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UCSB

11TH HIGGS HUNTING

Six Questions

Does the Higgs…

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1. …have a size?

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2. …interact with itself?

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Does the Higgs…

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3. …mediate a yukawa force?

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A Fundamental Scalar?

Figure of merit: Higgs “size” vs Compton wavelength. Beginning to probe the size of the Higgs at the LHC, but not yet to π-like compositeness

More precisely: bound “size” corrections, e.g. $\mathcal{O}_H = \frac{1}{2\Lambda^2}\left(\partial_\mu |H|^2\right)^2$

Now

$\frac{1}{4m_h}$

HL-LHC

$\frac{1}{10m_h}$

ILC500
(for example)

$\frac{1}{33m_h}$

[1905.03764]

LHC, Higgs factories will ultimately probe size of the Higgs well beyond this, providing strong evidence that the Higgs is elementary. *If not, abundant new physics awaits.*

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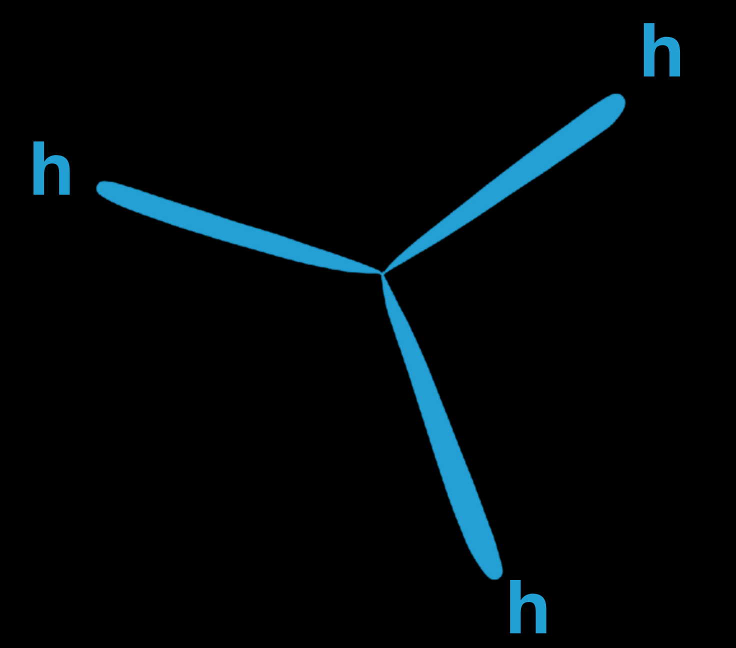
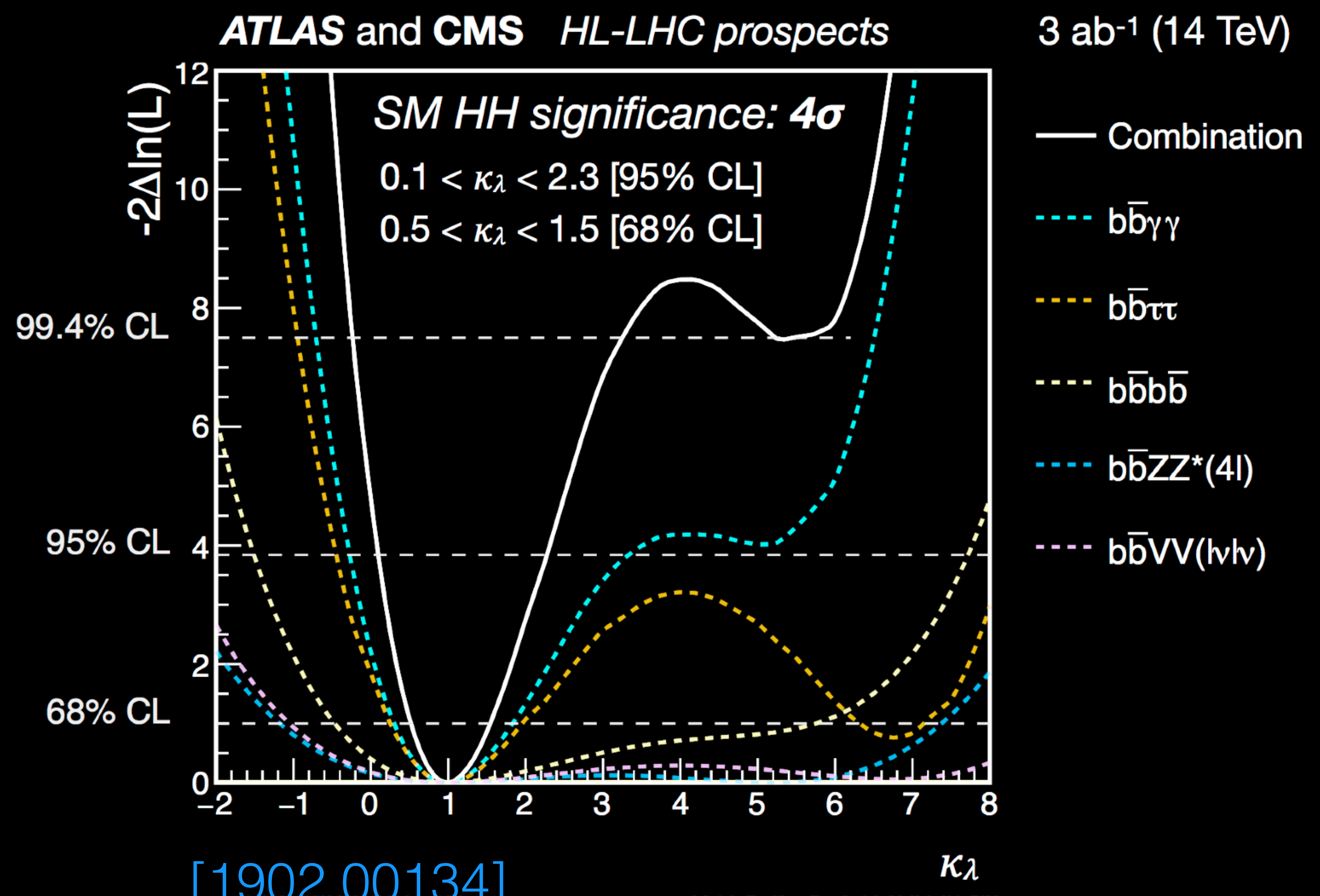
A Self-Interacting Particle?

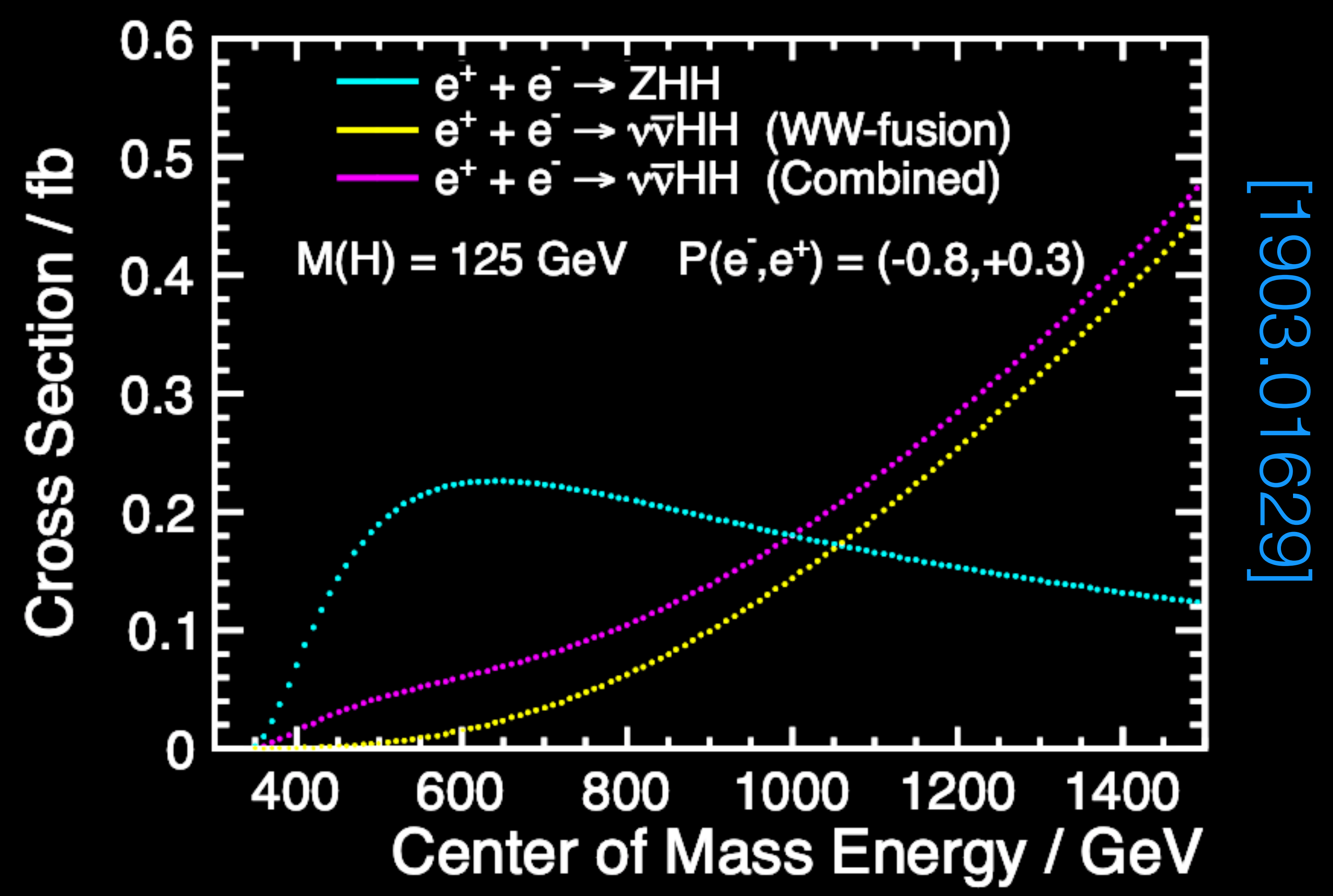
A self-interacting Higgs (as SM predicts) would be unlike anything yet seen in nature; all other interactions change particle identity.



Classically test Higgs self-coupling via Higgs pair production; quantum tests via loop corrections also relevant [McCullough '13].



[1902.00134]



ILC 4/ab @ 500 GeV: Higgs self-interactions at ~**27%** level

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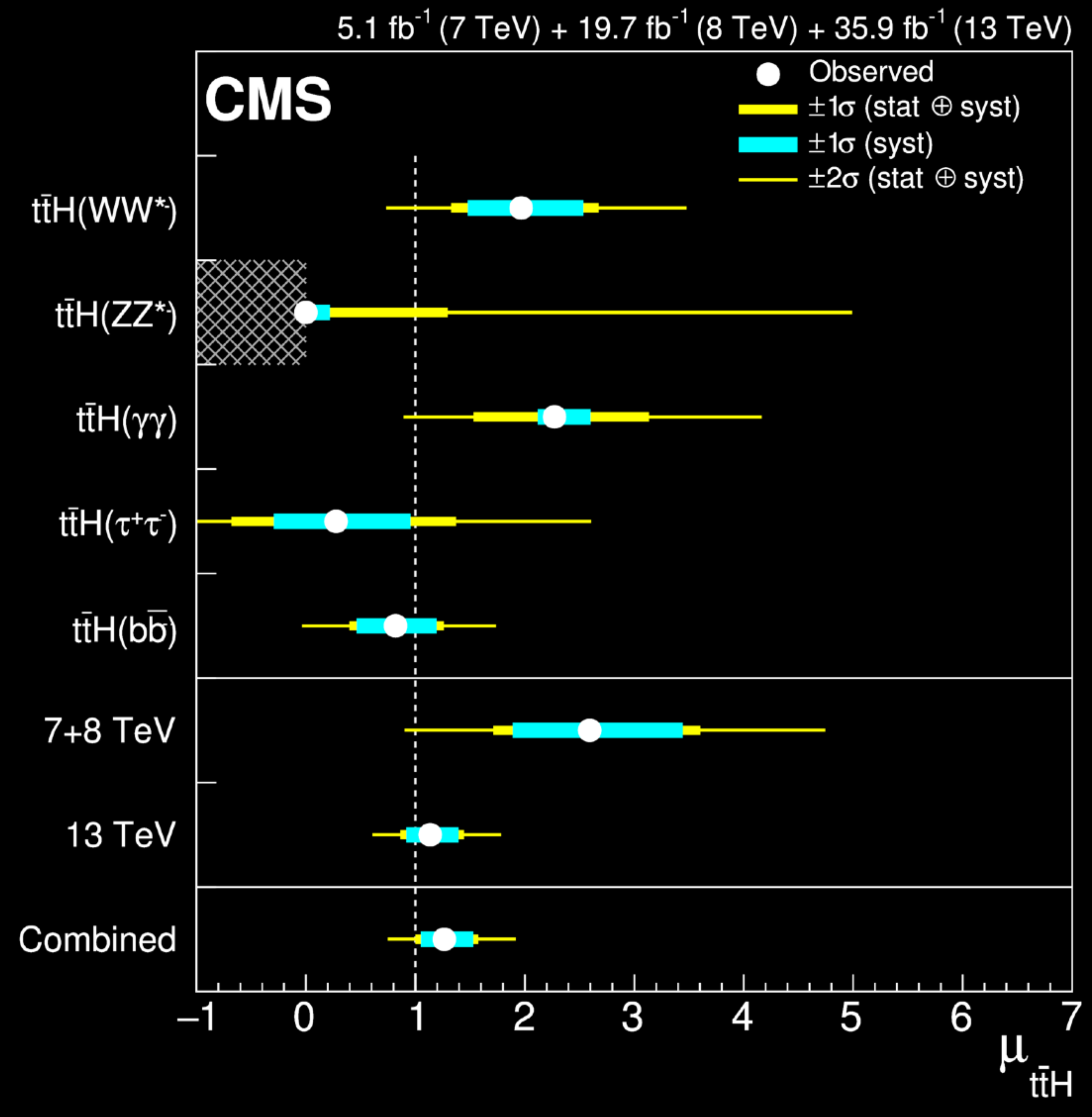
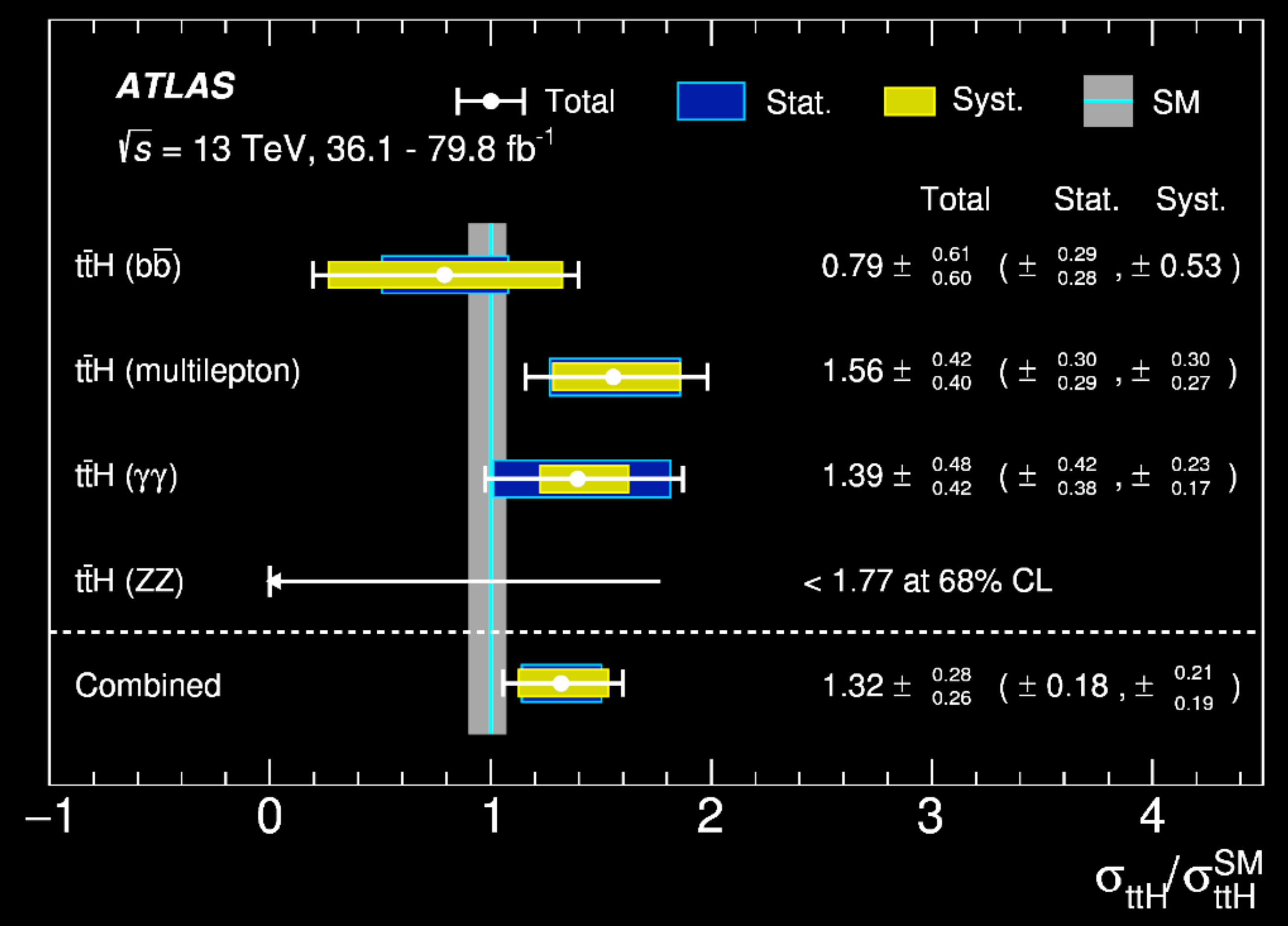
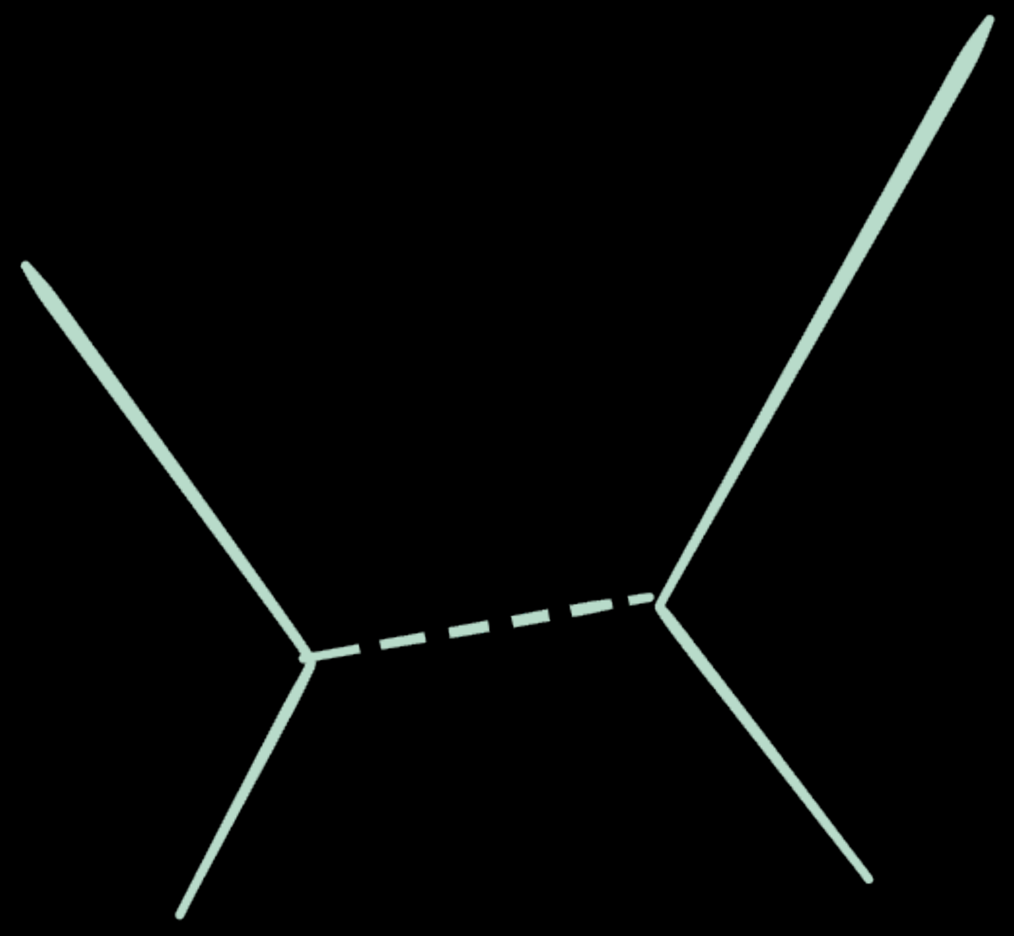
A Yukawa Force?





Yukawa force between fundamental particles: never seen until now



Established by >5σ observation of ttH, H→bb and H→ττ in LHC Run 2

$$\frac{V_{\mathrm{Higgs}}(r)}{V_{\mathrm{Weak}}(r)} \sim \frac{y^2}{g^2} e^{-(m_h - m_Z)r}$$

"Is this any less important than the discovery of the Higgs boson itself? My opinion: no, because fundamental interactions are as important as fundamental particles"

— G. Salam

A Yukawa Force?

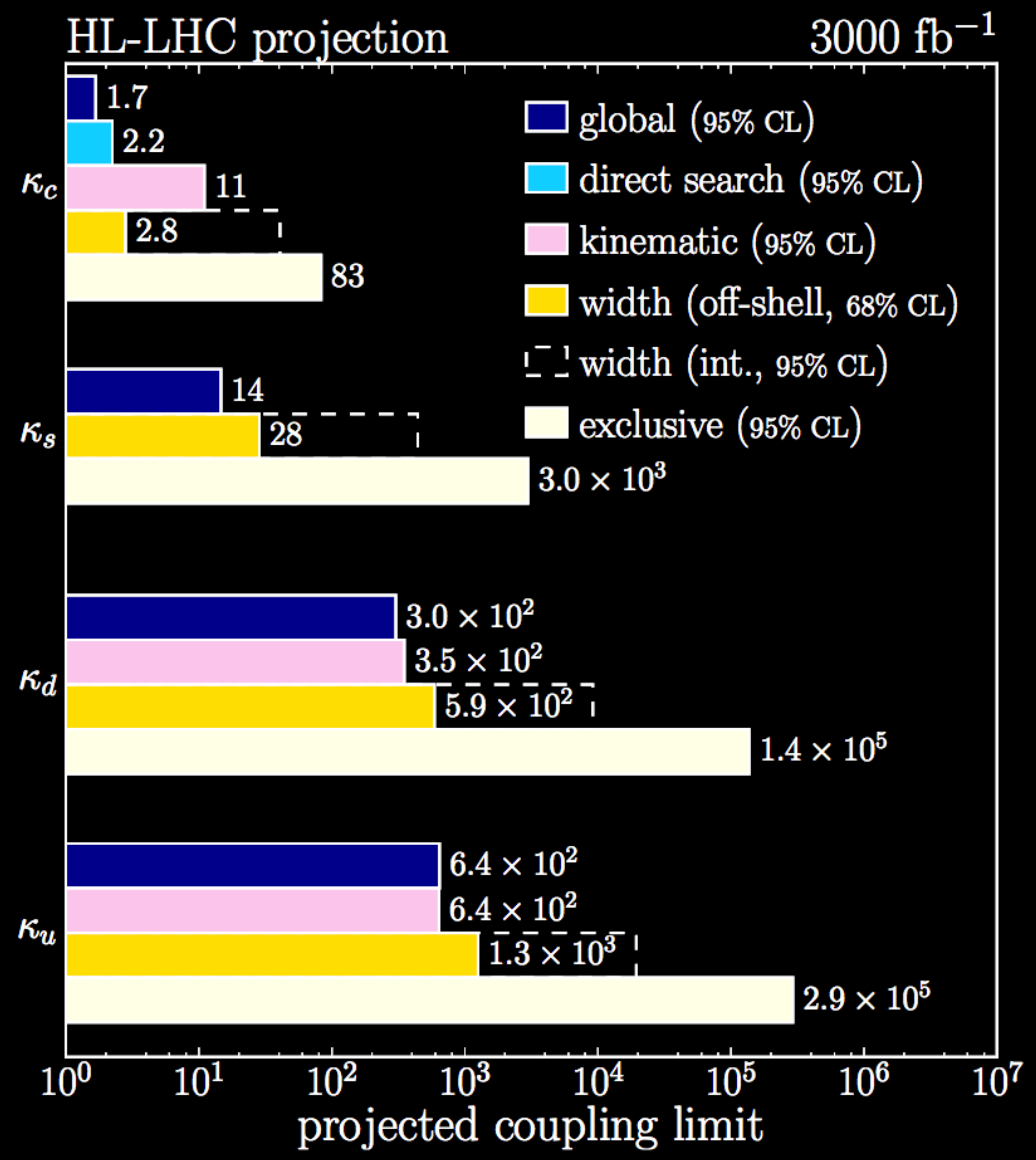
Situation no less interesting for 1st & 2nd generation. Relative lightness makes flavor puzzle compelling, measurements could hold key to flavor puzzle.

E.g. Yukawa from irrelevant operator
$\Rightarrow \kappa = 3$

$H \rightarrow \mu^+\mu^-$ $\quad$ 3000fb^{-1}

Experiment	ATLAS		CMS	
Process	Combination		Combination	
Scenario	S1	S2	S1	S2
Total uncertainty	$^{+15\%}_{-14\%}$	$^{+13\%}_{-13\%}$	13%	10%
Statistical uncert.	$^{+12\%}_{-13\%}$	$^{+12\%}_{-13\%}$	9%	9%
Experimental uncert.	$^{+3\%}_{-3\%}$	$^{+2\%}_{-2\%}$	8%	2%
Theory uncer.	$^{+8\%}_{-5\%}$	$^{+5\%}_{-4\%}$	5%	3%

[1902.00134]



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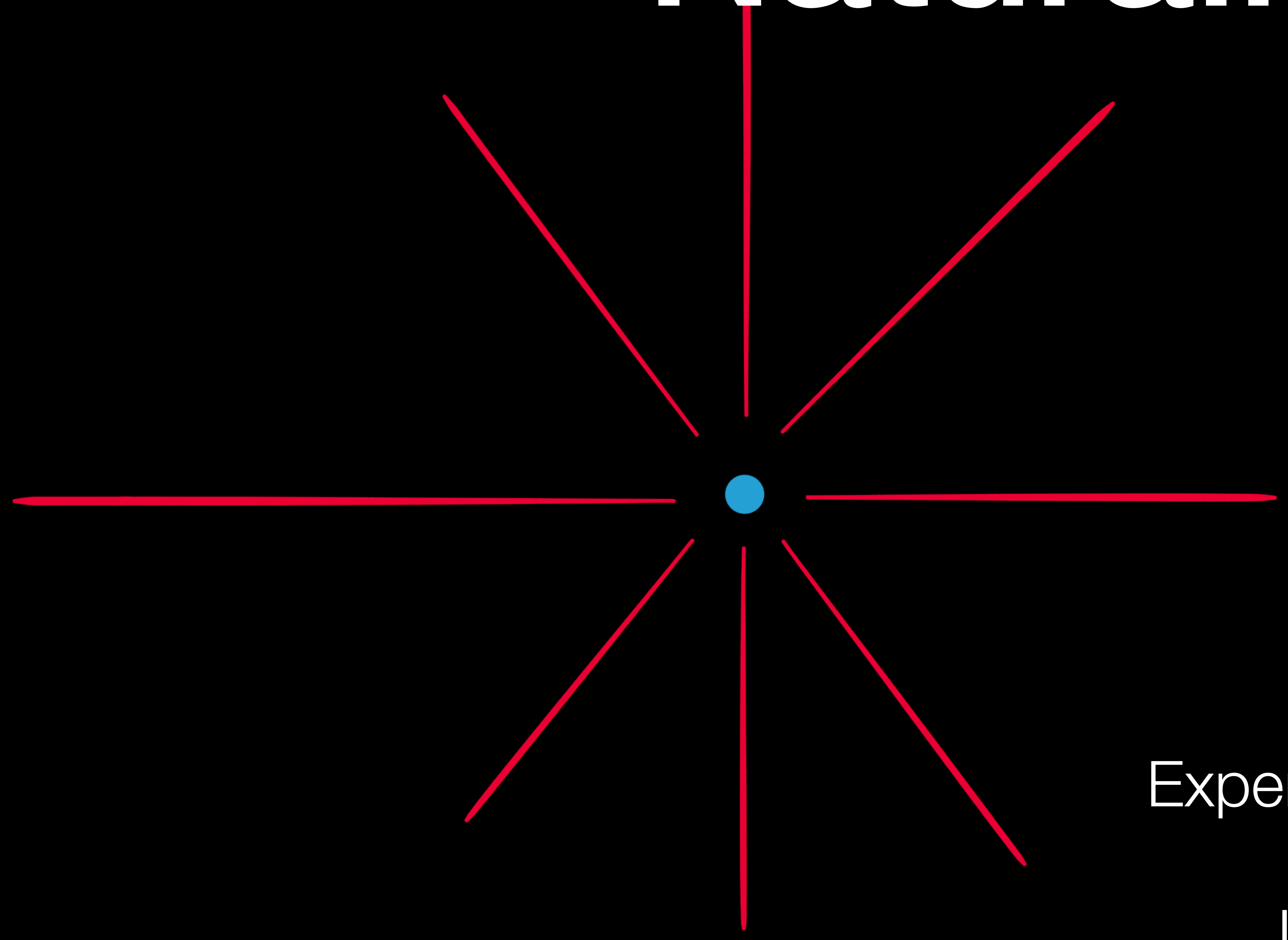
~~Hierarchy Problem~~
Naturalness Strategy



The naturalness strategy: an **analogy** from E&M

$$\Delta E_C = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}$$

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_C$$

Experimentally $r_e \lesssim 10^{-18}\,\mathrm{cm} \Rightarrow \Delta E_C \gtrsim 100\,\mathrm{GeV}$

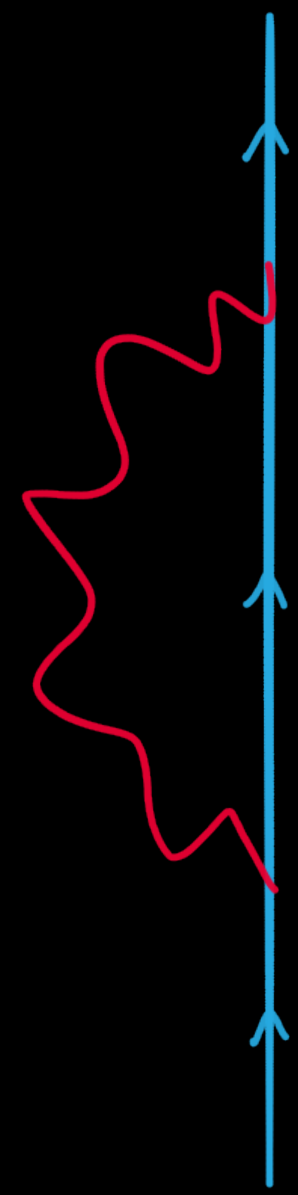
If so, $0.511 = -99999.489 + 100000.000\,\mathrm{MeV}$

To avoid fine-tuning, i.e. for the theory to be “natural”, need picture to change on scales below 2.8×10^{-13} cm

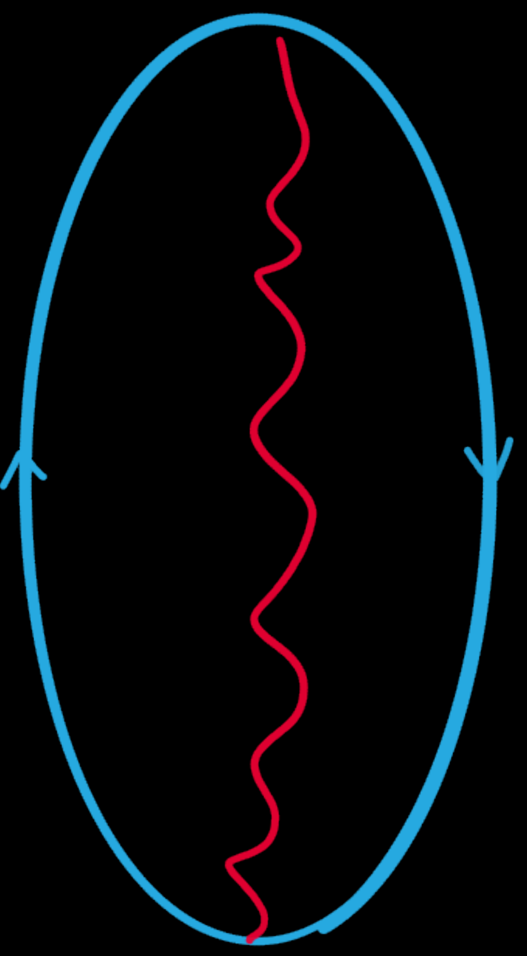
The Naturalness Strategy

Dirac (1928/29): There is a new state in the relativistic quantum theory

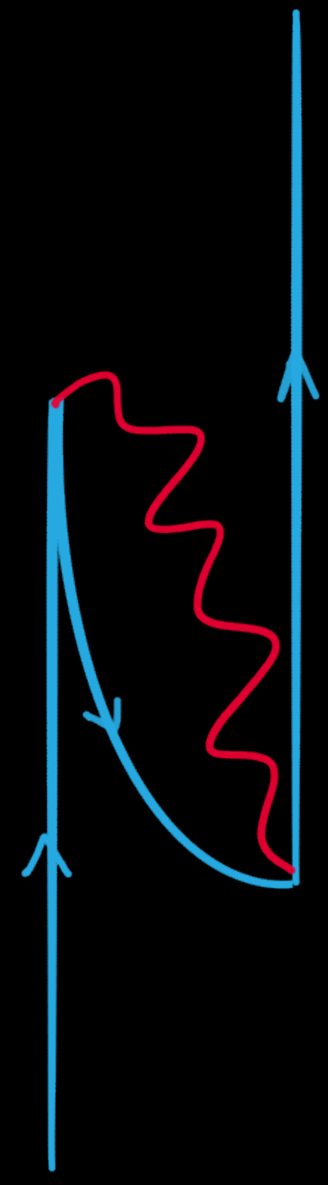
Weisskopf (1939): Compute the self-energy including the positron



$$\Delta t \sim \hbar/\Delta E \sim \hbar/(2m_e c^2)$$



$$d \sim c\Delta t \sim 200 \times 10^{-13}\ \mathrm{cm}$$



$$\Delta E = \Delta E_C + \dots$$

$$\Delta E = -\Delta E_C + \dots$$

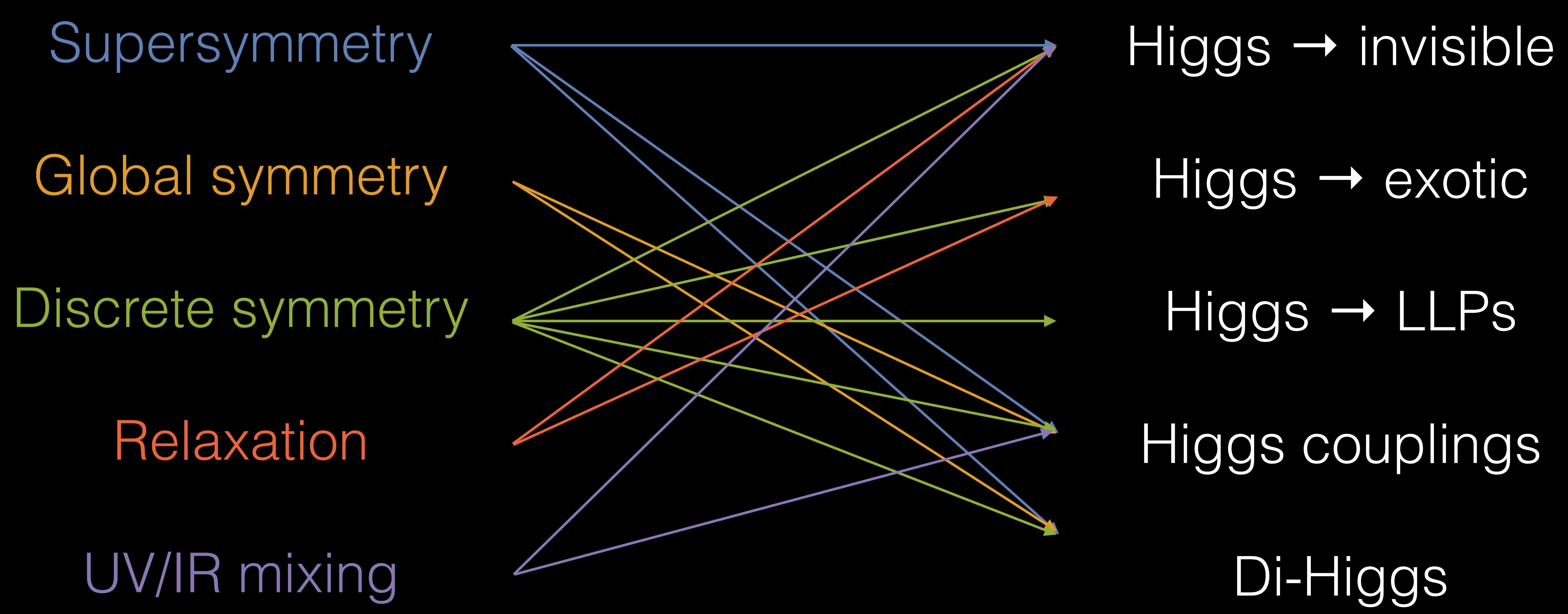
$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

The Naturalness Strategy

Param	UV sensitivity	Natural if	NP	Scale	Natural?
"m_e"	$e^2\Lambda$	Λ ≲ 5 MeV	Positron	511 keV	✓
$m_{\pi\pm}^2$ - $m_{\pi 0}^2$	$\frac{3\alpha}{4\pi}\Lambda^2$	Λ ≲ 850 MeV	Rho	770 MeV	✓
m_{KL}-m_{KS}	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4}\Lambda^2$	Λ ≲ 2 GeV	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2}\Lambda^2 + \ldots$	Λ ≲ 500 GeV	?	?	?

The Naturalness Strategy?

Still in the early days of exploring alternative realizations of the “naturalness strategy,” far from identifying all of the possibilities! *Higgs properties always central.*



Failure of the naturalness strategy would also be remarkable, as the first such instance.

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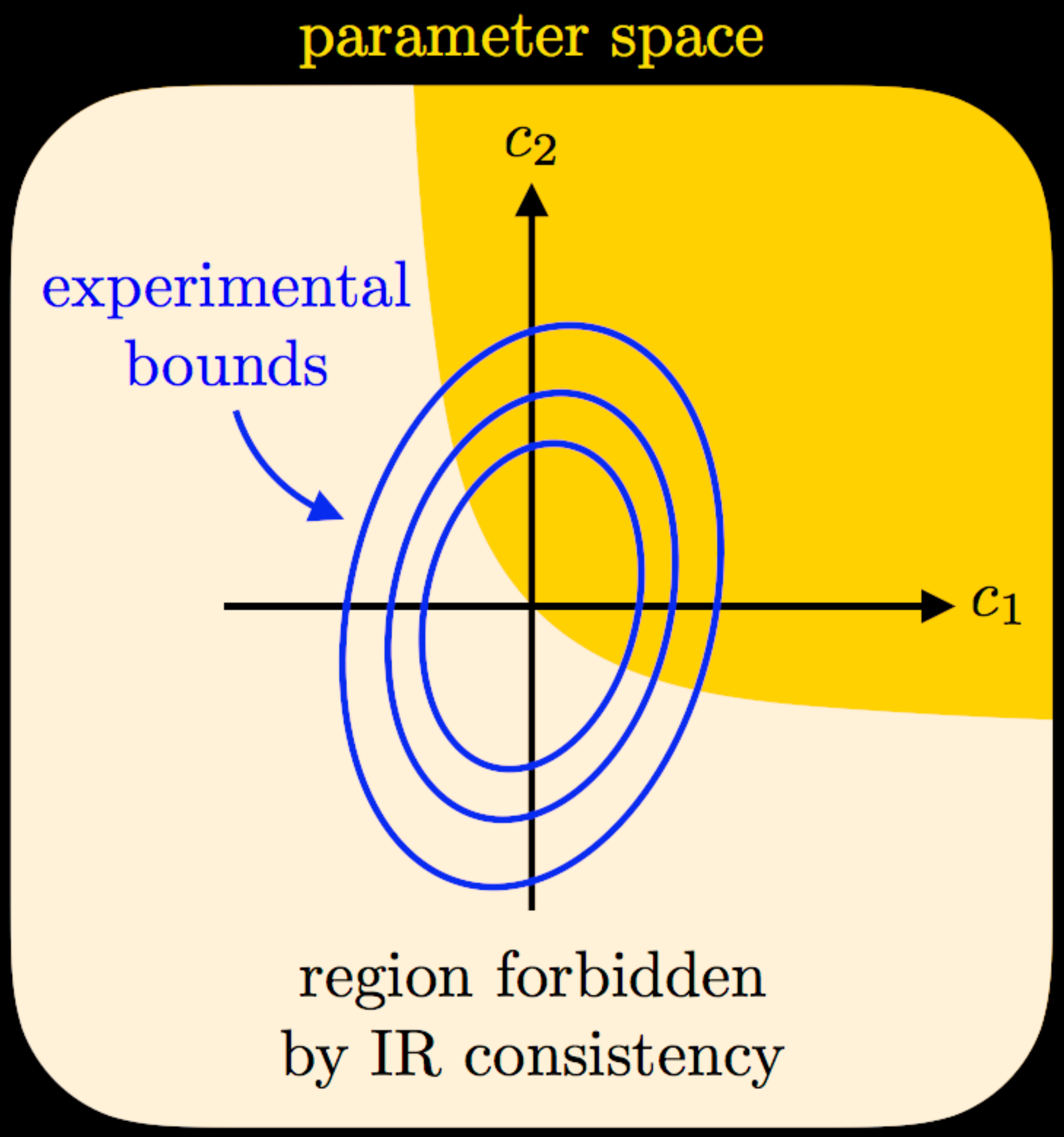
Thinking Positively

Locality, **unitarity**, and **analyticity** constrain EFT corrections to SM ("positivity bounds")

Long history, revived in [Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi '06; Distler, Grinstein, Porto, Rothstein '06; …]

More recently: extensive application directly to Wilson coefficients in SMEFT, e.g. [Bellazzini, Riva 1806.09640; Zhang, Zhou 1808.00010; Bi, Zhang, Zhou 1902.08977; Remmen, Rodd 1908.09845; Remmen, Rodd, 2004.02885; Zhang, Zhou 2005.03047; Fuks, Liu, Zhang, Zhou 2009.02212; Yamashita, Zhang, Zhou 2009.04490; Remmen, Rodd 2010.04723; Gu, Wang, Zhang 2011.03055; Trott 2011.10058; Bonnefoy, Gendy, Grojean 2011.12855; Li, Yang, Xu, Zhang, Zhou 2101.01191, …]



[Remmen & Rodd, 1908.09845]

Improve global fits by imposing positivity bounds

OR

Interpret as experimental tests of bedrock principles of QFT.

(Ideally do both)

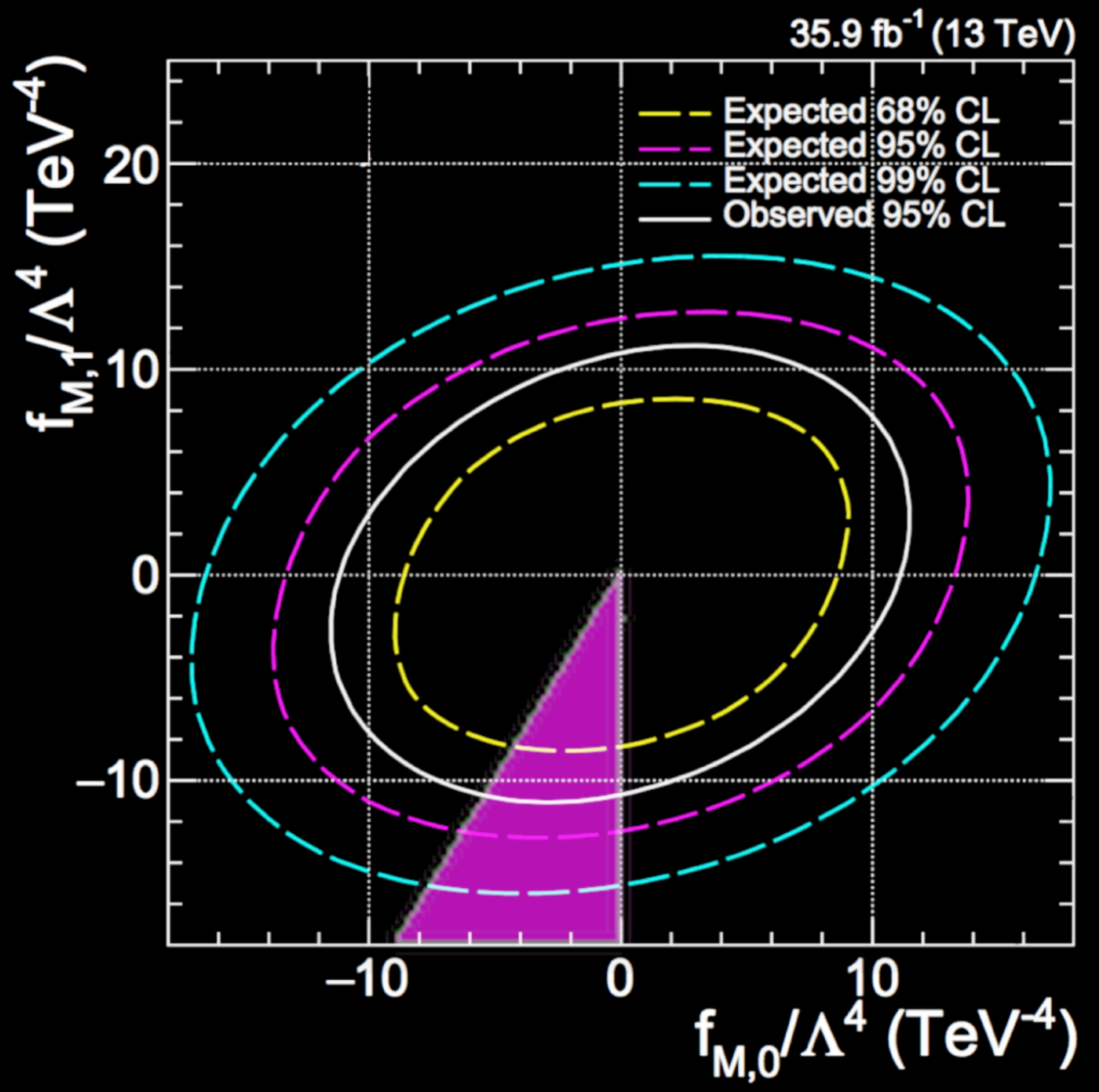
Thinking Positively

d=6: UV-sensitive positivity bounds, sum rules. **d=8**: UV-insensitive positivity bounds

Naive expectation: dim-8 operator effects always subleading

Reality: often leading due to non-interference thms and more pragmatic non-interference effects (color, phase space, …)

Thus far: primarily applied to aQGCs @ LHC
[Bellazzini & Riva '18, Zhang & Zhou, '18,…]
Interesting prospects in $e^+e^- \to e^+e^-, \gamma\gamma$ @ILC
[Fuks, Liu, Zhang, Zhou '20, Gu, Wang, Zhang '20]



[Bi, Zhang, Zhou 1902.08977]

To understand: space of observables where dim-8 operators provide leading effects at LHC & Higgs factories (see also: $\hat{H}$ parameter [Englert, Giudice, Greljo, McCullough '19]).

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Electroweak Symmetry?

We increasingly assume, but **do not know**, that *h* is* part of an electroweak doublet *H,* i.e. that $SU(2)_L x U(1)_Y$ is linearly realized by the known fields.

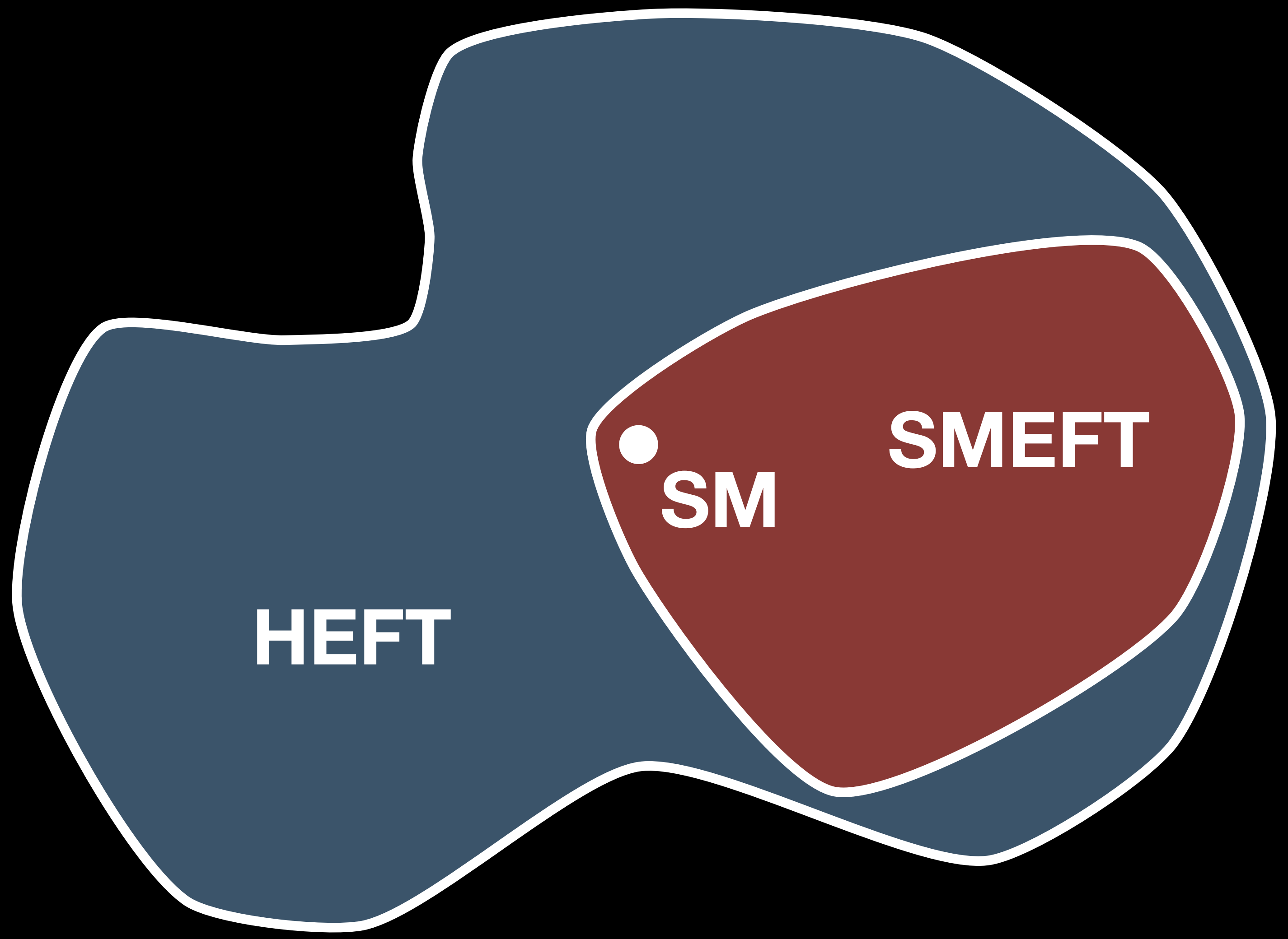
*"is" = theory suitably well behaved when *h* packaged into *H*

Equivalently: is the appropriate EFT

SMEFT: $SU(2)_L x U(1)_Y$, *H*

or

HEFT: $U(1)_{em}$, *h* & $\vec{\pi}$



Many consistent scenarios require HEFT. Often treat HEFT as an inconvenience to be tolerated, but HEFT vs. SMEFT is potentially the most interesting of the questions we face.

Three Views of HEFT vs. SMEFT

Unitarity

"Amplitudes violate unitarity by $4\pi v$"

Analyticity

"Lagrangian non-analytic at H=0"

[Falkowski & Rattazzi '19]

Geometry

"Manifold lacks SU(2)xU(1) f.p."

[Alonso, Jenkins, Manohar '15-'16]

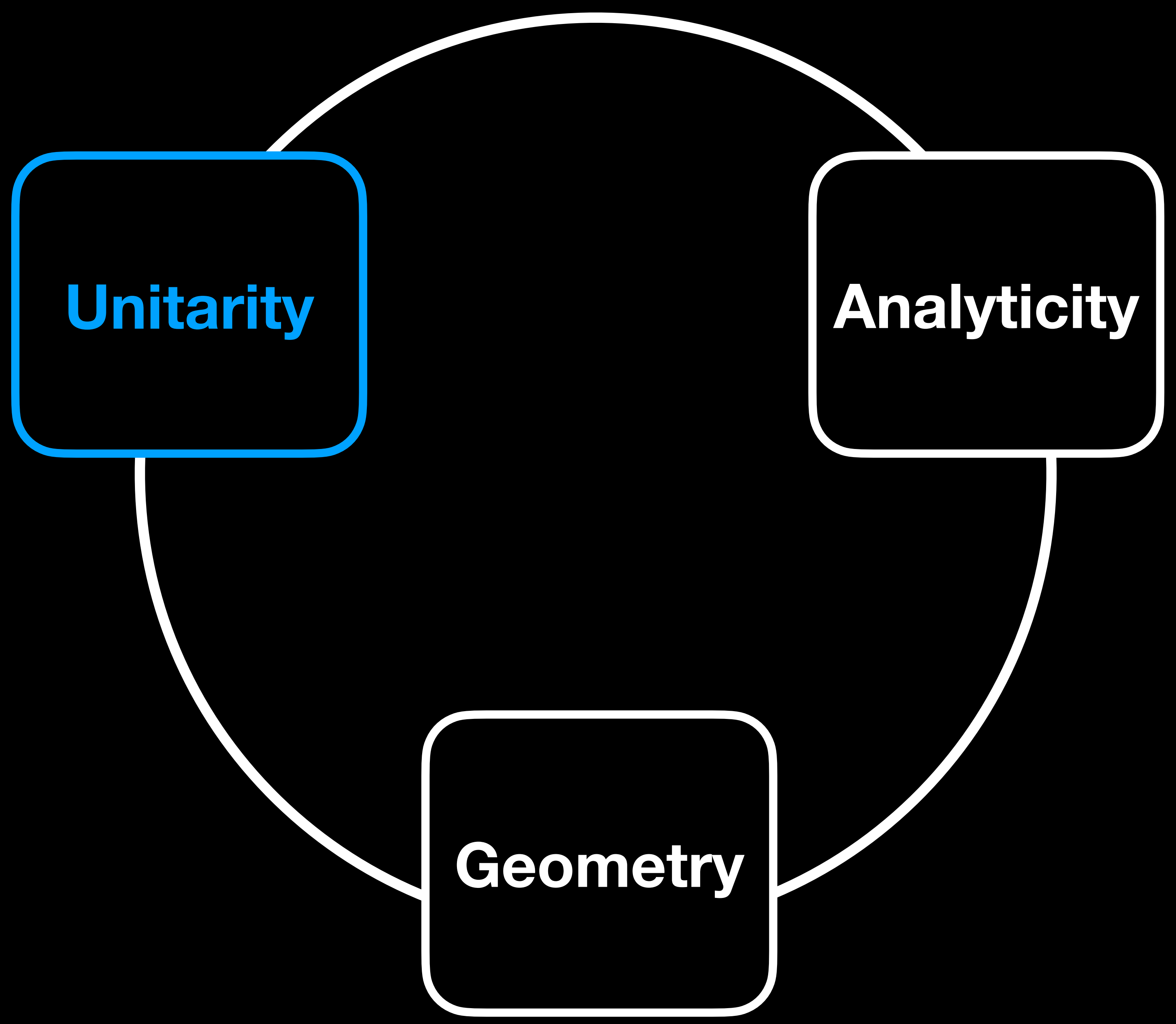
Three Views of HEFT vs. SMEFT

Long history of unitarity bounds in electroweak sector, a la [Lee, Quigg, Thacker '77]

Might expect HEFT vs. SMEFT is easy to settle by measuring $2 \to 2$ processes out to $4\pi v$.

Alas, for some instances of HEFT (e.g. Higgs trilinear-only), requires $2 \to \mathrm{many}$

[Chang & Luty '19; Falkowski & Rattazzi '19; Abu-Ajamieh, Chang, Chen, Luty '20]

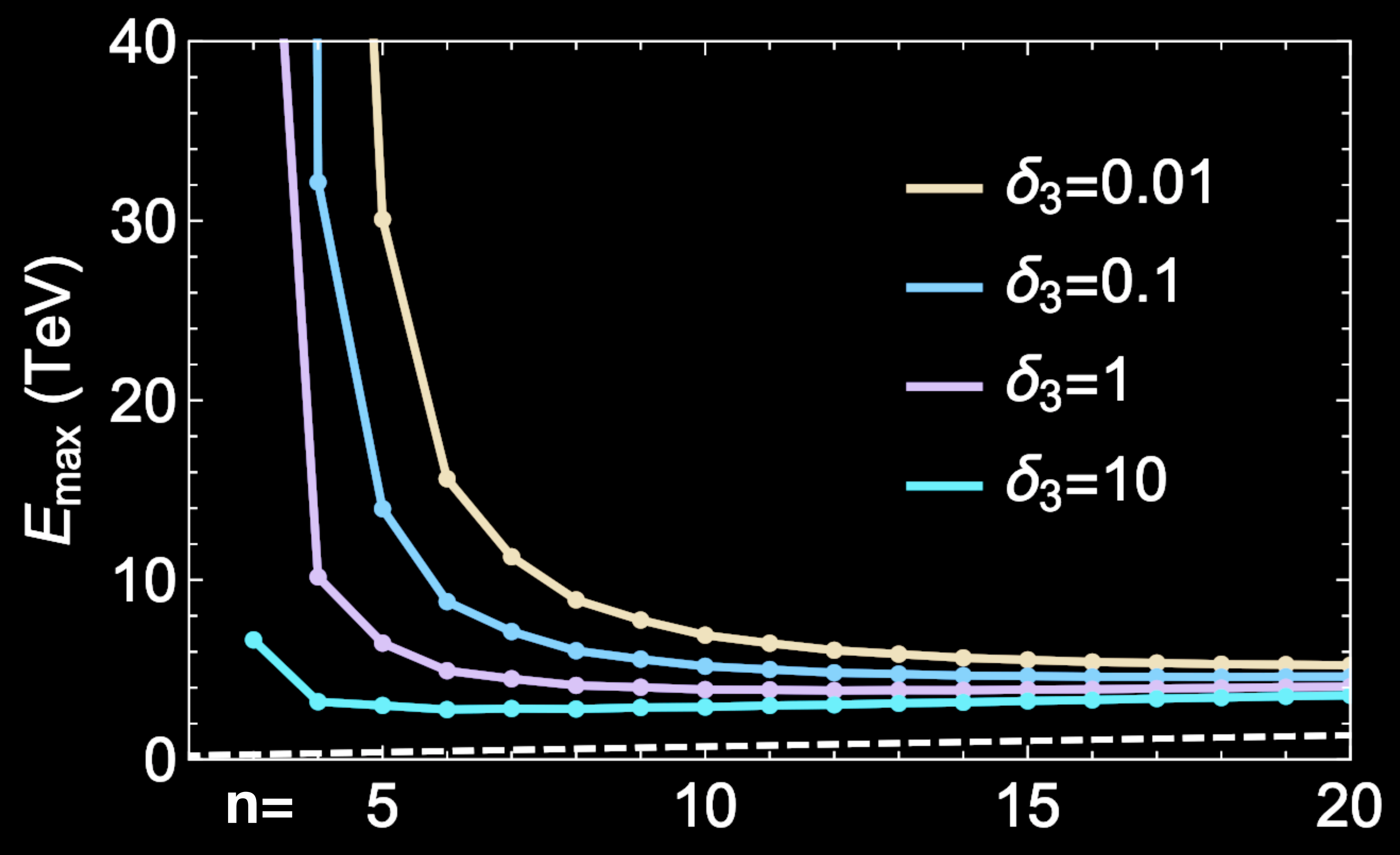


Scale of unitarity violation in

$$Z_L^2 h^n$$

for trilinear-only modification δ_3

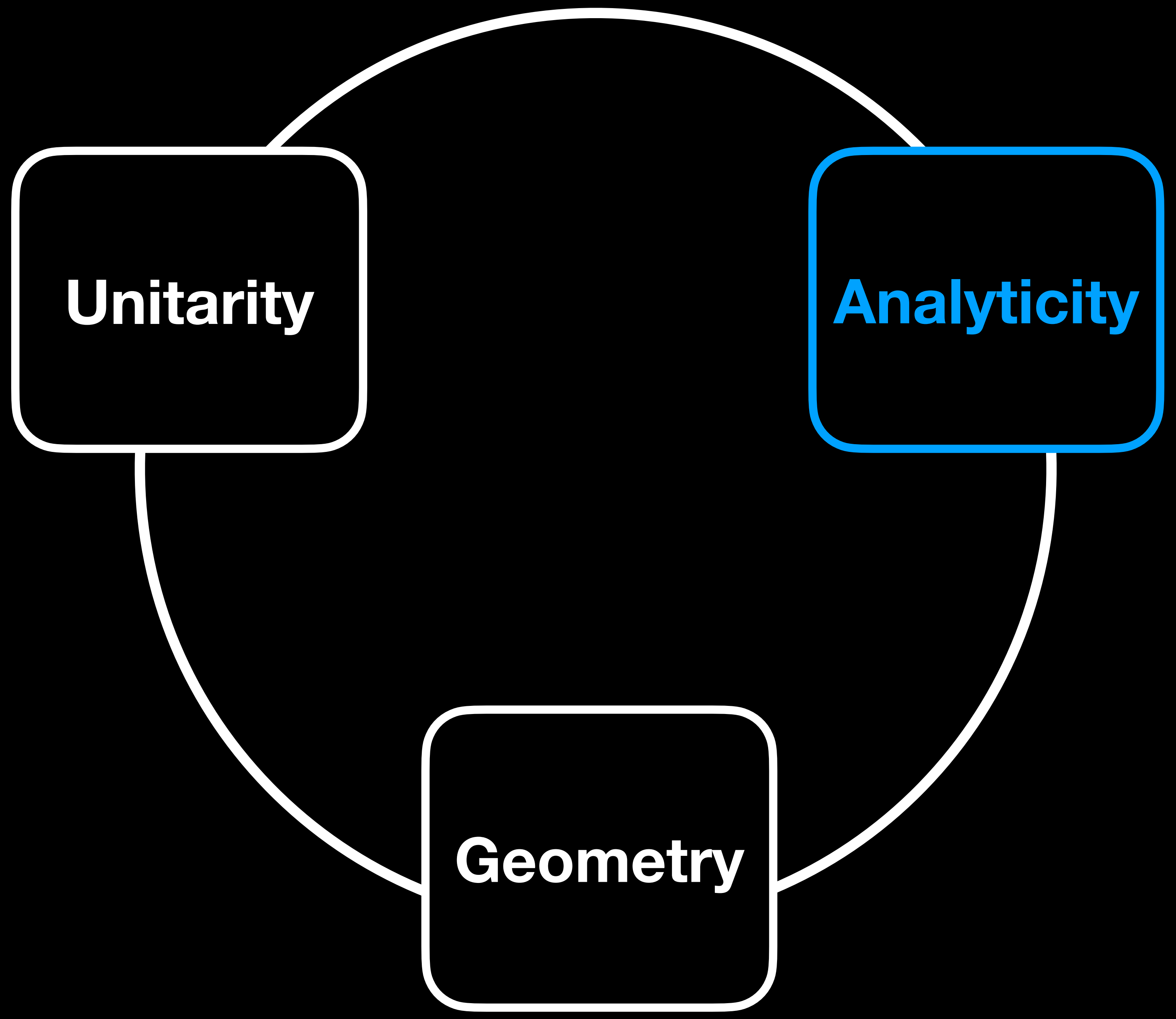
[Chang, Luty '19]



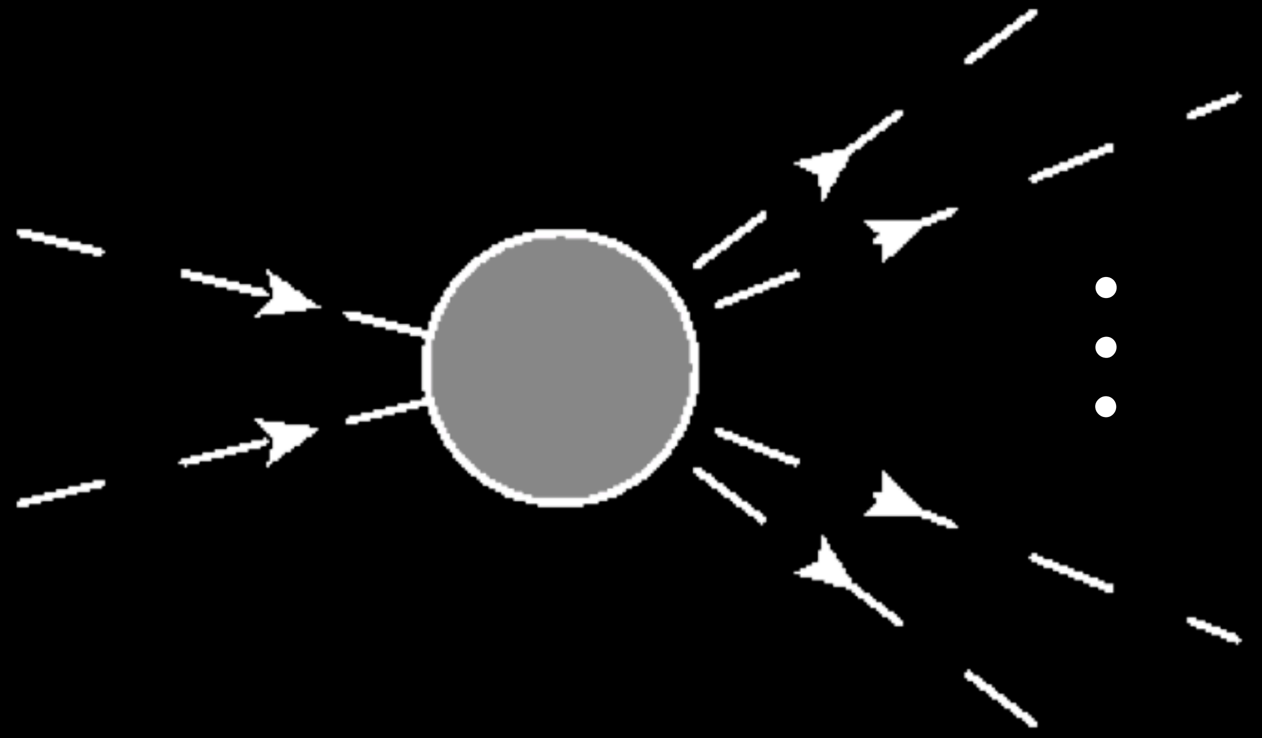
Three Views of HEFT vs. SMEFT

[Falkowski & Rattazzi '19]: HEFT arises whenever potential is non-analytic at H=0

$$\frac{m_h^2}{2v}(1+\Delta_3)h^3 + \frac{m_h^2}{8v^2}h^4 \leftrightarrow \frac{m_h^2}{8v^2}\left(2|H|^2 - v^2\right)^2 + \Delta_3 \frac{m_h^2}{2v}\left(\sqrt{2|H|^2} - v\right)^3$$



Physical consequence:
non-analyticity at *H=0*
gives perturbative unitarity
violation in *π π* → multi-*h*
at √s~4πv



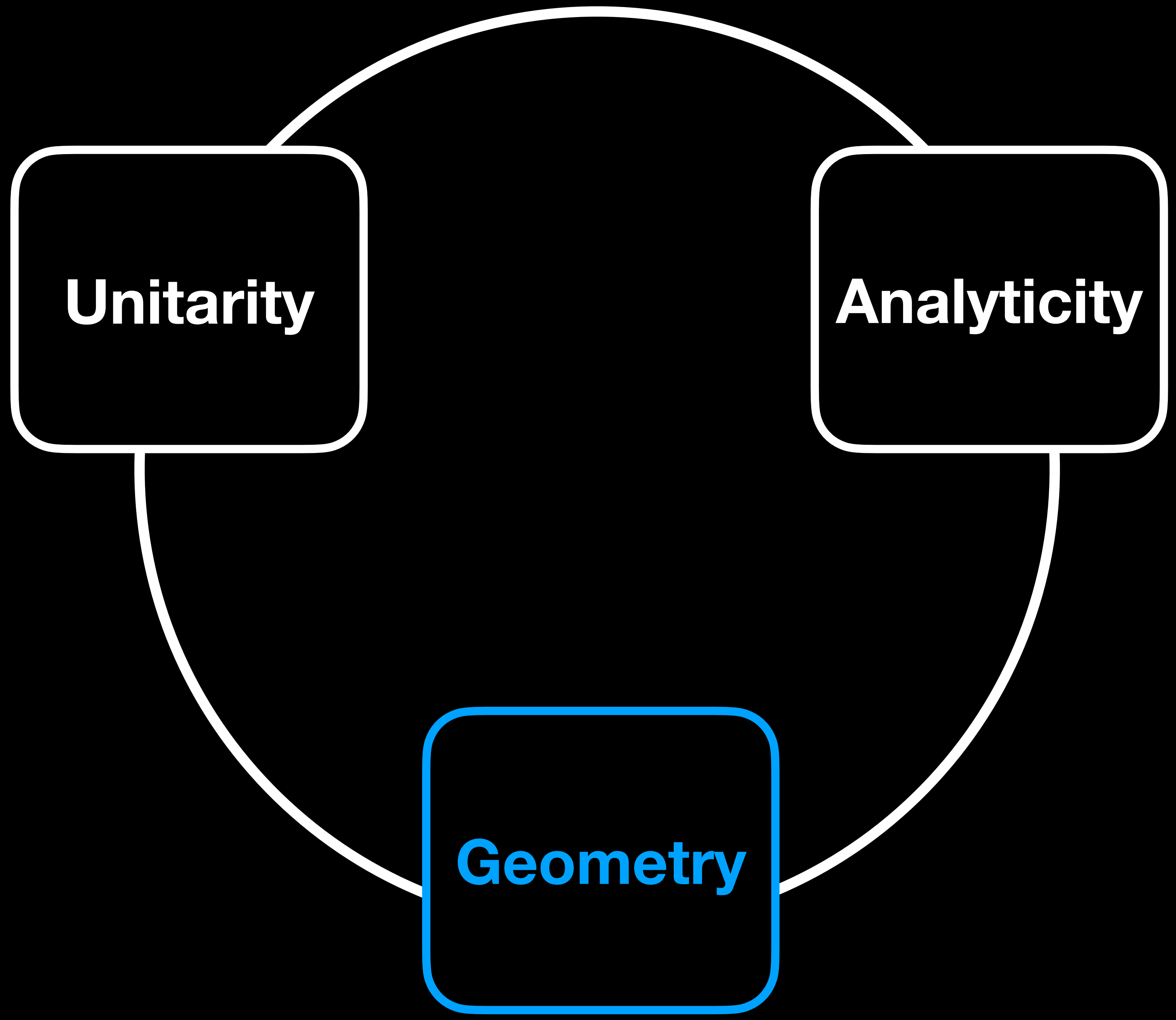
$$\sigma(\pi_i \pi_j \to X) \propto \Delta_3{}^2 \exp\left(\frac{s}{(4\pi v)^2}\right)$$

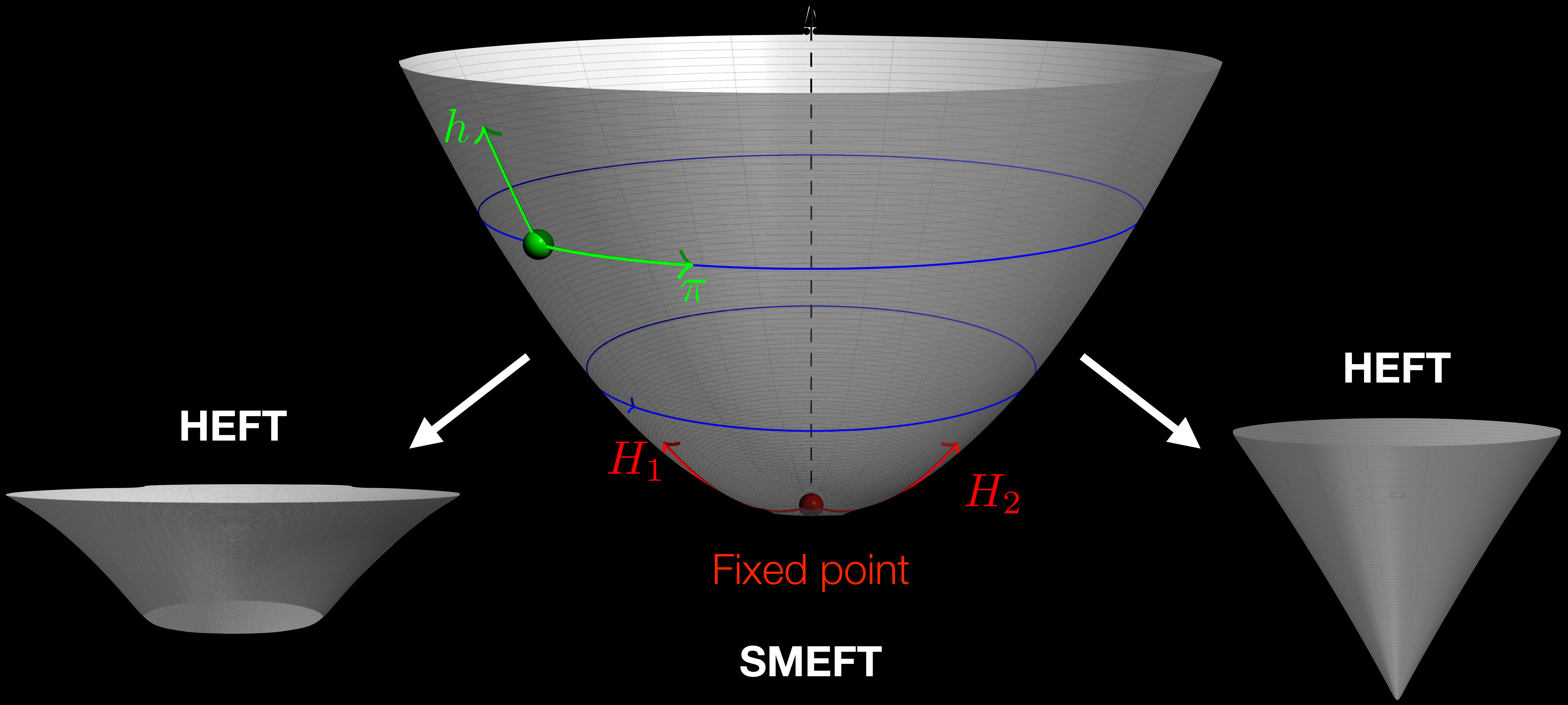
(Argument generalizes naturally to other interactions,
[Abu-Ajamieh, Chang, Chen, Luty '20])

Three Views of HEFT vs. SMEFT

[Alonso, Jenkins, Manohar ’15-‘16]: HEFT arises whenever EFT scalar manifold lacks SU(2)xU(1)-symmetric fixed point, e.g. extra EWSB.

[Cohen, NC, Lu, Sutherland ’20-’21]: and/or whenever there are singularities arising from new light states w/ more than half their mass from EWSB.



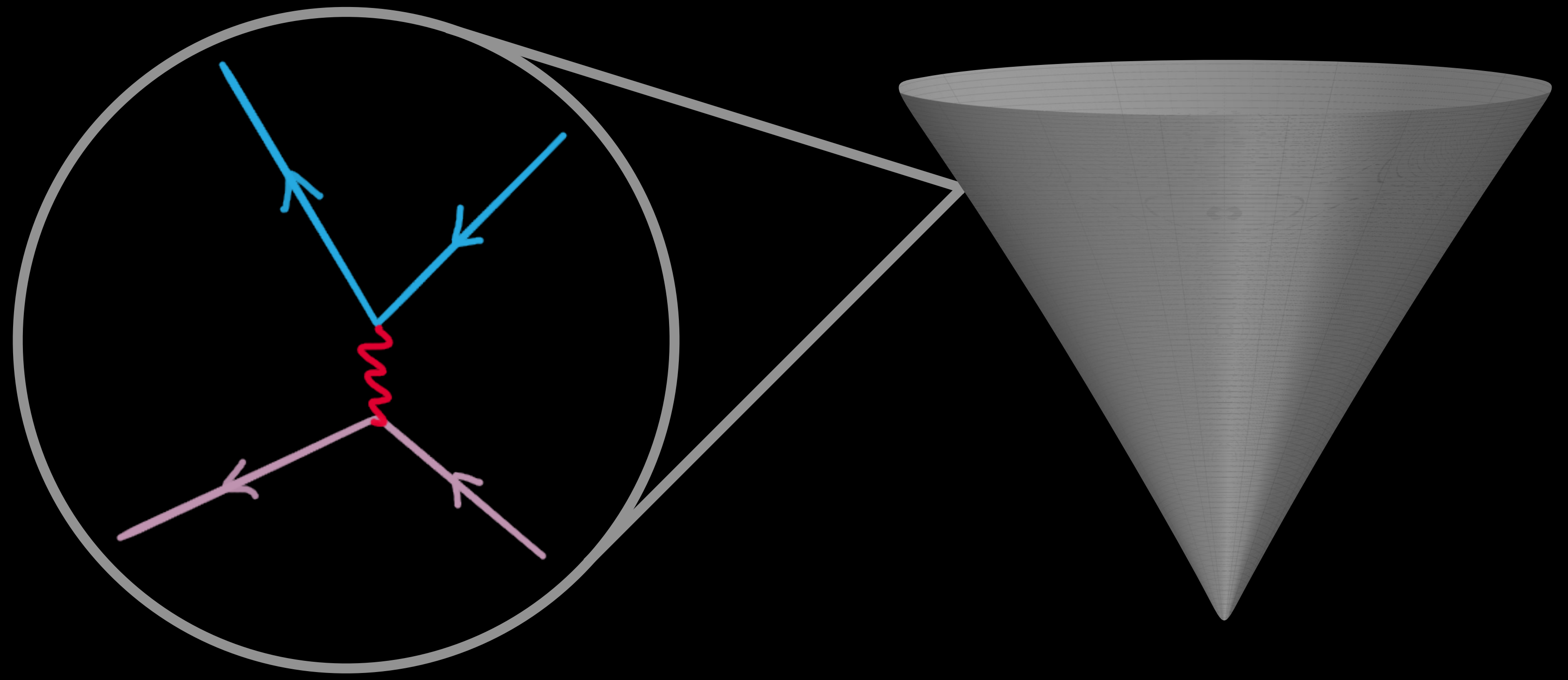


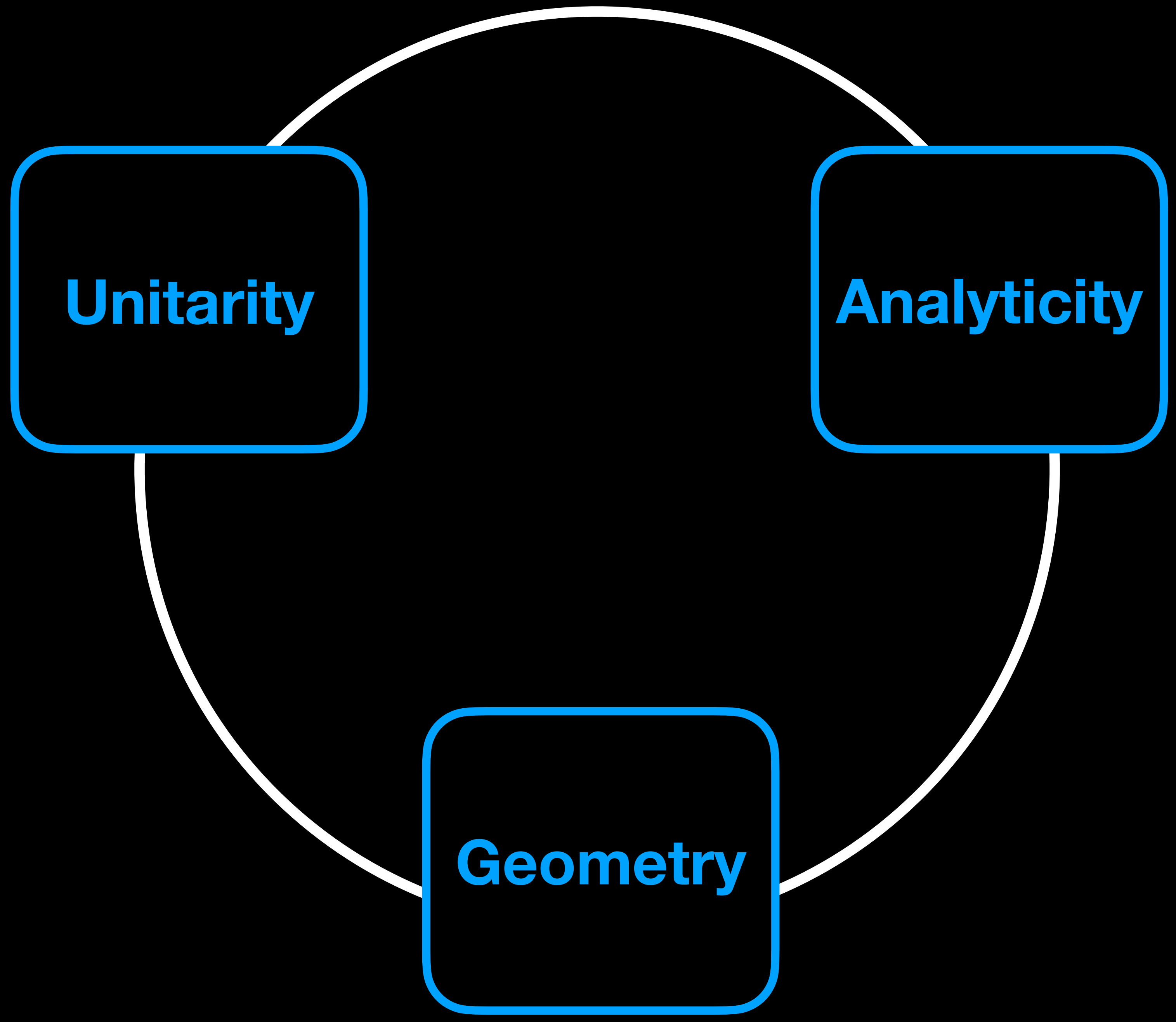
Three Views of HEFT vs. SMEFT

$2 \to 2$ amplitudes measure local sectional curvatures:
[Alonso, Jenkins, Manohar '15, Nagai, Tanabashi, Tsumura, Uchida '19]

$$\mathcal{A}\left(\pi_i \pi_j \to hh\right) = -\delta_{ij}\mathcal{K}_h(h = \pi_k = 0)E^2 + \ldots$$

$$\mathcal{K}_h \equiv \frac{R_{\pi_i h h \pi_j}}{-g_{hh} g_{\pi_i \pi_j}}$$





Parts of $2 \to n$ amplitudes (n>2) that grow with energy are *derivatives* of sectional curvatures:

$$\mathcal{A}(\pi_i \pi_j \to h^n) = -E^2 \delta_{ij} \partial_h^{n-2} \mathcal{K}_h + \mathcal{O}(E^0)$$

Higher-point amplitudes reconstruct coefficients in the Taylor expansion of geometric invariants on the EFT manifold.

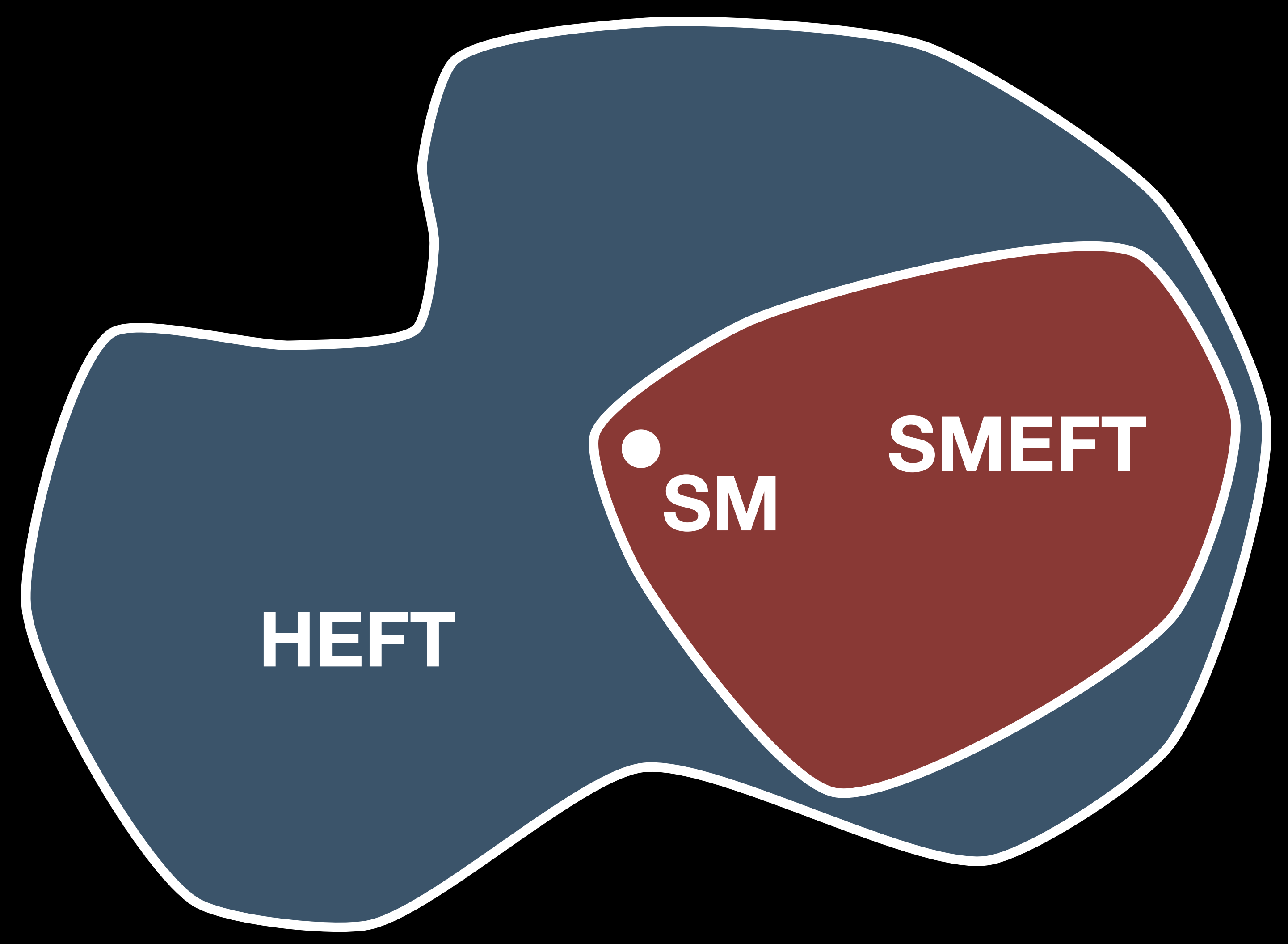
Directly connects geometry, analyticity, and $\sim 4\pi v$ scale of unitarity violation [Cohen, NC, Lu, Sutherland '21]

Electroweak Symmetry?

"Is electroweak symmetry linearly realized by the known fundamental particles?"

Equivalently: can we rule out HEFT?

- It is a well defined, bounded question…
- …but physical criteria need sharpening.
- We don't currently know the answer.
- We might be able to find out @ the LHC…
- …but future colliders are likely required.
- Null results (agreement w/SM) only help.



This is a "big" question that we can potentially answer even without departures from SM.

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