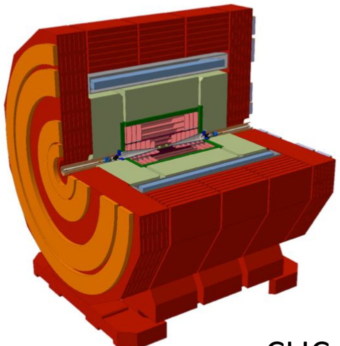
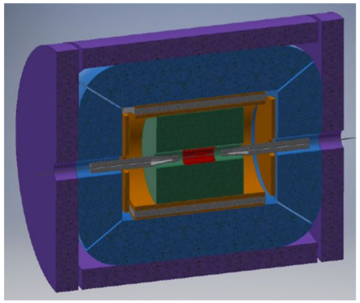
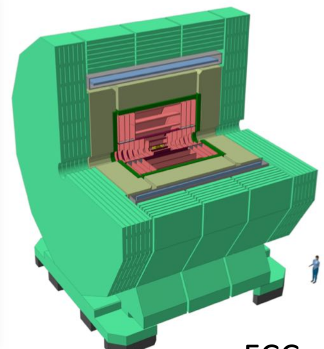
Future collider projects at CERN



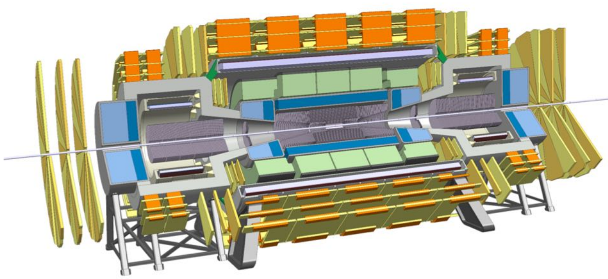
CLIC



FCC-ee



FCC-ee



FCC-hh

Lucie Linssen (CERN)

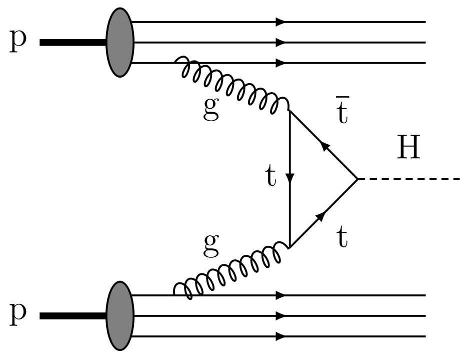
Vulcano workshop 2018

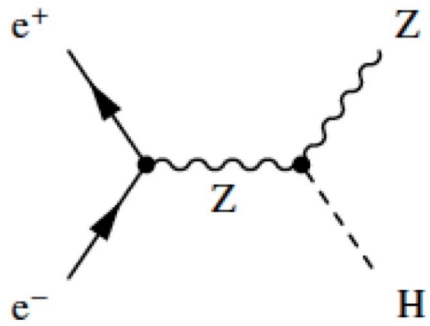
May 21st 2018

With many thanks to my CLICdp, FCC-ee and FCC-hh colleagues for presentation material

pp collisions / e^+e^- collisions

to address the open questions in particle physics

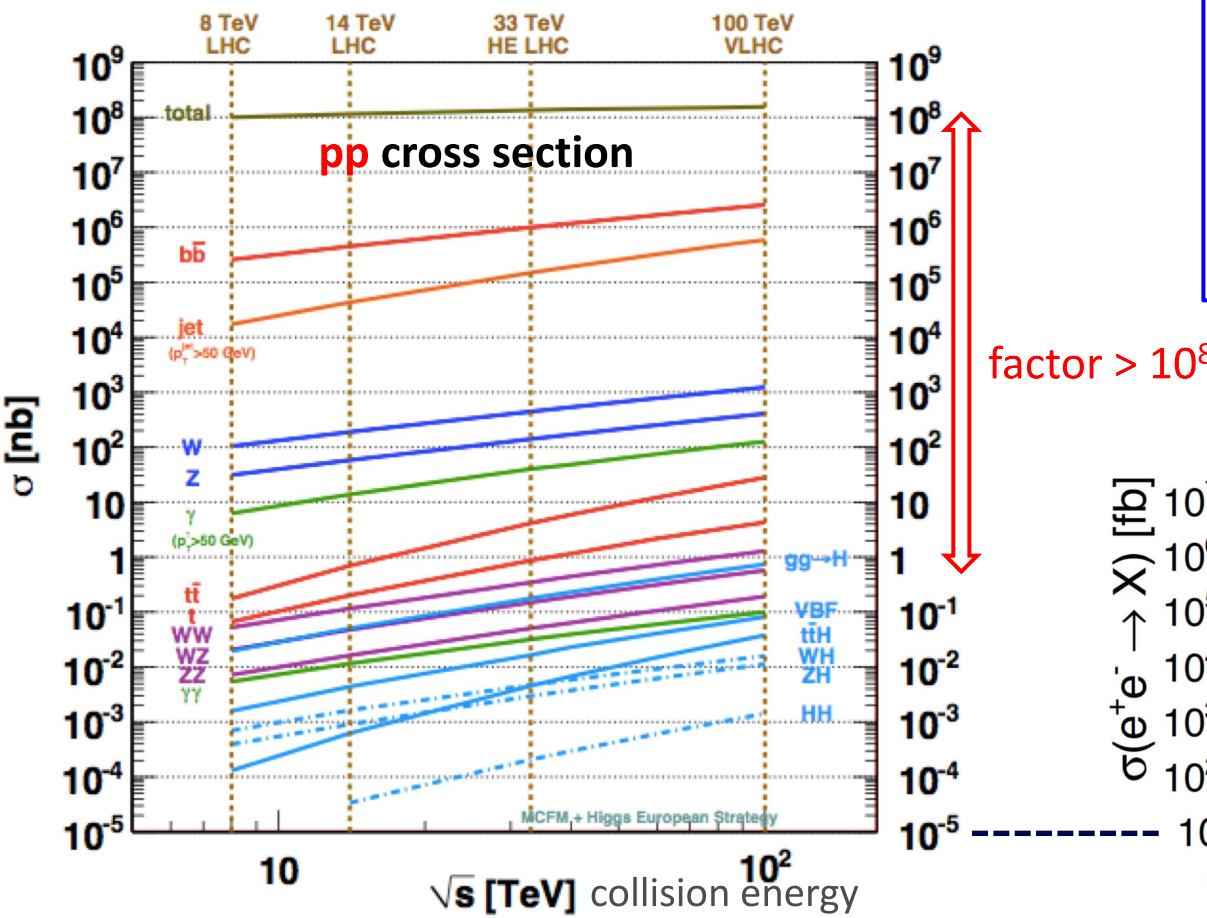


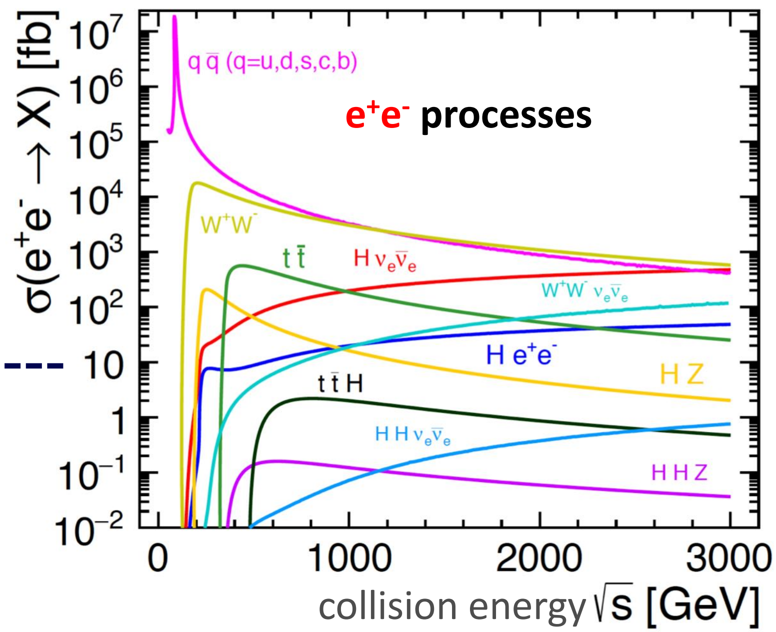


p-p collisions	e^+e^- collisions
Proton is compound object → Initial state unknown → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / opt: polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Cleaner experimental environment** → Less / no need for triggers → Lower radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
Very high-energy **circular** pp colliders feasible	High energies (>≈350 GeV) require **linear** collider

pp collisions / e^+e^- collisions

pp and e^+e^- collisions
provide complementary physics information
=> important for our field to have both !



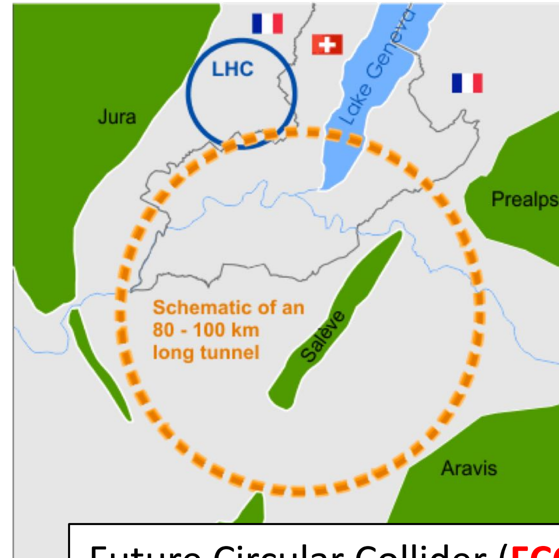


- Interesting **pp** events need to be found within a huge number of collisions

- **e^+e^-** events are more "clean"

high-energy pp collider studies

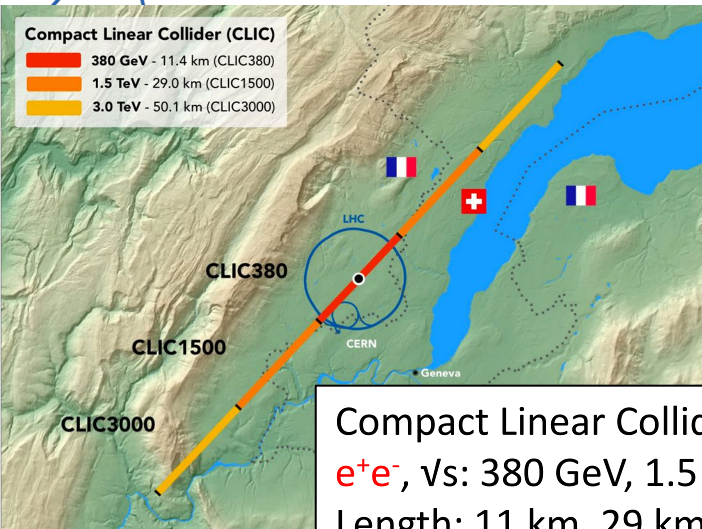
High-Energy LHC (**HE-LHC**): **CERN**
pp √s ~27 TeV
Circumference: 27 km



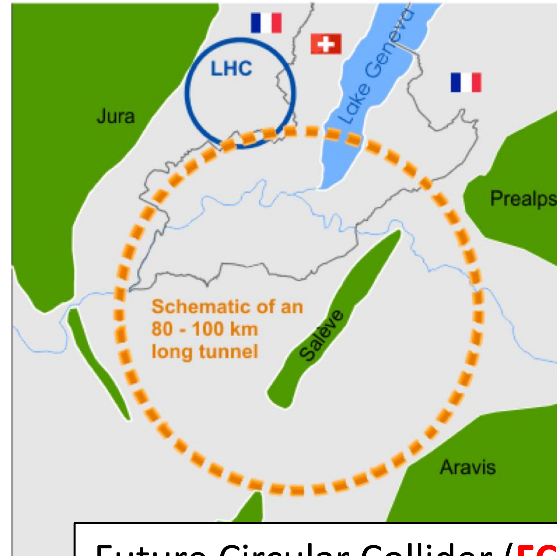
Future Circular Collider (**FCC-hh**): **CERN**
FCC-ee; **FCC-hh √s ~100 TeV**
Circumference: 97.75 km

Super proton proton Collider
(**SppC**), China
CEPC; **SPPC √s >70 TeV**
Circumference: 100 km

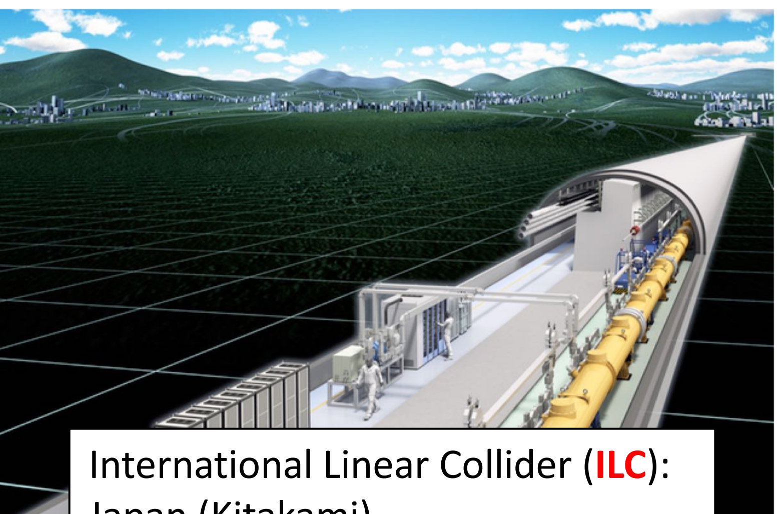
high-energy e^+e^- collider studies



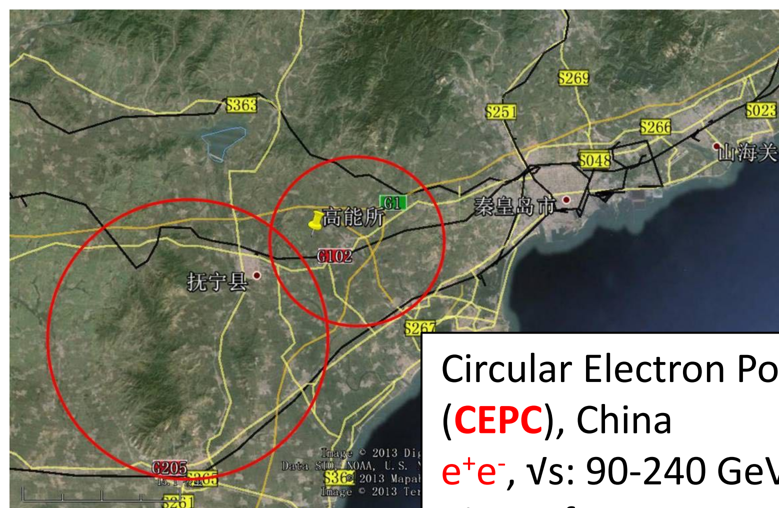
Compact Linear Collider (**CLIC**): **CERN**
e^+e^-, √s: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**): **CERN**
e^+e^-, √s: 90 - 365 GeV; FCC-hh pp
Circumference: 97.75 km

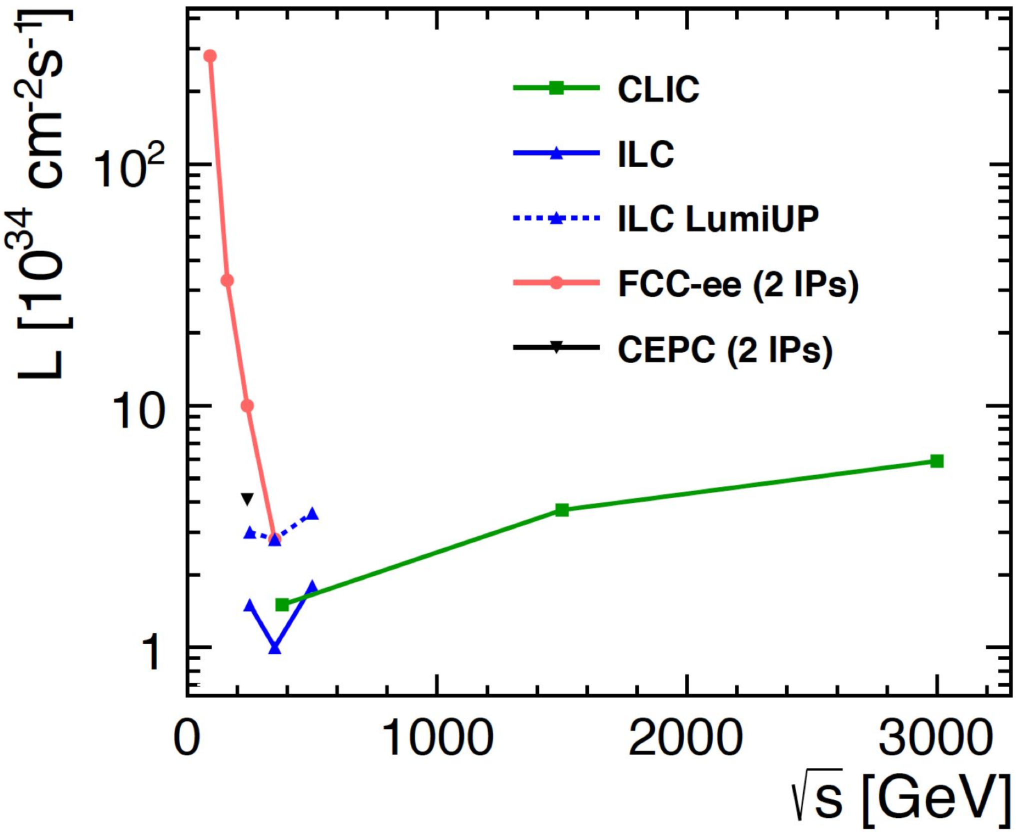


International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, √s: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



Circular Electron Positron Collider
(**CEPC**), China
e^+e^-, √s: 90-240 GeV; SPPC pp,
Circumference: 100 km

luminosity performance e^+e^- colliders



Linear colliders:

- Can reach much higher energies
- Luminosity rises with energy
- Beam polarisation at all energies

Circular colliders:

- Huge luminosity at lower energies
- Luminosity decreases with energy

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

Disclaimer: this plot is for illustrative purposes only; it may not have the latest performance numbers

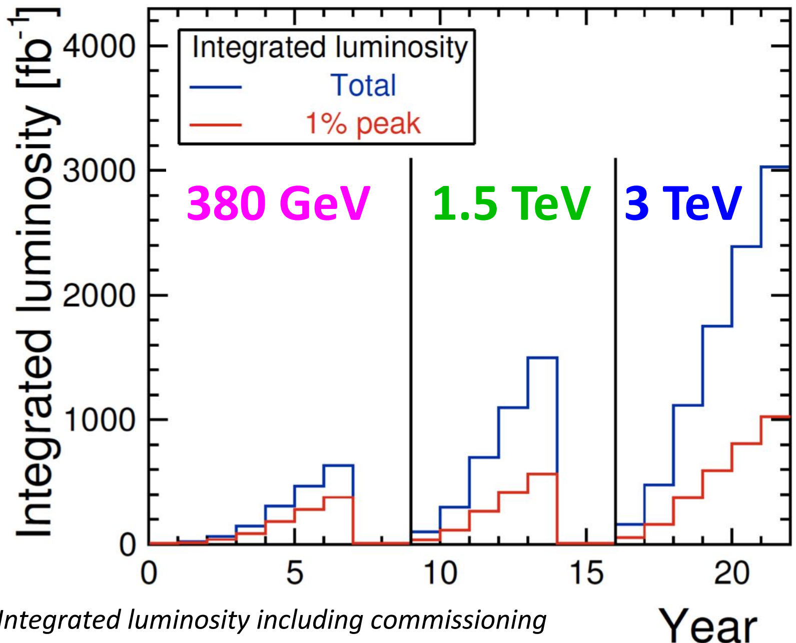
linear e^+e^-

CLIC physics scope and staging scenario

The CLIC program builds on energy stages:

- **380 GeV (350 GeV)**, 600 fb^{-1} : **precision Higgs and top physics**
- **1.5 TeV**, 1.5 ab^{-1} : **BSM searches, precision Higgs, ttH, HH, top physics**
- **3 TeV**, 3 ab^{-1} : **BSM searches, precision Higgs, HH, top physics**

BSM searches: direct (up to ~1.5 TeV), indirect (>> TeV scales)



Integrated luminosity including commissioning with beam and stops for energy upgrades

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

Dedicated to top mass threshold scan

Staging scenario can be adapted, e.g. to new results from (HL-)LHC

CERN-2016-004

CLIC accelerator parameters

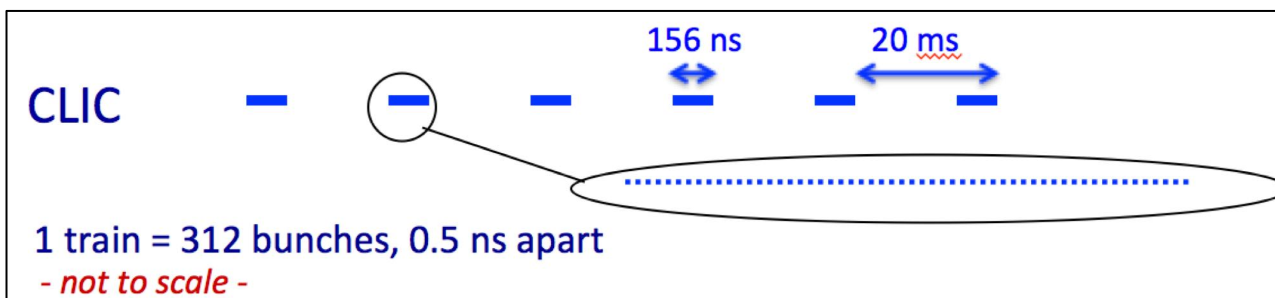
Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity $\mathcal{L}$ ($10^{34} cm^{-2} sec^{-1}$)	**1.5**	**3.7**	**5.9**
$\mathcal{L}$ above 99% of $\sqrt{s}$ ($10^{34} cm^{-2} sec^{-1}$)	0.9	1.4	2.0
Accelerator gradient (MV/m)	72	72/100	72/100
Site length (km)	**11.4**	**29**	**50**
Repetition frequency (Hz)	50	50	50
Bunch separation (ns)	0.5	0.5	0.5
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	70	44	44

Drives timing requirements for CLIC detector

Very small beam

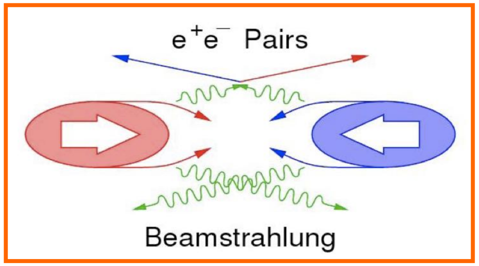
Crossing angle 20 mrad, electron polarization ±80%

Very low duty cycle
Allows for:
- Triggerless readout
- Power pulsing



CERN-2016-004

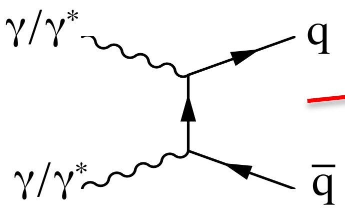
Beam-induced background at CLIC



Beam-beam background at IP:

- Small beams => very high E-fields
  - **Beamstrahlung**

  - **Pair-background** → Simplified picture: **Design issue** (small cell sizes)
    - High occupancies

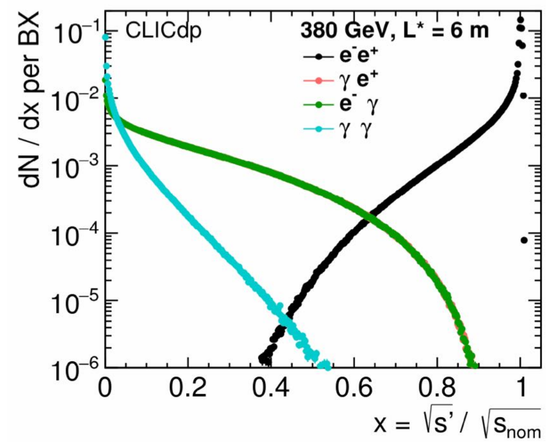


  - **γγ to hadrons** → Impacts on the physics **Needs suppression in data**
    - Energy deposits

Beamstrahlung ➔ important energy losses right at the interaction point

Most physics processes are studied well above production threshold => profit from full spectrum

Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV
Eur.Phys.J. C74 (2014) no.4, 2833



$\sqrt{s'}/\sqrt{s}$	380 GeV	3 TeV
> 0.99	58%	36%
> 0.90	87%	57%
> 0.80	96%	69%
> 0.70	98.7%	76.8%
> 0.50	99.96%	88.6%

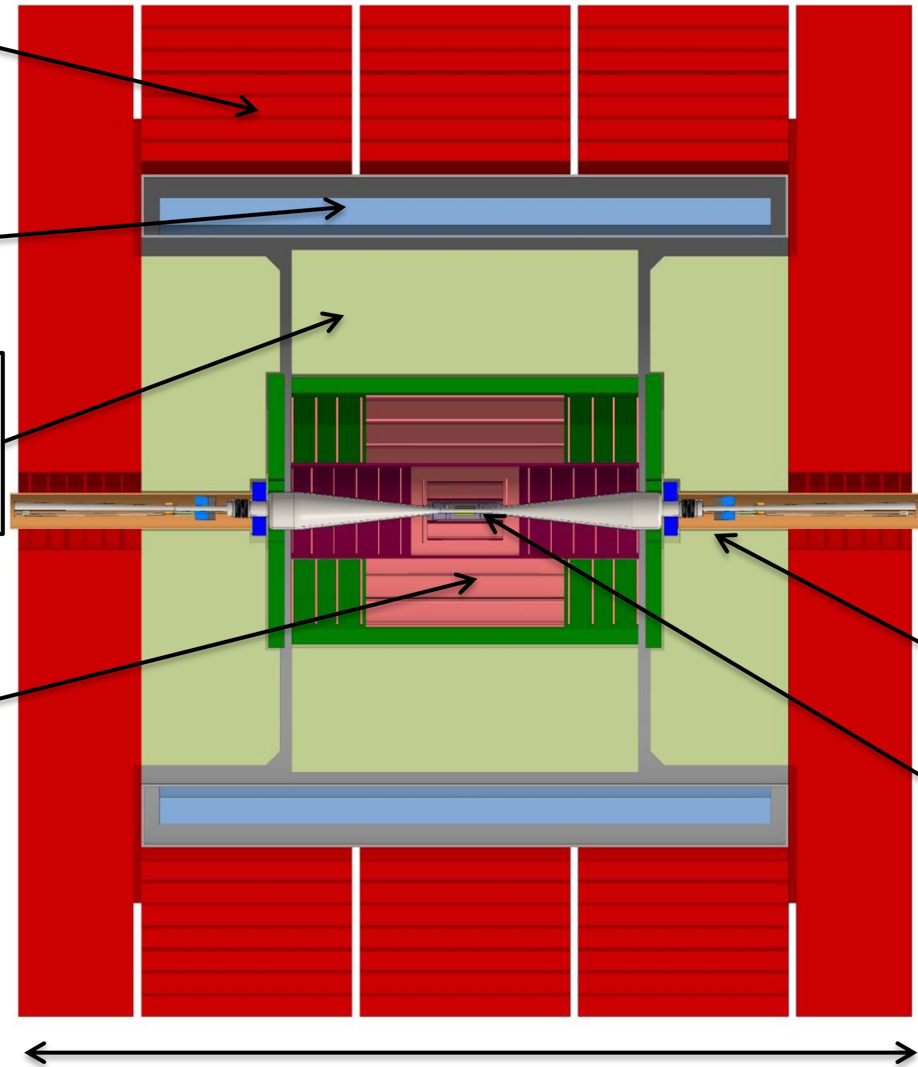
CLIC detector model

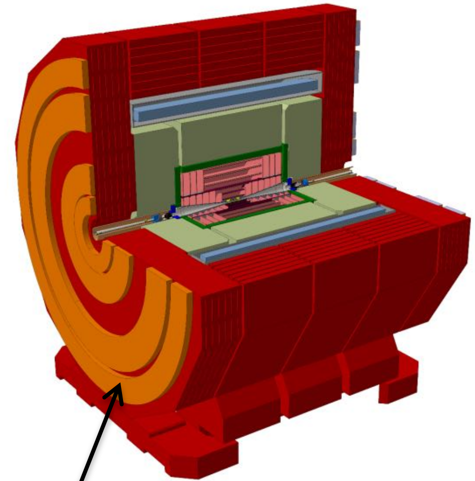
return yoke (Fe) with muon-ID detectors

superconducting solenoid, 4 Tesla

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i, Si-W ECAL, Sc-FE HCAL

silicon tracker, (large pixels)





end-coils for field shaping

forward region with compact forward calorimeters

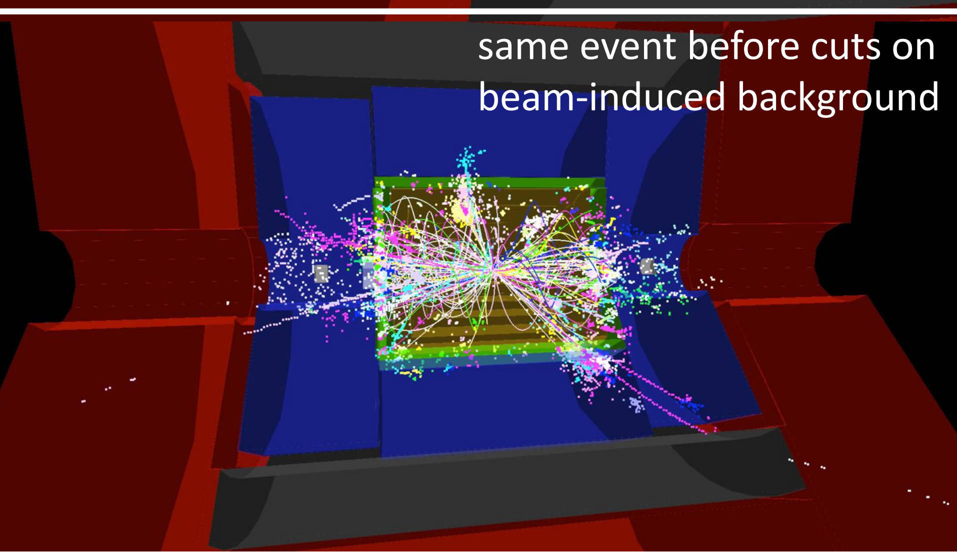
low-mass vertex detector, ~25 µm pixels

Final beam focusing is outside the detector

CLICdp-Note-2017-001

$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$

CLIC 1.4 TeV


same event before cuts on beam-induced background

Highly granular calorimetry + precise hit timing

↓

Very effective in suppressing backgrounds for fully reconstructed particles

↓

General trend for **e^+e^-** and **pp** options (e.g. CMS endcap calorimetry for HL-LHC)

circular e^+e^-

FCC-ee physics and staging scenario

Energy stages √s = 91 GeV **Z**, 160 GeV **W**, 240 GeV **Higgs**, 365 GeV **top quark**

m_Z, m_W, m_{top}, $\sin^2\theta_W^{eff}$, R_b, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z\ m_W)$, Higgs and top quark couplings

⇒ Very high precision measurements of electroweak parameters

⇒ Exploration of very high energy scale (>> TeV) via precision measurements

⇒ Search for (very) weakly coupled particles

	luminosity/IP [10^{34} cm^{-2}s^{-1}]	**total luminosity (2 IPs)/ yr**	**physics goal**	**run time [years]**
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	52 ab^{-1}/year		
W	25	7 ab^{-1}/year	10 ab^{-1}	1
H	7.0	1.8 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.36 ab^{-1}/year	1.5 ab^{-1}	4

total program duration: 14 years - *including machine modifications*

phase 1 (*Z, W, H*): 8 years, phase 2 (top): 6 years

P.Janot, Acad.Training, Oct 2017

M. Benedikt, FCC week 2018

FCC-ee accelerator parameters

	Z	W	H (ZH)	ttbar
beam energy [GeV]	**45.6**	**80**	**120**	**182.5**
SR energy loss / turn (GeV)	0.036	0.34	1.72	9.21
SR total power [MW]	100	100	100	100
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
no. of bunches / beam	16640	2000	393	48
Bunch crossing separation (ns)	**20**	160	830	8300
luminosity [10^{34} $cm^{-2}s^{-1}$] per IP	**>200**	>25	>7	>1.4

Beam transverse polarisation => beam energy can be measured to very high accuracy (~50 keV)

At Z-peak very high luminosities and high cross section

$\Rightarrow$ Statistical accuracies at 10^{-5} level (e.g. cross sections, asymmetries)

$\Rightarrow$ This drives the **detector performance**

$\Rightarrow$ This also drives requirement on **data rates**

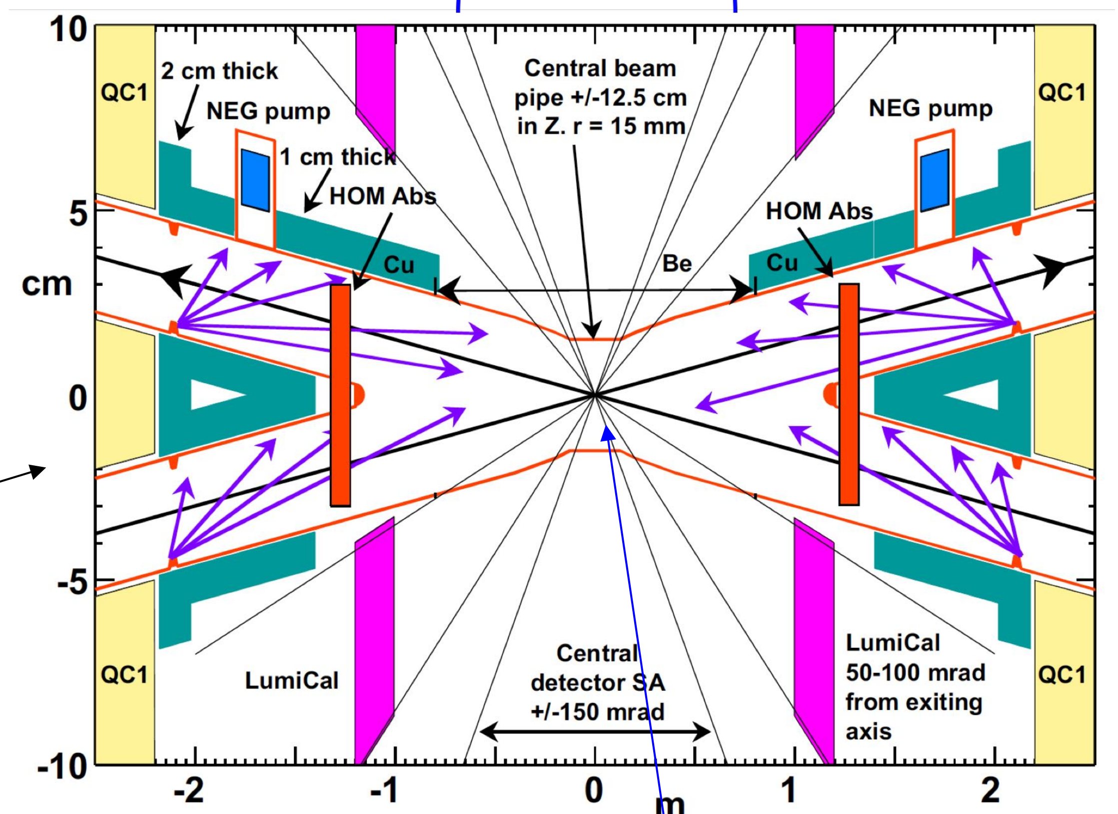
$\Rightarrow$ **Triggerless** readout likely still possible

FCC-ee interaction region

Designed to take background particles from **Beamstrahlung and Synchrotron radiation** into account

central detector down to ±150 mrad (θ ±8.6 deg)

Note different x/z scales !



Incoming beam

SR γs

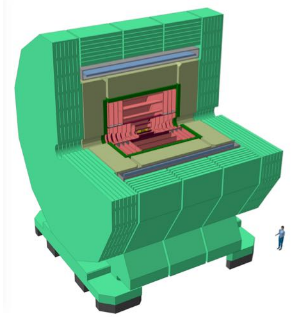
Crossing angle 30 mrad

Beam pipe radius : 15 mm

- FF quads
- LumiCal
- Tantalum
- HOM Abs.
- Vertex det

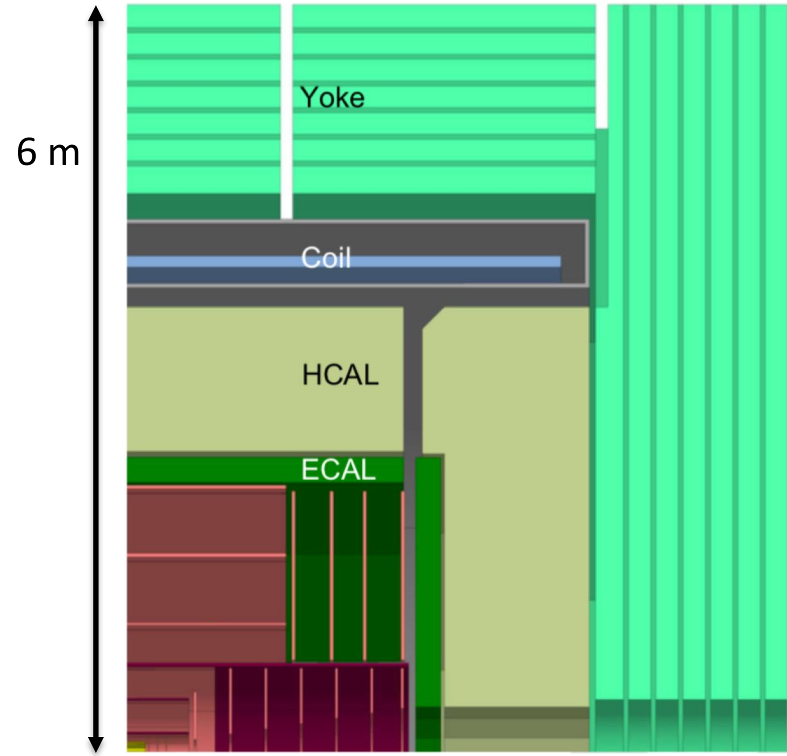
L* = 2.2 m

CLD detector for FCC-ee

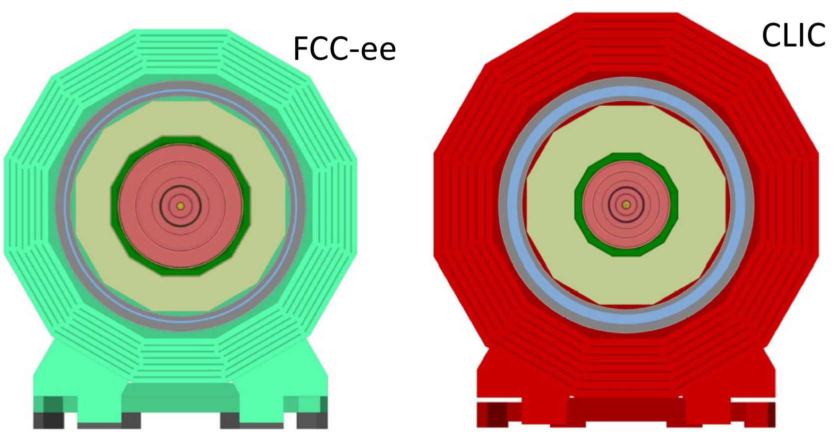


CLD is derived from the CLIC detector model
Adapted to FCC-ee conditions

Detector solenoidal field ↓ 2 T (4 T for CLIC)
Outer tracker radius ↑ 2.15 m (1.5 m for CLIC)
Beam pipe radius ↓ 15 mm (29 mm for CLIC)
Inner vertex radius ↓ 17 mm (31 mm for CLIC)
Max collision energy ↓ 365 GeV (3 TeV for CLIC)
Hadronic calorimeter depth ↓ 5.5 λ_I (7.5 λ_I for CLIC)
Layout respects the $\pm$150 mrad cone for detector



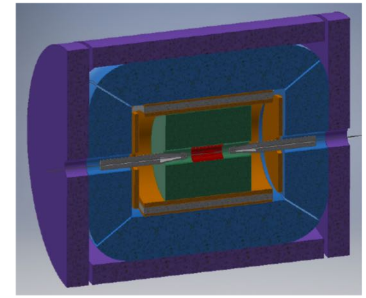
Constraint from FCC-ee continuous operation
Power pulsing not possible
Increased tracker "mass" in simulation model



"IDEA" concept for FCC-ee

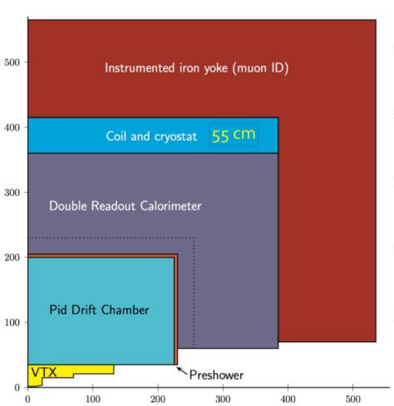
IDEA "International Detector for Electron-positron Accelerator"

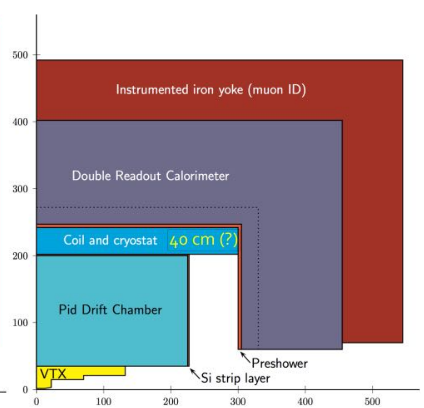
- Vertex detector, MAPS, R_{in}=15mm, 4-7 layers
- Ultra-light drift chamber with PID, 4 m long, R 30-200 cm
- Outer silicon layer
- Thin superconducting solenoid 2T, R=2.1m
- Pre-shower 1-2X_0
- Dual read-out calorimetry, 2m deep
- Instrumented return yoke

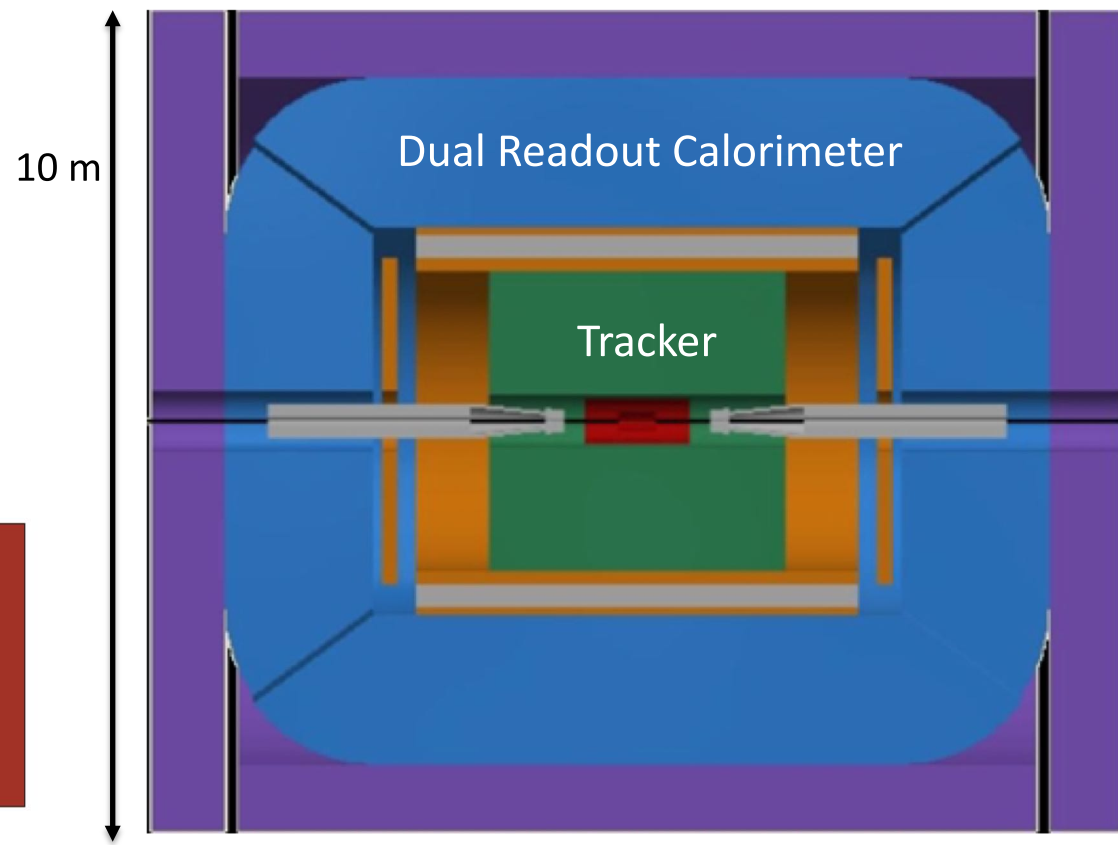


Optionally solenoid outside/inside calorimeter:

a. Classical 2T solenoid around the calorimeter, 7.2m bore, 8m long
b. Ultra light 2T solenoid around tracker, 4.2m bore, 6m long







circular pp

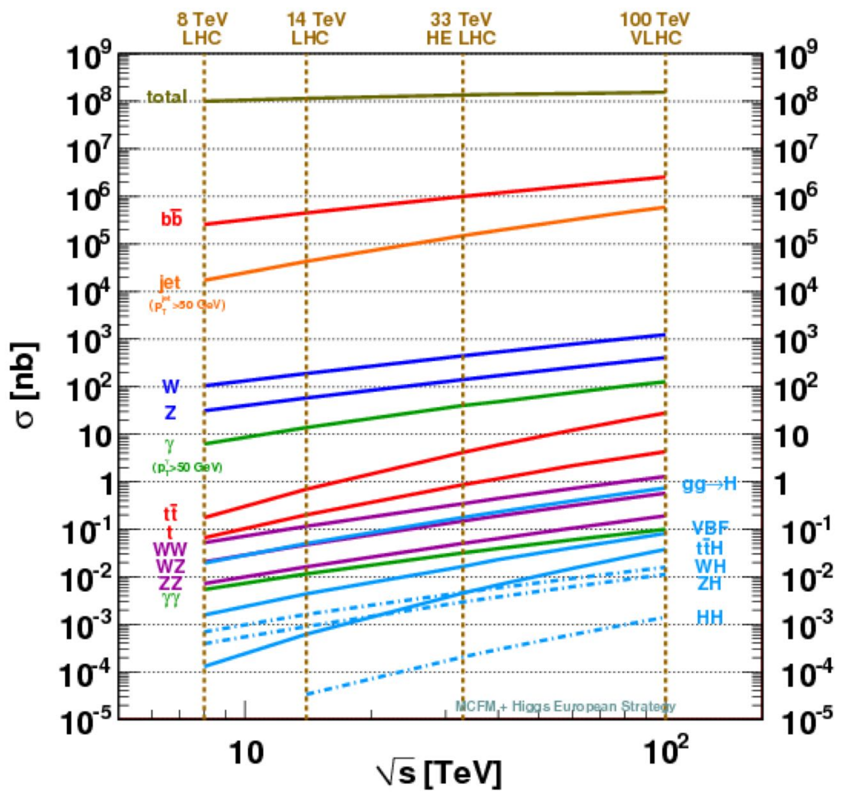
FCC-hh, HE-LHC, (HL)-LHC parameters

M. Benedikt, CAS, Zürich, 2018

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	98		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.1	(1.1) 0.58
bunch intensity [10^{11}]	1	1	2.2	(2.2) 1.15
bunch spacing [ns]	25	25	25	25
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	28	(5) 1
peak #events/bunch crossing	170	1020	800	(132) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
synchrotron rad. [W/m/beam]	28		4.6	(0.33) 0.17

FCC-hh and HE-LHC have similar detector requirements (resolution and radiation hardness) !!

FCC-hh physics scope



Total cross section and Minimum Bias multiplicity => modest increase from LHC to FCC-hh.

The cross section for interesting processes => significant increase !

→ **Interesting stuff is sticking out more !**

Going from **pileup of ~140 at HL-LHC** to **pileup of 1000 at FCC-hh** reduces this possible advantage (e.g. triggering)

The **Higgs** is still a key benchmark for the FCC-hh detector,

⇒ Highly forward boosted features (100 TeV, 125 GeV Higgs)

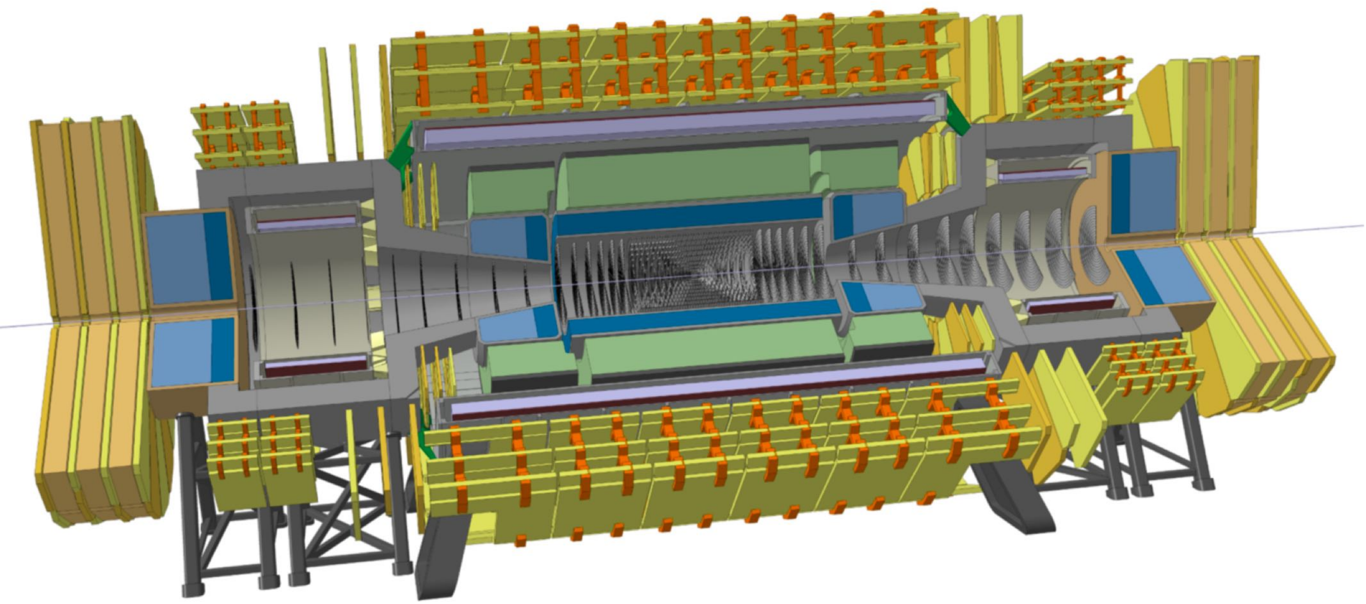
Many other physics goals: **Higgs self-coupling (λ), precision SM, heavy resonances, SUSY, etc.**

'general' purpose detectors with very large η acceptance and extreme granularity

Muon detection up to η = 4 ($\theta \approx 2°$) Calorimetry up to η = 6 ($\theta \approx 0.5°$)

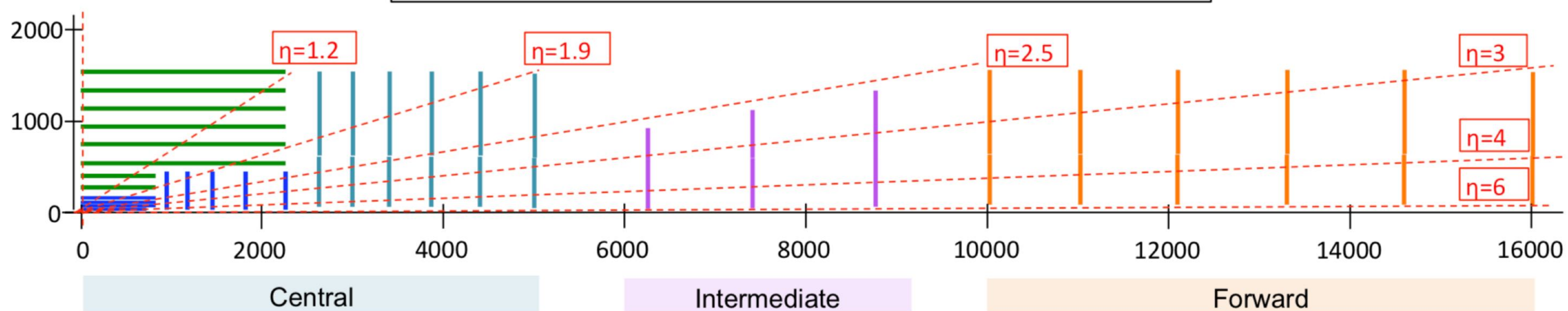
W. Riegler, Acad.Training, Oct 2017

FCC-hh reference detector for the CDR

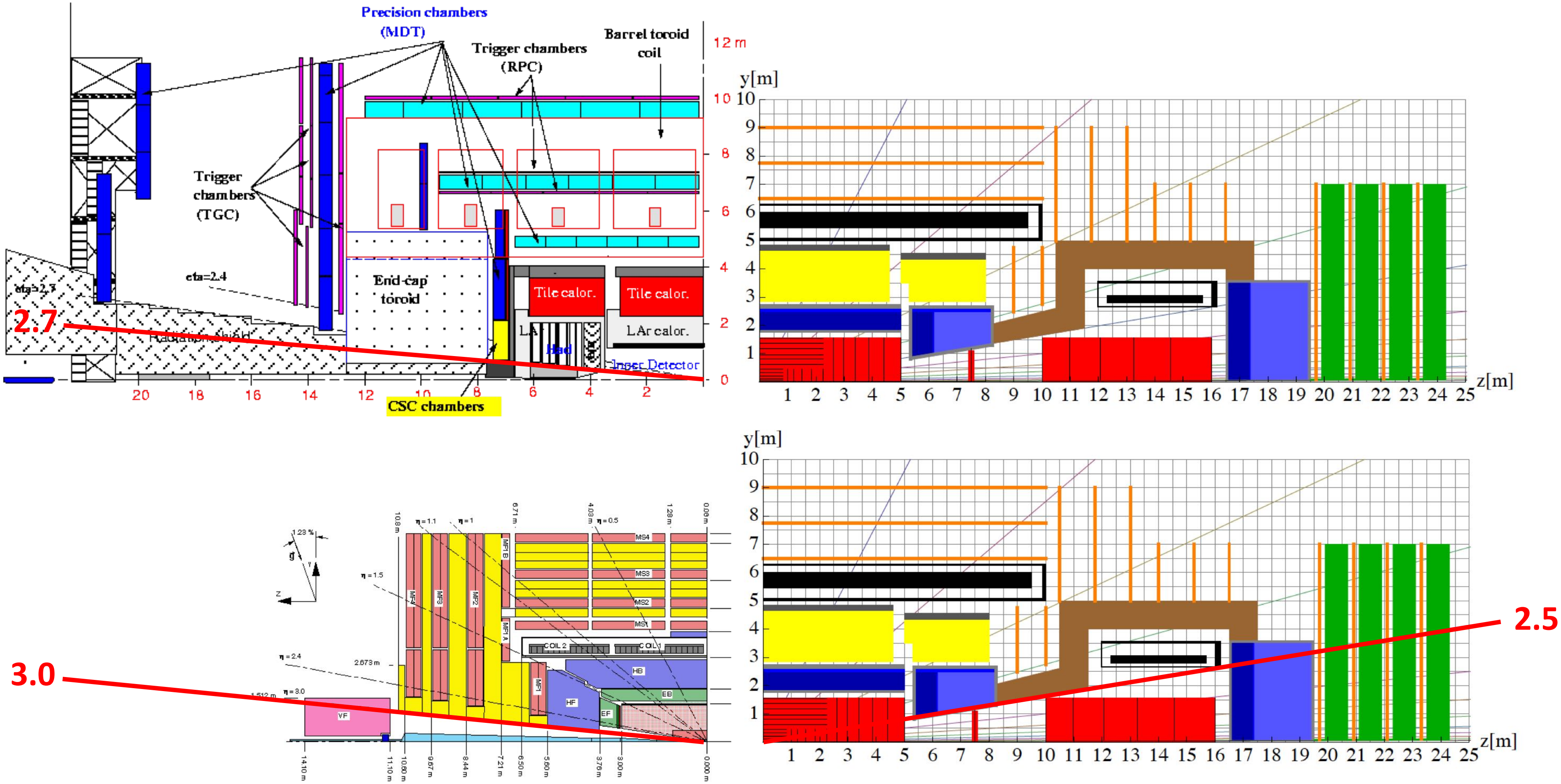


- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

Tracker radius: 1.6m , half-length: 16m



Comparison to ATLAS and CMS



- Compared to ATLAS / CMS, the forward calorimeters are moved far out in order to reach larger η, to reduce radiation load and increase granularity.
- Forward solenoid adds about 1 unit of η to tracking acceptance.
- A large shielding (brown) stops neutrons from escaping to cavern and muon system

W. Riegler, Acad.Training, Oct 2017

physics potential

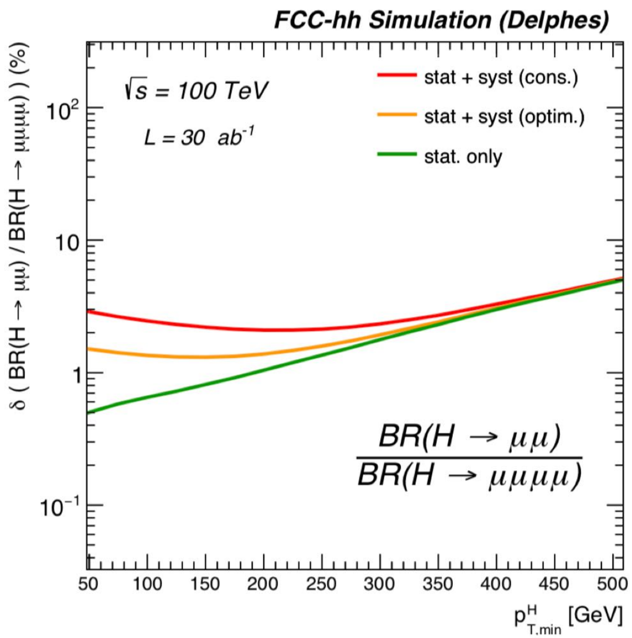
=>

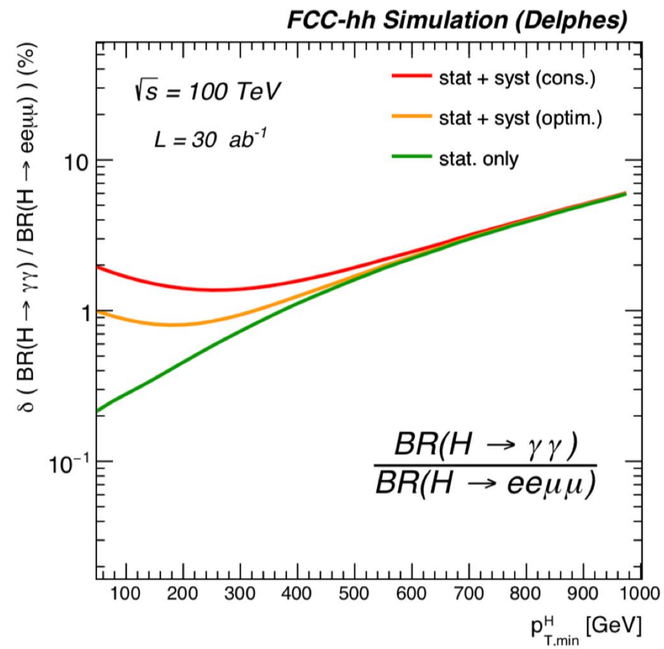
a few selected plots

Higgs physics at 100 TeV pp

- **High production rates => high accuracy on rare decay modes**
- **=> Information complementary to lepton colliders**

	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55



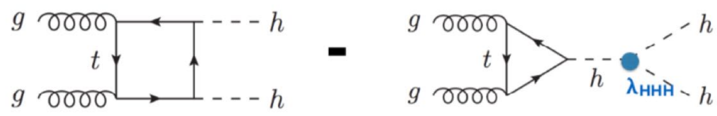


Statistical errors at 1% level in reach

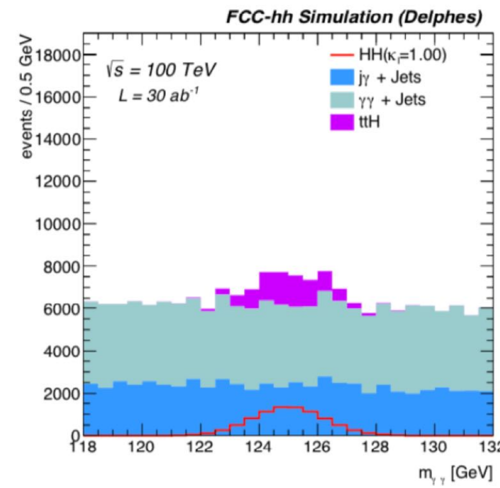
Michele Selvaggi, FCC week 2018

Double Higgs production at 100 TeV pp

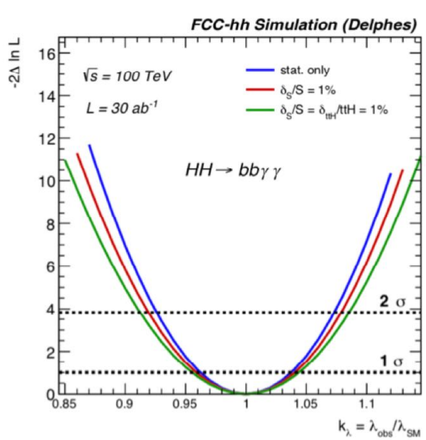
gluon fusion:



σ(100 TeV) / σ(14 TeV) ≈ 40

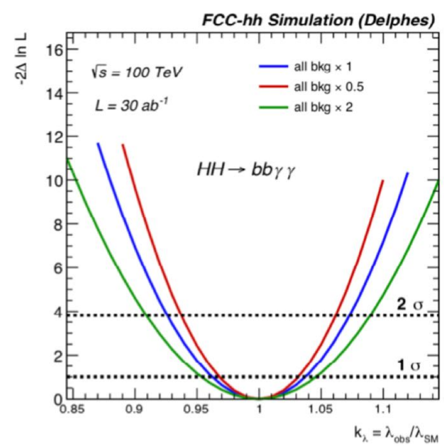


assuming QCD can be measured from sidebands



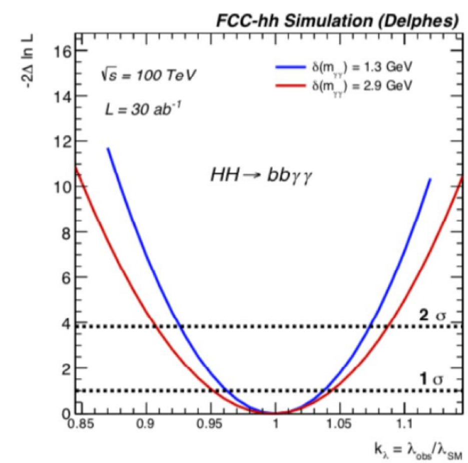
nominal background yields:

$\delta\kappa_\lambda$(stat) ≈ 3.5 %
$\delta\kappa_\lambda$(stat + syst) ≈ 4.5 %
δr(stat) ≈ 2.5 %
δr(stat + syst) ≈ 3 %



varying (0.5x-2x) background yields:

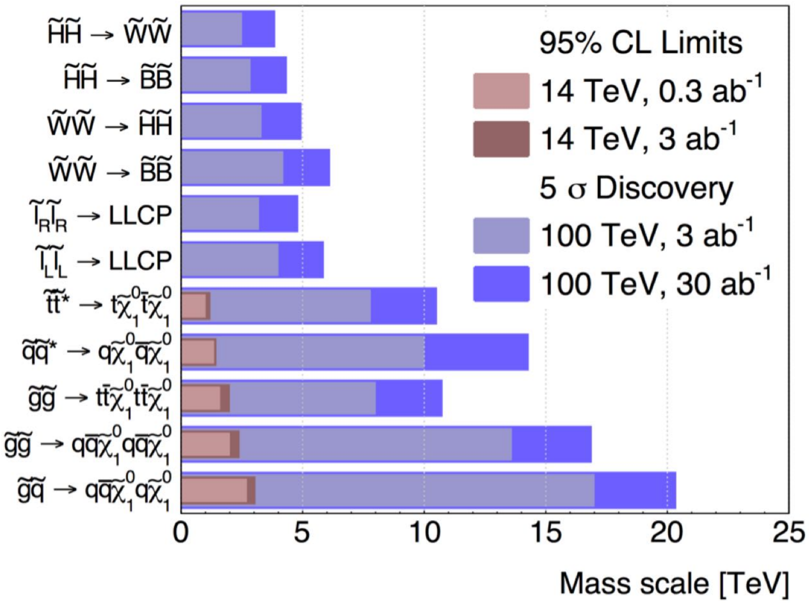
$\delta\kappa_\lambda$(stat) ≈ 3 - 5 %
δr(stat) ≈ 2 - 3%

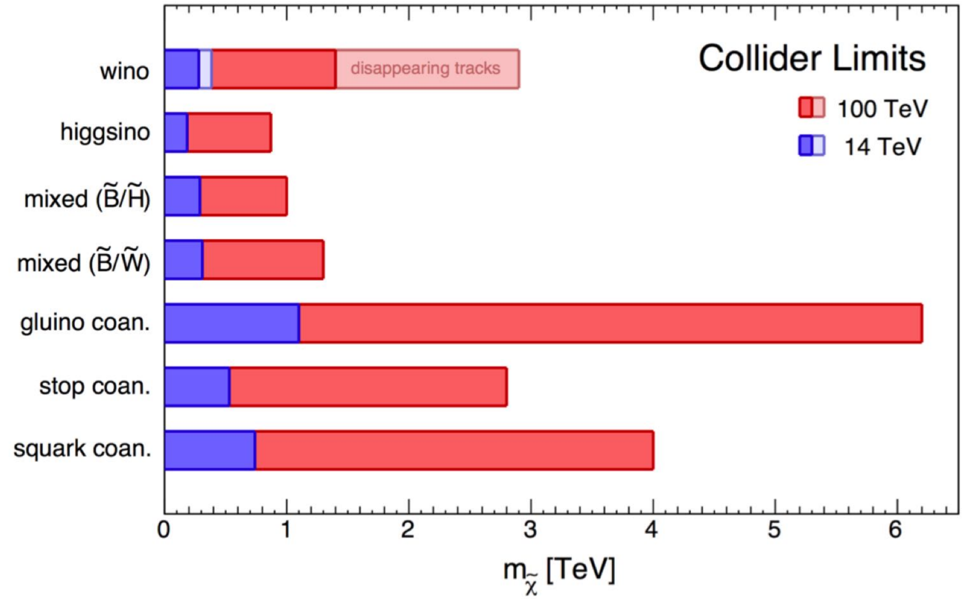


m(γγ) resolution

Giacomo Ortona, FCC week 2018

Direct SUSY and DM searches at 100 TeV



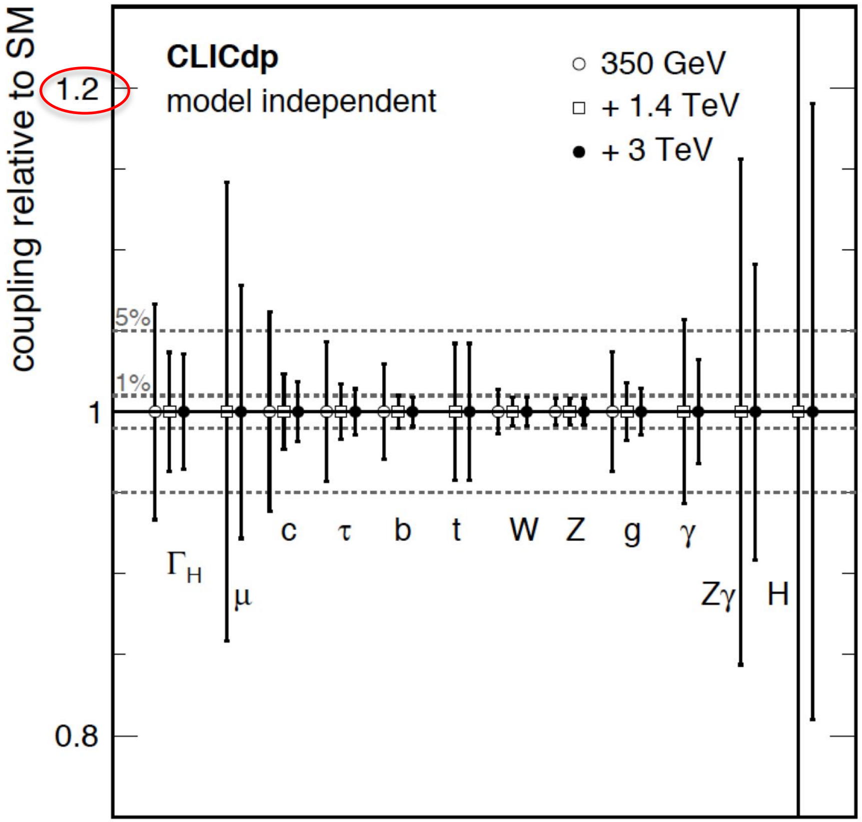


Mass reach typically increased by 5-7 compared to HL-LHC

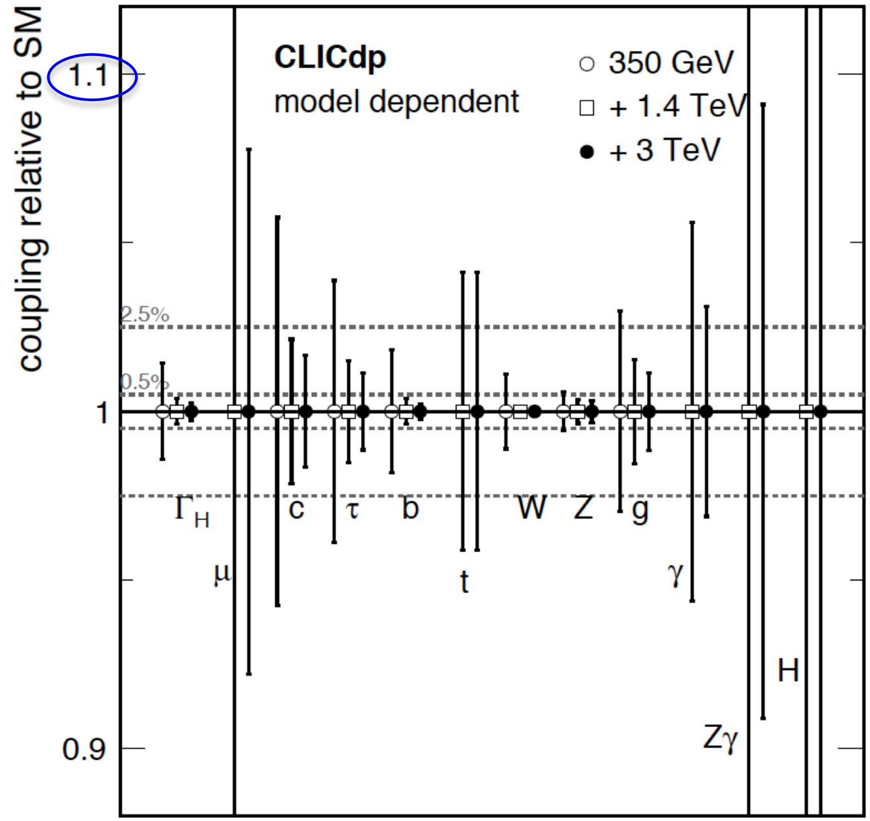
arXiv:1606.00947

combined CLIC Higgs coupling results

Model-independent



Model-dependent



arXiv:1608.07538

Higgs width is a free parameter, allows for additional non-SM decays

LHC-like fit, assuming SM decays only. Fit to deviations from SM BR's

Full CLIC program, ~5 yrs of running at each stage (plots assume 80% e^- polarisation above 1 TeV):

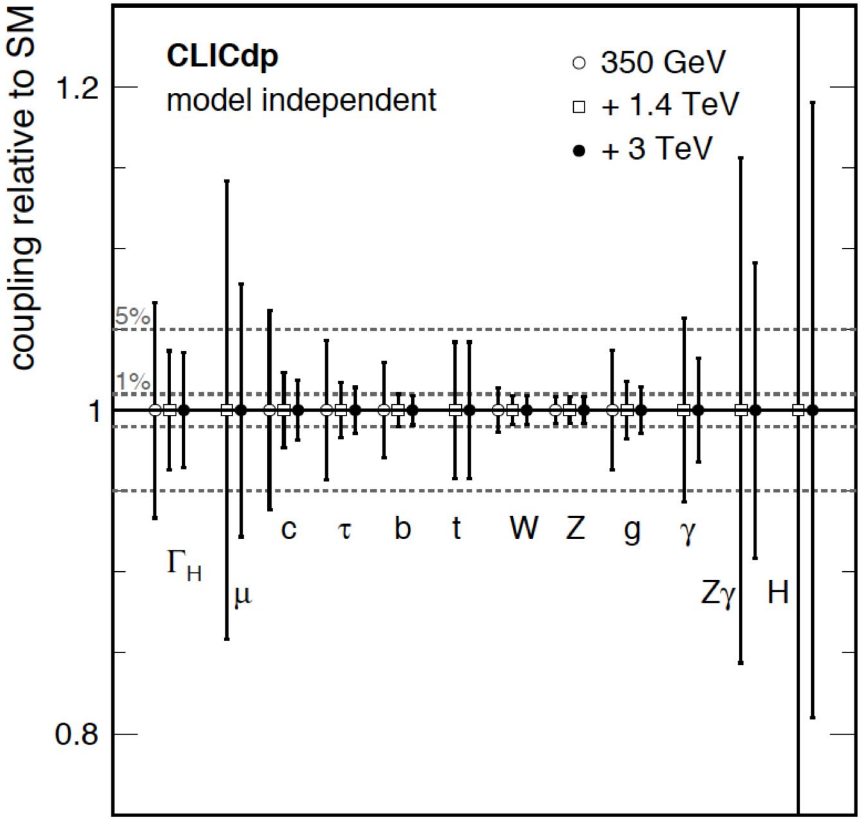
- Model-independent: down to ±1% for most couplings
- Model-dependent: ±1% down to ± few ‰ for most couplings
- Accuracy on Higgs width: ±3.5% (MI), ±0.3% (MD, derived)

combined CLIC Higgs coupling results

indicative comparison with HL-LHC capabilities

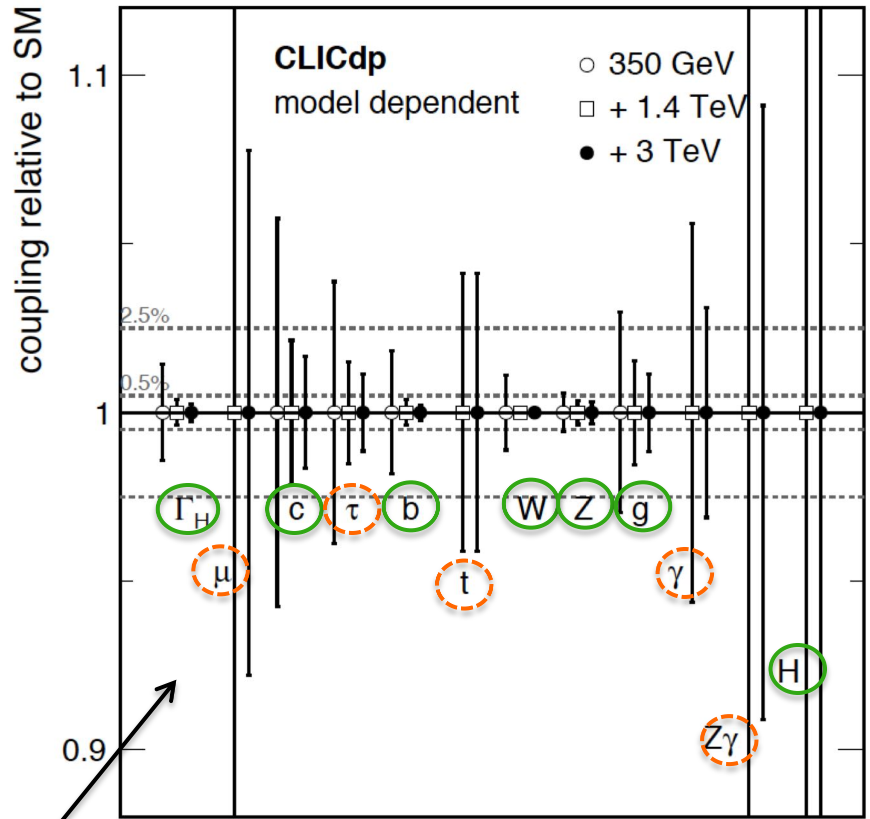
arXiv:1608.07538

Model-independent



e^+e^- colliders can perform model-independent measurements

Model-dependent

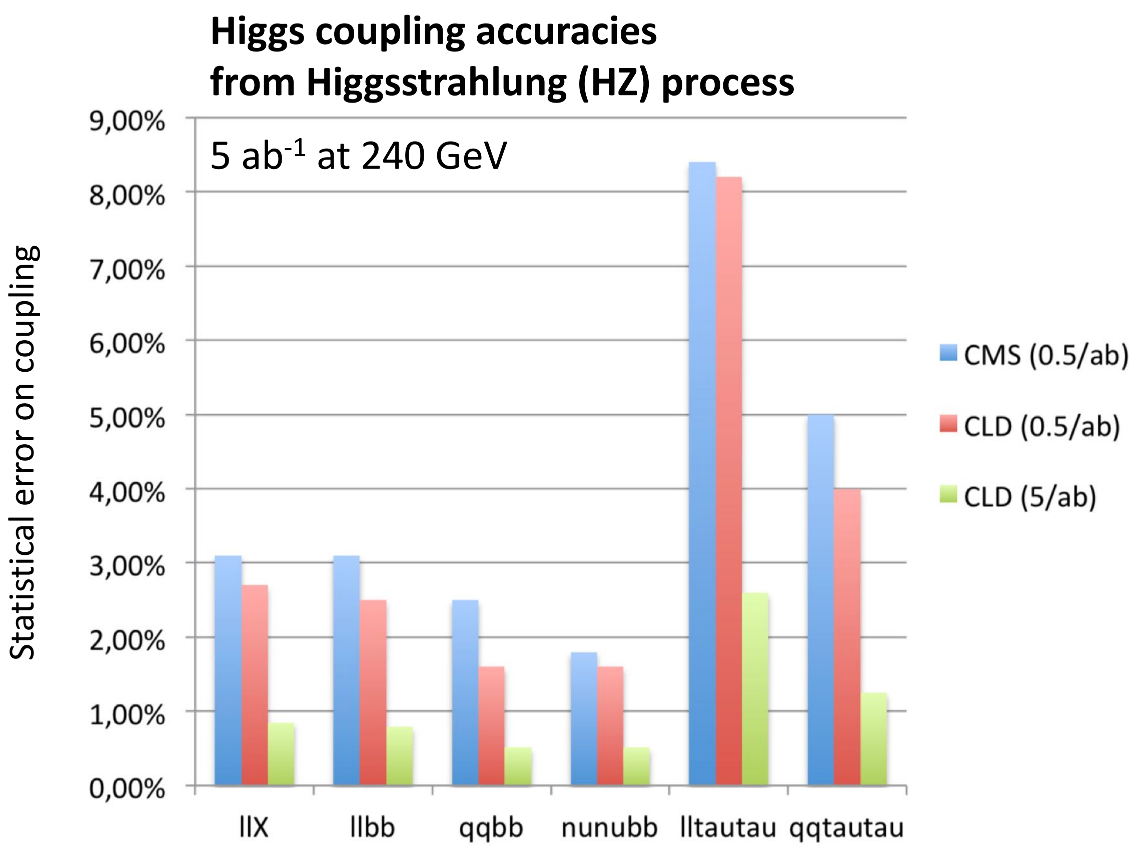


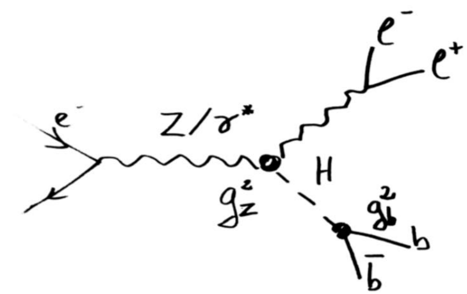
LHC-like fit, assuming SM decays only.
Fit to deviations from SM BR's

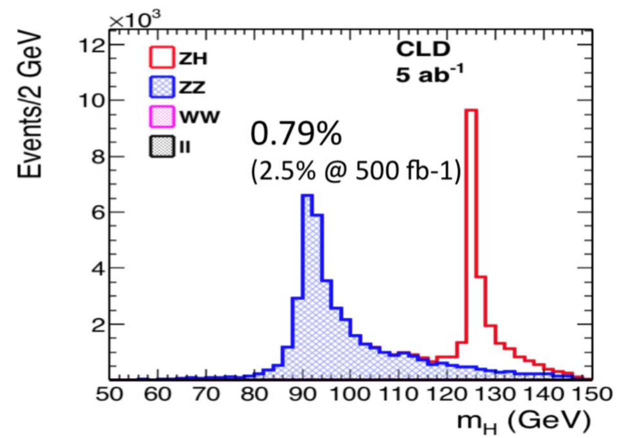
Accuracy significantly better than HL-LHC
Accuracy comparable to HL-LHC

FCC-ee Higgs measurements e^+e^-

Results based on PAPAS simulation
Parametrised method, using input from full simulation, includes Particle Flow aspects
Using CMS detector (earlier study) and FCC-ee CLD detector (recent)







[Colin Bernet, FCC week 2018]

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

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

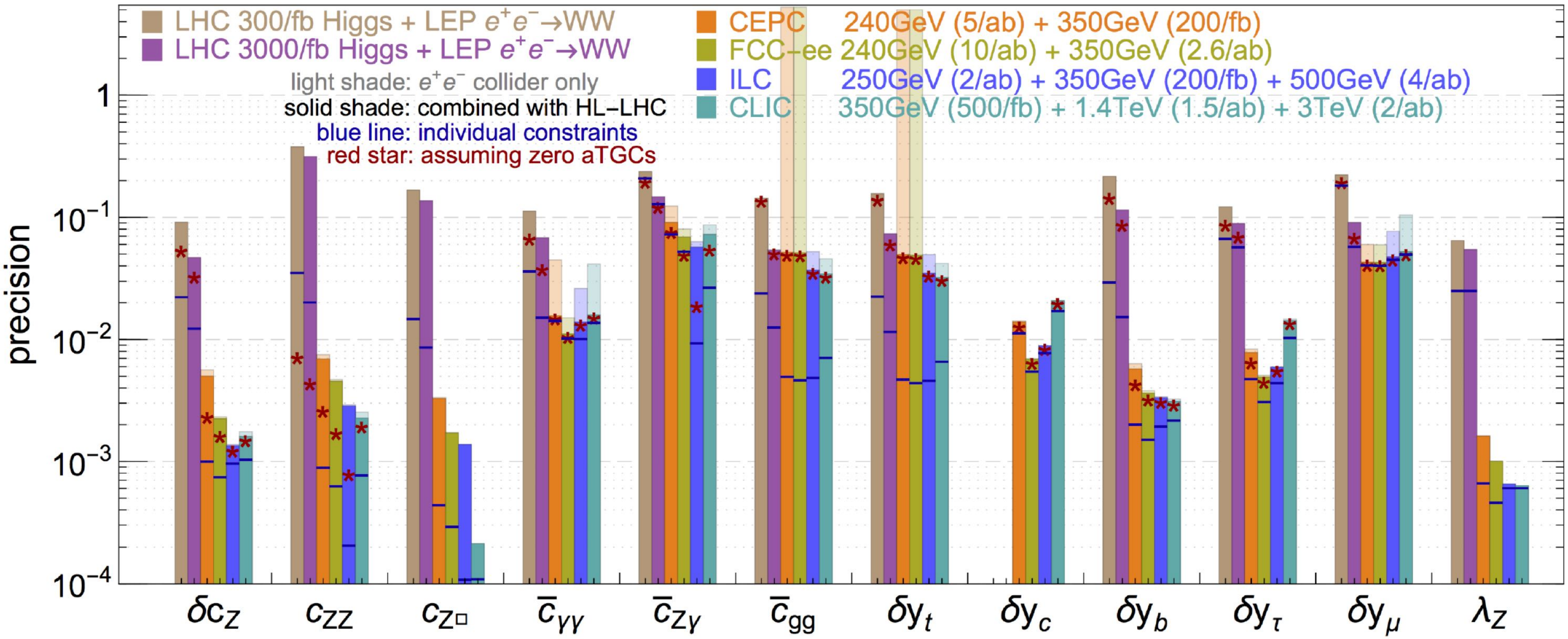
- Model-independent framework for probing indirect signs of new physics
  => useful for comparison of future collider options

- **Input to the fits**: Higgs production through HZ and WW fusion, $e^+e^- \rightarrow t\bar{t}H$, e^+e^- => W^+W^-

Complementarity between collider options

12-parameter fits on Higgs physics basis

(For e^+e^-: Higgs production through HZ and WW fusion, e^+e^- ➔ ttH, e^+e^- ➔ W^+W^-)

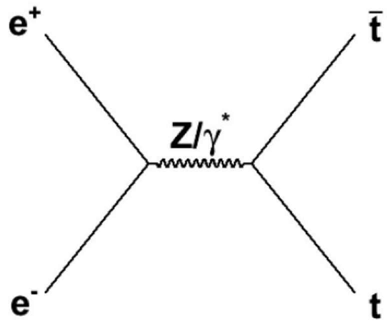


- Many EFT parameters can be measured significantly better with e^+e^- than with pp
- H➔$c\bar{c}$ only accessible at lepton colliders

arXiv:1704.02333

See also JHEP 1705, 096 (2017)

e^+e^- top quark physics examples



Threshold scan

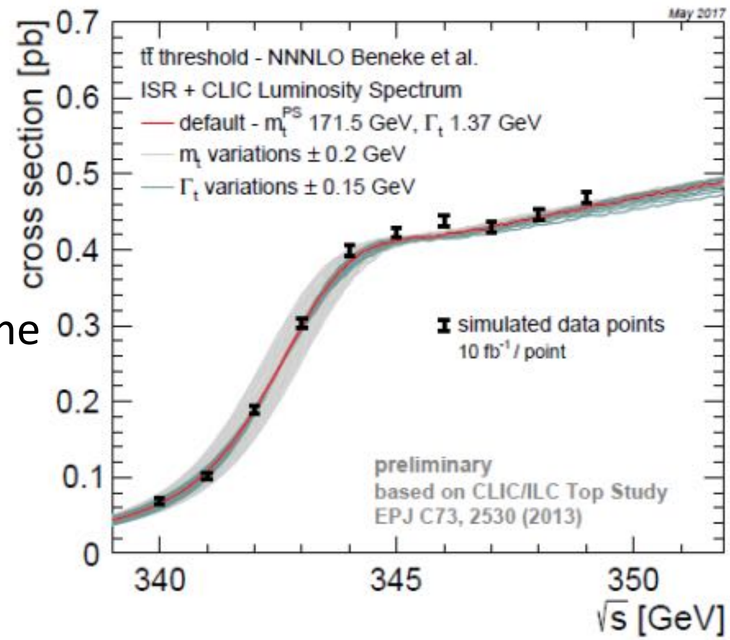
~100 fb^{-1} around 350 GeV

1S mass precision ~50 MeV

Dominated by theory scale NNNLO

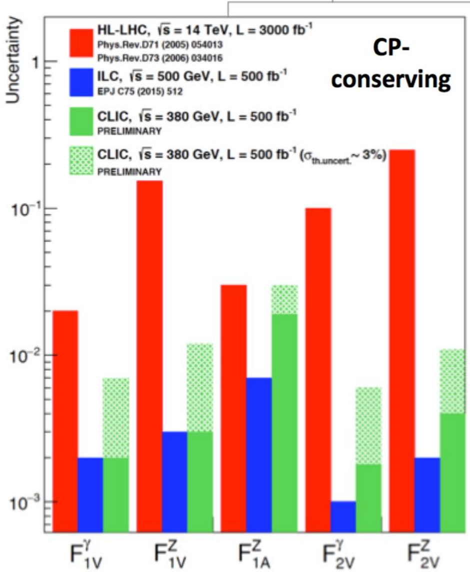
10 MeV uncertainty 1S to $\overline{MS}$ scheme

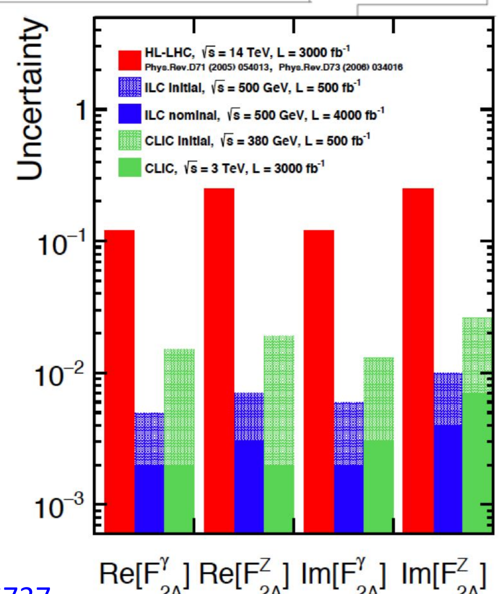
Phys. Rev. Lett. 114, 42002 (2015)



Expected coupling precision at LHC, ILC (500 GeV) and CLIC (380 GeV, 3 TeV)

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





arXiv:1608.07537 arXiv:1710.06737

Anomalous couplings

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

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

e^+e^- results of SUSY benchmarks

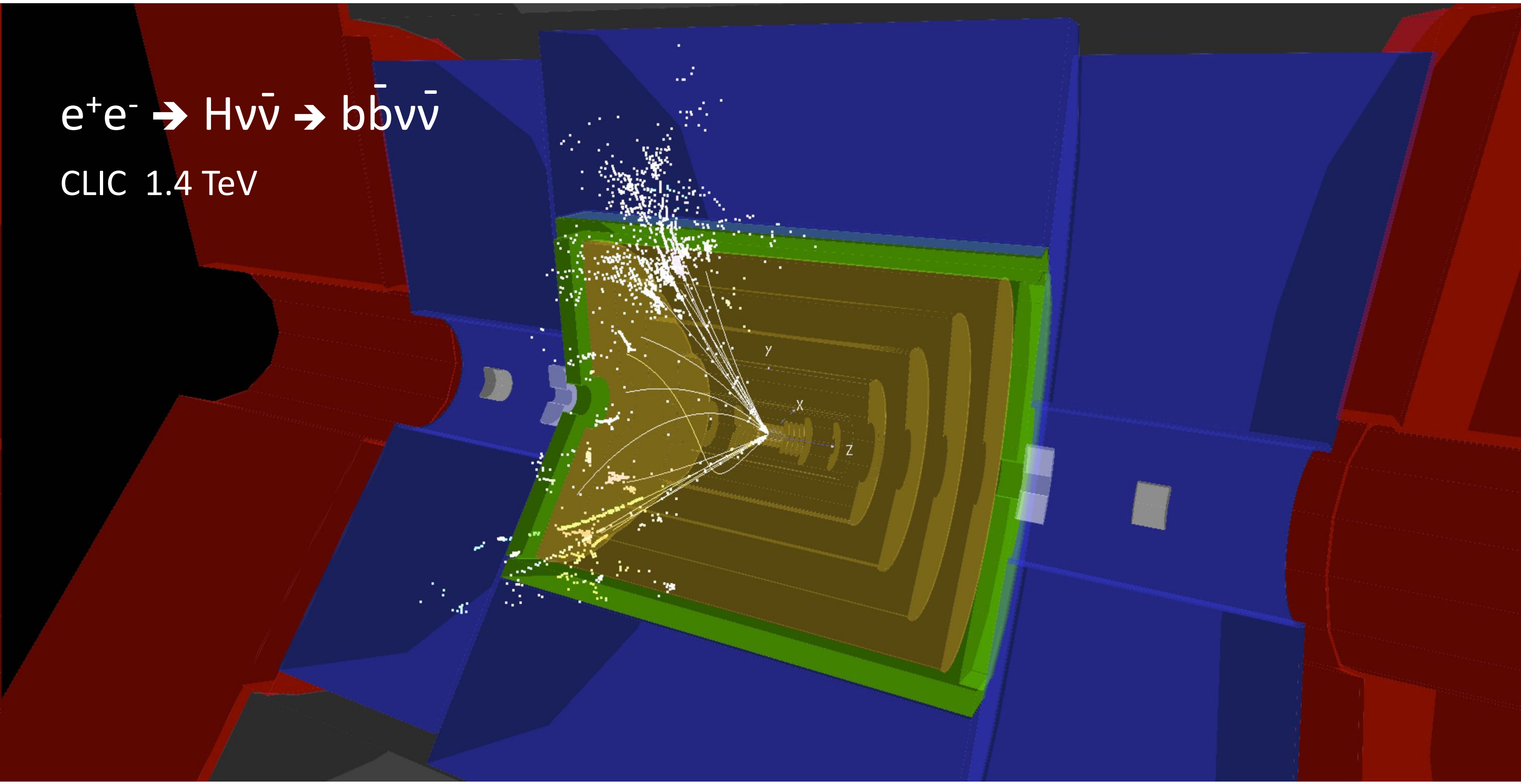
Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

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

CERN-2012-007

THANK YOU !



$H \rightarrow b\bar{b}$ (58% BR): selection efficiency ~40% (1.4 TeV), ~50% (380 GeV)

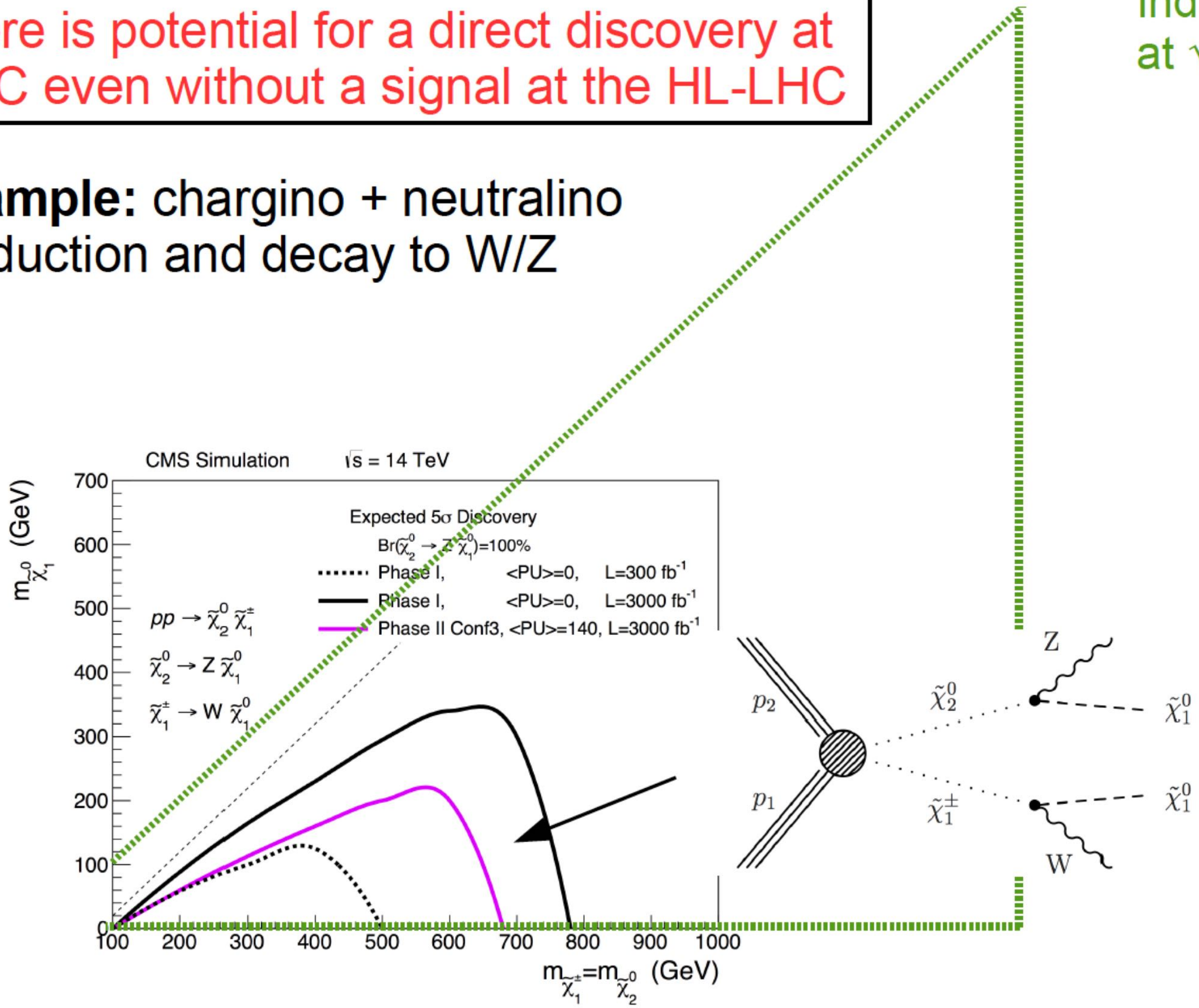
RESERVE SLIDES

heavy electroweak states (1)

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

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

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



CMS-PAS-FTR-13-014

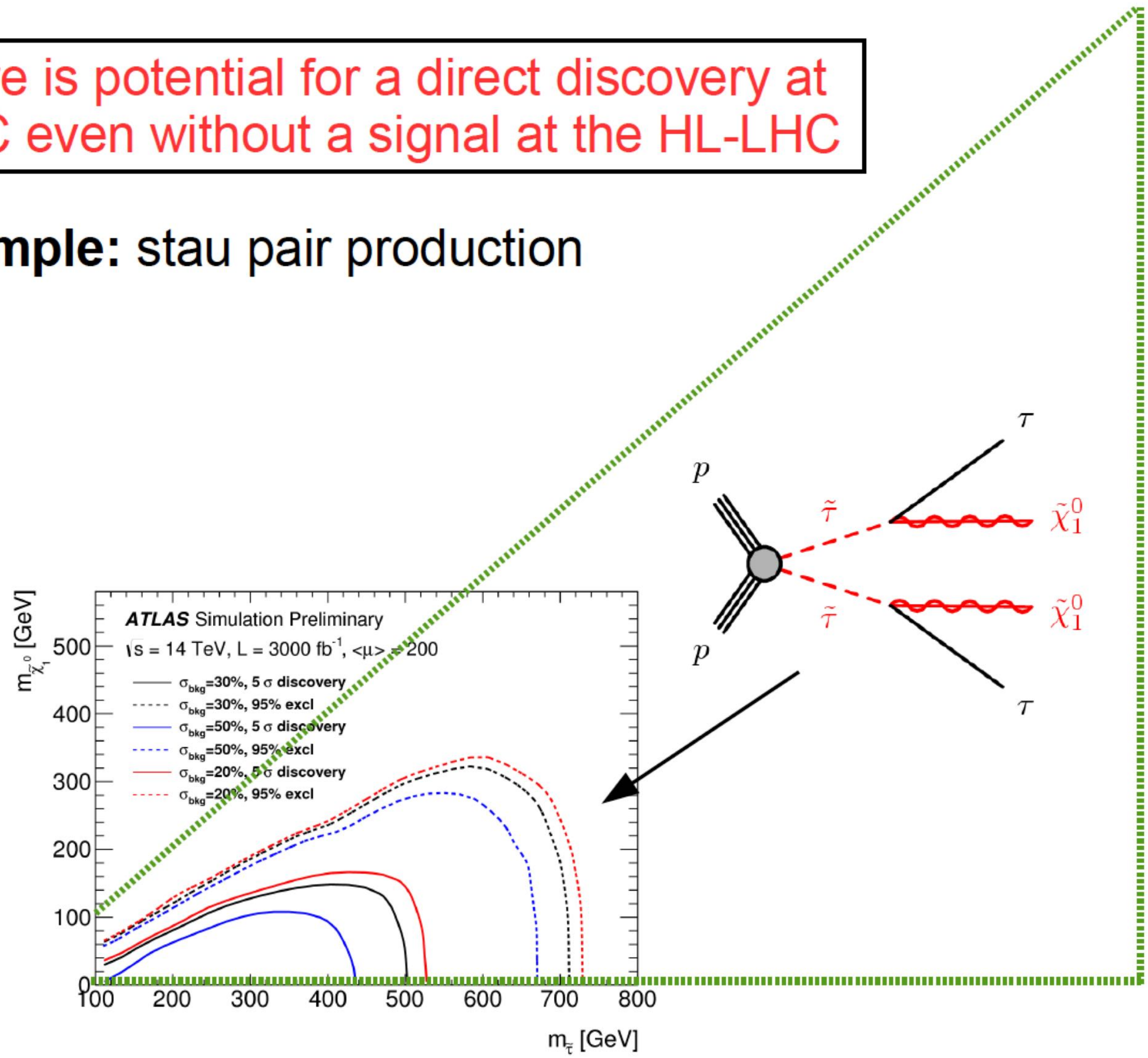
(similar projection: ATL-PHYS-PUB-2014-010)

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

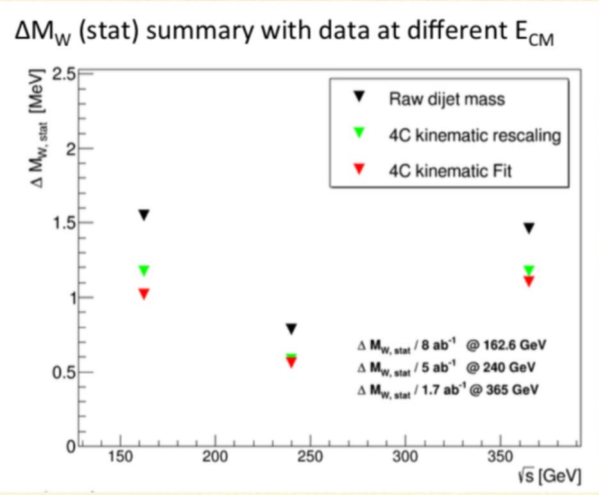


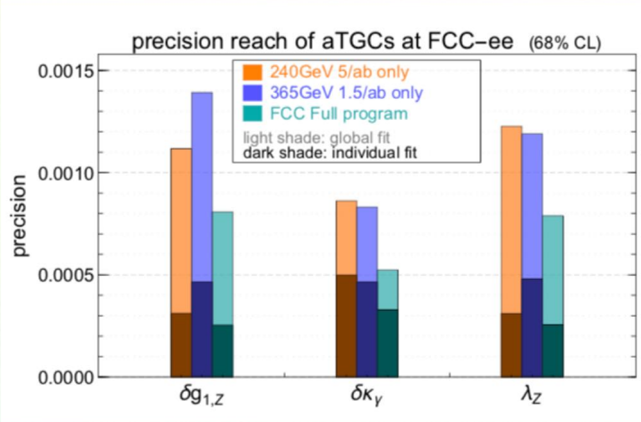
ATLAS-PHYS-PUB-2016-021

FCC-ee electroweak physics

EWK

- Integrated luminosity goals for Z and W physics
  - 150 ab^{-1} around the Z pole (~ 25 ab–1 at 88 and 94 GeV, 100 ab–1 at 91 GeV)
  - 10 ab^{-1} around the WW threshold (161 GeV with ±few GeV scan)
  - runs at 240 and at 350-365 GeV very important for WW physics as well
- **FCC-ee program will bring improvement of 1 to 2 orders of magnitude in precision of EWPO**
- New at this collaboration meeting:
  - Direct M(W) reconstruction in the 4-jet channel to be used above the WW threshold region. ΔM(W)=0.5MeV (stat) with 5ab^{-1} at $\sqrt{s}$=240 GeV
  - Study of TGC (leptonic mode only) shows a precision achievable of $O(10^{-3})$!

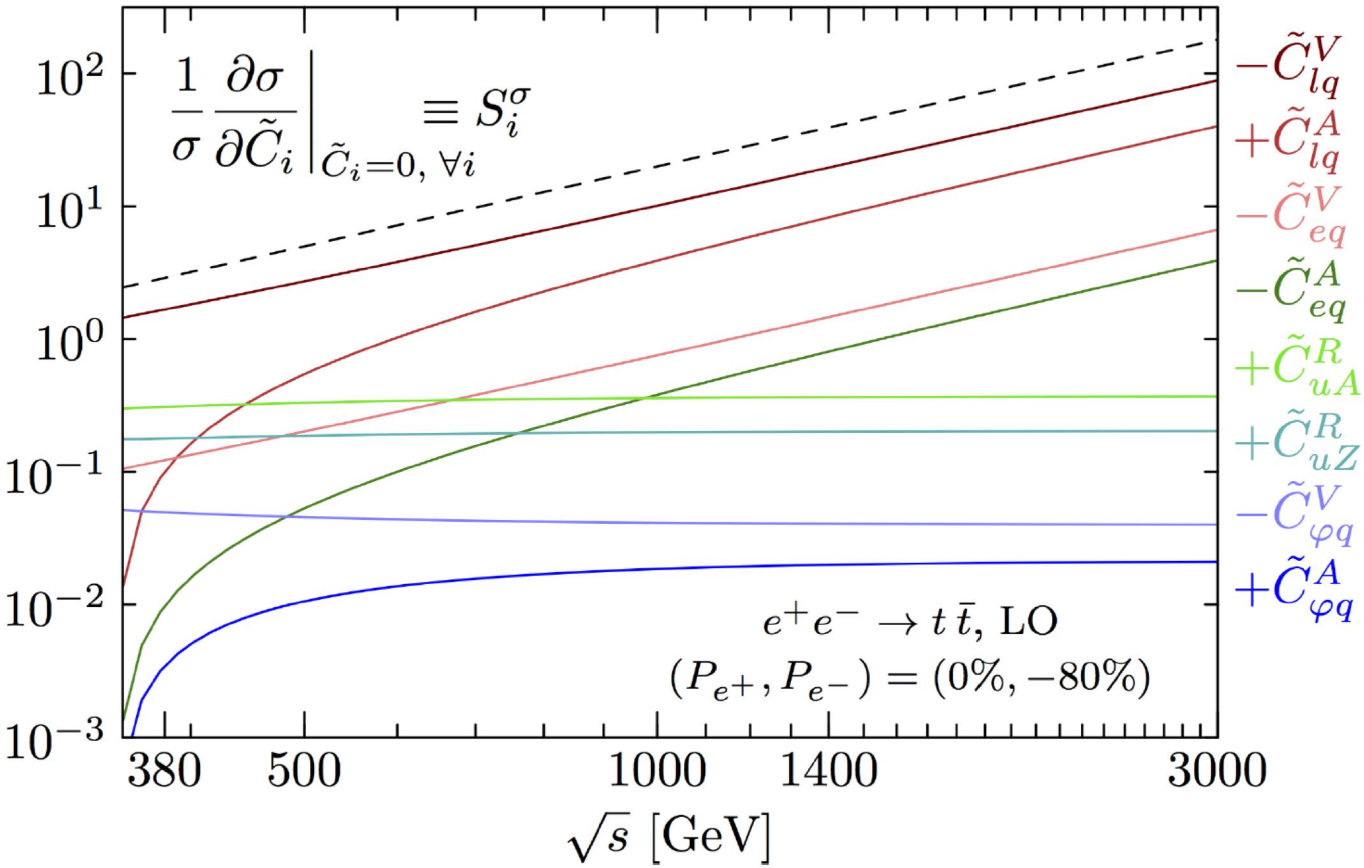




Patrizia Azzi, FCC week 2018

electroweak couplings to top at high √s

Studied at generator level in a *dimension-6 operator approach* (instead of Form Factor approach)



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

Vertex operators:
Sensitivity flat in E
→ best measured at 380 GeV stage
(most tt events)

Durieux, Perello, Vos, Zhang to be published

=> Full detector simulation studies of $t\bar{t}$ production at 1.4 TeV, 3 TeV are ongoing

CLIC BSM discovery reach

New particle / phenomenon	Unit	CLIC reach
Sleptons, charginos, neutralinos, sneutrinos	TeV	≈1.5 TeV
Z' (SM couplings)	TeV	20
2 extra dimensions M_D	TeV	20-30
Triple Gauge Coupling (95%) (λ_γ coupling)		0.0001
Vector boson scattering $\Delta F_{S,0,1}$	TeV^{-4}	5
μ contact scale	TeV	60
Higgs composite scale	TeV	70
Electron size (test of QED extension)	cm	3.1×10^{-18}

CLIC discovery reach for BSM phenomena, studied for 2 ab^{-1} at 3 TeV. Depending on the exact models used, quoted values generally extend significantly beyond the HL-LHC reach.

Higgs Global Fit: Effect of Theory Uncertainties

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
κ_{HZZ}	0.6 %	0.4 %	0.3 %
κ_{HWW}	1.1 %	0.2 %	0.1 %
κ_{Hbb}	1.8 %	0.4 %	0.2 %
κ_{Hcc}	5.8 %	2.1 %	1.7 %
$\kappa_{H\tau\tau}$	3.9 %	1.5 %	1.1 %
$\kappa_{H\mu\mu}$	–	14.1 %	7.8 %
κ_{Htt}	–	4.1 %	4.1 %
κ_{Hgg}	3.0 %	1.5 %	1.1 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	3.1 %
$\kappa_{HZ\gamma}$	–	15.6 %	9.1 %
$\Gamma_{H,md,derived}$	1.4 %	0.4 %	0.3 %

MD fit w/o theory uncertainties

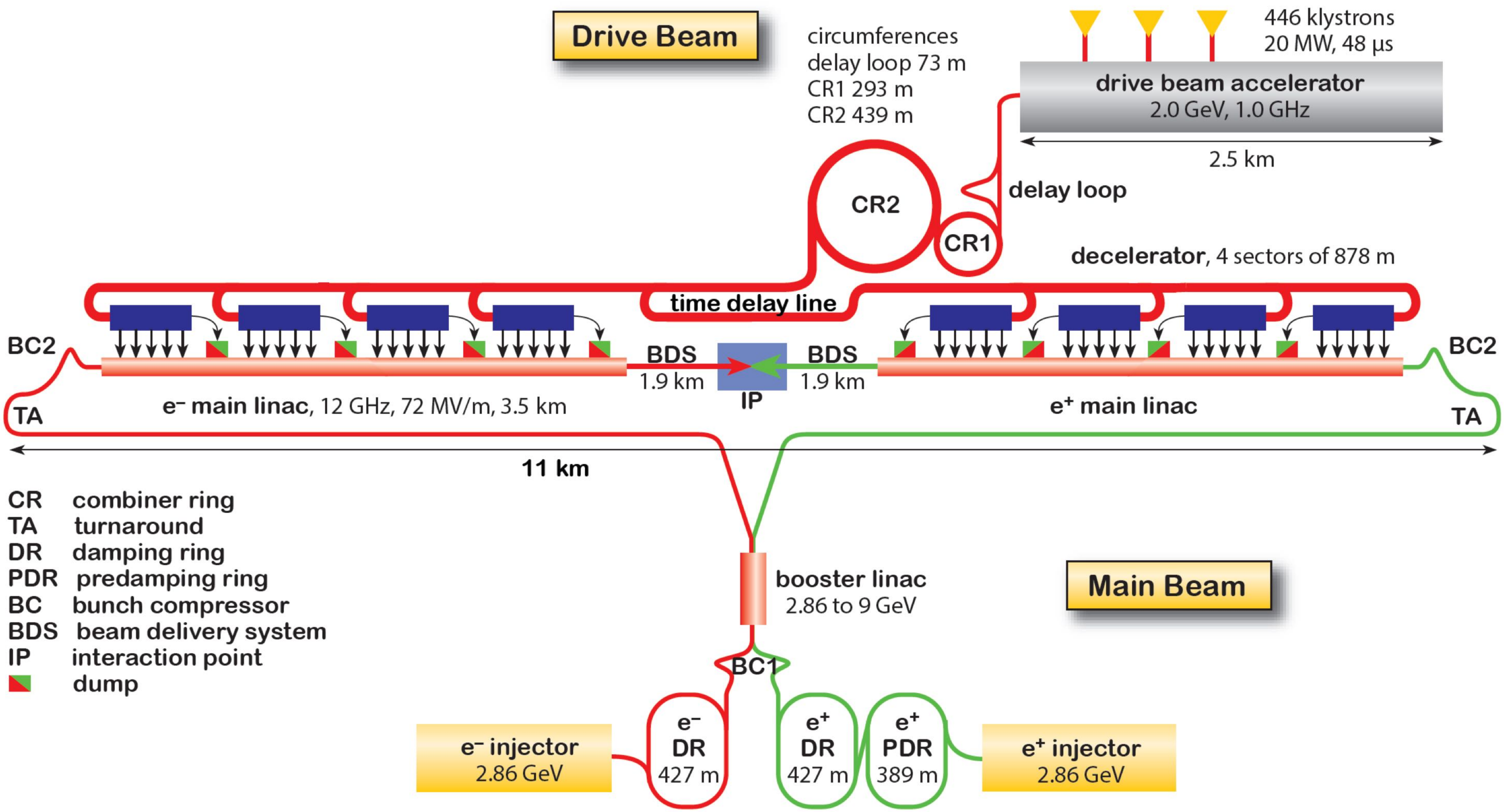
κ_{HZZ}	0.6 %	0.5 %	0.5 %
κ_{HWW}	1.2 %	0.5 %	0.5 %
κ_{Hbb}	2.6 %	1.5 %	1.4 %
κ_{Hcc}	6.3 %	3.2 %	2.9 %
$\kappa_{H\tau\tau}$	4.2 %	2.1 %	1.8 %
$\kappa_{H\mu\mu}$	–	14.2 %	7.9 %
κ_{Htt}	–	4.2 %	4.1 %
κ_{Hgg}	5.1 %	4.0 %	3.9 %
$\kappa_{H\gamma\gamma}$	–	5.9 %	3.5 %
$\kappa_{HZ\gamma}$	–	16.0 %	9.8 %
$\Gamma_{H,md,derived}$	2.0 %	1.1 %	1.1 %

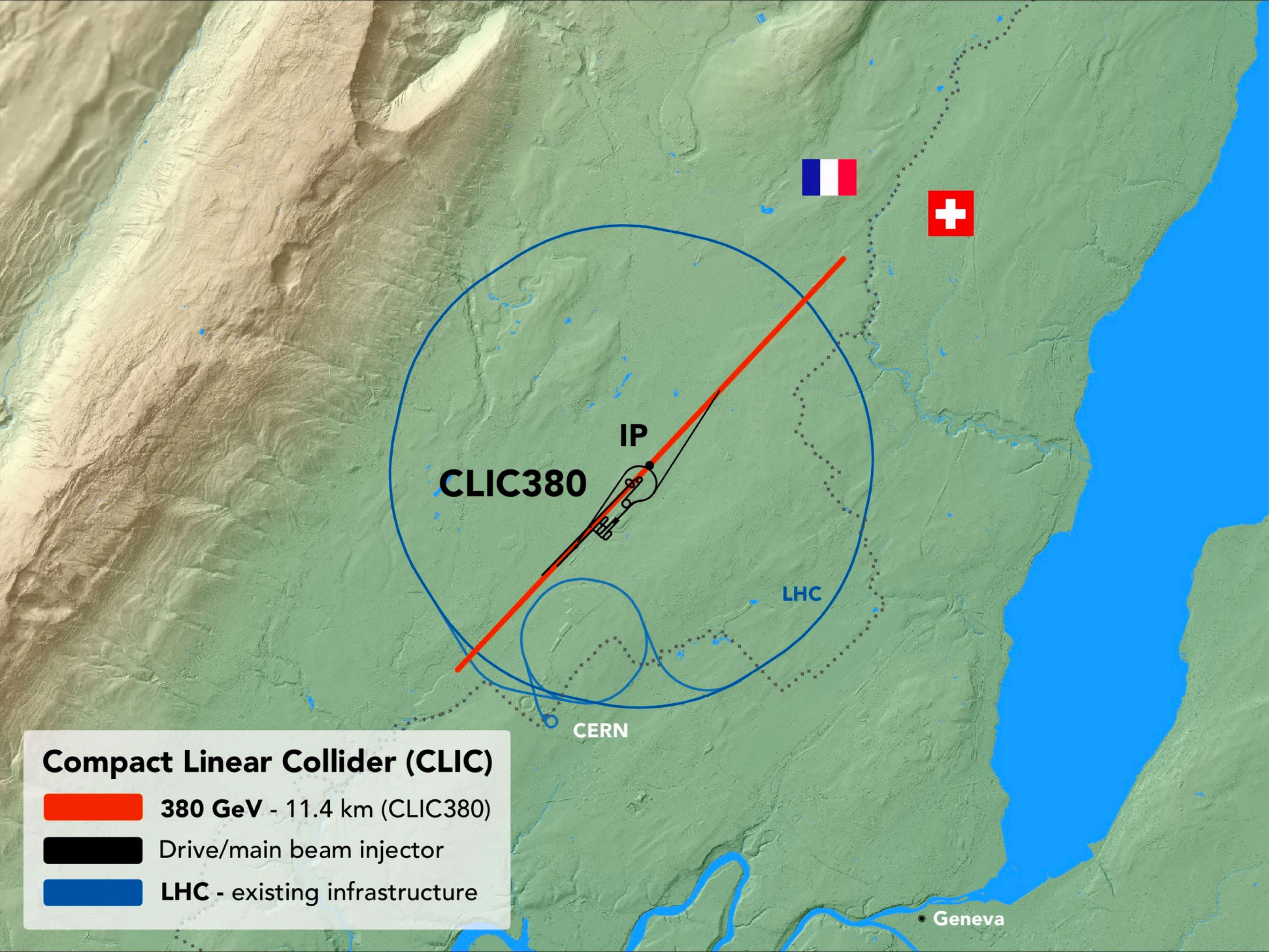
MD fit with theory uncertainties

decay mode	theo. uncertainty
ZZ	2.1 %
WW	2.1 %
γγ	2.8 %
Zγ	6.8 %
bb	1.8 %
cc	4.6 %
gg	7.2 %
ττ	2.3 %
μμ	2.4 %

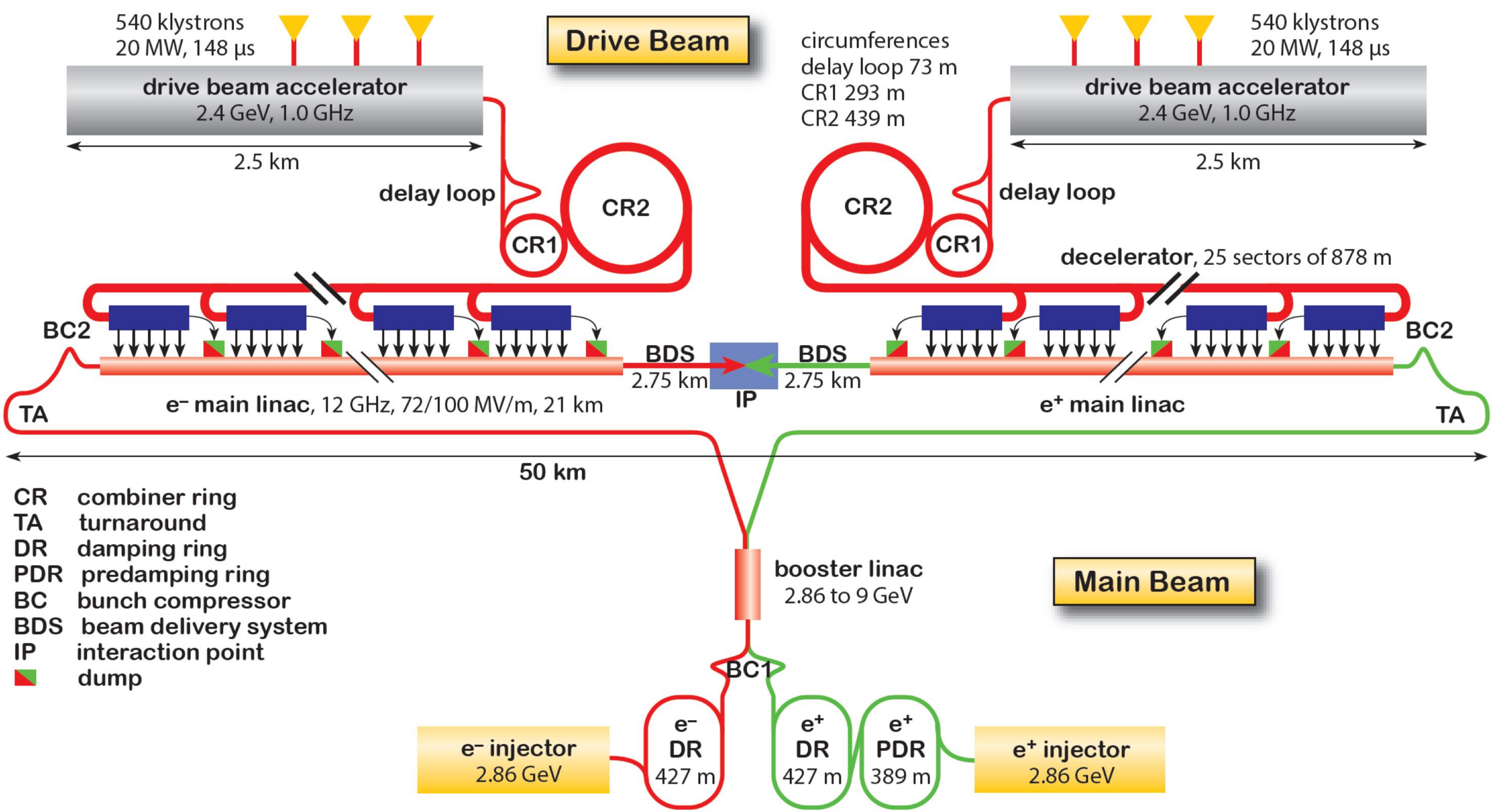
- Uncertainties from LHCHXSWG, combined theory and parametric (quark mass, α_s) uncertainties, symmetrized to preserve fit means

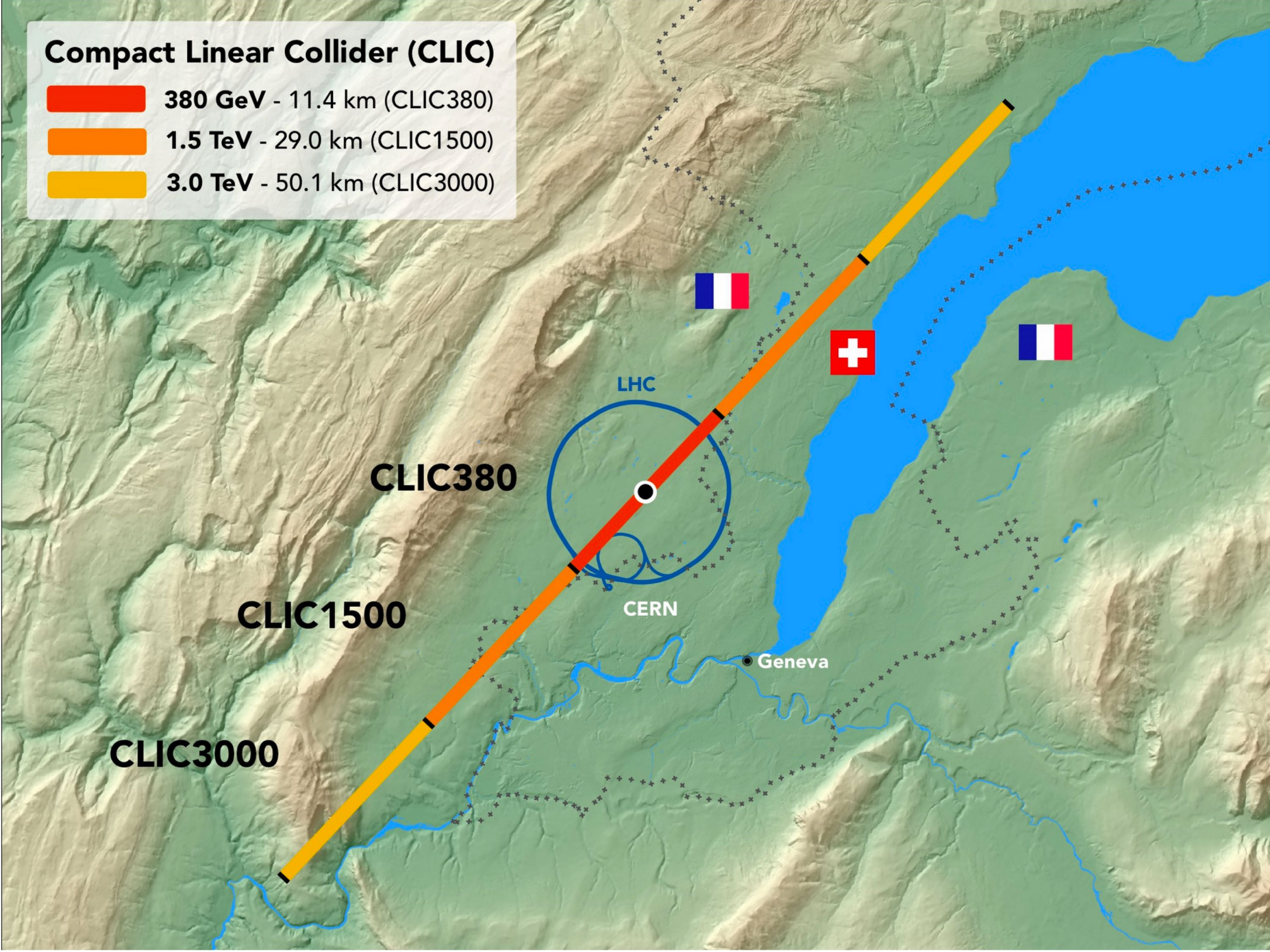
CLIC layout at 380 GeV




IP
CLIC380
LHC
CERN
Geneva
Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
Drive/main beam injector
LHC - existing infrastructure

CLIC layout at 3 TeV

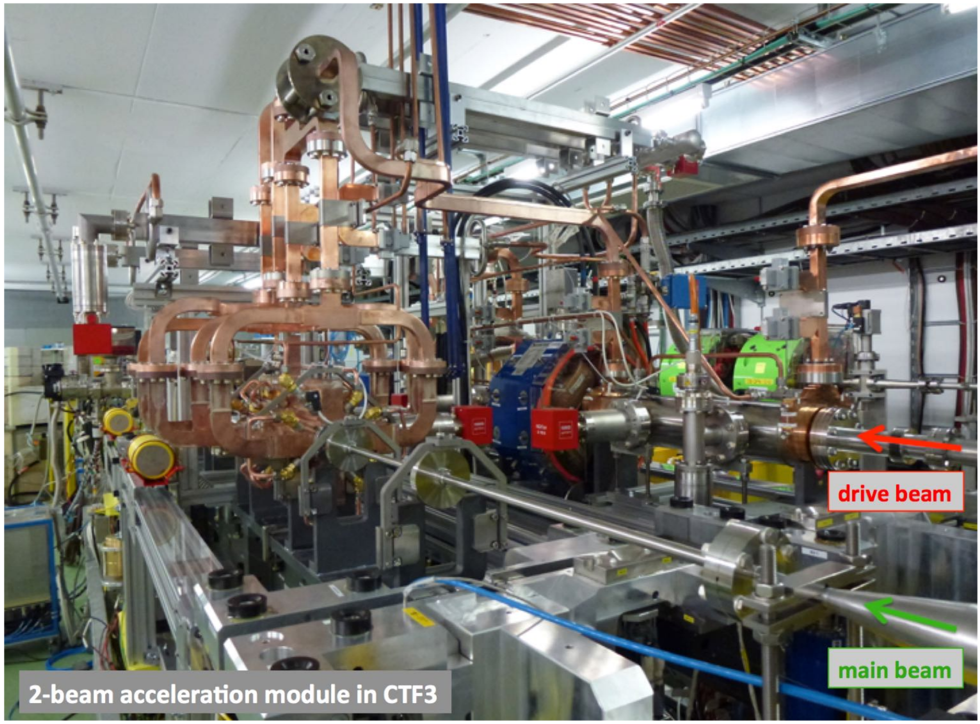



Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

CLIC test facility CTF3

CTF3 successfully demonstrated:

- ✓ drive beam generation
- ✓ RF power extraction
- ✓ two-beam acceleration up to a gradient of 145 MeV/m



experimental conditions e^+e^-

Linear Colliders

- **Beam-induced background**:
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - High occupancies in the detector => small readout cells needed
  - Precise (ns-level) timing required at CLIC
- **Low duty cycle**
  - Power pulsing of electronics possible
  - Triggerless readout
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)

Circular Colliders

- **Beam-induced background**
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - Synchrotron radiation
- **Circulating beams**
  - Maximum detector solenoid field of 2 T => need to increase tracker radius
  - Complex magnet shielding schemes
  - Beam focusing quadrupole closer to IP (~2.2m)
  - No power pulsing
- **High luminosity and many bunches at Z pole**
  - Moderate requirements on detector timing, high data rates

experimental conditions future pp colliders

Experimental conditions for a ~100 TeV pp collider have much in common with conditions as we know them from HL-LHC.

Challenge: preserve overall detector performance, despite huge pile up, high energies, very forward-going physics and high radiation conditions

A few extra remarks:

- Compared to HL-LHC, **radiation levels** increase in proportion to the luminosity
- Particles (e.g. Higgs) have more **forward boost**:
  - => precision tracking needed down η=4, θ=2° (η=2.5, 2.5° at LHC)
  - => calorimetry down to η=6, θ≈0.5°
- Aim for track resolution of 10-15% up to p_T of 10 TeV
  - => central solenoid 4 T with inner radius 5 m, track hit resolution ~10 µm
  - Forward solenoids are needed to increase angular coverage

Pile up of 1000 events?

- FCC-hh average distance at z=0 between events is 170 µm, 0.5 ps (1mm, 3 ps at HL-LHC)
- For tracks at η>1.7, multiple scattering effect due to 0.8 mm Be beam pipe is larger than average distance between two interaction vertices !
- Fine grained calorimetry required to help resolving pile up
- Excellent time (few ps) resolution required

better ask accelerator for 5 ns bunch spacing