

Motivations for New Physics

"A round the corner"

(ANTI-) PARTICLE PHYSICS NARRATIVE

BSM THEORISTS FULL OF
CRAP! ALL SHOCKED BY ONLY
HIGGS @ LHC. "NATURALNESS"
WAS BULLSHIT! ALL REASONS
FOR SEEING NEW PARTICLES
@ LHC OR BEYOND HAVE EVAPORATED!

(ANTI-) PARTICLE PHYSICS NARRATIVE

BSM THEORISTS FULL OF CRAP! ALL SHOCKED BY ONLY HIGGS @ LHC. "NATURALNESS" WAS BULLSHIT! ALL REASONS FOR SEEING NEW PARTICLES @ LHC OR BEYOND HAVE EVAPORATED!

F A L S E

FAILURE OF "PERFECT

NATURALNESS" NOT A SURPRISE

MYSTERY OF WEAK SCALE ORDER

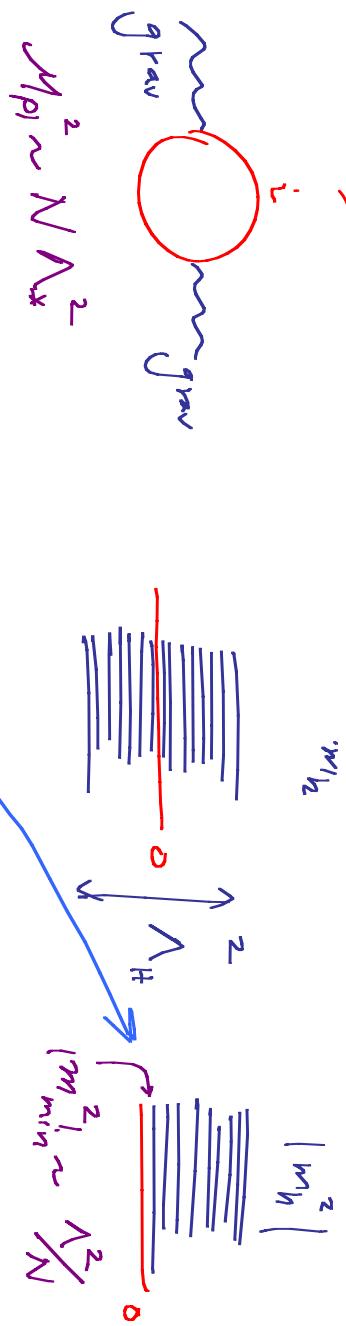
HAS ONLY BECOME DEEPER

THERE ARE DECENT → GOOD

THEORETICAL MOTIVATIONS FOR
NEW PARTICLES "AROUND THE CORNER"

- * My own best bet since $\sim 2004-5$,
- * Was $[+ \sim]$ minimal split SUSY
- * Heresy: SUSY + tuning $\sim 10^{-4} - 10^{-6}$ for EWsb
 $C_f \sim 10^{-10}$ for CC !
- * Simplest WIMP DM EWKinos/Higgsino
 $\sim 1-3 \text{ TeV}$, not made @ LHC or seen in DD.
- * Correctly predicted $120 \text{ GeV}/\text{cm}^2 \lesssim 135 \text{ GeV}$
- * Gluino might still in reach of LHC,
but both T wKinos + Gluino seen @ 10 TeV collider
- * And, EDM Searches!

$\sqrt{-g} \mathcal{M}_{\text{natural}}$



Cosmology Dominantly Reheats Bottom of Spectrum

$$M_p \sim \Lambda \sqrt{N}$$

Natural Limit

$$\Lambda_* \sim M_{\text{GUT}} \Rightarrow N \sim \frac{M_{\text{GUT}}^2}{M_p^2} \sim 10^2 - 10^4$$

$$\Lambda_H \Rightarrow m_{SUSY} \sim 10 \text{ TeV}$$

[not 10^2 TeV or higher]

$$m_h \sim \frac{\Lambda_H}{\sqrt{N}}$$

$$M_p \sim \Lambda_* \sqrt{N_1 N_2}$$

* UV / IR, Hidden Symmetries,
Tuning + Transcendality [w/ H. Grossman]

* The weak scale as a trigger
[w/ R. D'Agnolo + H.-D. Kim]

7th → 20th Century Physics
→
Contingency

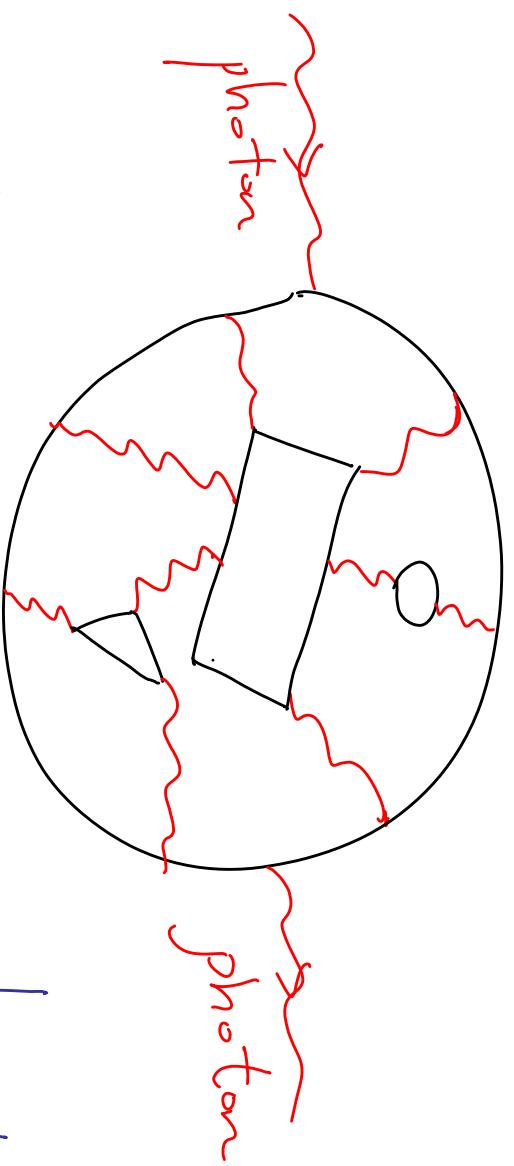
March of
REDUCTIONISM

March of
SYMMETRIES

2nd Century Revolutions

- * \Box Doom of Spacetime, End of Reductionism
- * Why is the Universe Big?

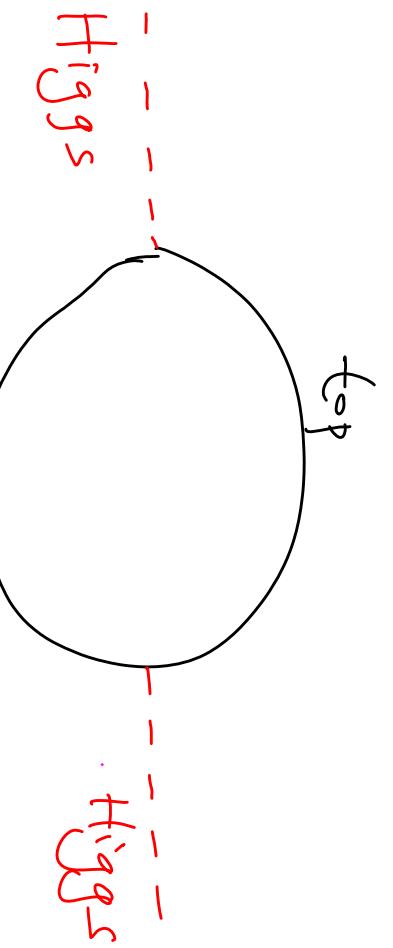
REALLY NEW IDEAS NEEDED,
beyond paradigms of spacetime + internal symmetries



Photon must stay massless, because

massless helicities $\rightarrow 2 \neq 3 \leftarrow$ # massive spins

[This is why gauge fields + chiral fermions can be easily engineered in Cond. Matter!]

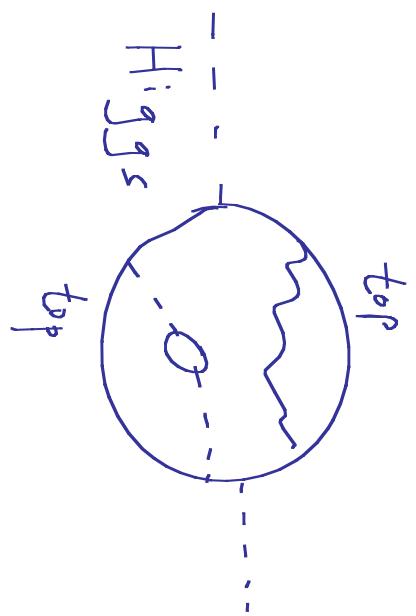


$\frac{1}{\text{massless spin } 0} = \frac{1}{\text{massive spin } 0}$
 NO DIFFERENCE

[Higgs is Special! Does NOT naturally arise in Cond. Mat.]
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WHY
 ISN'T
 HIGGS
 ENORMOUSLY
 MASSIVE?
 PLANCKIAN?

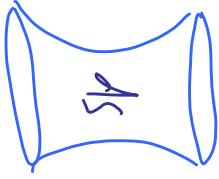
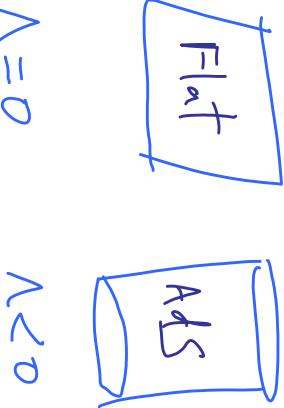
$\Delta + \text{Higgs} \rightarrow \text{Beyond Symmetries}$



| dof whether $m_h^2 > 0, = 0, < 0$
No DIFFERENCE
Hierarchy Problem

Same amount of symmetry
 $[SO(5,1) \rightarrow \text{Poincaré} \rightarrow SO(4,2)]$

Cosmological Constant Problem



$\Lambda > 0$

$\Lambda = 0$

$\Lambda < 0$

Emergent Spacetime

We are clearly missing something
HUGE about Quantum Mechanics of
our Relativistic Vacuum!

Macroscopic Universe

Higgs Discovery Crucial

Our
Relativistic

Vacuum

is Quantitatively

Different than anything we've seen elsewhere in physics

NOT JUST @ Planck Scale

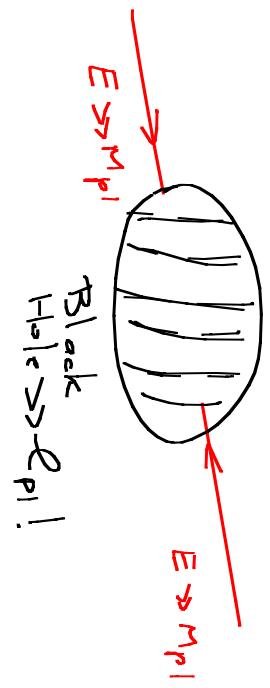
ALREADY @ TeV scale

CIVITIR

Hidden Symmetries,

Transcendental Uniting

UV/IIR



High Energies
Long Distances!

EFT Paradigm is False

Nothing like that if

Redactionism + Wilsonian
Fundamental Laws Nothing like that if
Con densed Matter Physics = FAR

DETER + MORE RADICAL

[But maybe only at Planck Scale?]

* Crucial to Probe on-shell (Lorentzian)

+ off-shell (Euclidean) couplings of the

figs. Wilsonian paradigm is fundamental of

Euclidean Standard local QFT relies

on Euclidean \rightarrow Lorentzian continuation,

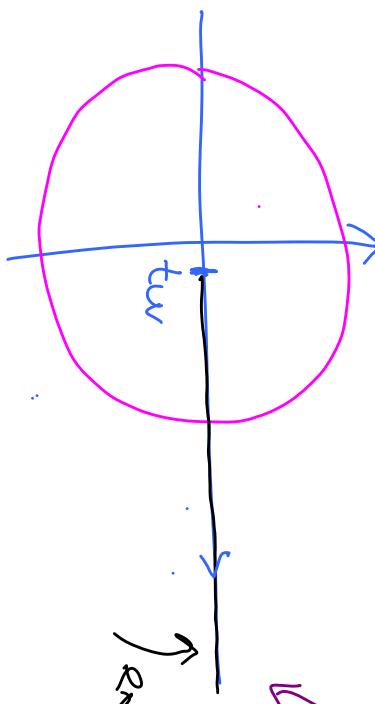
but UV/IR can radically change this!

Example: $F^{\exp}(t) = \frac{1}{t}$ for $t > 0, t \gg t_{\text{cut}}$

Effective field [Thems]: "Oh, $F^{\exp}(t) = \frac{1}{t}$!"

Analytically confirmed

$$\frac{1}{2\pi i} \oint dt F(t) = 1!$$



\rightarrow exp measured

Big Circle
Reliable
EFT Comp.

* WRONG! $F(t) = \frac{1 - e^{-2\pi t/t_{\text{cut}}}}{t}$, $\oint dt F(t) = 0$!

{ Mechanism for removing "busting" in AdS/CFT }

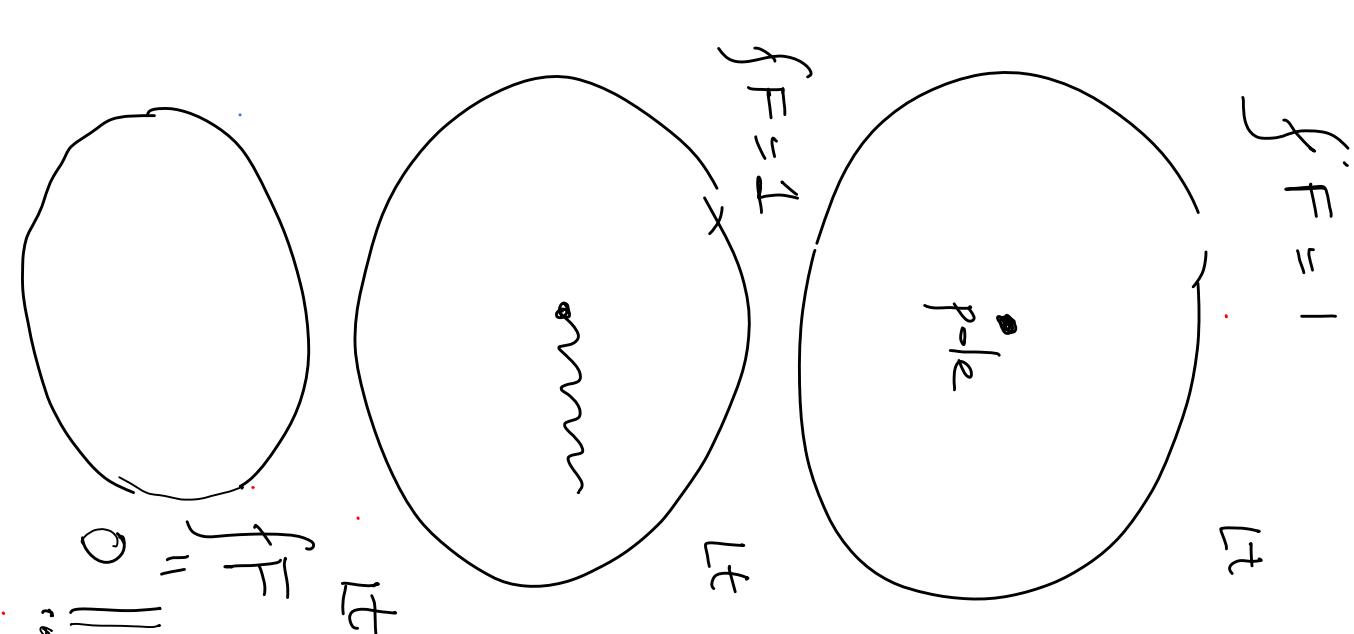
$$\frac{1}{t} = \int_0^{\infty} dE \frac{e^{-Et}}{e}$$

$$i\epsilon \int_0^{\infty} \frac{dE}{(1 + E/k)^{\frac{1}{2}}} e^{-Et}$$

"Field Theoretic"

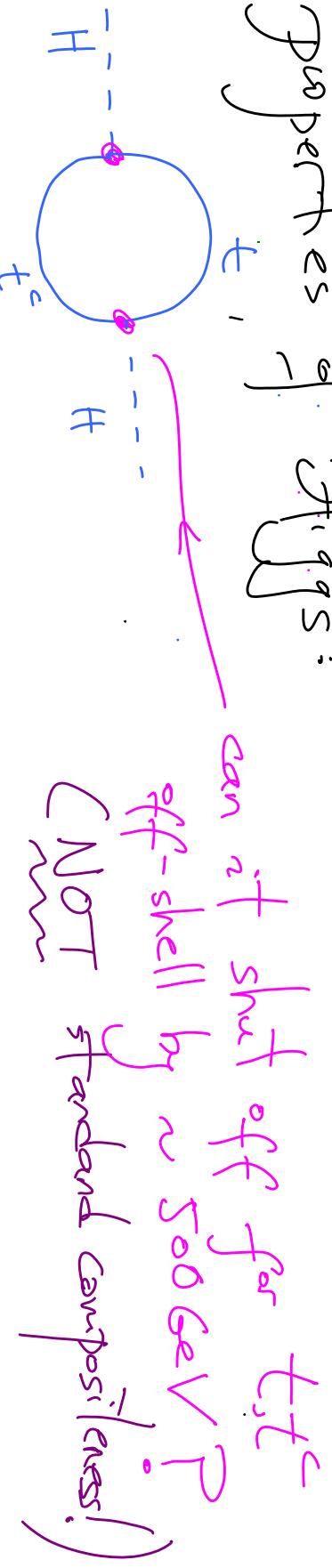
$$i\epsilon \int_0^{\infty} dE \frac{e^{-Et - E^2/k^2}}{e}$$

"Gravitational"



* So, crucial to probe Euclidean, off-shell

Properties of Higgs:



can it shut off for $t\bar{t}$ off-shell by $\sim 500 \text{ GeV}$?
(NOT standard compositeness!)

$$\Rightarrow H \rightarrow gg \text{ modified} @ \sim 3\% \\ H \rightarrow jj \text{ modified} @ \sim 10\%$$

[Perfect for Higgs Factory]

Also
 t t H t t
should shut off for $P_{\text{Higgs}}^T \gtrsim 500 \text{ GeV}$
[Perfect for 100 TeV collider]

Hidden

Symmetries

Emergent
+
 \mathcal{M} + Spacetime

Positive Geometries

* Amplitudes for $\gamma\gamma\gamma + \phi$ ³ colored are tied to "Positive Geometries"

Gluons

"Amplihedra"

"Associahedra"

"Surfacehedra"

ϕ_3

\times Manifest hidden symmetries, reflected in
Surpassing Cancellations at infinite momentum.

(Dual Conformal Invariance, Projective Invariance)

Speculation

There is a dual formulation of physics that represents physical amplitudes/observables by association w/ abstract geometries. [cf. "positive geometries", amplituhedra, associahedra etc.]

In this formulation $\Lambda + m_h^2$ obviously exp. small! But not obviously local physics. Another "fang". Will look like (ca) — but fine-tuned appearing! — physics

Transcendent Union



MV-IR, Tuning + Transcendality

UV-sensitivity + hierach problem:

$$\text{V}^{1-\text{loop}} = \text{Stir } M^4(k) \log M^2(k)$$

$$= \lambda_t^4 h^4 \log(\lambda_t^2 h^2) + \underbrace{(M^2 h)^4 \log(M^2 h)^2}_{\text{UV states}}$$

+ Why should tree
cancel "loop"?

$$\subset \lambda^2 M^2 h^2 + \dots$$

Calculable...

Tree = "Rational"
→ Loop = "Transcendental"

... but long known "funny tunings" in
QFT computations ...

e.g. $\Gamma(\text{positronium}) = \dots \times (\pi^2 - q)$

Accidentally
Small?

No! There is a mechanism @ work here ...

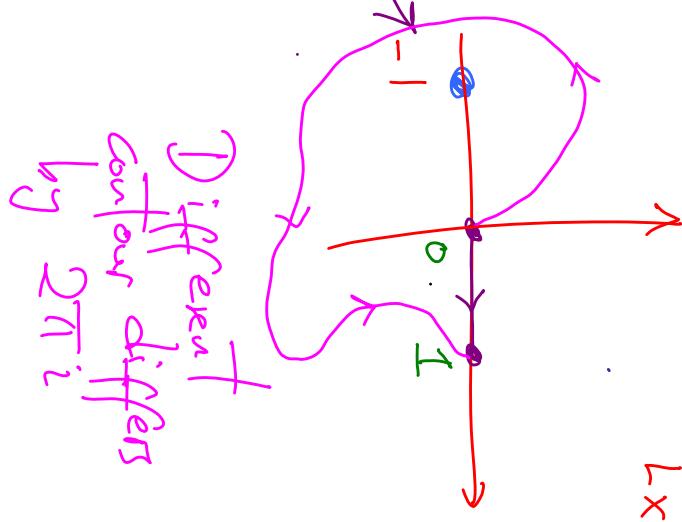
Rational Approximations to Transcendental Numbers

$$\log 2 = \int_0^1 \frac{dx}{1+x}$$

transcendental



because
of simple
pole @ $x = -1$



$$\int_0^1 \frac{dx}{1+x} = \int_0^1 \frac{dx}{1+x} \cdot \varphi(x) = \varphi(-1) \log 2 + \text{Rational}$$

$$\int_0^1 \frac{dx}{1+x} - \left[\frac{x(1-x)}{2} \right]_0^1 = \pm \log 2 + \text{Rational}$$

$$\left(\frac{1}{2} \right)^N$$

Huge "Apparent Tuning" → Rational Approx to $\log 2$

$$\text{e.g. } N=5 : \log 2 = \frac{2329}{3360} \approx 10^{-5}$$

{ Same idea:

$$\int_0^4 \frac{dx}{(1+x^2)} \left(\frac{x(1-x)}{4}\right)^{4N} = \pi + \text{rational}$$

$$N=1 \quad \pi = \frac{22}{7} \approx 10^{-3}$$

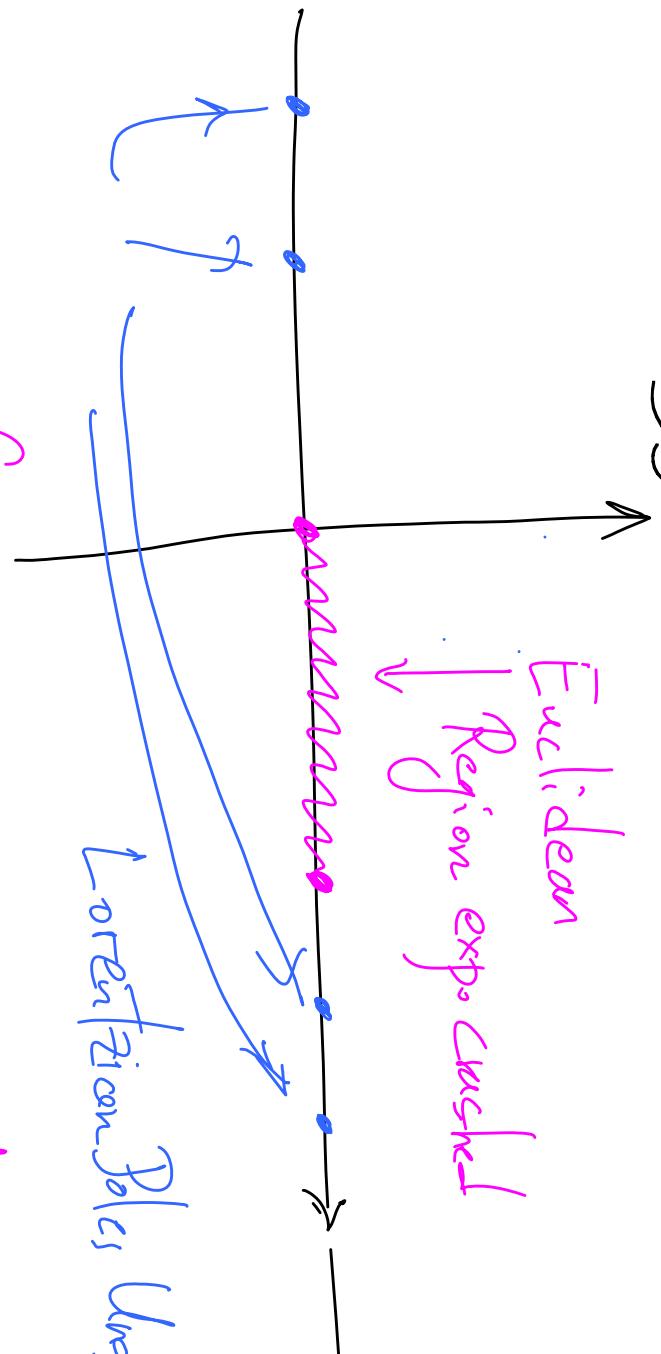
$$\pi = \frac{47171}{15015}$$

$$\sim 10^{-6}$$

{ It explains $\pi^2/9!$. Small phase-space
integrals = Transc. - rational

Strategy for Flags

Euclidean
Region exp. clash



$$\sqrt{h} = \int dk^2 F(k^2) = \text{Logs + Ratios}$$

Euclidean

= exp. small but
apparently "fine-tuned"

Concrete Example

$$F(h) = \int_h^1 \frac{dx}{1+x} (x-h)^4 \left(\frac{x(1-x)}{2}\right)^N$$

$$\begin{aligned} V(h) &= F(l) + F(h) \\ &= \sum_{\pm} (l \pm h)^4 \log(l \pm h) + \text{Rational} \end{aligned}$$

$\underbrace{\quad}_{\text{"UV loop"}}$

$\underbrace{\quad}_{\text{"free"}}$

BUT GUARANTEED TO BE "TUNED"

So e.g.

$$N=5$$

"tree"

$$\checkmark(h)$$

$$= \frac{142733/102960 + (97411 h^2)/73920 - (1557 h^4)/560 + h^6/15 + h^8/140 + (31 h^{10})/20160}{+ h^{12}/3960 + h^{14}/160160 - \text{Log}[4] - h^4 \text{Log}[4] - 2 h^2 \text{Log}[64] + (-1+h)^4 \text{Log}[1-h] + (1+h)^4 \text{Log}[1+h]}$$

"|-loop"

$$= (142733/102960 - \text{Log}[4]) + (614851/73920 - 2 \text{Log}[64]) h^2 + (2329/1680 - \text{Log}[4]) h^4 - h^{10}/20160$$

$$= 10^{-6} + 10^{-5} h^2 + \dots + h^{10}$$

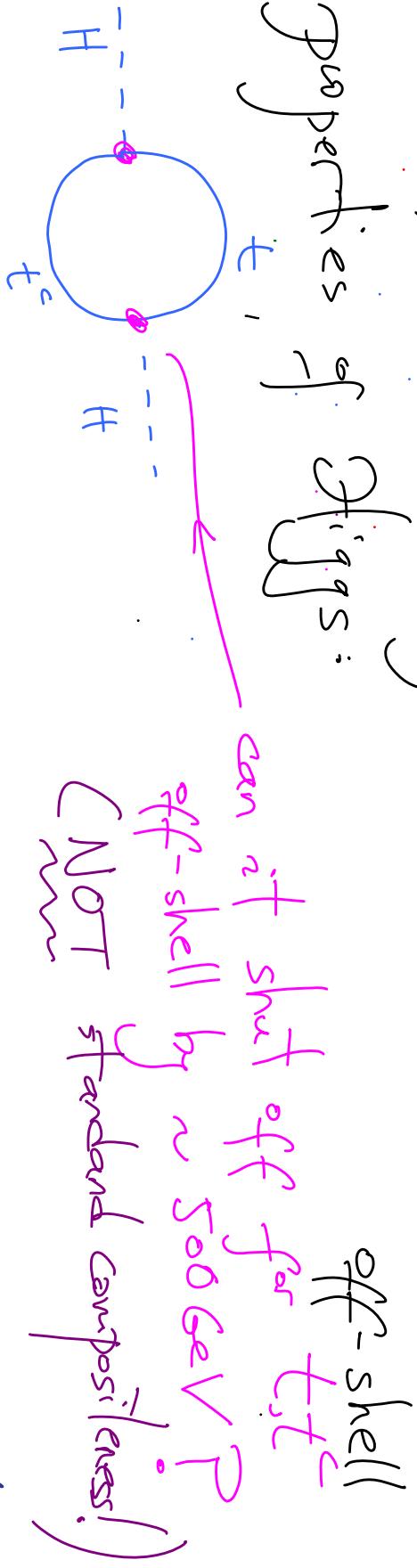
Surprise:

$$\begin{array}{c} \text{"tuned"} \\ \text{"tuned"} \end{array} \wedge \begin{array}{c} \text{"tuned"} \\ \text{h}^6, h^8 \end{array}$$

MISSING!

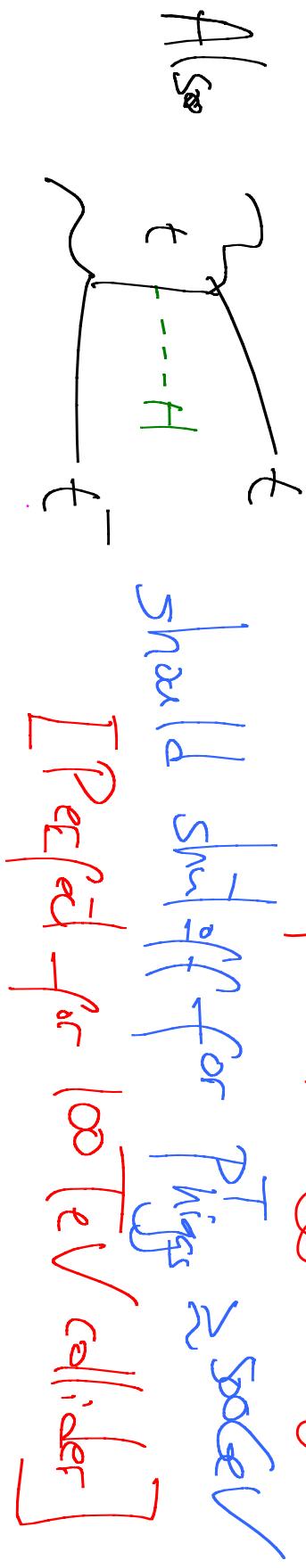
* So, crucial to probe Euclidean,

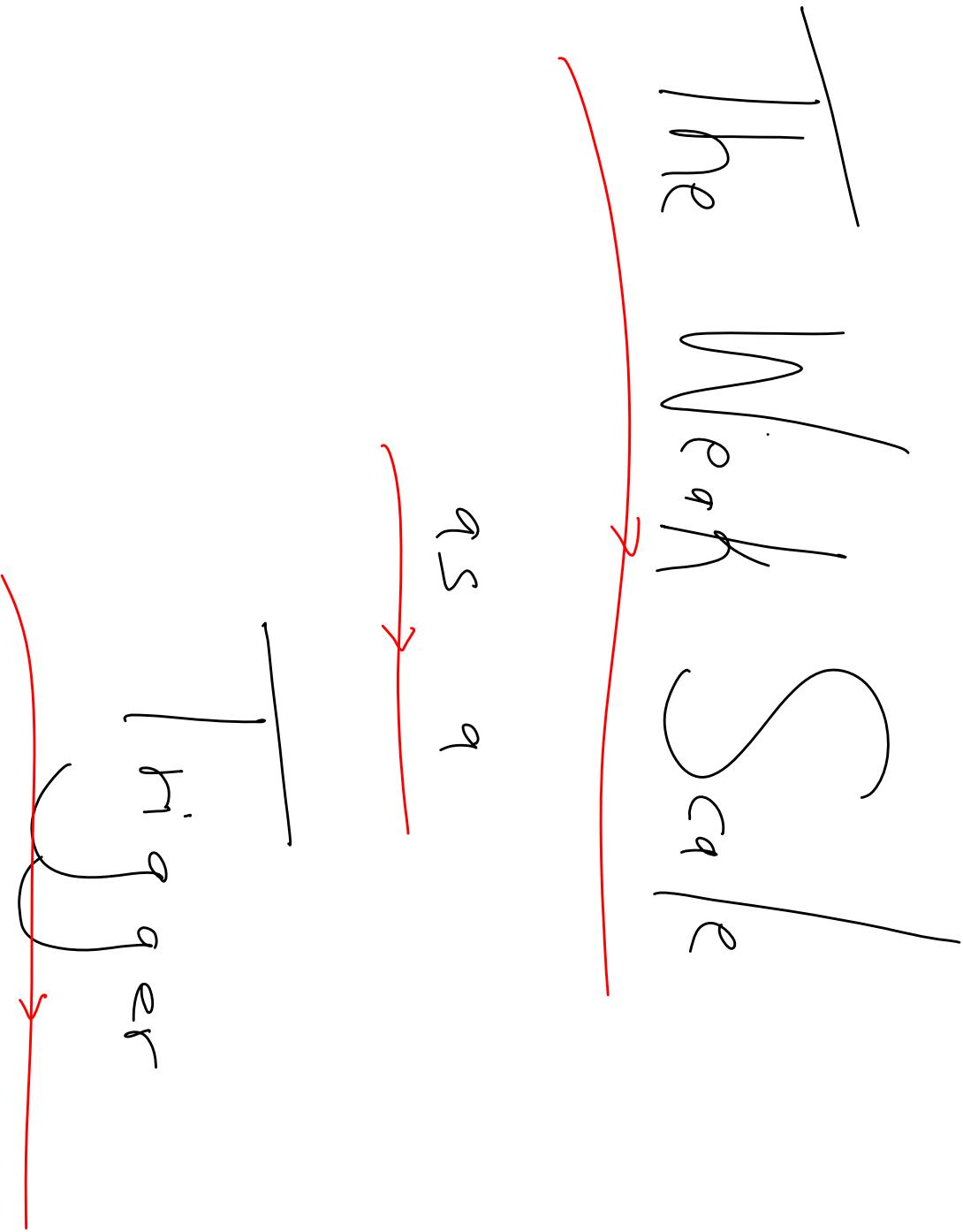
Properties of Higgs:



$$\Rightarrow \begin{array}{c} \text{H} \rightarrow gg \text{ modified } @ \sim 3\% \\ \text{H} \rightarrow jj \text{ modified } @ \sim 10\% \end{array}$$

[Perfect for Higgs Factory]





Q : What happen in the SM as we
vary m_h^2 ? What $\langle \phi(\theta = 0) \rangle$
care about m_h^2 ? P

A : Obviously, spectrum [B] - these
are met $\langle \phi(x) \rangle = \langle \phi(y) \rangle$, rather
 $\langle \phi(x) \phi(y) \rangle \rightarrow \langle \phi(x) \phi^2 \rangle \dots$

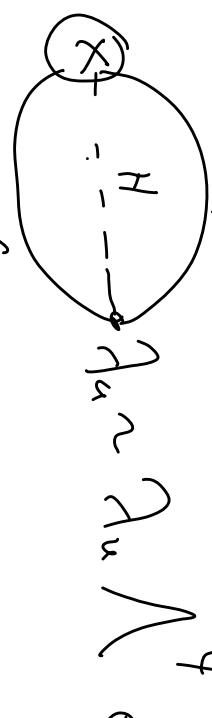
* Indeed this is a sharp characterization

of the hierarchy problem. In Sm:

$\langle Th \rangle \rightarrow$ can't compute! since

$\dots, \text{ usual } \sim \wedge^2$

* Similarly for (almost) all local ops e.g.

$\langle QH_U \rangle :$ 

Said another way : imagine weakly coupling
 $(\bar{h} h)$ to some field ϕ :

$E \phi \bar{h} h$ but same spinities as $E \phi H_x^2$



μ^3
 ϕ
) μ not cancellable,
" take from experiment"

* Well-known exception - the anomaly:

$$\langle \tilde{G} \tilde{G} \rangle = 0$$

naively since \tilde{G} is
derivative ... but,

$$= \Delta_{\text{QCD}} m_u^3$$

which depends sensitively on m_h^2 !

* $\langle \tilde{G} \tilde{G} \rangle$ is "triggered" by weak scale

* "Trigger used cosmologically in Relaxion models"

Other triggers?

* N_0 in SM

* But possible in 2HDM extensions of SM.

Consider $H_{1,2}$ with $(H_1 H_2)$ charged under PQ; (H_2 couples to fermions)

Note $\tilde{H}_u = \begin{pmatrix} \tilde{H}_1 \\ \tilde{H}_2 \end{pmatrix}$ can't close because of $\tilde{H}_d = \begin{pmatrix} \tilde{H}_1 \\ \tilde{H}_2 \end{pmatrix}$ PQ, calculable!

$$\langle H_1 H_2 \rangle = 0$$

$$\langle H_1 H_2 \rangle = 0$$

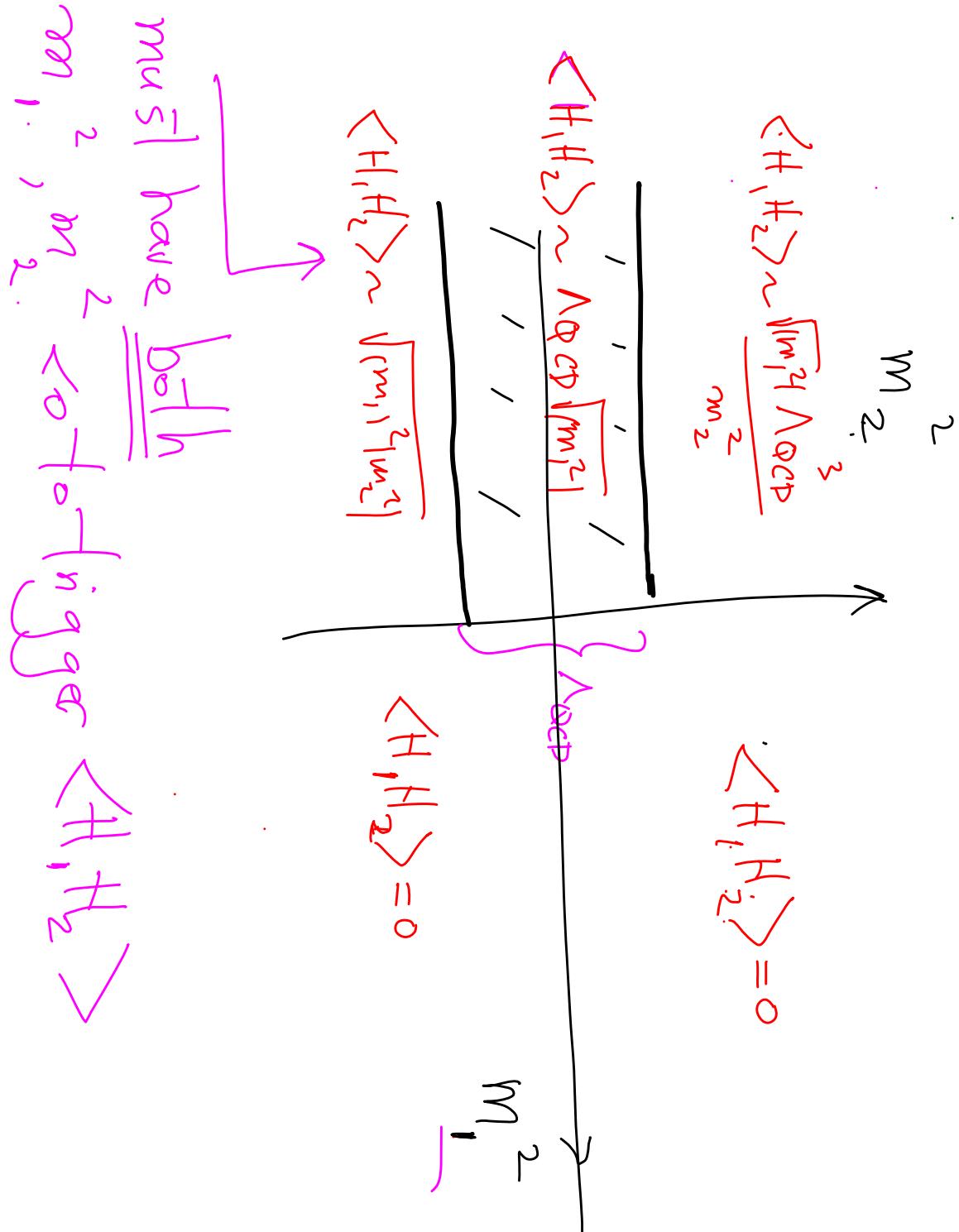
$$m_2$$



$$\langle H_1 H_2 \rangle = \sqrt{[m_1]^2 + [m_2]^2}$$

$$\langle H_1 H_2 \rangle = 0$$

m₁
m₂ have both
m₁, m₂ rotating (rigid) $\langle H_1 H_2 \rangle$



* Of course, the PQ symmetry must be broken [otherwise weak-scale axion...].

* Conventionally: B -term $B H_u H_d$,

ruins trigger mechanism:

$\begin{matrix} \textcircled{X} \\ \textcircled{X} \end{matrix} B \Rightarrow \langle H_u H_d \rangle \sim B,$
independent of $m^2_{h_d}$.

~~Trigger-happy 2HDM~~

* Break $PQ \rightarrow Z_4$ with quartic

$$\mathcal{A} (H_1 H_2)^2, \quad B = 0$$

$\langle H_1 H_2 \rangle$ can be generated by \mathcal{A} , add w/ even P charge!

* And crucially, need both $m_{1,2}^2 > 0$ to trigger!

~~trigger-happy 2HDM~~

$$\begin{aligned} & \quad \checkmark \\ &= m_u^2 |h_u|^2 + m_d^2 |h_d|^2 + \lambda_1 |h_u|^4 + \lambda_2 |h_d|^4 + \lambda_{ud} |h_u| |h_d|^2 \\ &+ \lambda (f_u h_d)^2 + \text{h.c.} \end{aligned}$$

only PQ breaking has charge 2

Impossible To Decouple

- * 2 HDM w/ Z_4 PQ Symmetry, $\beta = 0$
- * Must have $m_{h_1}, h_2 < 0$
- * Must have $V_d/V_u \approx 0.3$
- * $m_H \sim 100 \text{ GeV}$
 - Everyone else $\approx 200 \text{ GeV}$
 - Can't hide — but remarkably seems alive!
- * INCISIVE PROBE @ HL-LHC
HUGE SIGNALS @ Higgs Factory

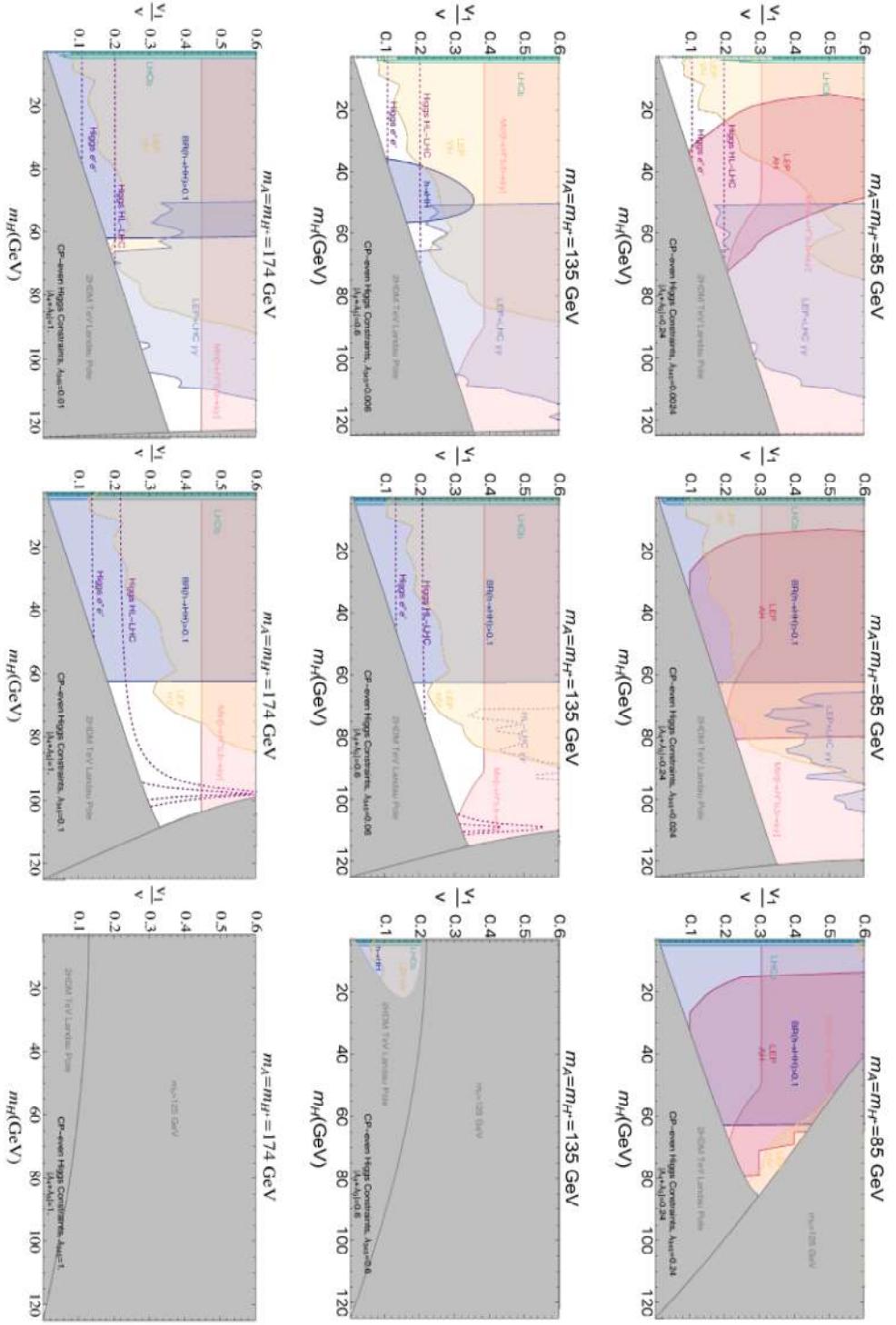
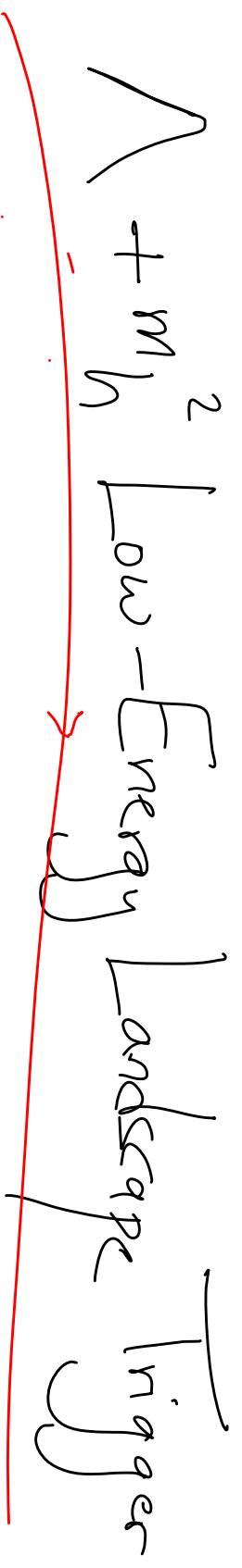
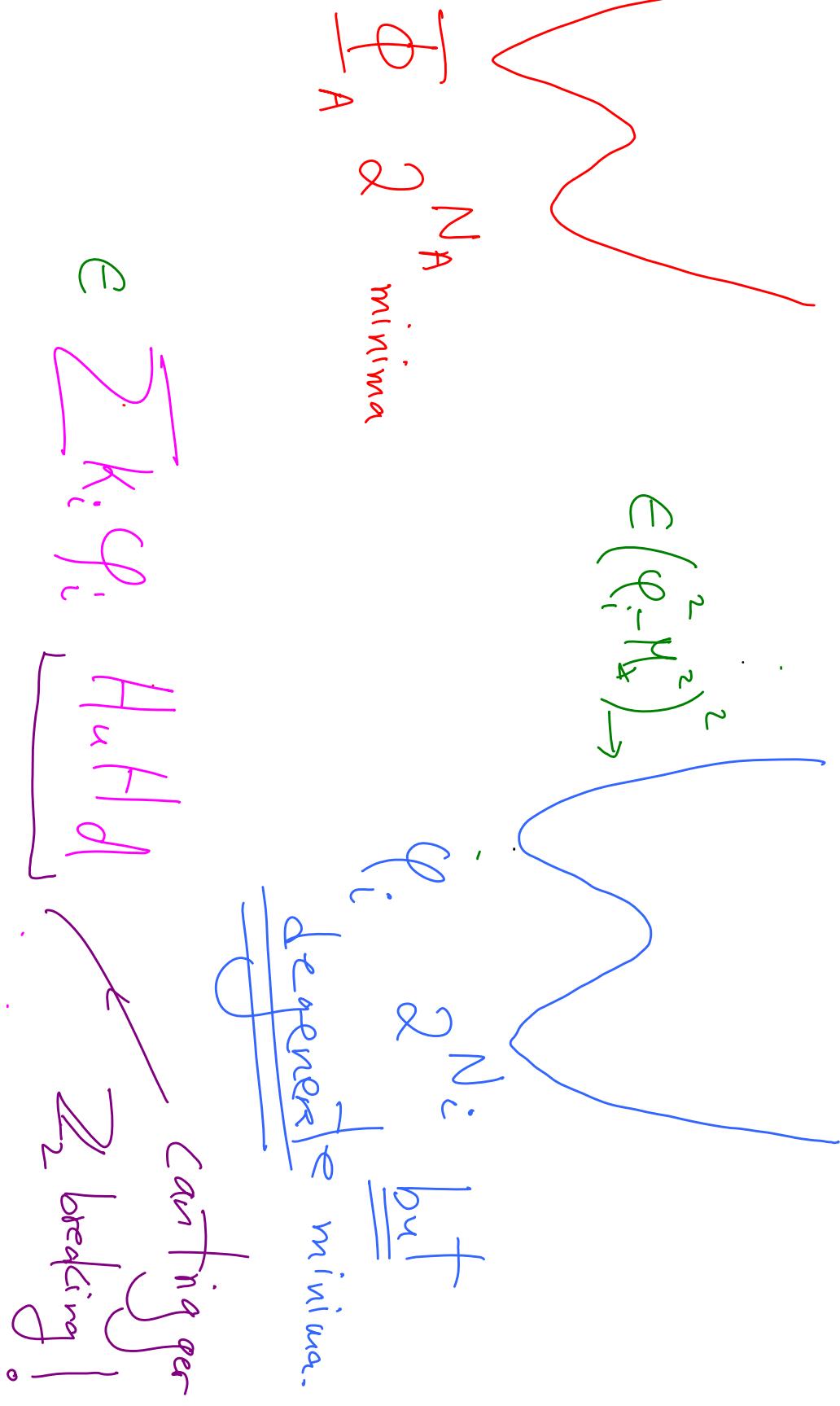


FIG. 5. Experimental Constraints on the CP-even Higgs H for $m_{H^\pm} = m_A$ and different values of λ_{345} . From top to bottom we increase m_{H^\pm} . From left to right we move from 1% tuning ($\lambda_{345} = 0.01|\lambda_4 + \lambda_5|$) to natural values of the quartics ($\lambda_{345} = |\lambda_4 + \lambda_5|$). In red we show the bound from $e^+e^- \rightarrow Z \rightarrow AH$ at LEP [3] and in yellow from HZ associated production [3] followed by decays to fermions. In light blue we display the current sensitivity of $H \rightarrow \gamma\gamma$ at LEP and the LHC [23–25] and a projection for the HL-LHC obtained rescaling [25]. In light green we show bounds from searches for $B \rightarrow K^{(*)}H \rightarrow K^{(*)}\mu\mu$ at LHCb [26, 27]. Indirect constraints from Higgs coupling measurements (purple and blue) are discussed in Section III B 2. The pink shaded area shows the strongest bound point-by-point between searches for flavor changing processes, mainly $b \rightarrow s\gamma$ [7, 8], and LHC searches for $t \rightarrow H+b$ [9–12]. Theoretical constraints (in gray) from low energy Landau poles and the SM Higgs mass are summarized at the beginning of Section III B.

$\nabla + m_h^2$ Low-Energy Landscape Trigger


$$e^{(\varphi_i^2 - \mu_\star^2)^2}$$

φ_i
 $2N_i$
 but
degenerate minima.



$\lambda + m_h^2$ [Low-Energy Landscape] Trigger

Low Energy Landscape

$$m_\phi \sim v^2/M_* \quad \langle \phi \rangle \sim M_*$$

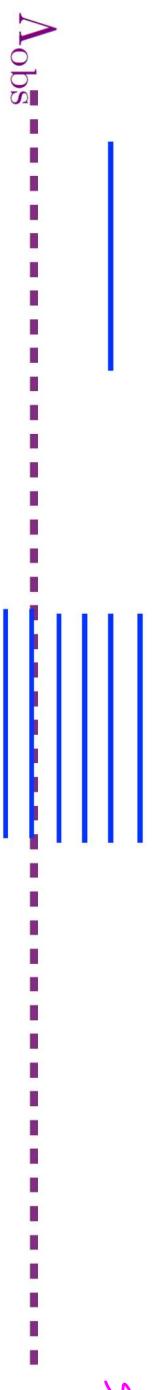
$$\langle h \rangle = 0$$

$$\langle h \rangle \simeq v$$

$$\langle h \rangle \gg v$$



Can only
split vacuum
+ get
small



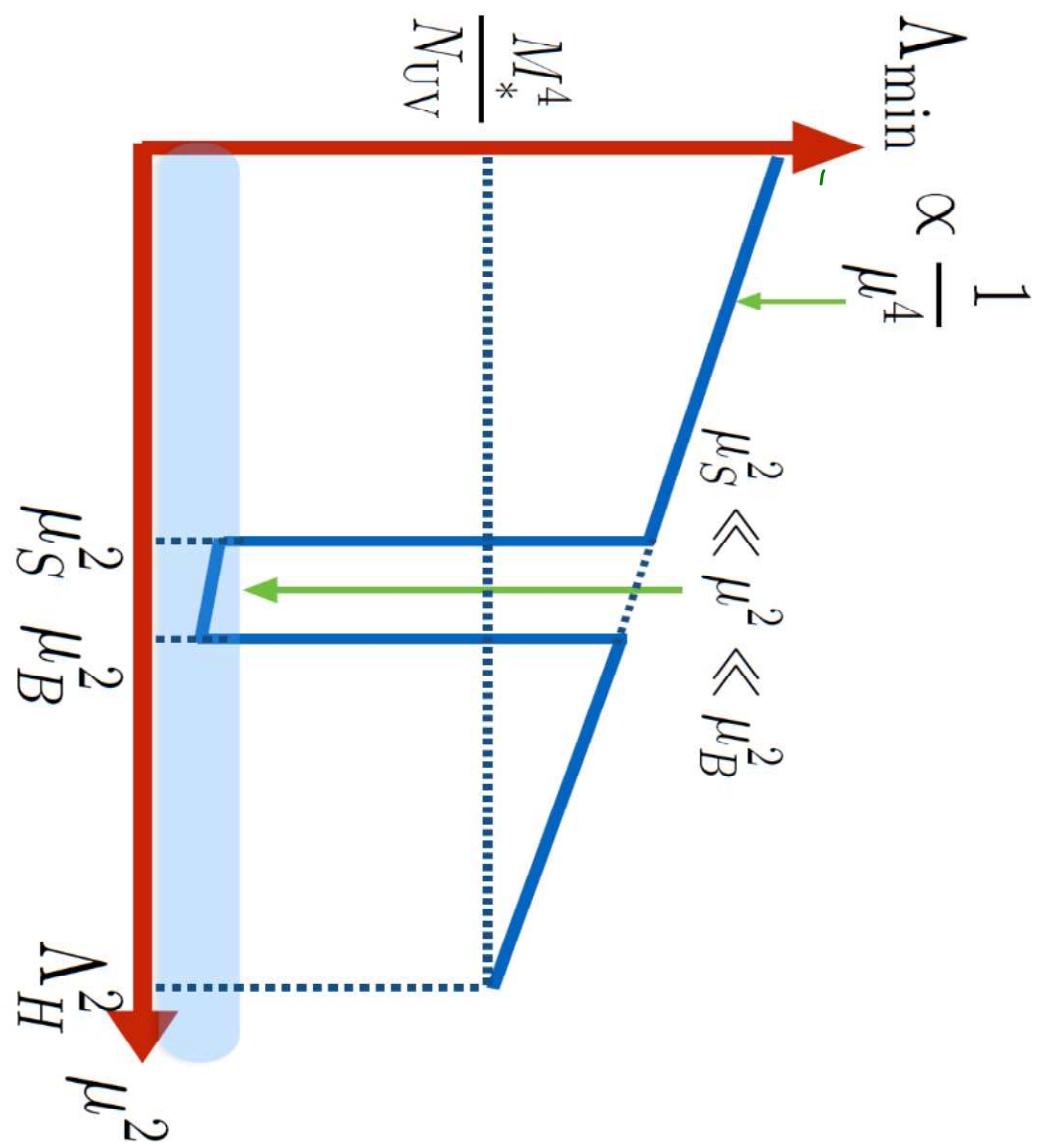
CC.

$i\langle H_u H_d \rangle$
triggered

\mathcal{Q}_{N_2}

vacua

$$V_\phi = \sum_{i=1}^{N_2} \frac{\epsilon_i^2}{4} (\phi_i^2 - M_{*,i}^2)^2 + \kappa_i \frac{\epsilon_i M_{*,i}}{\sqrt{N_2}} (\phi_i H_u H_d + \text{h.c.})$$



* For high scales, $\sim 100's$ of aHnlights
 $\phi_i \rightarrow$ bounds/signals from long-range forces

* Also: EW SB triggers displacement
 $\phi_i \rightarrow$ coherent oscillations as DM.

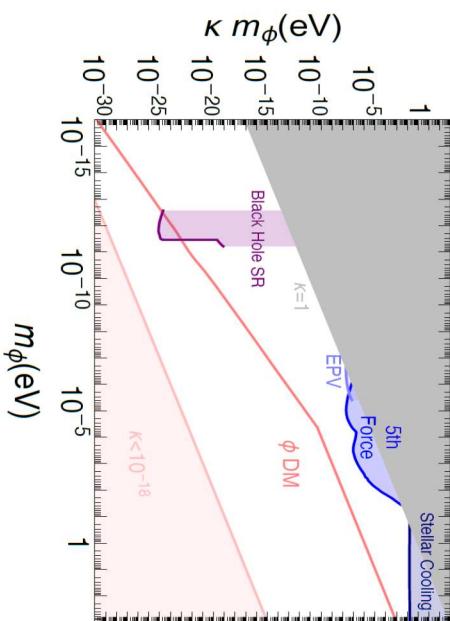


FIG. 9. Laboratory and astrophysical constraints on scalars coupled to the Higgs boson via the trilinear interaction $\kappa m_\phi \sum_{i=1}^{n_\phi} \phi_i |H|^2 / \sqrt{n_\phi}$ (we neglect unimportant $\mathcal{O}(1)$ factors introduced by the mixing of the two Higgses). The bounds include tests of the equivalence principle [142–145], tests of the Newtonian and Casimir potentials (5th force) [146–154], stellar cooling [155] and black hole superradiance [156, 157]. The pink solid line shows the target given by the scalars being dark matter. The light pink shaded area at the bottom of the plot is the theoretical constraint on κ discussed in Section IV B. We shaded in gray the region where $\kappa > 1$ (i.e. $\Lambda_H \lesssim \text{TeV}$).

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MYSTERY OF WEAK SCALE ORDER

HAS ONLY BECOME DEEPER

THERE ARE DECENT → GOOD

THEORETICAL MOTIVATIONS FOR
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