Questions on Higgs Physics

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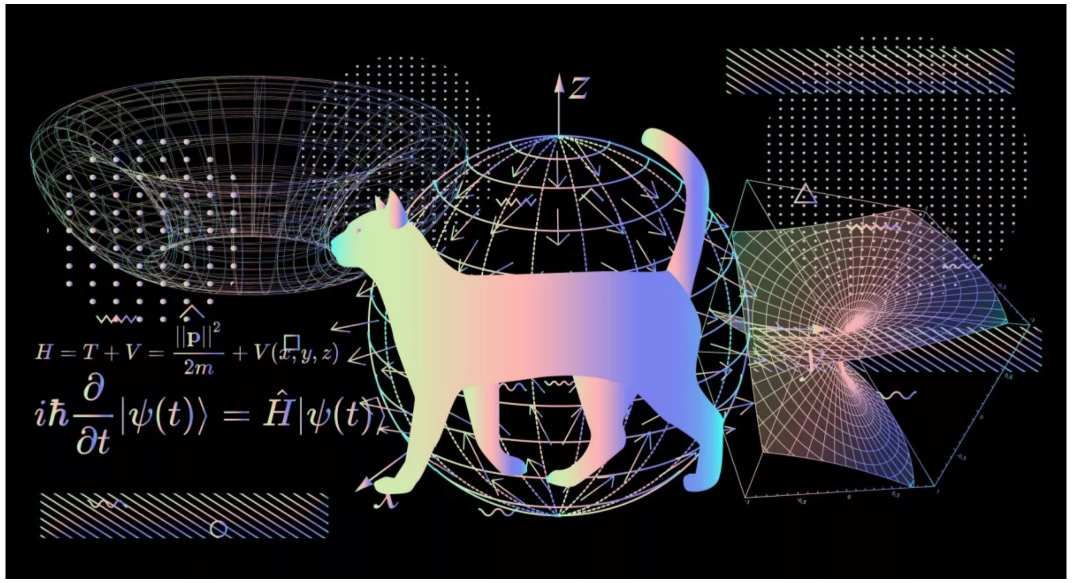
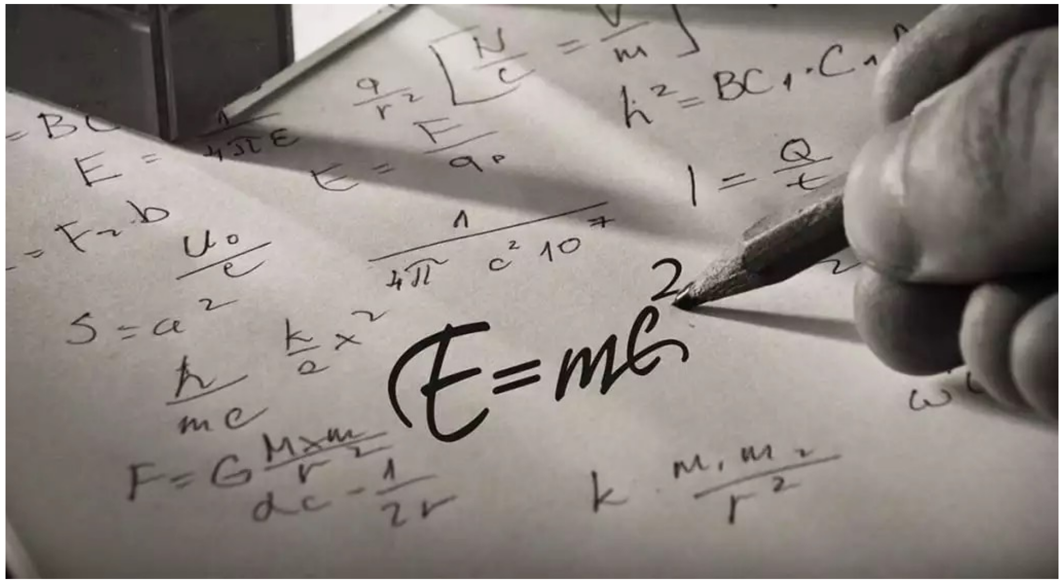
Introduction

Quantum Mechanics + **Special Relativity**





¿ = ? Quantum Field Theory

¿ = ? The Standard Model

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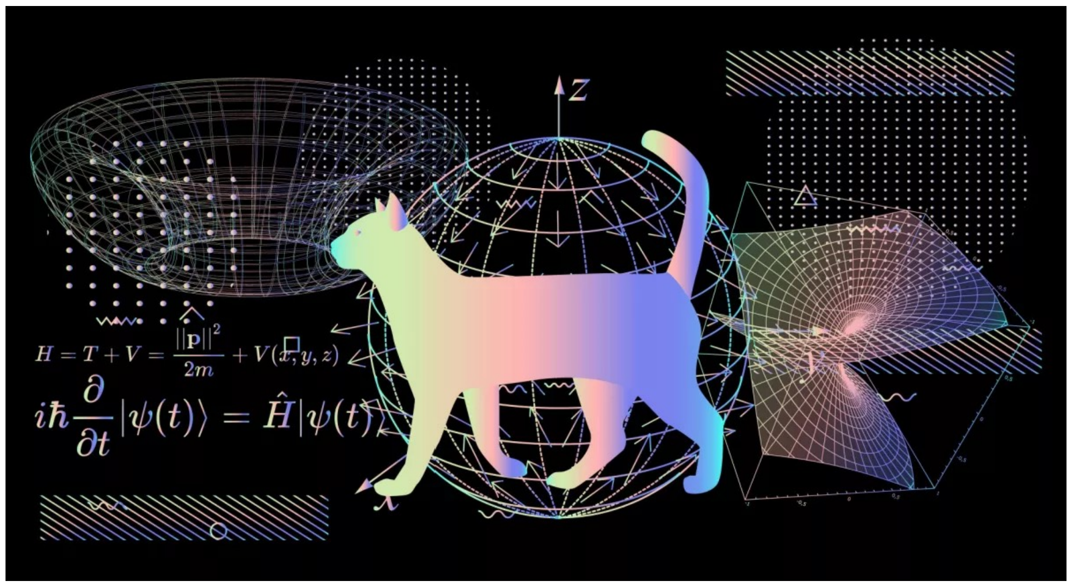

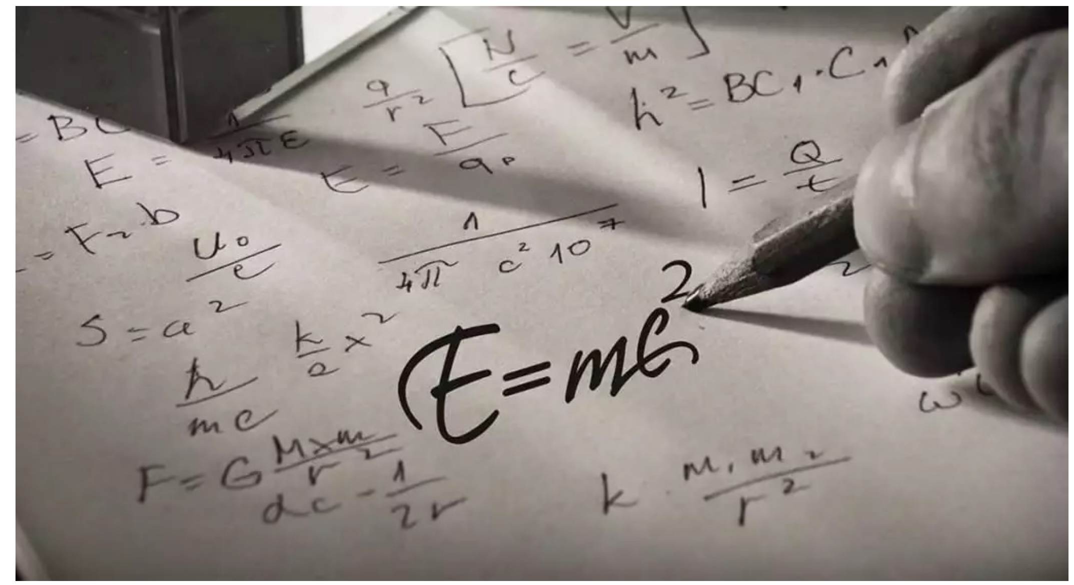

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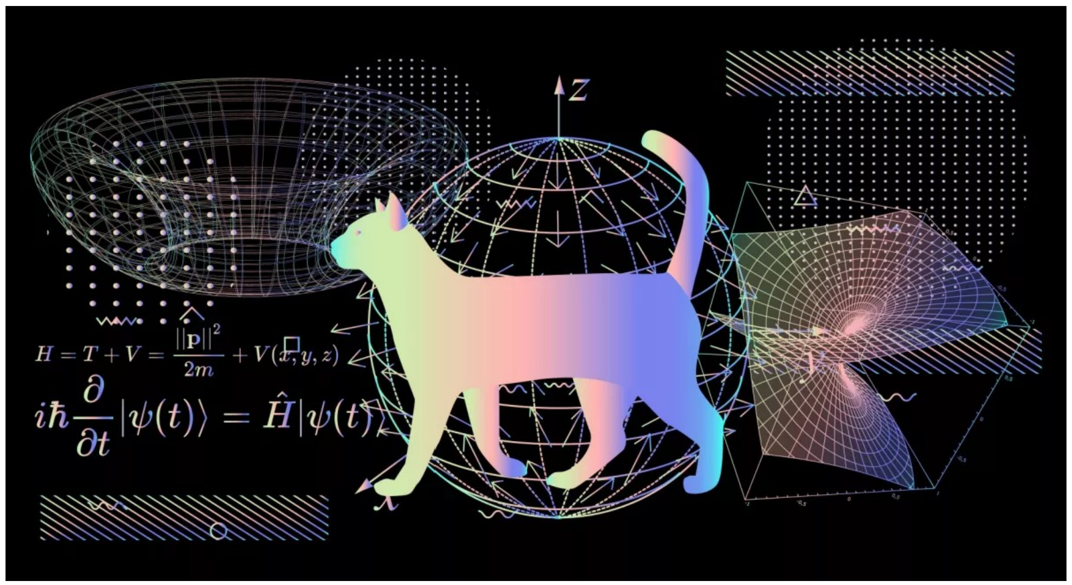

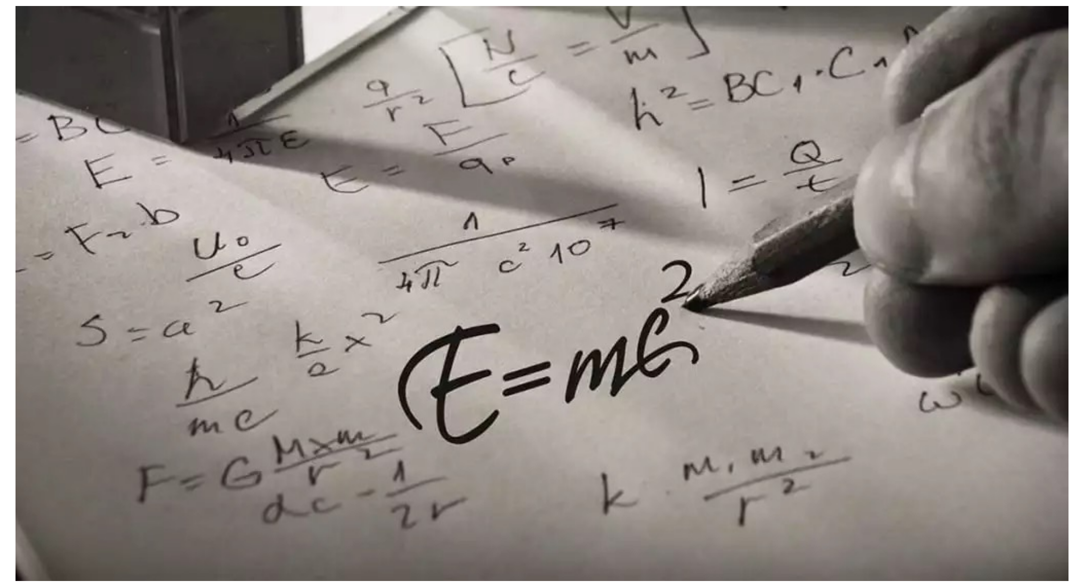

¿ = ? Quantum Field Theory

No! Quantum fields with local Lagrangian and gauge theories are **one implementation** of QM+SR principles (the only one found so far). Its extra ingredients surely stem from an even deeper unknown underlying principle.

¿ = ? The Standard Model

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The Higgs is revolutionary!

One more direct experimental confirmation of the QFT implementation of QM+SR principles (and indirectly of the principles).

The **first manifestation of** a new class of theories: **massive gauge theories**

The Standard Higgs model is not unique, not even within the QFT machinery: We could **“theoretically predict”** it only **because we knew all other particles experimentally and we relied on a field and particle “economy” principle.**

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Higgs Physics questions in this talk:

Is it the Standard Model Higgs Particle?

- Single-Higgs couplings
- Trilinear Higgs coupling

What is it made of?

- Composite Higgs

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Is it the Standard Model Higgs Theory?

- High-energy EW (with Higgs) Physics

Single-Higgs couplings

Coupling modifiers "κ" in front of SM interaction vertices

- Most basic **stress test of the SM,** where all $\kappa = 1$. SM couplings prediction is intricate manifestation of massive gauge theory machinery.
- $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$ are not vertices of SM Feynman rules, but are also left floating

Single-Higgs couplings

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From ECFA 2019 report

[1905.03764]

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Adding muon collider

[2303.08533]

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for the MuC

In short:

percent-level from HL-LHC

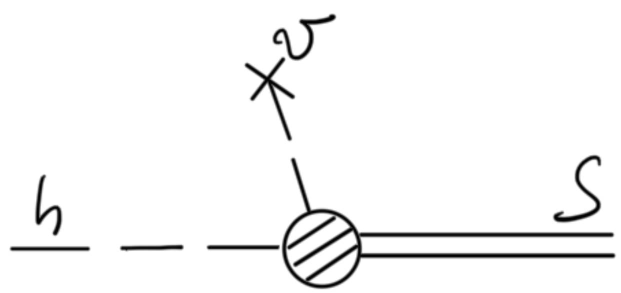
permille-level with several future collider options

Single-Higgs couplings

BSM Interpretations:

Not only a (fundamental) SM stress test. Higgs couplings are effective BSM probes

A new sector with mass M_*, mixed with Higgs, typically gives:



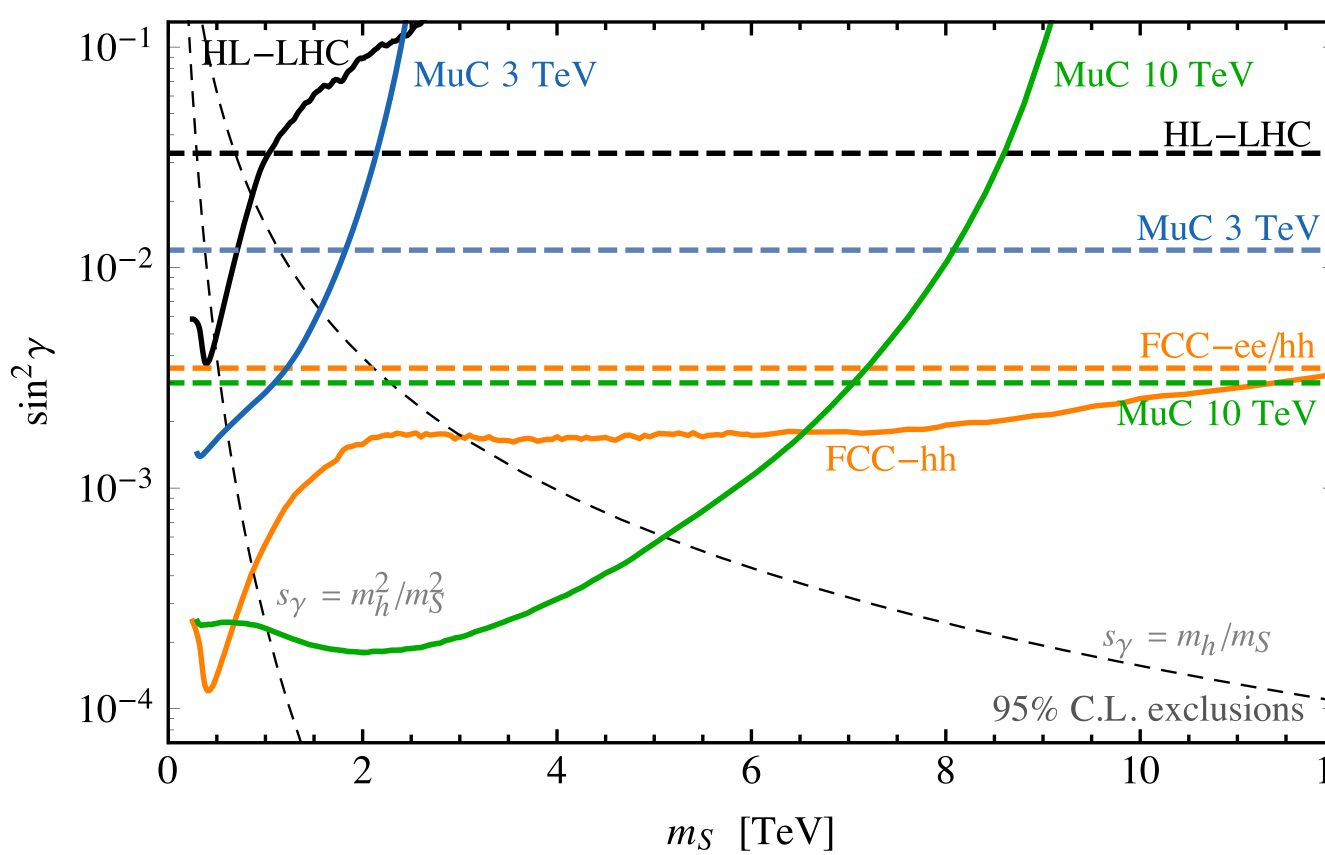
$$\simeq \frac{g_* v}{M_*}$$

$$\sin\gamma \simeq \frac{g_* v}{M_*}$$

$$\kappa = \cos\gamma \simeq 1 - \frac{g_*^2 v^2}{2M_*^2}$$

$$\frac{\delta\kappa}{[1\%]} \simeq \left(\frac{g_*}{g_w}\right)^2 \left(\frac{M_*}{[\mathrm{TeV}]}\right)^2$$

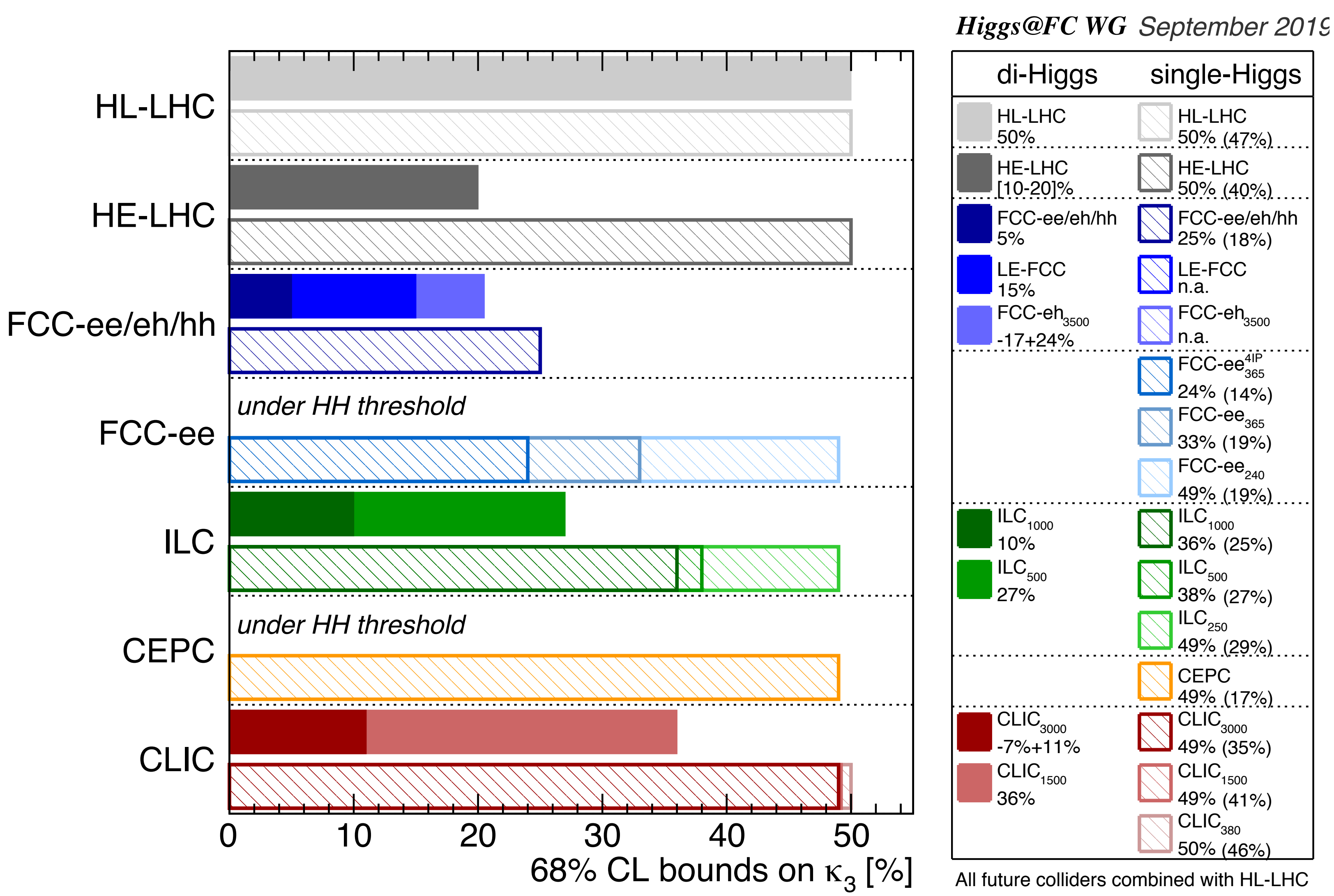
Need < % to start testing well above LHC direct reach for EW-like g_* coupling

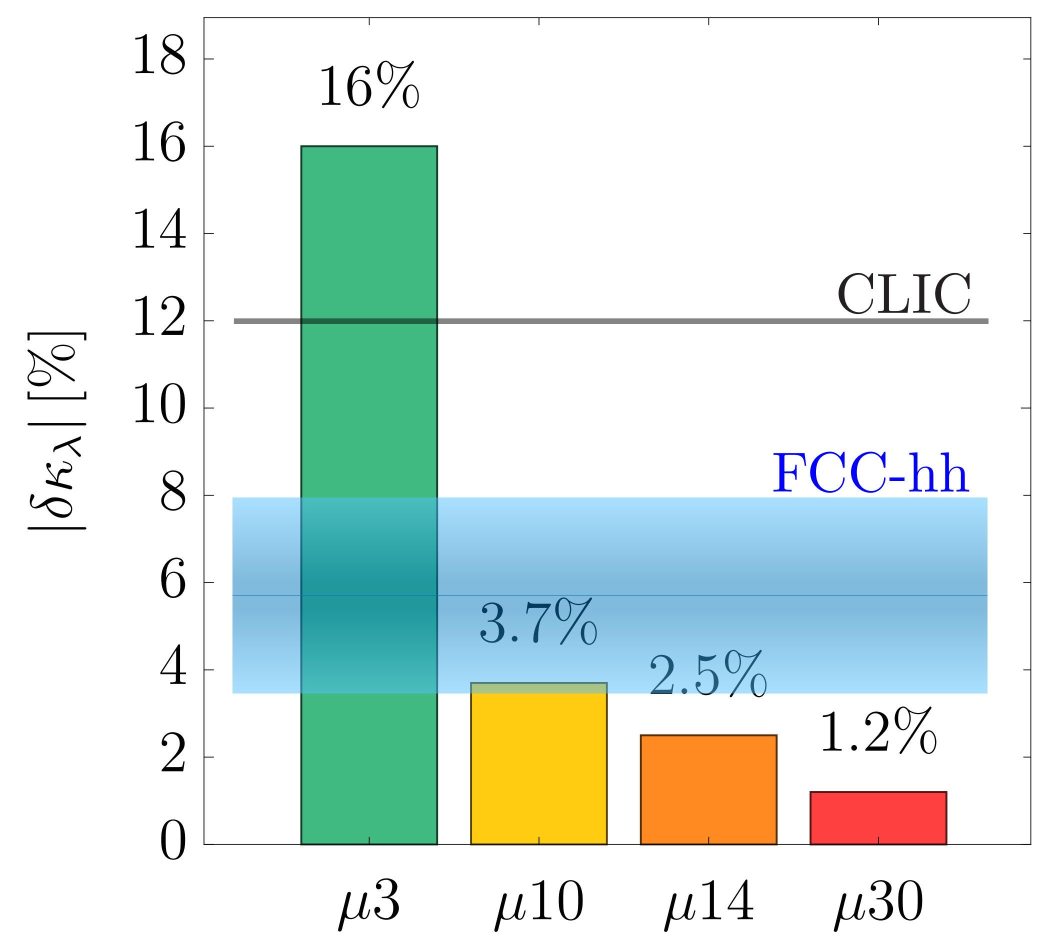


The Higgs self-coupling

The first (Scalar)^3 vertex to be ever seen at work

- HL-LHC will perhaps demonstrate its existence
- Low-energy e^+e^- could see its indirect effect through loops
- **A direct measurement requires high energy: FCC-hh, CLIC-3, MuC**





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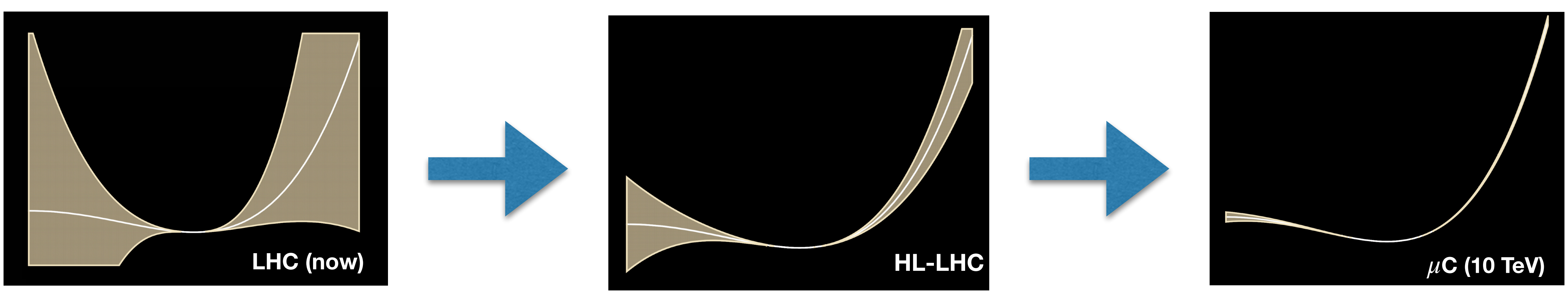
Why measuring it **precisely?**

1. This drawing is already one good enough reason



Courtesy of N. Craig

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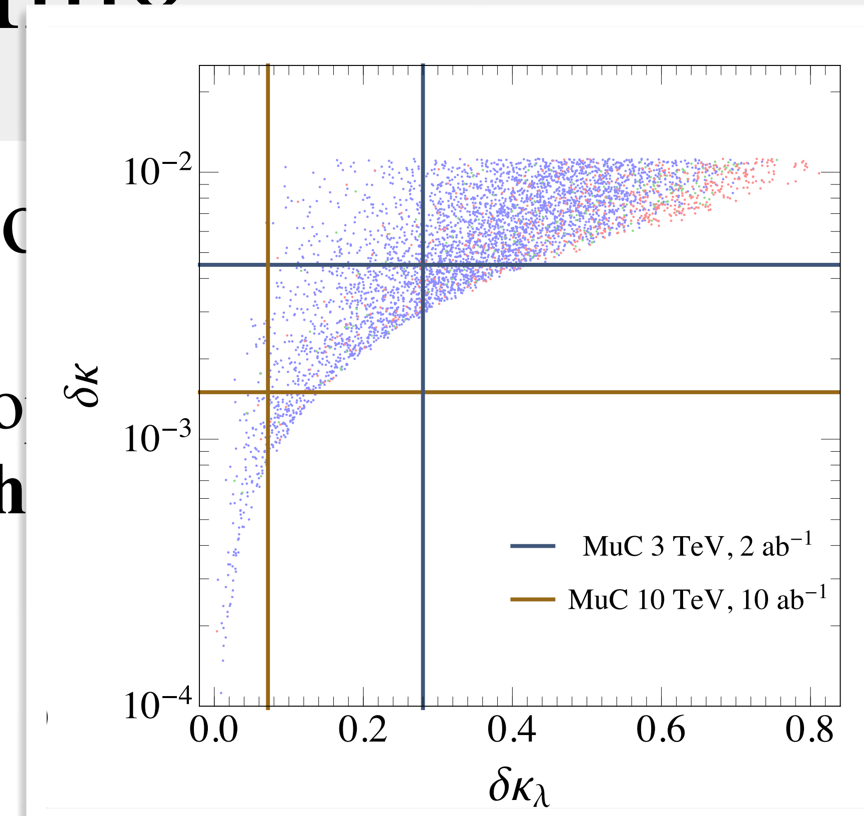
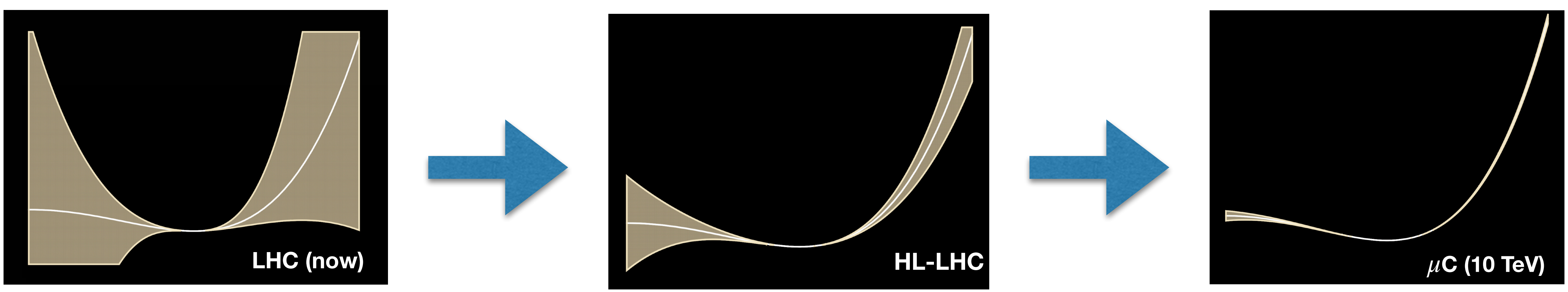


Why measuring it **precisely?**

1. This drawing is already one good enough reason
2. Additionally, below-10% sensitivity starts probing models with 1st order EW phase transition in the Early Universe better than 0.1% single -Higgs couplings



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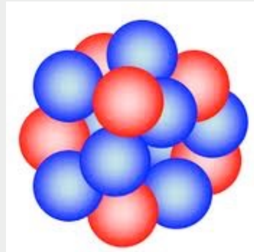
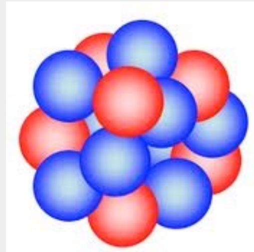


Composite Higgs

We must check if the Higgs is elementary.

If so, it is the first spin-zero elementary particle



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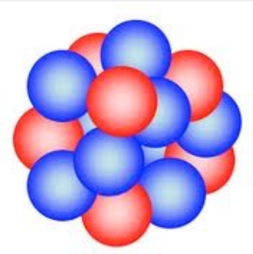

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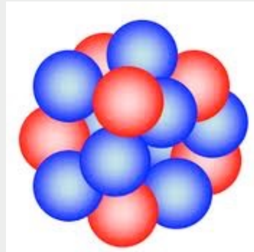
Higgs must be a Goldstone boson of a new symmetry group.

Tuning one single parameter $\xi = \frac{v^2}{f^2} < 1$ we make all its coupling SM-like



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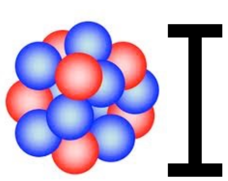
Rich phenomenology: Composite sector resonances; Higgs couplings modifications; new EFT interactions of d>4. All this, broadly controlled only by:

$m_* = 1/r_H$
The Higgs inverse size

$g_* = m_*/f$
The coupling-strength of resonances

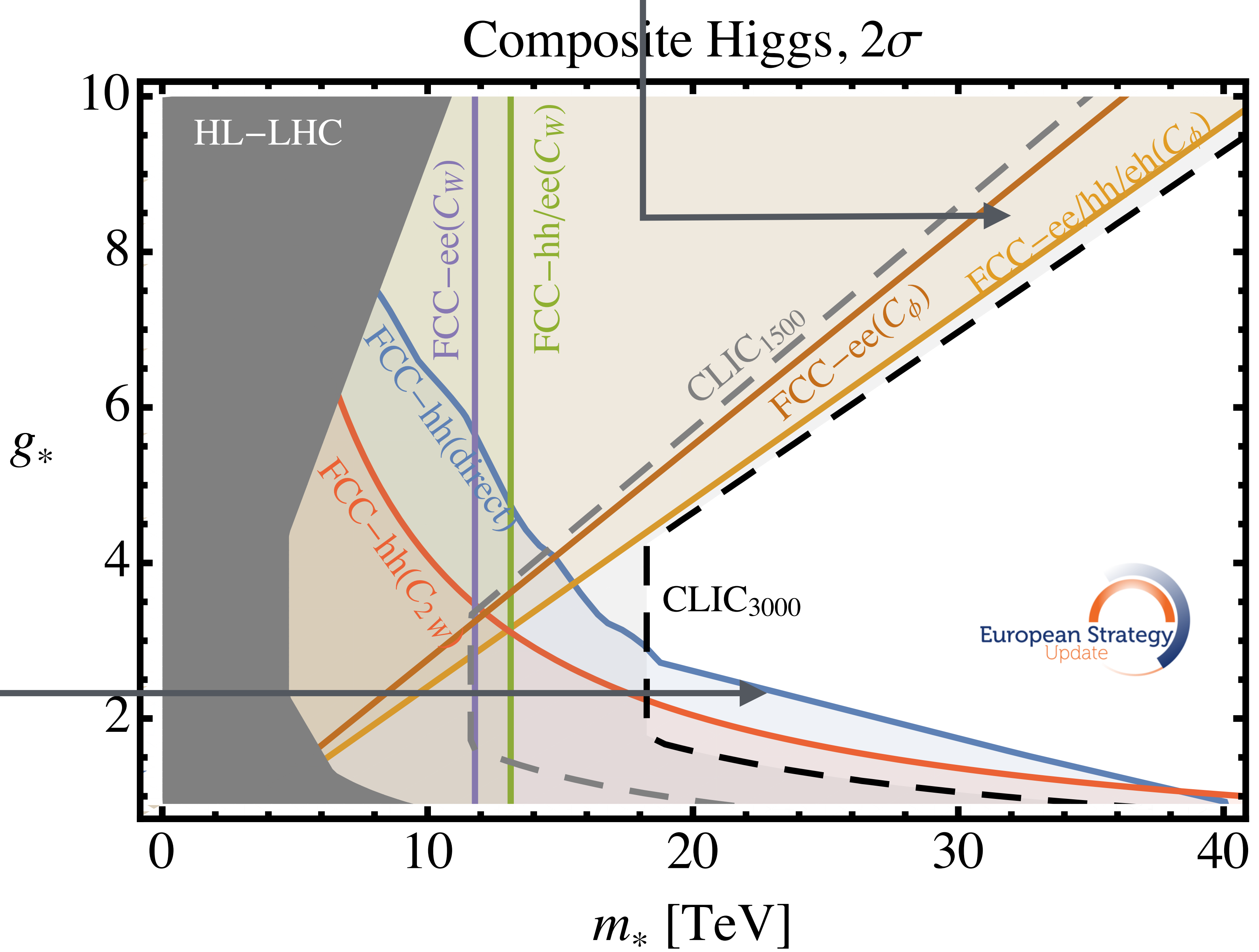


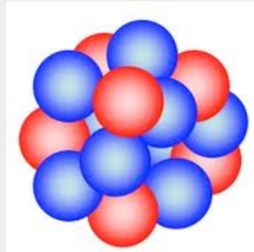
$r_H = 1/m_*$

Composite Higgs

Complementary role of precision and energy

Direct Searches vs Higgs Couplings vs High-Energy Probes





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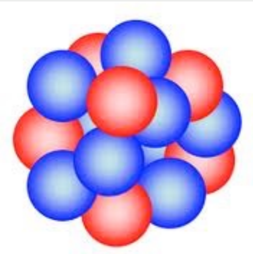
Obviously, a one that displays that is not point-like (i.e., not elementary).



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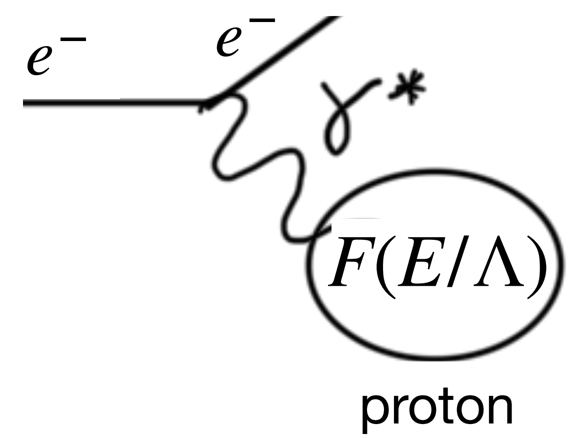
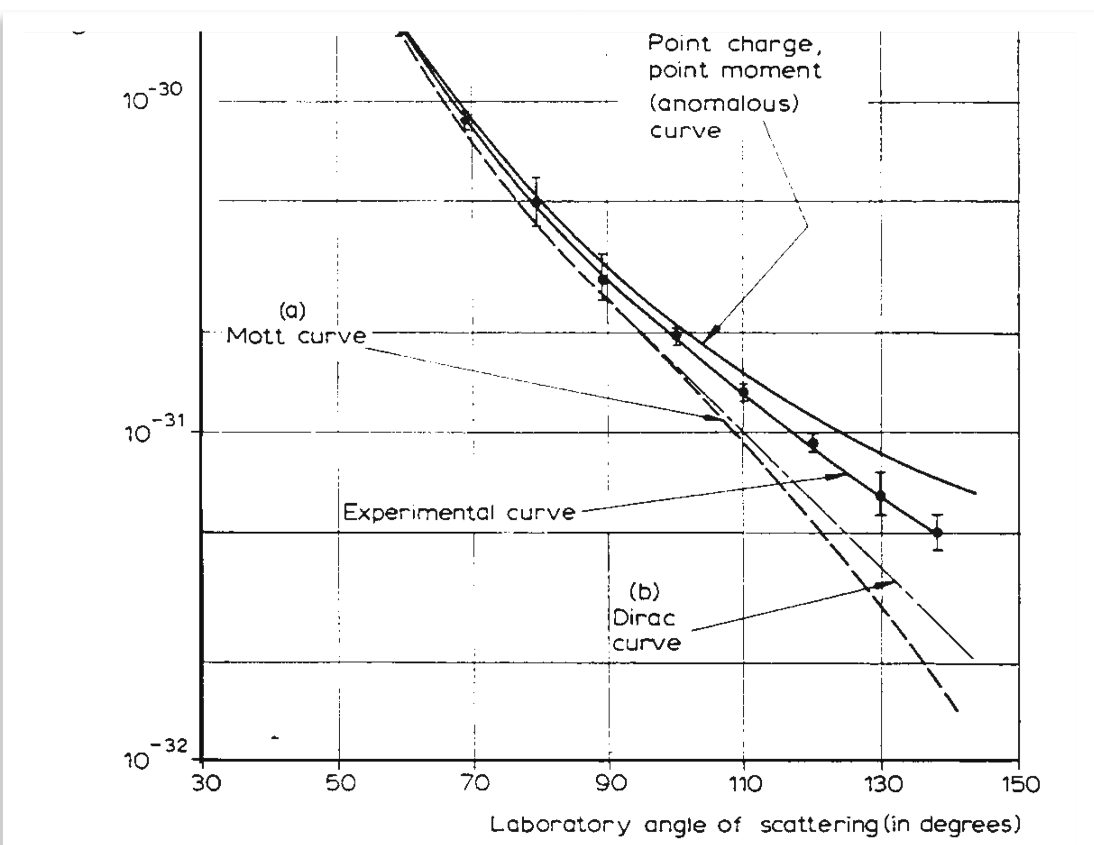
Proton compositeness discovery:

Order 10% departure from point-like prediction.

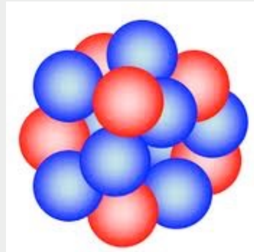
Visible form-factor effects required **large energy**

$E \nearrow \Lambda \sim 1/r_p$





Electron scattering from the proton at an incident energy of 188 MeV.



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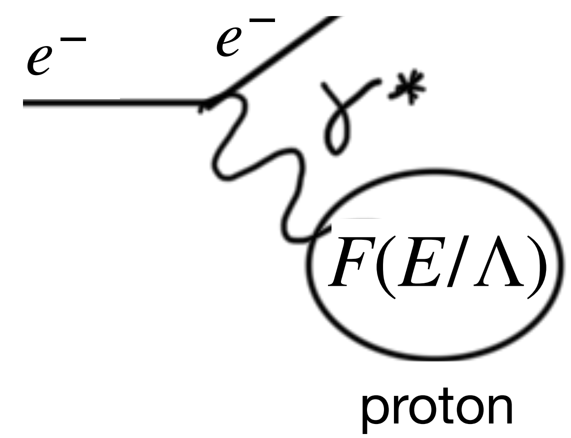
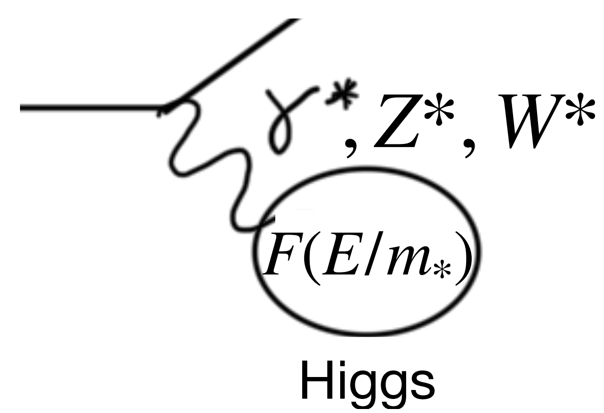


We can probe Higgs form-factors by virtual s-channel EW bosons

Same as proton, with **larger energy**

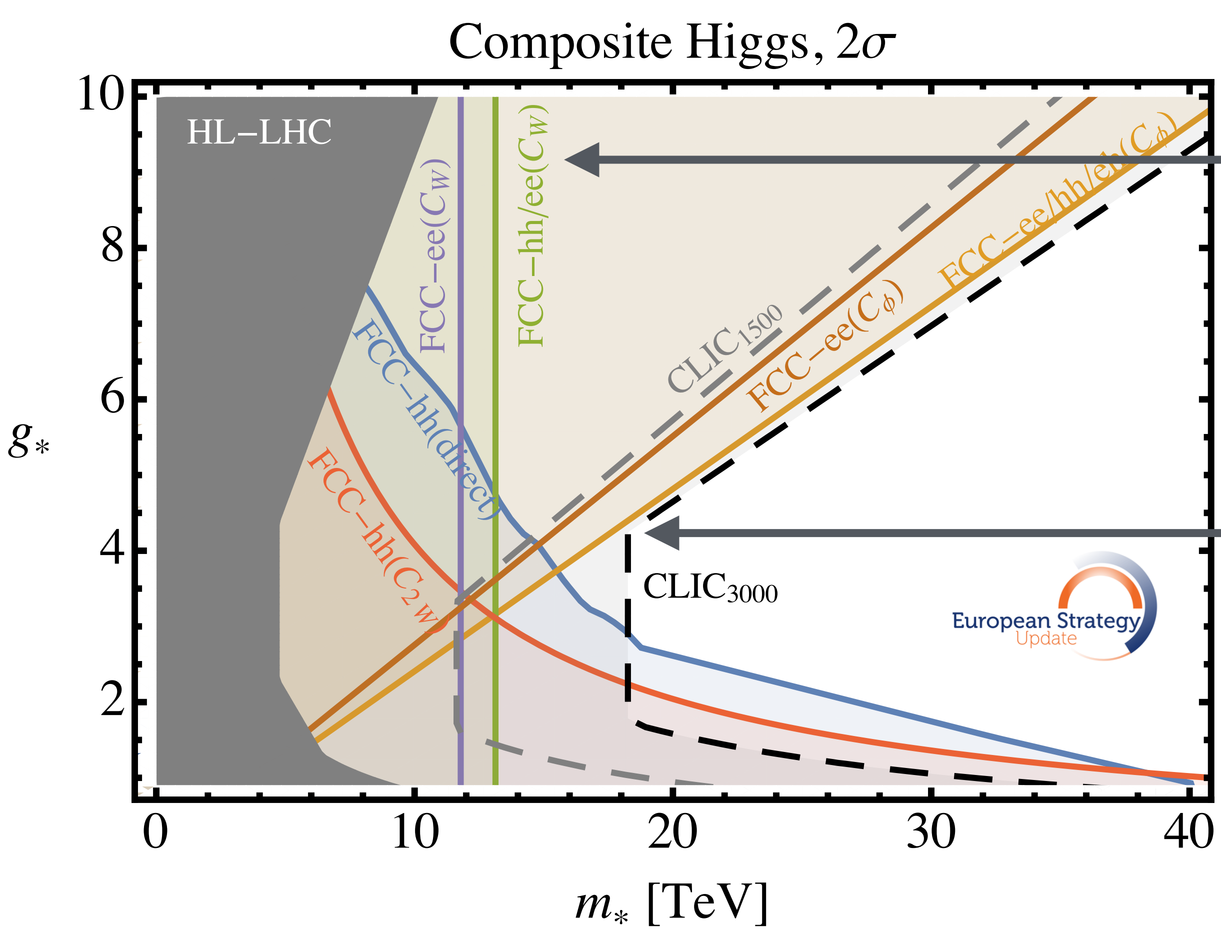
$$E \nearrow m_* \sim 1/r_H$$

HZ and HW at cross-section measurement at a very high energy collider



Composite Higgs

Direct test of Higgs Compositeness at FCC-hh, CLIC, and MuC



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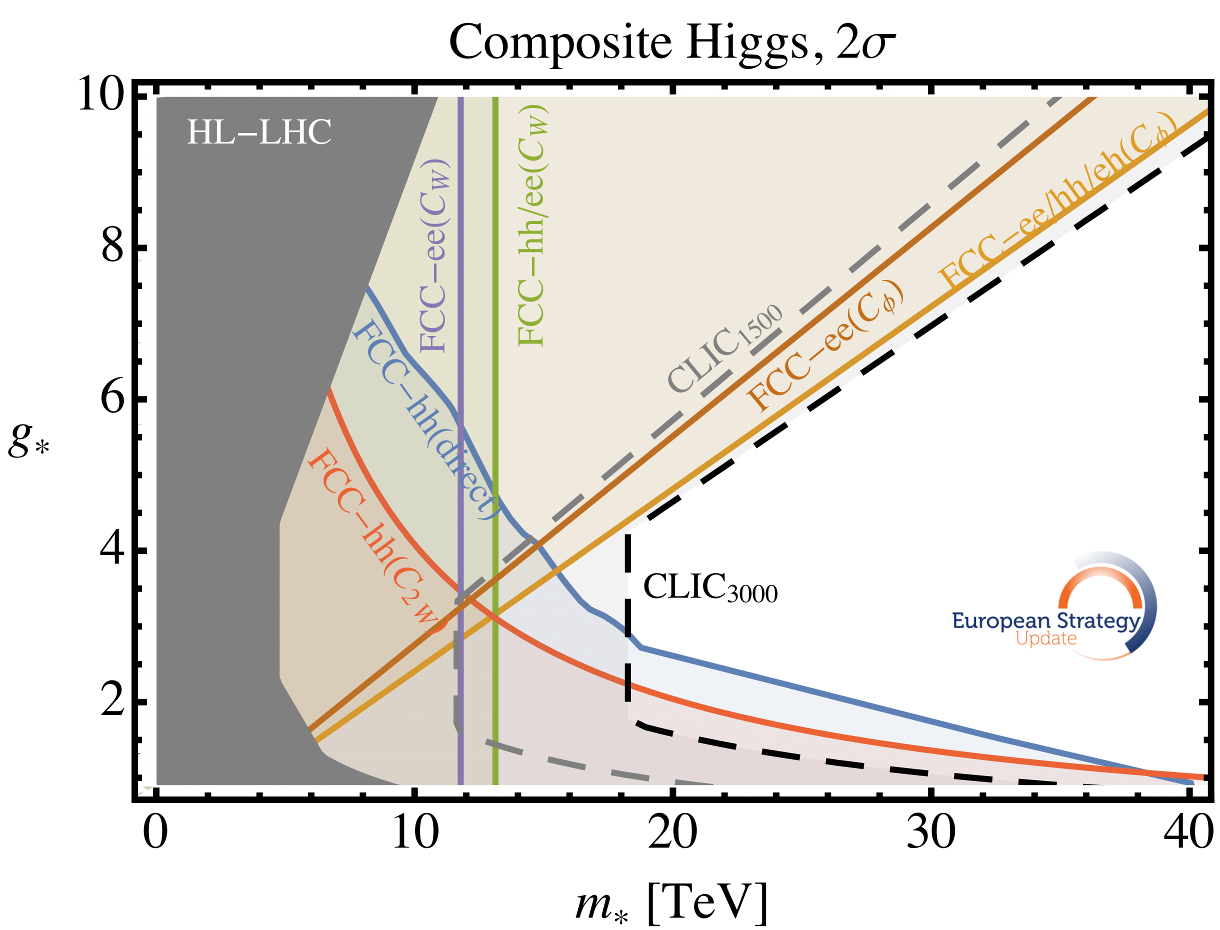
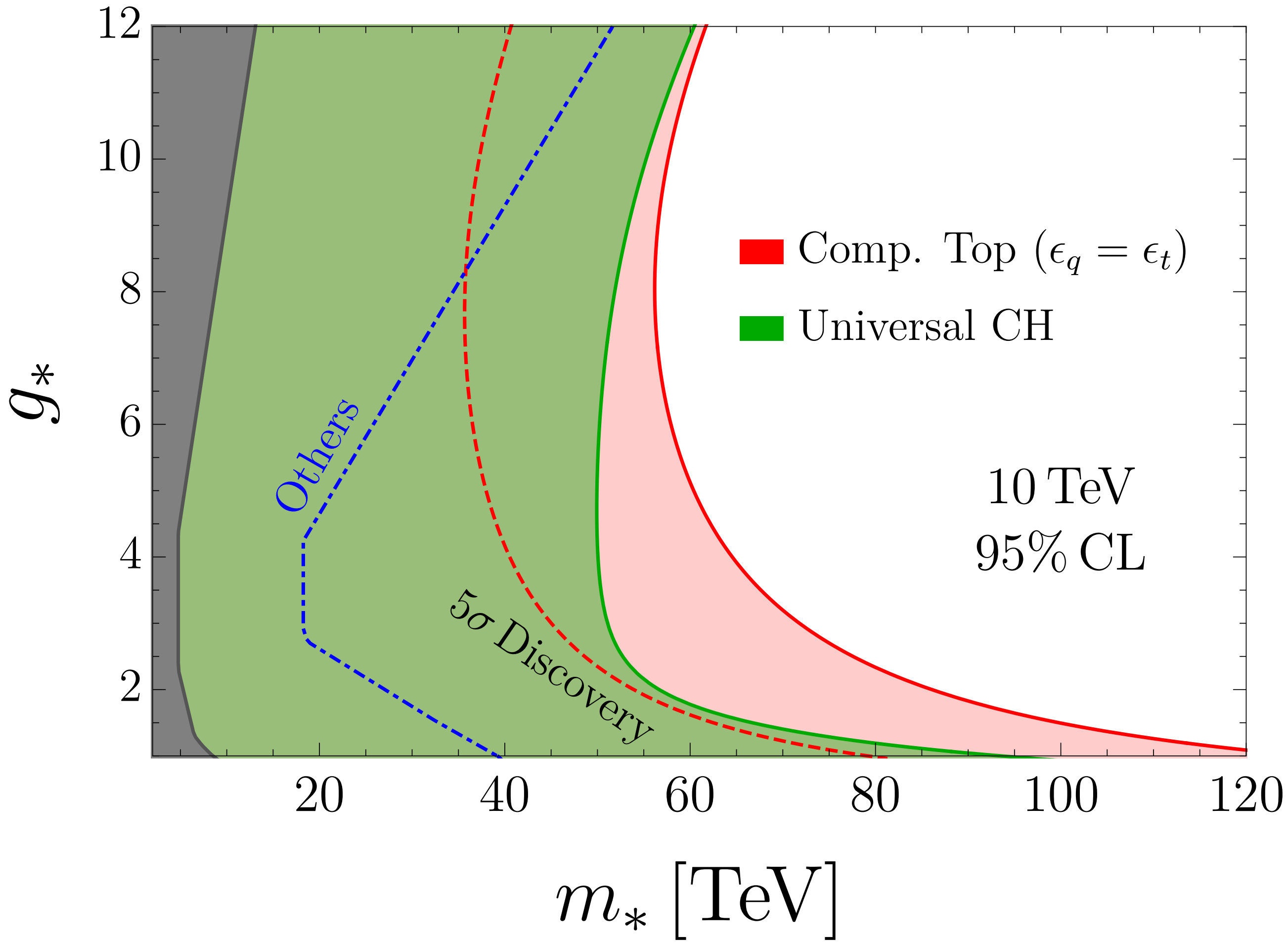
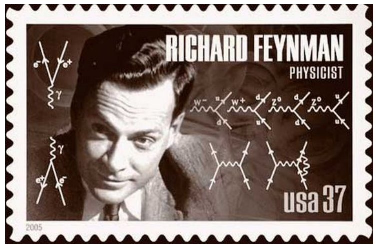
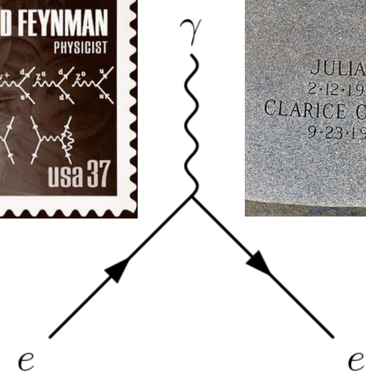
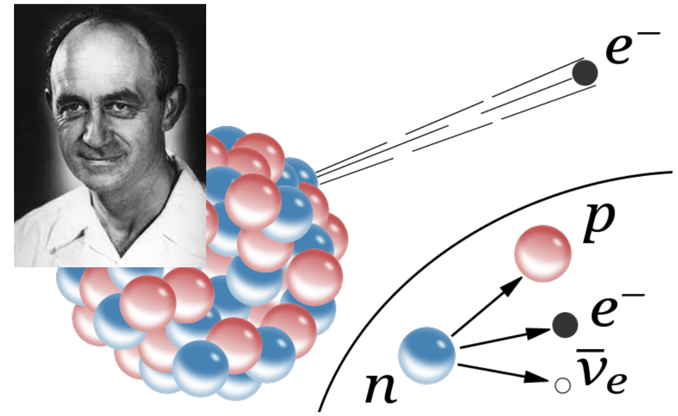




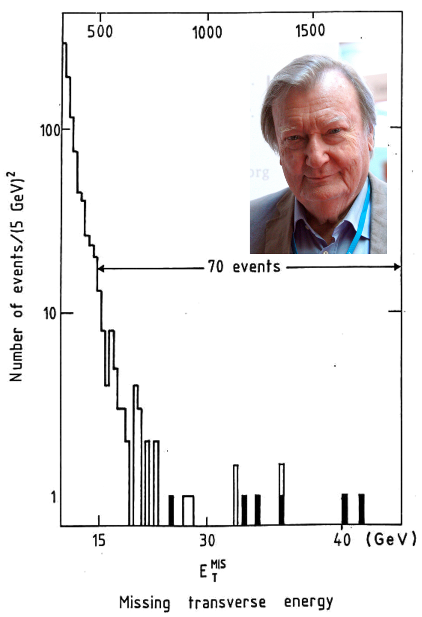
The Standard Model Higgs **Theory** ?

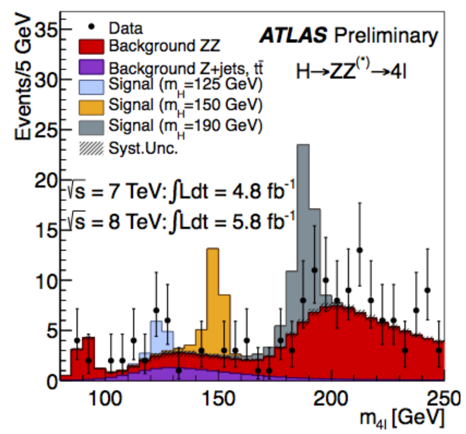


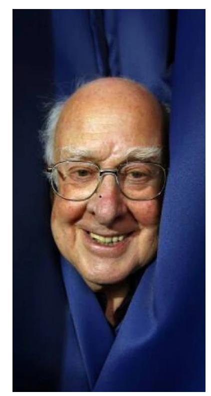


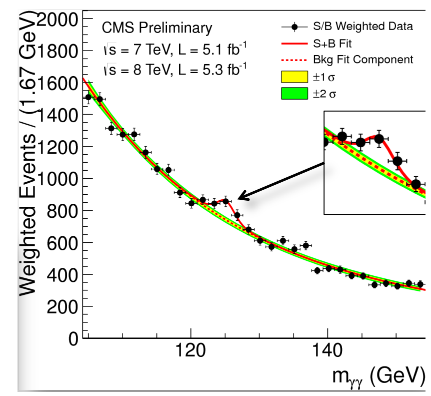


$$E \ll m_W$$





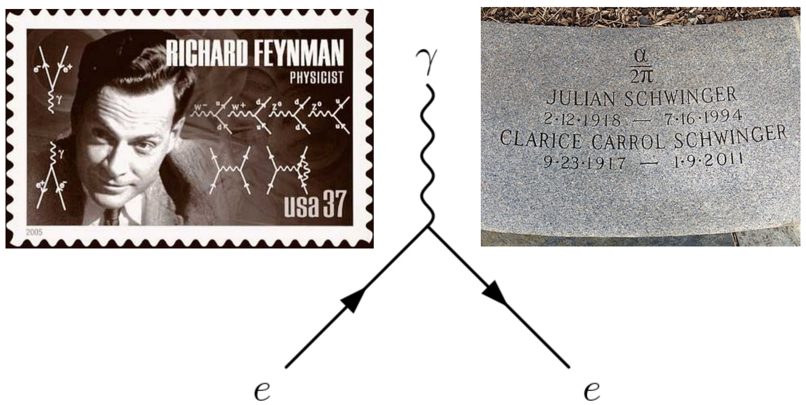


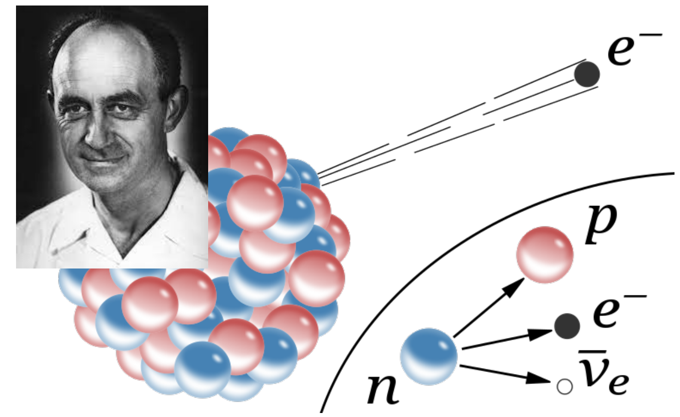


$$E \gtrsim m_W$$

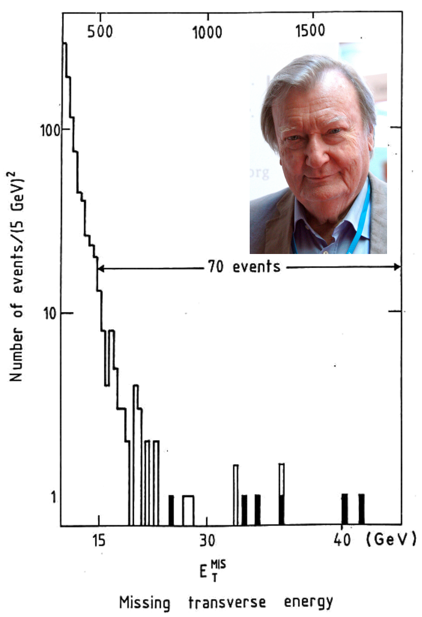
$$E \gg m_W$$

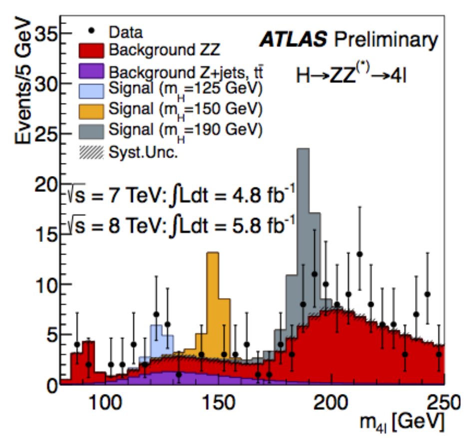
The Standard Model Higgs **Theory** ?

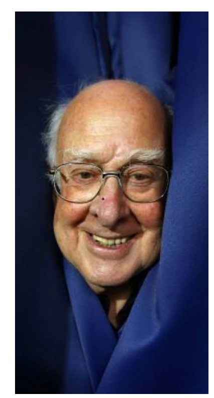


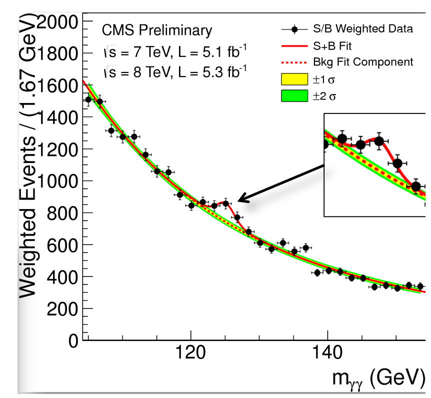


$E \ll m_W$









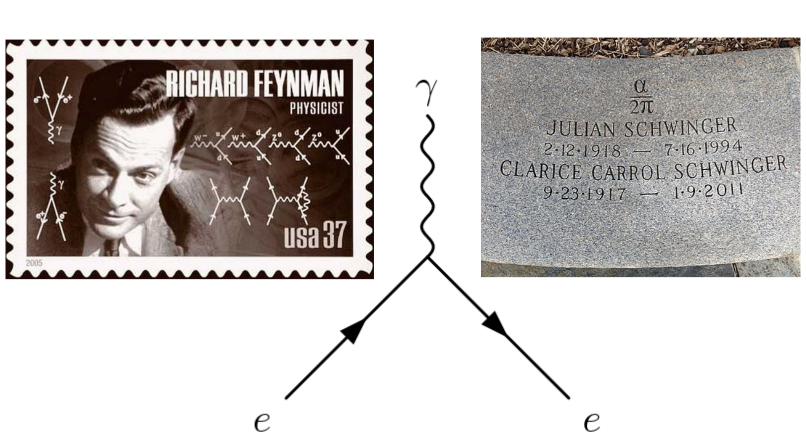
$E \gtrsim m_W$

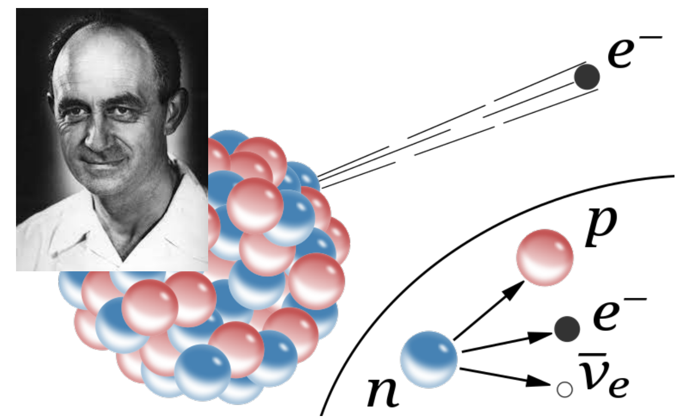
The Higgs particle shows up **here**

but theory needs it in order to go **there**

$E \gg m_W$

The Standard Model Higgs **Theory** ?





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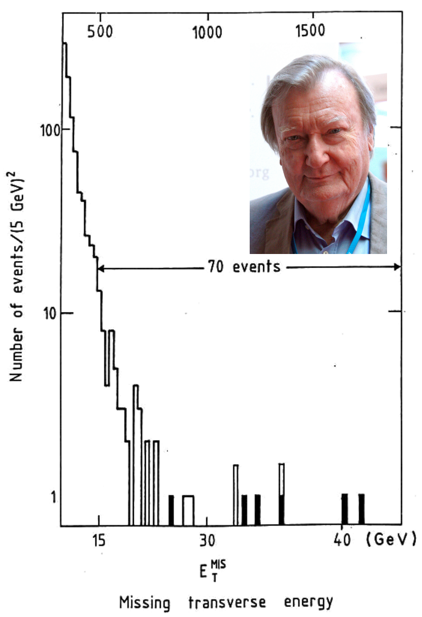

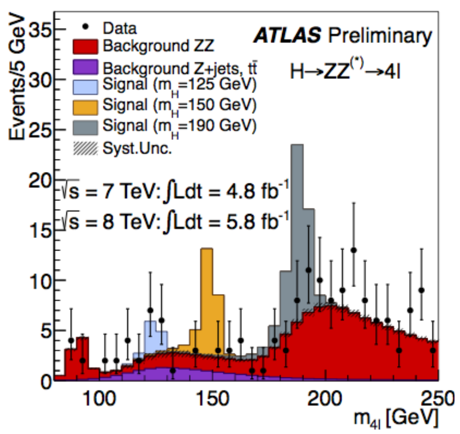

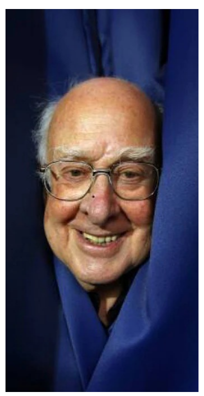

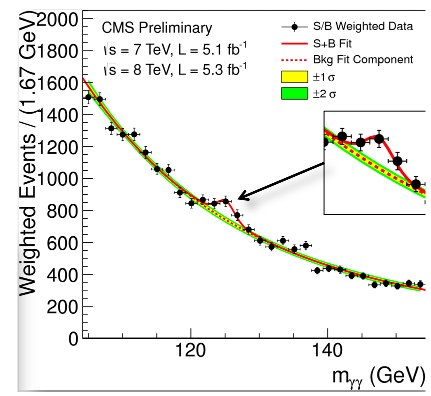

$E \gtrsim m_W$

The Higgs particle shows up **here**

but theory needs it in order to go **there**

Most direct theory implications are at high En.

The role of the Higgs as part of the microscopic description of the EW force must be verified by **high energy** experiments

$E \gg m_W$

Higgs questions at increasing energy

Is the Higgs alone? (100 GeV — TeV energy)

- No prior theoretical reason for the Higgs to be minimal. Extended Higgs sectors must be investigated, also in connection with broader BSM questions, e.g. SUSY
- Relevant mass-range not much above order TeV. LHC can do quite a lot. Progress requires high-energy collider like CLIC-3, FCC-hh, or MuC

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Restoration is direct prediction of the massive gauge theory formalism. A vastly non-trivial one that we can verify directly by high-energy measurements.

Higgs should be part of a doublet: symmetry relations between H and V_L amplit.

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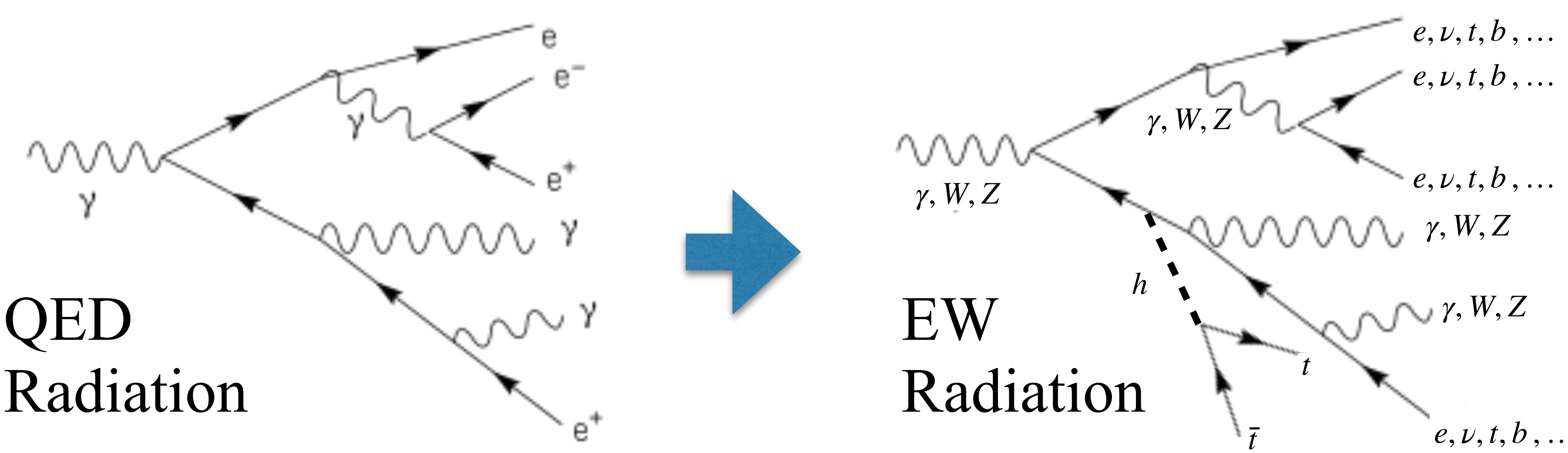
EW Radiation (10 TeV energy):

Transition to masseless vector bosons regime: $-g^2/16\pi^2 \log^2(E_{\rm cm}^2/m_{\rm w}^2) \times \text{Casimir} \approx 1$



Conclusions

The Standard Model Higgs Particle is very new!

- First direct manifestation of massive gauge theory formalism
- First elementary scalar particle
- We must test if it has SM properties, or not, as precisely as we can

Per-mille level Single-Higgs couplings:

- Possible at several future facilities, including a 10 TeV MuC
- Inform us on Extended Higgs sectors, Composite Higgs, and many other BSM

Learning more requires access to order 10 TeV energies

- The direct (and most effective) probe of Higgs compositeness
- The Higgs trilinear (and possibly 4-linear) coupling
- Searching for other Higgses/composite resonances directly
- Observing the restoration of the EW symmetry
- **Directly probe the SM description of short-distance EW force!**

Thank You

Backup

Single-Higgs couplings + Width

Could the Higgs decay to invisible or untagged BSM states?

Signal-strength measurements **do answer** this question:

$$\sigma(i \to H \to j) \sim \frac{g_i^2 g_j^2}{\Gamma_H}$$

We probe $BR_{BSM} = \Gamma_{BSM}/\Gamma_H$ just as precisely as we probe $\delta\kappa$, with the same measurements

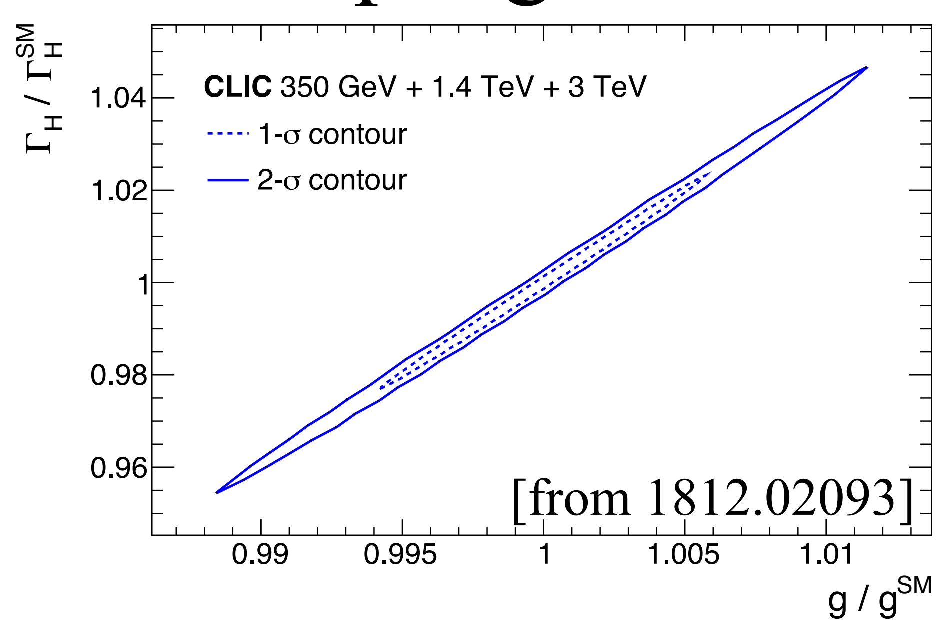
"Direct" searches for exotic or invisible Higgs decay, at e.g. FCC-hh are also possible and worthy.

There is a flat direction in the global fit to couplings+width

In a very tuned configuration where all couplings conspire with Γ_{BSM}

Is not really very important to resolve this degeneracy.

So, don't use the coupling+width fit to rank Higgs factories.



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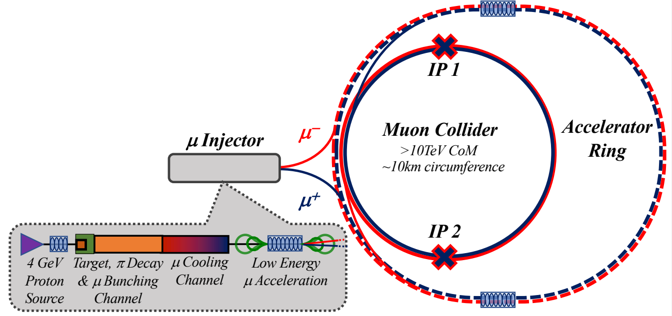


Muon Colliders

International MUON Collider Collaboration

muoncollider.web.cern.ch

MuC now part of European Roadmap for Accelerator R&D

International Muon Collider Collaboration working full steam

Also financed by European Union

Aim is establish maturity for CDR/Demonstrator program after 2026 ESPPU

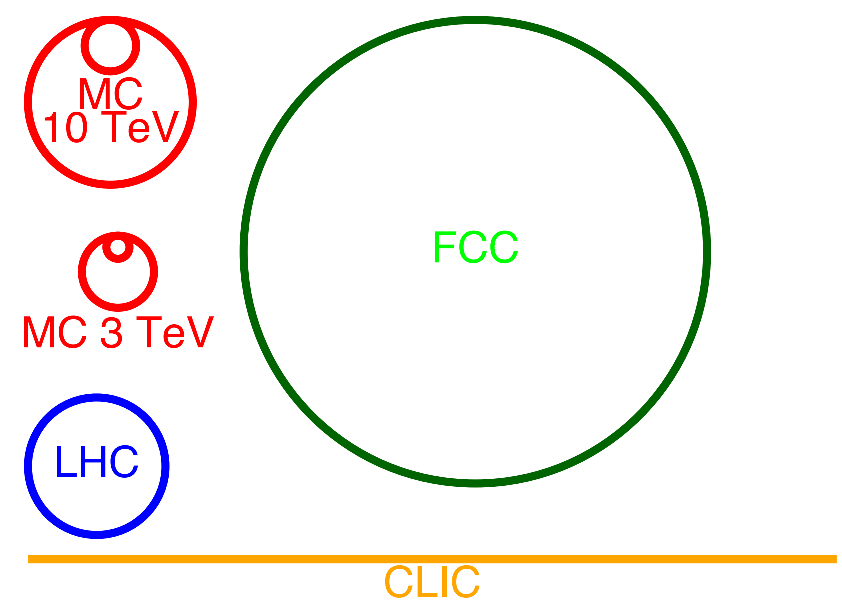
No showstopper identified

Might have technology ready in ‘30s and operation in ‘40s

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14

5 yrs run, 1 IP: $\mathfrak{L}_{\mathrm{int}} = 10\,\mathrm{ab}^{-1}\left(\frac{E_{\mathrm{cm}}}{10\,\mathrm{TeV}}\right)^2$

Natural quadratic lumi scaling at MuC



The status of muon collider facility design, physics and detector, in this EPJC Review:

Towards a Muon Collider