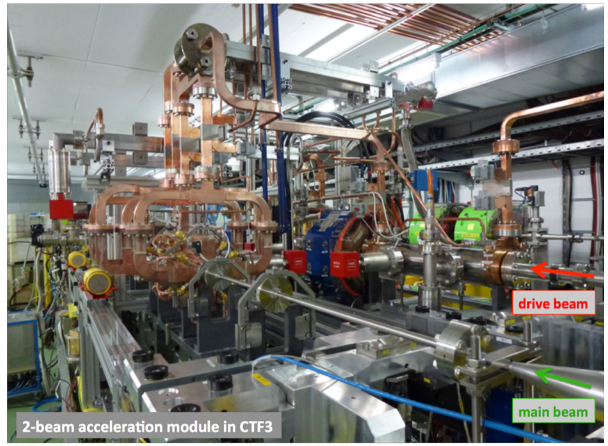
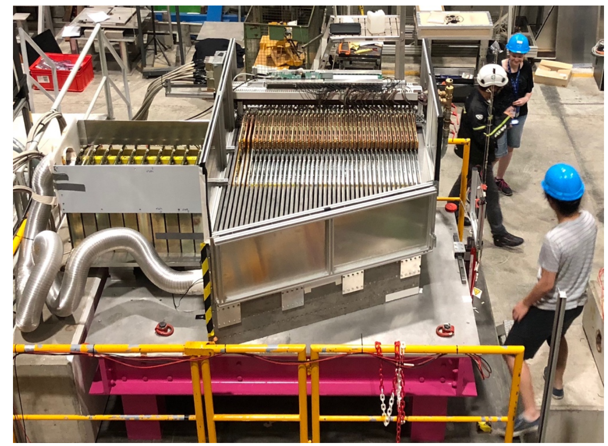
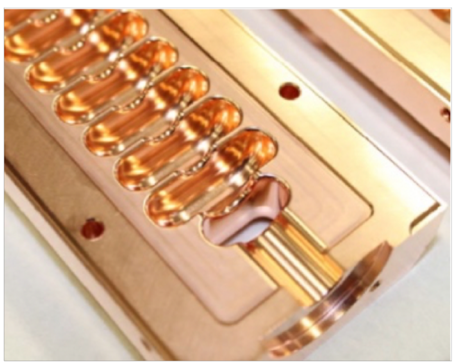
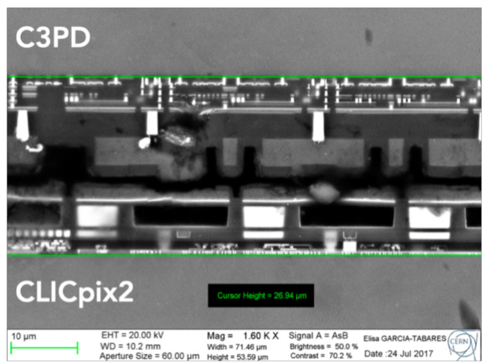
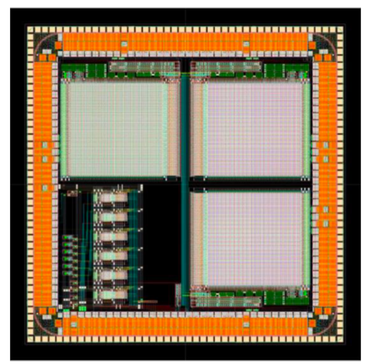
A detector for CLIC

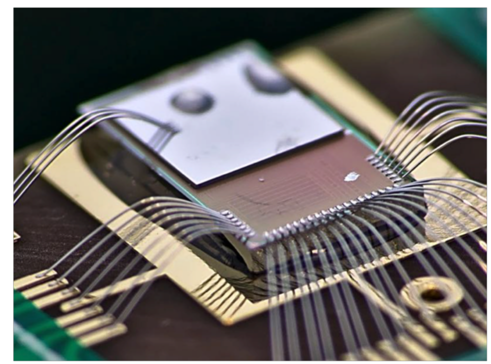












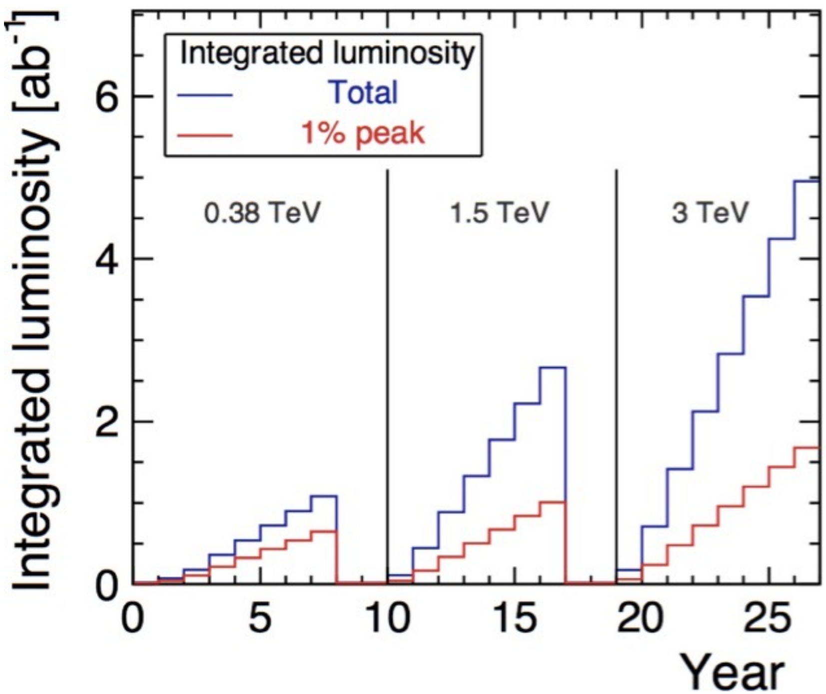
Lucie Linssen, CERN
on behalf of the CLICdp collaboration

CLIC physics and staged operation

Linear e^+e^- collider, staging scenario motivated by maximum physics output

380 GeV (350 GeV) :	precision Higgs and top physics
1.5 TeV :	BSM searches, precision Higgs, ttH, HH, top physics
3 TeV :	BSM searches, precision Higgs, HH, top physics

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



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

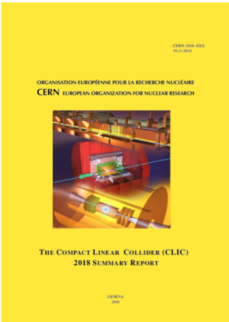
Polarised electron beam (–80%, +80%)

Ratio (50:50) at $\sqrt{s}$=380GeV ; (80:20) at $\sqrt{s}$=1.5 and 3TeV

Coherent approach for CERN future colliders (running times, luminosity performance)

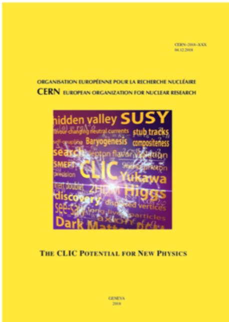
1.2×10^7 sec/year arXiv:1810.13022, Bordry et al.

Recent CLIC overview documents



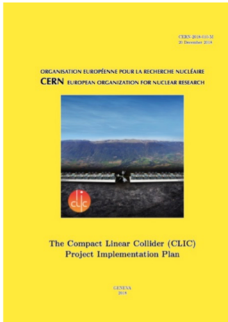
CERN-2018-005-M

http://dx.doi.org/10.23731/CYRM-2018-002



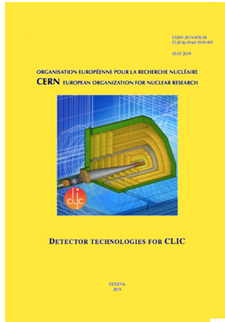
CERN-2018-009-M

http://dx.doi.org/10.23731/CYRM-2018-003



CERN-2018-010-M

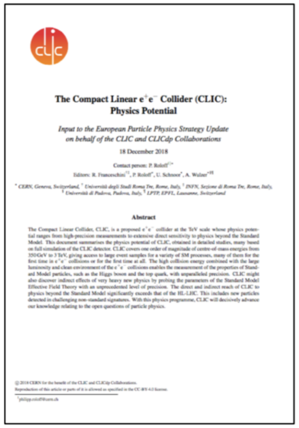
http://dx.doi.org/10.23731/CYRM-2018-004



in collaboration review

Covering: Accelerator
Detector
Physics

Links: http://clic.cern/european-strategy



CLIC accelerator collaboration

CLICdp collab. (det&phys)

clic.cern

Formal European Strategy submissions

- **The Compact Linear e+e- Collider (CLIC): Accelerator and Detector** (arXiv:1812.07987)
- **The Compact Linear e+e- Collider (CLIC): Physics Potential** (arXiv:1812.07986)

Yellow Reports

- **CLIC 2018 Summary Report** (CERN-2018-005-M, arXiv:1812.06018)
- **CLIC Project Implementation Plan** (CERN-2018-010-M)
- **The CLIC potential for new physics** (CERN-2018-009-M, arXiv:1812.02093)
- **Detector technologies for CLIC** [In collaboration review]

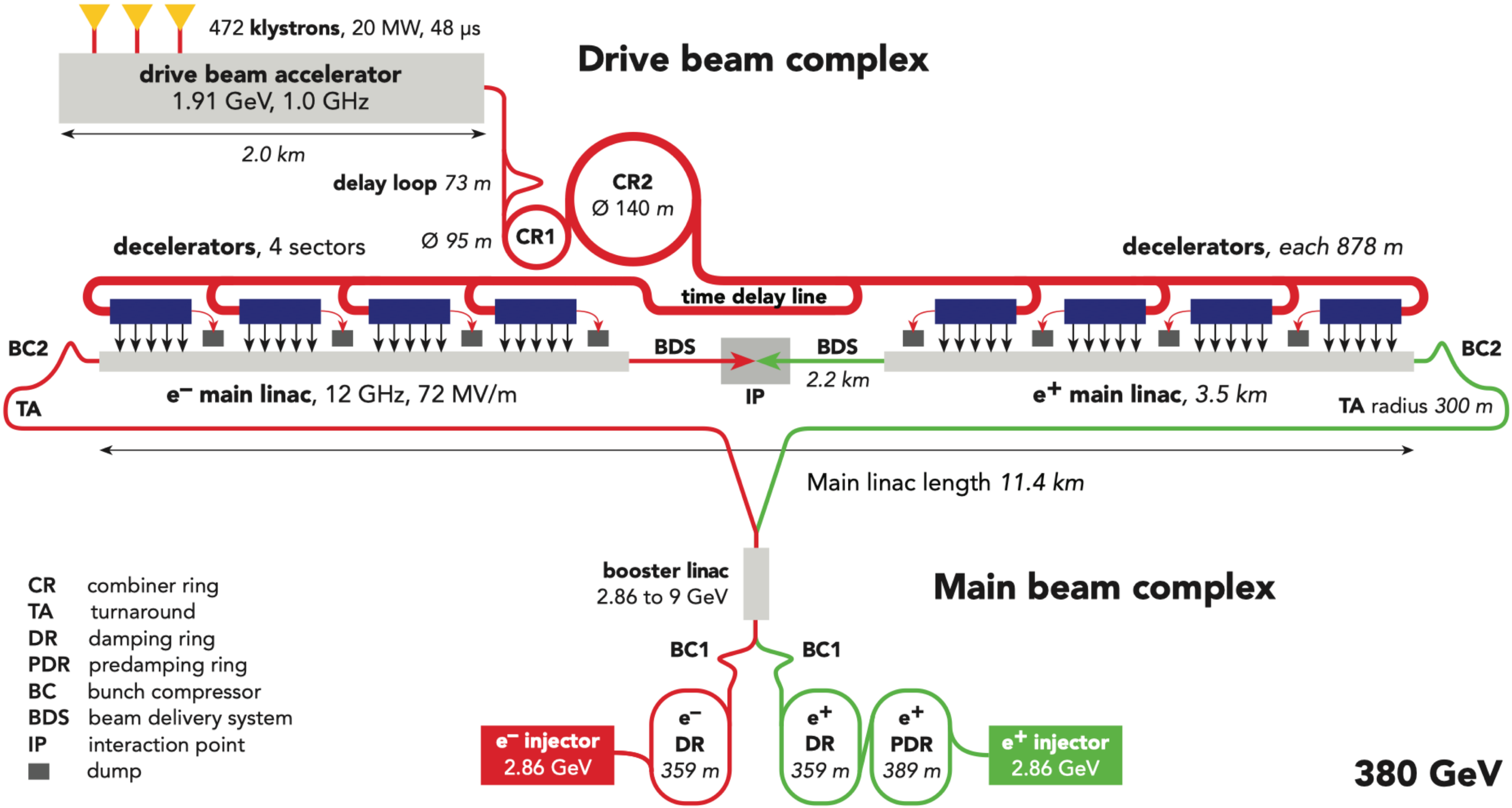
Journal publications

- **Top-quark physics at the CLIC electron-positron linear collider** [In journal review] (arXiv:1807.02441)
- **Higgs physics at the CLIC electron-positron linear collider** (Journal, arXiv:1608.07538)
  - Projections based on the analyses from this paper scaled to the latest assumptions on integrated luminosities can be found here: CDS, arXiv.

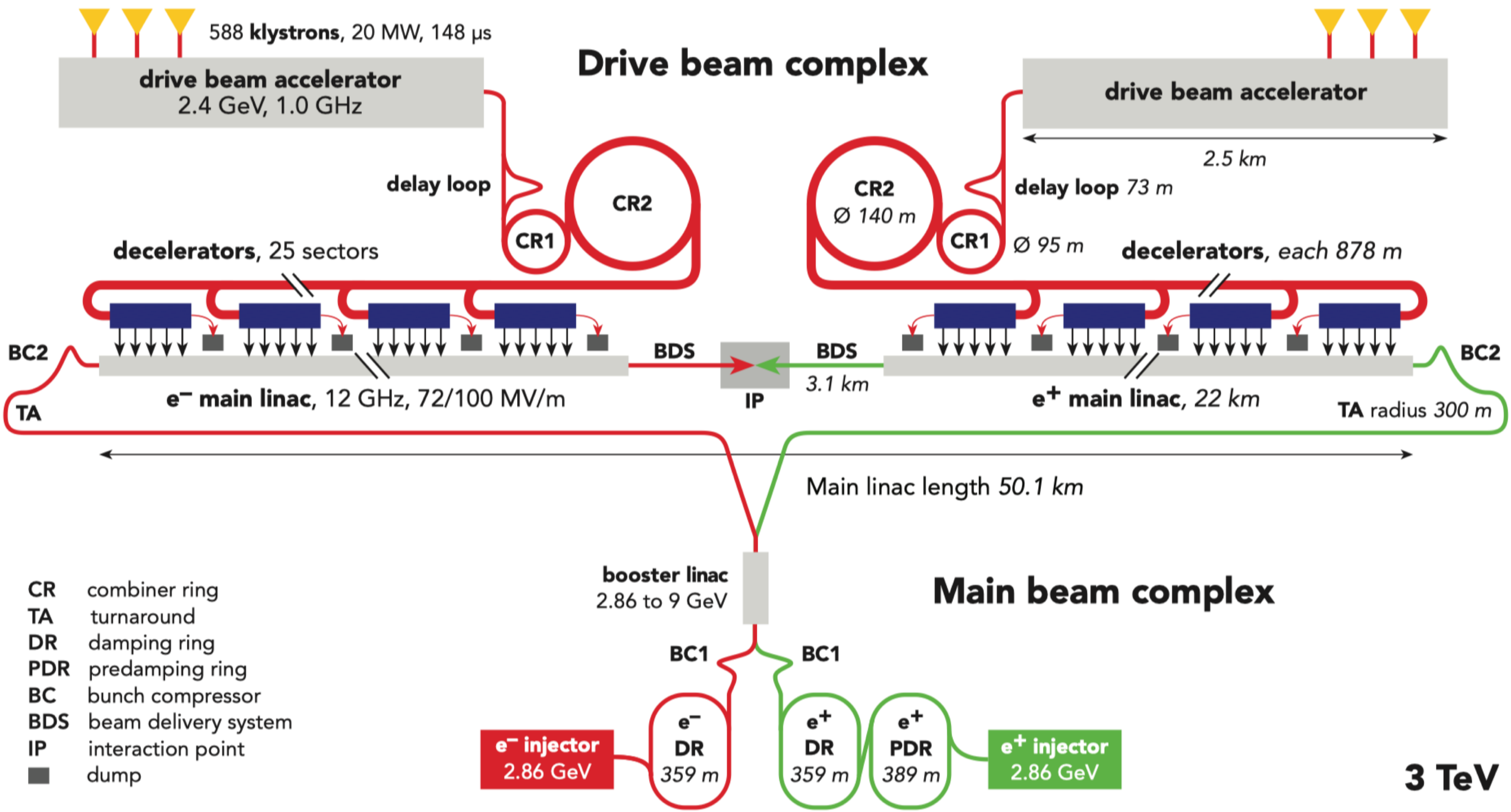
CLICdp notes

- **Updated CLIC luminosity staging baseline and Higgs coupling prospects** (CERN Document Server, arXiv:1812.01644)
- **CLICdet: The post-CDR CLIC detector model** (CERN Document Server)
- **A detector for CLIC: main parameters and performance** (CERN Document Server, arXiv:1812.07337)

CLIC complex, 380 GeV



CLIC complex, 3 TeV



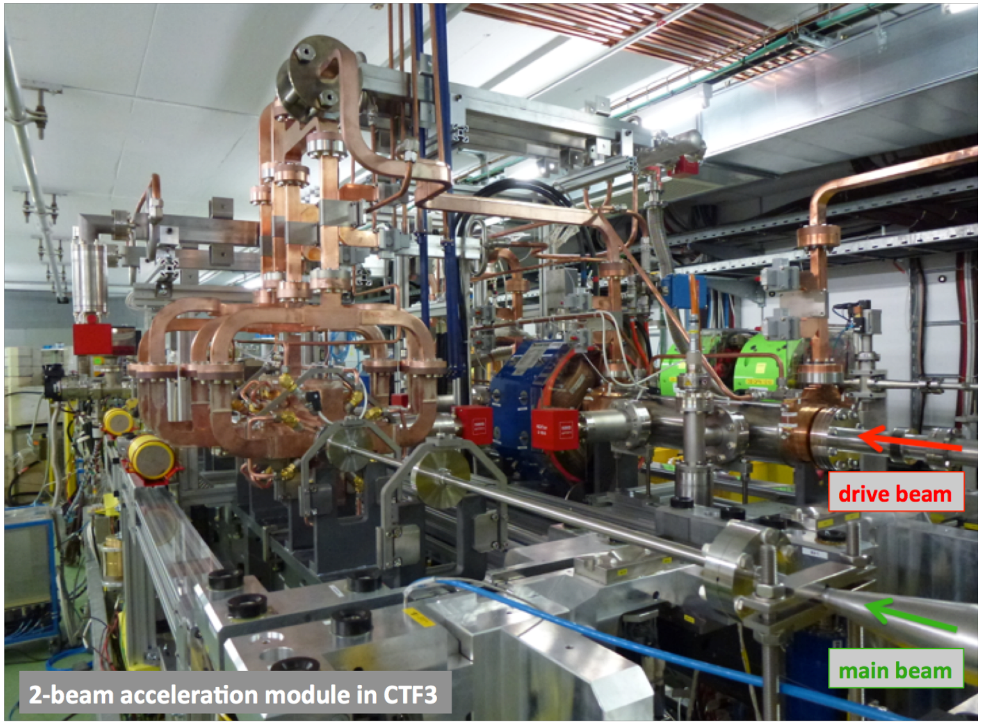
overview of CLIC parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\mathrm{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

arXiv:1812.06018

readiness of CLIC technology

Many simulations, large diversity of hardware tests, system tests at many labs…
→ *beyond the scope of this talk*



E.g. CTF3 successfully demonstrated:

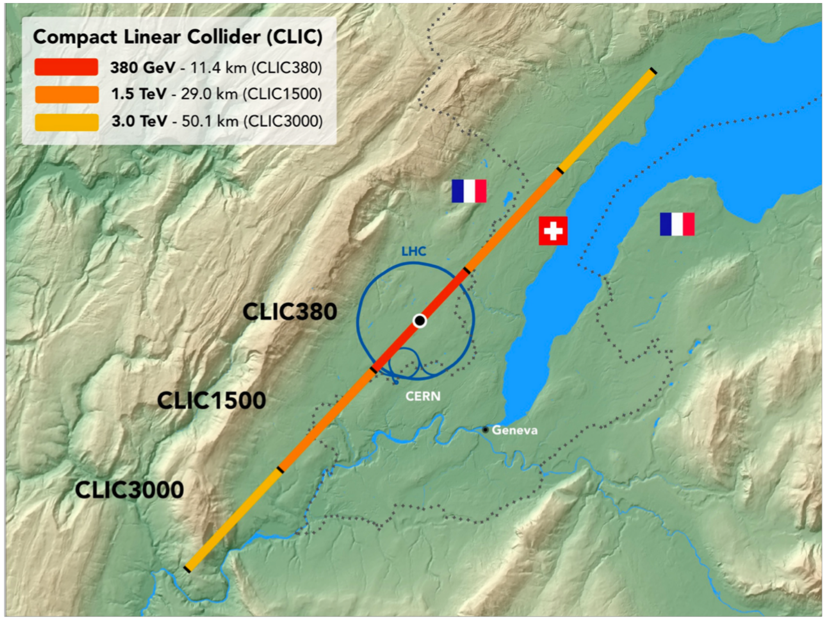
- ✓ drive beam generation
- ✓ RF power extraction
- ✓ two-beam acceleration up to a gradient of 145 MeV/m

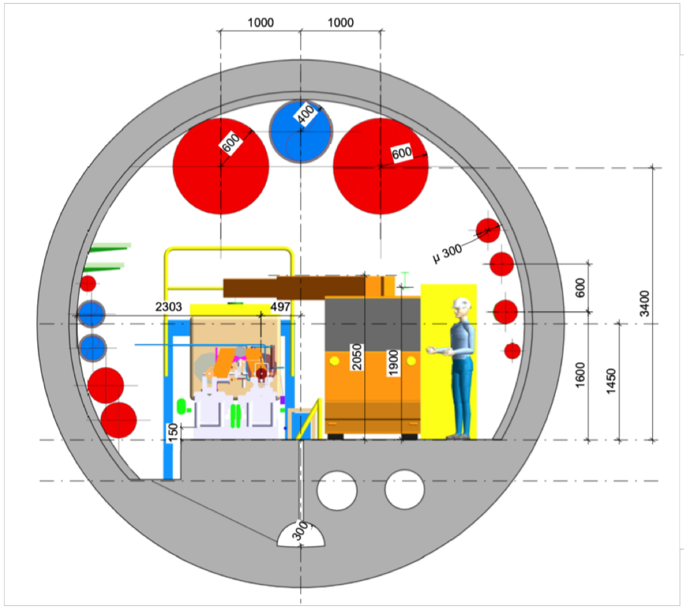
civil engineering and infrastructure

Detailed recent updates on:

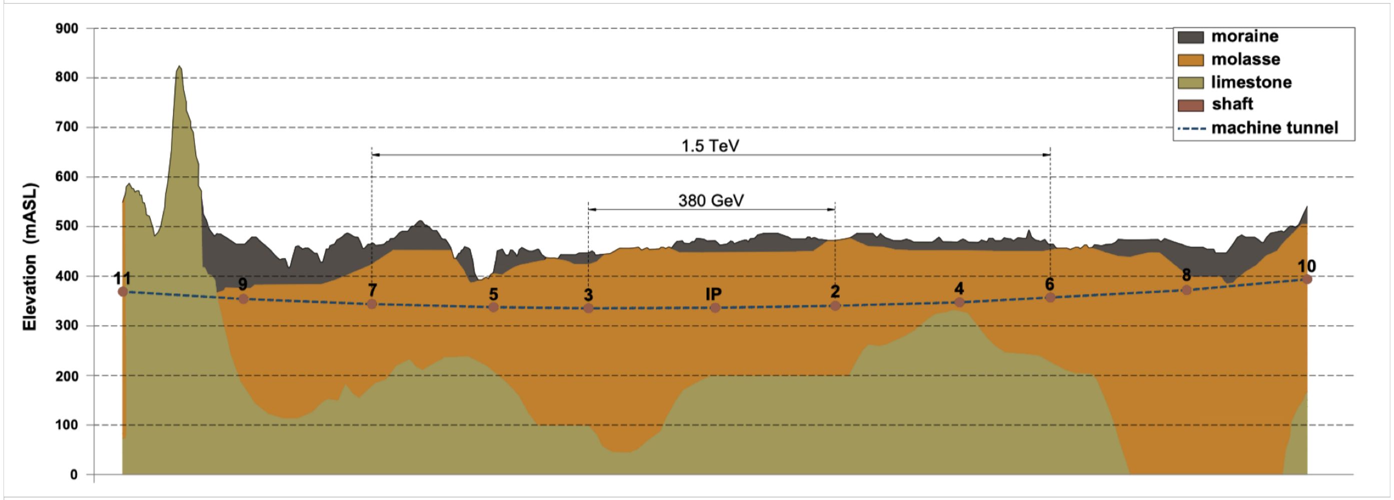
- Civil engineering
- Electrical systems
- Cooling and ventilation
- Transport, logistics and installation
- Safety, access and radiation protection systems

Crucial for cost/power/schedule





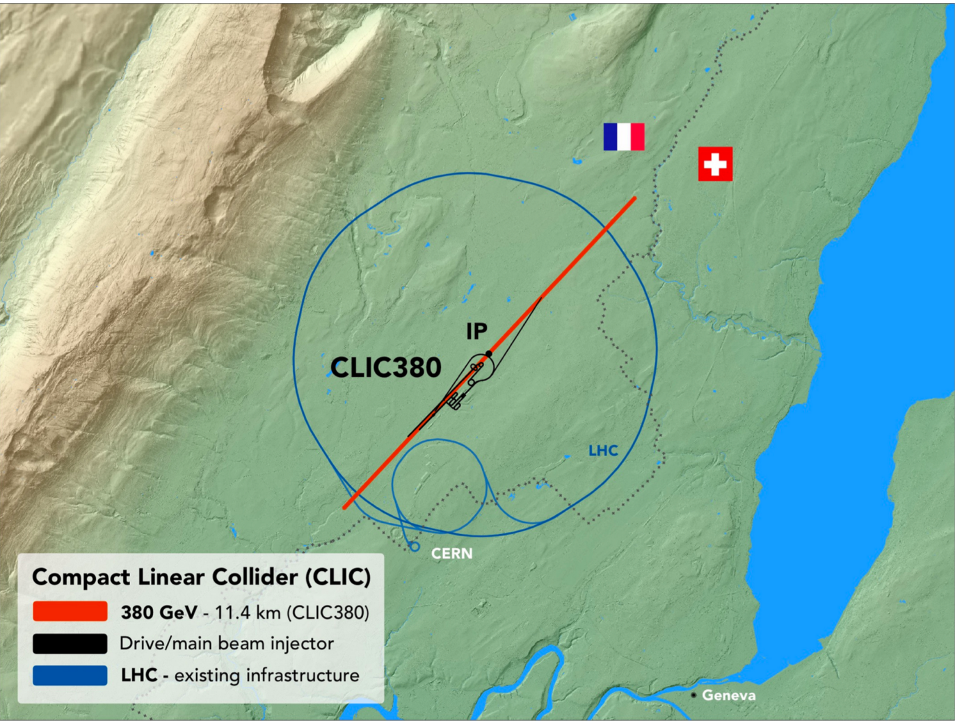
Tunnel inner diameter 5.6 m



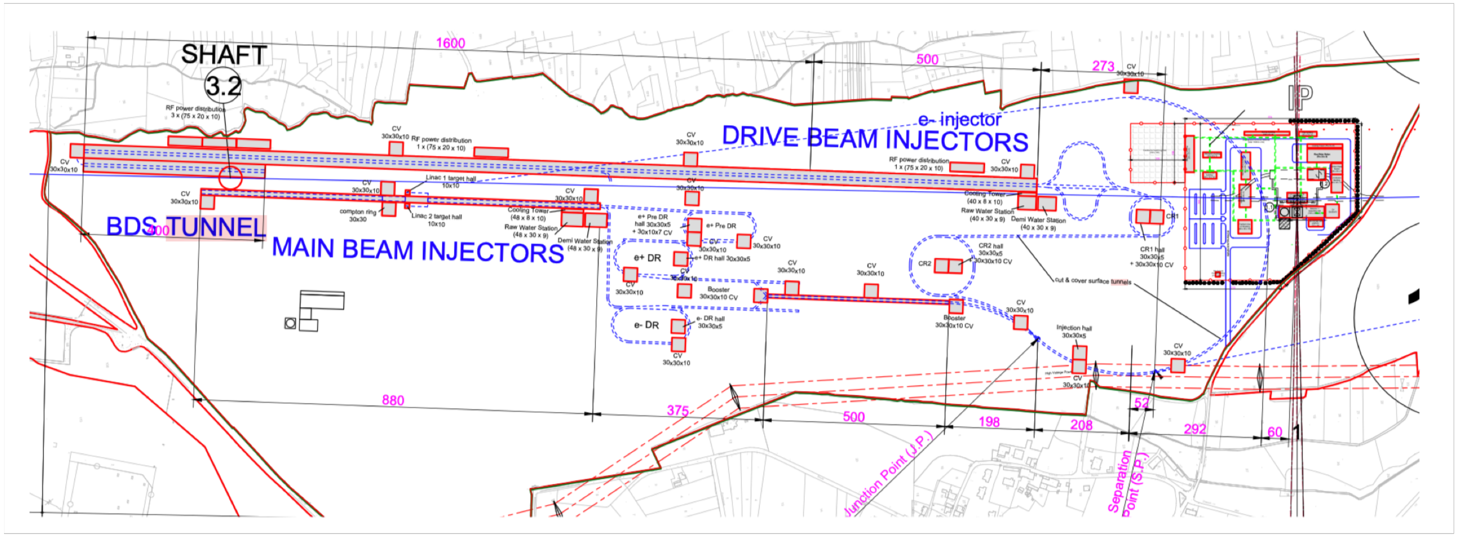
Geological profile (flat earth surface projection)

arXiv:1812.06018

civil engineering

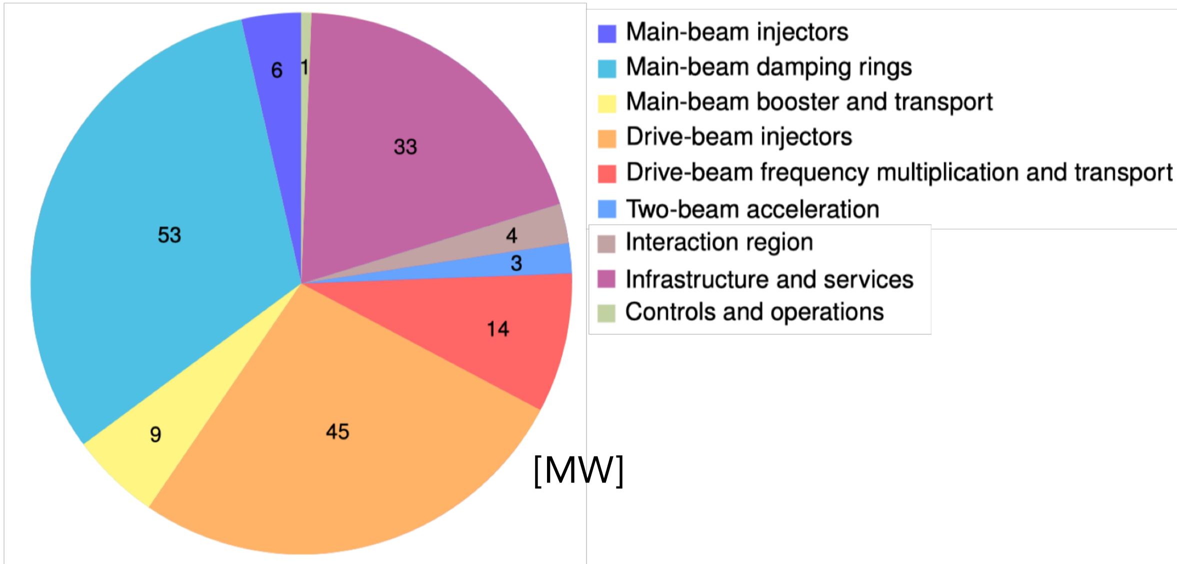


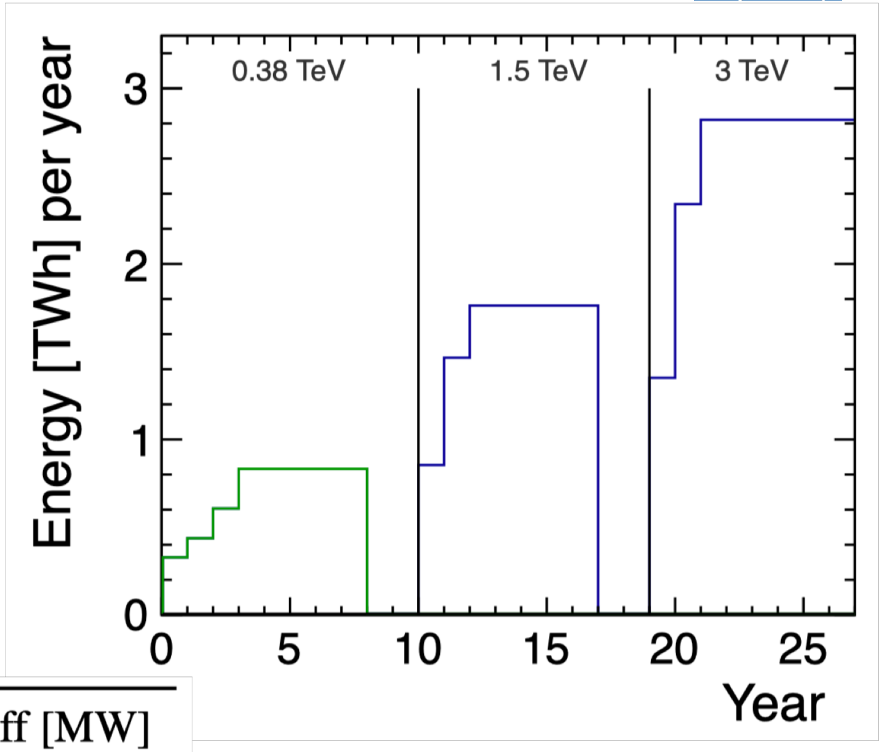
Main 380 GeV surface infrastructures fit on CERN-owned land



arXiv:1812.06018

power





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

Power estimate studied bottom up (focus on 380 GeV case)

- Large reductions since CDR: better estimates of nominal settings, optimised drive-beam complex, more efficient klystrons, optimized injectors, etc

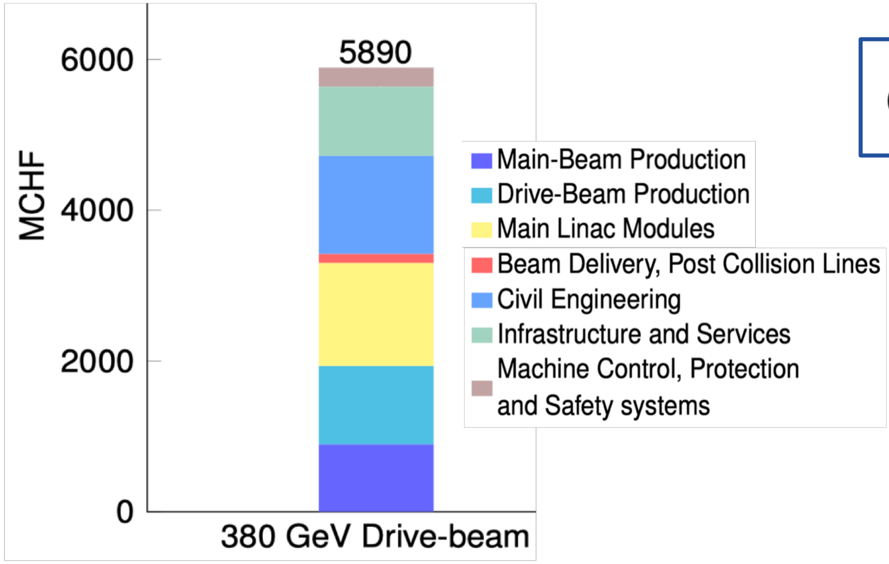
Further savings possible

1.5 TeV and 3 TeV power *not yet optimized* => will be done next

arXiv:1812.06018

cost estimate

Accelerator cost (incl. infrastructures)



CLIC 380 GeV drive-beam based : 5890^{+1470}_{-1270} MCHF

For upgrade to 1.5 TeV → add ~5100 MCHF
For upgrade to 3 TeV → add another ~7300 MCHF

Cost of the experiment

System	Cost fraction	Cost[MCHF]
Vertex		13
Silicon Tracker		43
Electromagnetic Calorimeter		180
Hadronic Calorimeter		39
Muon System		16
Coil and Yoke		95
Other		11
	0 10% 20% 30% 40% 50%	
Total		397

arXiv:1812.06018

CLIC technology applications

Collaboration with many facilities
Photon sources, medical applications
Lots of experience being built up

See academic training W. Wuensch
https://indico.cern.ch/event/668151/

One example: **SwissFEL**
- 104 C-band structures, 5.7 GHz, 2 m long
- Beam up to 6 GeV at 100 Hz
- Similar μm-level tolerances
- Length ⇔ 800 CLIC structures

CLIC experimental conditions

Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity $\mathscr{L}$ ($10^{34}cm^{-2}sec^{-1}$)	1.5	3.7	5.9
$\mathscr{L}$ above 99% of $\sqrt{s}$ ($10^{34}cm^{-2}sec^{-1}$)	0.9	1.4	2.0
Repetition frequency (Hz)	**50**	**50**	**50.1**
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)	**149/2.9**	**~60/1.5**	**~40/1**
Beam size at IP σ_z (μm)	**70**	**44**	**44**

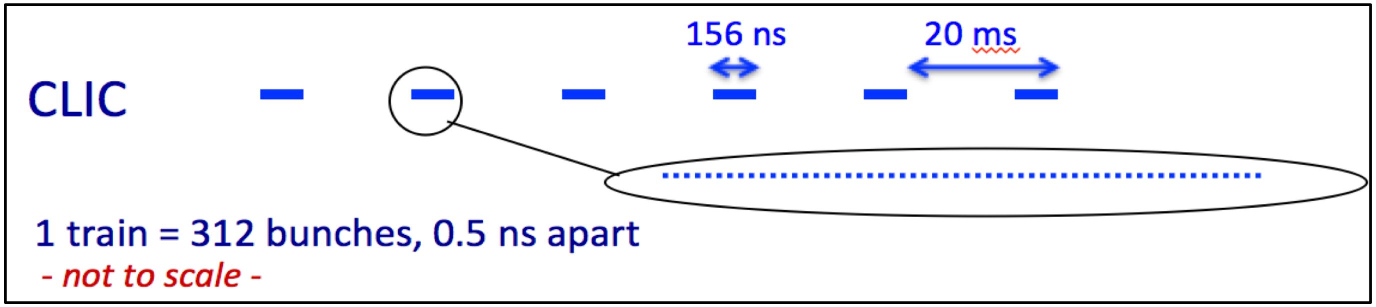
Drives timing requirements for CLIC detector

Very small beam

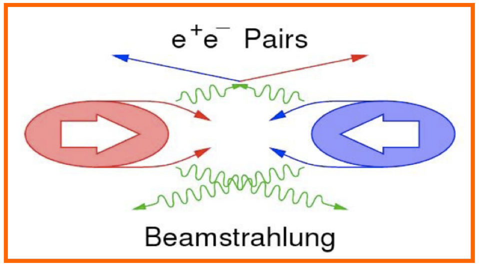
Crossing angle ~20 mrad, electron polarization ±80%

Very low duty cycle allows for:

Triggerless readout
Power pulsing

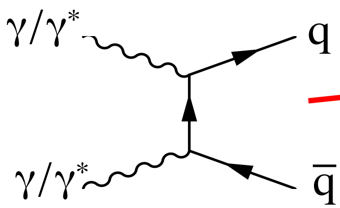


beam-induced backgrounds at CLIC



Beam-beam background at IP:

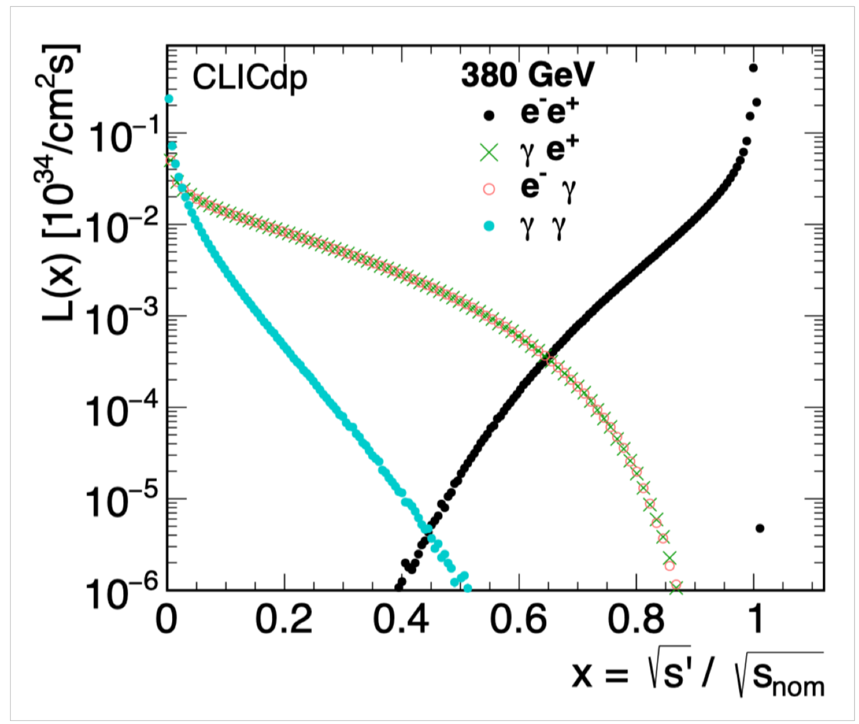
- Small beams => very high E-fields
  - **Beamstrahlung**
  - **Pair-background** → Simplified picture: **Design issue** (small cell sizes)
    - High occupancies
  - **γγ to hadrons** → Impacts on the physics **Needs suppression in data**
    - Energy deposits



Beamstrahlung ➔ important energy losses right at the interaction point

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

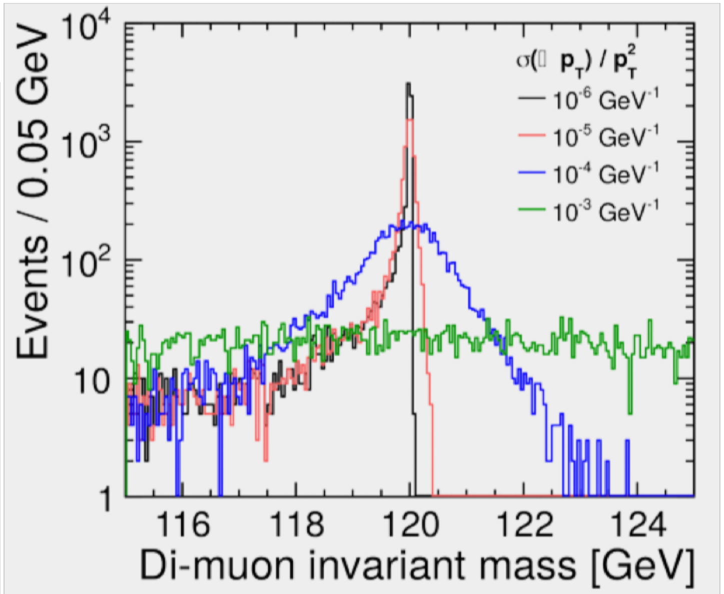
Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV
[Eur.Phys.J. C74 (2014) no.4, 2833]

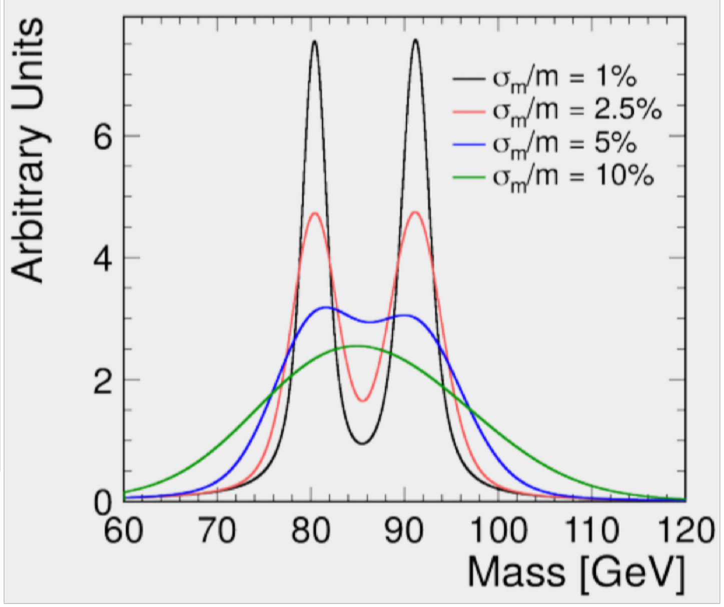


[arXiv:1812.06018]

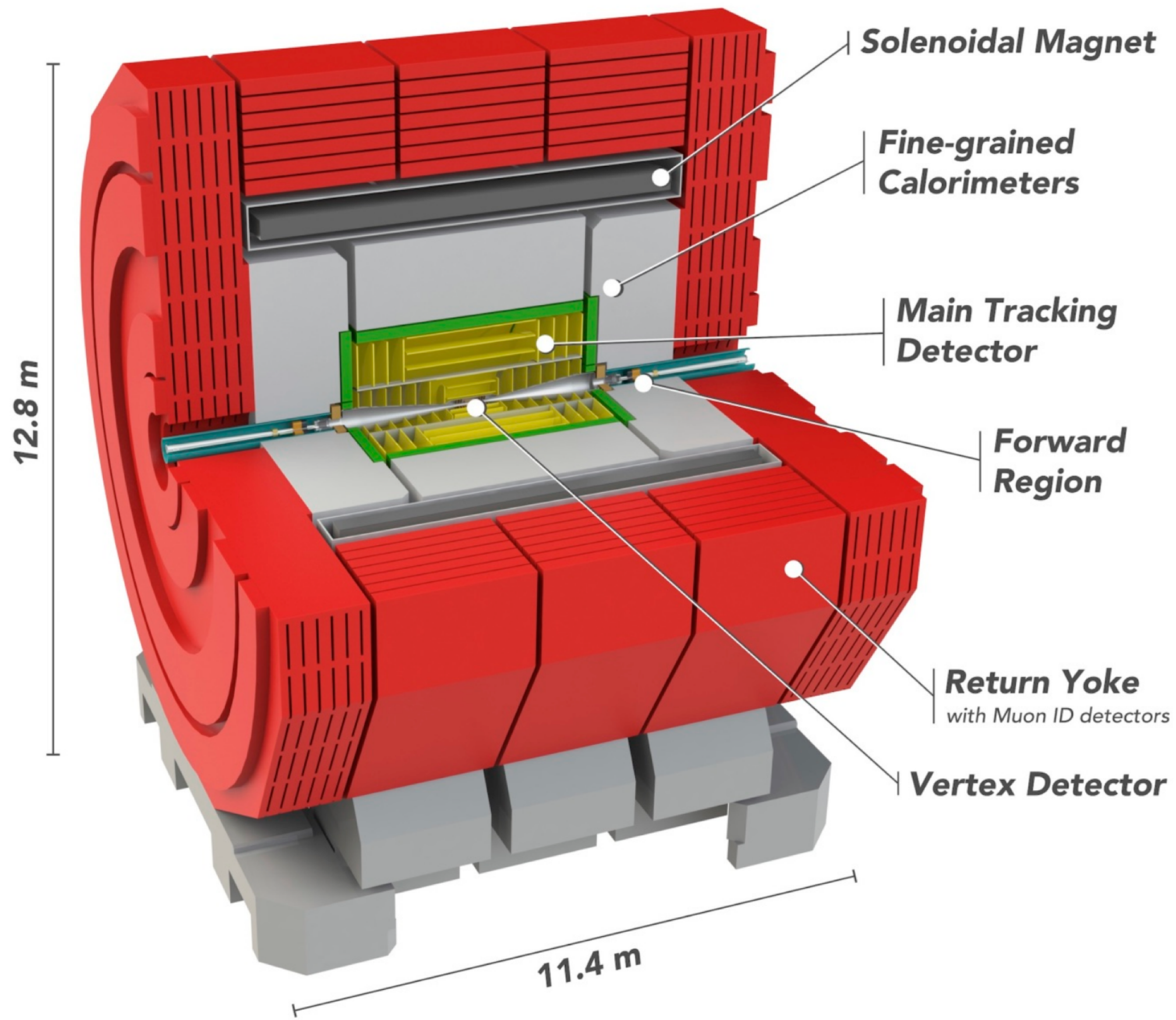
detector performance requirements

- Momentum resolution
  - Higgs recoil mass, Higgs coupling to muons
  - $\boldsymbol{\sigma_{p_T}/p_T \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}}$ above 100 GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - $\boldsymbol{\sigma_{r\phi} \sim a \oplus b\ /\ (p[\mathrm{GeV}]\ \sin^{3/2}\theta)\ \mu m}$ with a = 5 µm, b = 15 µm
- Jet energy resolution
  - Separation of W/Z/H di-jets
  - $\boldsymbol{\sigma_E/E \sim 5\% - 3.5\%}$ for jets at 50 GeV – 1000 GeV
- Angular coverage
  - Very forward electron and photon tagging
  - Down to θ = 10 mrad (η = 5.3)



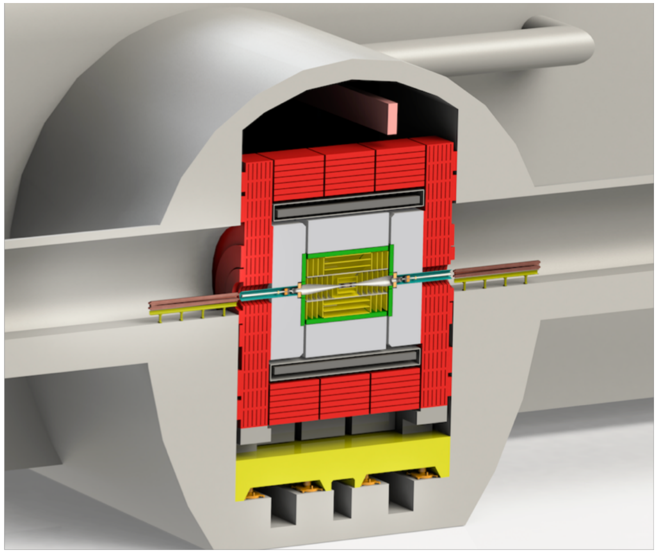


CLIC detector

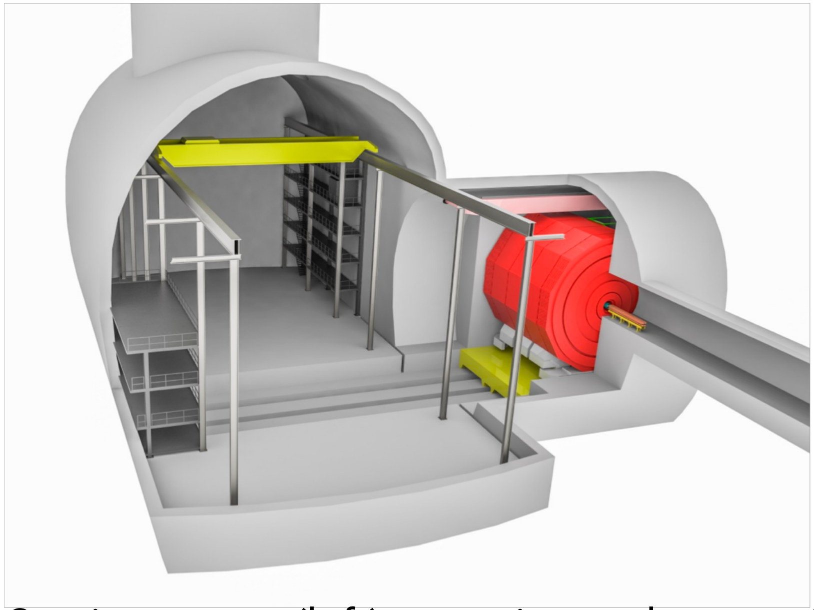


B-field = 4 T

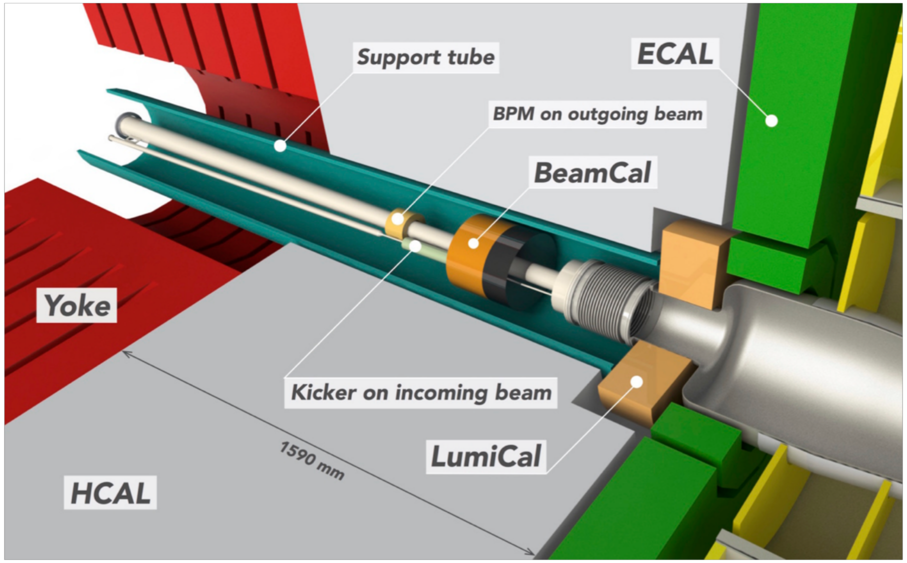
forward region and MDI



Last focusing elements in accelerator tunnel, L*=6 m. Detector kept short along beam line.



Service cavern (left), experimental cavern (right)



Forward detector region comprising beam feedback system and forward calorimeters:

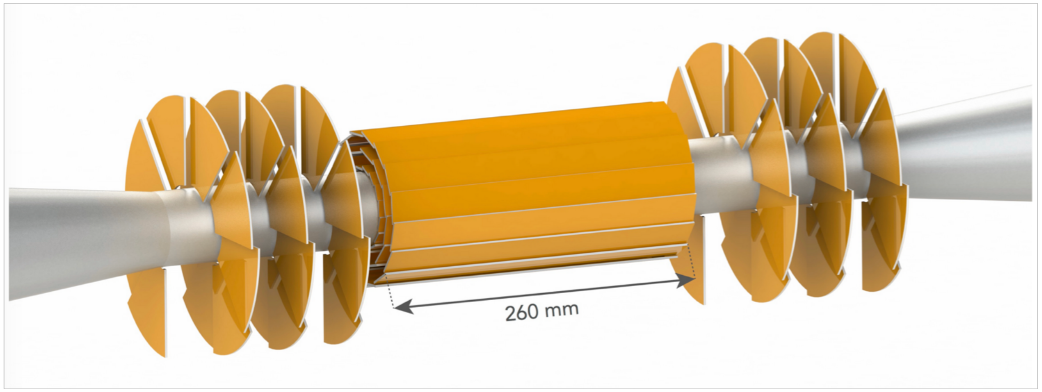
- LumiCal (39 > θ >134 mrad)
- BeamCal (10 > θ > 46 mrad)

⇐ *FCAL collaboration*

Luminosity measurement down to *few* 0.1%
Forward coverage for electrons/photons

vertex and tracking detectors

Vertex detector

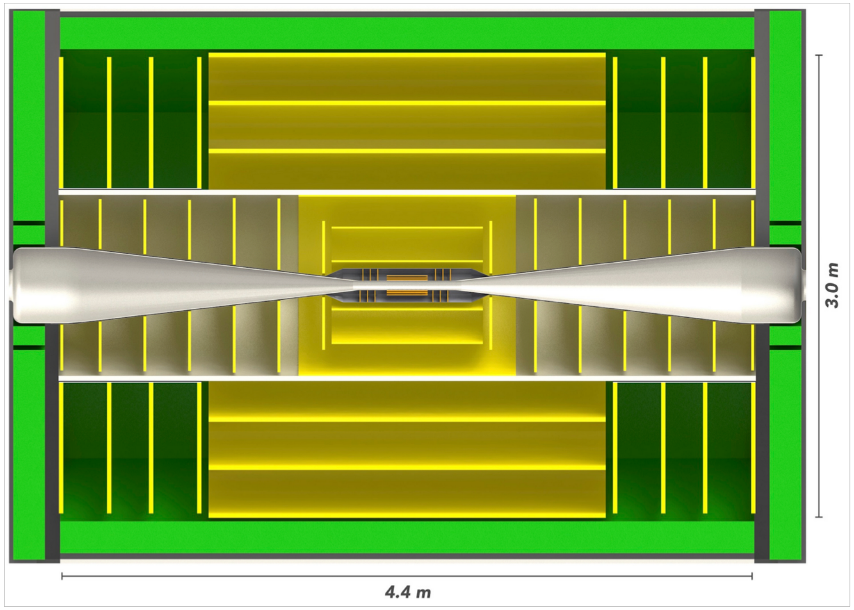


Requirements:
- low mass: $0.2\%X_0$ per layer
- low power: 50 mW/cm^2 for air cooling
- single point resolution: 3 μm
- hit time resolution: ~5 ns

Implementation and R&D:
- silicon-based (pixels, hybrid or monolithic)
- 3 double layers
- spiraling petals to facilitate air cooling
- power pulsing

See talk: Simon Spannagel

Tracker



Requirements:
- low mass: 1-$2\%X_0$ per layer
- single point resolution: 7 μm
- hit time resolution: ~5 ns

Implementation and R&D:
- silicon-based (pixels, monolithic)
- power pulsing
- water cooling (below atm. pressure)

calorimetry and PFA

Jet energy resolution + background suppression for optimal detector design

=> => fine-grained calorimetry + Particle Flow Analysis (PFA)

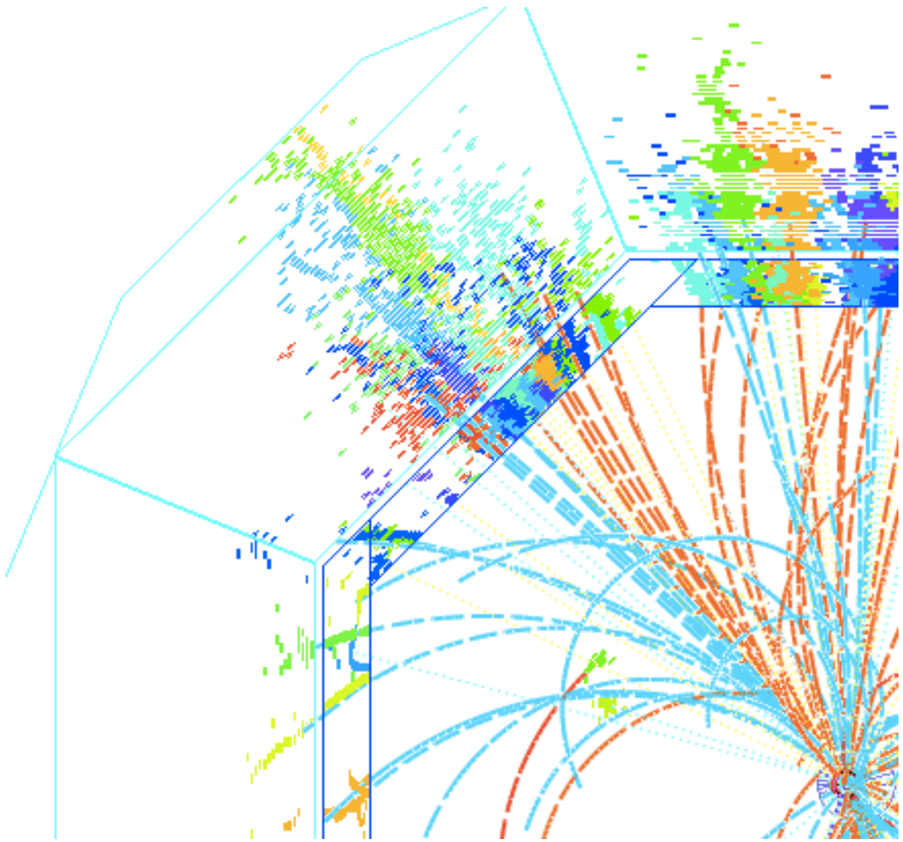
What is PFA?

Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutral hadrons

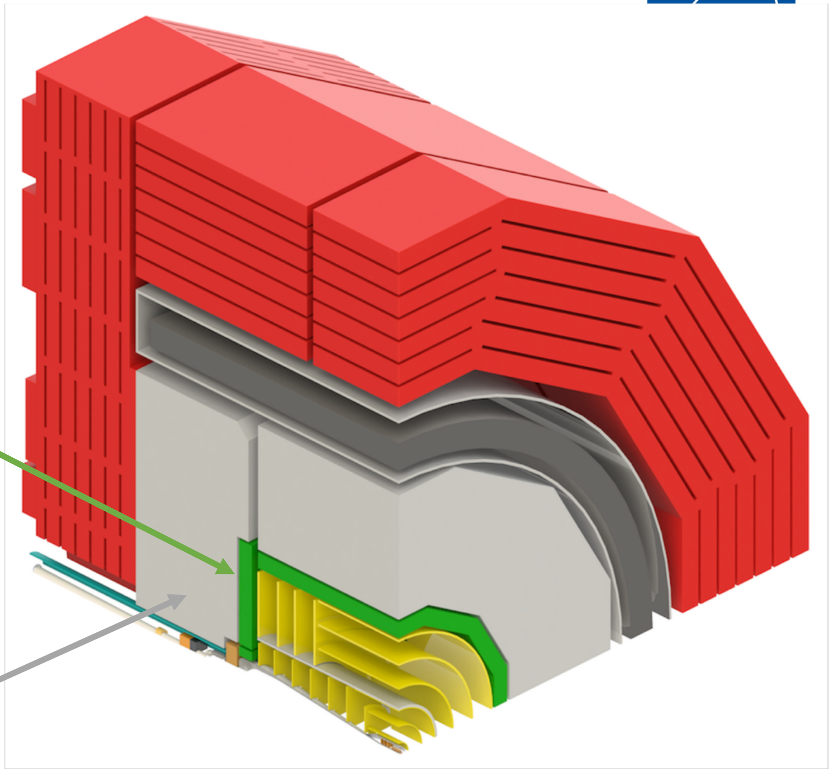
↓

Typical jet composition:
- 60% tracker 🙂 🙂
- 30% ECAL 🙂
- 10% HCAL 🙁

Hardware + software !



calorimetry



Electromagnetic calorimeter: Silicon – tungsten
- 2 mm tungsten plates, 500 μm silicon sensors
- 40 layers, 22 X_0 or 1 λ_I, 5×5 mm^2 cells
- ~2500 m^2 silicon, 100 million channels

Hadronic calorimeter: Scintillator – steel
- 19 mm steel plates, 3 mm plastic scintillators + SiPM
- 60 layers, 7.5 λ_I, 30×30 mm^2 cells
- ~9000 m^2 scintillator, 10 million channels

⇧

Developed by CALICE collaboration

Technology choices similar to CMS HGCal upgrade project

See talks: Christian Graf and Thorben Quast

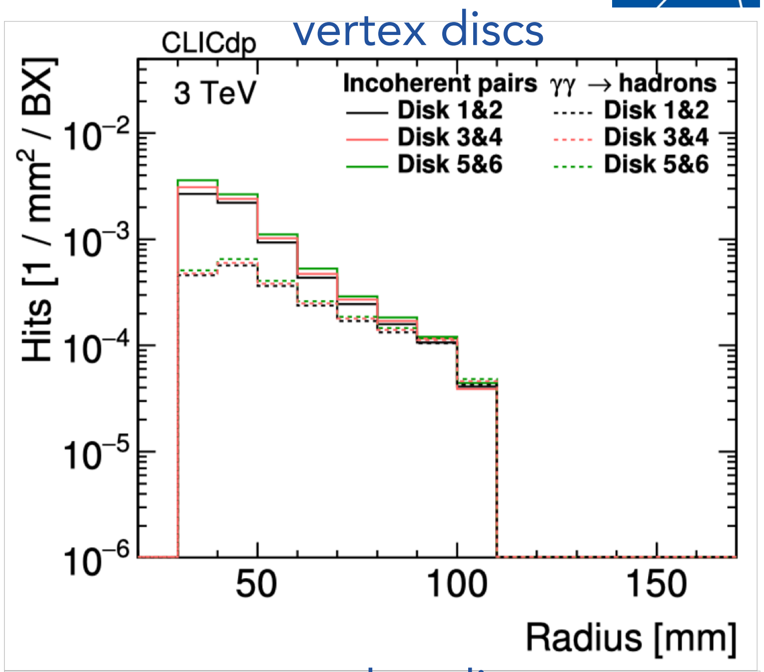
detector occupancies

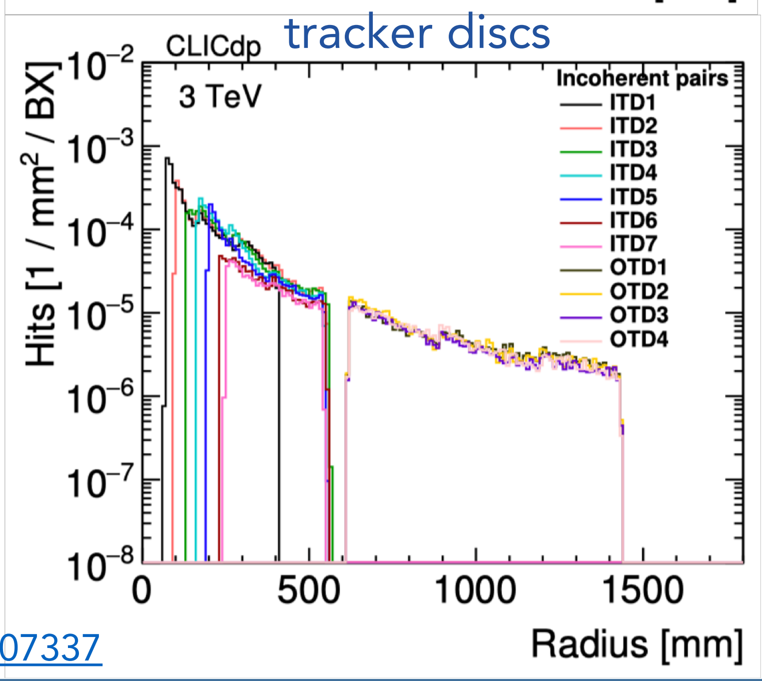
Triggerless readout, once per full (156 ns) bunch train

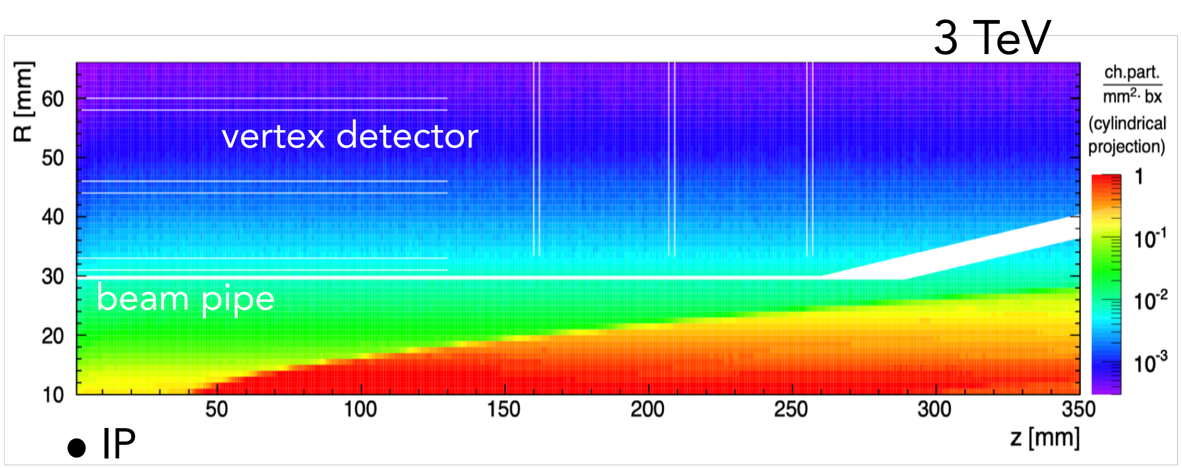
Expect at most one hard e^+e^- collision per bunch train
Detector occupancies dominated by beamstrahlung

Detector designed to achieve occupancies below 3-4%

Drives cell sizes:
- Max. vertex pixel size 25*25 μm^2
- Max. tracker cells size depends on location: max 0.05 mm^2 – 0.5 mm^2

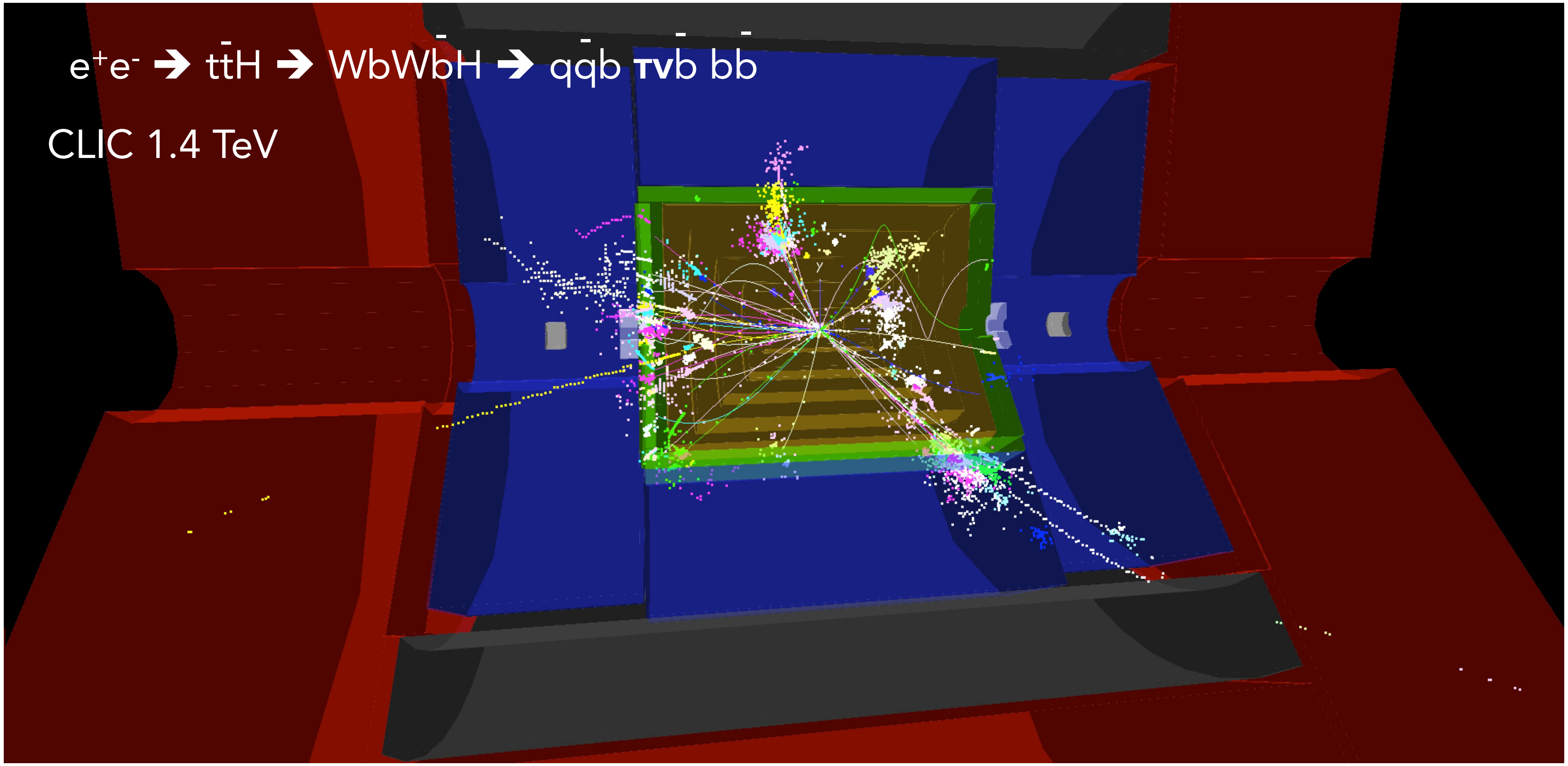


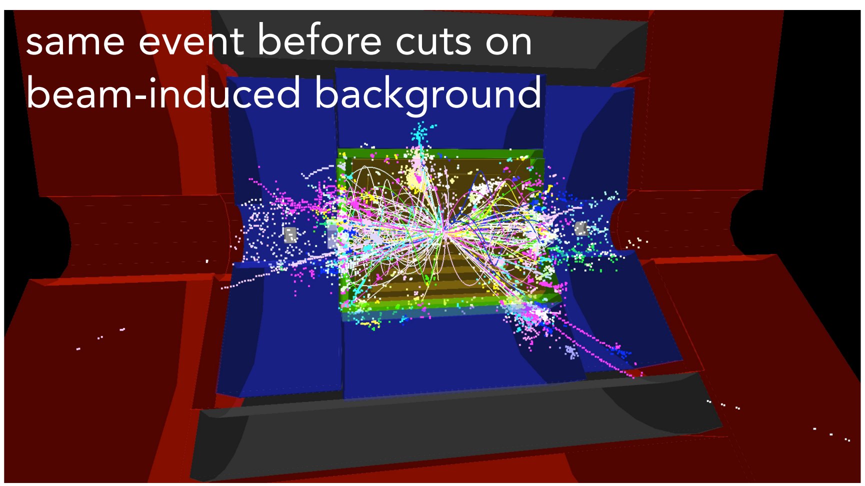




arXiv:1812.07337

background suppression





Highly granular calorimetry + precise hit timing

↓

Very effective in suppressing backgrounds
for fully reconstructed particles

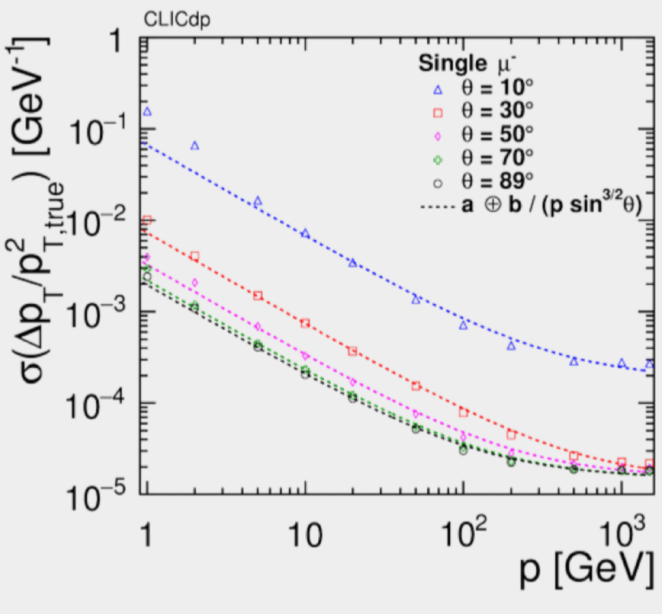
↓

General trend for **e^+e^-** and **pp** colliders

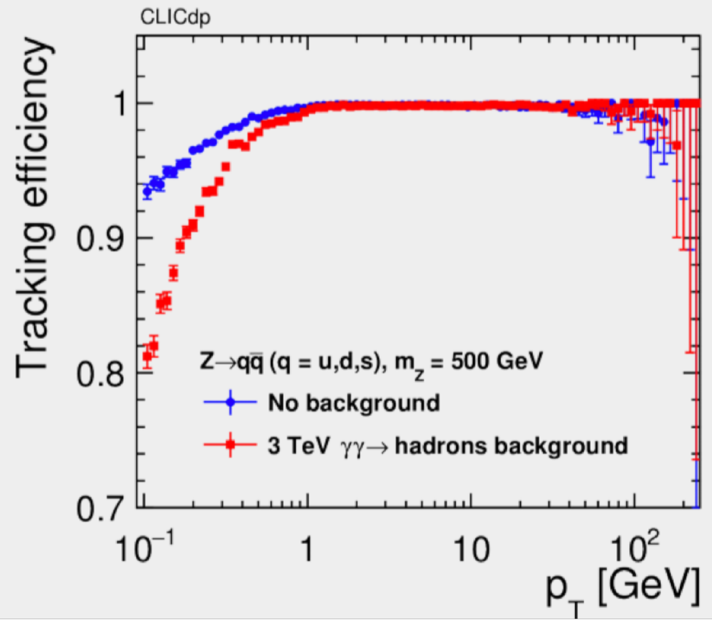
tracking performance

Detector description (*in DD4hep*), detector simulation (*in Geant4*) and reconstruction implemented in **iLCSoft framework**

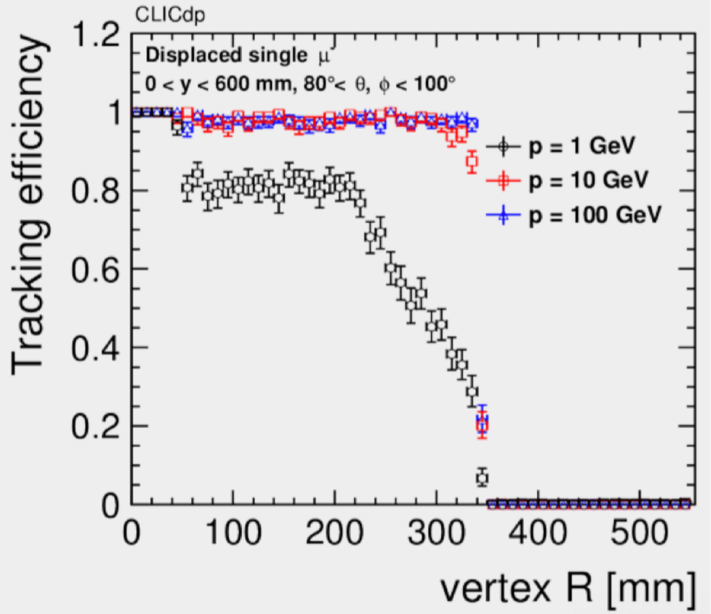
Tracking based on **conformal tracking** and **Kalman-filter based fit**



Track momentum resolution for single particles
2×10^{-5} dp_T/p_T^2 achieved for high-momentum tracks



Tracking efficiency within light quark jets
With and without background



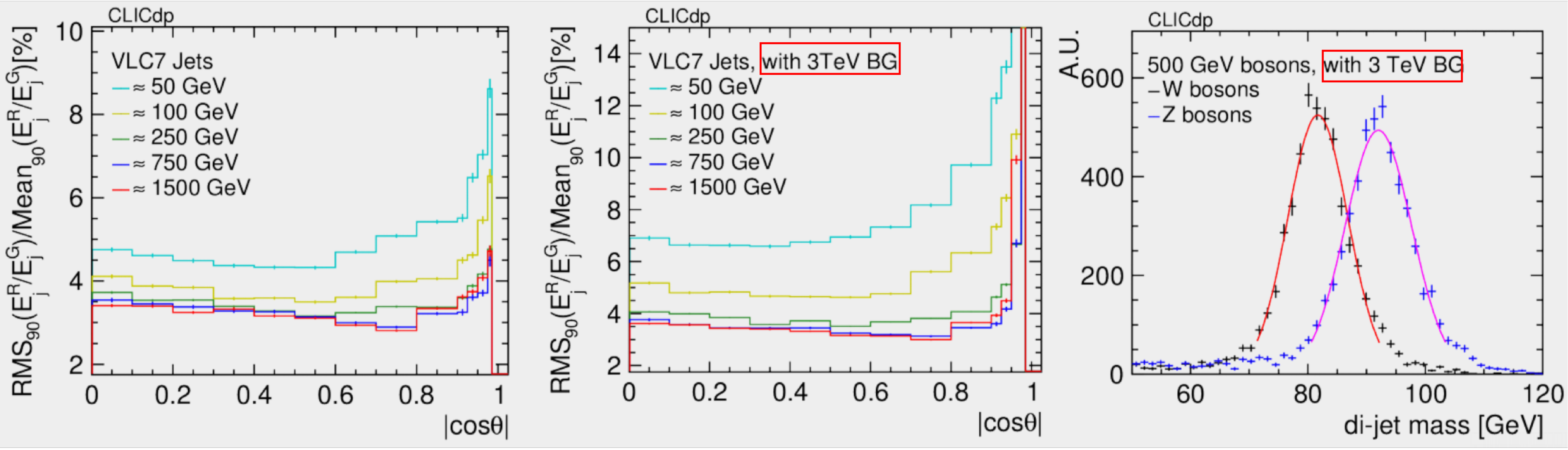
Tracking efficiency for displaced tracks
(min 4 hits required)

arXiv:1812.07337

PFA, jet energy reconstruction

PandoraPFA particle flow analysis used for jet energy reconstruction and particle ID. Combined with **jet clustering optimized for e^+e^-** (**VLC** Valencia algorithm)

- Jet energy resolution from $Z/\gamma^* \rightarrow qq$, compare reconstruction with MC truth
  - → Objective of 3.5-5% jet energy resolution achieved for high-E jets in most of angular range
  - → Impact from 3 TeV backgrounds largest for low-energy jets, resolution 6-8%
- W/Z mass separation in 2-jet events: 2σ separation with VLC7 jets, including 3 TeV bkg

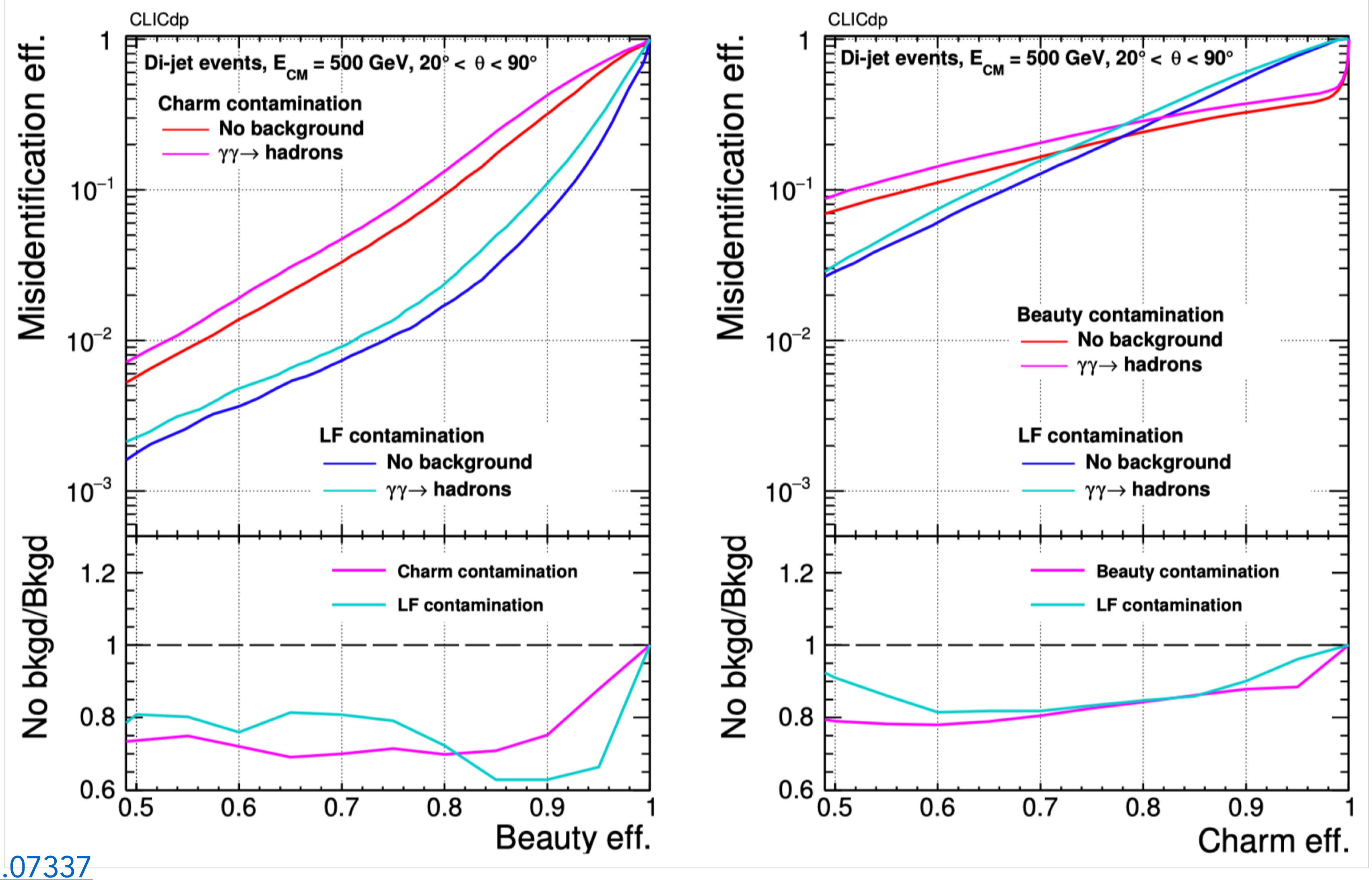


[arXiv:1812.07337](https://arxiv.org/abs/1812.07337)

flavour tagging performance

LCFIplus package used for flavour tagging

Studied in 500 GeV di-jet events, with and without $\gamma\gamma \rightarrow$ hadrons background (3TeV equivalent)



arXiv:1812.07337

physics at CLIC

Measurement of SM particles with high precision:
in particular **Higgs boson** and **top quark**

BSM sensitivity through:

– **probing SM Effective Field Theories** with unprecedented precision

– **direct and indirect BSM searches** that significantly extend reach of HL-LHC, including new particles in challenging non-standard signatures

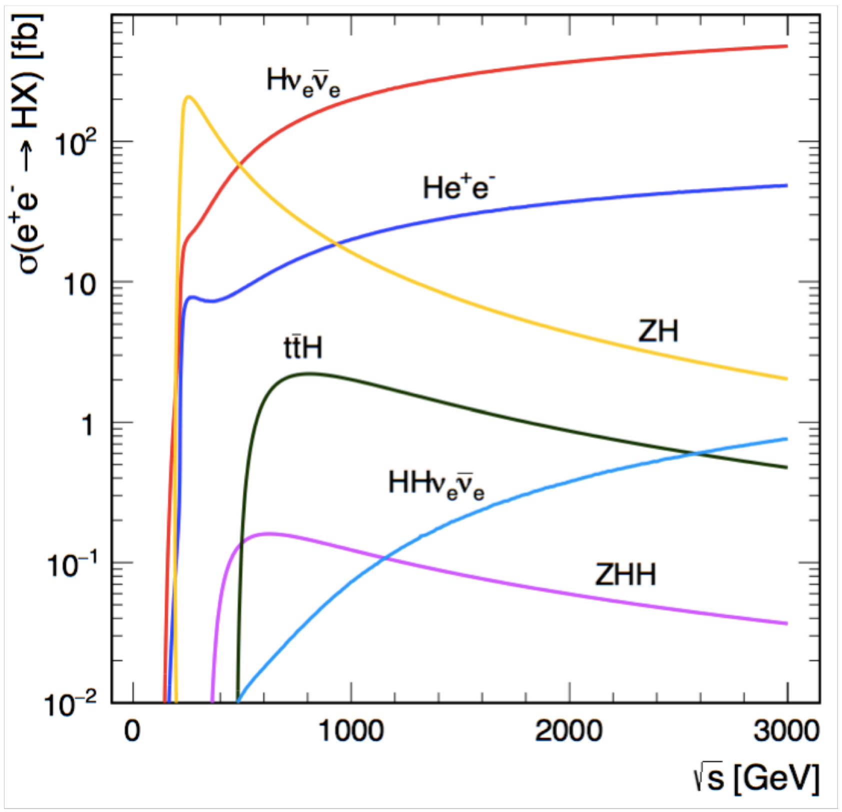
Higgs coupling sensitivity

Full Geant4 simulation/reconstruction (including beam backgrounds) at all 3 stages → global fit including correlations

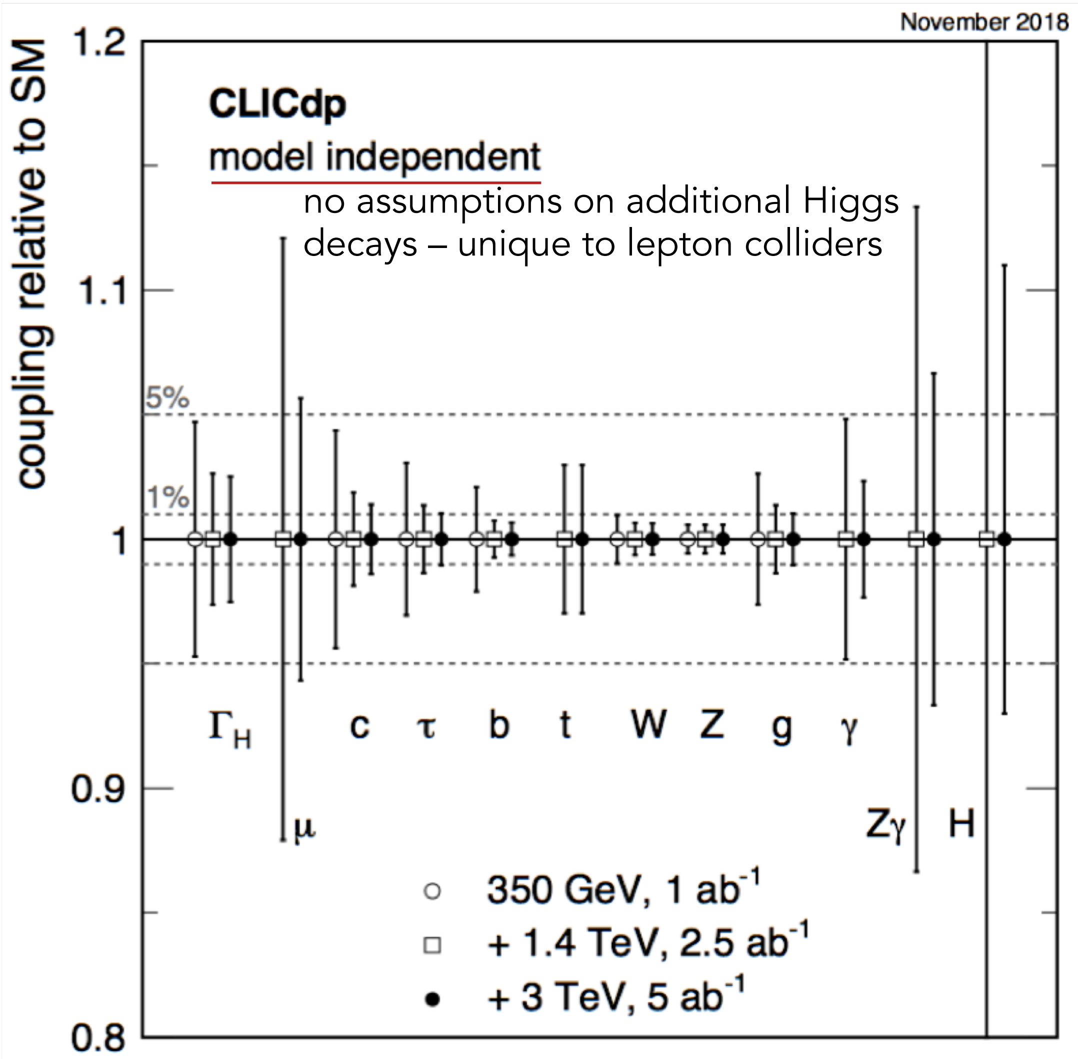
Precision <1% for most couplings

c/b/W/Z/g couplings significantly more precise than HL-LHC even after 380 GeV stage

Γ_H is extracted with 4.7 – 2.5% precision



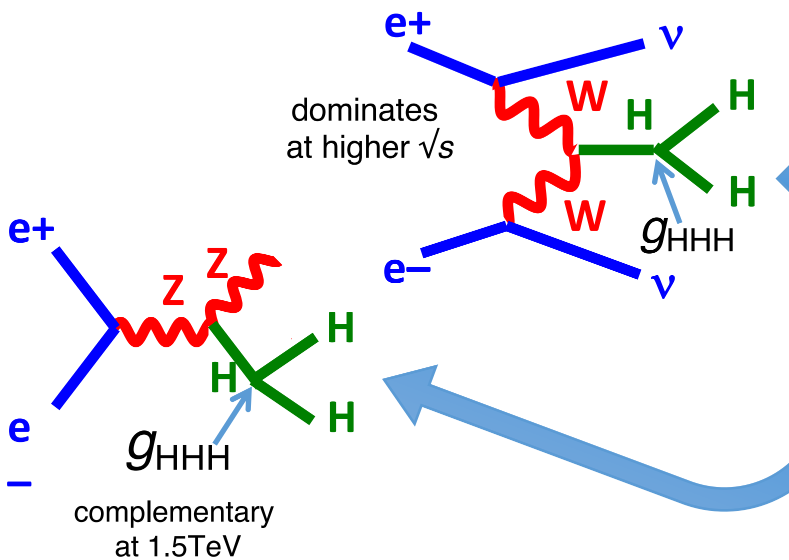
Each energy stage contributes significantly



Based on Eur. Phys. J. C 77 475 (2017) updated to new luminosity scenario

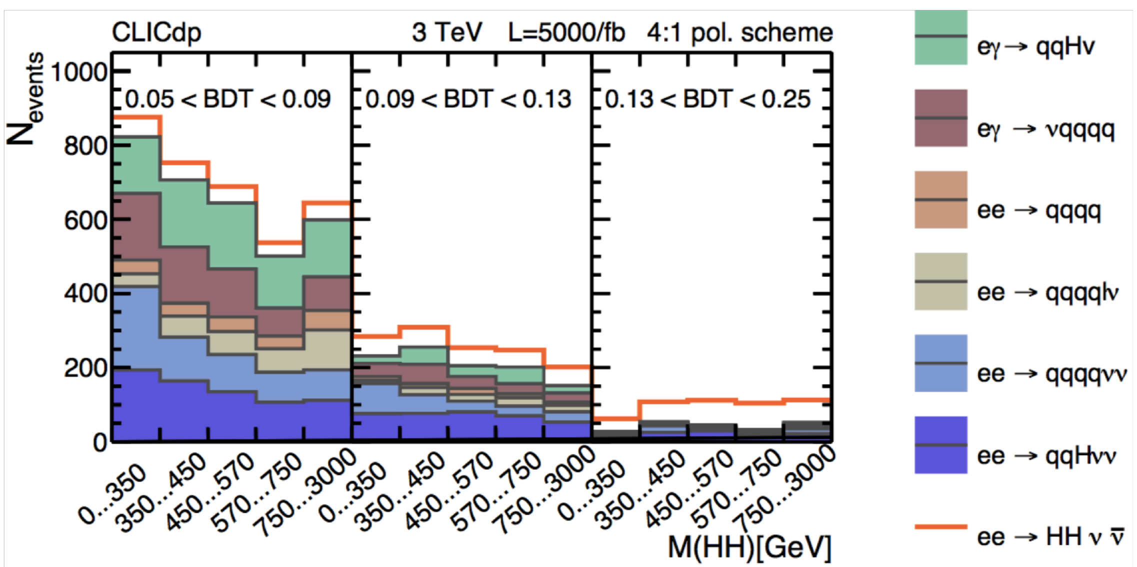
Higgs self-coupling

Higgs self-coupling requires high energy



CLIC double Higgs and Higgs self-coupling programme:

	1.4 TeV	3 TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	$3.6\,\sigma$ $\frac{\Delta\sigma}{\sigma} = 28\,\%$ EVIDENCE	$> 5\,\sigma$ for $\mathcal{L} \geq 1100\,\text{fb}^{-1}$ $\frac{\Delta\sigma}{\sigma} = 7.3\,\%$ OBSERVATION
$\sigma(ZHH)$	$5.9\,\sigma$ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4 TeV: -34 %, +36 % rate only analysis	1.4 & 3 TeV: -7 %, + 11 % differential analysis



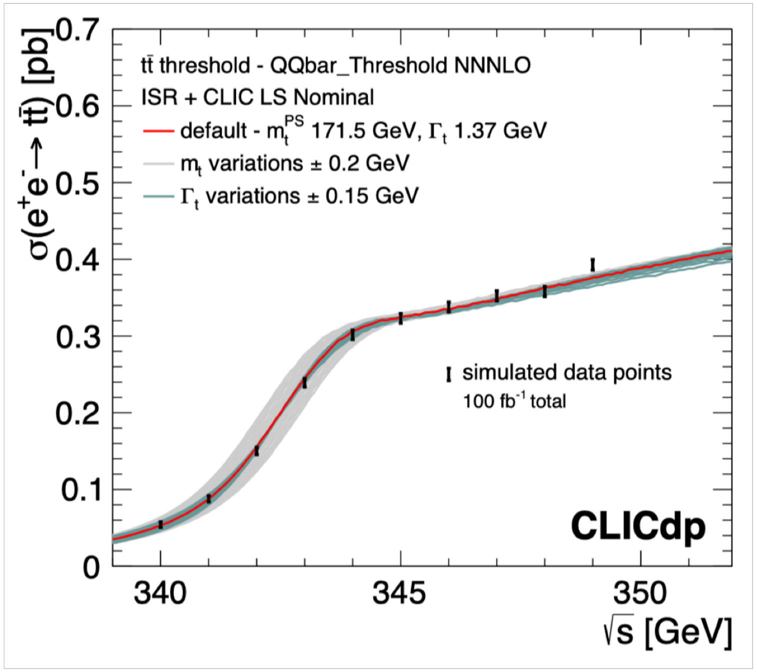
Template fit at 3TeV using two variables: *M*(HH) differential distribution and BDT score

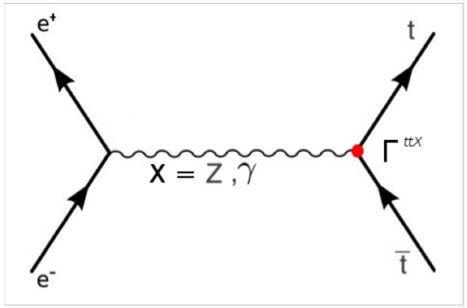
Gives unrivalled sensitivity to Higgs self-coupling:

$$\boxed{\Delta g_{HHH}/g_{HHH} = {}^{+11\%}_{-7\%}}$$

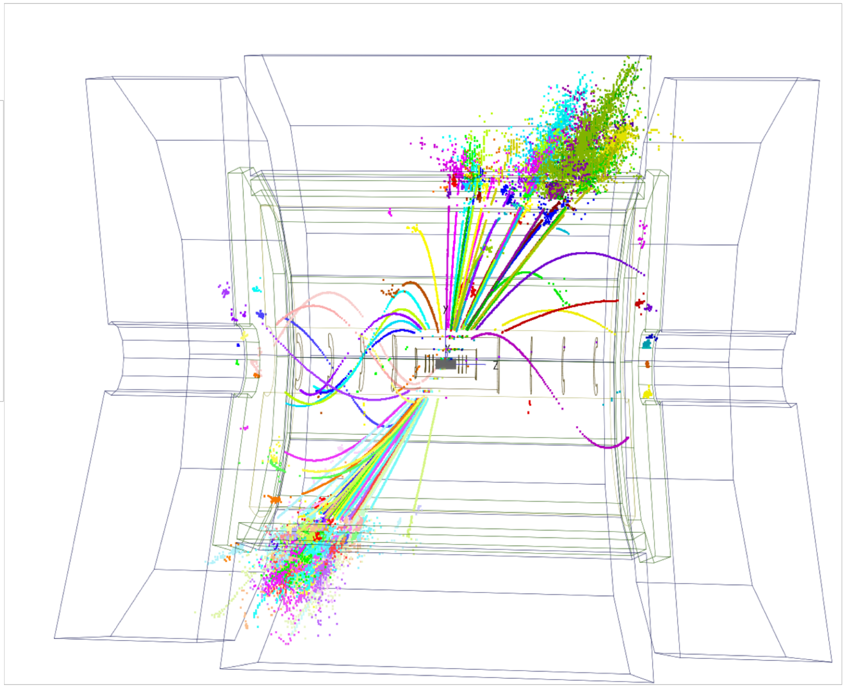
arXiv:1901.05897

top quark physics at CLIC





$e^+e^- \to tt \to WbWb$



Top mass from threshold scan around 350 GeV (100 fb^{-1})

observe 1S 'bound state', Δm_t ~ 50–75 MeV

$e^+e^- \to tt$ at all CLIC energies

$\to$ complementarity

- coupling to Z and γ
- forward-backward asymmetry
- EFT interpretation

also:

- FCNC top decays
- ttH incl. CP analysis

arXiv:1807.02441

First e^+e^- study of boosted top production, using jet substructure in reconstruction

EFT

Standard Model

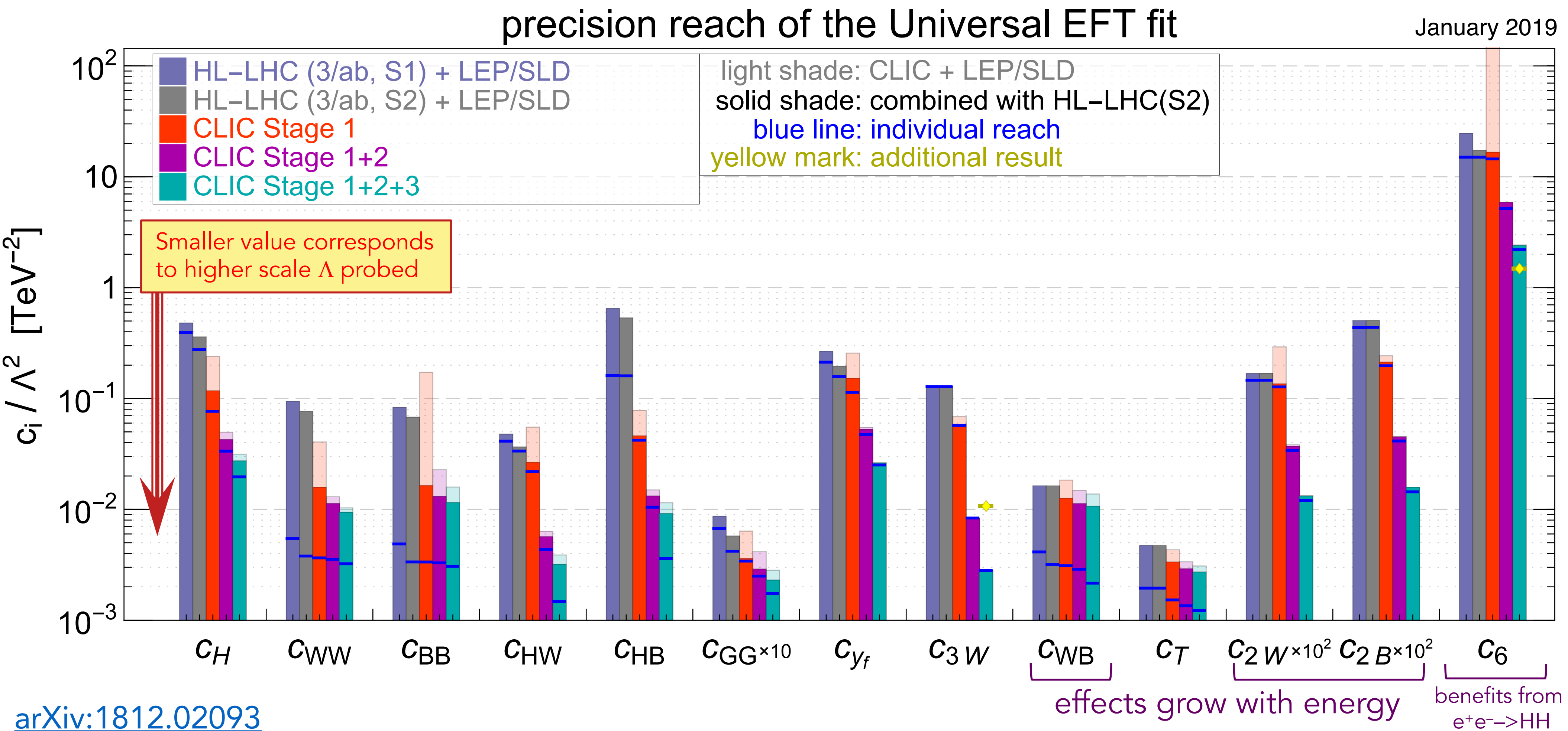
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Scale of new decoupled physics

Dimension-6 operators

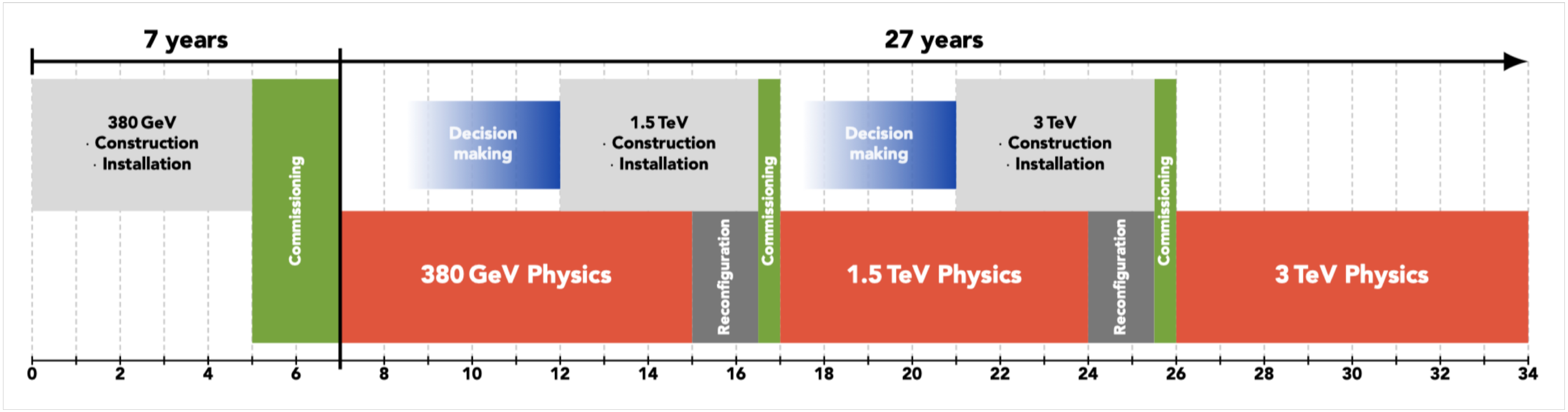
Include CLIC Higgs, top, WW, and $e^+e^- \to f\bar{f}$ measurements in global fit to constrain dimension-6 EFT operators

Strongly benefits from high-energy running



arXiv:1812.02093

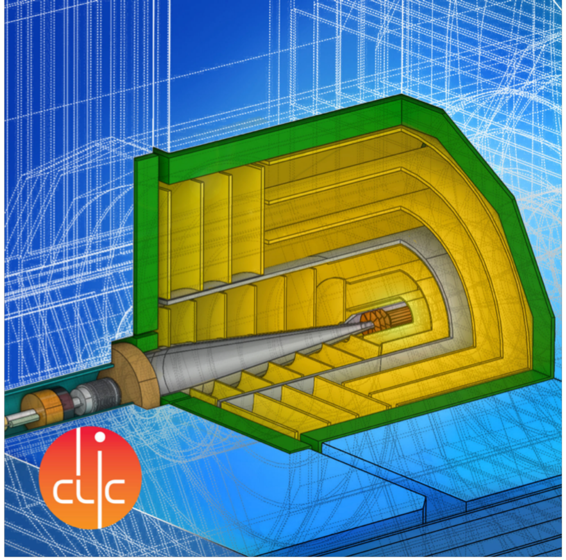
time line

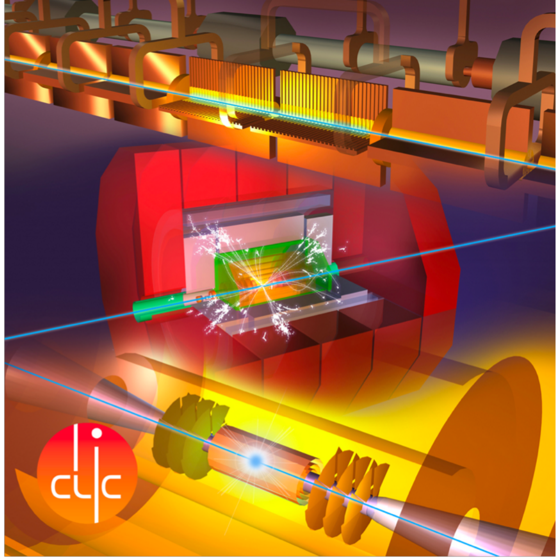


Technology-driven schedule, from start of construction.

After an *in principle go ahead*, min. 5 years are needed before construction can start.

=> First beams could be available by 2035





CLIC is a very attractive post-LHC facility for CERN

Unprecedented, diverse and guaranteed excellent physics reach

thanks to lepton collider precision AND multi-TeV collisions

Demonstrated accelerator technologies

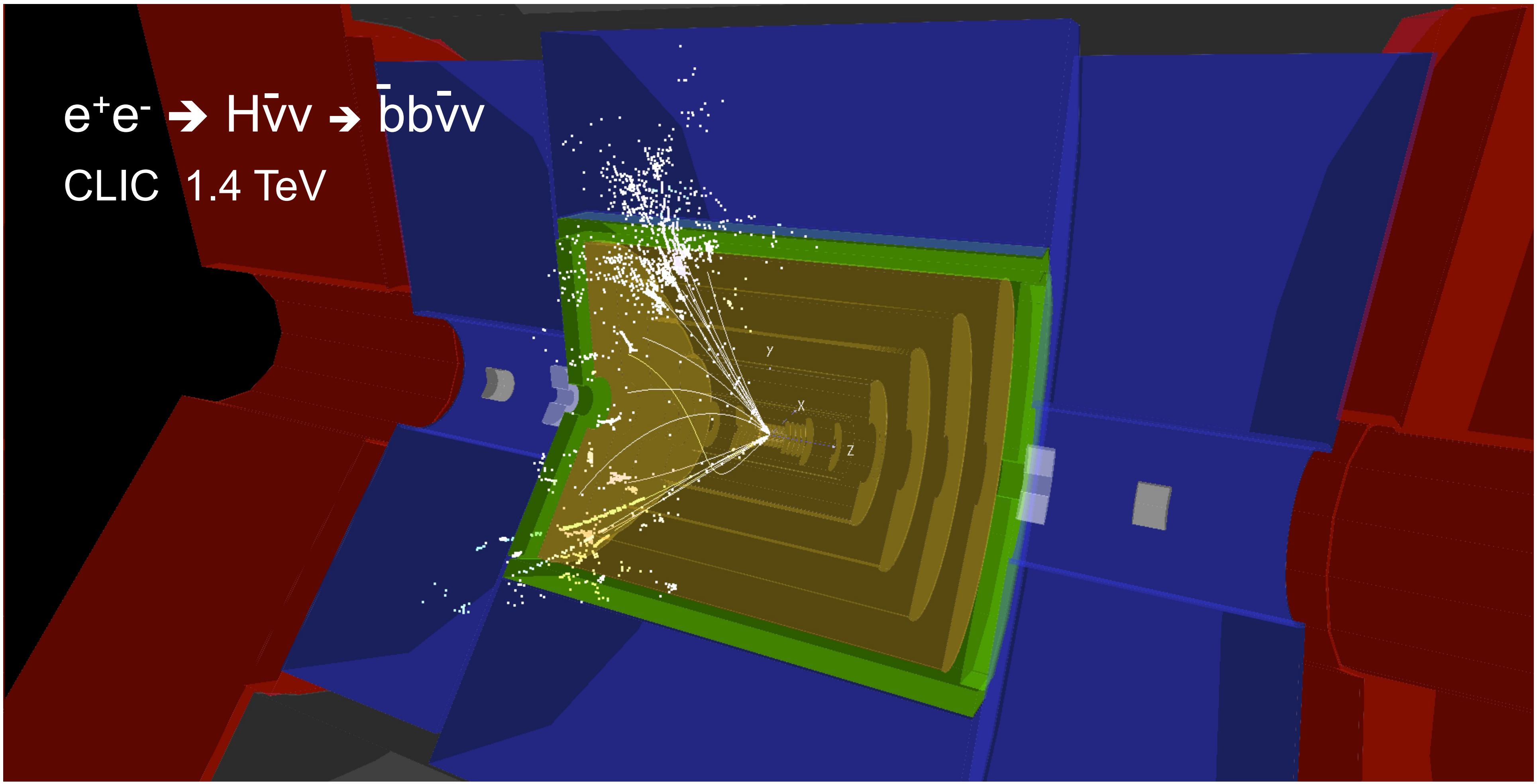
Feasible timescale

CLIC staging brings cost staging, and accompanying affordability

(cost of CLIC 380 GeV + 1.5 TeV < cost of FCC-ee)

Linear tunnel provides a natural infrastructure for future, beyond CLIC

THANK YOU !

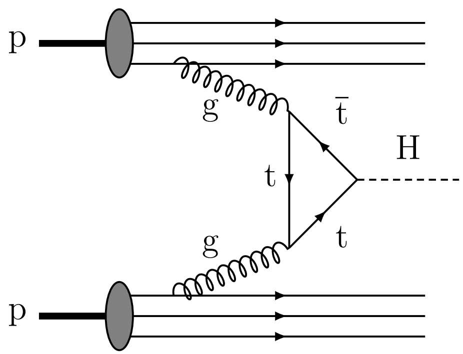


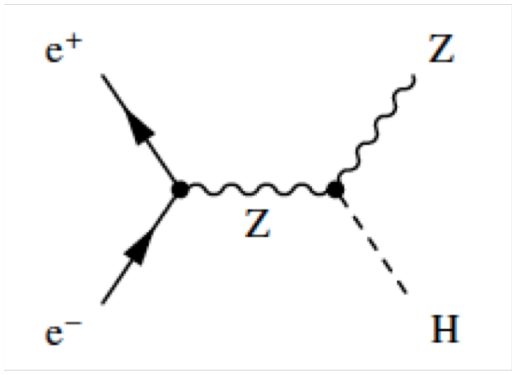
$H \rightarrow b\bar{b}$ (58% BR): selection efficiency ~40% (1.4 TeV), ~50% (380 GeV)

reserve slides

pp collisions / e^+e^- collisions

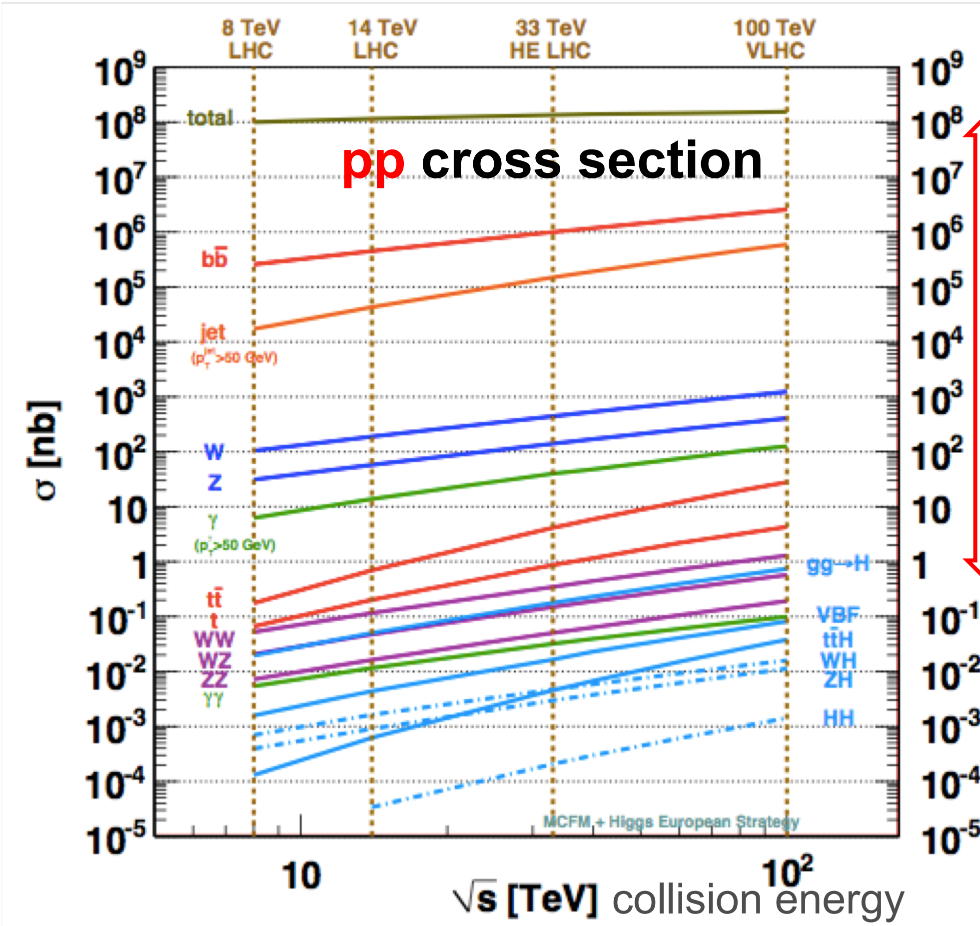
to address the open questions in particle physics





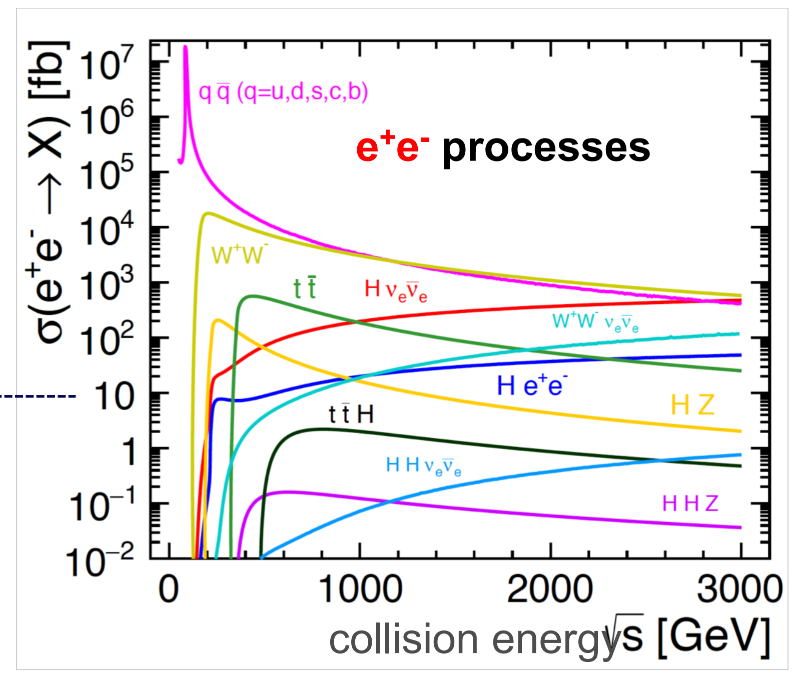
p-p collisions	e^+e^- collisions
Proton is compound object → Initial state unknown → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / opt: polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**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



factor > 10^8

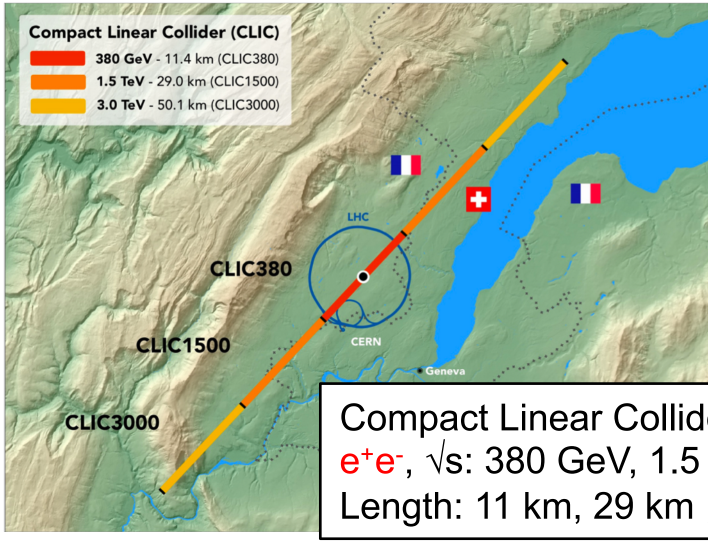
pp and e^+e^- collisions
provide complementary physics information
=> important for our field to have both !



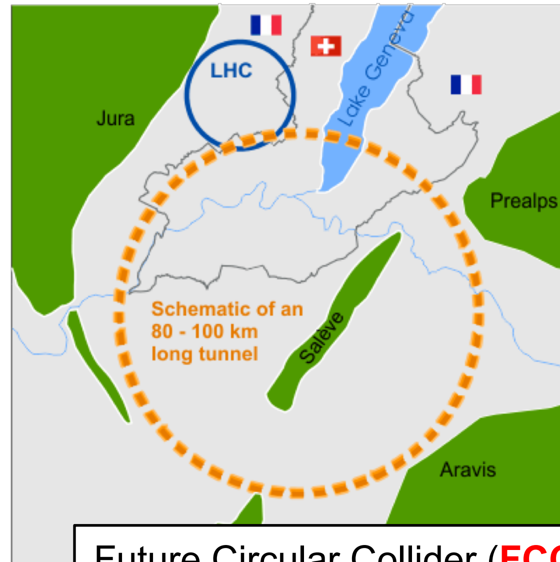
- Interesting **pp** events need to be found within a huge number of collisions

- **e^+e^-** events are more “clean”

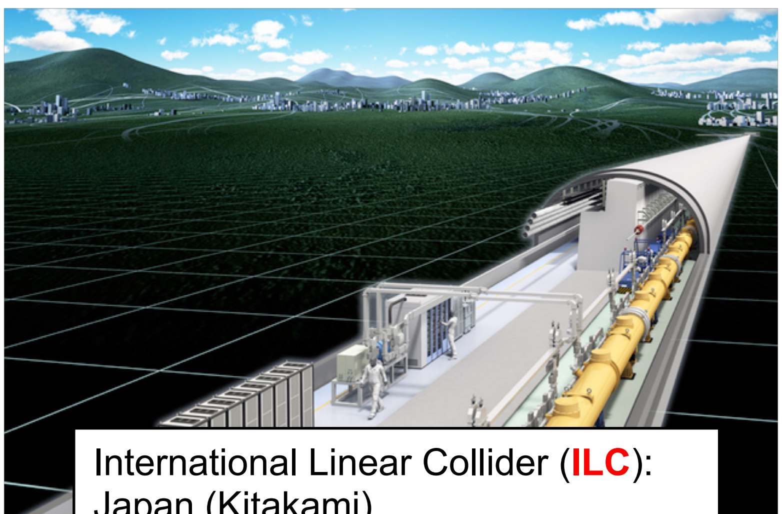
high-energy e⁺e⁻ collider studies



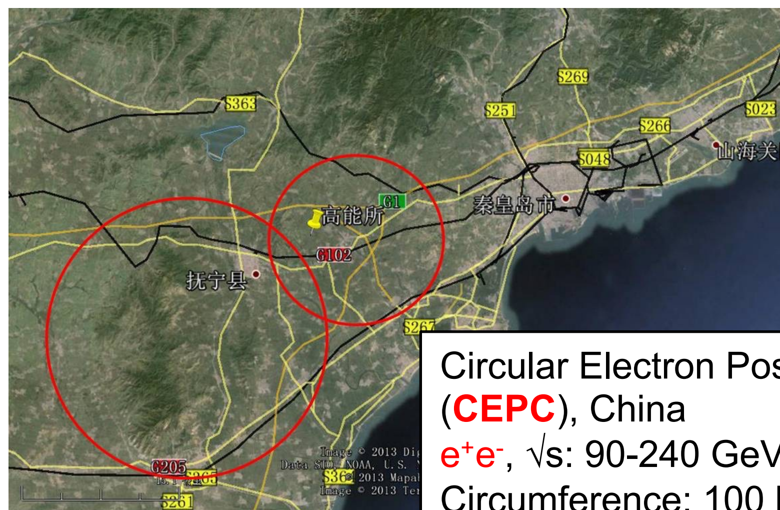
Compact Linear Collider (**CLIC**): **CERN**
e^+e^-, √s: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



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



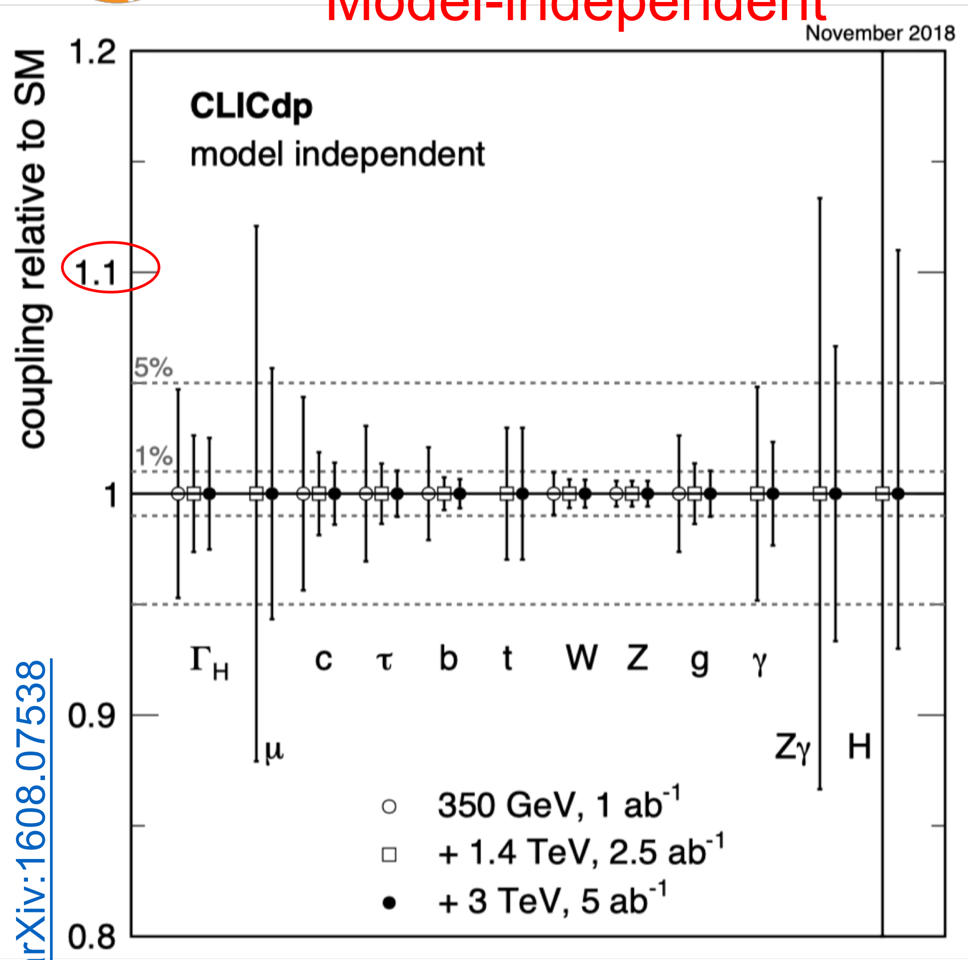
International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, √s: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



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

combined CLIC Higgs coupling results

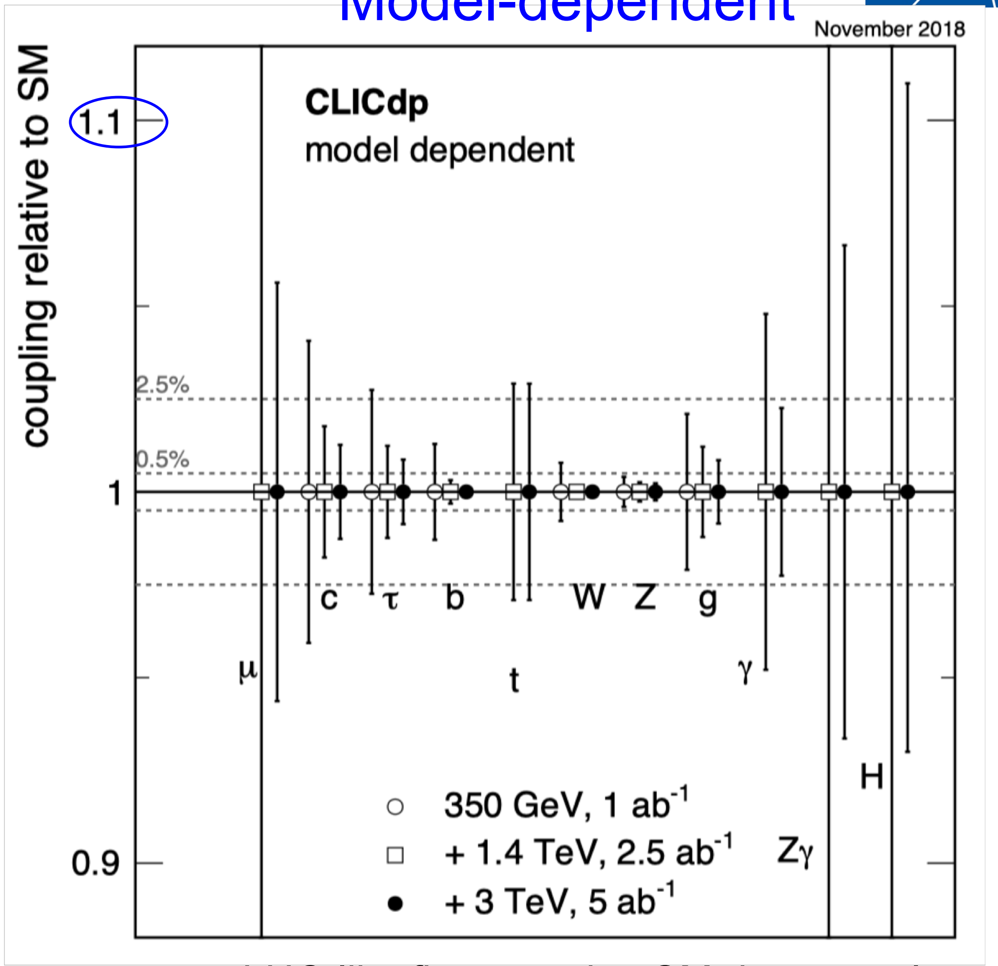
Model-independent



arXiv:1608.07538

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

Model-dependent



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

Scaled from: Eur. Phys. J. C 77 475 (2017)

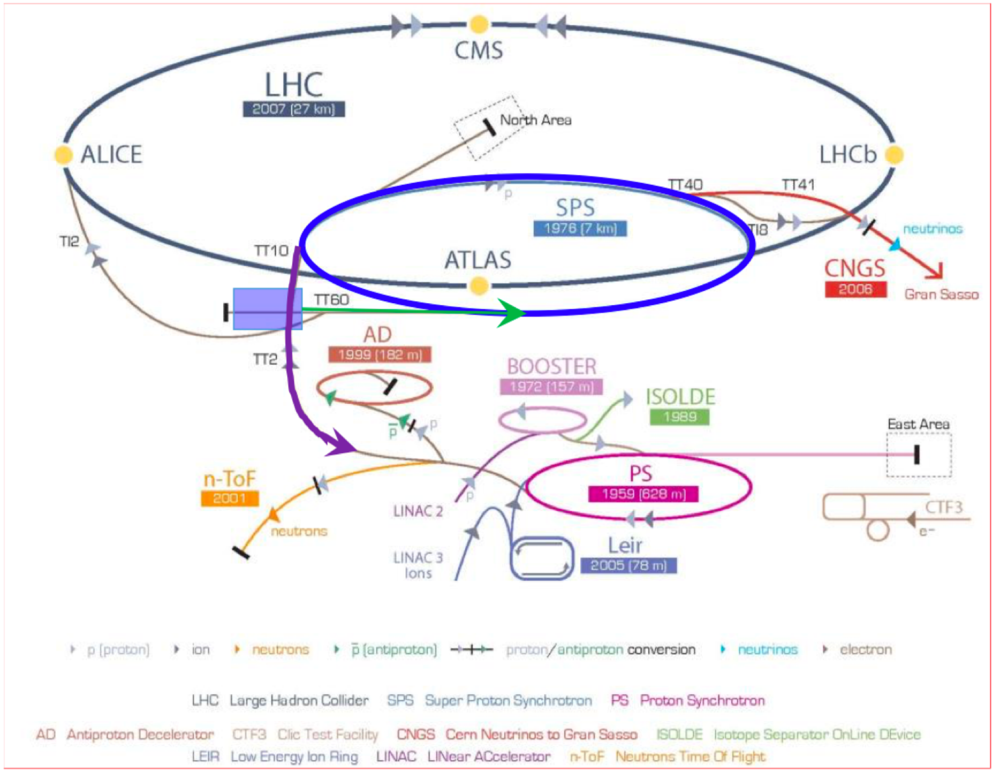
Full CLIC program, ~7 yrs of running at each stage:

- Model-independent: down to ±1% for most couplings, ultimately limited by g_{HZZ} ±0.6%
- Model-dependent: ±1% down to ± few ‰ for most couplings
- Accuracy on Higgs width: ±2.5% (MI)

eSPS electron beam (16 GeV)

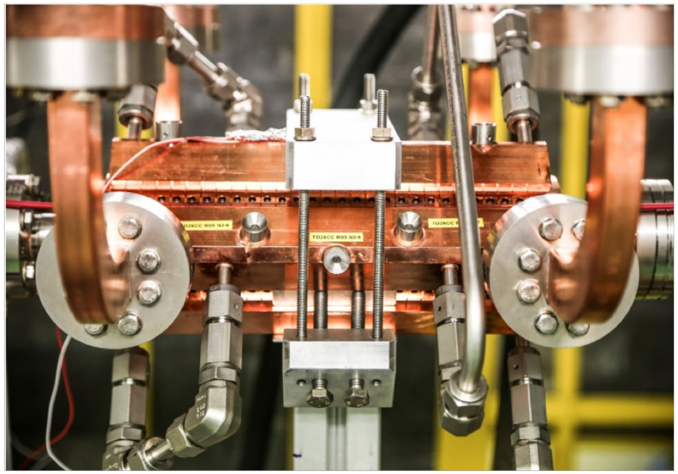
Accelerator implementation at CERN of LDMX type of beam

- X-band based 70m LINAC to ~3.5 GeV in TT4-5
- Fill the SPS in 1-2s (bunches 5ns apart) via TT60
- Accelerate to ~16 GeV in the SPS
- Slow extraction to experiment in 10s as part of the SPS super-cycle
- Experiment(s) considered by bringing beam back on Meyrin site using TT10

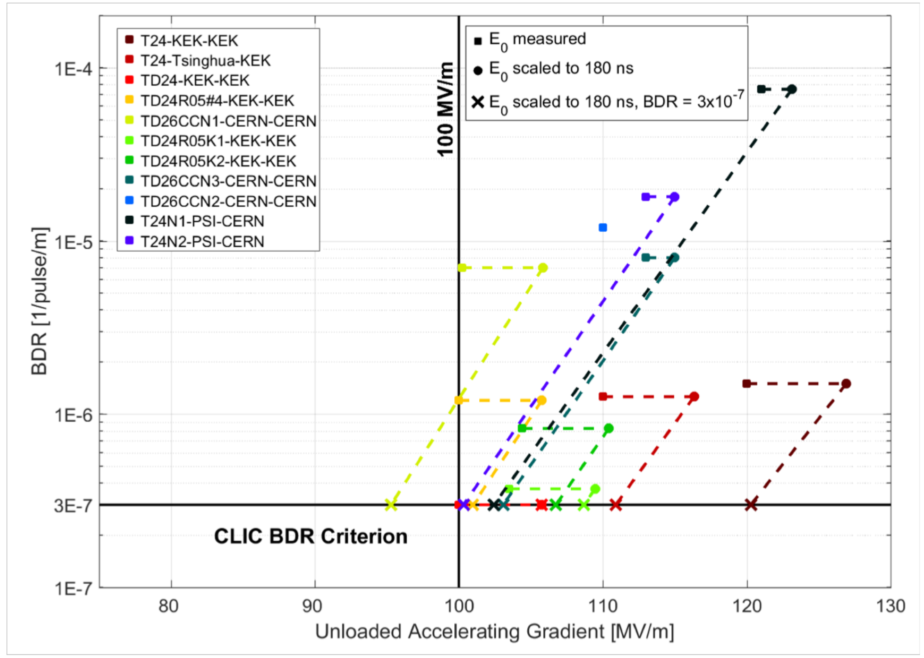


X-band and high-gradient technology

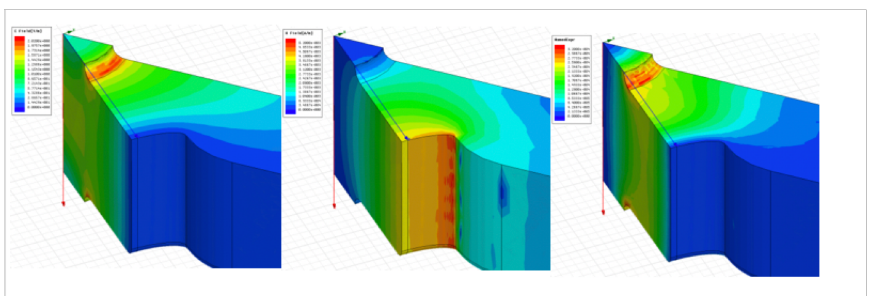
Significant increase in test infrastructures at CERN



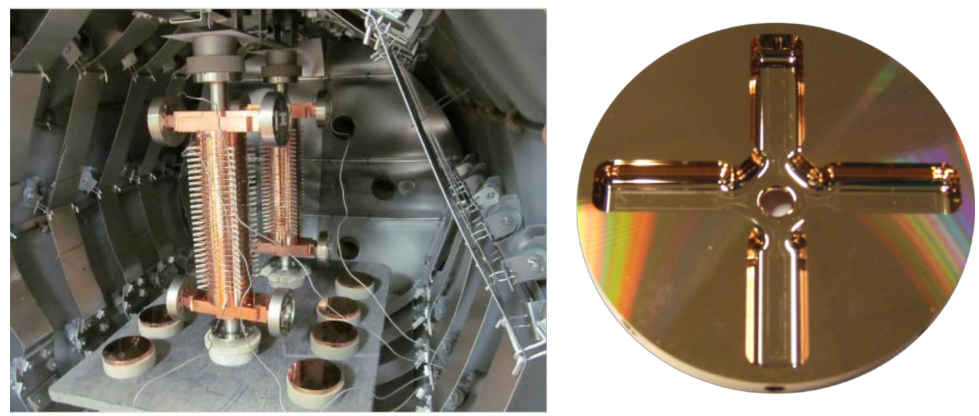
>100 MV/m accelerating structures



Prototype performance



rf design methodology



Fabrication technology

New physics reach

The precision measurements and searches can be interpreted in a wide range of model frameworks

Indicative CLIC reach for new physics. Sensitivities are given for the full CLIC programme covering the three centre-of-mass stages. All limits are at 95% C.L. unless stated otherwise. Details on many of these examples are given in The CLIC Potential for New Physics: https://e-publishing.cern.ch/index.php/CYRM/issue/view/71

Process	HL-LHC	CLIC
Higgs mixing with heavy singlet	$\sin^2\gamma < 4\%$	$\sin^2\gamma < 0.24\%$
Higgs self-coupling $\Delta\lambda$	$\sim 50\%$ at 68% C.L.	$[-7\%, 11\%]$ at 68% C.L.
BR(H $\rightarrow$ inv.) (model-independent)		$< 0.69\%$ at 90% C.L.
Higgs compositeness scale m_*	$m_* > 3$ TeV (> 7 TeV for $g_* \simeq 8$)	Discovery up to $m_* = 10$ TeV (40 TeV for $g_* \simeq 8$)
Top compositeness scale m_*		Discovery up to $m_* = 8$ TeV (20 TeV for small coupling g_*)
Higgsino mass (disappearing track search)	> 250 GeV	> 1.2 TeV
Slepton mass		Discovery up to ~ 1.5 TeV
RPV wino mass ($c\tau = 300$ m)	> 550 GeV	> 1.5 TeV
Z' mass (SM couplings)	Discovery up to 7 TeV	Discovery up to 20 TeV
NMSSM scalar singlet mass	> 650 GeV ($\tan\beta \leq 4$)	> 1.5 TeV ($\tan\beta \leq 4$)
Twin Higgs scalar singlet mass	$m_\sigma = f > 1$ TeV	$m_\sigma = f > 4.5$ TeV
Relaxion mass (for vanishing mixing)	< 24 GeV	< 12 GeV
Relaxion mixing angle ($m_\phi < m_H/2$)		$\sin^2\theta \leq 2.3\%$
Neutrino Type-2 see-saw triplet		> 1.5 TeV (for any triplet VEV) > 10 TeV (for triplet Yukawa coupling $\simeq 0.1$)
Inverse see-saw RH neutrino		> 10 TeV (for Yukawa coupling $\simeq 1$)
Scale $V_{LL}^{-1/2}$ for LFV $(\bar{e}e)(\bar{e}\tau)$		> 42 TeV

https://arxiv.org/abs/1812.07986