Beyond Standard Model in light of the LHC results

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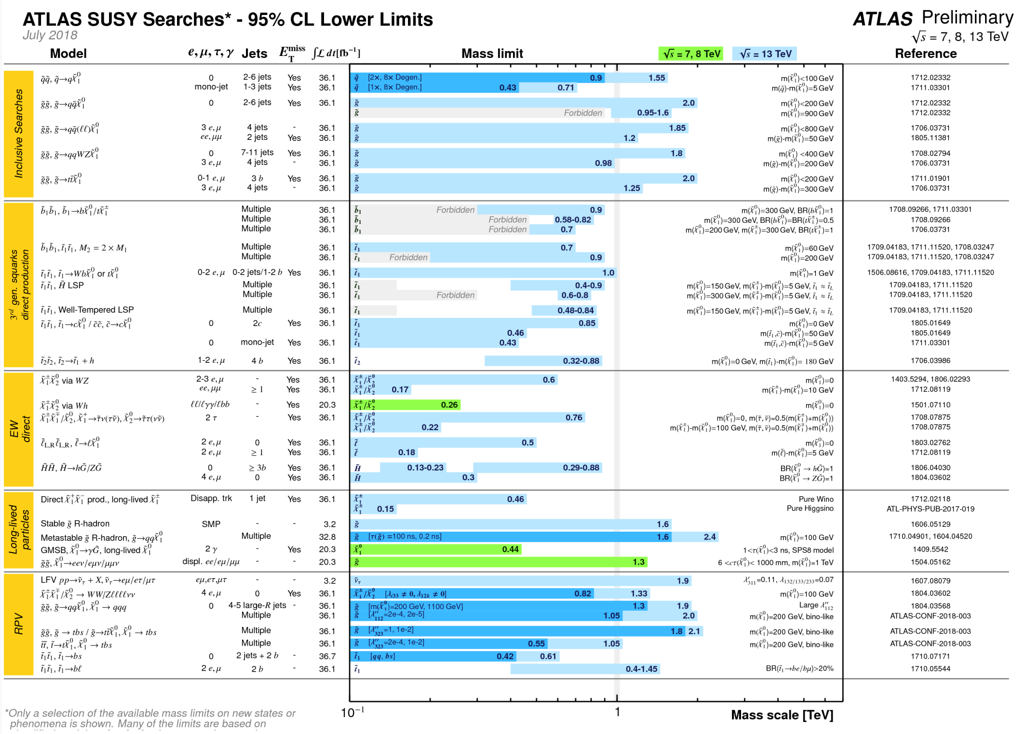
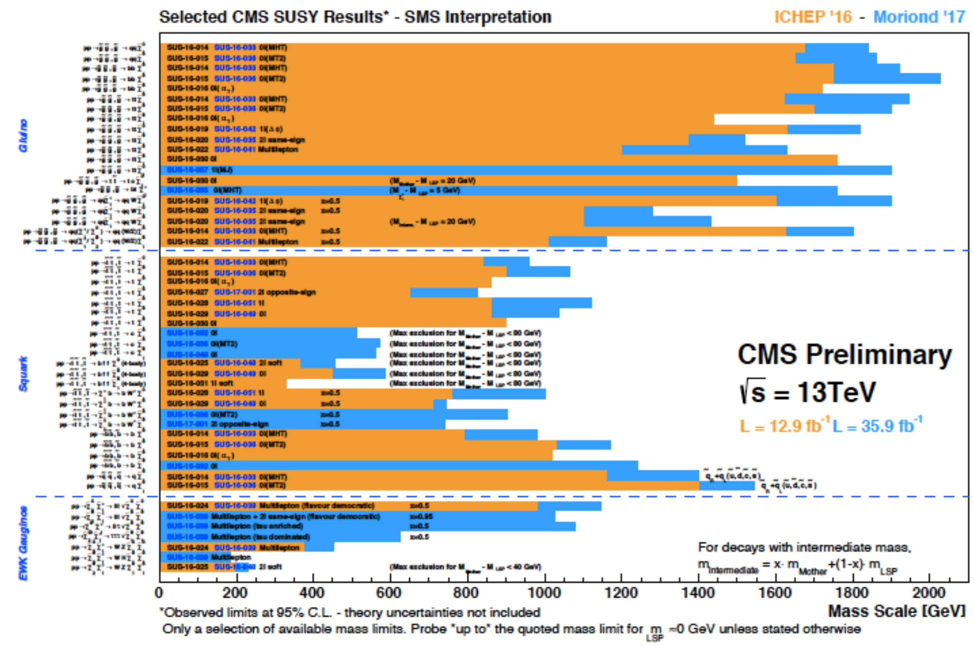
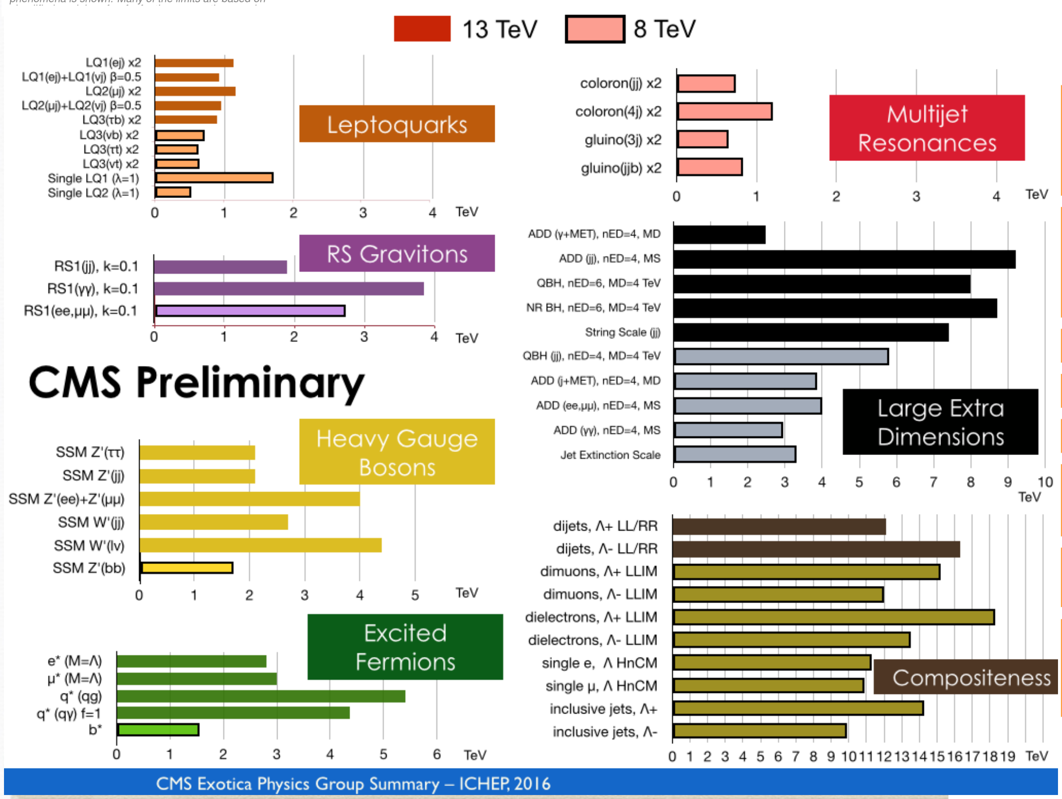
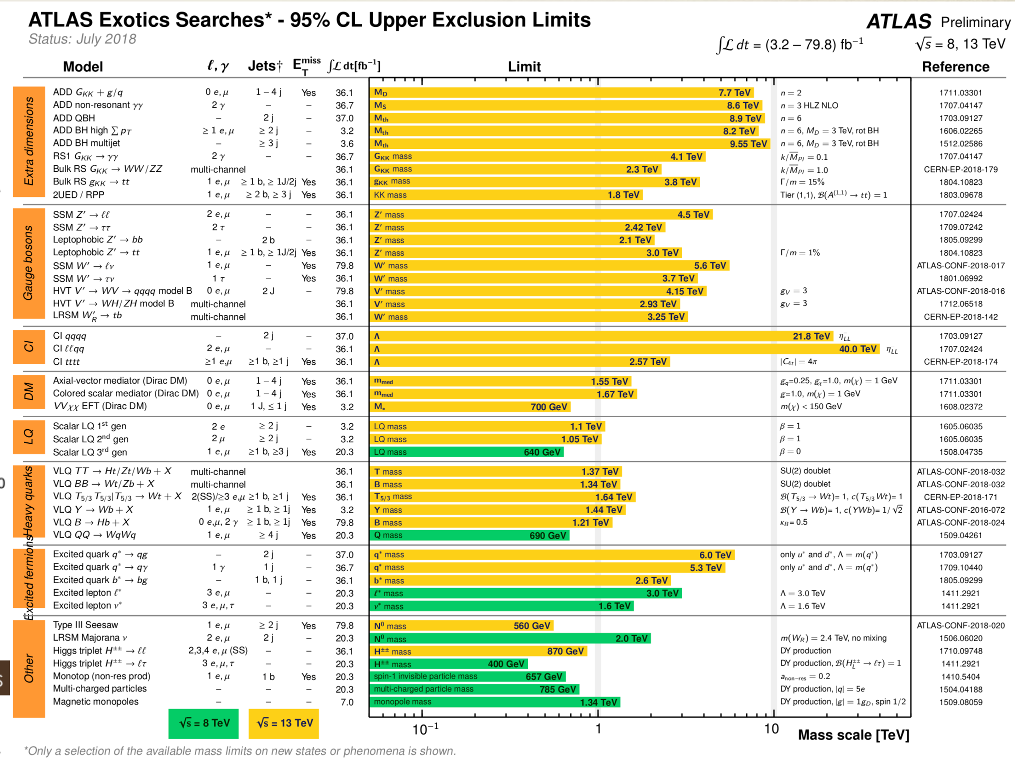
Brown University
TeVPA, Berlin, 2018


ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
Jets
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on
Mass scale [TeV]


Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP ~0 GeV unless stated otherwise
Mass Scale [GeV]


13 TeV
8 TeV
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
CMS Preliminary
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
TeV
CMS Exotica Physics Group Summary – ICHEP, 2016


ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018
ATLAS Preliminary
∫L dt = (3.2 – 79.8) fb⁻¹
√s = 8, 13 TeV
Model
Jets†
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
√s = 8 TeV
√s = 13 TeV
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

So far LHC has carried out an amazing number of searches. (More LHC talks this afternoon)

There is no confirmed signal of new physics yet. Yet before forming any strong opinion, it's worthwhile to know a bit what LHC has excluded and what are the implications of the LHC results for big physics questions.

A two-sentence summary of LHC results:

Strongly-interacting particles (colored particles) are strongly constrained.
E.g., gluinos ~ 2 TeV; scalar or fermonic top partners ~ (1 - 1.5) TeV;

Relatively weak constraints on weakly-interacting particles: depend on the final states.
(one example with essentially no constraints beyond LEP will be discussed later).

Outline

* Origin of electroweak scale
  — Implications of LHC results;
  — Loop holes and new search directions;
  — New theory directions: connection between electroweak physics and cosmology/astrophysics;
* Dark matter at the LHC
* Flavor anomalies
* Future collider frontier

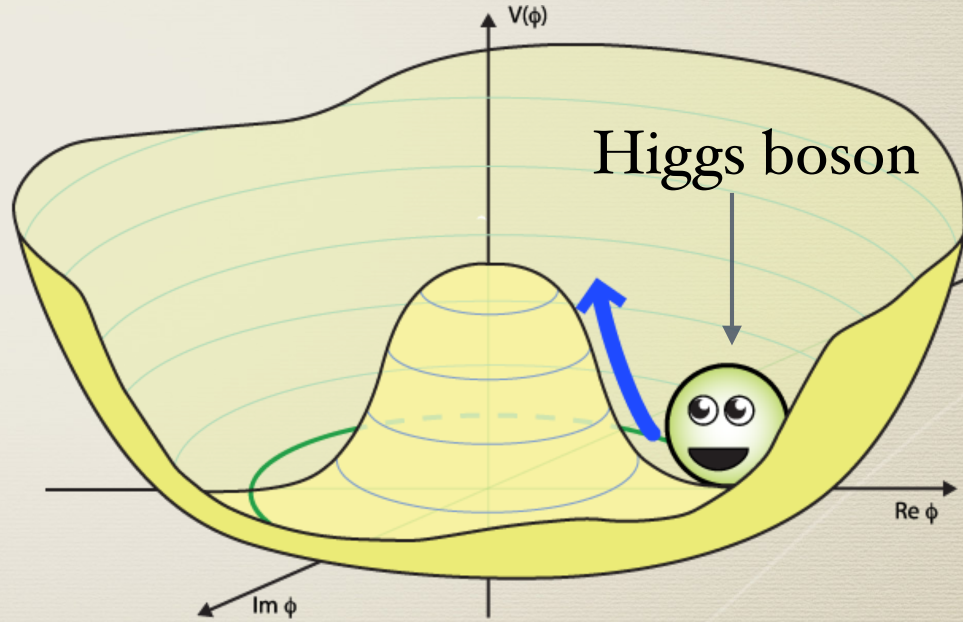
Higgs and EWSB in a Nutshell

Higgs is a field that permeates the vacuum. It can store energy, depending on the field value in some region.

The Higgs has a non-zero "**expectation value**": at the minimal of its potential, the field value is non-zero.

The non-zero expectation value is responsible for electroweak symmetry breaking (EWSB) and masses of elementary particles such as fermions and W/Z gauge bosons.

Higgs potential energy



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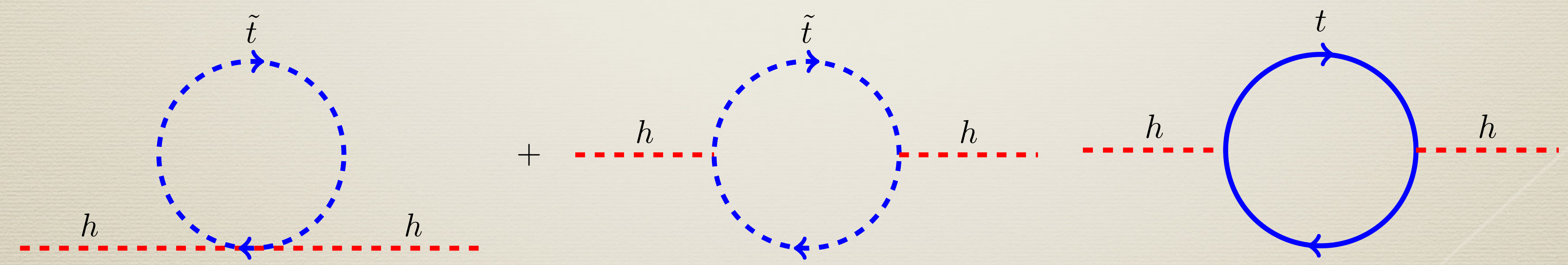
Electroweak Naturalness

The Higgs potential is something we put in by hand in Standard Model.

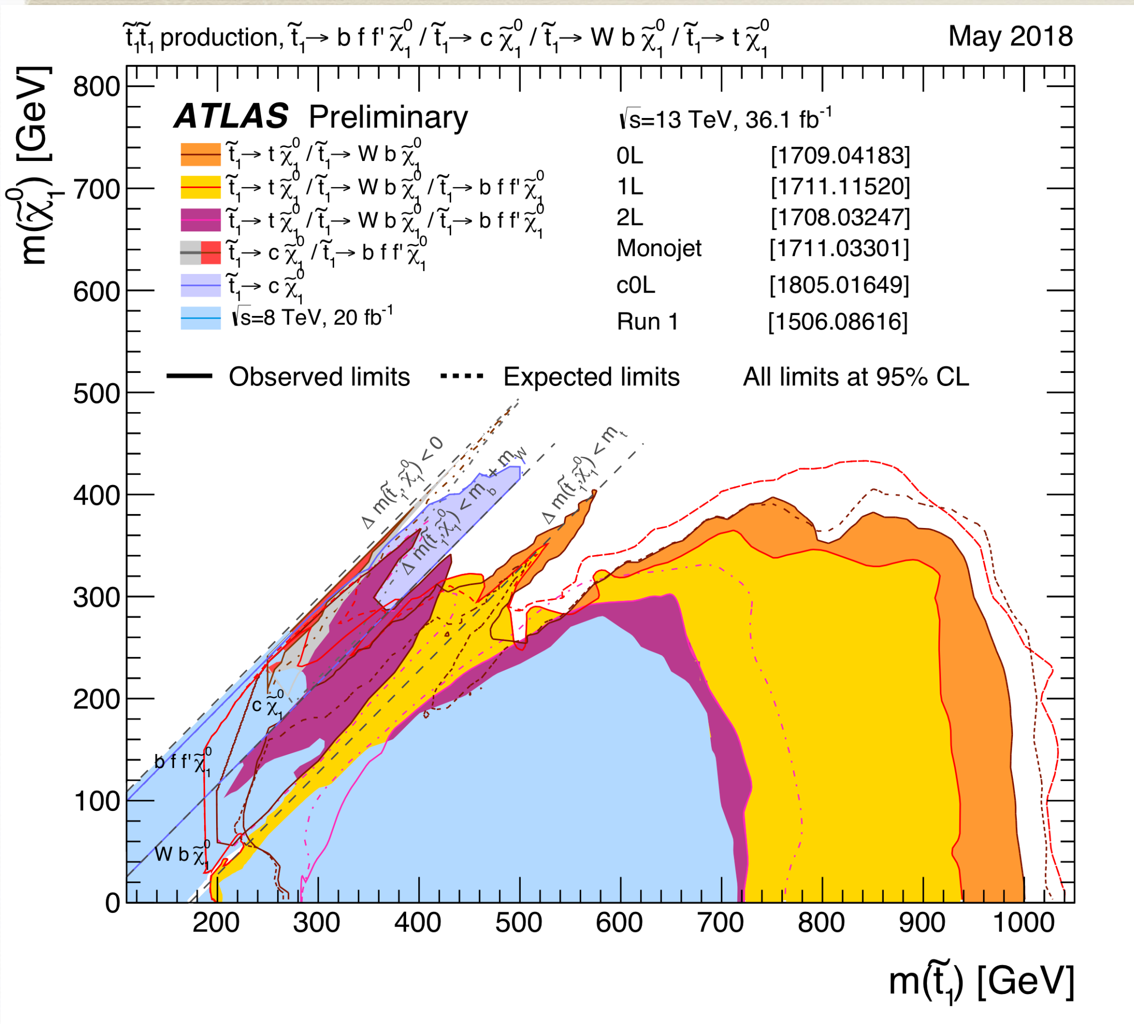
We want to ***explain*** it → new physics beyond the SM;

Natural ways to explain it: new physics with **colored** top partners close to weak scale.
Classic examples: weak-scale SUSY and composite Higgs. In SUSY,



“Stop” or “scalar top”: cancels the biggest correction from the top loop. ~10% tuned if mass ~ 700 GeV.

Implications of LHC Results

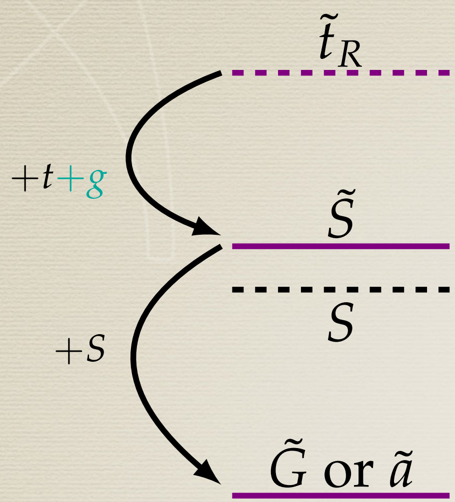


Impressive reach with 13 TeV data for **simplest** stop decays (at both CMS and ATLAS): exclude stop ~ 1 TeV (for neutralino below 400 GeV) and cover the compressed region (stop mass ~ top + heavy neutralino).

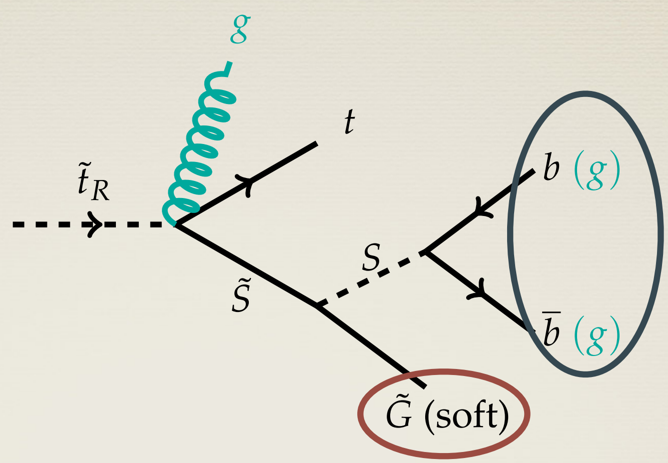
Null results teach us valuable lessons: traditional natural scenarios with electroweak fine-tuning no worse than 10% are very cornered.

There are still **loopholes** in existing searches.
The theoretical models may look more complicated and the main point is to motivate new experimental signals and searches.

Stealth stop signals



light invisible fermion



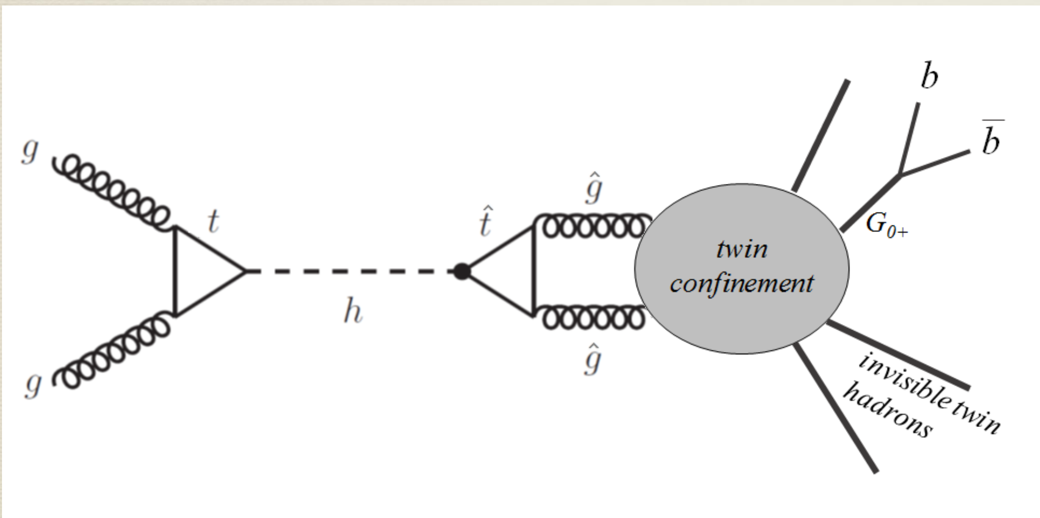
top pairs + jets (very little additional missing momentum); similar to SM top background

Stealth SUSY:
Approximate SUSY in the *hidden sector* suppressing missing momentum;
visible particles at the end of long cascades through the hidden sector have less energies.

Fan, Krall, Pinner, Reece, Ruderman, 2015

Neutral naturalness and exotic Higgs decay

Top partners that are crucial for stabilizing the Higgs potential at the weak scale do not feel strong dynamics. They are either SM gauge singlets or electroweakly charged (difficult to be found).
Chacko, Goh, Harnik, 2005; revived recently with many papers



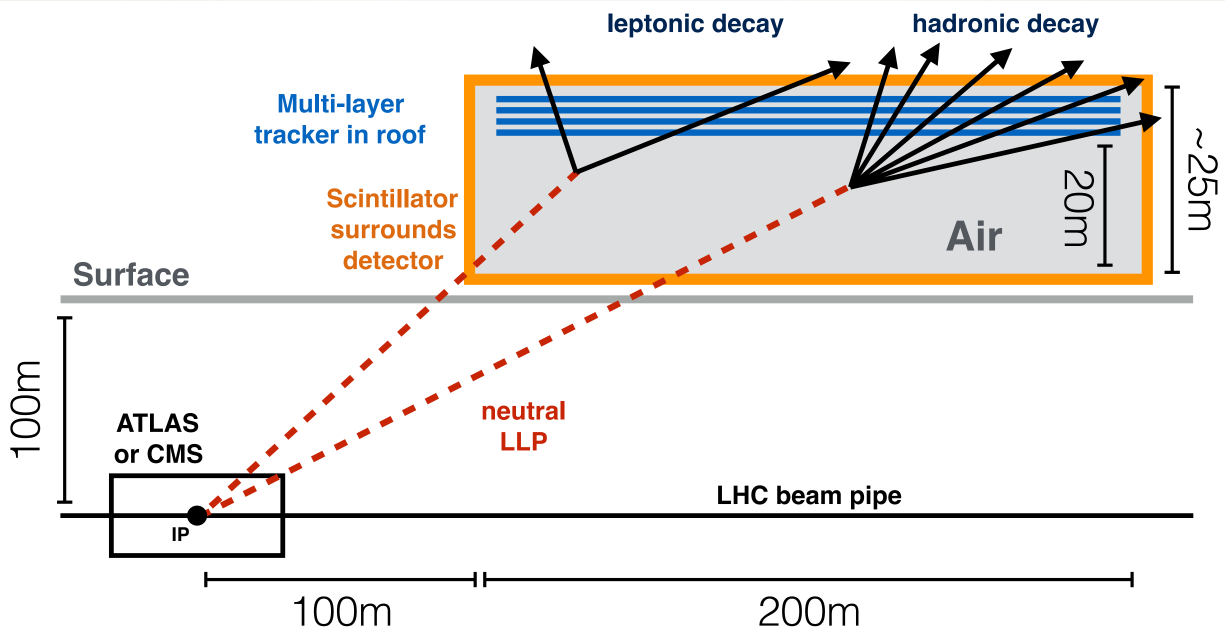
Craig, Katz, Strassler, Sundrum 2015

Exotic Higgs decays to hidden sector glueballs, which then decay back to SM, including displaced vertex
collider study see Curtin, Verhaaren 2015

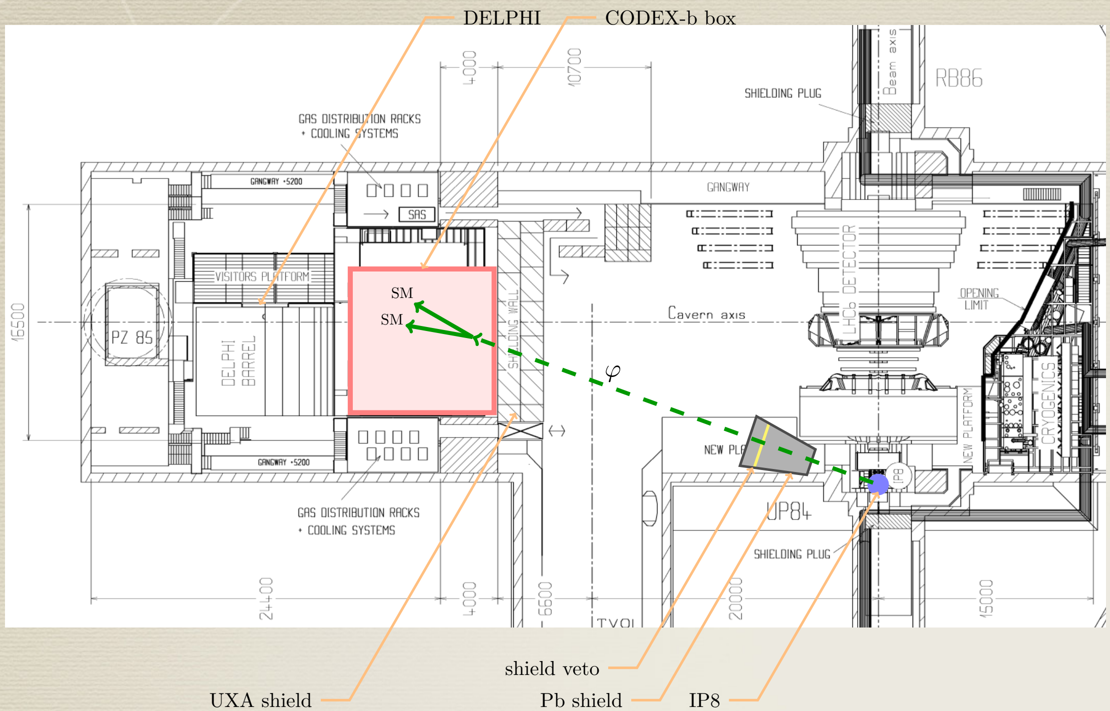
Searching for long-lived Particles

MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles) Curtin et.al 2018: Surround a large volume with inexpensive scintillator as a veto; put a tracking detector inside.

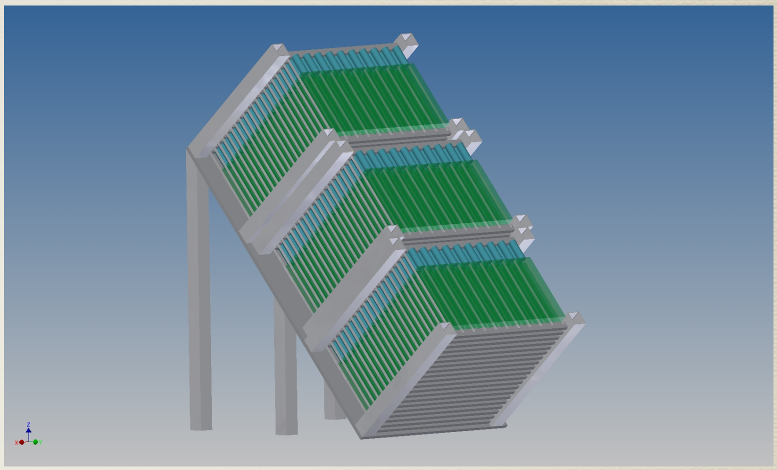
search for LLPs with lifetimes much greater than the size of the LHC main detectors, $c\tau \gg 100$ m.



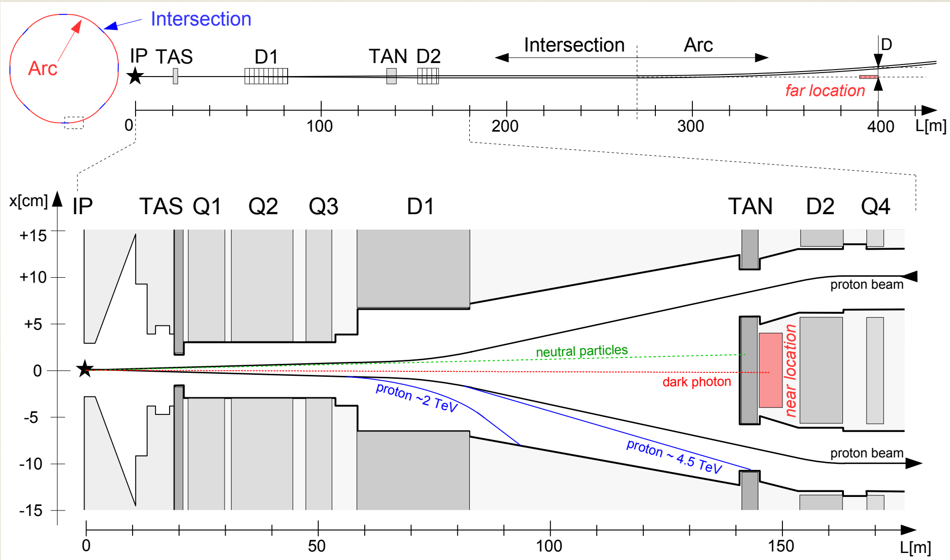
CODEX-b: Gligorov et.al



MilliQan: Haas et.al



Faser: Feng et.al



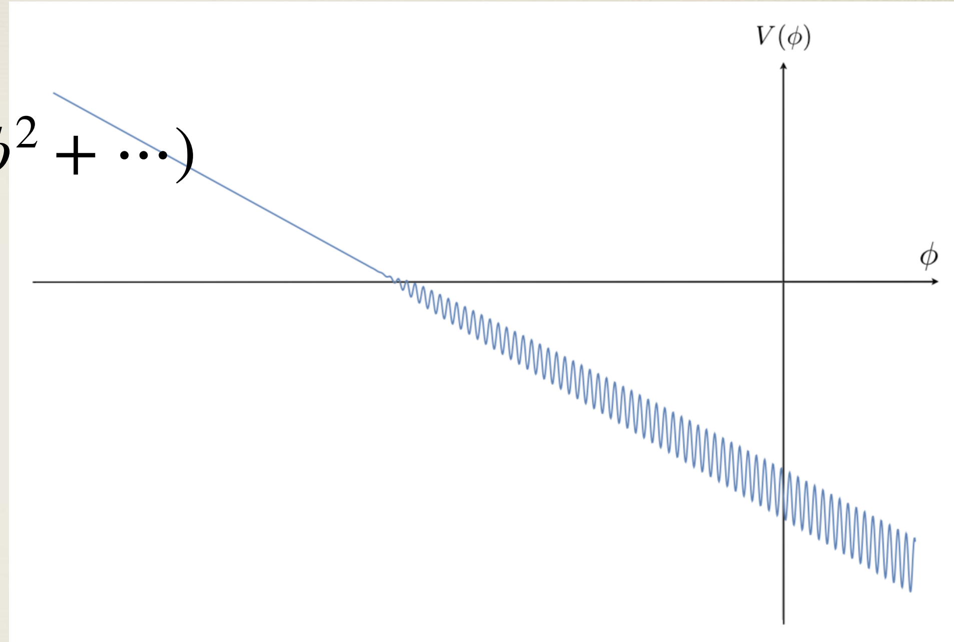
Relaxing the little hierarchy?

Cosmological selected electroweak vacuum

$$(-M^2 + g\phi)|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots)$$

$$+\Lambda(h)^4 \cos(\phi/f)$$

Graham, Kaplan, Rajendran 2015



Original version requires: exponentially small g, exponentially many e-folds, exponentially large field range beyond the Planck scale; (constraints from UV completion: McAllister et.al 2016)

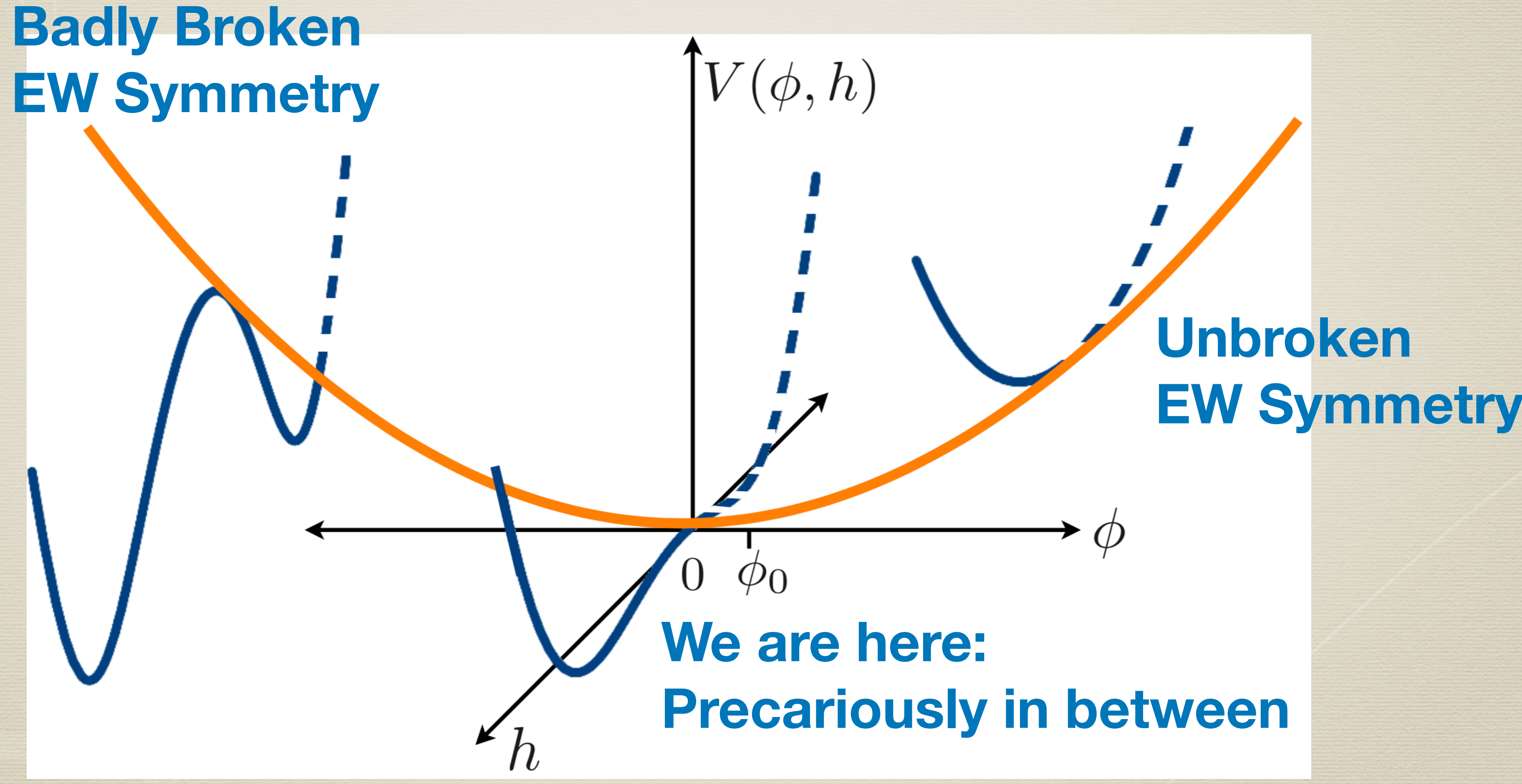
Many further attempts based on it:

Relaxion chiral supermultiplet with relaxino as gravitino.
Split-SUSY like spectrum with little hierarchy explained dynamically (Batell, Giudice, McCullough 2015)

Other interesting developments: alternative friction during relaxation from particle production (Hook, Marques Tavares 2016; Fonseca, Morgante, Servant, 2018) Smaller field range needed. Closer to plausibility?

Cosmological Signal of a Fine-tuned Higgs

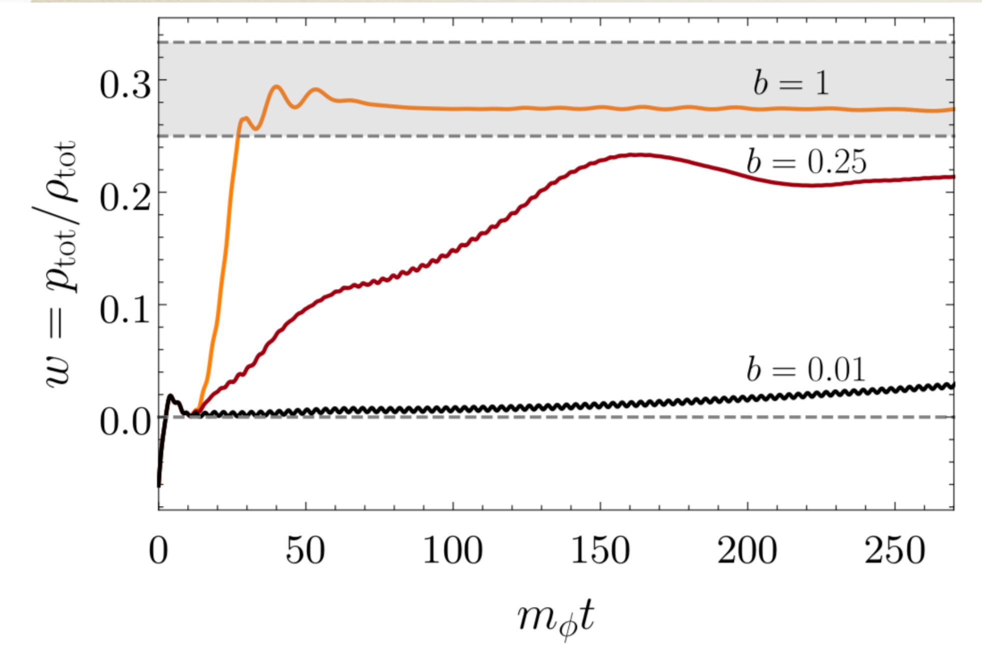
A time-dependent Higgs mass (due to coupling to an oscillating scalar) in the early Universe.



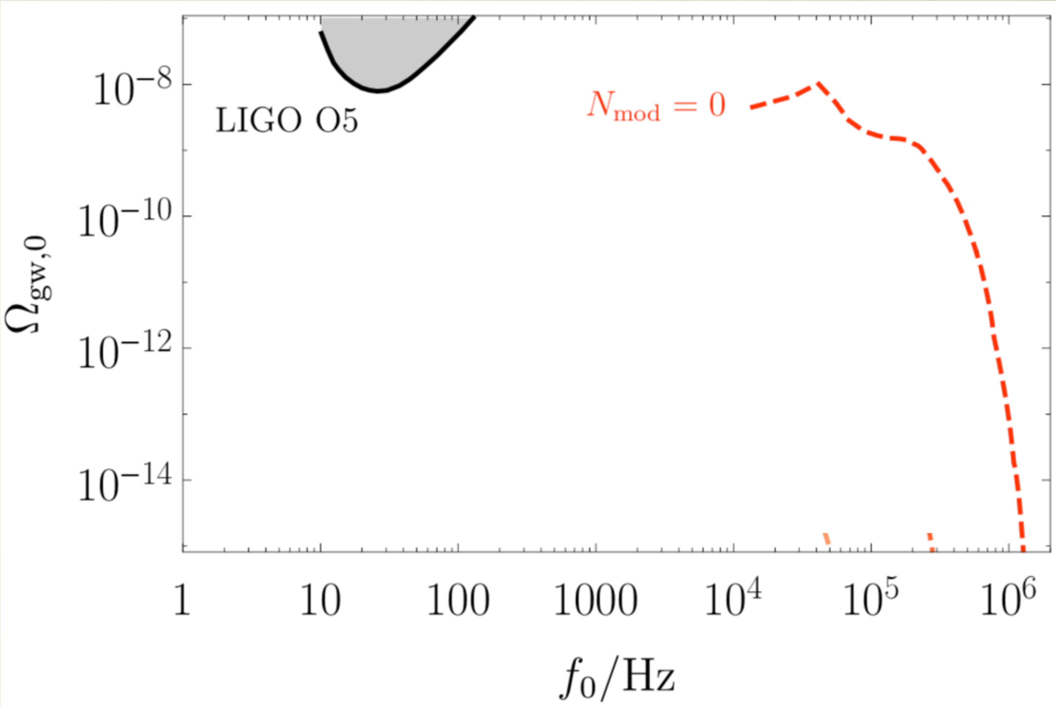
Amin, Fan, Lozanov, Reece 1802.00444

If the Higgs potential is *tuned*, particle production of the Higgs and fragmentation of the oscillating scalar

nontrivial equation of state



stochastic gravitational waves



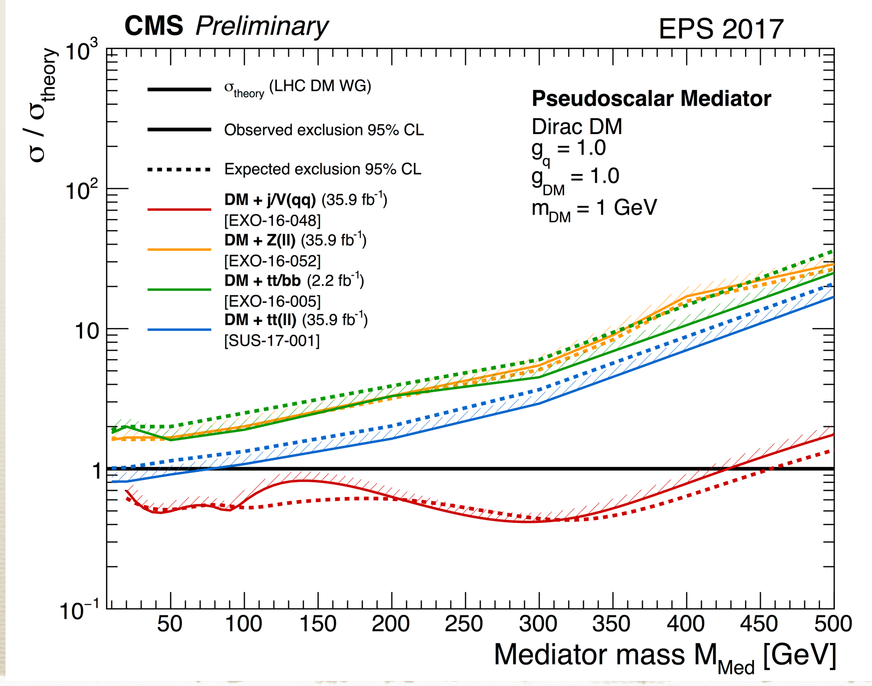
Amin, Fan, Lozanov, Reece 1802.00444

Dark Matter at the LHC

There has been a well-established DM program at the LHC: mono-X (X = jet, Higgs,....) based on model-independent effective operator parametrization or simplified models. Provide interesting *complementary* probe to direct/indirect dark matter searches.

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2000; summary reports: 1506.03116; 1507.00966

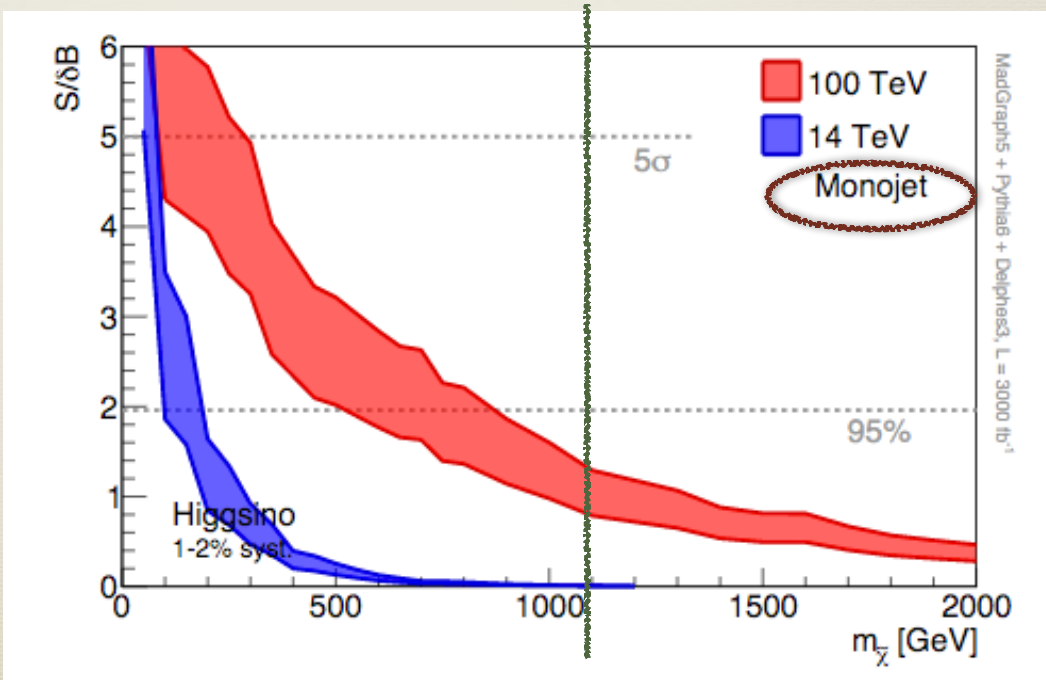
e.g., axial scalar mediator not constrained by direct detection



Simple WIMP at large: Higgsino DM

Simple WIMP model still **alive (elusive to all DM detections so far)**: higgsino dark matter, a fermionic electroweak doublet (fermionic copy of the Higgs doublet) with little mixing with other fermions, with the right thermal relic at 1.1 TeV.

Thermal higgsino benchmark

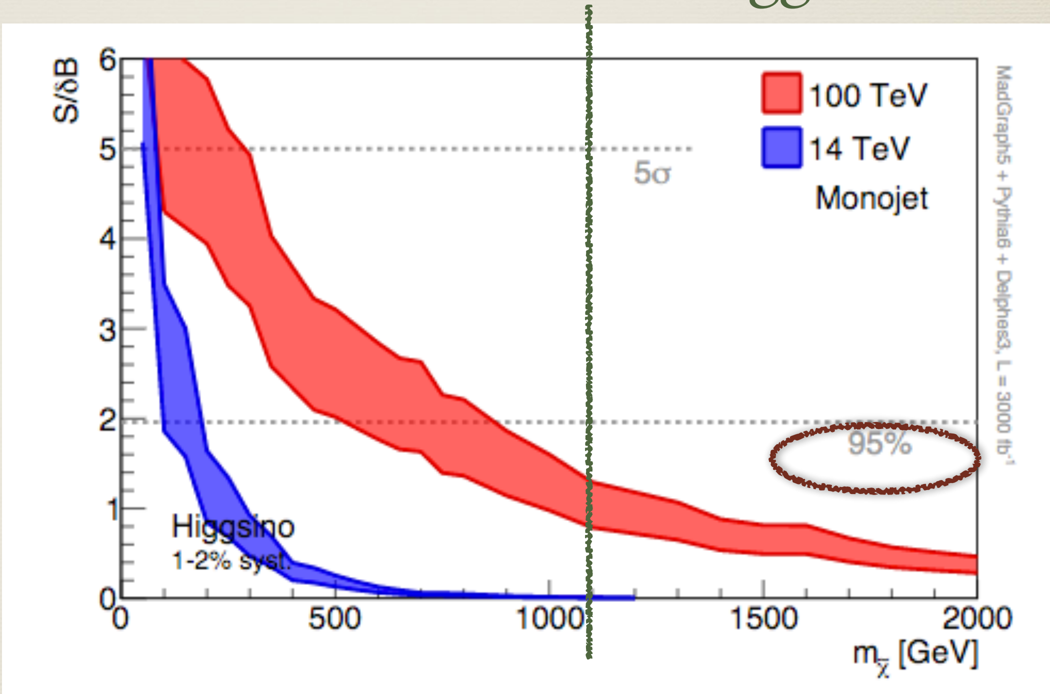


Low, Wang: 2014

Simple WIMP model still **alive (elusive to all DM detections so far)**: higgsino dark matter, a fermionic electroweak doublet (fermionic copy of the Higgs doublet) with little mixing with other fermions, with the right thermal relic at 1.1 TeV.

Thermal higgsino benchmark

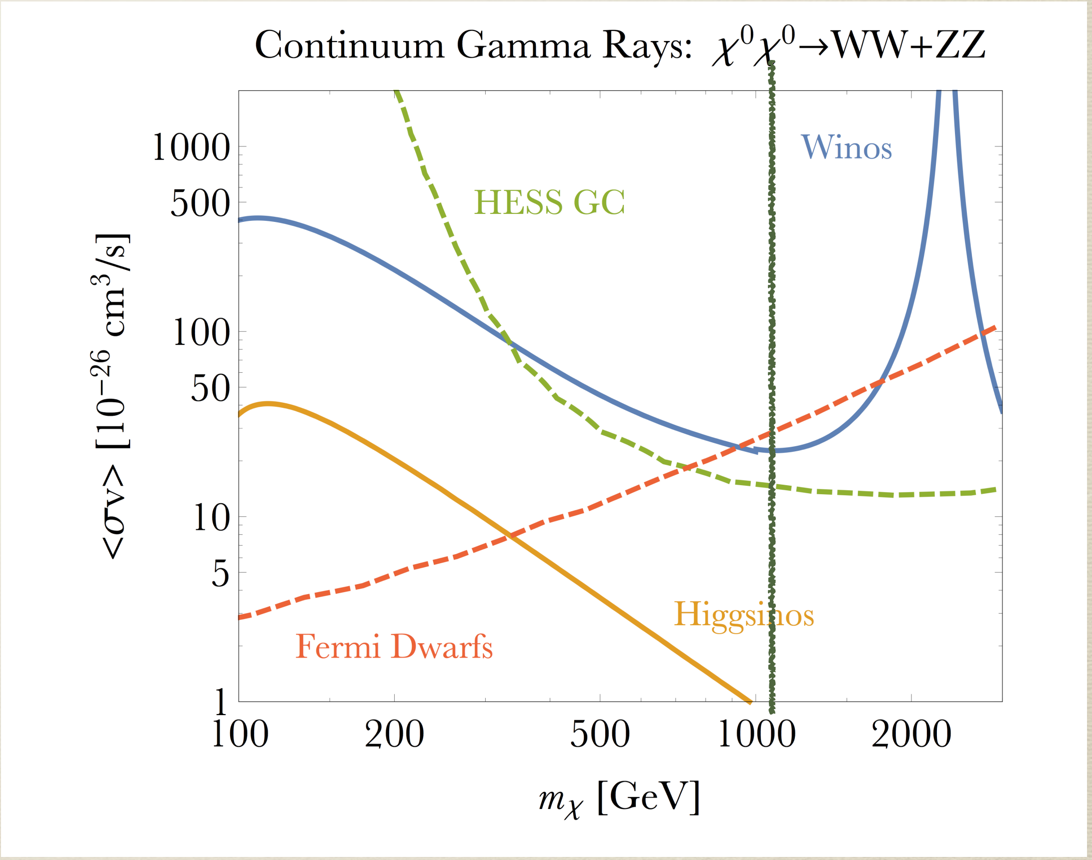
Low, Wang: 2014



Notice **wide bands**: varying background systematics 1-2%. Big experimental challenge is well-characterized background!

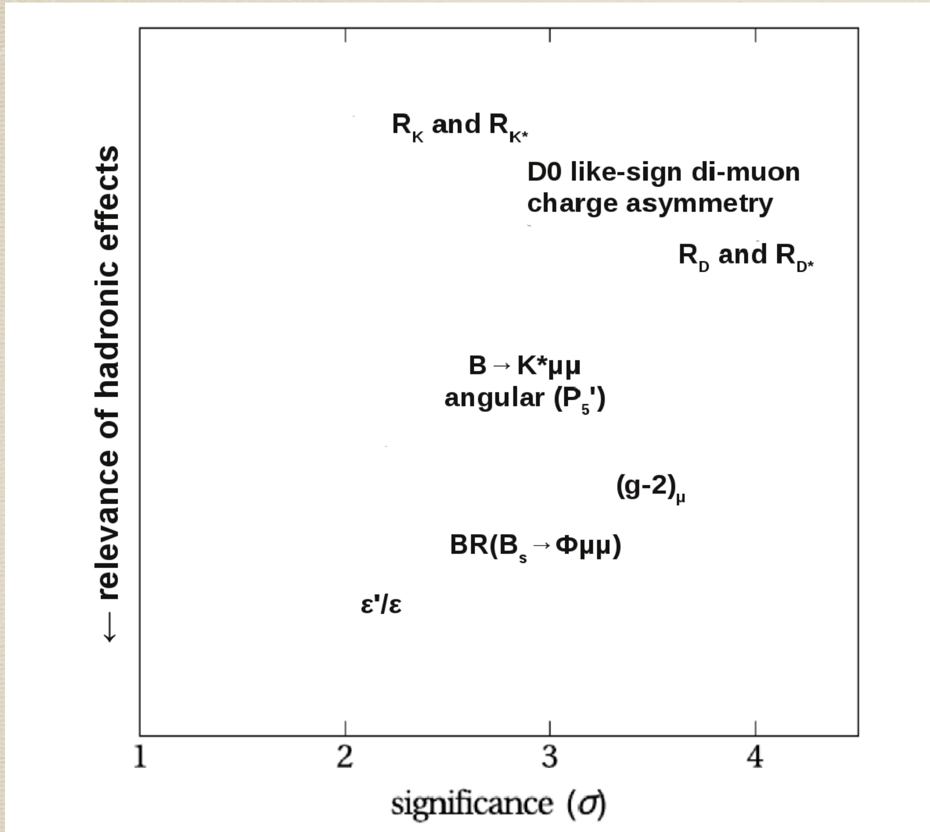
Direct detection: scattering with nucleus happens at one loop level with a cross section <~ neutrino floor;

Indirect detection:
about a factor of 50 below the current Fermi/HESS sensitivity. Future indirect detection?



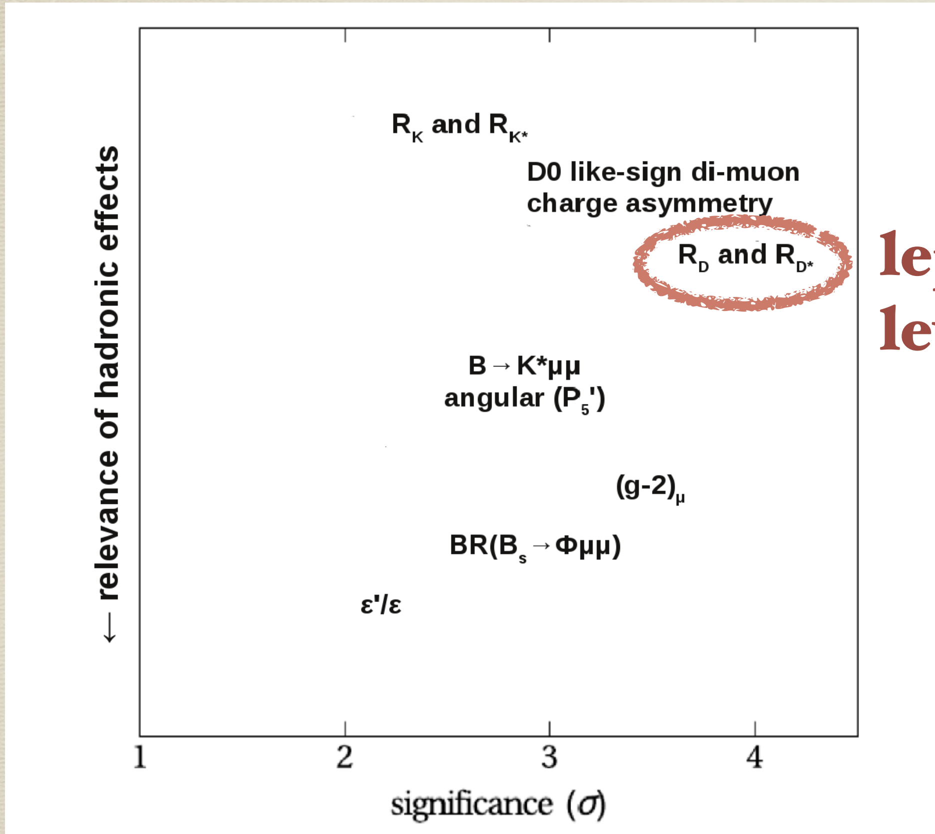
Krall, Reece 1705.04843

Flavor Anomalies



taken from Altmannshofer's 2018 winter aspen talk (is also adapted from Ligeti)

Flavor Anomalies



lepton universality tests in tree level charged current decays

$$b \to c\ell\nu$$

$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)} \qquad 2.3\sigma$$

$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)} \qquad 3.4\sigma$$

$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

taken from Altmannshofer's 2018 winter aspen talk (also adapted from Ligeti)

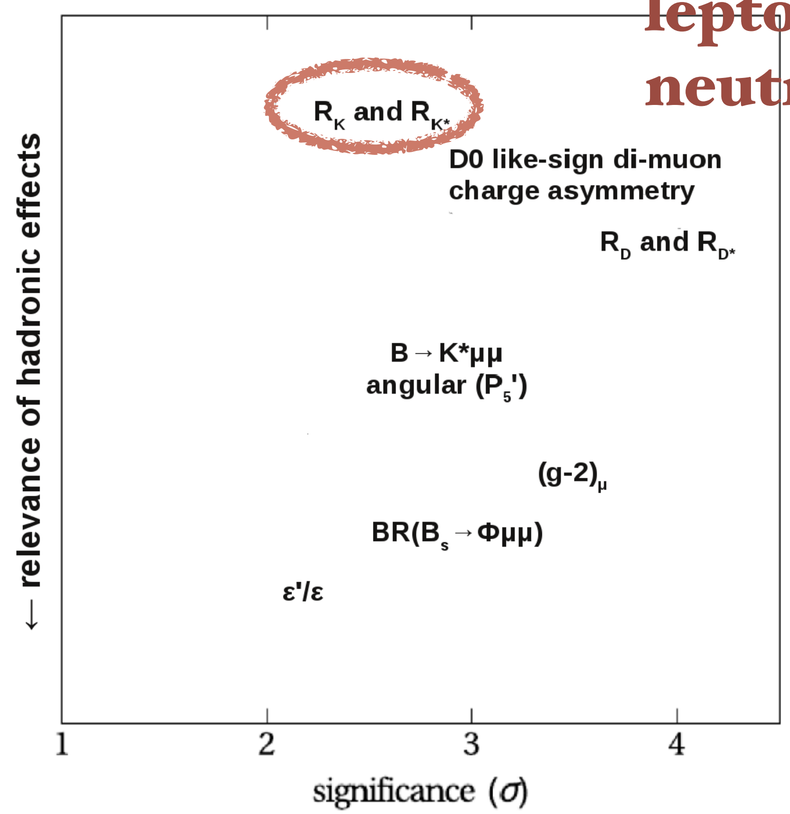
Operator analysis: Freytsis, Ligeti, Ruderman, 2015

$$\mathcal{O}'_{V_L} = (\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu) \quad \mathcal{O}_{S_R} - \mathcal{O}_{S_L} \sim (\bar{c}\gamma^5 b)(\bar{\tau} P_L \nu)$$

Models: lepto-quarks, RPV SUSY, W' bosons

(Greljo et.al; Bauer, Neubert 2015; Deshpande, He; Bhattacharya et.al 2016; Altmanshofer et.al 2017.....)

Flavor Anomalies



lepton universality tests in loop level neutral current decays

$$b \to s\ell\ell$$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

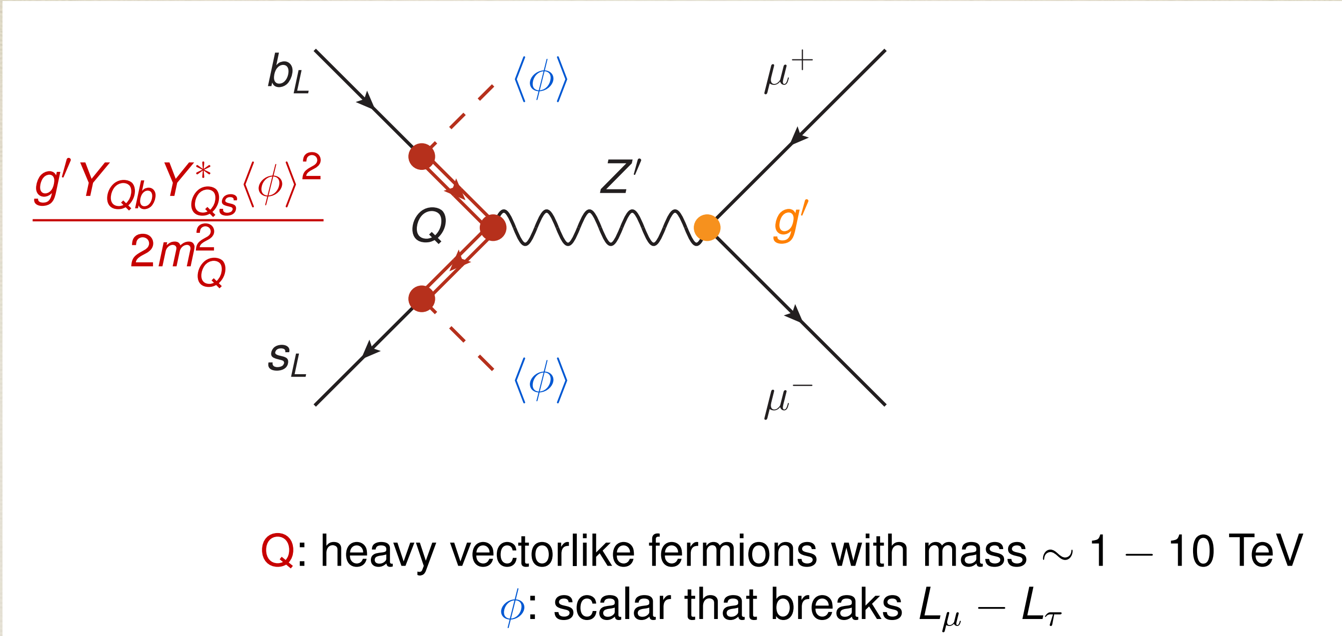
new physics in final states with muons

$$C_9^\mu(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

SM-like final states with electrons

taken from Altmannshofer's winter aspen talk (is also adapted from Ligeti)

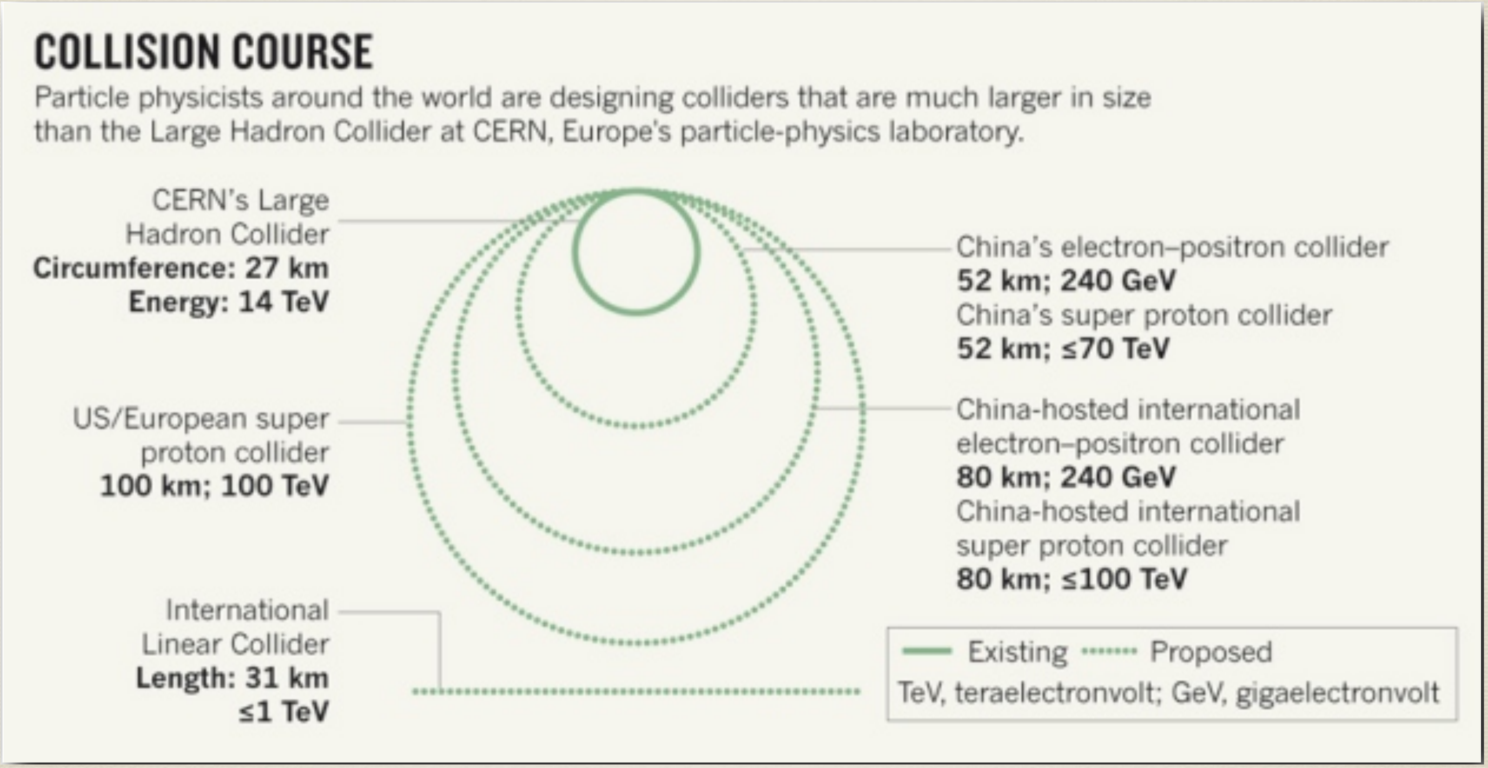
One example of model: Z' from gauging L_μ - L_τ



Altmannshofer et.al; 2014, 2015

If true, who orders it?

Beyond the near future:
High-energy LHC and future colliders



Nature News (E. Gibney), 2014
http://www.nature.com/news/china-plans-super-collider-1.15603

A lot of questions to address:

What are the physics goals? Naturalness, dark matter, electroweak phase transition…

To achieve the physics goals, what technology developments are needed? And how to achieve them?

Each community will have its own future planning. Yet to obtain a cohesive picture and a complete answer, we need to put together all the information we could have:
interplay between future colliders and other future experiments?

Have to think about it from now rather than wait to make future colliders built!

The party is under way already

CEPC-SPPC

Preliminary Conceptual Design Report: Physics and Detector

Physics at a 100 TeV *pp* collider: beyond the Standard Model phenomena

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Physics at a 100 TeV *pp* collider: Higgs and EW symmetry breaking studies

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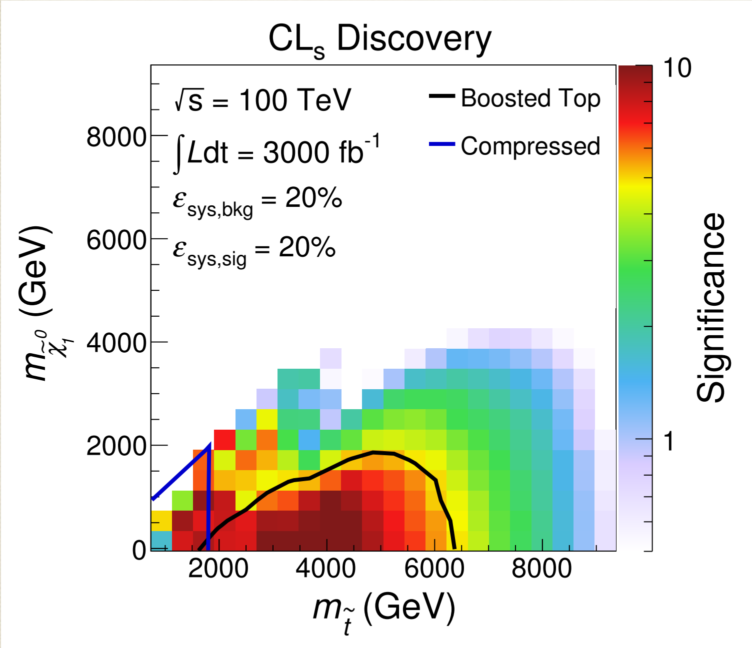
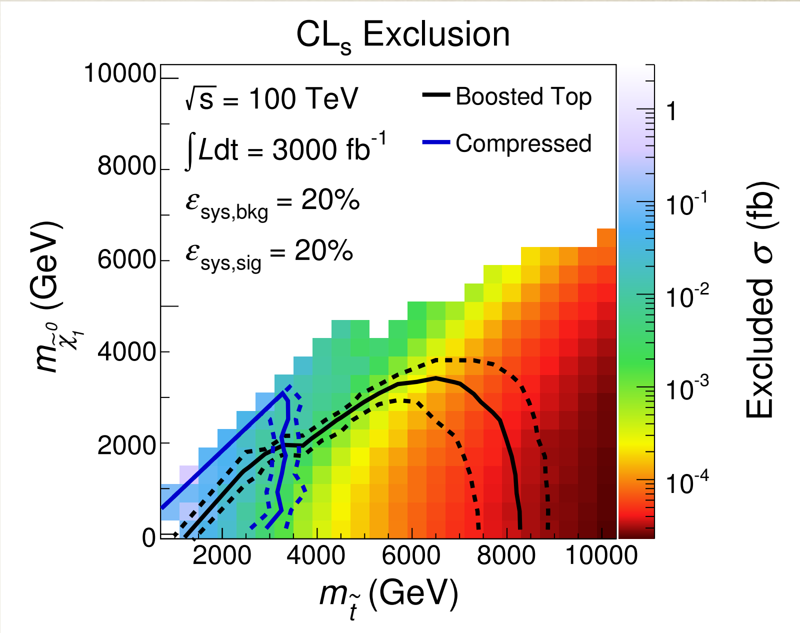
More work is on the way and needed.

Physics cases for a future hadron collider: leap in searching for new particles





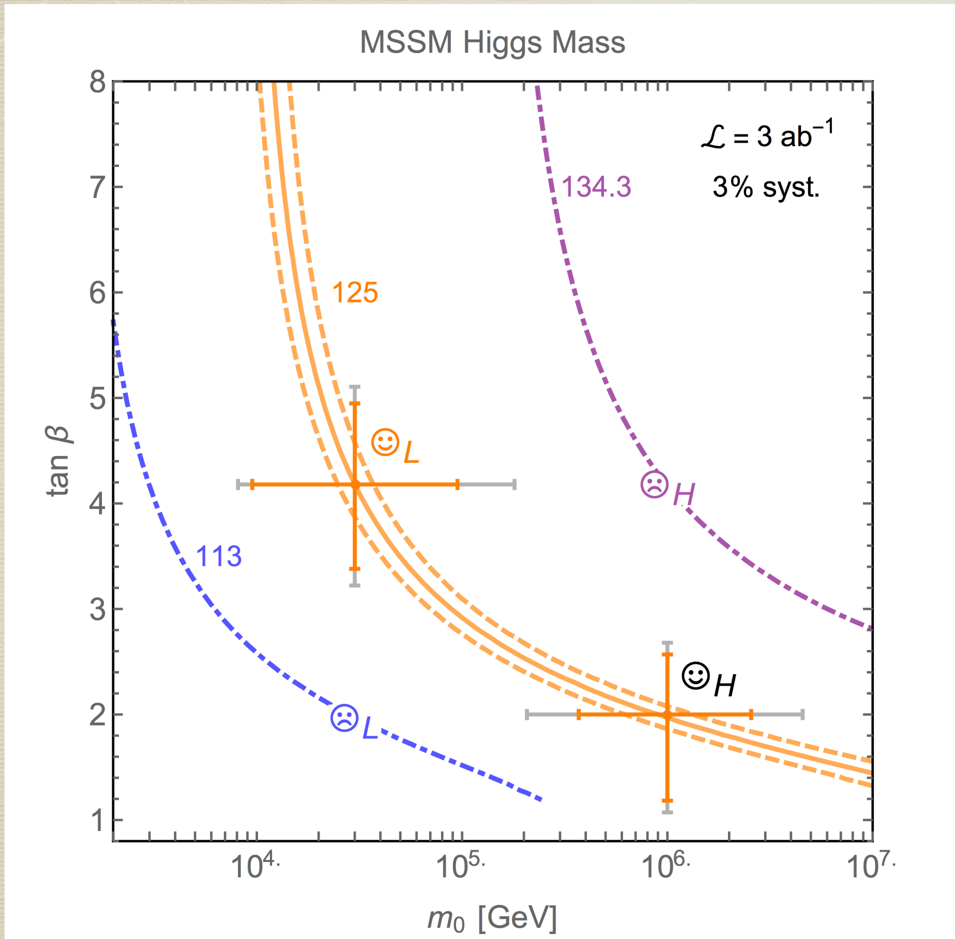
Cohen, D'Agnolo, Hance, Lou, Wacker 2014

A factor of 5~6 improvement in the discovery reach:

Discovery Reach ~ 6 TeV stop and exclude 8 TeV stops at 95%.

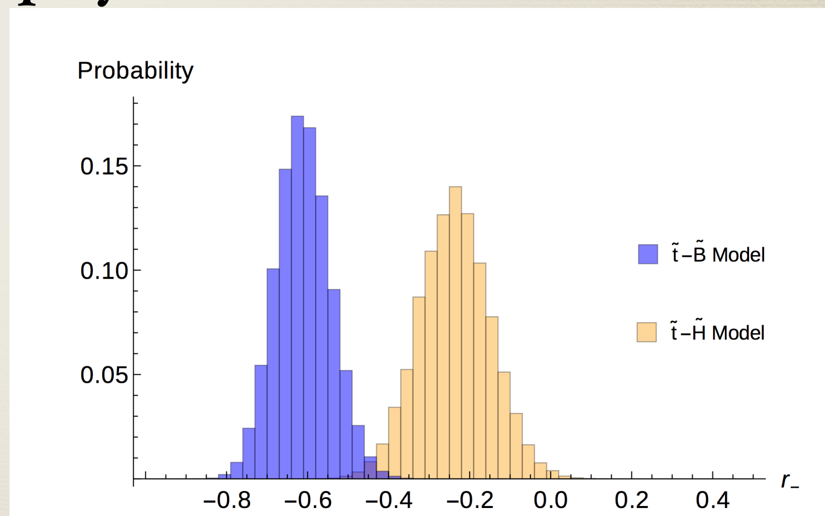
Probe electroweak fine tuning ~ 3000.

Reveal and test the underlying mechanism: e.g, MSSM explanation of the Higgs mass



Agrawal, Fan, Reece, Xue 2017

Ideal playground to apply jet substructure tools to discover and distinguish new physics models



Fan, Jaiswal, Leung 2017

Keep searching!

Backup

Many other related studies aiming to improve the sensitivity at colliders for higgsino DM: e.g., a better tracker?

Charged and neutral higgsino nearly degenerate in mass, one-loop induced mass splitting ~ 360 MeV;
nominal decay length of charged higgsino, $c\tau$~ **6.6 mm**

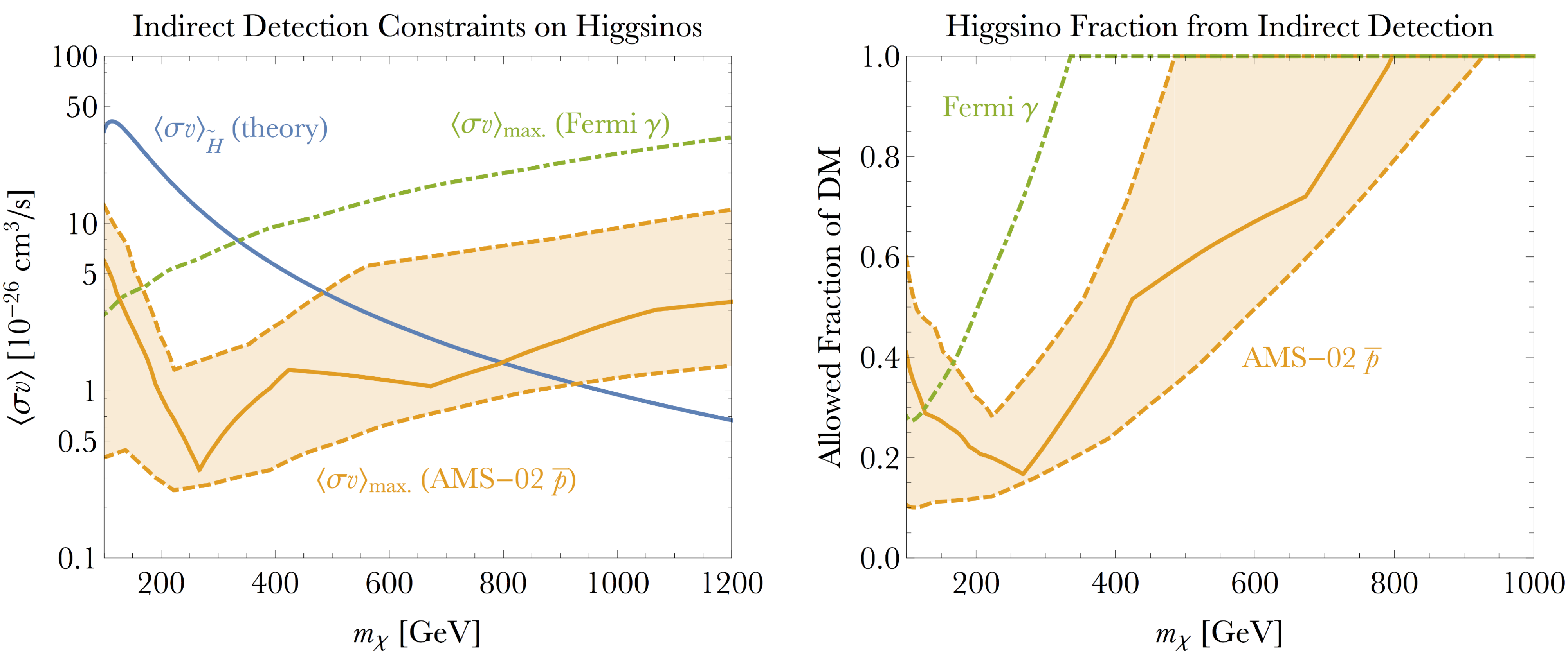
Disappearing charged track: need large boost (~ 100) (more easy to get large forward than transverse boost)

Increase the tracker granularity below r=10 cm (r: transverse distance from the beamline): need 10 hits at r = 10 cm.

In the future, may consider having a forward tracker covering $2 \leq |\eta| \leq 4$,

Mahbubani, Schwaller, Zurita;
Fukuda, Nagata, Otono, Shirai, 2017

AMS anti-proton constraint on higgsino



Krall, Reece 2017