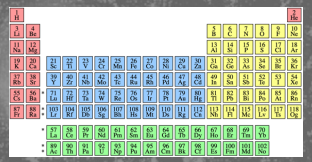
Physics Landscape and Motivation

Young Nordic Future Collider Day
May 14th 2024

Matthew McCullough

Where do we stand in 2024?



?

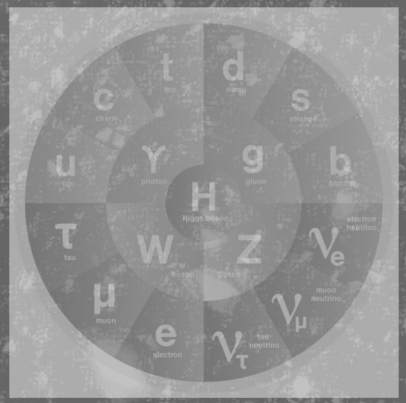
Microscopic Scale

Calculability

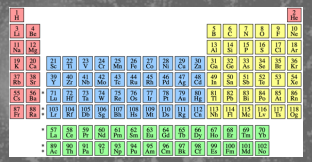
Calculability

Calculability

Interaction Strength



Where do we stand in 2024?



Microscopic Scale

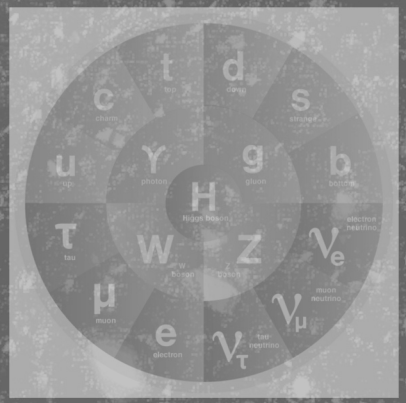
Calculability

Calculability

Calculability

Interaction Strength

?



Where should we go next?

Personal theorist perspective: The **broadest exploration possible** is the best plan for progress.

Electroweak. QCD. Flavour. Higgs. BSM.

Any future Physics landscape should cover each area in paradigm-shifting depth.

FCC-ee

600000000000 Clean Z-Bosons

FCC-ee

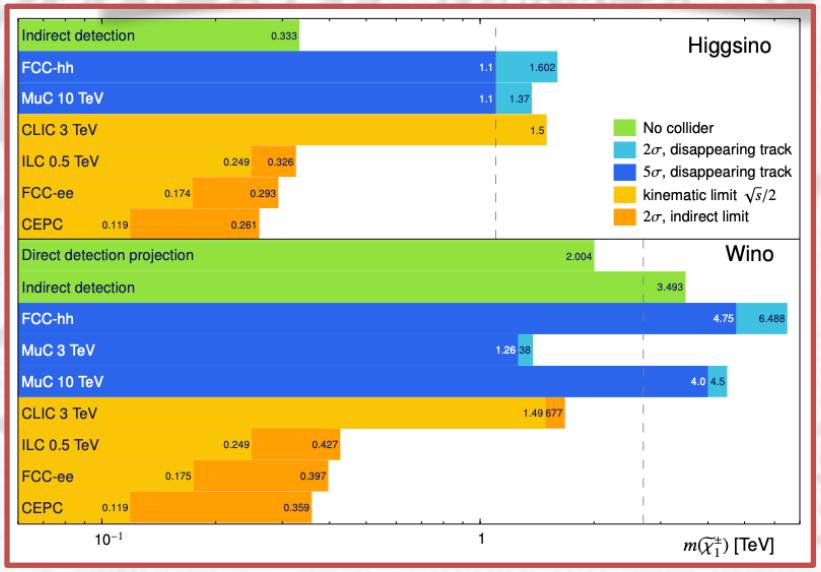
2000000 Clean Higgs Bosons

Up to 3 TeV CLIC

Of Order Millions Clean Higgs Bosons

Clean Higgs Boson Pairs

$\sqrt{s} =$	350 GeV	1.4 TeV	3 TeV
$\int \frac{d\mathscr{L}}{ds'} ds'$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
$\sigma(e^+e^- \to ZH)$	133 fb	8 fb	2 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	34 fb	276 fb	477 fb
$\sigma(e^+e^- \to He^+e^-)$	7 fb	28 fb	48 fb
No. ZH events	68,000	20,000	11,000
No. $H\nu_e\bar{\nu}_e$ events	17,000	370,000	830,000
No. He^+e^- events	3,700	37,000	84,000

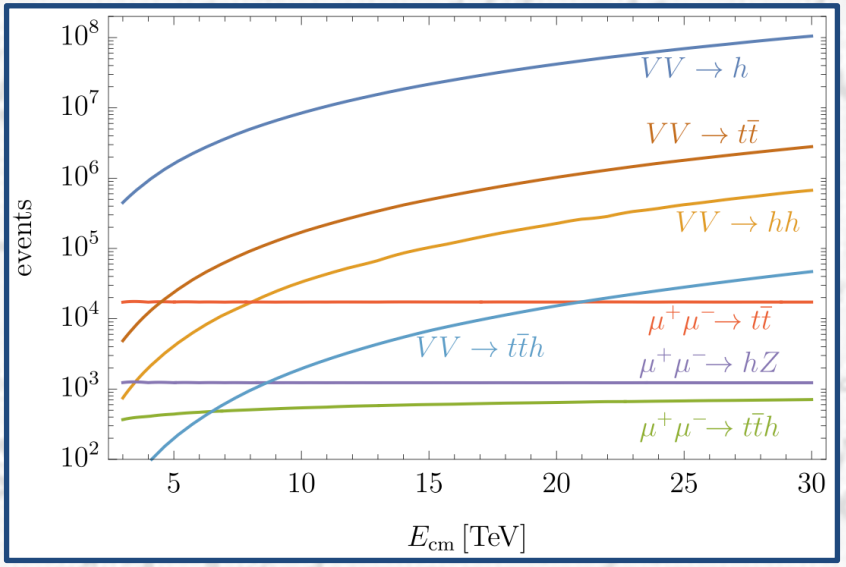


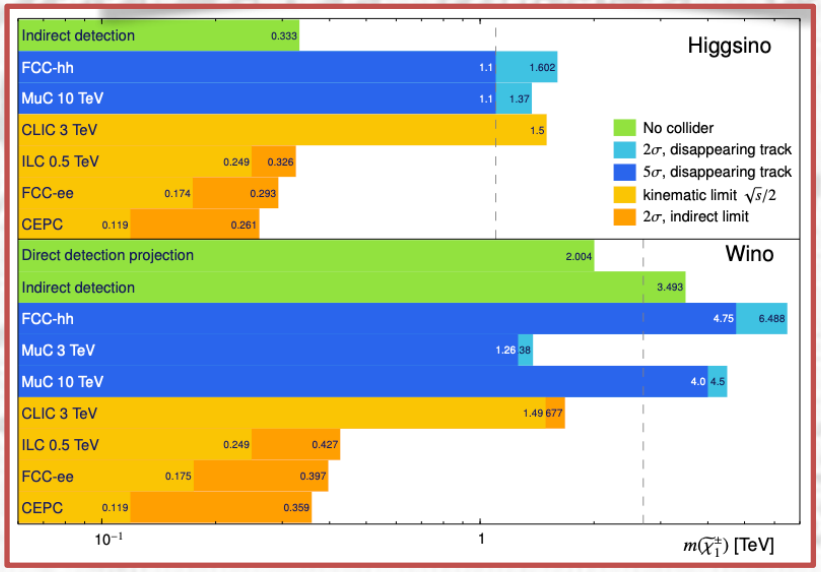
Electroweak states probed at high energies, low background

10 TeV Muon Collider

8000000 Clean Higgs Bosons

30000 Clean Higgs Boson Pairs

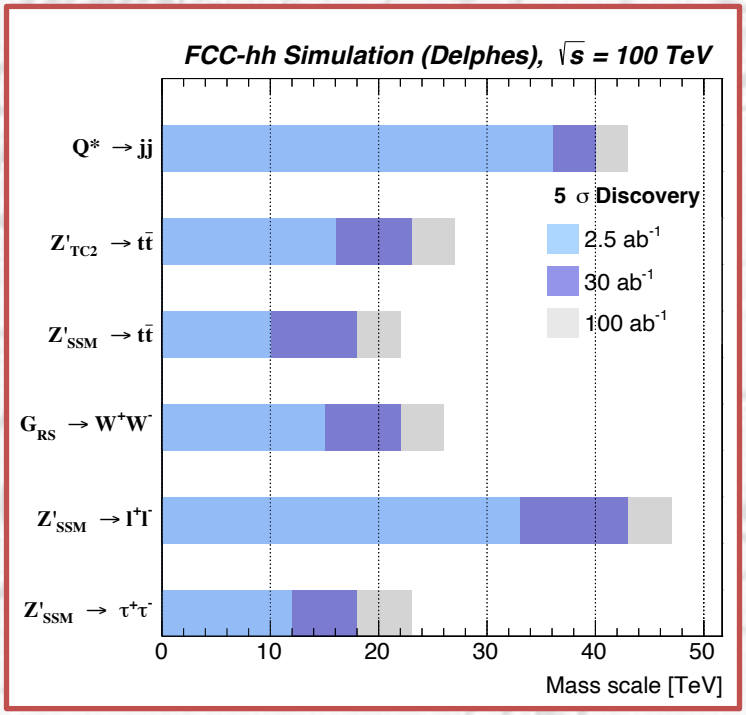




Electroweak states probed at high energies, low background

FCC-hh

Energy frontier is about direct exploration of new states. Across photon, gluon, (W&Z) and five-flavour scheme for quarks, FCC-hh collides $N = 144\ , 196$ different initial states.

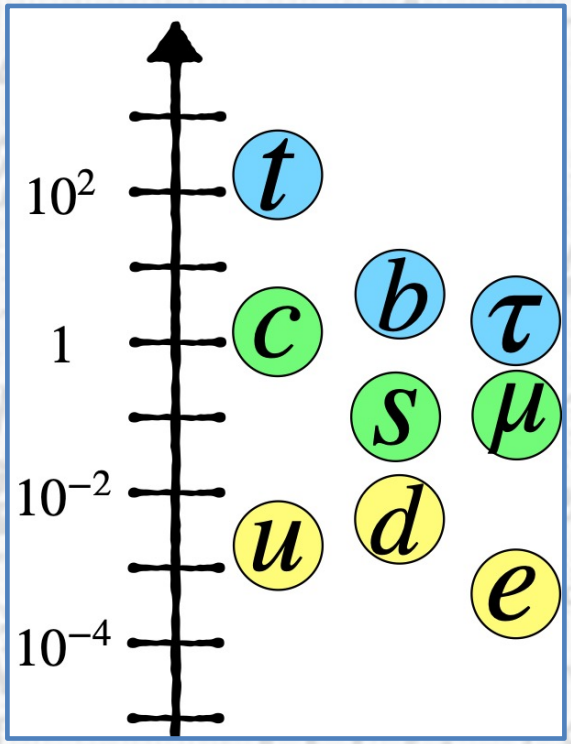


Broadest exploration at highest conceivable energy.

What are the questions we want answered?

What's going on with flavour?

Where do matter mass patterns come from?



$$V_{\text{CKM}} \sim \begin{pmatrix} \blacksquare & \blacksquare & \\ \blacksquare & \blacksquare & \\ & \blacksquare & \blacksquare \end{pmatrix}$$

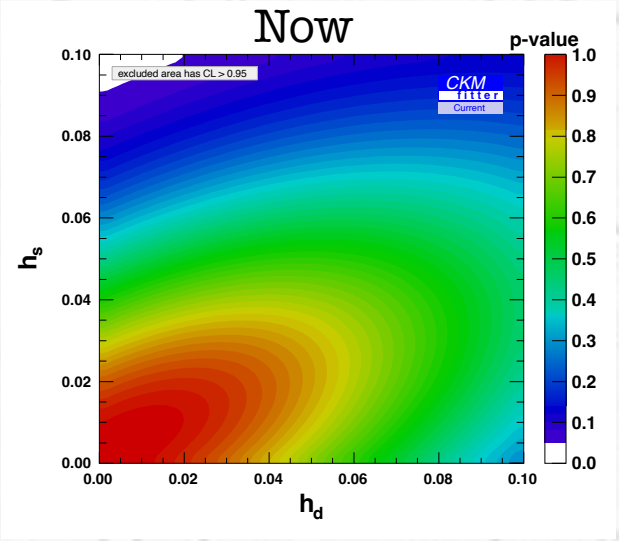
Clearly something going on here… Present state of affairs à la Periodic Table, if we're being honest with ourselves…

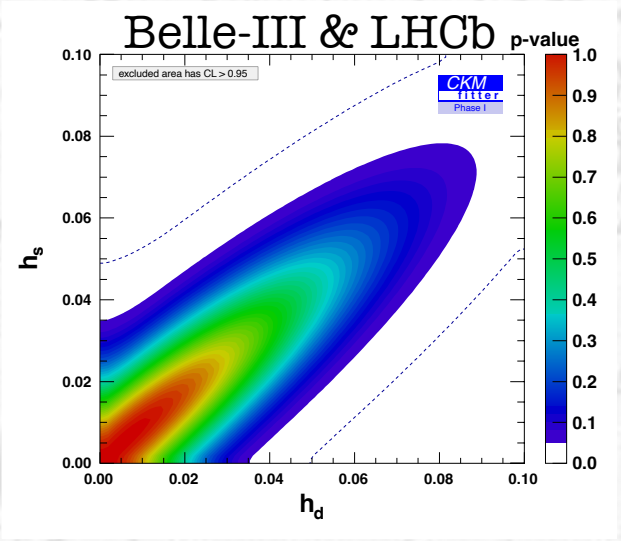
Figures borrowed from A. Greljo.

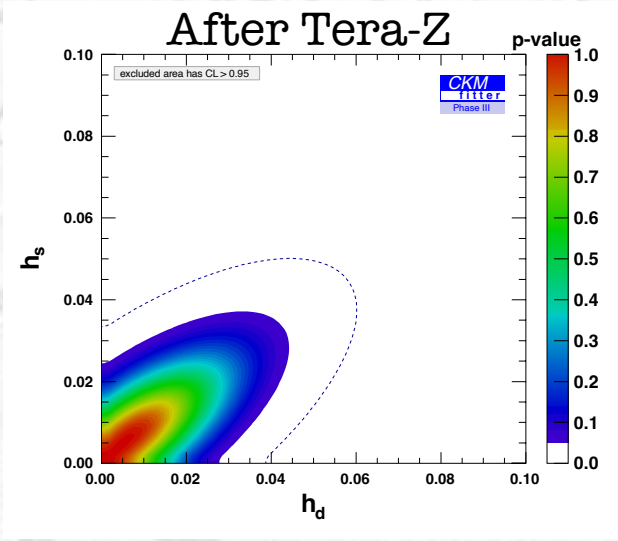
600000000000 Clean Z-Bosons

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B_s^0 / $\overline{B}_s^0$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

Incredible flavour factory!





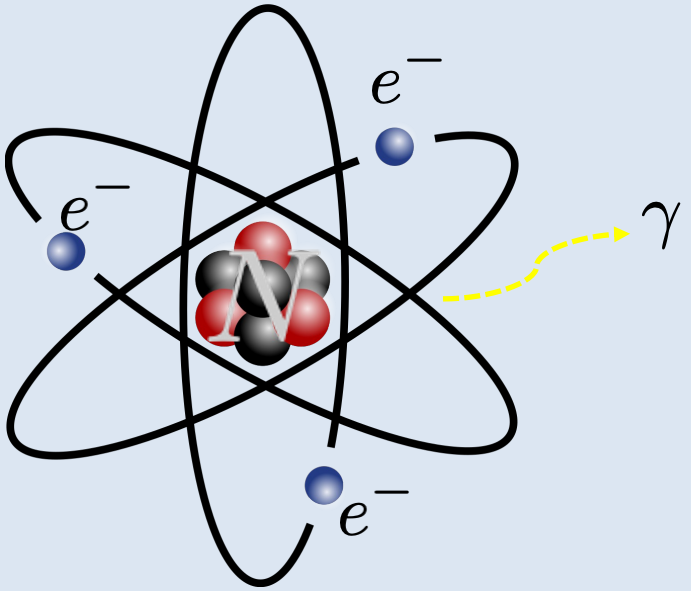


$$M_{12} = \left(M_{12}\right)_{\mathrm{SM}} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

Taken from 2106.01259

Effective Field Theory Basics

Consider exploring a neutral atom at eV energies:



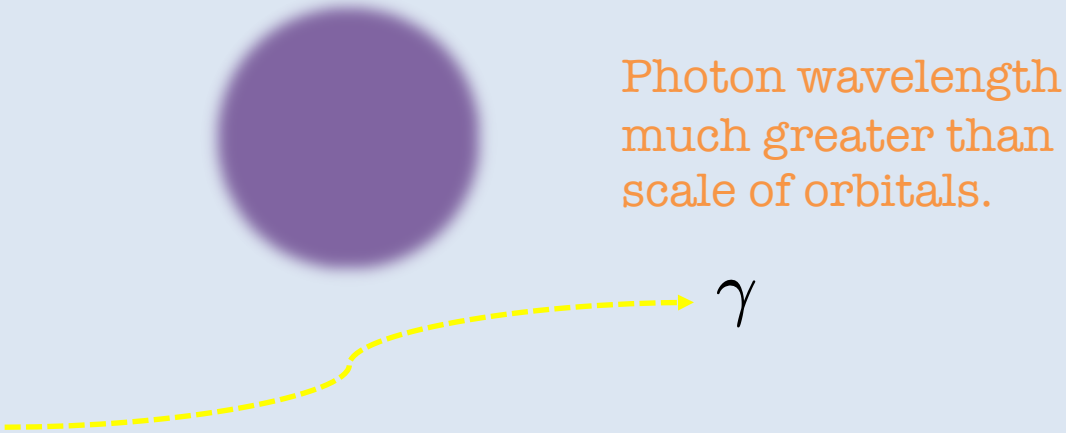
Photon wavelength on scale of orbitals.

The appropriate theory at this length scale contains the photon, electrons and nucleus:

$$\mathcal{L} = \mathcal{L}(\gamma, e^-, N)$$

Effective Field Theory Basics

Consider exploring a neutral atom at much lower energies:

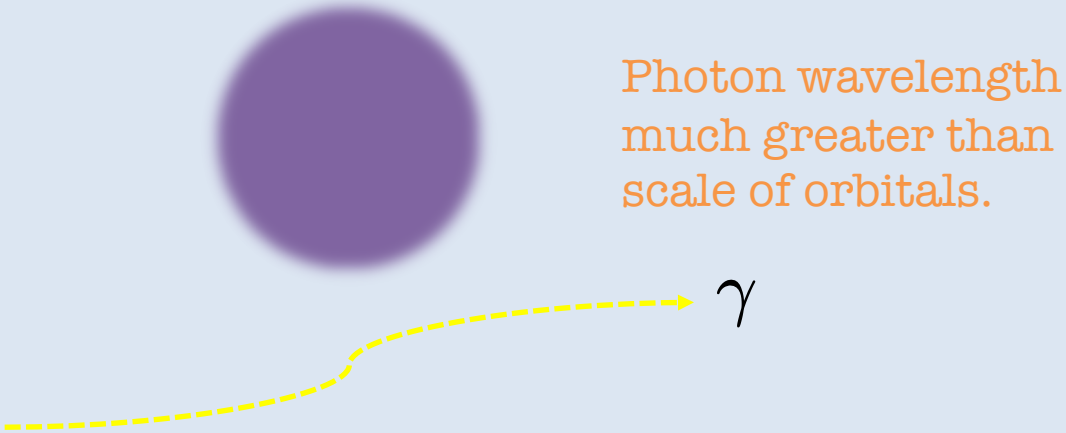


The appropriate theory at this length scale contains the photon and neutral atom...

$$\mathcal{L} = \mathcal{L}(\gamma, \chi)$$

Effective Field Theory Basics

Consider exploring a neutral atom at much lower energies:



Crucially, the substructure is encoded in "higher dimension operators", like dipoles or Rayleigh...

$$\mathcal{L} = \ldots + \frac{\chi^2}{\Lambda^2} F^{\mu\nu} F_{\mu\nu} + \ldots$$

Effective Field Theory Basics

The same is true for particle physics!

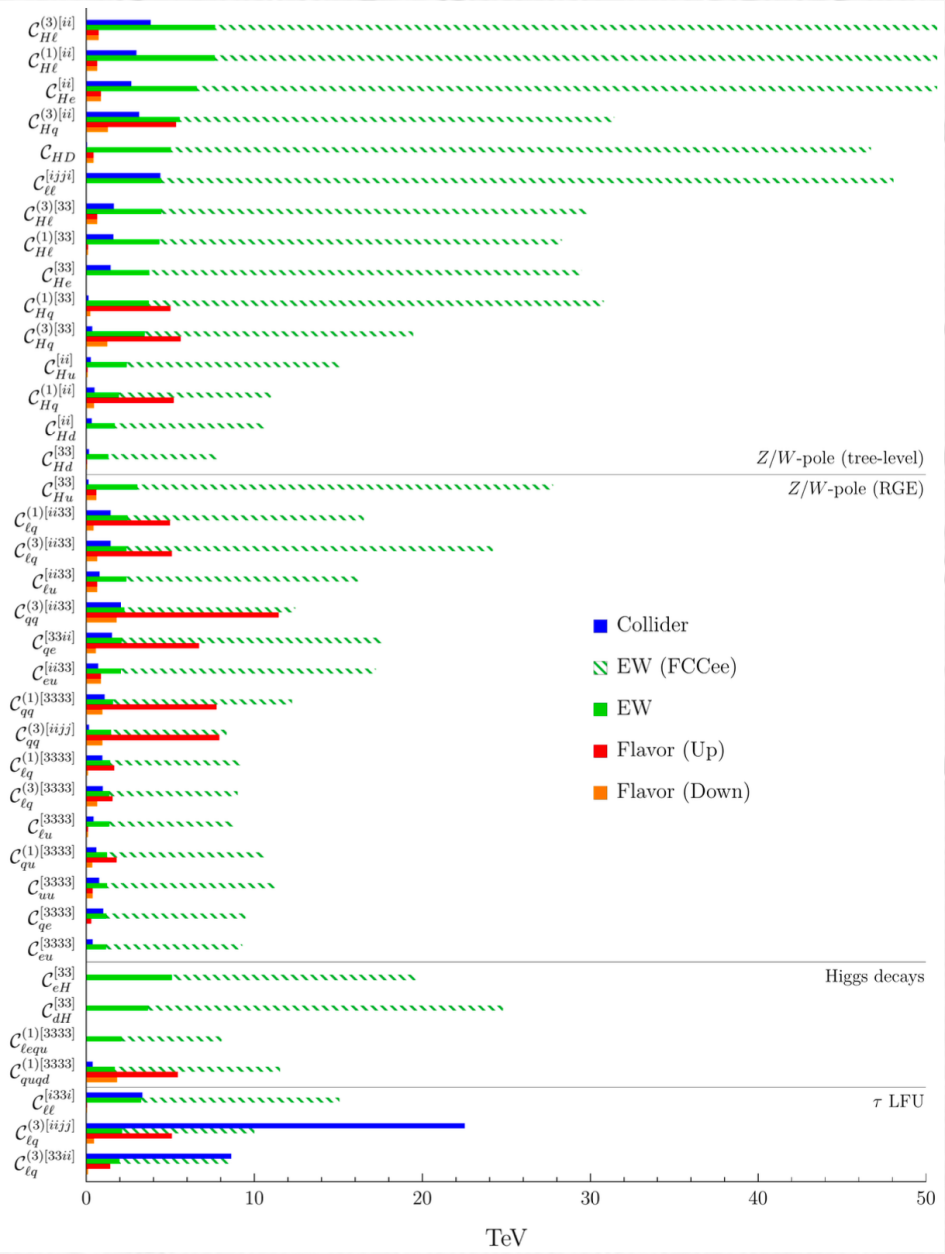
Collider wavelength greater than scale of microscopic new physics...

$$\gamma, W, Z, g, \ldots$$

The Standard Model is an "Effective Field Theory". Unknown smaller distance physics in extra "operators":

$$\mathcal{L} = \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\chi}\not{D}\chi + \chi_i y_{ij} \chi_j \phi + \text{h.c.} + |D_\mu \phi|^2 - V(\phi) + \sum_{jk} \frac{c_j}{\Lambda^k} \mathcal{O}_{jk}$$

600000000000 Clean Z-Bosons



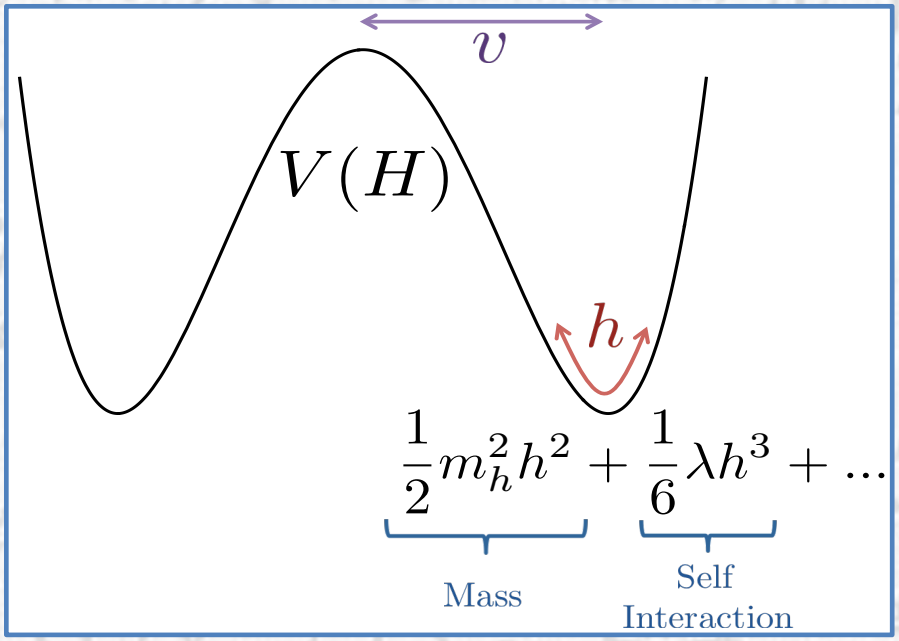
Many interactions generated by new heavy states would be most deeply explored by Tera-Z!

Tera-Z is not a LEP re-run, but a literal quantum leap towards the smallest distance scales...

Taken from 2311.00020

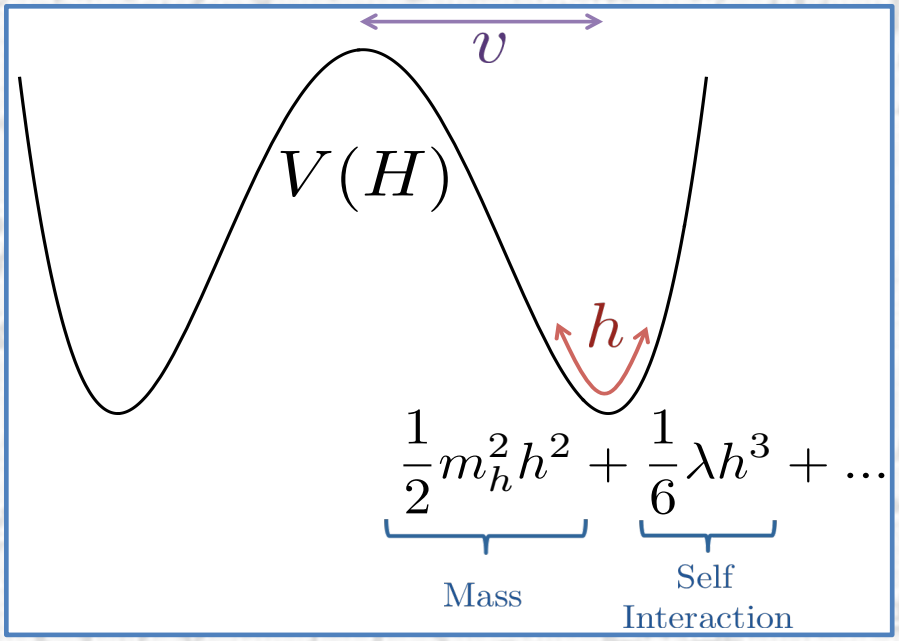
What's up with the Higgs Boson?

What is the Higgs Potential?



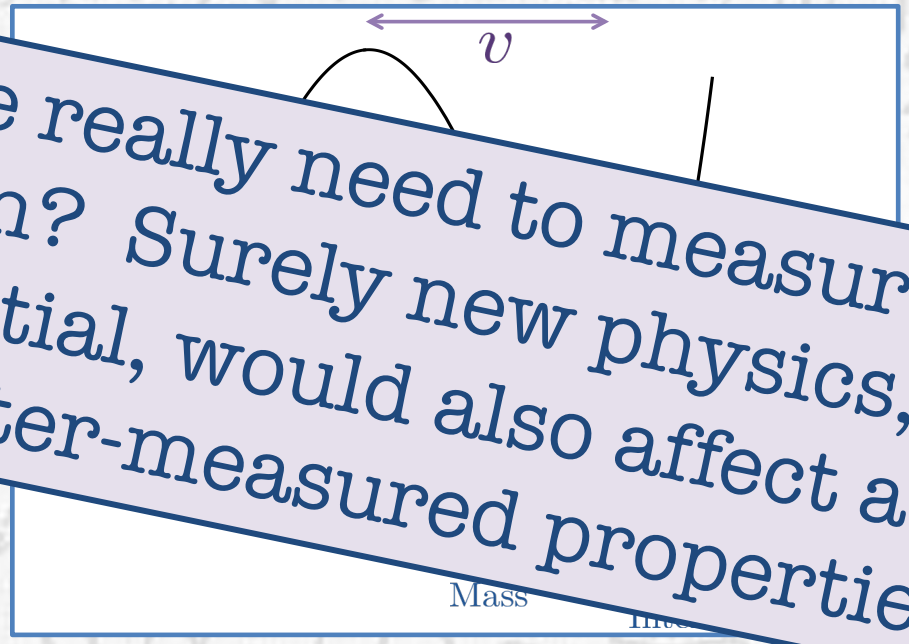
Important because it determines how the Universe froze in the EW sector, giving mass to gauge bosons, fermions, the Higgs...

What is the Higgs Potential?



...because it determines how the Universe will end...

What is the Higgs Potential?



But, do we really need to measure Higgs self-interaction? Surely new physics, if it affects the potential, would also affect additional, better-measured properties?

...because it determines how the Universe will end...

Custodia adruplet

A theory where Higg modified by much more than ar ll calculable, giving

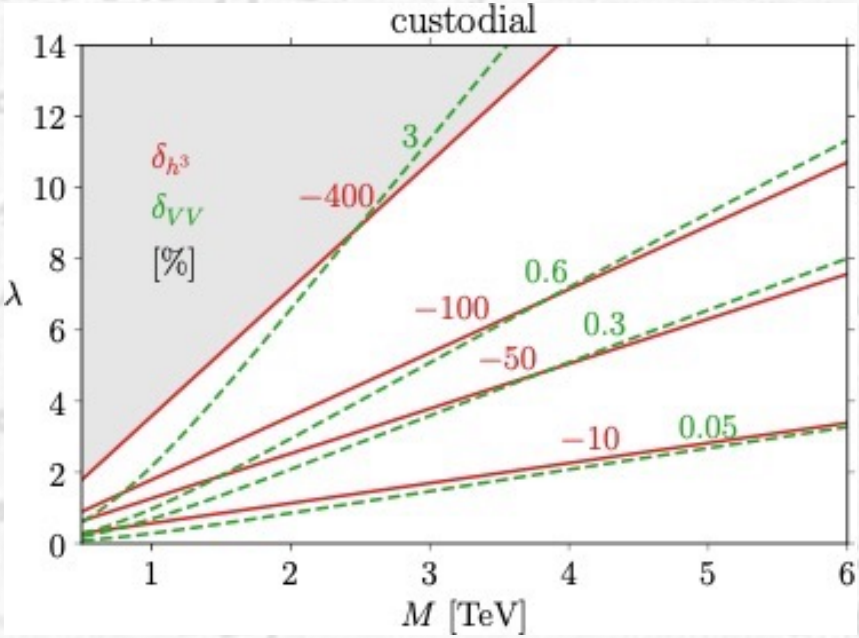
$$-\frac{\delta_{VV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right) + \frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2$$

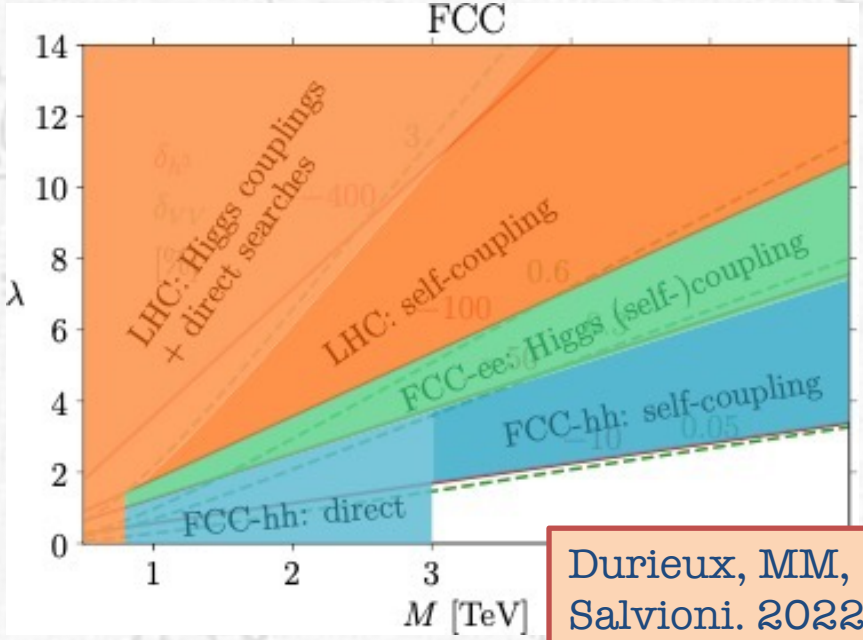
Durieux, MM, Salvioni. 2022

Custodial Quadruplet

A theory where Higgs self-coupling is modified by much more than any other property. All calculable, giving

$$-\frac{\delta_{VV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right)^2 + \left(\frac{m_h}{M}\right)^2 \approx \frac{1}{200} + \frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2$$



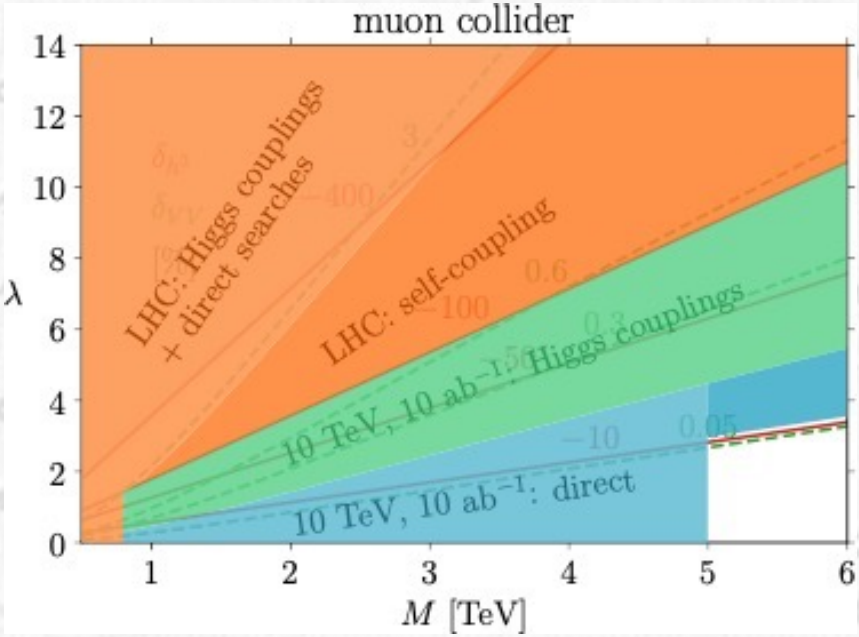


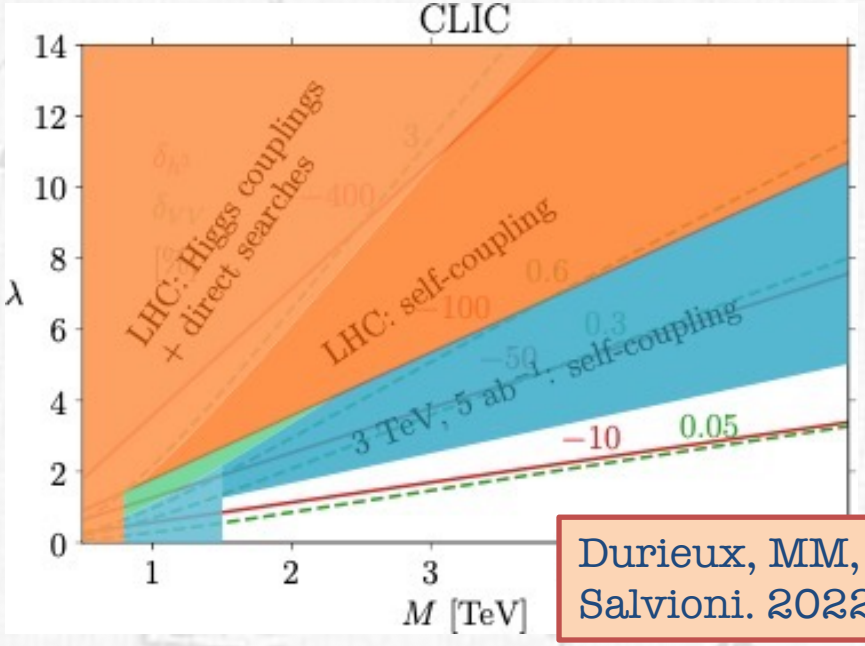
Durieux, MM, Salvioni. 2022

Custodial Quadruplet

A theory where Higgs self-coupling is modified by much more than any other property. All calculable, giving

$$-\frac{\delta_{VV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right)^2 + \left(\frac{m_h}{M}\right)^2 \approx \frac{1}{200} + \frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2$$

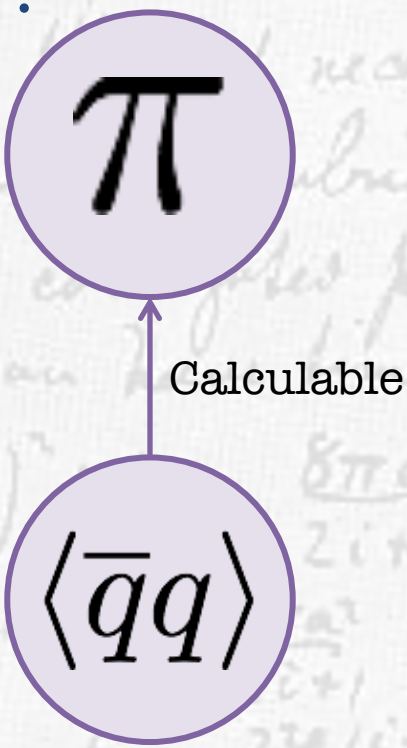




Durieux, MM, Salvioni. 2022

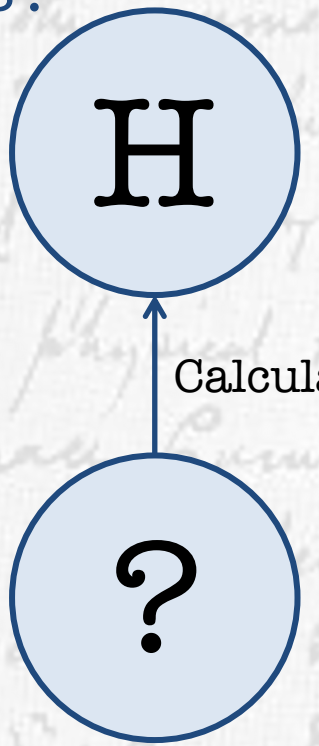
What's in the Higgs Boson?

Every scalar we encountered until now had properties (mass, background value, etc) that are calculable within some more fundamental, microscopic, theory:



What's in the Higgs Boson?

What about the Higgs?



The Standard Model, our best description of nature, breaks down at short distances: It is an effective field theory, to be replaced by something more fundamental at shorter distance scales.

What's in the Higgs Boson?

What about the Higgs?

Could the Higgs be a composite, like the Pion?

Question that's been asked many times... Kaplan, Georgi, Dimopoulos 1984 etc.

The Standard Model, our best descrip[illegible]e, breaks down at short distances: It is an effective field theory, to be replaced by something more fundamental at shorter distance scales.

Gegenbauer's Twin

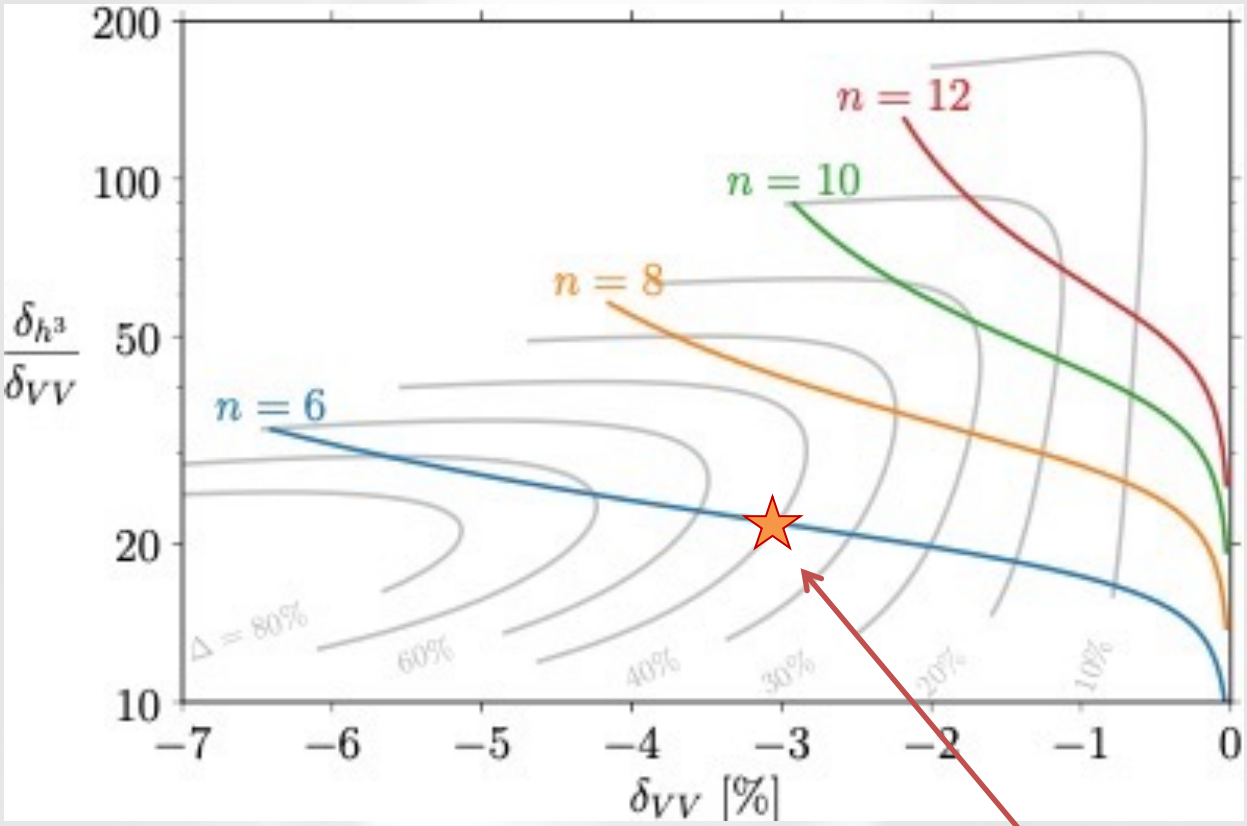
Durieux, MM, Salvioni. 2022

An example of a recently-proposed possibility for a Pion-like Higgs which naturally predicts very Standard Model-like Higgs properties.

Whether or not nature is described by this theory is an open question. For our purposes: It highlights the importance of Higgs Factory Precision.

Gegenbauer's Twin

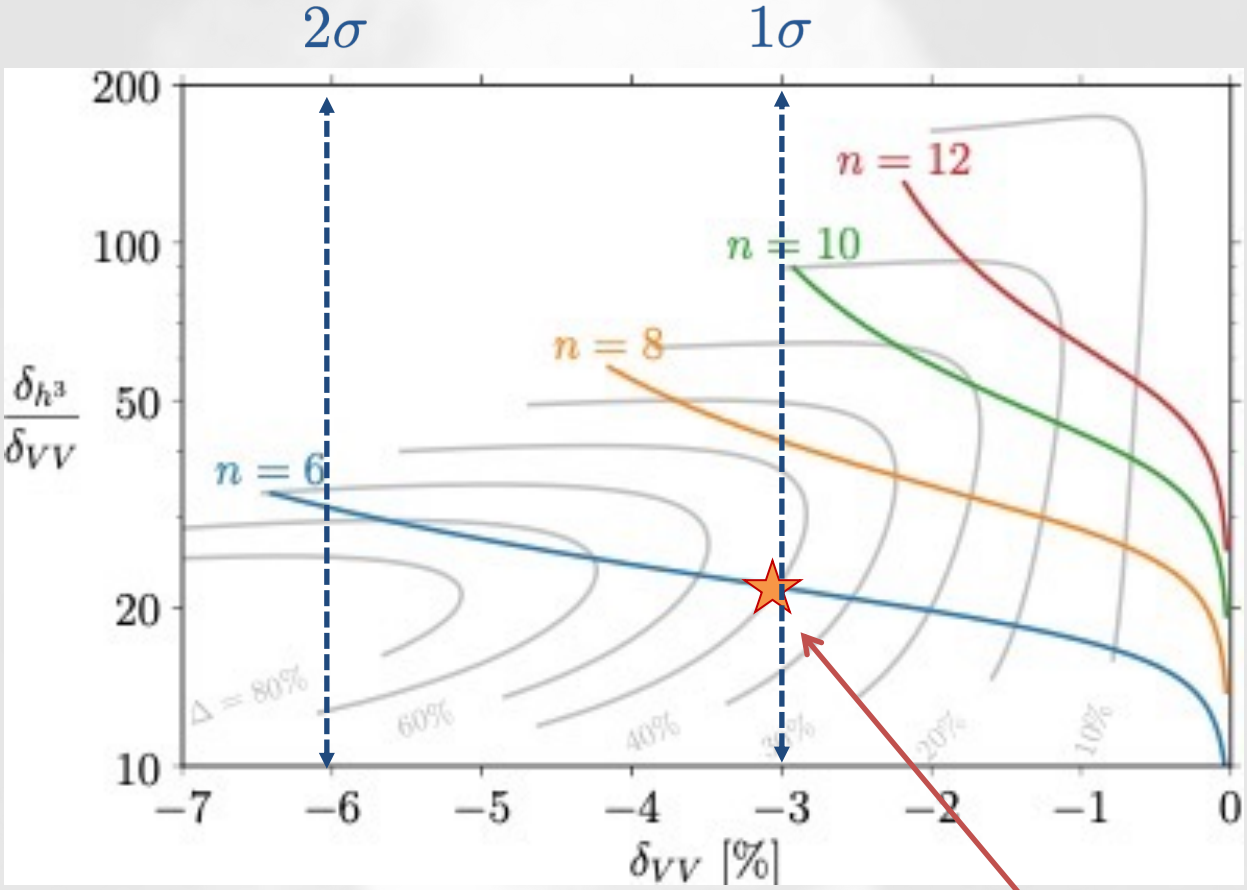
Predictions, in absolute terms:



Example point. Low tuning, 3% single-coupling correction, 70% self-coupling correction.

Gegenbauer's Twin

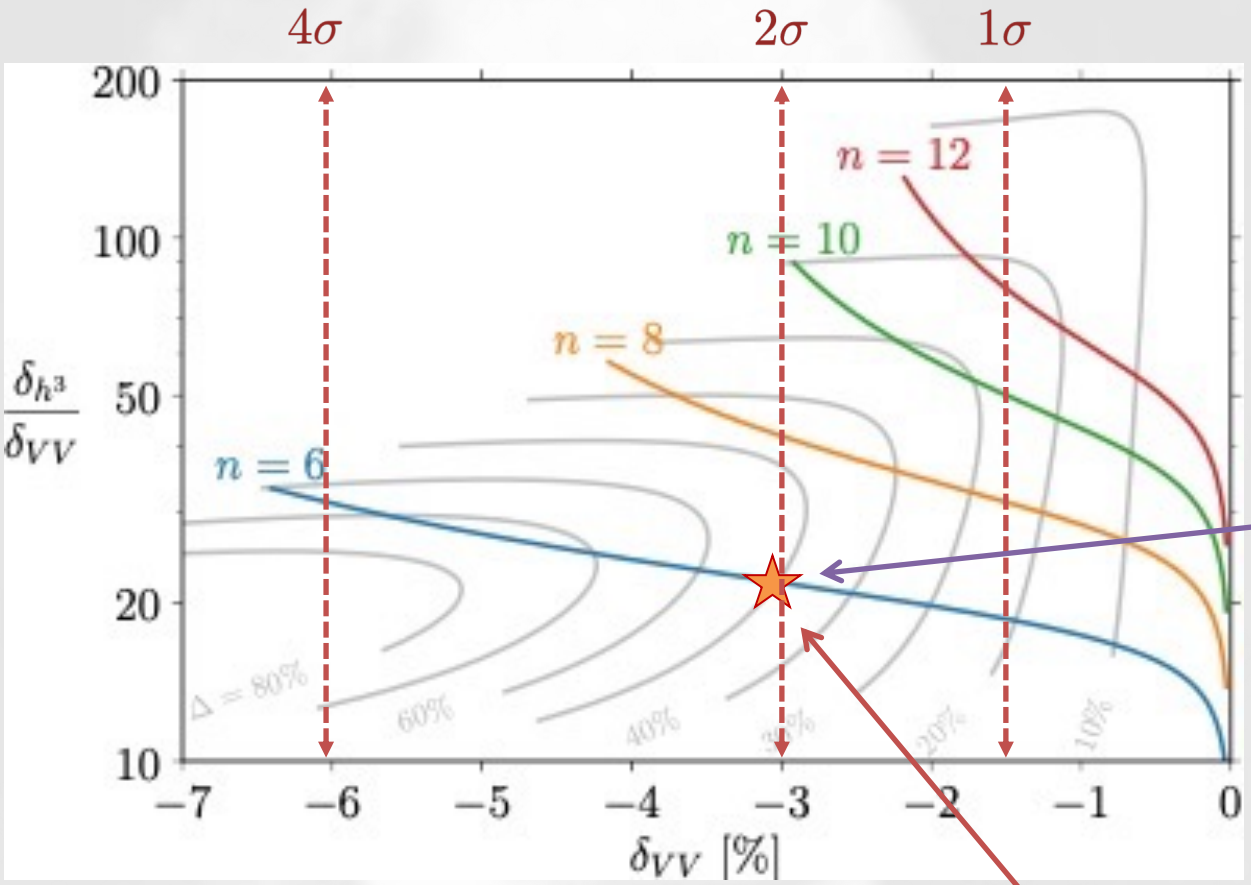
Present Limits



Example point. Low tuning, 3% single-coupling correction, 70% self-coupling correction.

Gegenbauer's Twin

HL-LHC Expectations

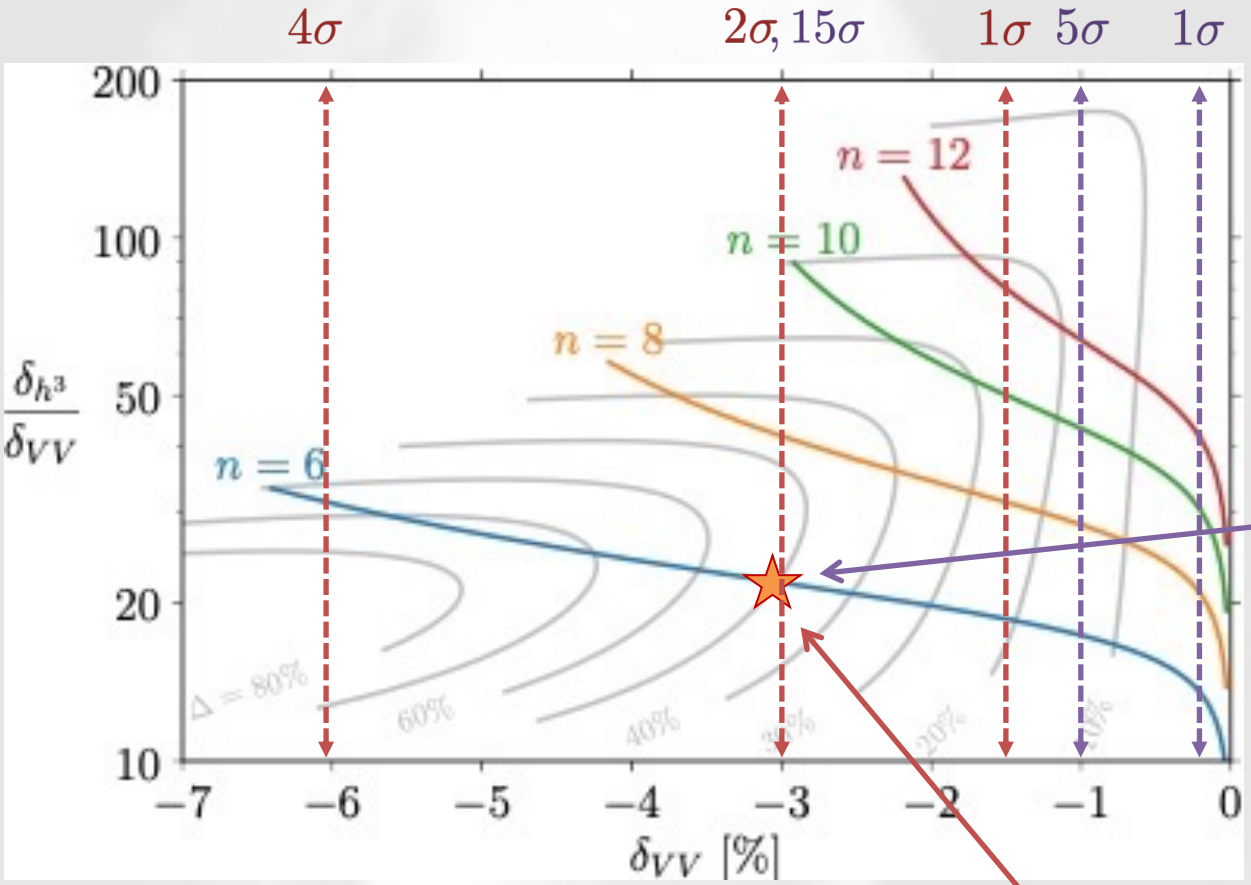


Only 2σ at HL-LHC.

Example point. Low tuning, 3% single-coupling correction, 70% self-coupling correction.

Gegenbauer's Twin

HL-LHC Expectations & FCC-ee

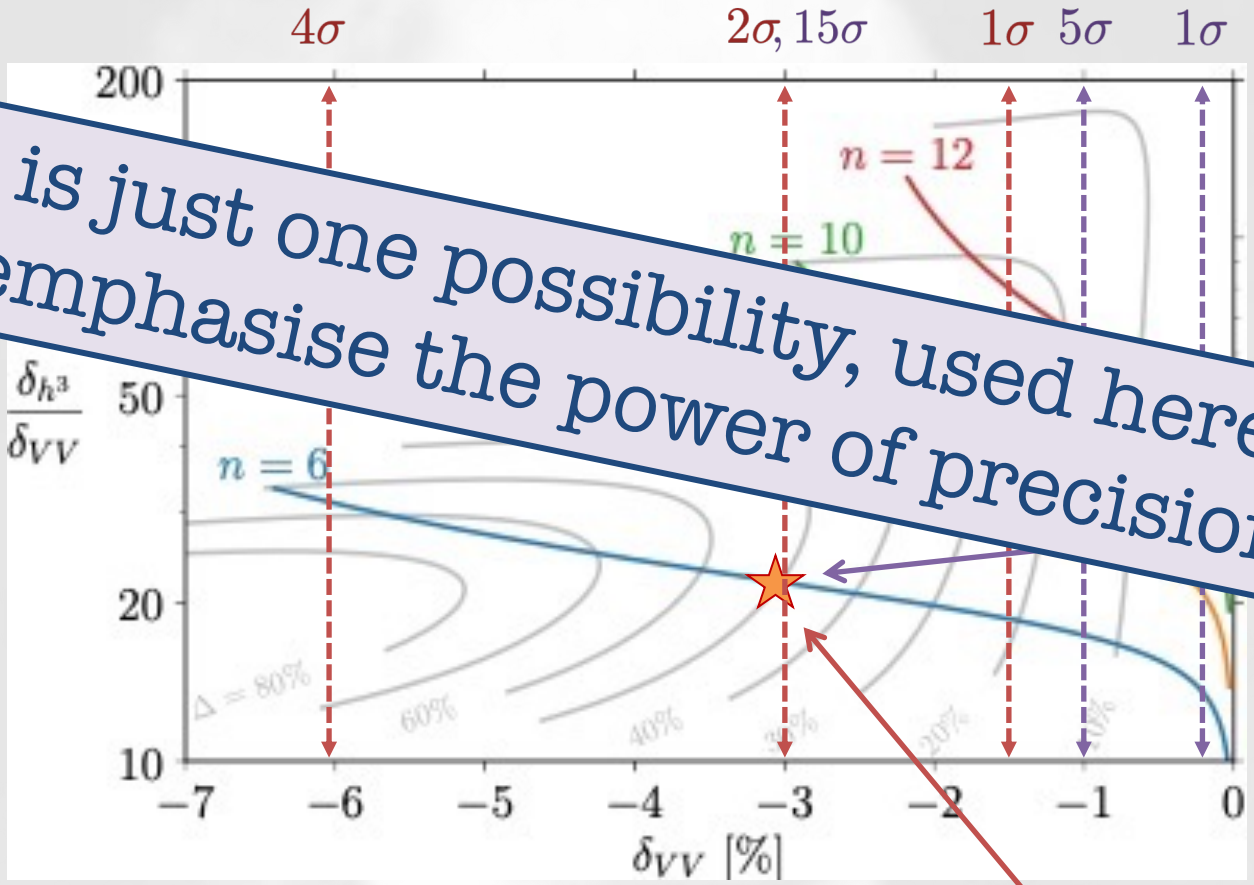


Only 2σ at HL-LHC but 15σ at FCC-ee!

Example point. Low tuning, 3% single-coupling correction, 70% self-coupling correction.

Gegenbauer's Twin

HL-LHC Expectations & FCC-ee



This is just one possibility, used here just to emphasise the power of precision...

FCC-ee!

Example point. Low tuning, 3% single-coupling correction, 70% self-coupling correction.

Dark Sectors

Evidence for dark matter is now overwhelming

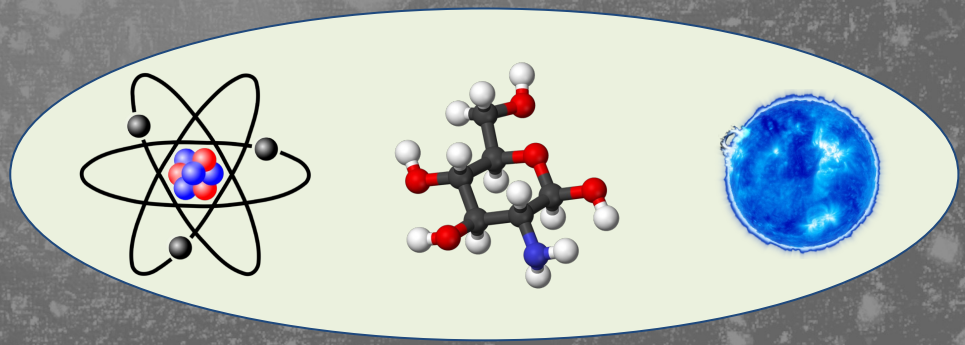
- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!

Only 18% of all matter in Universe is visible.

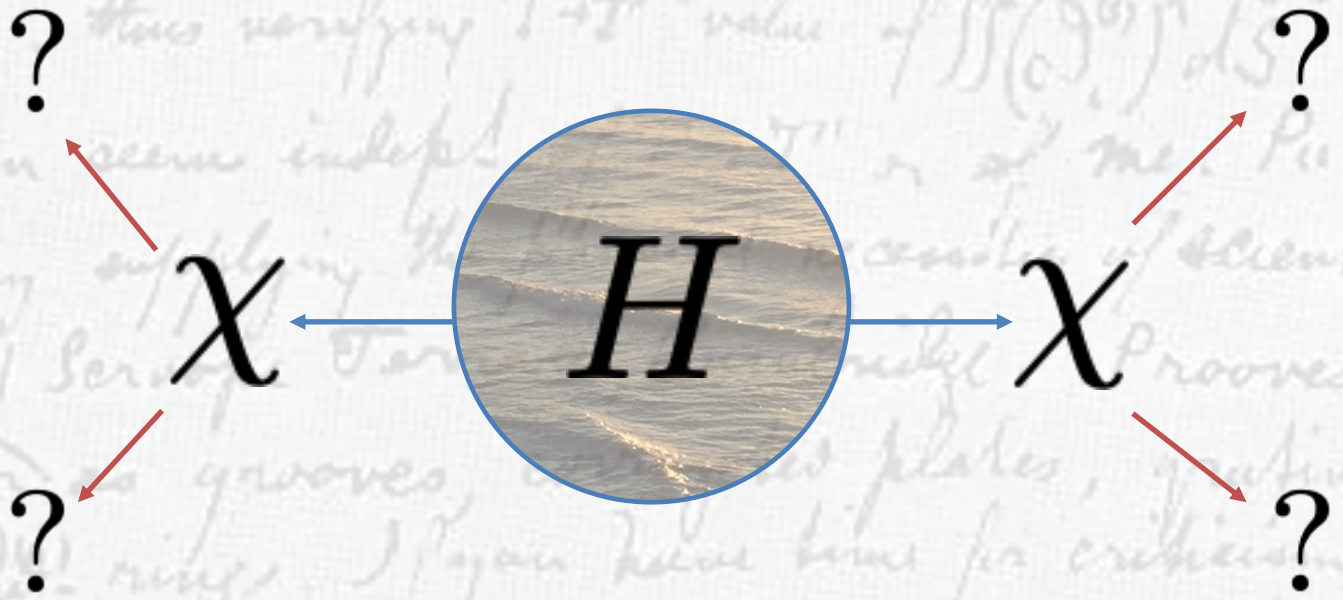
e u d Z h
μ c s g
τ t b γ W

Within that 18% we observe extraordinary complexity.



Similarly, the dark sector, and dark matter, may be much more complex than just a single state.

Is the Higgs a portal to new dark sector states?

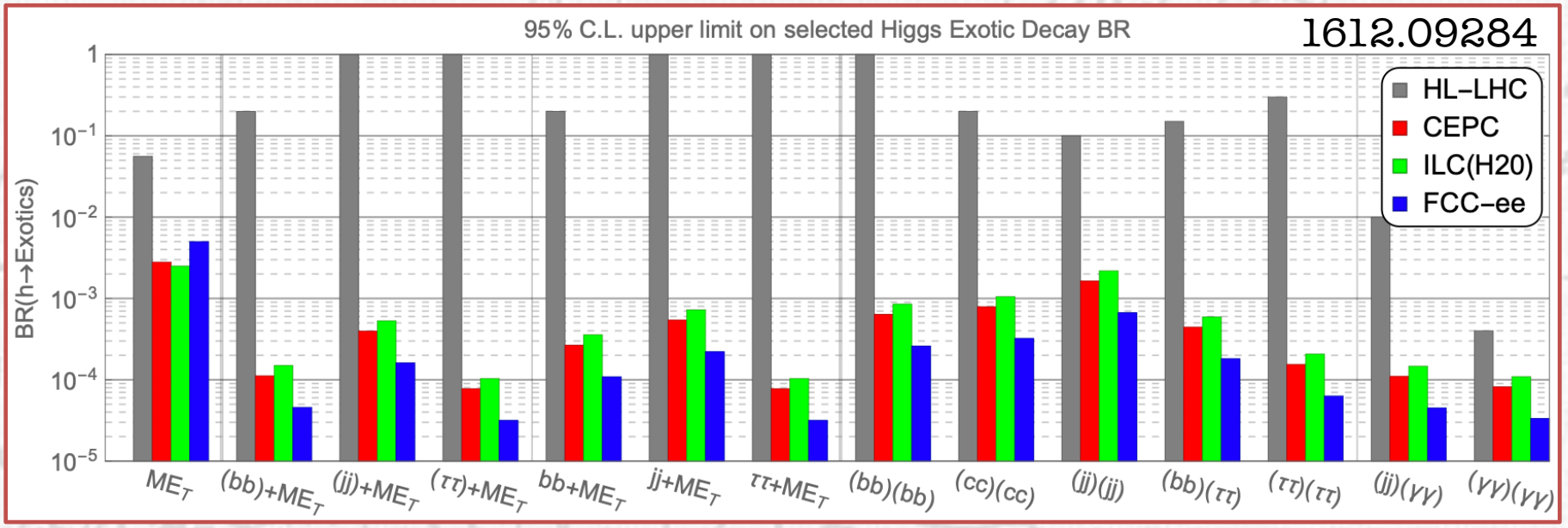


After all, $|H|^2$ is the most relevant interaction involving SM fields! Even if generated at microscopic scales

$$|H|^2\chi^2$$

stays relevant all the way down to the Higgs scale...

Is the Higgs a portal to new dark sector states?



Orders of magnitude improvement in coverage of exotic Higgs decays.

Conclusions

Any “perspective” is subjective. I have presented snippets of my own, subjective, perspective.

However, we will create the most exciting future for particle physics with a strategy that is **as robust as possible** against theory perspectives!

Conclusions

QCD.

Higgs.

Electroweak.

BSM.

Flavour.

O.T.' R.U. ATOME? $\iint$ Spheric dS was done in the most general form in 1867. I have now bagged ξ & η from T & T' and done the numerical value of $\iint (Y_i^{(s)})^2 dS$ in 4 lines, thus verifying T+T''s value of $\iint (\vartheta_i^{(s)})^2 dS$

Your plan seems indep^t of T + T' or of me. Publish!

I am busy supplying the physical necessities of scientific life.

Address 11 Scroope Terrace, Cambridge. Grooves have got as far as grooves, corrugated plates, gratings & rings. If you have time for criticism then answer [illegible]

$$\iint (Y_i^{(s)})^2 dS = \frac{8\pi a^2}{2i+1} \frac{\lfloor i+s \; \lfloor i-s}{2^{2s} \lfloor i \; \lfloor i}$$

except when $s=0$ when $\iint (Q_i)^2 dS = \frac{4\pi a^2}{2i+1}$

Hence

$$\int_{-1}^{+1} (\vartheta_i^{(s)})^2 d\mu = \frac{2}{2i+1} \frac{2^{2s} \lfloor i-s \; \lfloor s \; \lfloor s}{\lfloor i+s}$$

without exception

yes $\frac{dp}{dt}$