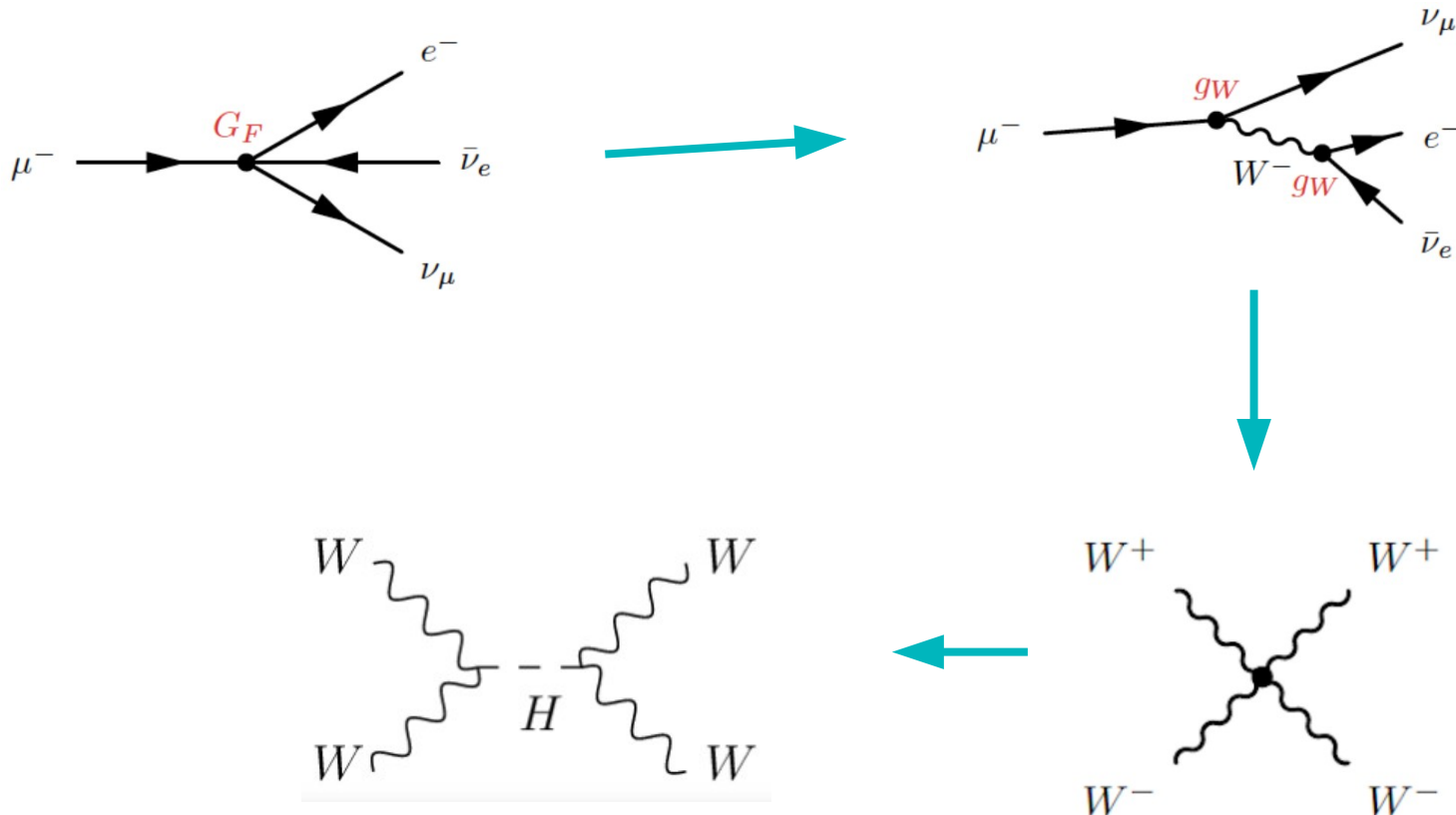# Physics potential of CLIC @3TeV

perspectives towards higher energies

Marc Riembau
Université de Genève

Muon Collider Meeting, 31st March 2020

It is easy judge the past, but with our knowledge of QFT,
starting from the discovery of muon decay,
the history of particle physics seems straightforward...

But the Higgs potential is put by hand in the SM, and there is neither dark matter nor a way to generate baryon asymmetry.

So it would be tempting to keep going:
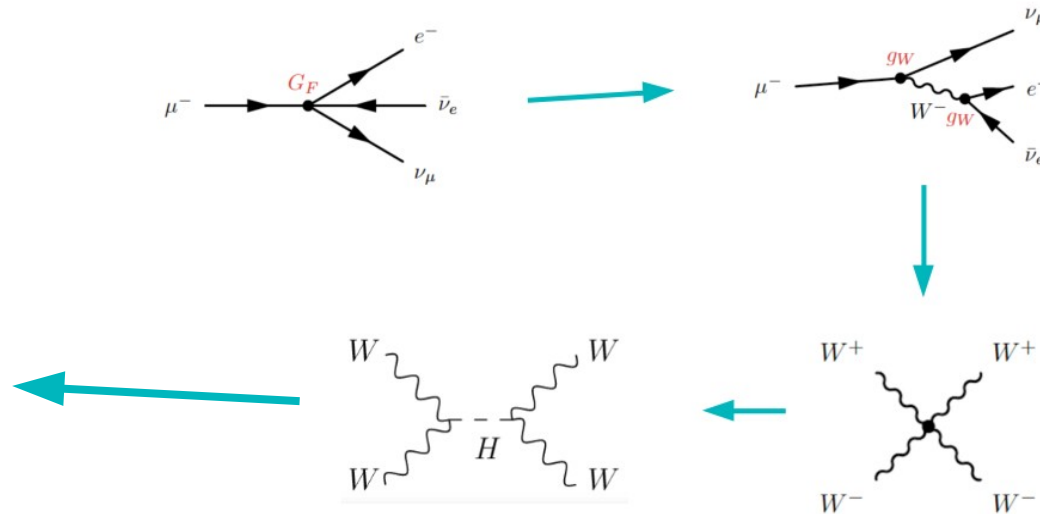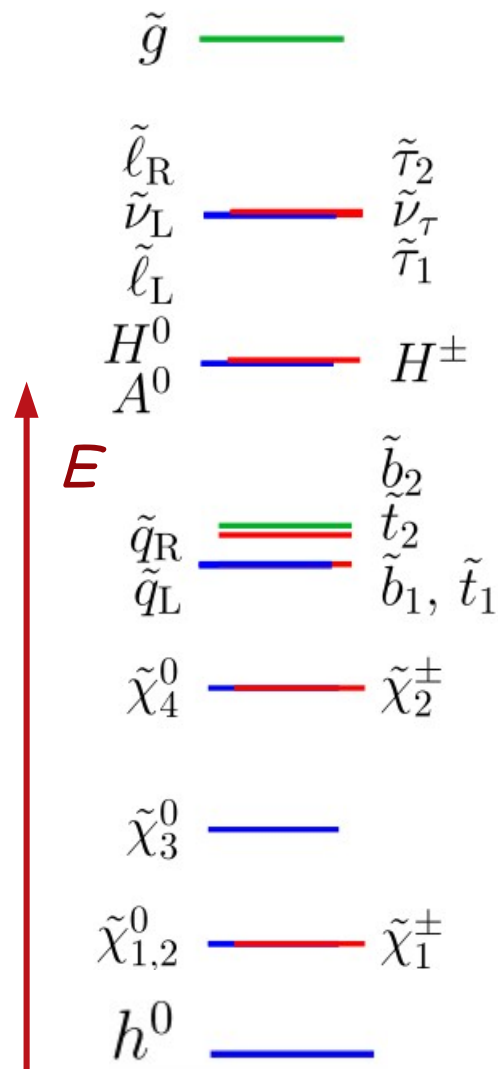
It is easy to imagine a world like this, SUSY was very well motivated and would have given us a DM, GUT, etc...

It would mean, also, that the exploration of Nature at shorter distances would be over. We solved everything. Done.

It is not the case, and
Particle physics is now pure exploration.

In the next years, there will be many experiments testing dynamics at multi-TeV energies:

- DM searches
- muon g-2
- mu3e
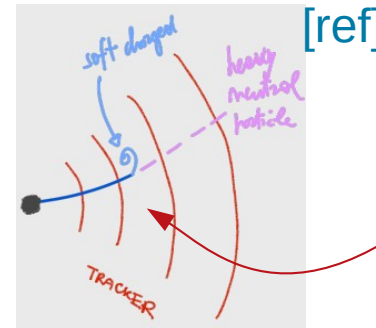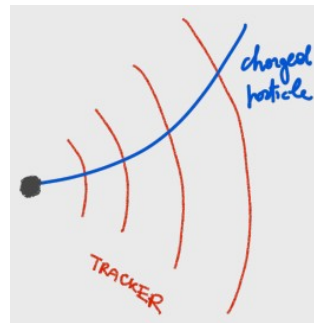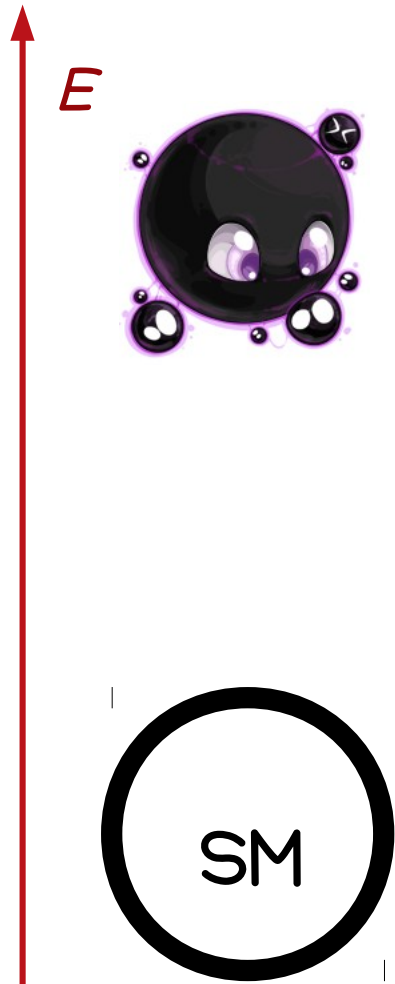- Electron EDM experiments
- Flavour
- ...

The only outcome will be hints to be explored **directly** with high energy colliders.
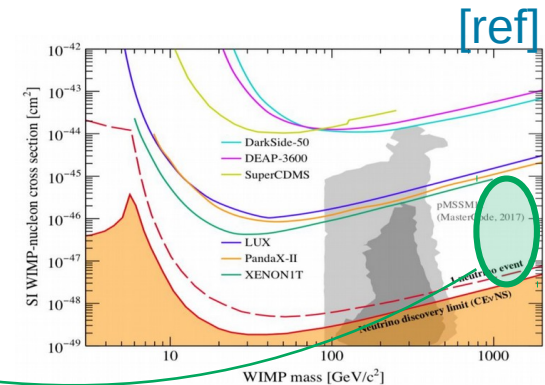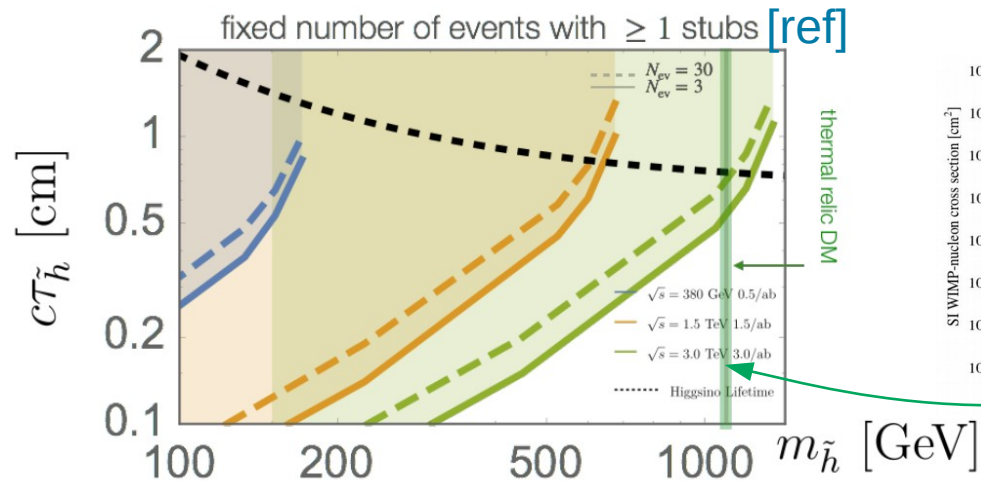
E

SM
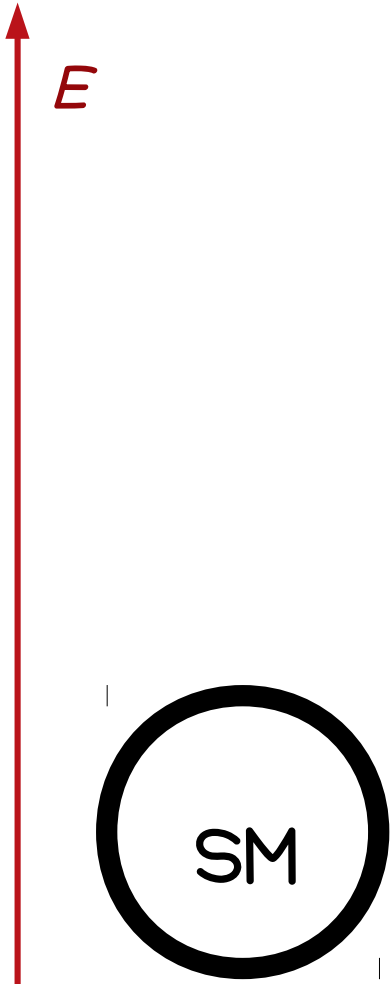
Some **definite questions** might have **definite answers** at a 3TeV lepton collider:

Is **DM** a **WIMP**? A **Higgsino**?

A small splitting between the charged and neutral components gives a displaced vertex:

E

[ref]

$$\chi^\pm \to \chi^0 \pi^\pm$$

fixed number of events with ≥ 1 stubs [ref]

$c\tau_{\tilde{h}}$ [cm]

thermal relic DM

$N_{ev} = 30$
$N_{ev} = 3$

$\sqrt{s} = 380$ GeV 0.5/ab
$\sqrt{s} = 1.5$ TeV 1.5/ab
$\sqrt{s} = 3.0$ TeV 3.0/ab

Higgsino Lifetime

$m_{\tilde{h}}$ [GeV]

[ref]

- Charged track too short to be resolved by LHC
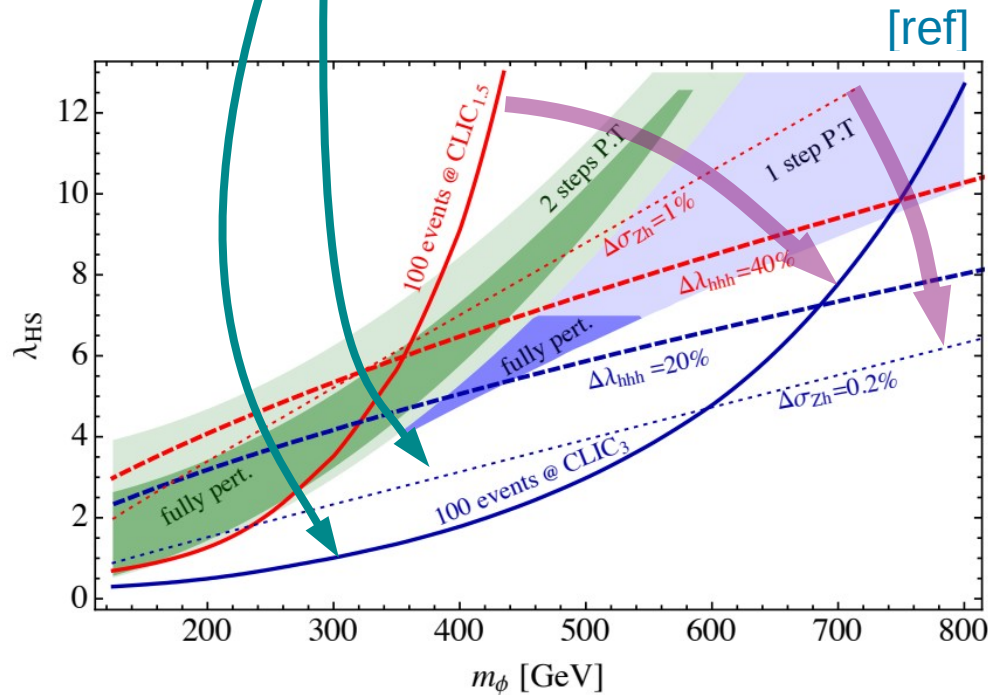- Even at CLIC, high dependence on detector design.

SM

Some **definite questions** might have **definite answers** at a 3TeV lepton collider:
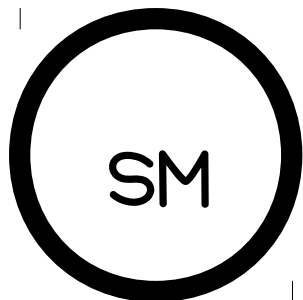
Is there a **singlet** assisting **EW Baryogenesis**?

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} H \\ S \end{pmatrix}$$

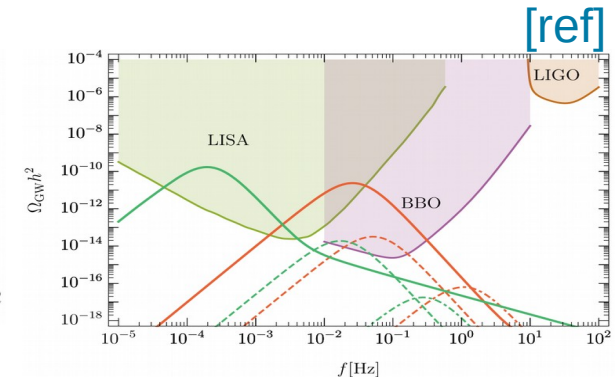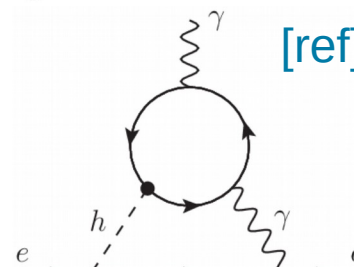**S inherits H properties**: look for heavy, weakly coupled H

S steals H properties: smaller rates for H production

E

[ref]

- 3TeV is enough to cover the relevant parameter space below 1TeV in the simplest scenarios

SM

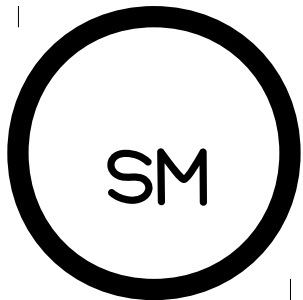- EW Baryogenesis puts together collider direct searches with EDM and GW experiments

[ref]

[ref]

$\mathcal{L}\,?$

E

But the most important aspect of a collider running at high energies is the **exploration of the unknown**.

SM

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$$
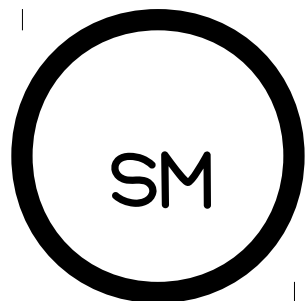
$$\mathcal{L}\,?$$

E

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda}\mathcal{O}_i$$

EFT operators encode information
about the heavy dynamics,
and tells us in which way
the SM is deformed.

SM

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$$
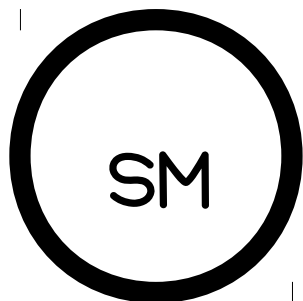
$\mathcal{L}\,?$

E

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda} \mathcal{O}_i$$
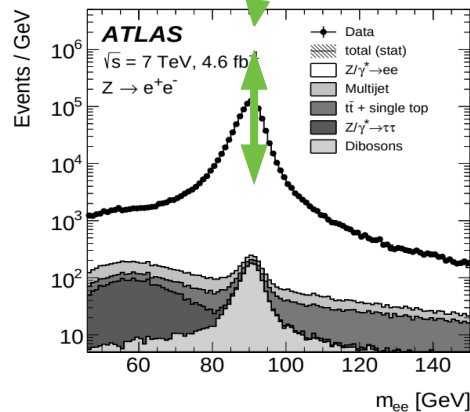
EFT operators encode information about the heavy dynamics, and tells us in which way the SM is deformed.

In a muon collider we might want to focus on high energy probes instead of high luminosity ones
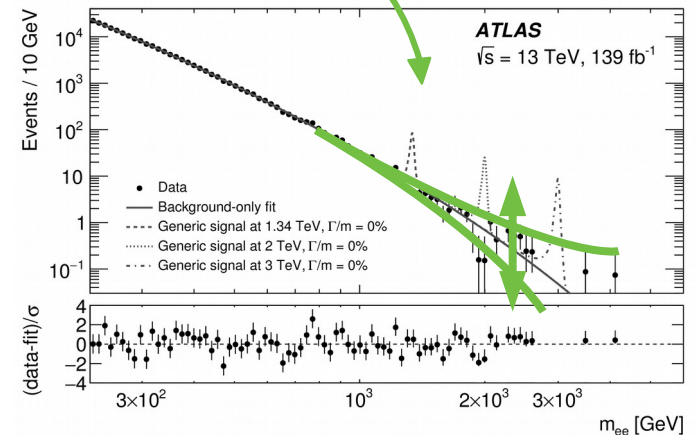
SM

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$$

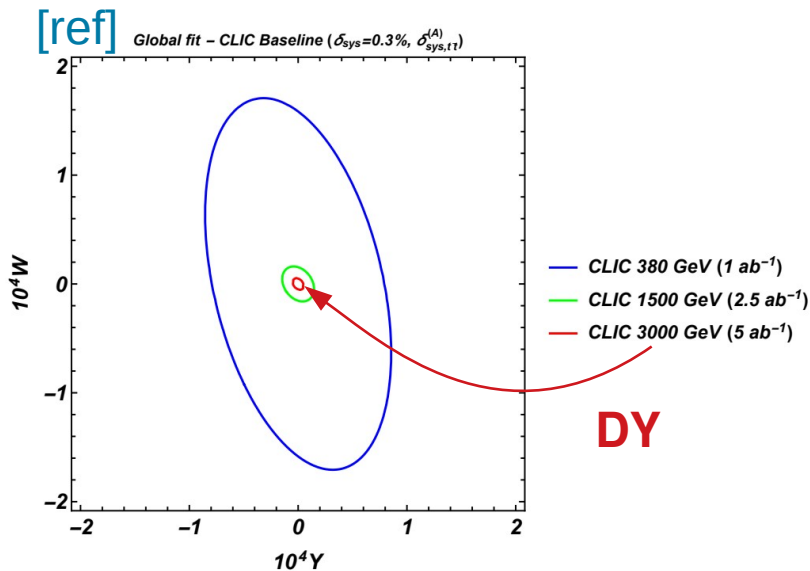$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda} \mathcal{O}_i$$

$$-\frac{W}{4m_W^2}(D_\rho W_{\mu\nu}^a)^2, \quad -\frac{Y}{4m_W^2}(D_\rho B_{\mu\nu})^2$$
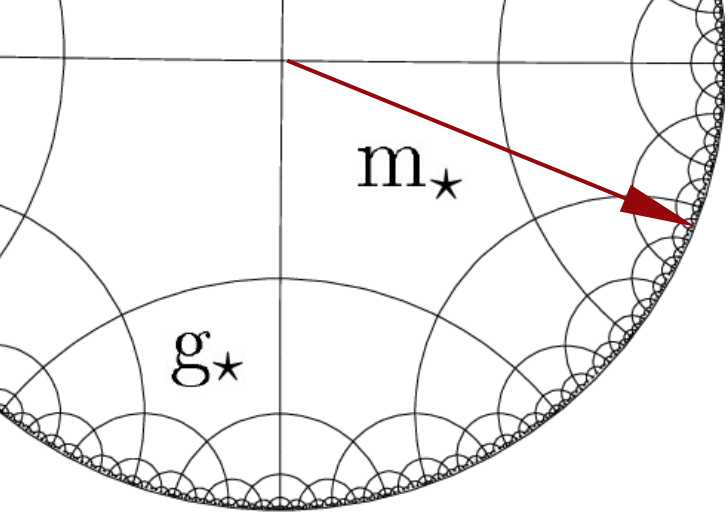

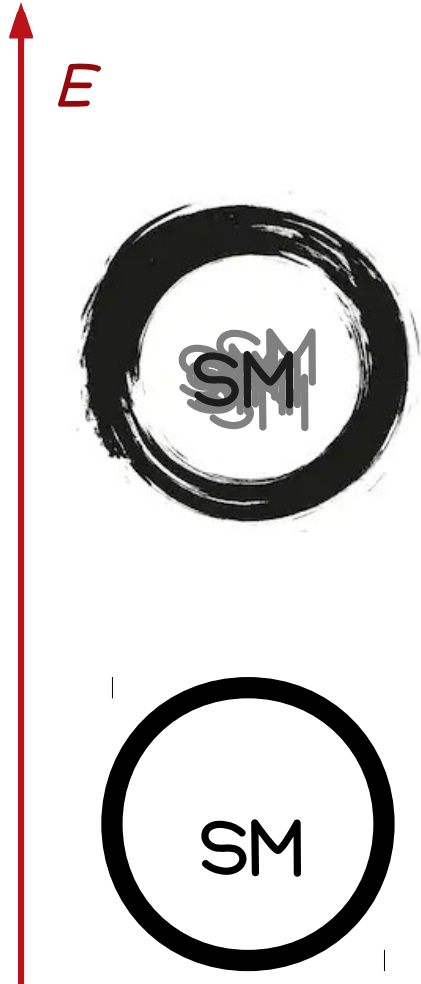High intensity probe

High energy probe

[ref]

DY

- Huge increase in the constraints by going at high energies.

- Reach on parameters similar to 0.001% precision on Z-pole observables.

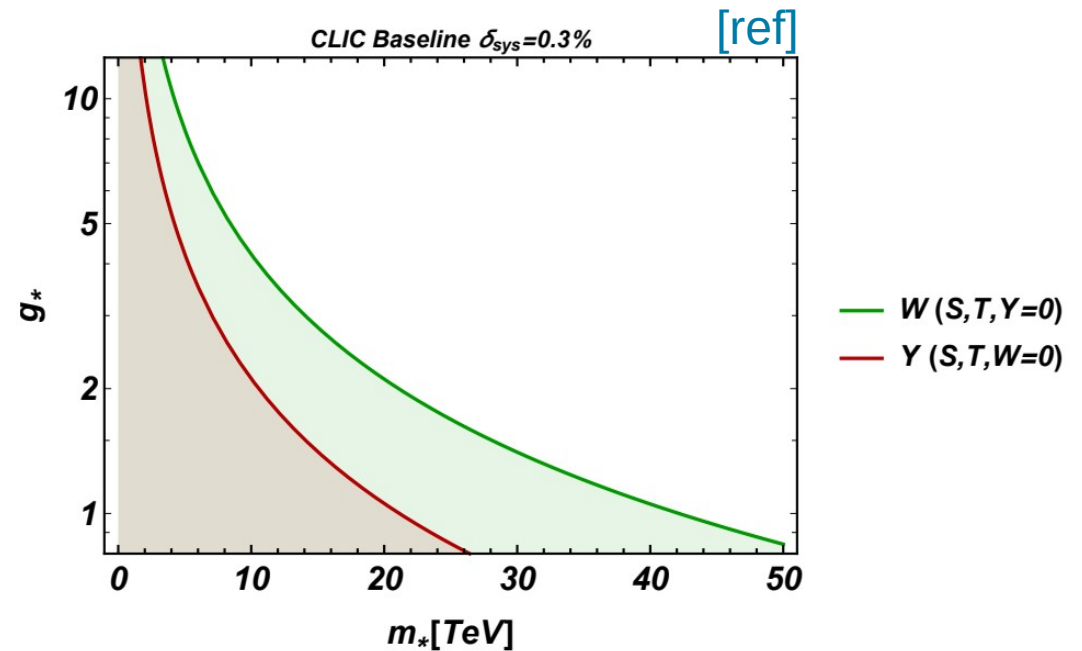It is important to **interpret the previous bounds** in physical terms:

In **Composite Higgs** scenarios the Higgs is part of a strongly coupled sector, parametrized by a single mass scale and coupling.

$$W = 2\frac{g^2}{g_*^2}\frac{M_W^2}{m_*^2}$$

$$Y = 2\frac{g'^2}{g_*^2}\frac{M_W^2}{m_*^2}$$

[ref]

CLIC Baseline $\delta_{sys}=0.3\%$ [ref]

g_* vs $m_*[TeV]$

— W (S,T,Y=0)
— Y (S,T,W=0)

- For ~O(1) couplings, 3TeV CLIC probes the 10TeV scale

$m_\star$

$g_\star$

It is important to **interpret the previous bounds** in physical terms:

In **Composite Higgs** scenarios the Higgs is part of a strongly coupled sector, parametrized by a single mass scale and coupling.
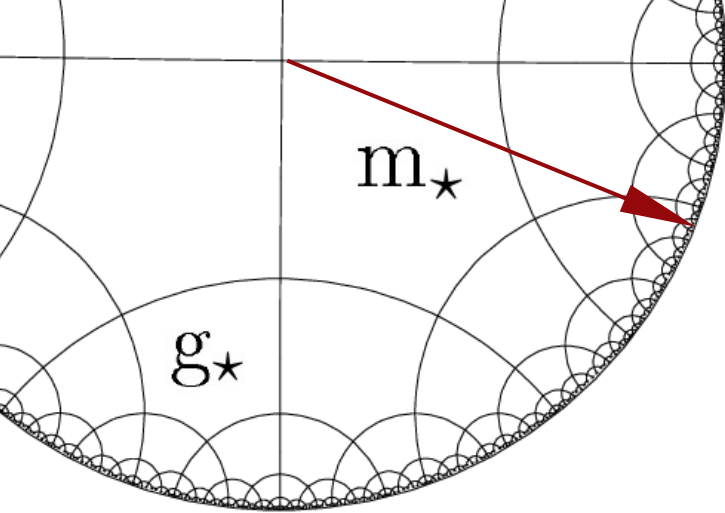
E

SM

$$W = 2\frac{g^2}{g_*^2}\frac{M_W^2}{m_*^2}$$

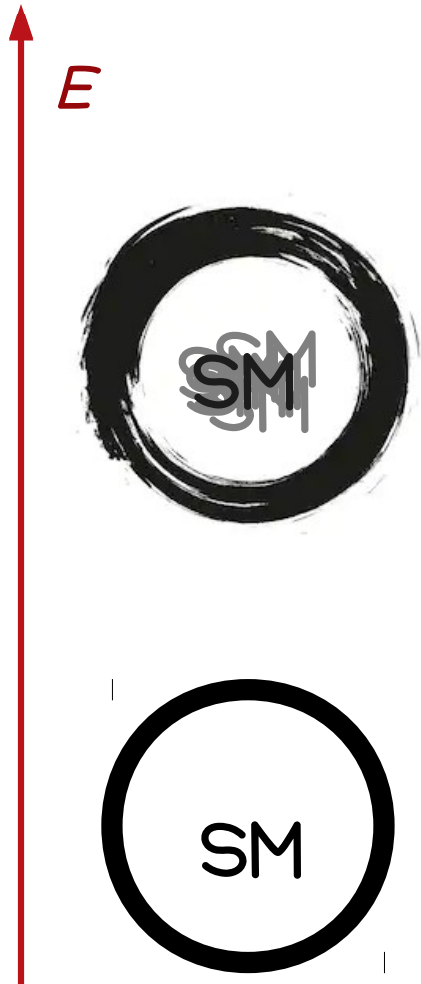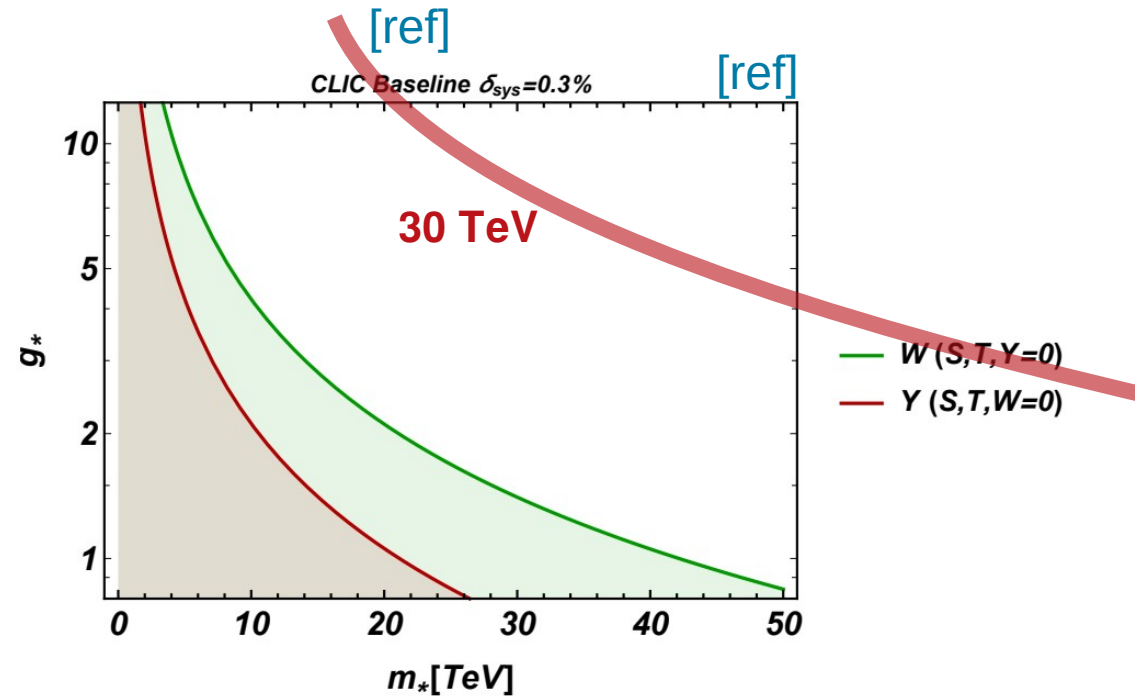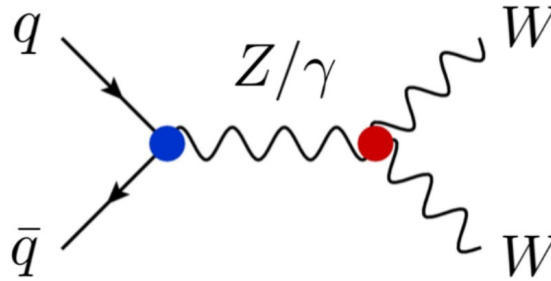$$Y = 2\frac{g'^2}{g_*^2}\frac{M_W^2}{m_*^2}$$
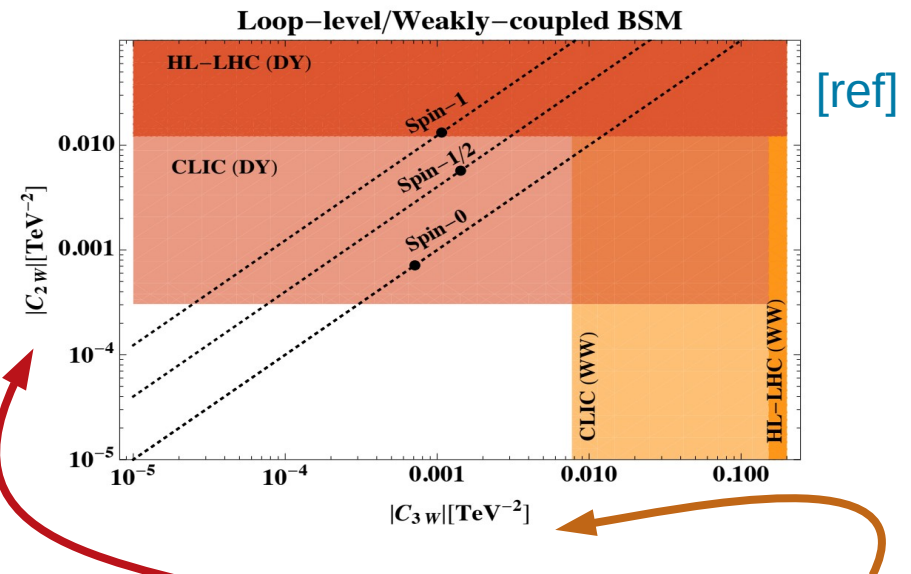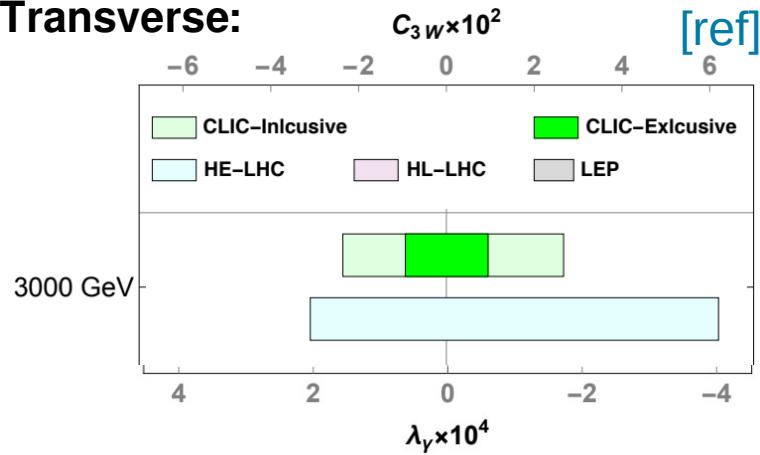
[ref]

SM

[ref]

[ref]

CLIC Baseline $\delta_{sys}=0.3\%$

30 TeV

g_*

— W (S,T,Y=0)
— Y (S,T,W=0)

m_*[TeV]

- For ~O(1) couplings, 3TeV CLIC probes the 10TeV scale

- For ~O(1) couplings, 30TeV probes the 100TeV scale

Diboson probes:

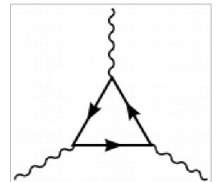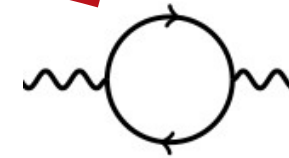**Transverse:**

[ref]

[ref]

Weakly coupled interpretation
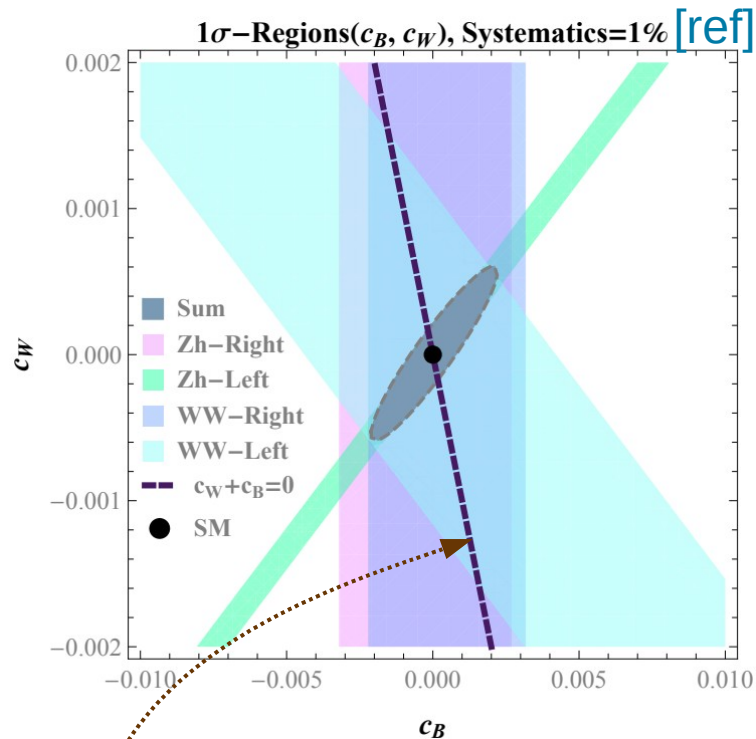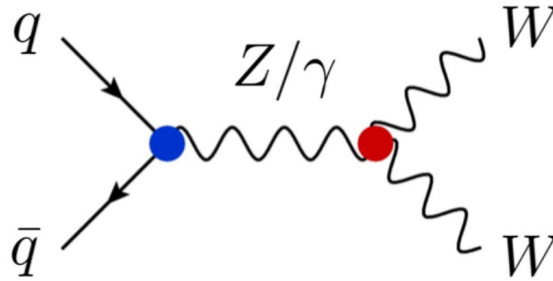of the constraints:

$$C_{2W}^i = \frac{1}{(4\pi)^2} \frac{1}{M_i^2} \frac{g^2}{60} \mu(R_i) \cdot a_{2W}^i$$

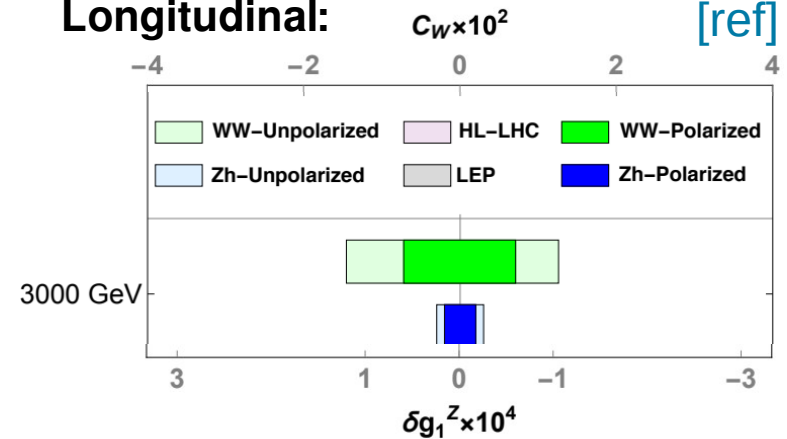$$C_{3W}^i = \frac{1}{(4\pi)^2} \frac{1}{M_i^2} \frac{g^2}{60} \mu(R_i) \cdot a_{3W}^i$$

	a_{2W}	a_{3W}	C_{2W}^i / C_{3W}^i
Real scalar	1	1	1
Complex scalar	2	2	1
Dirac fermion	16	−4	−4
Vector	−37	3	−37/3

Diboson probes:

Longitudinal: [ref]

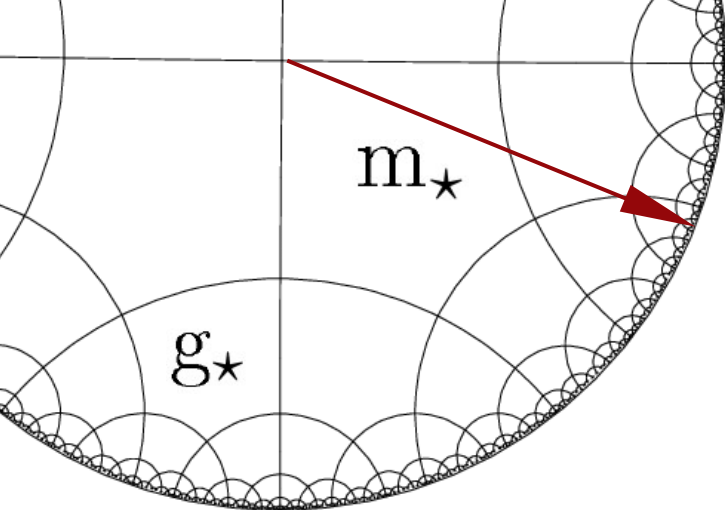Direction constrained from pole observables at 10^-3 level

- In **Composite Higgs** scenarios, longitudinal modes in diboson are a direct probe of the compositeness scale, without dependence on the strong coupling:

$$c_W \sim c_B \sim \frac{m_W^2}{m_\star^2} \quad \rightarrow \quad m_\star \leq 8\,\text{TeV}$$
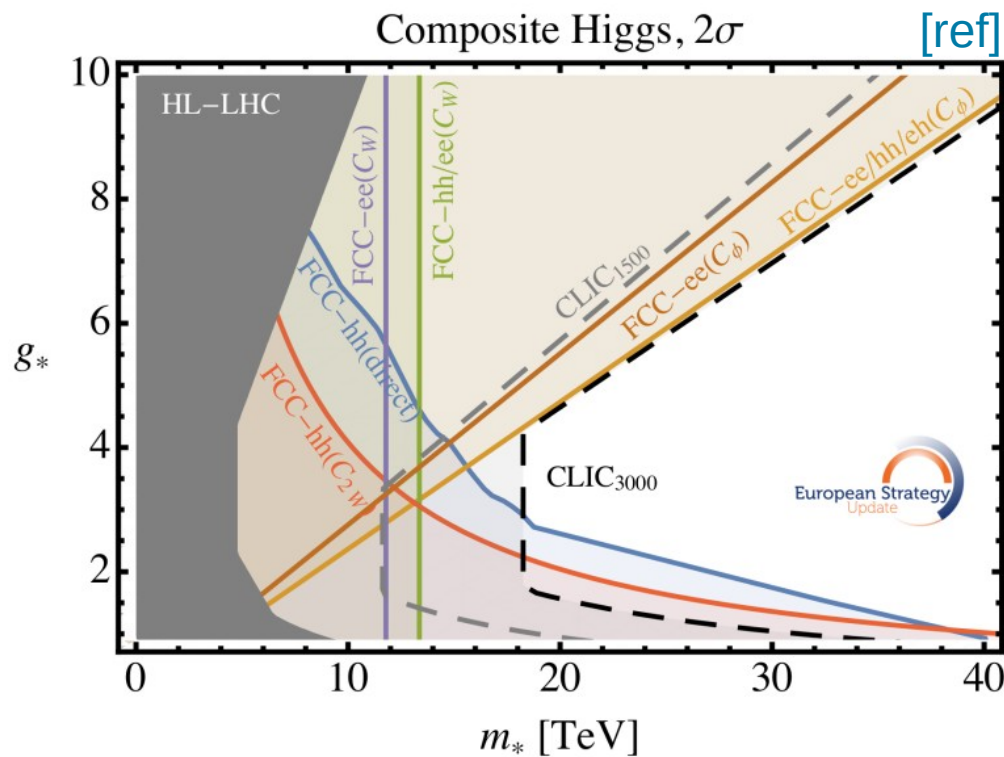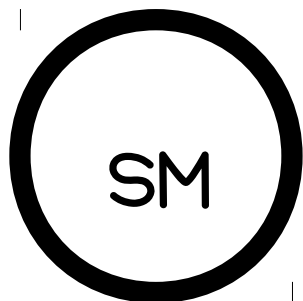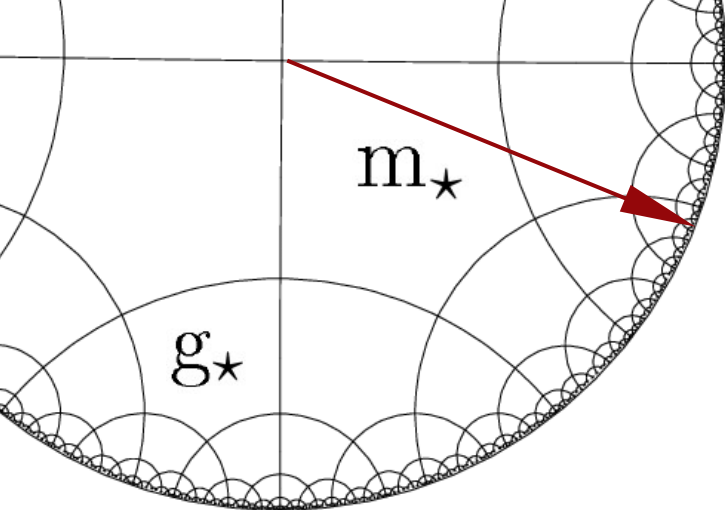
$m_\star$

$g_\star$

E

SM

- Higgs rates, instead, probe the coupling of the strong sector

$$\mathcal{L}_{universal}^{d=6} = c_H \frac{g_\star^2}{m_\star^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_\star^4}{(4\pi)^2 m_\star^2}\mathcal{O}_T + c_6 \lambda \frac{g_\star^2}{m_\star^2}\mathcal{O}_6 + \frac{1}{m_\star^2}[c_W \mathcal{O}_W + c_B \mathcal{O}_B]$$

$$+ \frac{g_\star^2}{(4\pi)^2 m_\star^2}[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}] + \frac{y_t^2}{(4\pi)^2 m_\star^2}[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}]$$

$$+ \frac{1}{g_\star^2 m_\star^2}[c_{2W}g^2\mathcal{O}_{2W} + c_{2B}g'^2\mathcal{O}_{2B}] + c_{3W}\frac{3!g^2}{(4\pi)^2 m_\star^2}\mathcal{O}_{3W}$$

$$+ c_{yt}\frac{g_\star^2}{m_\star^2}\mathcal{O}_{yt} + c_{yb}\frac{g_\star^2}{m_\star^2}\mathcal{O}_{yb}$$

Composite Higgs, 2σ [ref]

$m_\star$

$g_\star$

E

Composite Higgs, 2σ

HL–LHC

g_*

CLIC$_{1500}$

CLIC$_{3000}$

FCC–ee(C_W)
FCC–hh/ee(C_W)
FCC–ee(C_θ)
FCC–ee/hh/eh(C_θ)
FCC–hh($\theta_{c=1}$)
FCC–hh(C_{3W})

European Strategy Update

m_* [TeV]

0   10   20   30   40

30 TeV $\ell^+\ell^-$

80   120   160

[ref]

SM
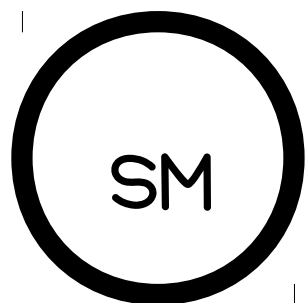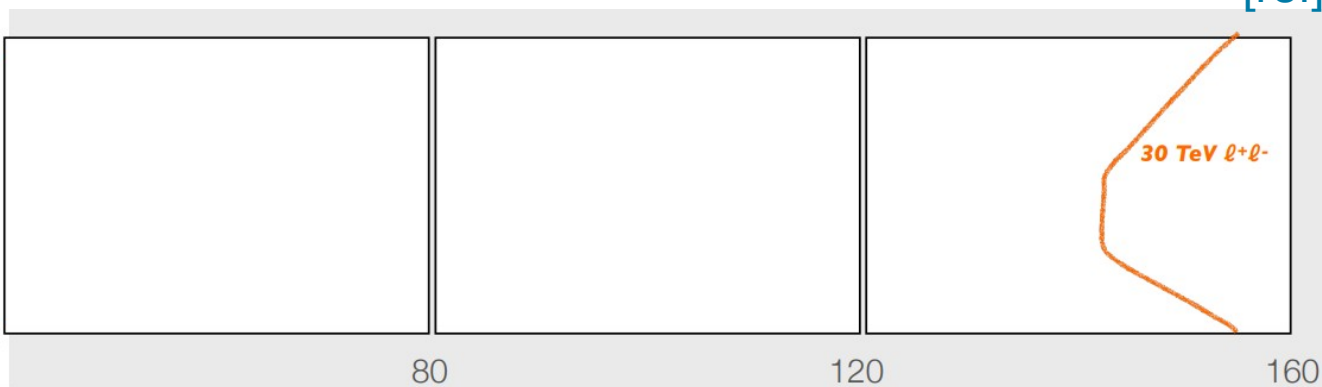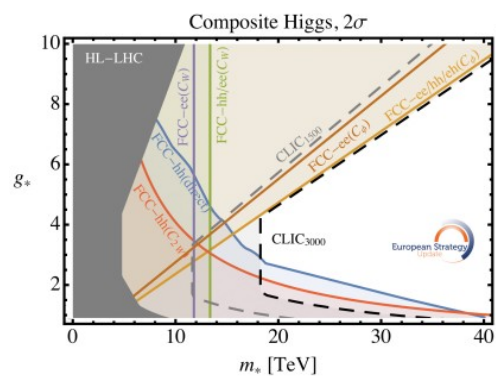
Higgs couplings
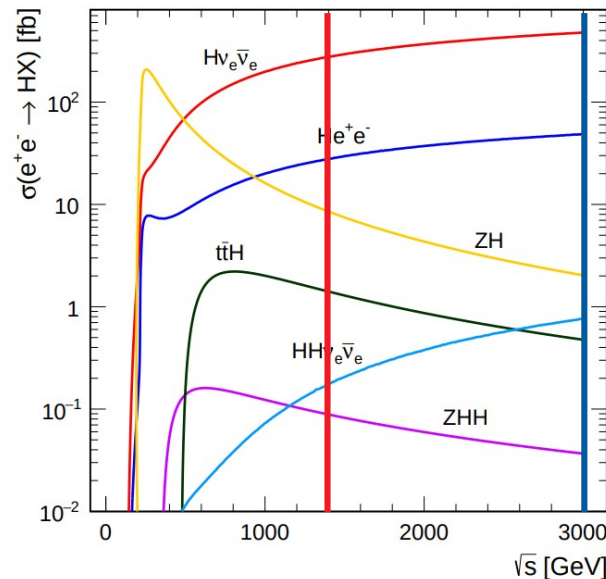
	Stage 1	Stage 1+2	Stage 1+2+3	HL-LHC S1 (S2)
κ_{HZZ}	0.4 %	0.3 %	0.2 %	1.8 (1.3) %
κ_{HWW}	0.8 %	0.2 %	0.1 %	2.0 (1.4) %
κ_{Hbb}	1.3 %	0.3 %	0.2 %	4.3 (2.9) %
κ_{Hcc}	4.1 %	1.8 %	1.3 %	—
$\kappa_{H\tau\tau}$	2.7 %	1.2 %	0.9 %	2.3 (1.7) %
$\kappa_{H\mu\mu}$	—	12.1 %	5.6 %	5.5 (4.4) %
κ_{Htt}	—	2.9 %	2.9 %	4.1 (2.5) %
κ_{Hgg}	2.1 %	1.2 %	0.9 %	2.8 (1.8) %
$\kappa_{H\gamma\gamma}$	—	4.8 %	2.3 %	2.3 (1.6) %
$\kappa_{HZ\gamma}$	—	13.3 %	6.6 %	11 (11) %

- Higgs production at 3TeV dominated by WW fusion.
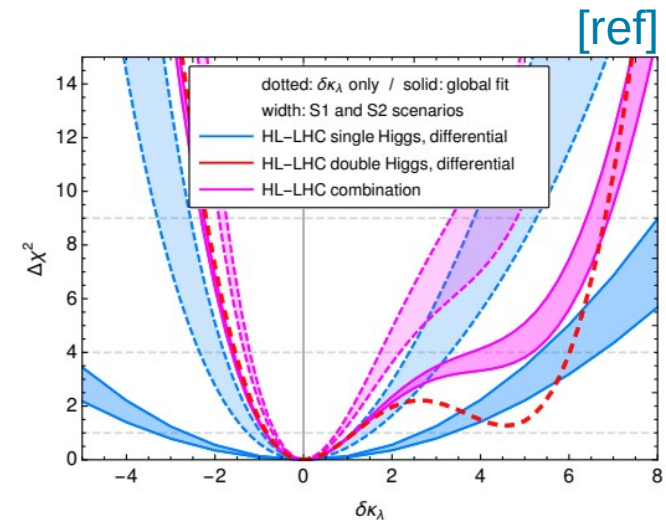- Marginal improvements with respect 1.4TeV run.
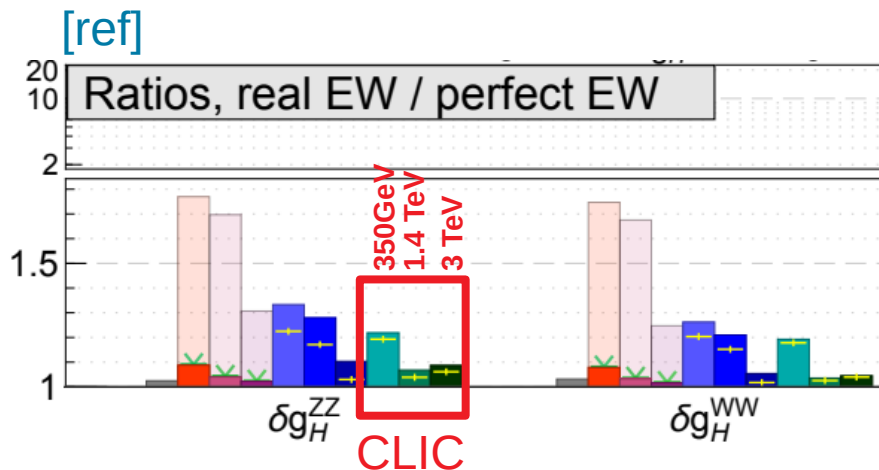
- Not having a FCC-ee Z-pole run in order to improve the EW parameters does not seem to be a bottleneck

Higgs couplings
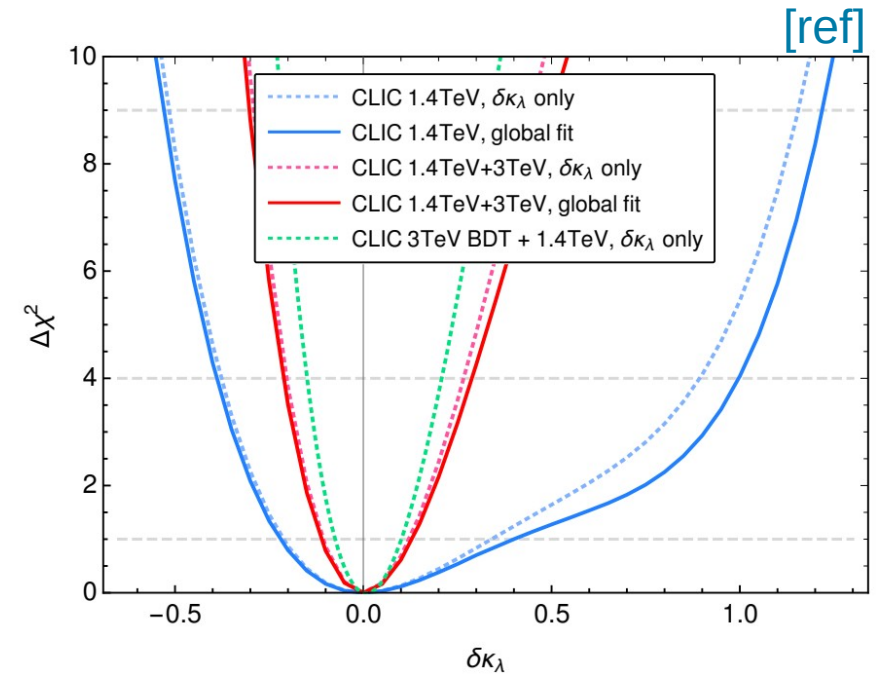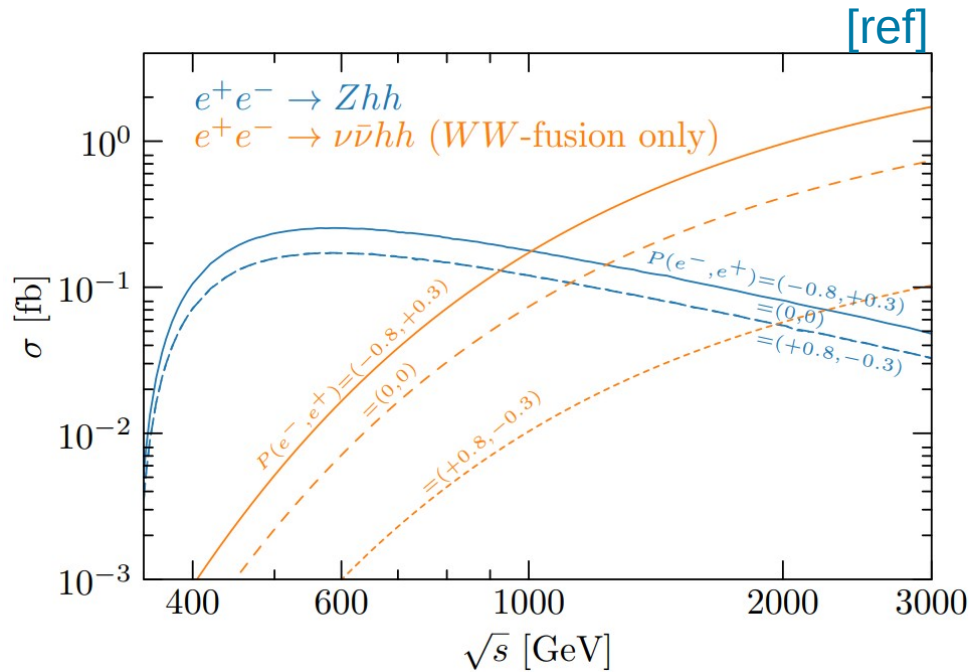
- For double Higgs production, the gain in cross section when going to 3TeV is crucial to improve the constraint

- More than an order of magnitude improvement with respect HL-LHC and better than HE-LHC (27TeV)

Conclusions:

- For the first time in 100 years, particle physics is in the dark, and therefore we need a collider that explores the highest energy possible.

- 3 TeV is enough to definetely answer an important subset of questions.

- High energy also means precise constraints on deviations away from SM parameters.

- A 30TeV muon collider may probe dynamics at 100's of TeV and show qualitatively different phenomena