LINEAR e^+e^- COLLIDERS – FUTURE HIGGS FACTORIES

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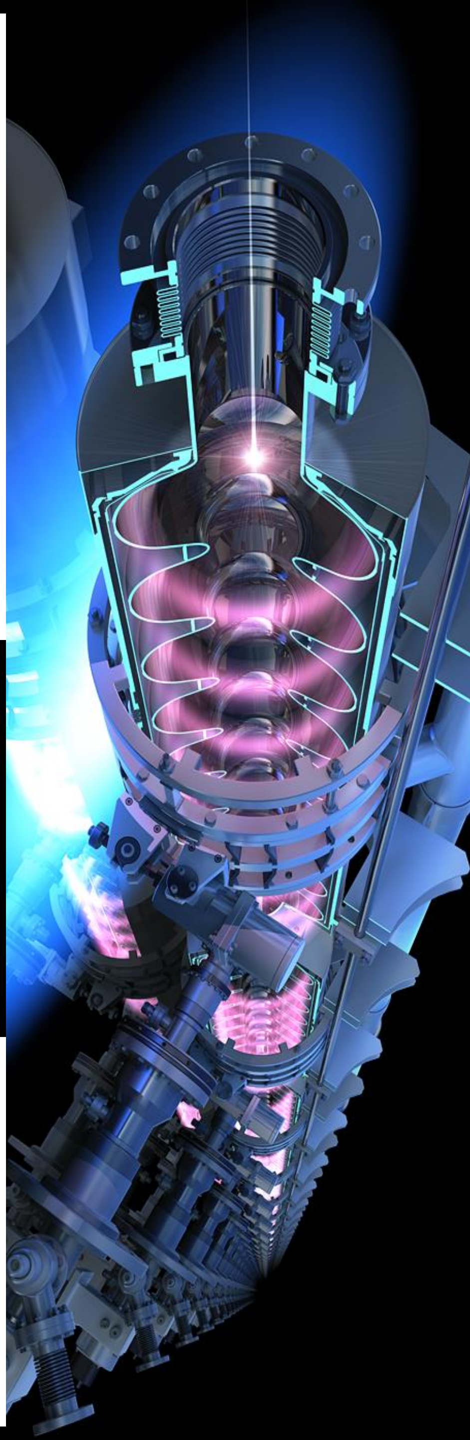
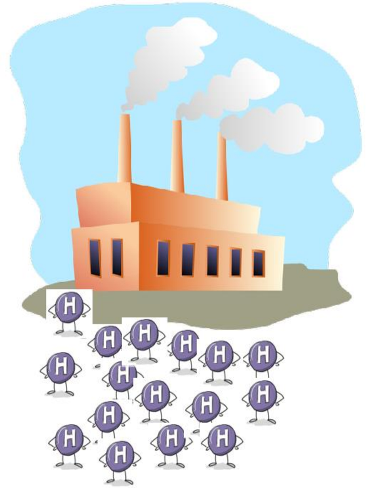


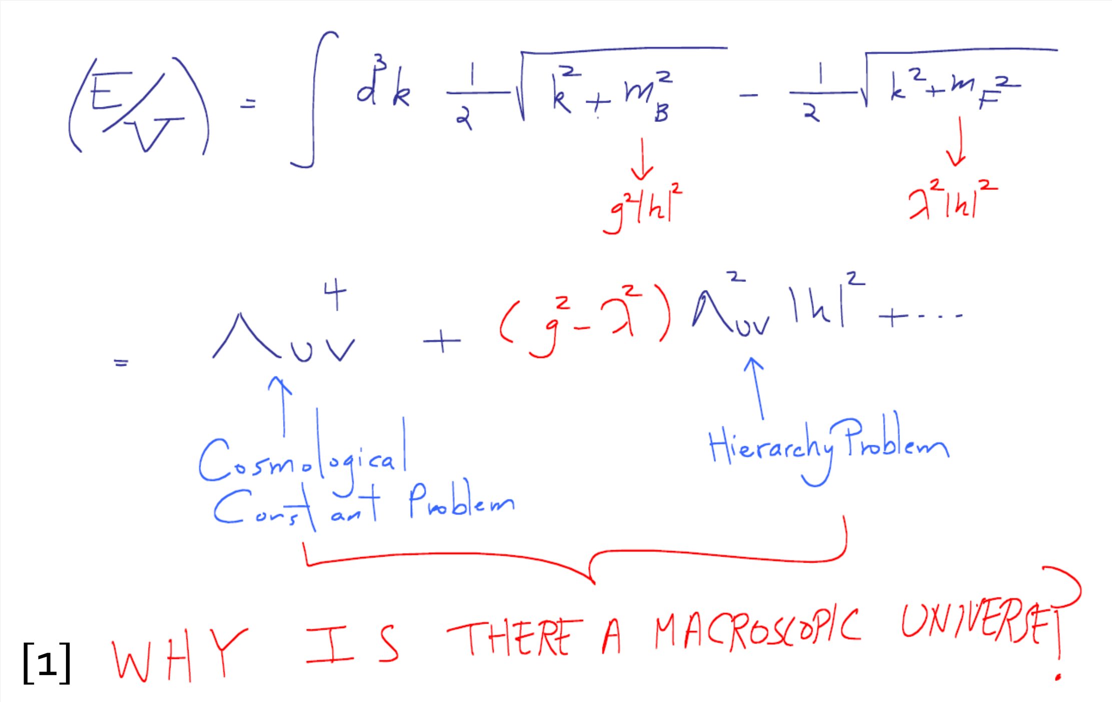
OVERVIEW

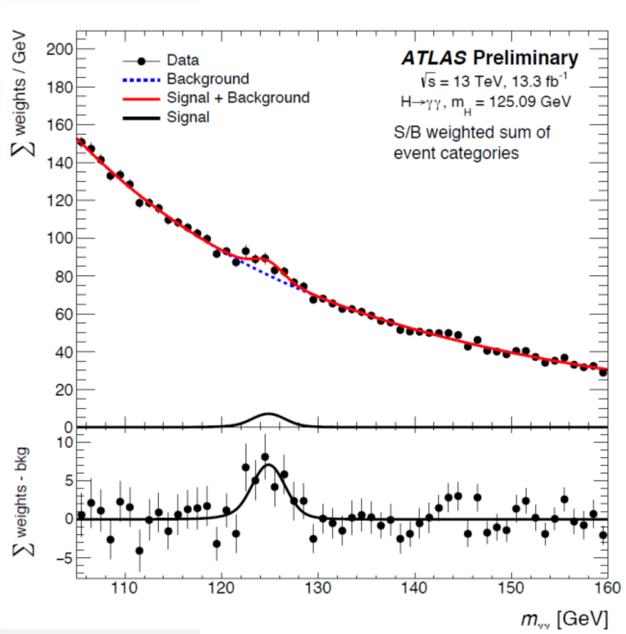
- WHY HIGGS FACTORIES?
- LINEAR COLLIDERS
- DETECTOR CONCEPTS & TECHNOLOGIES
- HIGGS PHYSICS AT LINEAR COLLIDERS
- OUTLOOK

WHY HIGGS FACTORIES?

- Higgs discovery ended era of reductionism and symmetries in particle physics [1]
- Never seen before fundamental scalar is discovered, unique (with exception of gravity) in its self-coupling
- Higgs discovery opened several important questions of nature of relativistic vacuum:
  - How can we accommodate it in energy density of the Universe?
  - Why the Higgs is not enormously massive (even Planckian)?

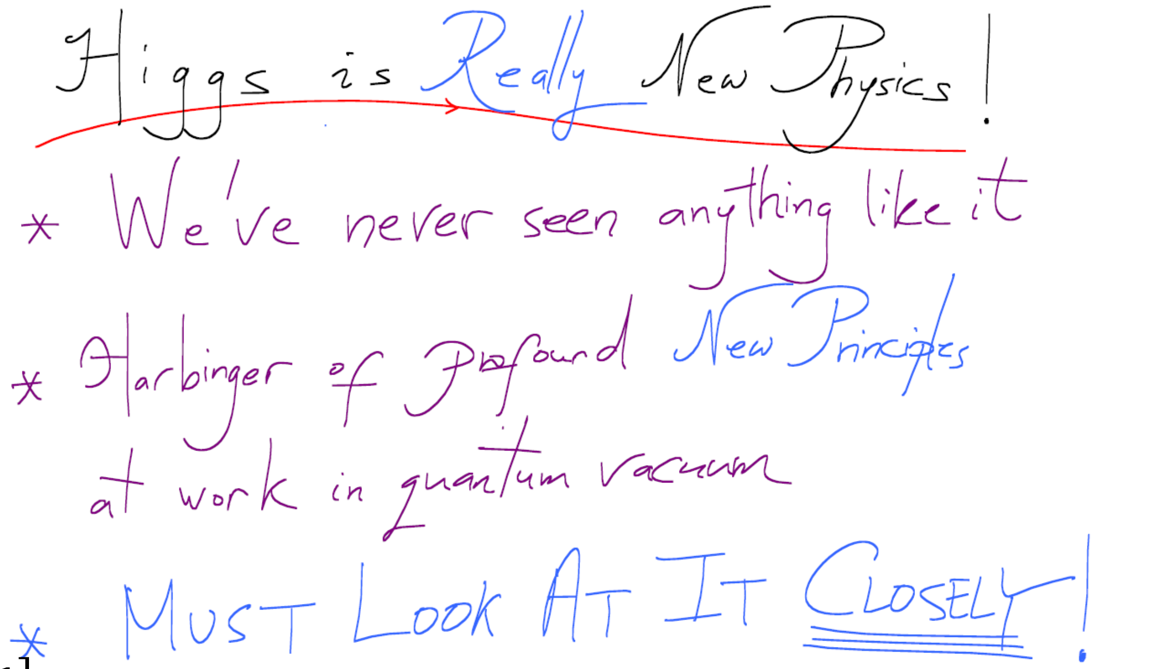






LIMITS, LIMITS,…

- No New Physics discovery at LHC
- With the LHC resolution to probe Higgs compositeness, the Higgs could be as elementary as pion. So, how pointlike is it?
- λ can be significantly enhanced in EW bariogenesis models. HL-LHC will probe λ with 50% uncertainty [2]



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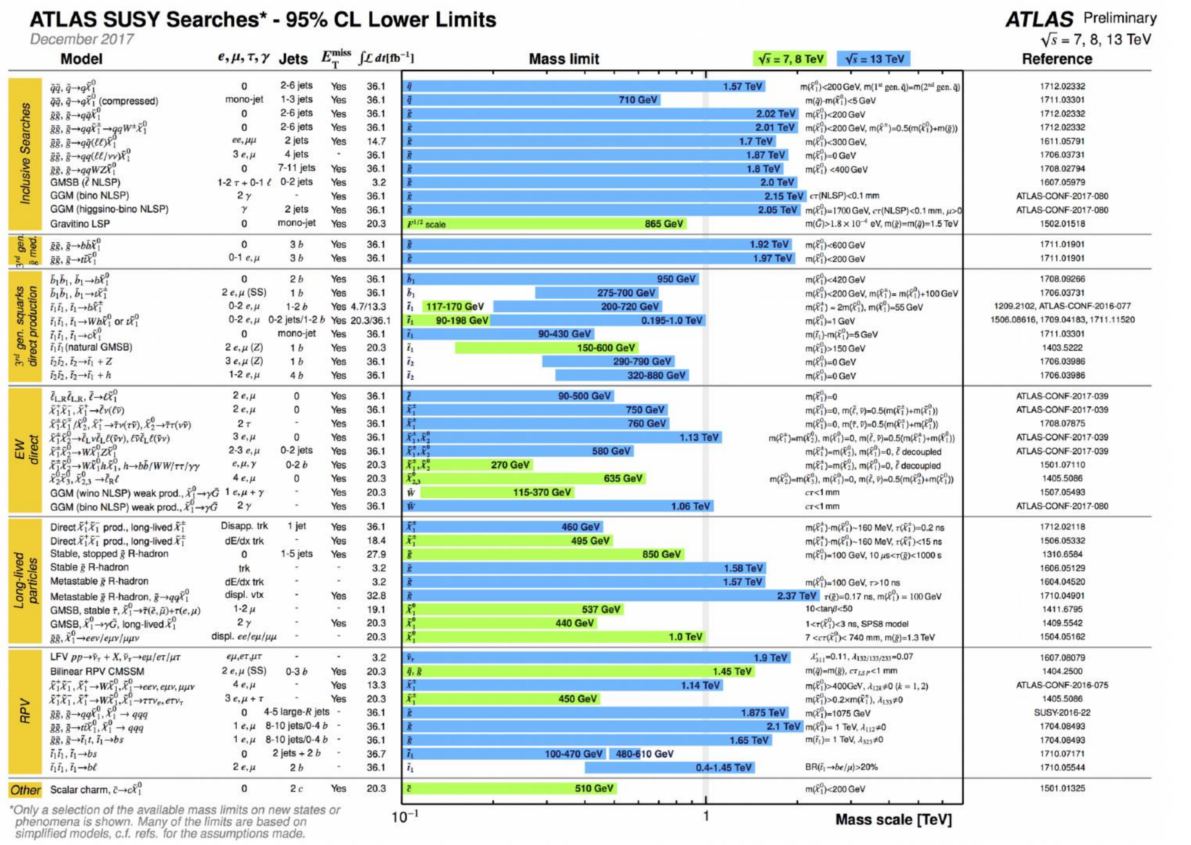
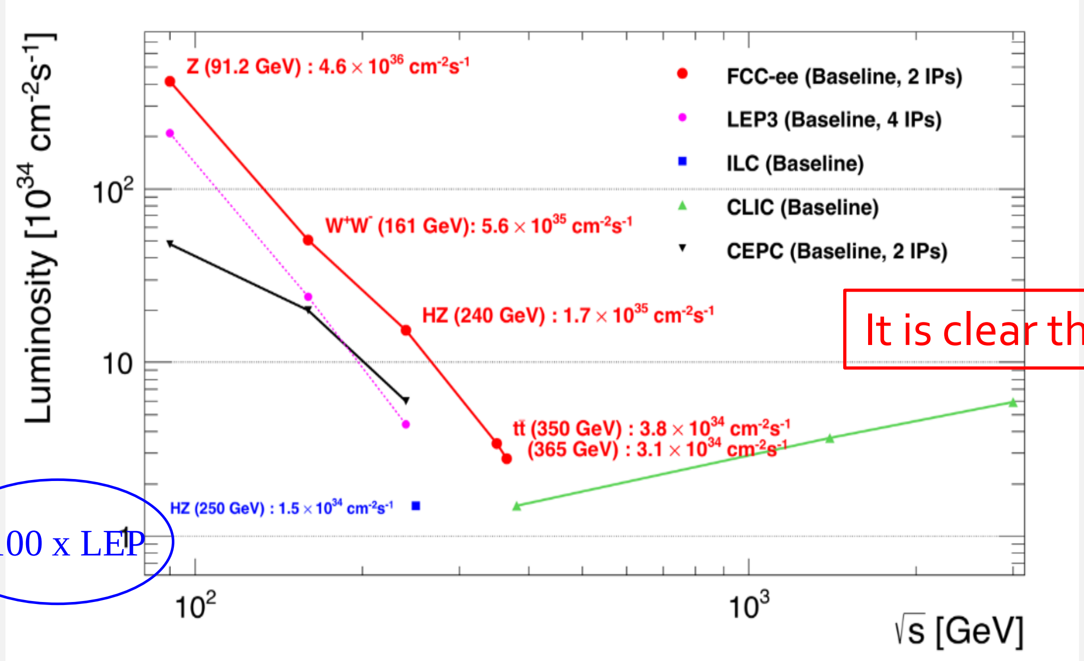


WHAT BRINGS US TO THE HIGGS FACTORIES

- In the European PP Strategy Update 2020, Higgs factories are the highest priority future initiatives [3]
- Several projects on the market (~ 10^6 Higgs bosons)
- All electron-positron colliders
  - Initial state well-defined
  - High (TeV) center-of-mass energies - LCs
  - Clean environment

→ High-precision measurements (dominated by statistical uncertainty)

- Linear (ILC, CLIC) vs. circular (CEPC, FCCee)



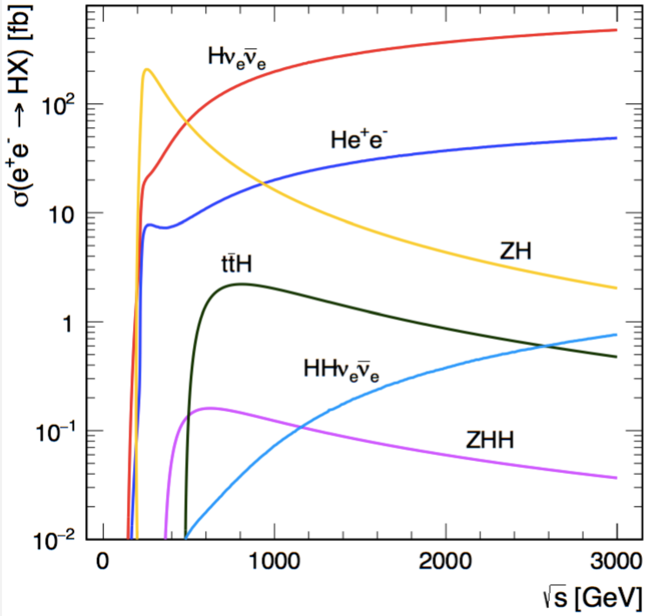
It is clear that it will be a run for statistical precision

But, other aspects are also important:

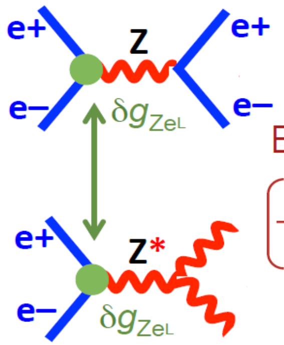
- Extensibility of the physics span - flexibility to accommodate other options (pp, hh, ep, gamma gamma, plasma....)
- Flexibility to accommodate changes in scenario (i.e. unexpected HL-LHC discovery)
- Technological feasibility and cost
- Politics (it's a game of supremacy , unfortunately)

LINEAR COLLIDERS

- Comes as mature technological options developed for decade(s) – 'ready to take'
- Staged, upgradable machines
  - Various Higgs production mechanisms accessible over the energy scale span
  - Less precise determination of an observable at high energy leads to the same precision on coupling as at low energy
- Beam polarization
  - Chiral nature of charge currents results in significant sensitivity of WW-fusion cross-section on polarization scheme ($\sim 2 \cdot \mathcal{L}$)
  - Provides new observables sensitive to New Physics
  - Helps characterization of newly discovered particles
- A few technical benefits
  - Triggerless
  - Power-pulsing



At low energy ($\sqrt{s}=m_Z$)



Effect grows as s

$$\left(\frac{3000}{91.2}\right)^2 \sim 1000$$

At high energy ($\sqrt{s}$=3TeV)

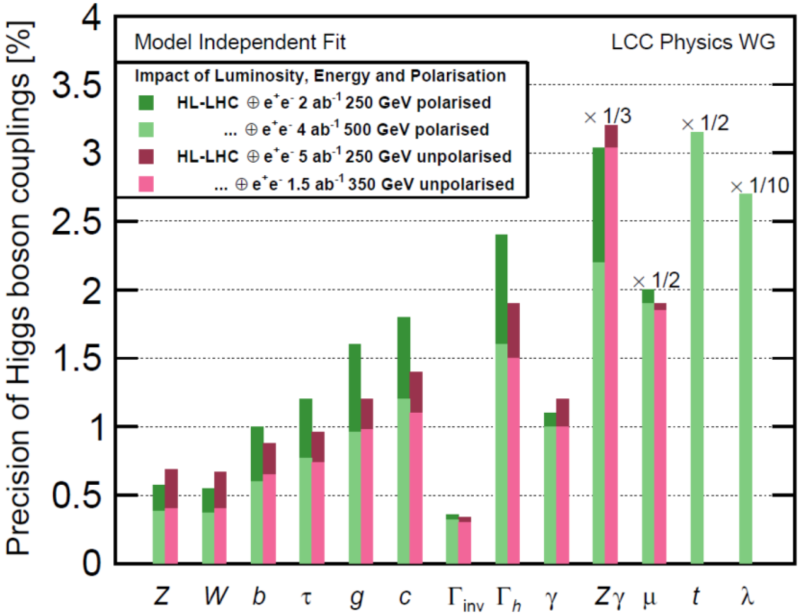
[4]

Imagine measuring $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$ => $\delta g_{ZeL} \sim 10^{-4}$

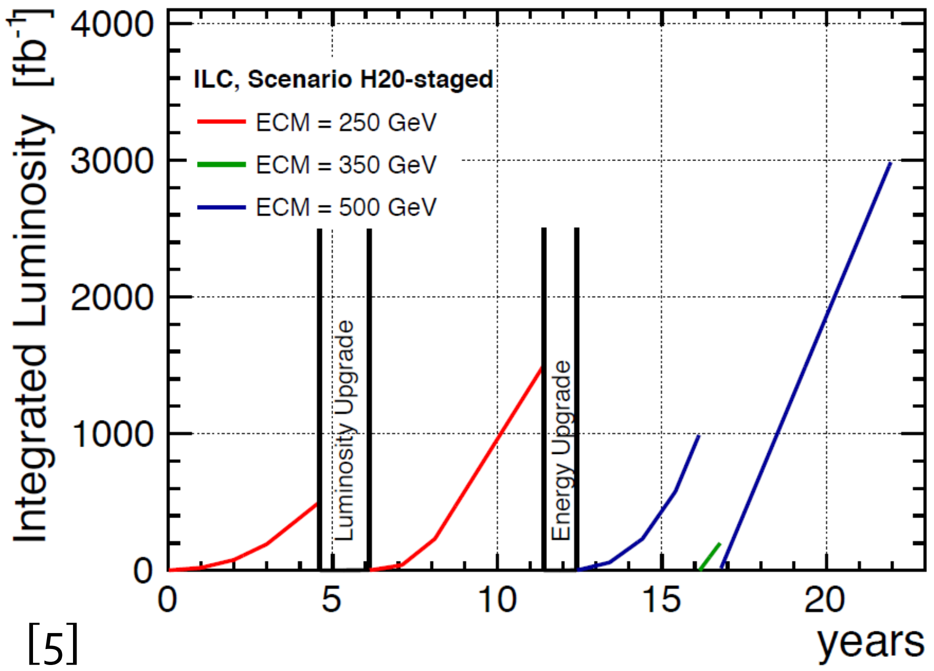
same precision!

...equivalent to $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=3\text{TeV}} \sim 10\%$ => $\delta g_{ZeL} \sim 10^{-4}$

–> strongly benefit from high energies



- e^+e^- centre-of-mass energy
  - first stage: 250 GeV
  - tunable
  - upgrades: 500 GeV, 1 TeV
  - further options:
    running at Z pole & WW threshold
- luminosity at 250 GeV:
  - 1.35×10^{34} /cm^2 /s
  - upgrade 2.7×10^{34} /cm^2 /s (cheap)
  - upgrade 5.4×10^{34} /cm^2 /s (expensive)
- beam polarisation
  - $P(e^-) \geq \pm 80\%$
  - $P(e^+) = \pm 30\%$,
    at 500 GeV upgradable to 60%
- total length (250 GeV): 20.5 km



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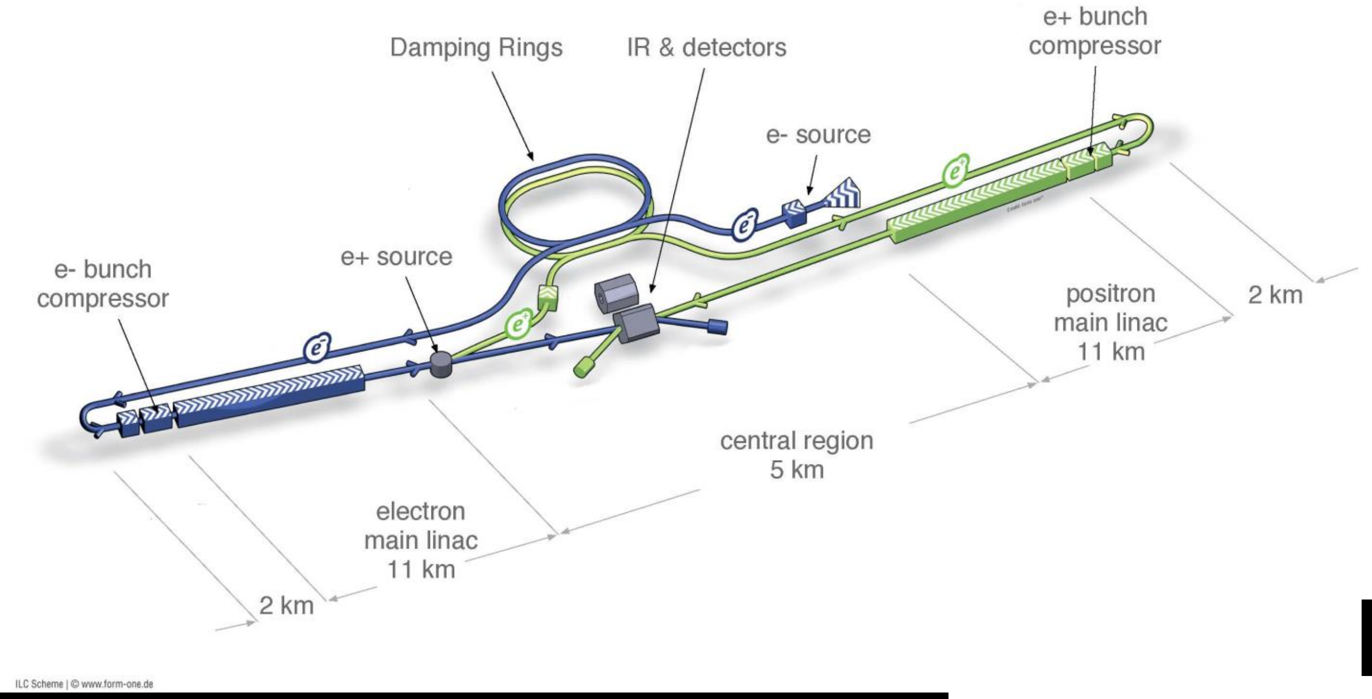
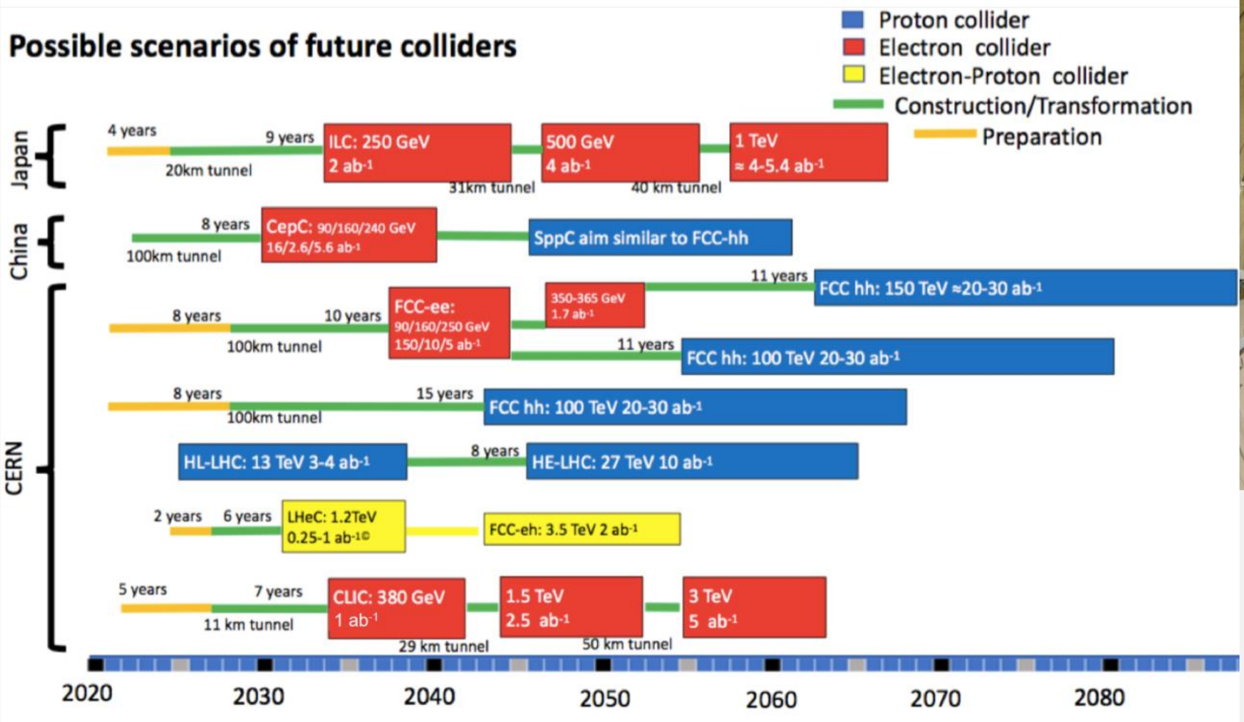
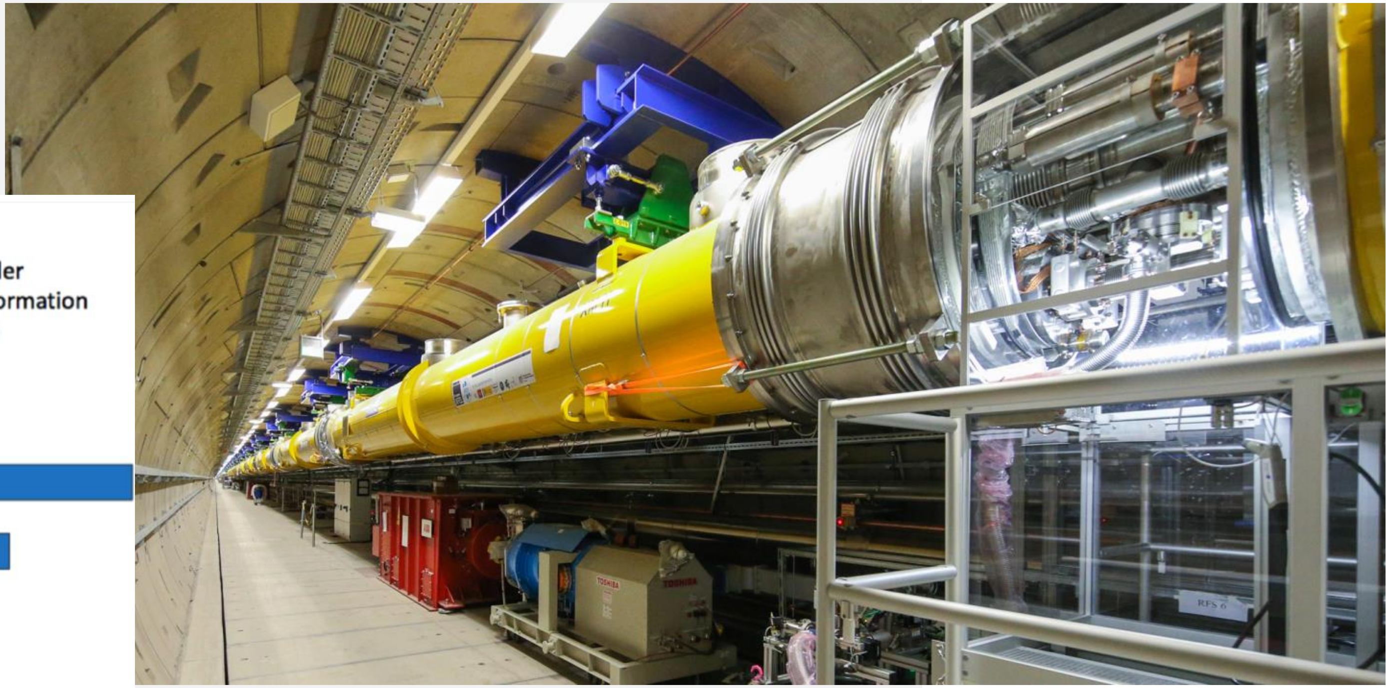


Timeline:

- Around 2000's – TESLA, NLC, JLC
- (2004) ILC based on 'cold' TESLA technology
- (2013) Technical Design Report [6]
- (2020) International Development Team (IDT)
- (?) Preparatory lab in Japan
- (2035) First collisions [7]

- Largest ever accelerator prototype (operating now as E-XFEL)
- Full industrialization of RF cavity production

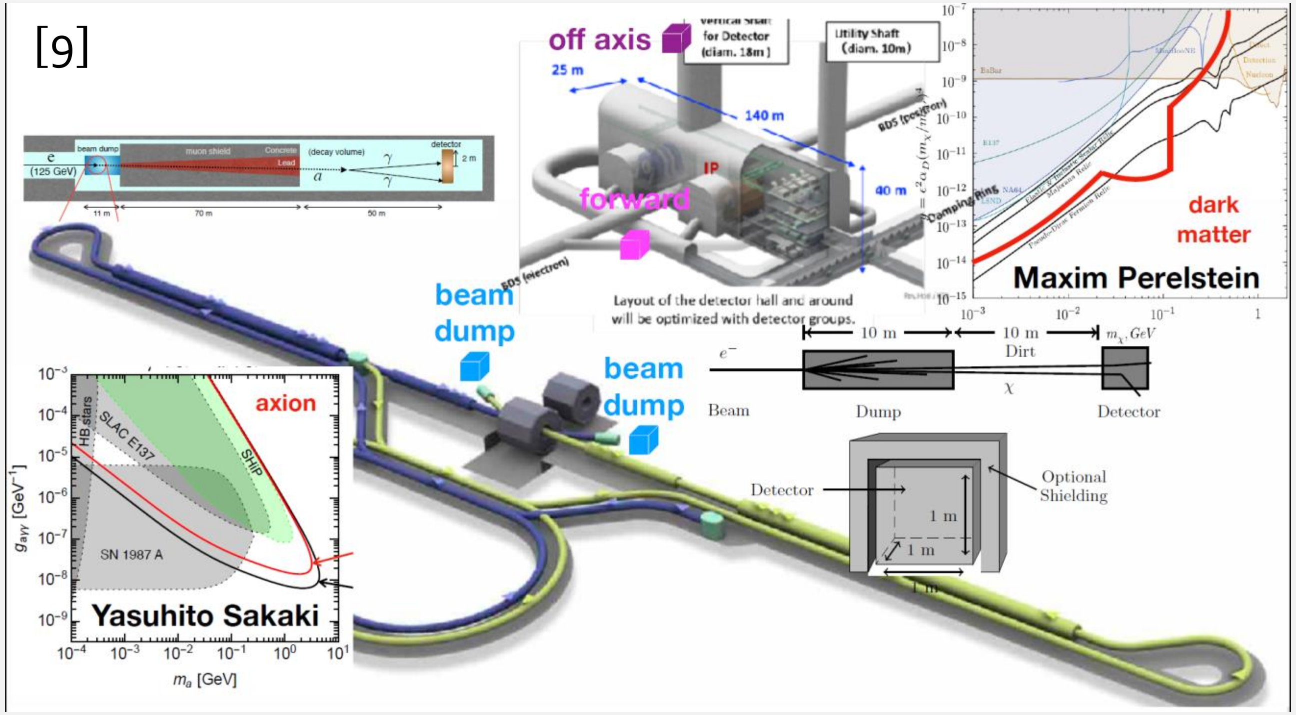




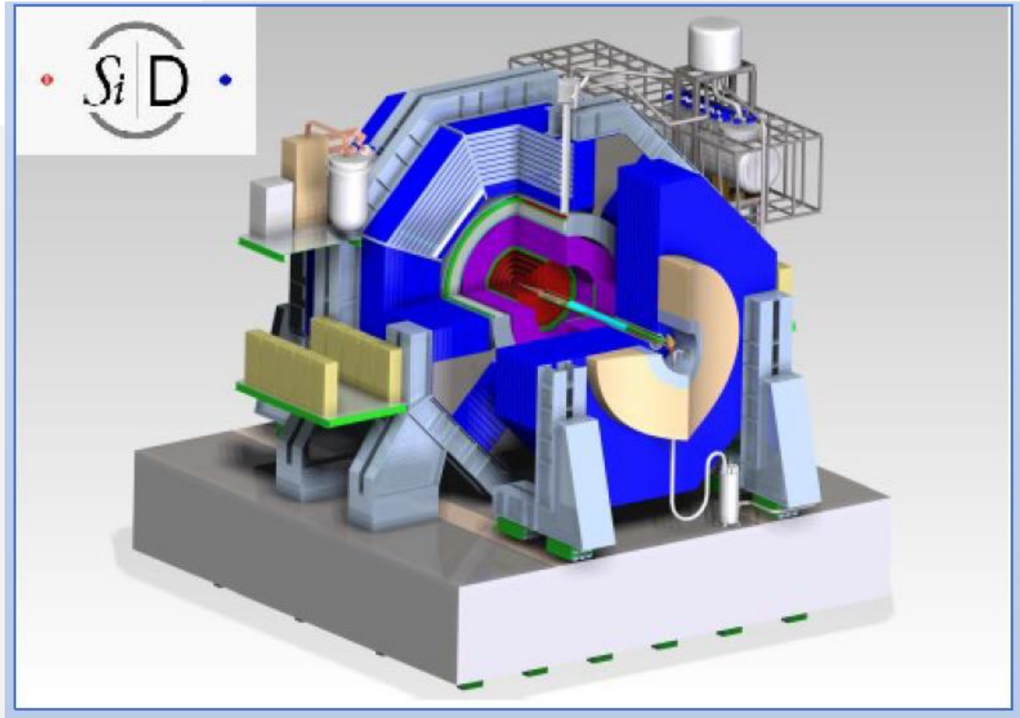
ILC comes with the collider program and rich auxiliary experiments

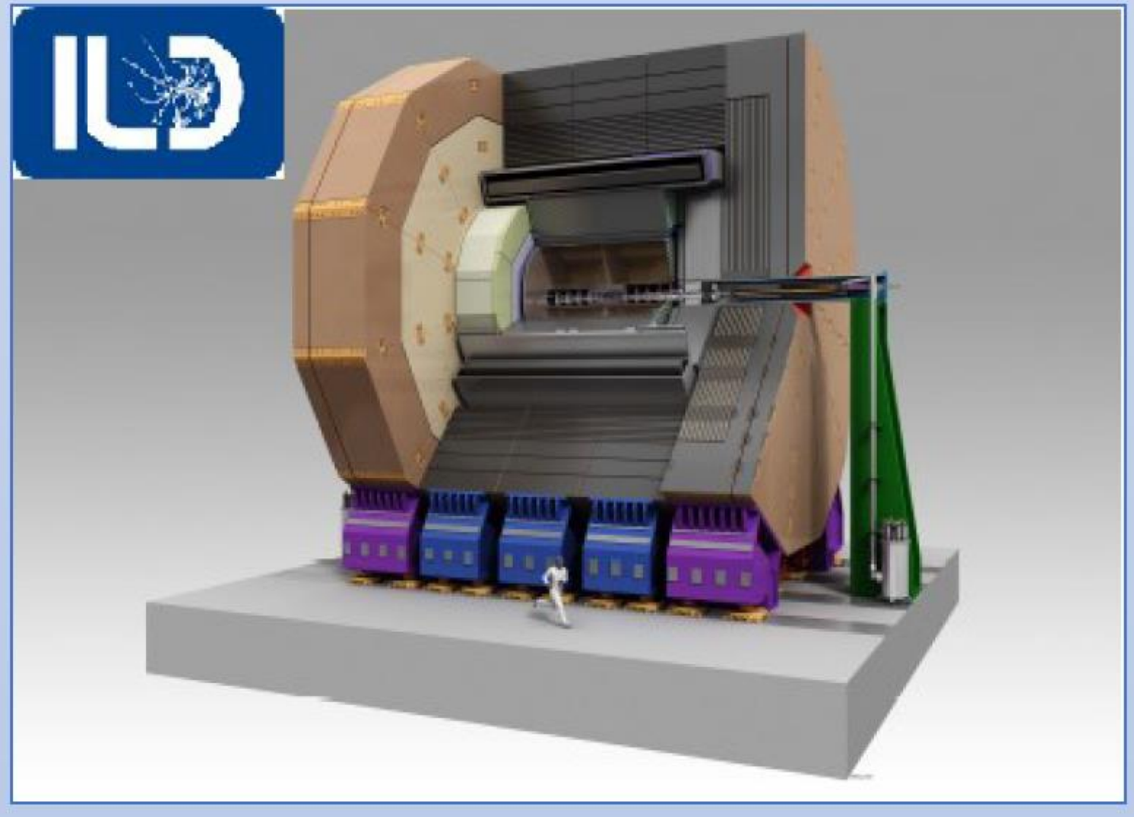
- At the LHC, experiments search for dark particles produced by pp collisions are placed in existing tunnels and caverns at CERN (FASER @ATLAS, MilliQan @CMS)

- Dark sector (ILC-BDX), fixed-target and beam dump experiments (ILCX)



Potential ILC site in Kitakami





SiD Detector

- 5 T field
- More compact
- All Si

ILD Detector

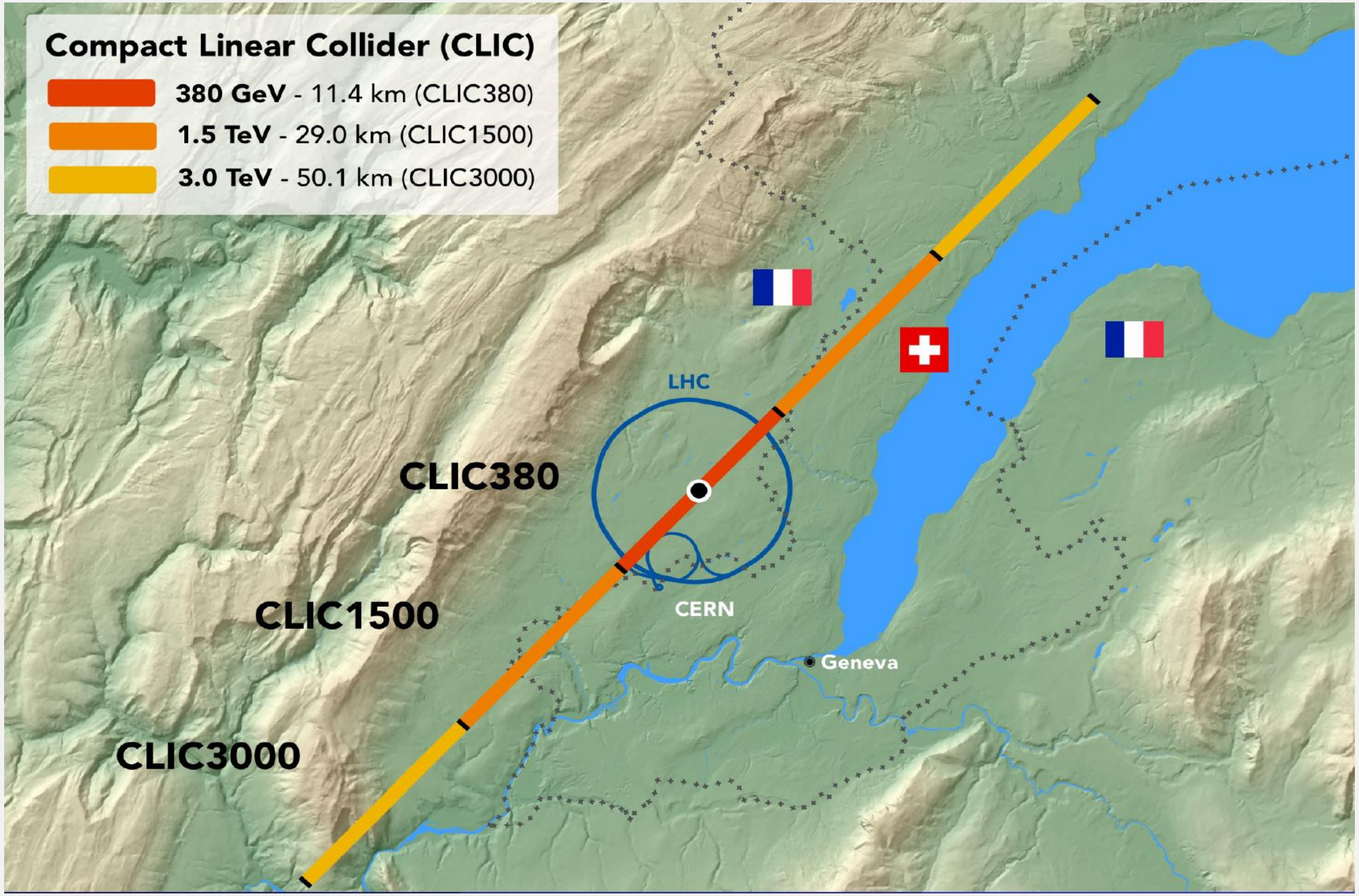
- 3.5 T field
- Optimized for CM energies 90 GeV - 1 TeV
- Si/gaseous tracking
- Particle flow calorimetry
- Mature design and available technologies

Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$ CMS/40

Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$ CMS/4

Jet energy resolution: $\sigma_E/E = 3-4\%$ (for highest jet energies) ATLAS/2

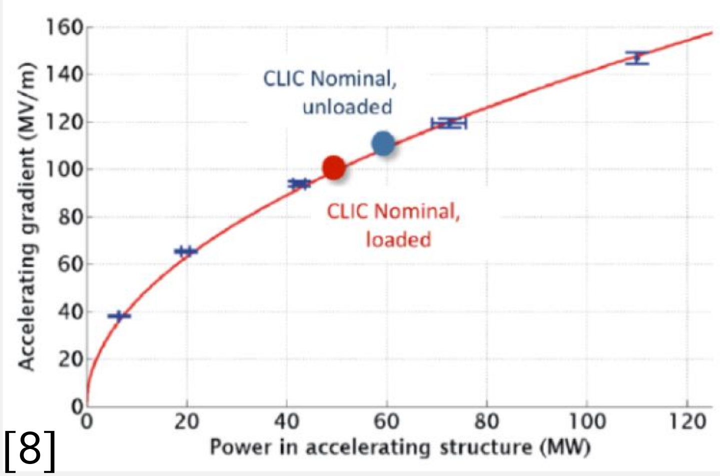
Hermecity: $\Theta_{min} = 5$ mrad ATLAS/3


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

The only LC to go above 1 TeV

- CLIC Test Facility, CTF3, at CERN now the 'CERN Linear Electron Accelerator for Research' facility, CLEAR

- Normal conductive high-current drive beam
- 380 GeV and 1.5 TeV – one drive-beam
- 3 TeV two drive-beam complexes
- 100 MV/m gradient in the main-beam cavities



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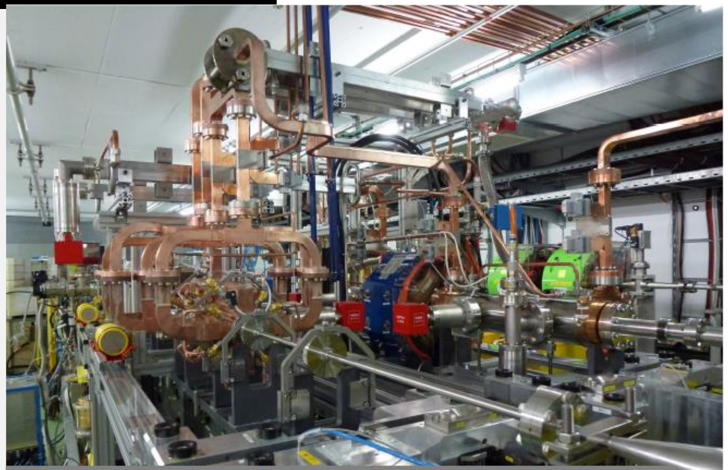
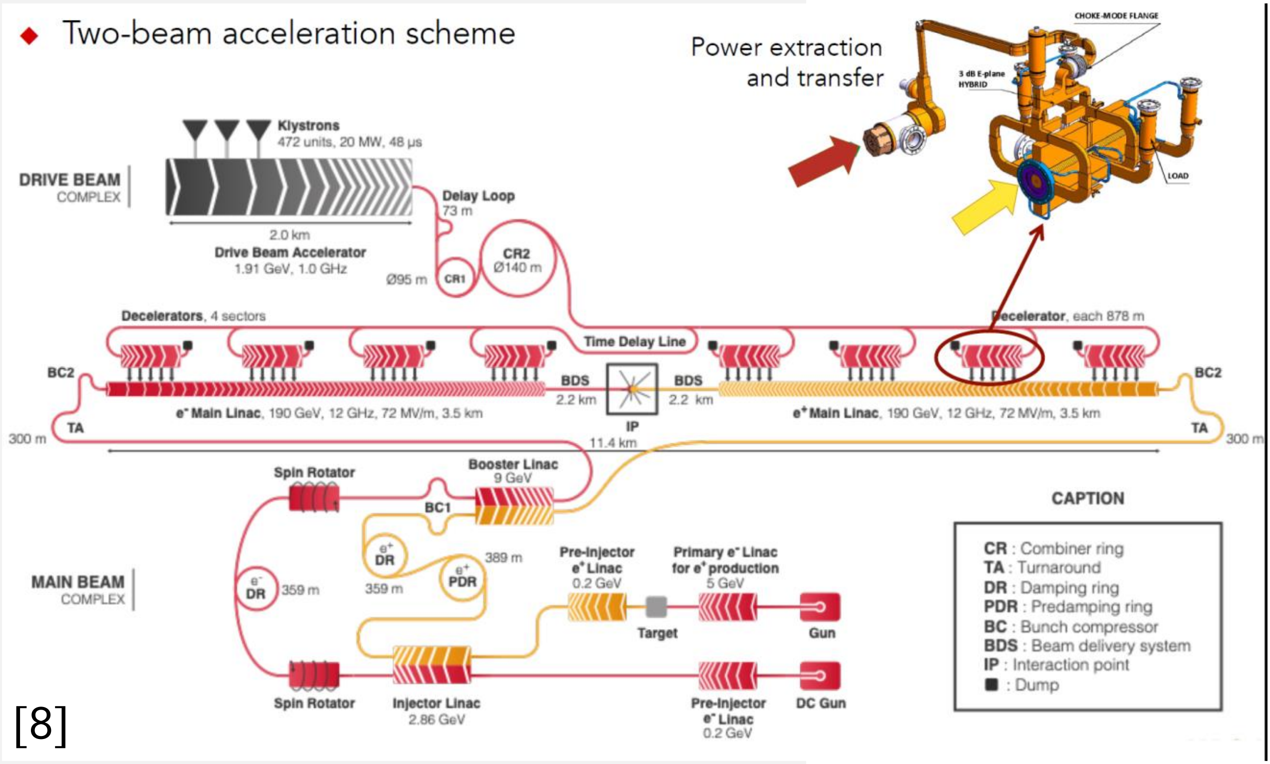


2-beam acceleration module in CTF3
First 2-beam tests stand reached 145 MV/m



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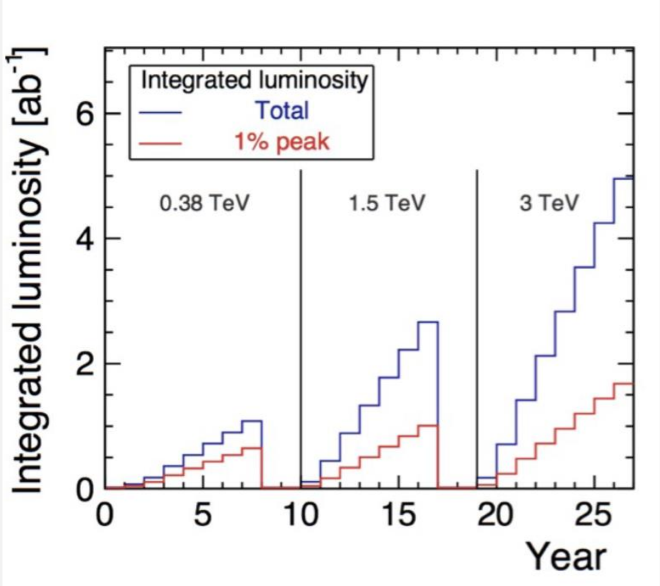
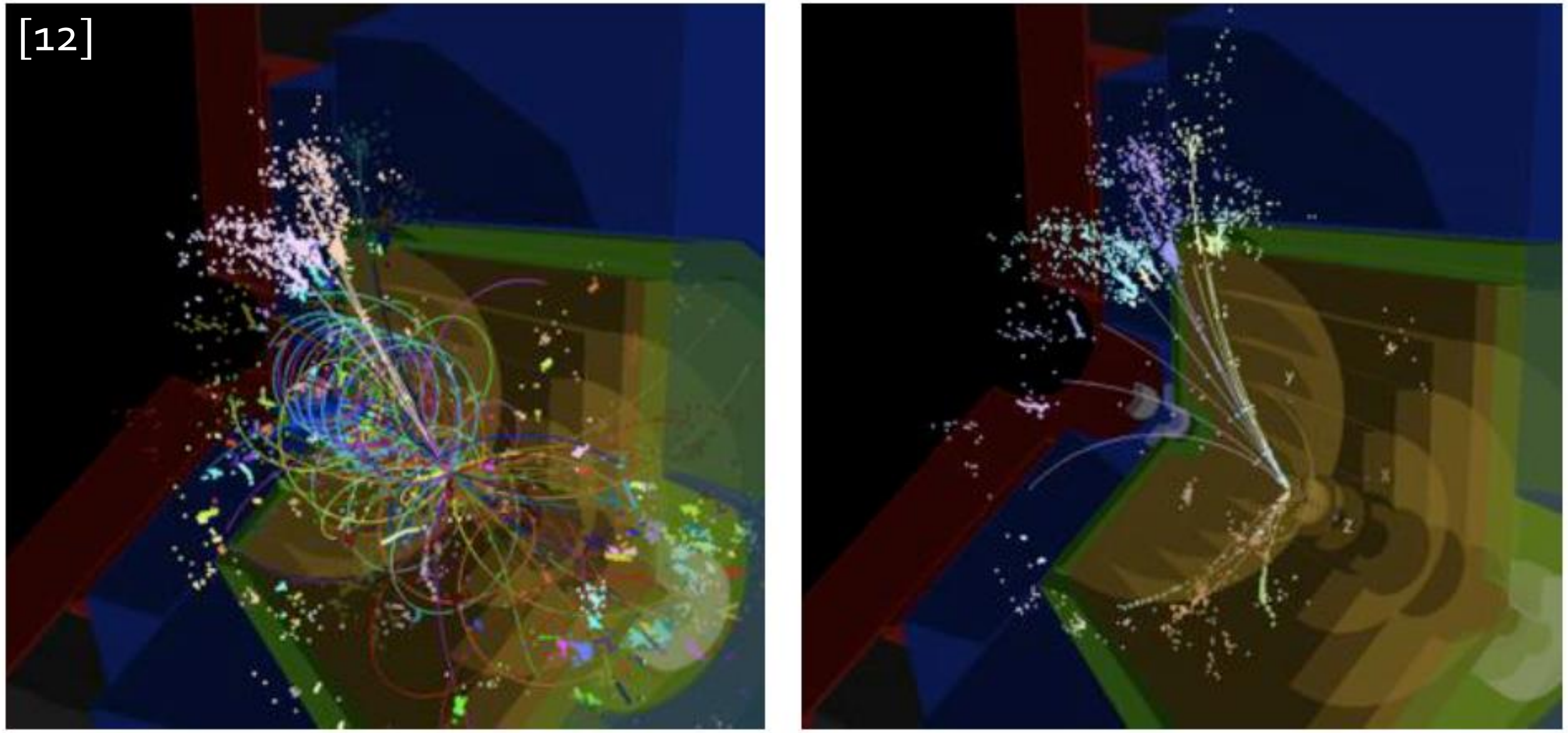


CLIC det

- 4 T field
- Ultra low-mass VTX
- All Si tracking
- Particle flow calorimetry
- Time-stamped readout (10 ns) due to pronounced Beamstrahlung background at higher energies



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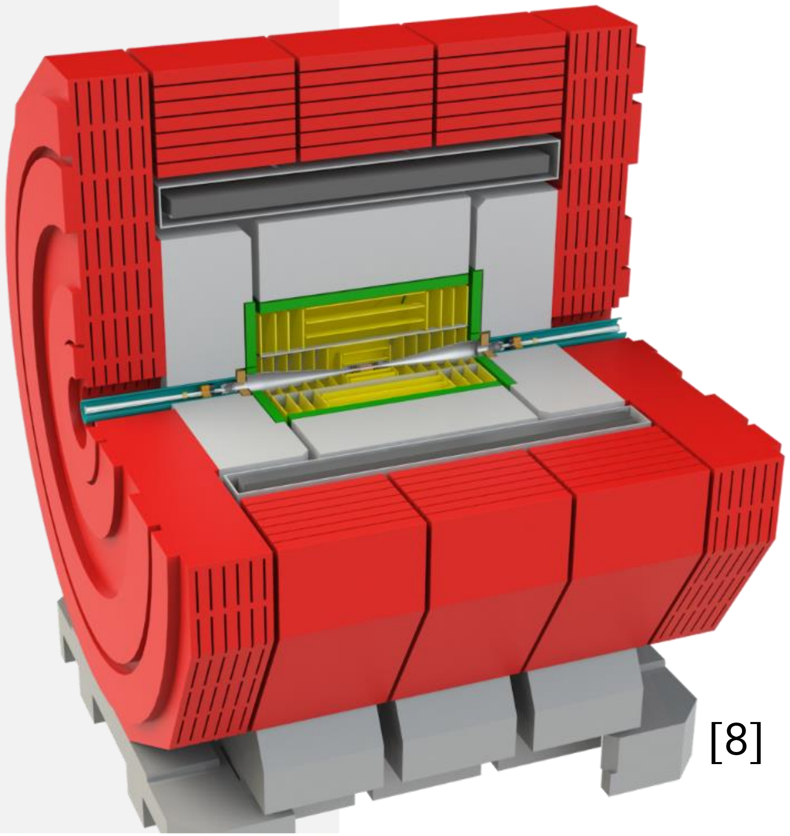
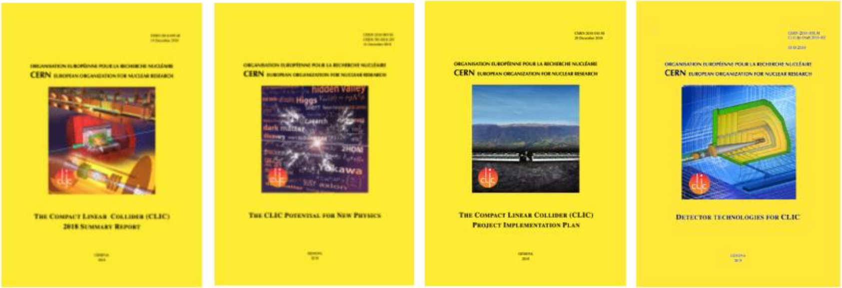


[8]

◆ 4 Yellow Reports 2018

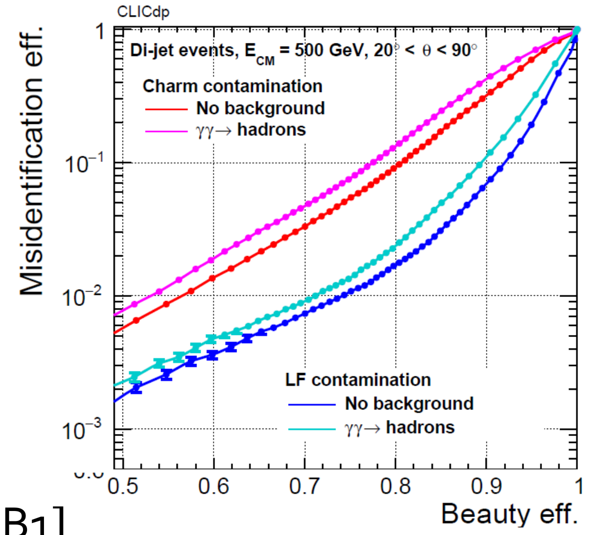


Summary Report | Physics Potential | Project Implementation | Detector Technologies

SIMILAR PERFORMANCE OF LC DETECTORS

c/b-tagging, Higgs branching ratios

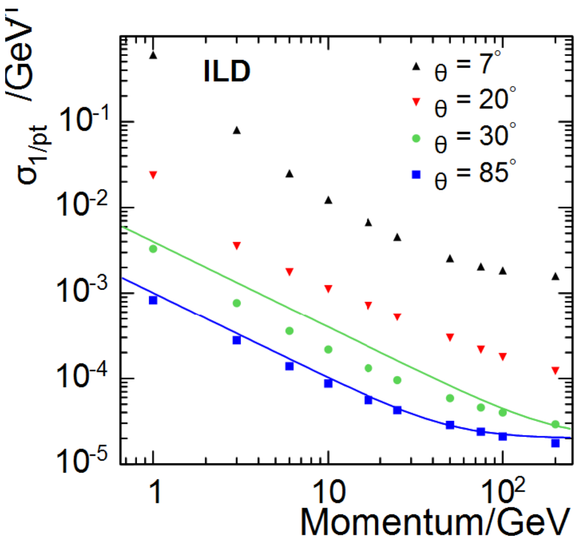
b-tagging @ CLIC



[B1]

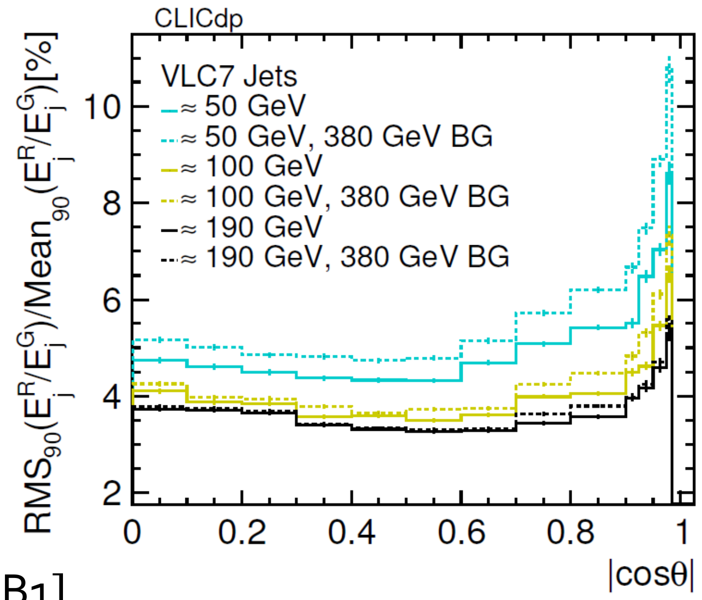
Higgs recoil mass, smuon endpoint,
Higgs coupling to muons

p_T resolution for muons:



Separation of W/Z/H di-jets

3%–4% jet energy resolution gives ~ 2.6 – 2.3σ W/Z separation



[B1]

Particle Flow is the 'key word'. Only neutral particles ID (γ (30%), neutral hadrons (10%)) are left to calorimeters.

PHYSICS PROGRAMME AT A LC

- **HIGGS PHYSICS**
  - HIGGS COUPLINGS: model-independent measurements
    - κ-framework
    - EFT approach
  - HIGGS SELF-COUPLING
  - HIGGS AS A PROBE TO DARK SECTOR AND BSM IN GENERAL
  - CPV IN THE HIGGS SECTOR

  High E (for HIGGS SELF-COUPLING, HIGGS AS A PROBE TO DARK SECTOR AND BSM IN GENERAL, and CPV IN THE HIGGS SECTOR)

- **t-PHYSICS**
  - top-quark mass
  - electroweak couplings
  - rare decays

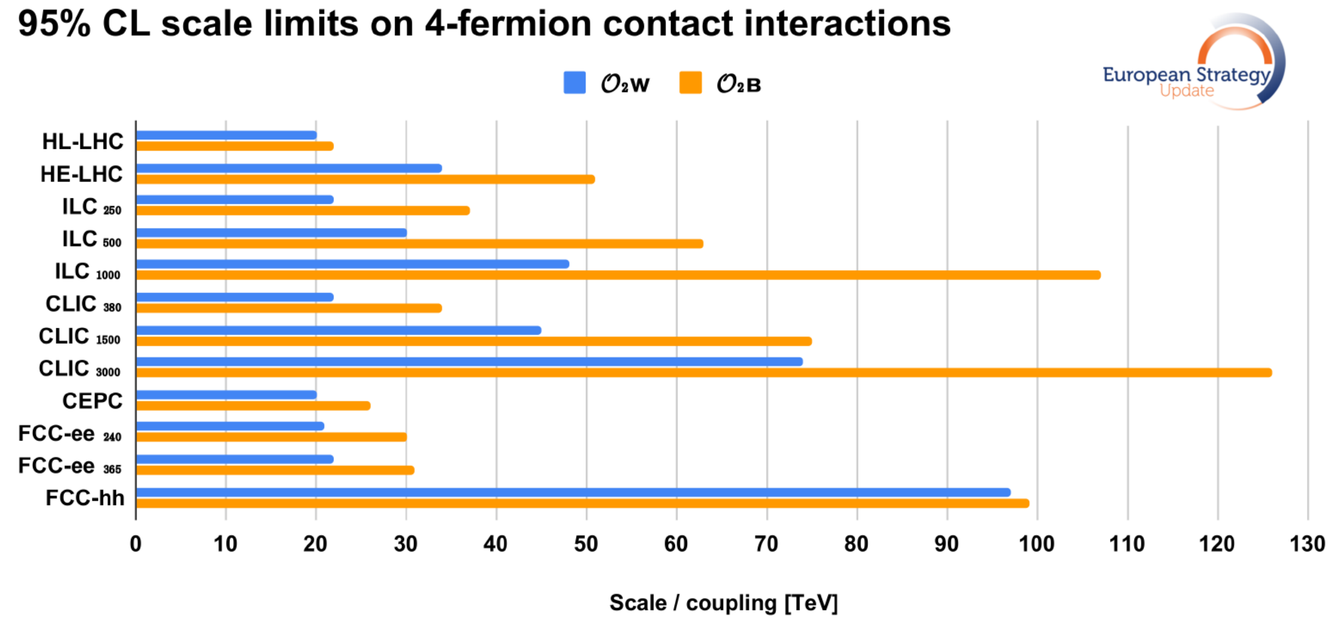
  Low E

  - top Yukawa coupling
  - CP properties
  - BSM constraints

  High E

- **BSM**
  - direct searches
  - models with weak couplings or soft signatures
  - indirect searches
  - high sensitivity

  High E

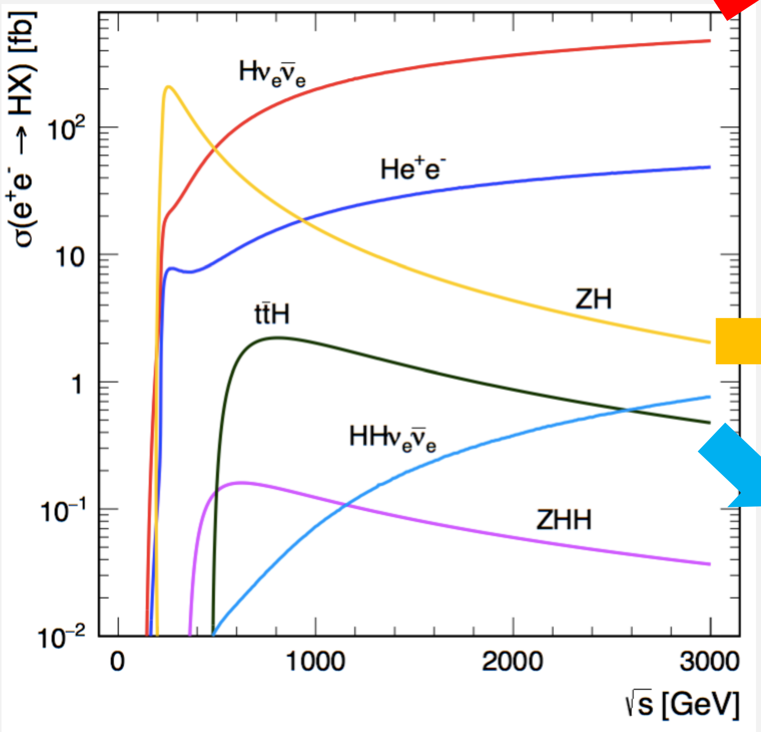


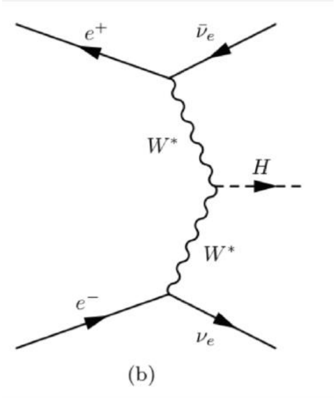
Due to staged realization of LCs, these are ideal machines to explore large physics span, with indirect access to the ~ 100 TeV scale

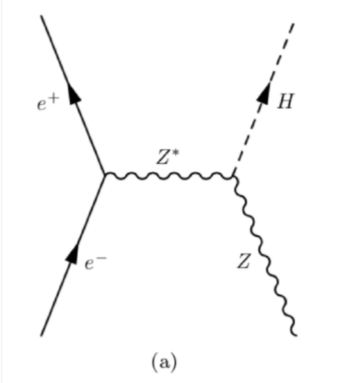
HIGGS PRODUCTION MECHANISMS AT LC

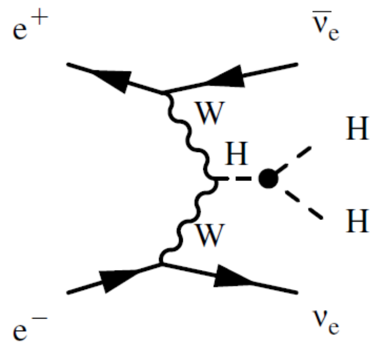
- Higgsstrahlung (ZH) is a unique feature of particle-antiparticle collisions (i.e. e+e- colliders)
- It facilitates g_{HZZ} measurement in a **model-independent way** * (ZH cross-section)
- Higgs invisible width can be determined from the recoil mass
- Most of the Higgs couplings can be determined with a better precision than at HL-LHC only from ZH

- Linear colliders foreseen as staged machines benefit from additional statistics from WW-fusion (clear example is CLIC with ~ 3M Higgs bosons at all stages)
- Double Higgs production at higher energies enables self-coupling measurement







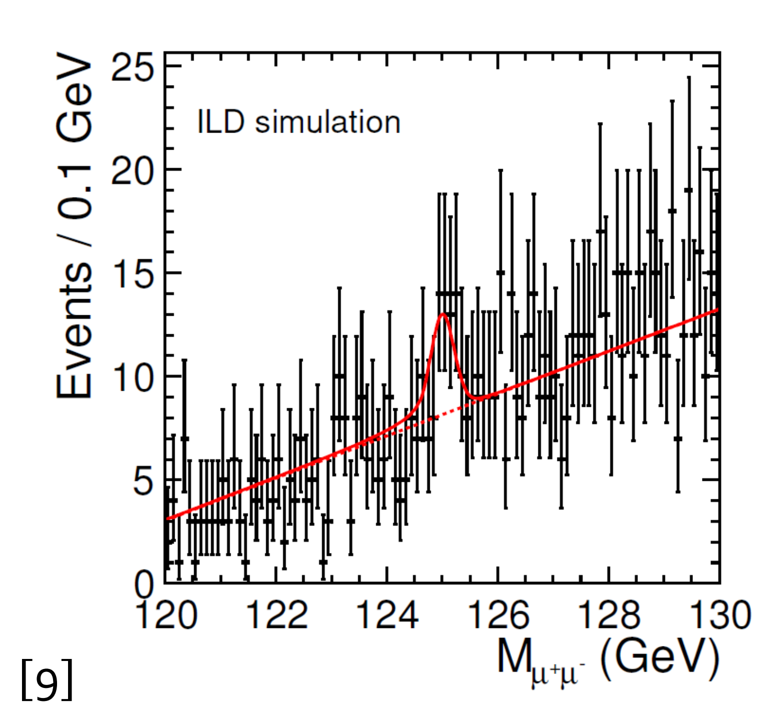


* Theory warning: level of accuracy <1% requires incorporation of loop-corrections → loss of strict model-independence

High-energy benefits, polarization, combination ➡ access to rare Higgs decays

- Clear advantage from rising cross-section for WW-fusion with energy
- ttH production, suitable i.e. for CPV study in the Higgs sector
- Multiple-Higgs production → self-coupling measurement
- Less precise determination of the observable at high energy leads to the same precision on coupling as at low energy

Decay mode	Branching ratio
$H \to b\bar{b}$	56.1%
$H \to WW^*$	23.1%
$H \to gg$	8.5%
$H \to \tau^+\tau^-$	6.2%
$H \to c\bar{c}$	2.8%
$H \to ZZ^*$	2.9%
$H \to \gamma\gamma$	0.23%
$H \to Z\gamma$	0.16%
$H \to \mu^+\mu^-$	0.021%
Γ_H	4.2 MeV



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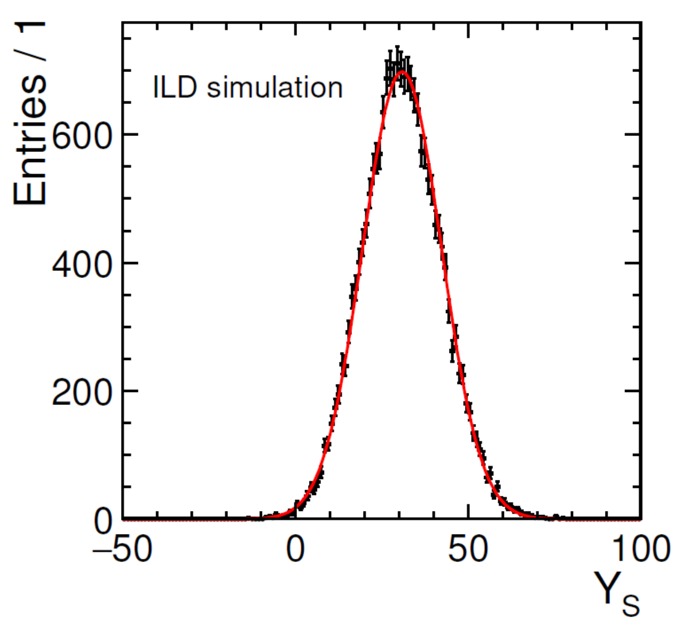


$\sqrt{s} = 250$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC250	ILC250+500
L	34%	113%	23%	17%
R	36%	111%		
$\sqrt{s} = 500$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC500	
L	43%	37%	24%	
R	48%	106%		

HIGGS PHYSICS

Situation at LHC (HL-LHC, and pp in general)

- No absolute measurement of the production cross-section (like ZH at e+e- colliders)
- Higgs couplings come in combination:

$$\sigma(H) \times \mathrm{BR}(H \to a + b) \sim \frac{\Gamma_{\mathrm{prod}}\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}}$$

- Only ratio of couplings can be directly determined (i.e. $g^2_{H\tau\tau}/g^2_{HWW}$)

e+e- colliders

- Absolute measurement of the ZH cross-section
- Absolute measurement of the Higgs BRs
- Nearly model-independent determination of the Higgs total width and couplings
- High energy benefits of LCs: λ, CPV, BSM extensions of the Higgs sector

HIGGS COUPLINGS

How well do we need to know Higgs couplings?

- In many BSM models one expects only % level deviations from the SM couplings for BSM particles in the TeV range
- Higgs to EW bosons couplings are particularly sensitive to BSM; λ even more
- Example, 2HDM-type model in decoupling limit [B2]

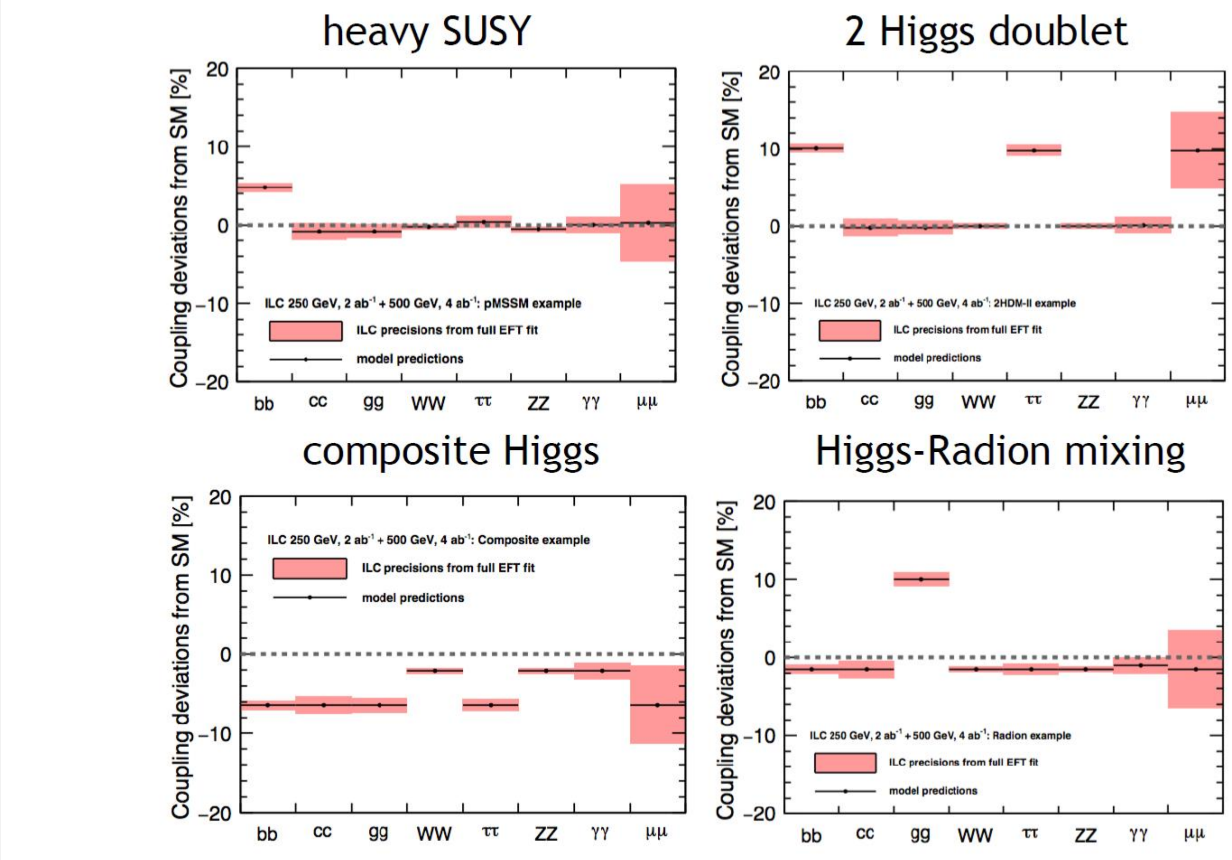
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \text{GeV}}{m_A}\right)^4$$

$$\frac{g_{htt}}{g_{h_{SM}tt}} = \frac{g_{hcc}}{g_{h_{SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2.$$

The models below are outside the HL-LHC reach

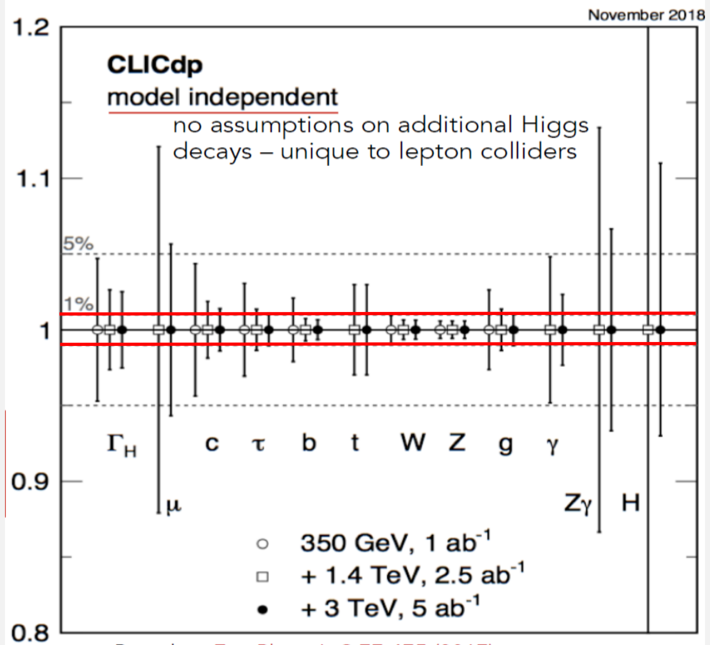
[T. Barklow et al. '17]



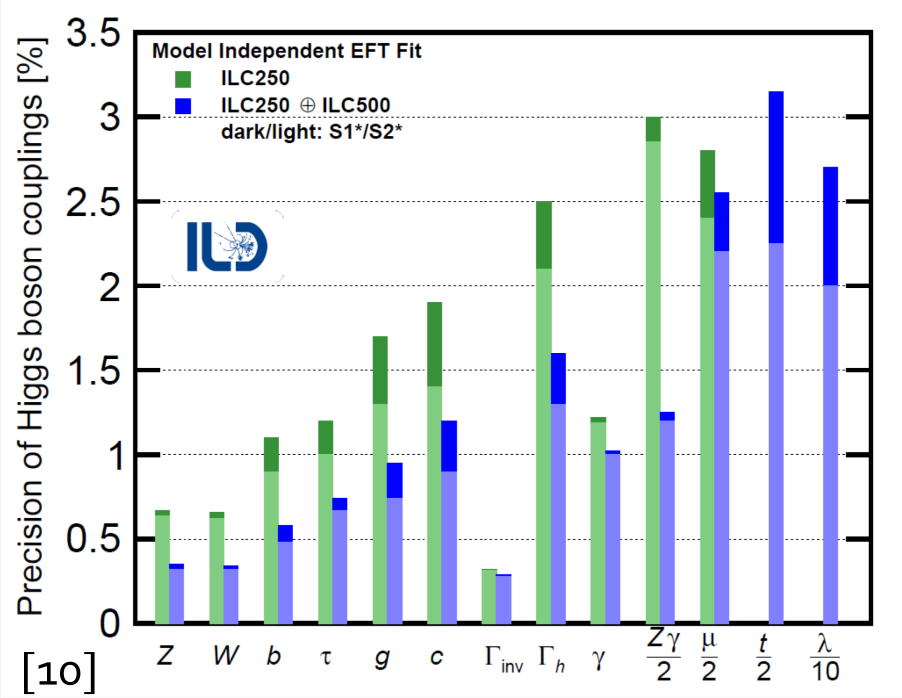
Percent order accuracy on Higgs couplings offers access to various BSM scenarios

HIGGS COUPLINGS

Model independent approach*,
precision better than 1% for most couplings



Based on Eur. Phys. J. C 77 475 (2017)
updated to new luminosity scenario arXiv:1812.01644



[10]

Similar at circular colliders...

in %	FCC-ee 240 GeV	+FCC-ee 365 GeV	+HL-LHC
δg_{HZZ}	0.25	0.22	0.21
δg_{HWW}	1.3	0.47	0.44
δg_{Hbb}	1.4	0.68	0.58
δg_{Hcc}	1.8	1.23	1.20
δg_{Hgg}	1.7	1.03	0.83
$\delta g_{H\tau\tau}$	1.4	0.8	0.71
$\delta g_{H\mu\mu}$	9.6	8.6	3.4
$\delta g_{H\gamma\gamma}$	4.7	3.8	1.3
δg_{Htt}			3.3
$\delta\Gamma_H$	2.8	1.56	1.3

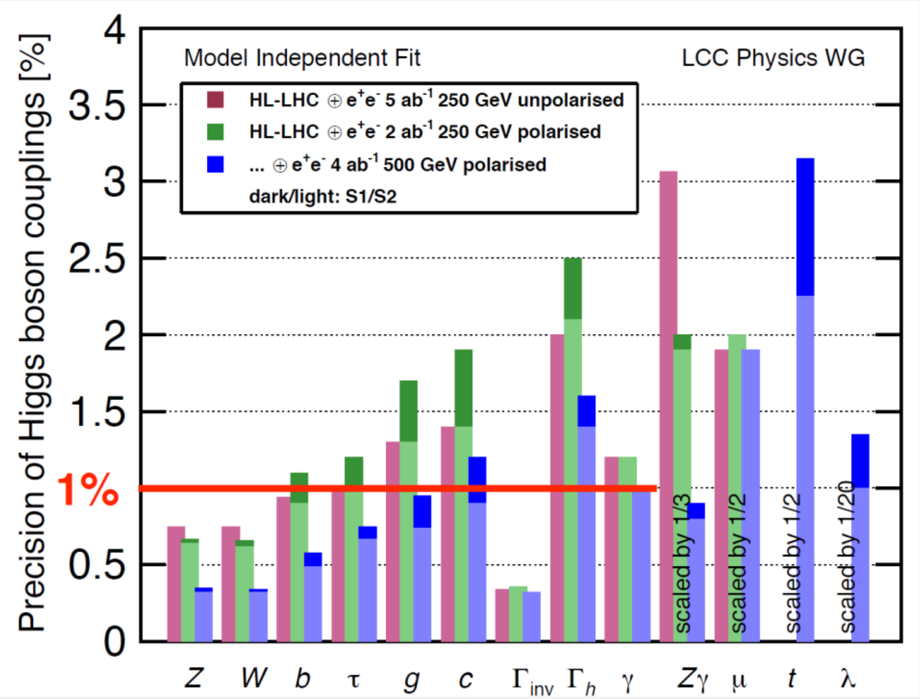
Statistical uncertainties are shown for 5 ab^{-1}@240 GeV and 1.5 ab^{-1}@365 GeV (from FCC-ee CDR)

COMBINATION WITH HL-LHC

To what extent future e+e- experiments are synergistic with the HL- LHC?

Evident synergy

- An example: ILC250 with 250 fb^{-1}
- Already the single measurement of the HZ cross section at ILC 250 yields a very large improvement of the HL-LHC accuracies



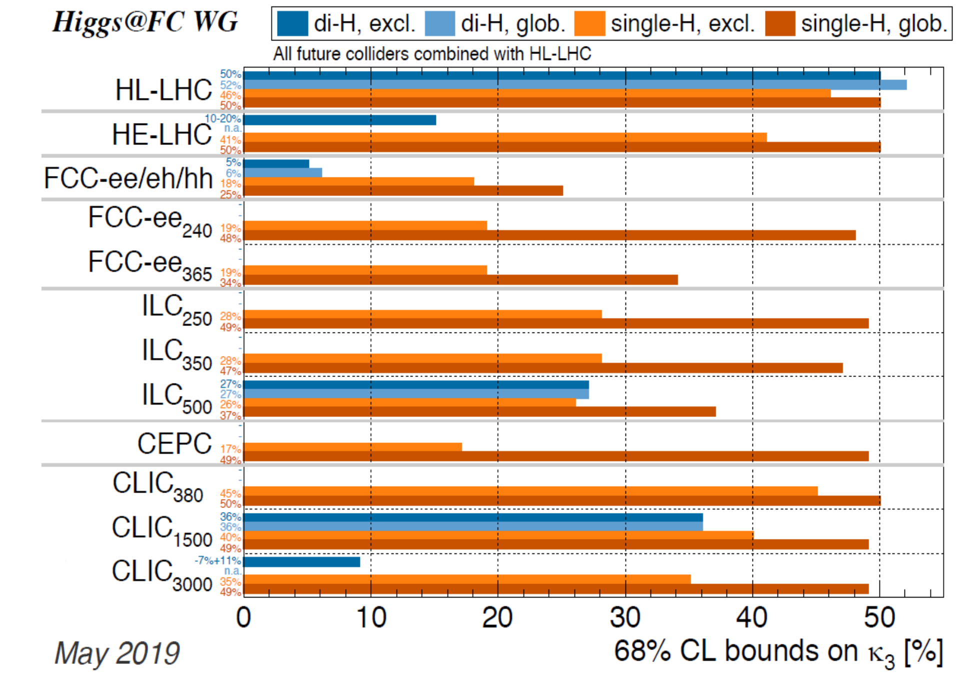
[11]

	Benchmark	HL-LHC	HL-LHC + CLIC 380 ($4\,ab^{-1}$)	HL-LHC + CLIC 380 ($1\,ab^{-1}$) + 1500 ($2.5\,ab^{-1}$)	HL-LHC + FCC-ee 240	HL-LHC + FCC-ee 365
$g^{eff}_{HZZ}[\%]$	$SMEFT_{ND}$	3.6	0.3	0.2	0.5	0.3
$g^{eff}_{HWW}[\%]$	$SMEFT_{ND}$	3.2	0.3	0.2	0.5	0.3
$g^{eff}_{H\gamma\gamma}[\%]$	$SMEFT_{ND}$	3.6	1.3	1.3	1.3	1.2
$g^{eff}_{HZ\gamma}[\%]$	$SMEFT_{ND}$	11.	9.3	4.6	9.8	9.3
$g^{eff}_{Hgg}[\%]$	$SMEFT_{ND}$	2.3	0.9	1.0	1.0	0.8
$g^{eff}_{Htt}[\%]$	$SMEFT_{ND}$	3.5	3.1	2.2	3.1	3.1
$g^{eff}_{Hcc}[\%]$	$SMEFT_{ND}$	—	2.1	1.8	1.4	1.2
$g^{eff}_{Hbb}[\%]$	$SMEFT_{ND}$	5.3	0.6	0.4	0.7	0.6
$g^{eff}_{H\tau\tau}[\%]$	$SMEFT_{ND}$	3.4	1.0	0.9	0.7	0.6
$g^{eff}_{H\mu\mu}[\%]$	$SMEFT_{ND}$	5.5	4.3	4.1	4.	3.8
$\delta g_{1Z}[\times 10^2]$	$SMEFT_{ND}$	0.66	0.027	0.013	0.085	0.036
$\delta \kappa_{\gamma}[\times 10^2]$	$SMEFT_{ND}$	3.2	0.032	0.044	0.086	0.049
$\lambda_Z[\times 10^2]$	$SMEFT_{ND}$	3.2	0.022	0.005	0.1	0.051

The same holds for CLIC (and FCCee, CEPC)

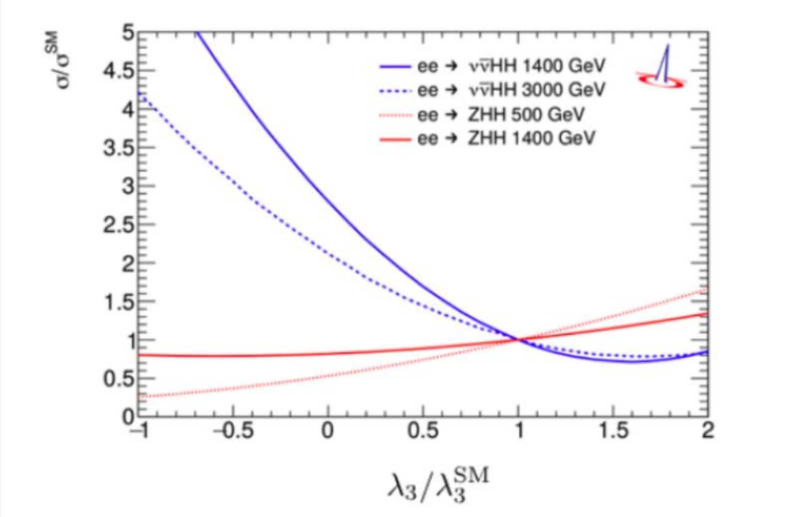
HIGGS SELF-COUPLING

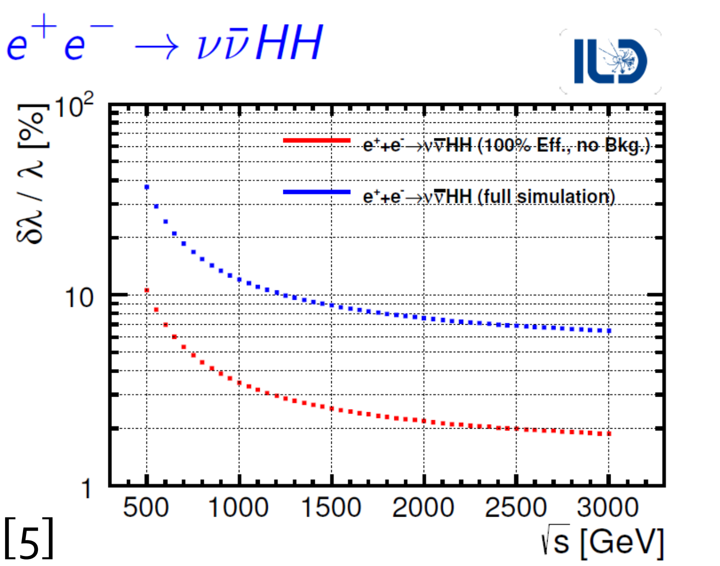
- High energy (>1 TeV) e+e- collider is superior in determination of the Higgs self-coupling
- High energy (double) Higgs production is the most sensitive to deviations of the Higgs self-coupling
- λ is determined from the total rate of HH events (ILD) or template fit of m_{HH} and BDT output (CLICdp)
- Polarization (i.e. -80%) almost doubles the HHνν rate



Low energy e+e- colliders (single Higgs production) in combination with HL-LHC:

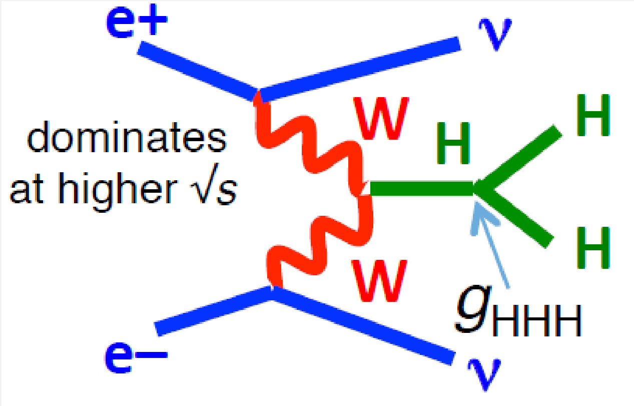
- **ILC250 and FCCee365, ±35%**
- **Double-Higgs production:**
  - **HL-LHC: ~ ±50%**
  - **ILC500 ~ ± 27%**
  - **CLIC3000 ~ ± 9%**
  - **FCC-hh ~ ± 5%**

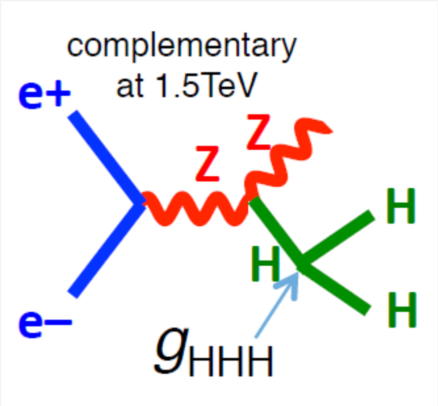




[5]

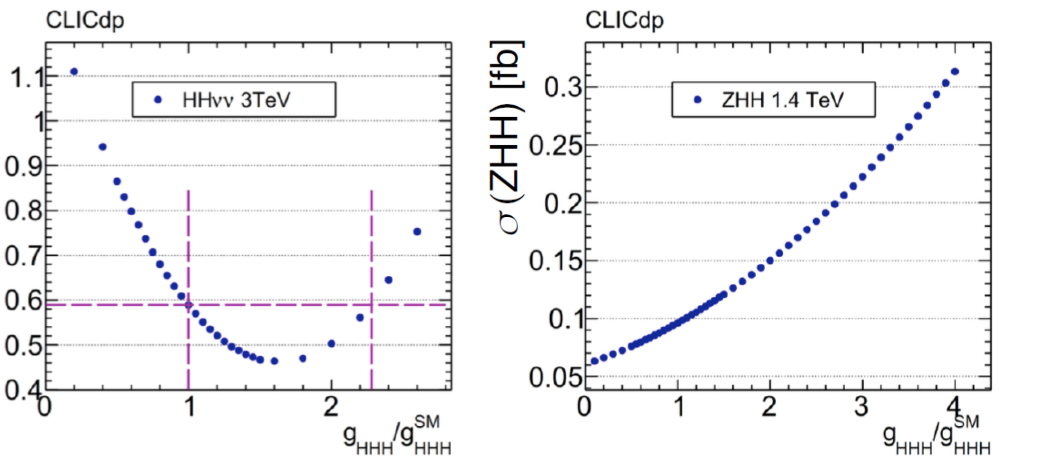
LC BENEFITS: STAGING, COMBINATIONS…



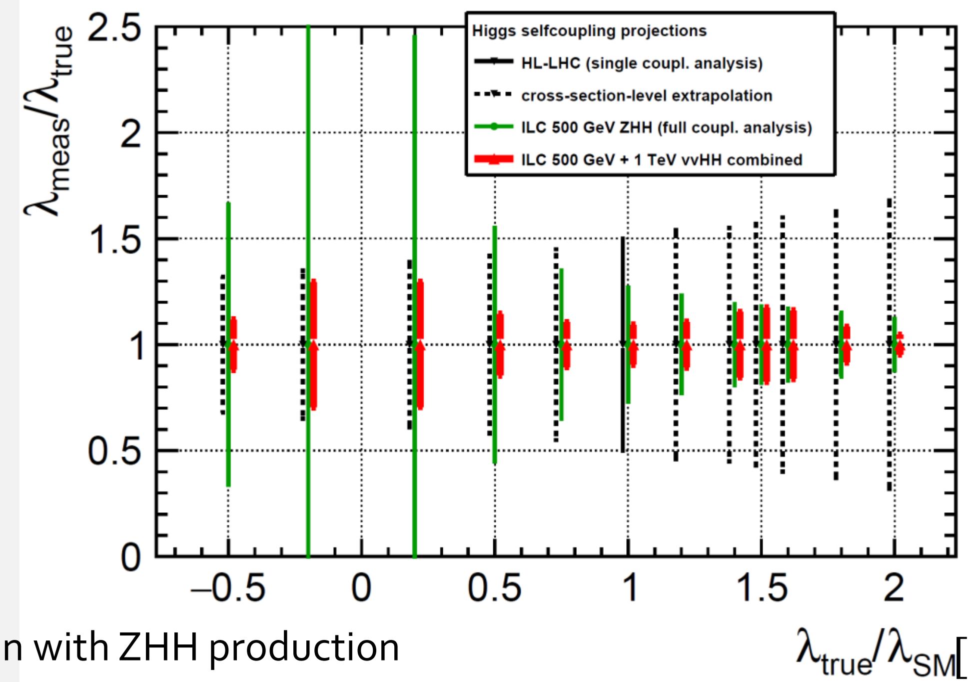


[7]	$\Delta\lambda_{hhh}/\lambda_{hhh}$
4 ab^{-1} at ILC500	27%
+8 ab^{-1} at ILC1000	10%

Higgs self-coupling



[4]

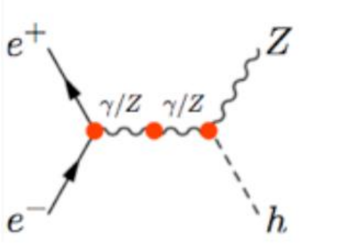


[B4]

- Intermediate energy (1.4(5) TeV) at CLIC provides complementarity to 3 TeV option with ZHH production
- Different behavior of ZHH and double-Higgs production in WW-fusion, for non-SM values of triple Higgs couplings resolves ambiguity from interference
- Statistical uncertainty reduction in combination
- **Clear gain from high center-of-mass energies**

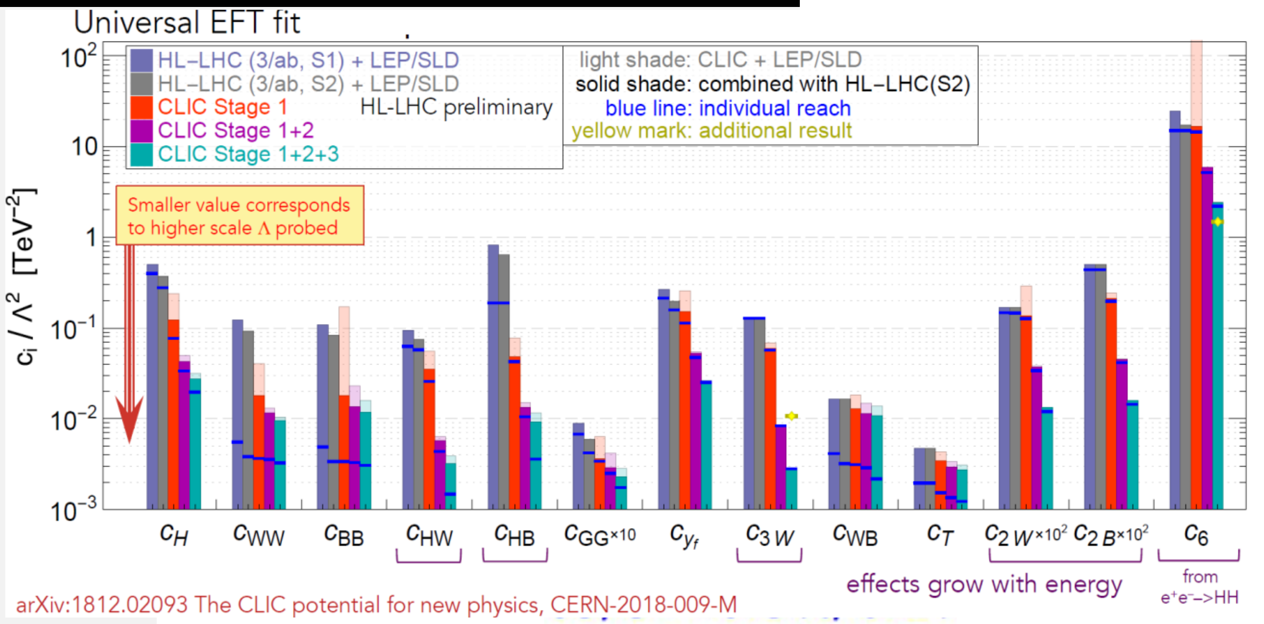
HIGGS AS A PROBE TO BSM

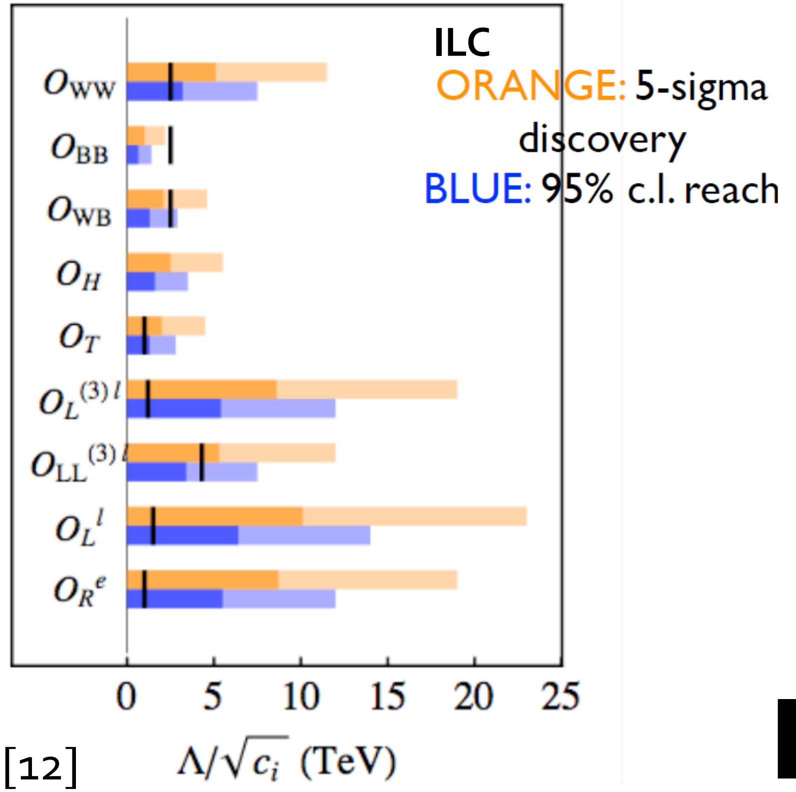
$$\mathcal{L}_{\text{pre-EWSB}} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$



[12] $\delta\sigma/\sigma = 0.5\%/0.1\%$

- BSM physics can manifest itself in the Higgs sector in several ways:
  - Contribution from the higher order operators (EFT approach)
  - Higgs compositeness
  - Extended Higgs sector
  - DM portal
  - CPV



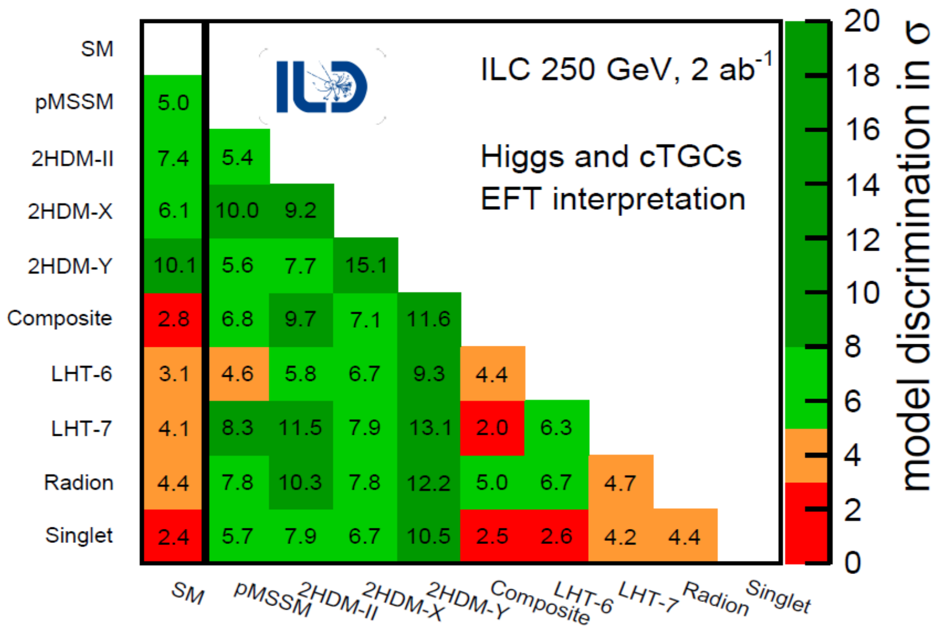


[12]

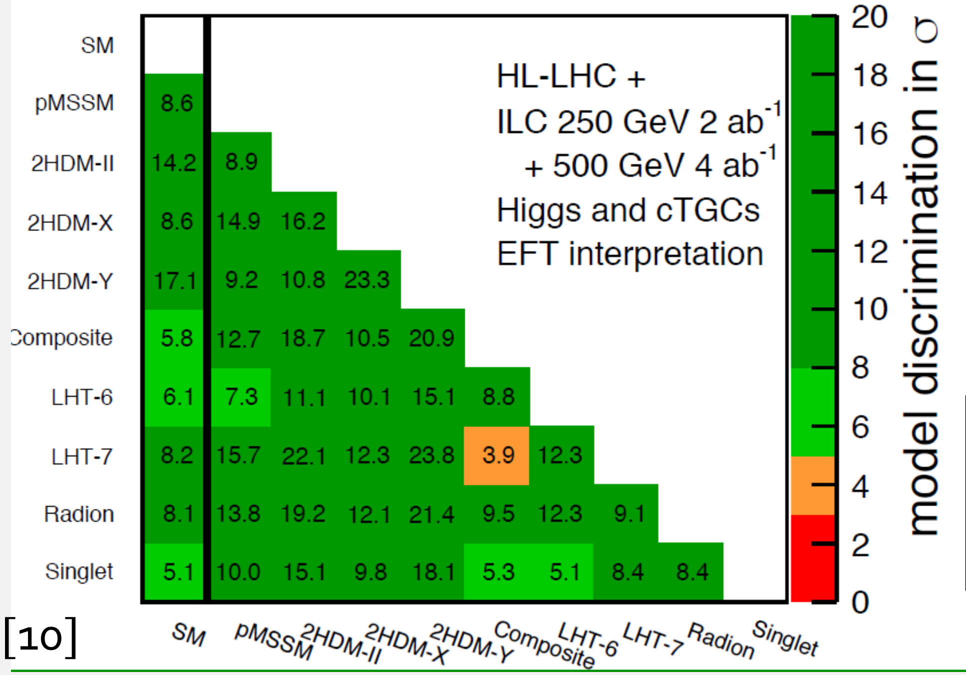
High energy Higgs production is the most sensitive to contributions from the 6D operators in the EFT approach and thus can probe the highest New Physics scale Λ

HIGGS AS A PROBE TO BSM – EFT INTERPRETATIONS

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [40]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5



Above 5σ model discrimination already with 250 Gev ILC

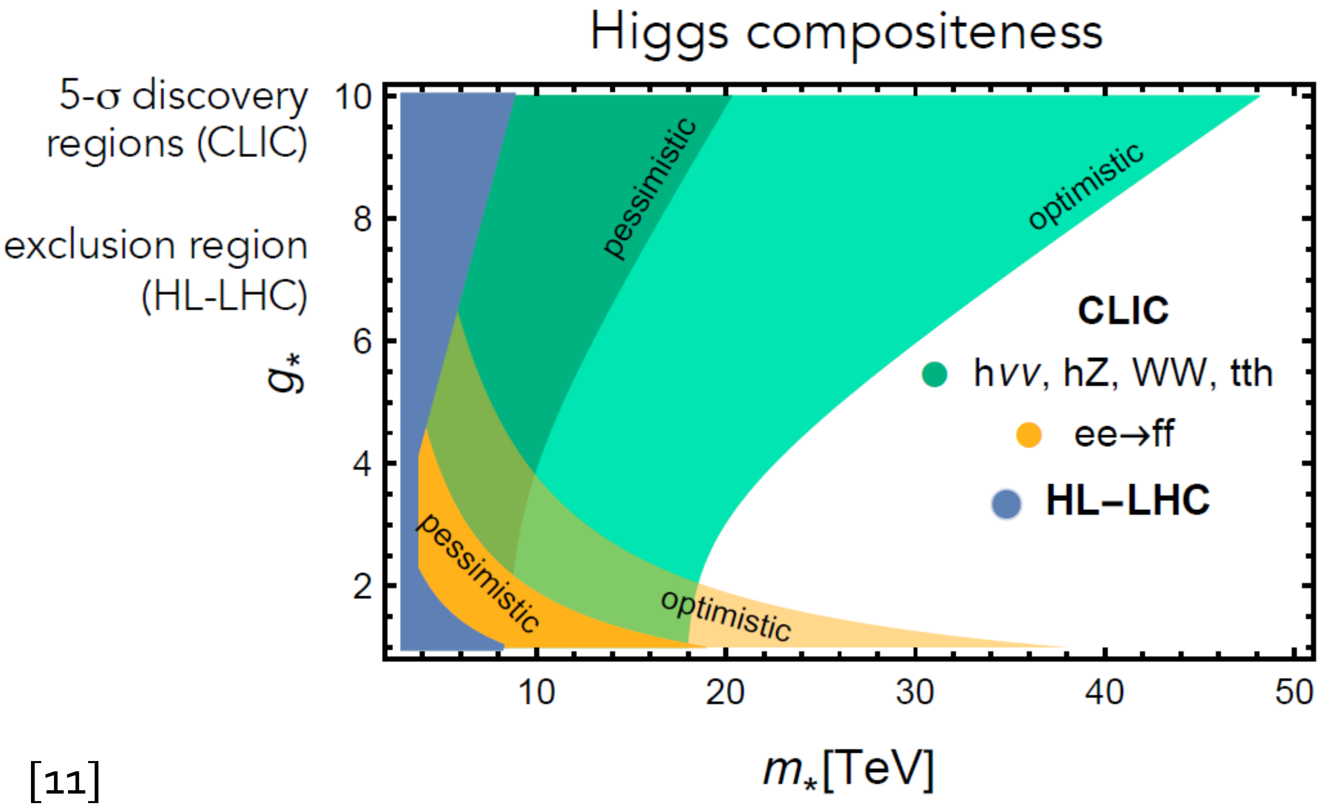


[10]

- Substantial improvement at higher energies (linear e+e- colliders):
@ILC a factor 2 in Higgs couplings precision with 500 GeV polarized beams
- Complementarity with HL-LHC

HIGGS AS A PROBE TO BSM

- BSM physics can manifest itself in the Higgs sector in several ways:
  - Contribution from the higher order operators (EFT approach)
  - <u>Higgs compositeness</u>
  - Extended Higgs sector
  - DM portal
  - CPV

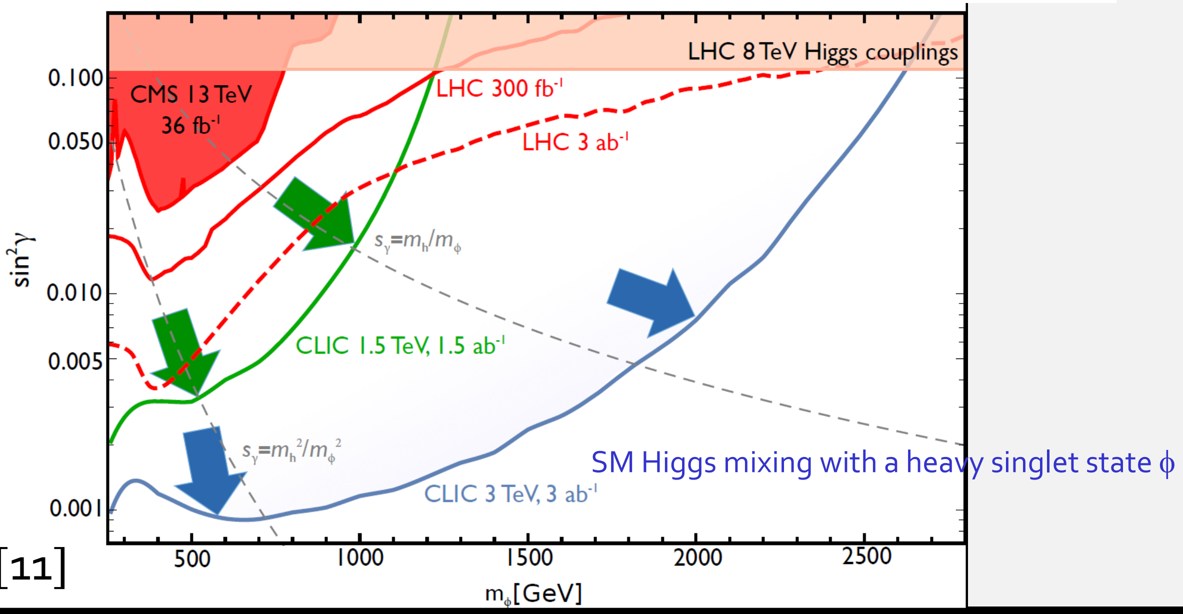


[11]

The scale of compositeness can be probed significantly higher from the high-energy collider kinematic limit

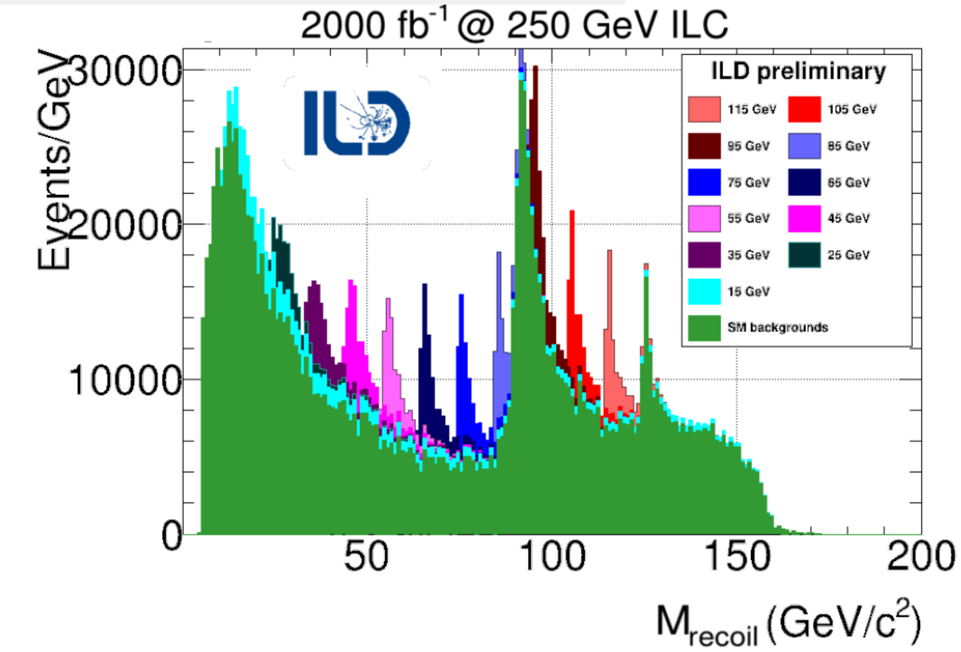
HIGGS AS A PROBE TO BSM

- BSM physics can manifest itself in the Higgs sector in several ways:
  - Contribution from the higher order operators (EFT approach)
  - Higgs compositeness
  - Extended Higgs sector
  - DM portal
  - CPV



[11]

- In majority of BSM models, SM Higgs comes with additional Higgses (2HDM, SUSY in general, compositeness,..etc.)
- Can be a lighter scalar than SM Higgs – it is important to be capable of probing such states at future colliders
- If SM Higgs is the lightest, other states are nearly mass-degenerated

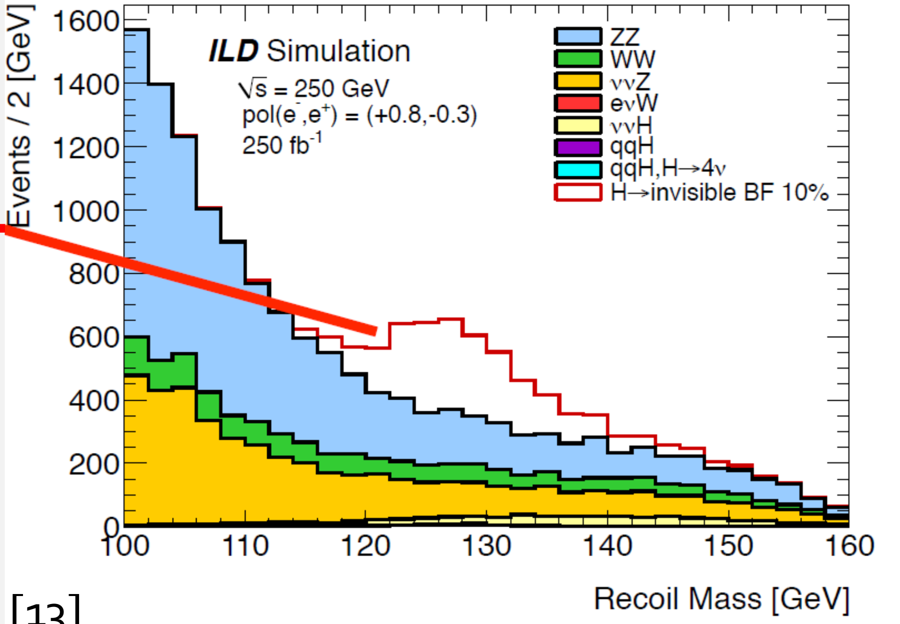


[5] $e^+e^- \to Z\,S^0 \to \mu^+\mu^- + inv$

HIGGS TO INVISIBLE

- BSM physics can manifest itself in the Higgs sector in several ways:
  - Contribution from the higher order operators (EFT approach)
  - Higgs compositeness
  - Extended Higgs sector
  - DM portal
  - CPV

H→inv.

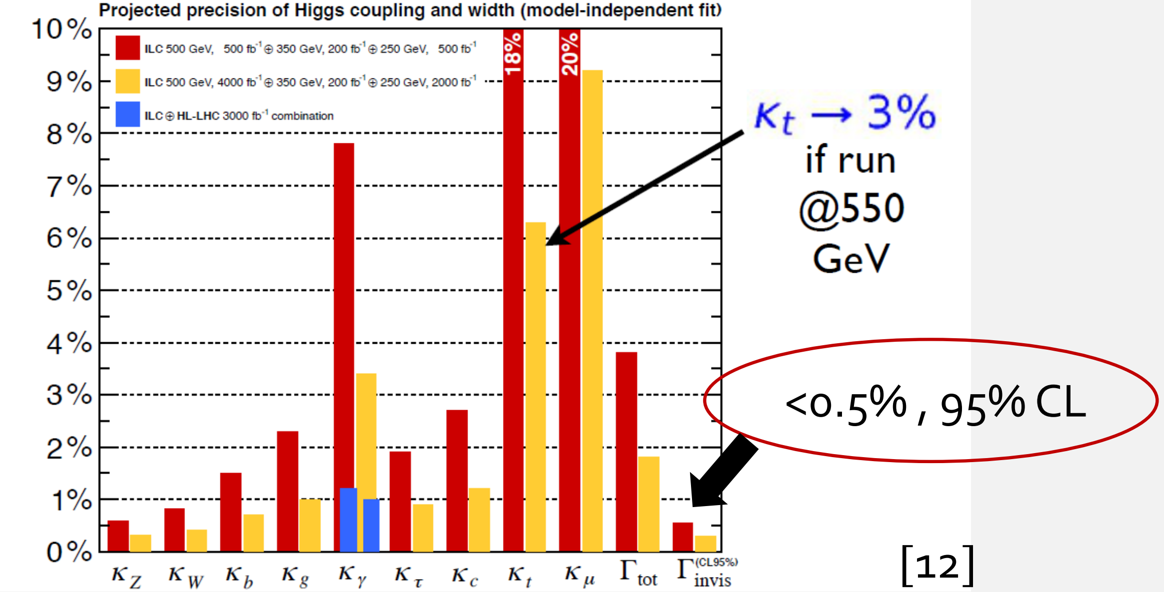


[13]

- Looking at the recoil mass under the condition that nothing observable is recoiling against the *Z* boson (only one Z per event)
- Access to DM connected to SM particles through a specific set of operators (portals)

$$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu} \qquad \epsilon_H |H|^2 |\Phi|^2 \qquad \epsilon_a \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

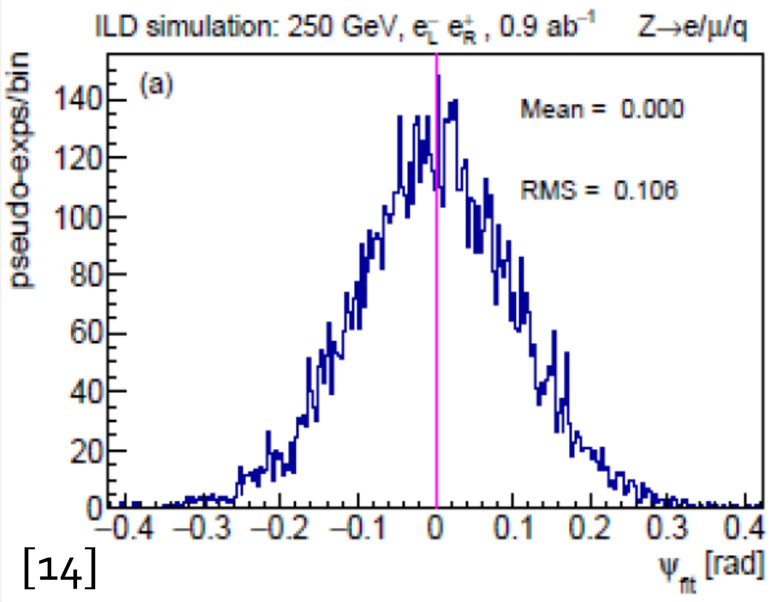
RED - "initial" ILC running, 8 years
ORANGE - "full" ILC running, 20 years



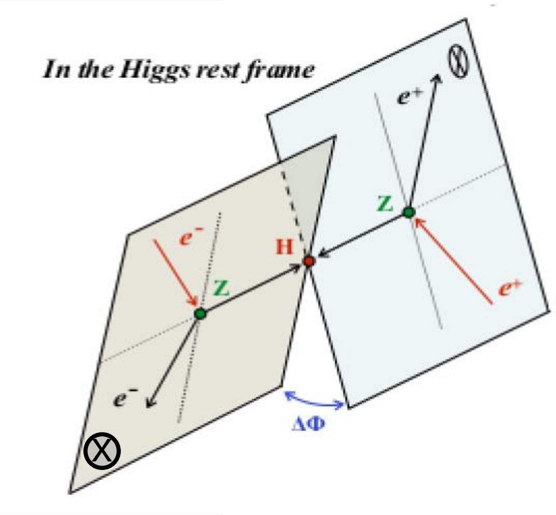
[12]

CPV IN THE HIGGS SECTOR

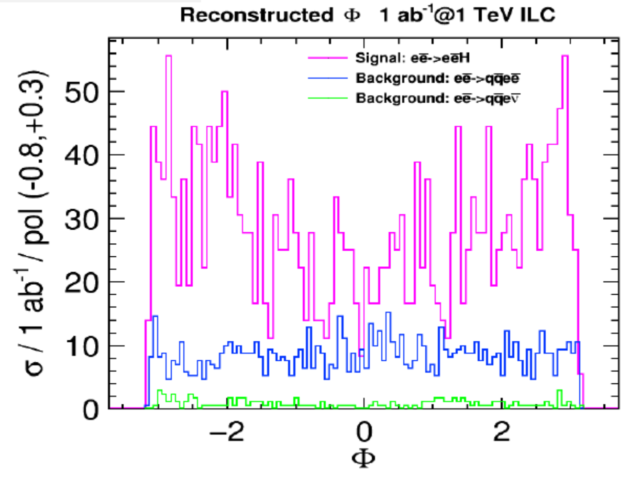
- More difficult than just a spin/parity determination: Higgs can be a mixture of different CP eigenstates
  $$h = H \cdot \cos\psi \; + \; A \cdot \sin\psi$$
- Can be measured in Hff and HVV vertices, both in Higgs production and decays
- Hff (HVV) sensitive to CPV contributions at the tree (loop) level
- Only lose bounds (at present) on a quantum superposition od different CP states, while experimentally disfavored hypothesis on purely CP odd state



[14]



Collider	ψ_{CP}
HL-LHC	8°
HE-LHC	–
CEPC	–
FCC-ee$_{240}$	10°
ILC$_{250}$	4°

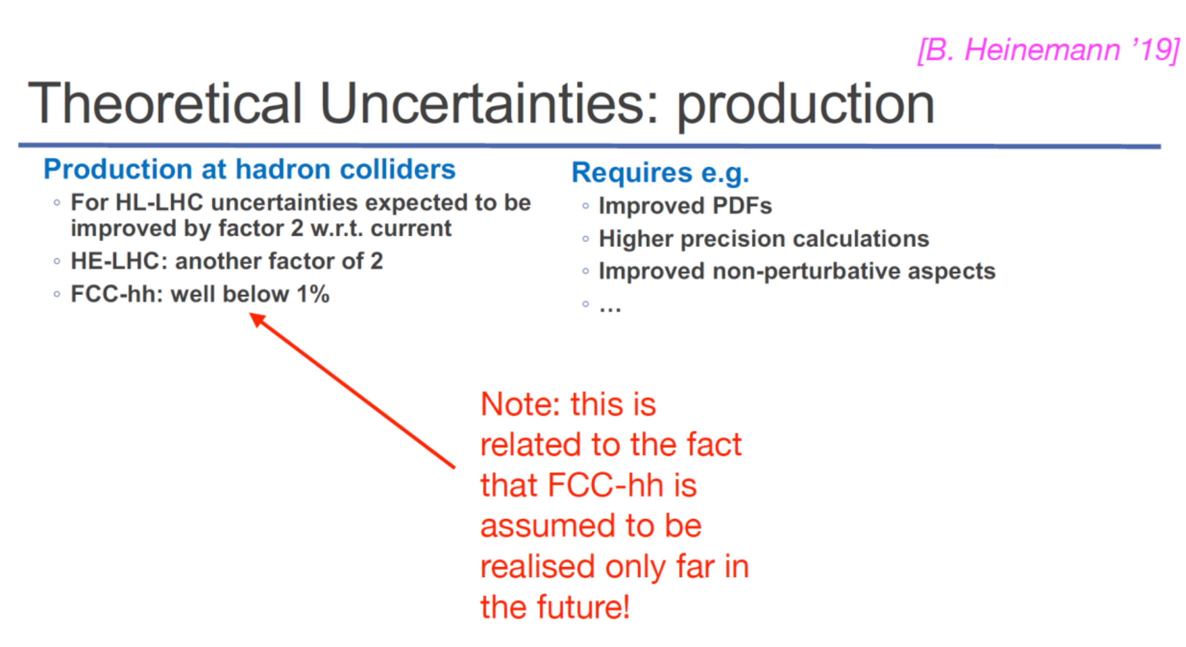


ILC250 – benefit from polarization & combination (Hττ)
1 TeV – optimal for ZZ-fusion

LINEAR VS. CIRCULAR

A word from theory

- Precision vise, linear and circular colliders' precision is comparable when it comes to the Higgs couplings
- Due to high-energy access of high cross-section Higgs production mechanisms, LCs are superior in probing of the Higgs self-coupling
- Extensibility of the physics span (pp collisions, 100 TeV center-of mass energy) is a great advantage of circular colliders
- But, + a 100 TeV hadron-collider, comes at the moment with quite a few open issues:
  - Accelerator & detector technologies
  - Huge pile-up
  - Systematics control and theoretical uncertainties

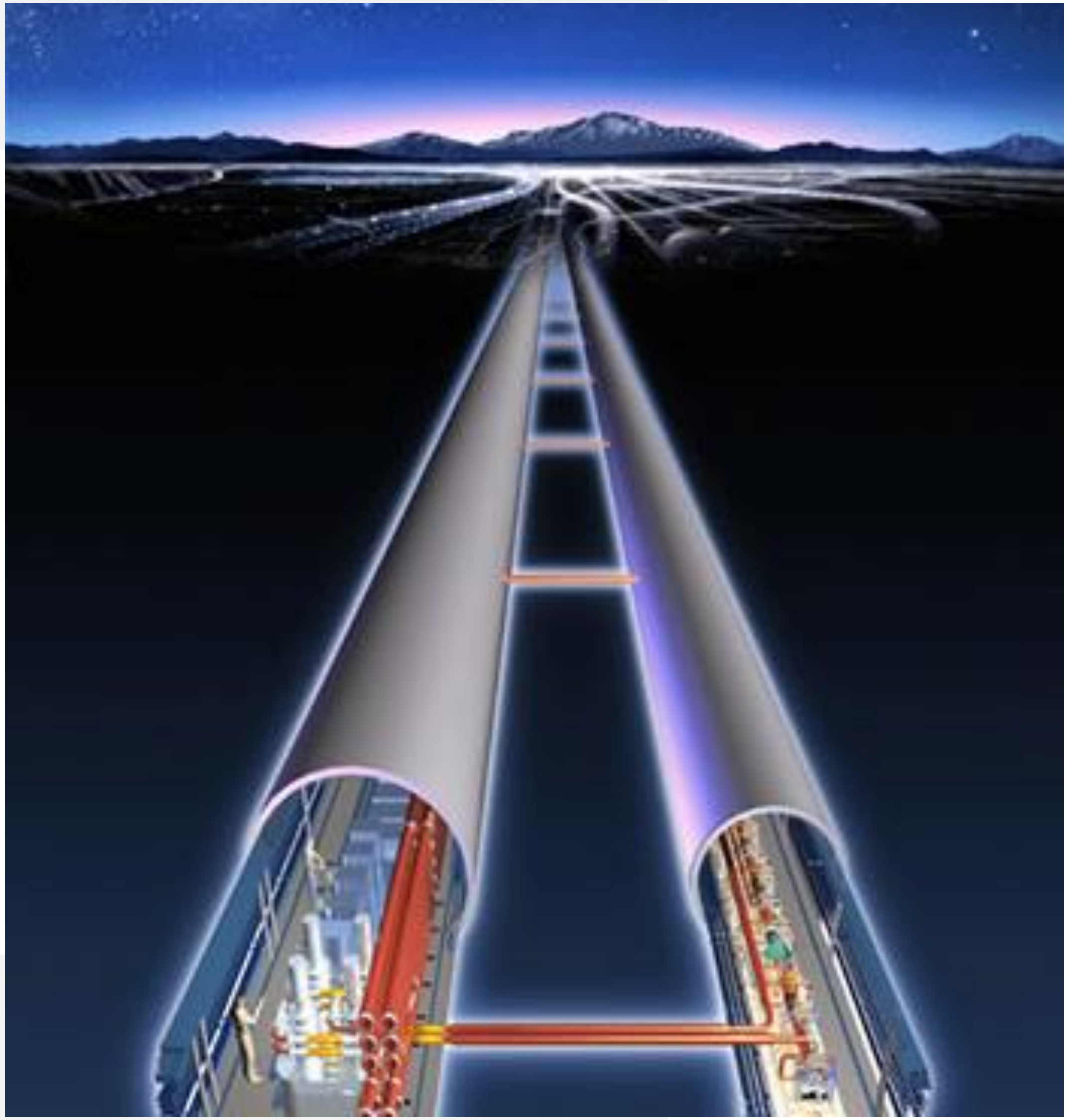


- Precision measurement of couplings at hadron colliders are limited by the systematic (theoretical) uncertainties
- This is also a reason for the fact that the Higgs coupling projections for HE-LHC show only relatively small improvements over HL-LHC
- FCC-hh projections, in particular when taken separately, depend on a drastic reduction of theory uncertainties [B2].

SUMMARY

- All future e+e- projects bring significant added value to the projected HL-LHC sensitivities in the Higgs sector…
- … enabling discrimination of BSM models inaccessible at HL-LHC
- Already lowest energy phases brings sensitivity far beyond the projected HL-LHC precision
- Higher center of mass energies significantly extends physics span of a LC (Higgs self-coupling, BSM scenarios)
  ➡ upgrade is important – genuine advantage of a LC
- Additional enhancement from polarization (precision, model discrimination)

READY-TO-WEAR PROJECTS



Corfu Summer Institute

Workshop on the Standard Model and Beyond

29.08.-08.09. 2021

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THANK YOU

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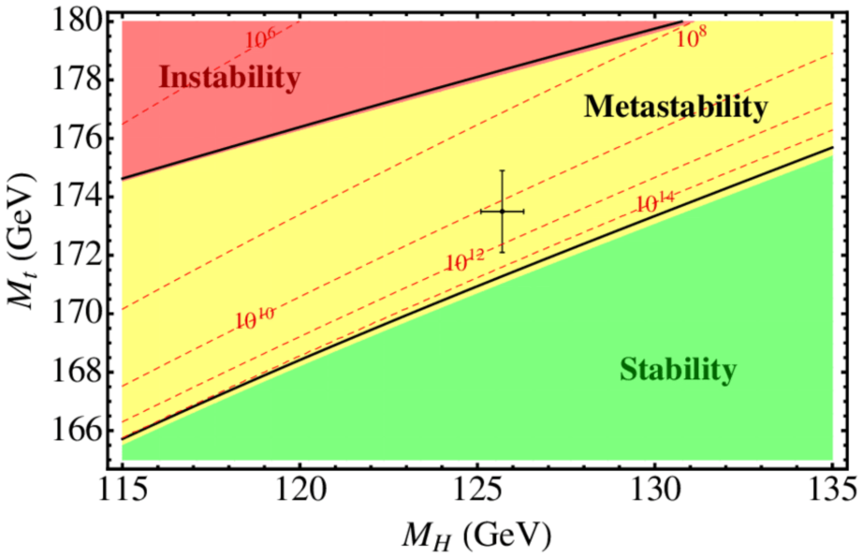
BACK UP

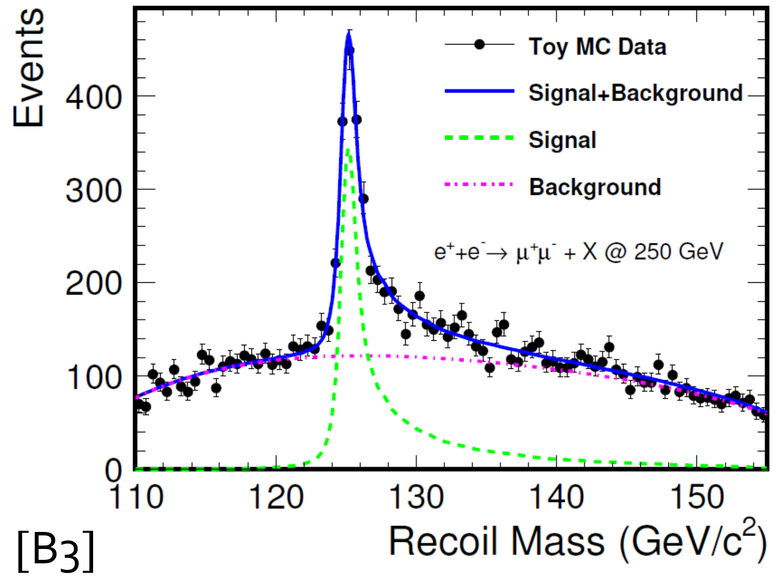
HIGGS MASS

- Which precision of the Higgs mass is needed?
  - Vacuum stability (at least several GeV)
  - Impact on H→ZZ* width (a few tens of MeV)
- Current precision 160 MeV
- Comparable precision with HL-LHC

Collider Scenario	Strategy	δm_H (MeV)	$\delta(\Gamma_{ZZ^*})$ (%)
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	1.9
HL-LHC	$m(ZZ)$	10-20	0.12-0.24
ILC_{250}	ZH recoil	14	0.17
$CLIC_{380}$	ZH recoil	78	1.3
$CLIC_{1500}$	$m(bb)$ in $H\nu\nu$	30[15]	0.56
$CLIC_{3000}$	$m(bb)$ in $H\nu\nu$	23	0.53
FCC-ee	ZH recoil	11	0.13
CEPC	ZH recoil	5.9	0.07

M. Cepeda, Higgs precision measurements at future colliders, IFT UAM-CSIC, Madrid, Spain, July 2019 and [2]





[B3]

HIGGS WIDTH

- Being less than 5 MeV, Higgs decay width can not be *directly* measured at any proposed e+e- collider
- Can be determined from individual decays (quasi-direct measurement), i.e. H→WW decays in WW-fusion, H→ZZ in HZ)

$$\sigma(\mathrm{ee} \to \mathrm{ZH}) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$

- In a combination of measurements:

$$\frac{\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{WW})\cdot\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}{\sigma(\mathrm{ee}\to\nu\nu\mathrm{H})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}$$

$$\propto \frac{g^2_{\mathrm{HZ}}\cdot g^2_{\mathrm{HW}}}{\Gamma} \cdot \frac{g^2_{\mathrm{HZ}}\cdot g^2_{\mathrm{Hb}}}{\Gamma} \cdot \frac{\Gamma}{g^2_{\mathrm{HW}}\cdot g^2_{\mathrm{Hb}}} = \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$

- The ultimate precision is reached in a global fit, (model-independent or in the LHC-style, so called κ-framework):

$$\Gamma_H = \frac{\Gamma_H^{SM}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

- Or in a global (model-dependent) EFT fit (assumes the new physics scale $\Lambda >> M_H$)

Statistical accuracy of 1-2%

Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH,\nu\bar{\nu}H)$, $\mathrm{BR}(H\to Z,b\bar{b},WW)$ [90]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2

arXiv:1905.03764

ILC and CLIC parameters

Property	unit	ILC at 500 GeV	ILC at 1 TeV	CLIC at 380 GeV	CLIC at 3 TeV
L	$cm^{-2}s^{-1}$	$1.8 \cdot 10^{34}$	$3.5 \cdot 10^{34}$	$1.5 \cdot 10^{34}$	$5.9 \cdot 10^{34}$
$L_{0.01}$	$cm^{-2}s^{-1}$	$1.0 \cdot 10^{34}$	$1.2 \cdot 10^{34}$	$0.9 \cdot 10^{34}$	$2.0 \cdot 10^{34}$
$L_{0.01}/L$	%	58	59	60	34
Repetition rate	Hz	5 Hz	4 Hz	50 Hz	50 Hz
Train duration	ns	727 µs	897 µs	178 ns	156 ns
BX / train		1312	2450	356	312
Bunch separation	ns	554 ns	366 ns	0.5 ns	0.5 ns
Duty cycle	%	0.36	0.36	0.00089	0.00078
σ_x/σ_y	nm	474/5.9	481/2.8	∼150/3	∼40/1
σ_z	µm	300	250	70	44