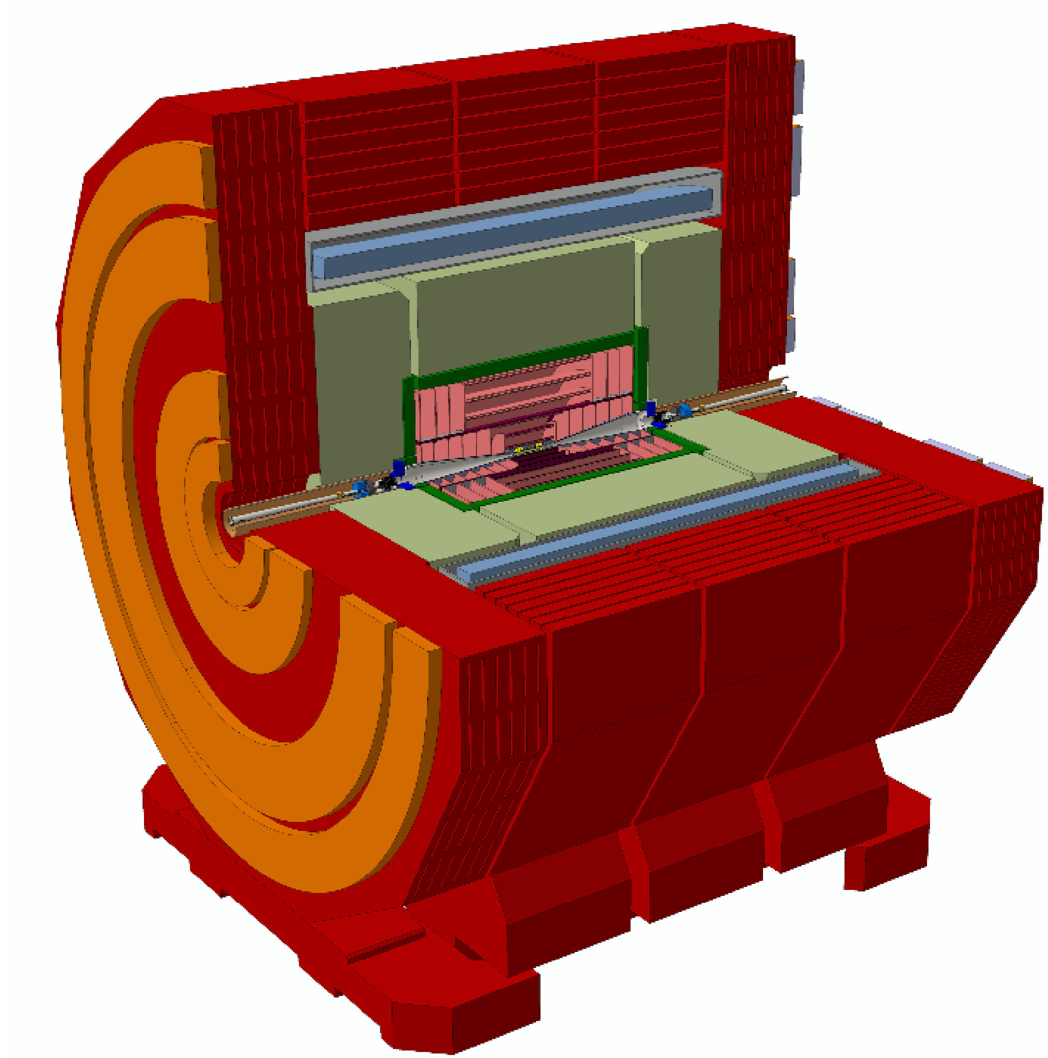
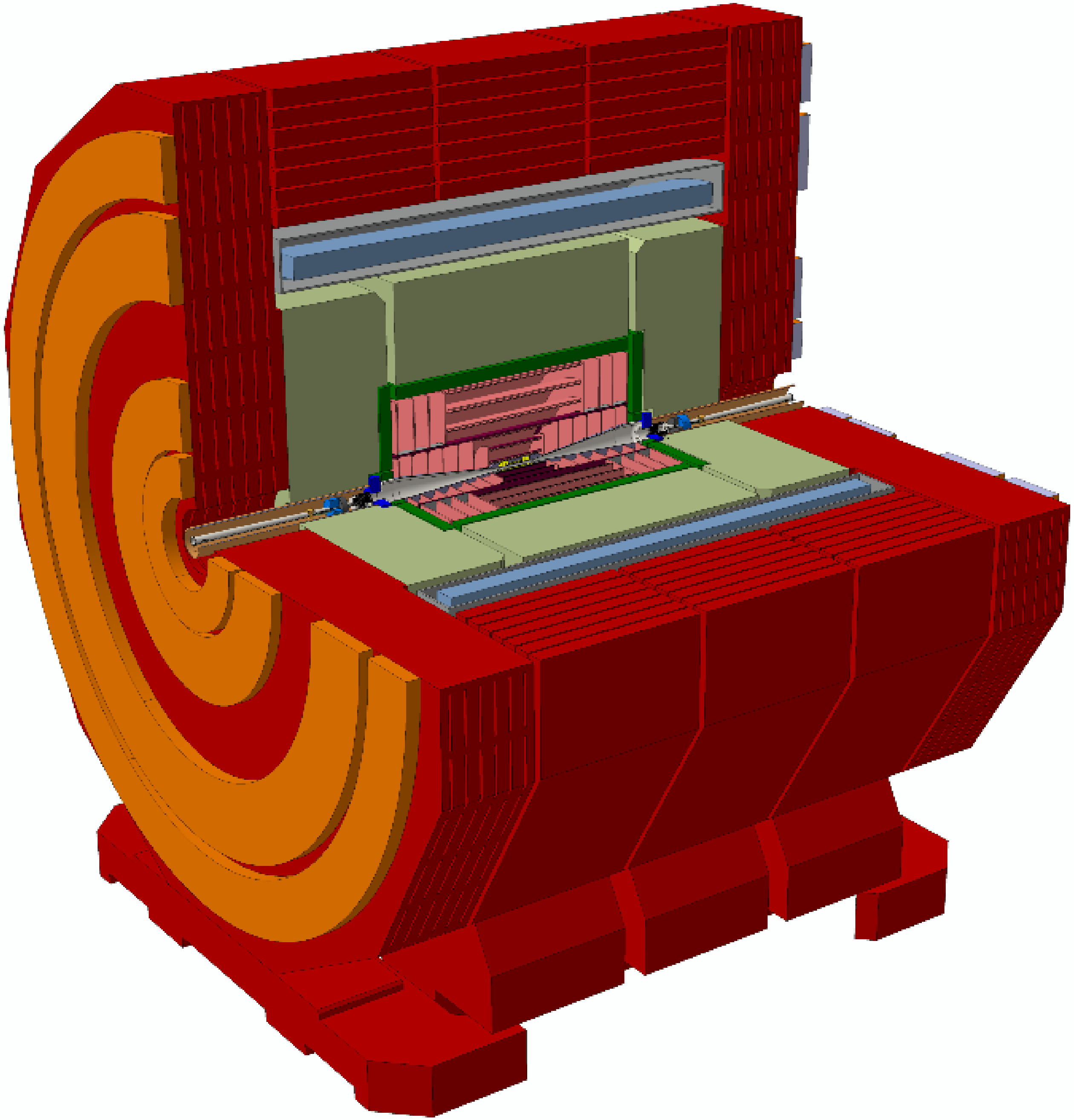
CLIC project: status and physics programme



A.F.Zarnecki

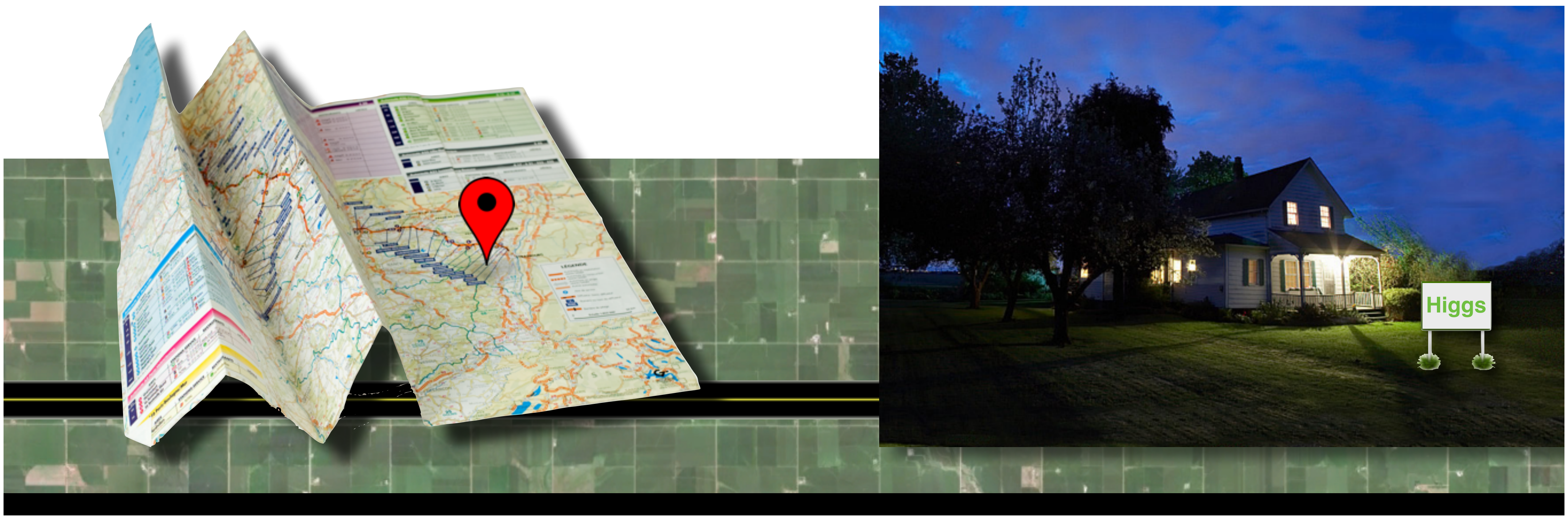
Fundamental Interactions Seminar, University of Warsaw, April 24, 2017

Introduction



Particle Physics at the Energy Frontier

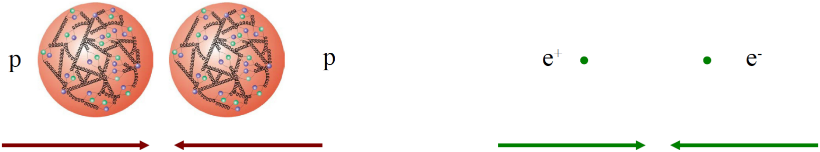
- The discovery of the Higgs boson at the LHC in 2012 marks the end of an era: All particles predicted to exist by the Standard Model of particle physics have now been observed
- We have followed an unexpectedly accurate map all the way to the end…



… and for the first time in 40 years we are left without clear guidance.

Motivation

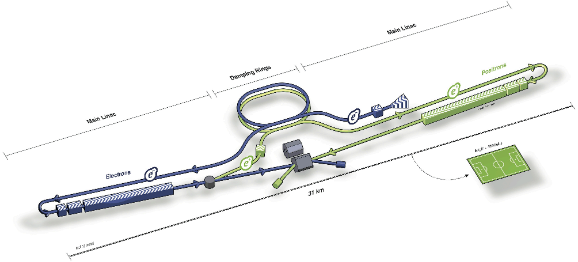
Lepton Colliders



Advantages of the Lepton Colliders

- interactions of fundamental, point-like objects
- well defined (adjustable) initial state energy and polarisation
- low radiation levels (all instrumentation very close to the beam line)
- low background rates (trigger-less readout)
- electroweak interactions dominate
- precise theoretical predictions

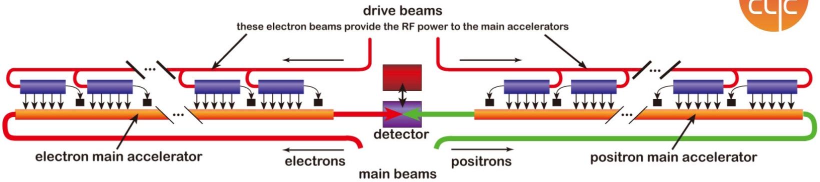
International Linear Collider



Technical Design (TDR) completed in 2013 arXiv:1306.6328

- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 31 km
- polarisation for both e^- and e^+ (80%/30%)

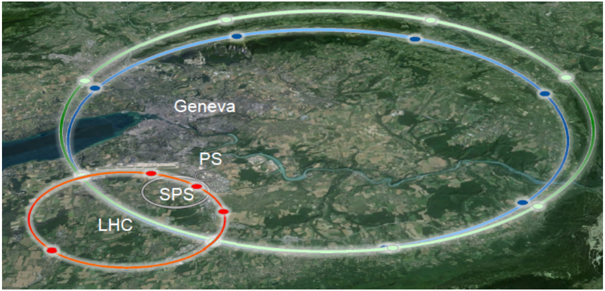
Compact LInear Collider



Conceptual Design (CDR) presented in 2012 CERN-2012-007

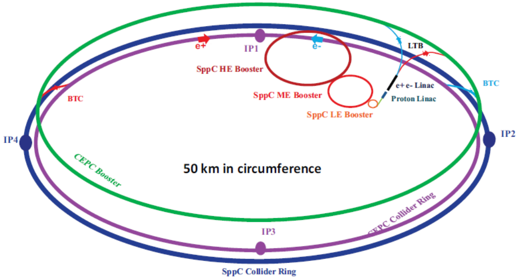
- high gradient, two-beam acceleration scheme
- staged implementation plan with c.m.s energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^- polarisation, e^+ polarisation as possible upgrade
- ongoing R&D and large-scale system tests

Circular Colliders



FCC-ee @ CERN

- 80-100 km ring
- focus on 250 GeV
  $\Rightarrow$ Higgs factory
- 350 GeV possible
- no polarization



CEPC @ China

- 50 km ring
- up to 240 GeV
  $\Rightarrow$ Higgs factory

$t\bar{t}$ threshold not reachable

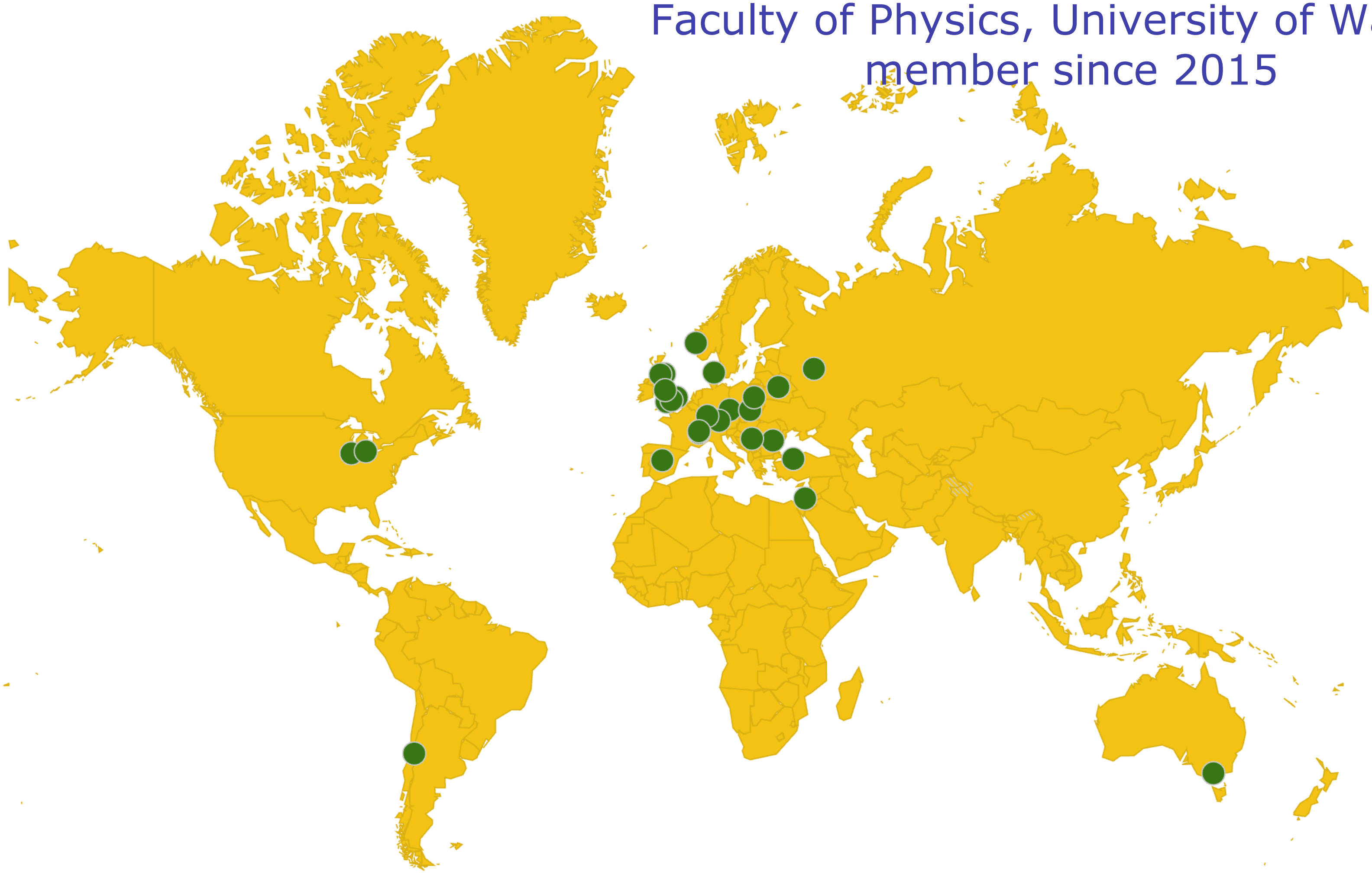
LINEAR COLLIDER COLLABORATION

CLIC Collaborations

31 Countries – over 70 Institutes

CLIC detector & physics collaboration

Faculty of Physics, University of Warsaw
member since 2015



- CLICdp collaboration addresses detector and physics issues for CLIC
- CERN acts as host laboratory
- Currently 29 institutes from 18 countries, ~180 members http://clicdp.web.cern.ch/
- Close connection to ILC detector concepts, CALICE, FCAL, AIDA-2020

Presentation based on results presented at:

CLIC/CLICdp workshop 2017

Workshop 2017:

- ~220 registrants (226 in 2016)
- ~80 physics/detector registrants (~67 at last CLICdp 2-day meeting)
- ~50 physics/detector presentations (all plenary)

Topical sessions and conveners:

- Physics and Analysis (Igor Boyko, Wolfgang Kilian, Victoria Martin, James Wells)
- Detector Validation / Detector Calibration and Alignment (Jean-Jacques Blaising, Philipp Roloff, Matthias Weber)
- Software (Frank Gaede, Aidan Robson, Andre Sailer)
- Vertex and Tracker R&D (Daniel Hynds, Andreas Nurnberg, Joost Vossebeld)
- FCAL / ECAL / HCAL R&D (Marek Idzik, Eva Sicking)

Workshop dinner => Wednesday evening in CERN restaurant R1, included in workshop fee

CLICdp dinner => Thursday evening in St Genis => 47 participants ≈ maximum

Unfortunately, no snowshoe outing on Friday, due to weather conditions

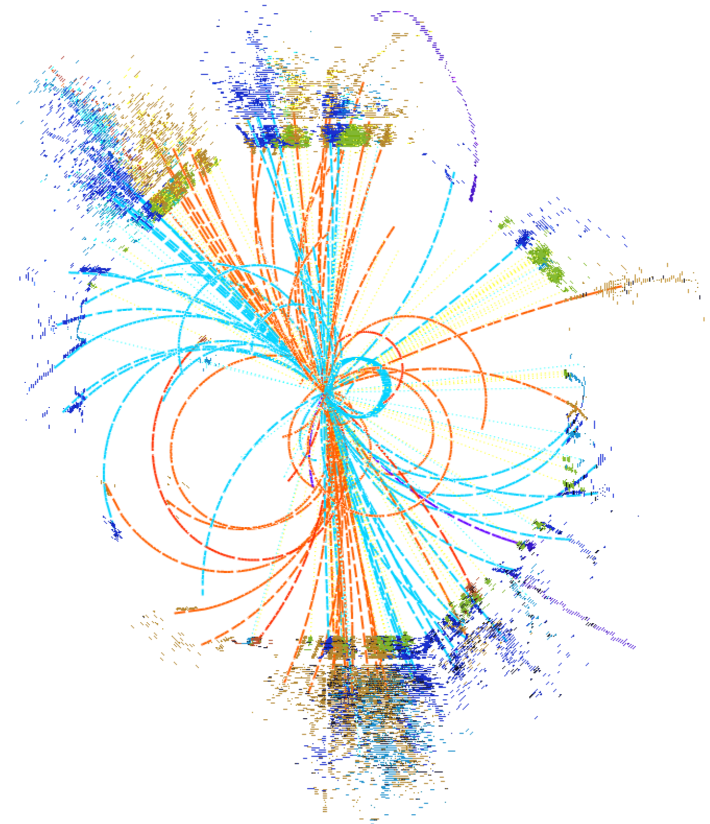
Future Linear Colliders
ILC & CLIC

Frank Simon
Max-Planck-Institute for Physics
on behalf of CLICdp and ILC

ALPS2017, Obergurgl, Austria, April 2017

Physics considerations for multi-TeV collisions

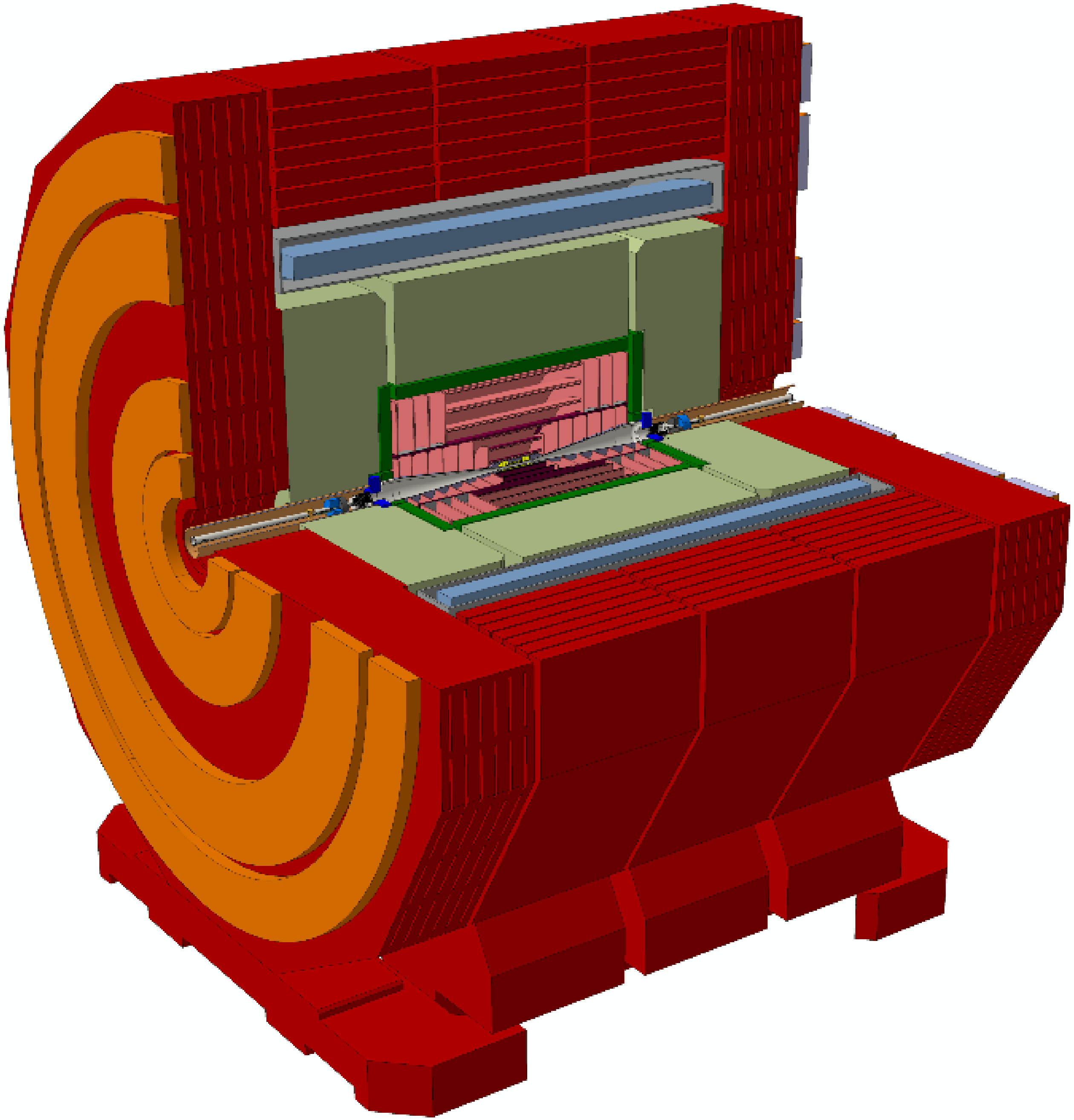
Philipp Roloff (CERN)

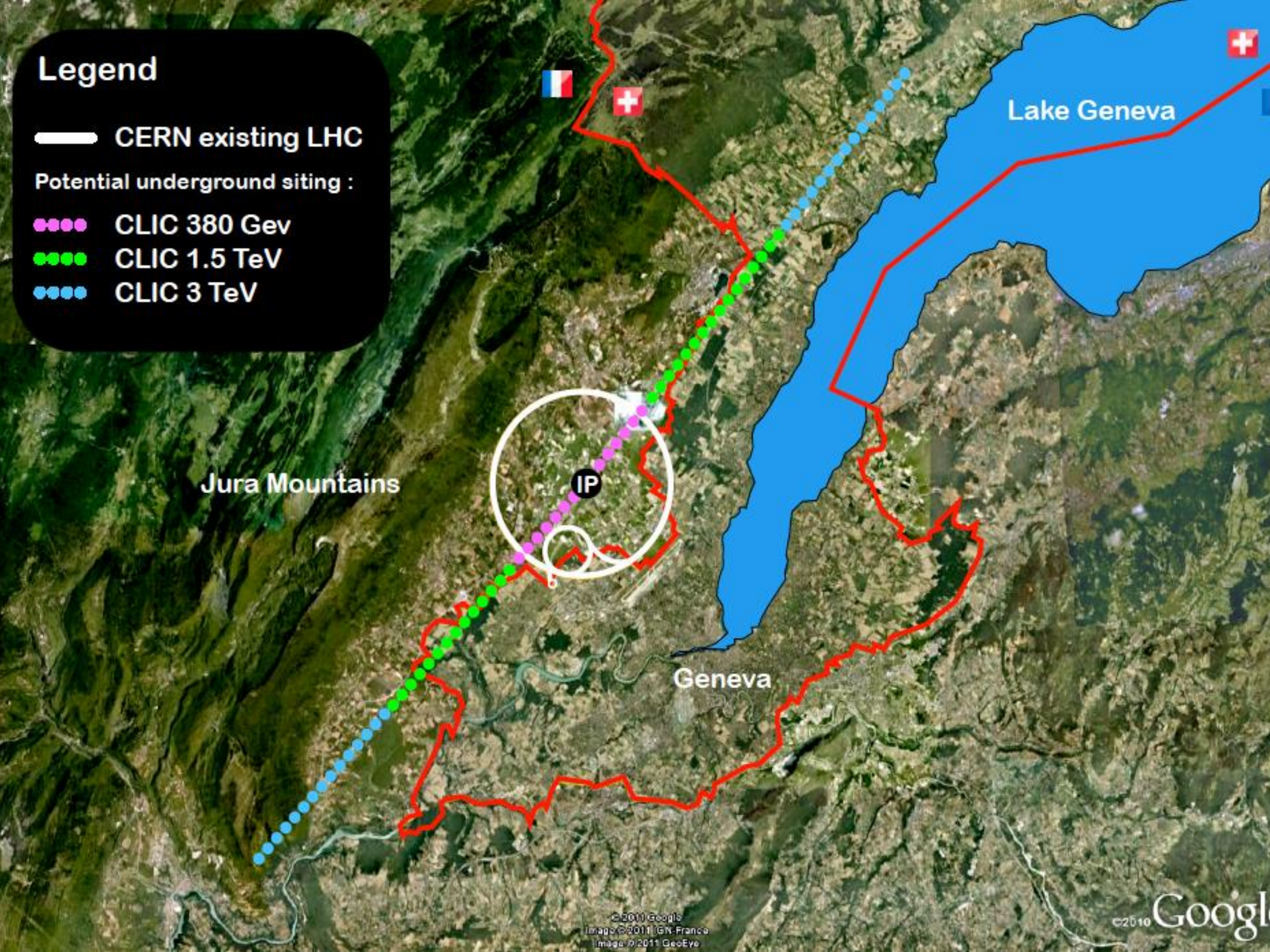


CLIC novel accelerator methods meeting

21/04/2017
CERN, Geneva

Status of the CLIC accelerator design





Legend
CERN existing LHC
Potential underground siting :
CLIC 380 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
©2010 Google

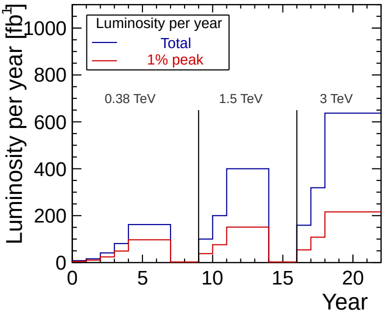
Conclusion on CLIC first energy stage

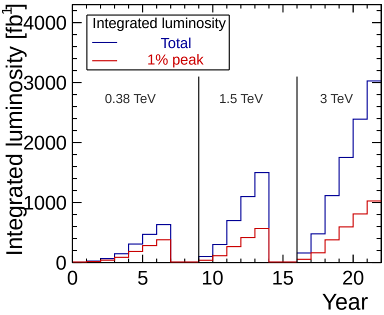
Find compromise for comprehensive physics programme of initial stage

- Higgs recoil mass measurement
  $\rightarrow$ 250 GeV$< \sqrt{s} <$ 420 GeV
- Higgs production via Higgsstrahlung and WW-fusion
  $\rightarrow$ 250 GeV$< \sqrt{s} <$ 450 GeV
- Top pair production
  $\rightarrow$ $\sqrt{s} >$ 350 GeV, maximum at $\sqrt{s} \approx$ 420 GeV
- Top as probe for BSM
  $\rightarrow$ $\sqrt{s} >$ 360 GeV
- Top not too close to threshold (theory uncertainties, boost)
  $\rightarrow$ $\sqrt{s} >>$ 350 GeV

$\rightarrow \sqrt{s} = 380$ GeV

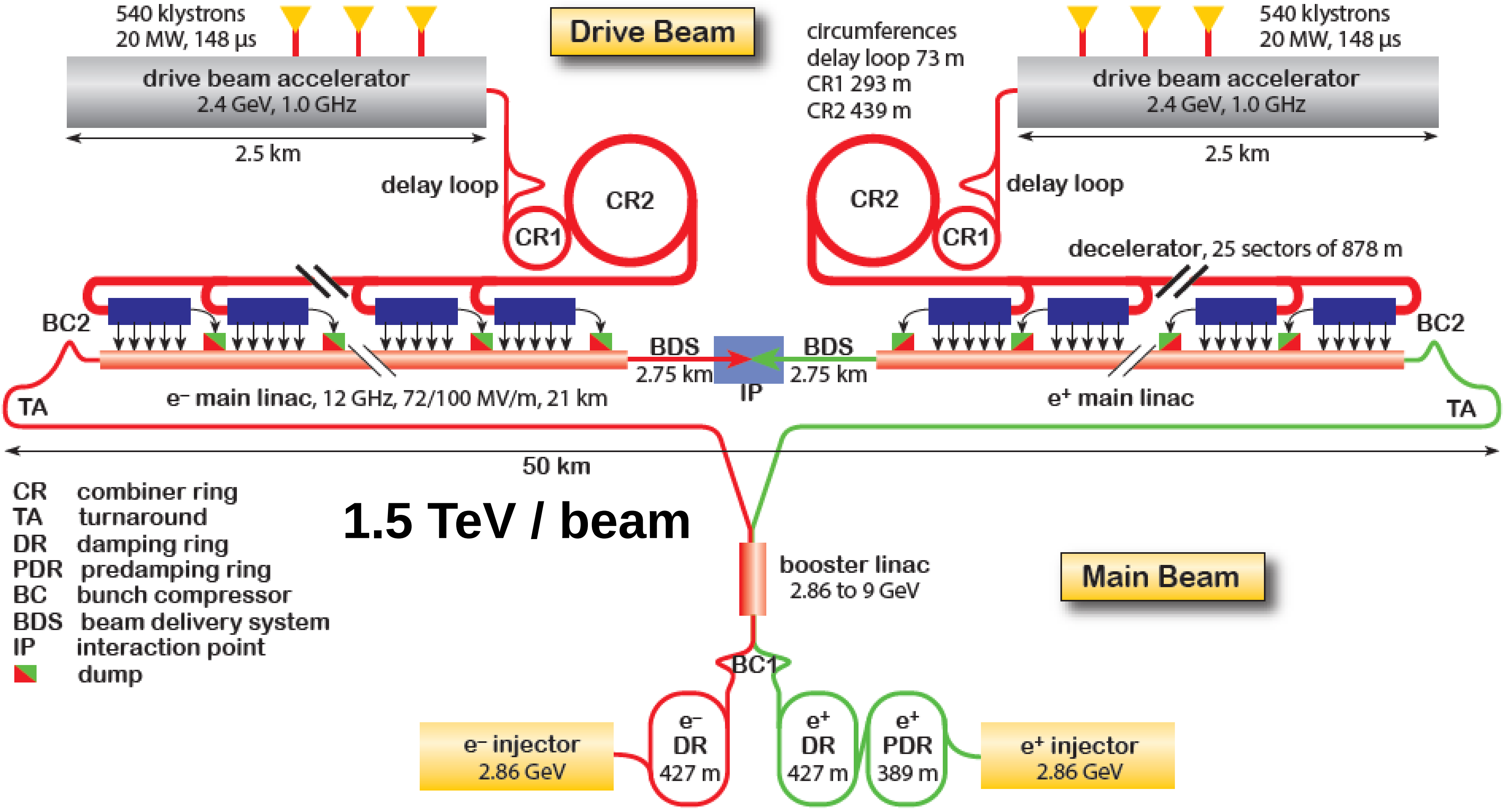
Updated luminosity development





- CLIC programme of 22 years:
  7 years (380 GeV), 5 years (1.5 TeV), 6 years (3 TeV)
  interleaved by 2-years upgrade periods
- Luminosity ramp up of 4 years / 2 years
  (5%, 10%,) 25%, 50%, 100%

CLIC layout (3 TeV)



R&D studies at CTF3 completed in 2016

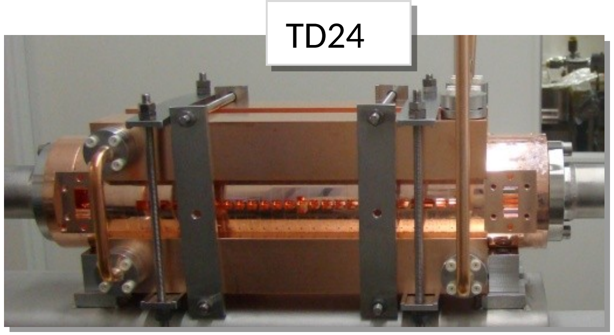
Recently installed 2-beam acceleration module in CTF3
(according to latest CLIC design)

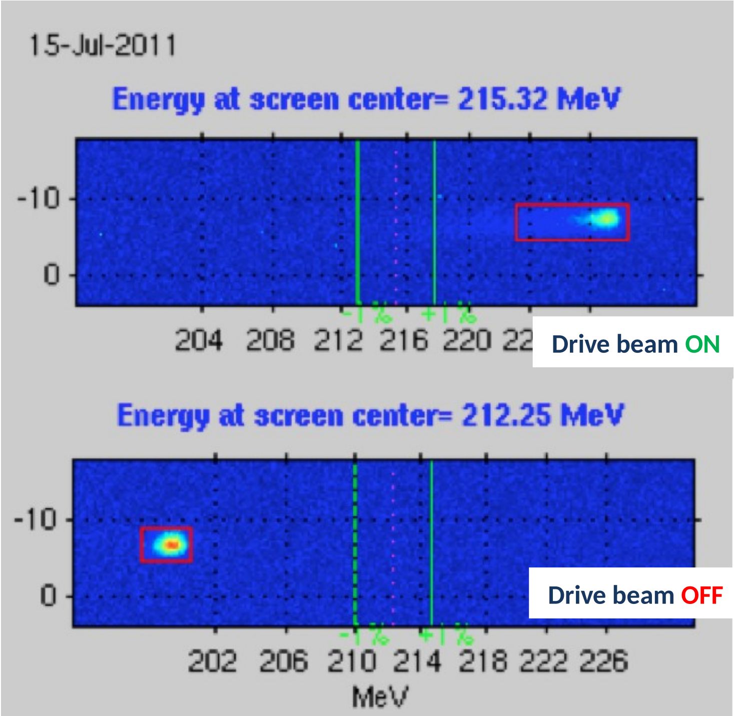
Two-Beam Acceleration

Two-Beam Acceleration demonstration in TBTS

Up to 145 MV/m measured gradient

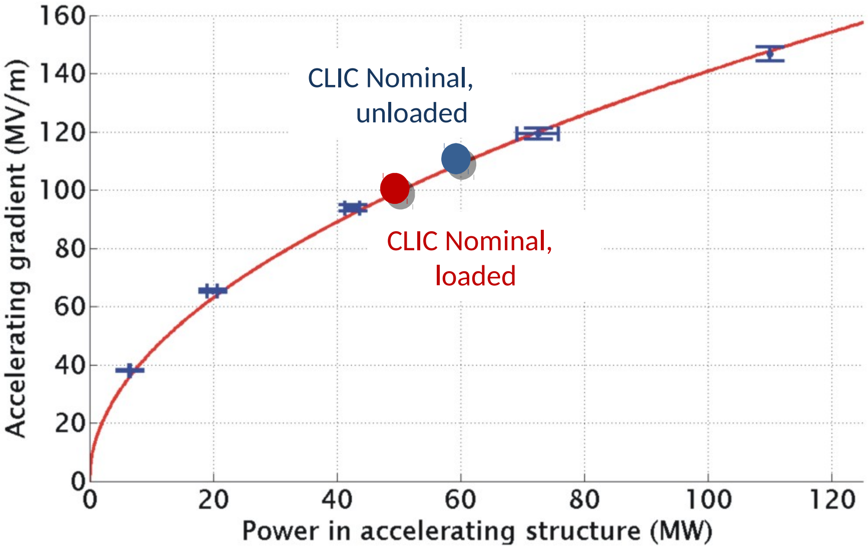
Good agreement with expectations (power vs. gradient)



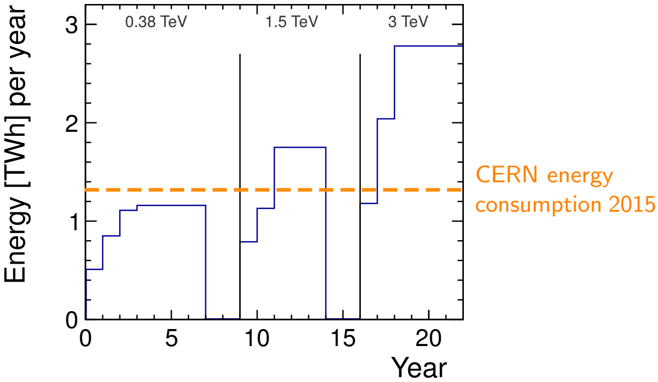


Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of **145 MV/m**



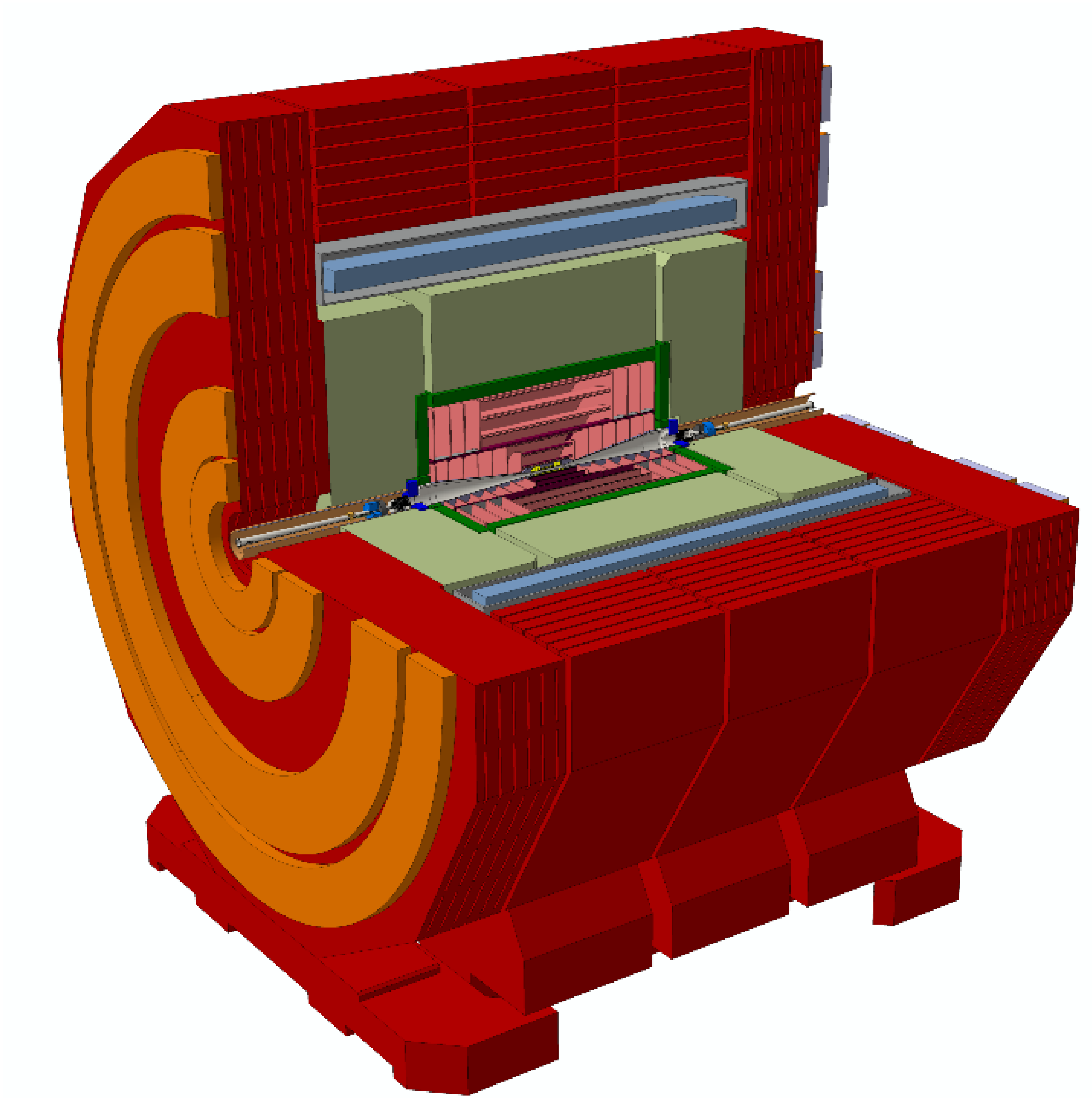
Yearly energy consumption



- Including reduced operation in the first years at each energy
- At 380GeV, a single positron target is used for the first three years (-10 MW with respect to nominal)

(Note → 380 GeV numbers scaled from CDR design at 500 GeV
→ To be repeated with detailed tech. description of 380 GeV CLIC)

Status of the CLIC detector design

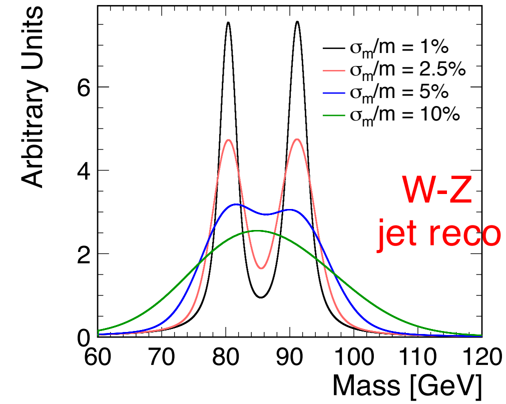


Detector requirements

→ Jet-energy resolution

e.g. W/Z/H di-jet mass separation, ZH with Z➔ qq

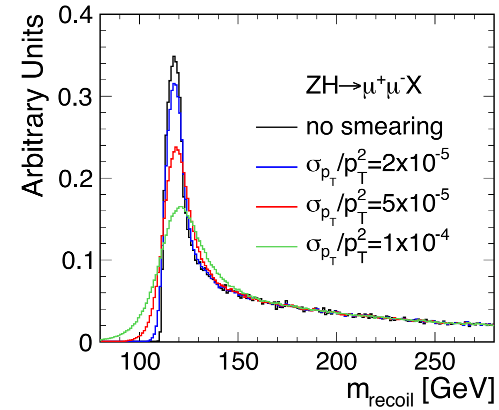
$$\frac{\sigma_E}{E} \sim 3.5 - 5\ \%$$ (for high-E jets, light quarks)



→ momentum resolution:

e.g, $g_{H\mu\mu}$, Smuon endpoint

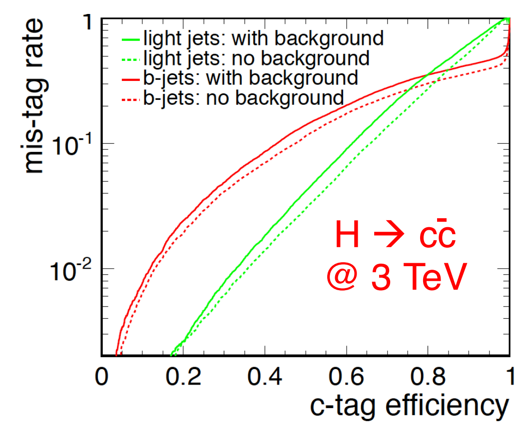
$$\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$$



→ impact parameter resolution:

e.g. c/b-tagging, Higgs BR

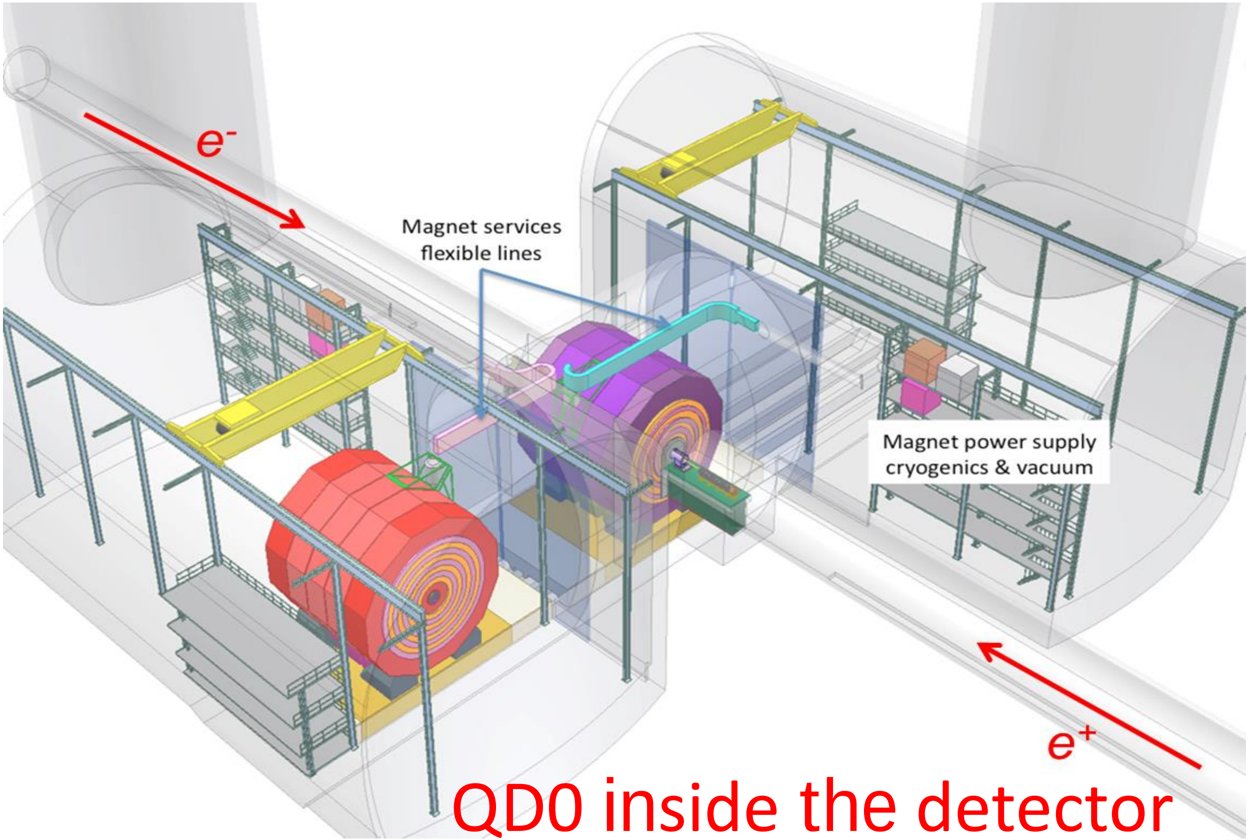
$$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}] \sin^{\frac{3}{2}}\theta)\ \mu\mathrm{m}$$



→ angular coverage, very forward electron tagging

+ requirements from CLIC experimental conditions

The CDR concept (2012)

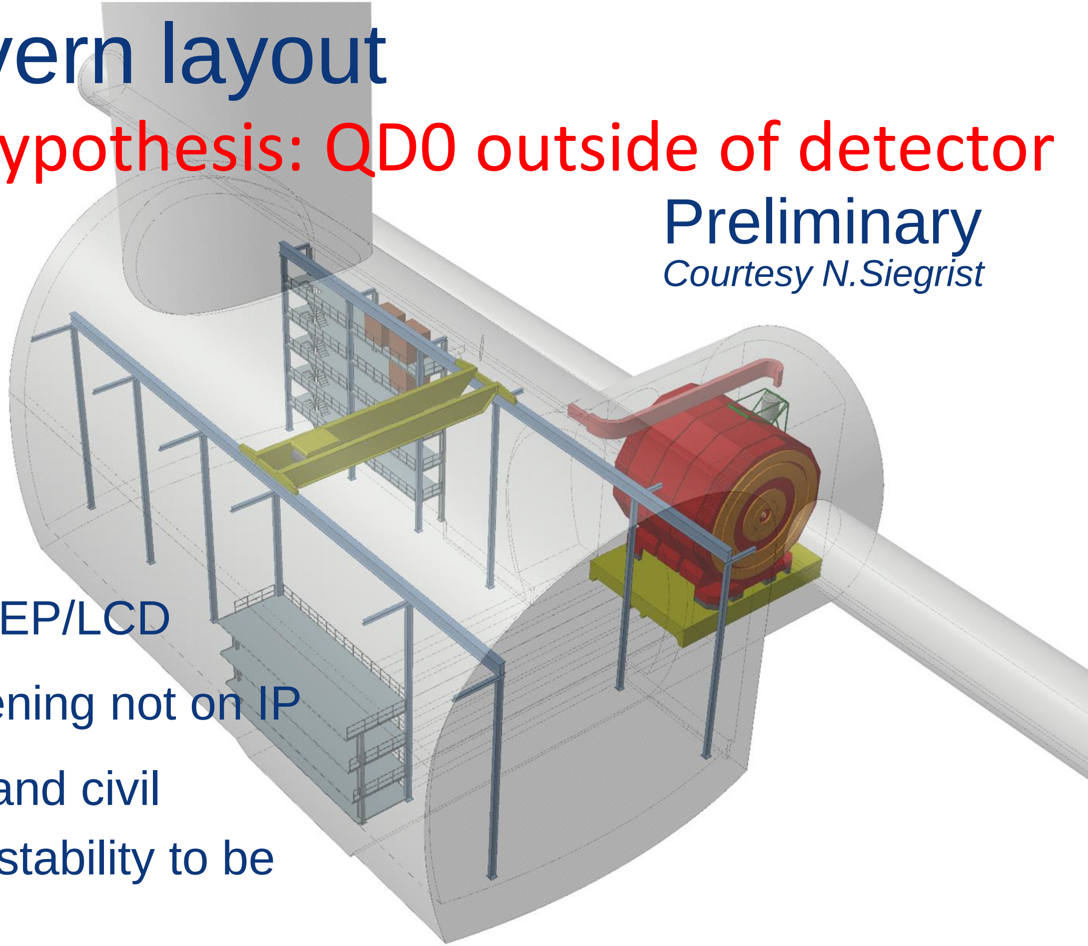


New cavern layout

Working Hypothesis: QD0 outside of detector

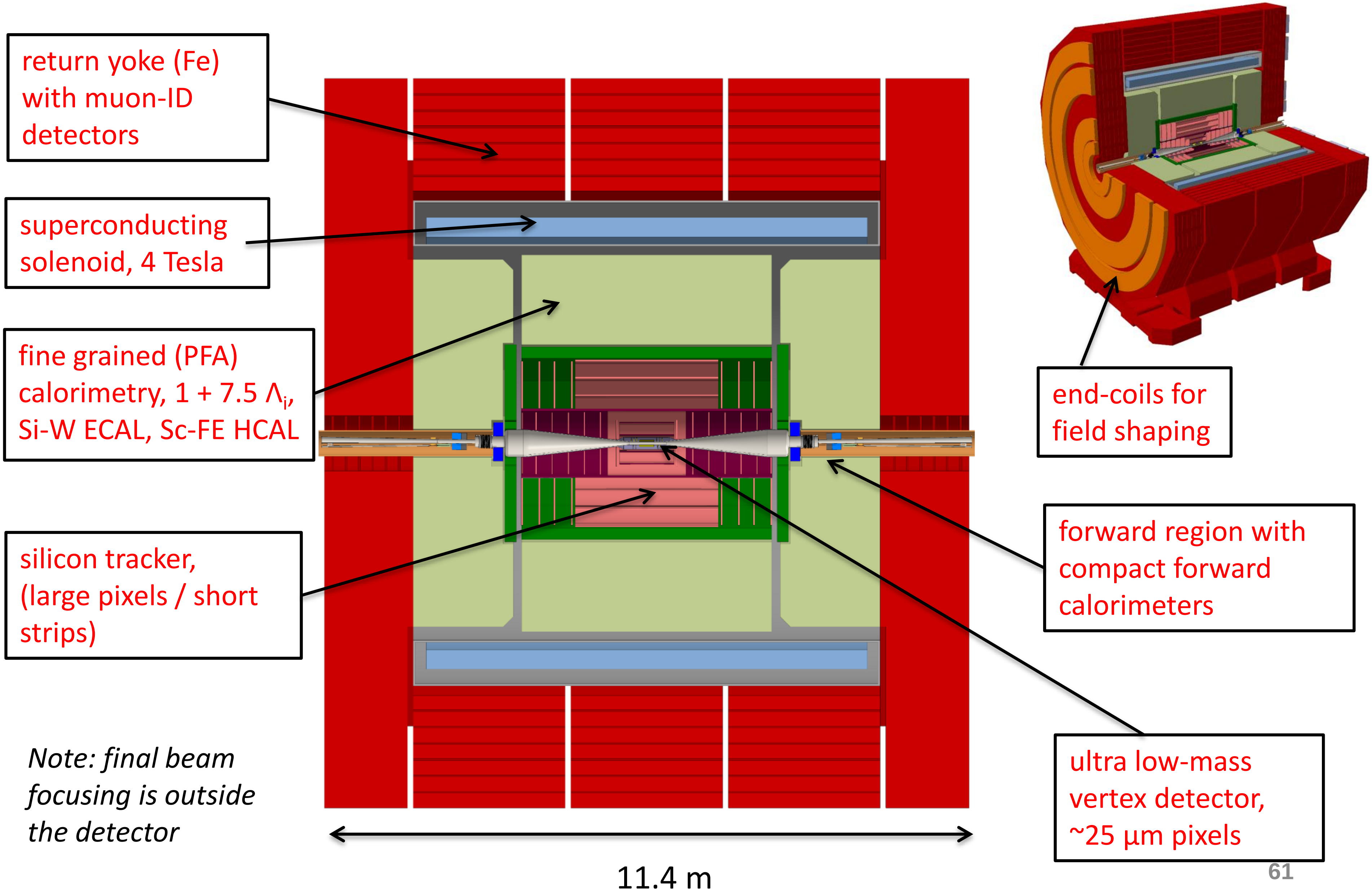
Preliminary

Courtesy N.Siegrist



- Proposal by EP/LCD
- Detector opening not on IP
- Mechanical and civil engineering stability to be verified

New CLIC detector model



Note: final beam focusing is outside the detector

Emerging silicon technologies

- In the last (~5) years many novel detectors have been designed taking advantage of recent commercially available CMOS processes
  - Plethora of new devices, many with only subtle differences, processes typically differ by Foundry and technology size…

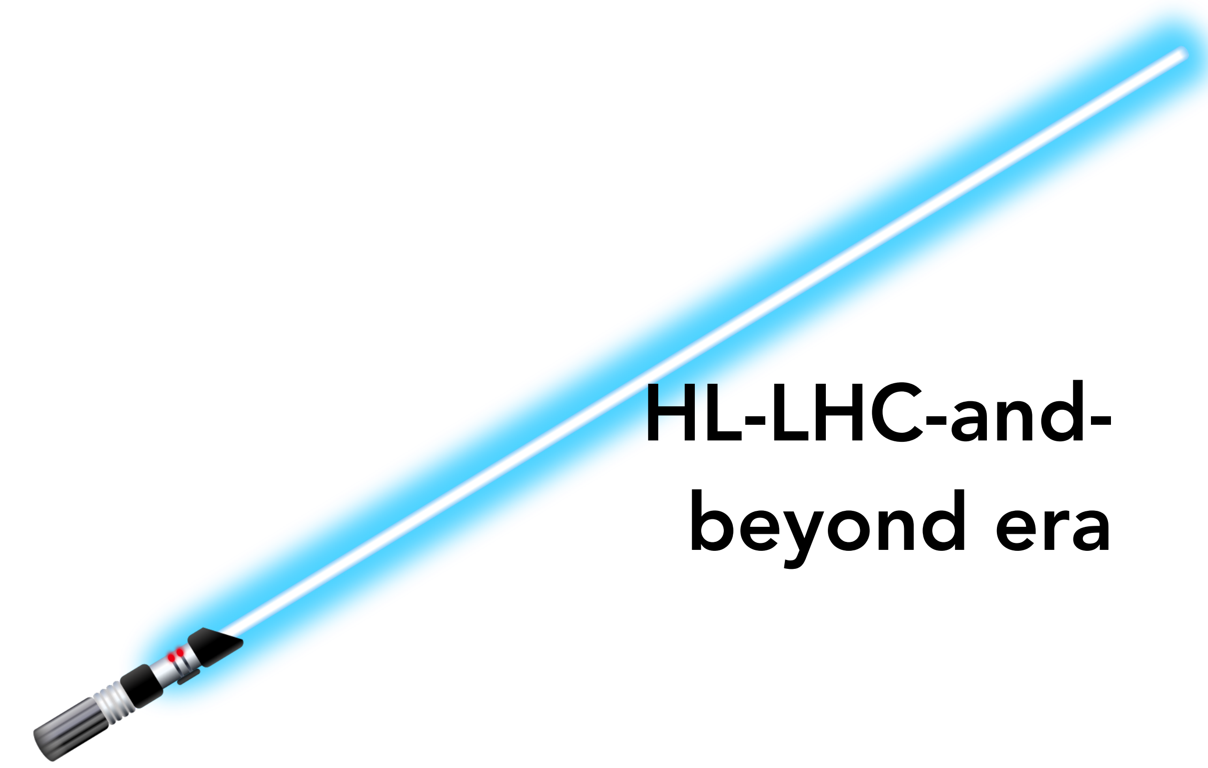
- CLIC has been heavily involved in several of these areas, which are also of interest for high luminosity LHC upgrades, as well as more broadly to HEP and medical imaging

LEP era

=>

LHC era

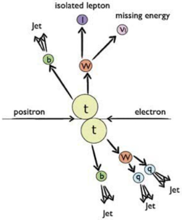
=>



HL-LHC-and-beyond era

Detector Requirements

Jet reconstruction and jet energy measurement based on "Particle Flow" concept



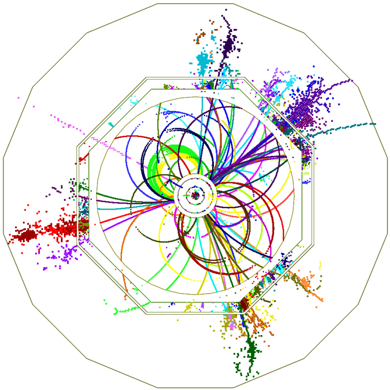
High detector granularity
$\Rightarrow$ reconstruction of single particles

Excellent momentum measurement
$\Rightarrow$ best possible jet energy estimate

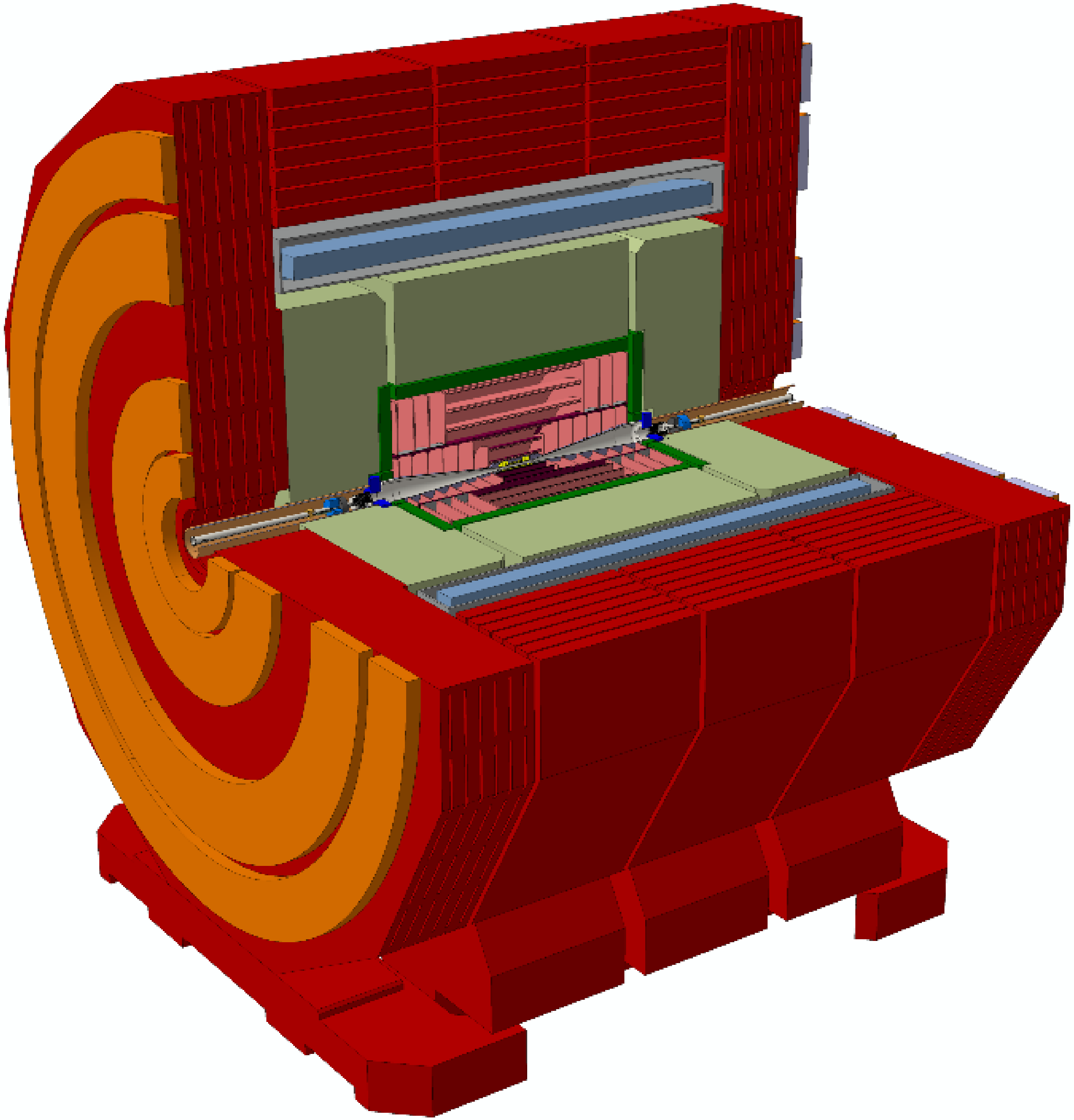
High precision vertex detector
$\Rightarrow$ very efficient flavour tagging

Hermecity
$\Rightarrow$ missing energy measurement

$e^+e^- \to t\bar{t} \to 4j + l + \nu$



CLIC physics



Physics at Linear Colliders - Overview

- Three main pillars:

Higgs

Full exploration of the Higgs sector:

a model-independent measurement of all relevant Higgs couplings

direct study of the Higgs potential: Measurement of the self coupling

top

Precision measurements of top quark properties in theoretically well-defined schemes

Use of top quark observables as an indirect probe for New Physics at high mass scales

electroweak precision measurements

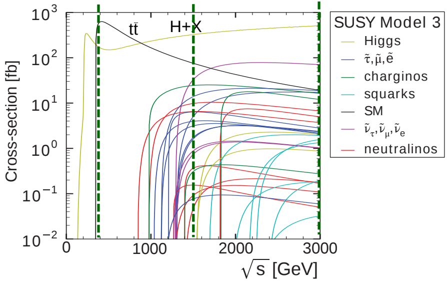
New Physics

Direct search for new particles complementary to the LHC: additional light Higgs bosons, electroweak states, Dark Matter candidates, …

Indirect search for new force carriers at high mass scales

Proposed CLIC staging baseline

- CLIC energy stages defined by physics
- Proposed scenario
  1) $\sqrt{s} = 380\,\mathrm{GeV}$
     - SM Higgs physics including total width measurement
     - Top precision measurements
     - New physics
  2) $\sqrt{s} = 1.5\,\mathrm{TeV}$
     - New physics
     - $t\bar{t}H$, Higgs self coupling
     - Rare Higgs decays
  3) $\sqrt{s} = 3\,\mathrm{TeV}$
     - New physics
     - Higgs self coupling
     - Rare Higgs decays

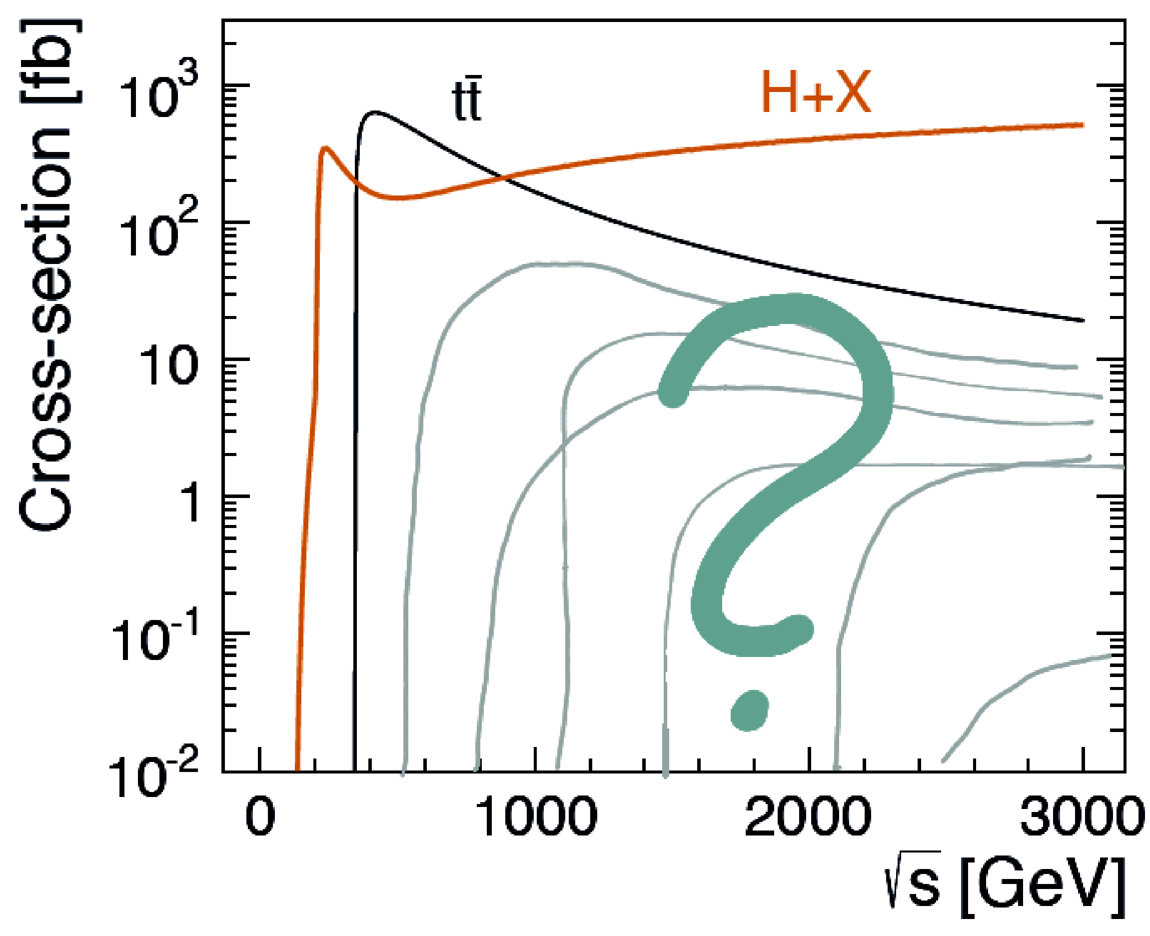


Stage	$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

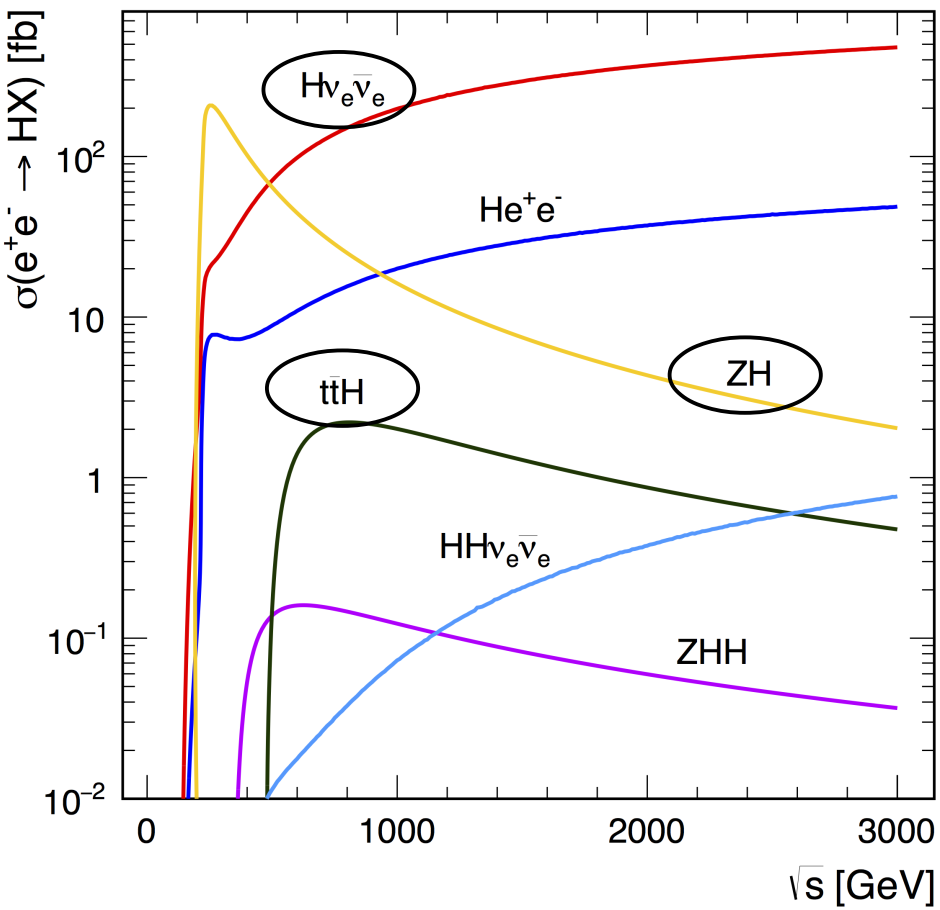
CLIC physics context

Energy-frontier capability for electron-positron collisions,

for precision exploration of potential new physics that may emerge from LHC



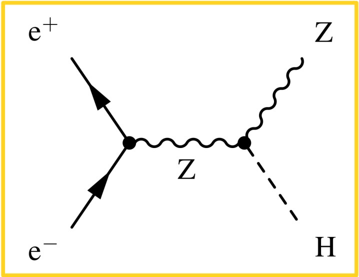
Single Higgs production

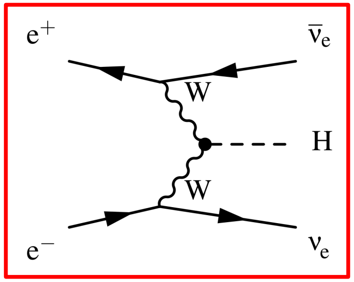


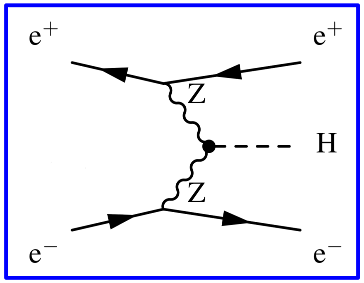
Higgsstrahlung: $e^+e^- \to ZH$
- $\sigma \sim 1/s$, dominant up to ≈ 450 GeV

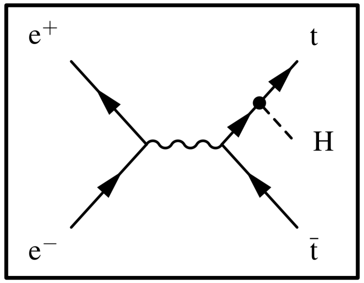
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$
- $\sigma \sim \log(s)$, dominant above 450 GeV
- Large statistics at high energy

$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$
- Accessible ≥ 500 GeV, maximum ≈ 800 GeV
- Direct extraction of the top-Yukawa coupling



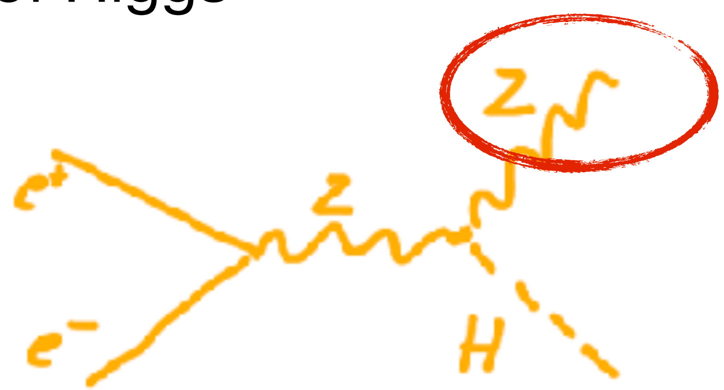




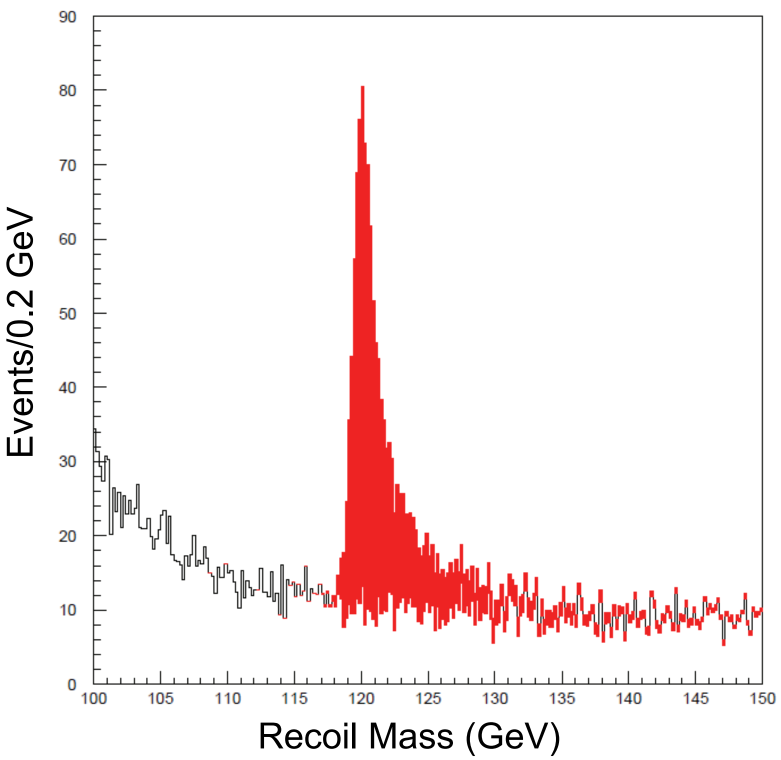


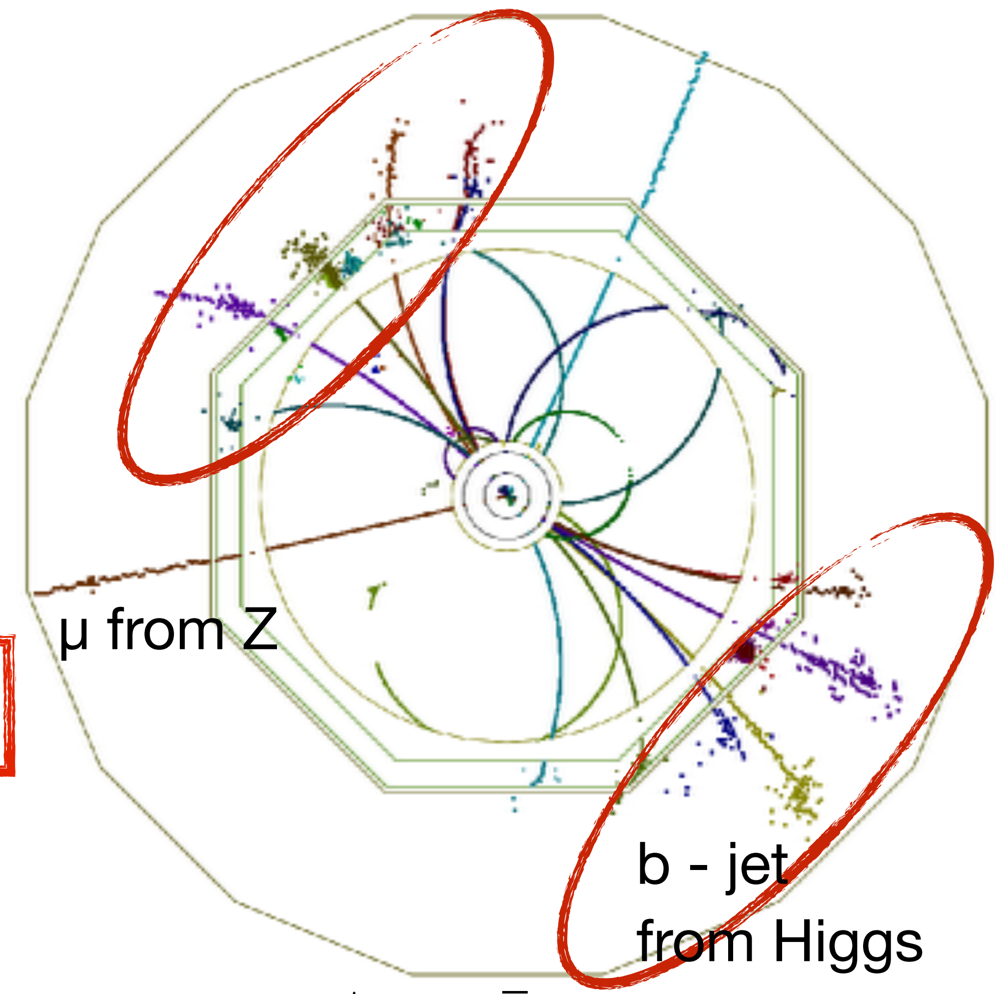
Higgs: Model Independence

- A key capability of e^+e^- colliders: Model-independent measurement of Higgs coupling to Z
  - Measure only recoiling Z boson



$$m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$





$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

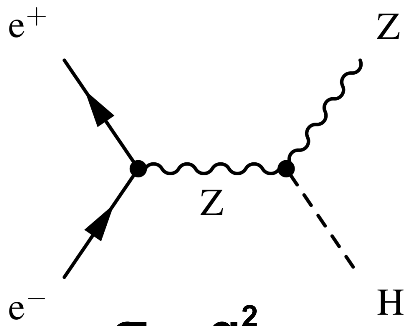
- Also possible in hadronic Z decays keeping model independence: substantial boost in statistics compared to extremely clean di-lepton final state

Highest cross section at 250 GeV, good sensitivity also at 350/380 GeV

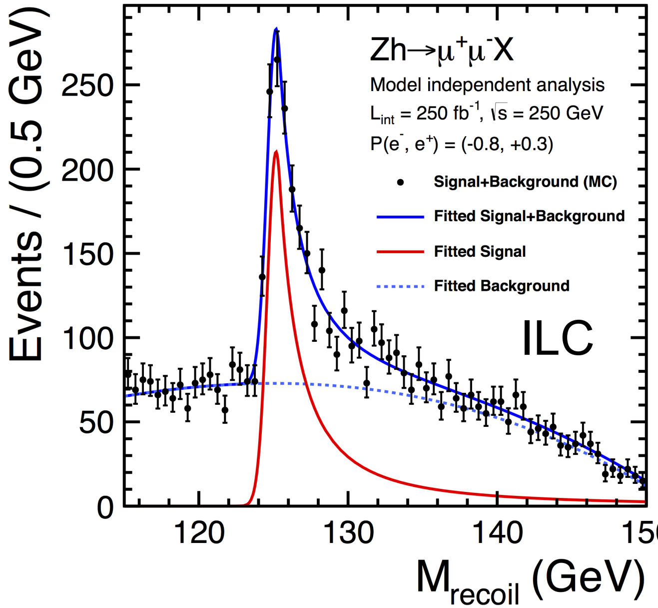
Higgsstrahlung: $e^+e^- \rightarrow ZH$

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)

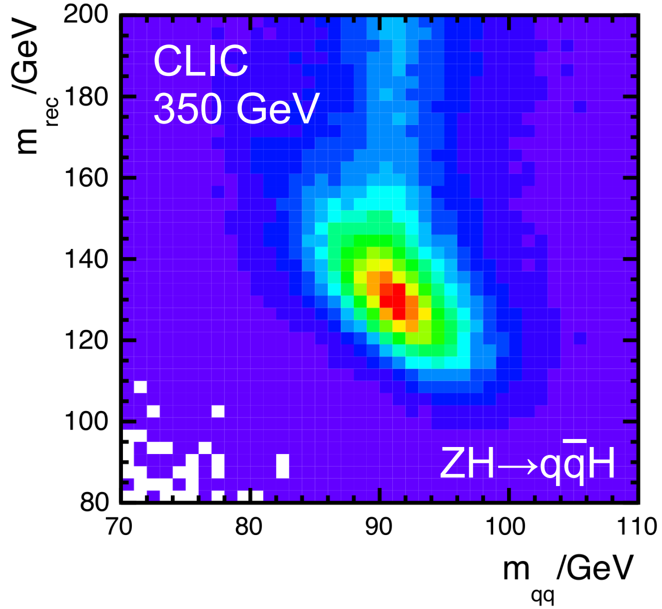


$\sigma \sim g^2_{HZZ}$



Using $Z \rightarrow q\bar{q}$:
• Almost model-independent measurement of g_{HZZ} possible using hadronic Z decays
→ Substantial improvement in precision possible

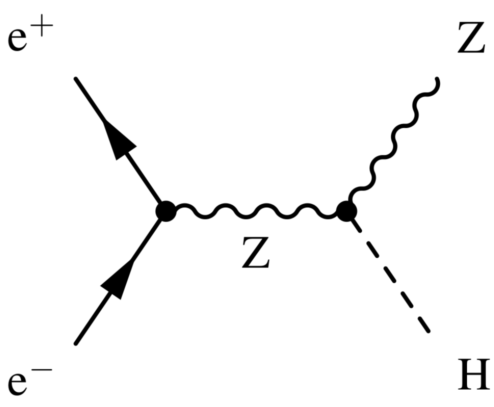
• Better precision at 350 GeV found than at 250 GeV or 420 GeV

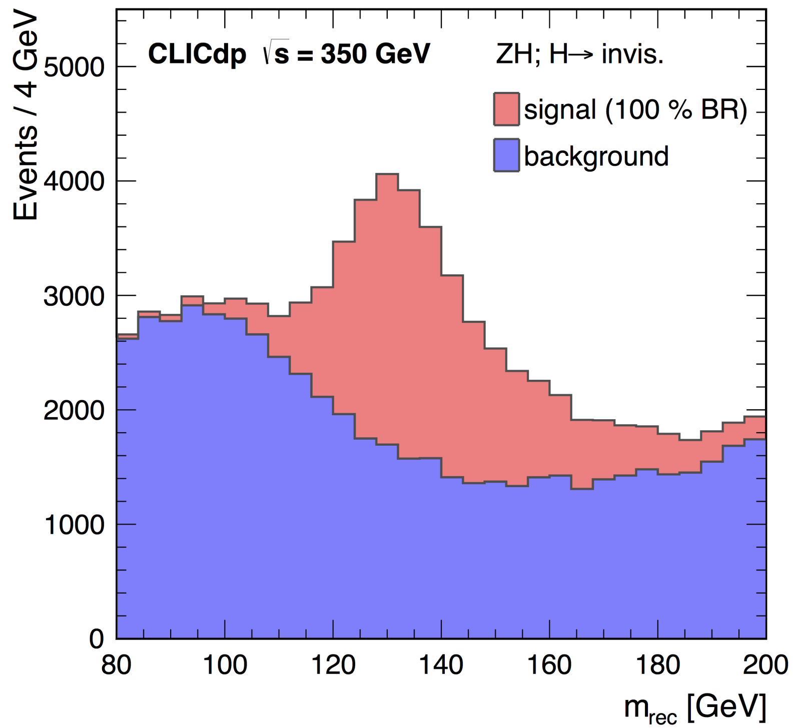


Invisible Higgs decays

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

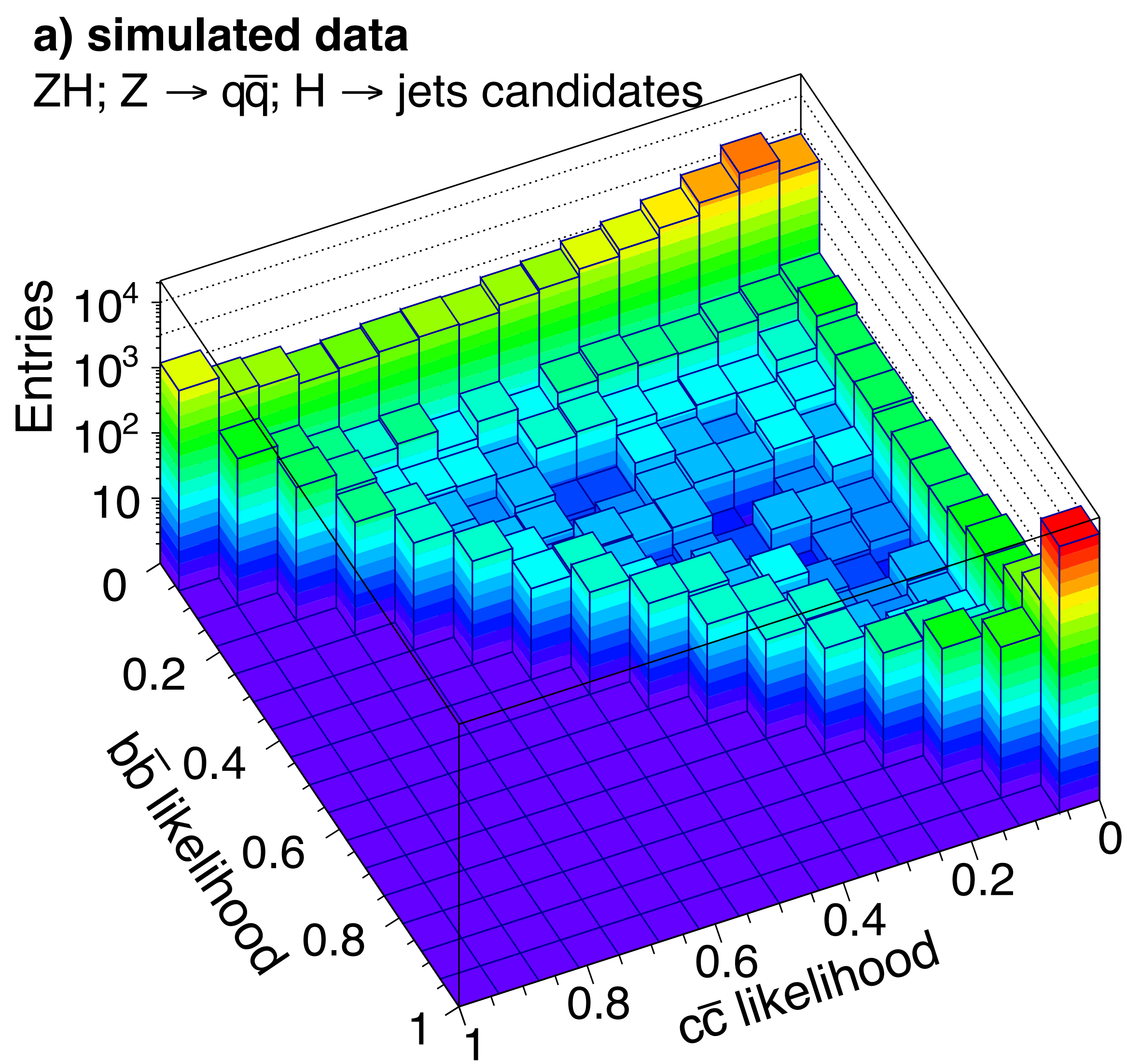


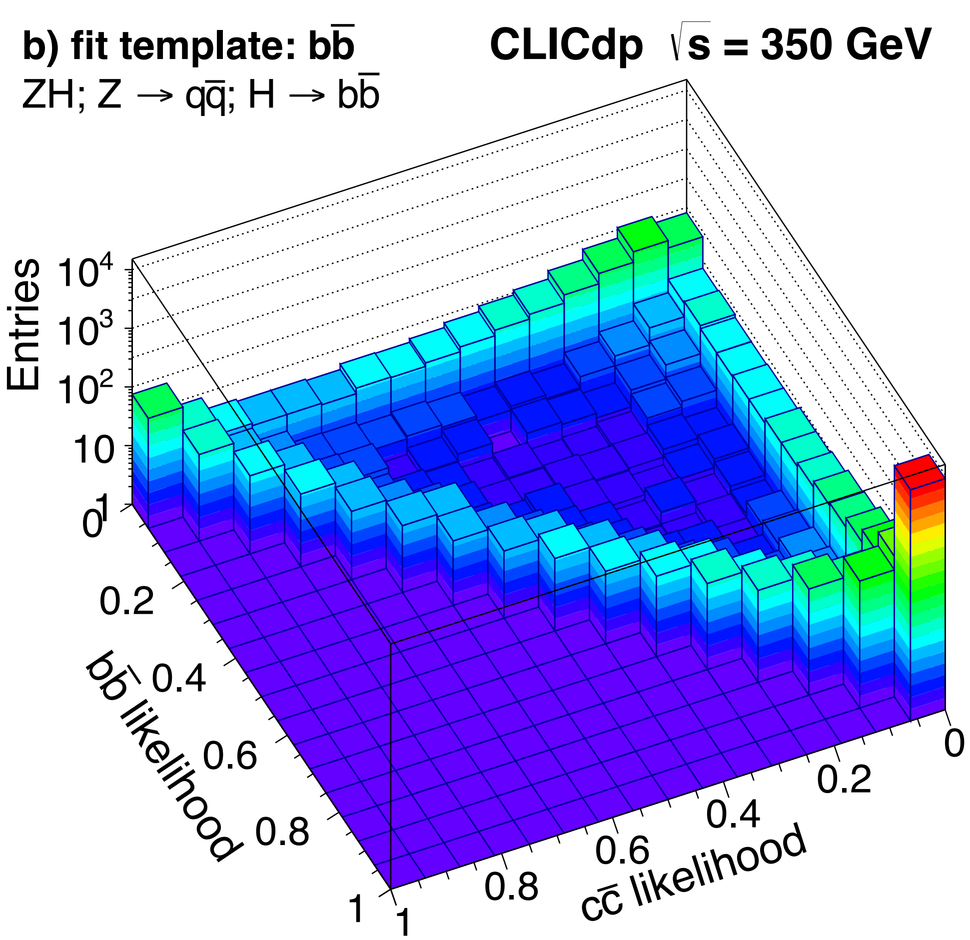


Recoil mass from Z→$q\bar{q}$ assuming all Higgs bosons decay invisibly

Higgs -> Jets: b,c, gluon couplings

- Selection of hadronic final states, separated by flavor tagging: Example CLIC @ 350 GeV
  - BRs from template fit in flavor space





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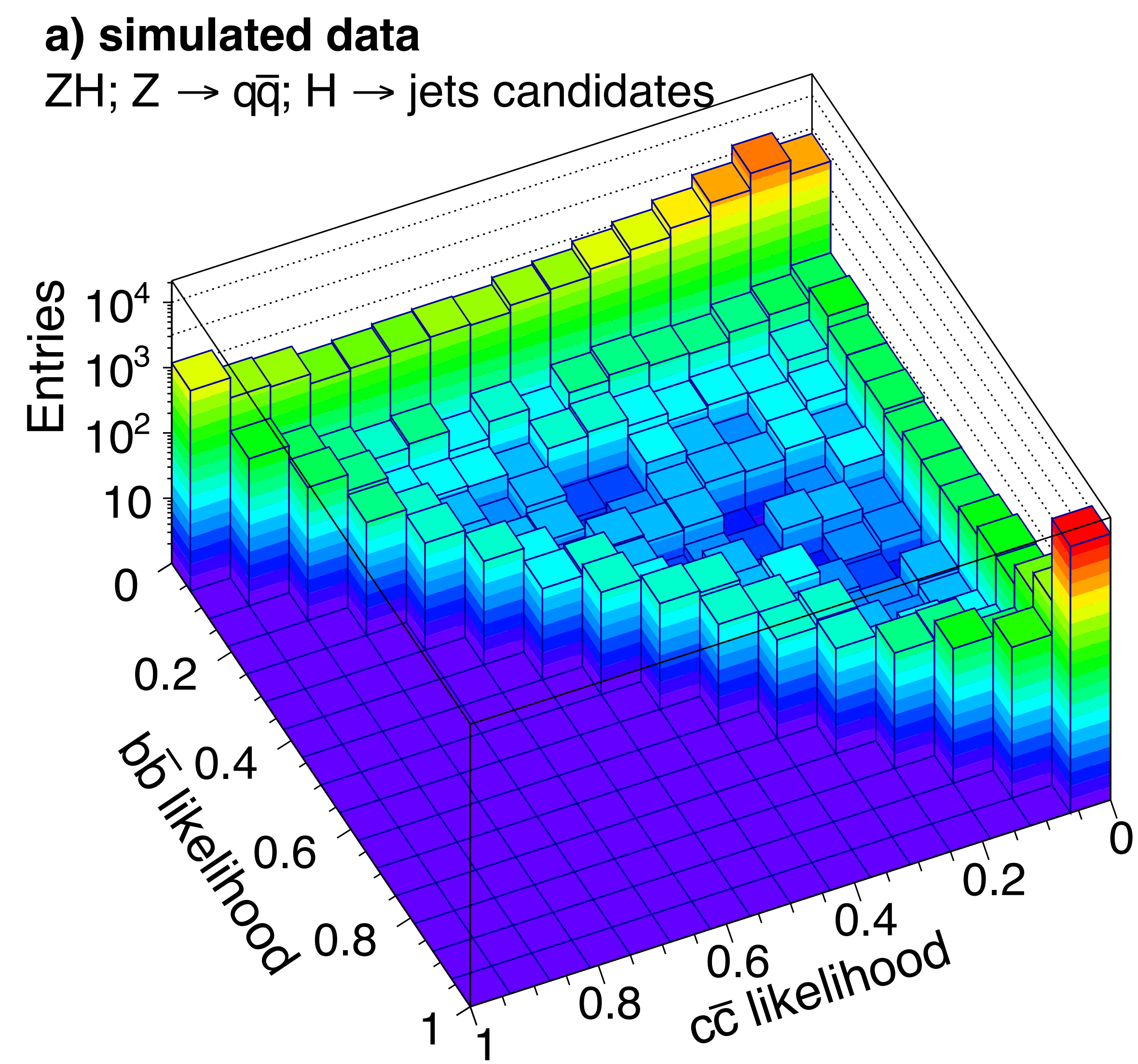
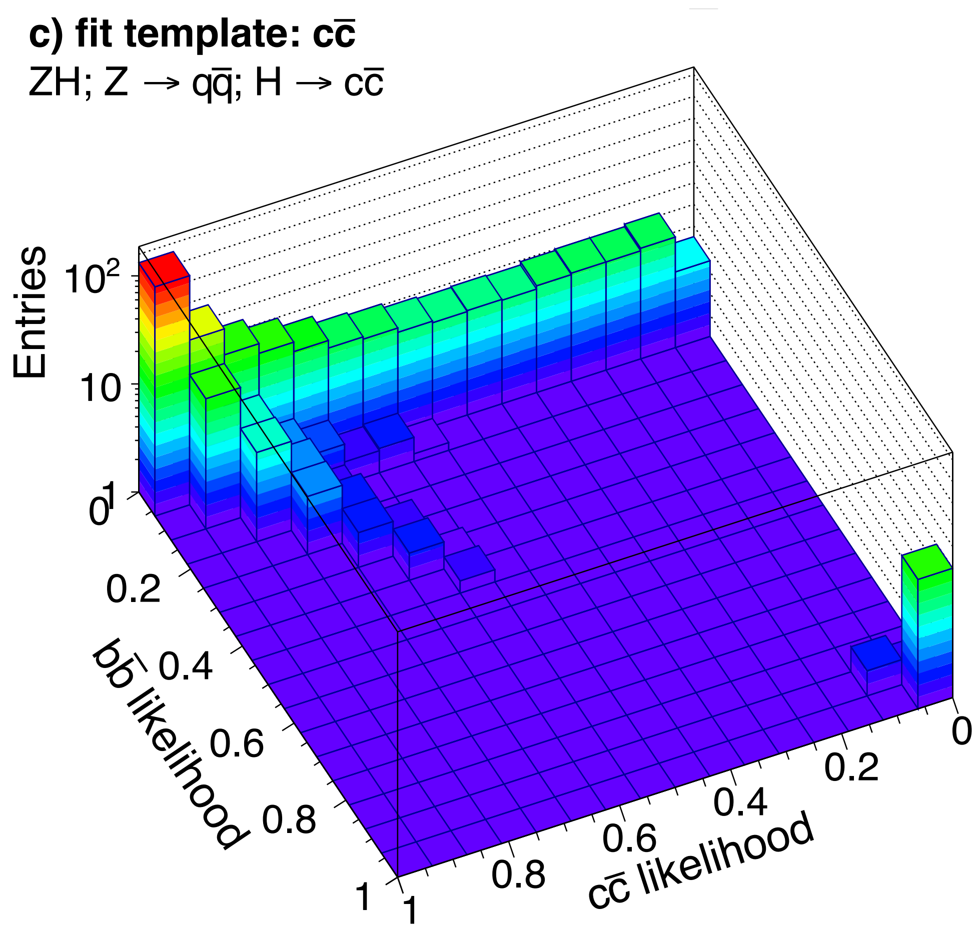
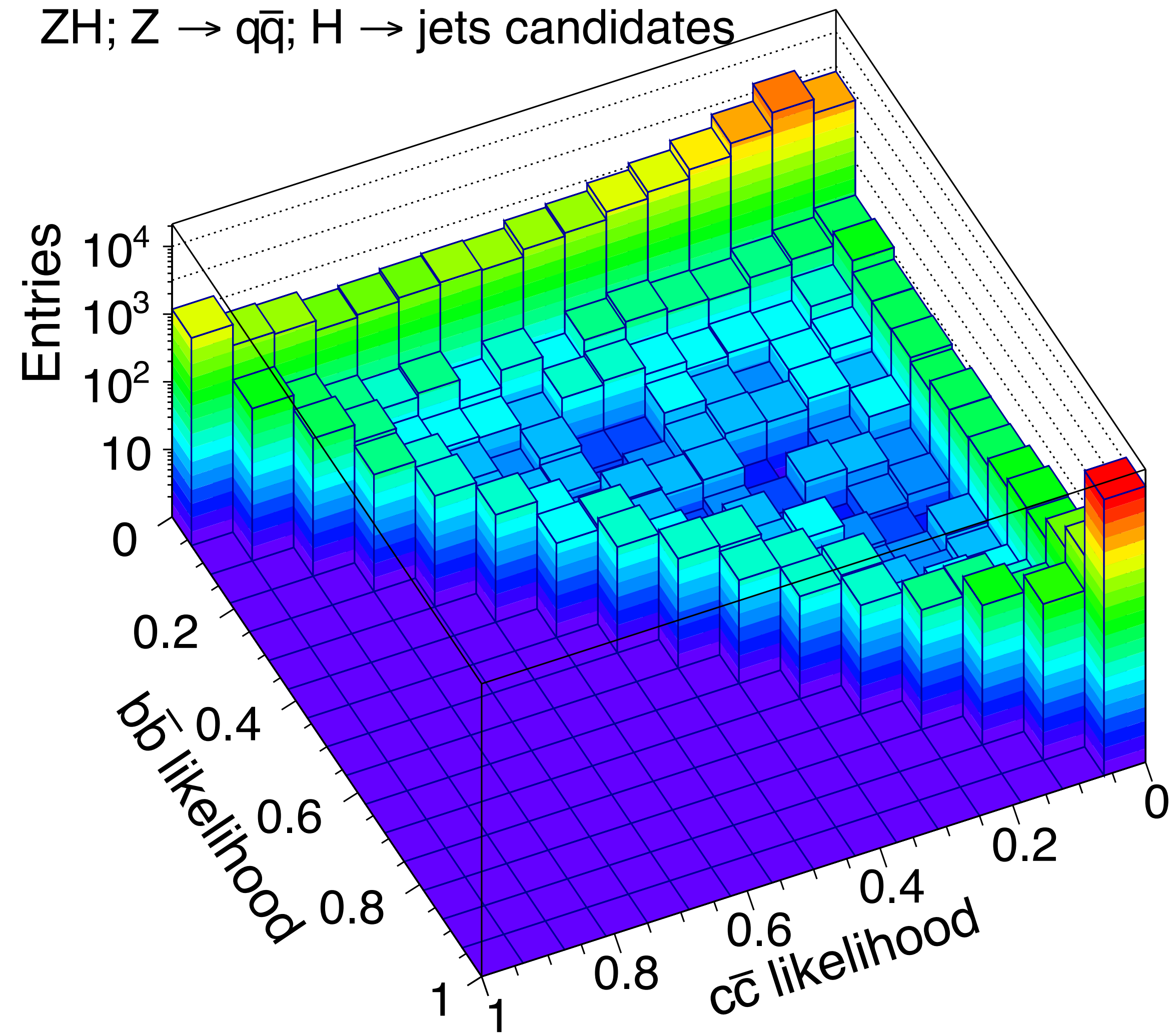




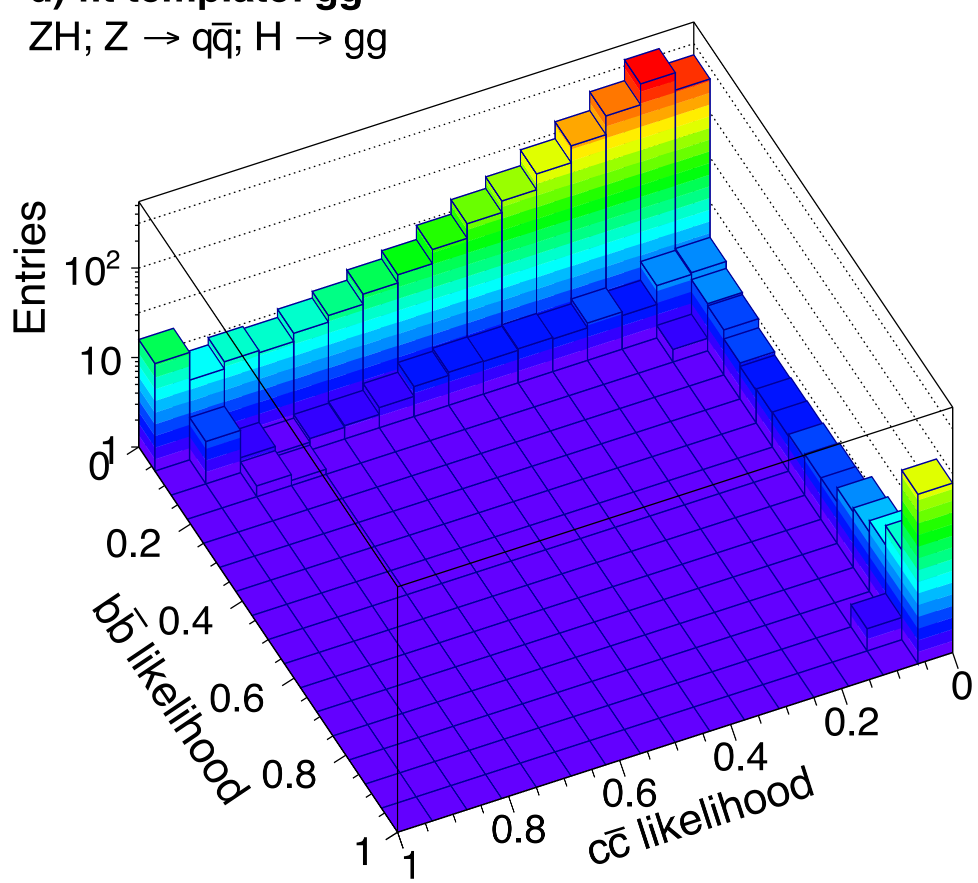
Higgs -> Jets: b,c, gluon couplings

- Selection of hadronic final states, separated by flavor tagging: Example CLIC @ 350 GeV
    - BRs from template fit in flavor space

a) simulated data
ZH; Z → $q\bar{q}$; H → jets candidates

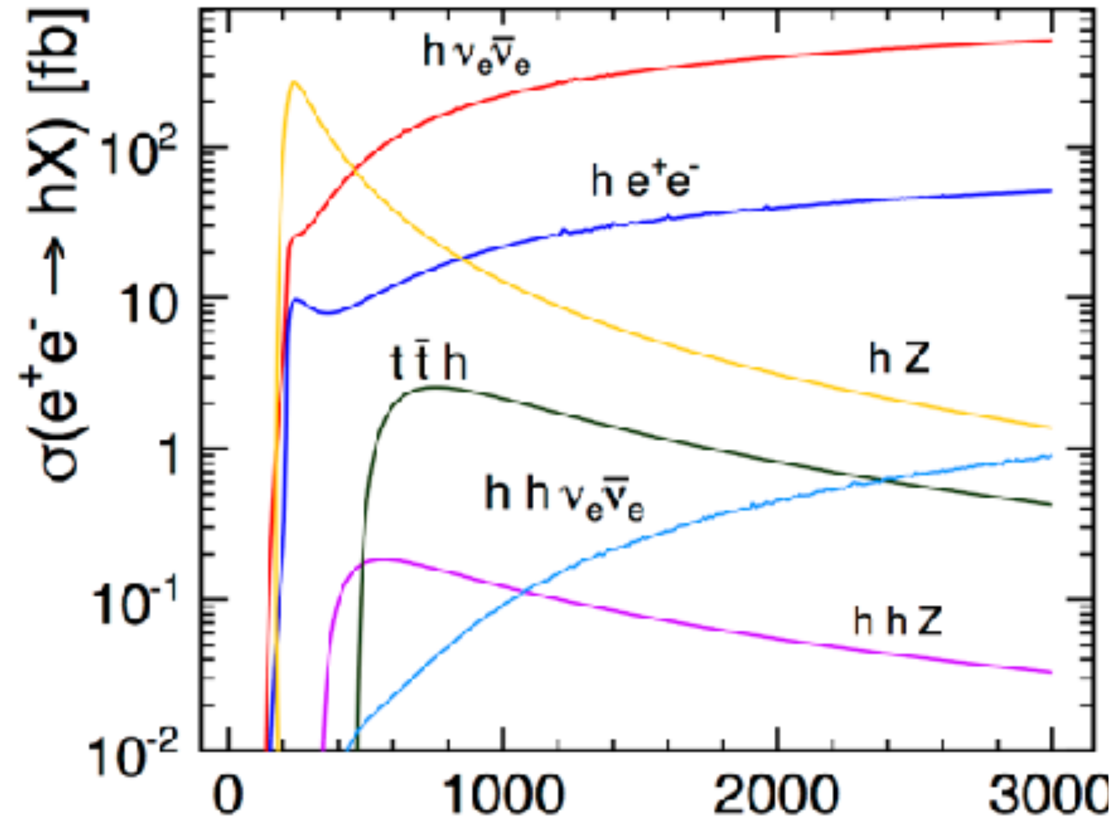


d) fit template: gg
ZH; Z → $q\bar{q}$; H → gg



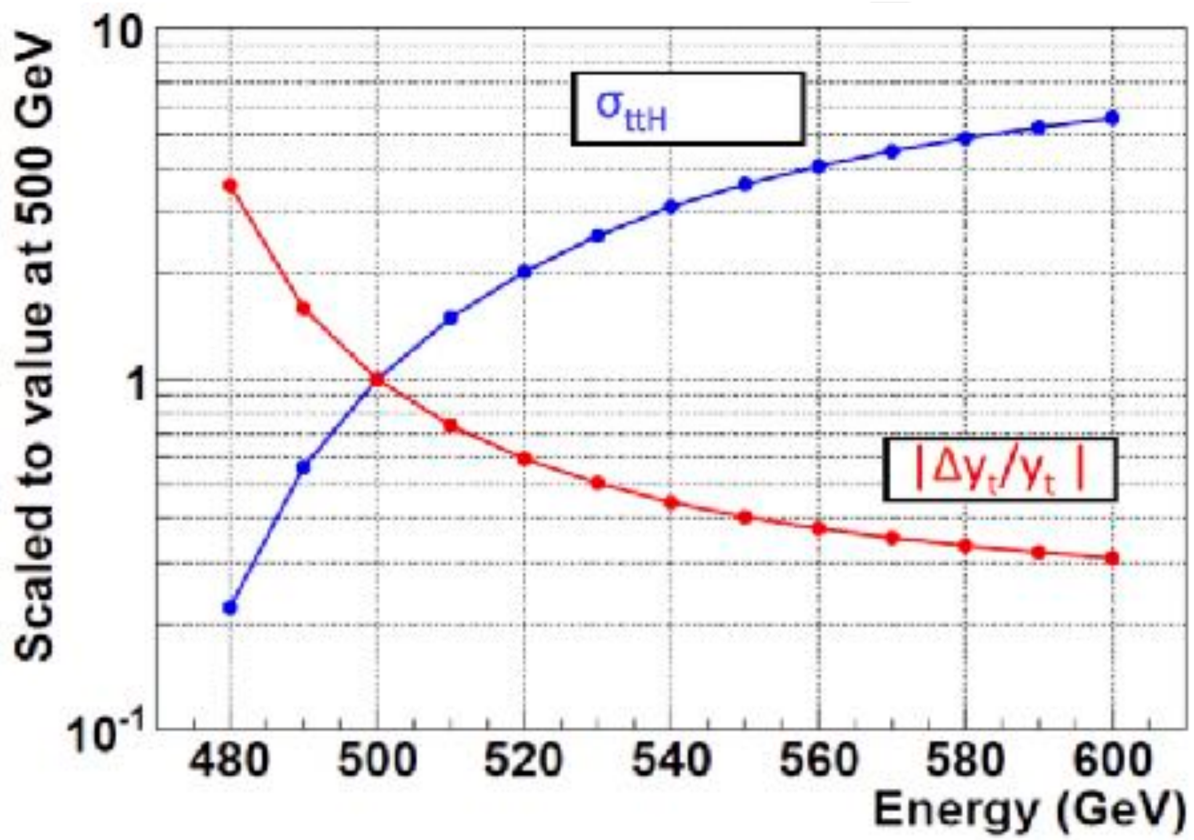
- … and the same for WW fusion: Combined extraction of 6 σxBRs, with full extraction of correlations (important for combined fits)

Higgs: Direct Access to Top Yukawa Coupling



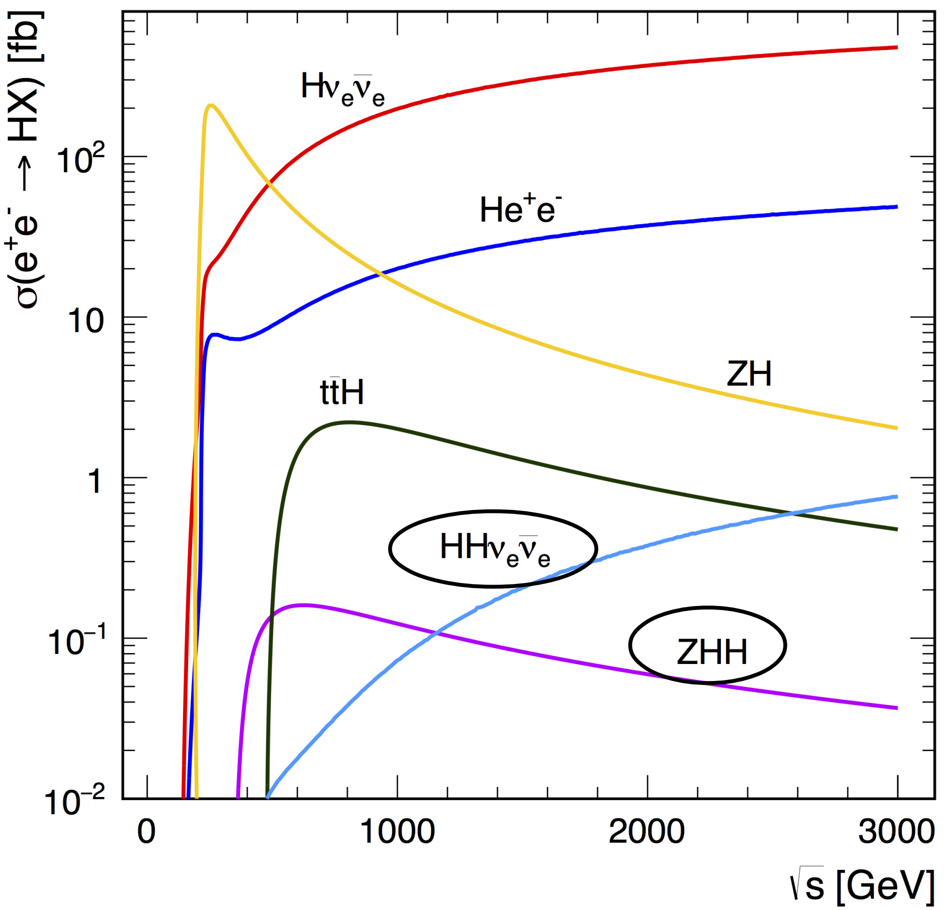
- Energies of 500 GeV and above enable direct access to the top Yukawa coupling via ttH production

- At ILC: 10% measurement with 1 ab^{-1} at 500 GeV, 6.3% in full running scenario (see later)



- Slight increase of energy helps substantially
- CLIC @ 1.4 TeV (1.5 ab^{-1}): 4.1% precision

Double Higgs production



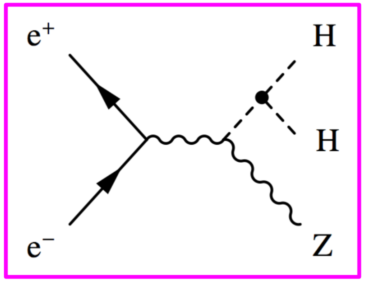
$e^+e^- \to$ ZHH:
- Cross section maximum ≈ 600 GeV

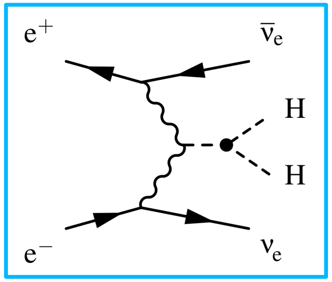
$e^+e^- \to HH\nu_e\bar{\nu}_e$ (CLIC):
- Allows simultaneous extraction of triple Higgs coupling, λ, and quartic HHWW coupling
- Benefits from high-energy operation

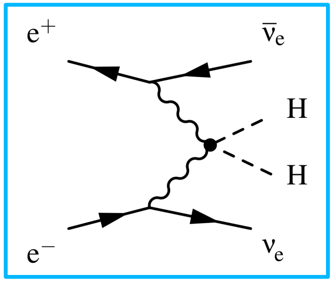
Projected precision:
Δ(λ) ≈ 10% for CLIC
(1.4 TeV and 3 TeV operation combined)

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$
LHC 3 ab^{-1} [36]	$[-20\,\%, +30\,\%]$

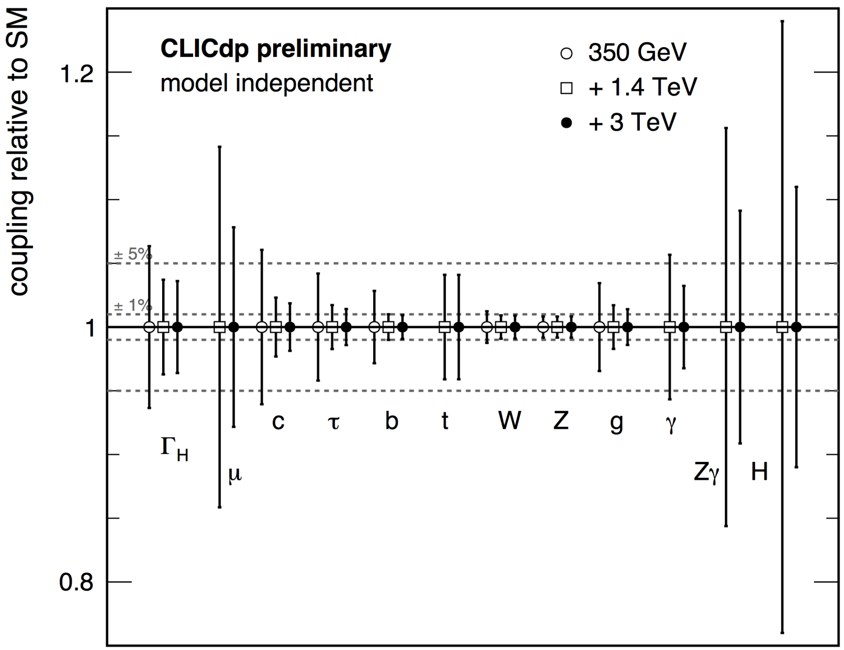
arXiv:1305.6397







Putting it all together



Parameter	Relative precision		
	350 GeV $500\,\mathrm{fb}^{-1}$	+ 1.4 TeV + $1.5\,\mathrm{ab}^{-1}$	+ 3 TeV + $2\,\mathrm{ab}^{-1}$
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.2 %	0.9 %	0.9 %
g_{Hbb}	2.8 %	1.0 %	0.9 %
g_{Hcc}	6.0 %	2.3 %	1.9 %
$g_{H\tau\tau}$	4.1 %	1.7 %	1.4 %
$g_{H\mu\mu}$	–	14.1 %	7.8 %
g_{Htt}	–	4.1 %	4.1 %
$g^{\dagger}_{Hgg}$	3.4 %	1.7 %	1.4 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	3.2 %
$g^{\dagger}_{HZ\gamma}$	–	15.6 %	9.1 %
Γ_H	6.3 %	3.7 %	3.6 %

-80% electron polarisation at 1.4 and 3 TeV

- Fully model-independent, only possible at a lepton collider
- All results limited by 0.8% from σ(HZ) measurement
- The Higgs width is extracted with 6.3 - 3.6% precision

Examples for BSM sensitivity

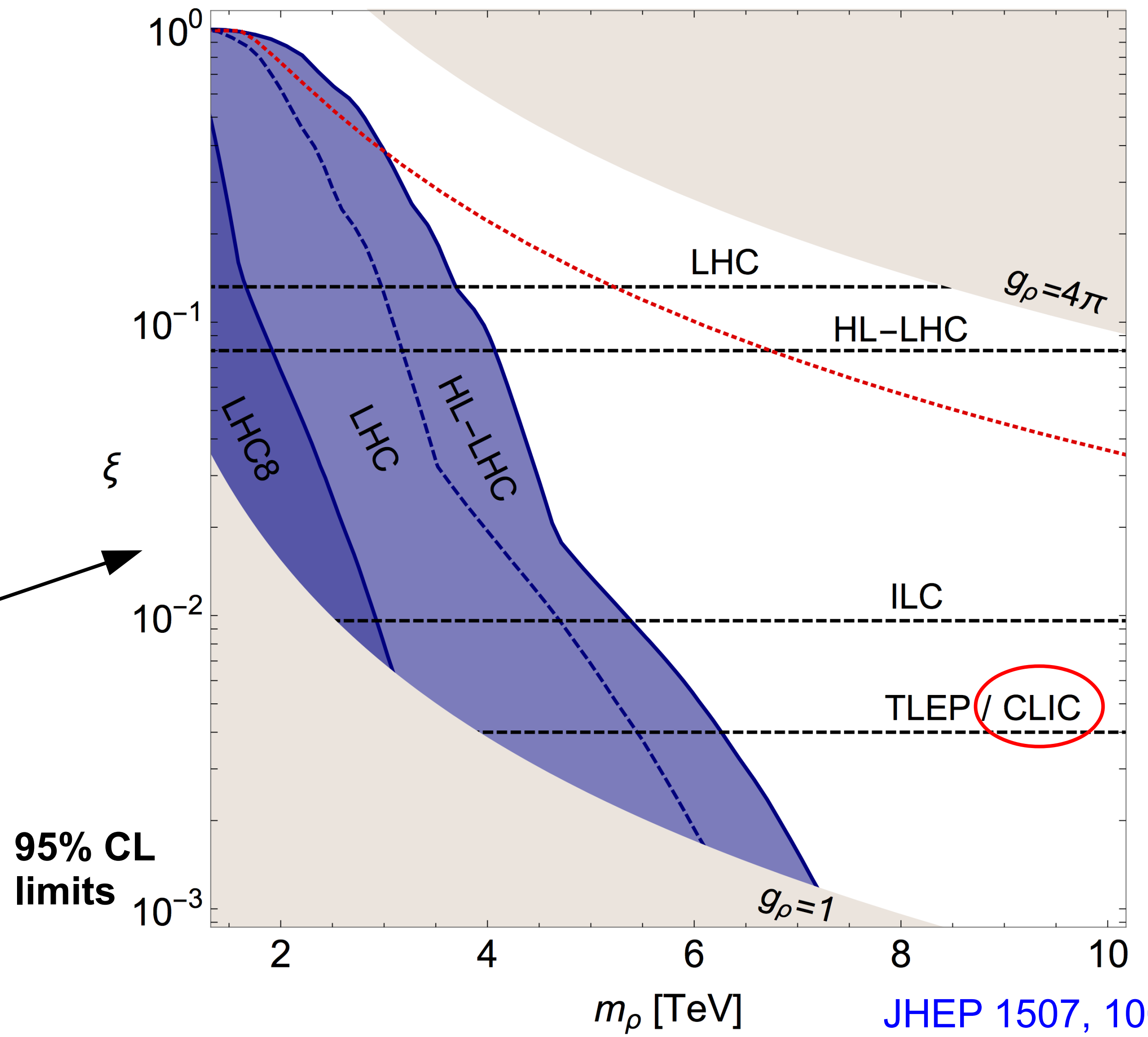
M ~ 1 TeV for new particles

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$
CLIC precision: (model independent)	0.8%	0.9%	3%

arXiv:1310.8361

Composite Higgs bosons

- Higgs as composite bound state of fermions
- m_ρ: mass of the vector resonance of the composite theory
- $\xi = (v / f)^2$ measures the strengths of the Higgs interactions



JHEP 1507, 100

CLIC provides an indirect probe of a Higgs composite scale of 70 TeV

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

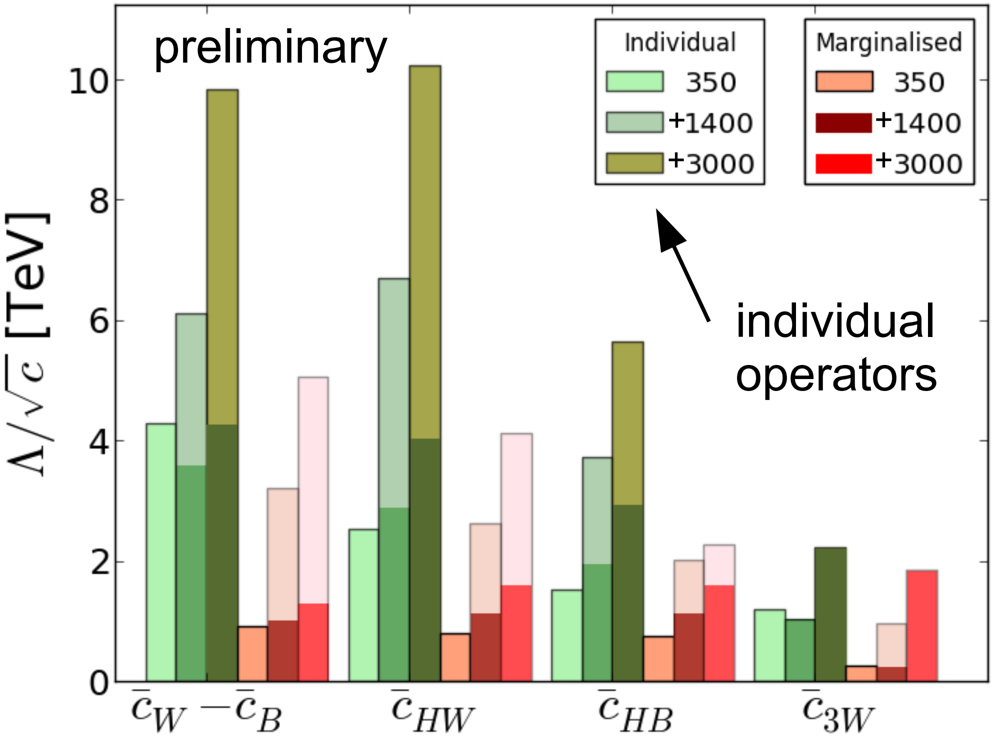
Scale of new decoupled physics

- Model-independent framework for probing indirect signs of new physics
$\rightarrow$ very useful for comparison of future collider options

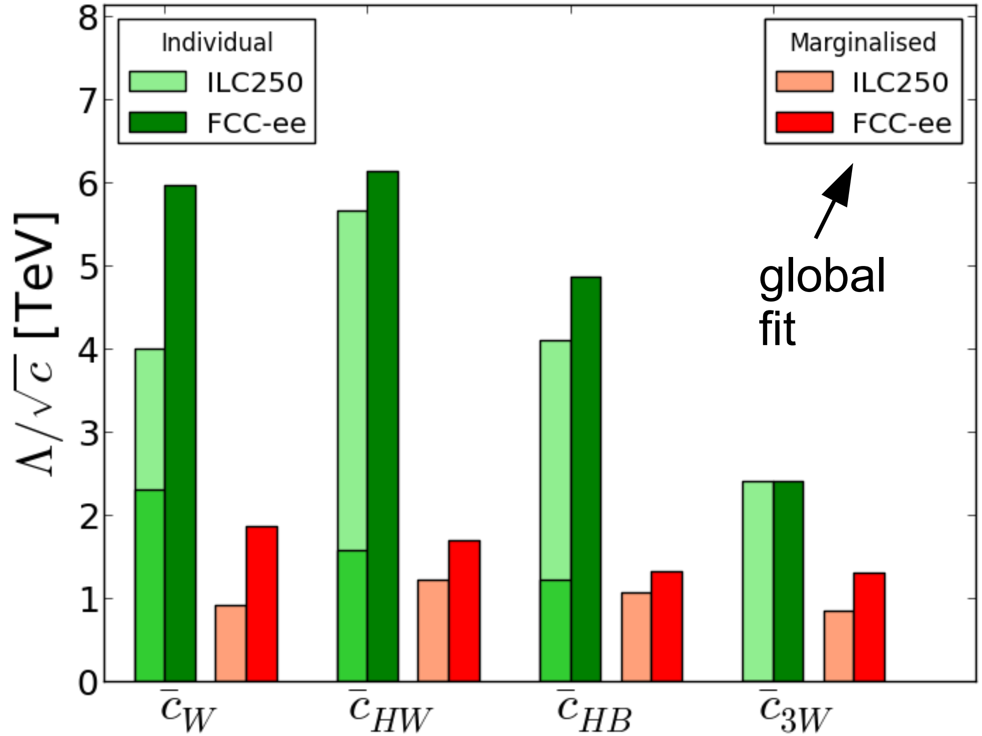
- **Input to fit:** Higgs measurements using WW-fusion and Higgsstrahlung, $e^+e^- \rightarrow W^+W^-$

Comparison to other options

CLIC



FCC-ee / ILC

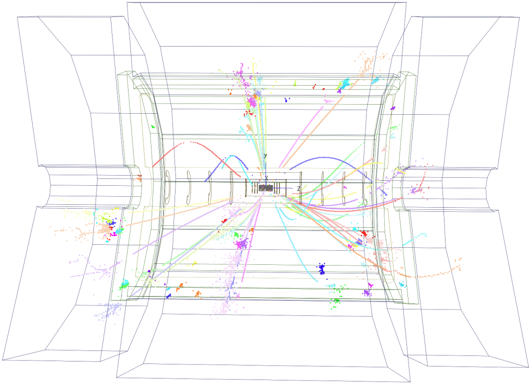


CLIC has better sensitivity for several operator coefficients

NB: FCC-ee / ILC includes EWPT observables

Ellis, You, JHEP 1603, 089 (2016)
Based on Ellis, PR, Sanz, You, arXiv:1701.04804

Final state



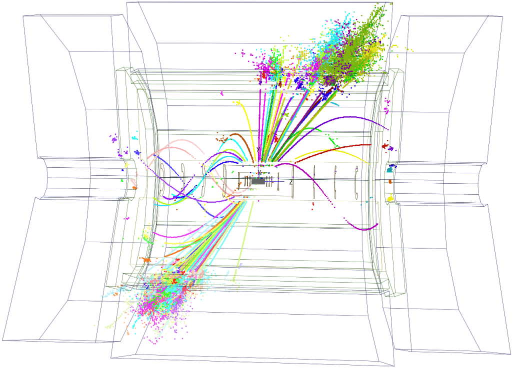
$e^+e^- \longrightarrow t\bar{t} \longrightarrow 6\,j$ at $\sqrt{s} = 380$ GeV

At low energy stage, top decay products (jets) well separated.

Direct reconstruction of the decay kinematics possible.

Crucial for efficient background suppression

Final state



$e^+e^- \longrightarrow t\bar{t} \longrightarrow 6\,j$ at $\sqrt{s} = 3$ TeV

At higher energy stages, top quarks produced with large boost.

Decay products cluster in two "fat" jets.

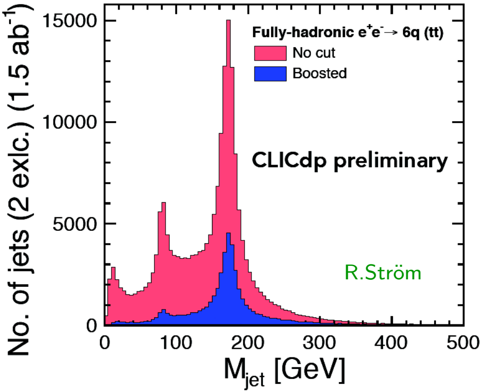
$\Rightarrow$ dedicated tools needed to discriminate between top and background events

Top event reconstruction

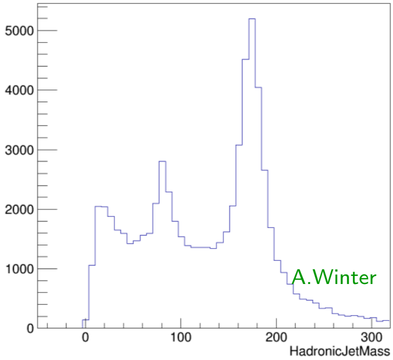
Final state

Invariant mass for "fat jets" (events clustered into 2 jets) $\sqrt{s} = 1.4$ TeV

$t\bar{t} \longrightarrow 6j$



$t\bar{t} \longrightarrow 4j\ l\ \nu$

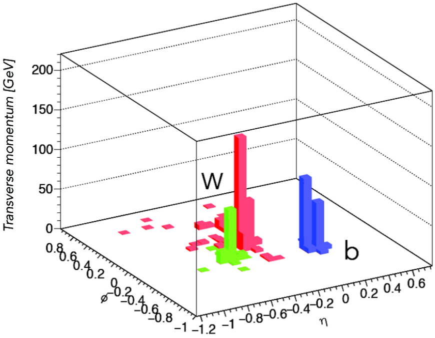


Two analyses ongoing

Using jet substructure

to distinguish boosted top jets from light-quark and gluon jets using

Method proposed in Kaplan et al. Phys. Rev. Lett. 101, 142001



Structure of a single top jet

Cluster event into two jets, top candidates

Try to recluster candidate jet into three subjets to reconstruct decay kinematics

Impose kinematic constraints

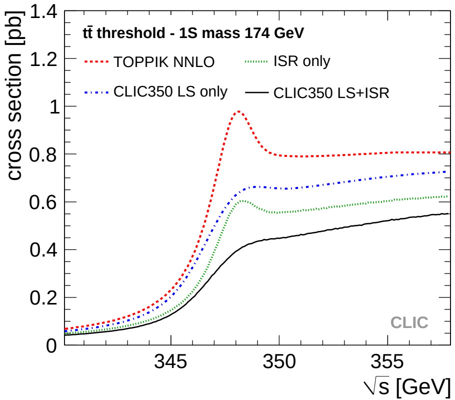
Look also at relative angles, jet multiplicity...

Threshold scan

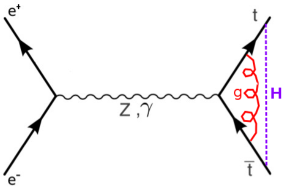
Top pair production cross section around threshold:

resonance-like structure corresponding to narrow $t\bar{t}$ bound state.

Very sensitive to top properties and model parameters:



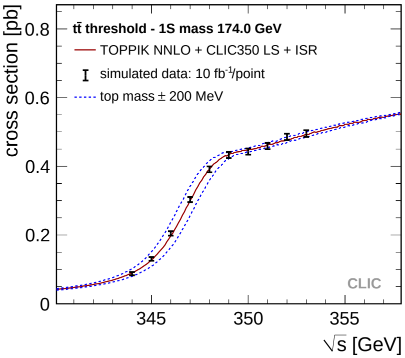
- top quark mass m_t
- top quark width Γ_t
- strong coupling α_s
- top Yukawa coupling y_t

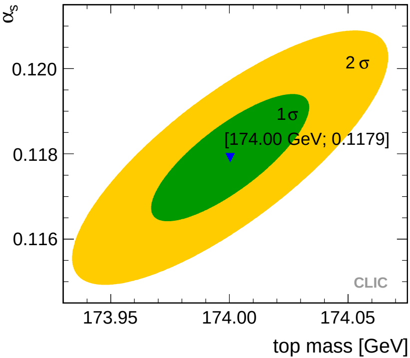


Significant cross section smearing due to luminosity spectra and ISR

Top mass determination

Already 100 fb^{-1} at the threshold sufficient for top mass measurement
Energy scan: 10 cross section measurements, 10 fb^{-1} each (to be optimised)





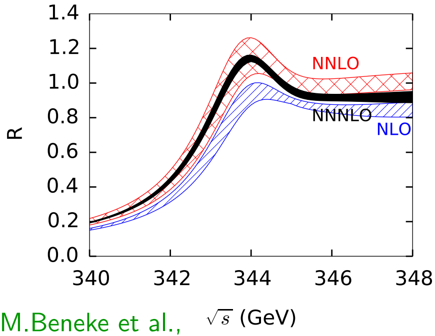
K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

Expected statistical uncertainty	on top mass:	15–20 MeV
	on top width:	~40 MeV

Threshold scan

Main advantage: mass well defined from theoretical point of view

Enormous progress in precision of theoretical calculations



M.Beneke et al., Phys. Rev. Lett. 115, 192001 (2015)

Estimates for top mass systematic uncertainties:

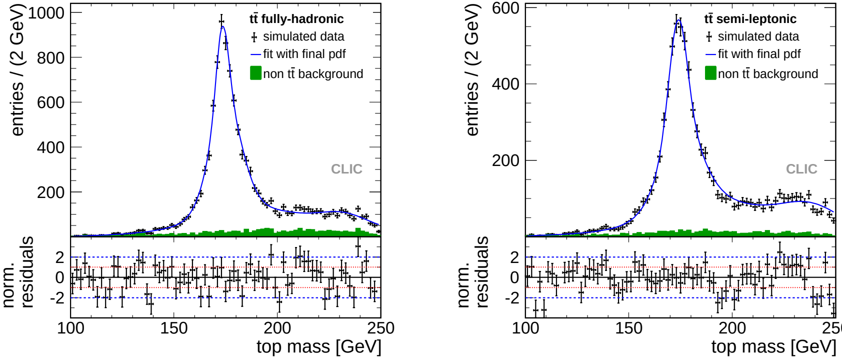
- theoretical predictions (NNNLO): $\sim$40 MeV
- parametric α_s uncertainty: $\sim$30 MeV (for today's WA)
- other uncertainties (backgrounds, spectra, etc.): on 10–20 MeV level

$\Rightarrow$ total uncertainty on the top mass of $\sim$50 MeV feasible dominated by systematics

Direct reconstruction

Possible for all energies above the threshold (continuum)

High statistical precision: 80 MeV estimated for 100 fb^{-1} at 500 GeV



K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

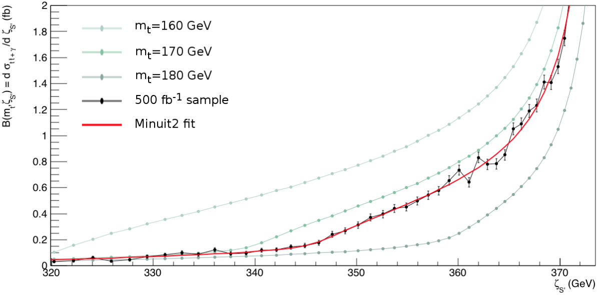
Suffers from significant theoretical uncertainties
when converting to particular mass scheme (as in LHC).

Radiative events

M.Boronat @ CLIC'2016

At higher energies, we are still sensitive to $t\bar{t}$ threshold in radiative events.
When measuring the ISR photon, we can calculate "true" collision energy.

Reconstructed energy spectra

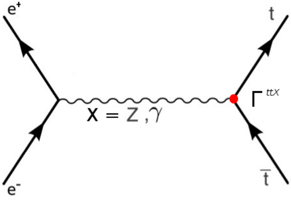


Particle level
$\sqrt{s} = 380$ GeV
$\zeta_{s'} = \sqrt{s'}$

Parton and particle level studies indicate that statistical uncertainty of $\sim$100 MeV can be obtained by combining the ISR and FSR measurements
Full simulation study is under development

Pair production: direct access to top electroweak couplings

Possible higher order corrections
$\Rightarrow$ sensitive to "new physics"



Form factor approach:

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

Electroweak couplings

Pair production: direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics"

Couplings can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle in top decays

Form factor approach:

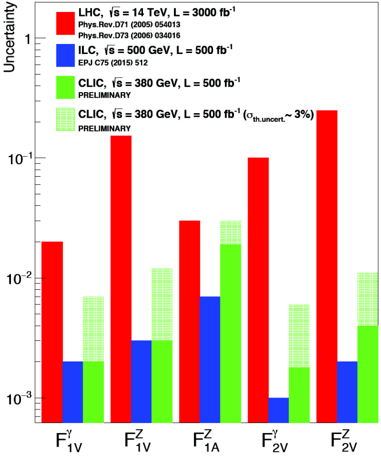
$$\Gamma_\mu^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$

Electroweak couplings

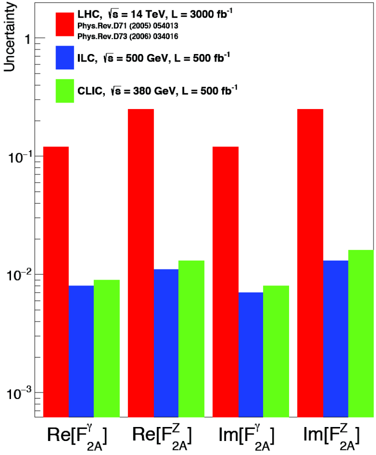
Expected coupling precision at LHC, ILC (500 GeV) and CLIC (380 GeV)

initial stage

CP conserving couplings



CP violating couplings

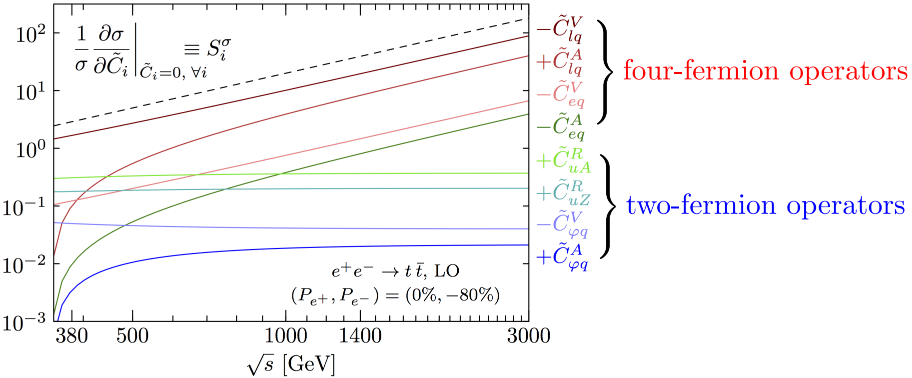


IFIC-LAL Collaboration, M.Perello @ ECFA LC'2016

EFT prospects

M.Perello, this workshop

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



Multi-TeV operation gives high sensitivity to four-fermion operators

High sensitivity to two-fermion operators at the initial stage

FCNC top decays

Strongly suppressed in the Standard Model (GIM mechanism + CKM):

$BR(t \to c\,\gamma) \sim 5 \cdot\ 10^{-14}, \quad BR(t \to c\,Z) \sim 1 \cdot 10^{-14}, \quad BR(t \to c\,H) \sim 3 \cdot 10^{-15}$

Significant enhancement possible in many "new physics" scenarios

Two channels under study for CLIC at 380 GeV

$t \to c\ h$

- enhancement up to 10^{-5}–10^{-2}
- test of Higgs boson couplings
- well constrained kinematics
- seems most difficult for LHC
  Run II: $BR < 0.46\%$
  HL-LHC: $BR < 2 \cdot 10^{-4}$

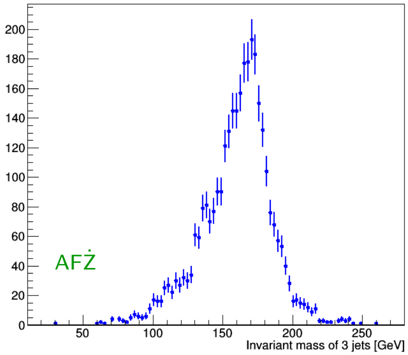
$t \to c\ \gamma$

- enhancement up to 10^{-7}–10^{-5}
- clear signature
- less constrained kinematics
- expected limits from HL-LHC
  $BR < 2.5 \cdot 10^{-5}$

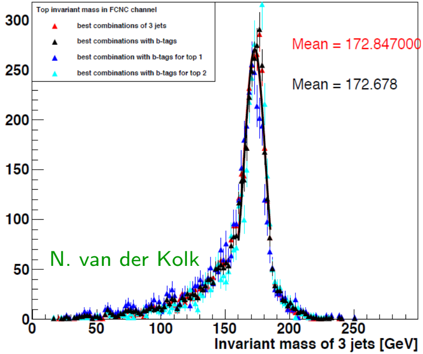
Reconstruction of FCNC events

Preliminary results from the full simulation study for $\sqrt{s} = 380\,GeV$
Invariant mass distributions for "spectator" top candidates (SM decay)

$t \to c\ h$ events

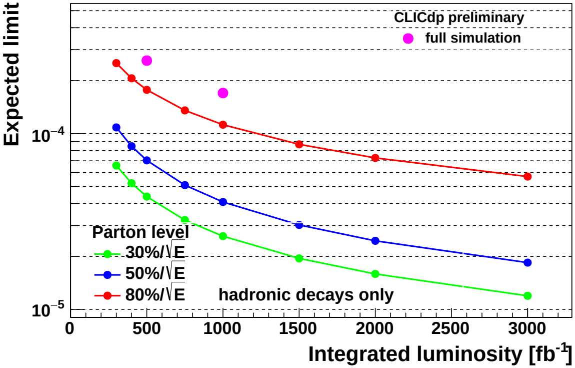


$t \to c\ \gamma$ events



Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$ at $\sqrt{s} = 380$ GeV

Comparison with parton level results, different jet energy resolutions



AFŻ @ LCWS'16

Kinematic fit performance still to be optimised

Background reduction primarily based on flavour tagging!

Vector boson scattering

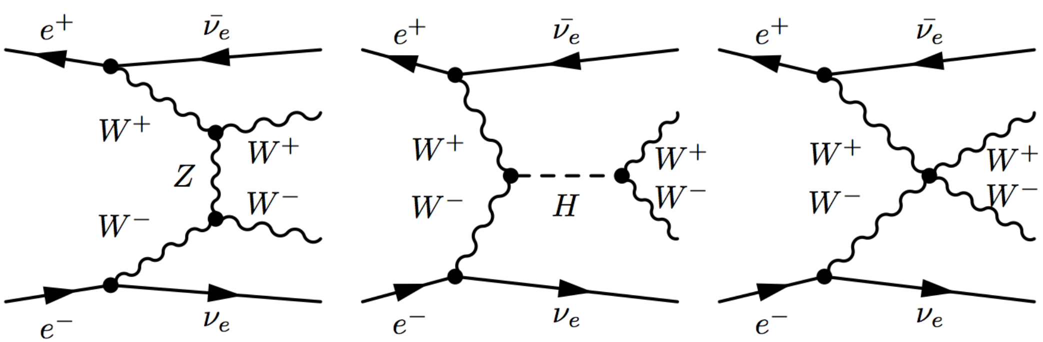
- Vector boson scattering (VBS) gives insight into the mechanism of electroweak symmetry breaking

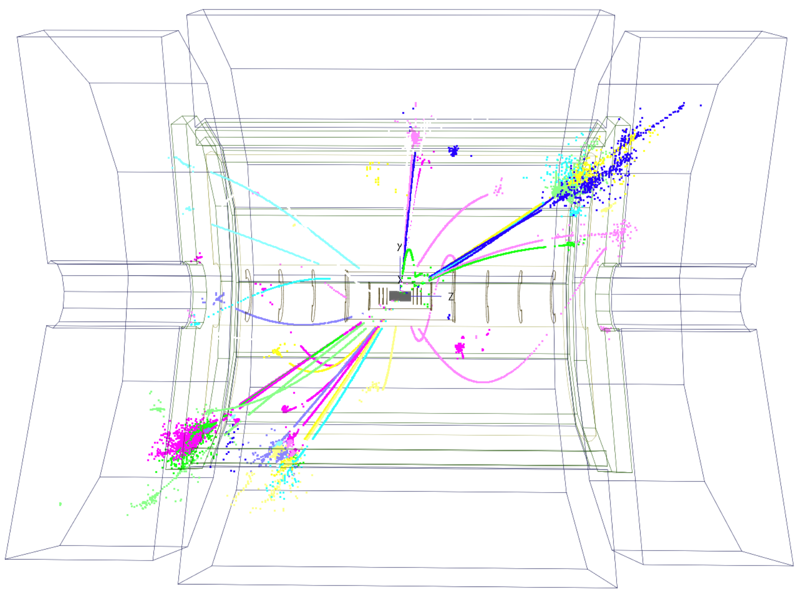
- Investigated processes for high-energy CLIC operation:

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

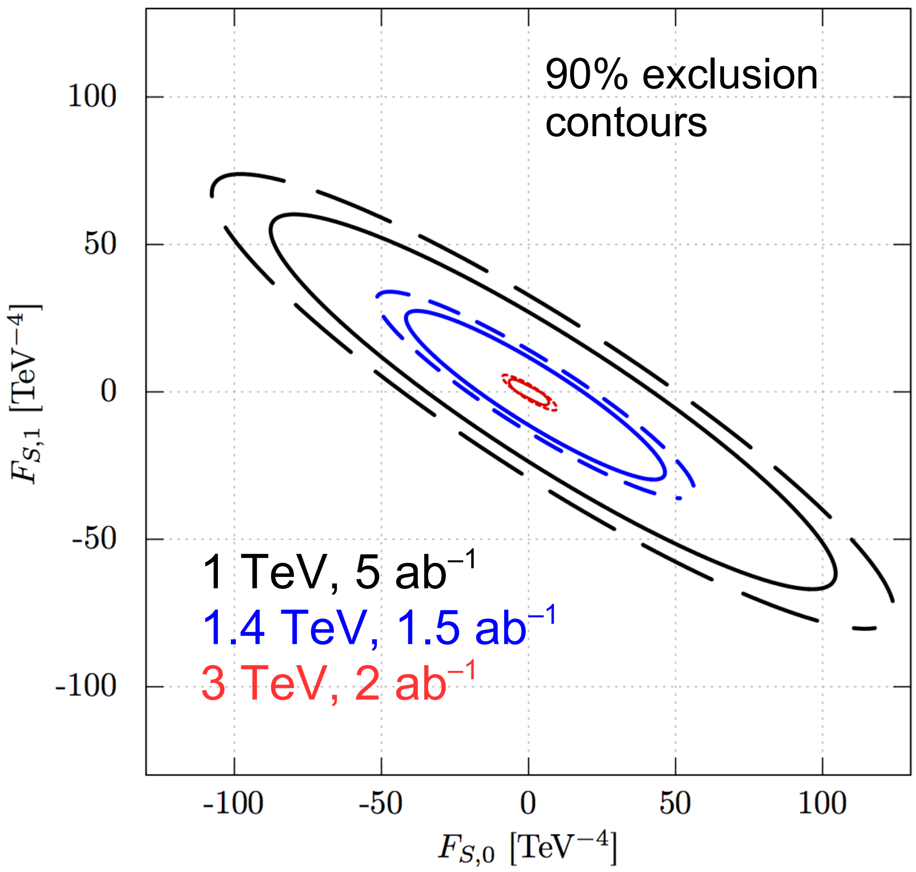
- Search for additional resonances or anomalous couplings

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





Expected precisions



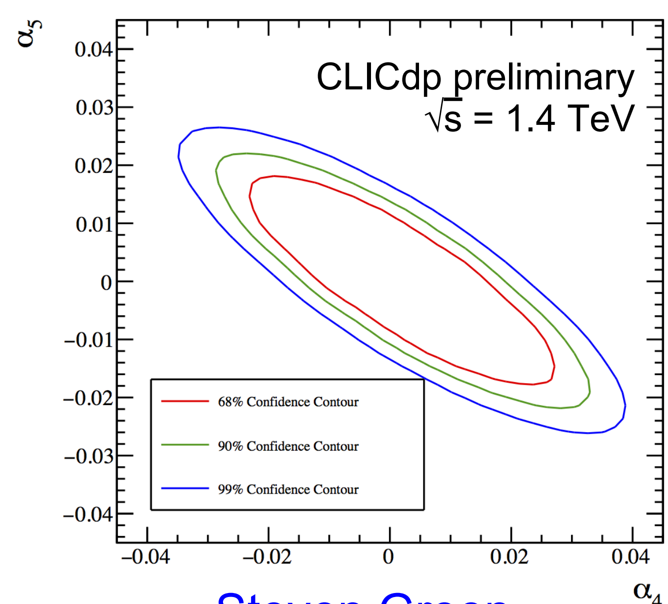
The sensitivity rises steeply with the centre-of-mass energy

Fleper, Kilian, Reuter, Sekulla, Eur. Phys. J. C (2017) 77:120

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

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

Full simulation result at 1.4 TeV (3 TeV soon):



Steven Green

CLIC at 1.4 (3) TeV about one (two) orders of magnitude more precise than LHC at 8 TeV

Indirect searches through precision measurements

- Possibility to reach much higher mass scales than $\sqrt{s}/2$.
- Examples for CLIC at 3 TeV:

Process	Measurement	CLIC 3 TeV	HL-LHC
$e^+e^- \to \mu^+\mu^-$	M(Z')	50 TeV	7 TeV
$e^+e^- \to W^+W^-\nu\bar{\nu}/ZZ\nu\bar{\nu}$	$F_{S,0}$, $F_{S,1}$	5 TeV^{-4}	unclear
$e^+e^- \to H\nu\bar{\nu}$	Higgs comp. scale	70 TeV	9 - 12 TeV
$e^+e^- \to \gamma\gamma$	Electron size	3 x 10^{-18} cm	impossible?

→ All of these measurements would benefit from higher energies

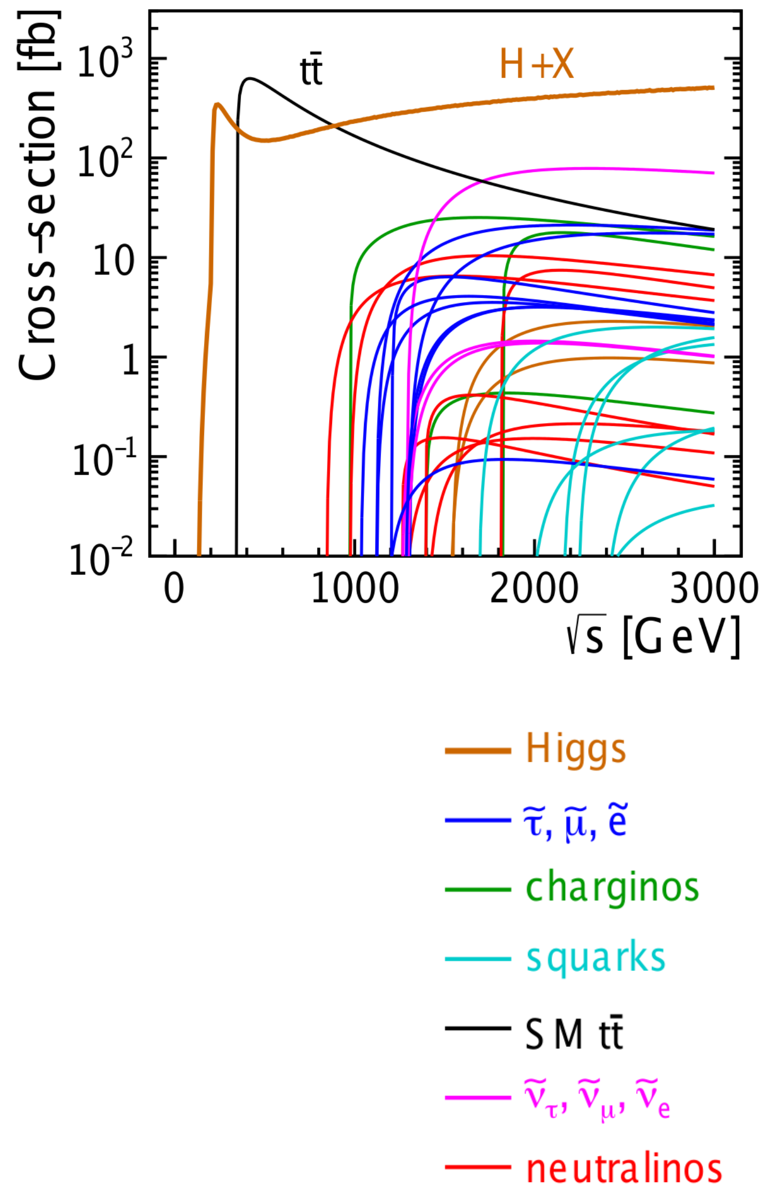
Direct searches for new physics in e^+e^- collisions

- 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) → CLIC especially suitable for electroweak states

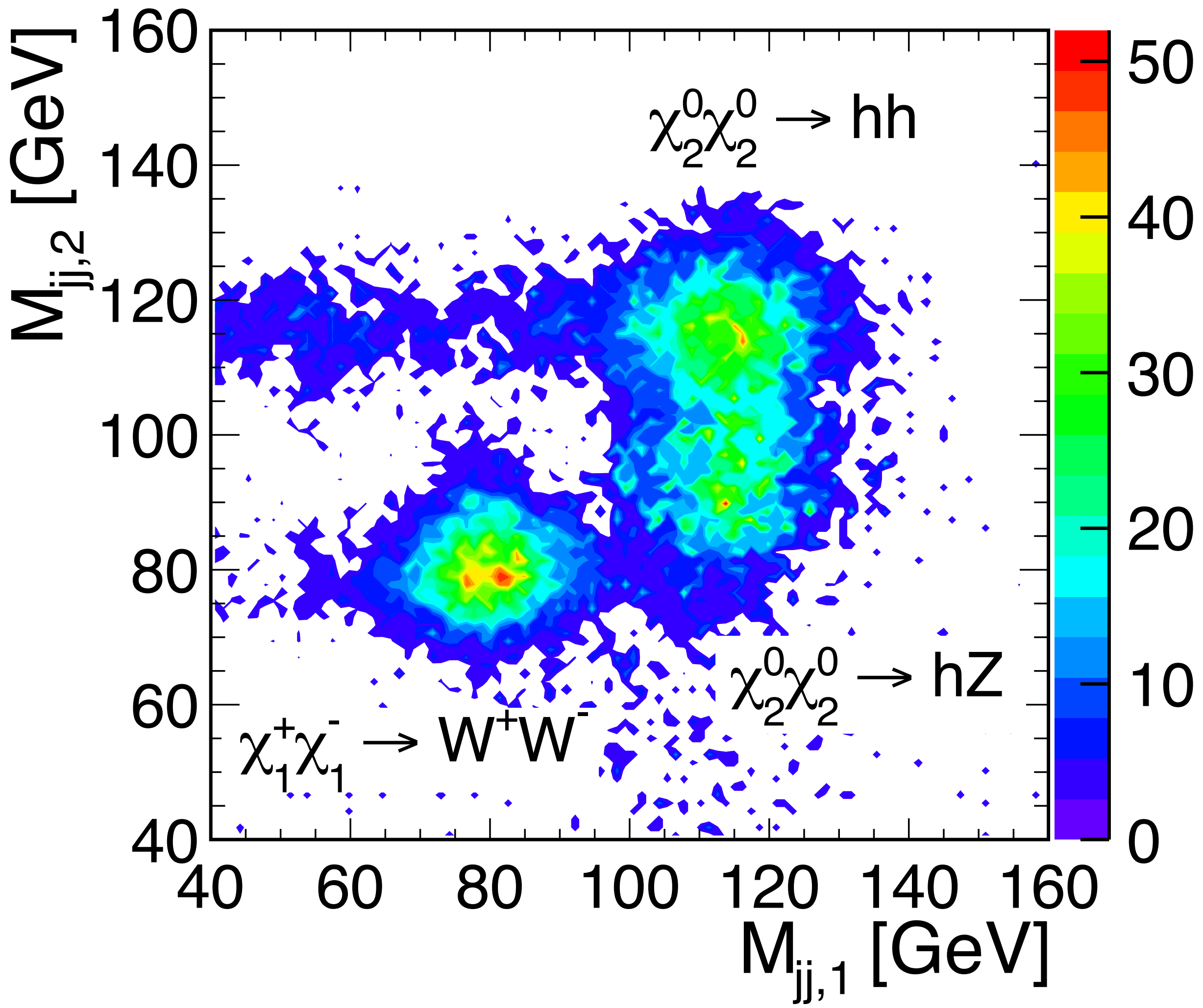
- Polarised electron beam and threshold scans might be useful to constrain the underlying theory

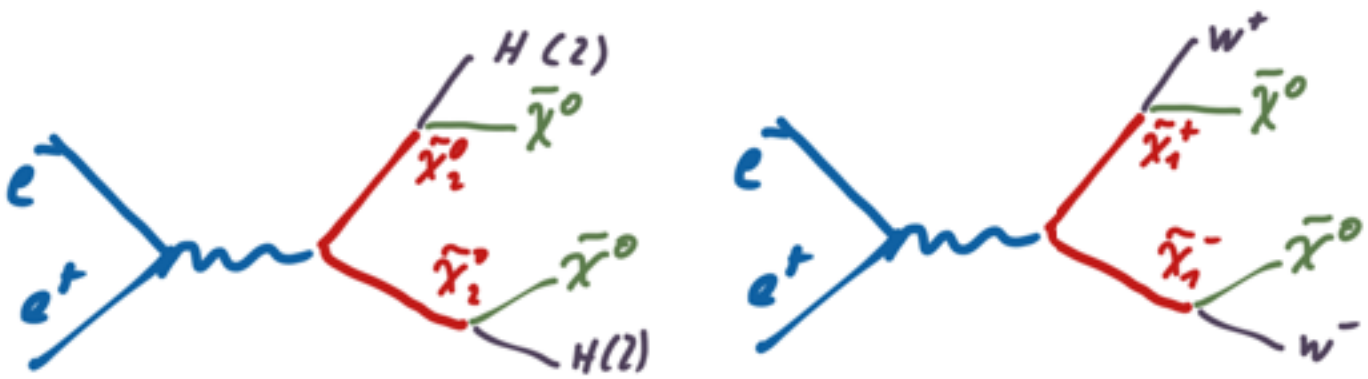


BSM Examples: Direct Measurements

- Potential for discovery directly linked to maximum energy: Sensitivity for pair-produced new particles up to ~ $\sqrt{s}/2$

A CLIC example: mass-degenerate gauginos - mass measurements at few GeV precision





mass-degenerate charginos / neutralinos, $m_{gaugino}$ ~ 650 GeV (3 TeV benchmark)

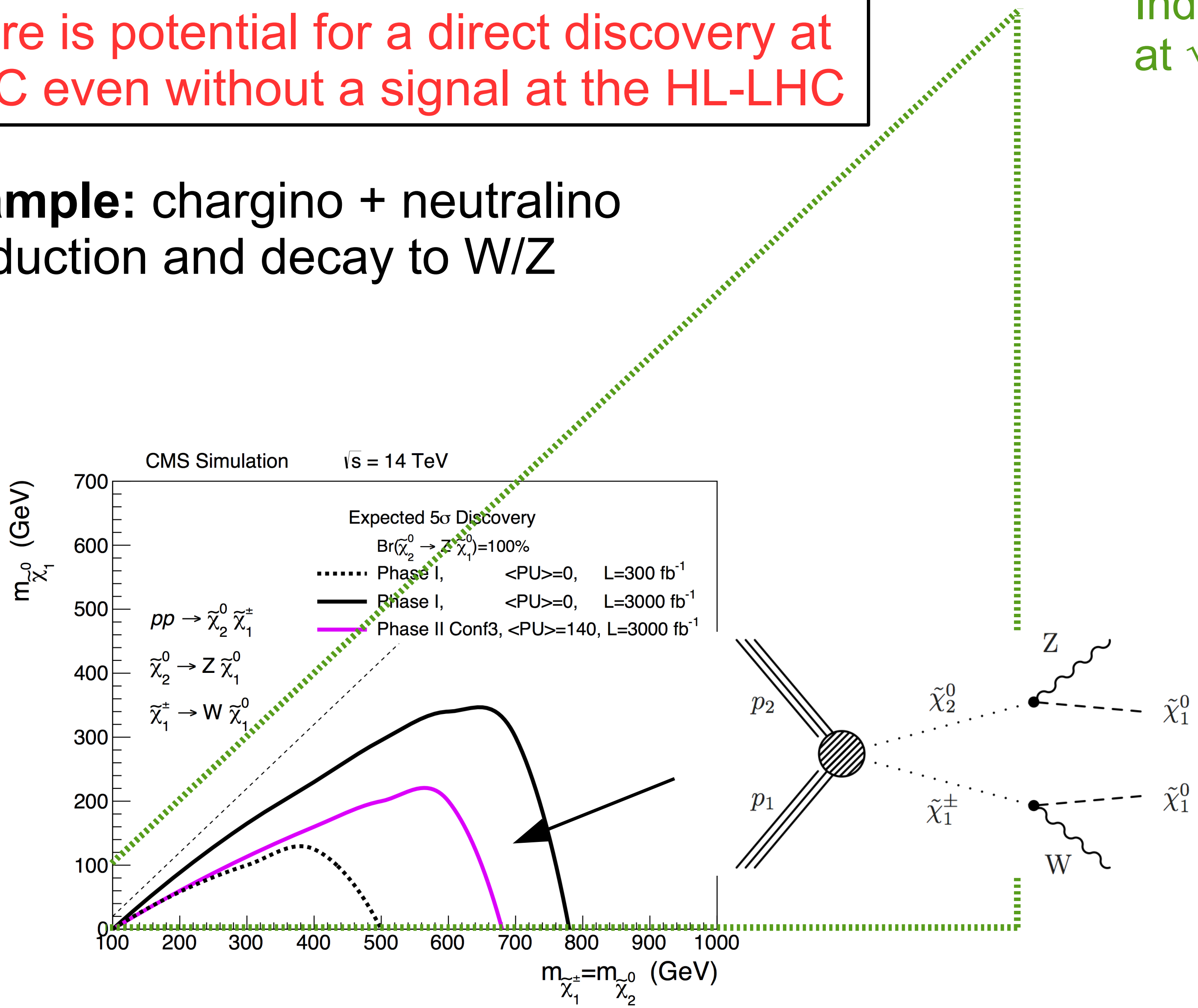
Precise reconstruction of hadronic final states enables separation of different particles - capitalizes on PFA-optimized detectors

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



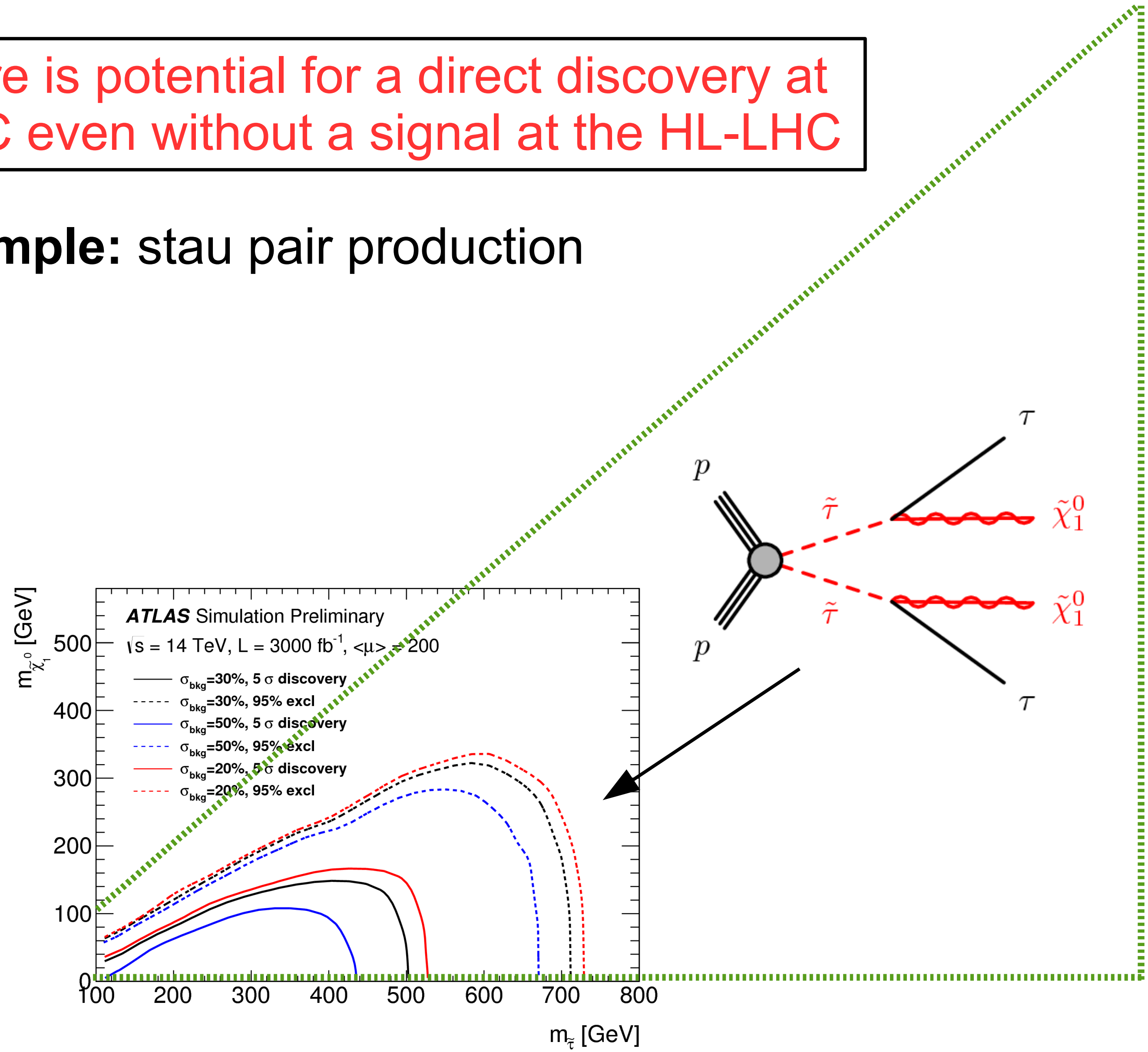
CMS-PAS-FTR-13-014

(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

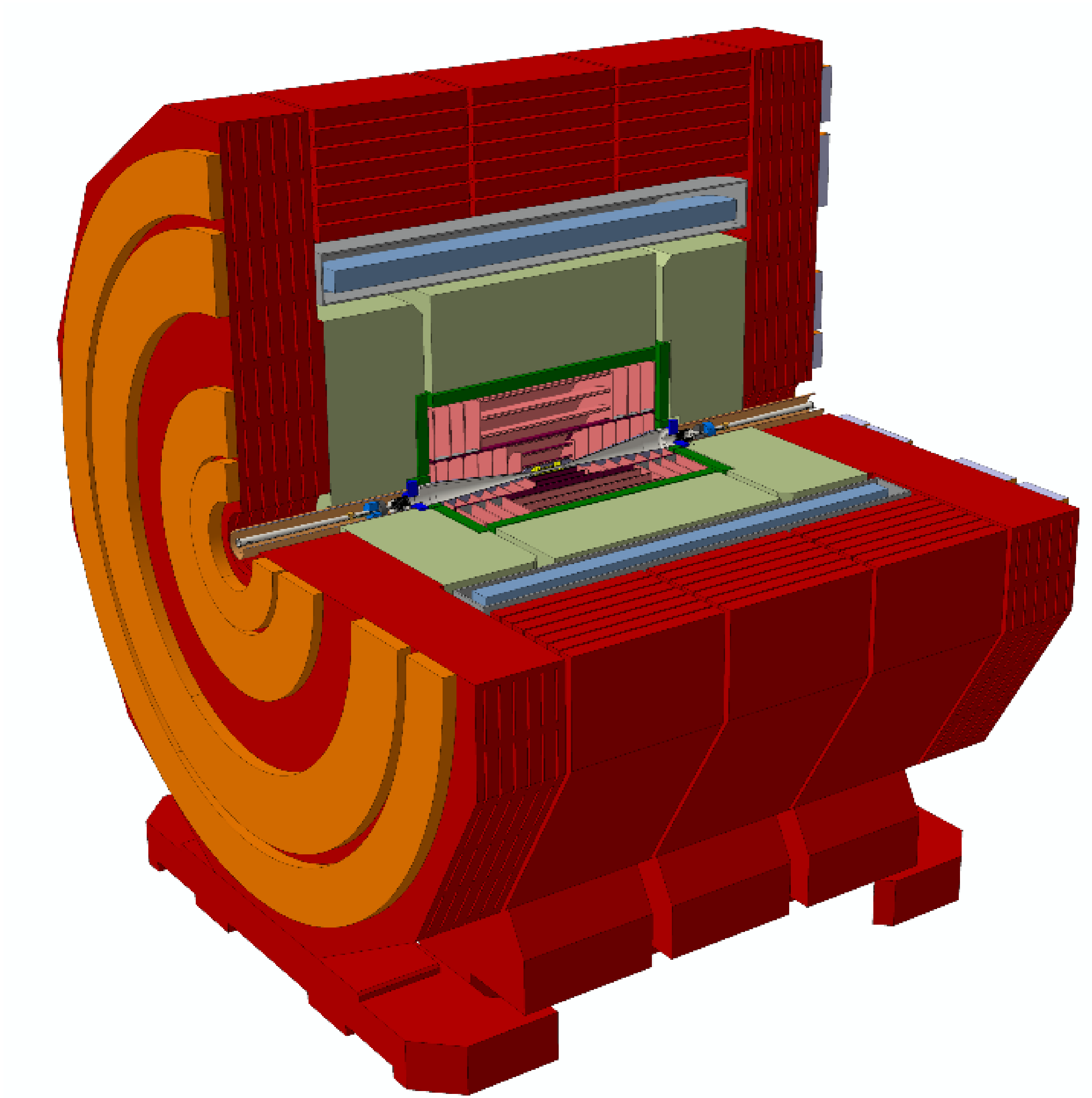
Example: stau pair production



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

ATLAS-PHYS-PUB-2016-021

Conclusions and plans



Outlook → European Strategy

Aim to:

- **Present CLIC as a credible post-LHC option for CERN**
- **Provide optimized, staged approach starting at 380 GeV, with costs and power not excessive compared with LHC, and leading to 3 TeV**
- **Upgrades in 2-3 stages over 20-30 year horizon**
- **Maintain flexibility and align with LHC physics outcomes**

CLICdp documents
in preparation for next European Strategy

CLICdp reports serving as ingredients for a CLIC summary report:

- Updated Baseline for a Staged Compact Linear Collider (380 GeV, 1.5 TeV, 3 TeV) ✓
  - arXiv:1608.07537, CERN-2016-004
- Higgs Physics at the CLIC Electron-Positron Linear Collider ✓
  - arXiv:1608.07538
- The new optimised CLIC detector model CLICdet ✓✓
  - CLICdp note CLICdp-Note-2017-001 (detector/SW validation in progress)
- An overview of CLIC top physics
  - CLIC top physics publication => complete draft before the end of 2017
- Extended BSM studies (hopefully also motivated by LHC discoveries)
  - CLIC BSM overview publication in 2018
- CLIC R&D report => with main CLIC technology demonstrators
  - Summary publication(s) in 2018
- Plan for the period ~2019-2025 in case CLIC would be supported by next strategy

CLIC roadmap

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

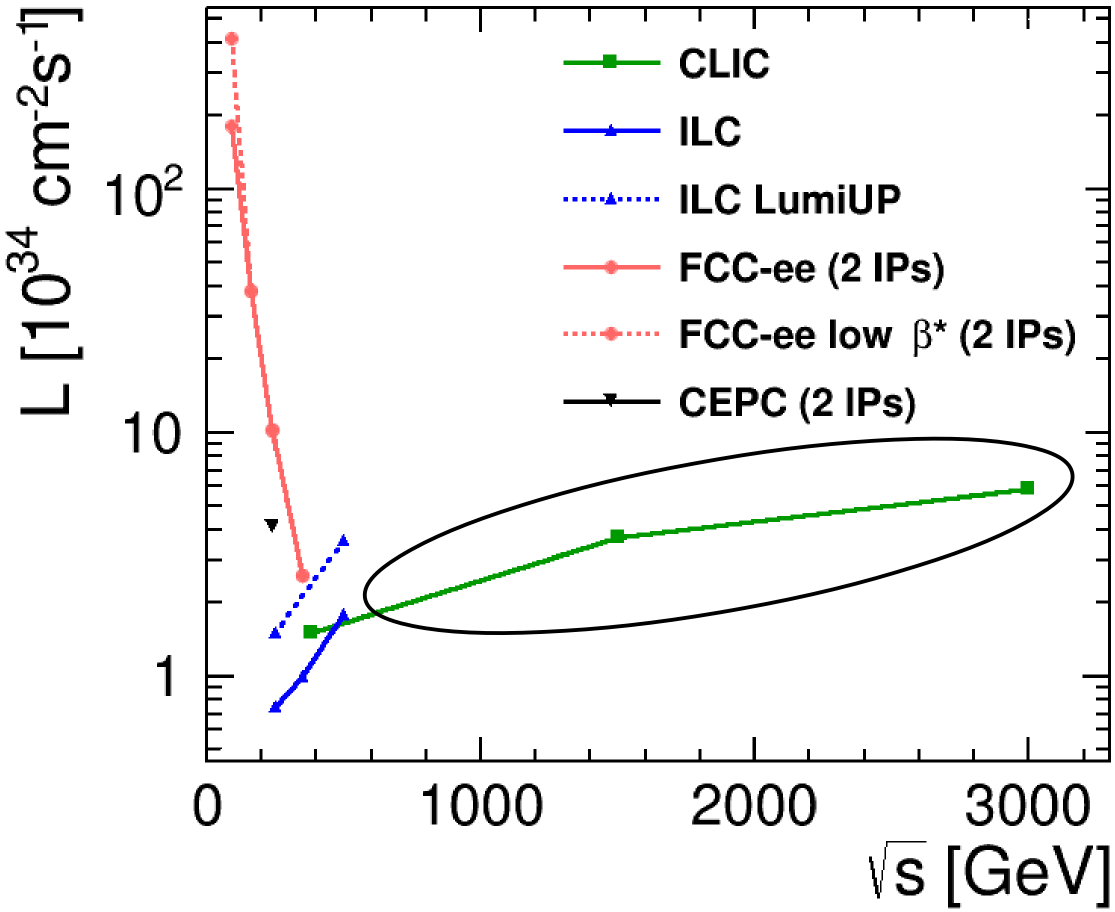
Ready for construction; start of excavations

2035 First Beams

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

Thank you!

Comparison to other e^+e^- collider options



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

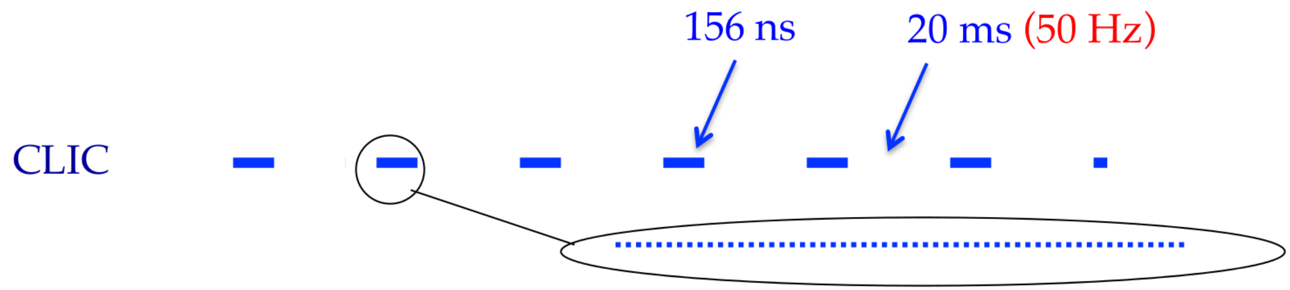
Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

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

CLIC is the only mature option for a multi-TeV e^+e^- collider

CLIC (and LHC) beam structure

Beam structure



	CLIC 3 TeV	LHC 14 TeV (nominal)
Bunch crossing separation [ns]	0.5	25
Crossing angle	20 mrad	200 μrad
Instantaneous luminosity [$cm^{-2}s^{-1}$]	6×10^{34}	1×10^{34}

Low duty cycle at CLIC:

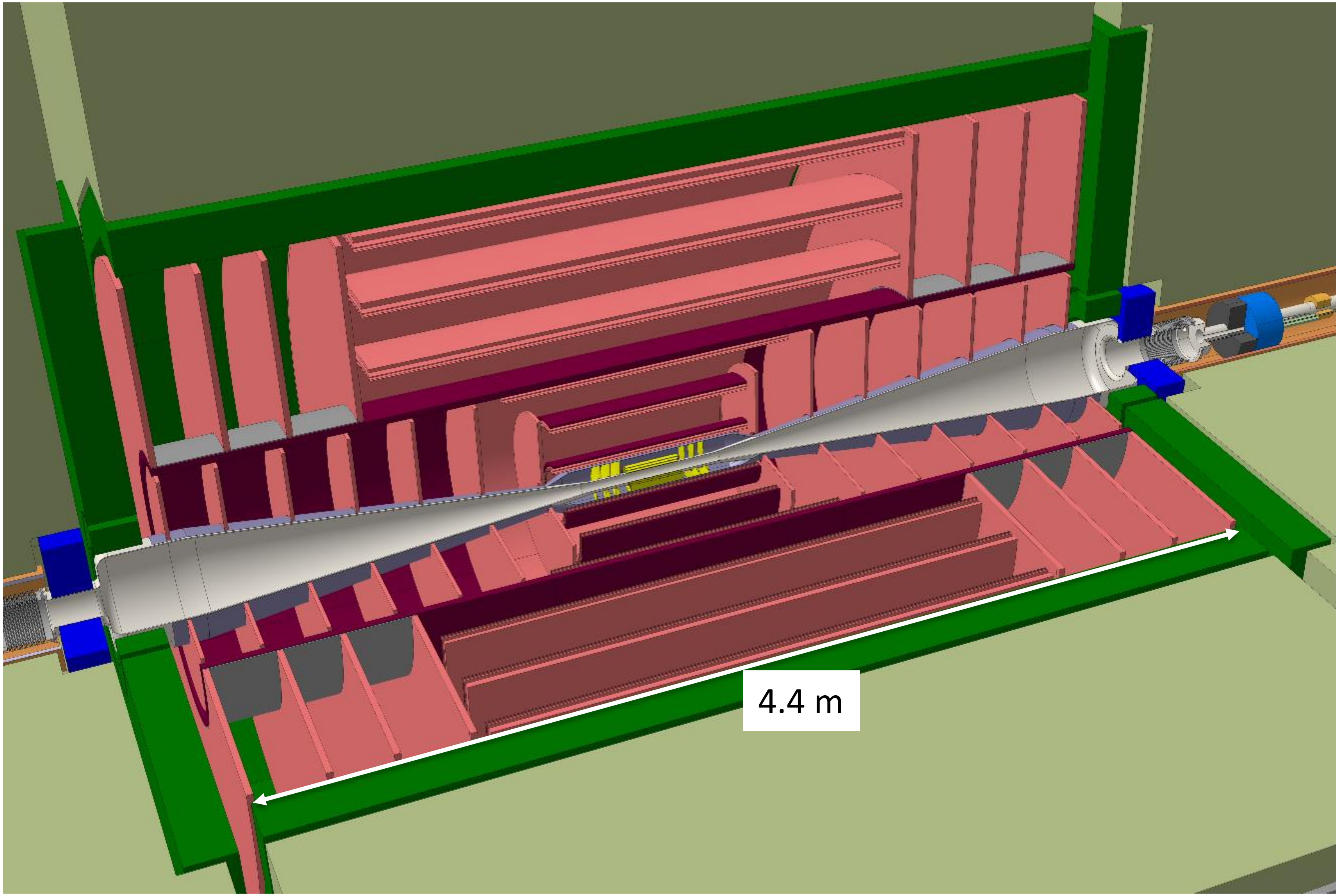
- 312 BXs per train; all BXs read out in-between bunch trains. No trigger.
- All subdetectors will implement power pulsing schemes at 50 Hz, to reduce needed cooling systems

Evolution of Detector Designs

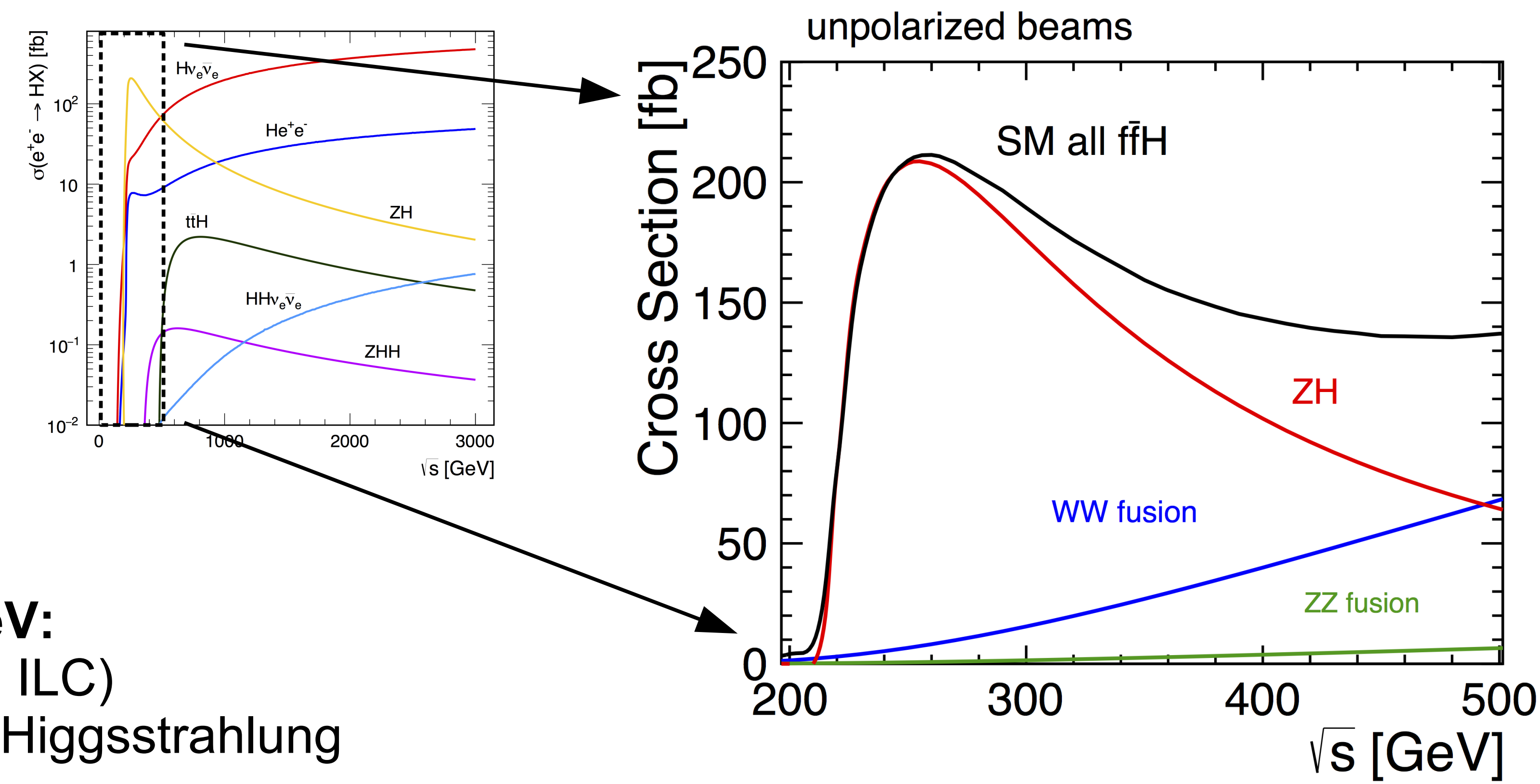
- For the CLIC CDR (2012): Two general-purpose CLIC detector concepts
  - Based on initial ILC concepts (ILD and SiD) but optimised and adapted to CLIC conditions

Concept	CLIC_ILD	CLIC_SiD	CLICdet_2015	CMS
Tracker	TPC/Silicon	Silicon	Silicon	Silicon
B Field [T]	4	5	4	3.8
Solenoid R [m]	3.4	2.7	3.4	3
Solenoid L [m]	8.3	6.5	8.3	13
VTX R [mm]	31	27	31	40
ECal R [m]	1.8	1.3	1.5	1.3
ECal ΔR [mm]	172	135	159	500
HCal Absorber B / E	W/Fe	W/Fe	Fe	Cu+Zn
HCal λ_I B / E	7.5	7.5	7.55	5.8/10
Overall Height [m]	14	14	12.8	14.6
Overall Length [m]	12.8	12.8	11.4	21.6

zoom into the ECAL/tracker/vertex region

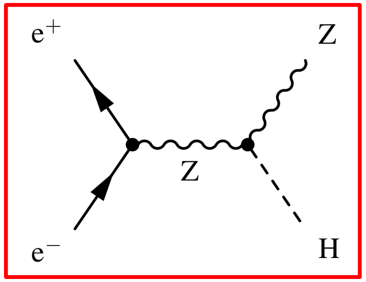


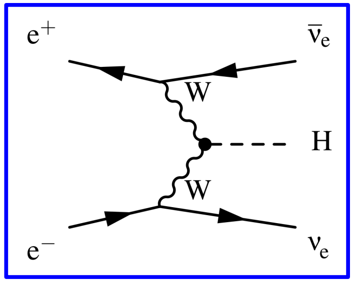
Closer look at $\sqrt{s}$ < 500 GeV



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

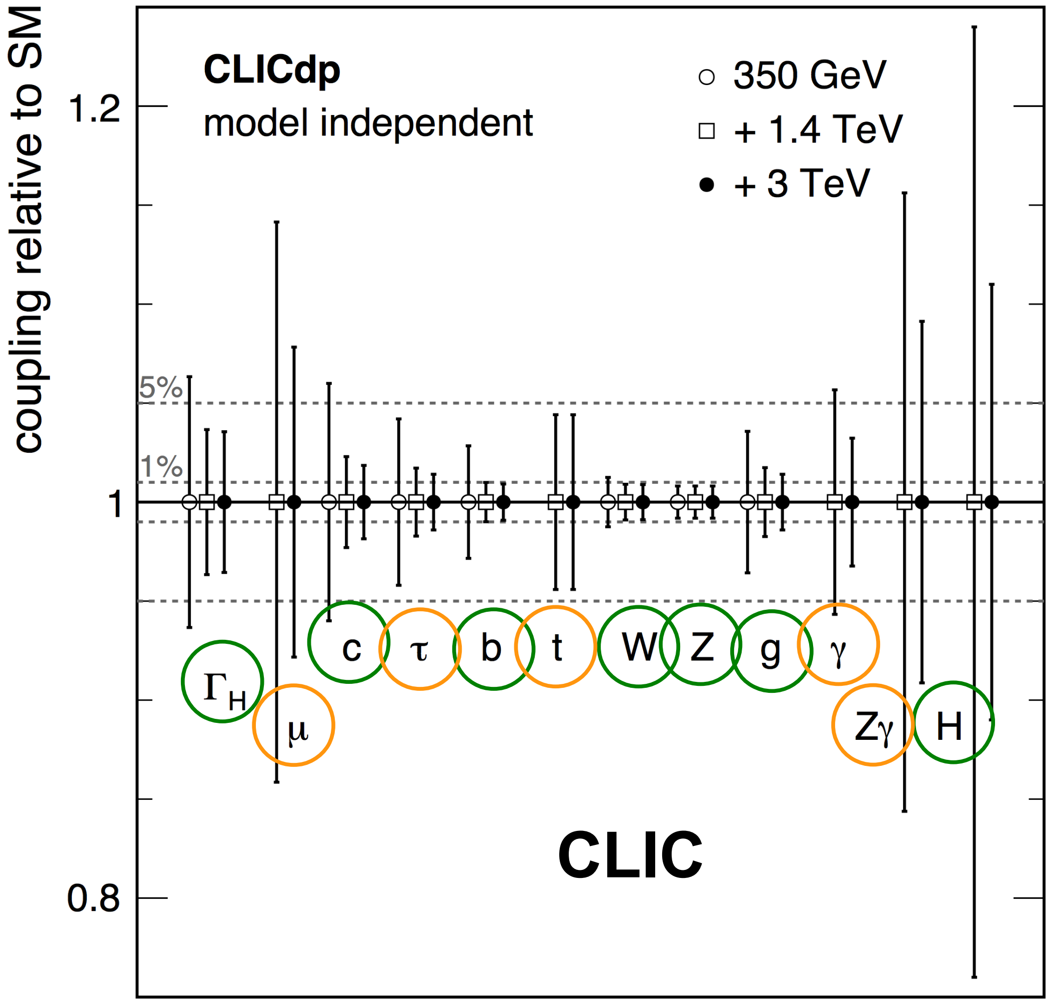
$\sqrt{s}$ = 350/380 GeV:
(FCC-ee, ILC, CLIC)
Also allows to access the WW fusion process
→ Additional information for combined analysis

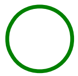




Higgs properties at CLIC

Lepton collider predictions are model-independent in contrast to hadron machines!



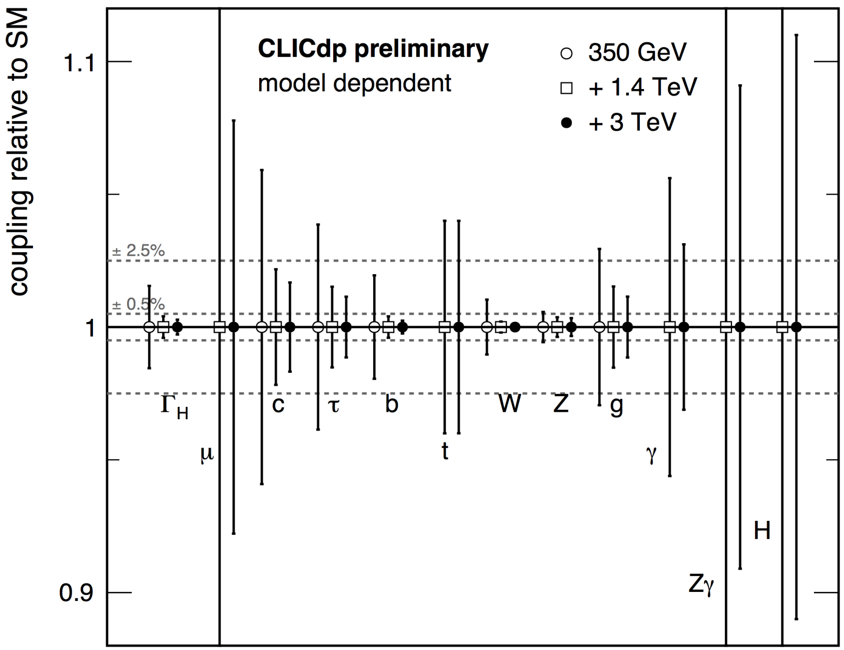


significantly better than HL-LHC or not possible at hadron colliders

similar to HL-LHC

arXiv:1608.07538

Analysis similar to LHC experiments



Parameter	Relative precision		
	350 GeV $500\,\mathrm{fb}^{-1}$	+ 1.4 TeV $+\,1.5\,\mathrm{ab}^{-1}$	+ 3 TeV $+\,2\,\mathrm{ab}^{-1}$
κ_{HZZ}	0.57 %	0.37 %	0.34 %
κ_{HWW}	1.0 %	0.21 %	0.14 %
κ_{Hbb}	1.9 %	0.40 %	0.24 %
κ_{Hcc}	5.9 %	2.1 %	1.6 %
$\kappa_{\mathrm{H\tau\tau}}$	3.9 %	1.5 %	1.1 %
$\kappa_{\mathrm{H\mu\mu}}$	–	14.1 %	7.8 %
κ_{Htt}	–	4.0 %	4.0 %
κ_{Hgg}	2.9 %	1.5 %	1.1 %
$\kappa_{\mathrm{H\gamma\gamma}}$	–	5.6 %	3.1 %
$\kappa_{\mathrm{HZ\gamma}}$	–	15.6 %	9.1 %
$\Gamma_{\mathrm{H},md,derived}$	1.6 %	0.41 %	0.28 %

-80% electron polarisation at 1.4 and 3 TeV

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{\mathrm{SM}}}$$

No invisible decays:

$$\Gamma_{\mathrm{H,model}} = \sum_i \kappa_i^2 \cdot BR_i^{\mathrm{SM}}$$

(Sub-)percent precisions at high energy
→ Results strongly dependent on fit assumptions