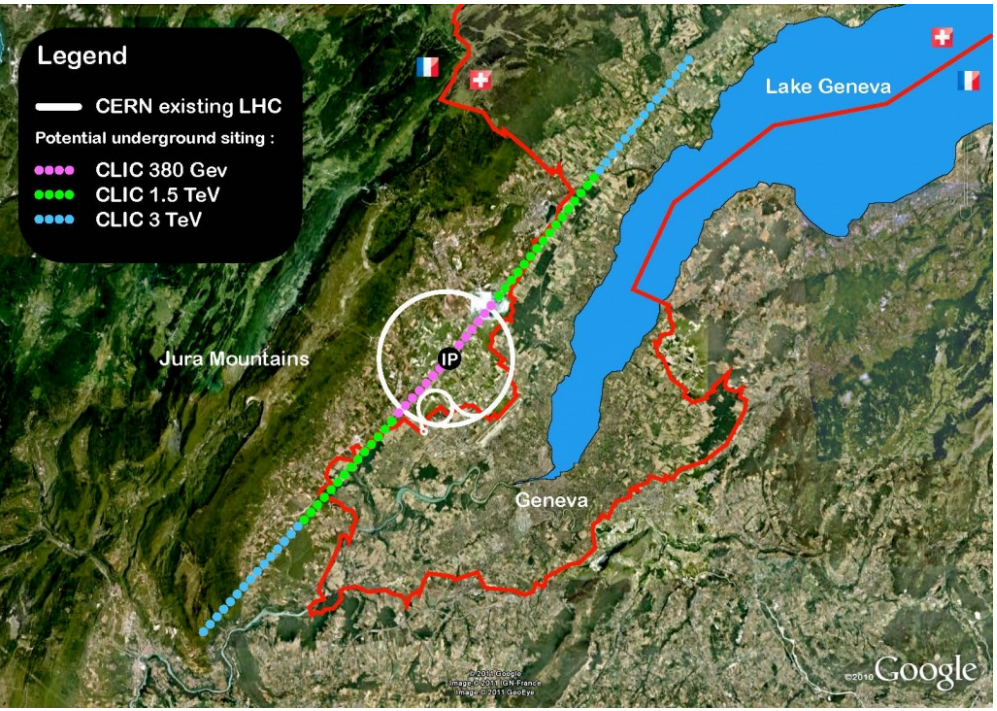
BSM physics at CLIC

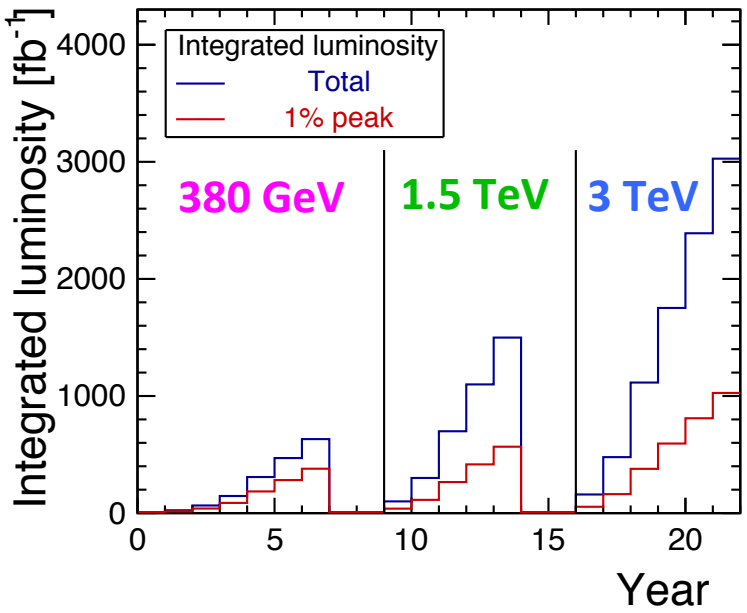
Rosa Simoniello (CERN)
On behalf of the CLICdp collaboration

ICHEP, Chicago
3-11 August 2016

The Compact Linear Collider (CLIC)

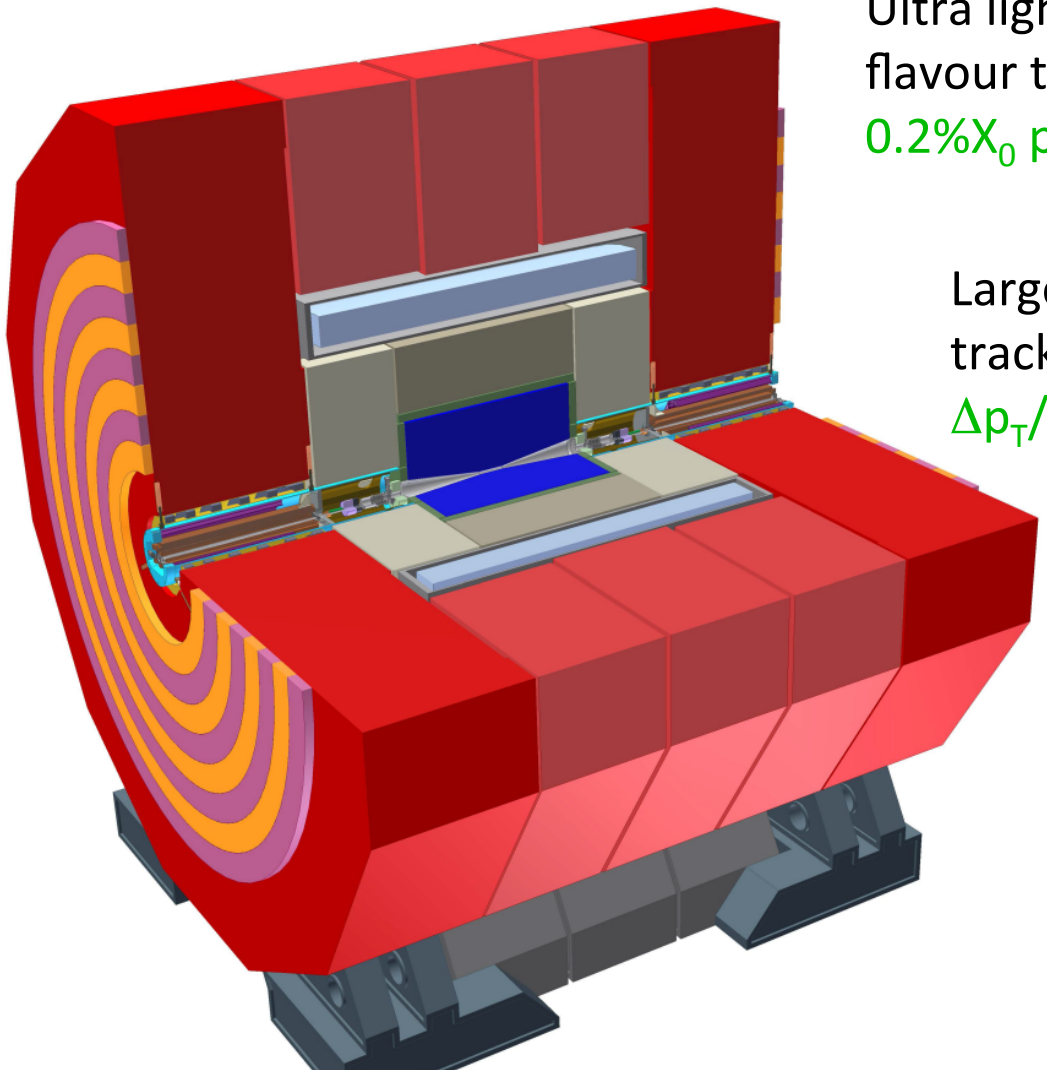


"Updated baseline for a staged Compact Linear Collider" → soon available as CERN Yellow Report



- 2-beam acceleration scheme with 100 MV/m gradient at room temperature
- Physics program over 20 years:
  - √s = 380 GeV: precision Higgs and top physics → *S. Lukic's talk*
  - √s = 1.5 TeV: *BSM* and rare Higgs decays → *A.F. Zarnecki's talk*
  - √s = 3 TeV: *BSM* and rare Higgs decays
- Stages can be re-defined in case of discoveries at LHC

Detector requirements



Ultra light vertex detector with excellent flavour tagging performance

$0.2\%X_0$ per single layer, 3 μm resolution

D. Dannheim's talk

Large and light tracker with excellent track momentum resolution

$\Delta p_T/p_T^2 \sim 2 \cdot 10^{-5}$ GeV^{-1}

Highly granular calorimeters designed for particle flow

$\Delta E_j/E_j \sim 3\text{-}5\%$

High forward coverage for electromagnetic physics objects down to 10 mrad

- 2 detailed detector models based on ILC concepts: different technology choices

CLIC BSM physics program

- Large physics potential + complementary to LHC
  - More sensitive to *electroweak processes*
  - Very rare processes accessible due to *low level of backgrounds*
  - *Beam polarisation* can enhance analyses sensitivity → not always included in the results in this talk

Direct searches *(SUSY, Dark Matter, Hidden Valley, etc…)*

- Possible direct observation of new phenomena and corresponding precision properties measurement
- Accessible up to the kinematic limit of 3 TeV

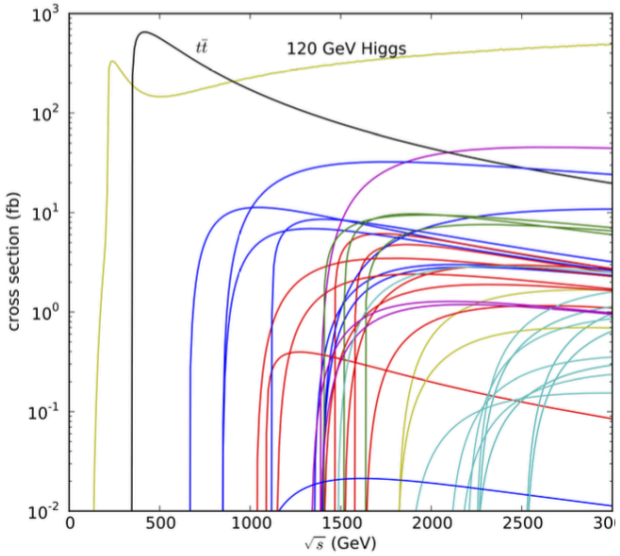
Indirect searches *(ee → γγ, vector boson scattering, etc…)*

- Precision measurements – possible deviation from SM prediction
- Possibility to reach higher energy probes, tens of TeV

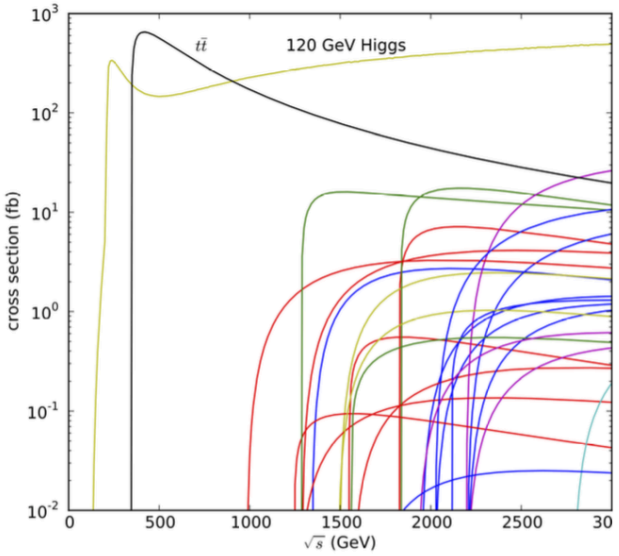
CLIC benchmark analyses chosen to emphasize the potential physics reach and to demonstrate key aspects of the detector performance

DIRECT SEARCHES

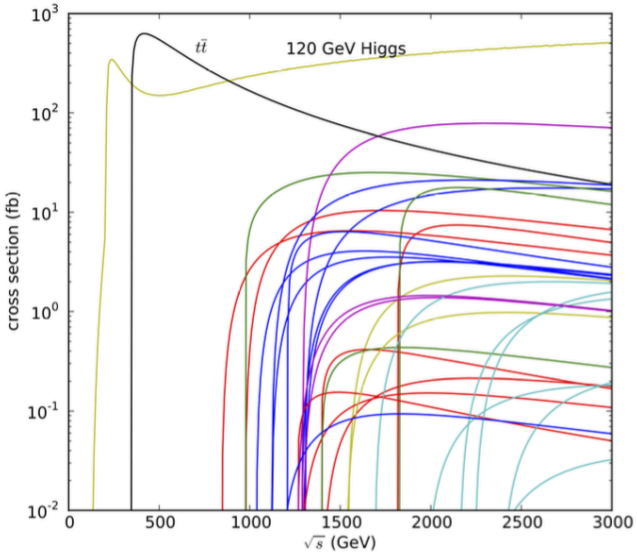
SUSY models



Model I, 3 TeV
- Squarks
- Heavy Higgs



Model II, 3 TeV
- Smuons, selectrons
- Gauginos



Model III, 1.4 TeV
- Smuons, selectrons
- Stau
- Gauginos

Higgs
$\tilde{\tau},\tilde{\mu},\tilde{e}$
charginos
squarks
SM
$\tilde{\nu}_{\tau},\tilde{\nu}_{\mu},\tilde{\nu}_{e}$
neutralinos

Wide range of mass, spin and quantum numbers tested
→ wider applicability than only SUSY

SUSY results

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass $\tilde{\chi}_1^0$ mass	1010.8 340.3	0.6% 1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass $\tilde{\chi}_1^0$ mass	1010.8 340.3	0.3% 1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass $\tilde{\chi}_1^\pm$ mass	1097.2 643.2	0.4% 0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$ $\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$	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	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass $\tilde{\chi}_1^0$ mass	560.8 357.8	0.1% 0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass $\tilde{\chi}_1^0$ mass	558.1 357.1	0.1% 0.1%
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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%
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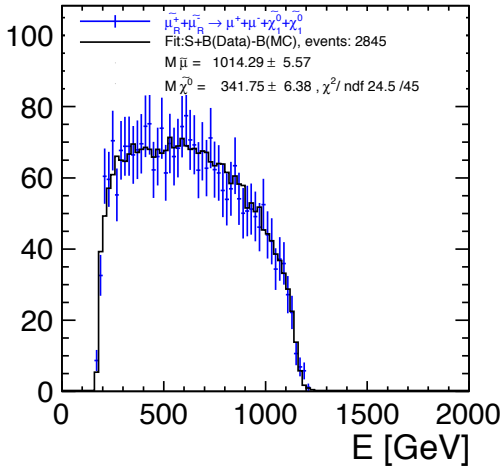
SUSY results

Mass from endpoint of energy spectra



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				$\tilde{\chi}_1^0$ mass	357.8	0.1%
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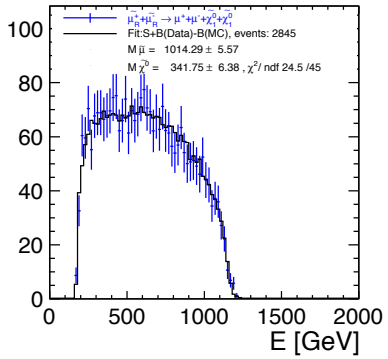
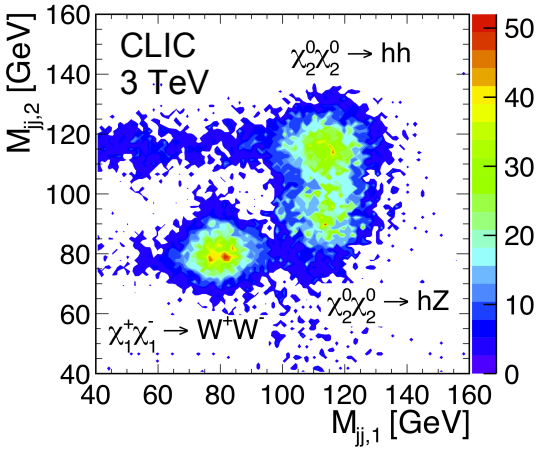


Final state discrimination



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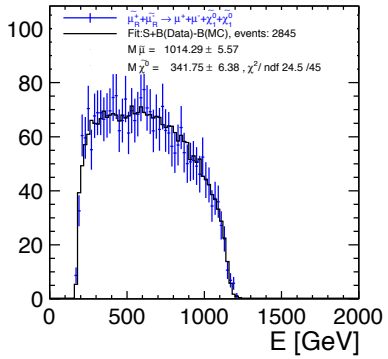

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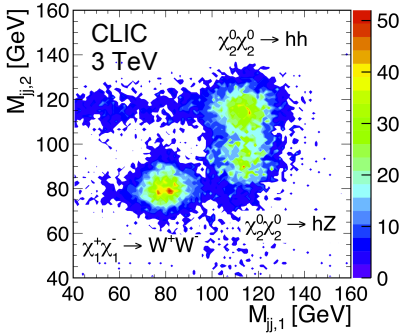
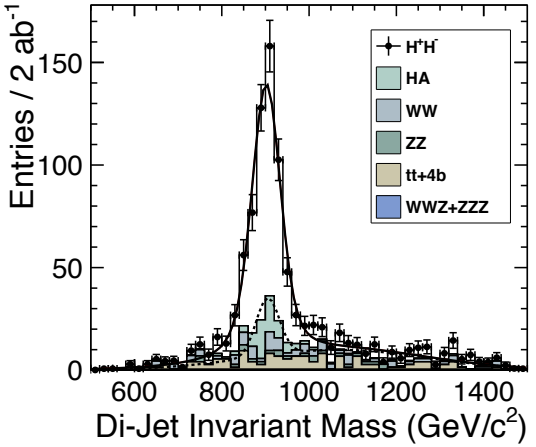


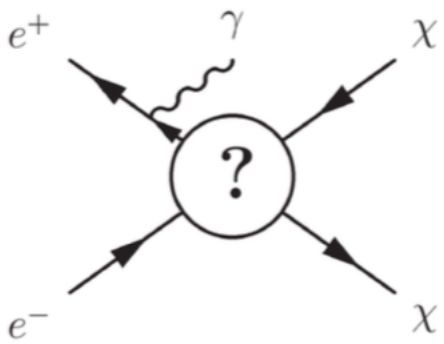
Complex final state



Dark Matter

- ~25% of the universe made up by Dark Matter
- Search for direct *WIMP production*
  - Assumption of weak interaction with SM
  - SUSY only one of the interpretation
- Identify events asking for *single photon + E_T^{miss}*
- Main backgrounds:
  ee → ννγ (irreducible),
  ee → eeγ, ee → $\gamma\gamma$
  → forward e/γ identification is crucial
- Assuming similar energy distribution between signal and SM background, the total *systematic error* (theory, luminosity, γ id, $e^{\pm}$ veto) is larger than the statistical error
- Detail studies using full detector simulation on-going

ee → γ + E_T^{miss}

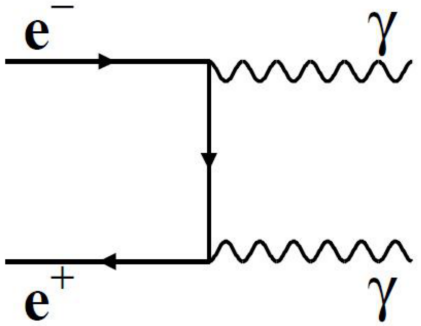


Statistical error	$6 \cdot 10^{-4}$
Systematic error	
$\Delta\varepsilon_{id}(\gamma)/\varepsilon_{id}$	10^{-2}
$\Delta\varepsilon_{veto}(e^{\pm})/\varepsilon_{veto}$	10^{-2}
$\Delta L/L$	$5 \cdot 10^{-4}$
$\Delta\sigma_{th}/\sigma_{th}$	10^{-3}

INDIRECT SEARCHES

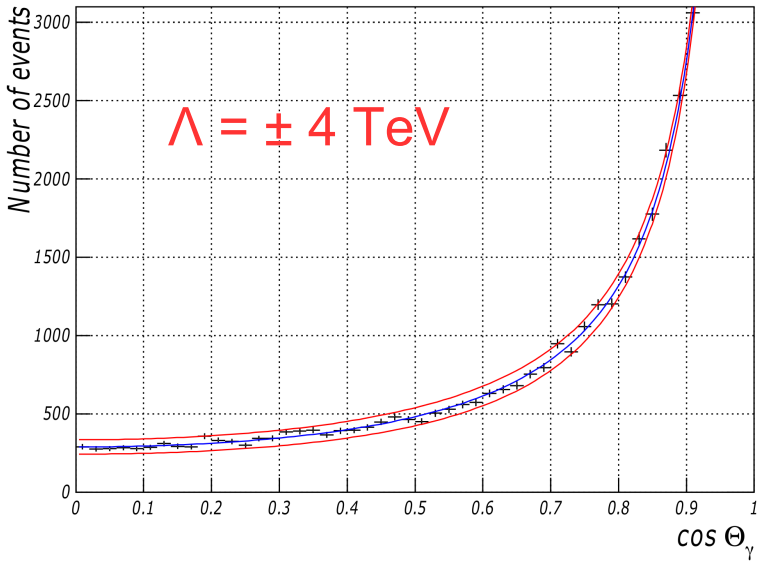
$e^+e^- \rightarrow \gamma\gamma$: test of QED

- Possible deviation between measured and predicted QED cross-sections and angular $\gamma\gamma$ spectrum can be used to *test extension of the QED* (*finite electron size, extra dimension, mass of excited electrons, …*)



- Finite electron size → energy cut-off Λ

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



- Events with small energy loss due to Beamstrahlung and ISR are selected
  → *two back-to-back photons*
  (veto on 3rd γ with E>50 GeV)

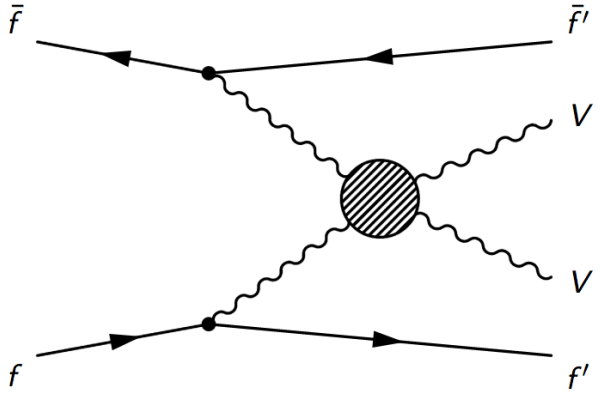
- Main backgrounds:
  ee → ee, eγ → eγ
  → e-γ identificaton in the forward region is crucial

Fit result: Λ > 6.33 TeV
(or electron size < 3.1 x 10^{-18} m)

Combined LEP data: Λ > 431 GeV
(or electron size < 4.6 x 10^{-17} m)

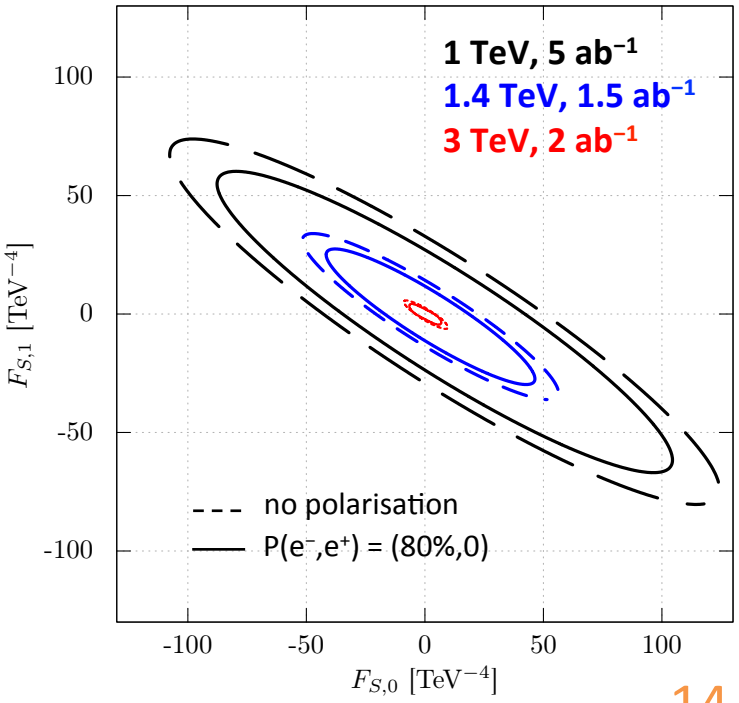
Vector boson scattering: test of EWSB

- Vector boson scattering provides an important test of the electroweak symmetry breaking
  → *sensitive to new physics in the Higgs sector*
- Search for *additional resonances* and *anomalous quartic gauge boson couplings*
- Deviations from the SM parametrised in terms of 2 parameters: couplings (F_{S0}, F_{S1})



in this analysis VV = WW or ZZ

- Study done at generator level with separation of hadronic Z and W decays from full simulation
- Main backgrounds:
  ee → WWνν (irreducible),
  ee → WWee, ee → WZeν
  → forward electron tagging is crucial

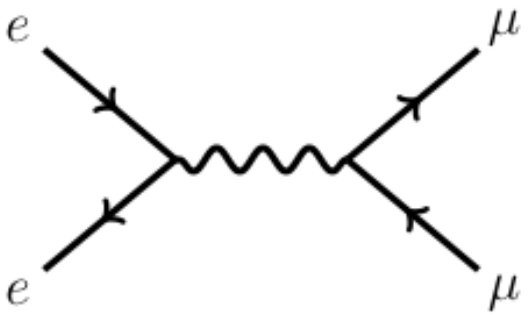


$\Delta F_{S,0,1}$ ~ 5 TeV^{-4} (@ 3 TeV)
~100 times better than at LHC @ 8 TeV

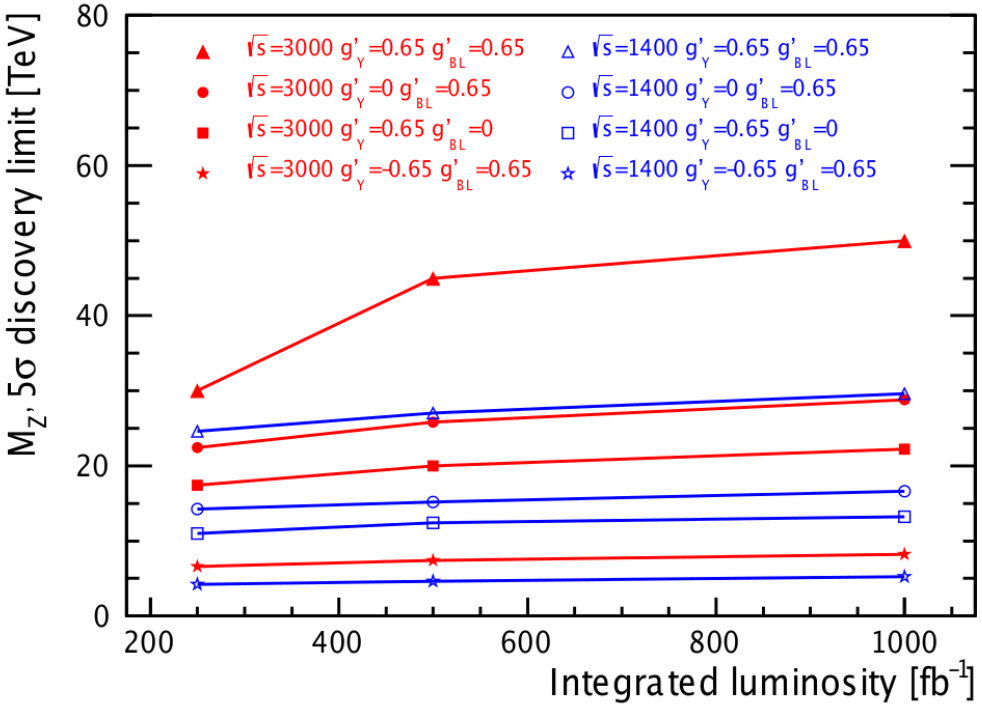
arXiv:1607.03030

$e^+e^- \rightarrow \mu\mu$: test of Z'

- Test *extension of SM* → additional gauge group (GUT, string theory, little/composite Higgs, etc…)
- *Minimal anomaly-free Z' model: U'(1)*
  - No extra exotic fermions in particle spectrum
  - 3 free parameters: M(Z'), g'_Y, g'_{BL}
    $Q_f = g'_Y(Y_f) + g'_{BL}(B-L)_f$



- Precise measurement of cross section $\sigma(ee \rightarrow \mu\mu)$, A_{FB}, A_{LR} (±80% beam polarisation)
- In case of discovery at LHC, precision measurements of the effective couplings
- Otherwise possible discovery at CLIC or limits set up to tens of TeV
- Systematic uncertainties dominant for L > 500 fb^{-1}



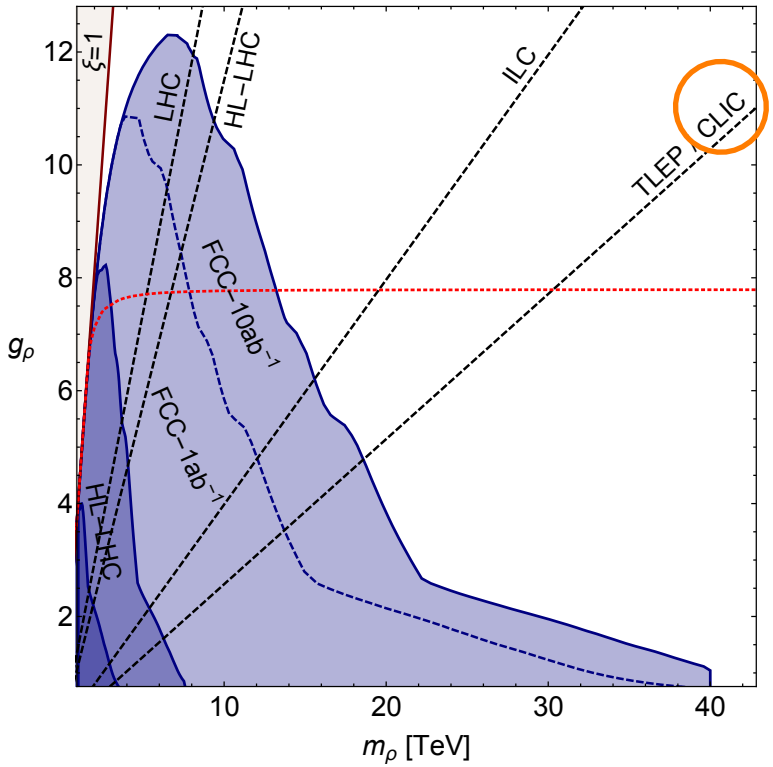
arXiv:1208.1148

Composite Higgs

- *Minimal composite Higgs* scenario
  - It predicts direct and indirect effects
- Indirect: modification of the SM *Higgs coupling* proportional to $\xi = v^2/f^2$
  → CLIC very suited for it
- Direct: production of *EW vector resonances* (vector triplet mass $m_{\rho,}$ coupling to SM g_ρ) narrow resonance assumed
  → hadron colliders more suited: high √s
- Relation between indirect and direct

$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2$$

arXiv:1502.01701

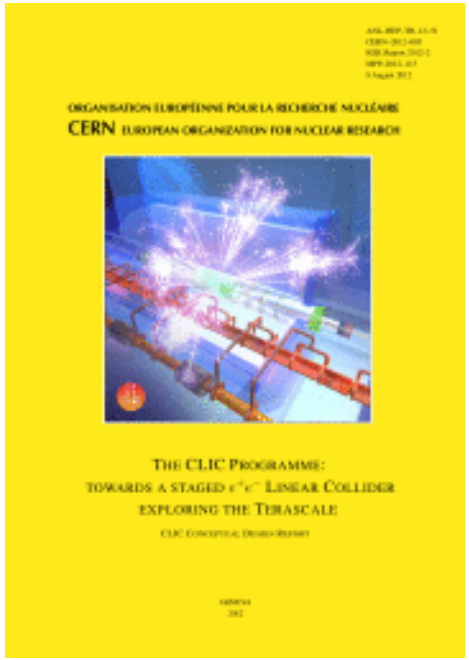


Indirect searches more effective for large g_ρ, while direct searches for small g_ρ

Conclusion

- CLIC has a large discovery potential for BSM physics
- In case of discovery (either at LHC or CLIC) precision measurement of the new particle properties is possible
- Indirect searches can constrain new BSM physics up to tens of TeV
- More information at: http://clicdp.web.cern.ch/

CDR vol 2:
arXiv:1202.5940



CDR vol 3:
arXiv:1209.2543

Physics at the CLIC e^+e^- Linear Collider
Input to the Snowmass process 2013

October 1, 2013

This paper summarizes the physics potential of the CLIC high-energy e^+e^- linear collider. It provides input to the Snowmass 2013 process for the energy-frontier working groups on The Higgs Boson (HE1), Precision Study of Electroweak Interactions (HE2), Fully Understanding the Top Quark (HE3), as well as The Path Beyond the Standard Model – New Particles, Forces, and Dimensions (HE4). It is accompanied by a paper describing the CLIC accelerator study, submitted to the Frontier Capabilities group of the Snowmass process [1].

The CLIC Detector and Physics Study

H. Abramowicz[1], A. Abusleme[2], K. Afanaciev[3], G. Alexander[1], N. Alipour Tehrani[4], O. Alonso[5,6], K.K. Andersen[7], S. Ardu[4], C. Balazs[8,9], T. Barklow[10], M. Battaglia[11], M. Benoit[4], B. Bilki[12], J-J. Blaising[13], M. Boland[8,14], M. Bozovic[5,15], I. Bozovic Jelisavcic[16], P. Burrows[17], M. Chefdeville[18], R. Cootinx[18], D. Dannheim[4], M. Demarteau[12], M.A. Diaz Gutierrez[2], A. Dieguez[5,6], J. Duarte Campderros[5,19], G. Eigen[20], K. Elsener[4], D. Felikman[21], U. Felzmann[22], M. Firlej[23], E. Firu[24], T. Fiutowski[23], K. Francis[12], F. Gaede[24], I. Garcia Garcia[5,19], V. Ghenescu[25], G. Gindice[4], N. Graf[10], C. Grefe[4], C. Grojean[4,26], R.S. Gupta[21], M. Hauschild[4], H. Holmestad[4], M. Idzik[22], C. Joram[4], S. Kananov[1], Y. Karyotakis[13], M. Killenberg[27,4], W. Klempt[4], S. Kramp[20], B. Krupa[22], S. Kulis[4,28], T. Lalovic[29,*], G. Leflang[8,14], A. Levy[1], I. Levy[1], L. Linssen[4,*], A. Lucaci Timoce[4], S. Lukic[16], V. Makarenko[2], J. Marshall[30], V. Martin[29], R.E. Mikkelsen[7], G. Milutinovic-Dumbelovic[16], A. Miyamoto[31], K. Mönig[32], G. Moortgat-Pick[24,33], J. Moron[22], A. Münnich[4,28], A. Neagu[25], M. Pandurovic[16], D. Pappadopulo[34,35], B. Pawlik[23], W. Porod[36], S. Poss[4], T. Preda[25], R. Rassool[8,37], R. Rattazzi[38], S. Redford[4], J. Repond[12], S. Riemann[39], A. Robson[29], P. Roloff[4,*], E. Ros[5,15], J. Rosen[10], A. Ruiz-Jimeno[5,19], H. Rzehak[4], A. Sailer[4,*], D. Schlatter[4], D. Schulte[4], F. Sefkow[4,28], K. Seidel[40], N. Shumeiko[3], E. Sicking[4], F. Simon[40,*], J. Smith[12], C. Soldner[40], S. Stapnes[4,*], J. Strube[8], T. Suehara[41], K. Świentek[22], M. Szalay[40], T. Tanabe[42], M. Teixé[40], A. Thamm[4,28], M. Thomson[29,*], J. Tomado Garcia[5,6], U.I. Uggerhoj[7], E. van der Kraaij[20], I. Vila[5,19], E. Villella[5,6], M.A. Villarejo[5,15], M.A. Vogel Gonzalez[2], M. Vos[5,15], N. Watson[43], H. Weerts[12], J.D. Wells[21,*], L. Weuste[44], T.N. Wistisen[7], K. Wootton[8,37], L. Xia[12], L. Zawiejski[23], I.-S. Zgura[25]

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arXiv:1307.5288v3 [hep-ex] 30 Sep 2013

Snowmass paper:
arXiv:1307.5288

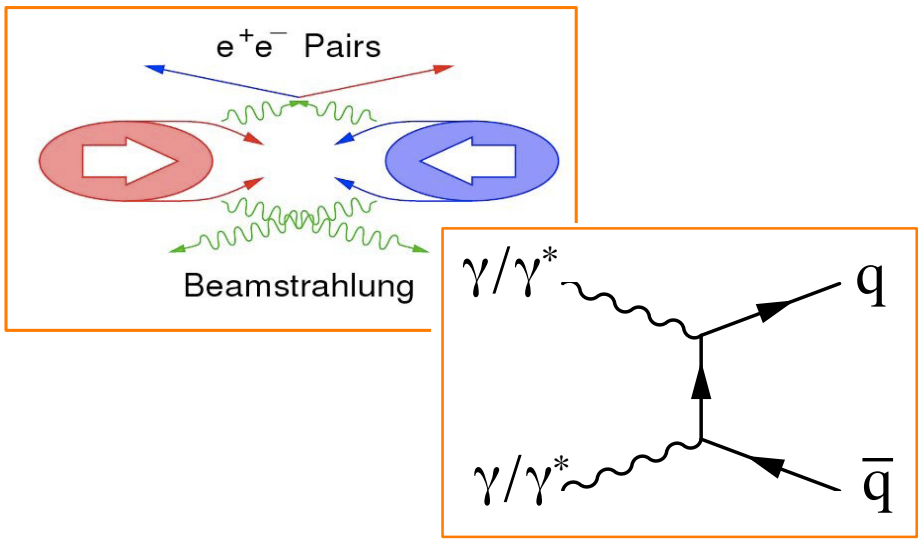
BACK-UP

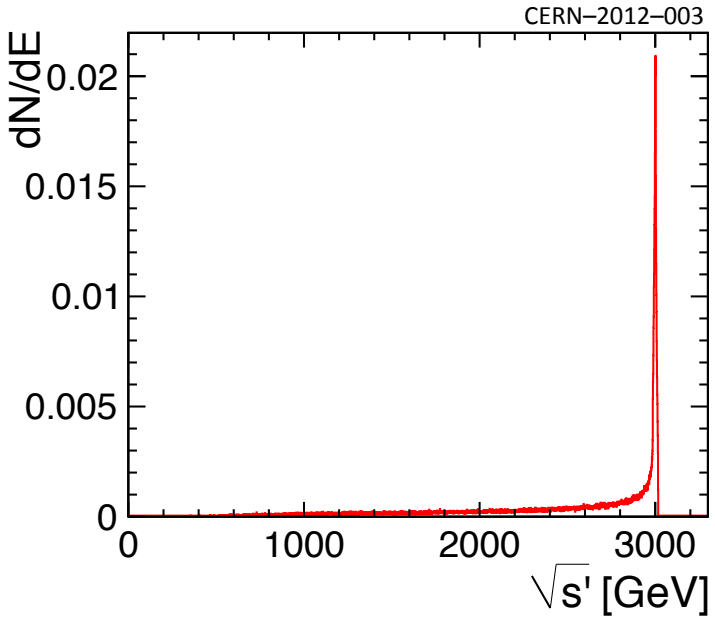
Machine environment

- Small beams at IP lead very high E field → Beamstrahlung
- Beam induced background: pair production and γγ->hadrons

  → *Strongly reduced with subdetector specific timing cuts (p_T, θ)*
- Luminosity spectrum: it can distort kinematics edges

  → *Important issue for analyses*





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

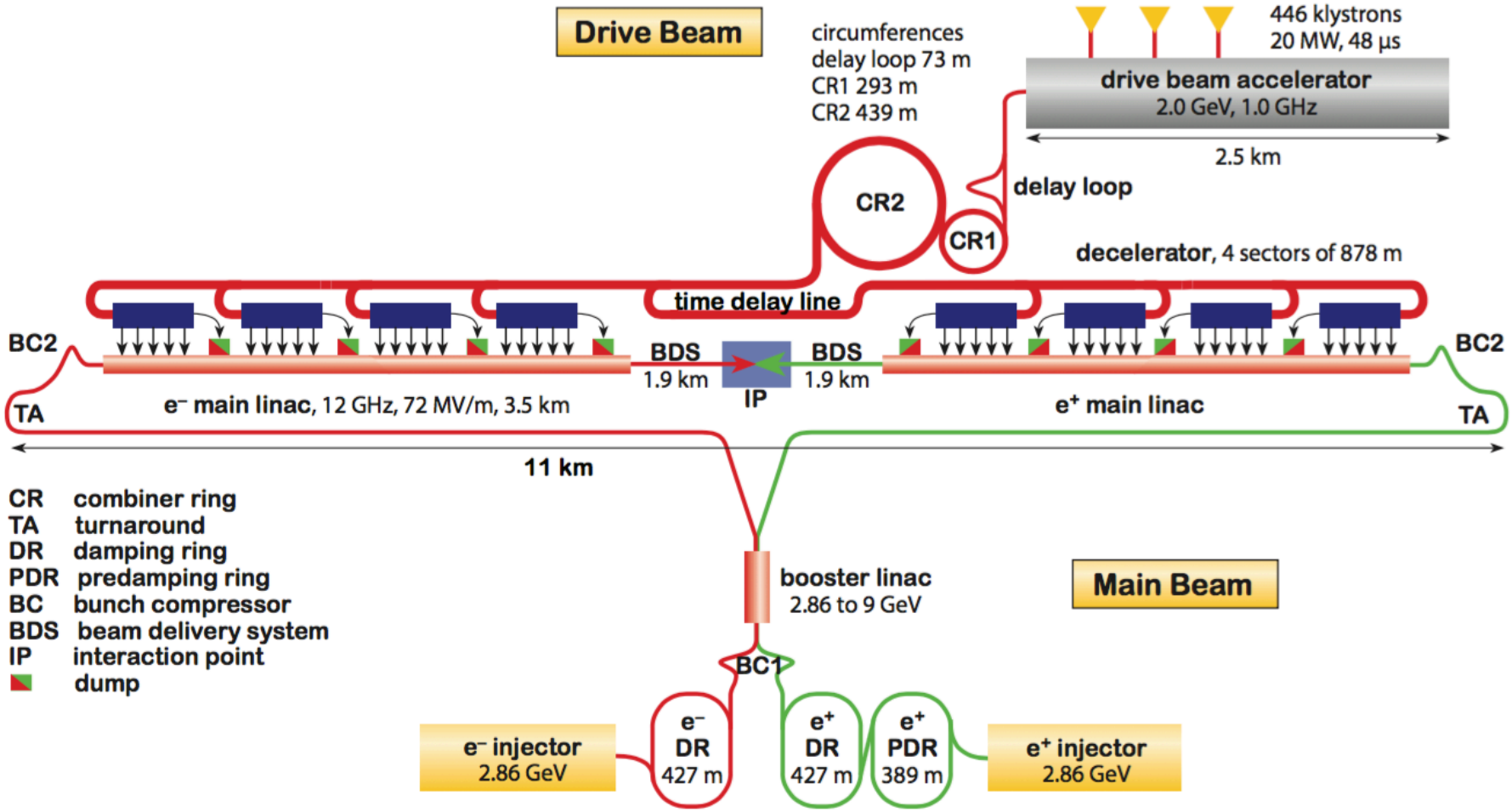
Ready for construction; start of excavations

2035 First Beams

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

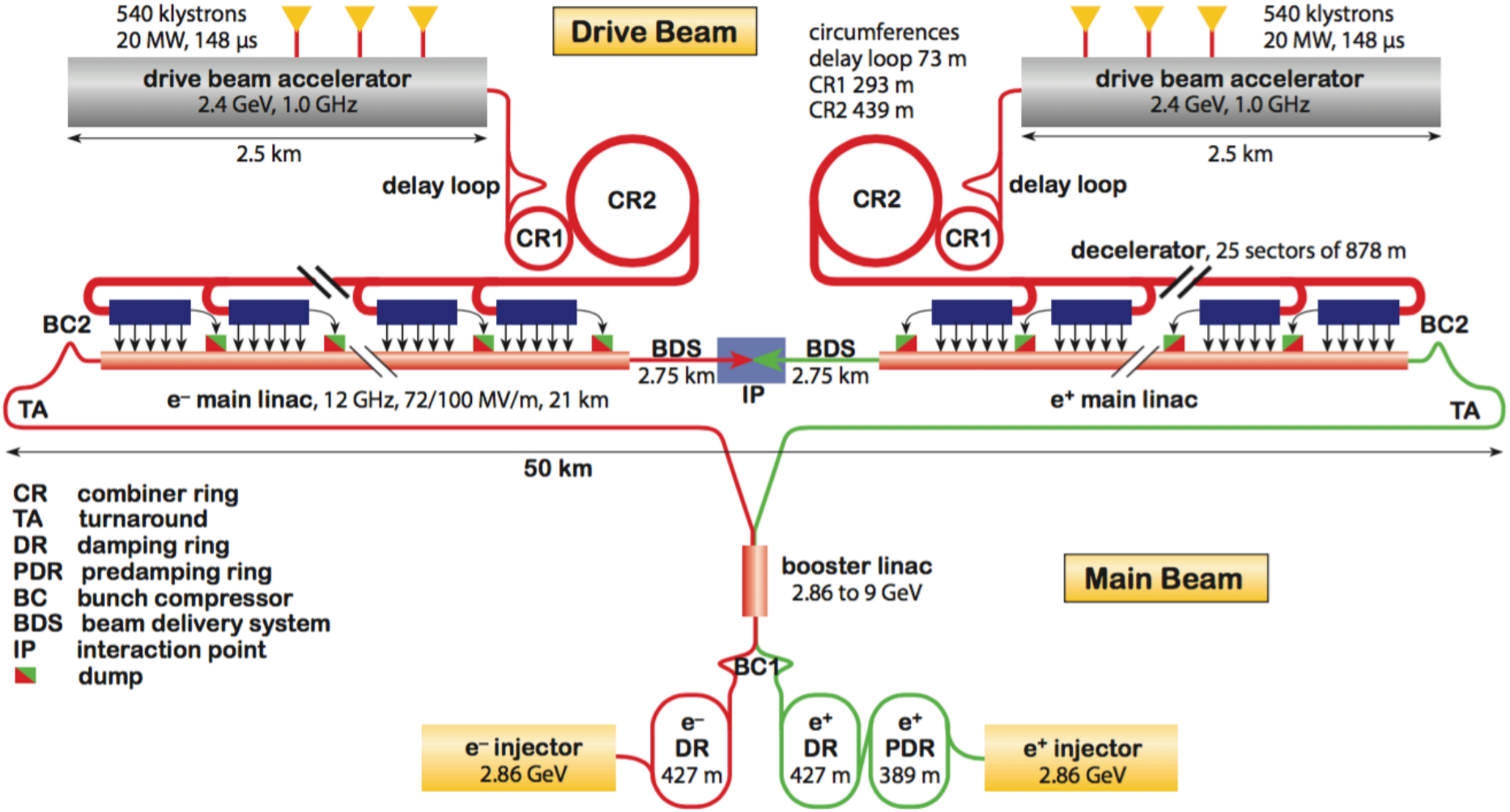
CLIC dual beam scheme

1 drive beams accelerator for 380 GeV and 1.5 TeV

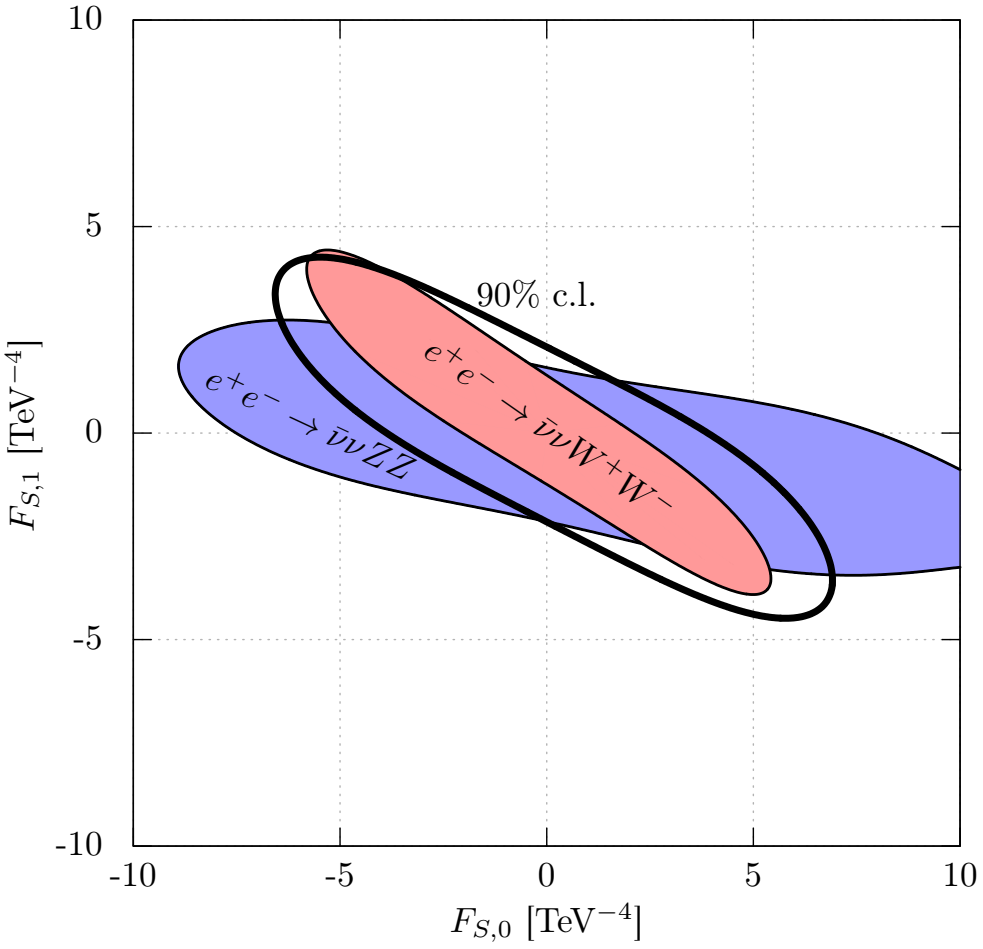


CLIC dual beam scheme

2 drive beams accelerators for 3 TeV

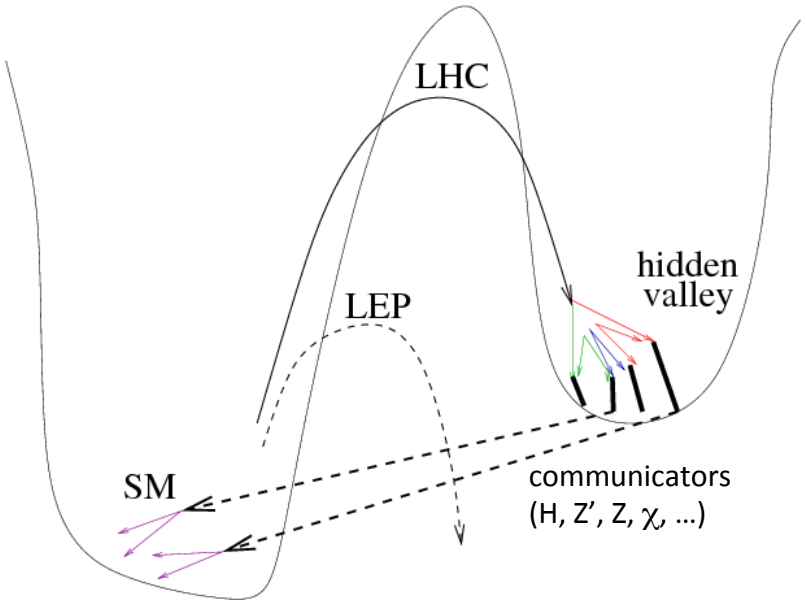


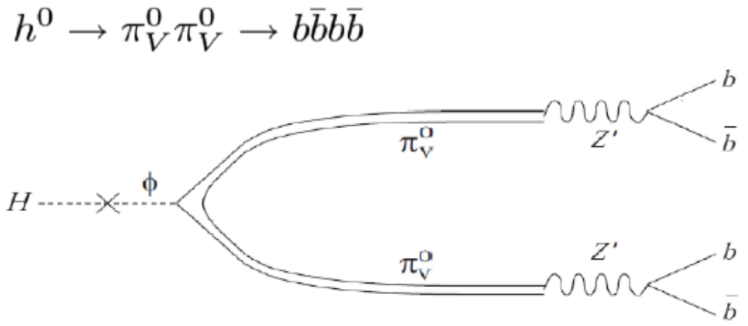
Vector boson scattering



Hidden valley

Promising channel at CLIC → Studies in the full simulation to extract final sensitivity





- Search for *neutral long lived particles* (1ps−1ns)
  - *Hidden valley* model (but not only!)
- Wide range of final state → starting with:
  H decaying in hidden valley pions decaying in bb
  - Reconstruction of *displacement vertices*
- Main backgrounds: multi-jets final state