Theory Perspective

Marcela Carena

Fermilab/UChicago

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Outline

- A theorist's view
- Where we are today
- Where we may be heading to

Consensus theorist's view of the road ahead: 2009

Consensus theorist's view of the road ahead: 2022

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A lot of Particle Physics is Missing in the Standard Model

- Why Electroweak Symmetry Breaking occurs?
  What is the history of the Electroweak Phase Transition ?
- The reason for the **Hierarchy in Fermion Masses and their Flavor Structure**
- The Nature of **Dark Matter**
- The origin of the **Matter-Antimatter Asymmetry**
- The generation of **Neutrino Masses**
- The cause of the Universe's accelerated expansion **- Dark Energy**
- What are the quantum properties of Gravity?
- What caused Cosmic Inflation after the Big Bang?

The SM is silent about all the above BUT,
LHC data could provide decisive clues to help us decipher many of these mysteries

The Interplay of Theory and Experiments

Theory:
Grand Ideas/
Frameworks
to answer big
questions

Discoveries

Experiments

Theory:
Models to account
for BSM features
and/or to explain
anomalies

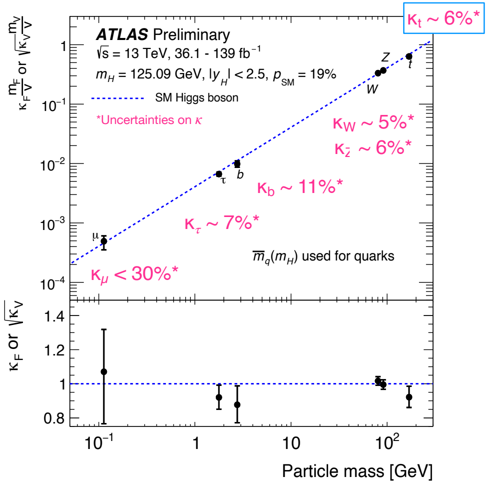
Constraints

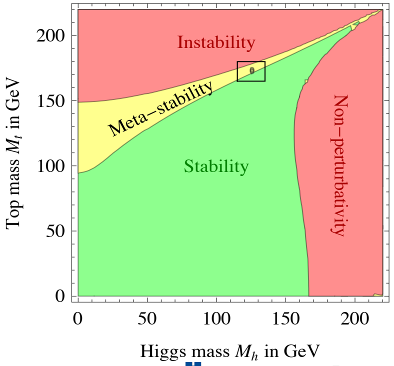
Anomalies

The Higgs boson: its great features and open questions

❖ The Higgs mechanism requires the existence of a 'light" new type of particle - a scalar - ATLAS and CMS discovered it!
Its existence gives *a first portrait* of the EWSB mechanism and makes the SM by itself self consistent up to very high energies

- With m_H = 125 GeV, its mass is at a lucky spot to test Higgs boson couplings to many particles and look for surprises
  - EFT approach can provide a useful tool for exploration -
- Implies a new force in nature, that can give mass to all known matter particles, but calls for an explanation of the mass hierarchies
- Hints at - but does not explain - Baryogenesis, Dark Matter/Sector portals and possibly Inflation.





- In the SM, the Higgs potential is fixed by hand to give EWSB
- the SM Higgs potential is unstable – catastrophic runaway at some point
- Scalar's masses are associated with quadratic divergences

What is behind the EWSB mechanism?

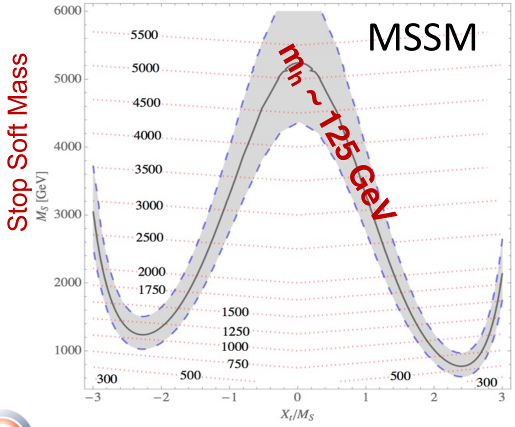
- Radiative breaking
- Compositeness
- Other more exotic/exoteric alternatives

Radiative EWSB

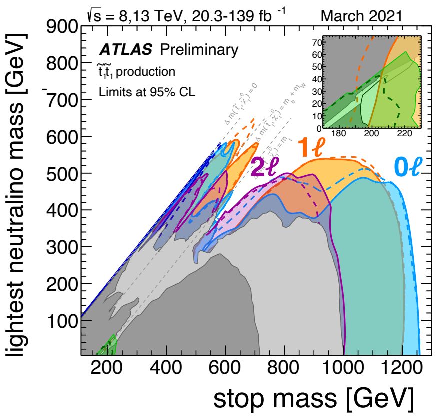
e.g. Supersymmetry, provides dynamical radiative EWSB mainly governed by the mass difference between top-quarks and it super-partners

The LHC experiments are probing the SUSY particle spectrum

- Colored SUSY particles, squarks & gluinos, have the highest σ's at hadron colliders.
- Given the Higgs mass value, simplest SUSY models imply stops are expected to be in the TeV range



Stop mixing



Top-squark projections: R-parity conserving SUSY, prompt searches

5σ observation is 5–10%
Lower for each process

Current LHC program has a long way ahead in the search for SUSY

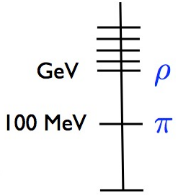
Compositeness

Bosonic states are always suggestive of compositeness, e.g., in condensed matter we encounter composite states that trigger phase transitions and symmetry breaking,

> "The purpose of the present note is to report that...the spin-one quanta of some of the gauge fields acquire mass...This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson has drawn attention" **-- Peter Higgs, 1964**

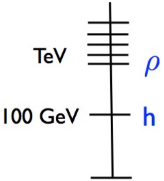
vev is the order parameter of EWSB

Many BSM theories allow for composite Higgs Boson/s



Inspired by pions in QCD

Higgs as a PNGB



The inverse of the confinement scale is the most important parameter to understand if the Higgs boson is composite
It can be probed at HL-LHC

Higgs emerges as bound state of a new strongly interacting composite sector, like QCD, but with a much higher confinement scale

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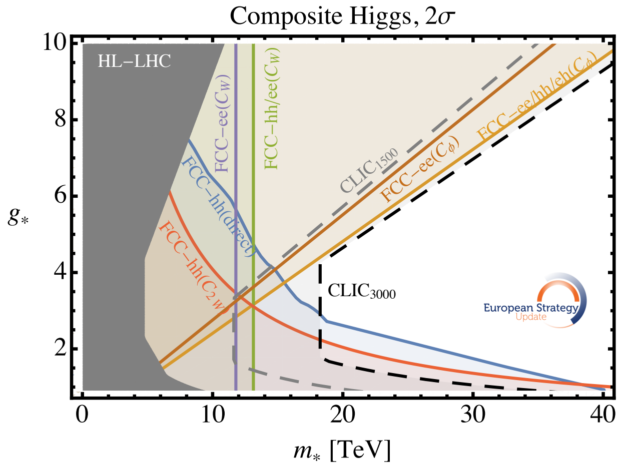
Compositeness

Composite-sector characterized by a coupling $g^* \gg g_{SM}$ and a confinement scale m*

m* controls the masses of the new vector-like fermion and gauge boson resonances and sets the scale of EFT operators that describe at low energy the indirect effects of Higgs compositeness

From probes of operators in the EFTCH and direct resonance searches HL-LHC will probe scales in the 5-10 TeV range



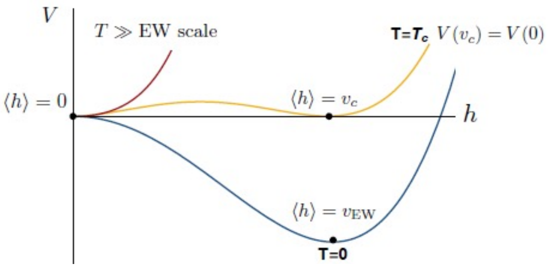
Many LHC opportunities for discovery of extra gauge bosons and vector like fermions

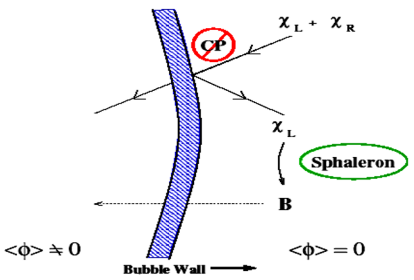
Additional scalars beyond the Higgs boson, motivated by many puzzles

- Can help explain the dynamics of the Higgs potential – hence EWSB -
- Can help stabilize the SM Higgs potential
- Can be portals for Dark Matter
- Can play a role in generating light fermion masses

- Provide a strong first order EW phase transition
- Provide new sources of CP violation

} Electroweak Baryogenesis ?





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Electroweak Baryogenesis demands new Physics/ New Scalars

EW Baryogenesis fails in the Standard Model, but many BSM scenarios have been studied which allow for EWBG

- Singlet extensions, including models with many scalars and EW symmetry non restoration or delayed restoration
- New models of EWNR, with multiple singlets + an inert doublet
- Two Higgs doublet Models
- Models with Dark CP violation and gauged lepton or baryon number
- Supersymmetric models: MSSM ruled out by Higgs precision, but NMSSM is an appealing possibility

Different thermal histories, with 1 or 2 step phase transitions and strong first order EWPT **- - - Important to perform nucleation calculation** – and may lead to Gravitational Wave signals

➔ Distinct rich phenomenology at colliders: Higgs precision, Higgs trilinear coupling, double Higgs production, direct new scalar searches, possible effects of CPV

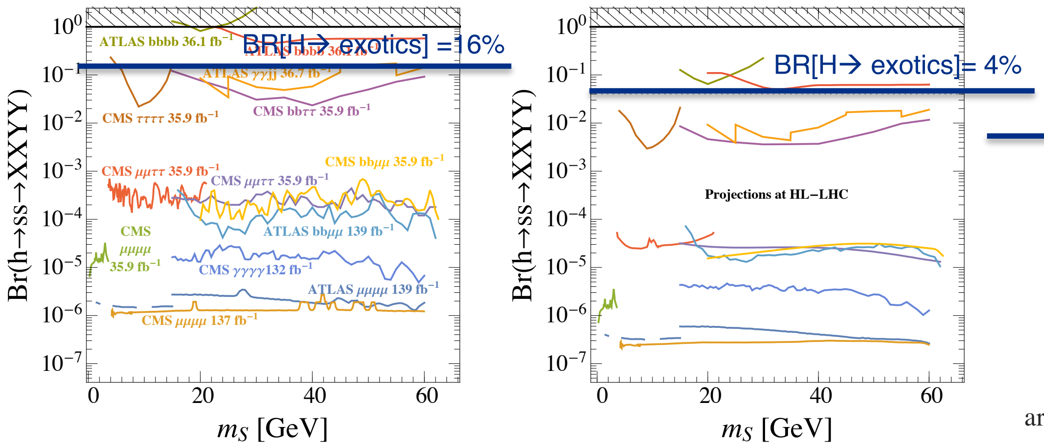
Higgs cousins probes at LHC Run 3 and HL-LHC

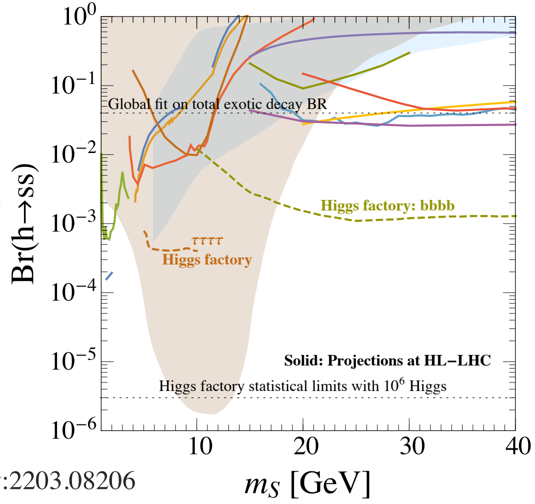
- can shed light on understanding the Higgs potential and the EW phase transition
- may relate to the flavor structure and new sources of light-fermions-Higgs couplings

➢ Lower bound on BR(H) $_{inv}$ or related associated production or VBF with Higgs decay into a pair of “invisible” scalar singlets

➢ Probing Z_2 breaking SM-Singlet Extensions via Higgs Exotic Decays

Bounds on exotic Higgs decays: current vs HL-LHC



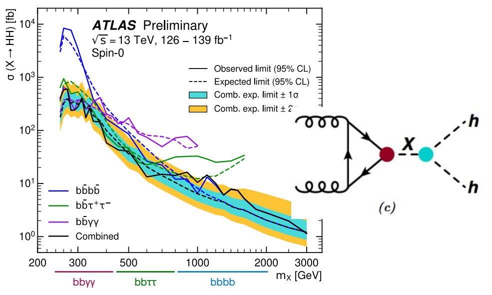


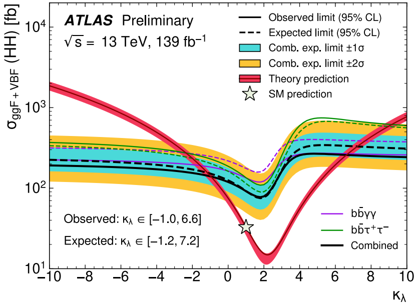
arXiv:2203.08206

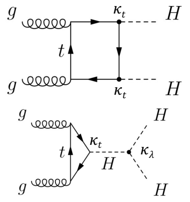
Higgs cousins probes at LHC Run 3 and HL-LHC

- can shed light on understanding the Higgs potential and the EW phase transition
- may relate to the flavor structure and new sources of light-fermions-Higgs couplings

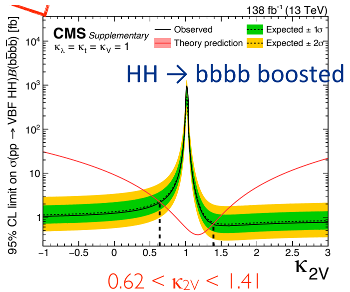
➢ Enhanced Di-Higgs production via a heavy resonance - including interference effects - or a non-resonant contribution is being probed already at the LHC.

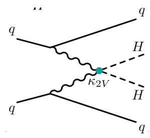






+ higher order EFT operators





$0.62 < \kappa_{2V} < 1.41$

$(0.66 < \kappa_{2V} < 1.37)$ @ 95% CL

➢ Many BSM Higgs searches: Higgs singlets: h_S, A_S; doublets: H, A, H^{+-} ; triplets: H, A, H^{+-}, H^{++}
Some 3σ excesses to keep an eye on and explore in many appealing theory scenarios

Different search strategies depending on how SM-like is the 125 GeV Higgs (Alignment)

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Lepton flavor opportunities

In the quark sector no compelling evidence for flavor effects beyond CKM. What about the lepton sector?

Could there be new particles that couple differently to electrons/muons/taus

- new gauge bosons, new scalars, leptoquarks, vector-like fermions with extended scalar sectors or squarks in special types of supersymmetry

Have we already seen such effects?

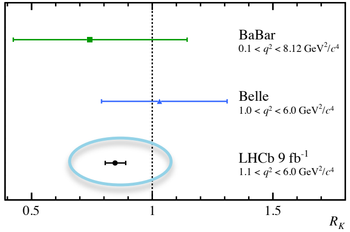
- Evidence of lepton universality violation in b→ s ll and b → cτν transitions

R_K anomaly: 3.1 sigma; R_{D^*} anomaly@ 3.4 sigma

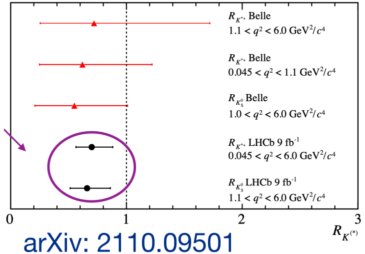
Run 3 data will be crucial to clarify these anomalies

- The muon g-2 anomaly :
  4.2 standard deviation from SM expectation
  Lattice theory calculations under scrutiny

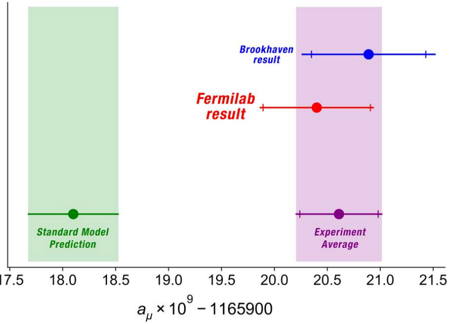
Nat. Phys. 18 (2022) 277

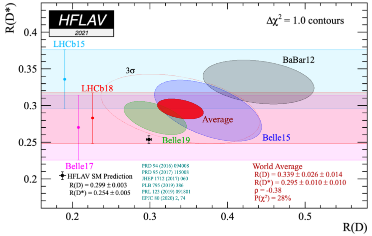


$B^0 \to K_S^0 \ell^+\ell^-$ **and** $B^+ \to K^{*+}(K_S^0\pi^+)\ell^+\ell^-$



arXiv: 2110.09501





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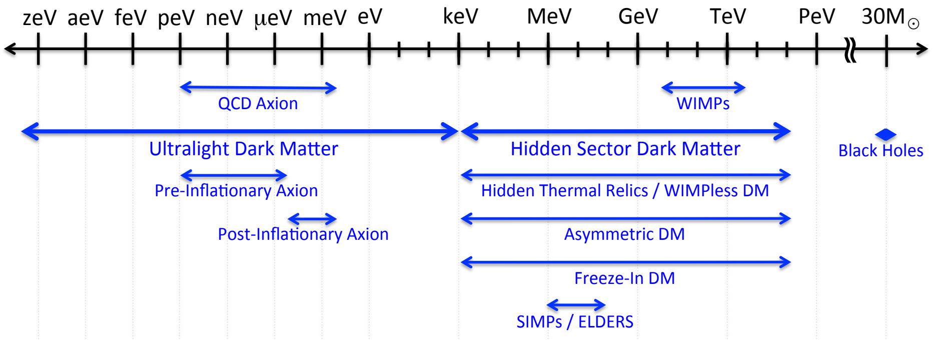
What do we know about Dark Matter   very little -

- Couples gravitationally
- It is the most abundant form of matter
- It can be part of an extended hidden, dark sector
- It can be made of particles or compact objects

  - ultralight DM is best described as wavelike disturbances (e.g axions) -

- Its mass can be anything from as light as 10^{-22} eV to as heavy as primordial black holes of tens of solar masses

Too small mass
⇒ won't "fit"
in a galaxy!



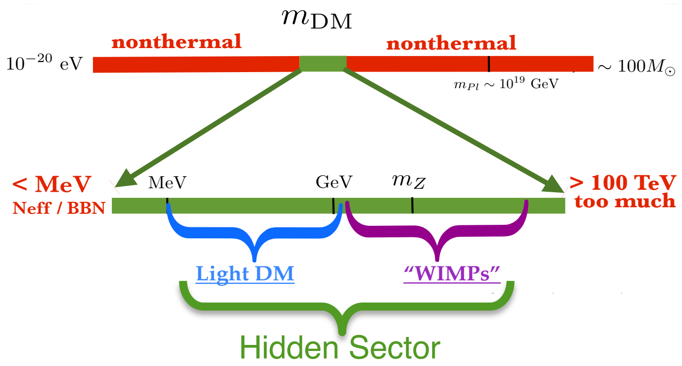
From MACHOs searches

Creating/Detecting DM in the laboratory is one of the greatest challenges

What do we know about Dark Matter ?

- Assumptions about early Universe cosmology provides some guidance

Thermal Equilibrium in early Universe narrows the viable mass range



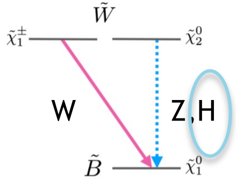
- It can have weak SM charges and be part of an extended SM sector
  ➔ Weakly Interacting Massive Particles **(WIMPs)**
- It can belong to a Hidden Sector & interact indirectly with SM particles via a Mediator
  Mediators may be SM singlets that mix/interact with SM particles such as the Higgs boson, the photon or neutrinos **or** they may directly carry SM charges
- It can have different type of properties with itself (e.g. collisionless, self interacting)

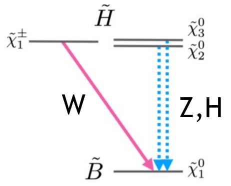
Explorable at accelerator-based DM searches: colliders and fixed target/beam dump exp.

Phenomenology of low mass region [MeV-GeV] thermal DM is quite different from Standard WIMP: it demands light mediator/s that in themselves are a search target

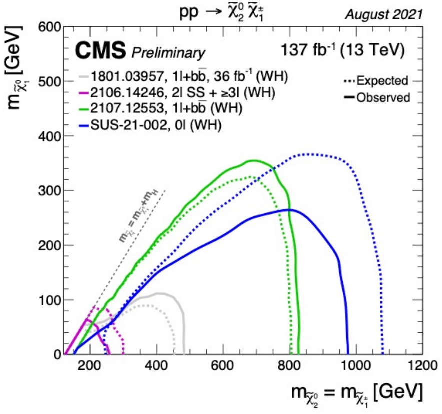
Making WIMPs at the LHC ?

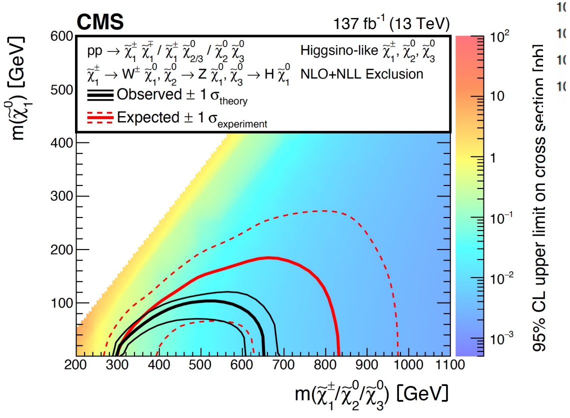
Direct detection experiments are starting to probe the Higgs portal, close to the neutrino floor but, in extended Higgs sector models, it is possible to be in regions where WIMP-nucleon cross section becomes very suppressed - blind spots -
Such regions may still yield the observed DM thermal relic abundance and be at LHC reach





Run 3/HL-LHC expected to have discovery potential a few to several hundred GeV beyond Run 2





Caveats:
Squarks in the TeV region may suppress DM production in a relevant manner (> 10%)
Assuming NLSP Br's 100% into Z or H should be done with care depending on NLSP composition

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Entering a new era in exploring the Dark Sector:

Standard Model → Portal → Dark Sector

- Dark Sector dynamics not fixed by SM:
  New forces, new symmetries and multiple new states, including mediators and DM candidates
- Portals can be the Higgs itself or Feeble Interacting Particles (FIPs):

Portal (mediator)	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N L H N$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$

Mediators can have masses larger or smaller than the DM candidate mass
Mediators can decay to light DM or to SM particles through portal couplings

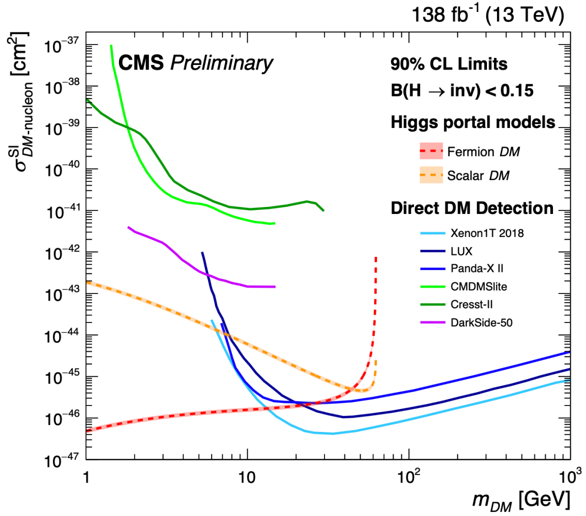
Distinctive phenomenology connected to the existence of Long-Lived Particles/FIPs

Collider searches are looking to the full menu of potential Dark Sector particles

Simplified Models with DM portals/DM-Mediators at the LHC

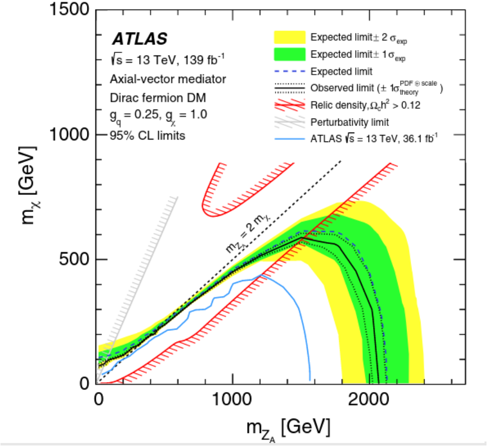
Simplified models are useful toy models to compare the reach of Colliders with that of Direct Detection and Indirect Detection experiments (many caveats!)

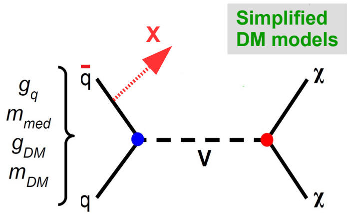
Higgs portal:
direct searches for invisible Higgs decays



LHC has great sensitivity for low DM masses

Simplified DM model with a mediator V;
g_q (g_{DM}) – mediator coupling to quarks (DM)
m_{med} (m_{DM}) – mass of mediator (DM)





Monojet search for axial vector mediator

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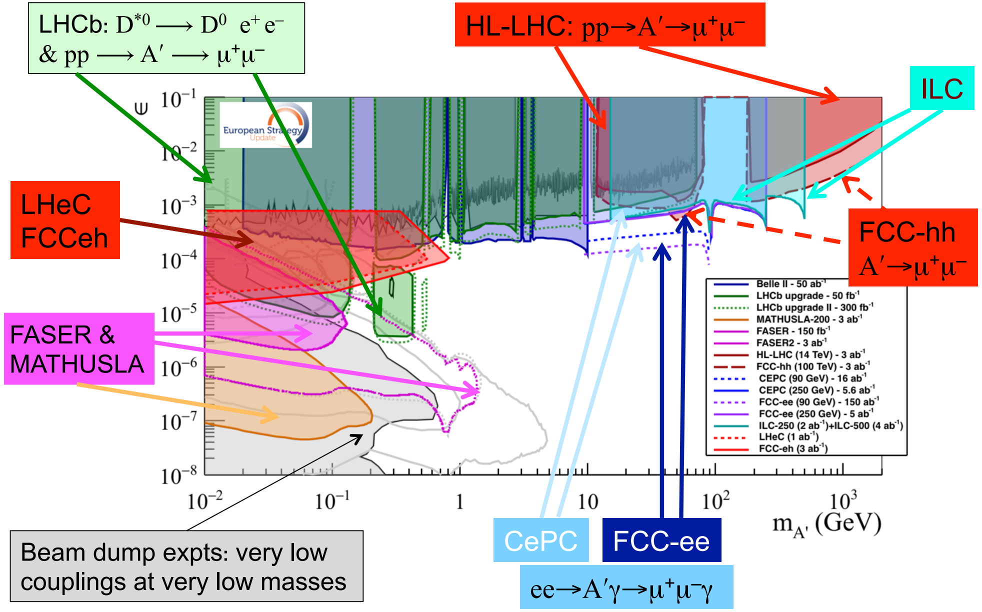
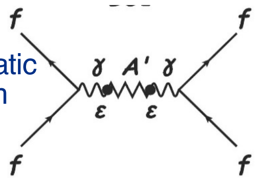
Feebly Interacting Particles at Accelerator-based experiments

Dark Photon Portal: visible decays



Schematic diagram



Run 3 and HL-LHC will cover new territory for a large mass range of dark photons/larger couplings

Auxiliary detectors can give extra reach at low mass/smaller couplings

Beam dump experiments have reach in the low mass, small coupling regime

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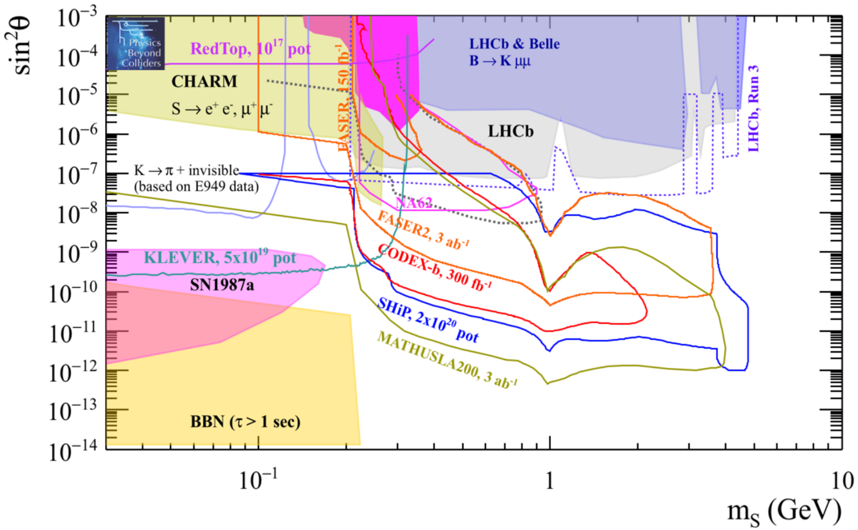
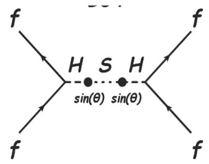
Feebly Interacting Particles at Accelerator-based experiments

Dark Higgs Portal: SM decays



Schematic diagram



LHCb at Run 3 will cover new territory for a large mass range of the dark Higgs.

Auxiliary detectors can give extra reach at smaller couplings

Beam dump experiments have reach in the small coupling regime

Dark Higgs couplings/masses are also constrained from Higgs invisible width beyond the range shown here

LHC prospects

In addition to looking for the things that we know are hard to see and therefore require more data, we are doing new things that increase the discovery potential

Therefore, the discovery potential for Run 3 or HL-LHC is NOT a straightforward extrapolation of current sensitivities

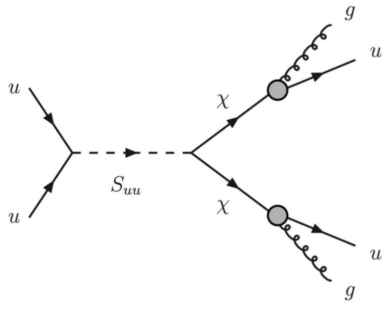
Many new opportunities already underway, e.g.:

- New channels not yet constrained by other searches
- Improved techniques yielding greater sensitivity/smaller error bars
- Use the existing detectors in more creative ways

New LHC auxiliary detectors will open new opportunities for LLPs of many types

New channels not yet constrained by other searches

e.g.: looking for an ultraheavy resonance, an 8 TeV diquark or coloron that can decay into a pair of ~ 2 TeV vector-like quarks, not at the reach of LHC yet. e.g.



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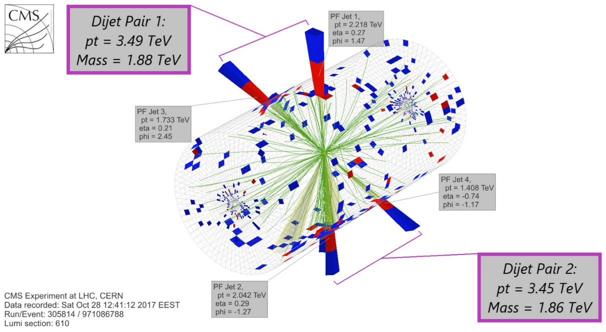
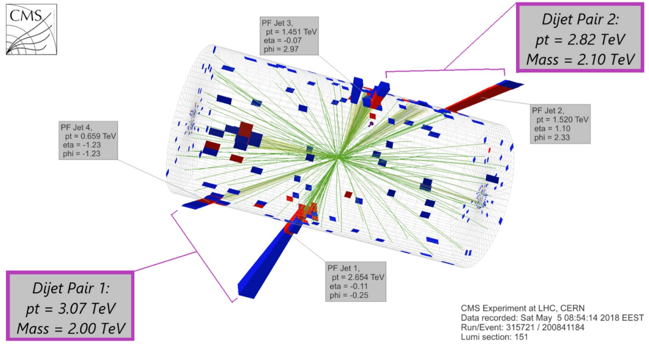
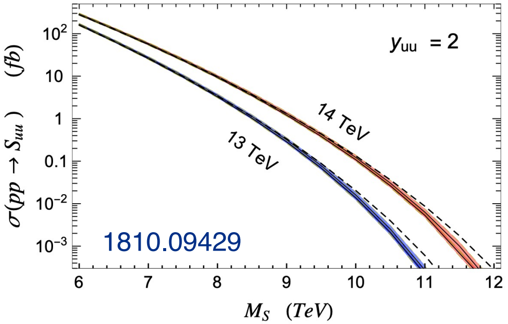
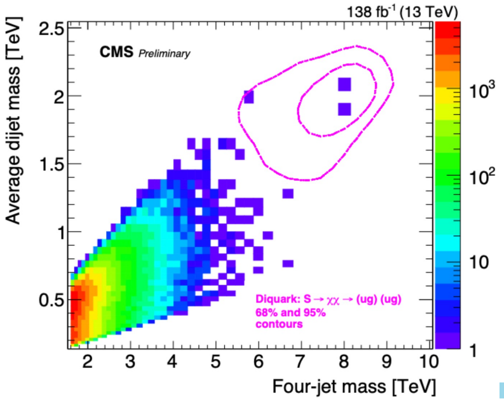








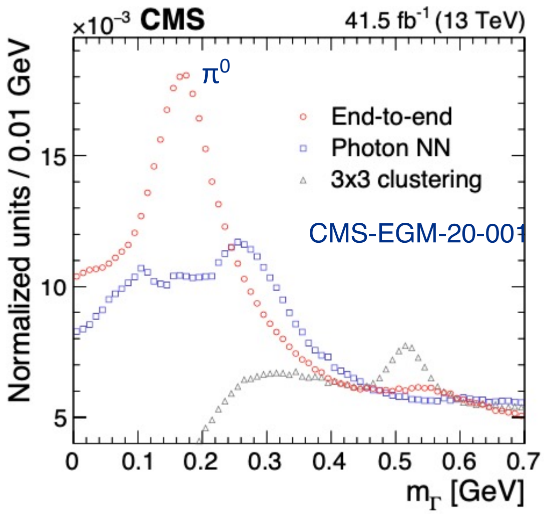
CMS PAS-EXO-21-010

Improved techniques yielding greater sensitivity/smaller error bars

e.g.: Machine Learning for reconstruction of decays to merged photons

Consider Higgs decay to a pair of ALPs with mass < 1 GeV: $h \to AA \to \gamma\gamma\gamma\gamma$

- Dominant decay of each axion-like particle is to two photons
- But decaying particle is highly boosted, so each pair of photons reconstructs as a single photon
- Hard to distinguish this signal from regular Higgs diphoton decays



New: use machine learning trained on minimally processed data

ML finds the $\pi^0 \to \gamma\gamma$ peak in the sub-leading "photon" of a diphoton data sample

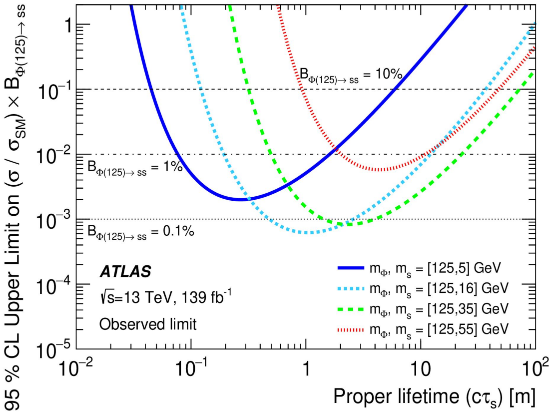
Use the existing detectors in more creative ways

e.g. using the muon detectors to search for Long-lived particles

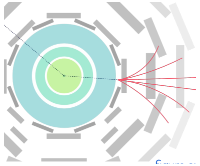
Search for $H \to SS$;
$S \to qq$, S long-lived

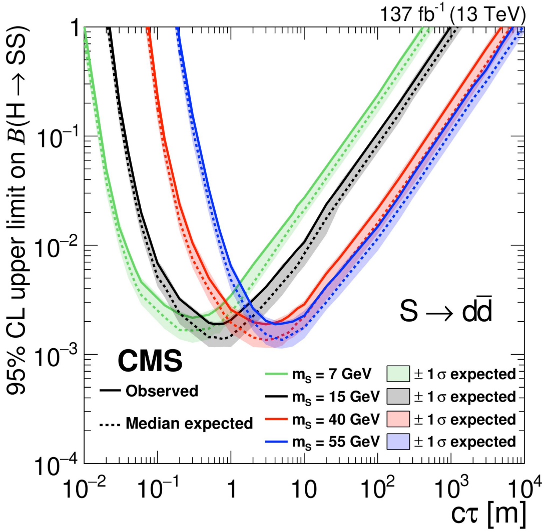
Most stringent bounds on BR($H \to SS$) in a given mass and decay length region

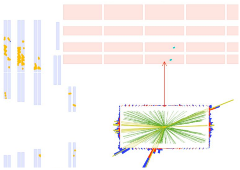
Broadening possibilities for LLPs searches appearing in many BSM scenarios



ATLAS search for displaced **vertices** in the muon system
arXiv:2203.00587







CMS search for hadronic showers in muon system
Phys. Rev. Lett. 127.261804

See also projections for HGCAL reach arXiv:2005.10836

LHC Discovery Program

Run 3 and HL-LHC with upgraded detectors, exploring the unknown and pushing the boundaries with many ideas for new search channels, novel techniques for scrutinizing the data and new opportunities for expanding the capabilities of the existing detectors plus possibly new auxiliary ones

Many discoveries possible

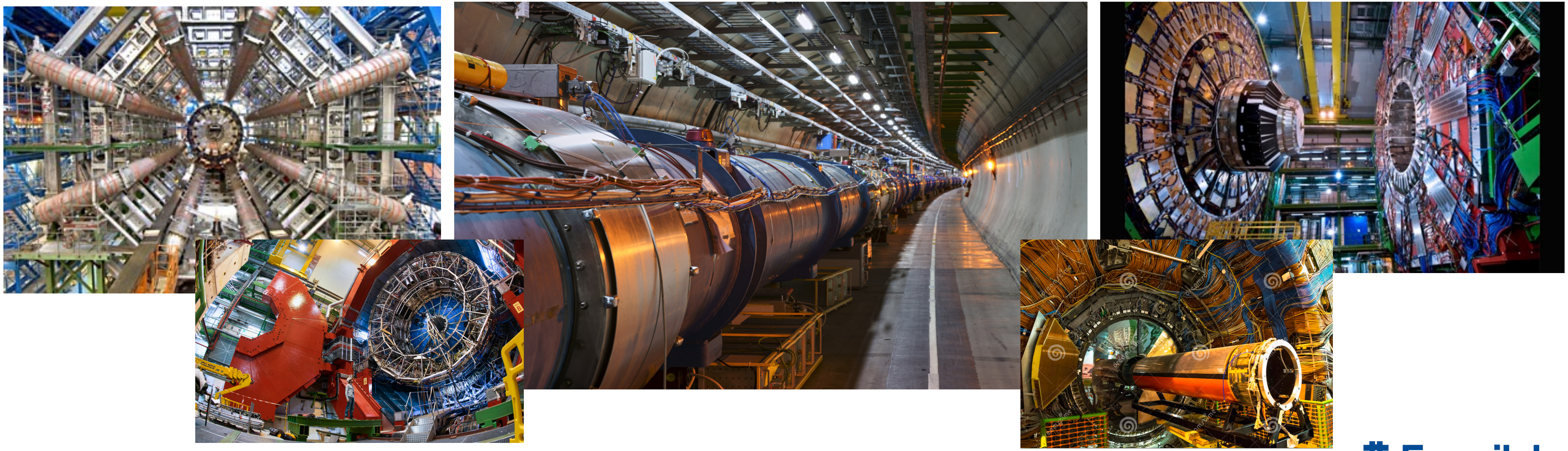
- Higgs cousins of many types with many possible implications
- Dark matter, dark sector, feebly-interacting particles, long-lived particles
- LHCb lepton flavor anomaly could be confirmed (and related to Muon g-2?)
- New forces (gauge bosons)
- Leptoquarks
- New kinds of fermions
- Higgs boson is composite
- Higgs flavor violation, Higgs CP violation, etc…

HEP landscape today

We should dream big about what we may achieve

Run 3 starts the next phase of exploration and discovery with the most powerful and technologically advanced machine humankind have ever built

We are probing many of the deepest secrets of our universe



Thank you !