Theory Perspective on FCC Physics

Zurich Phenomenology Workshop
Jan 9th 2024

Matthew McCullough

CERN

A Theorist's Perspective on FCC Physics

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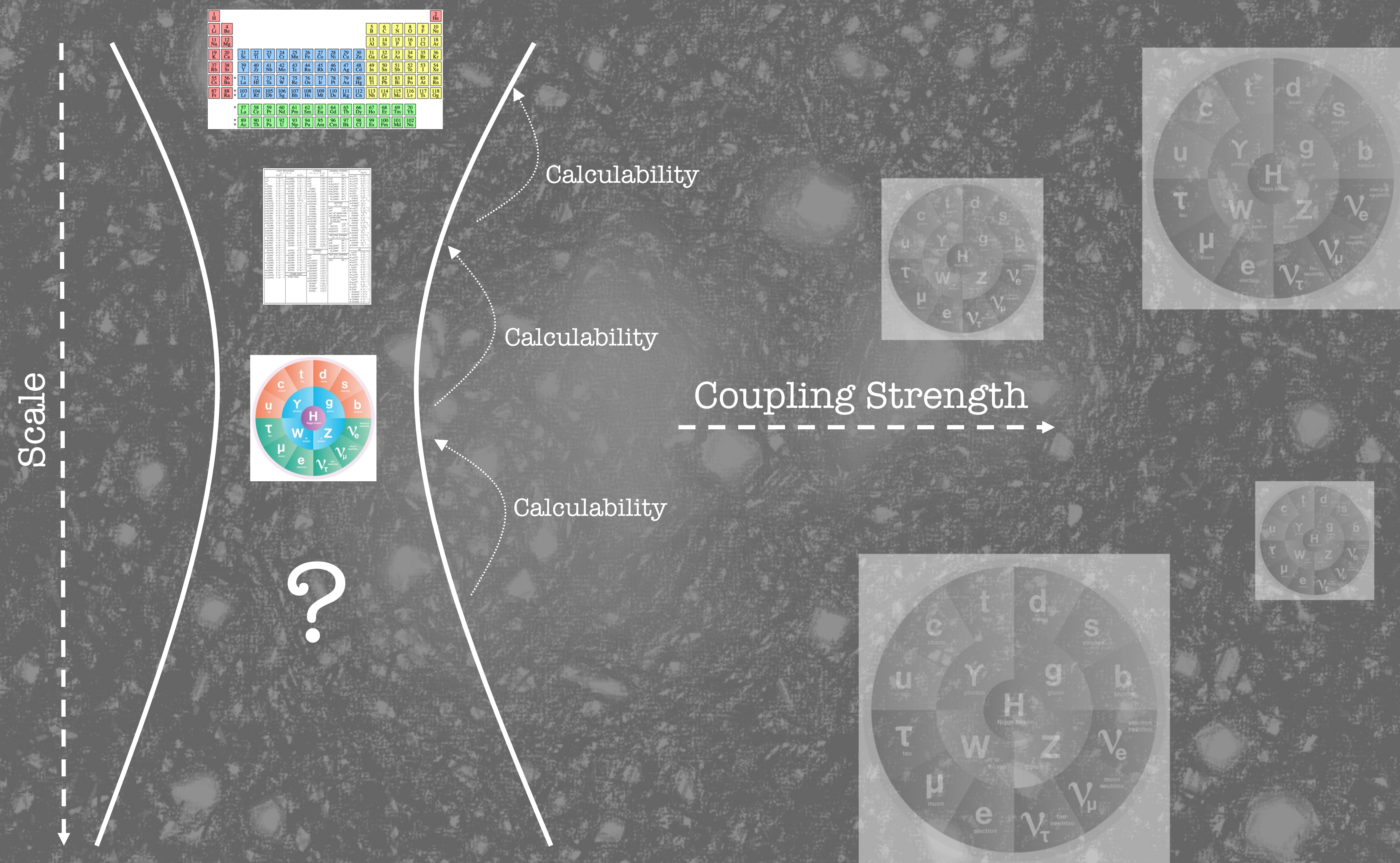
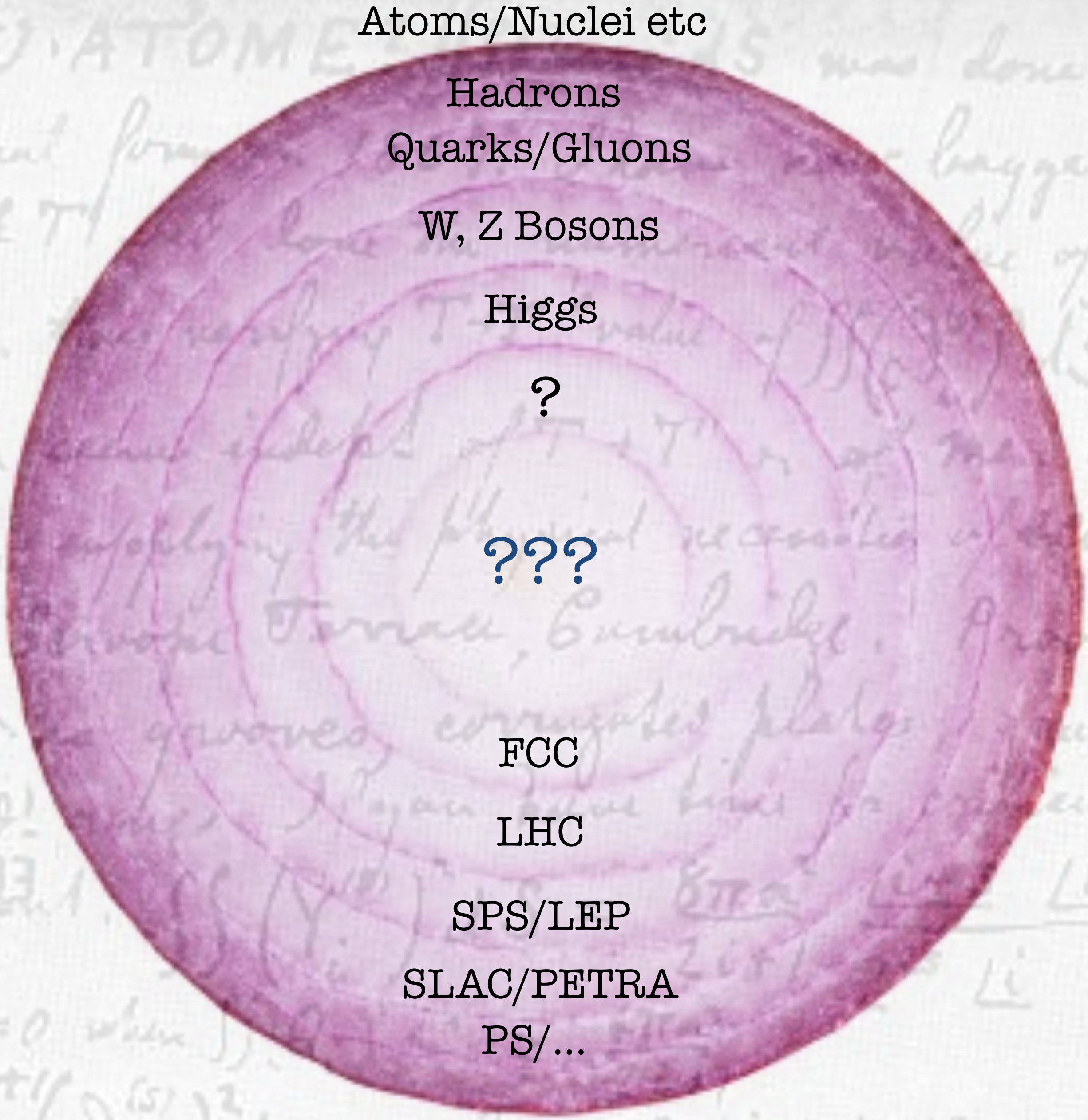
Where do we stand in 2024?





We should be honest with ourselves about ignorance.

Personal theorist perspective: The broadest exploration possible is the best hope we have for progress. Leaning too heavily on theorist priors makes me very nervous...

FCC-ee

6000000000000 Clean Z-Bosons

FCC-ee

2000000 Clean Higgs Bosons

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. **Broad exploration.** Plenty of partons colliding at very high energy.

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. **Broad exploration.** Writing resonance cross section as

$$\sigma = r\frac{C_{yy}}{s}$$

where

$$C_{gg} = \frac{\pi^2}{8}\int_\tau^1 \frac{dx}{x}\, f_g(x) f_g(\tau x)\;, \quad C_{q\bar{q}} = \frac{4\pi^2}{9}\int_\tau^1 \frac{dx}{x}\, [f_q(x) f_{\bar{q}}(\tau x) + f_{\bar{q}}(x) f_q(\tau x)]$$

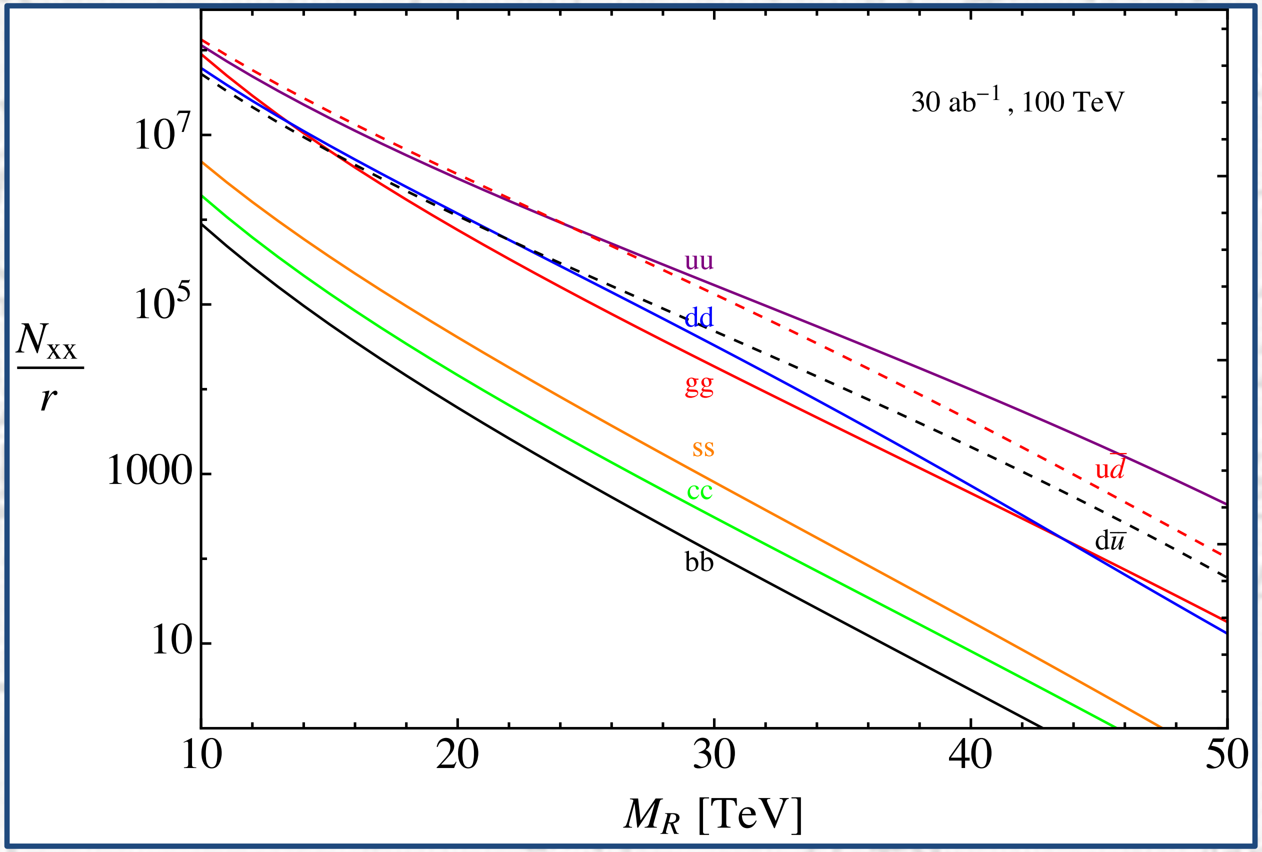
and

$$r = (2S+1) B_{yy} B_{xx} \frac{\Gamma_R}{M_R}$$

FCC-hh

Then, recalling, $r = (2S+1)B_{yy}B_{xx}\frac{\Gamma_R}{M_R}$

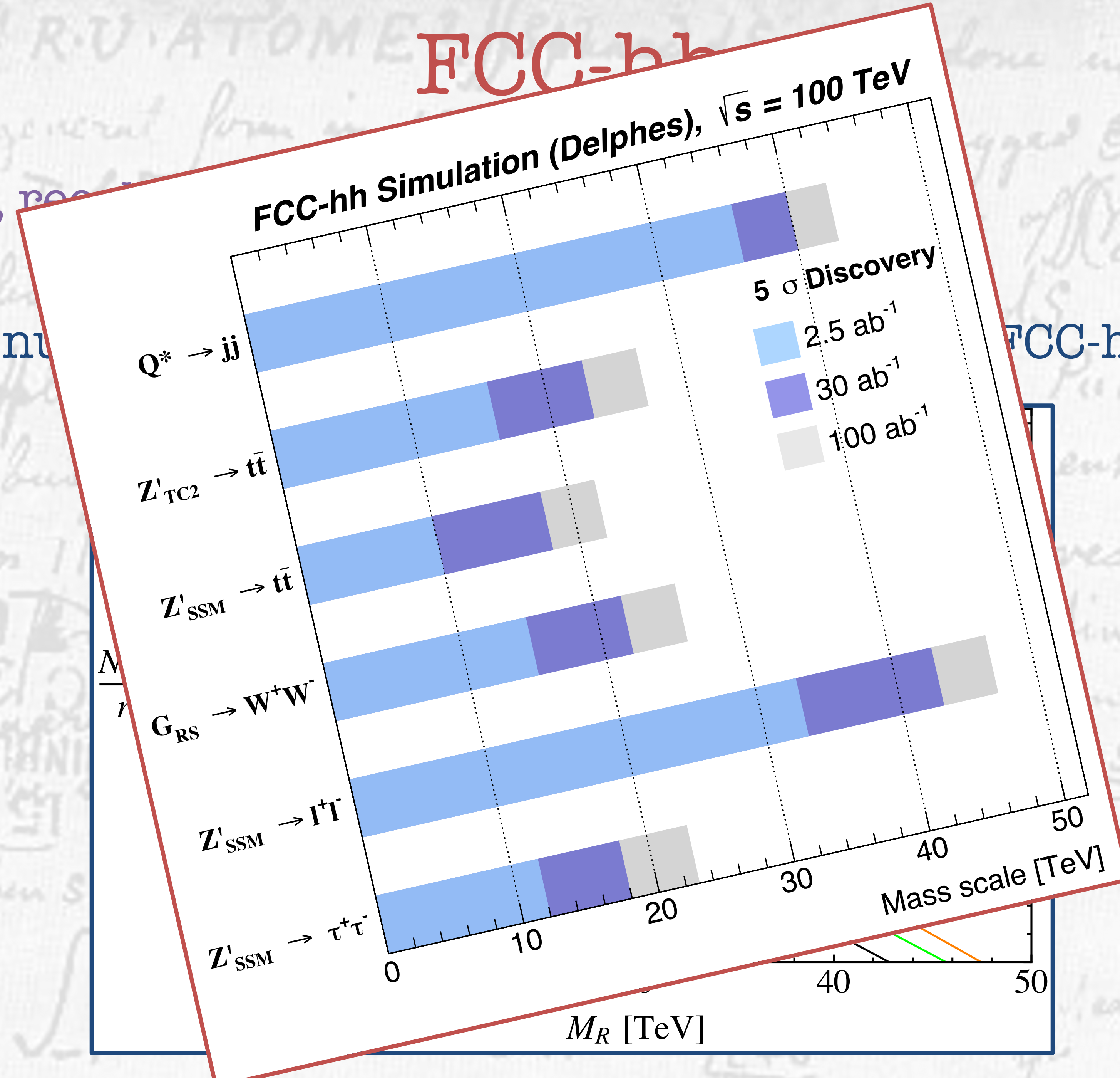
...the number of direct resonance production events you get above 10 TeV at FCC-hh is:



FCC-hh

Then, re

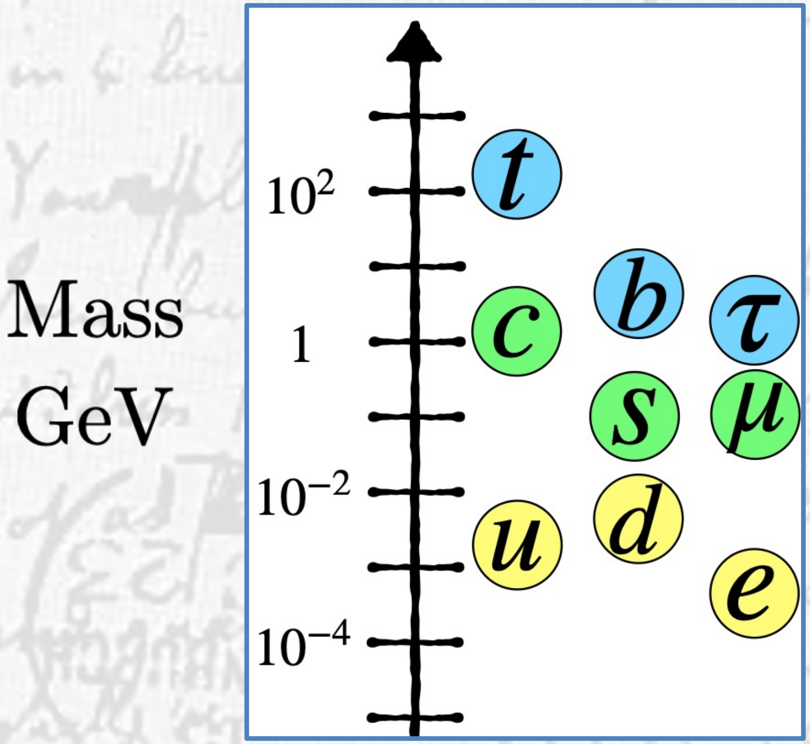
...the nu FCC-hh is:

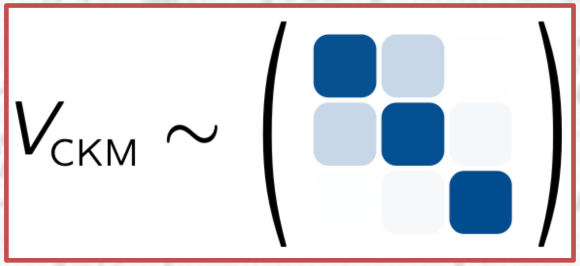


What are the questions we want answered?

What’s going on with flavour?

Where do matter mass patterns come from?





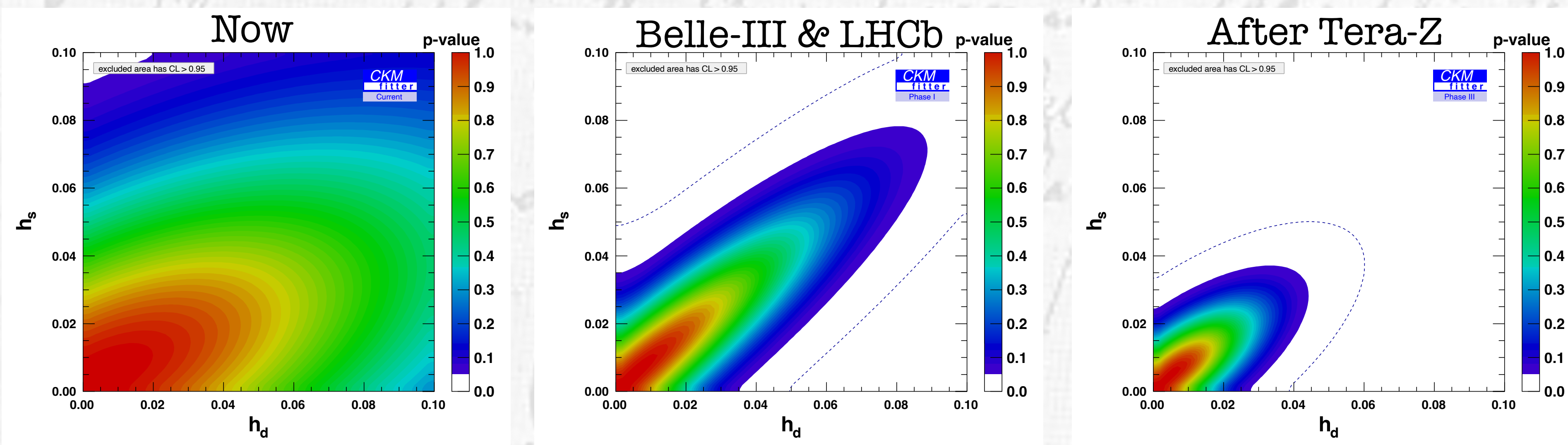
Clearly something going on here... Present state of affairs à la Periodic Table, if we're being honest with ourselves...

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!



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

$$h \simeq 1.5\, \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2}\, \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2$$

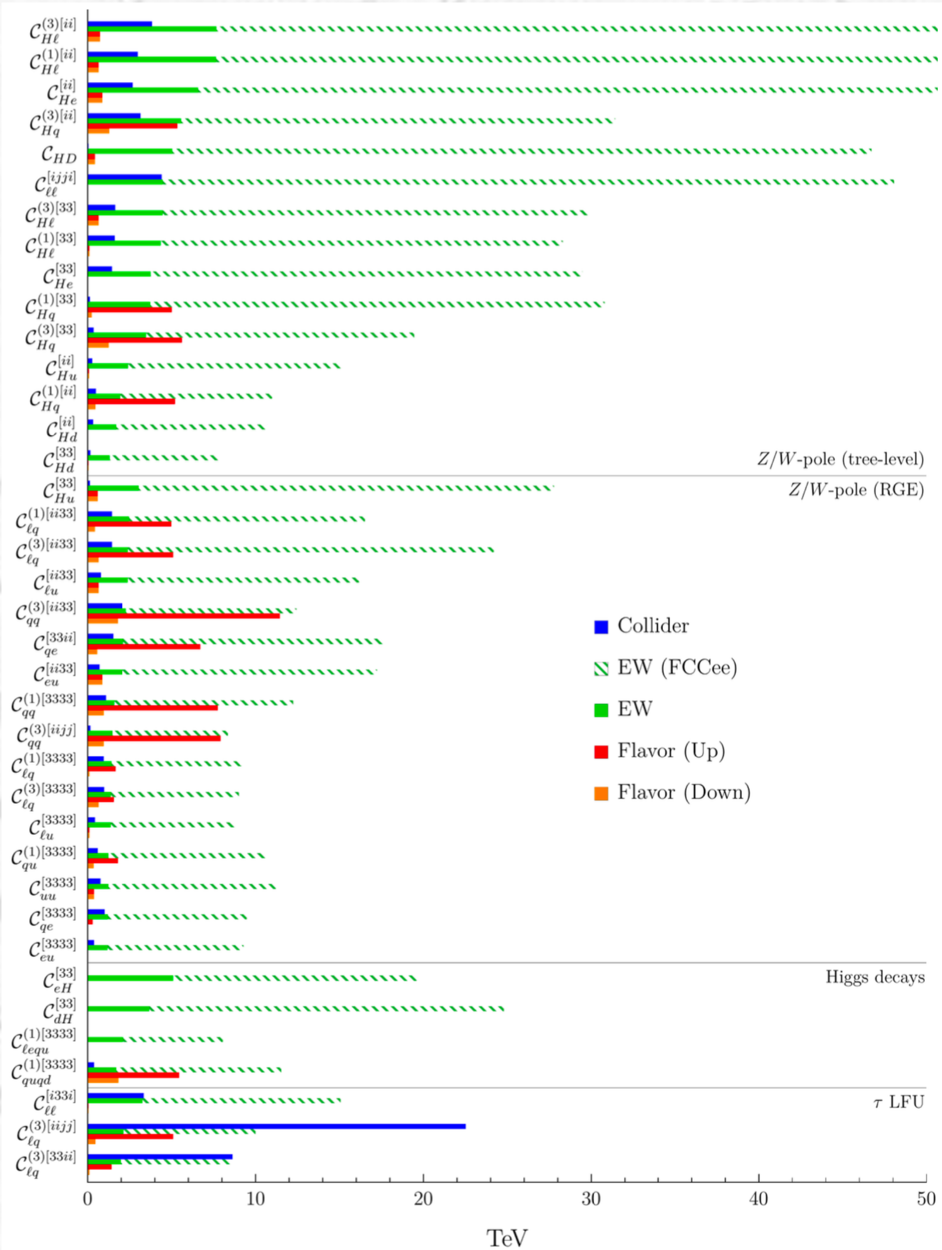
$$\sigma = \arg(C_{ij}\, \lambda_{ij}^{t*}),$$

$$\frac{C_{ij}^2}{\Lambda^2}\, \left(\bar{q}_{i,L}\gamma_\mu q_{j,L}\right)^2$$

$$\lambda_{ij}^t = V_{ti}^* V_{tj}$$

Taken from 2106.01259

6000000000000 Clean Z-Bosons



A number of flavour-violating interactions generated by new heavy states would be <u>most strongly constrained</u> by their running into unflavoured EW precision observables!

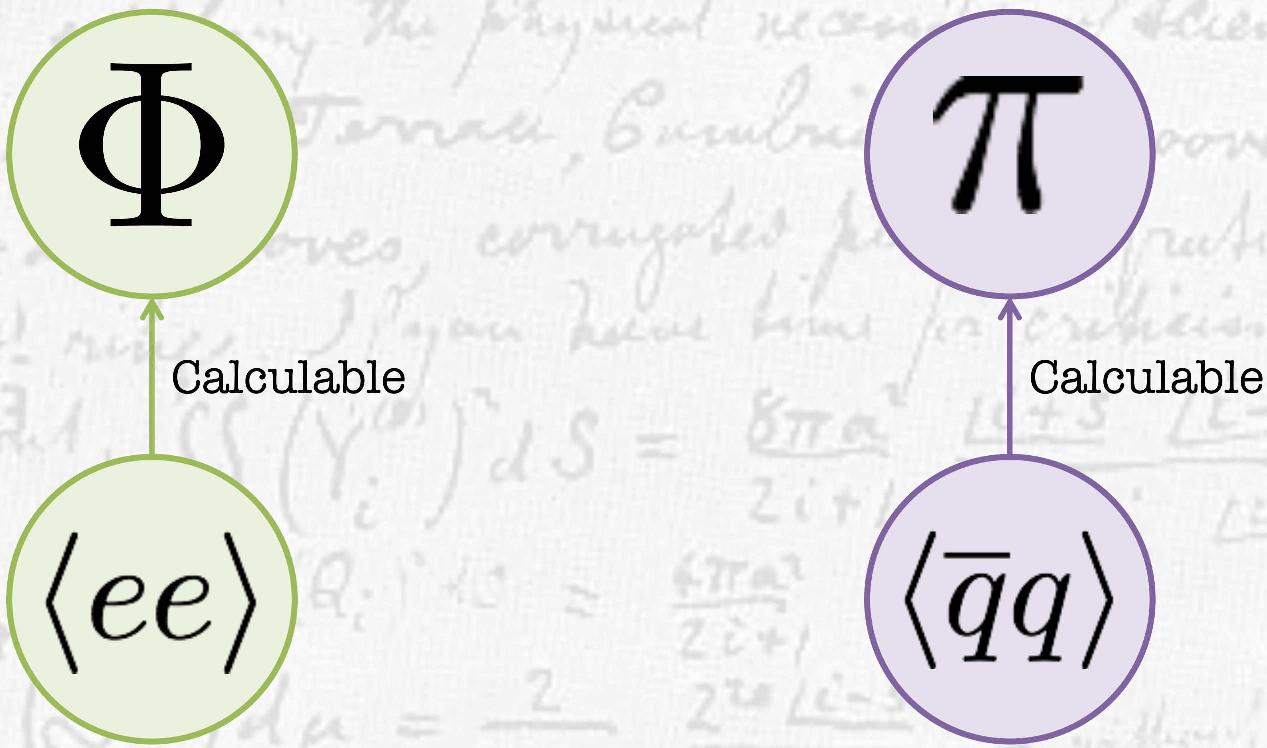
Tera-Z is not another LEP, but a literal <u>quantum leap</u> towards the smallest distance scales…

Taken from 2311.00020

What’s up with the Higgs Boson?

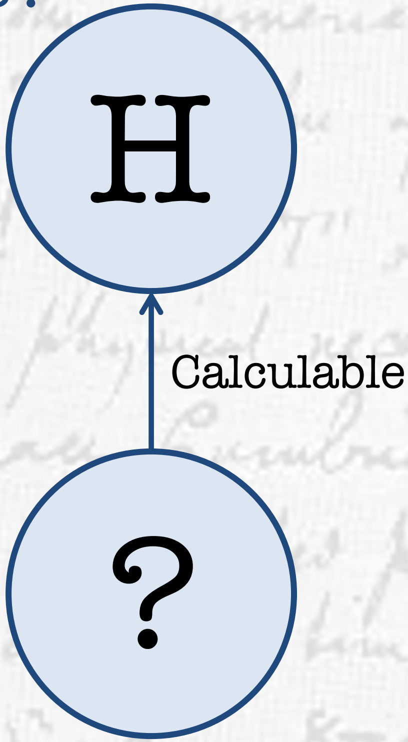
What's up with the Higgs Boson?

Every scalar we encountered until now has properties (mass, vev, etc) that are calculable within some more fundamental theory:



What's up with the Higgs Boson?

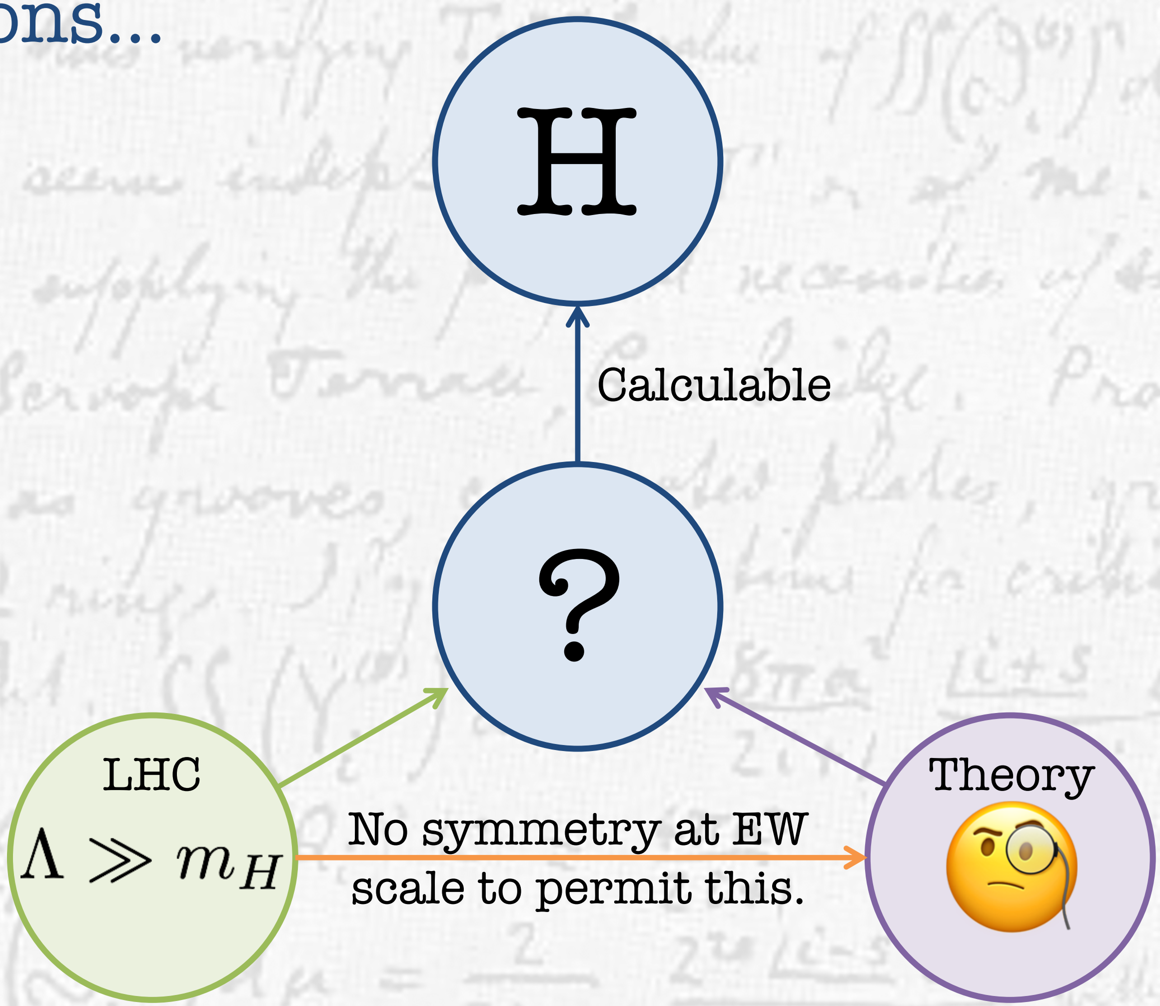
What about the Higgs?



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

Backdrop

What about the Higgs? We know what happens with pions…

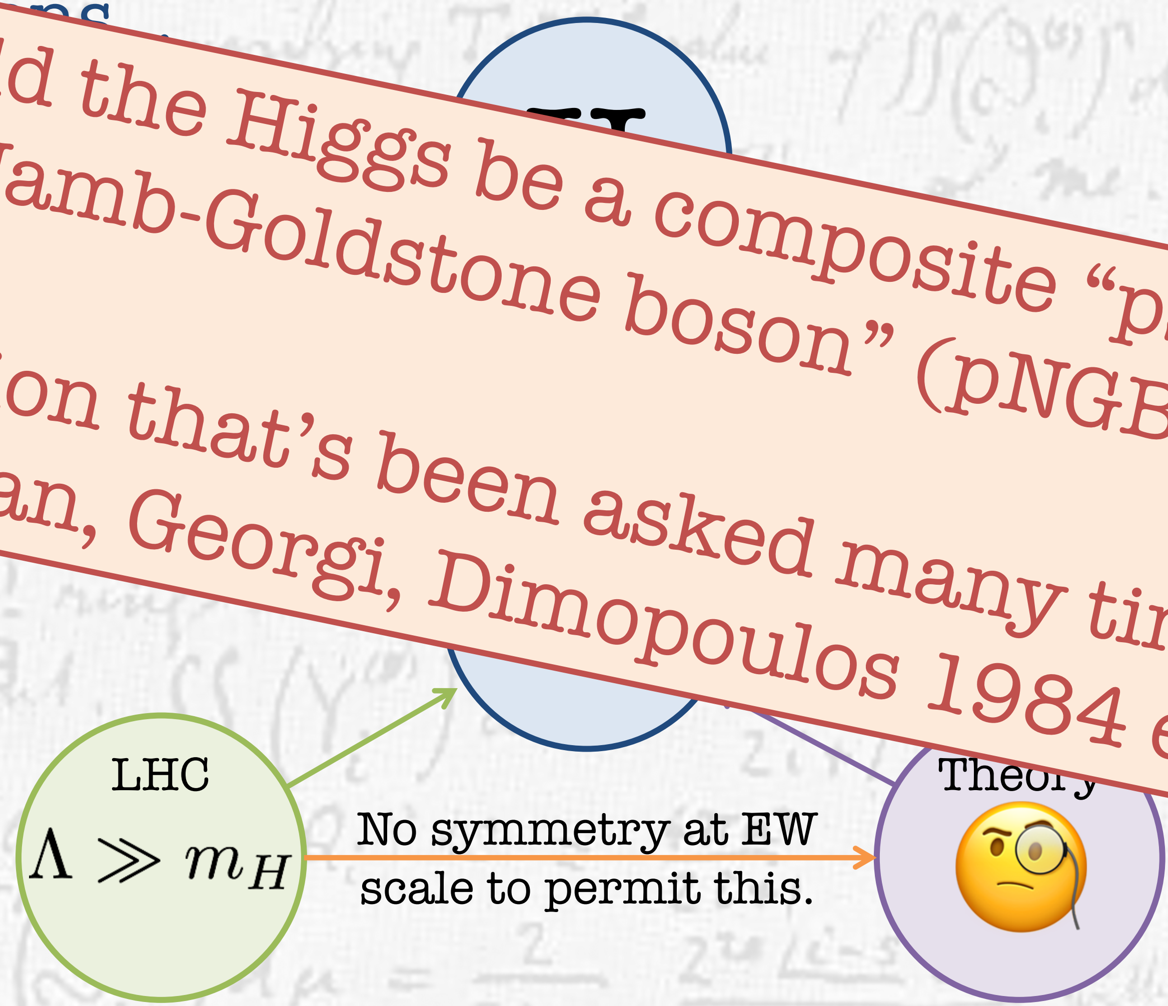


Backdrop

What about the Higgs? We know what happens

Could the Higgs be a composite "pseudo-Namb-Goldstone boson" (pNGB)?

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



Naturalness – pNGB Higgs

Vanilla pNGB Higgs scenarios have a potential which looks like

"Compositeness" Scale

$$V(h) = \epsilon f^2 \Lambda^2 F(h/f)$$

Where F is a generic function. Not so difficult to have a light Higgs

$$m_h^2 \sim \epsilon \Lambda^2$$

If one has $\epsilon \ll 1$. This is not fully possible in concrete models, since this is controlled by a symmetry which is already broken in SM.

However...

Naturalness – pNGB Higgs

Vanilla pNGB Higgs scenarios have a potential which looks like

"Compositeness" Scale

$$V(h) = \epsilon f^2 \Lambda^2 F\left(h/f\right)$$

Where F is a generic function. The position of the minimum of the potential doesn't care about the overall coefficient:

$$V'(h) = 0 \Leftrightarrow F'(h/f) = 0$$

So, if this is to occur at $h = v \ll f$ then one has to fine-tune the contributions to the potential from the UV physics.

Naturalness – pNGB Higgs

Vanilla pNGB Higgs scenarios have a potential which looks like

Compositeness Scale

$$V(h) = \epsilon f^2 \Lambda^2 F(h/f)$$

Where F is a generic function. However, it is generic that the operator

$$\mathcal{O}_H \sim \frac{1}{f^2}\left(\partial^\mu |H|^2\right)^2$$

is generated. This modifies all Higgs couplings by an amount

$$\delta_\kappa \sim \frac{v^2}{f^2}$$

Naturalness – pNGB Higgs

Vanilla pNGB Higgs scenarios have a potential which looks like

Compositeness Scale

f)

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$$\delta_\kappa \sim \frac{v^2}{f^2}$$

So, in vanilla scenarios, Higgs coupling measurements suggest that if the Higgs is a pNGB then there must be some fine-tuning of parameters at least at the 10% or so level!

Naturalness – pNGB Higgs

Var NGB Higgs scenarios have a potential
wh

Compositeness
Scale

The Composite Nambu-Goldstone Higgs

Giuliano Panico, Andrea Wulzer

Download PDF

The composite Higgs scenario, in which the Higgs emerges as a composite pseudo-Nambu-Goldstone boson, is extensively reviewed in these Notes. The material is presented in a pedagogical fashion, with great emphasis on the conceptual and technical foundations of the construction. A comprehensive summary of the flavor, collider and electroweak precision phenomenology is also presented.

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by an amount

$$\delta_\kappa \sim \frac{v^2}{f^2}$$

Naturalness – pNGB Higgs

Let's scrutinize the assumptions...

$$V(h) = \epsilon f^2 \Lambda^2 F\left(h/f\right)$$

How much symmetry breaking (ϵ)

How the symmetry is broken... (F)

Assumption until now has been that the symmetry is broken in the most minimal ways.

Technically: Breaking "spurion" is in a low-index irrep of the global symmetry.

Beyond Minimality

Now assume some small explicit breaking "spurion" in a symmetric irrep with "n" indices:

$$V_\epsilon = \frac{\lambda}{f^{n-4}} \epsilon_{a_1,a_2,\ldots,a_n} \phi^{a_1} \phi^{a_2} \ldots \phi^{a_n}$$

How the symmetry is broken...

For the pNGB fields this generates a potential:

$$V = \epsilon m_\rho^2 f^2 \, G_n^{(N-1)/2}(\cos \Pi / f)$$

Gegenbauer function!

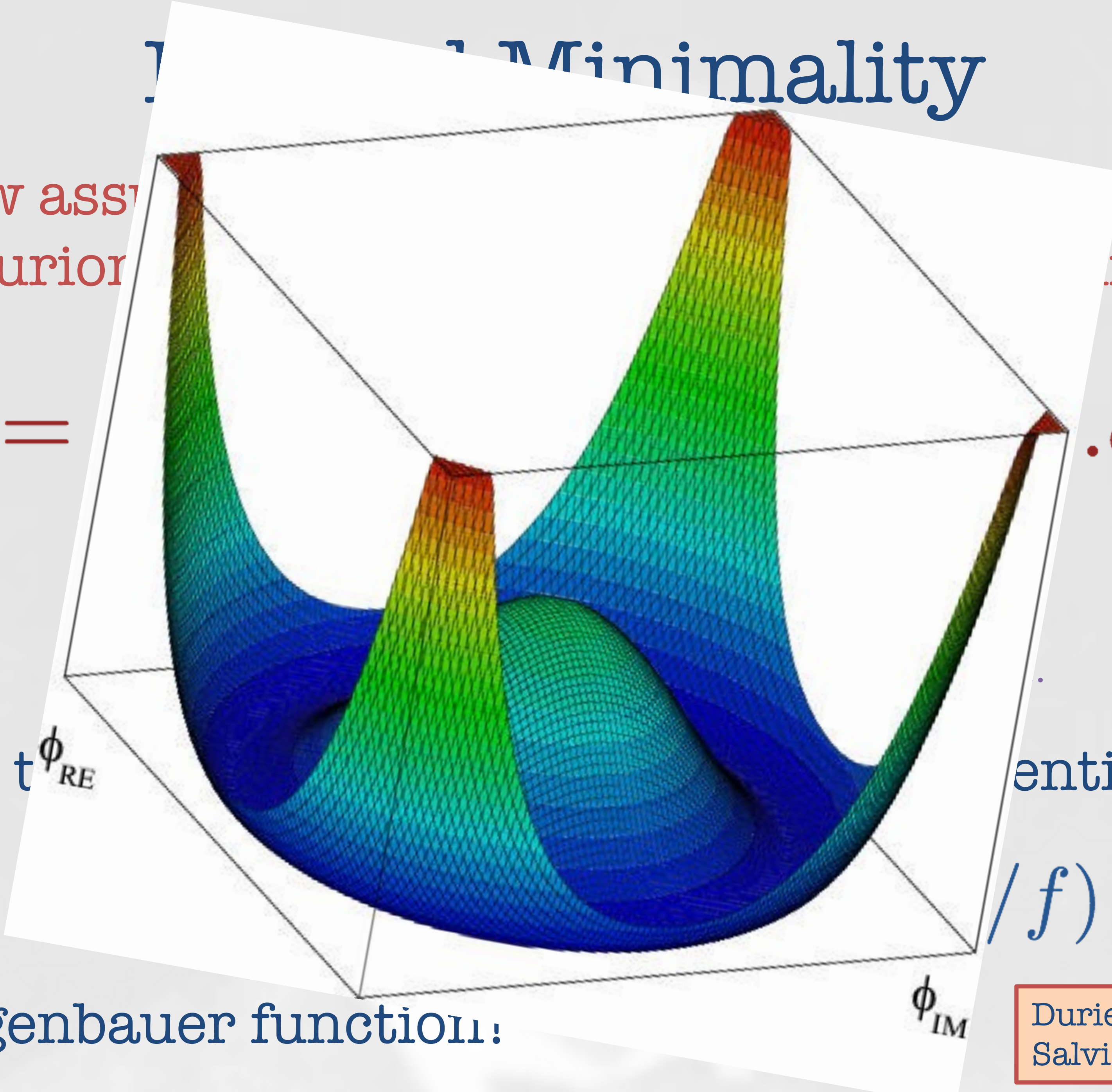
Durieux, MM, Salvioni. 2021

... Minimality

Now assu...

“spurion... ...ices:

$$V_\epsilon = \;\ldots\; .\phi^{a_n}$$



For t... ...ential:

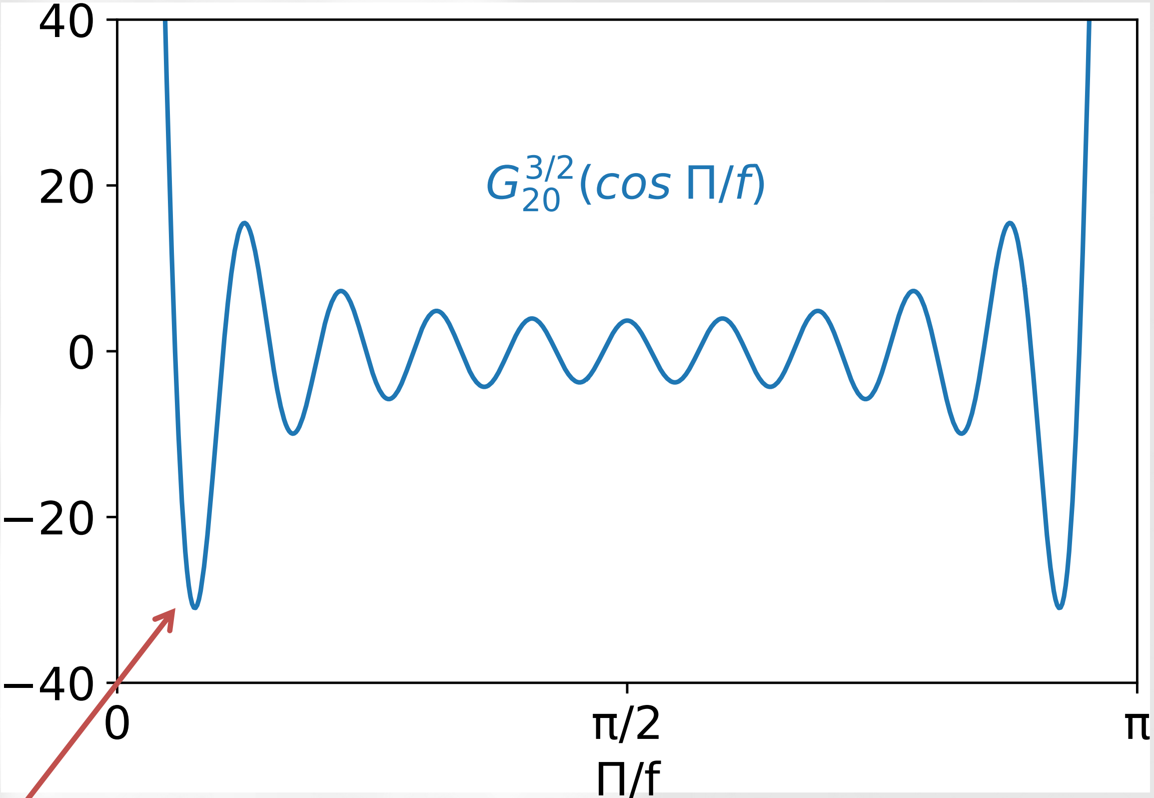
$$\ldots / f)$$

Gegenbauer function:

Durieux, MM, Salvioni. 2021

Getting to know Gegenbauer

The Gegenbauer potential looks like:



Global minimum at naturally small field values:

$$\frac{\langle \Pi \rangle}{f} \approx \frac{j_{\lambda+1/2,1}}{n+\lambda} \approx \frac{5.1}{n}$$

Gegenbauer's Twin

Durieux, MM, Salvioni. 2022

Gegenbauer contribution allows to naturally realise v<<f. On the other hand, for a standard pNGB Higgs model the top sector doesn't allow ϵ to be arbitrarily small...

Twin Higgs models, however, address that particular aspect. Could "Gegenbauer's Twin" allow both $\epsilon \ll 1$ and $v \ll f$?

Application

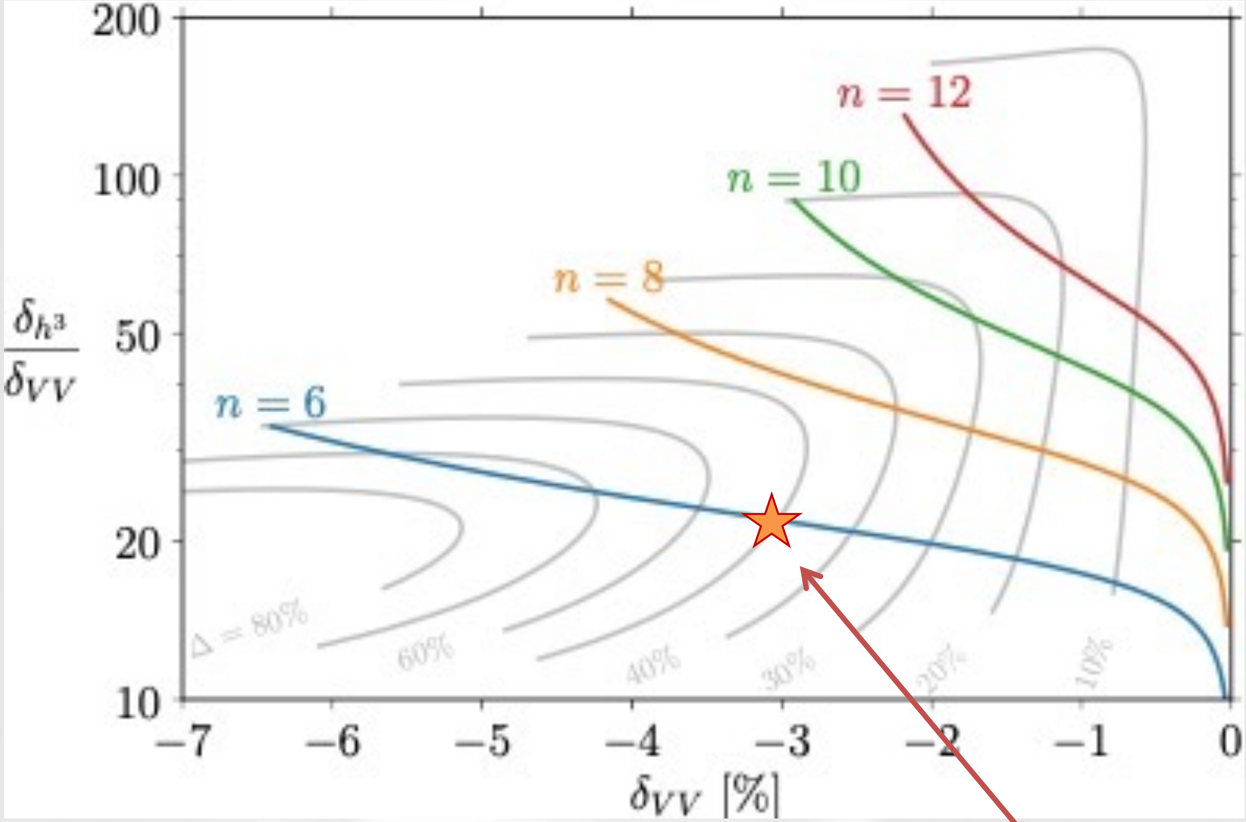
Consider some standard pNGB Higgs construction and, inspired by pions, allow for an additional source of explicit symmetry breaking, in n-index irrep of global symmetry.

$$\mathcal{L} = \mathcal{L}_{\mathrm{Old}} + \epsilon \mathcal{L}_{S_n \neq 0}$$

What happens?

Gegenbauer's Twin

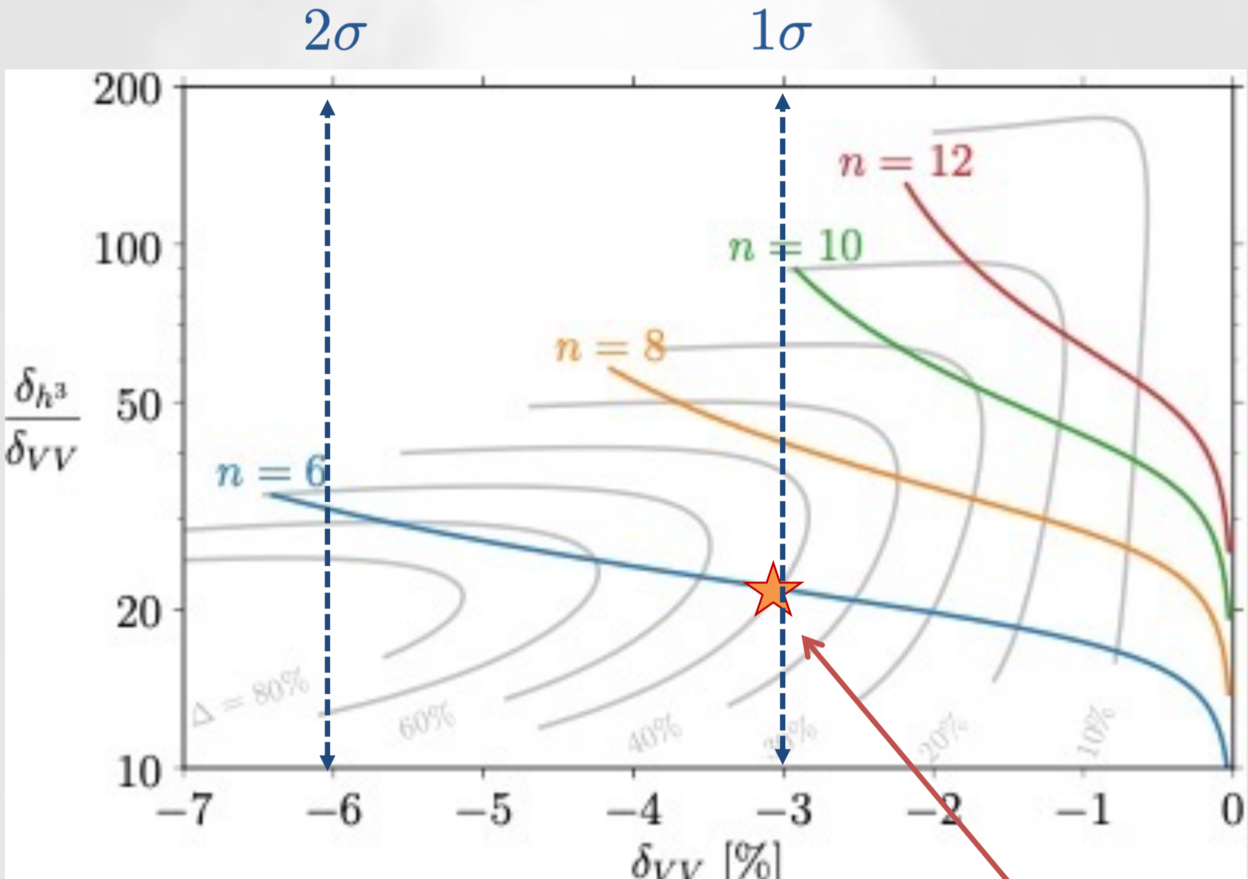
Predictions, in absolute terms:



Example point. Low tuning (low cutoff), 3% single-coupling correction, 70% self-coupling correction.

Gegenbauer's Twin

Present Limits



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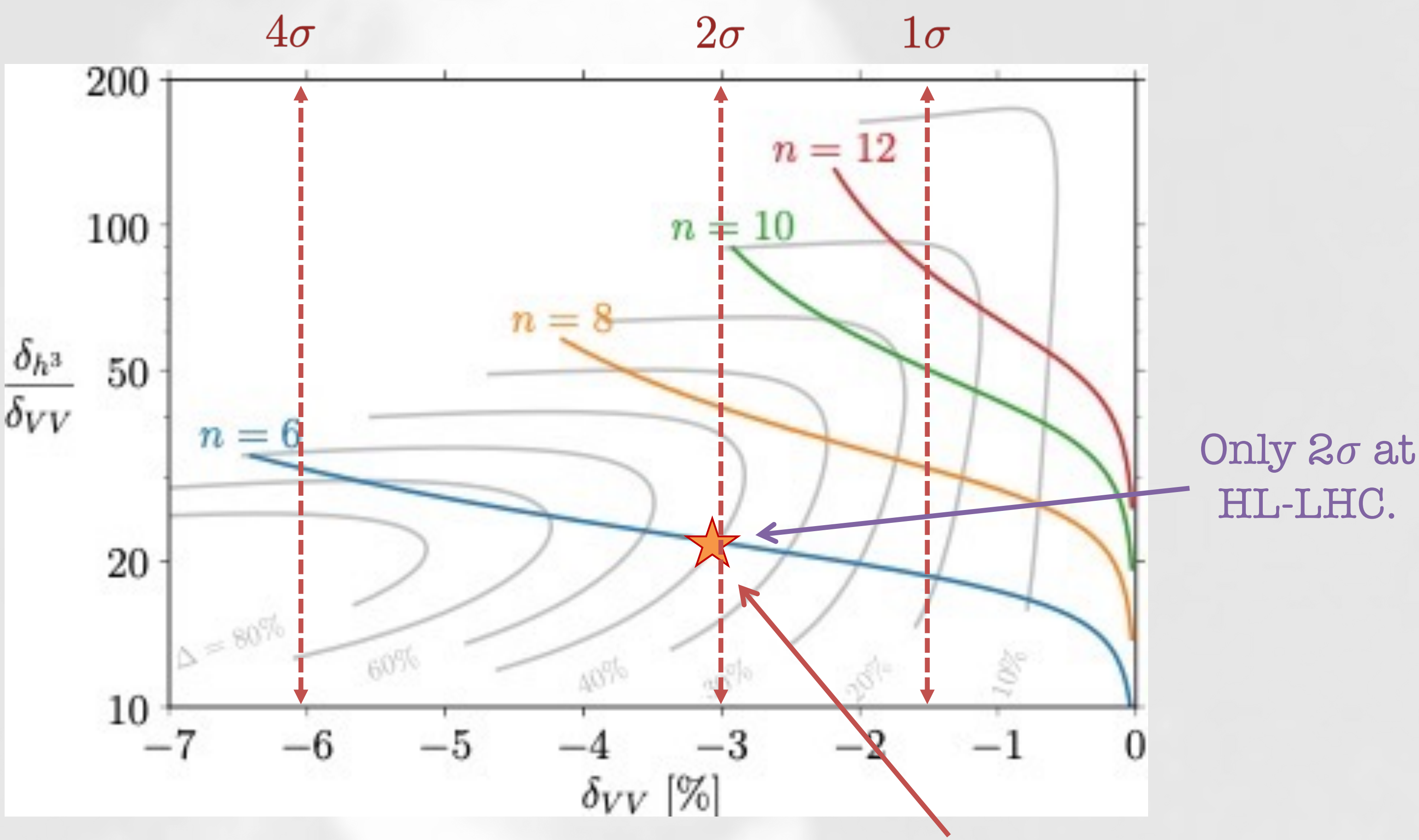
Gegenbauer's Twin

HL-LHC Expectations



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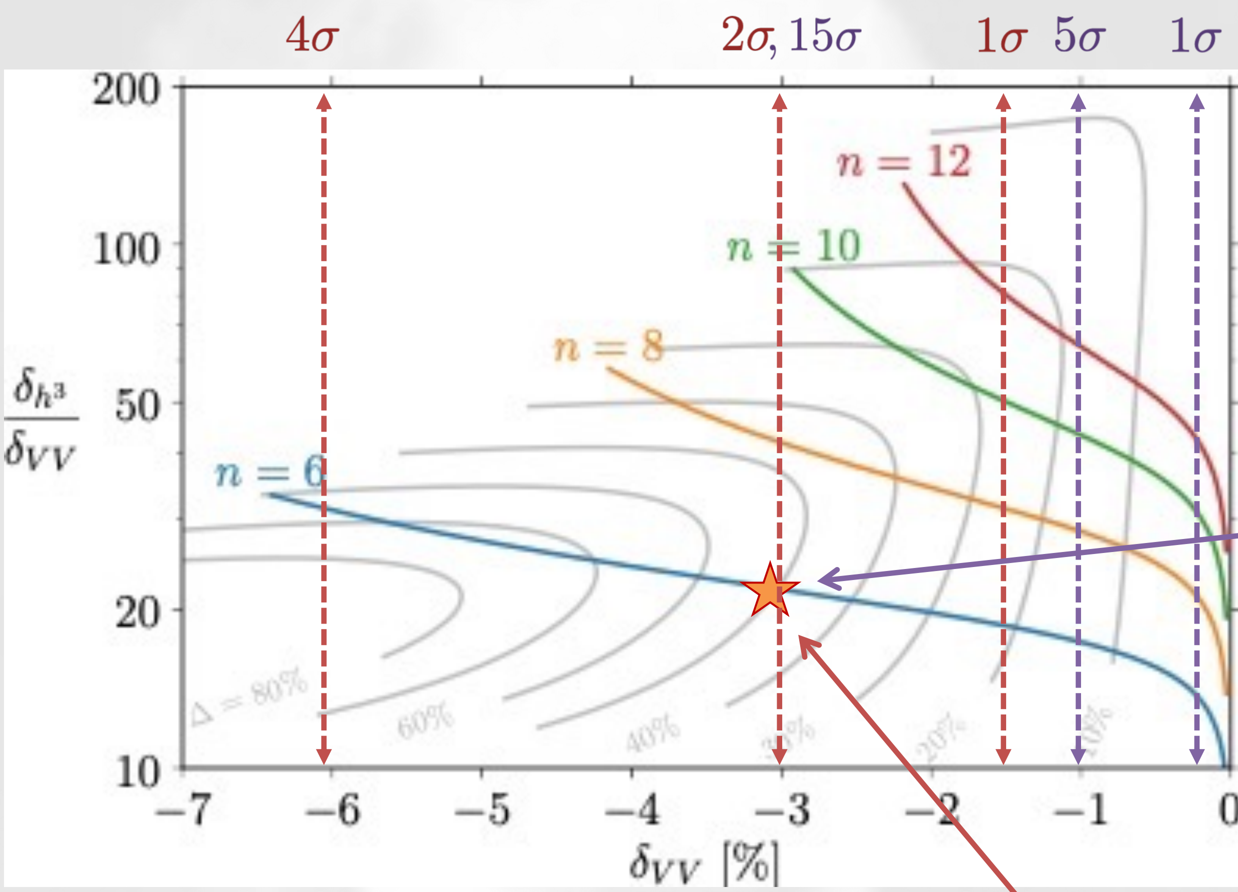
Gegenbauer's Twin

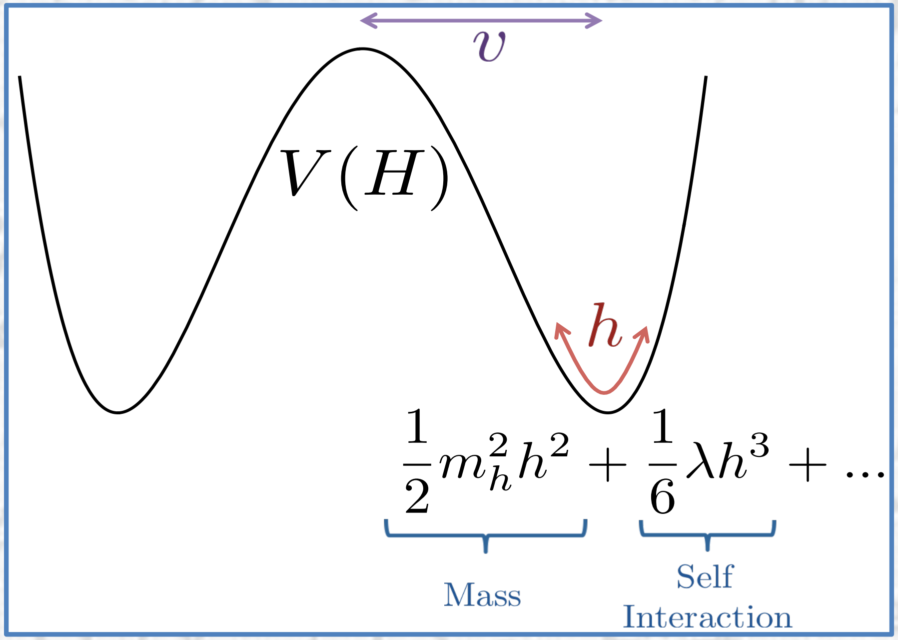
HL-LHC Expectations & FCC-ee



Only 2σ at HL-LHC but 15σ at FCC-ee!

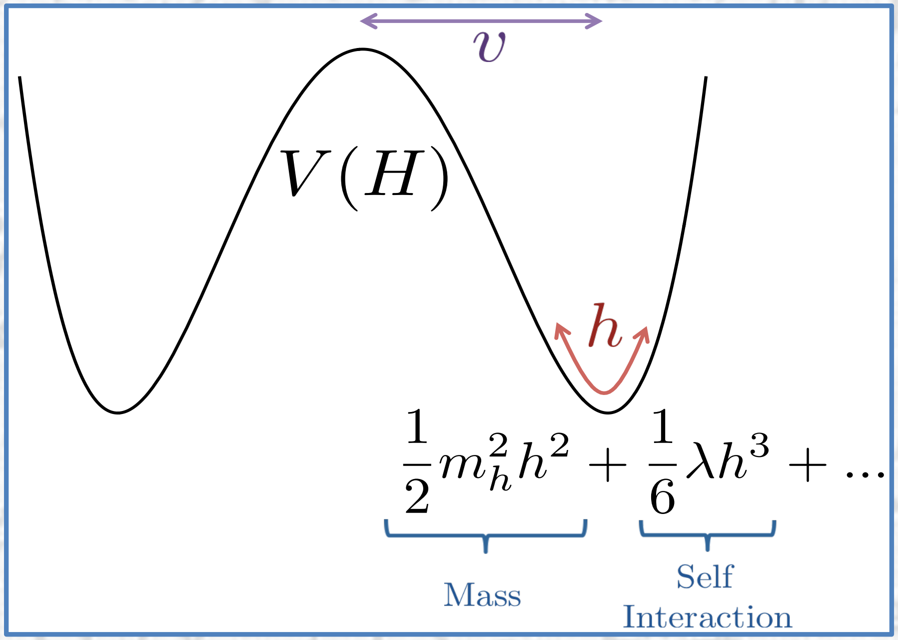
Example point. Low tuning (low cutoff), 3% single-coupling correction, 70% self-coupling correction.

What is the Higgs Potential?



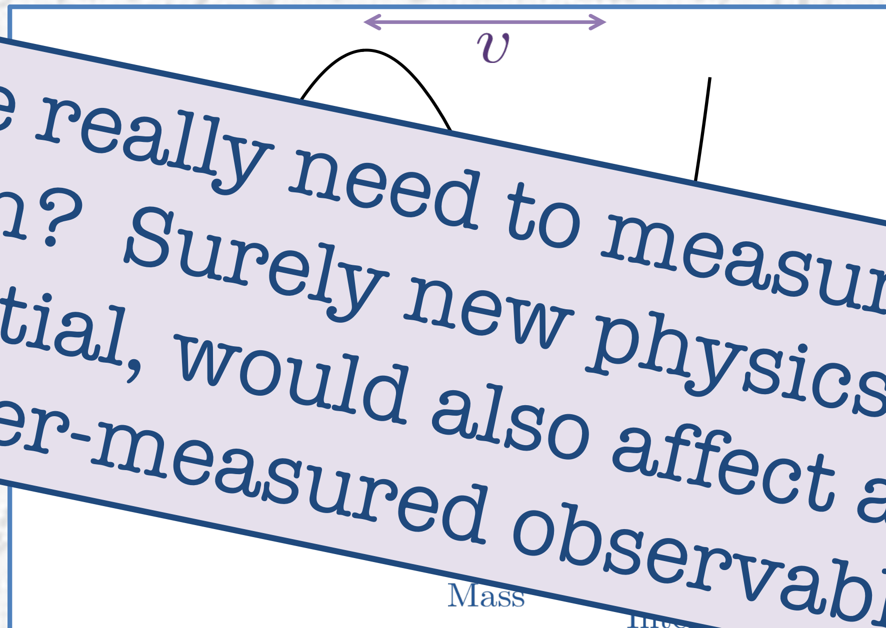
Important because it determines how the Universe froze in the EW sector, giving mass to gauge bosons, fermions, the Higgs…

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 observables?

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

Custodial Quadruplet

Could such a theory actually exist? Yes: The custodial quadruplet scalar. Projecting the $(4,4)$ of

$$SU(2)_L \times SU(2)_R$$

onto EW group we have

$$(\mathbf{4},\mathbf{4}) \quad \rightarrow \quad \mathbf{4}_{1/2} + \mathbf{4}_{3/2}$$

and including all couplings to the Higgs we have for scalar quadruplet

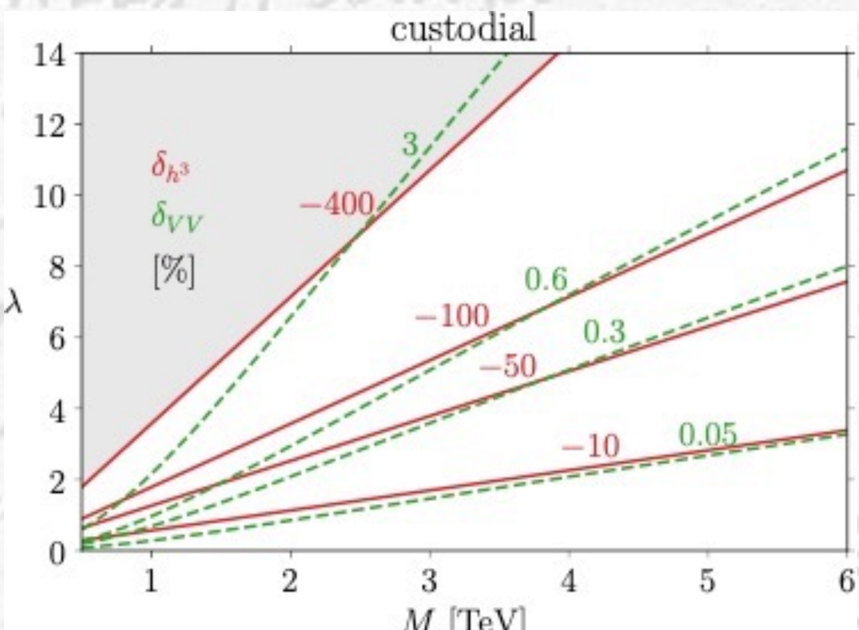
$$\mathcal{L}_{SO(4)} = -\lambda\Big(H^* H^* (\epsilon H)\Phi + \frac{1}{\sqrt{3}} H^* H^* H^* \widetilde{\Phi} \Big) + \text{h.c.}$$

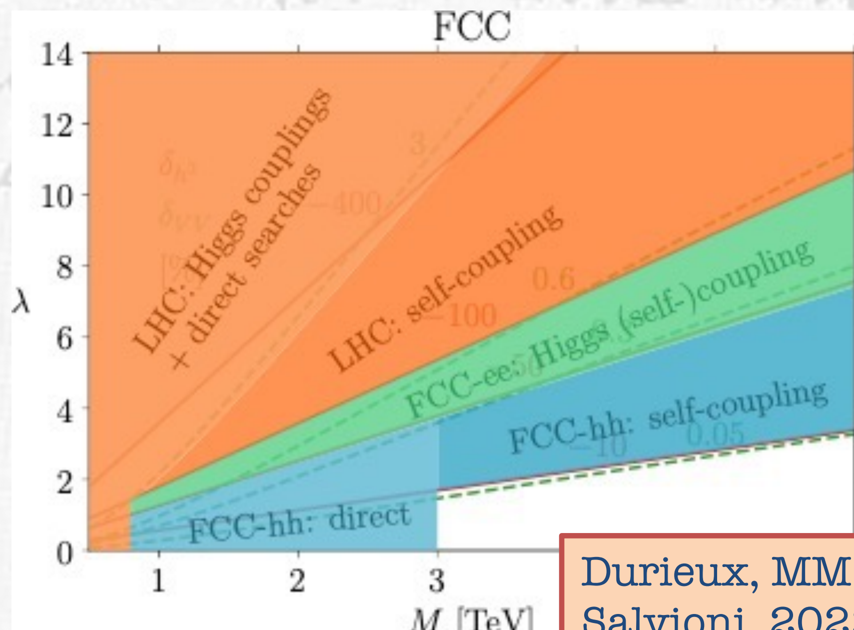
which has exactly the pattern described.

Custodial Quadruplet

Higgs self-coupling is modified at dim-6 at tree-level, all other couplings modified at dim-6 one-loop, or dim-8. All calculable, giving

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





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Custodia[...]uadruplet

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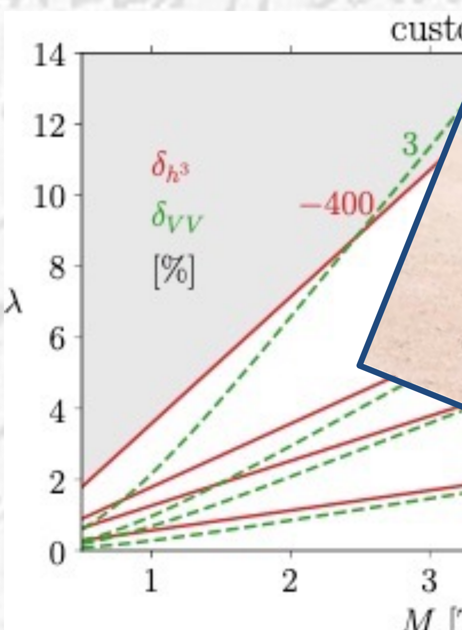

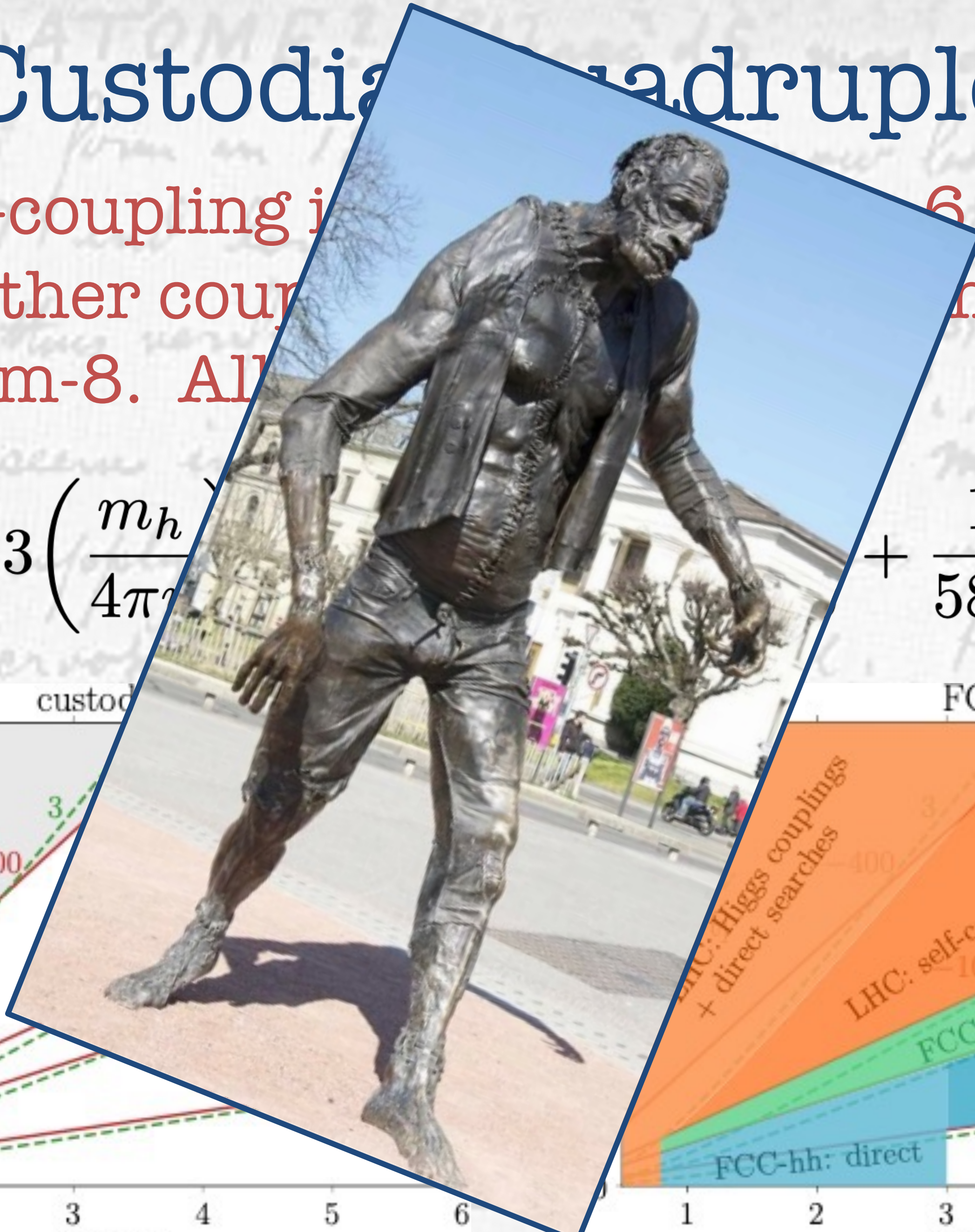

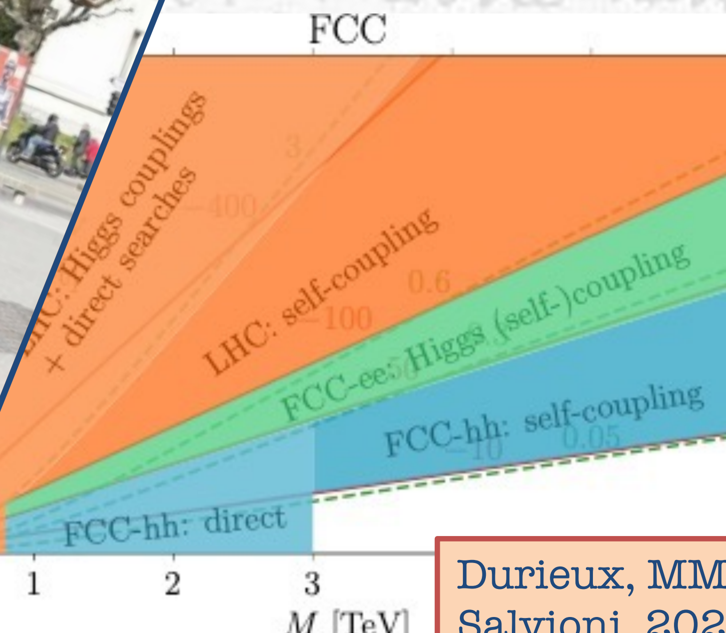

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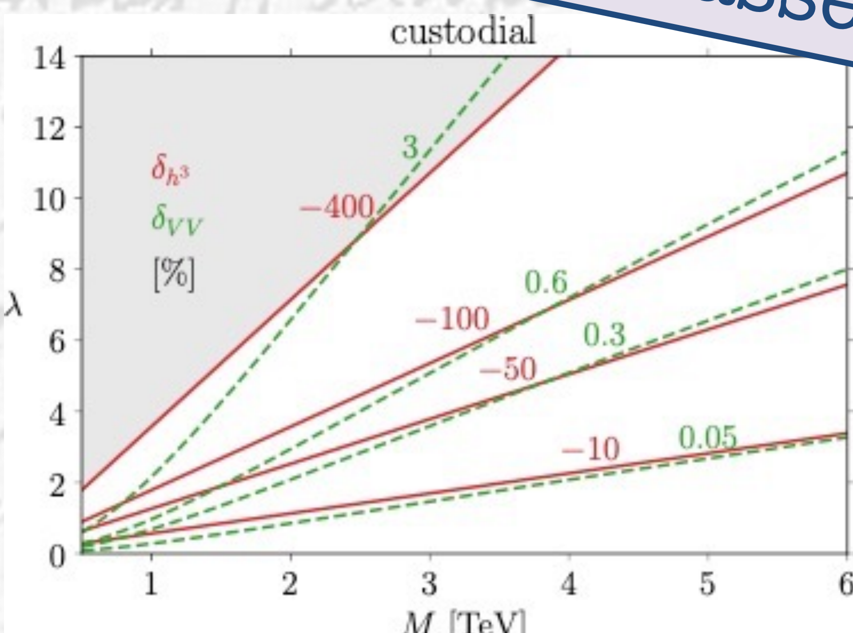
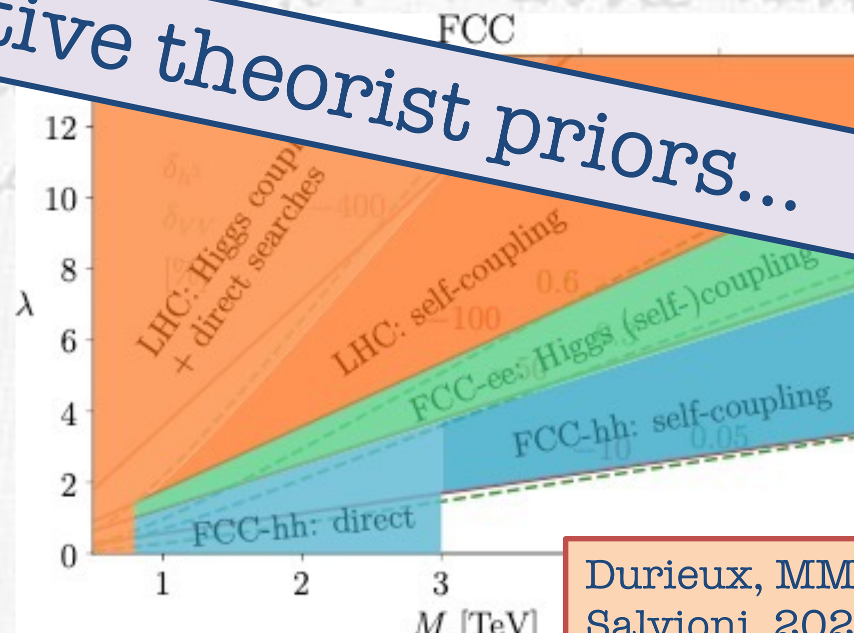
Beware overly-assertive theorist priors...





Durieux, MM, Salvioni. 2022

Dark Sectors

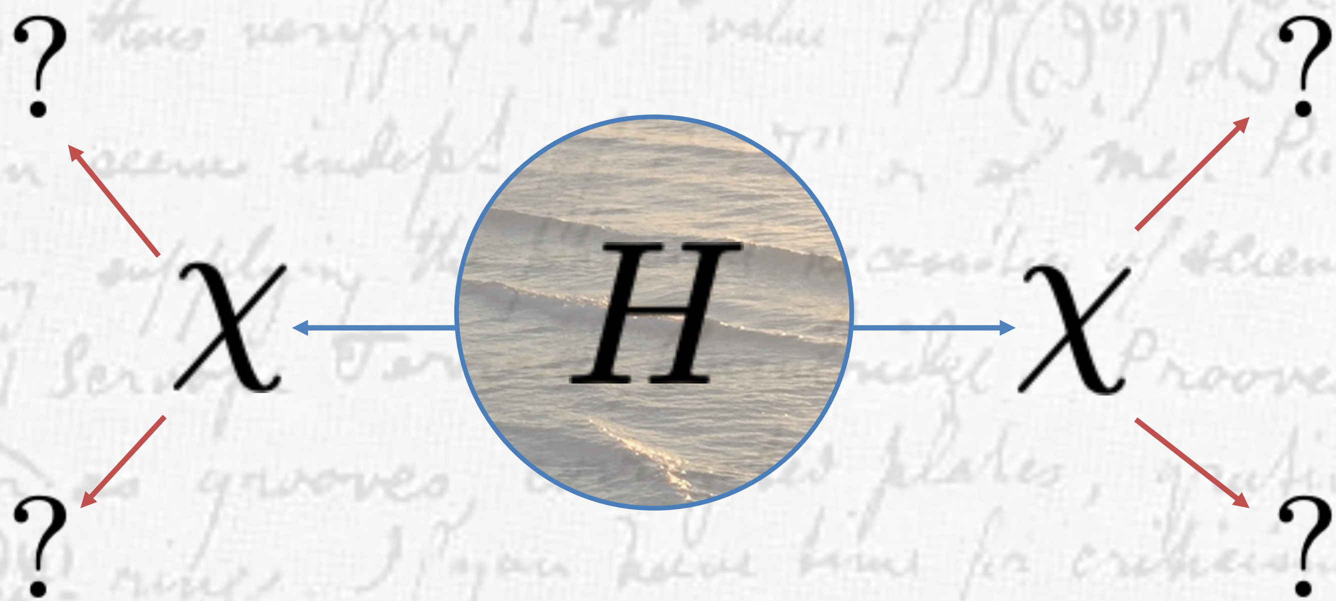
Evidence for dark matter is now overwhelming

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

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

?

Is the Higgs a portal to new dark sector states?

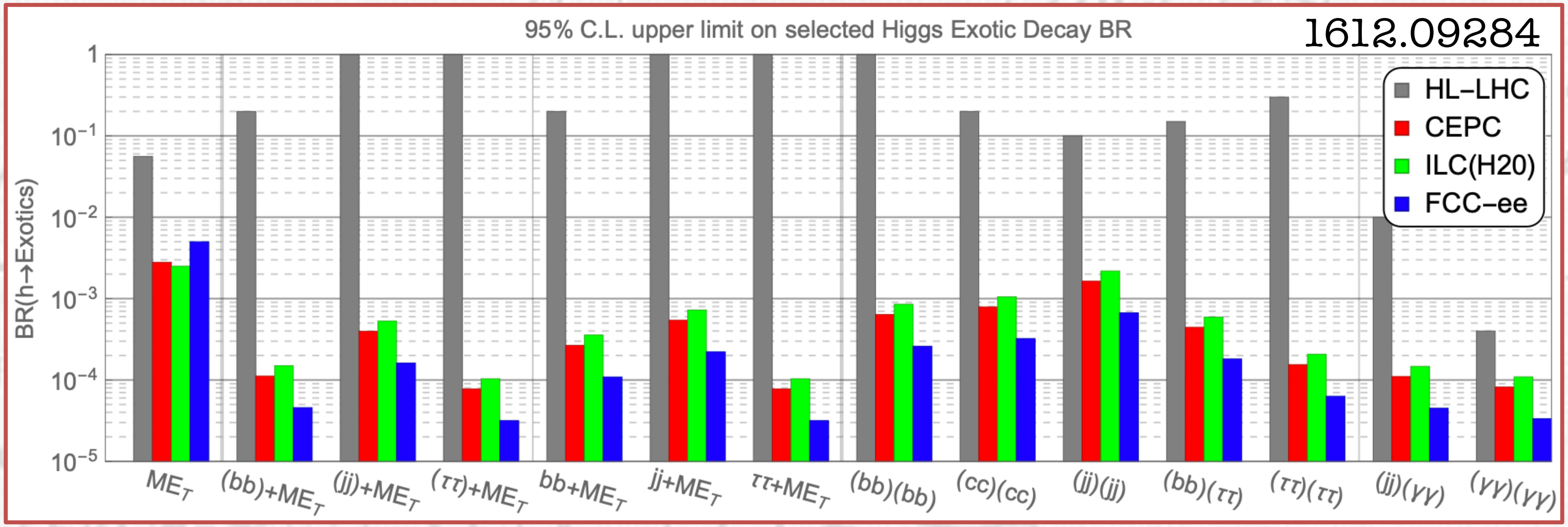


After all, $|H|^2$ is the most relevant interaction involving SM fields! Even if generated at microscopic scales

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

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.

A final word on SM theory…

Numerous exciting challenges for SM theory calculations. EW and QCD precision calculations pushed to new frontiers.

- Mixed 3 and partial 4-loop calculations required for EWPOs.
- Also increased precision in simulation, resummation, hadronization, Monte Carlo, non-perturbative understanding required…
- See talks by Frixione, Weinzierl, Monni, Skands, Rojo, Ferrario Ravasio.

Generally: Factor 500 reduction in stat uncertainty compared to LEP, so big theory targets…

Conclusions

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

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

Conclusions

Electroweak. QCD. Flavour. Higgs.

The FCC Physics Programme uniquely covers each area in paradigm-shifting depth.

O.T'. R.U. ATOME? $\iint \text{Sphaer}^2\, dS$ 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 at Devon 11 Scroope Terrace, Cambridge. Prooves have gone as far as grooves, corrugated plates, gratings and rings. If you have time for criticism then

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

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

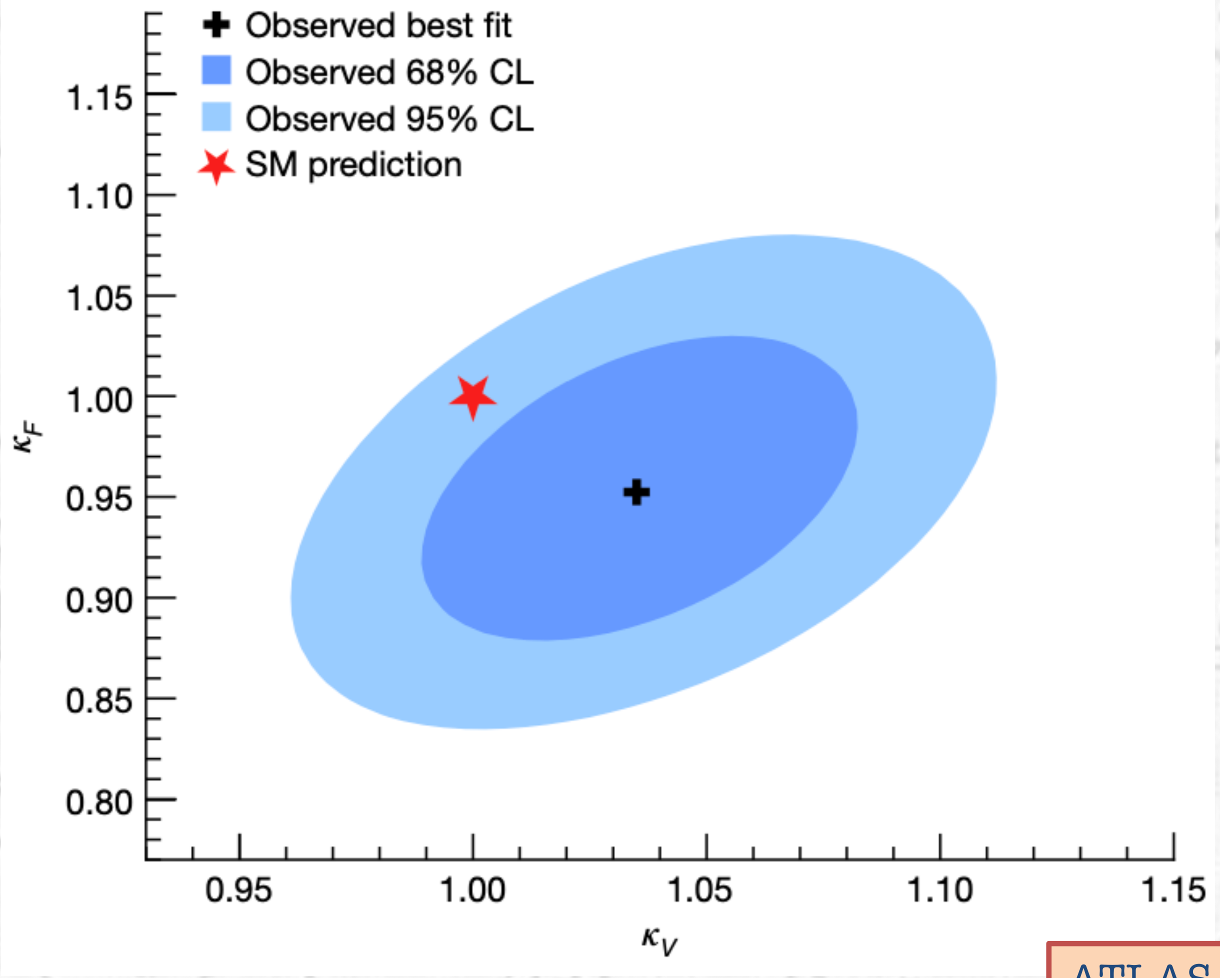
Hence $$\int_{-1}^{+1} (\vartheta_i^{(s)})^2 d\mu = \frac{2}{2i+1}\,\frac{2^{2s}\lfloor i-s\,\lfloor s\,\lfloor s}{\lfloor i+s}$$ without exception

yes $\frac{dp}{dt}$

EDINBURGH

Status of Higgs Couplings

What are experimental limits on modifications of couplings relative to Standard Model prediction?



ATLAS, Nature, 2022

Status of Higgs Couplings

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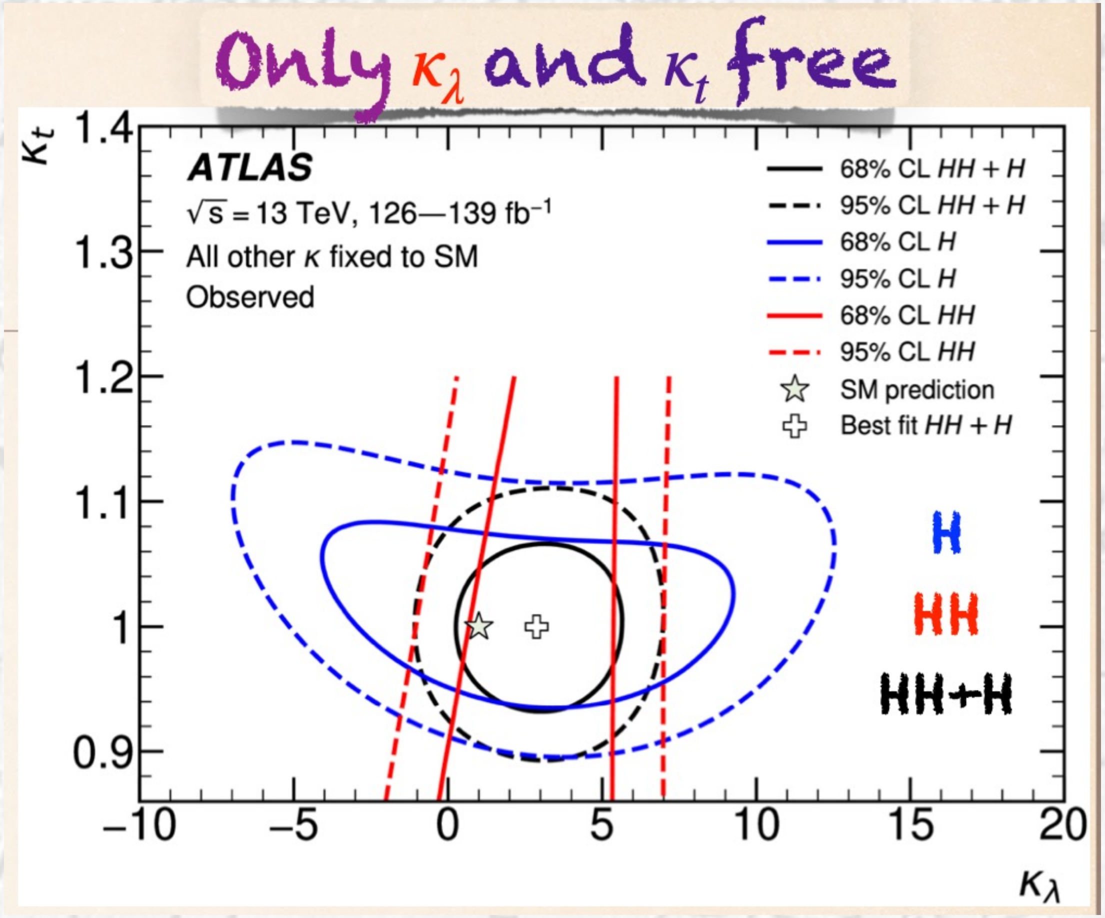

Lidija Živković, Yesterday

Status of Higgs Couplings

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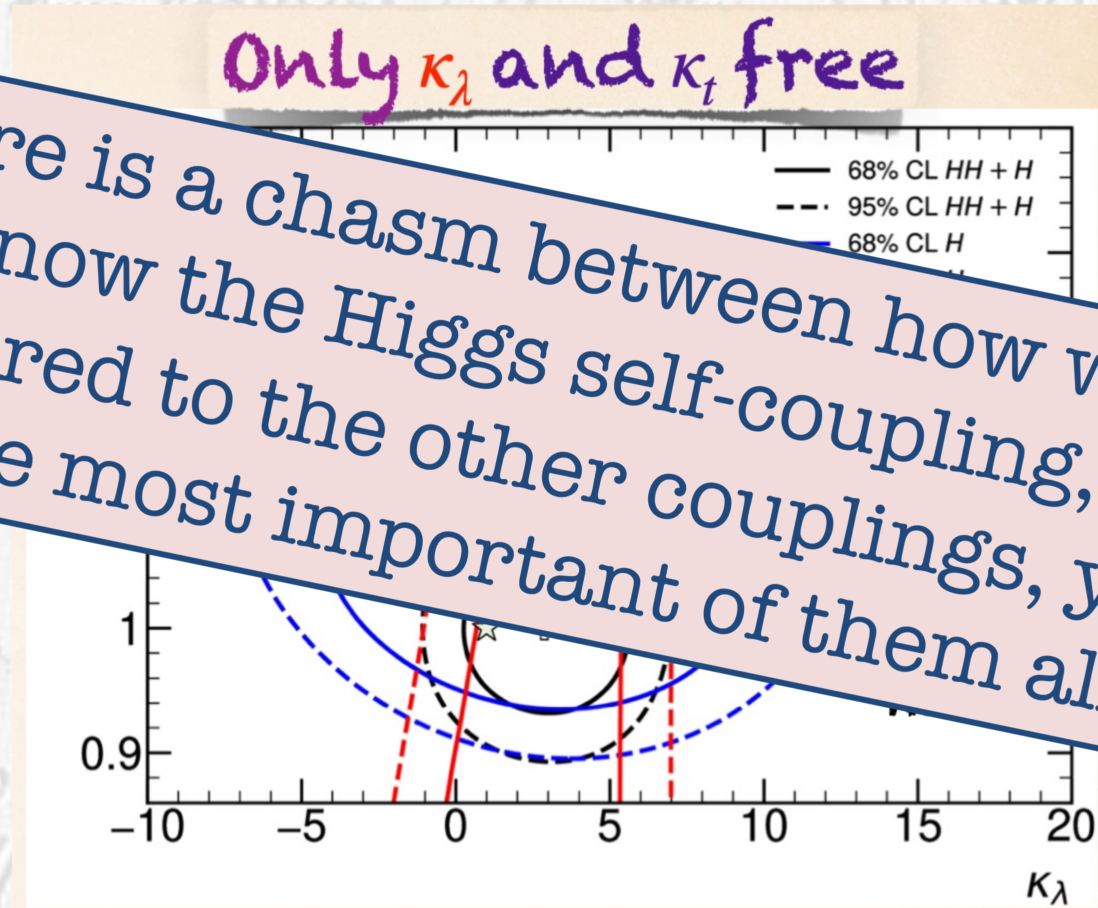
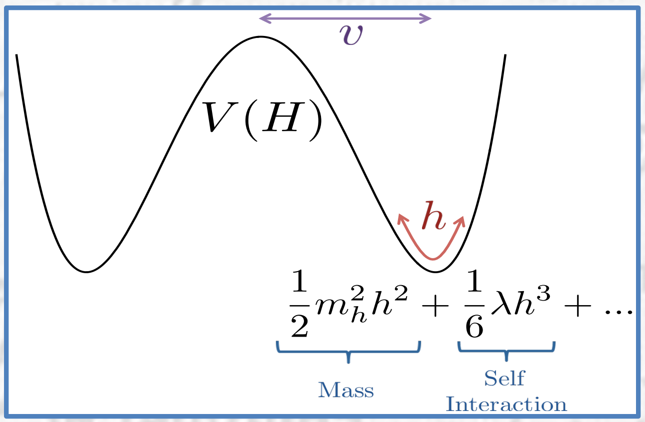


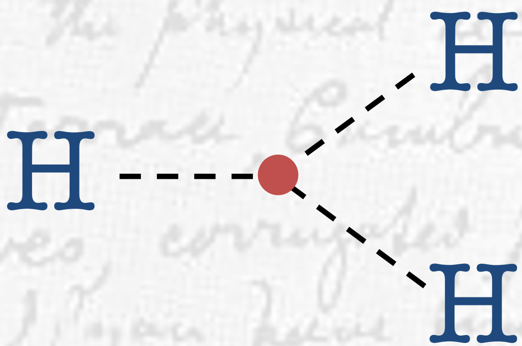
There is a chasm between how well we know the Higgs self-coupling, as compared to the other couplings, yet it is the most important of them all!

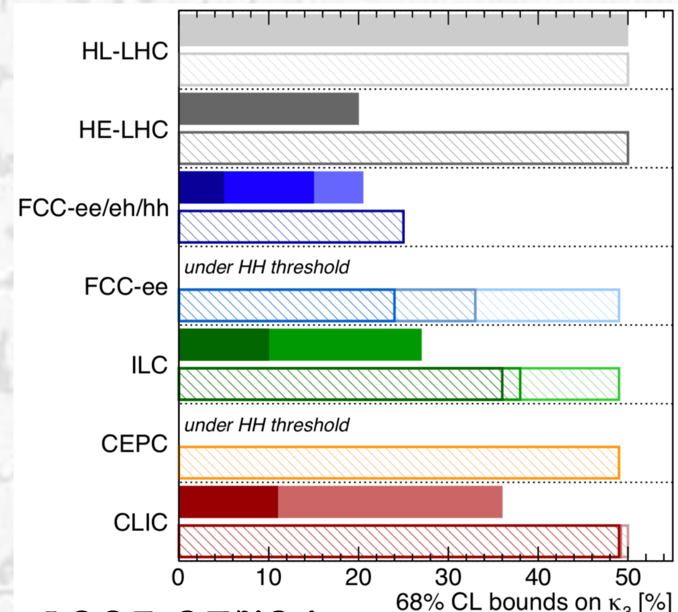
Lidija Živković, Yesterday

Future of Higgs Self-Coupling

Future facilities can give us valuable new insights into the nature of the Higgs potential.







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Rich interplay between direct/indirect, HL-LHC, Higgs factory, future High energy machines.

Gegenbauer's Twin

If tuning calculations interest you (I understand if not…), we followed conservative approach

$$\delta = \begin{pmatrix} \frac{\partial \log v^2}{\partial \log \epsilon} & \frac{\partial \log v^2}{\partial \log a} \\ \frac{\partial \log m_h^2}{\partial \log \epsilon} & \frac{\partial \log m_h^2}{\partial \log a} \end{pmatrix} \qquad \Delta = \left(\sum \text{eigenvalues}\,(\delta^T \delta)\right)^{-1/2}$$

As Gegenbauer gives vev, tuning dominated by

$$\left(\frac{\partial \log v^2}{\partial \log a}\right)^{-1} = \frac{8\pi^2 m_h^2}{3y_t^4 f^2 \left(1 - \frac{3v^2}{f^2} + \frac{2v^4}{f^4}\right)}$$

So, compared to standard Twin expect improvement of

$$\frac{\Delta}{2v^2/f^2} \approx \frac{4\pi^2 m_h^2}{3y_t^4 v^2} \approx 4$$

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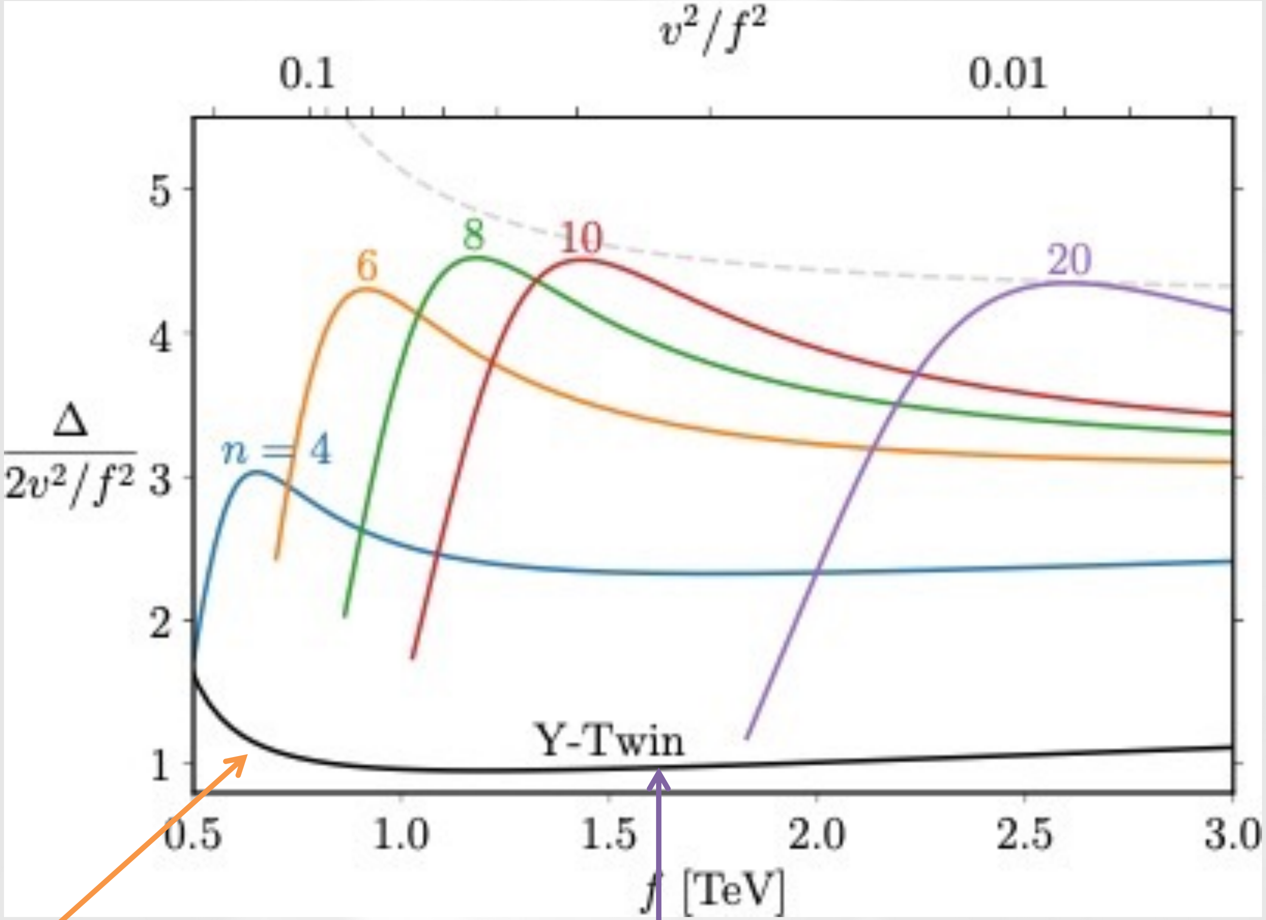
Quantitatively:



Estimate of Craig & Howe seems robust.

Twin model of Barbieri, Greco, Rattazzi, Wulzer.

Gegenbauer's Twin

Generalising Gegenbauer story to pNGB Twin Higgs for $SO(8) \rightarrow SO(7)$ and going to Unitary gauge the top-sector contributions to the Higgs potential are

$$V_t \approx \frac{3y_t^4 f^4}{64\pi^2}\left[\sin^4\frac{h}{f}\log\frac{a}{\sin^2 h/f} + \cos^4\frac{h}{f}\log\frac{a}{\cos^2 h/f}\right]$$

Whereas the symmetric n-index irrep gives

$$V_G^{(n)} = \epsilon\, m_\rho^2 f^2 G_n^{3/2}\left(\cos 2h/f\right)$$

Note: This is radiatively stable at all scales.

Beyond Minimality

Consider a simple scenario that could apply to the Higgs boson.

Example SO(N+1):

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \cdot \partial^\mu \phi - \frac{\lambda}{4}\left(\phi \cdot \phi - \frac{f^2}{2}\right)^2$$

We get N massless pNGBs with decay constant "f" and unbroken SO(N).

Beyond Minimality

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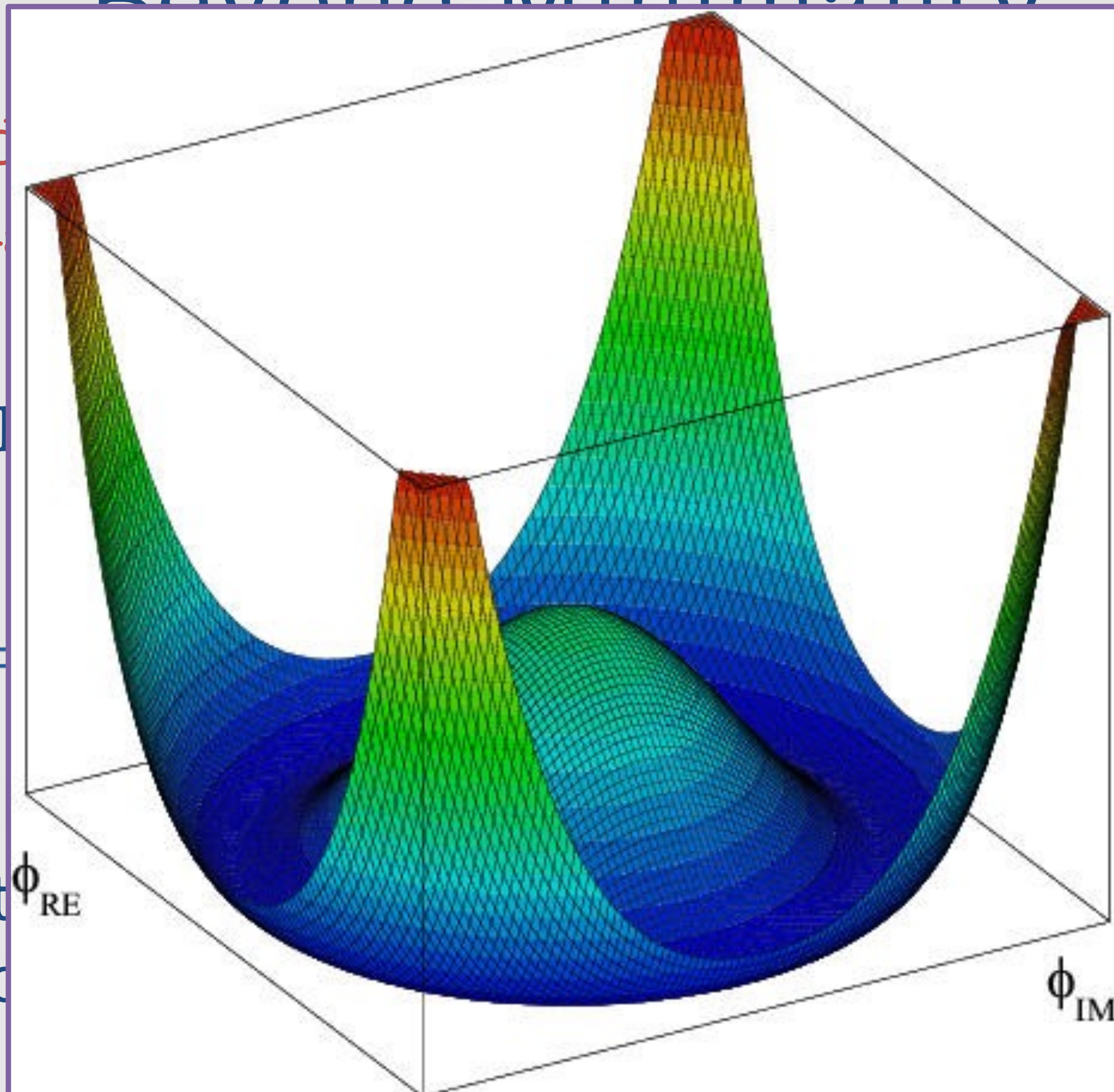
Examp ...

$\mathcal{L} = \quad \ldots \quad \Big)^2$



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“f” and ...