After the Top

11th International Workshop on Top Quark Physics

Bad Neuenahr, 17.09.18

Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)
(christophe.grojean@desy.de)

Top Status

The Top is Special

Maltoni @ LHCP2018

1. It is rich m_t~173GeV
2. It is strong y_t~1
3. It is naked t_{decay}>t_{had}
4. It is popular σ_{tt}~1nb @ LHC_{13} top is sensitive to QCD&EW
5. It goes beyond

$$\delta m_H^2 = -\frac{3G_F m_t^2 \Lambda^2}{2\sqrt{2}\pi^2} \quad \lambda(M_{Pl}) = -0.0113 - 0.0065(m_t/\mathrm{GeV} - 173.10)$$

The Top is Special

Maltoni @ LHCP2018

1. **It is rich** $m_t \sim 173\text{GeV}$
2. **It is strong** $y_t \sim 1$
3. **It is naked** $t_{decay} > t_{had}$
4. **It is popular** $\sigma_{tt} \sim 1\text{nb}$ @ LHC_{13} top is sensitive to QCD&EW
5. **It goes beyond**

$$\delta m_H^2 = -\frac{3G_F m_t^2 \Lambda^2}{2\sqrt{2}\pi^2} \qquad \lambda(M_{Pl}) = -0.0113 - 0.0065(m_t/\text{GeV} - 173.10)$$

1. **He is rich**
2. **He is strong**
3. **He is (often) naked**
4. **He is (un)popular**
5. **He goes beyond (reason)**

The Top is Special

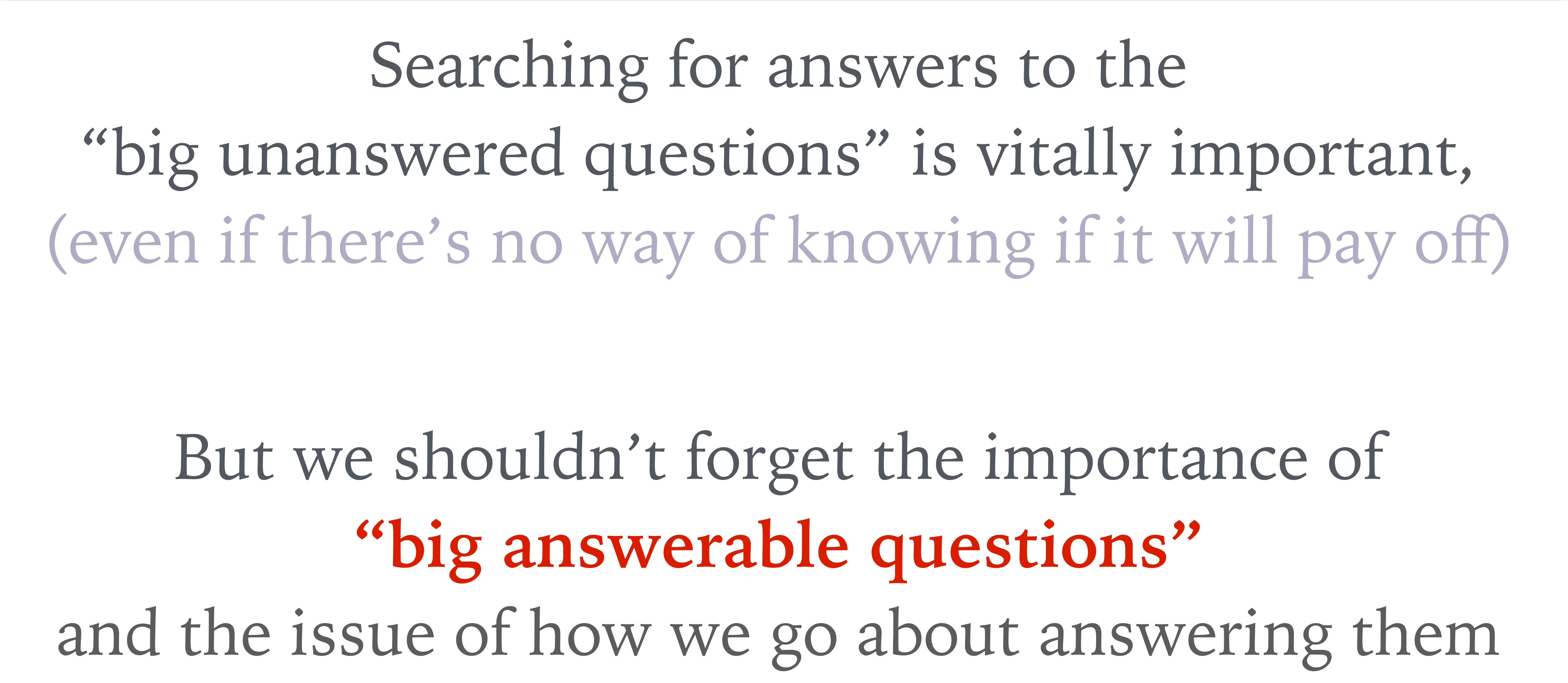
Maltoni @ LHCP2018

1. It is rich
2. It is strong
3. It is naked
4. It is popular
5. It goes beyond

The top quark is the Ronaldo of elementary particles

The Top is a cross-road SM-BSM

Salam @ LHCP2018

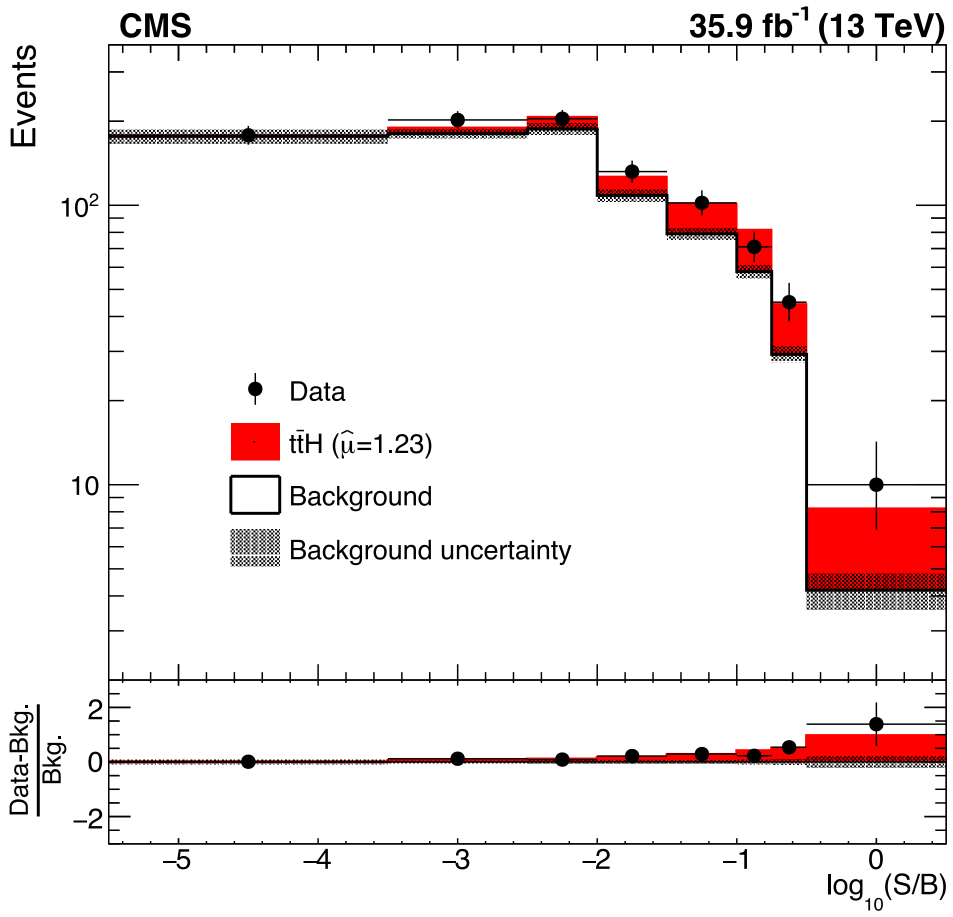


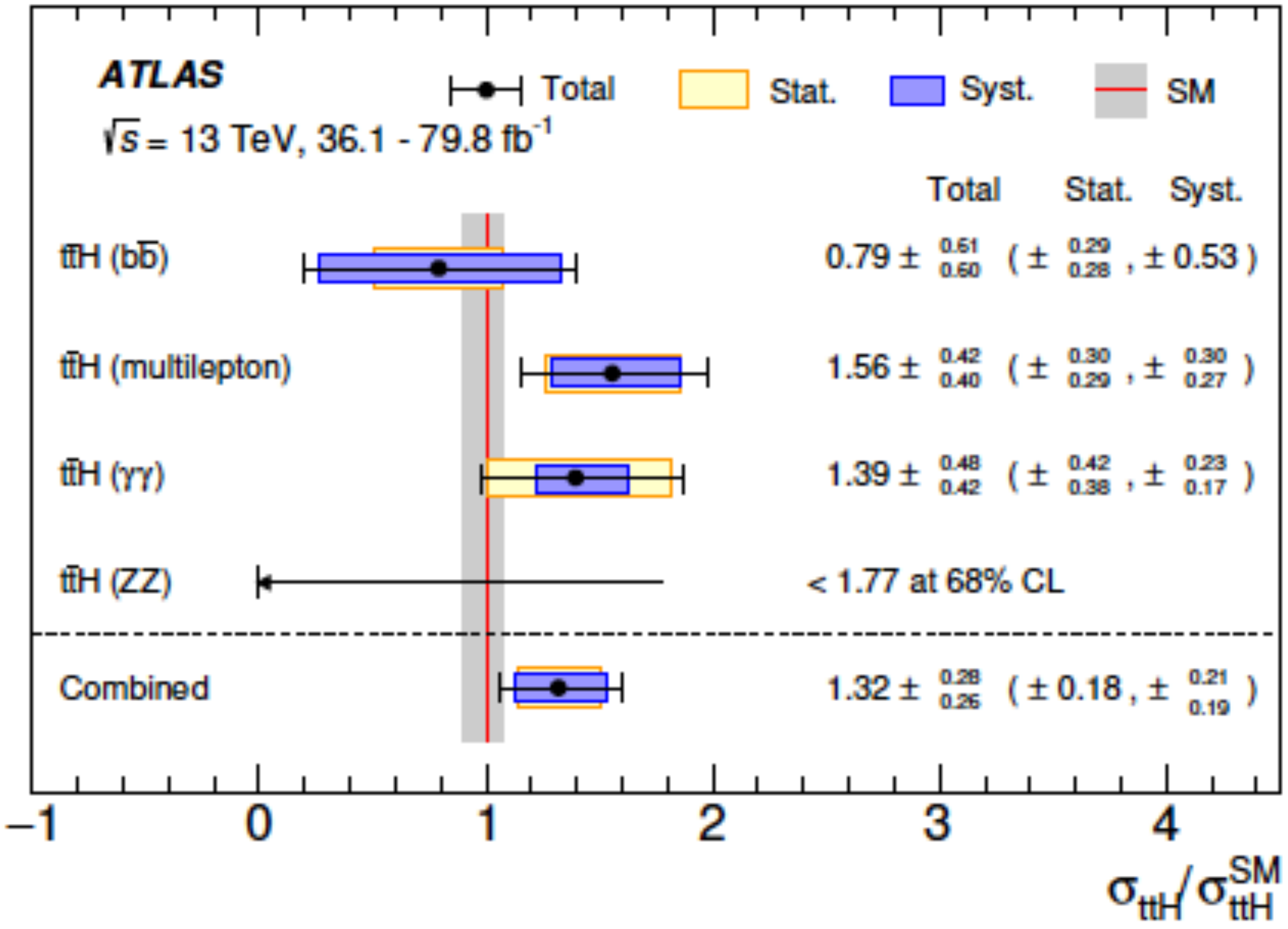
Searching for answers to the
“big unanswered questions” is vitally important,
(even if there’s no way of knowing if it will pay off)

But we shouldn’t forget the importance of
“big answerable questions”
and the issue of how we go about answering them

Top sector is directly concerned with both types of questions

The Top is Alive

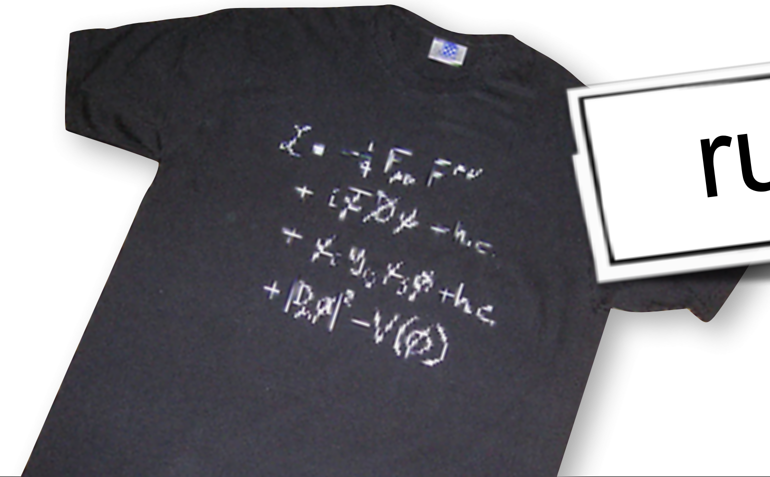




Direct evidence for Yukawa interactions

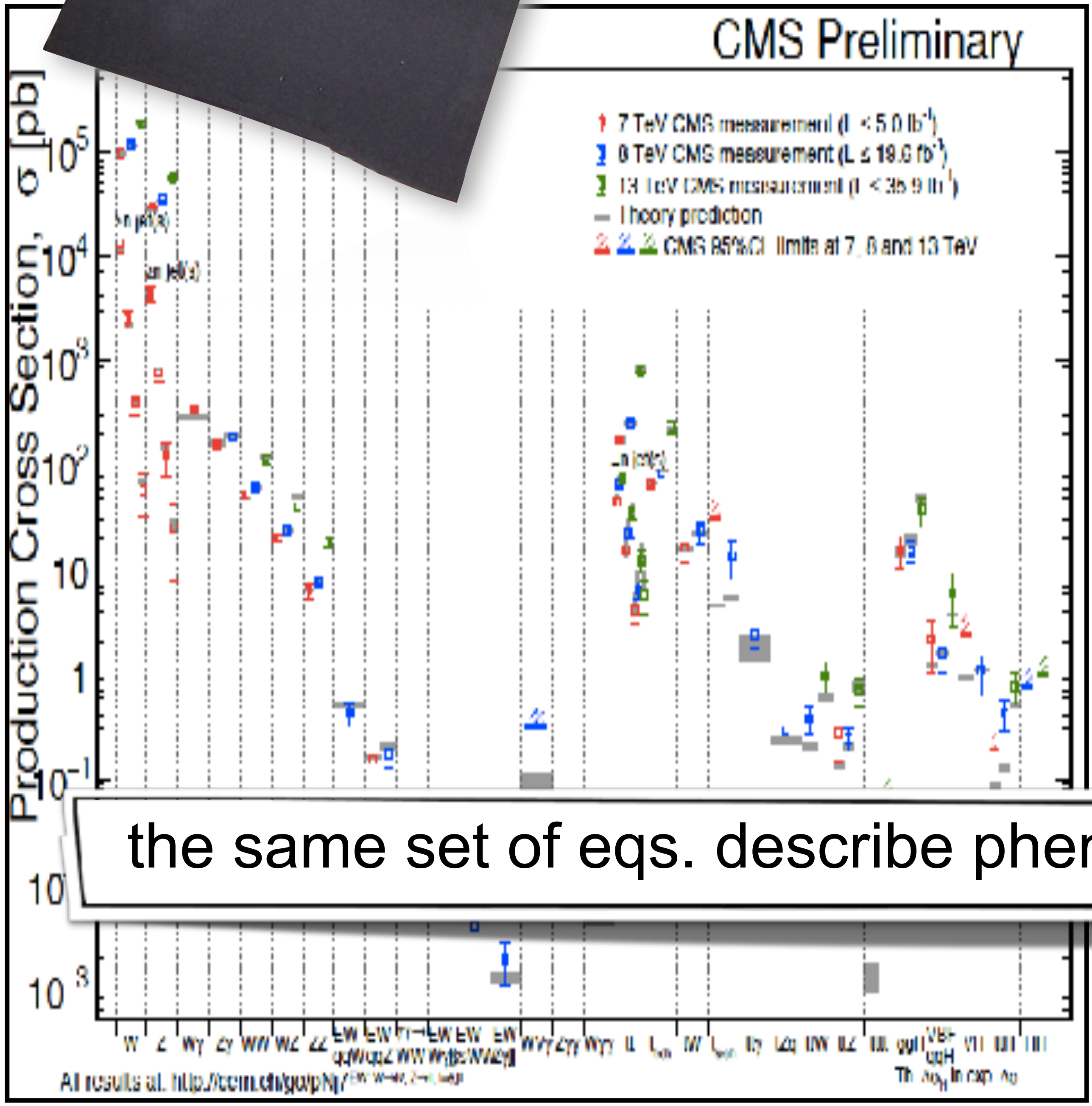
1) first fundamental non-gauge interactions
2) Responsible for matter stability ($m_p<m_n$)
3) Responsible for vacuum stability?

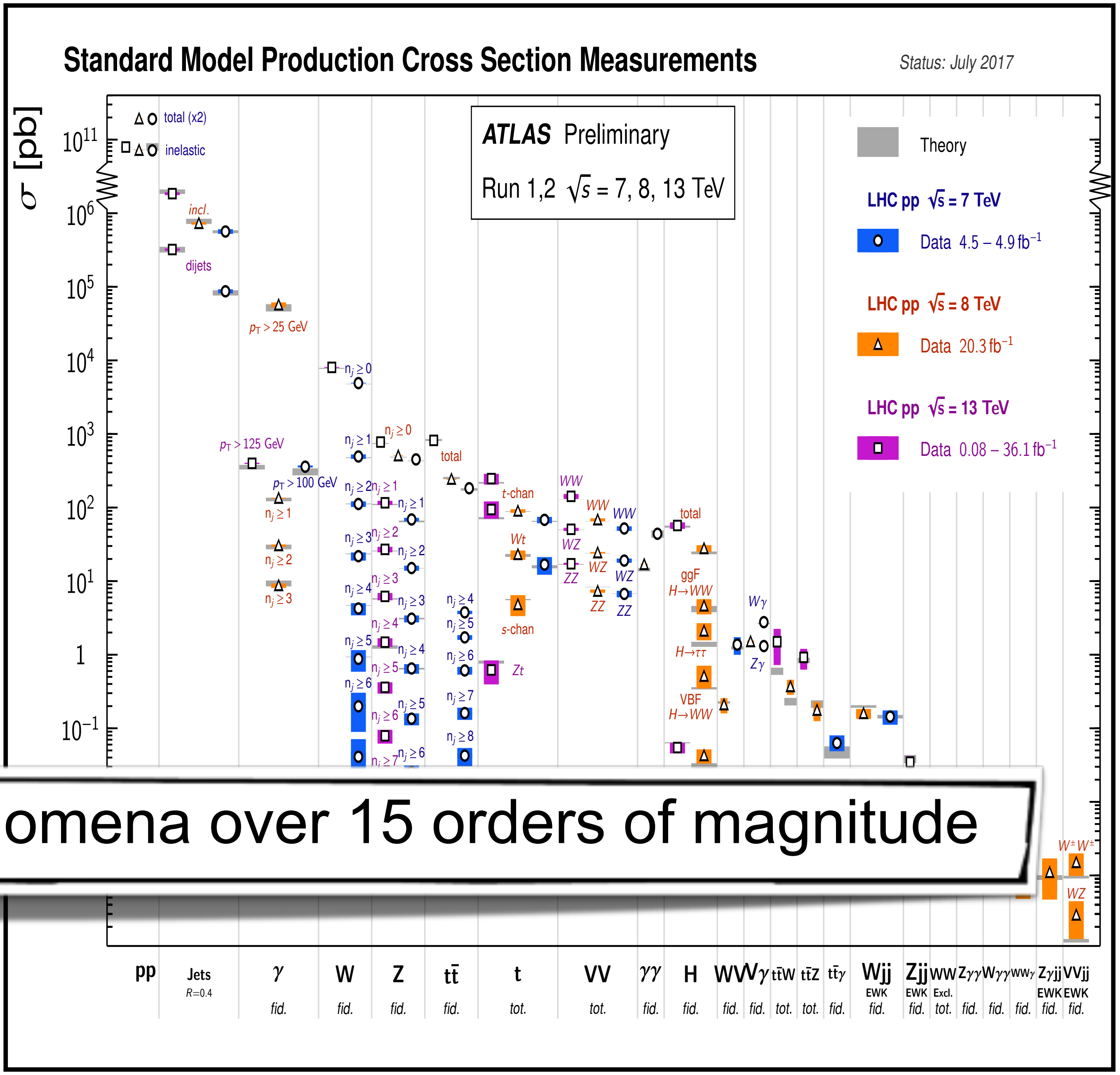
The SM and... the LHC data so far



rules the world!

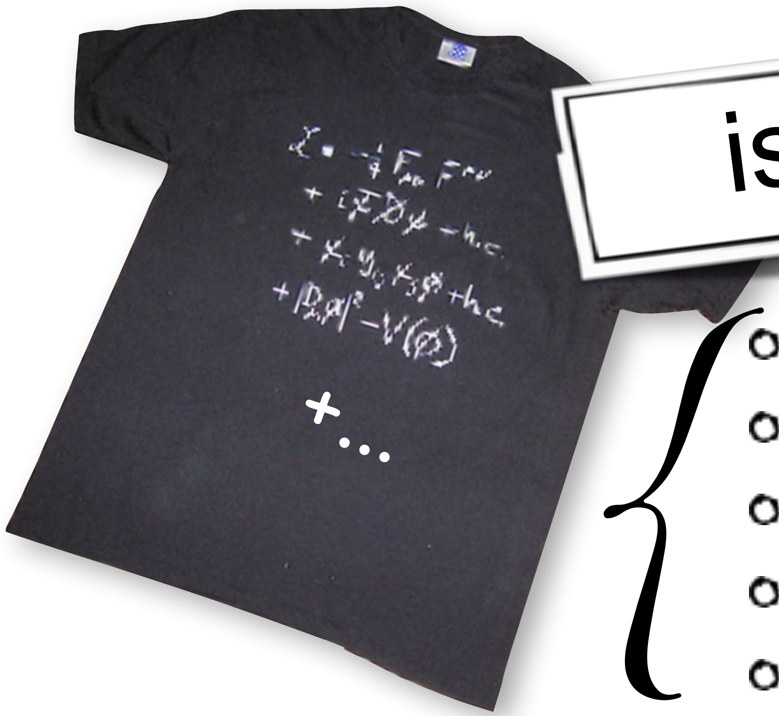
[and we, HEP practitioners, are all entitled for some royalties!]





the same set of eqs. describe phenomena over 15 orders of magnitude

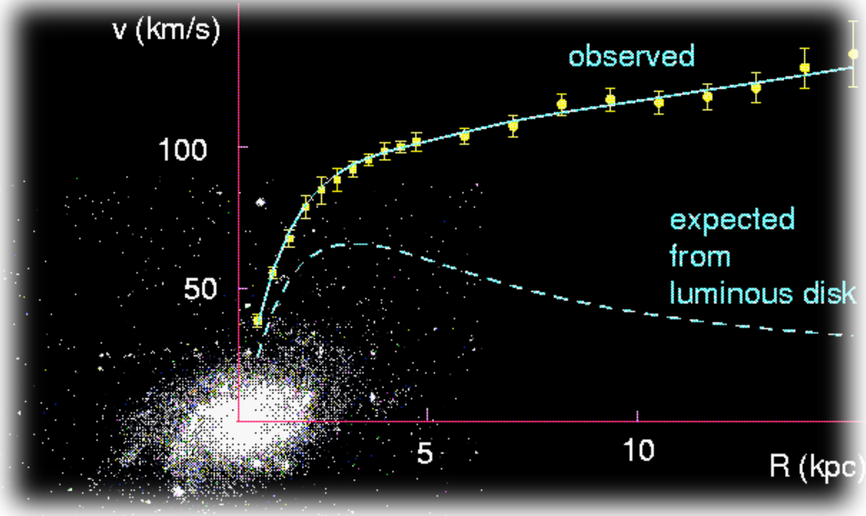
The SM and... the rest of the Universe

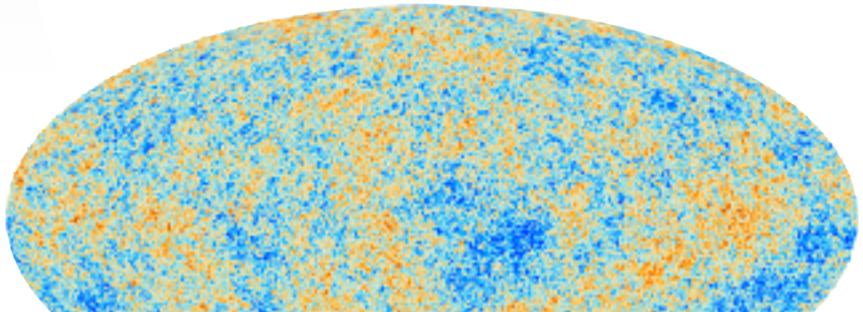


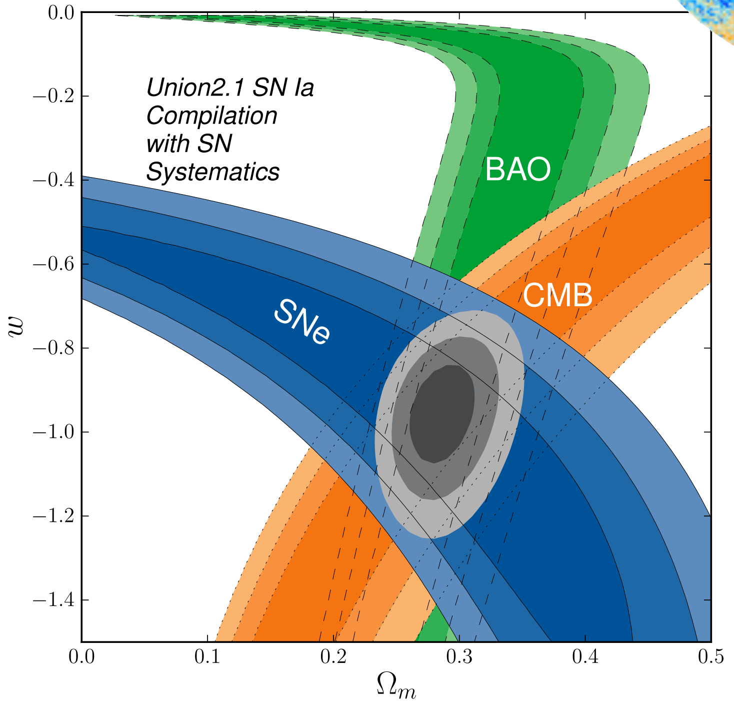
is not enough

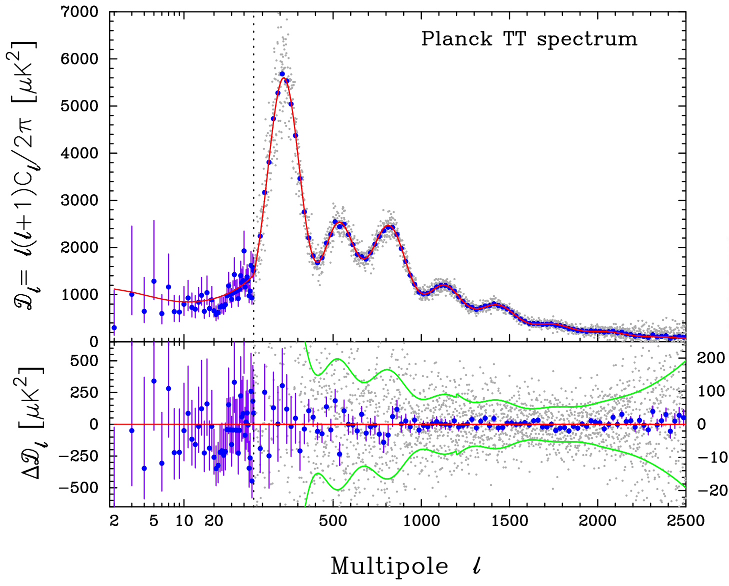
[and we all have to return our royalties!]

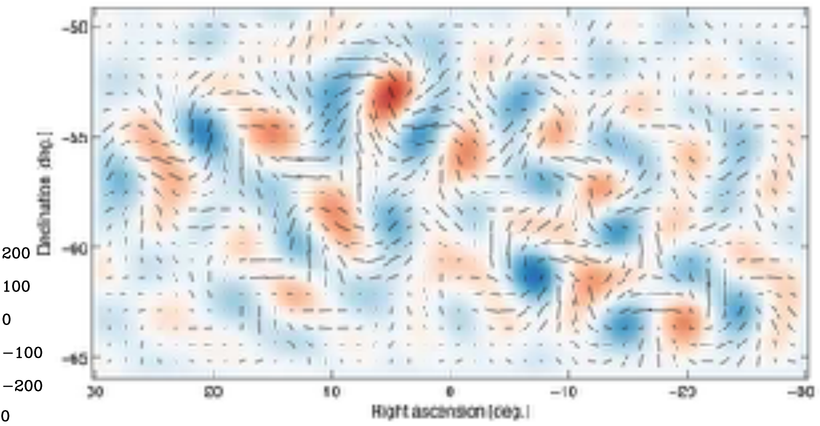
- neutrino masses
- matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Quantum gravity











Beyond the Top Status

What is physics beyond the Standard Model?

?

I don’t know. Nobody knows
If it were known, it would be part of the SM!
You won’t learn during this talk what BSM is
You might learn what BSM could be.

“ Looking and not finding is different than not looking”

Different directions in model building

- neutrino masses & flavour
- matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Quantum gravity

Each of these puzzles drives
its own model-building activity

Need
1) **new interactions** among SM particles
2) **new particles** beyond SM

At which scale?
Which experiment will probe that scale?

Still model-builders strive for understanding the **SM Lagrangian**
And the fact that the SM works so well challenges our understanding of QFT

- Why QCD doesn't break CP?
- Why is gravity so weak compared to other interactions?
- Why is the acceleration of the expansion rate of the Universe so small?

Theorists have reasonable ideas to solve the (first two) problems
And fascinating **signatures** are/were expected at colliders

Naturalness

Given the null searches, people tend to dismiss the hierarchy problem.
It is not because we don't have the solution that the problem doesn't exist!

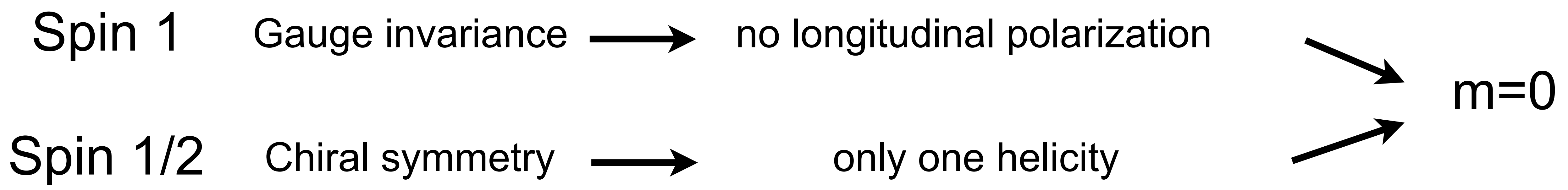
The spin trick

a particle of spin s:

2s+1 polarisation states

...with the only exception of a particle moving at the speed of light

... fewer polarisation states



Spin 1 Gauge invariance ⟶ no longitudinal polarization

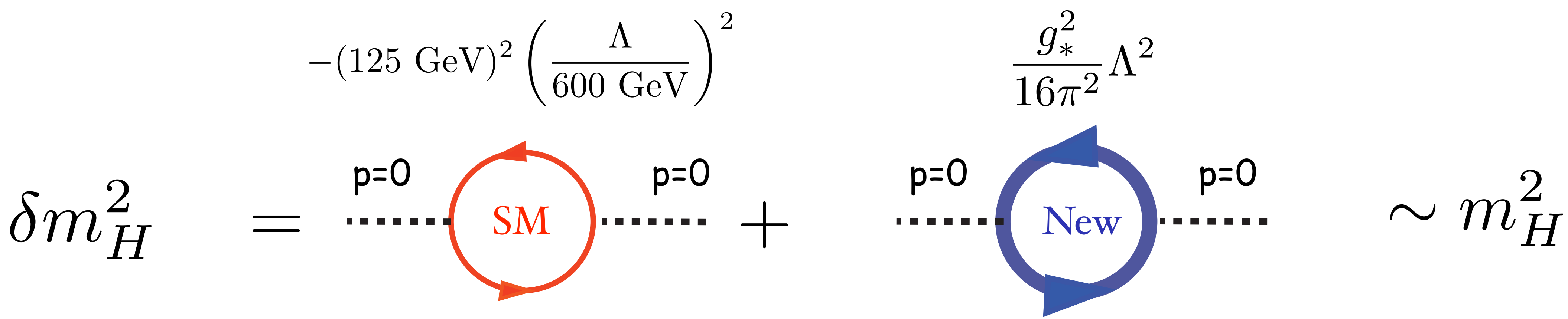
Spin 1/2 Chiral symmetry ⟶ only one helicity

m=0

If the symmetries are broken, the radiative mass will be set by the scale of symmetry breaking, not the UV/Planck scale

... but the Higgs is a spin 0 particle

Different Ways to be Natural



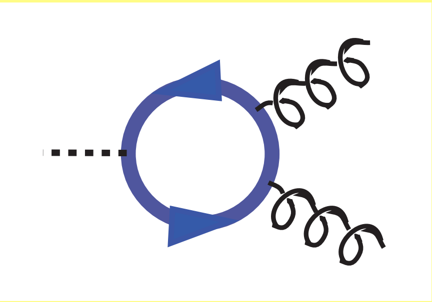
$$-(125\ \text{GeV})^2\left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$$\delta m_H^2 = \text{SM} + \text{New} \sim m_H^2$$

charged particles

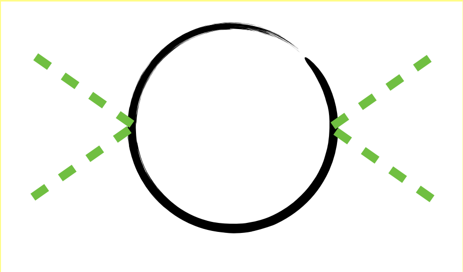
generically

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colourful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

aka twin Higgs

Different Ways to save Naturalness

giving the null search results, the top partners should either be

- **heavy** (harder to produce because of phase space)
- **stealthy** (easy to produce but hard to distinguish from background, e.g. $m_{stop} \sim m_{top}$)
- **colourless** (hard to produce, unusual decay)

need to go beyond traditional searches

only little corner
of theory/model space
has been explored so far

(C. Verhaaren@NKPI'16)

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

require **hidden QCD**
with a higher confining scale:

⇒ 1) hidden glueball (0^{++}) that can mix with Higgs
$h \to G_0 G_0 \to 4l$ with displaced vertices

Curtin, Verhaaren '15

⇒ 2) emerging jets

Schwaller, Stolarski, Weiler '15

Different Ways to save Naturalness

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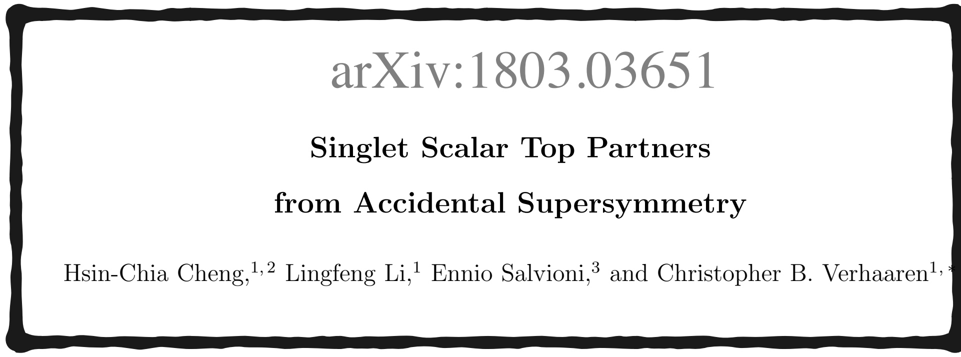
need to go beyond traditional searches

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

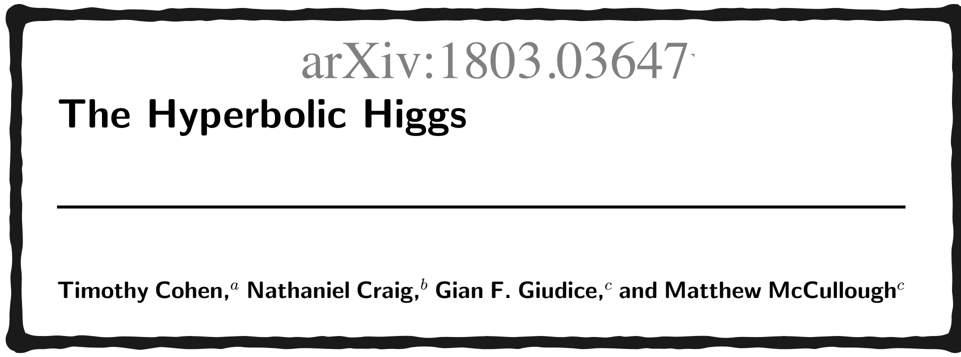
Last model building opportunities filled up recently



arXiv:1803.03651

Singlet Scalar Top Partners from Accidental Supersymmetry

Hsin-Chia Cheng,[1,2] Lingfeng Li,[1] Ennio Salvioni,[3] and Christopher B. Verhaaren[1,*]

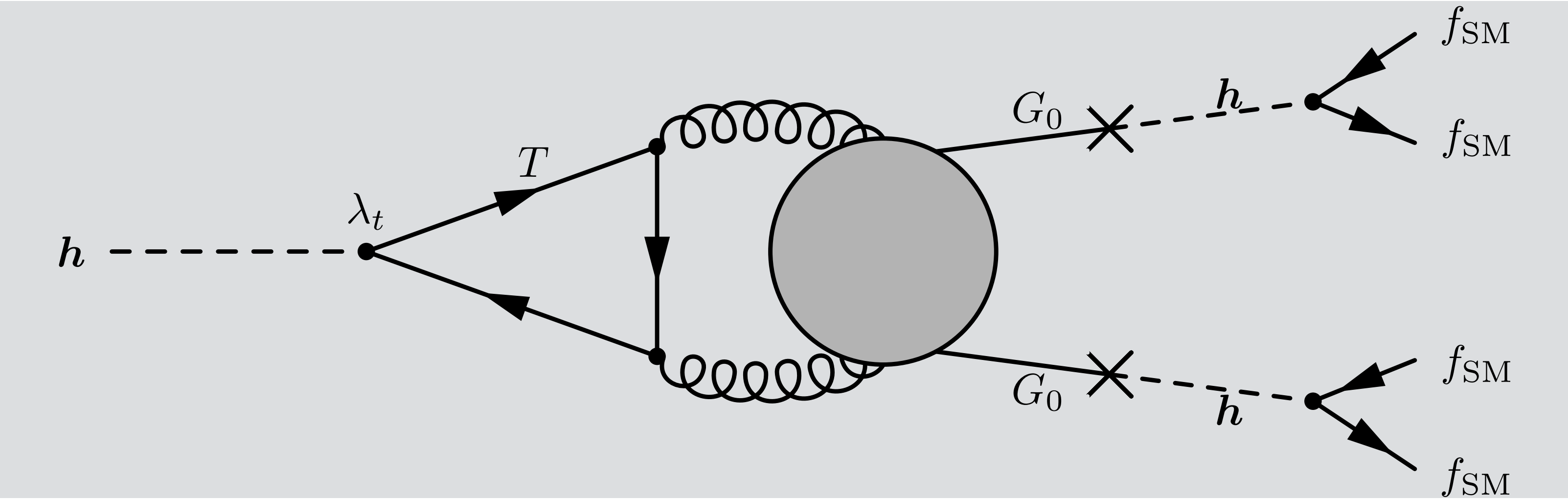


arXiv:1803.03647

The Hyperbolic Higgs

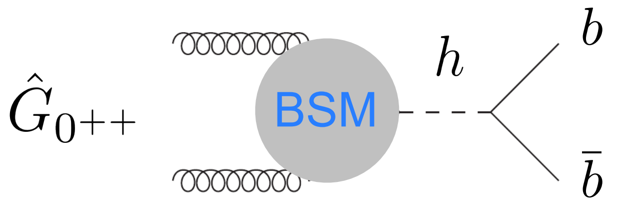
Timothy Cohen,[a] Nathaniel Craig,[b] Gian F. Giudice,[c] and Matthew McCullough[c]

Neutral Naturalness

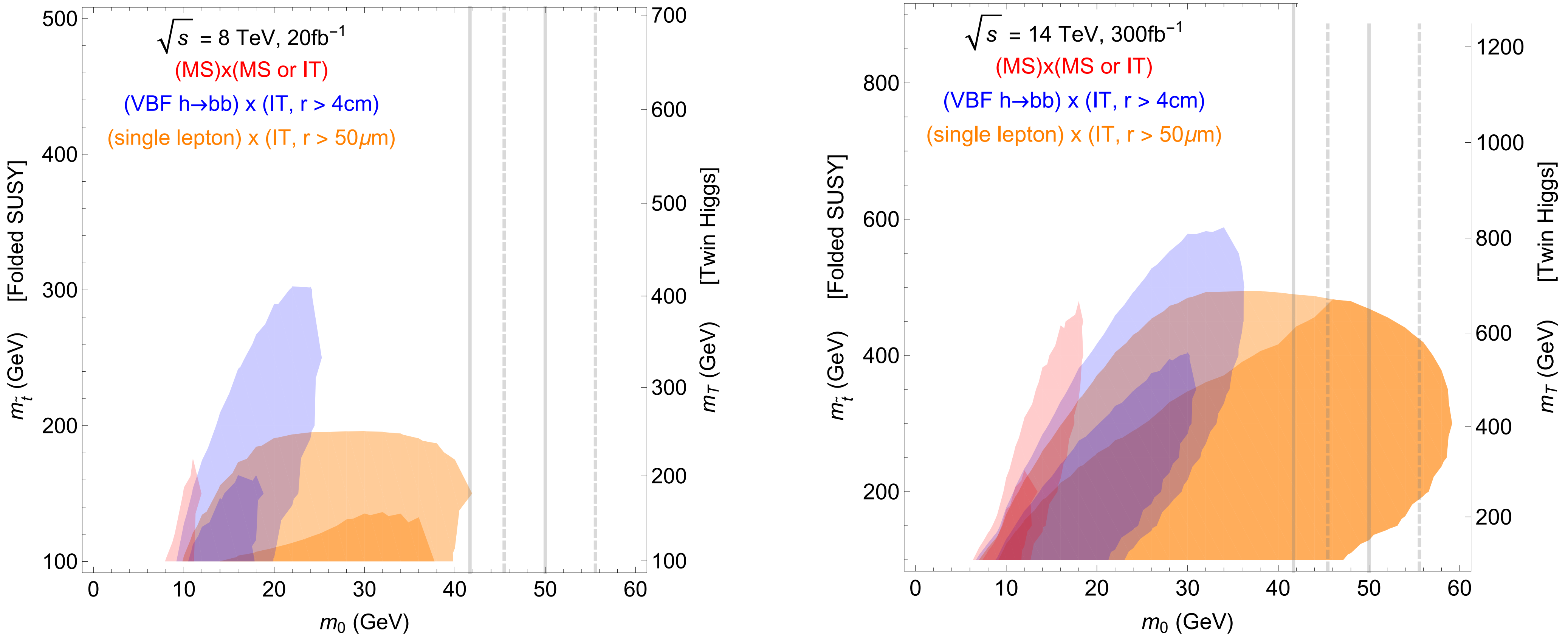


top parters are EW charged: m>100GeV (LEP)
Lightest hidden states are glueballs of QCD'
that can mix with the Higgs boson

Exotic Higgs decays with displaced vertices



Curtin, Verhaaren '15



Mathusla to detect Long Lived Particles?
Precise timing within ATLAS/CMS detectors?

Searches through Precision

New Particle or New Force?

Search for a bump over precisely known background
but one can do more with precision

Nima AH: *“If you do particle physics with the goal of discovering a new particle, better you think what to do with your life now.”* (in the context of “direct discovery vs “indirectprecision physics” at future colliders)

LHCP ‘2017

New physics doesn’t necessarily mean new particle,
it could also mean new dynamics.
And it could reveal through precision measurements

$$m_* = g_* f_*$$

g_* weak:
resonances before interactions

g_* strong:
interactions before resonances

energy helps accuracy

Farina et al ’16

$\frac{\Delta \mathcal{O}}{\mathcal{O}} \propto E^2$ ⟺ precision of 0.1% @ 100GeV ≈ precision of 10% @ 1TeV
same sensitivity to new physics

at high energy, you can be sensitive without having to be precise

New Particle or New Force?

e.g. measurement of p^4 EW oblique parameters

	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2 \times 10^7\ Z$	0.3/ab	3/ab	10/ab	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3/ab	1/ab	1/ab
W $\times 10^4$	$[-19, 3]$	± 0.7	± 0.45	± 0.02	± 4.2	± 1.2	± 3.6	± 0.3	± 0.5	± 0.15
Y $\times 10^4$	$[-17, 4]$	± 2.3	± 1.2	± 0.06	± 1.8	± 1.5	± 3.1	± 0.2	$\sim \pm 0.5$	$\sim \pm 0.15$

energy helps accuracy

Farina et al '16

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} \propto E^2$$

⬌ precision of 0.1% @ 100GeV ≈ precision of 10% @ 1TeV
same sensitivity to new physics

at high energy, you can be sensitive without having to be precise

Composite Higgs

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

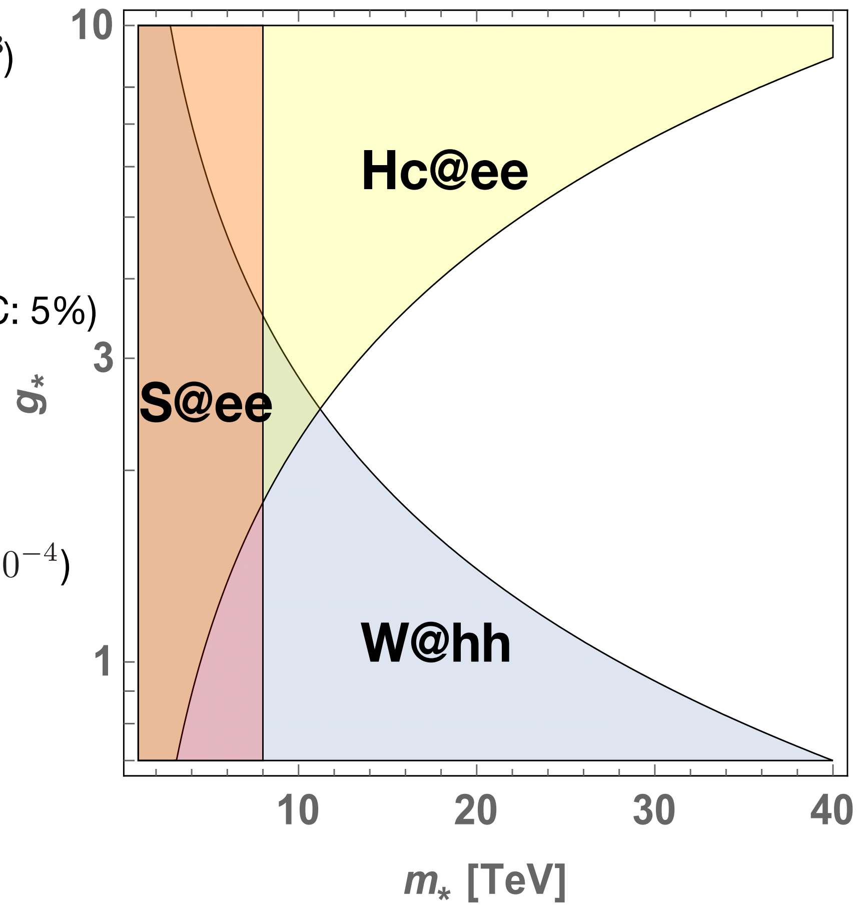
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \Rightarrow \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$

W @hh: (energy + accuracy) (HL-LHC<10^{-4})

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \Rightarrow W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < \ 10^{-5}$$



Grojean-Wulzer @ FCC physics week '17

Composite Top

Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}^{d=6}_{\text{BSM}} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2\overline{q}_L H t_R \Rightarrow \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

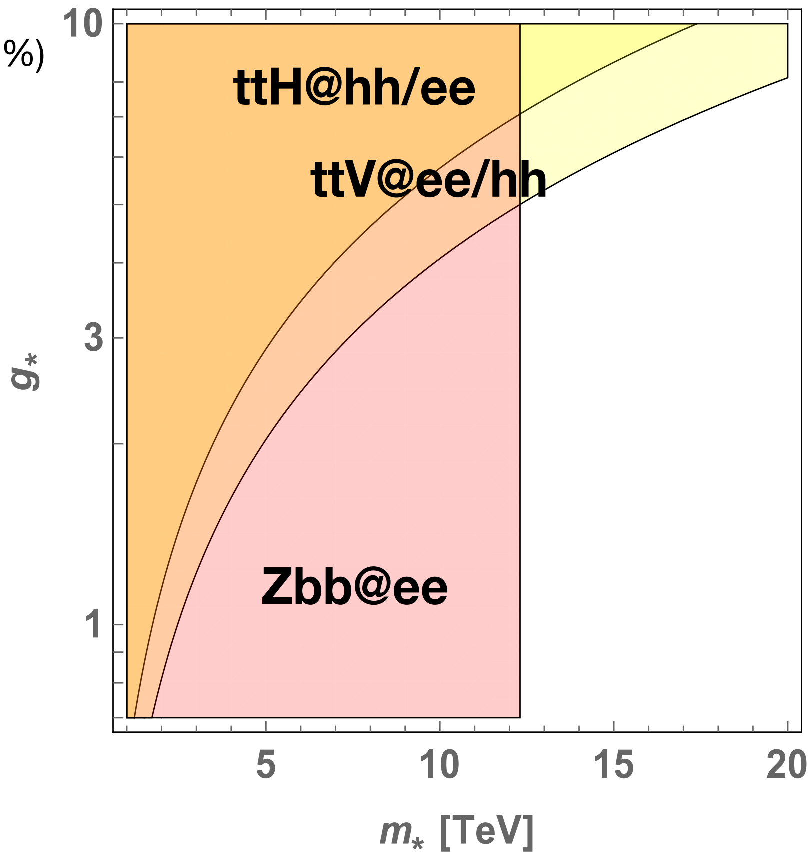
ttV coupling @ee/hh: [Janot / Farina et.al.]

$$\frac{g_*^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\,\bar{t}_R\gamma^\mu t_R \Rightarrow \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reach from en. + acc.?

Zbb coupling @ee: [ee Report] (LEP: 10^{-3})

$$\frac{y_t^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\,\overline{q}_L\gamma^\mu q_L + .. \Rightarrow \frac{\delta g_b}{g_b} = \frac{m_t^2}{m_*^2} < 2\,10^{-4}$$



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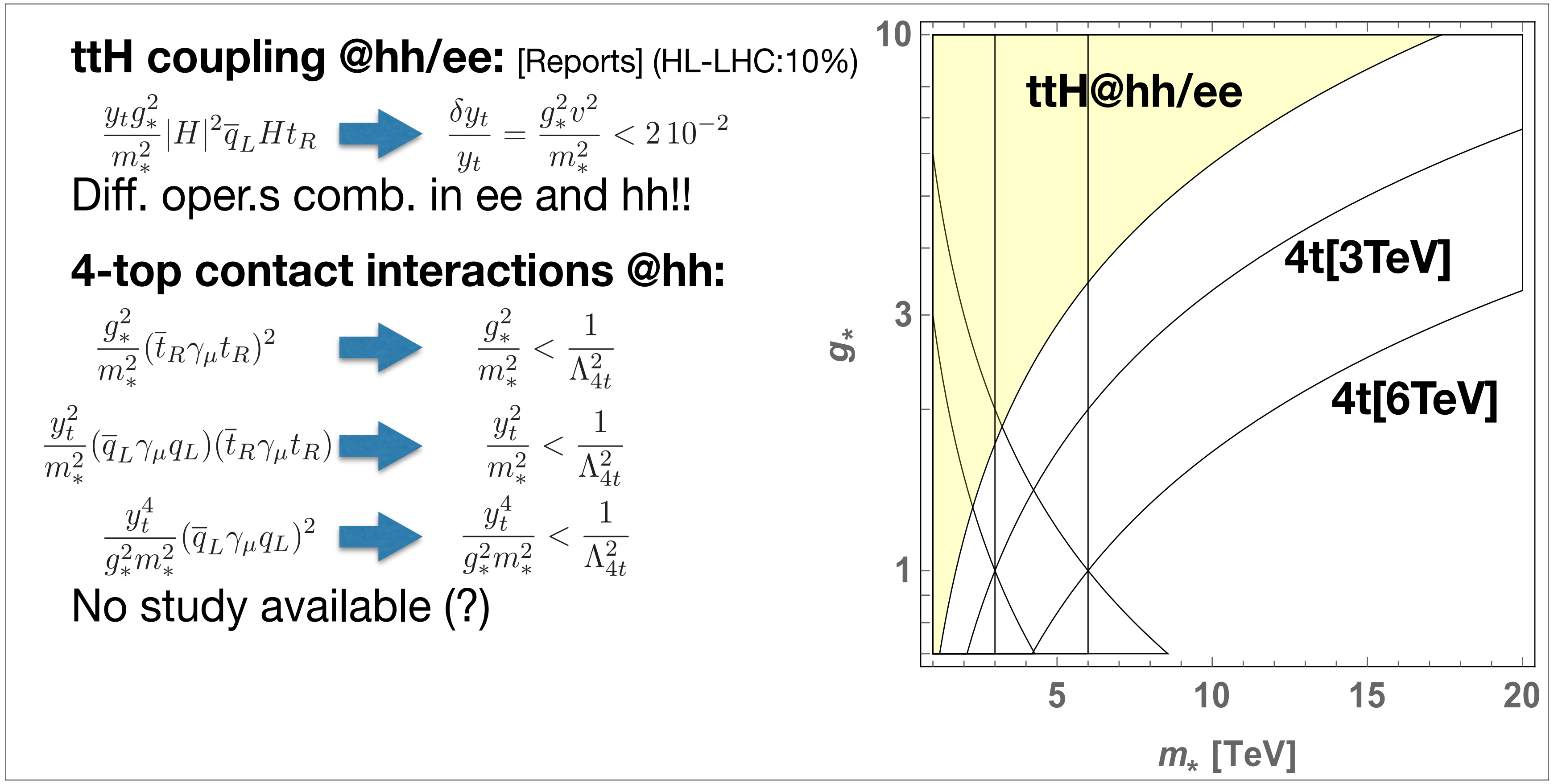

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2\bar{q}_L H t_R \rightarrow \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

4-top contact interactions @hh:

$$\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)^2 \rightarrow \frac{g_*^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^2}{m_*^2}(\bar{q}_L\gamma_\mu q_L)(\bar{t}_R\gamma_\mu t_R) \rightarrow \frac{y_t^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^4}{g_*^2 m_*^2}(\bar{q}_L\gamma_\mu q_L)^2 \rightarrow \frac{y_t^4}{g_*^2 m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

No study available (?)

Grojean-Wulzer @ FCC physics week '17

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Composite tR, comp. Higgs, **elementary tL** and gauge

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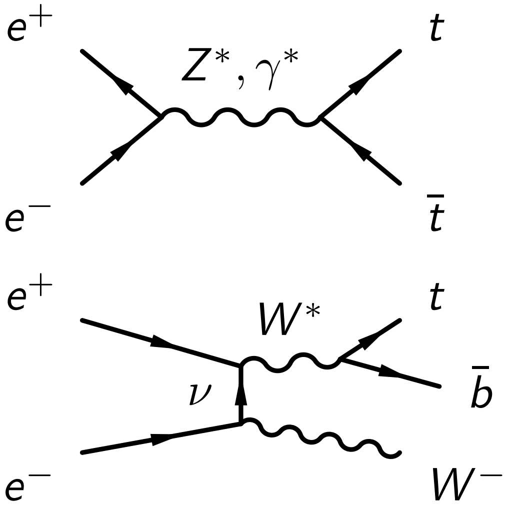
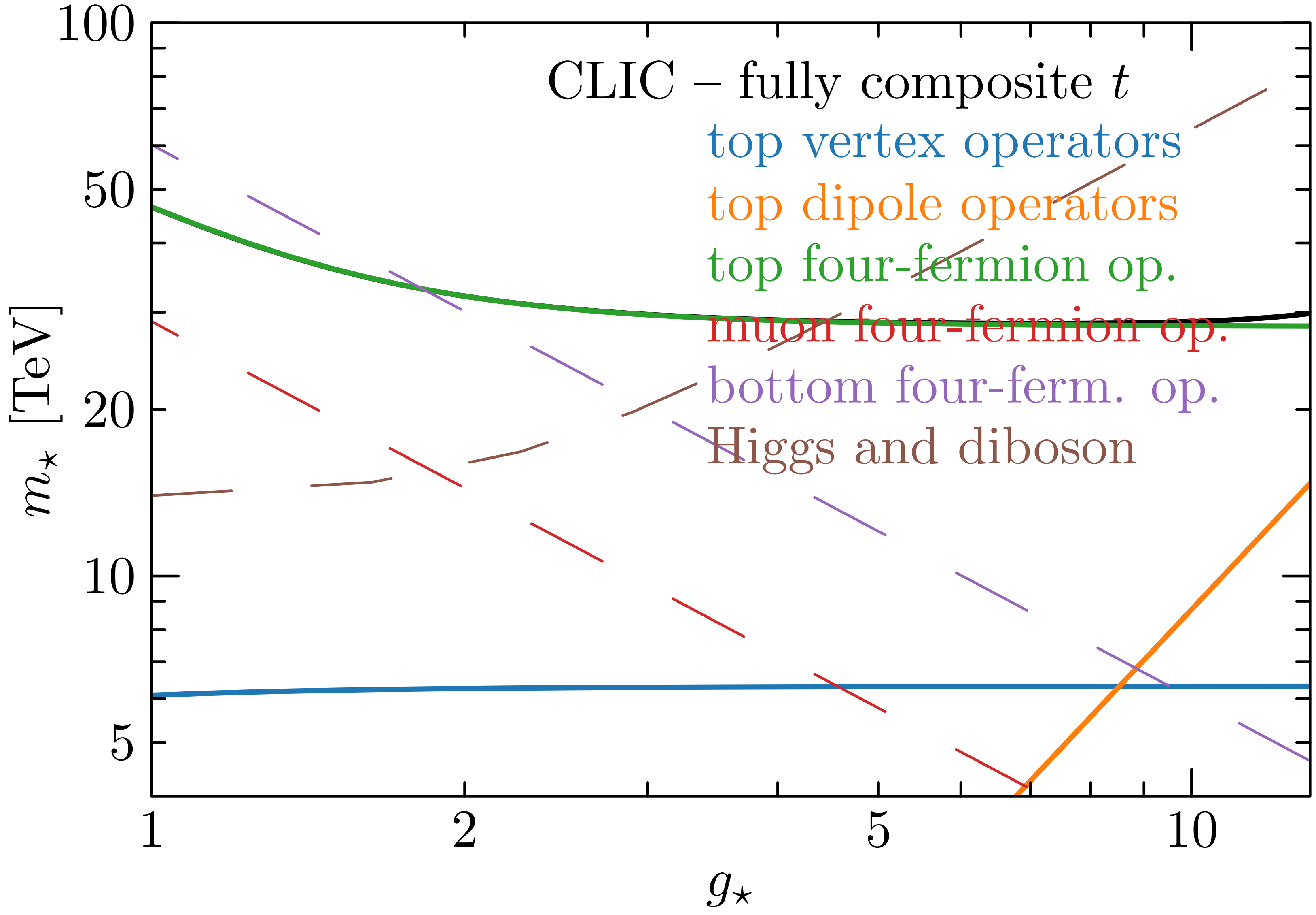
$e^+e^- \to bW^+\,\bar{b}W^-$





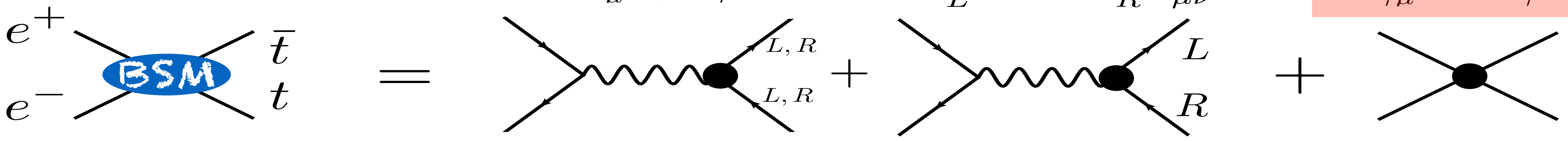
Durieux, Perello, Vos, Zhang ‘18

Durieux, Matsedonskyi ‘18

Composite Top @ high energy LC

Riva @ Top@LC '17

$H^\dagger \overleftrightarrow{D}_\mu H \bar{\Psi}^3\gamma^\mu\Psi^3$ | $\bar{\Psi}^3_L\sigma^{\mu\nu}H\Psi^3_R F_{\mu\nu}$ | $\bar{\Psi}^e\gamma_\mu\Psi^e\bar{\Psi}^3\gamma^\mu\Psi^3$



$\sim c_{H\Psi^3}\frac{v^2}{M^2}$ $\sim c_{F\Psi^3}\frac{vE}{M^2}$ $\sim c_{(\Psi)^4}\frac{E^2}{M^2}$

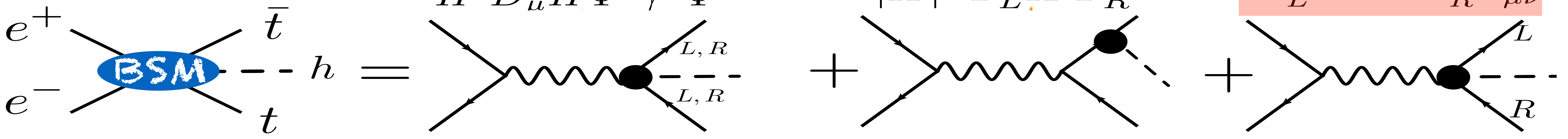
best measured @ threshold

$M \gtrsim \sqrt{c_{H\Psi^3}}\ 8\,\mathrm{TeV}$

best measured @ tail

$M \sim 30\,\frac{\sqrt{c_{(\Psi)^4}}}{g}\,\mathrm{TeV}$

$H^\dagger \overleftrightarrow{D}_\mu H \bar{\Psi}^3\gamma^\mu\Psi^3$ | $|H|^2\bar{\Psi}^3_L H\Psi^3_R$ | $\bar{\Psi}^3_L\sigma^{\mu\nu}H\Psi^3_R F_{\mu\nu}$



$c_{H\Psi^3}\frac{vE}{M^2}$ $\sim c_{y_t}\frac{v^2}{M^2}$ $c_{F\Psi^3}\frac{E^2}{M^2}$

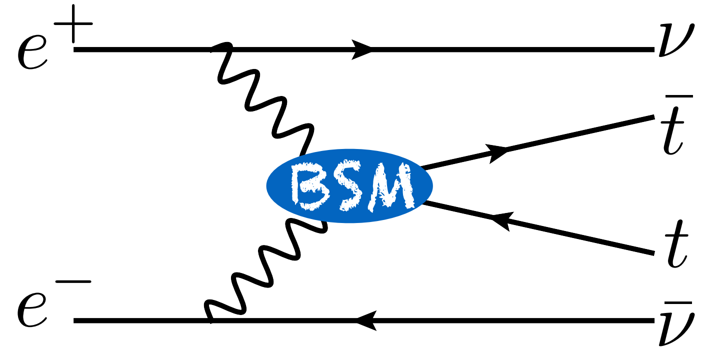
$M \gtrsim \sqrt{c_{y_t}/y_t}\ 1\,\mathrm{TeV}$

$M \gtrsim 15\sqrt{\frac{c_{F\Psi^3}}{gY_t}}\ \mathrm{TeV}$

Composite Top @ high energy LC

Riva @ Top@LC ’17

$$H^\dagger \overleftrightarrow{D}_\mu H \bar{\Psi}^3 \gamma^\mu \Psi^3$$



$$\sim c_{H\Psi^3} \frac{E^2}{M^2}$$

?

Grojean, Wulzer, You and Zhang ‘in progress

Probing interactions forbidden in SM

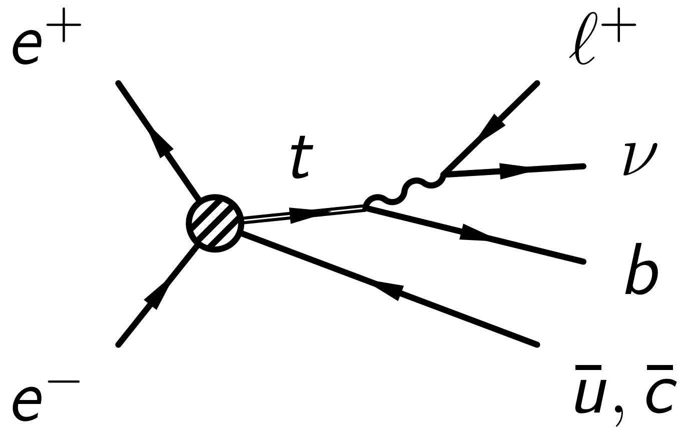
Top FCNC

Craig @ Top2017

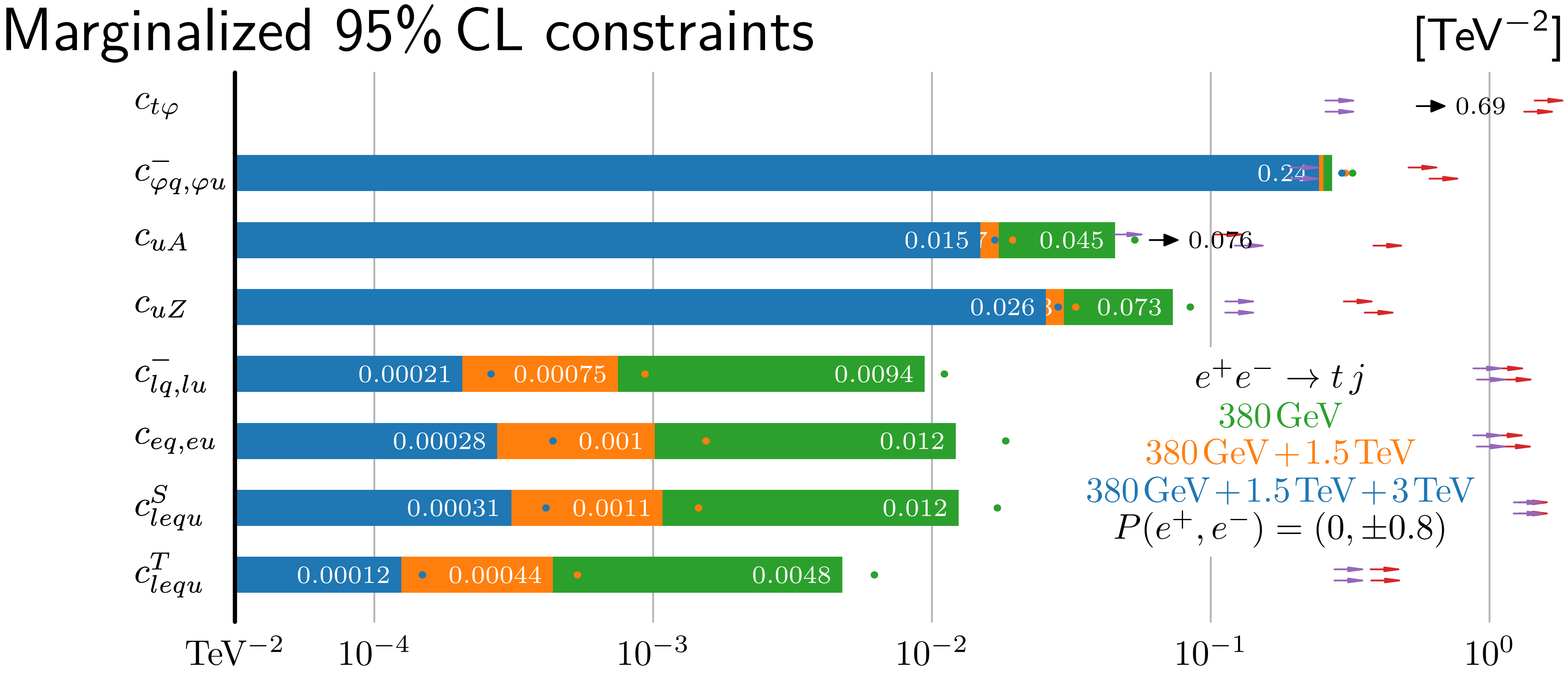
Mode	SM BR	BSM BR	LHC bound
t → ch	3×10^{-15}	10^{-3} (2HDM)	4.6×10^{-3}
t → uh	2×10^{-17}	10^{-5} (2HDM)	4.2×10^{-3}
t → cg	5×10^{-12}	10^{-4} (2HDM)	2×10^{-4}
t → ug	4×10^{-14}	10^{-6} (2HDM)	4×10^{-5}
t → cZ	1×10^{-14}	10^{-5} (RS)	2×10^{-4}
t → uZ	8×10^{-17}	10^{-8} (2HDM)	1.7×10^{-4}
t → cγ	5×10^{-14}	10^{-7} (2HDM)	1.7×10^{-3}
t → uγ	4×10^{-16}	10^{-9} (2HDM	1.3×10^{-4}

Probing interactions forbidden in SM

Top FCNC



Durieux et al, ‘in progress



[CLIC YR]

- compared to decay: black arrows
- compared to current limits: red arrows up charm
- compared to HL-LHC estimates: purple arrows up charm
- without beam polarization: blobs

Beyond Colliders

Physics probed at Colliders

Colliders are best places to search for

Heavy objects
With short lifetime
That are rarely produced
That have a direct coupling to quarks/gluons or electrons

Are we sure that BSM falls in this category?
No, and actually, we only have evidence that BSM has gravitational interactions
There are compelling arguments that BSM can be seen at colliders
But we can also find mind-boggling BSM signatures beyond colliders
And more and more connections to the “big unanswered questions” in physics

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran ’15

Espinosa et al ’15

- m$_H$(t): $m_H^2(t=-\infty) = \Lambda^2_{\mathrm{cutoff}} \to m_H^2(\mathrm{now}) = -(125\,\mathrm{GeV})^2$
- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe and scans a vast range of Higgs mass. But “Why/How/When does it stop evolving?”
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking back-reacts on the relaxion field and stops the time-evolution of the dynamical system

Self-organised criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

Hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

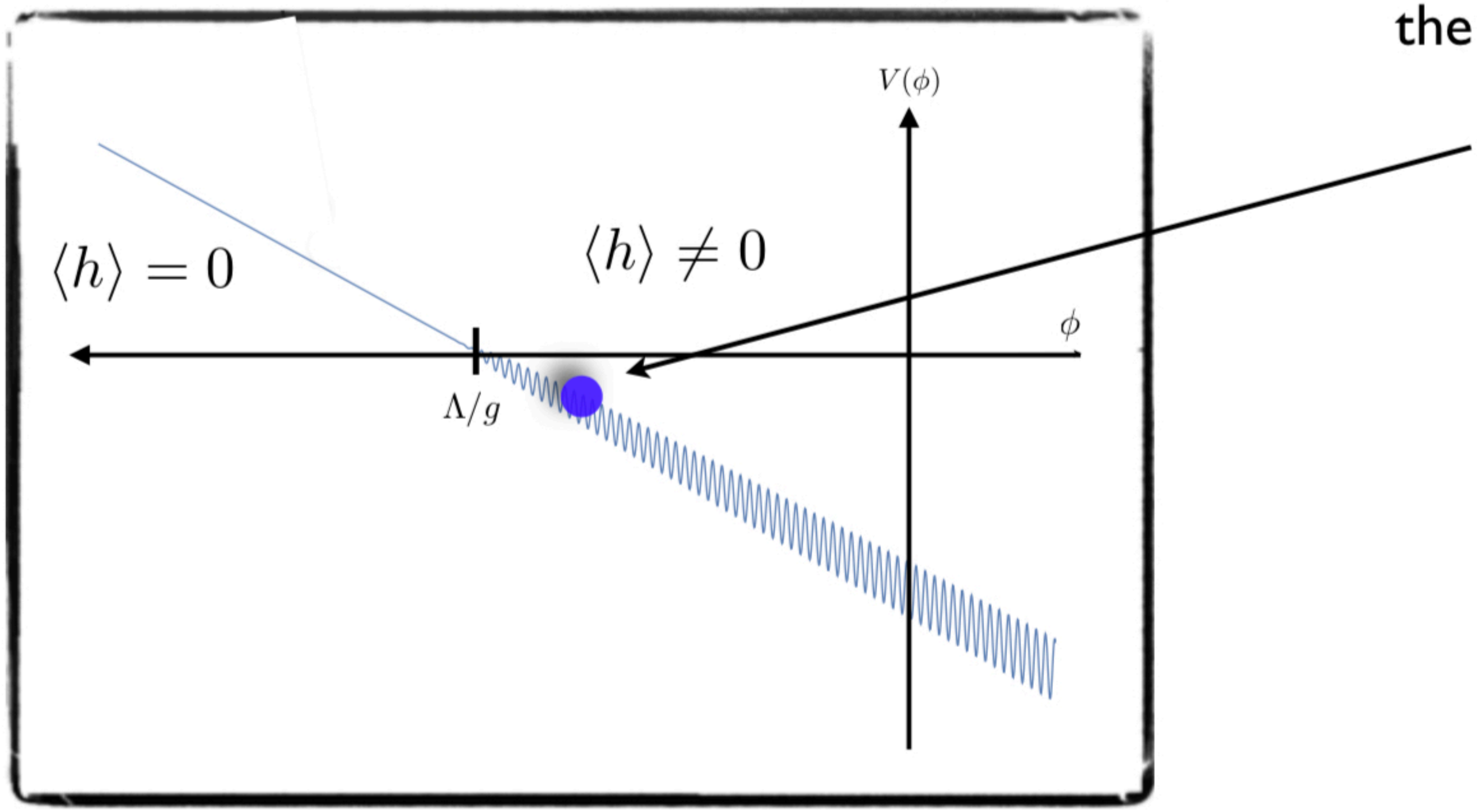
ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev



$$\Lambda^3_{\rm QCD}\, h\, \cos\frac{\phi}{f}$$

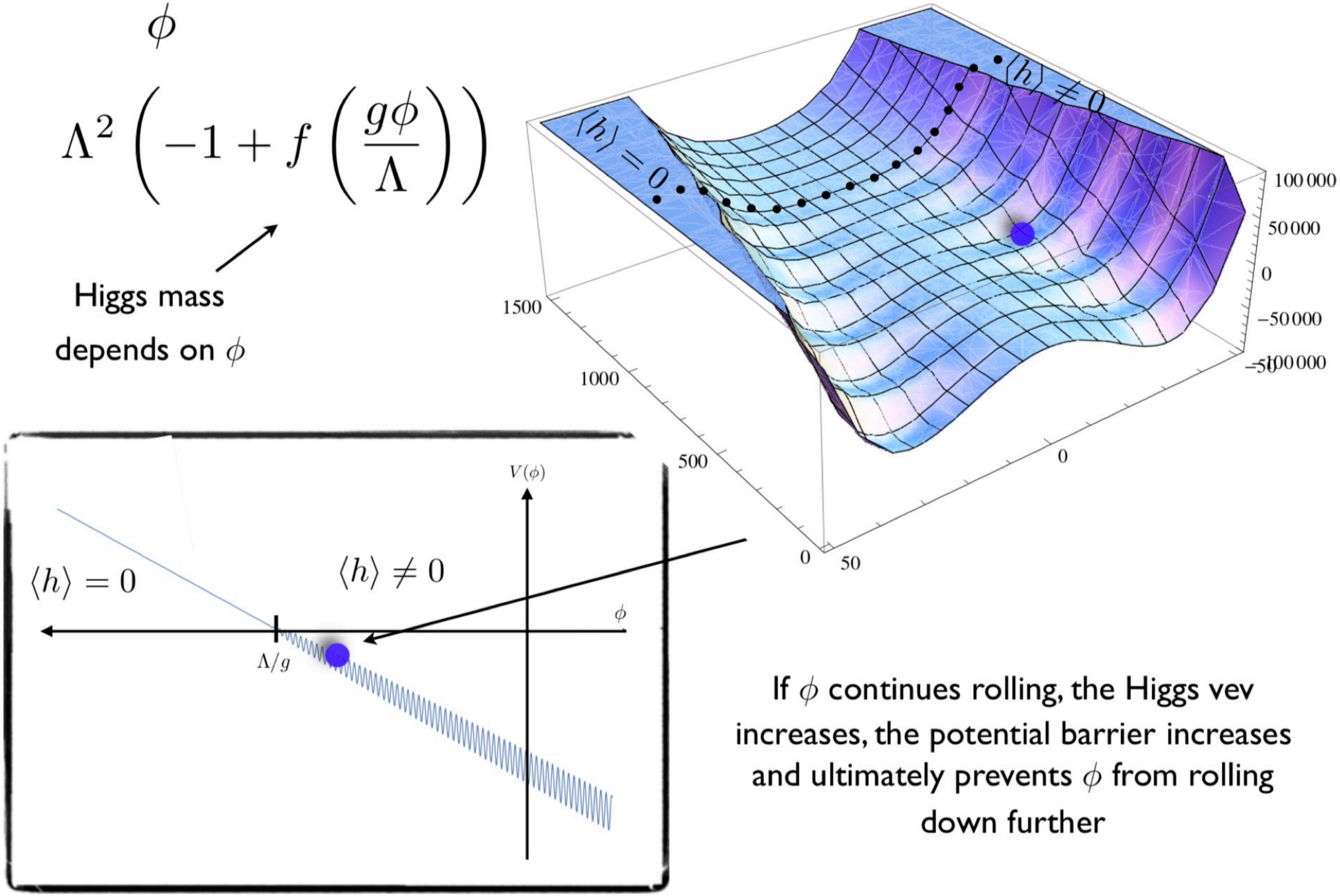
Higgs-axion cosmological relaxation

ham, Kaplan, Rajendran ’15

$$\phi$$

$$\Lambda^2 \left(-1 + f\left(\frac{g\phi}{\Lambda}\right)\right)$$

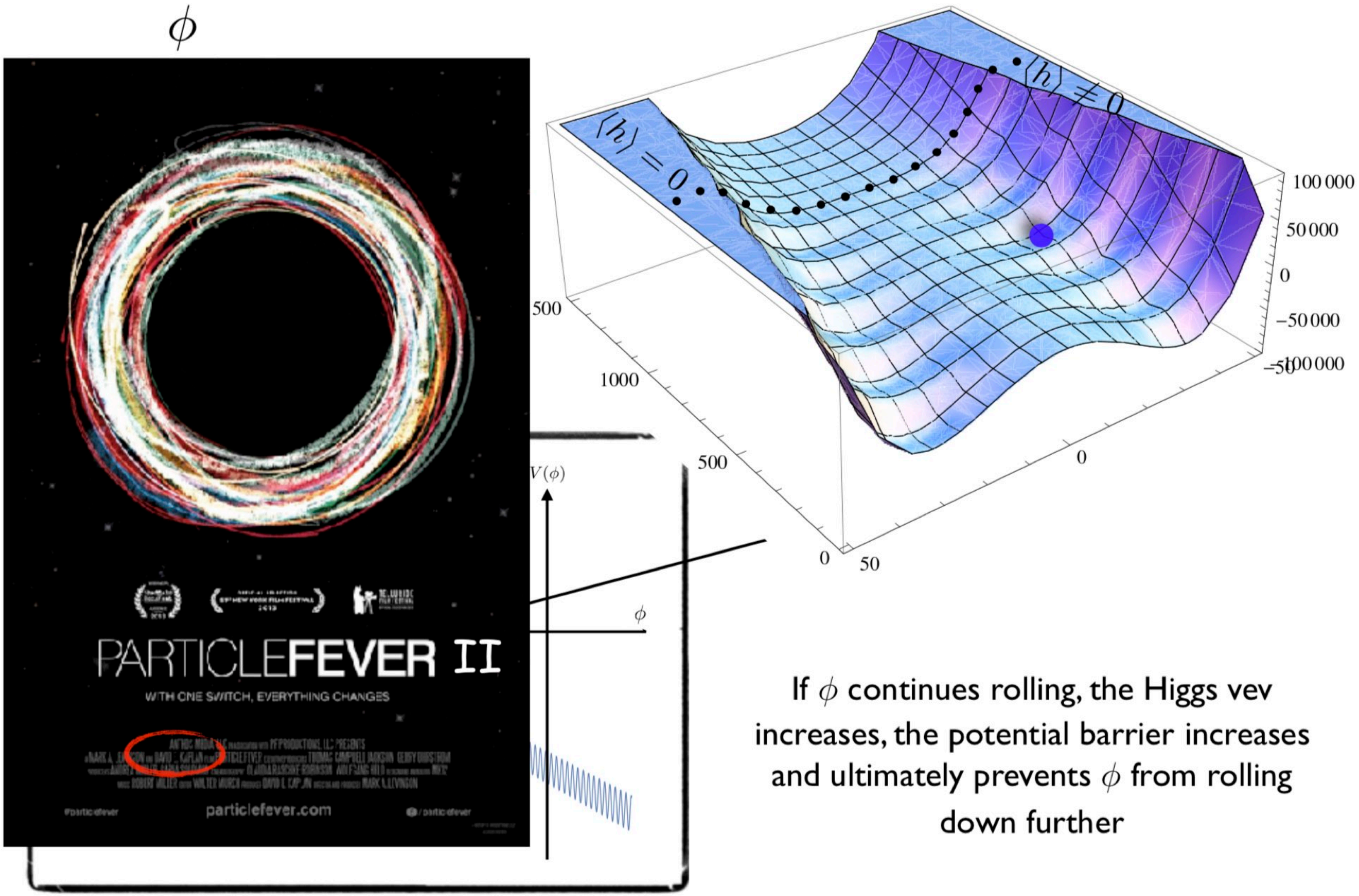
Higgs mass depends on ϕ



If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

Higgs-axion cosmological relaxation

ham, Kaplan, Rajendran '15



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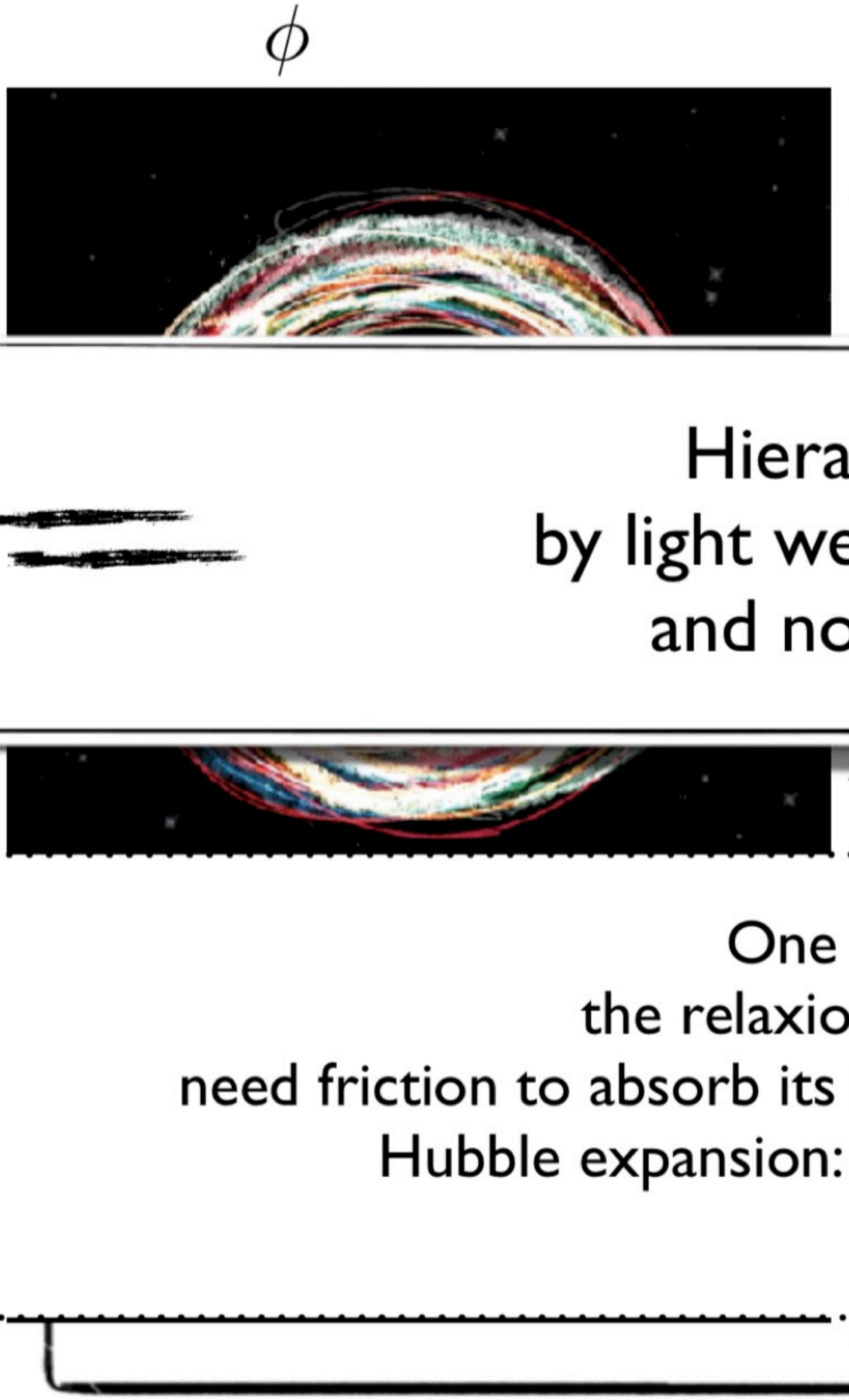
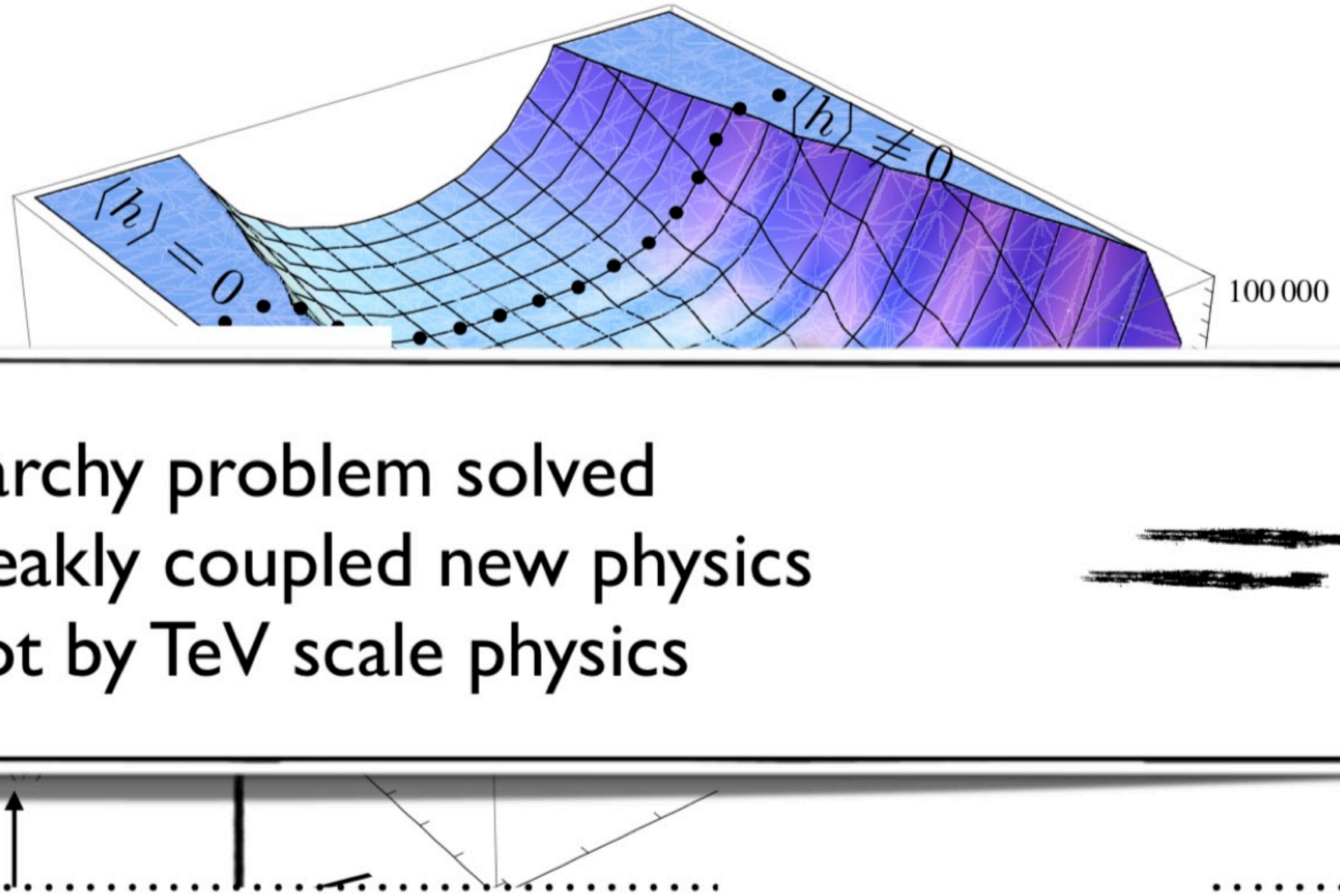
Higgs-axion cosmological relaxation

ham, Kaplan, Rajendran '15





Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

One needs to make sure that
the relaxion doesn't overshot the bumps
need friction to absorb its kinetic energy when rolling down its potential
Hubble expansion: energy makes the Universe expanding

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below Λ

one/two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

interesting signatures in cosmology

Phenomenological signatures

~interesting cosmology signatures~

◎ BBN constraints

◎ decaying DM signs in γ-rays background

◎ ALPs

◎ superradiance (BH losing angular momentum by accelerating relaxion)

~ interesting signatures @ beam dump experiments (e.g. SHiP) ~

◎ production of light scalars by B and K decays

only BSM physics below Λ

one/two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^2)\,\mathrm{GeV}$$

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Phenomenological signatures

~interesting cosmology signatures~

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~ interesting signatures @ beam dump experiments (e.g. SHiP) ~

◎ production of light scalars by B and K decays

~connections with DM~

◎ coherent oscillations of the relaxion around its minimum ≈ DM

~interesting signatures in atomic physics~

◎ oscillations of the relaxion around its minimum

⇛ oscillations of the Higgs vev

⇛ oscillations of the mass of the proton, of the size of the atoms

◎ isotope shifts, piezo-electric atoms...

Views from the top

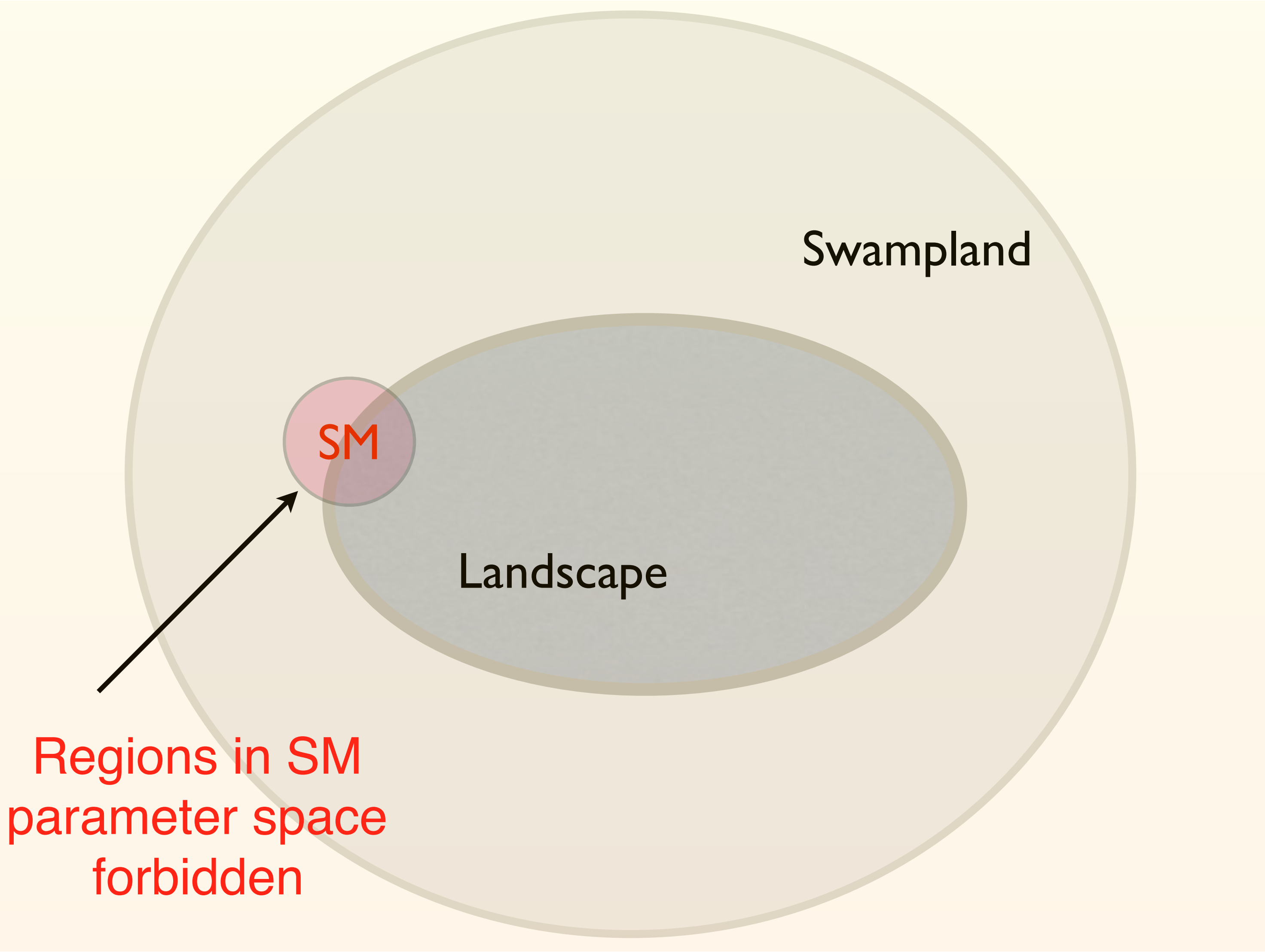
Swampland: UV/IR mixing

Particle Physics & Quantum Gravity

Can the SM be embedded in a theory of quantum gravity at the Planck scale?
Can QG be really decoupled at low energy?

Would certainly be true if any QFT can be consistently coupled to QG

Instead Vafa conjectured in 2005 that there exists a **swampland**



Ibanez @ SUSY'18

Regions in SM parameter space forbidden

This conjecture has potentially far-reaching implications for phenomenology

Swampland Conjectures

0) No exact global symmetry

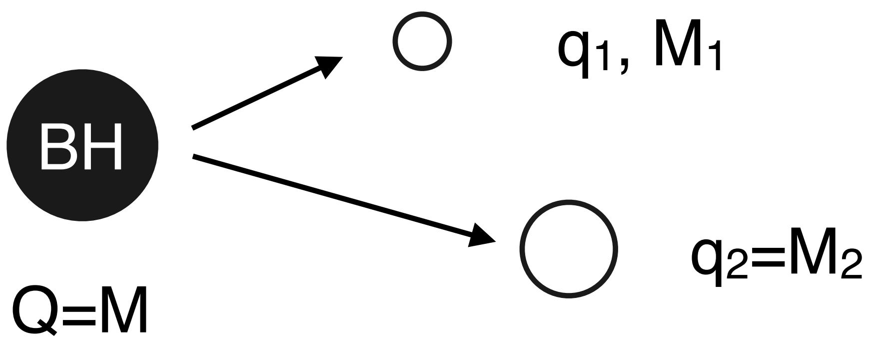
For a review, see Banks, Seiberg '10

1) Gravity is the weakest force

Arkani-Hamed, Motl, Nicolis, Vafa '06

In any UV complete U(1) gauge theory there must exist at least one charged particle with mass M such that: $M/M_P < g \,.\, q$

Why? otherwise extremal charged BH cannot decay!



BH can decay iff $M_1+M_2<M$, i.e. $M_1<M-M_2=Q-q_2=q_1$

Swampland Conjectures

2) non-susy AdS vacua (Vmin<0) are unstable

Ooguri, Vafa '16

Consider the SM (with cc) compactified on a circle of radius R

Ibanez, Martin-Lozano, Valenzuela '17

$$V(R) \simeq \frac{2\pi r^3 \Lambda_4}{R^2} - 4\left(\frac{r^3}{720\pi R^6}\right) + \sum_i (2\pi R)(-1)^{s_i} n_i \rho_i(R)$$

From 4D c.c.

$\gamma, g_{\mu\nu}$

ν_i

$$\rho(R) = \mp \sum_{n=1}^{\infty} \frac{2m^4}{(2\pi)^2} \frac{K_2(2\pi R m n)}{(2\pi R m n)^2}$$

Ibanez @ SUSY'18

Heavier particles have exponentially small contribution

Majorana neutrinos leads to an AdS vacuum ⇒ in swampland

Dirac neutrinos avoid AdS vacuum iif $m_\nu^4 < \Lambda_4$

$\langle H \rangle < 1.6 \frac{\Lambda_4^{1/4}}{Y_\nu}$ ⇒ Large quantum corrections end up in swampland (for fixed Λ_4 and Y_ν)

SM with 3 families but without Higgs also develops AdS vacuum ⇒ in swampland

Swampland Conjectures

3) $M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel > c\, V(\phi_i)$ with c is O(1) for any field configuration

Obied, Ooguri, Spodyneiko, Vafa '18

- Pure positive cosmological constant, i.e. vacuum energy, (dS vacuum) is forbidden

- Quintessence: Agrawal, Obied, Steinhart, Rafa '18

$$V(\phi) = \Lambda^4 e^{-\kappa\phi/M_P}$$

$$0.6 > \kappa > c$$

Planck data ⤴ ⤴ swampland conjecture

- Quintessence + Higgs: Denef, Hebecker, Wrase '18

$$V(H,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \lambda(|H|^2 - v^2)^2 + V_0$$

$$M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel = \begin{array}{ll} \dfrac{\kappa\Lambda^4}{\Lambda^4 + \lambda v^4 + V_0} & @(H=0,\phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(H=v,\phi=0) \end{array}$$

at least one of them is as small as

$$\mathcal{O}\left(\frac{\text{cc}}{\text{EW}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(100\,\text{GeV})^4} \sim 10^{-56}$$

- Quintessence + axion: Murayama, Yamazaki, Yanagida '18

$$V(\theta,\phi) = \Lambda^4 e^{-\kappa\phi/M_P} + \Lambda^4_{QCD}(1-\cos(\theta/f)) + V_0$$

$$M_P \parallel \vec{\nabla}_{\phi_i} V(\phi_i) \parallel = \begin{array}{ll} \dfrac{\kappa\Lambda^4}{\Lambda^4 + V_0} & @(\theta=0,\phi=0) \\ \dfrac{\kappa\Lambda^4}{\Lambda^4 + \Lambda^4_{QCD} + V_0} & @(\theta=\pi f,\phi=0) \end{array}$$

at least one of them is as small as

$$\mathcal{O}\left(\frac{\text{cc}}{\text{QCD}^4}\right) \sim \frac{(10^{-3}\,\text{eV})^4}{(200\,\text{MeV})^4} \sim 10^{-44}$$

Swampland Conjectures

It is not that SM as we know it rules out string theory
But non-trivial interactions among seemingly decoupled sectors must exist
UV forces interactions among IR dof
like anomaly condition forces WZ interactions below the top quark

Conclusion(s)

Status of HEP: Executive summary

BAD NEWS

Experimentalists haven't found (yet)
what theorists told them they will find

GOOD NEWS

There are rich opportunities
for mind-boggling signatures
@ colliders and beyond

Technology is being developed to explore
the energy and intensity frontiers of knowledge

“Looking and not finding is different than not looking”

M. Zuckerberg created FaceMash before Facebook

J.K. Rowling got rejected 12 times by editors before she published Harry Potter

Beyonce wrote hundreds of songs before ‘Halo’

... Physicists searching for BSM ...

one doesn’t have to succeed on the first try

“the success comes from the freedom to fail”

M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017