General experimental requirements

Search for HS particles in Heavy Flavour decays

HS produced in charm and beauty decays have significant $P_T$.

Detector must be placed close to the target to maximize geometrical acceptance.

Effective (and "short") muon shield is essential to reduce muon-induced backgrounds.
A unique moment in the history of physics

The Higgs discovery is the triumph of XX\textsuperscript{th} century physics combination of Quantum Mechanism + Special Relativity
A unique moment in the history of physics

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For the first time in the history of physics, we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up $M_{\text{Planck}}$?)
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The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don’t understand, we do understand the Matter we’re made from, and that we encounter in normal life - even if we’re chemists, engineers, or astrophysicists (sic: DM!)
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The SM is not free of inadequacies:

1. Only a description of EW symmetry breaking, not an explanation
   furthermore Higgs field requires a delicate cancelation of large radiative corrections
2. No place for the particle(s) that make up the cosmic DM
3. Does not explain the asymmetry matter-antimatter
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we do not understand the Matter the Universe is made from
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Where and how does the SM break down?
Which machine(s) will reveal this breakdown?

The SM is not free of inadequacies:

1. Only a description of EW symmetry breaking, not an explanation
   furthermore Higgs field requires a delicate cancelation of large radiative corrections
2. No place for the particle(s) that make up the cosmic DM
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we do not understand the Matter the Universe is made from
The world according to LHC

LHC
- splice consolidation
- collimation, cryogenics, ...
- HL-LHC installations

- LS1
  - 13-14 TeV
  - ~30 fb⁻¹

- LS2
  - 14 TeV
  - ~100 fb⁻¹
  - 2020, 2021, 2022, 2023

- LS3
  - 14 TeV
  - ~300 fb⁻¹
  - 2024, 2025

~3000 fb⁻¹ until 2035
The world according to LHC

Direct exploration of an uncharted territory

A significative energy step
(maybe the last one before a long time)
The world according to LHC

LHC

splice consolidation

collimation, cryogenics, ...

HL-LHC installations

~30 fb⁻¹

13-14 TeV

14 TeV

14 TeV

~100 fb⁻¹

~300 fb⁻¹

~3000 fb⁻¹ until 2035


Based on partonic luminosities using MSTW2008NNLO central

ΣΣ

Σg

Σ_i q_i \bar{q}_i

gg

~300 fb⁻¹

~30 fb⁻¹

300 fb⁻¹

3000 fb⁻¹

Direct exploration of an uncharted territory

A significative energy step
(maybe the last one before a long time)

What can be discovered @ 100/fb-14TeV knowing what is excluded @ 20/fb-8TeV?
The world according to LHC

LHC

splice consolidation

collimation, cryogenics, ...

HL-LHC installations

~3000 fb\(^{-1}\) until 2035

CERN, July 2, 2015

Christophe Grojean

What can be discovered @ 100 fb\(^{-1}\) 14 TeV
knowing what is excluded @ 20 fb\(^{-1}\) 8 TeV?

The world according to LHC

Direct exploration

of an uncharted territory

14 TeV

HL-LHC

splice

consolidation

LHC

13-14 TeV

~100 fb\(^{-1}\)

LS2

14 TeV

~300 fb\(^{-1}\)

~3000 fb\(^{-1}\)

LS3

14 TeV

2013

2024

2035

collimation, cryogenics, ...

LS1

2014

2025

LS2

2015

2036

LS3

2016

2037

~30 fb\(^{-1}\)

300 fb\(^{-1}\)

3000 fb\(^{-1}\)

~30 fb\(^{-1}\)

system mass [TeV] for LHC14

system mass [TeV] for LHC8 20 fb\(^{-1}\)

Based on partonic luminosities using MSTW2008NNLO central

G.P. Salam and A. Weiler for ECFA HL-LHC WG

ΣΣ

Σ

g

Σ

q

i

−

q

i

Σ

gg

mass reach x O(2)

A significative energy step (maybe the last one before a long time)

Future colliders comparison

• The ILC new physics program has been studied in great detail, and has excellent capabilities to discover and measure the properties of new physics, including dark matter, with almost no loopholes. A necessary requirement is that the new physics must be accessible. Essentially this means particles at sufficiently low mass missed by LHC due to blind spots, or heavy physics indirectly accessible through precision measurement. Discovery of physics beyond the standard model at LHC that is accessible at ILC would make the case even more compelling.

• A 100 TeV pp collider has unprecedented and robust reach for new physics that is evident even with the preliminary level of studies performed so far. It can probe an additional two orders of magnitude in fine-tuning in supersymmetry compared to LHC14, and can discover WIMP dark matter up to the TeV mass scale. Any discovery at the LHC would be accessible at this machine and could be better studied there, making the case for these options even more compelling.

• High energy e\(^{+}\)e\(^{-}\) colliders such as CLIC and muon colliders offer a long-term program that can extend precision and reach of a wide range of physics.

A summary of the energy reach for a range of physics beyond the SM at various proposed facilities is shown in Fig. 1-1. This is a highly simplified plot. In particular, although the mass reach of hadron colliders is generally very impressive, hadron colliders searches often have blind spots, for example due to compressed spectra or suppressed couplings. Searches at e\(^{+}\)e\(^{-}\) colliders are much more model independent, but generally have more limited mass reach. Many examples of this complementarity are discussed in the body of this report.

Figure 1-1.

95% confidence level upper limits for masses of new particles beyond the standard model expected from pp and e\(^{+}\)e\(^{-}\) colliders at different energies. Although upper mass reach is generally higher at pp colliders, these searches often have low-mass loopholes, while e\(^{+}\)e\(^{-}\) collider searches are remarkably free of such loopholes.

Community Planning Study: Snowmass 2013

Energy Frontier Snowmass Study ('13)

Energy Frontier Snowmass Study ('13)
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model

Higgs

TeV scale
squarks & gluinos
extra Higgses
neutralino
We had a dream...

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solution
to hierarchy pb

(g-2)_{\mu}
nice signatures in
flavor physics
(\mu \rightarrow e\gamma, B_s \rightarrow \mu\mu)
baryogenesis
matter-antimatter
asymmetry

DM
relic abundance
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model

- Higgs
- TeV scale squarks & gluinos
- extra Higgses
- neutralino
- solution to hierarchy pb

\[(g-2)_\mu\]

- nice signatures in flavor physics: \(\mu \rightarrow e\gamma, B_s \rightarrow \mu\mu\)
- DM relic abundance
- baryogenesis matter-antimatter asymmetry

- gauge coupling unification

\(E\)
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model

- Higgs
- TeV scale
- squarks & gluinos
- extra Higgses
- neutralino

➾

- gauge coupling unification

- string theory

- solution to hierarchy pb
- \((g-2)_\mu\)
- nice signatures in flavor physics \((\mu \rightarrow e\gamma, B_s \rightarrow \mu\mu)\)
- DM relic abundance
- baryogenesis
- matter-antimatter asymmetry
- Quantum gravity
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model

There were many evidences that made this grand picture plausible

- Higgs
- TeV scale squarks & gluinos
- extra Higgses
- neutralino

(solution to hierarchy pb)

(g-2)$_\mu$

- nice signatures in flavor physics ($\mu \rightarrow e\gamma$, $B_s \rightarrow \mu\mu$)
- baryogenesis
- matter-antimatter asymmetry

- gauge coupling unification

- string theory

- Quantum gravity

- E
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It could have been true!

- Higgs
- TeV scale
- squarks & gluinos
- extra Higgses
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- gauge coupling unification
- string theory
- Quantum gravity

Christophe Grojean

Physics Landscape

CERN, July 2, 2015
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model

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solution to hierarchy pb

(g-2)$_{\mu}$

nice signatures in flavor physics ($\mu \rightarrow e\gamma$, $B_s \rightarrow \mu\mu$)

baryogenesis

matter-antimatter asymmetry

DM relic abundance

It could have been true!

It can still be true (modulo little tunings)

string theory

quantum gravity
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model yesterday.
We had a dream...

Theorists had a clear agenda for physics beyond the Standard Model

yesterday

today dreaming about tomorrow
HEP with a Higgs boson

"If you don't have the ball, you cannot score"

"If you don't have the ball, you cannot score"
HEP with a Higgs boson

"If you don’t have the ball, you cannot score"

Now with the Higgs boson in their feet, particle physicists can... play as well as Germans against Brazilians
HEP with a Higgs boson

“If you don’t have the ball, you cannot score”

Now with the Higgs boson in their feet, particle physicists can... play as well as Germans against Brazilians

Profound change in paradigm:
missing SM particle ⇔ tool to explore SM and venture into physics landscape beyond
HEP with a Higgs boson

The successes have been breathtaking

- in O(2) years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
- some of its couplings, e.g. $\kappa_\gamma$, have been measured with LEP accuracy ($10^{-3}$)
HEP with a Higgs boson

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The meaning of the Higgs

Particle physics is not so much about particles but more about fundamental principles

- About $10^{-10}$s after the Big Bang, the Universe filled with the Higgs substance because it saved energy by doing so: the vacuum is not empty!

- The masses are emergent quantities due to a non-trivial vacuum structure
HEP with a Higgs boson

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▷ in $O(2)$ years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
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Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, CepC, CppC, SHiP

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

M.L. Mangano, Washington '15
**HEP with a Higgs boson**

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multiple independent, synergetic and complementary approaches to achieve precision (couplings), sensitivity (rare and forbidden decays) and perspective (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

- rare Higgs decays: $h \rightarrow \mu\mu$, $h \rightarrow \gamma Z$
- Higgs flavor violating couplings: $h \rightarrow \mu\tau$ and $t \rightarrow hc$
- Higgs CP violating couplings
- exclusive Higgs decays (e.g. $h \rightarrow J/\Psi+\gamma$) and measurement of couplings to light quarks
- exotic Higgs decay channels:
  - $h \rightarrow E_T$, $h \rightarrow 4b$, $h \rightarrow 2b2\mu$, $h \rightarrow 4\tau,2\tau2\mu$, $h \rightarrow 4j$, $h \rightarrow 2\gamma2j$, $h \rightarrow 4\gamma$, $h \rightarrow \gamma/2\gamma+E_T$
  - $h \rightarrow$ isolated leptons+$E_T$, $h \rightarrow 2l+$ $E_T$, $h \rightarrow$ one/two lepton-jet(s)+X, $h \rightarrow bb+$ $E_T$, $h \rightarrow \tau\tau+$ $E_T$ ... 
- searches for extended Higgs sectors ($H, A, H^\pm, H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

M.L. Mangano, Washington '15
Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

Supersymmetry (MSSM)

MSSM ($\tan\beta = 5, M_A = 700 \text{ GeV}$)

Composite Higgs (MCHM5)

MCHM5 ($f = 1.5 \text{ TeV}$)

ILC Physics WG, '15
Higgs couplings and model discriminations

The pattern of Higgs coupling deviations is a signature of the underlying dynamics beyond the Standard Model

~~ expected largest relative deviations ~~

<table>
<thead>
<tr>
<th></th>
<th>hff</th>
<th>hVV</th>
<th>h(\gamma\gamma)</th>
<th>h(\gamma)Z</th>
<th>hGG</th>
<th>h(^3)</th>
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<td>MSSM</td>
<td>√</td>
<td></td>
<td>√</td>
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<td>√</td>
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<td>NMSSM</td>
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<td>PGB Composite</td>
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<tr>
<td>SUSY Composite</td>
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<tr>
<td>SUSY partly-composite</td>
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<td>“Bosonic TC”</td>
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<td>Higgs as a dilaton</td>
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A. Pomarol, Naturalness ’15
The Higgs boson and the gauge principle

Particle physics is not so much about particles but more about fundamental principles
The Higgs boson and the gauge principle

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One of the most puzzling questions raised by the Higgs discovery:

Are gauge theories the right principle to understand/describe fundamental interactions?
The Higgs boson and the gauge principle

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\[ \mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + (y_{ij} \bar{\psi}_L \psi_R H + h.c.) \]

- vacuum energy
- hierarchy problem
- trivitiy/stability
- mass and mixing
- flavour & CP

Higgs interactions: many different couplings not set by any gauge symmetry
The Higgs boson and the gauge principle

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$$\mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + (y_{ij} \bar{\psi}_{Li} \psi_{Rj} H + h.c.)$$

- vacuum energy
- hierarchy problem
- trivality/stability of EW vacuum
- mass and mixing hierarchy
- flavour & CP

Higgs interactions: many different couplings not set by any gauge symmetry

What are the interactions of the non-SM matter?
The interactions of the non-SM matter

the jury is still out

The diagram illustrates the landscape of physics with the energy scale and interaction strength axes. The known physics region includes SUSY, extra dimensions, and Composite Higgs at the Energy Frontier, while the Intensity Frontier with hidden sectors is found at lower energy scales. The unknown physics region is yet to be explored. The diagram suggests that the jury is still out on the nature of physics beyond the Standard Model.
We expected TeV scale new physics with sizable couplings to solve the hierarchy problem, and, since it is easy to obtain DM out of it, there was no need for light/hidden sector
We expected TeV scale new physics with sizable couplings to solve the hierarchy problem, and, since it is easy to obtain DM out of it, there was no need for light/hidden sector

Except for the QCD axion,
light weakly coupled new sector was not part of the theory Grand Picture
Where is everybody: Should we worry?

In the context of a concrete model, here MSUGRA/cMSSM

- eg. for $m(\text{squark}) = m(\text{gluino})$, exclude below ~1800 GeV
- these searches typically target large $M_{\text{SN]}$ and large difference $m(\text{SUSY}) - m(\text{LSP})$
- the very inclusive searches keep sensitivity even for $m(\text{LSP})$
  up to several hundreds of GeV (at some stage trigger-constrained)

in the context of a simplified MSSM scenario

cMSSM ➔ Natural SUSY/RPV SUSY

There are still holes and the LHC will look at them
The energy scale(s) of new physics

Theories of Dark Matter

- Superpartner particles: Wino, Bino, Higgsino, sneutrino, ...
- Axions
- Kaluza Klein particles from extra dimensions
- Sterile neutrinos
- Asymmetric dark matter
- Wimpzillas (don’t ask…)
- Dark matter bestiary

T. Tait, DM@LHC '14
The energy scale(s) of new physics

Theories of Dark Matter

T. Tait, DM@LHC ’14

The prediction about the mass scale of DM comes with large error bars:

\[ 10^{-22} \text{ eV} < m_{DM} < 10^{20} \text{ GeV} \]

(ALPs) \quad \text{or} \quad \text{(Wimpzillas, Q-balls)}
An interesting experimental clue (?)

Distributions of DM are flatter than what $\Lambda$CDM predicts

S.H. Oh et al. ’15

$\rho \sim r^\alpha$

$\sigma/m_\chi \sim 1 \text{ cm}^2/\text{g} \approx 2 \text{ barns/GeV}$

S. Tullin, IFAE ’15
An interesting experimental clue (?)

Distributions of DM are flatter than what $\Lambda$CDM predicts

S.H. Oh et al. ’15

Cores in different systems are probing self-interactions at different energies

Dwarf galaxy
Spiral galaxy
Cluster of galaxies

Low energies (v/c \(\sim 10^{-4}\))
Medium energies (v/c \(\sim 10^{-3}\))
High energies (v/c \(\sim 10^{-2}\))

Like probing DM at different colliders w/ different beam energies
All consistent with the self-interacting DM picture

S. Tullin, IFAE ’15
Self-Interacting DM

~WIMP DM~

\[ \chi \rightarrow Z \rightarrow \chi \] self-interaction

\[ \sigma \sim \frac{g^4 m_{\chi}^2}{m_Z^4} \sim 10^{-36} \text{ cm}^2 \]

\[ m_{\chi} \sim 100 \text{ GeV} \]

\[ \sigma/m_{\chi} \sim 10^{-14} \text{ cm}^2/\text{g} \]

~Light mediator DM~

\[ \chi \rightarrow \phi \rightarrow \chi \] self-interaction

\[ \sigma \sim \frac{g^4 m_{\chi}^2}{m_{\phi}^4} \]

\[ \sigma/m_{\chi} \sim 1 \text{ cm}^2/\text{g} \]

\[ m_{\phi} \sim 1 - 100 \text{ MeV} \]

Dark photon? Dark Higgs?

Are DM self-interactions controlled by gauge symmetry? which one?
Naturalness & TeV scale new physics

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
( others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales )
Naturalness & TeV scale new physics

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Field  Symmetry as $m \rightarrow 0$  Implication

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<td>Spin-1/2</td>
<td>$\Psi \rightarrow e^{i\theta} \Psi$  $\bar{\Psi} \rightarrow e^{-i\theta} \bar{\Psi}$ (chiral symmetry)</td>
<td>$\delta m \propto m$ Natural!</td>
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<td>$m\Psi\bar{\Psi}$</td>
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<td></td>
</tr>
<tr>
<td>Spin-1</td>
<td>$A_\mu \rightarrow A_\mu + \partial_\mu \alpha$ (gauge invariance)</td>
<td>$\delta m \propto m$ Natural!</td>
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<td>$m^2 A_\mu A^\mu$</td>
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courtesy to N. Craig @ Blois ’15
Naturalness & TeV scale new physics

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<td>Spin-1</td>
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<td></td>
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<td>(gauge invariance)</td>
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The Higgs mass in the SM doesn’t break any (quantum*) symmetry

* it does break classical scale invariance, as the running of the gauge couplings does too!
Naturalness principle @ work

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
(others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales)

Beautiful examples of naturalness to understand the need of “new” physics

see for instance Giudice ’13 (and refs. therein) for a recent account
Naturalness principle @ work

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
( others are not necessarily theoretically inconsistent
but they require some conspiracy at different scales )

Beautiful examples of naturalness to understand the need of “new” physics

- the need of the positron to screen the electron self-energy
- the rho meson to cutoff the EM contribution to the charged pion mass
- the kaon mass difference regulated by the charm quark
- the light Higgs boson to screen the EW corrections to gauge bosons self-energies
- ...
- New physics at the TeV scale to cancel the UV sensitivity of the Higgs mass?
The Darwinian solution to the Hierarchy

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

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

Higgs mass-squared promoted to a field
The field evolves in time in the early universe
The mass-squared relaxes to a small negative value
The electroweak symmetry breaking stops the time-dependence
The Darwinian solution to the Hierarchy

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

Graham, Kaplan, Rajendran ’15

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe
- The mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-dependence

Self-organized criticality
when the Higgs mass becomes negative, it back-reacts and generates a potential barrier that stops the evolution of the scanning field
**Higgs-axion cosmological relaxation**

Graham, Kaplan, Rajendran ’15

\[ \phi \text{ slowly rolling field (inflation provides friction) that scans the Higgs mass} \]

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

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potential needed to force
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Higgs mass depends on \( \phi \)

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

\[ \Lambda^3_{\text{QCD}} h \cos \frac{\phi}{f} \]
Higgs-axion cosmological relaxation

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

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

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

\[ v \sim \frac{gf \Lambda^3}{\Lambda_{QCD}^3} \]

see also Espinosa, Grojean, Pomarol, Pujolas, Servant '15
Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran ’15

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

\[
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\]

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

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Hierarchy problem solved
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~interesting cosmology signatures~
- BBN constraints
- decaying DM signs in \( \gamma \)-rays background
- ALPs
- superradiance

~interesting signatures @ SHiP~
- production of light scalars by B and K decays

see also Espinosa, Grojean, Pomarol, Pujolas, Servant ’15
The HEP frontiers

EXP Frontiers

TH Frontiers

- SM precision

BSM model building
The HEP frontiers

EXP Frontiers

The Energy Frontier
- Origin of Mass
- Matter/Anti-matter Asymmetry
- Origin of Universe
- Unification of Forces
- New Physics Beyond the Standard Model

The Intensity Frontier
- Neutrino Physics
- Proton Decay

The Cosmic Frontier
- Dark Matter
- Dark Energy

TH Frontiers

SM precision

BSM model building

synergy fuels progress

➾

➾

➾
The HEP frontiers

EXP Frontiers

TH Frontiers

SM precision

BSM model building

synergy fuels progress

no BSM major discovery without a thorough understanding of SM background
The HEP frontiers

EXP Frontiers

TH Frontiers

The 3 frontiers might be more intertwined than originally thought

Synergy fuels progress

no BSM major discovery without a thorough understanding of SM background
Conclusions

- What are the weak points in our current understanding and practices?
- What are the growth areas in technique and capability?
- Where are the sweet spots where those two meet?
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Let us explore the unknown and be surprised!