SM and BSM Higgs Theory Overview

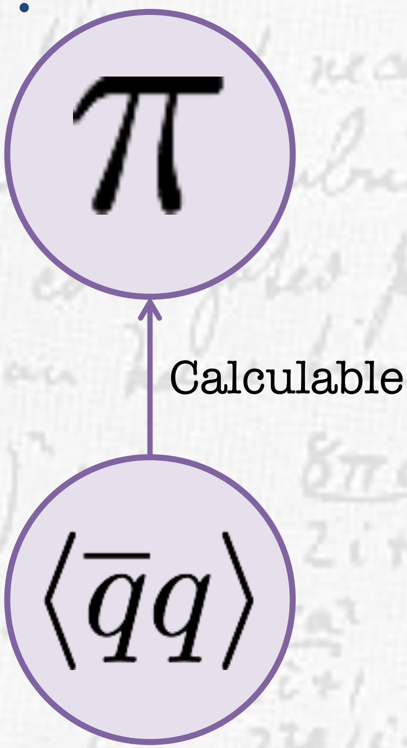
ICHEP 2024
July 22nd
Prague

Matthew McCullough
With thanks also to Mangano & Monni.
CERN

Zooming in on the Higgs

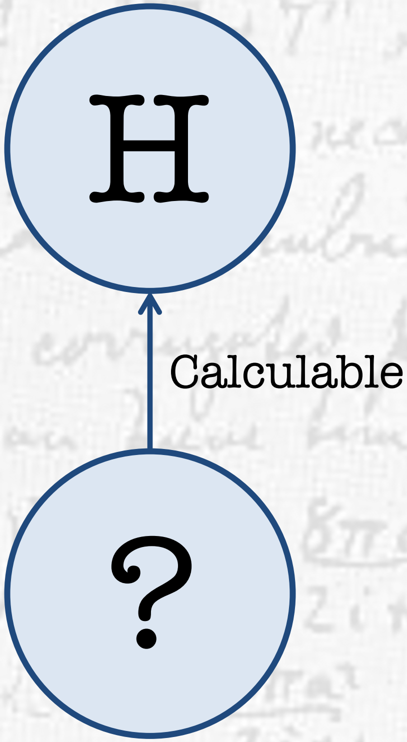
What’s in the Higgs Boson?

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?



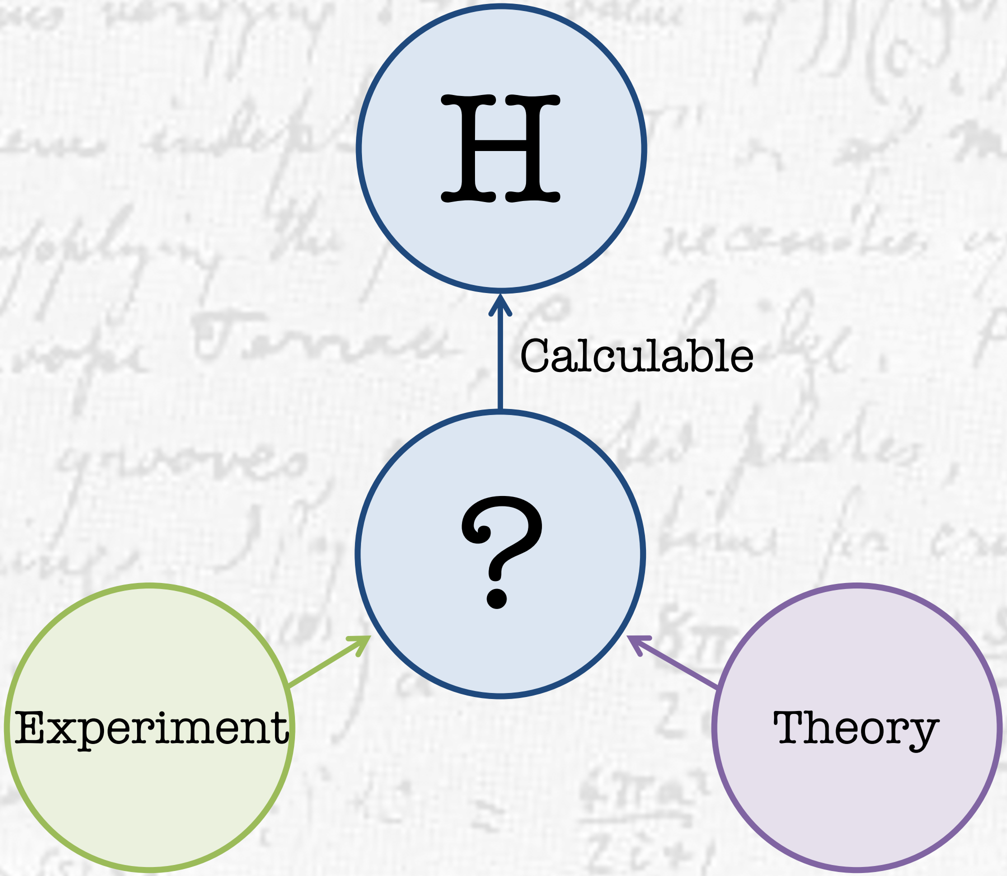
H

Calculable

?

Progress in SM Predictions

HL-LHC will deliver unprecedented precision (2%) towards answering this question.



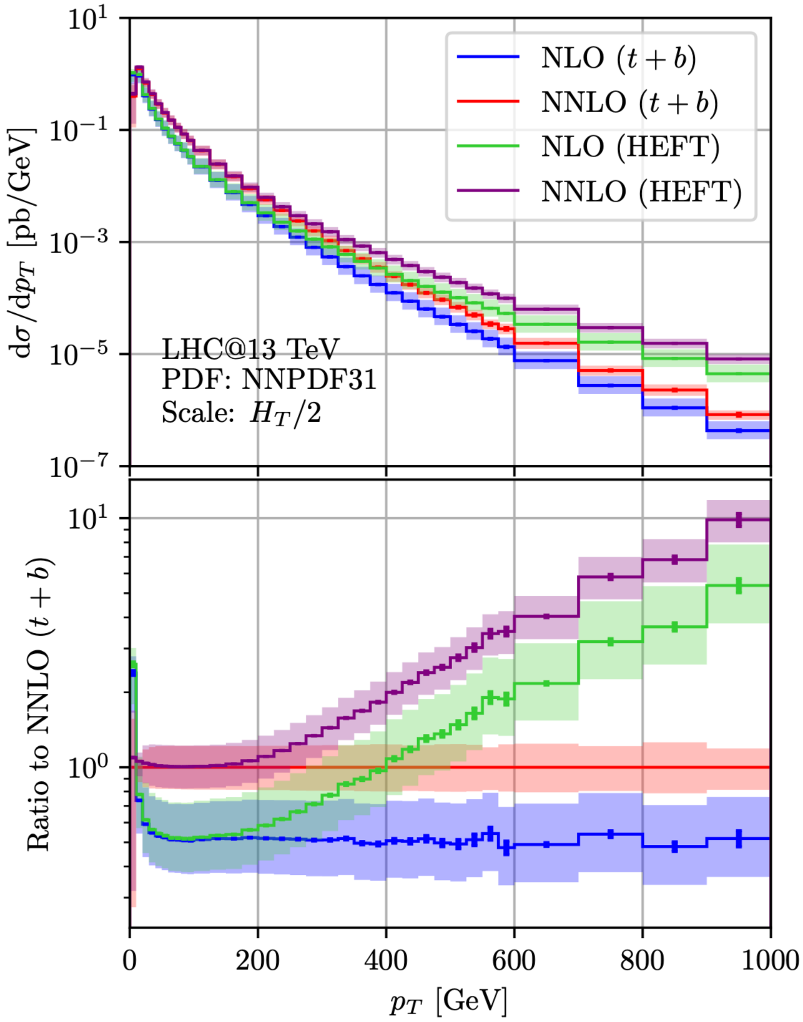
To know if the SM describes nature the SM predictions must match exp precision.

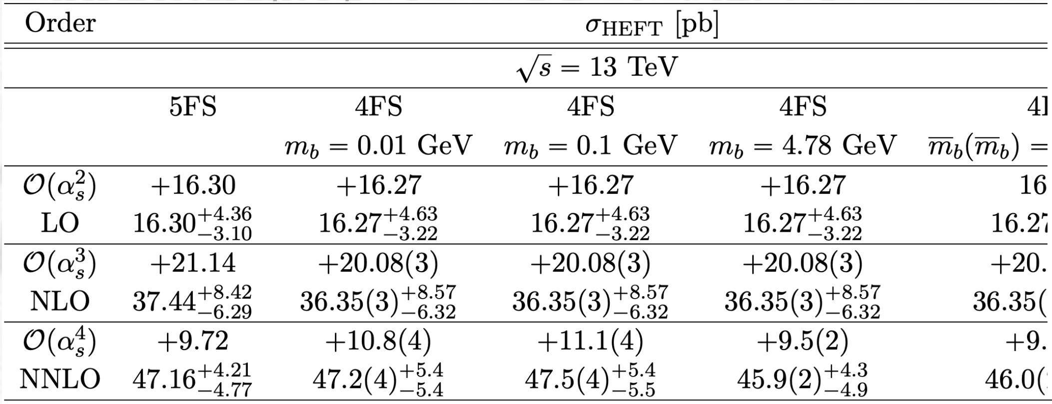
Progress in SM Predictions

Production

H at NNLO & q-masses!

Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 2407.12413





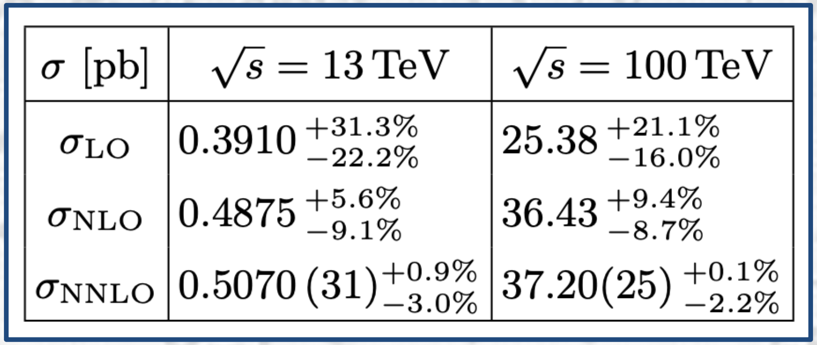
Order	σ_{HEFT} [pb]				
	$\sqrt{s} = 13$ TeV				
	5FS	4FS	4FS	4FS	4
		$m_b = 0.01$ GeV	$m_b = 0.1$ GeV	$m_b = 4.78$ GeV	$\overline{m}_b(\overline{m}_b) =$
$\mathcal{O}(\alpha_s^2)$	$+16.30$	$+16.27$	$+16.27$	$+16.27$	16
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	16.2
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$	+20.
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	36.35(
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+10.8(4)$	$+11.1(4)$	$+9.5(2)$	+9.
NNLO	$47.16^{+4.21}_{-4.77}$	$47.2(4)^{+5.4}_{-5.4}$	$47.5(4)^{+5.4}_{-5.5}$	$45.9(2)^{+4.3}_{-4.9}$	46.0(

Progress in SM Predictions

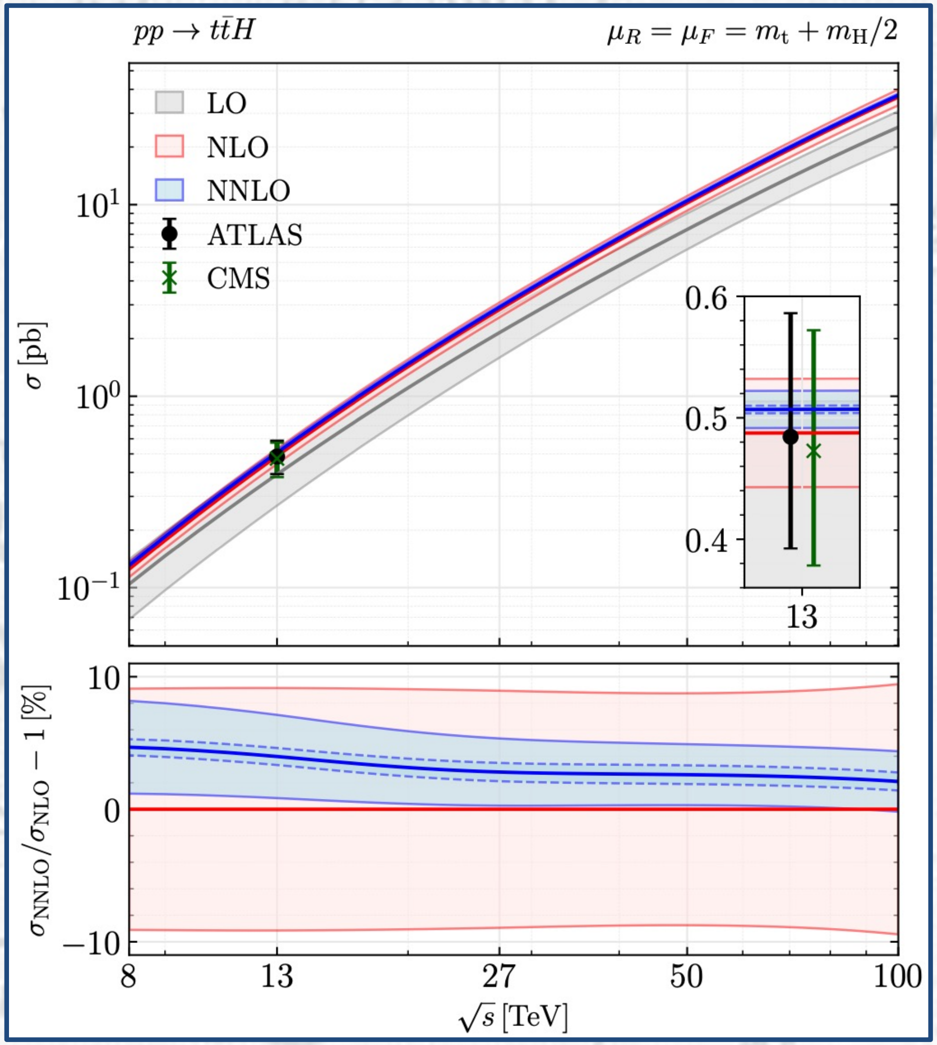
Production

ttH at NNLO!

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini 2210.07846



σ [pb]	$\sqrt{s} = 13\,\mathrm{TeV}$	$\sqrt{s} = 100\,\mathrm{TeV}$
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$



Progress in SM Predictions

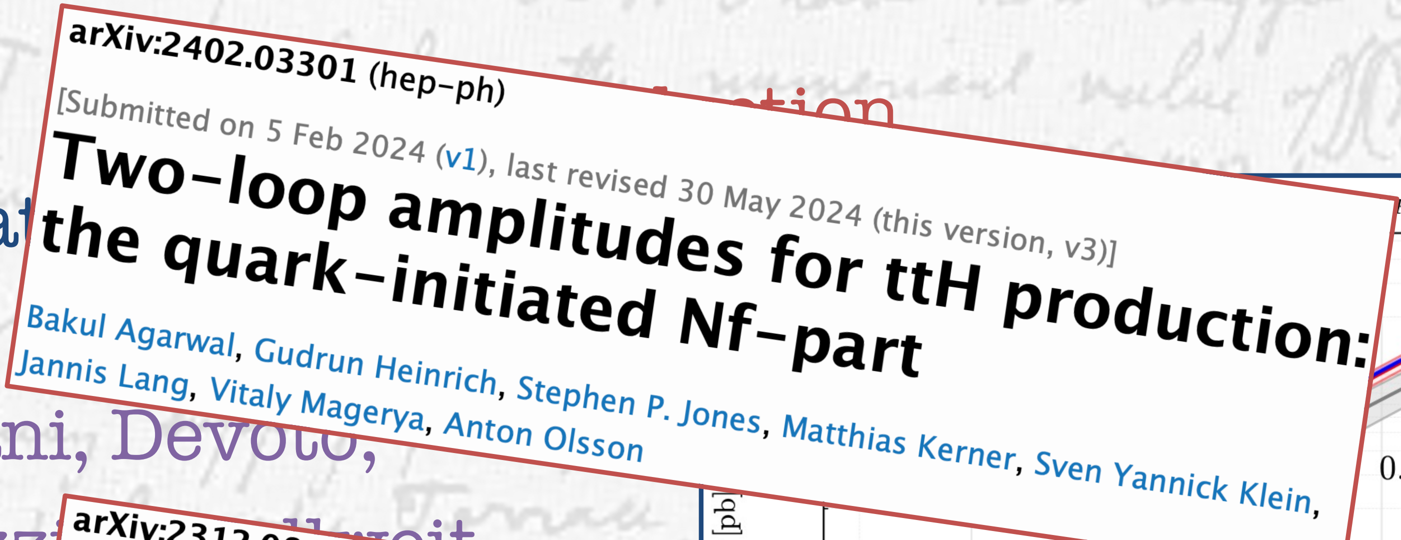
ttH at

Catani, Devoto,

Grazzi

Mazzi

2210

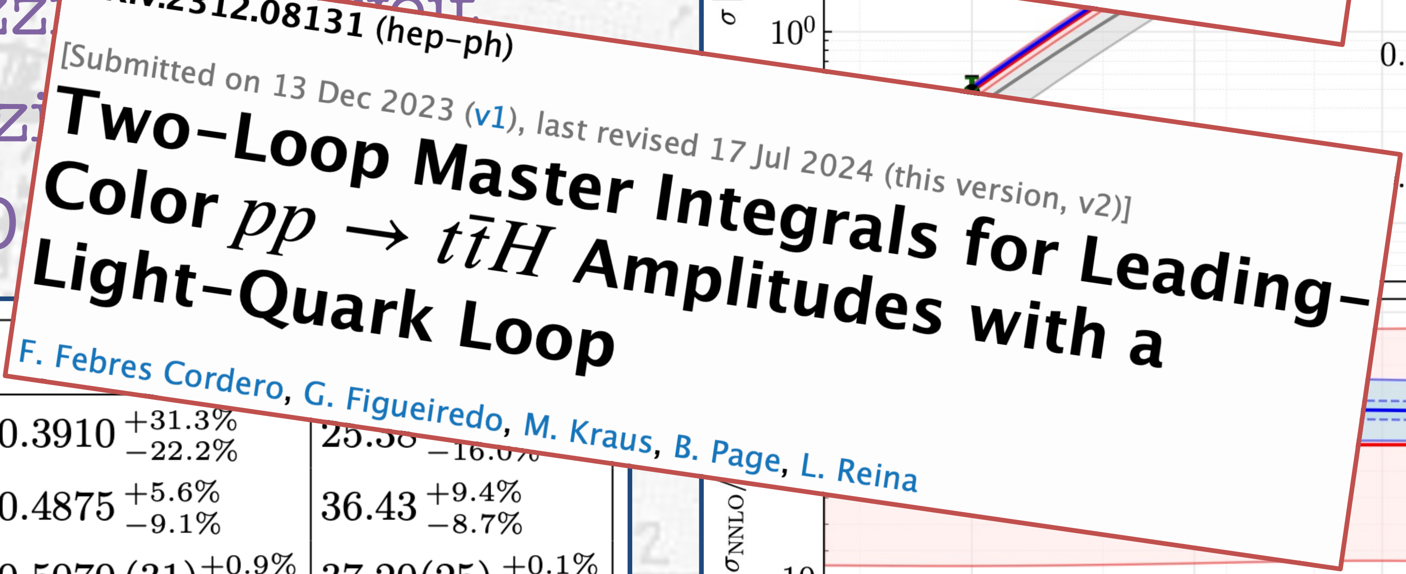


arXiv:2402.03301 (hep-ph)

[Submitted on 5 Feb 2024 (v1), last revised 30 May 2024 (this version, v3)]

Two-loop amplitudes for ttH production: the quark-initiated Nf-part

Bakul Agarwal, Gudrun Heinrich, Stephen P. Jones, Matthias Kerner, Sven Yannick Klein, Jannis Lang, Vitaly Magerya, Anton Olsson



arXiv:2312.08131 (hep-ph)

[Submitted on 13 Dec 2023 (v1), last revised 17 Jul 2024 (this version, v2)]

Two-Loop Master Integrals for Leading-Color $pp \to t\bar{t}H$ Amplitudes with a Light-Quark Loop

F. Febres Cordero, G. Figueiredo, M. Kraus, B. Page, L. Reina

σ [pb]		
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σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
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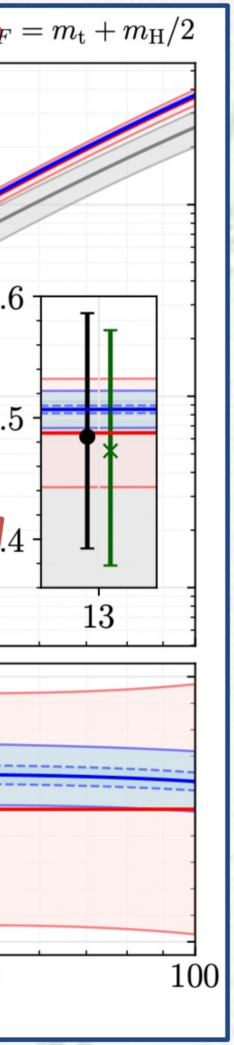
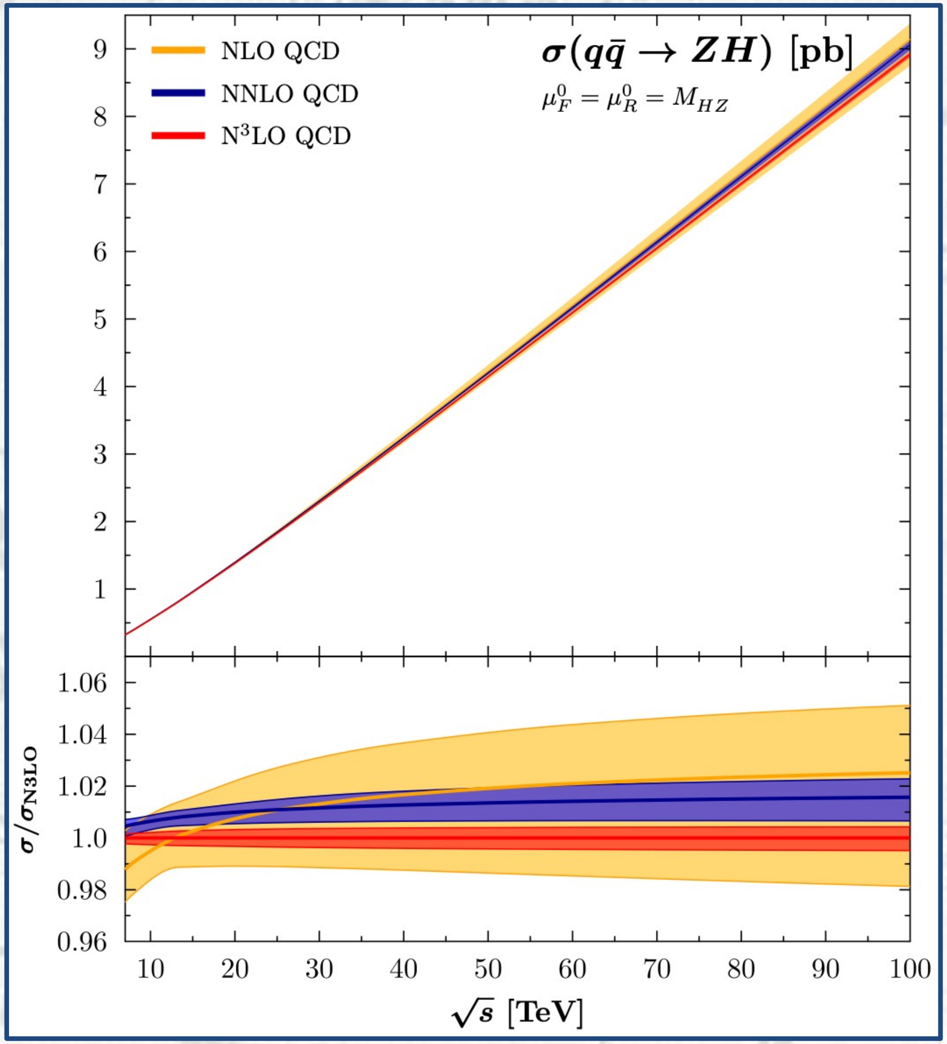


Progress in SM Predictions

Production

VH at NNNLO!

Baglio, Duhr, Mistlberger, Szafron 2209.06138



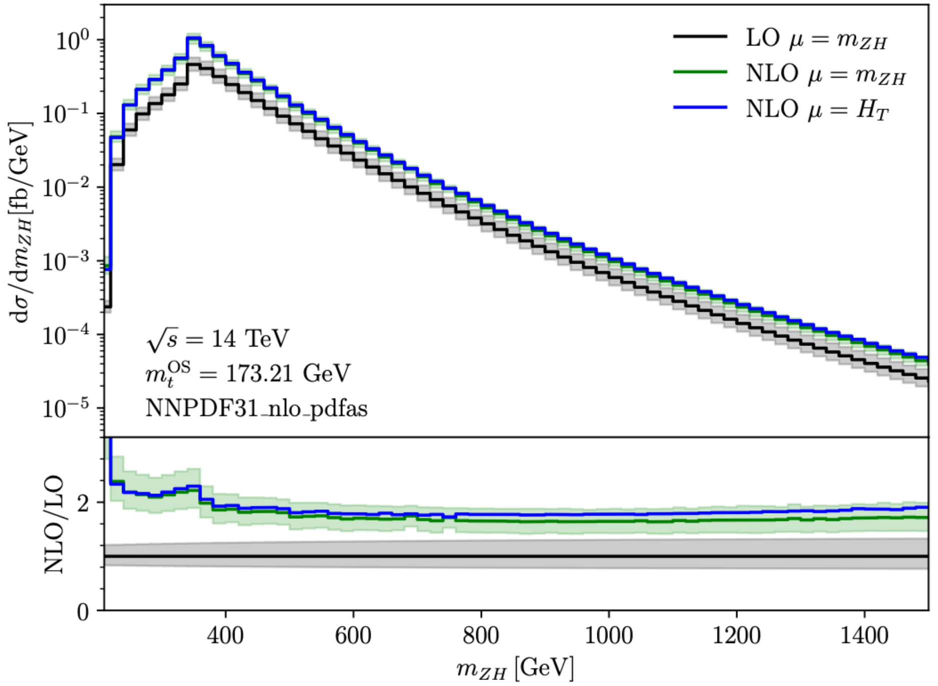
Process	$\sigma^{\mathrm{N^3LO}}$ [pb]	δ(PDF) [%]	$\delta(\mathrm{PDF}+\alpha_S)$ [%]	δ(PDF-TH) [%]
W^+H	0.883	±1.59	±1.80	±1.45
W^-H	0.558	±1.76	±1.93	±1.64
ZH	0.785	±1.82	±1.99	±1.54

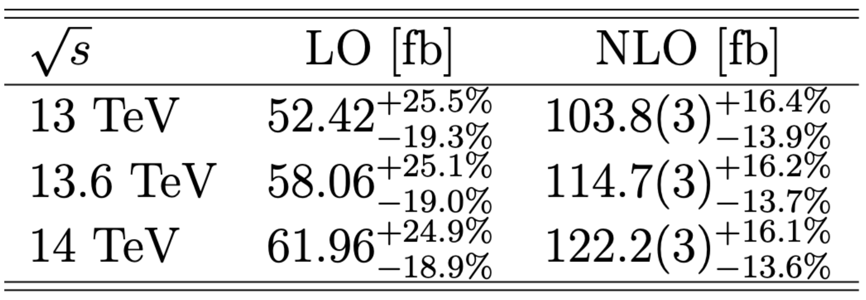
Progress in SM Predictions

Production

VH at NLO top!

Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser 2204.05225





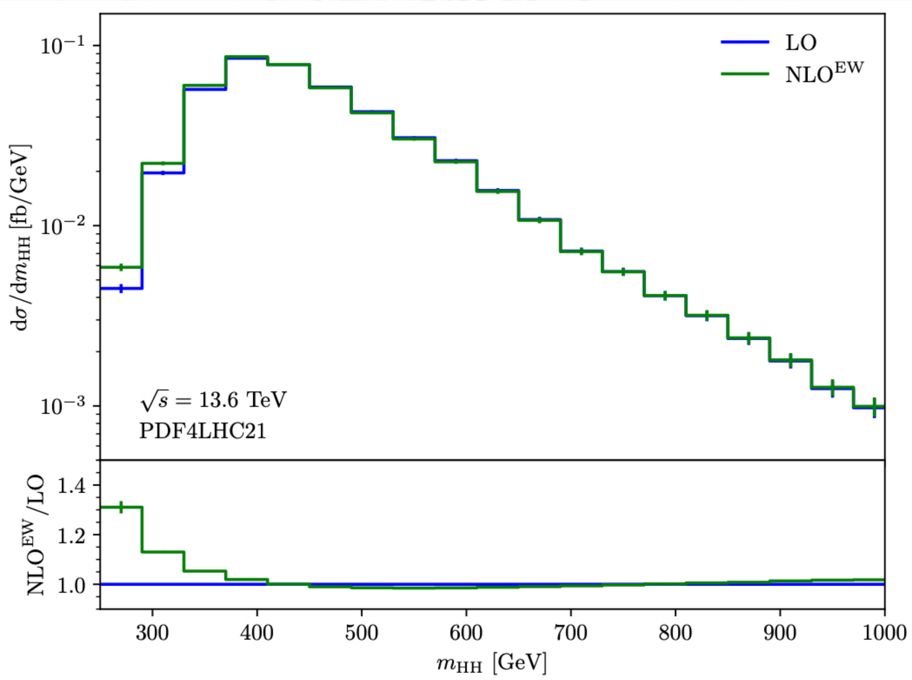
$\sqrt{s}$	LO [fb]	NLO [fb]
13 TeV	$52.42^{+25.5\%}_{-19.3\%}$	$103.8(3)^{+16.4\%}_{-13.9\%}$
13.6 TeV	$58.06^{+25.1\%}_{-19.0\%}$	$114.7(3)^{+16.2\%}_{-13.7\%}$
14 TeV	$61.96^{+24.9\%}_{-18.9\%}$	$122.2(3)^{+16.1\%}_{-13.6\%}$

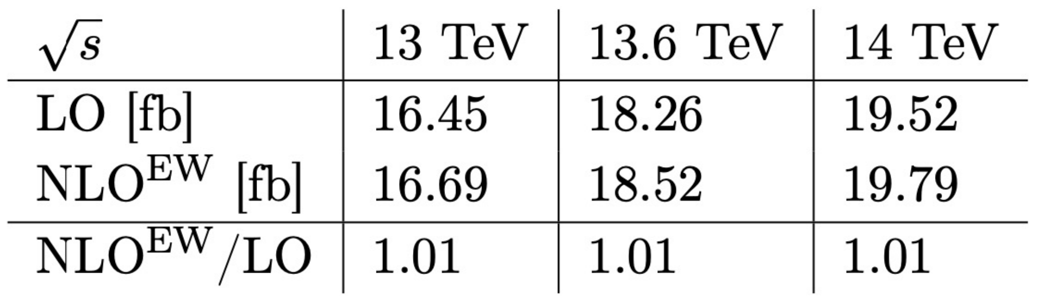
Progress in SM Predictions

Production

HH at NLO EW!

Heinrich, Jones, Kerner, Stone, Vestner 2407.04653





$\sqrt{s}$	13 TeV	13.6 TeV	14 TeV
LO [fb]	16.45	18.26	19.52
$\mathrm{NLO}^{\mathrm{EW}}$ [fb]	16.69	18.52	19.79
$\mathrm{NLO}^{\mathrm{EW}}/\mathrm{LO}$	1.01	1.01	1.01

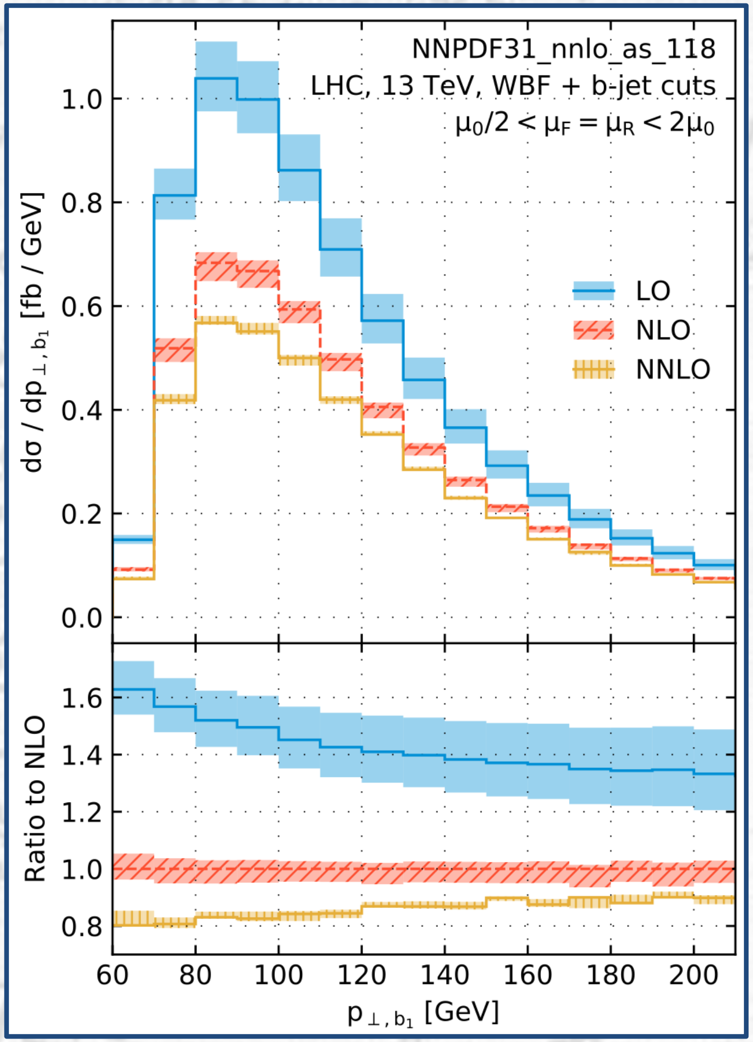
Progress in SM Predictions

Production and Decay

VBF at NNLO with decay!

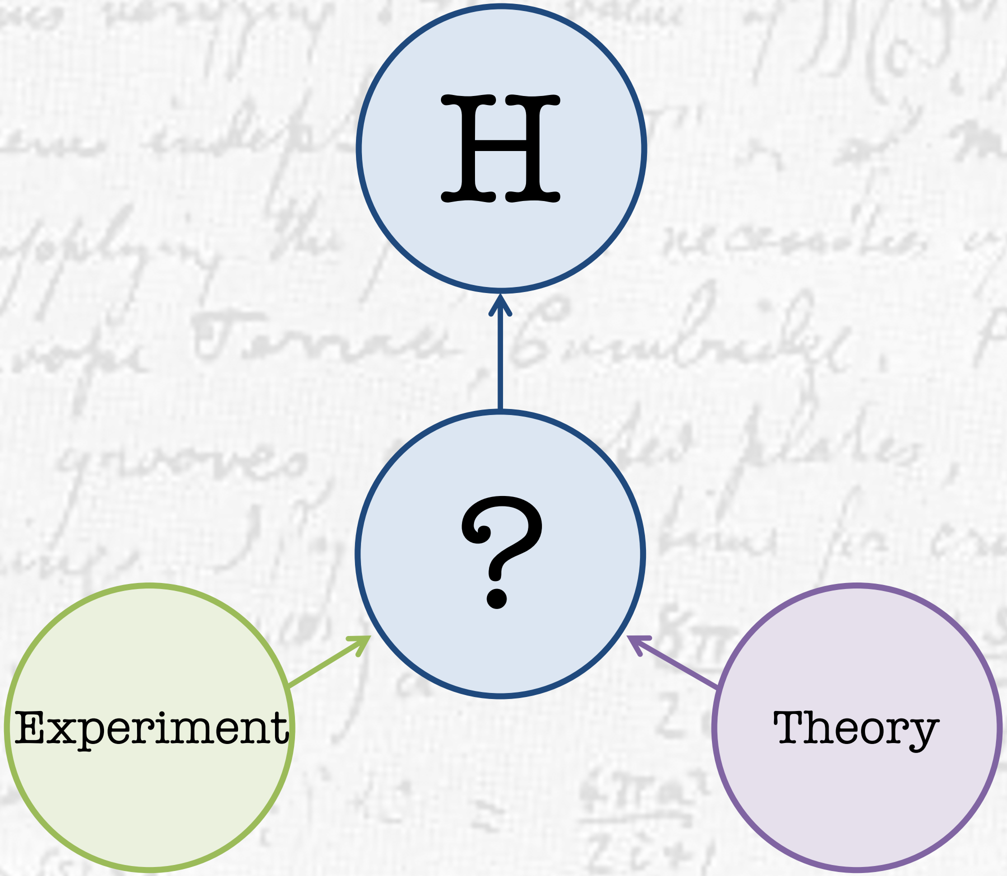
Asteriadis, Behring, Melnikov, Novikov, Röntsch 2407.09363

$$\sigma^{\rm LO} = 75.6^{-5.6}_{+6.5}\,{\rm fb}\,,$$
$$\sigma^{\rm NLO} = 52.4^{+1.5}_{-2.6}\,{\rm fb}\,,$$
$$\sigma^{\rm NNLO} = 44.6^{+0.9}_{-0.6}\,{\rm fb}\,,$$



Progress in SM Predictions

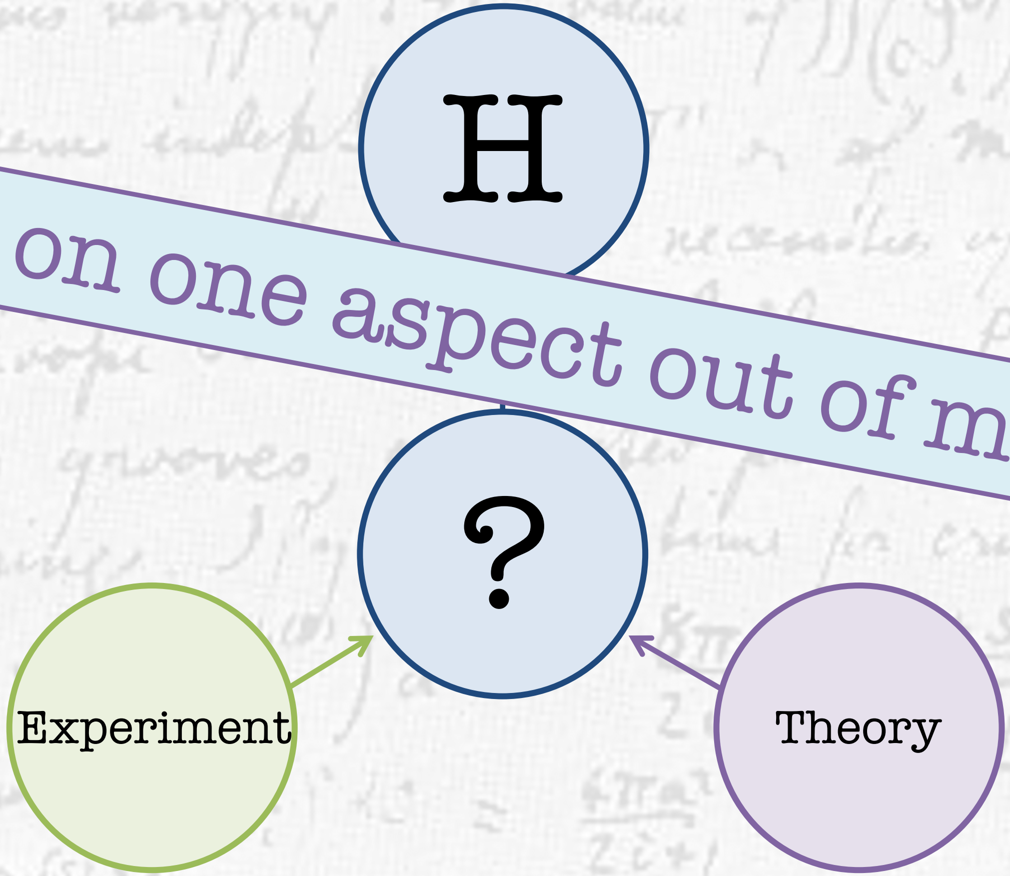
HL-LHC will deliver unprecedented precision (2%) towards answering this question.



What if SM predictions and measurements are discrepant?

Progress in SM Predictions

HL-LHC will deliver unprecedented precision (2%) towards answering this question.



H

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Experiment

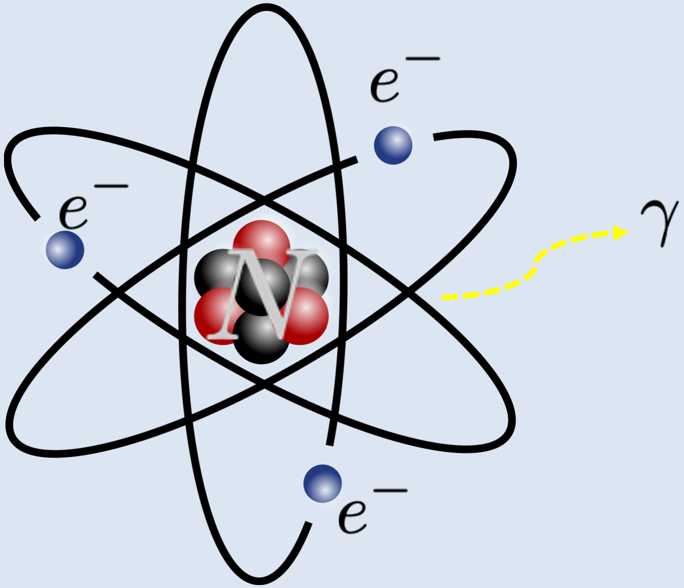
Theory

Focus on one aspect out of many...

What if SM predictions and measurements are discrepant?

Effective Field Theory Basics

Consider exploring a neutral atom at eV energies:



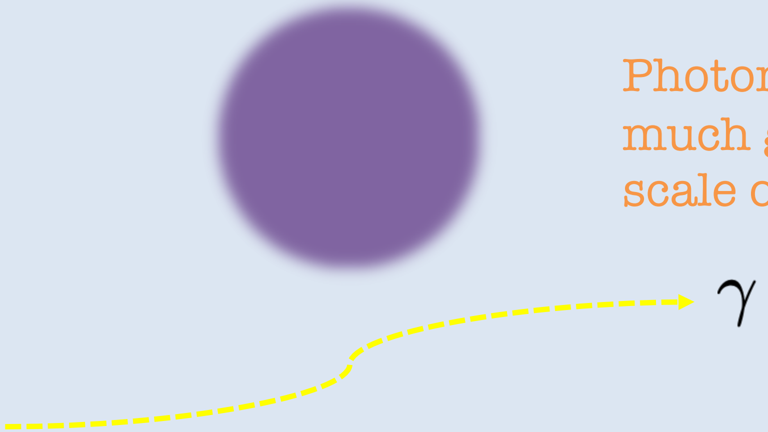
Photon wavelength on scale of orbitals.

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:



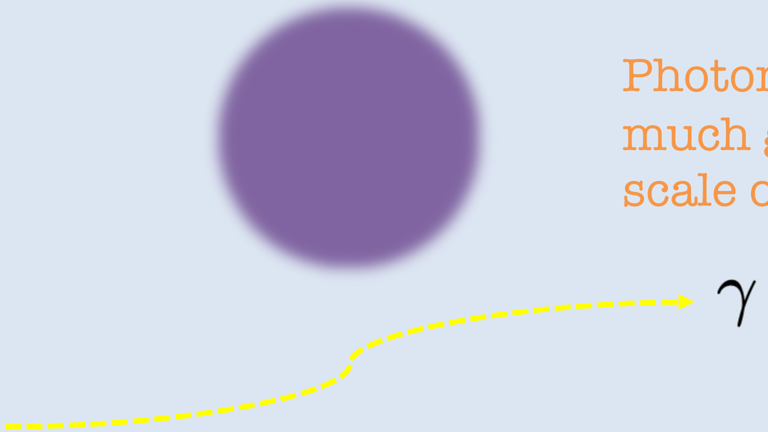
Photon wavelength much greater than scale of orbitals.

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:



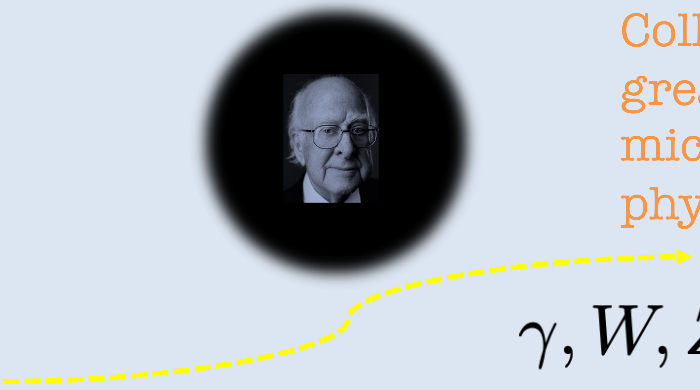
Photon wavelength much greater than scale of orbitals.

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 the Higgs boson!

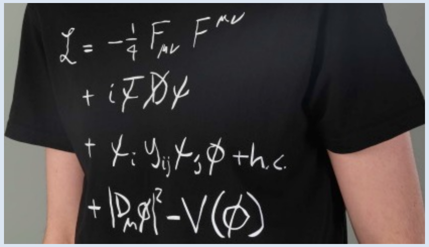


Collider wavelength greater than scale of microscopic new physics...

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

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

$$\mathcal{L} =$$



$$+ \sum_{jk} \frac{c_j}{\Lambda^k} \mathcal{O}_{jk}$$

Organizing the Unknown

Naïve dimensional analysis:

$$[H] = [A_\mu] = \frac{1}{LC} \quad , \quad [\psi] = \frac{1}{L^{3/2}C}$$

Fields carry not only dimension of inverse length, but also inverse coupling.

Fermi Scale

Interaction: $\mathcal{L} \sim \frac{\psi^4}{\Lambda^2}$

UV-completion

Dimension: $[\Lambda] = [G_F^{-1/2}] = \frac{[M_W]}{[g]}$

Coupling

Organizing the Unknown

Naïve dimensional analysis:

$$[H] = [A_\mu] = \frac{1}{LC} \quad , \qquad [\psi] = \frac{1}{L^{3/2}C}$$

Fields carry not only dimension of inverse length, but also inverse coupling.

New Physics Scale

Interaction: $\mathcal{L} \sim \frac{|H|^6}{\Lambda^2}$

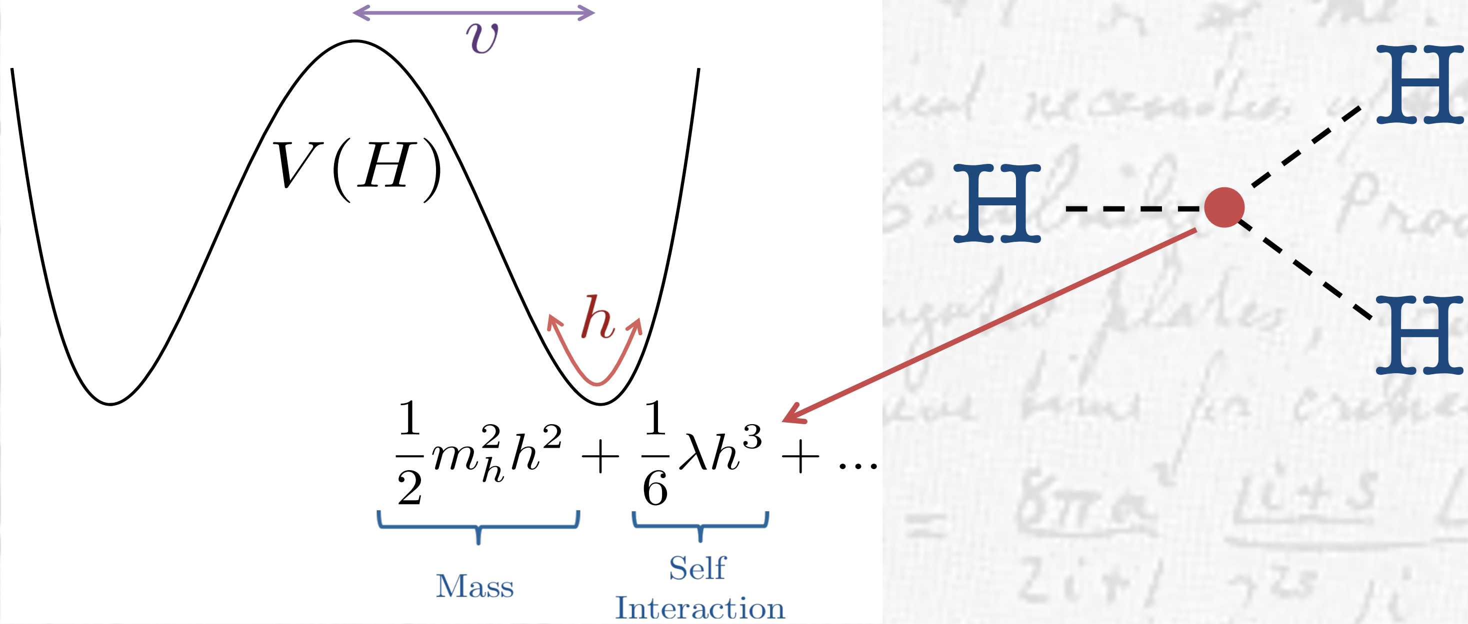
UV-completion

Dimension: $[\Lambda^2] = \frac{[M^2]}{[g^4]}$

Coupling

Naïve Dimensional Analysis

It's known that O_6 contributes to Higgs self-interaction, how it gives mass to itself, etc.



$$\underbrace{\frac{1}{2}m_h^2h^2}_{\text{Mass}} + \underbrace{\frac{1}{6}\lambda h^3}_{\text{Self Interaction}} + \dots$$

But less-well appreciated are the NDA aspects underlying it…

Naïve Dimensional Analysis

The fact that

$$[c_6] = [g^4]$$

and all other operator coefficients have

$$[c_j] \leq [g^2]$$

makes the self-coupling special, with one important implication I'll highlight today.

Self-Coupling Dominance

No obstruction to having Higgs self-coupling modifications a “loop factor” greater than **all** other couplings. Could have

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

without fine-tuning any parameters, as big as,

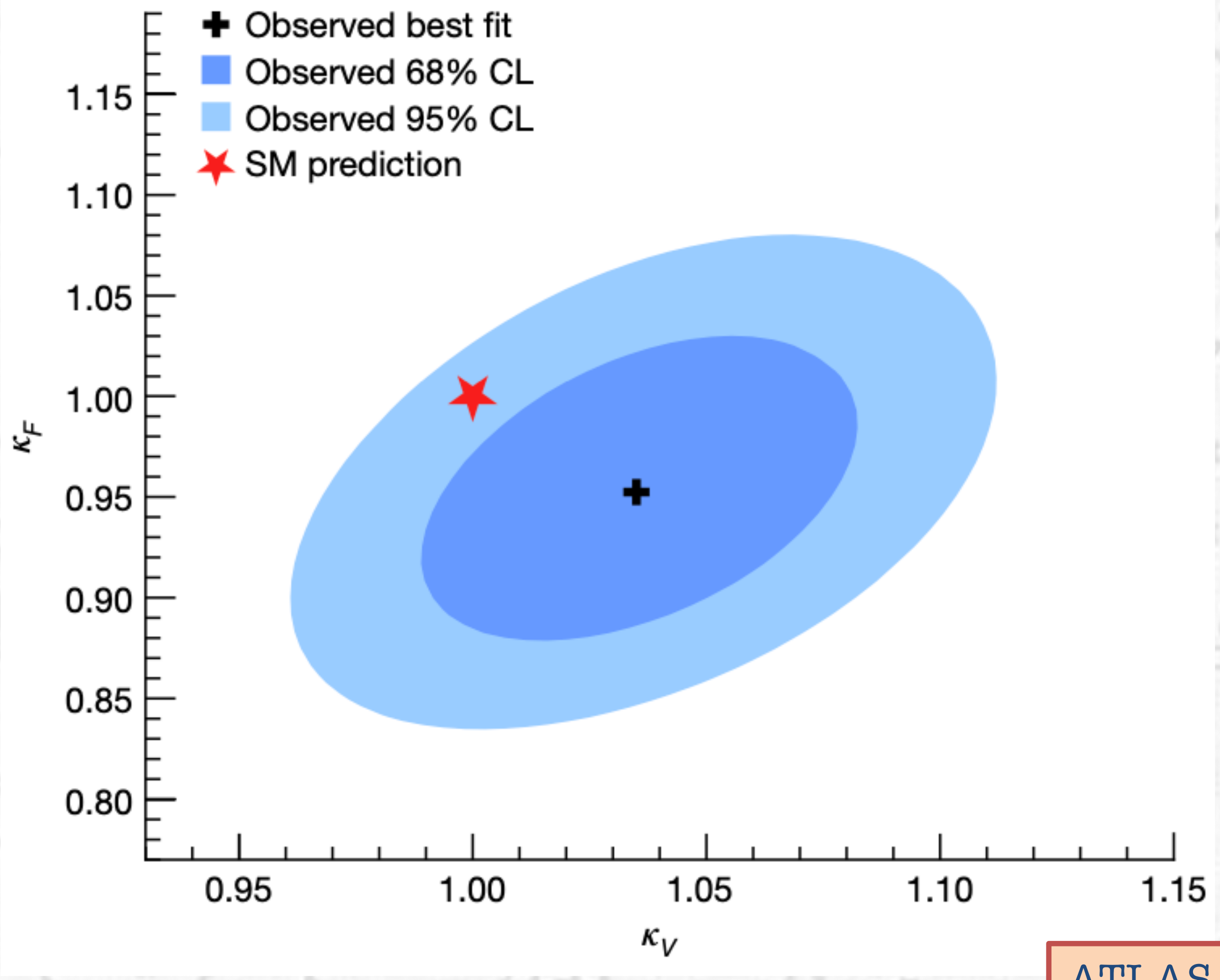
$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

Durieux, MM, Salvioni. 2022

Status of Higgs Couplings

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



ATLAS, Nature, 2022

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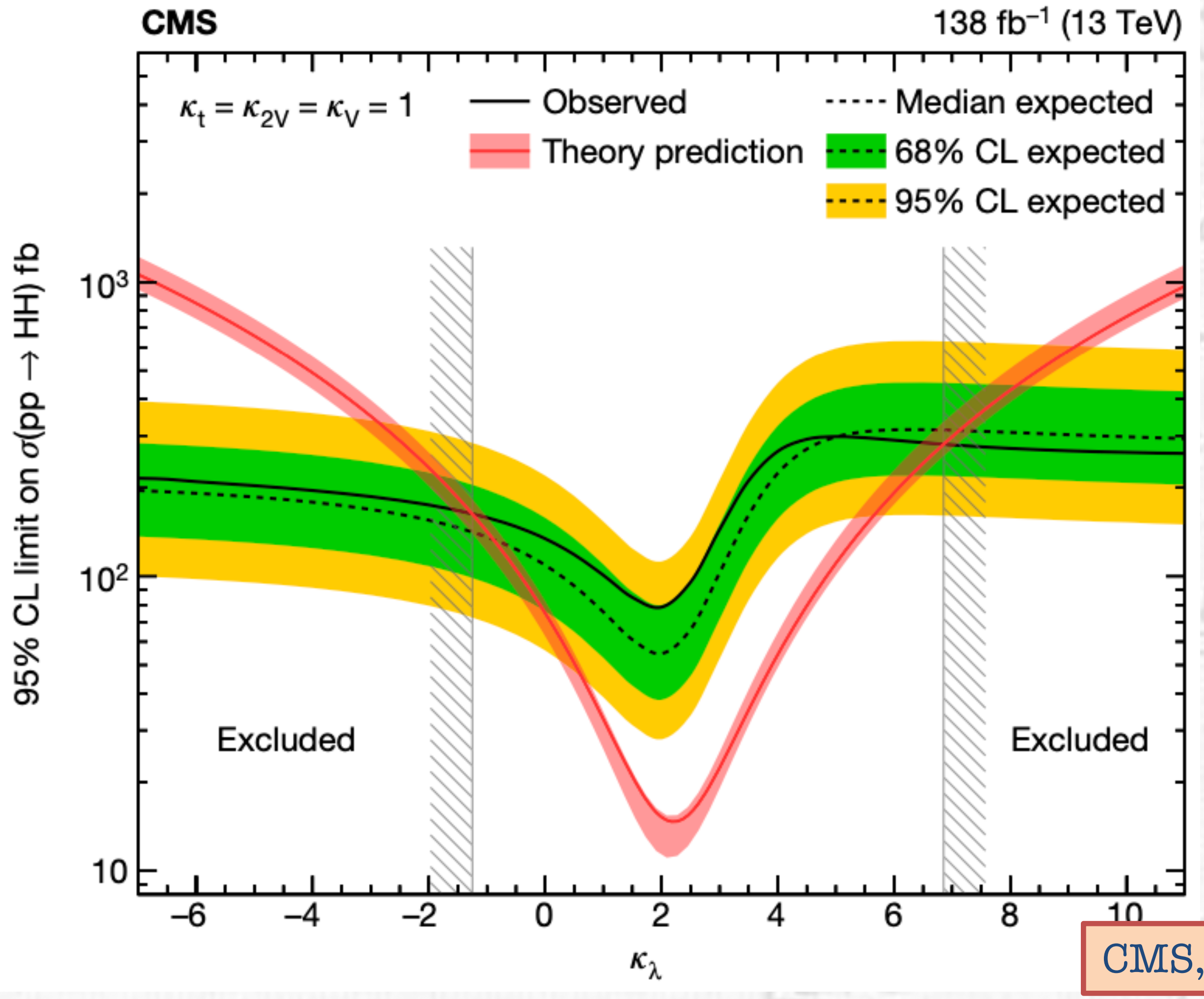

CMS, Nature, 2022

Status of Higgs Couplings

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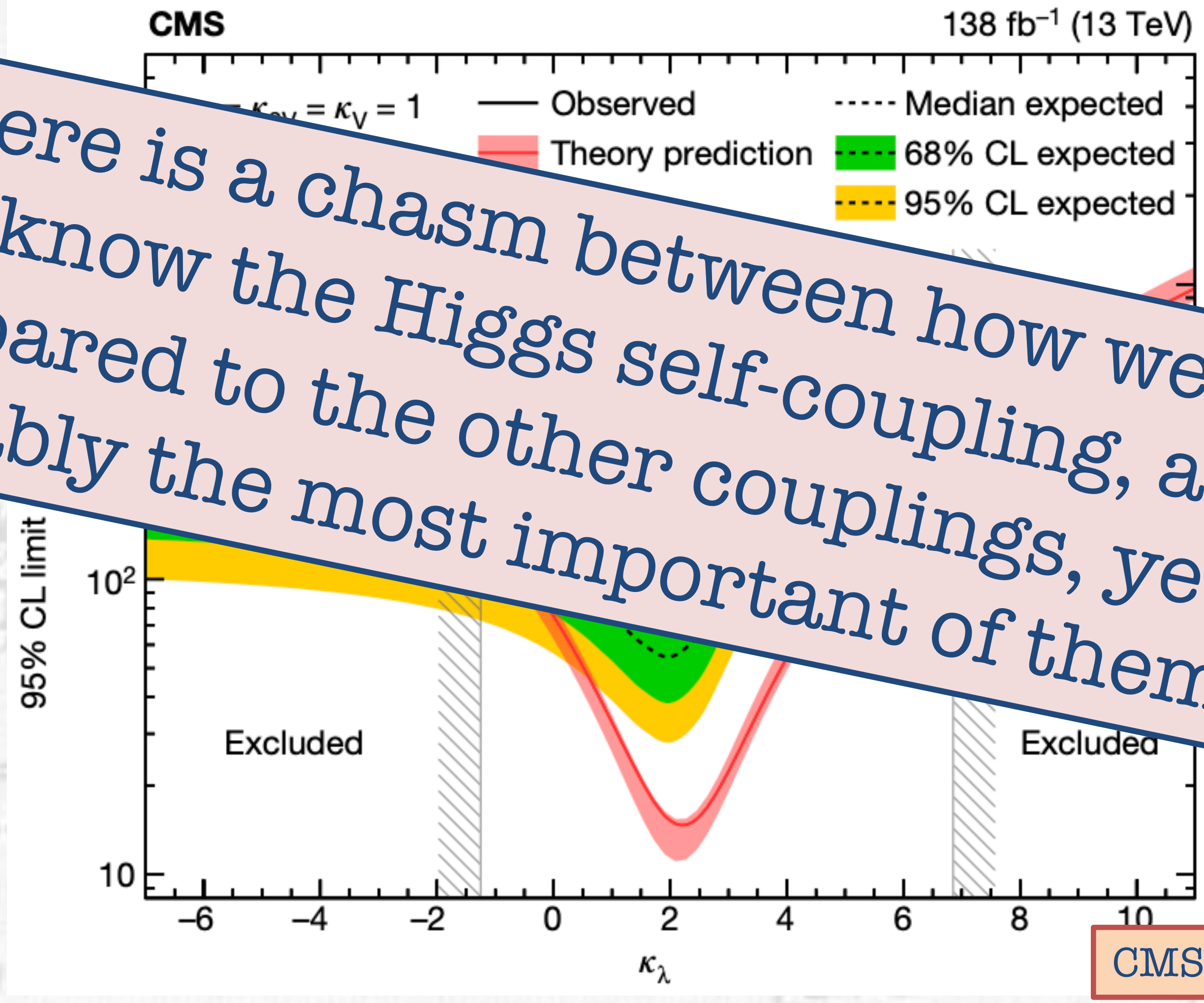


There is a chasm between how well we know the Higgs self-coupling, as compared to the other couplings, yet it is arguably the most important of them all!

CMS, Nature, 2022

Self-Coupling Dominance

In other words, no obstruction from to having Higgs self-coupling modifications a loop factor greater than **all** other couplings. Could have

$$\left|\frac{\quad}{\delta_{VV}}\right| \quad \left[\left(\frac{4\pi v}{\quad}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

But could such a theory exist in practice?

without fine-tuning any parameters, as

$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

Durieux, MM, Salvioni. 2022

Example: EW Quadruplets

This is all well and good, but does such a theory exist? Yes: A combination of EW quadruplet scalars:

$$\mathbf{4}_{1/2} + \mathbf{4}_{3/2}$$

Including all couplings to the Higgs we have for the two scalar quadruplets

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

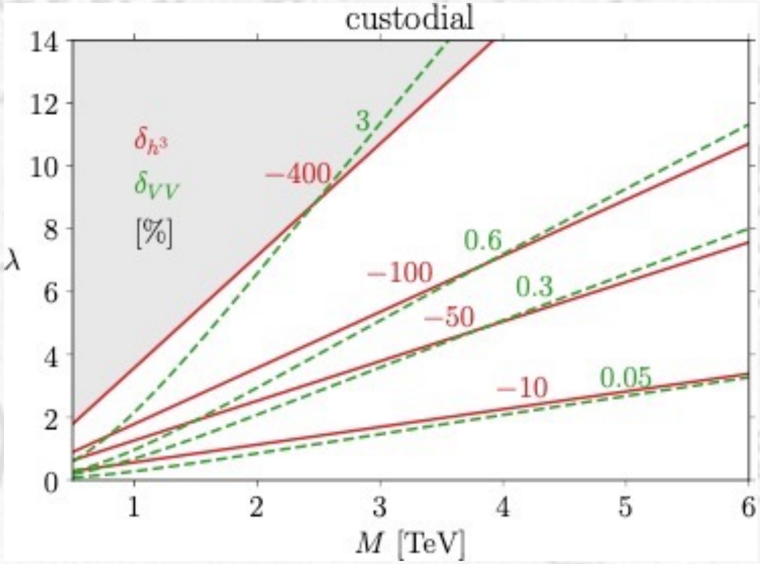
which respects "custodial" global symmetry, hence no leading precision EW contributions.

Example: EW Quadruplets

Higgs self-coupling is modified, all other couplings modified at one loop higher, or higher dimension. All calculable, giving

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

Remarkably close to naïve estimate!



Durieux, MM, Salvioni. 2022

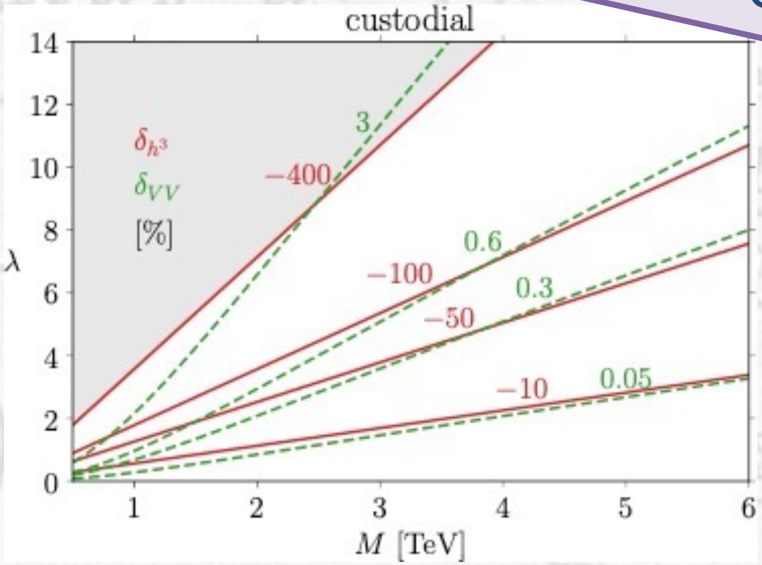
Example: EW Quadruplets

Higgs self-coupling is modified, all other couplings modified at one loop higher, or higher dimension. A calculable, giving

Existence proof of a scenario which automatically generates extra-large self-coupling corrections.

$$-\frac{\;}{\delta_{h^3}}\left(\frac{m_h}{\;}\right)^2 \simeq \frac{1}{200}+\frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2$$

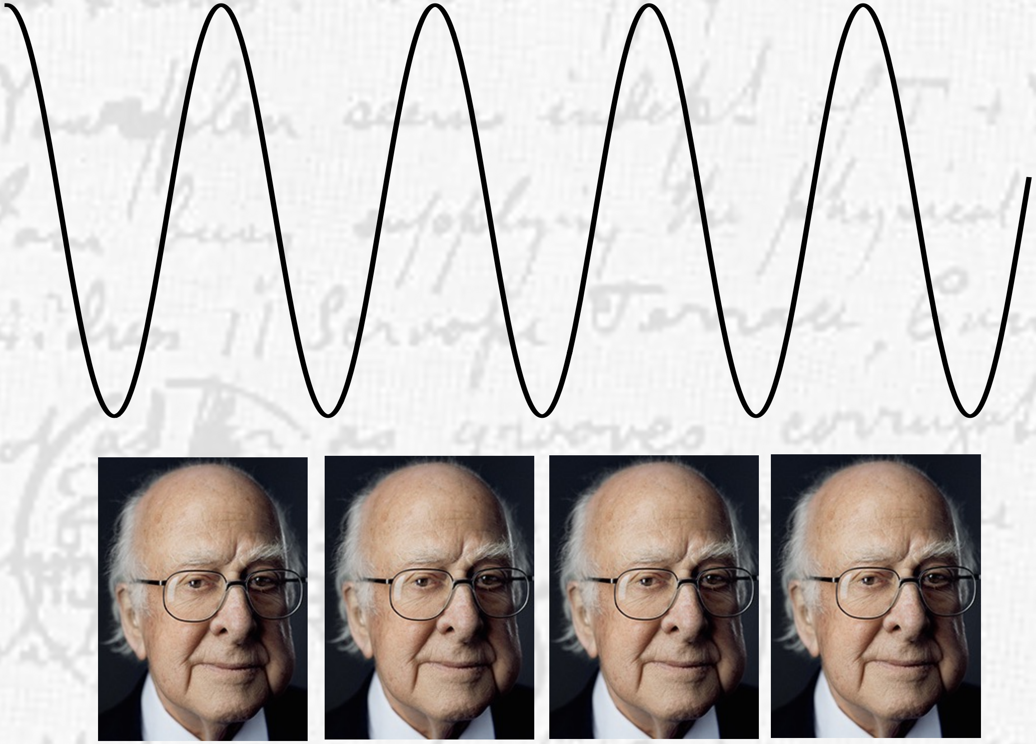
Remarkably close to NDA e



Durieux, MM, Salvioni. 2022

Is the Higgs Fundamental?

The Higgs boson has a size/wavelength. What's inside?



Precision measurements are different ways of probing the "compositeness of the Higgs".

$$\lambda_h \approx 10^{-17}\ \text{m}$$

$$\lambda_{10\ \text{TeV}} \approx 10^{-19}\ \text{m}$$

Backdrop

This is exactly what happened with the pions…

$$\boxed{m_\pi^2 \ll m_p^2}$$

Why not the Higgs boson then?

Naturalness – Composite Higgs

Composite Higgs scenarios have a potential which looks like

“Compositeness” Scale

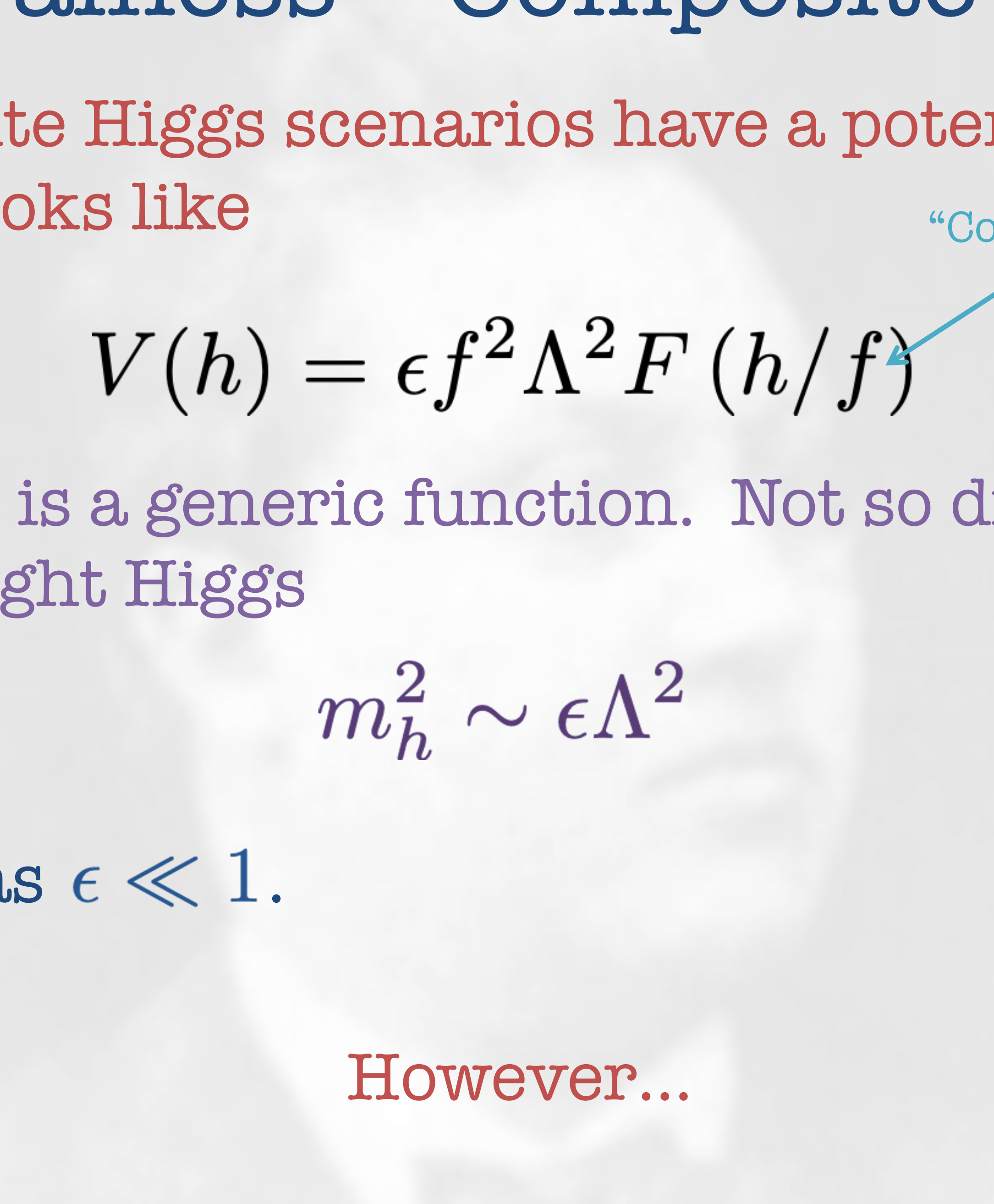
$$V(h) = \epsilon f^2 \Lambda^2 F\left(h/f\right)$$

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

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

If one has $\epsilon \ll 1$.

However...



Naturalness – Composite Higgs

Composite Higgs scenarios have a potential which looks like

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

“Compositeness” Scale

Position of minimum depends only on F:

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

For minimum at $h = v \ll f$ have to fine-tune the contributions from the microscopic physics.

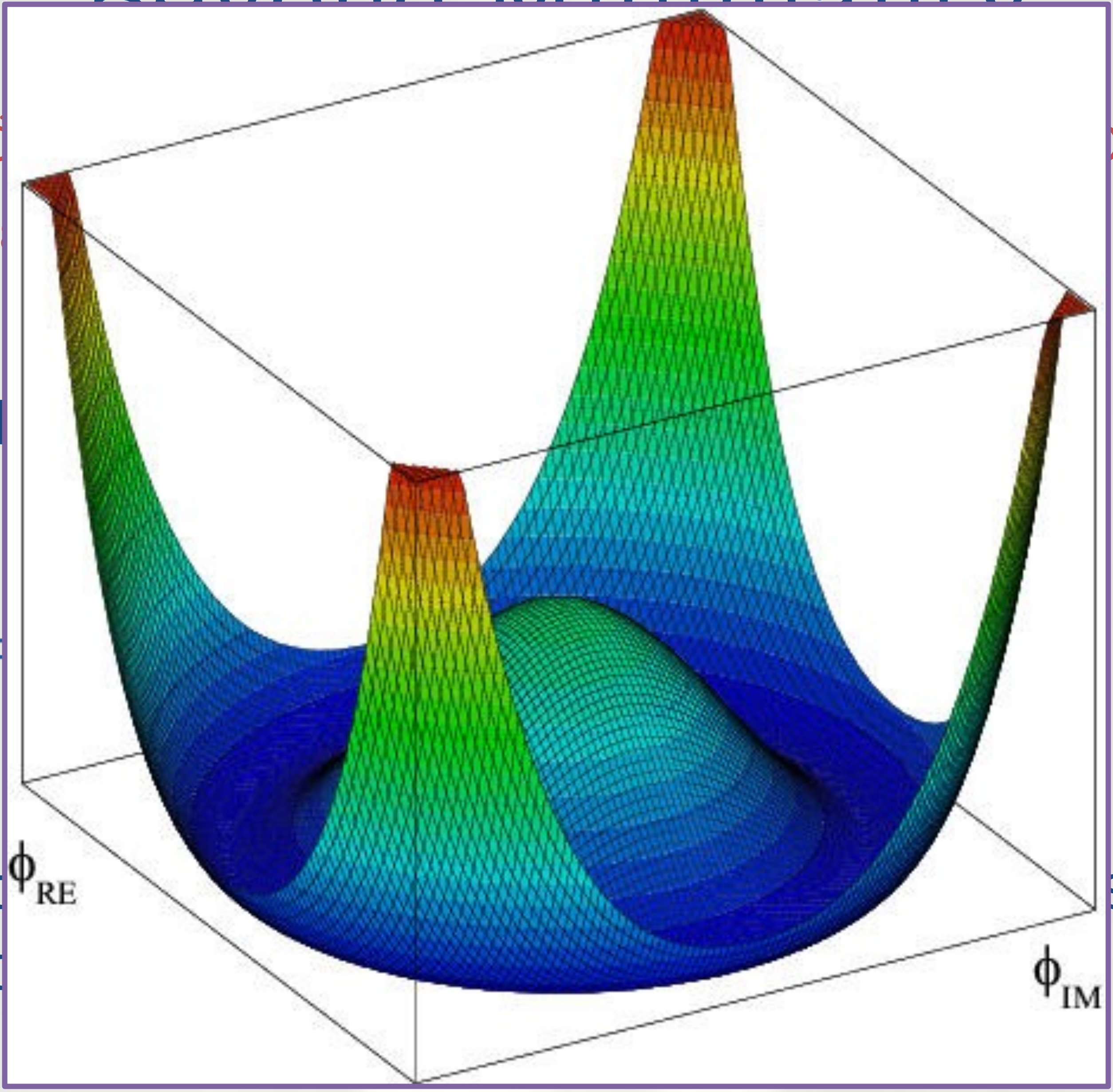
But Higgs couplings modified by $\delta_\kappa \sim \dfrac{v^2}{f^2}$.

Beyond Minimality

Consid ply to
the Hi

Examp

$$\mathcal{L} = \qquad \Big)^2$$



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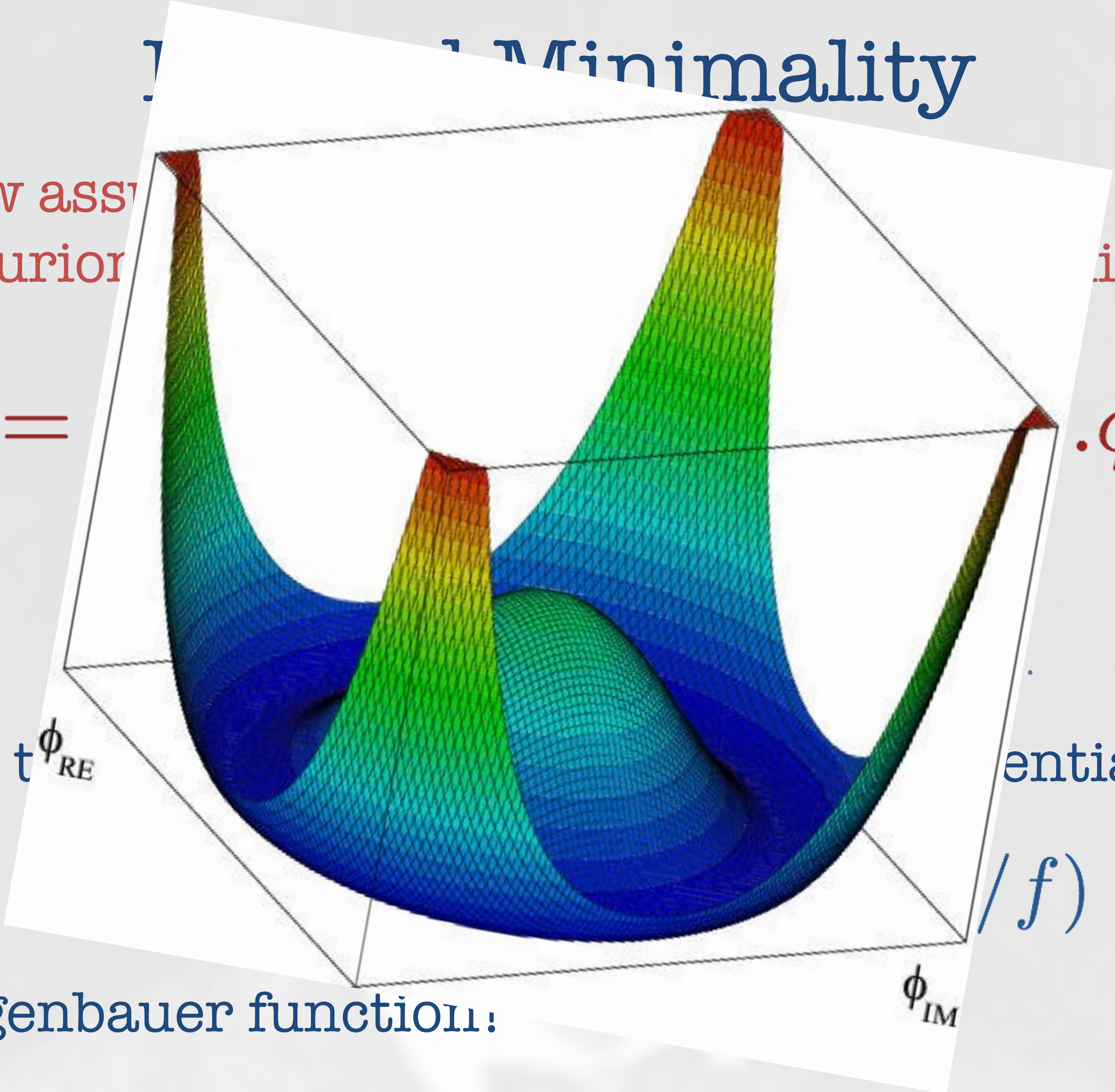


Now ass

“spurion ices:

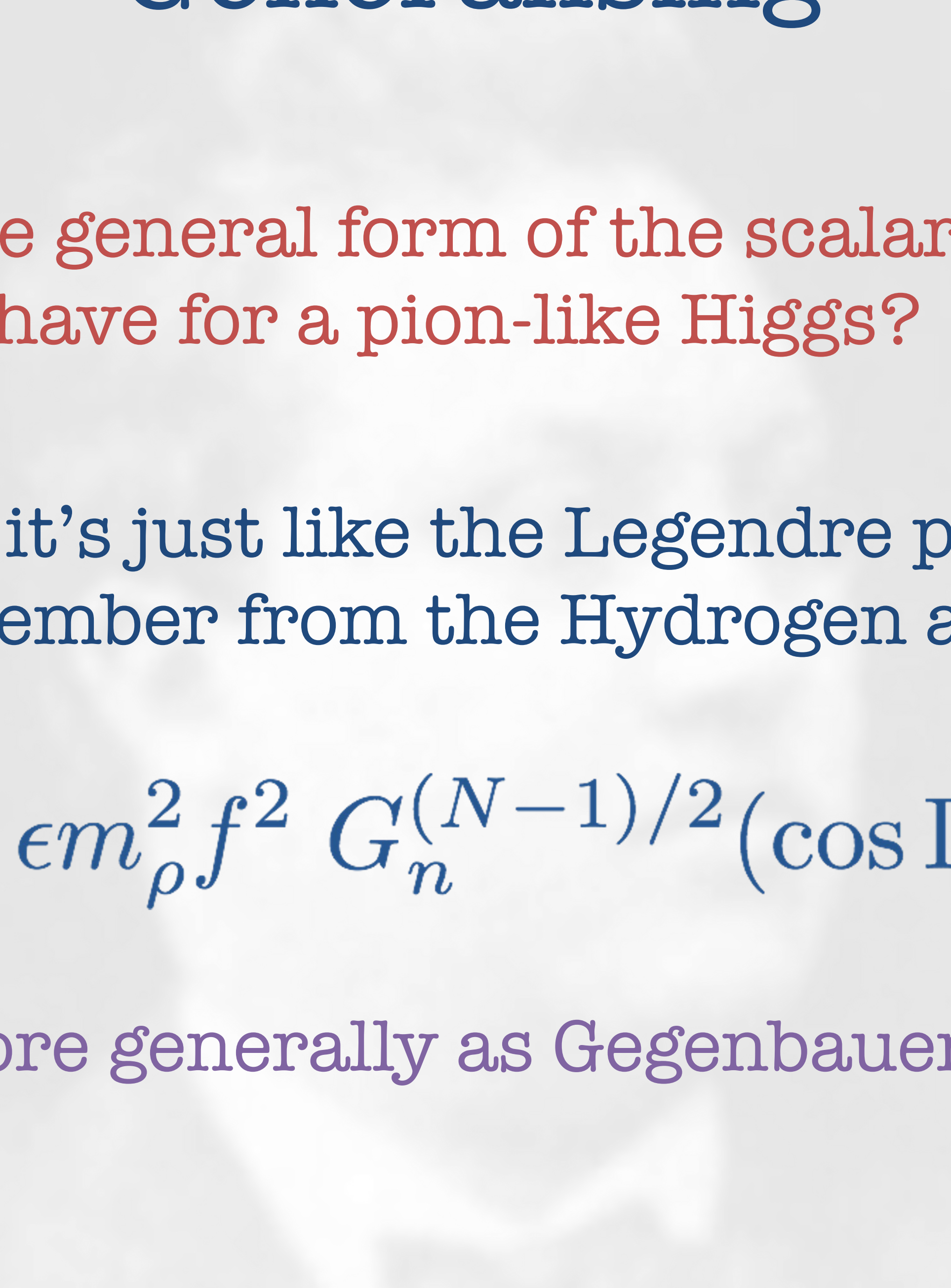
$$V_\epsilon = \quad .\phi^{a_n}$$

For t ential:

$$/f)$$

Gegenbauer function

Generalising



What is the general form of the scalar potential one could have for a pion-like Higgs?

Turns out it's just like the Legendre polynomials you'll remember from the Hydrogen atom:

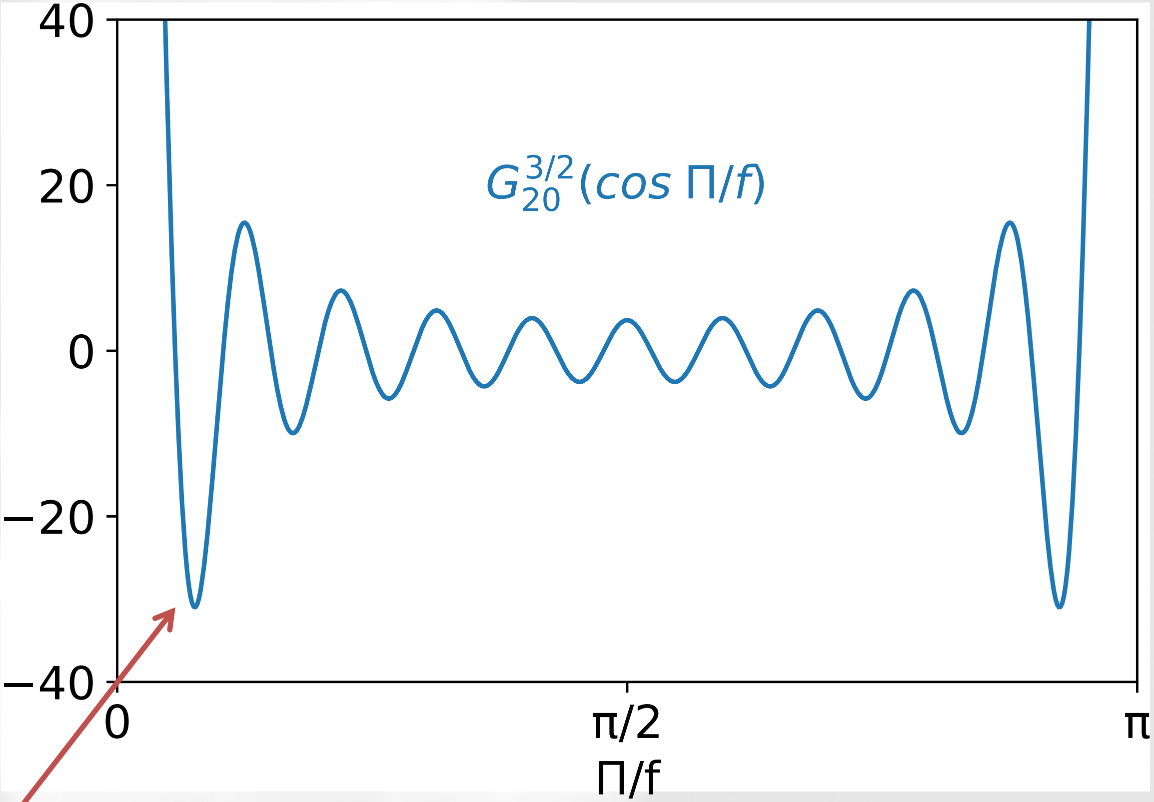
$$V = \epsilon m_\rho^2 f^2 \, G_n^{(N-1)/2}(\cos \Pi / f)$$

Known more generally as Gegenbauer functions!

Durieux, MM, Salvioni. 2021

Getting to know Gegenbauer

The Gegenbauer potential looks like:

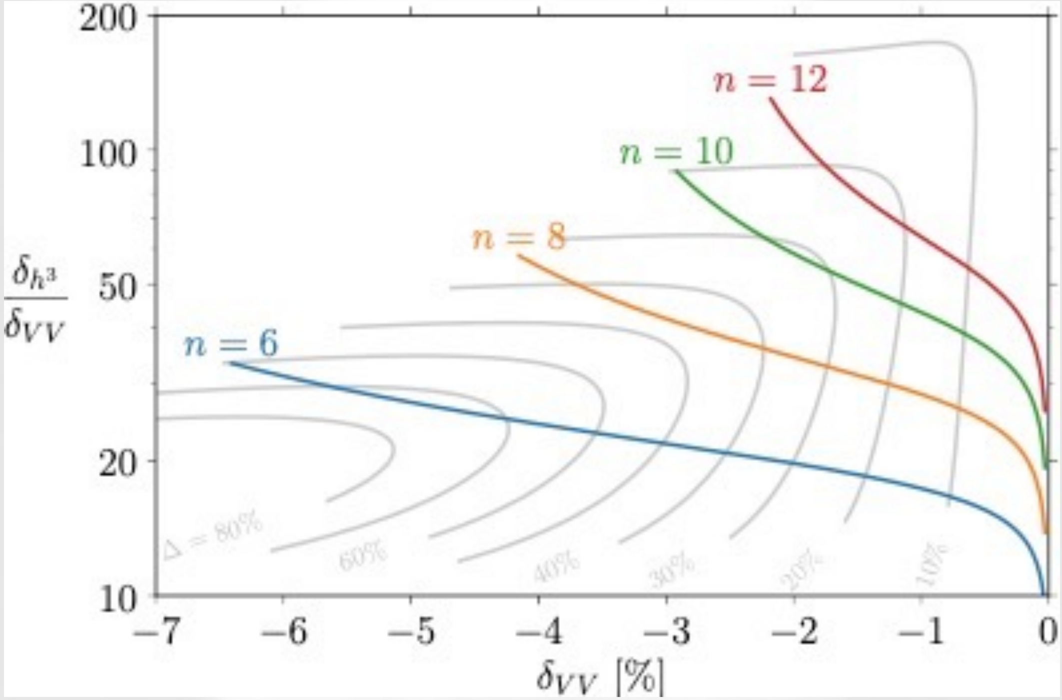


Global Higgs potential minimum at automatically small field values:

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

Example Gegenbauer Model

Modifications to self-interaction relative to other couplings are huge:

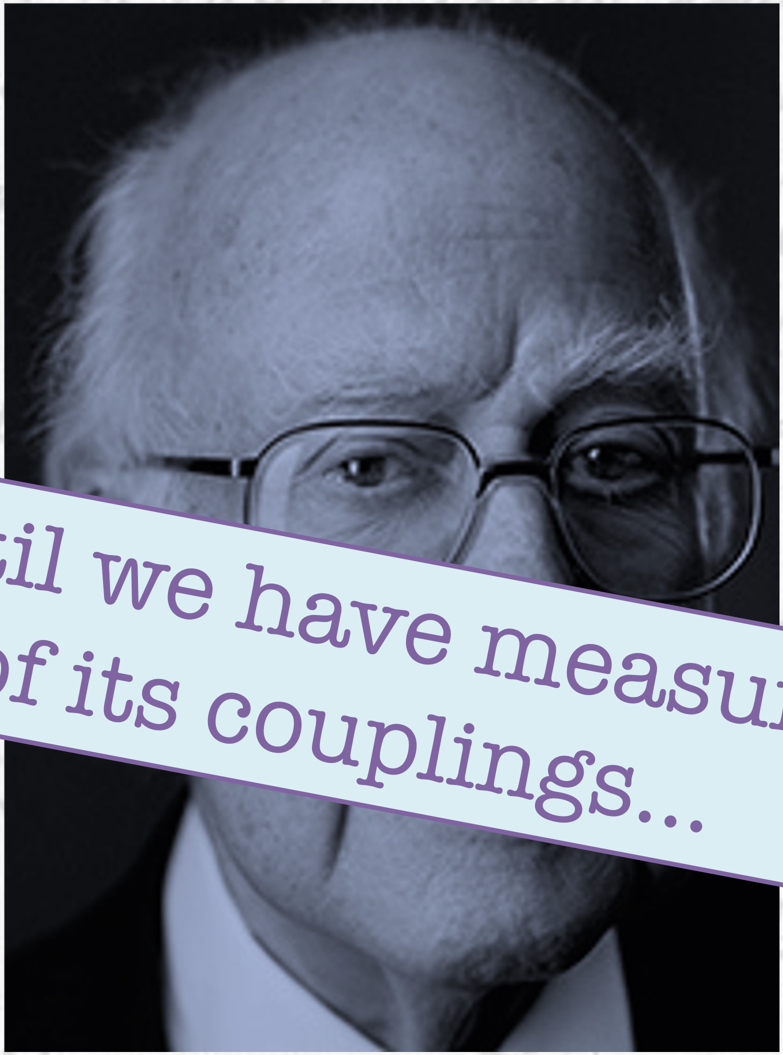


Naturalness could show up in self-interaction!

Fine-tuning is small. Huge corrections to Higgs self-coupling!

Durieux, MM, Salvioni. 2021

How well do we know the Higgs?



Until we have measured all of its couplings...

Barely.

Conclusions

Higgs physics is still in its nascence. Pions were discovered in the early 1940's. Their fundamental origin, QCD, was developed theoretically in the early 1970's and only experimentally established in the late 1970's.

Twelve years since discovery of the Higgs boson.

As it stands, we don't know how it interacts with itself, or if it is composite; with far-reaching implications.

We must be patient and determined to uncover its origins.

O·T'. R·U·ATOME?. $\iint$ Sphere^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 [illegible] 11 Scroope Terrace, Cambridge. Prooves have got as far as grooves, corrugated plates, gratings and rings. If you have time for criticism than [illegible]

and 1. $\iint (Y_i^{(s)})^2 dS = \frac{8\pi a^2}{2i+1} \frac{\underline{|i+s}\ \underline{|i-s}}{2^{2s}\ \underline{|i}\ \underline{|i}}$

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

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

yrs $\frac{dp}{dt}$