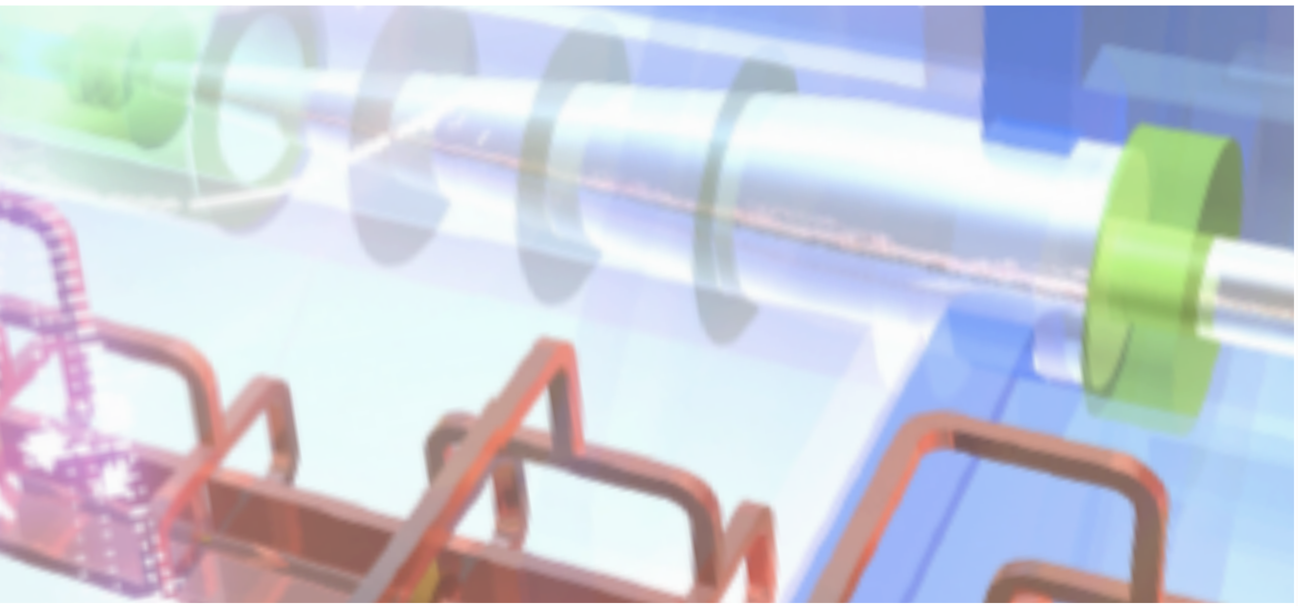
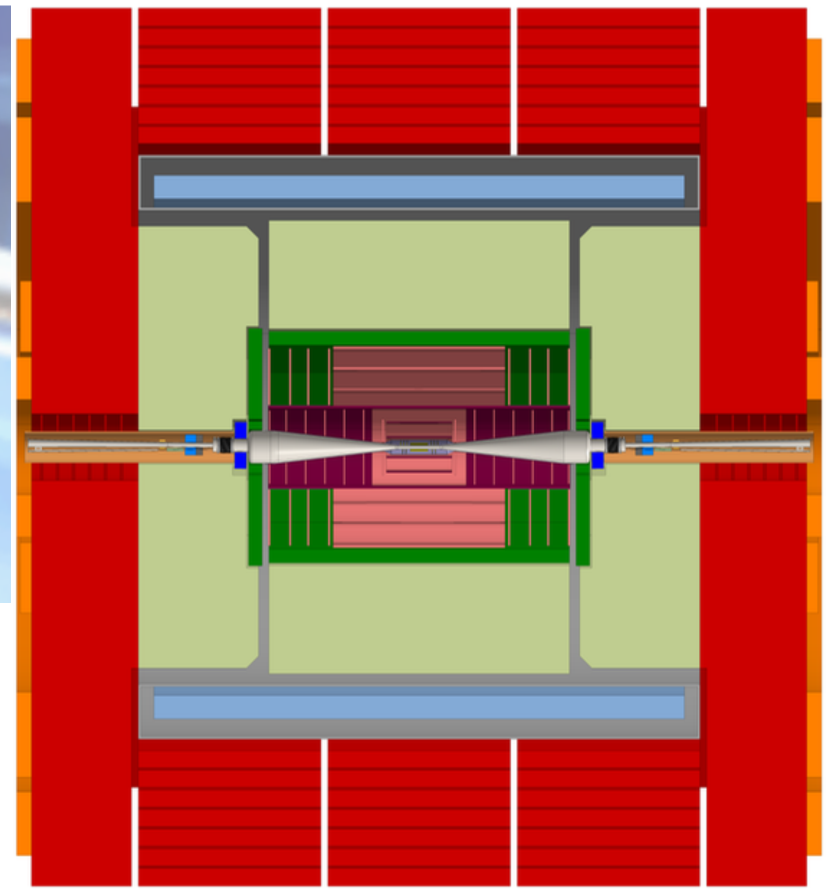
CLIC Overview

Workshop on top physics at linear colliders
CERN 7–9 June 2017





University of Glasgow

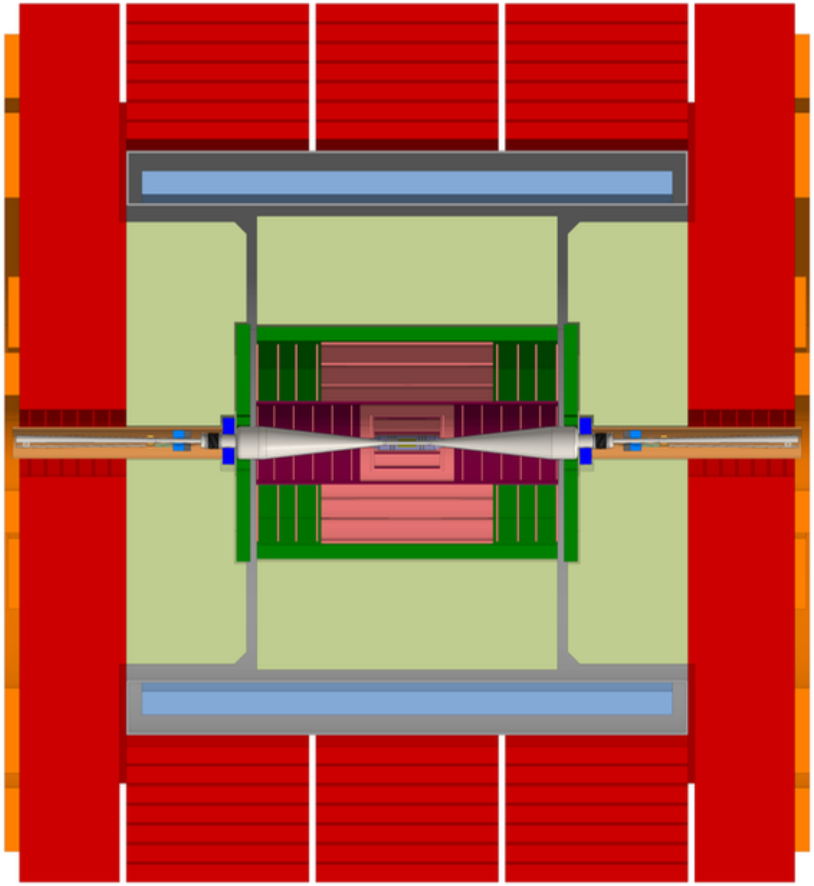
Aidan Robson

on behalf of the CLICdp collaboration

CLIC Overview

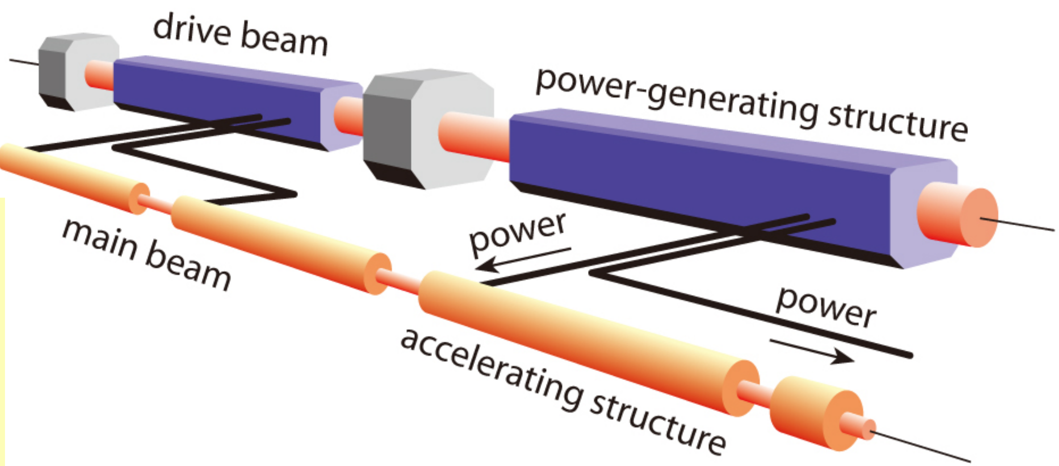
Workshop on top physics at linear colliders
CERN 7–9 June 2017

- CLIC Overview
- Physics highlights:
  - Higgs
  - top
  - BSM
- Outlook

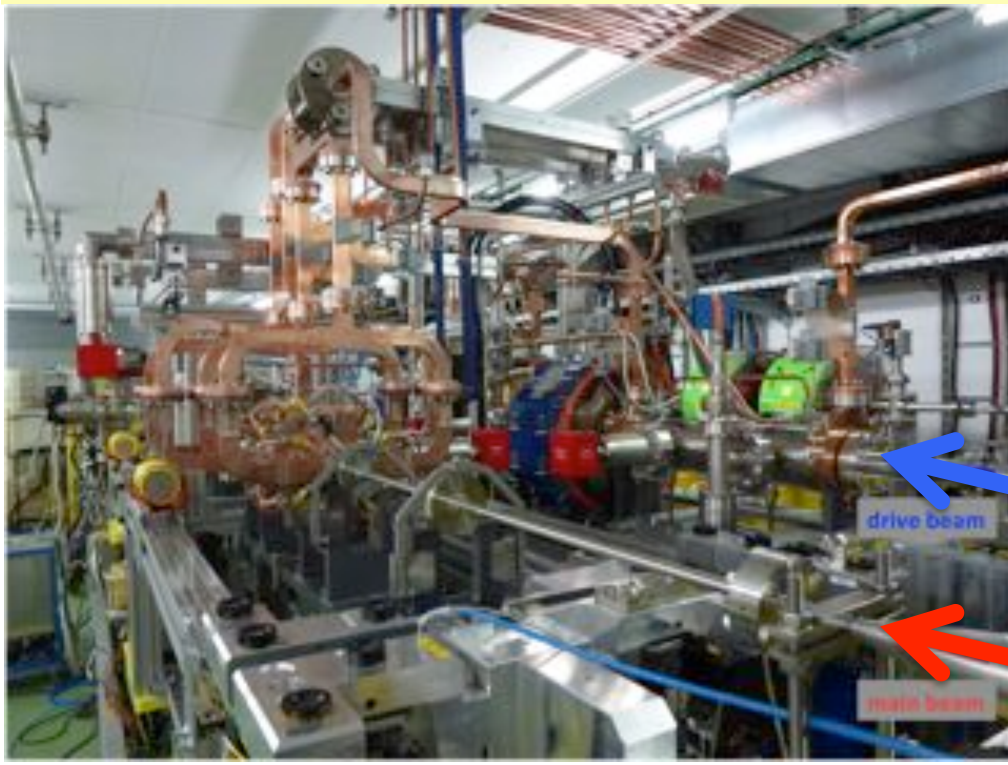


Compact Linear Collider: CLIC

e^+e^- collider with $\sqrt{s}$ up to 3 TeV



100 MV/m accelerating gradient needed for compact (~50km) machine
Based on normal-conducting accelerating structures and a two-beam acceleration scheme



Drive beam

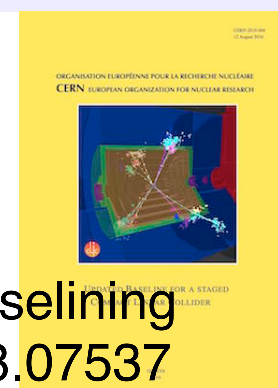
Main beam

CLIC foreseen as a staged machine:

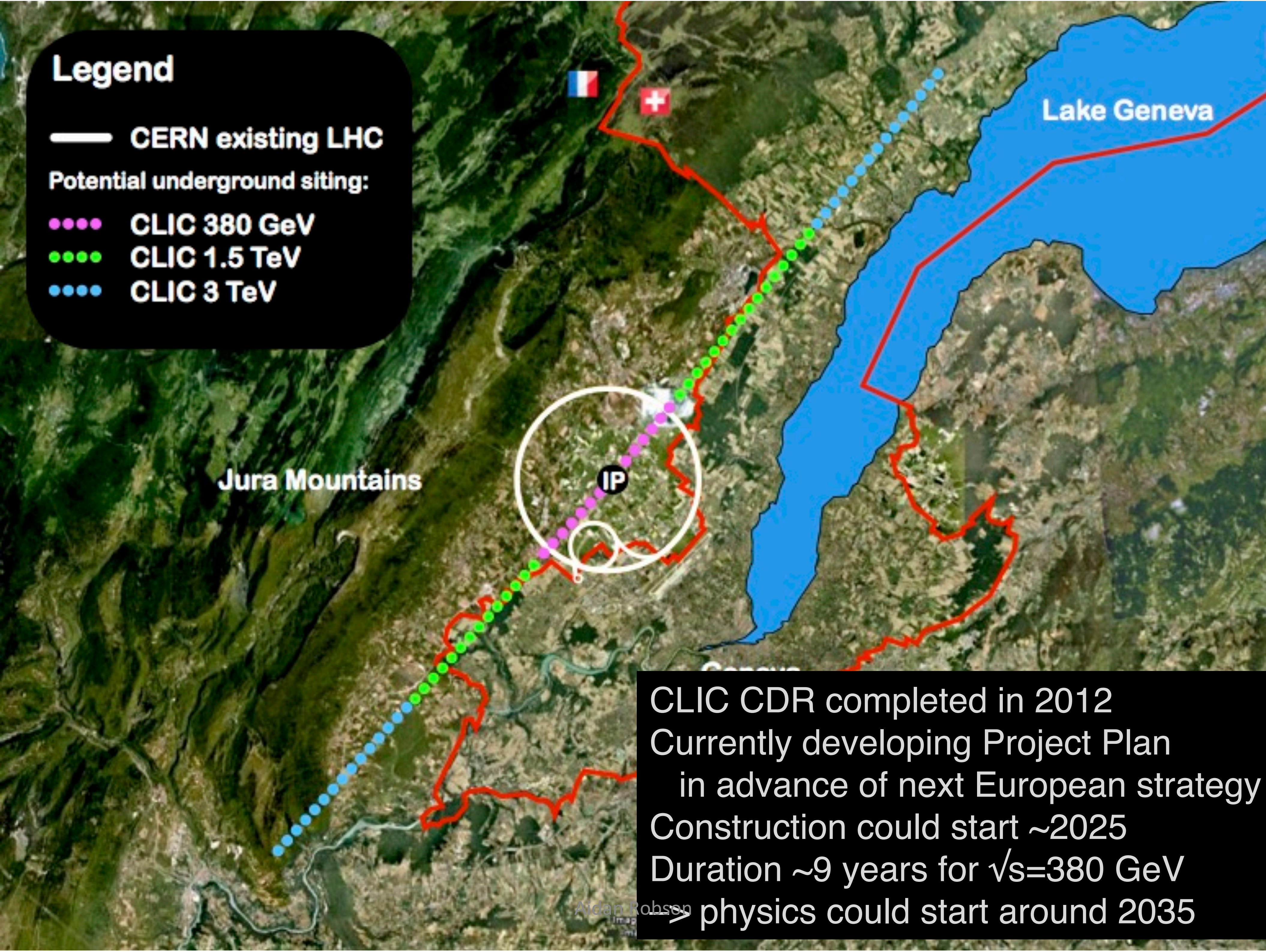
- Stage 1 baseline: $\sqrt{s}$=380GeV: precision SM physics: Higgs and top

Energies of subsequent stages motivated by physics

- Stages 2 & 3 baseline: 1.5 TeV, 3 TeV



CLIC rebaselining arXiv:1608.07537



CLIC CDR completed in 2012
Currently developing Project Plan
in advance of next European strategy
Construction could start ~2025
Duration ~9 years for $\sqrt{s}$=380 GeV
--> physics could start around 2035

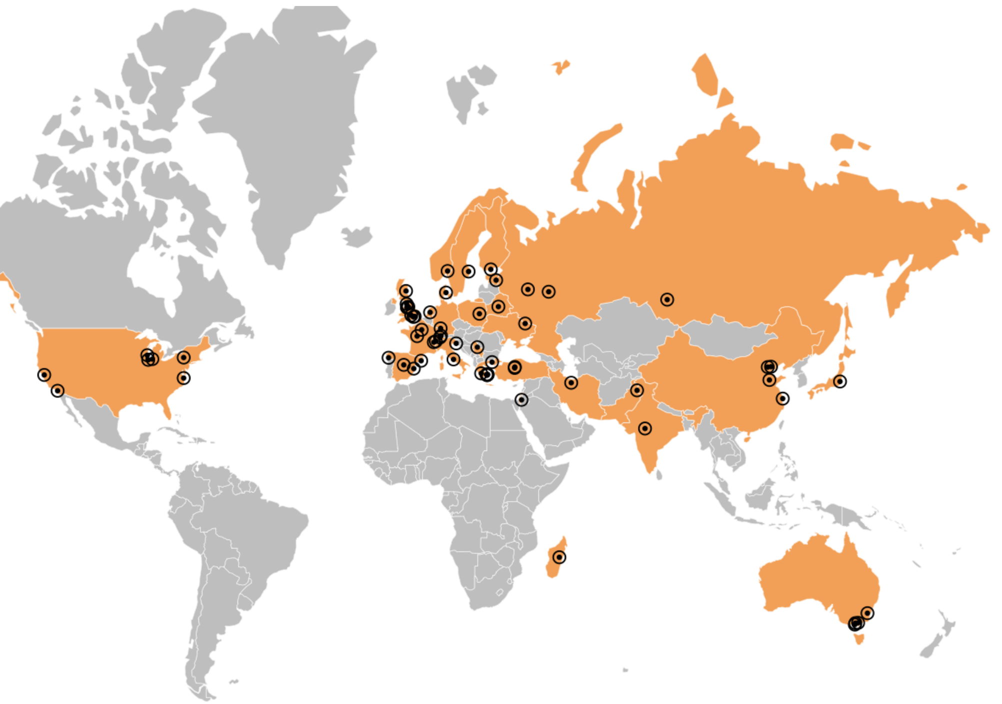
Aidan Robson

CLIC collaborations

CLIC/CTF3 accelerator collaboration
62 institutes from **28 countries**

http://clic-study.web.cern.ch/

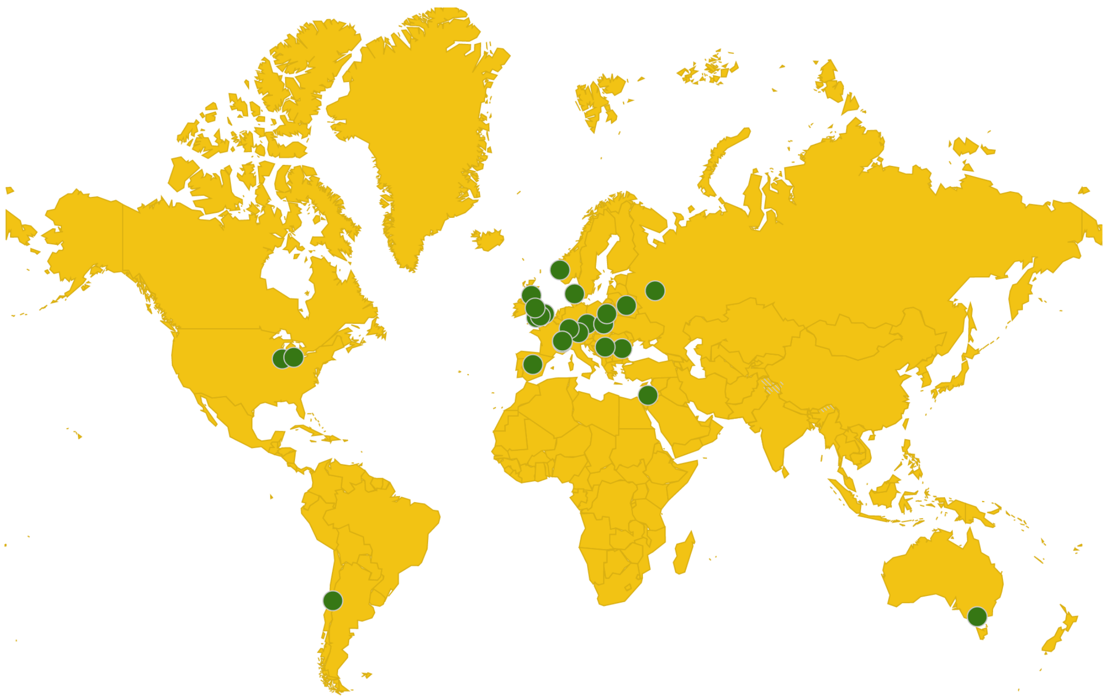
CLIC accelerator studies:
- CLIC accelerator design & development
- Construction and operation of CTF3



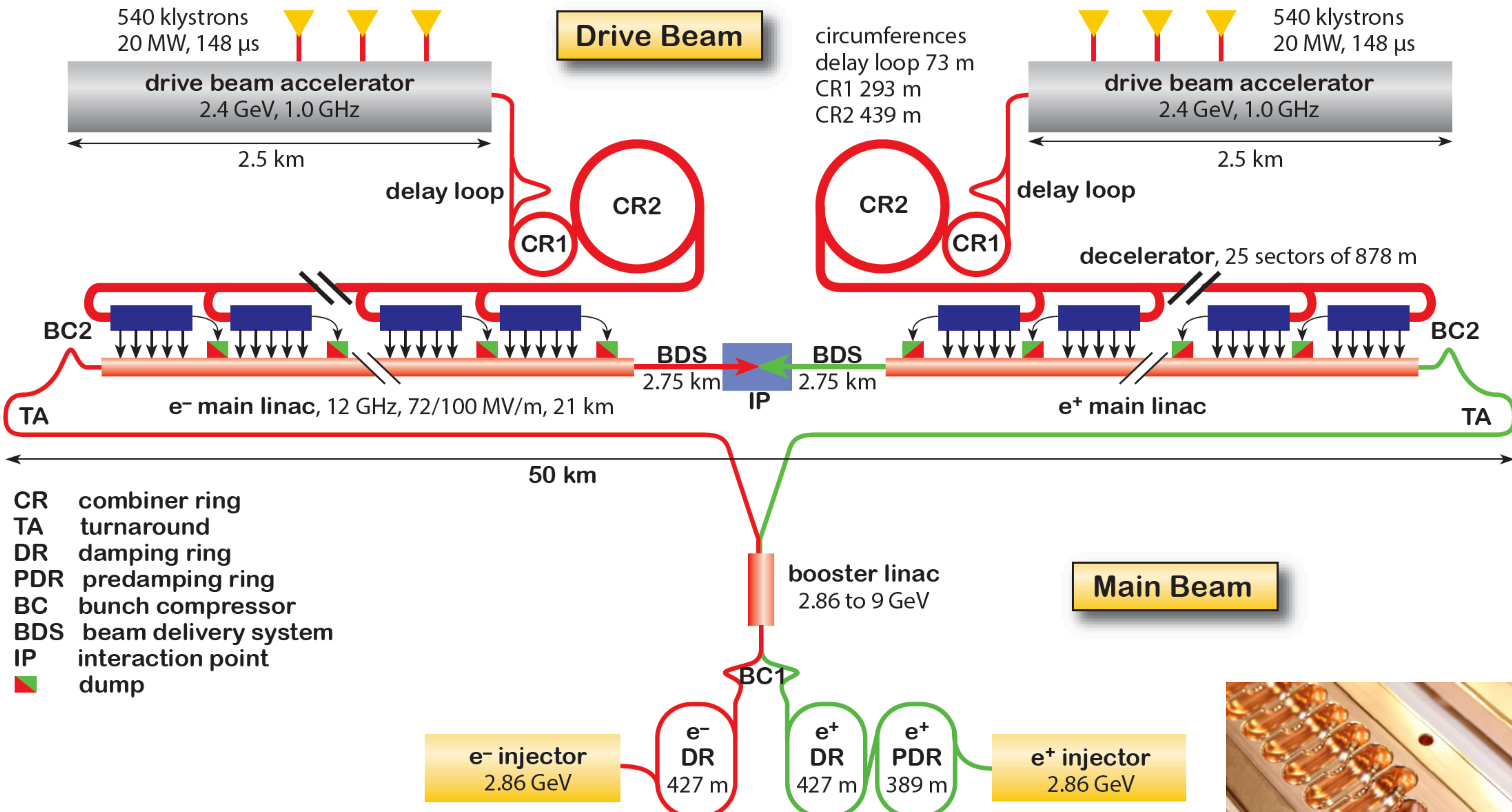
CLIC detector and physics (CLICdp)
29 institutes from **18 countries**

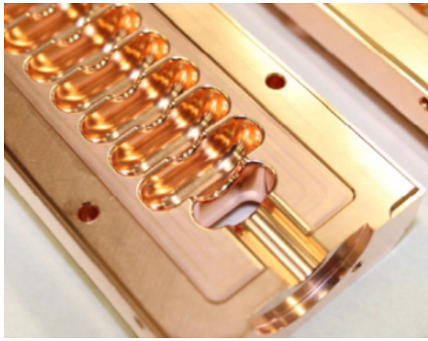
http://clicdp.web.cern.ch/

Focus of CLIC-specific studies on:
- Physics prospects & simulation studies
- Detector optimization + R&D for CLIC

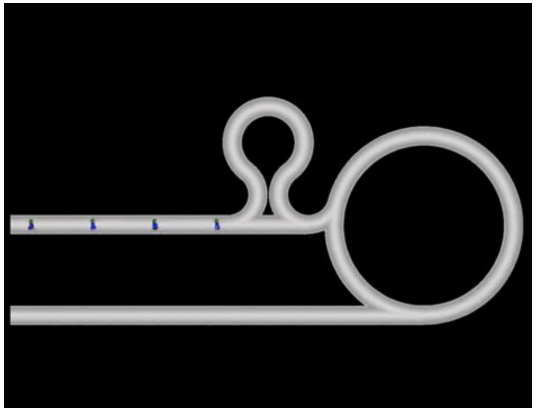


CLIC layout 3 TeV

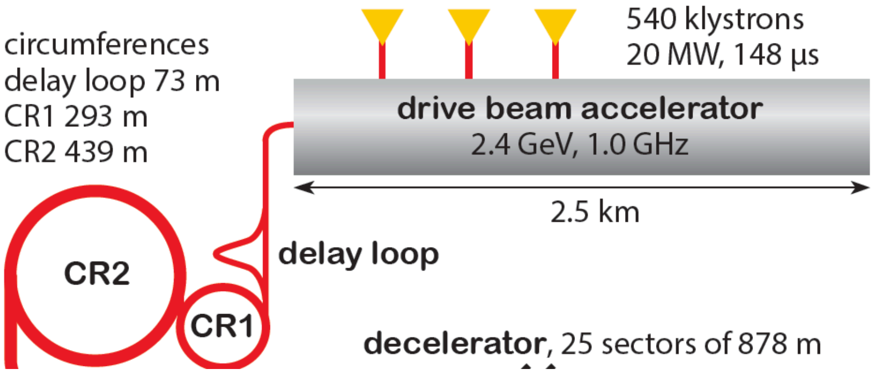


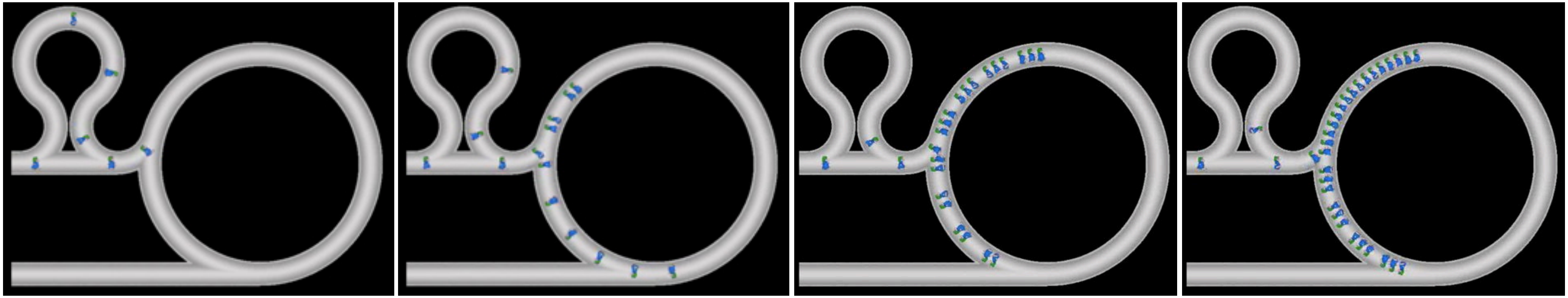


Machine context



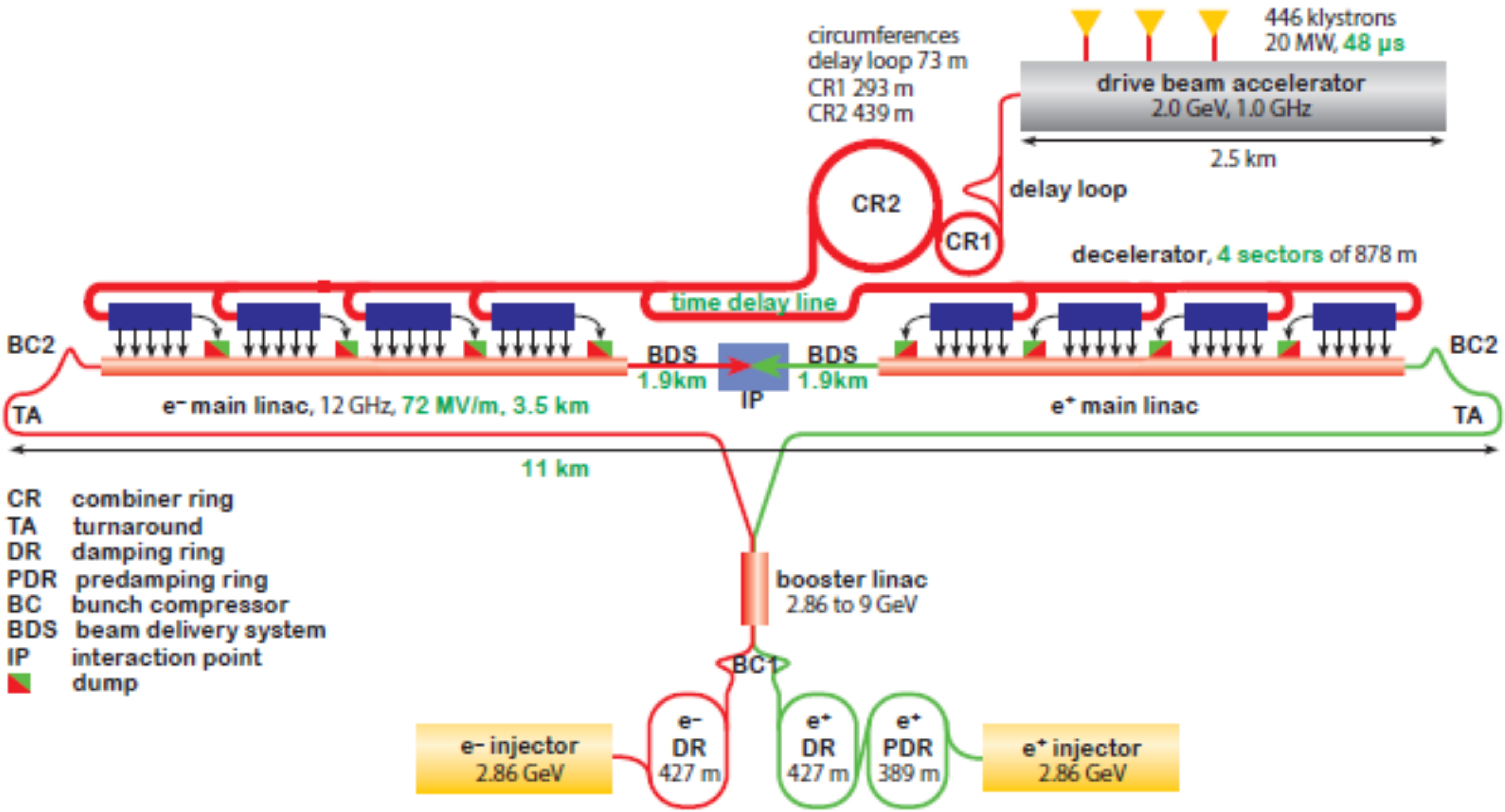
Delay loops create drive beam bunch-structure



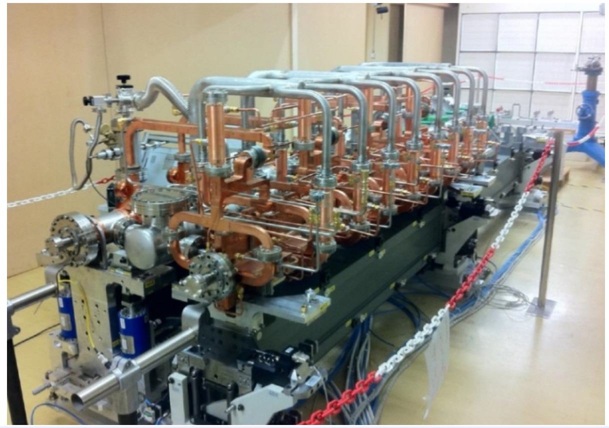


Low energy high current drive beam -> high energy low current main beam

CLIC layout 380 GeV

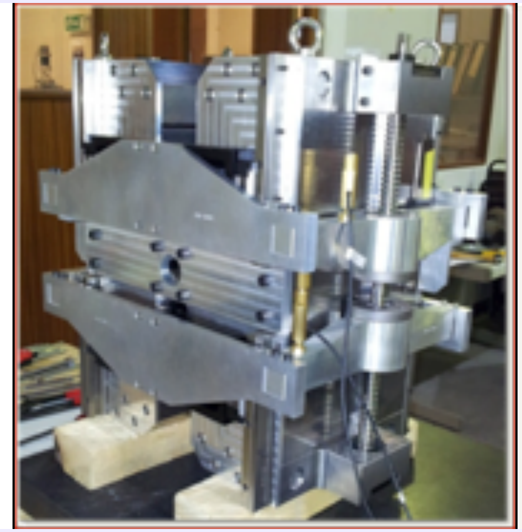


Machine context



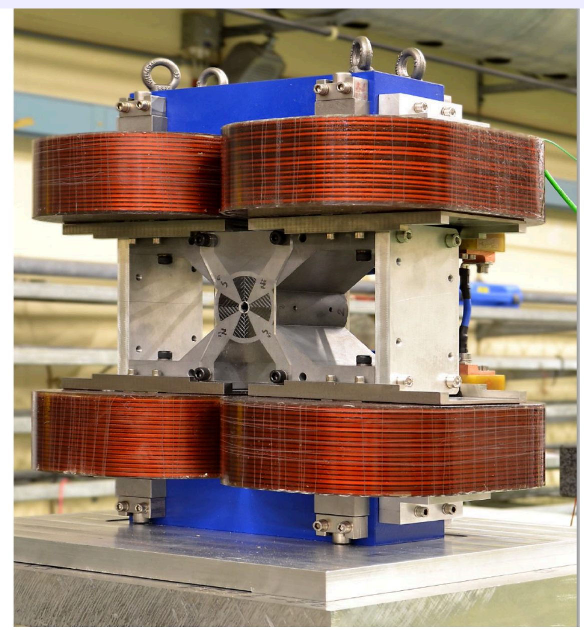
Mechanical tests of 2-beam module: active alignment and stabilisation

Tunable permanent magnet



CTF3 test facility at CERN has demonstrated drive beam generation, RF power extraction, and two-beam acceleration scheme (up to 135MV/m measured)

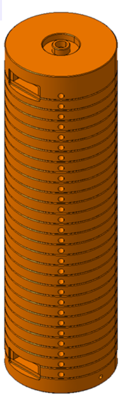
Prototype final-focus quadrupole



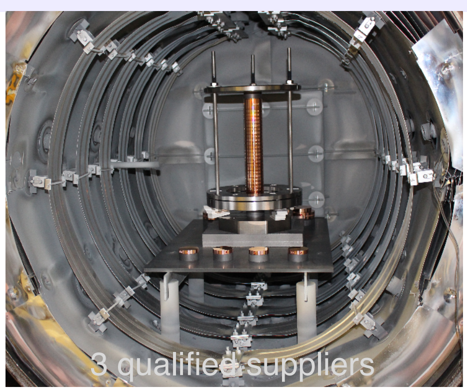
Assembly – towards industrialisation of accelerator structures

single disk

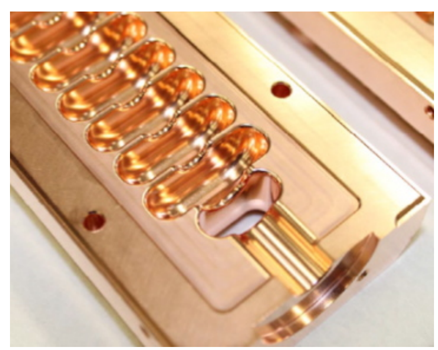
stack



brazing



cut-through



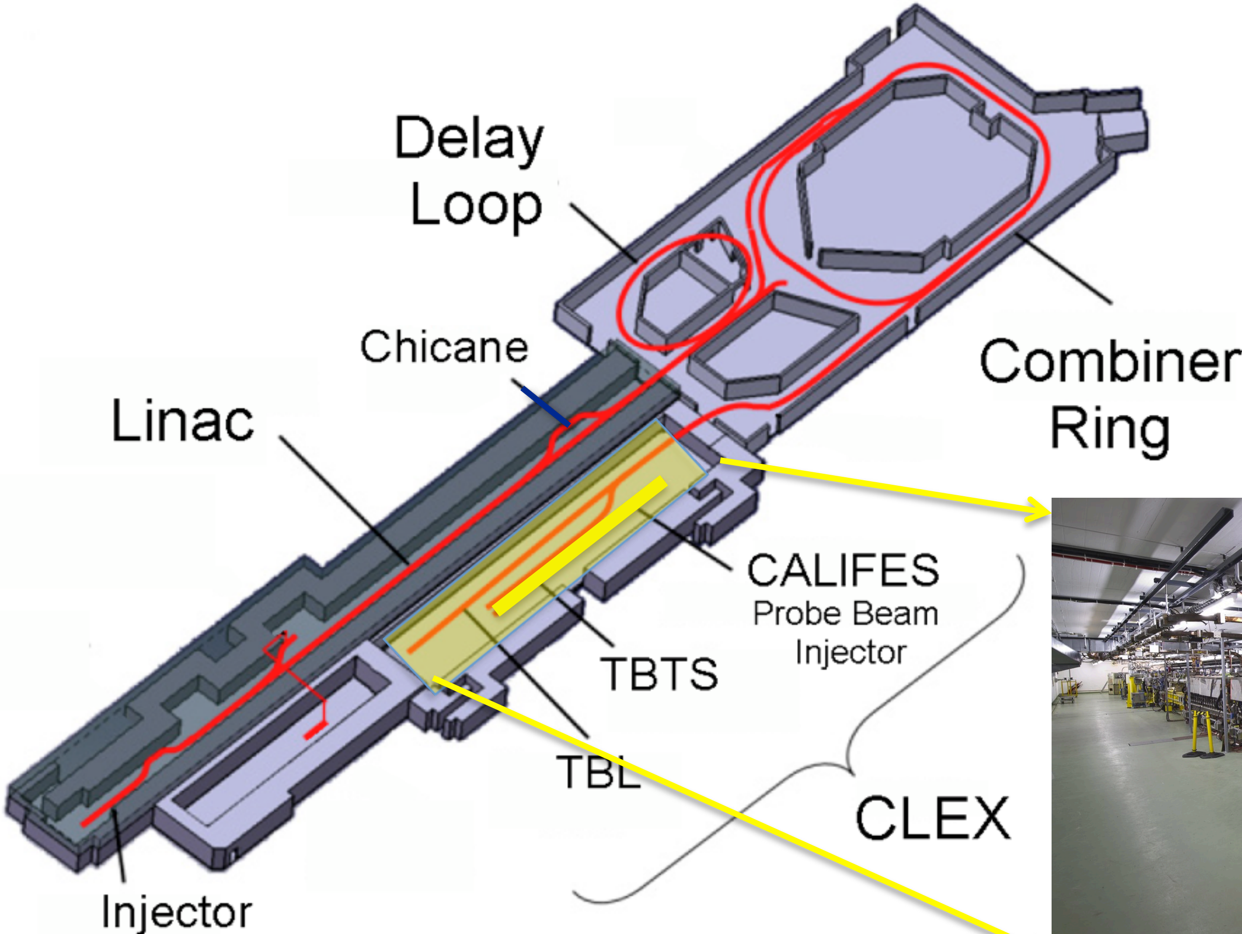
CTF3 -> CLEAR

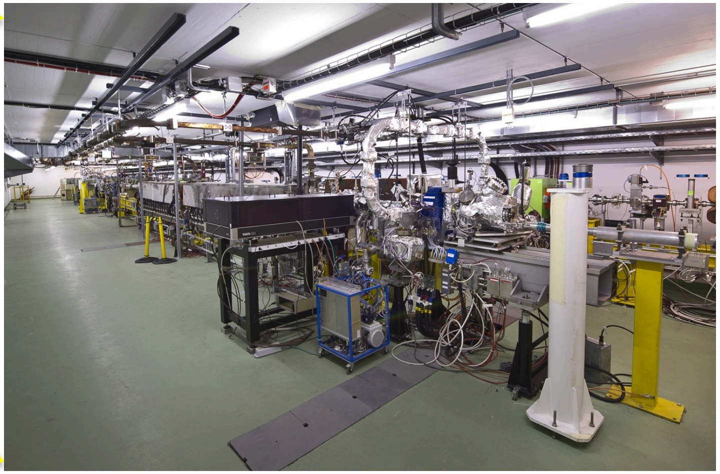
CTF3 programme ended at the end of 2016

Electron beam being maintained as new facility, 'CLEAR': CERN Linear Electron Accelerator for Research (2+2 year programme)

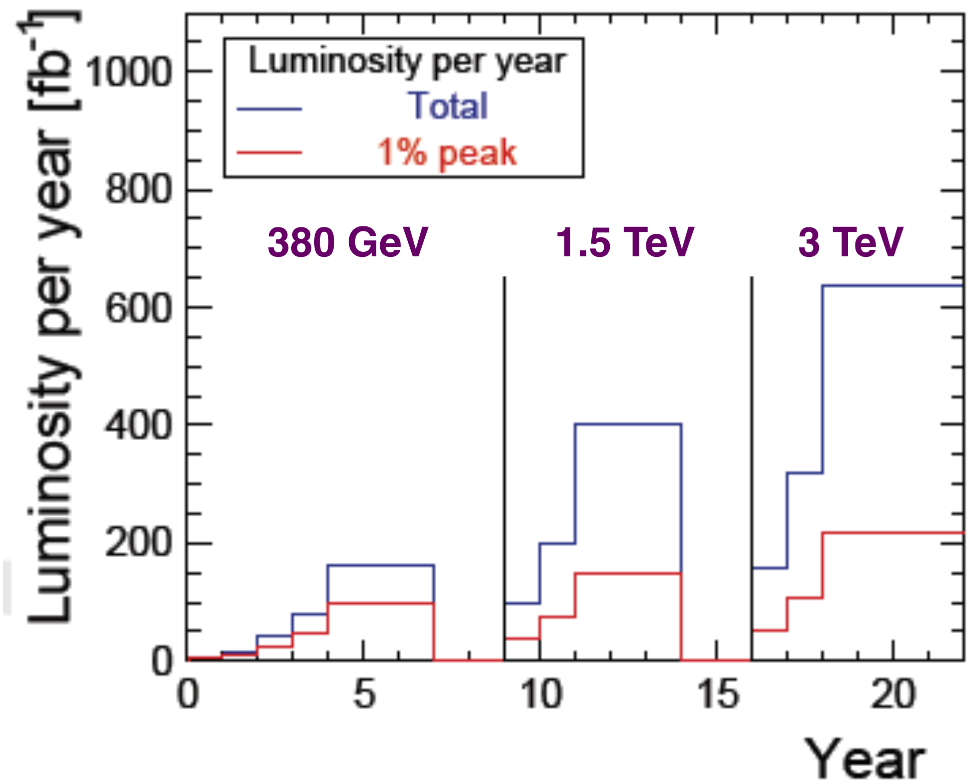
CLEAR = the CLEX experimental hall housing the 200 MeV S-band electron CALIFES linac

-> keeps beam test capability for CLIC (instrumentation, high gradient studies, components)
Will be connected to 12 GHz RF for high-gradient studies



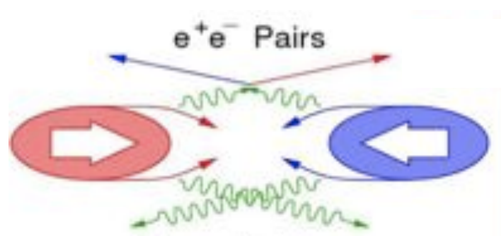


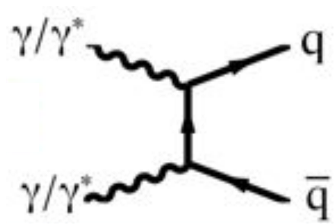
CLIC staging scenario

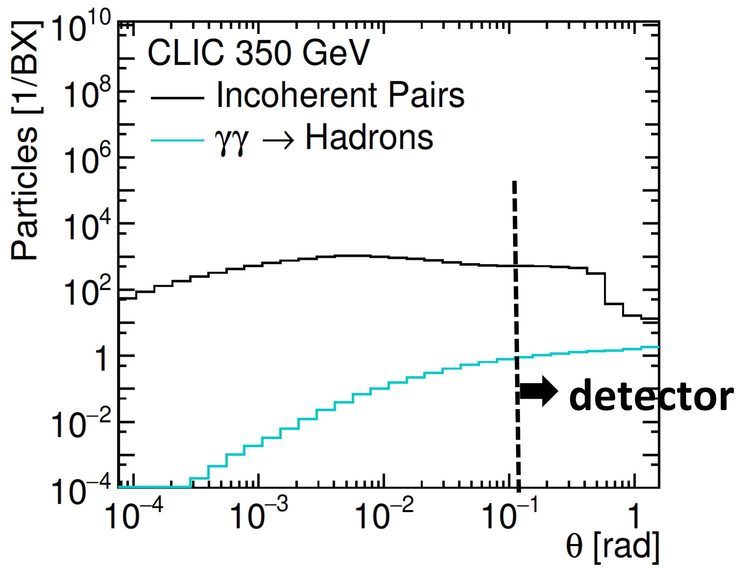


Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{int}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

Staging can be adapted to possible LHC discoveries

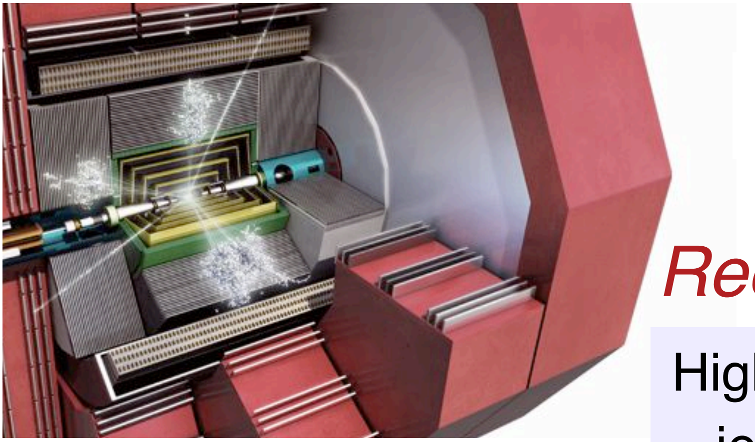


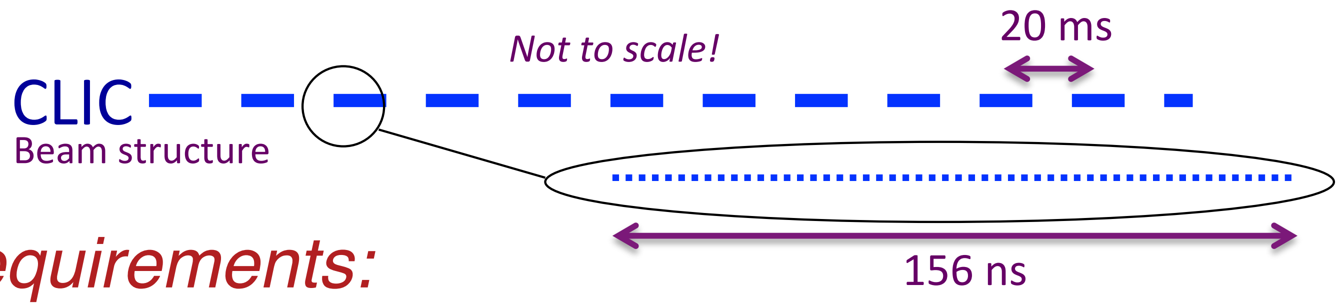




High bunch-charge density –> beamstrahlung
Incoherent e^+e^- pairs and γγ–>hadrons

CLIC detector and physics





Requirements:

High precision:
- jet energy resolution
  –> fine-grained calorimetry
- momentum resolution
- impact parameter resolution

$\sigma(E)/(E) \sim 3.5\%$ for E>100GeV

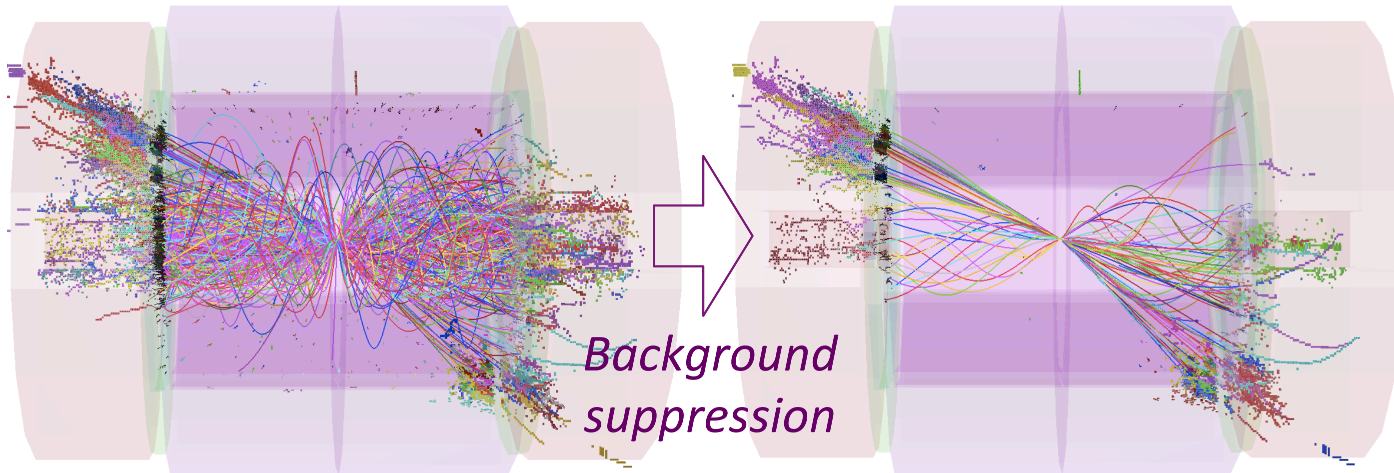
$\sigma(p_T)/p_T^2 \sim 2\text{x}10^{-5}\ \text{GeV}^{-1}$

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

CALICE / FCAL

CLICdp vertexing/ tracking programme

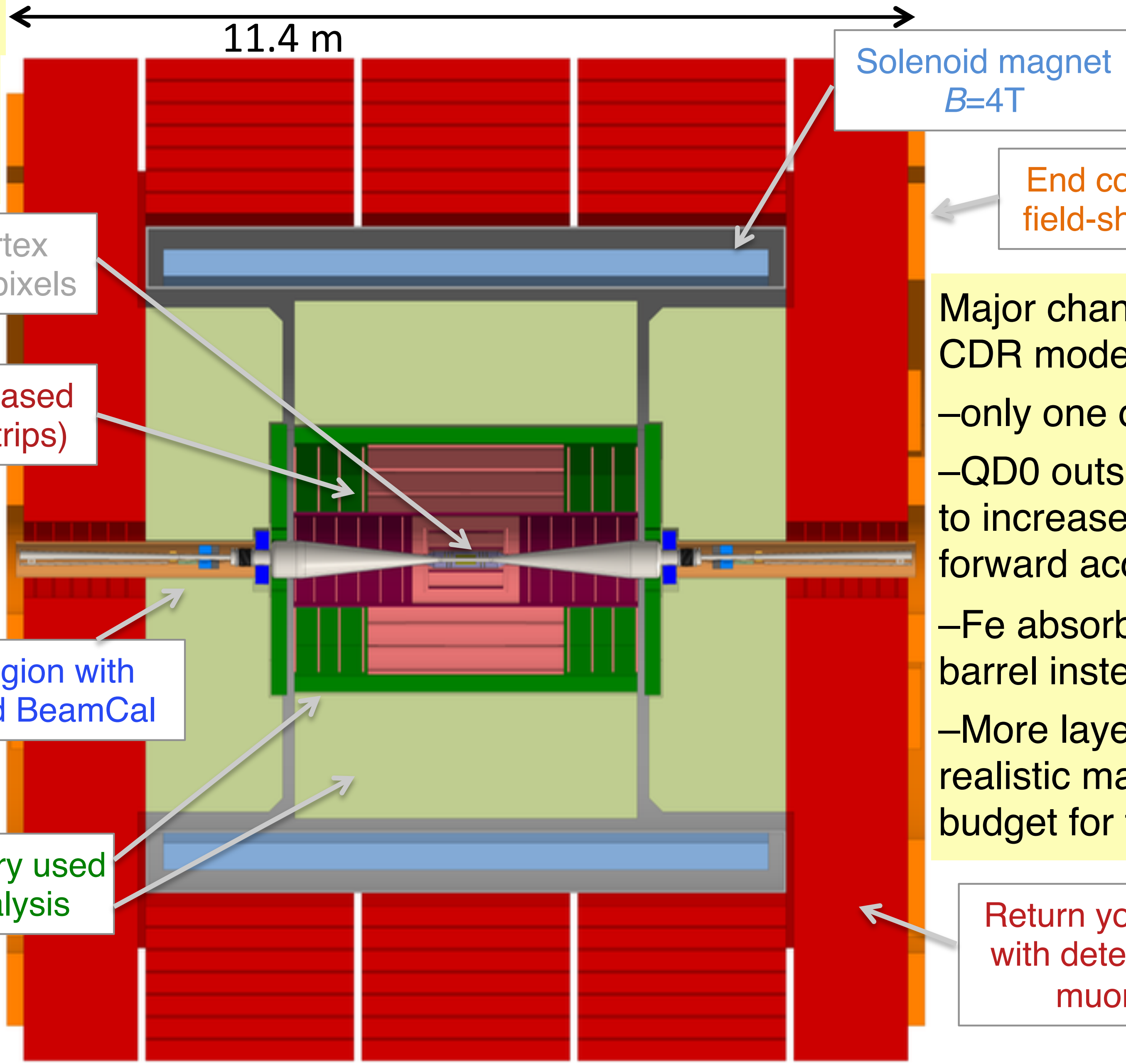
High occupancy
-> precise timing
(1ns, 10ns)



- Provide demonstrators for the main technical challenges

Detector optimization

Initial studies used variants of ILD/SiD; new CLICdet model now finalised



Major changes w.r.t. CDR models:

– only one detector

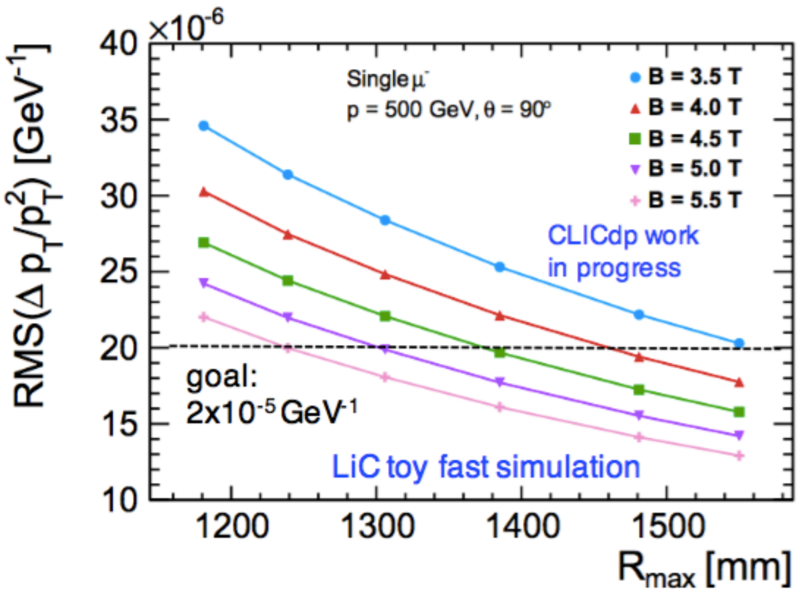
– QD0 outside detector to increase HCAL forward acceptance

– Fe absorber for HCAL barrel instead of W

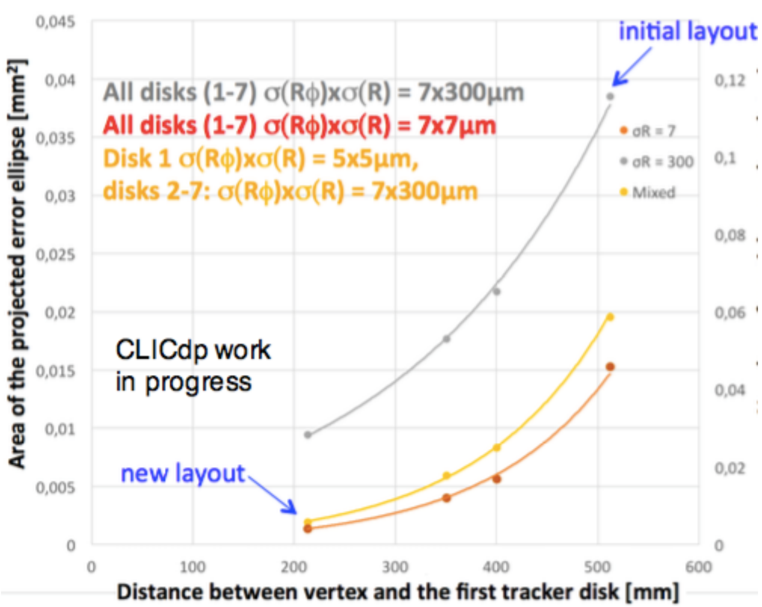
– More layers and more realistic material budget for tracker

Detector optimization

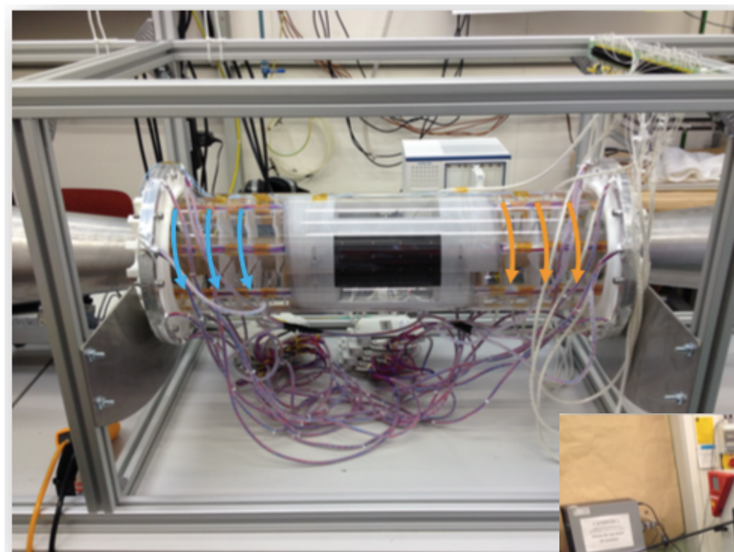
Momentum resolution for different radii and B-fields

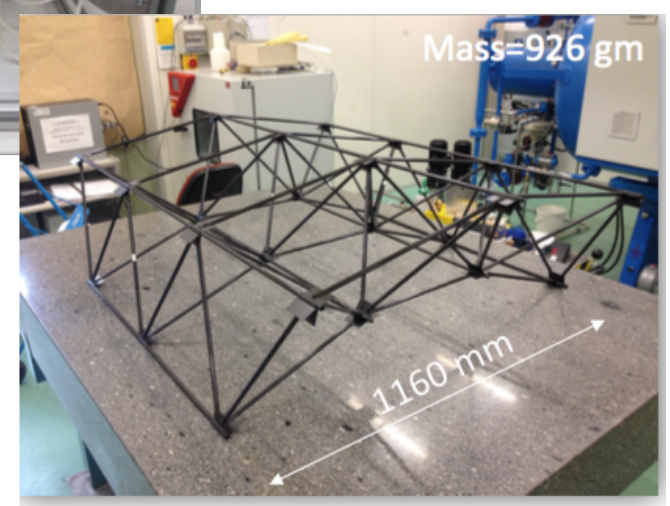


Optimization of end-cap layer spacing and r/o granularity



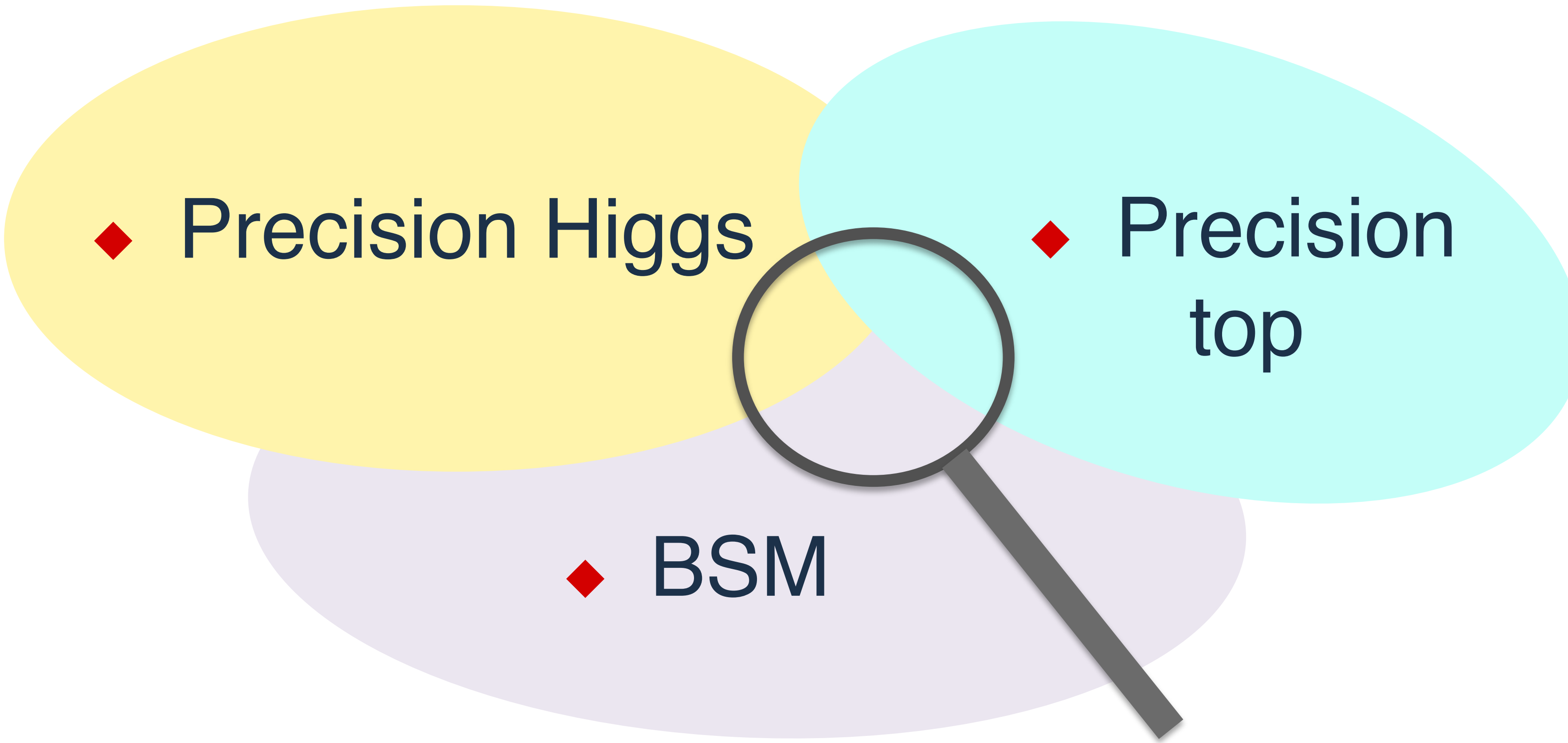
Optimizations of detector dimensions, spacings, granularities -> also informed by detector development, and full-scale cooling mockup and support structure development





-> much more in CERN Detector Seminar, Fri 9th June: ‘A detector for CLIC: performance optimisation and R&D’ by Rosa Simoniello

Physics motivations



Higgs overview

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

σ x Br → Br → g coupling

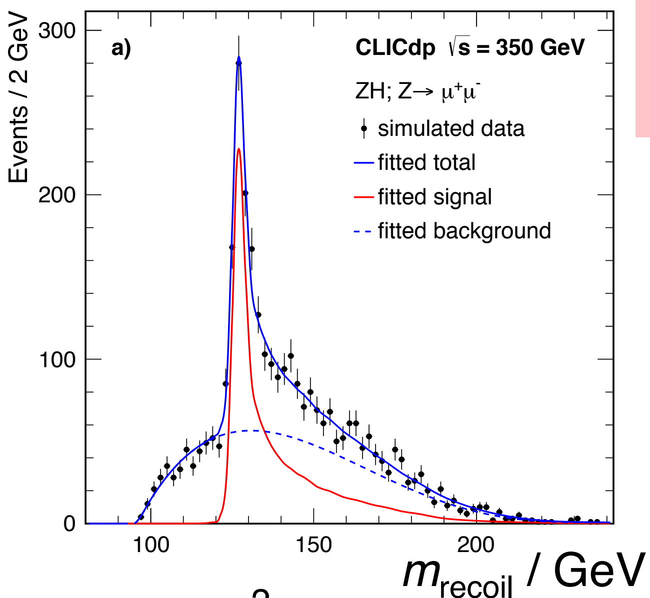
the key

σ from recoil mass

Γ_H total width

(need WW fusion for precision total width -> higher √*s*)

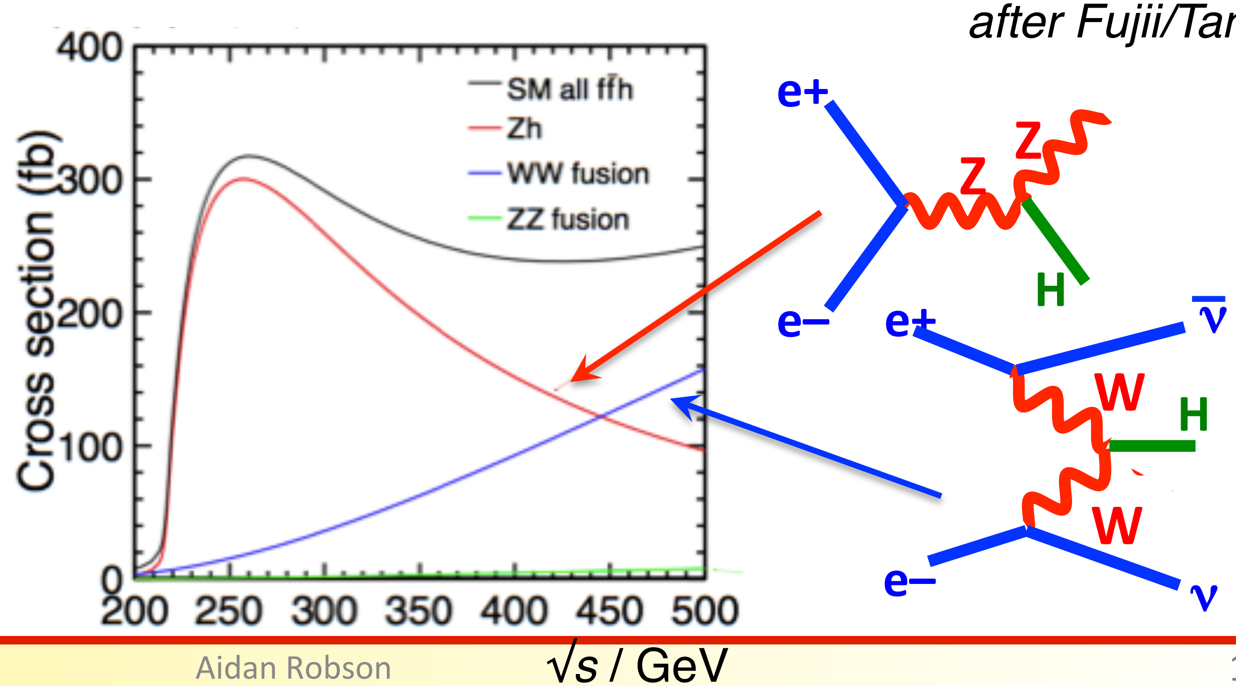
$$\frac{\sigma_{ZH} \,.\mathrm{Br(H\text{->}bb)}}{\sigma_{\nu\nu H} \,.\mathrm{Br(H\text{->}bb)}} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$



$\sigma_{ZH} \propto g^2_{HZZ}$

$\sigma_{\nu\nu H}$ .Br(H->WW) $\propto g^4_{HWW}/\Gamma_H$

after Fujii/Tanabe



Higgs overview

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

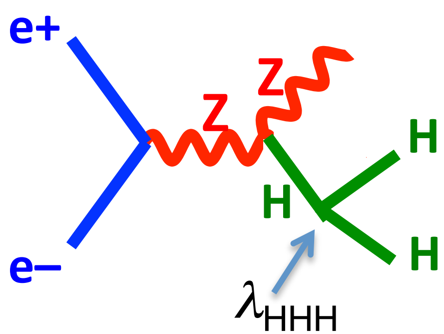
σ x Br → Br → g coupling

the key

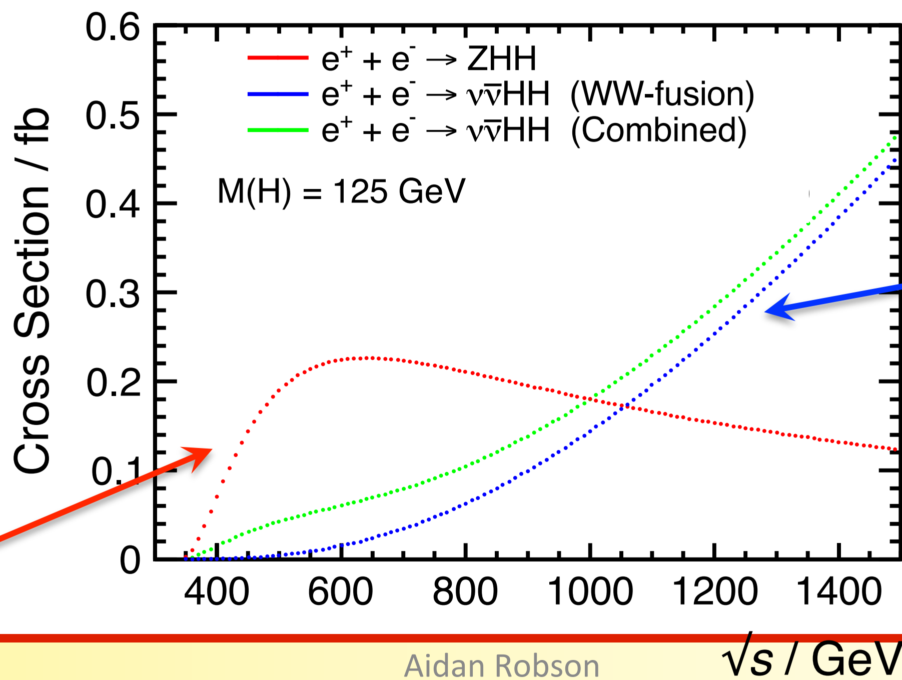
σ from recoil mass → Γ_H total width

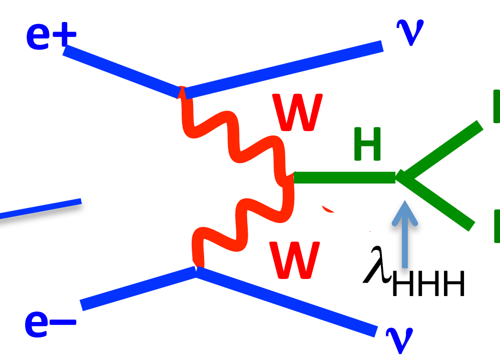
(need WW fusion for precision total width -> higher $\sqrt{s}$)

Higher energies: ttH, HH



dominates around $\sqrt{s}$=500GeV





dominates at higher $\sqrt{s}$

Higgs couplings – BSM sensitivity

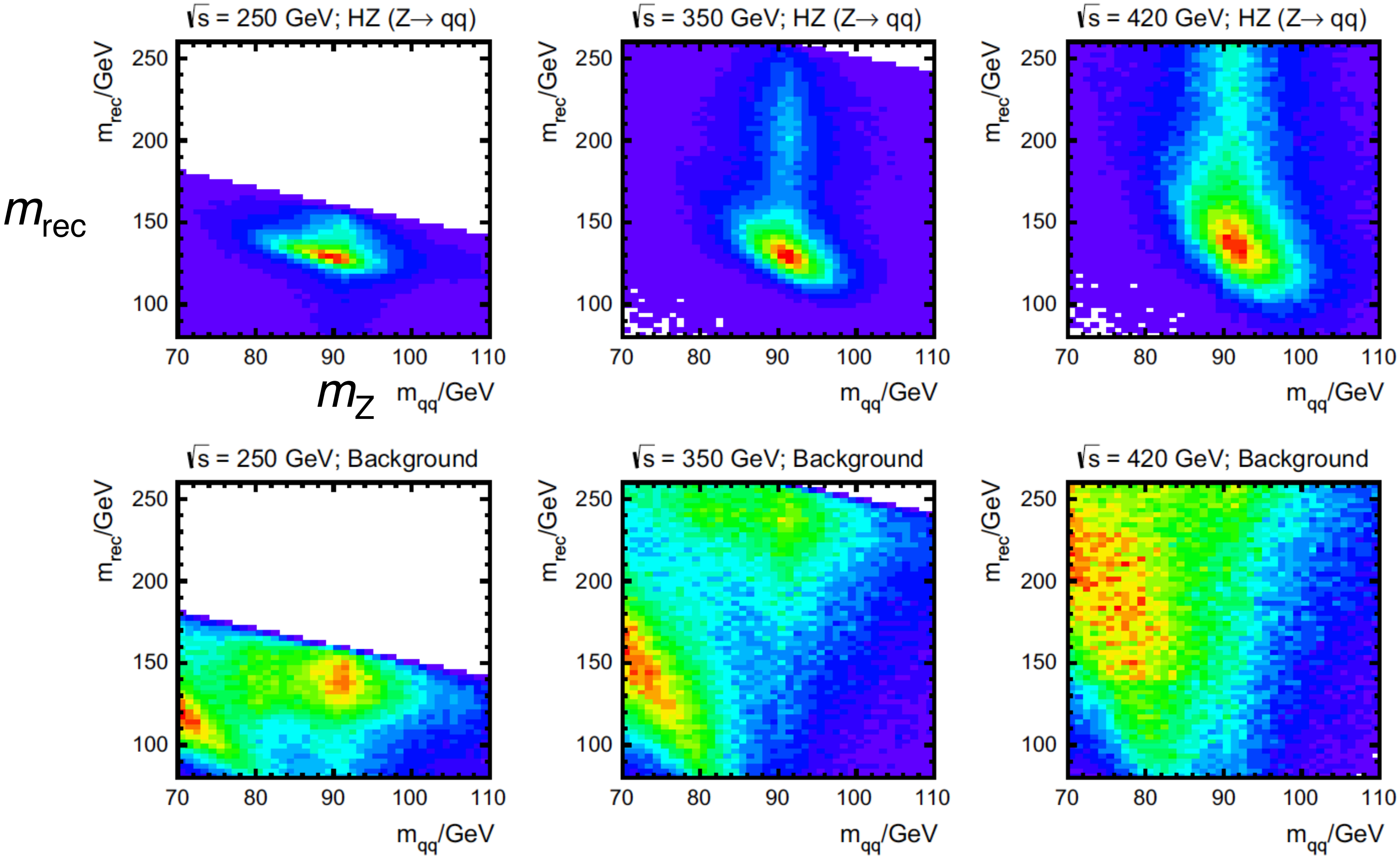
example scenarios in which $M \sim 1$TeV for new particles

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	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

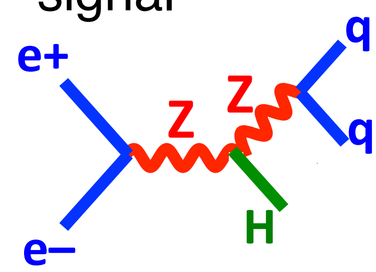
arXiv: 1310.8361

Hadronic events in recoil analysis

√s = 250 GeV √s = 350 GeV √s = 420 GeV



signal



background

Together with top physics this drives choice of 380 GeV for first stage

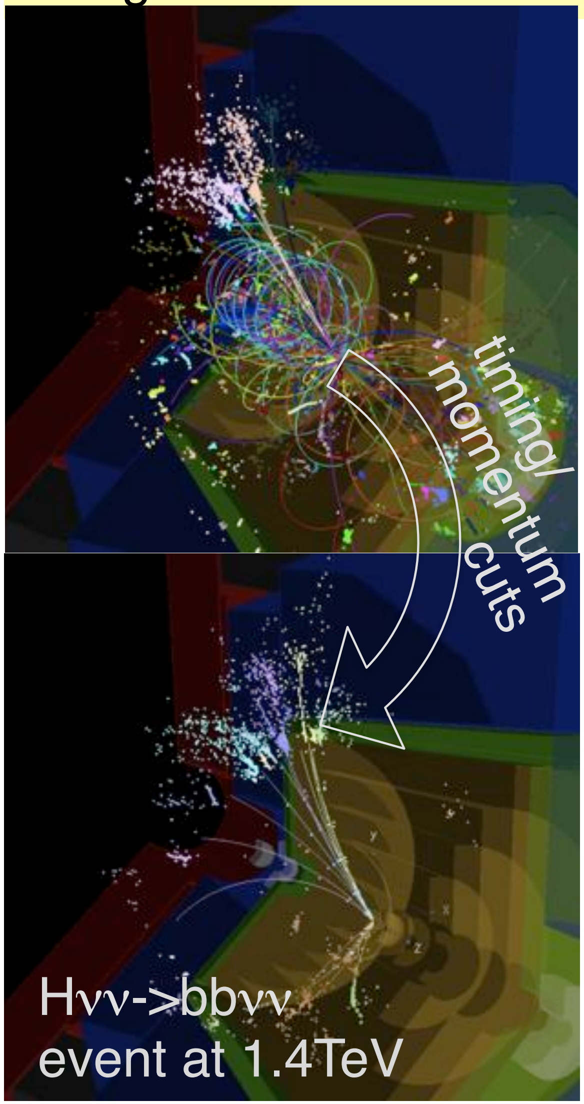
Eur. Phys. J. C (2016) 76: 72

$\sqrt{s}$	$\mathscr{L}$	σ(HZ)	$\Delta\sigma_{\text{vis.}}$	$\Delta\sigma_{\text{invis.}}$	$\Delta\sigma(\text{HZ})$
250 GeV	500 fb^{-1}	136 fb	±3.63 %	±0.45 %	±3.65 %
350 GeV	500 fb^{-1}	93 fb	±1.71 %	±0.56 %	±1.80 %
420 GeV	500 fb^{-1}	68 fb	±2.42 %	±1.02 %	±2.63 %

$\Delta\sigma_{HZ}$ ~ 4.2% for Z->ll
$\Delta\sigma_{HZ}$ ~ 1.8% for Z->qq
Δg_{HZZ} ~ 0.8% including all channels

Higgs -> bb/cc/gg

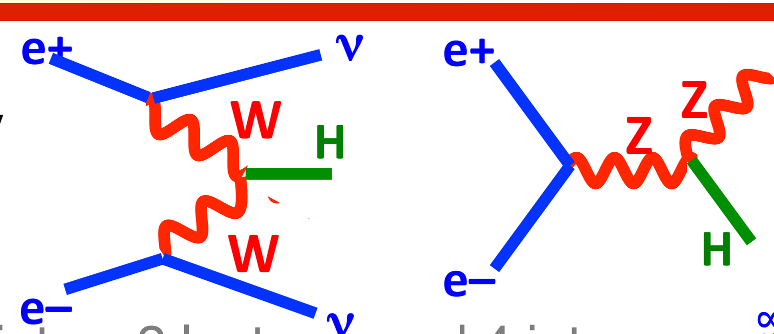
Separation of bb/cc/gg final state possible in e+e–, using excellent detector



Analyses at 3TeV, 1.4TeV, 350GeV

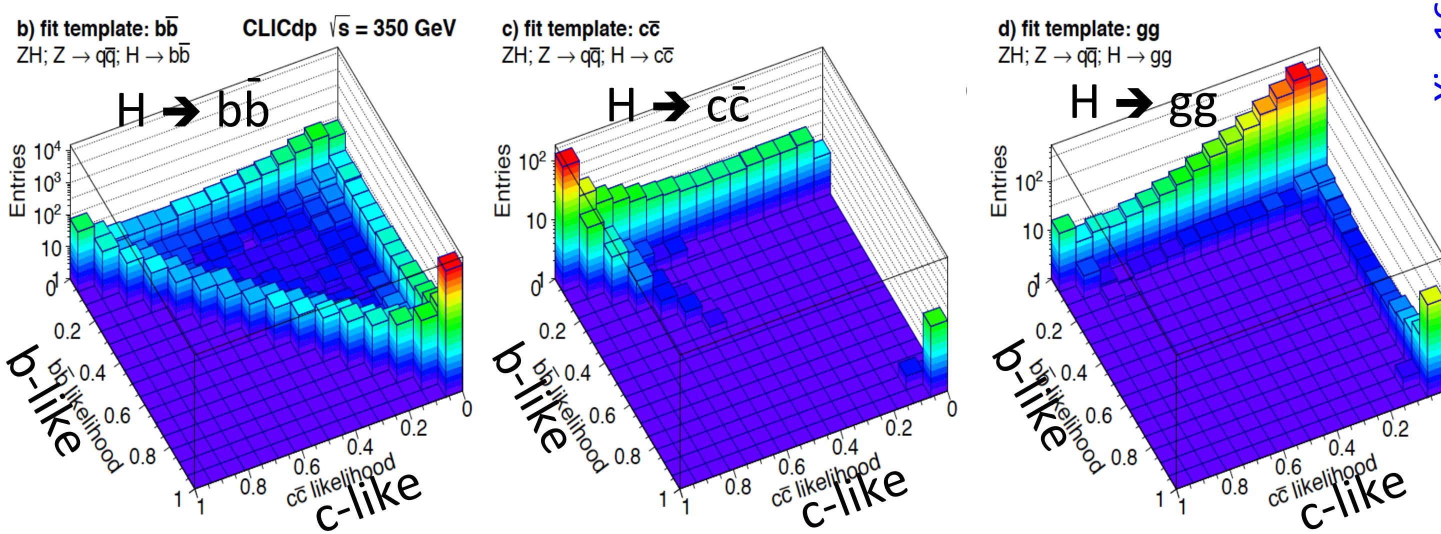
2jets+missing energy

also 2 jets + 2 leptons, and 4 jets



arXiv:1608.07538

- Train BDTs to classify events then fit templates

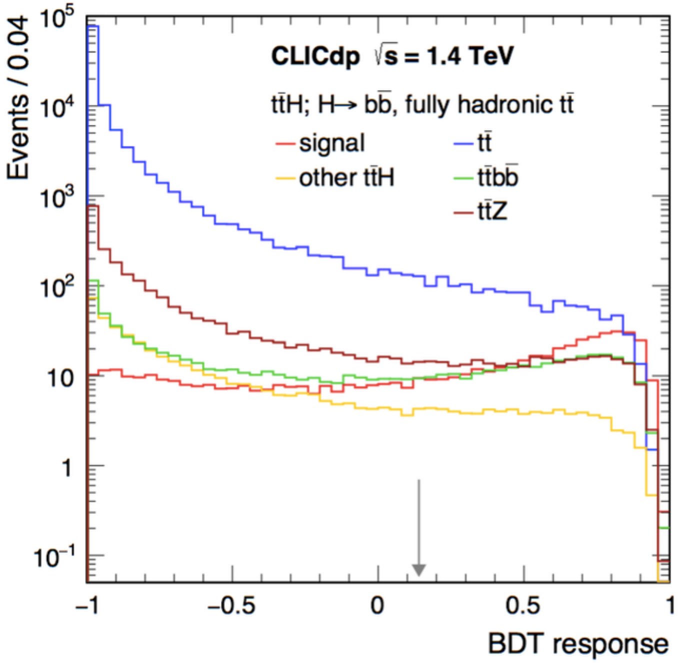


$\Delta(\sigma\times BR)_{SM}/(\sigma\times BR)_{SM}$ at 350 GeV, 500 fb^{-1}

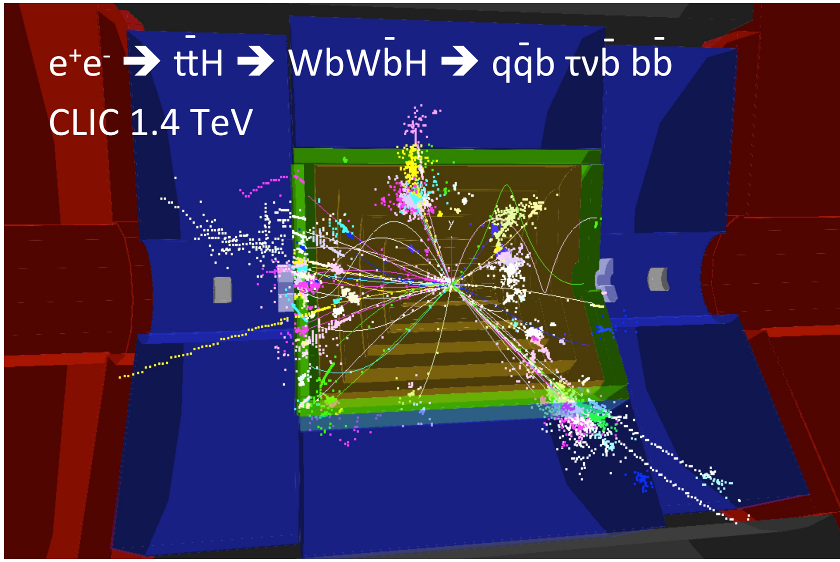
Decay	Statistical uncertainty Higgsstrahlung	Statistical uncertainty WW-fusion
$H \to b\bar{b}$	0.84 %	1.9 %
$H \to c\bar{c}$	10.3 %	14.3 %
$H \to gg$	4.5 %	5.7 %

top Yukawa & Higgs self-coupling

ttH:



Studied at 1.4TeV, 1.5ab^{-1}
– fully hadronic (8 jets)
– semi-leptonic (6 jets + lν)



combinatorics done by minimising χ^2 for W, t, H

BDT classifier trained

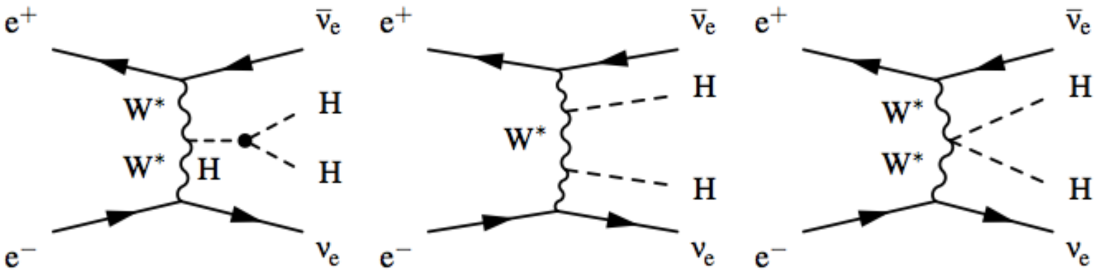
$\Delta\sigma(ttH)/\sigma$ = 8% translates to $\Delta g_{Htt}/g$ = 4.2% at 1.4TeV

(including effect of H radiating from intermediate Z)

Self-coupling:

Looking at HHνν -> bbbbνν
4-jet final state, require 4 b-tag jets

-> systematic studies of clustering and jet algorithm to optimize for energy flow



–> $\Delta\lambda/\lambda$ =22% from counting experiment at $\sqrt{s}$=3TeV (2ab^{-1})

Template fitting and simultaneous extraction of g_{HHWW} and g_{HHH} will improve precision (in progress)

Comprehensive Higgs studies

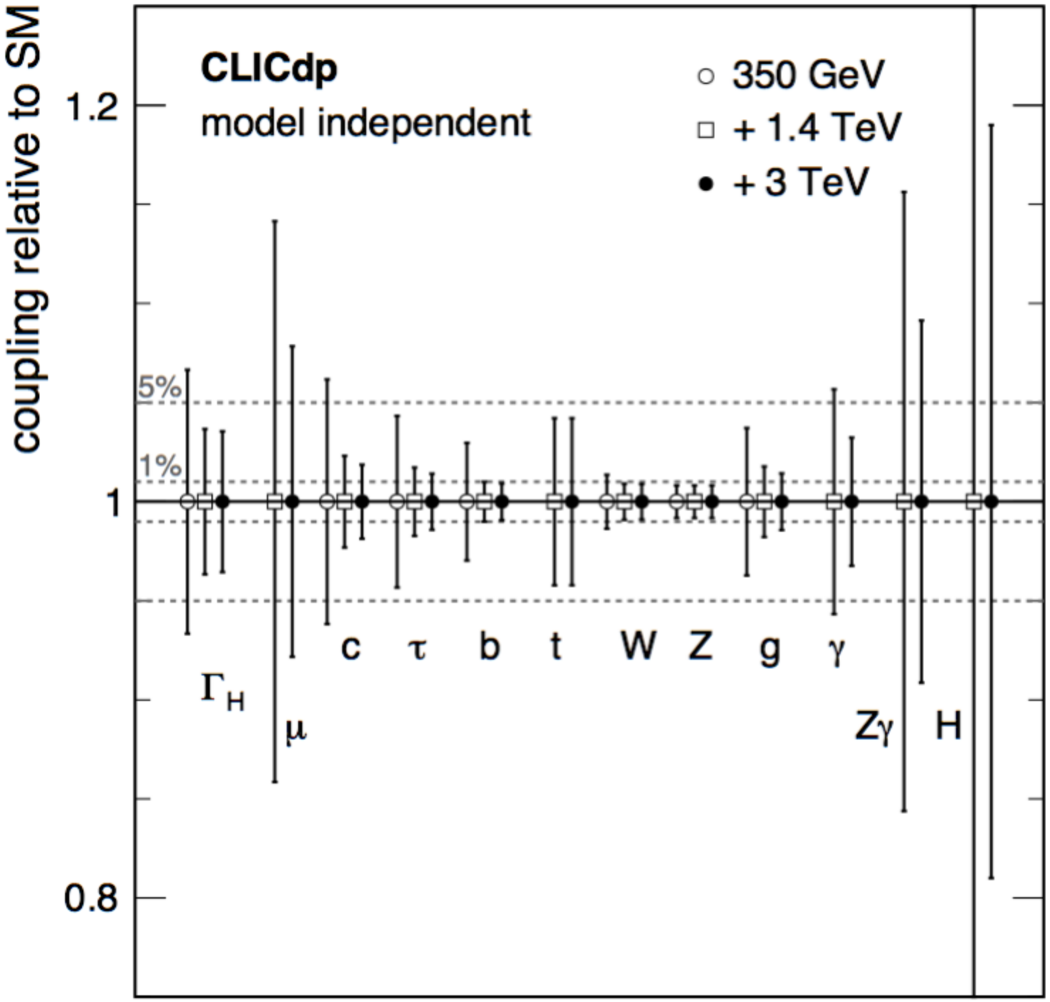
Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}
ZH	Recoil mass distribution	m_H	110 MeV
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6 %
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	3.8 %
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8 %
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	0.86 %
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ} g^2_{Hcc} / \Gamma_H$	14 %
ZH	$\sigma(ZH) \times BR(H \to gg)$		6.1 %
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau} / \Gamma_H$	6.2 %
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW} / \Gamma_H$	5.1 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	1.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	26 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		10 %

Channel	Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3 TeV 2.0 ab^{-1}
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	44 MeV
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	0.4 %	0.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	6.1 %	6.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0 %	4.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau} / \Gamma_H$	4.2 %	4.4 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	38 %	25 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15 %	10 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42 %	30 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW} / Γ_H	1.0 %	0.7 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ} / \Gamma_H$	5.6 %	3.9 %*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	1.8 %	2.3 %*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt} g^2_{Hbb} / \Gamma_H$	8 %	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	54 %	29 %
$HH\nu_e\bar{\nu}_e$	with −80 % e^- polarisation	λ	40 %	22 %

–> focus for ~3 years has been to measure many processes at all energy stages;
~20 individual analyses

- Combined fit of all the measurements
  –> extract fundamental parameters

Comprehensive Higgs studies

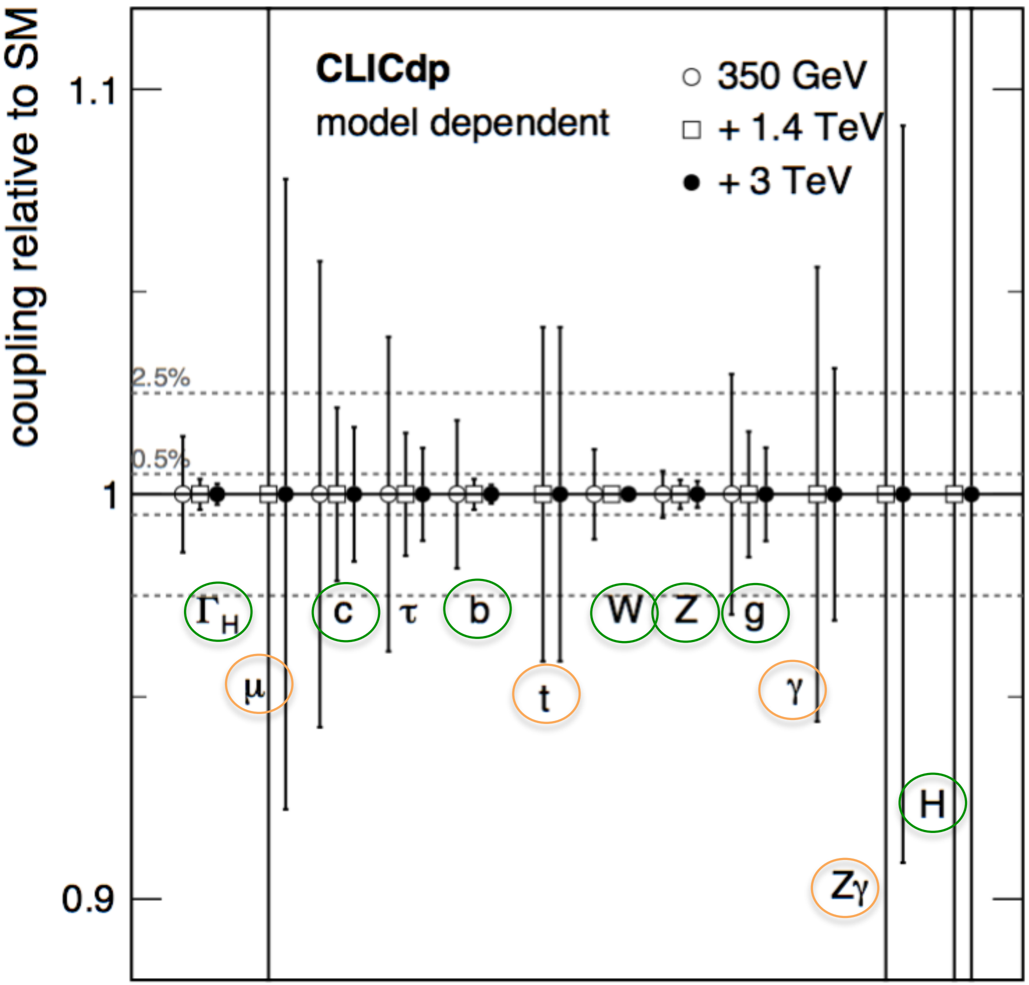


Each stage contributes significantly:
first stage provides crucial model-independent Z coupling measurement, and couplings to most fermions and bosons;
higher stages improve them, and add t, μ, γ couplings

- Large statistics at high energies allow unique measurements and high precision!

- Fully model-independent (possible only at a lepton collider), Γ_H free parameter
- All results limited by g_{HZZ} determination: 0.8% from σ(HZ) measurement
- Higgs width extracted with 6.7–3.5% precision

Comprehensive Higgs studies



'model-dependent' assumes fractional shift in κ is equal for u,c,t ; for d,s,b ; and for e,μ,τ ; and no Higgs decay to invisible/exotic particles

–> comparison with LHC projections

- sub-percent precisions at high energy

Precision significantly better than HL-LHC

Precision comparable to HL-LHC

- Comprehensive 'Higgs Physics at CLIC' paper arXiv:1608.07538 recently accepted by EPJC

- Now focusing on top and BSM physics

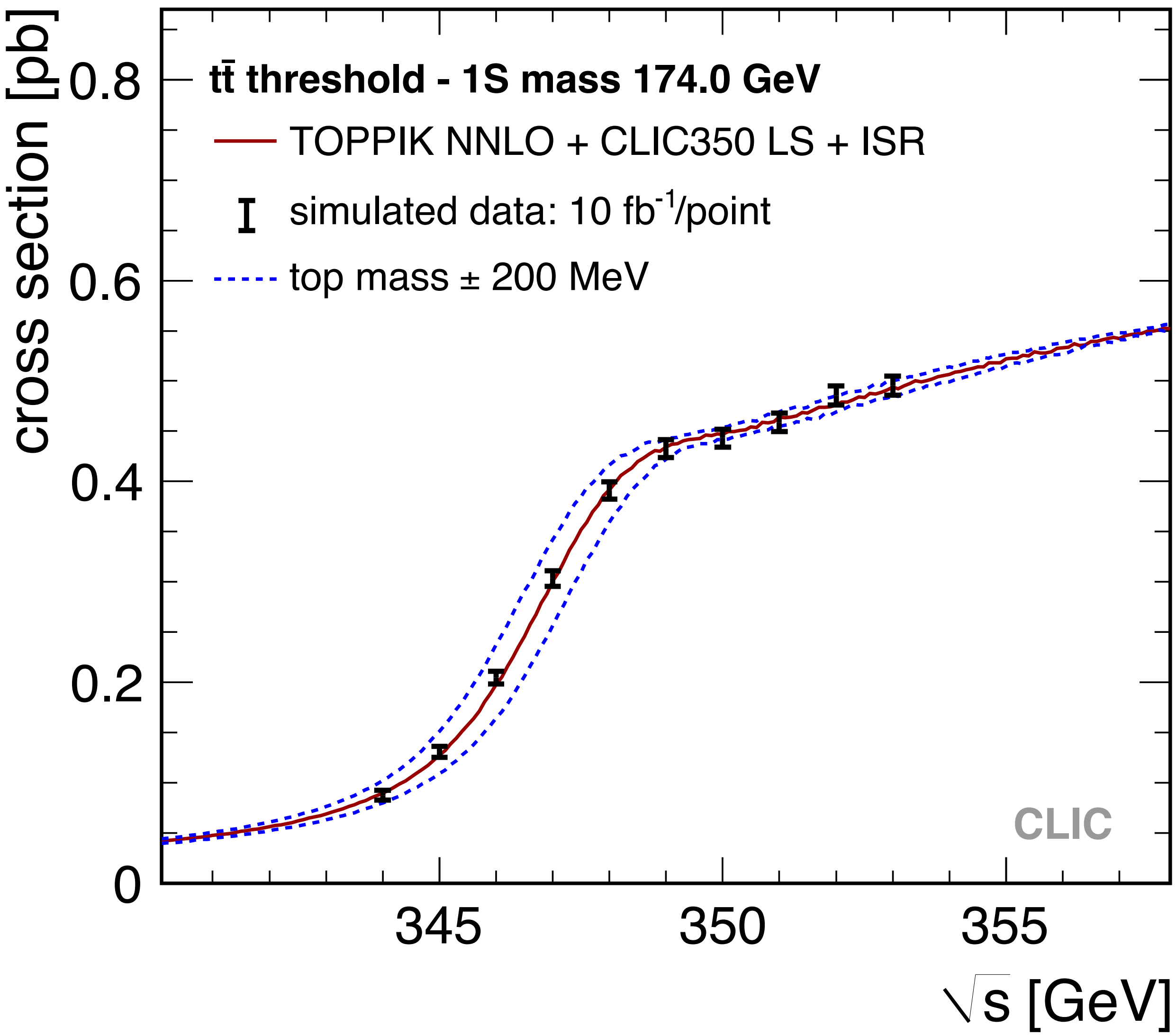
Higgs couplings – BSM sensitivity

example scenarios in which $M \sim 1$TeV for new particles

arXiv: 1310.8361

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%

Precision top physics



- Intending threshold scan around 350 GeV (10 points, ~1 year) as well as main stage 1 baseline √s=380GeV

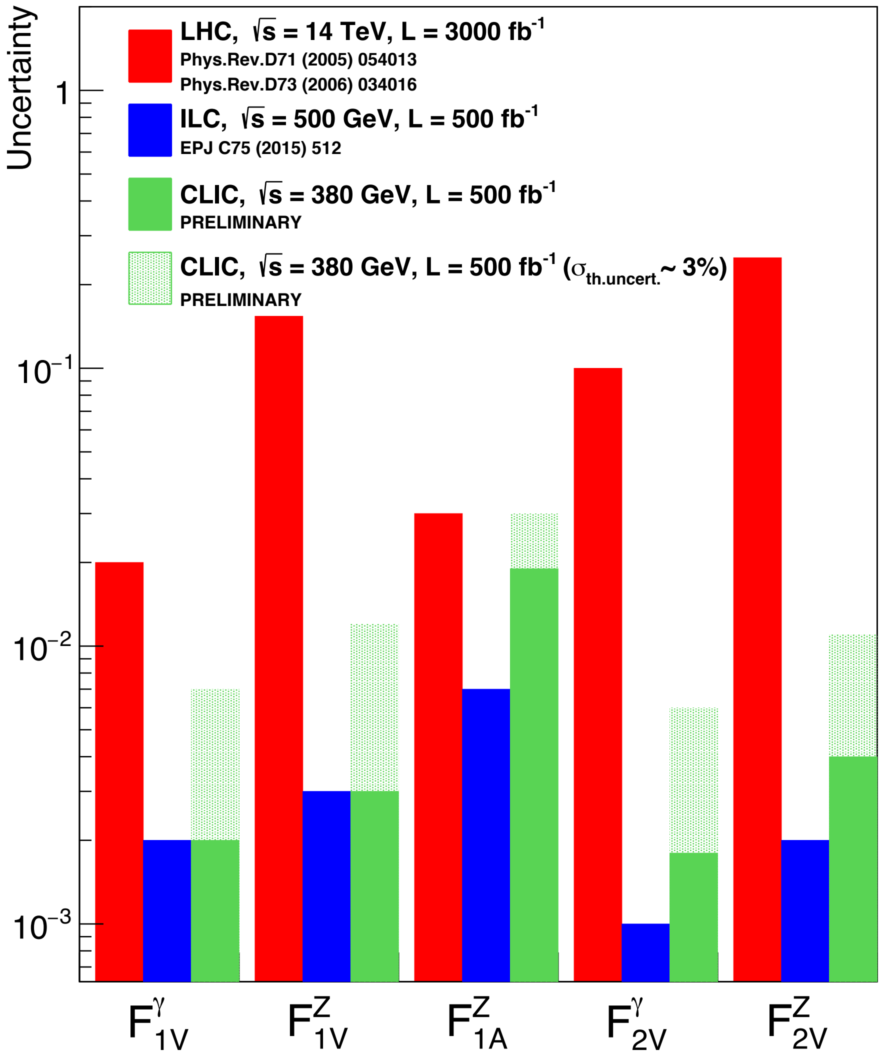
sensitive to top mass, width and couplings

observe 1S ‘bound state’
$\Delta m_t \sim 50$ MeV

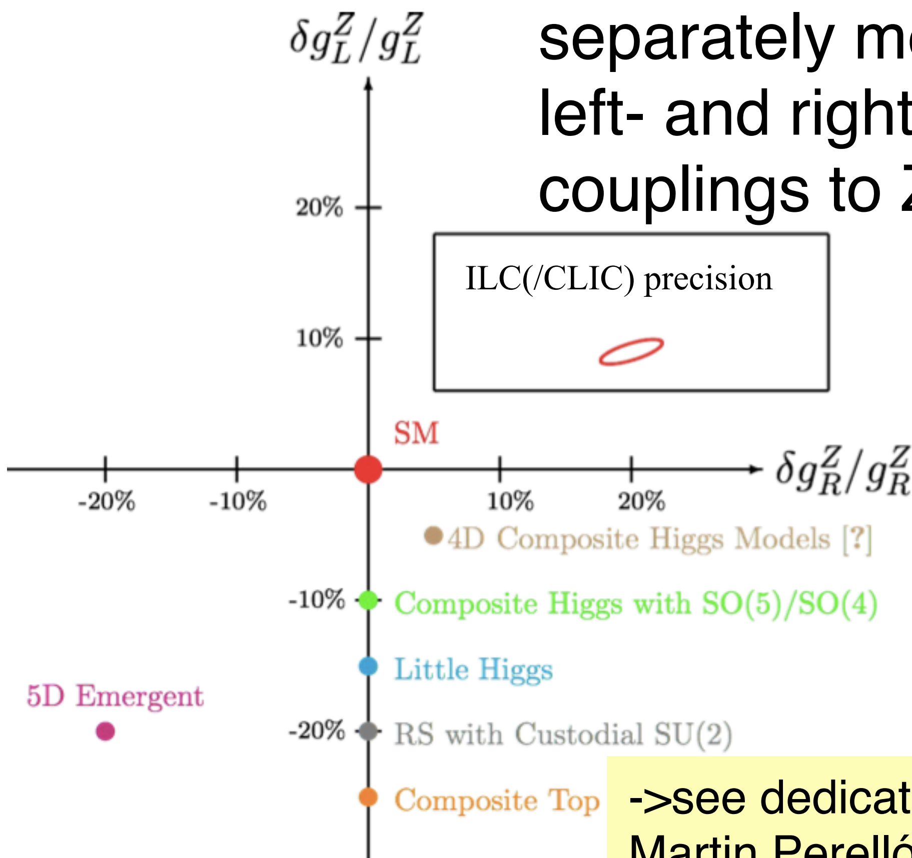
-> see dedicated threshold scan talk by Frank Simon parameterisation of ttX vertex

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

Vector Axial Tensorial CPV



separately measure left- and right-handed couplings to Z



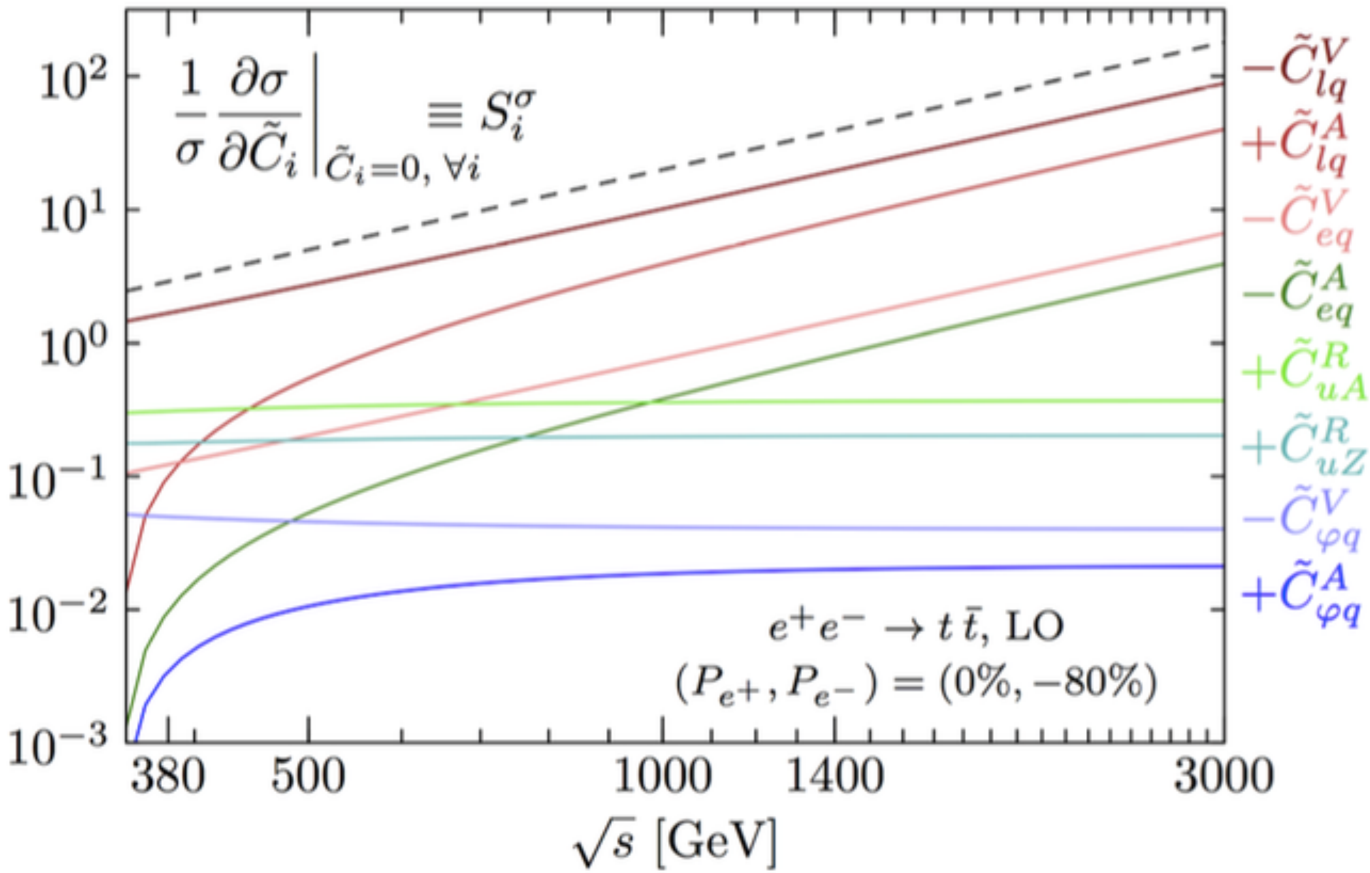
EPJ C (2015) 75:512

->see dedicated talk by Martin Perelló Roselló

-> sensitive to Higgs-sector resonance coupling to top; probes scales of ~25TeV in typical scenarios

Top physics at high energy

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



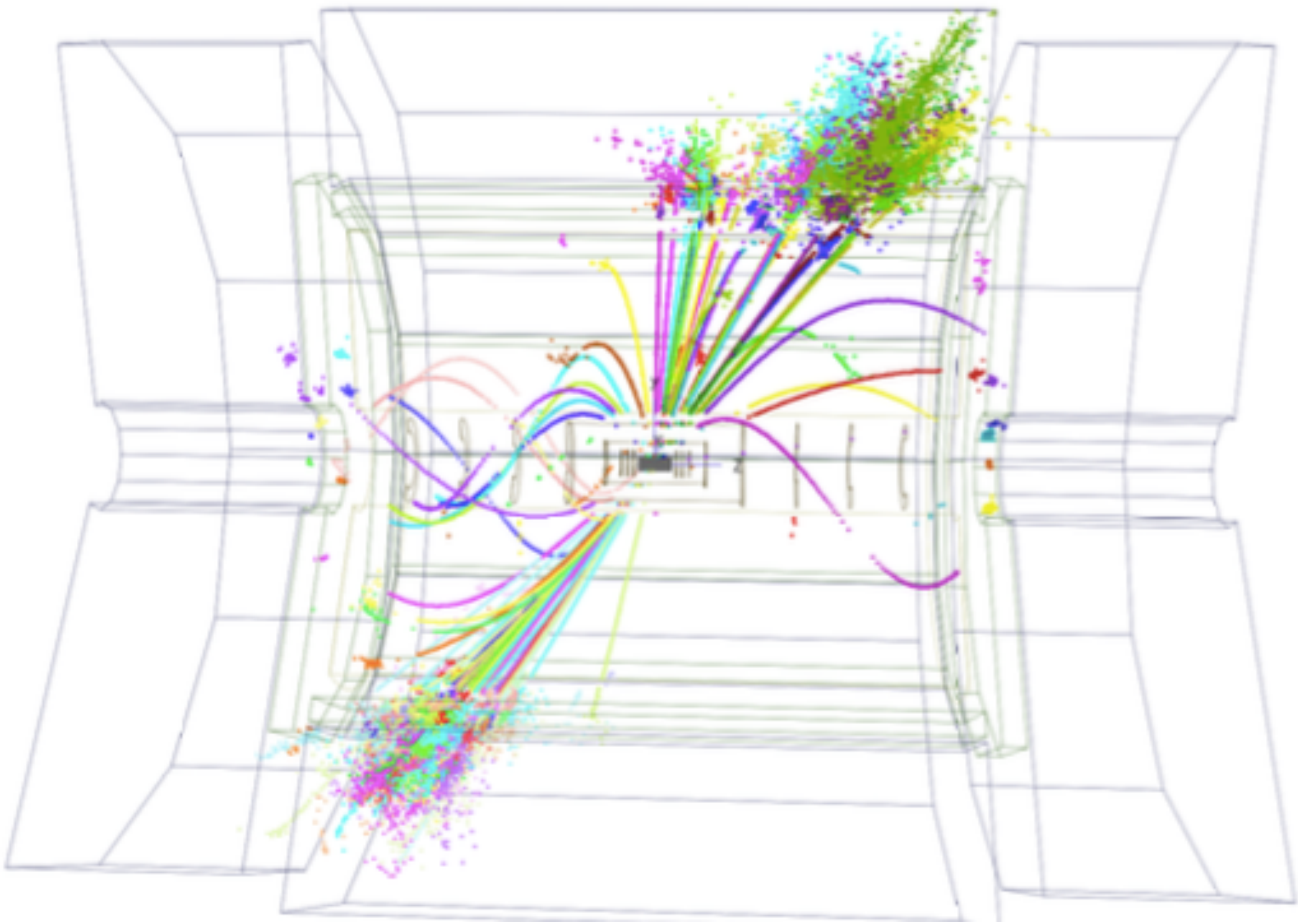
Four-fermion operators: sensitivity rises steeply with energy -> best measured at high energy

Vertex operators: sensitivity flat in energy for several operators -> best measured at 380 GeV where there are most events

Durieux, Perello, Vos, Zhang, to be published

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

Boosted top reconstruction



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

Hadronic decays of high-energy top quarks do not lead to 3 separated jets

-> identify substructure compatible with $t \to Wb \to qqb$ inside 'large' jet

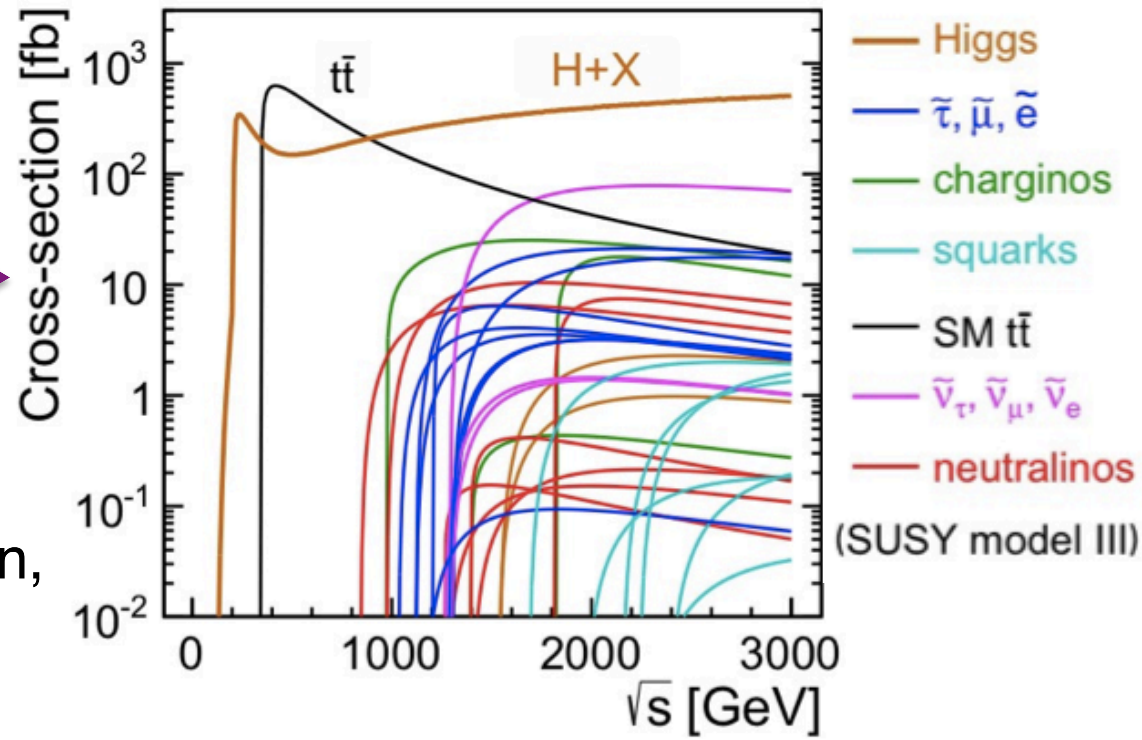
– active effort for CLIC

-> see dedicated boosted reconstruction talk by Rickard Ström

Direct BSM

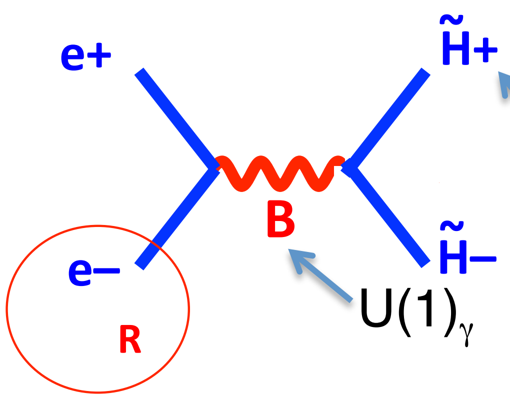
1. Pair production of new particles for $M < \sqrt{s}/2$:

Example: 'SUSY model III'



Wider applicability than just SUSY: classify reconstructed particles simply as states of given mass, spin, and quantum numbers

Polarized beams -> decomposition:



Only $\tilde{H}^\pm$ components of $\tilde{\chi}_1^\pm$ contribute

$$\tilde{\chi}_1^\pm = \alpha \tilde{W}^\pm + \beta \tilde{H}^\pm$$

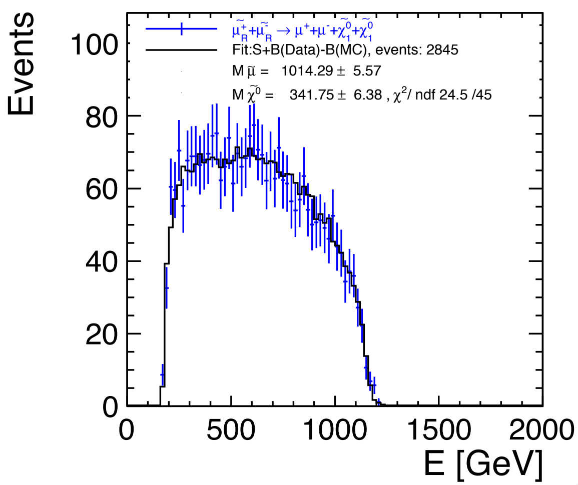
2. Rare FCNC top decays:

t->cH, t->cγ

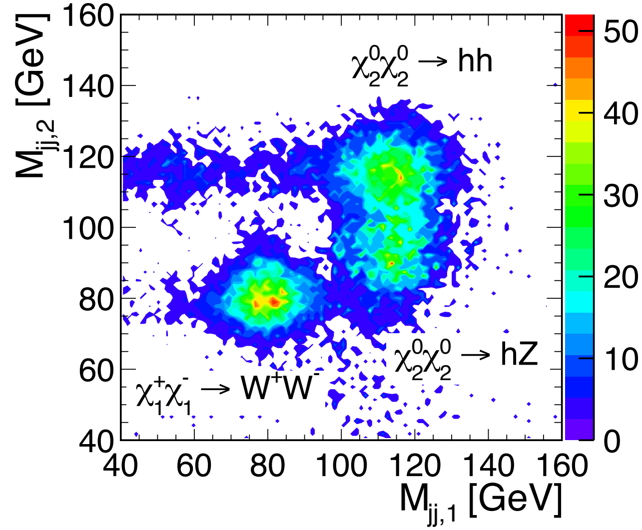
->see dedicated talks by Filip Zarnecki and Naomi van der Kolk

Direct BSM

3. Endpoints:



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



Precision on gaugino masses: 1–1.5% for few hundred GeV

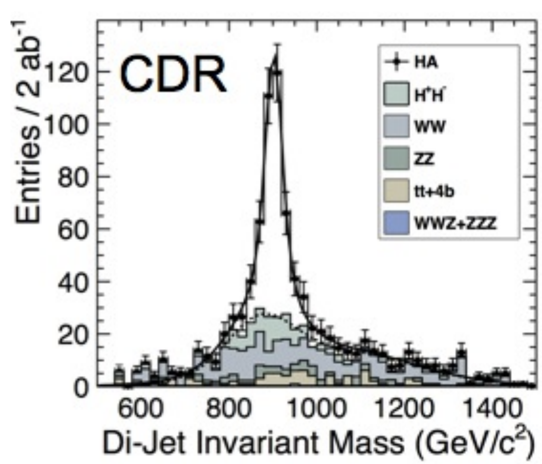
$$e^+e^- \rightarrow \tilde{\chi}_1^+\,\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\,\tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow hh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$
$$e^+e^- \rightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \rightarrow Zh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

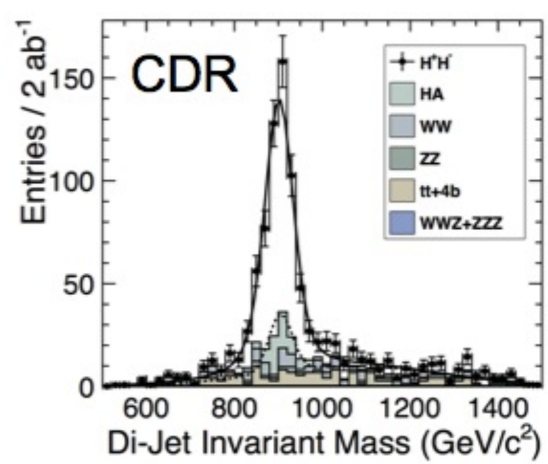
4. Complex final states:

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

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

~0.3% precision on heavy Higgs masses





Direct BSM

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

-> react on new discoveries

Indirect BSM

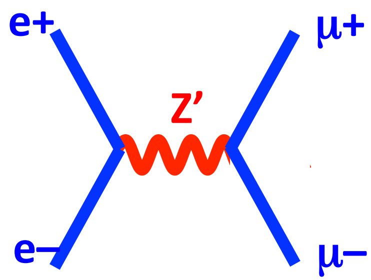
Precision studies of $e^+e^- \to \mu^+\mu^-$

e.g. minimal anomaly-free Z' model

Observables:

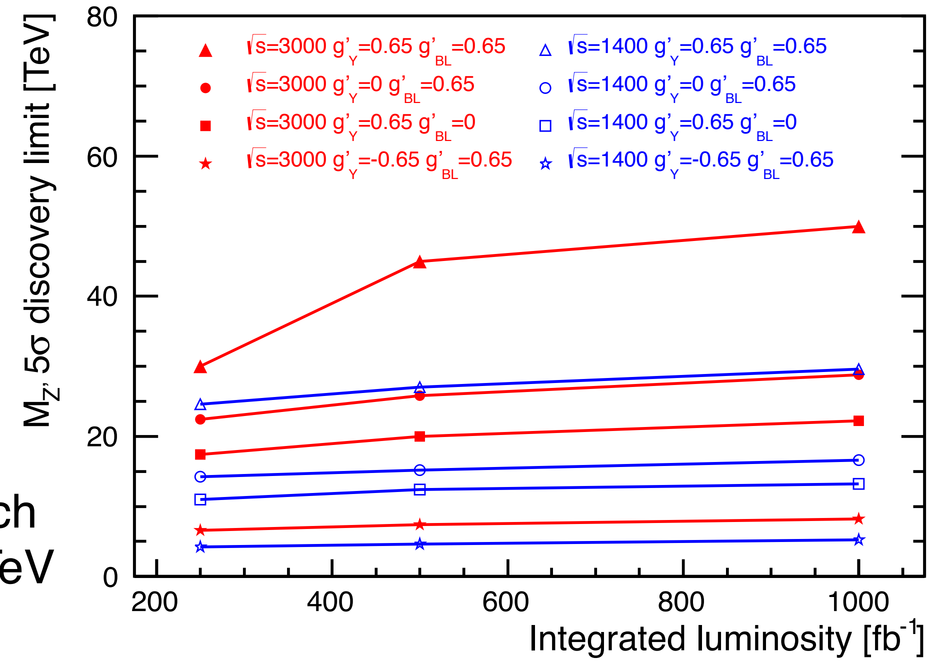
- total $e^+e^- \to \mu^+\mu^-$ cross-section
- forward–backward asymmetry
- left–right asymmetry

(±80% electron polarization)



Either: precise measurements of effective couplings following multi-TeV LHC discovery

Or: discovery reach up to tens of TeV

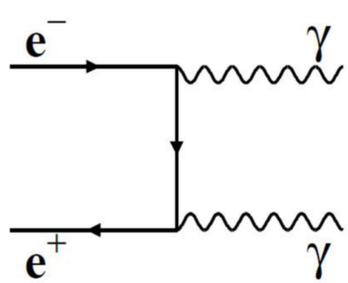


Precision studies of $e^+e^- \to \gamma\gamma$

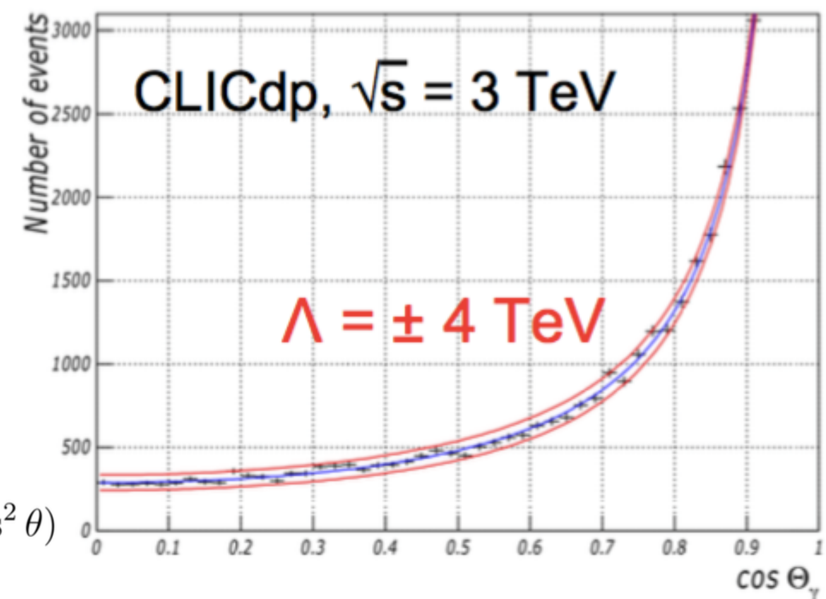
Unique to lepton colliders, CLIC at 3TeV around 25 times more sensitive than LEP2

$\Lambda > 6 - 6.3$TeV (or electron size less than 3×10^{-18}cm)

also interpreting as limits on contact interactions, extra dimensions, ...



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



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

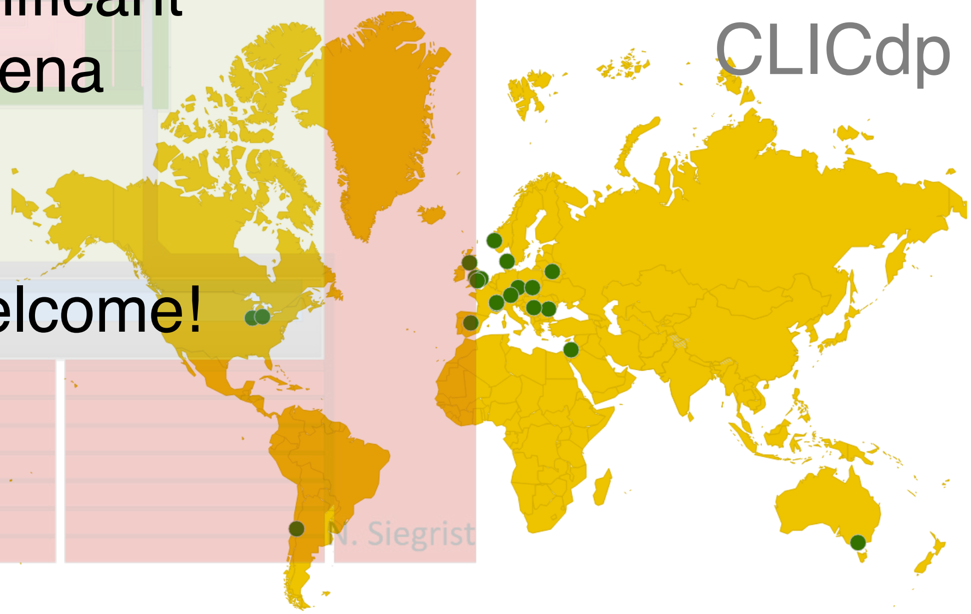
2035 First Beams

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

Summary

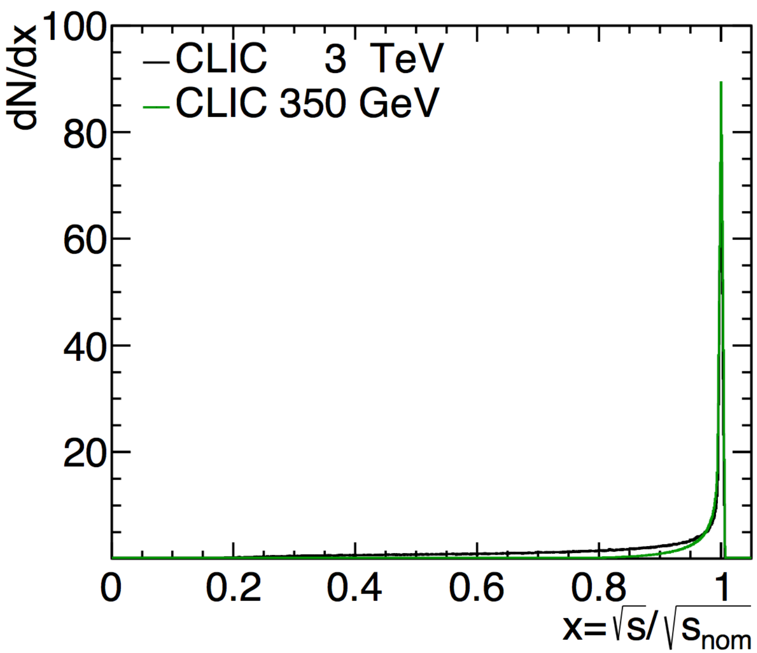
- CLIC accelerator in advanced state of development, and detector concept mature to present as a credible post-LHC option for CERN
- Presenting optimized, staged approach with costs and power not excessive compared with LHC:
  - –First energy stage provides precise measurements of many Higgs couplings, improved by subsequent high-energy running; comprehensive studies are complete
  - –High-energy running provides significant discovery potential for BSM phenomena
- Physics studies are ongoing
- New CLICdp collaborators are welcome!

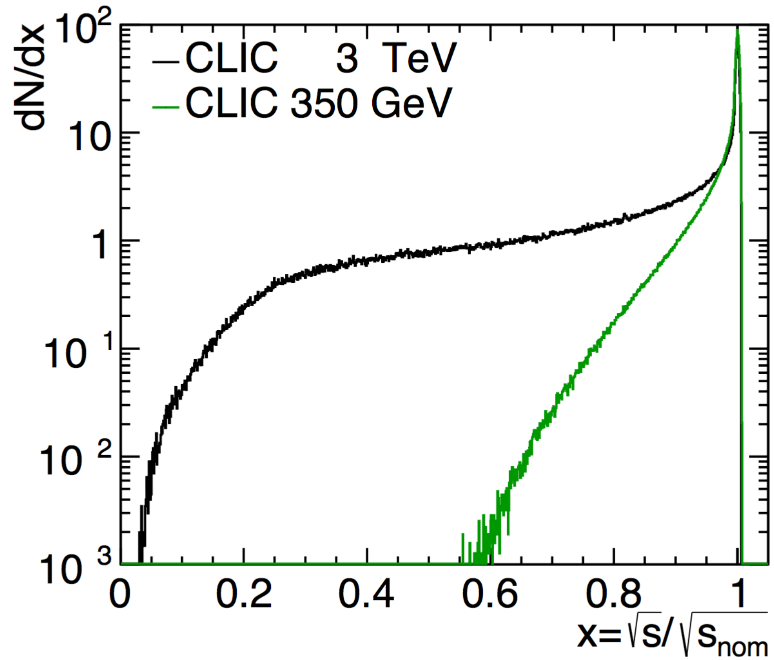
  http://clic-study.web.cern.ch
  http://clicdp.web.cern.ch



Backup

Luminosity spectrum





Beamstrahlung ➔ important energy losses right at the interaction point

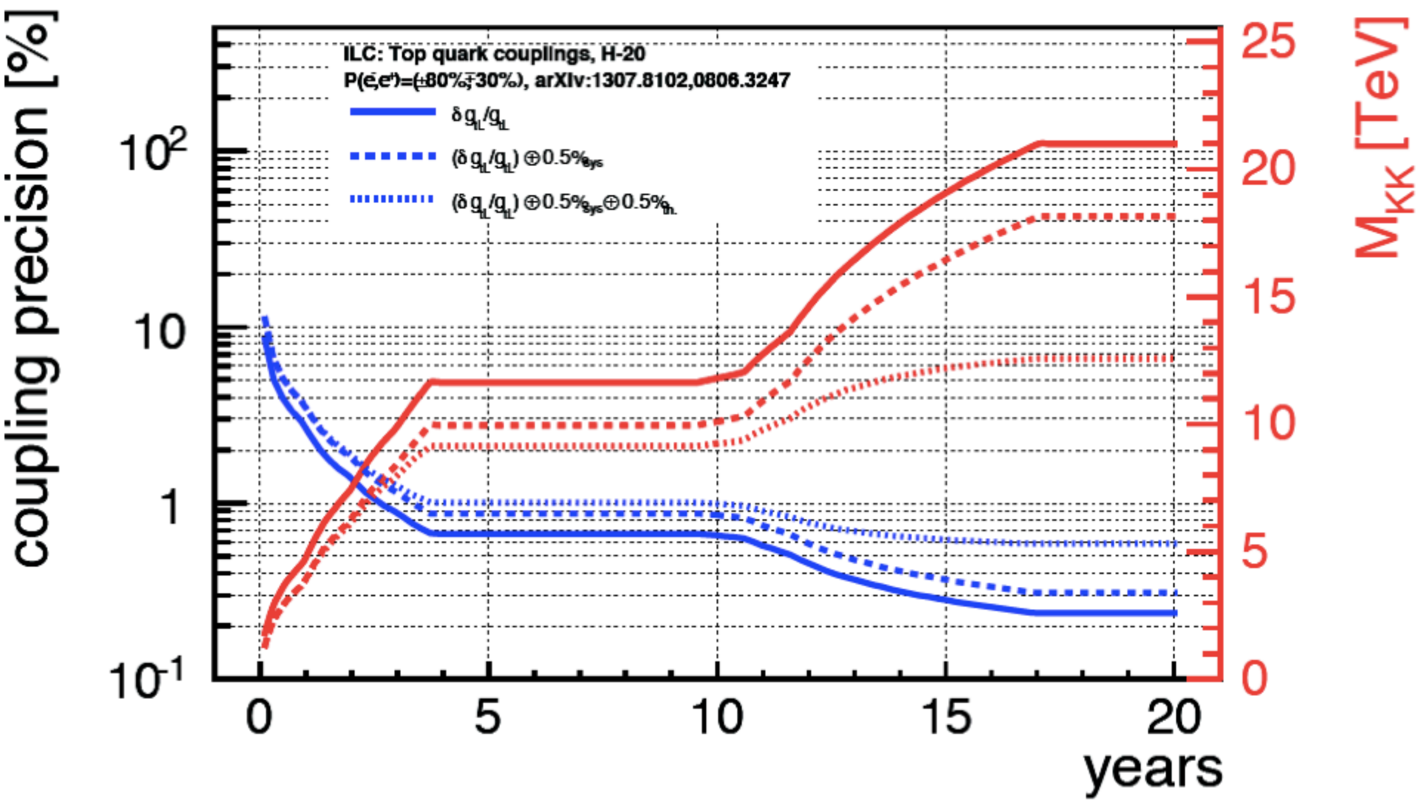
Most physics processes are studied well above production threshold => profit from full spectrum

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]

Fraction $\sqrt{s}/\sqrt{s_{nom}}$	350 GeV	3 TeV
>0.99	68%	36%
>0.9	95%	57%
>0.8	99.1%	68%
>0.7	99.9%	77%
>0.5	~100%	88%

Precision top physics

Sensitive to Higgs-sector resonance coupling to top;
probes scales of ~25TeV in typical scenarios



For ILC scenarios; similar analysis in progress for CLIC

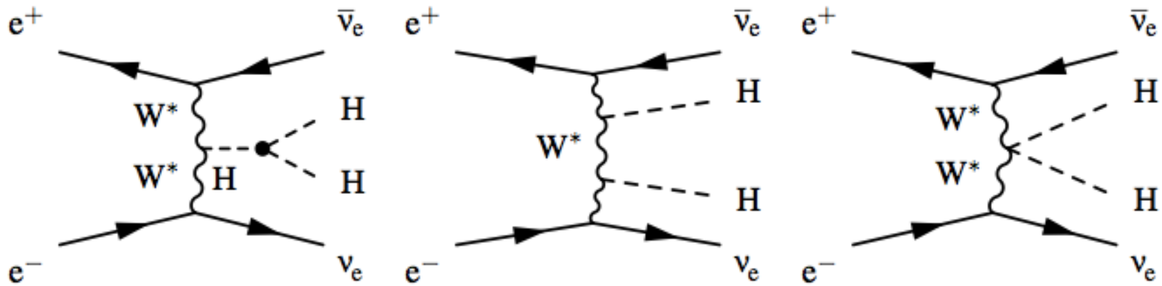
The impact of four-fermion operators increases strongly with √s

H20: 500/fb @ 500 GeV, 200/fb @ 350 GeV, 500/fb @ 250 GeV, 3500/fb @ 500 GeV, 1500/fb @ 250 GeV

Based on phenomenology described in Pomerol et al. arXiv:0806.3247

Higgs self-coupling and mass

Self-coupling:



Looking at HHνν -> bbbbνν
4-jet final state, require 4 b-tag jets

-> systematic studies of clustering and jet algorithm to optimize for energy flow

–> $\Delta\lambda/\lambda$ =22%
from counting experiment
at $\sqrt{s}$=3TeV (2ab^{-1})

Template fitting and simultaneous extraction of g_{HHWW} and g_{HHH} will improve precision (in progress)

Higgs mass:

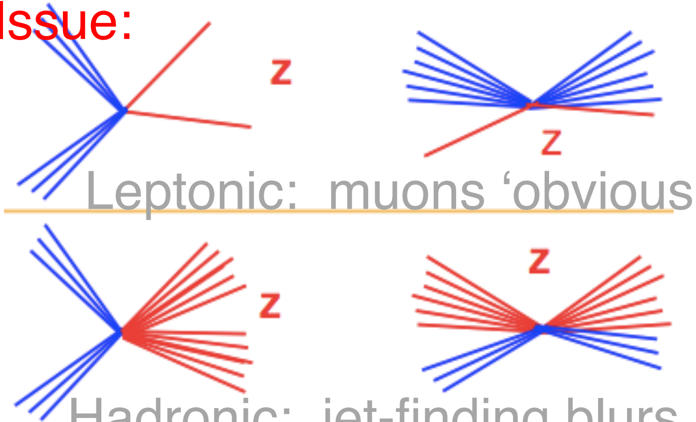
Dataset	Δm_H unpolarised	Δm_H p(e–)
1.4 TeV	47 MeV	35 MeV
3 TeV	44 MeV	33 MeV
1.4 + 3 TeV	32 MeV	**24 MeV**

HL-LHC projection:
Δm_H = 50 MeV   arXiv:1310.8361

Hadronic events in recoil analysis

at $\sqrt{s}$ above ZH cross-section peak: leptonic recoil does not provide required precision
–> can sensitivity be recovered using ***hadronic*** Z decay?

Issue:



Leptonic: muons 'obvious'

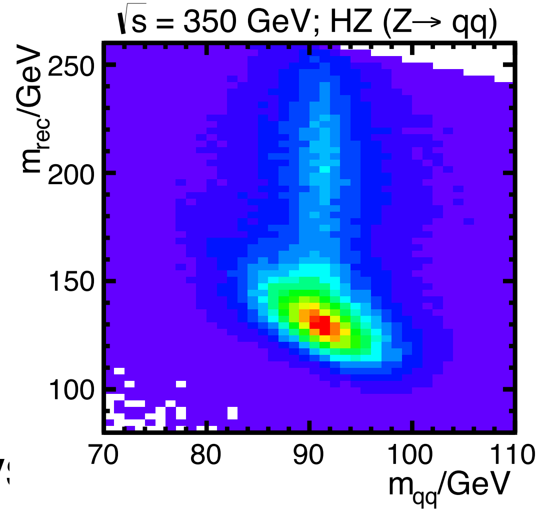
Hadronic: jet-finding blurs separation between H and Z

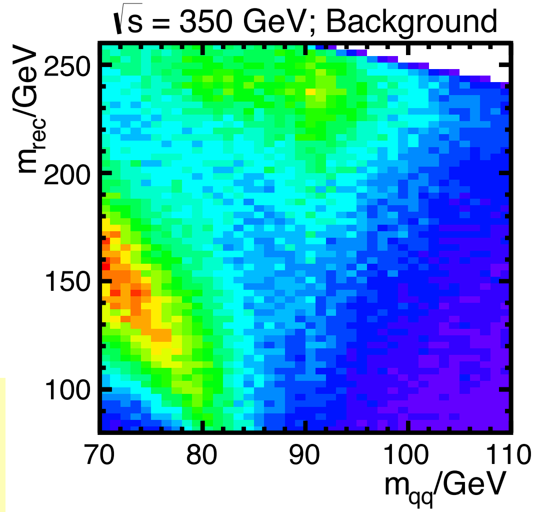
-> different efficiencies for different Higgs decays – can it be made model-independent?

-> YES ;

consider events as candidate invisible or visible Higgs decays
reconstruct visible Higgs candidates as 4 or 5 "jets"

use m_{qq} and m_{recoil} in likelihood separator





2 jets from Z->qq, plus Higgs decay

- H→qq : 2 jets = 4 'objects' to reconstruct
- H→γγ : 2 photons = 4 'objects'
- H→ττ : 2 taus = 4 'objects'
- H→WW*→lνlν : 2 leptons = 4 'objects'
- H→WW*→qqlν : 2 jets + lepton = 5 'objects'
- H→WW*→qqqq : 4 jets = 6 'objects'
- H→ZZ*→ννqq : 2 jets = 4 'objects'
- H→ZZ*→qqll : 2 jets + 2 leptons = 6 'objects'
- H→ZZ*→qqqq : 4 jets = 6 'objects'

$\Delta\sigma_{HZ}$ ~ 4.2% for Z->ll
$\Delta\sigma_{HZ}$ ~ 1.8% for Z->qq
Δg_{HZZ} ~ 0.8% including all channels

arXiv: 1509.02853

Higgs production