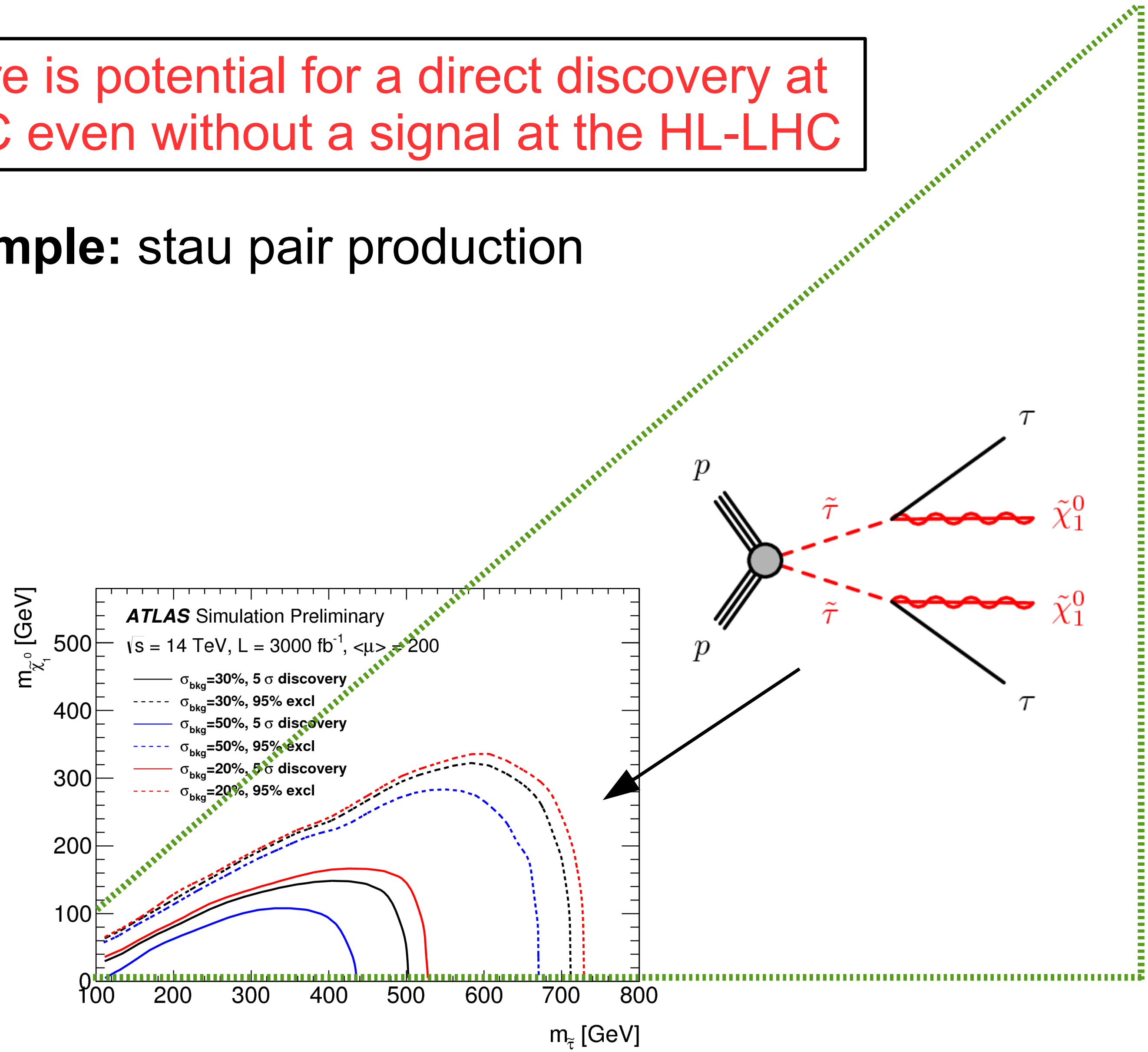
CMS-PAS-FTR-13-014

(similar projection: ATL-PHYS-PUB-2014-010)

Heavy electroweak states (2)

There is potential for a direct discovery at CLIC even without a signal at the HL-LHC

Example: stau pair production



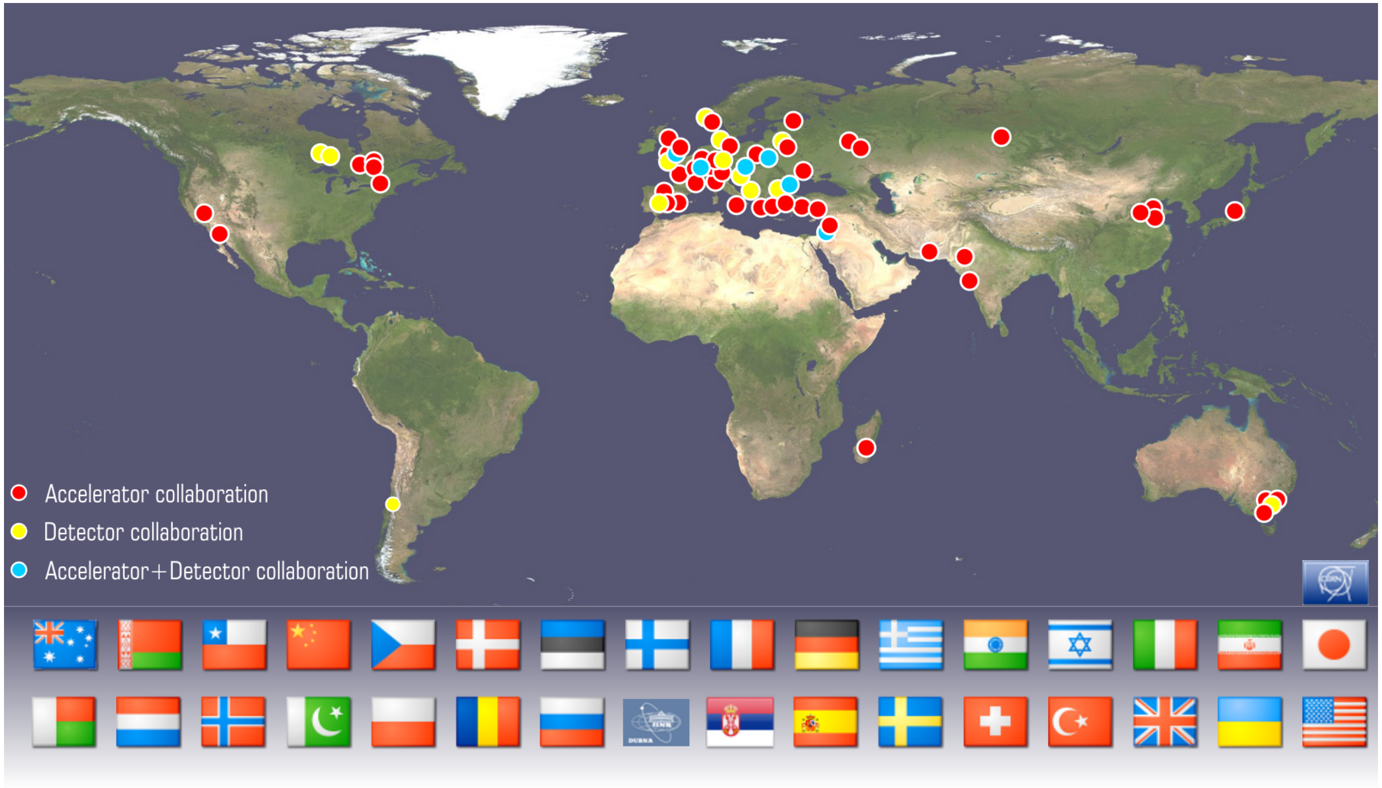
Indicative CLIC reach at $\sqrt{s}$ = 3 TeV

ATLAS-PHYS-PUB-2016-021

CLIC collaborations

The CLIC studies are carried by two active collaborations:
- CLIC accelerator collaboration: http://clic-study.web.cern.ch/
- CLIC detector and physics collaboration: http://clicdp.web.cern.ch/

Together
≈ 80 institutes



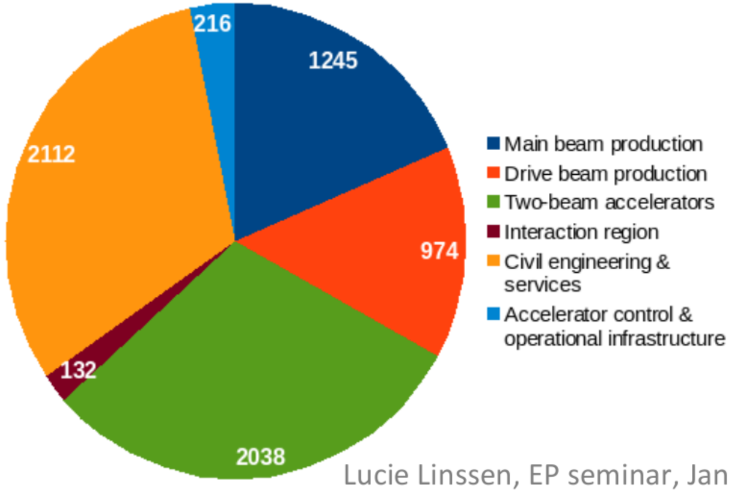
Upcoming events:
- Physics at CLIC workshop: http://indico.cern.ch/event/632228/
- CLICdp collaboration meeting: http://indico.cern.ch/event/633975/

CLIC cost estimate

Preliminary estimate (scaled from CDR) with room for improvement.
New estimate will be provided for European Strategy Update.

System	Value for 380 GeV (MCHF of Dec 2010)
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operation infrastructure	216
TOTAL	**6690**

Value for the CLIC accelerator at $\sqrt{s}$ = 380 GeV (11.4 km site length)



Lucie Linssen, EP seminar, January 24, 2017 57

CLIC timeline

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

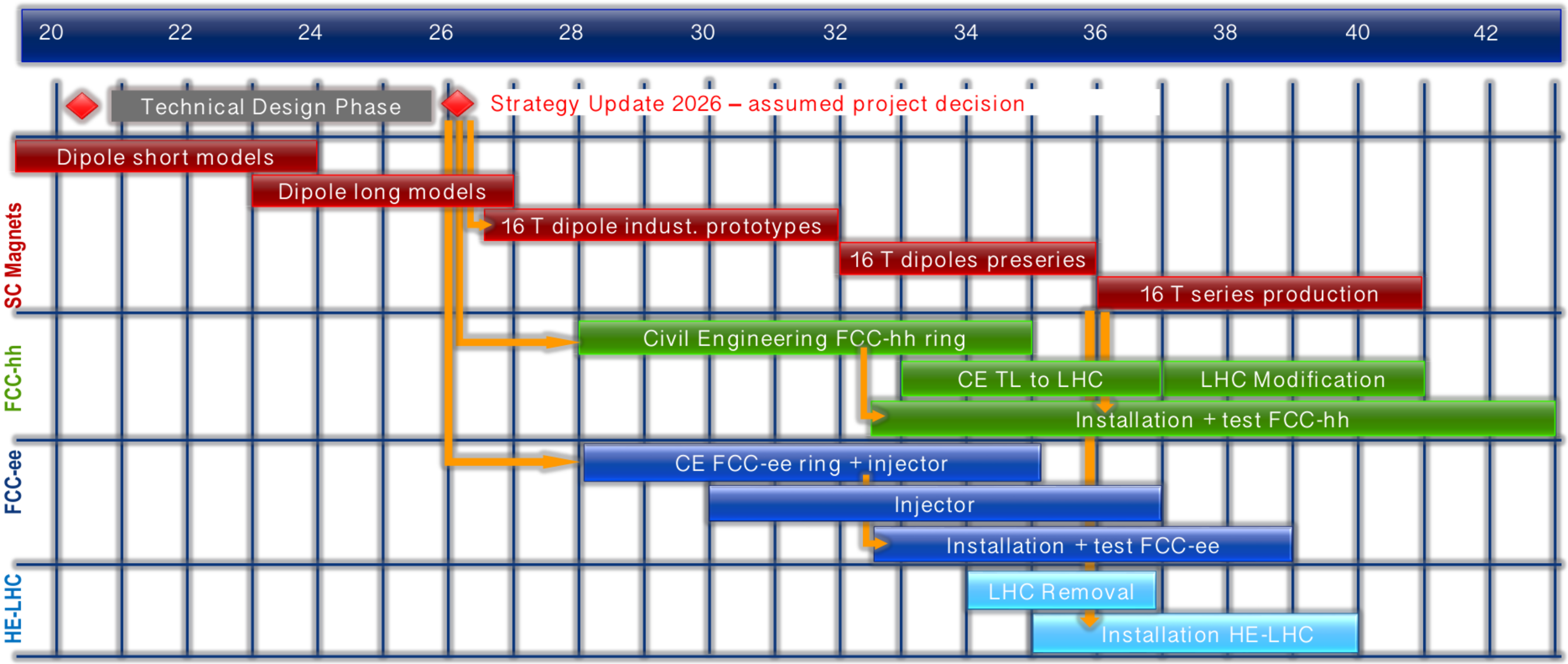
Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

Draft FCC timeline

Technically limited schedule



M. Benedikt,
FCC Week 2017