Beyond Standard Model Phenomenology

JiJi Fan
Brown University

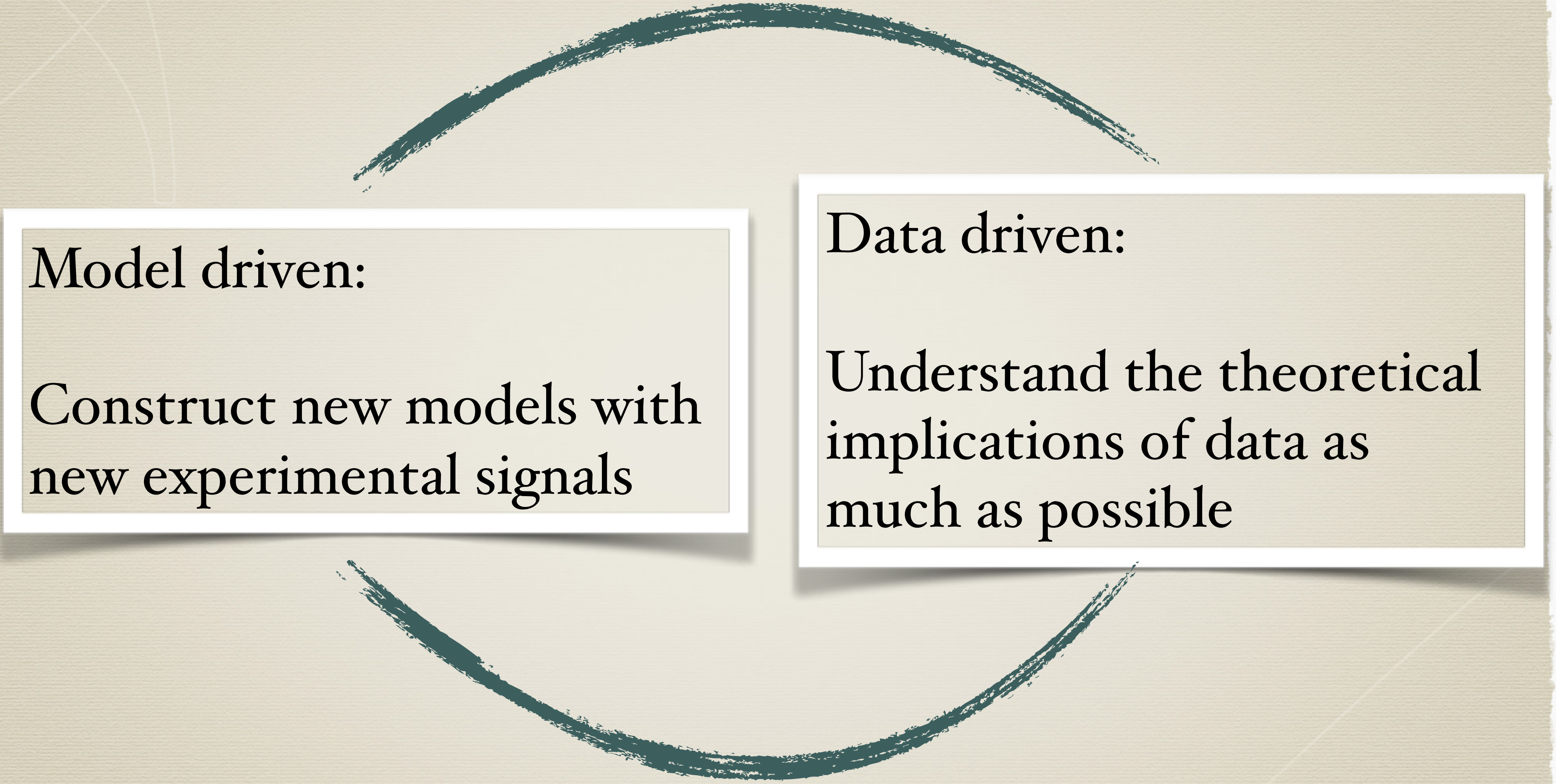
1st Workshop on High Energy Theory and Gender,
CERN, 2018

BSM phenomenology covers a very broad range of topics. Impossible to cover in 30 mins.

Select a couple of topics related to the origin of the weak scale and Higgs physics. (the choice of speculative theories discussed in the talk has personal bias)

Not cover neutrino, flavor physics, dark matter:
talk by Elvira Gamiz, Silvia Pascoli, Tracy Slatyer

In the era of data,



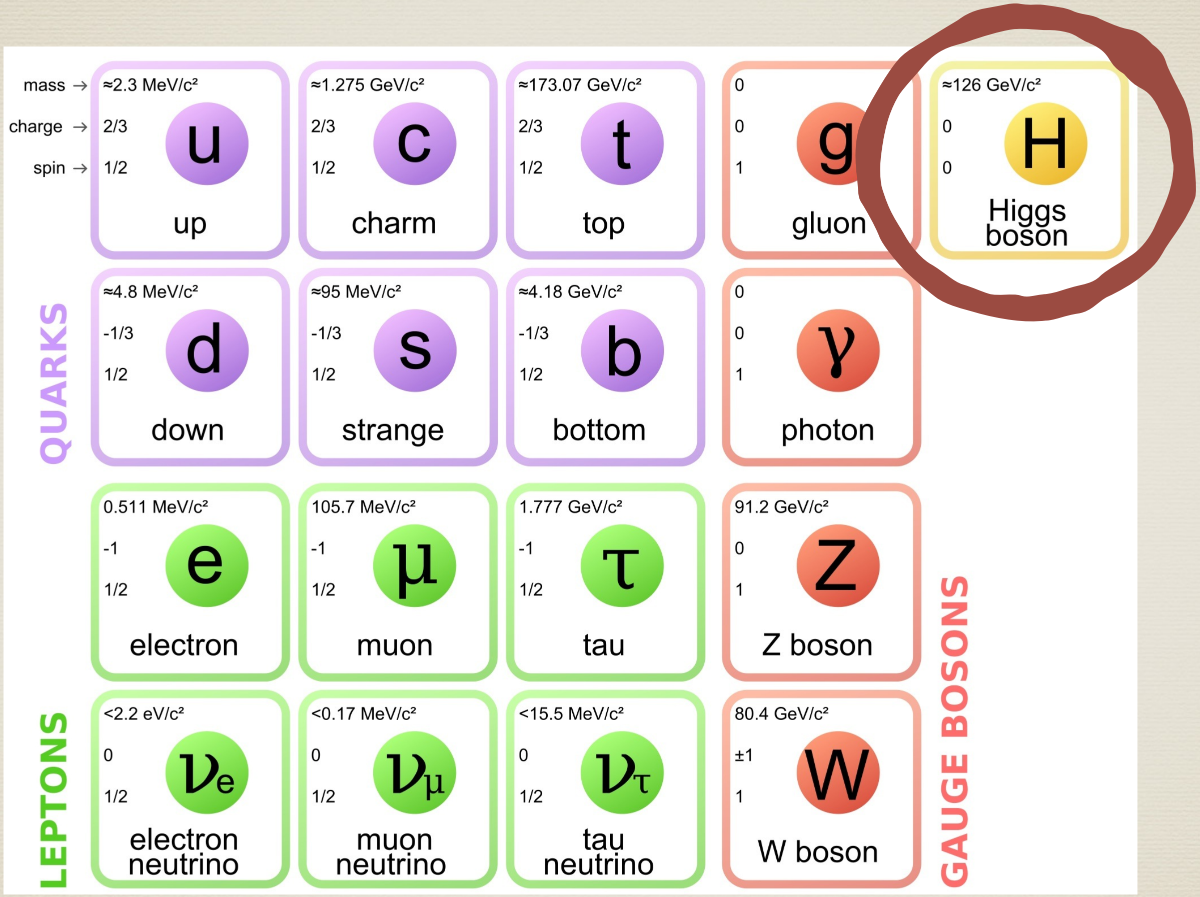
Model driven:

Construct new models with new experimental signals

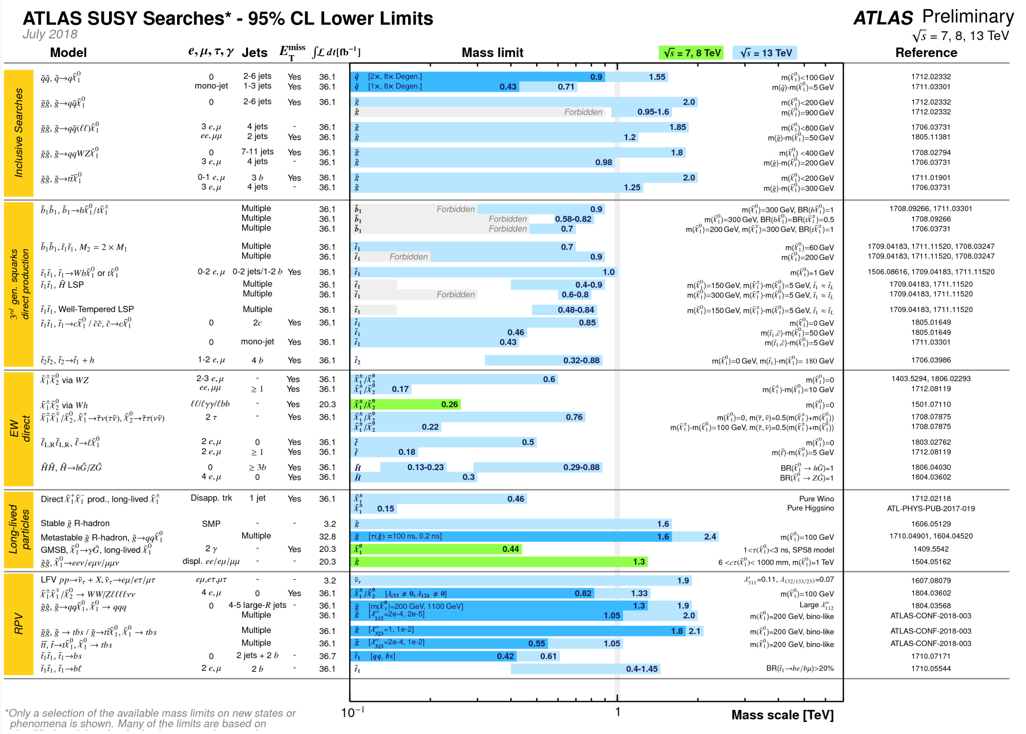
Data driven:

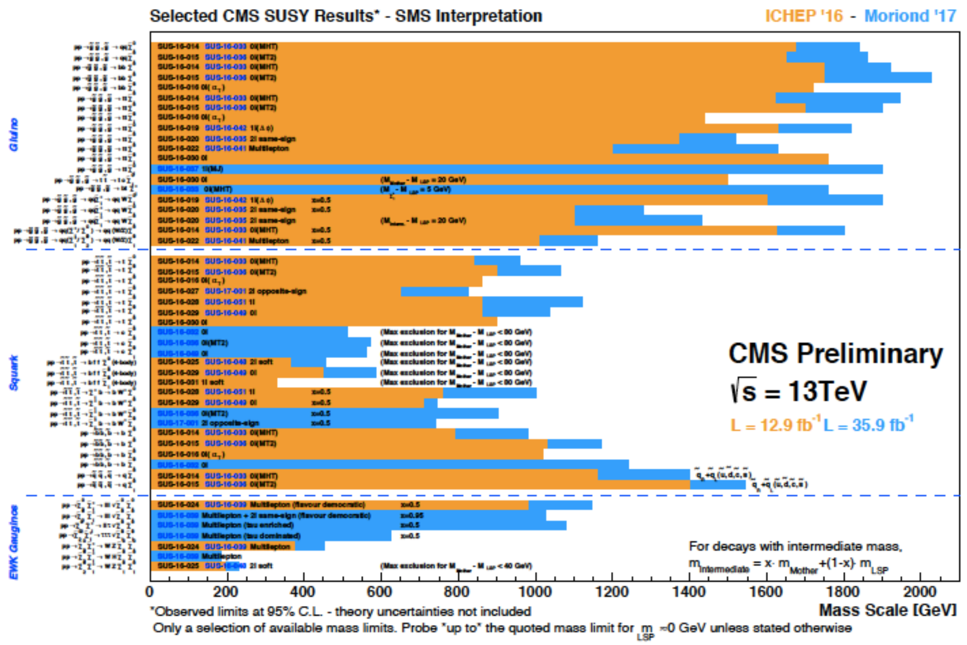
Understand the theoretical implications of data as much as possible

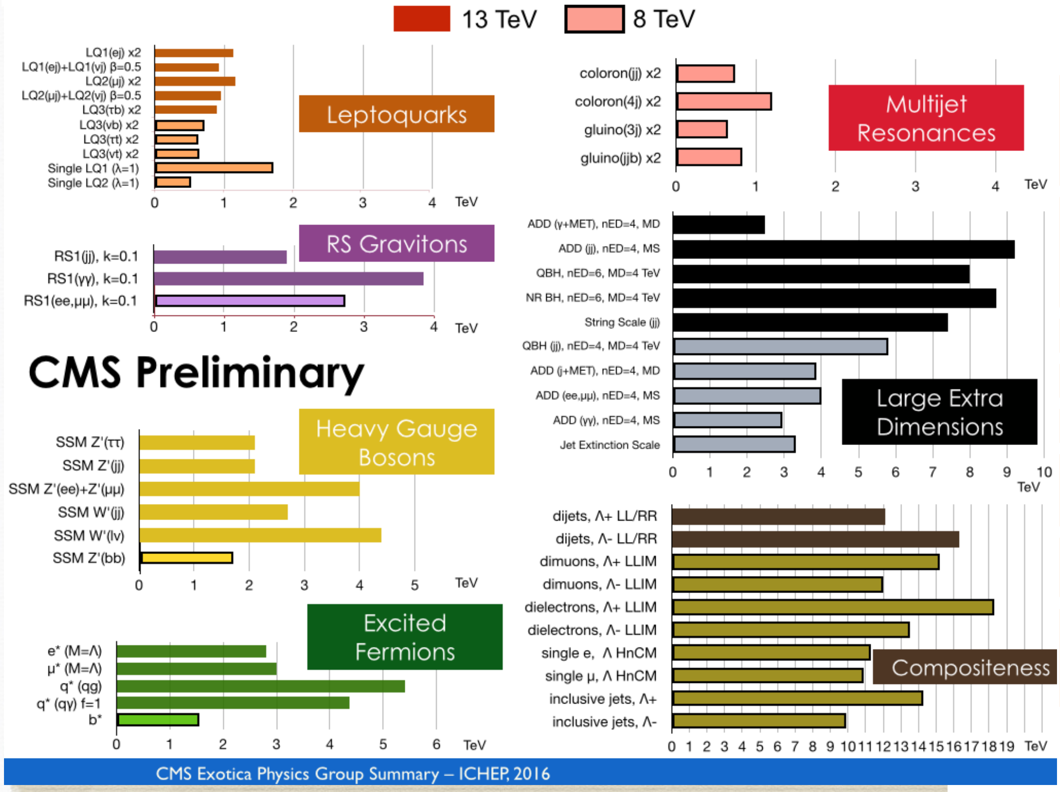
Quick Overview of LHC Results

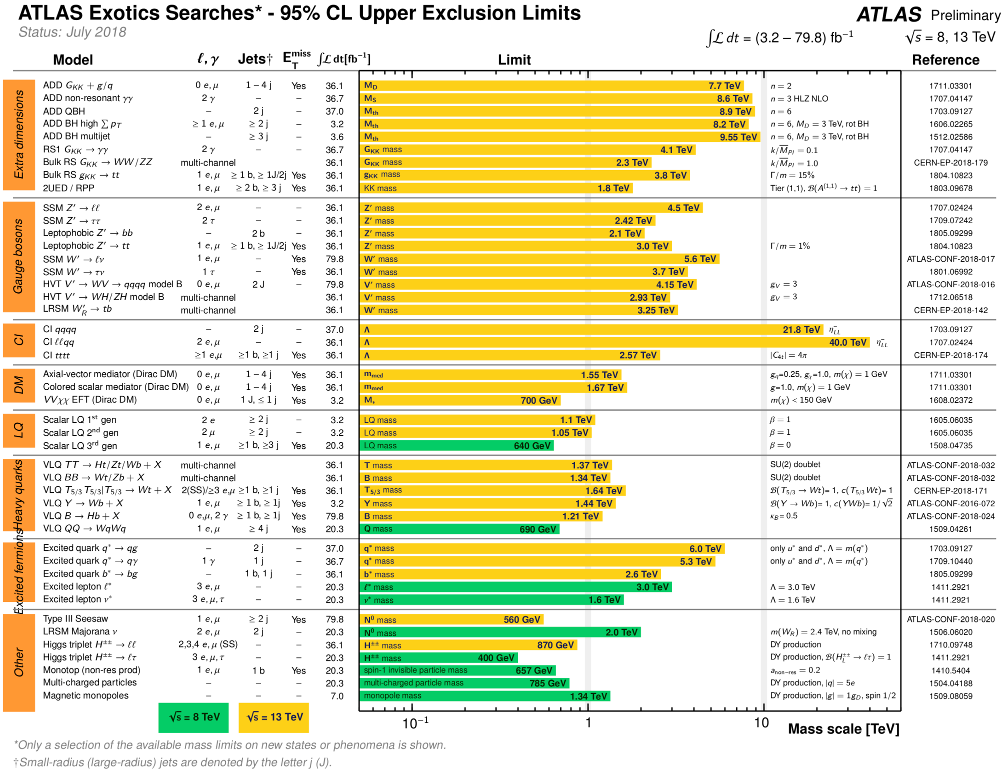


QUARKS	mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
		≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
LEPTONS		0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
		<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	


ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^miss
∫L dt[fb⁻¹]
Mass limit
√s = 7, 8 TeV
√s = 13 TeV
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
10⁻¹
1
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,
m_Intermediate = x· m_Mother + (1-x)· m_LSP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*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


13 TeV
8 TeV
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(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS Gravitons
CMS Preliminary
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Heavy Gauge Bosons
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
Excited Fermions
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
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
Large Extra Dimensions
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-
Compositeness
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
ℓ, γ
Jets†
E_T^miss
∫L dt[fb⁻¹]
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
√s = 8 TeV
√s = 13 TeV
10⁻¹
1
10
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).

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 such as the origin of weak scale.

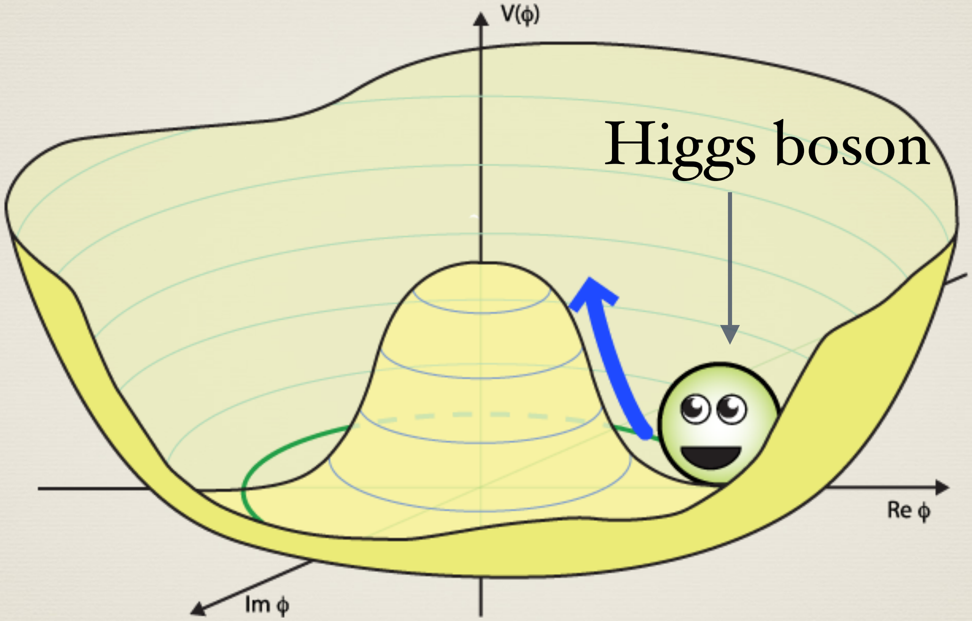
A two-sentence summary of LHC results:

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

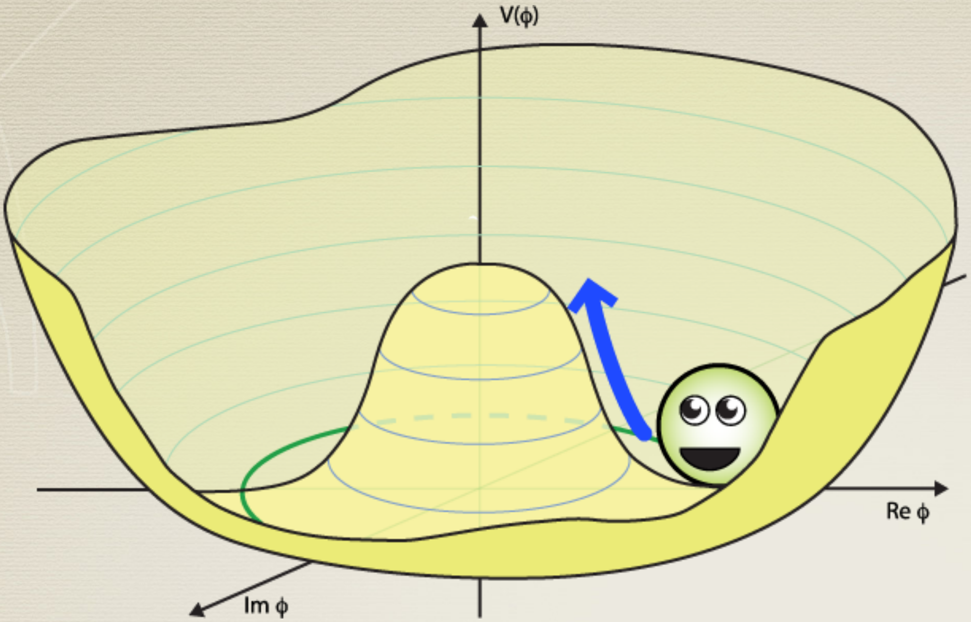
Relatively weak constraints on weakly-interacting particles: depend on the final states.
(one example with essentially no constraints beyond LEP will be discussed at the end).

Higgs Physics in a Nutshell

Higgs potential energy



Higgs boson



©P. Tanedo

The standard model ***assumes*** this potential but doesn't ***explain*** it.

The standard model doesn't ***explain*** the Higgs mass itself.

It is only an **effective** description of electroweak symmetry breaking. Yet the microscopic details aren't specified.

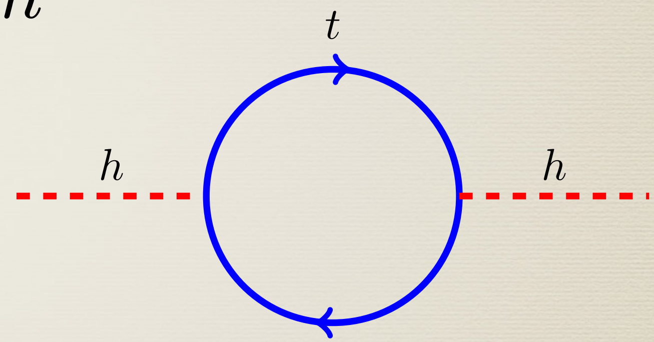
What we really want is a **dynamical** explanation:
what are the interactions driving the preference for a nonzero vacuum expectation value?

Hierarchy Problem of an Elementary Scalar (fine-tuning problem)

Physical mass
125 GeV

$$m_h^2 = m_0^2 + \Delta m_h^2$$

quantum correction such as



Bare mass,
parameter in the potential term

$$\sim \frac{y_t^2}{16\pi^2}\Lambda^2 \sim \frac{\Lambda^2}{100}$$

Λ: scale up to which SM is valid or **the scale of new physics that dynamically generates the Higgs potential**

Hierarchy Problem of an Elementary Scalar (fine-tuning problem)

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quantum correction

Bare mass,
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$$\Delta m_h^2 \sim \frac{y_t^2}{16\pi^2}\Lambda^2 \sim \frac{\Lambda^2}{100}$$

Λ: scale up to which SM is valid or **the scale of new physics that dynamically generates the Higgs potential**

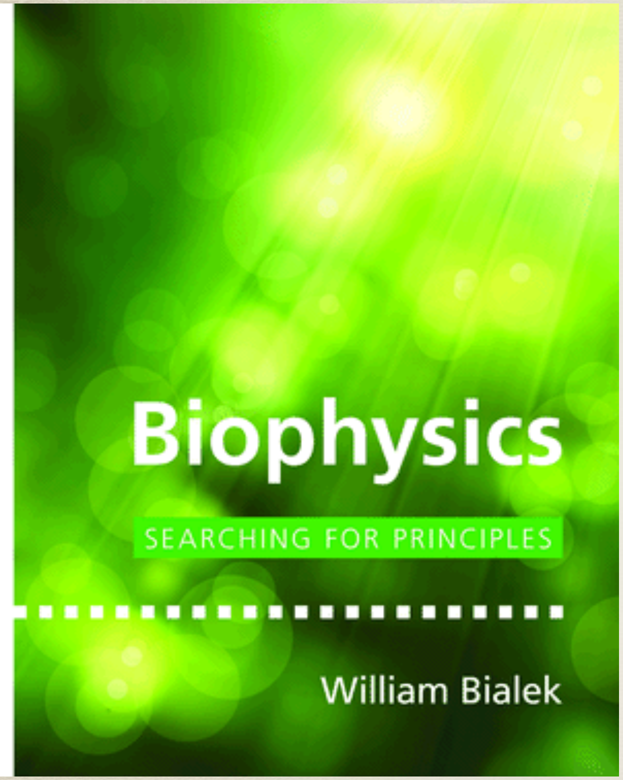
Suppose $\Lambda = 10^{19}$ GeV, and the observed Higgs mass is 125 GeV, we need, say, a huge bare mass to cancel the quantum fluctuations

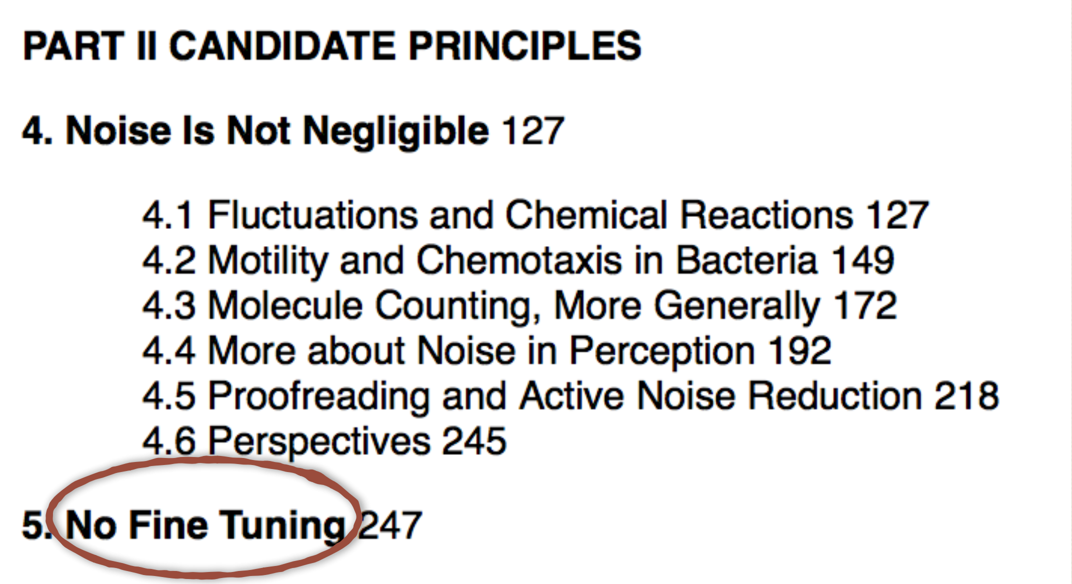
$m_0^2 = (1{,}500{,}473,\ 789,\ 254,\ 211{,}536\ \text{GeV})^2$;

If we miss by 10 GeV, $m_0^2 = (1{,}500{,}473,\ 789,\ 254,\ 211{,}5\mathbf{2}6\ \text{GeV})^2$;

The physical Higgs mass is ~ **10^9** GeV!

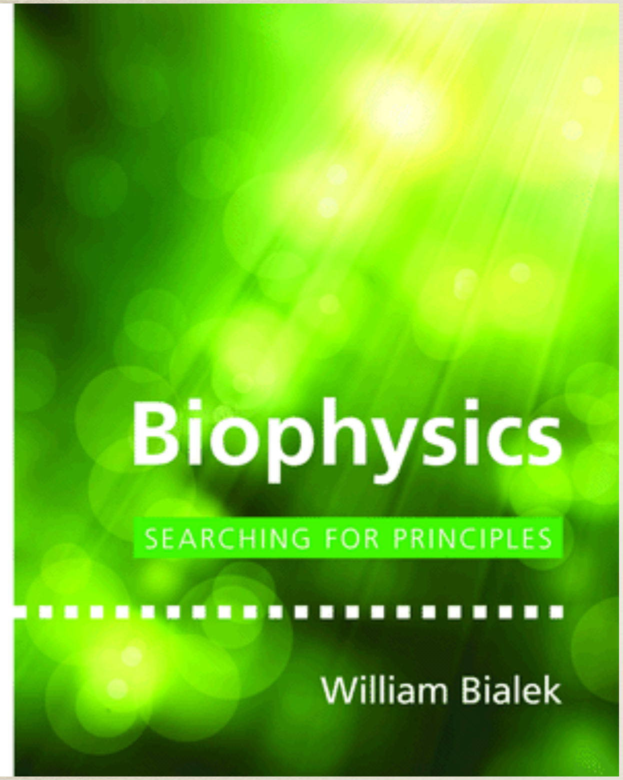
No fine-tuning is a possible candidate principle not only for particle physics

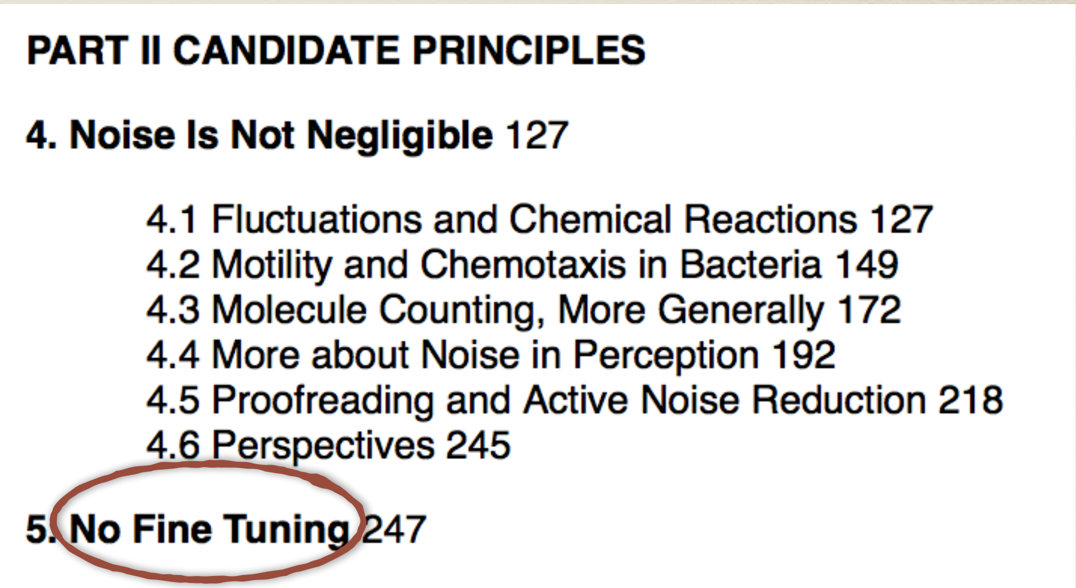



PART II CANDIDATE PRINCIPLES

Whether we like it or not, it could be probed **experimentally.**

No fine-tuning is a possible candidate principle not only for particle physics

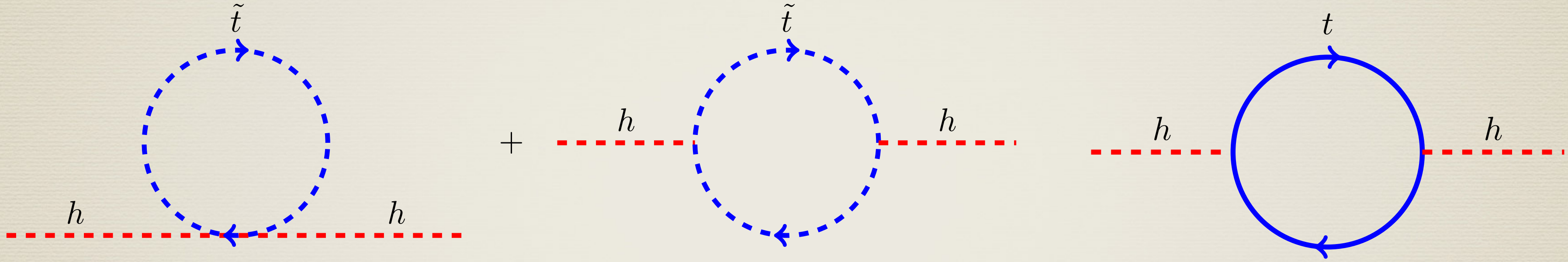



PART II CANDIDATE PRINCIPLES

Whether we like it or not, it could be probed **experimentally.** Whether the mechanism that generates the weak scale natural or unnatural, finding it will be ground-breaking!

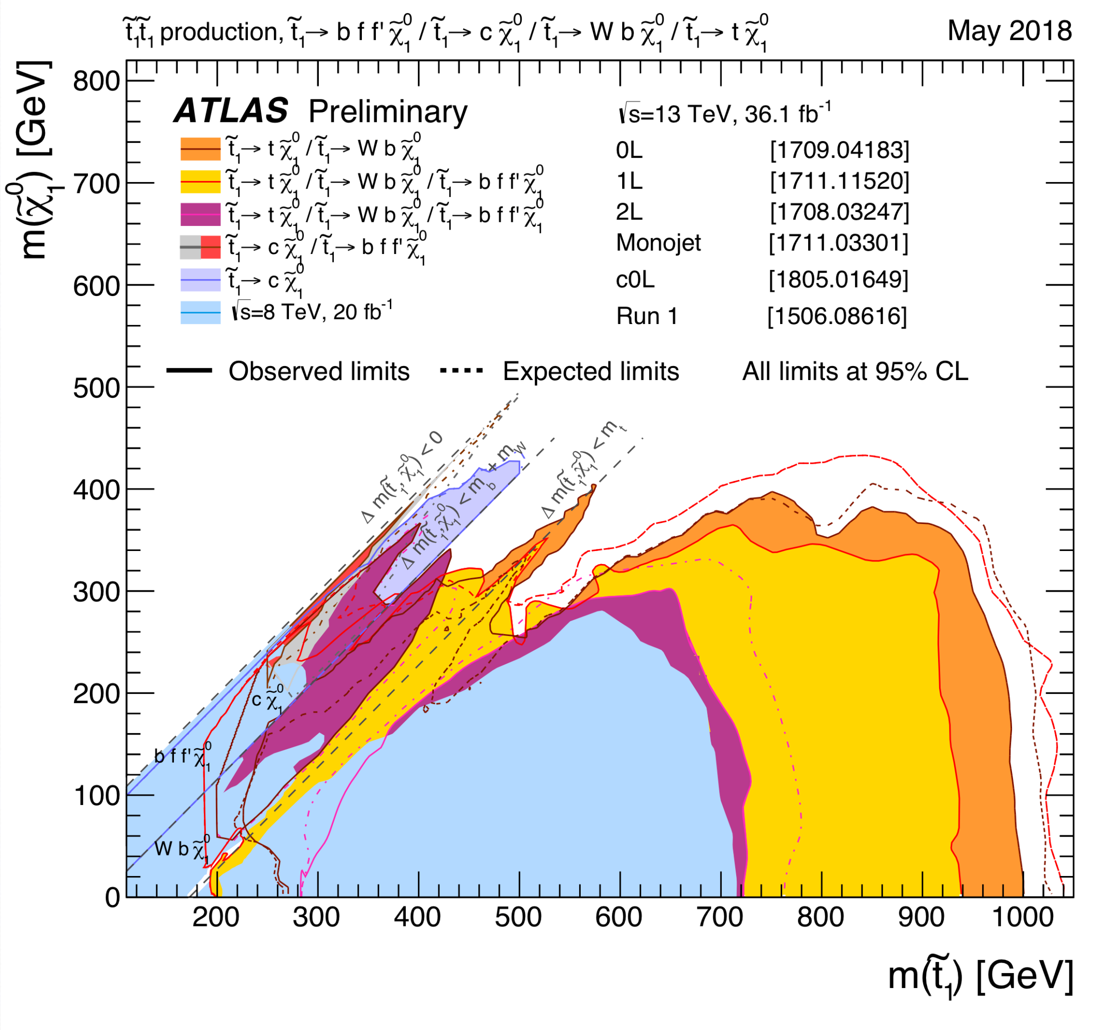
Electroweak Naturalness

Traditional natural ways to explain the weak scale: 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 quantum correction from the top loop. ~10% tuned if stop mass ~ TeV.

Implications of LHC Results

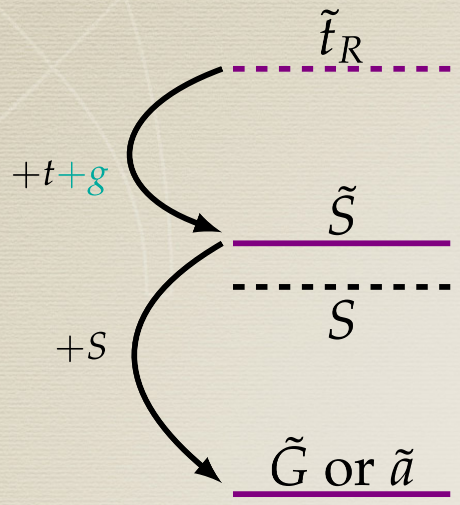


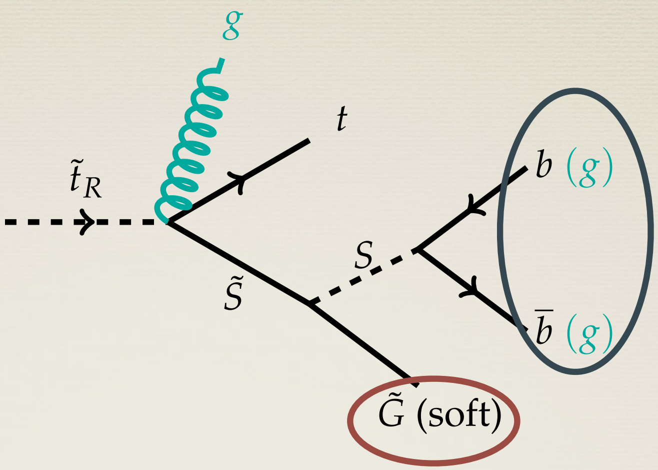
Impressive reach with 13 TeV data for **simplest** stop decays (at both CMS and ATLAS): exclude stop ~ 1 TeV (for neutralino below 400 GeV).

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.

Effect of a Hidden Sector





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

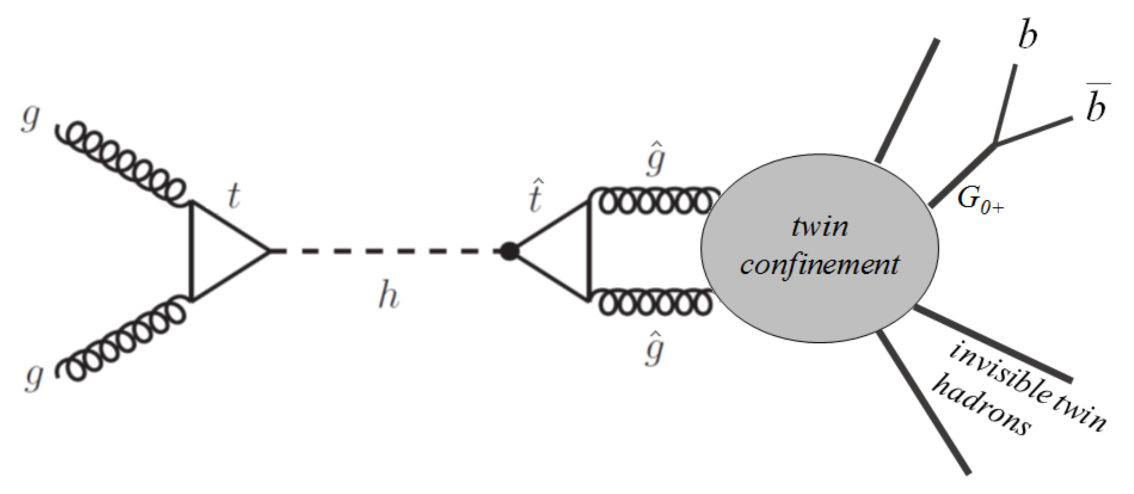
light invisible fermion

Stealth SUSY: Fan, Krall, Pinner, Reece, Ruderman, 2015
Approximate SUSY in the *hidden sector* suppressing missing momentum;
visible particles at the end of long cascades through the hidden sector have less energies.

In general, hidden valley could lead to dramatic new signatures:
Strassler, Zurek 2006

Neutral Naturalness

Top partners do ***not*** feel strong dynamics.
Either SM gauge singlets or electroweakly charged (difficult to be found).
Chacko, Goh, Harnik, 2005; revived recently with many papers

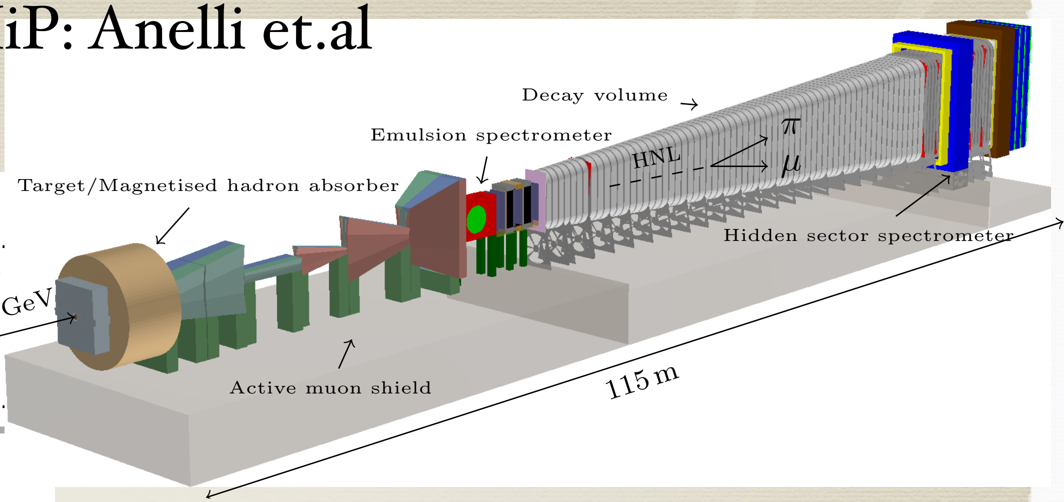


Craig, Katz, Strassler, Sundrum 2015

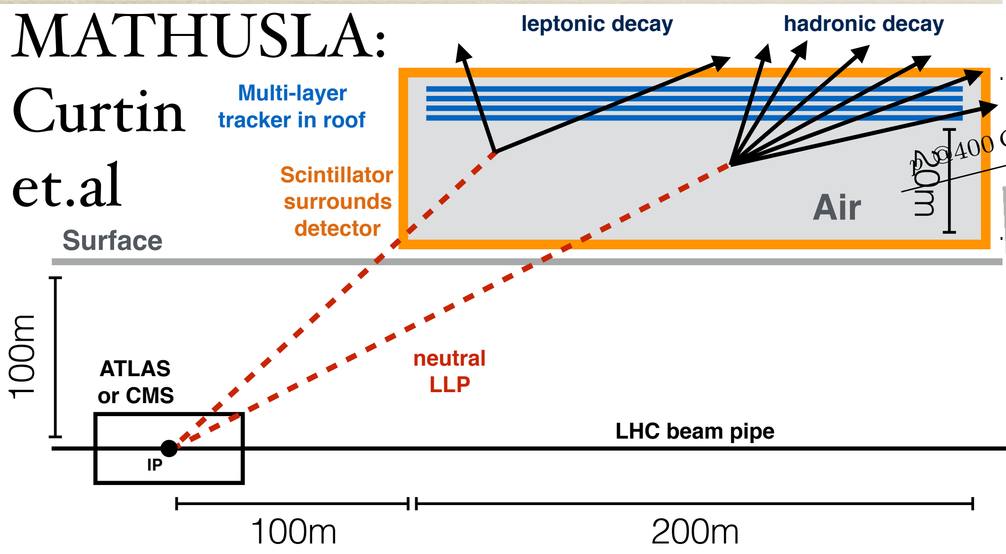
Exotic Higgs decays: $gg \to h \to 0^{++} + 0^{++} + \ldots;\ 0^{++} \to h^* \to b\bar{b}$
Long-lived, length scale ~ LHC detectors

Lifetime Frontier

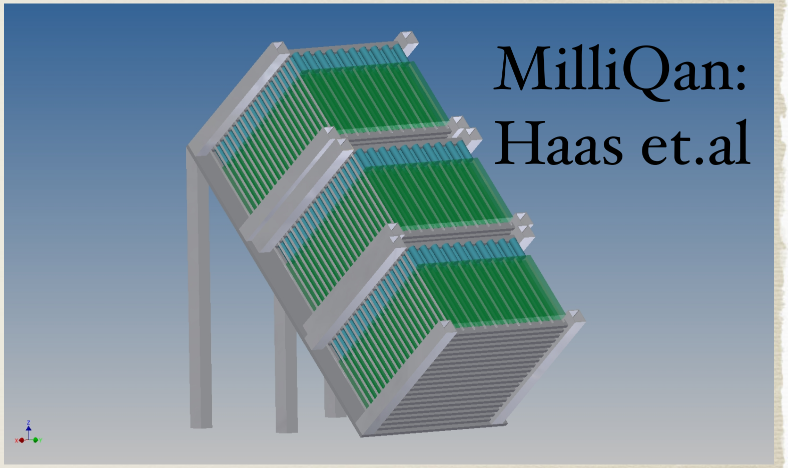
SHiP: Anelli et.al



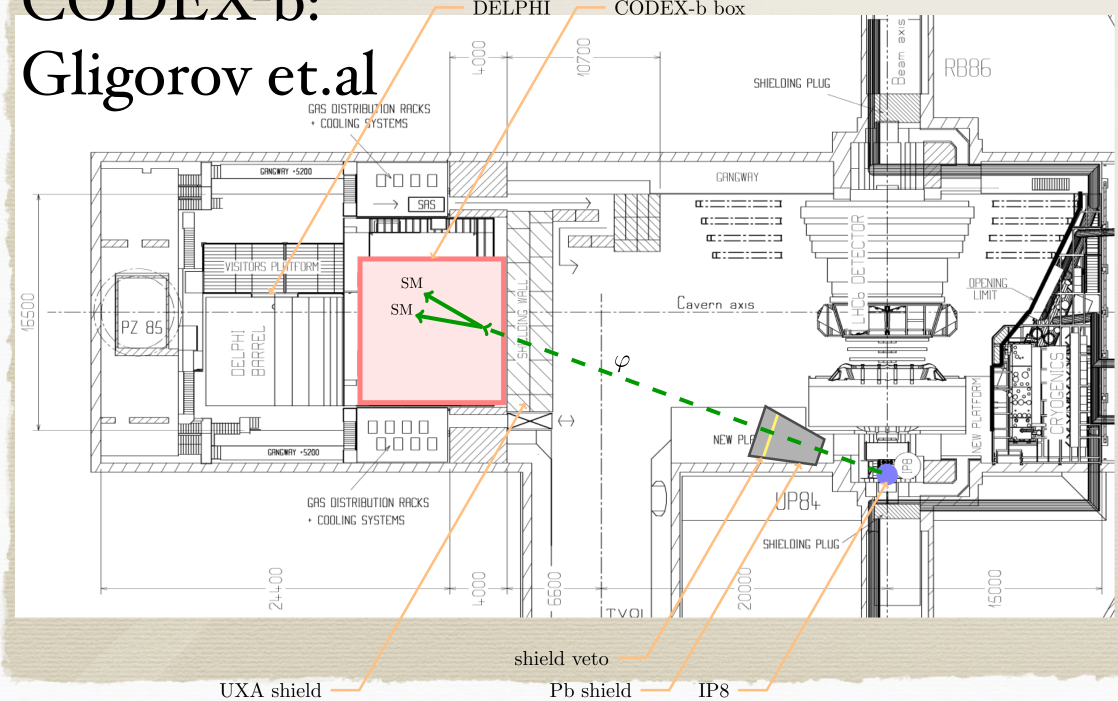
MATHUSLA: Curtin et.al



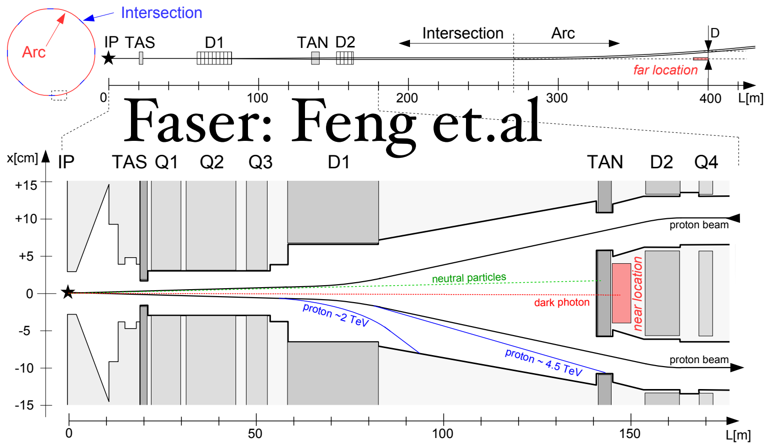
MilliQan: Haas et.al



CODEX-b: Gligorov et.al



Faser: Feng et.al

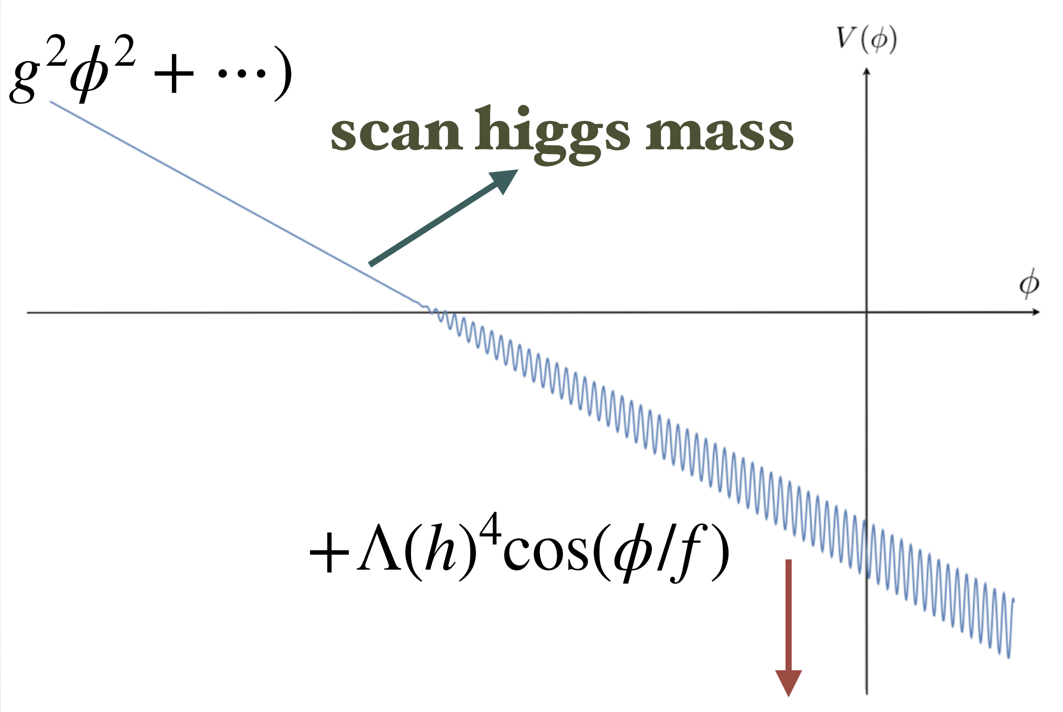


Relaxing the Little Hierarchy?

Graham, Kaplan, Rajendran 2015

Cosmological selected electroweak vacuum

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



scan higgs mass

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

select higgs VEV

Huge energy stored in the evolving relaxion, need **dissipation**: inflation.

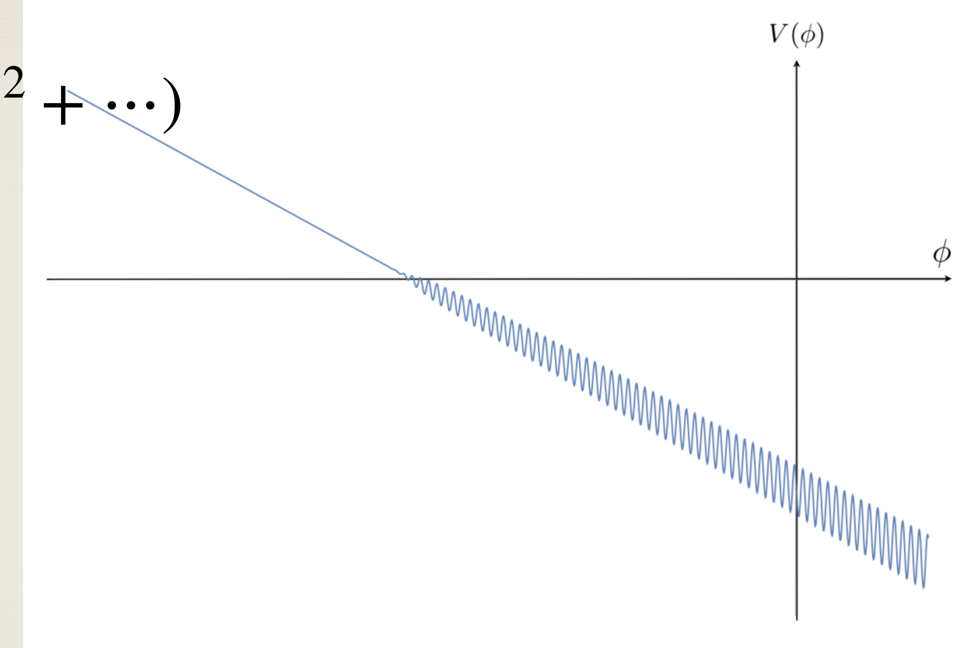
Relaxing the Little Hierarchy?

Graham, Kaplan, Rajendran 2015

Cosmological selected electroweak vacuum

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

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



Original version requires:

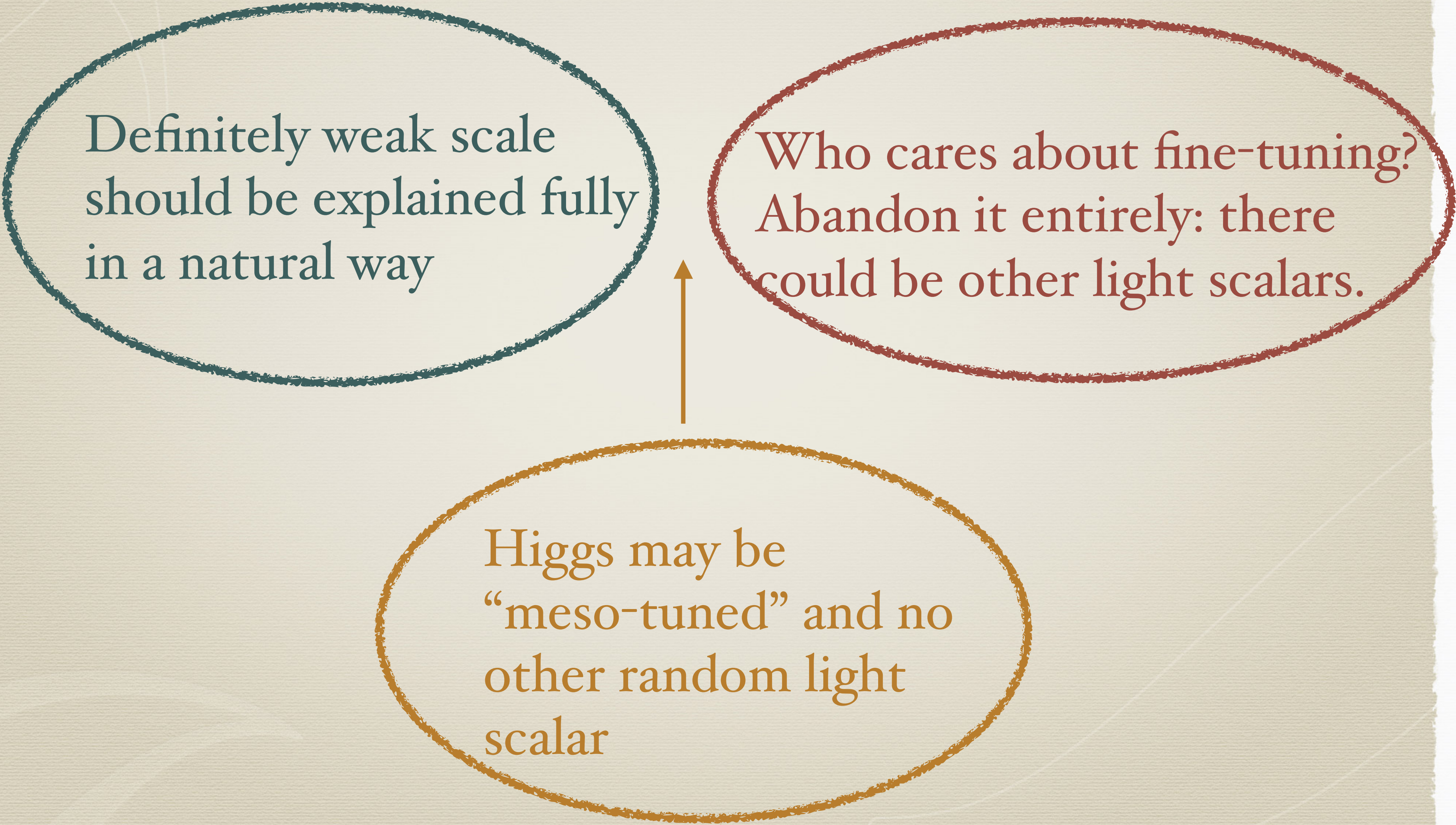
exponentially small g,
exponentially large field range beyond the Planck scale,
very low-scale inflation ($H << \Lambda_{QCD}$),
10 Giga-years of inflation...

Many further attempts based on it, to name a few,

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

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

An Intermediate View-point

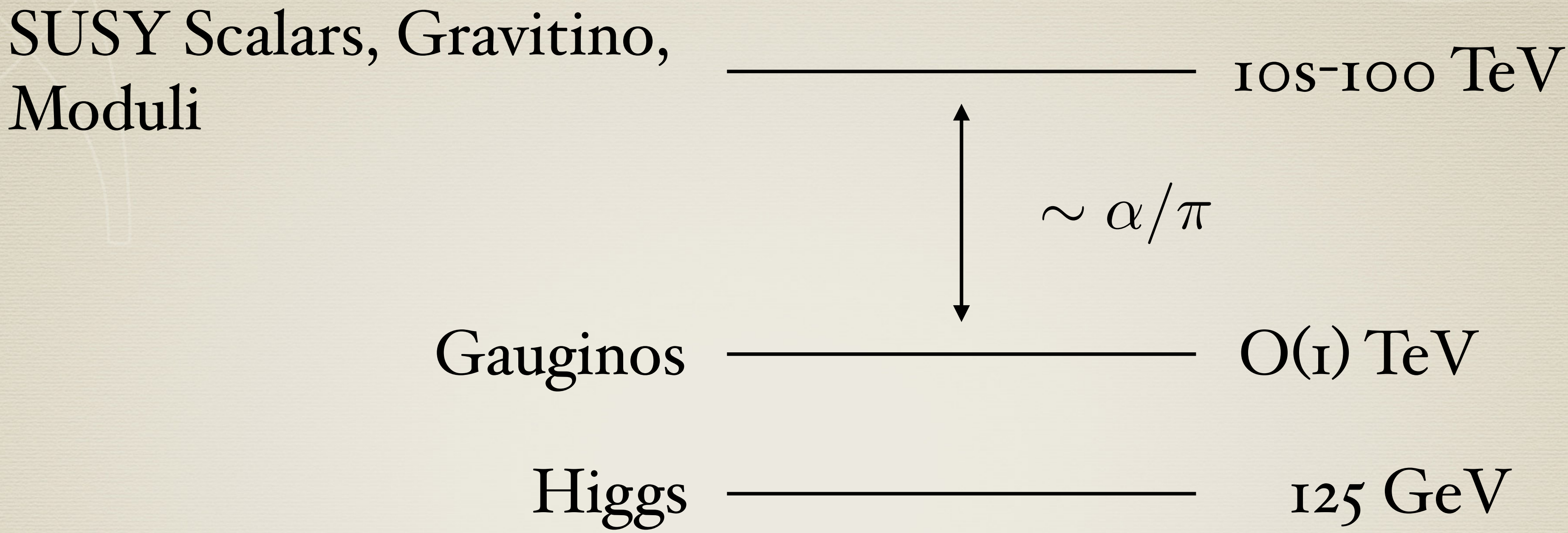


Definitely weak scale should be explained fully in a natural way

Who cares about fine-tuning? Abandon it entirely: there could be other light scalars.

Higgs may be “meso-tuned” and no other random light scalar

An example: mini-split



SUSY Scalars, Gravitino, Moduli — 10s-100 TeV

$\sim \alpha/\pi$

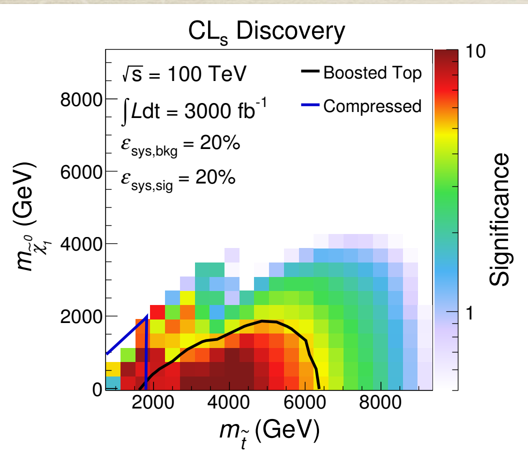
Gauginos — O(1) TeV

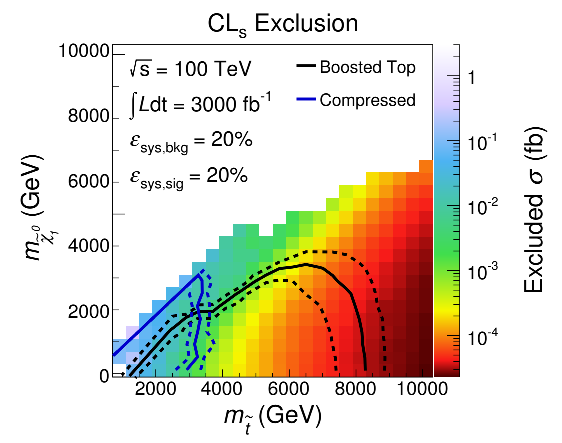
Higgs — 125 GeV

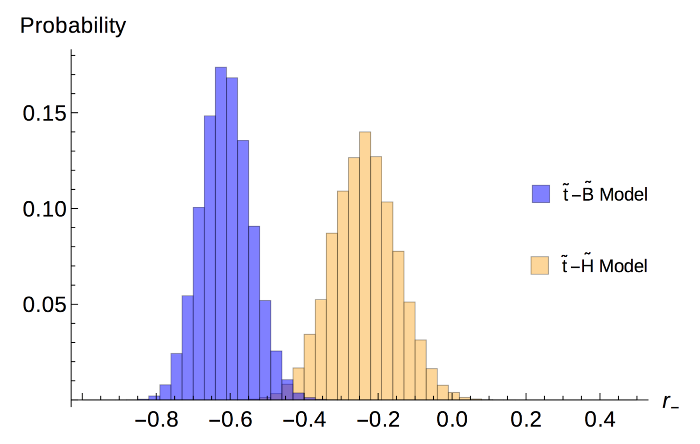
- Heavy scalars (10s of TeV) at large tan β: right Higgs mass
- Loop factor: arises in AMSB (Giudice, Luty, Murayama, Rattazzi; Randall, Sundrum) and some moduli mediation
- Late-time gravitino and/or moduli decays populate nonthermal dark matter, e.g. light winos around O(100) GeV (Moroi, Randall; Kane et al.)

Many papers on “Mini-Split”: Arvanitaki et al., Hall et. al, Arkani-Hamed et al., … 2012

How to probe meso-tuning?
Probe 1: future 100 TeV hadron collider

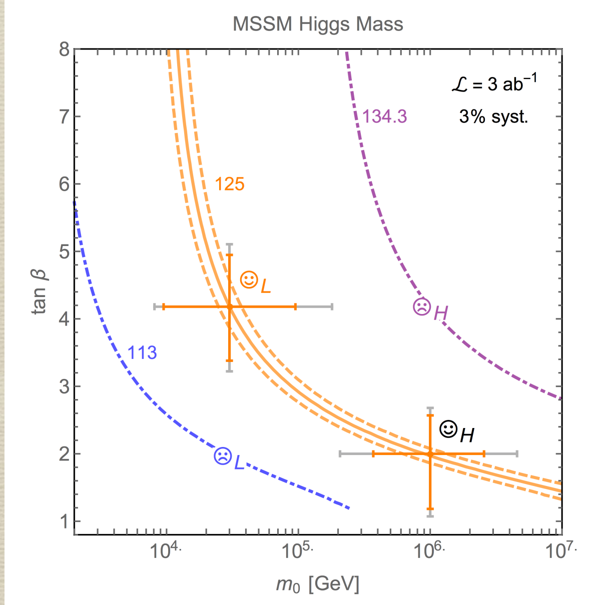






Cohen, D'Agnolo, Hance, Lou, Wacker 2014

Fan, Jaiswal, Leung 2017



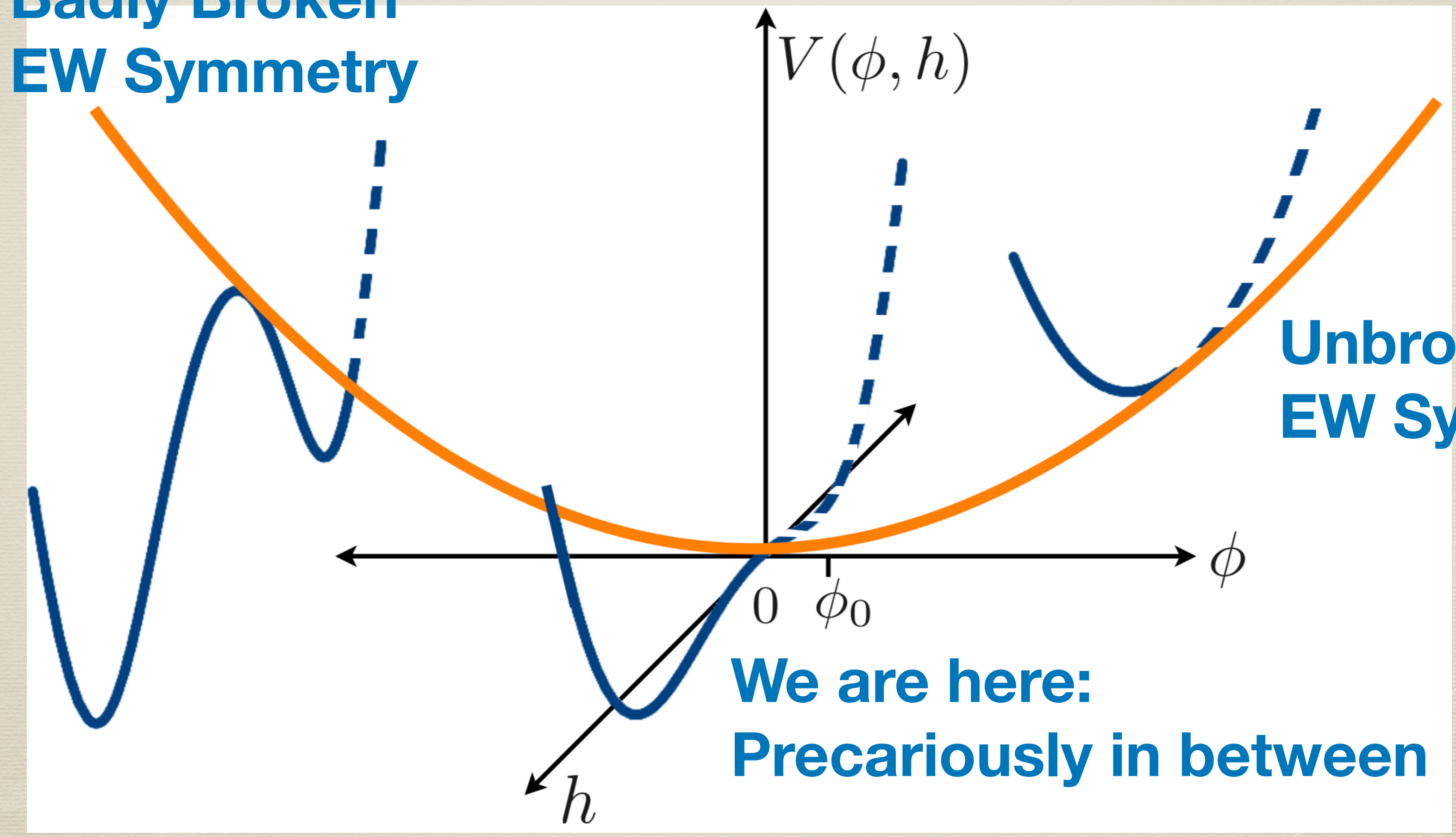
Directly search for new particles

Measure their couplings precisely

Agrawal, Fan,
Reece, Xue 2017

Probe 2: Cosmological Signal of a Fine-tuned Higgs

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



Badly Broken EW Symmetry

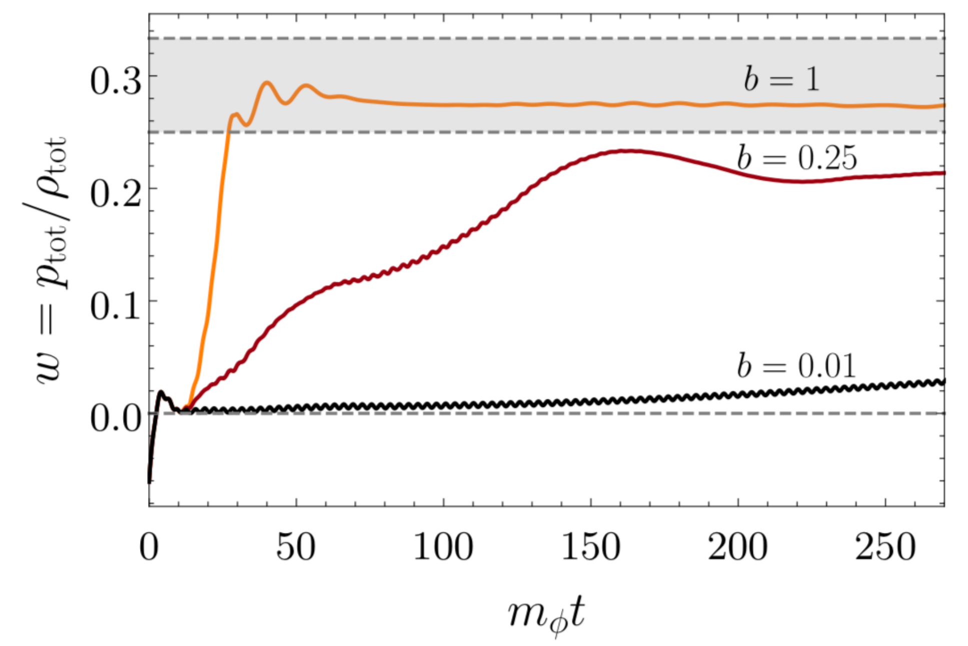
Unbroken EW Symmetry

We are here: Precariously in between

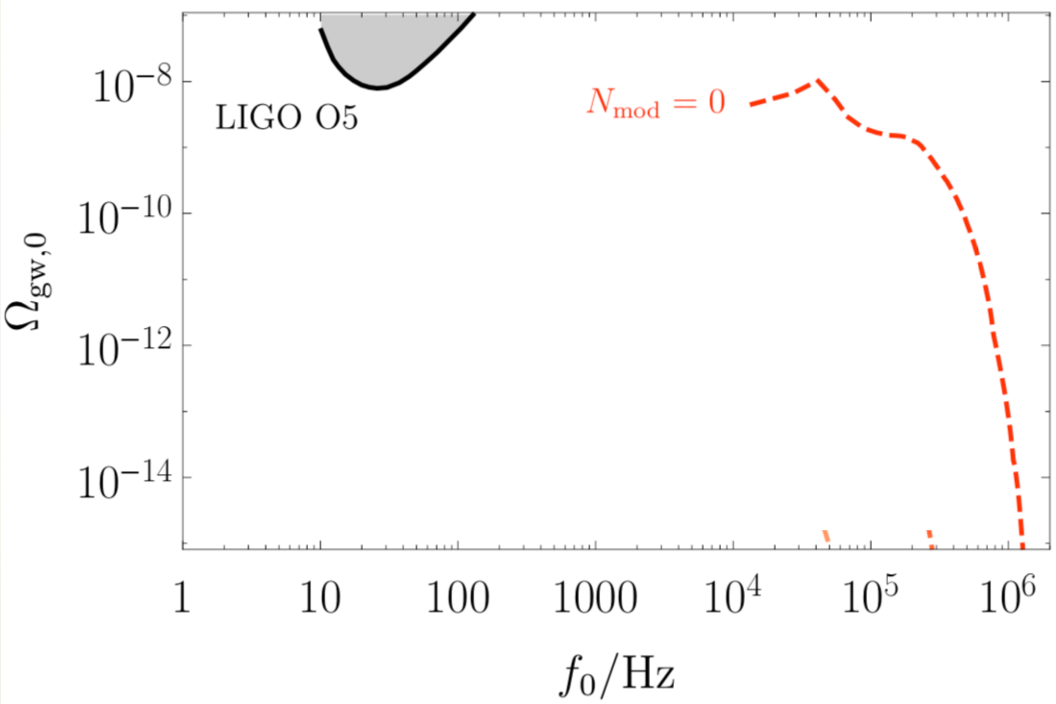
Amin, Fan, Lozanov, Reece 1802.00444

If the Higgs potential is *tuned*, rapid particle production of the Higgs and fragmentation of the oscillating scalar (modulus)

nontrivial equation of state



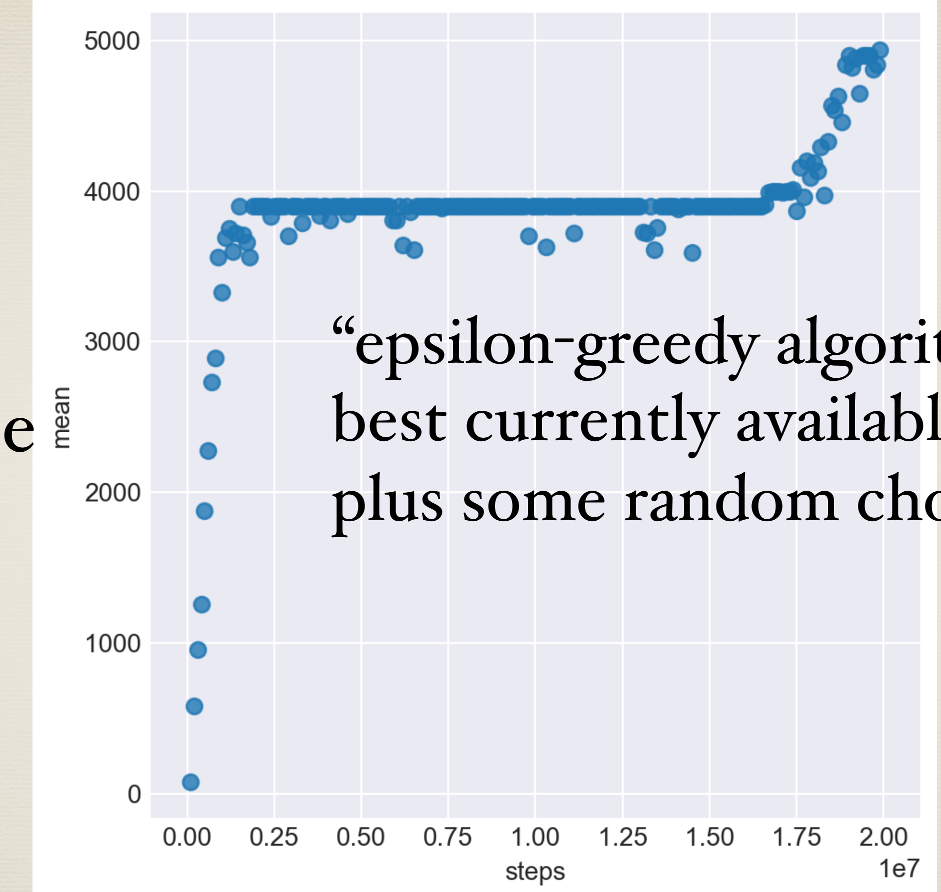
stochastic gravitational waves



Amin, Fan, Lozanov, Reece 1802.00444

Concluding Remarks

Performance

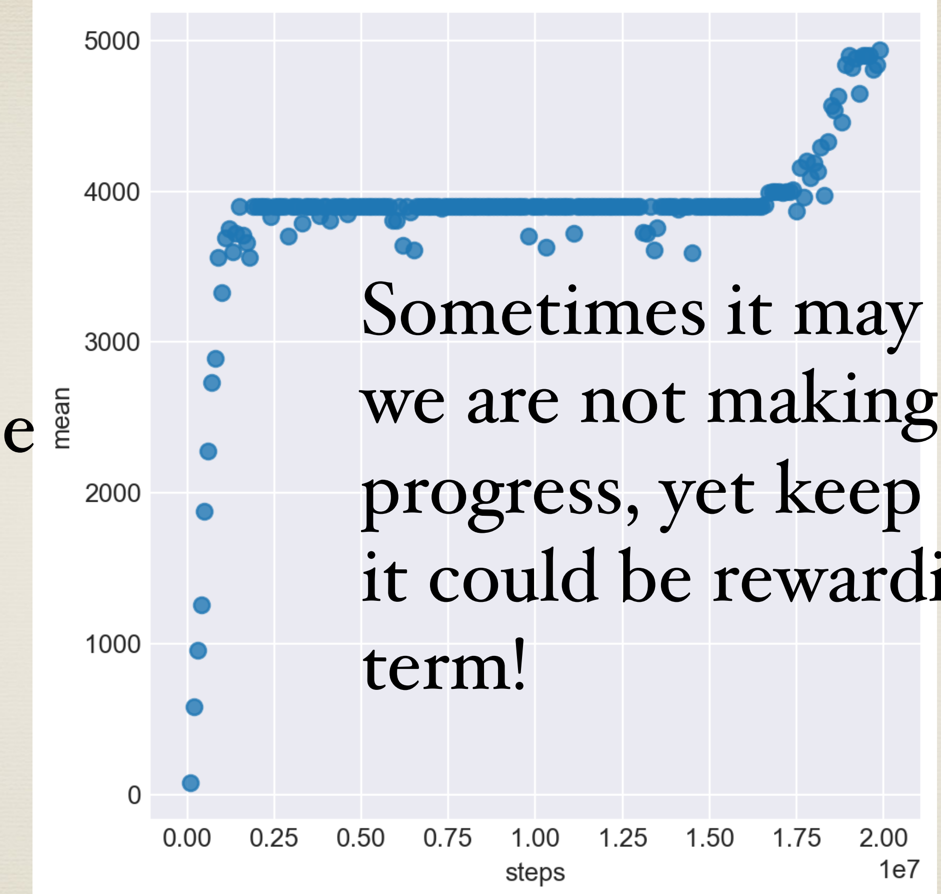


“epsilon-greedy algorithm”:
best currently available option
plus some random choices

Time

Reinforcement learning to scan string landscape (results thanks to Halverson)

Performance



Sometimes it may seem that we are not making that much progress, yet keep trying and it could be rewarding in the long term!

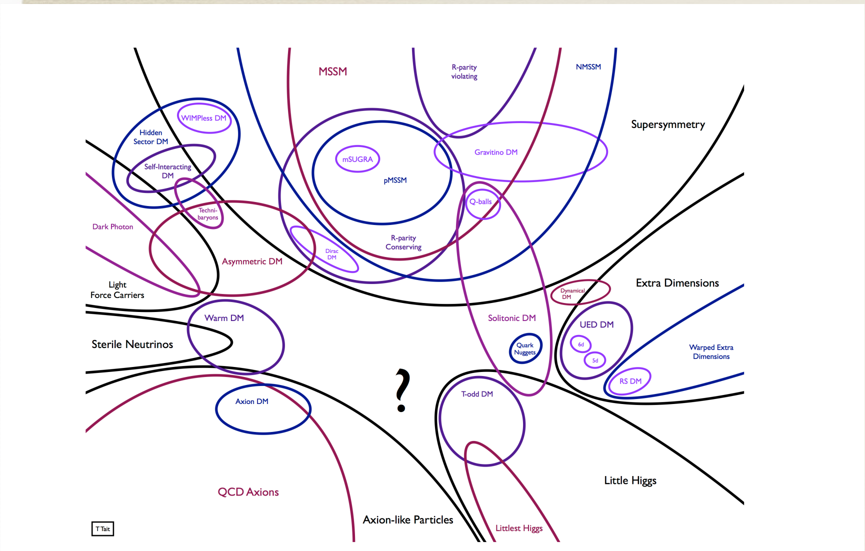
Time

Thank you!

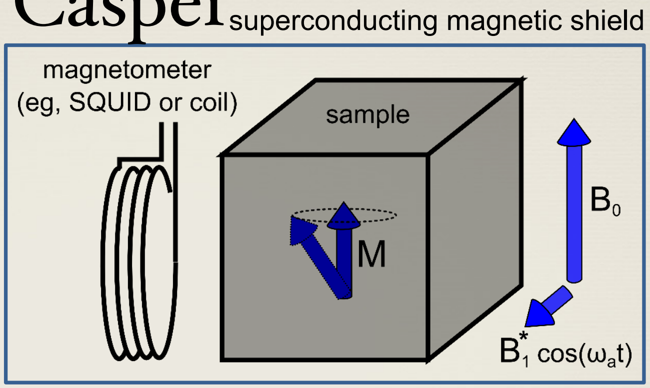
Backup

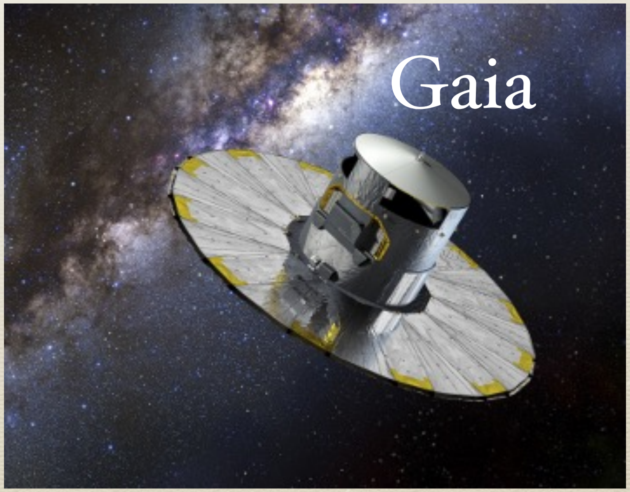
A Little Bit on Dark Matter

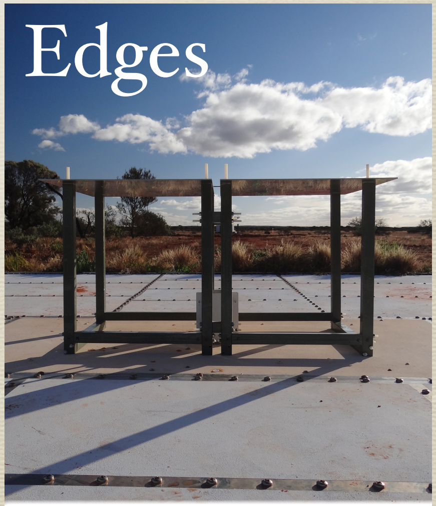
Rapid expansion in both theory and experiment



Casper



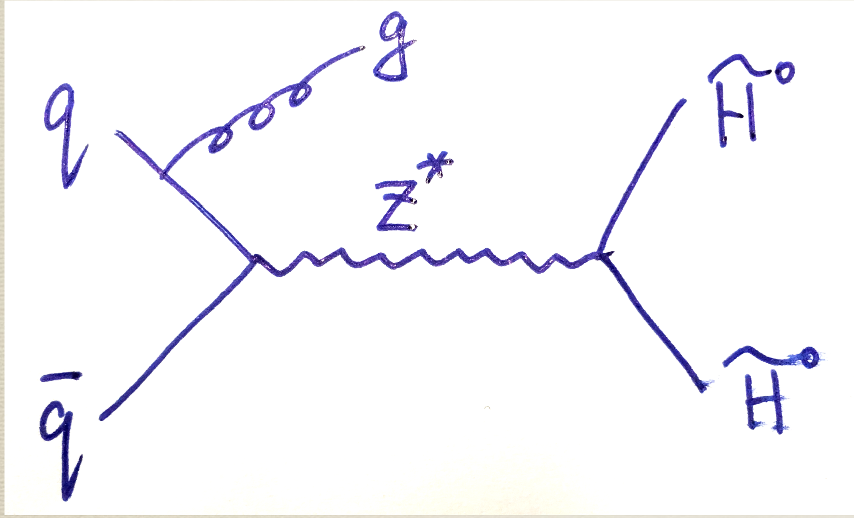




EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)

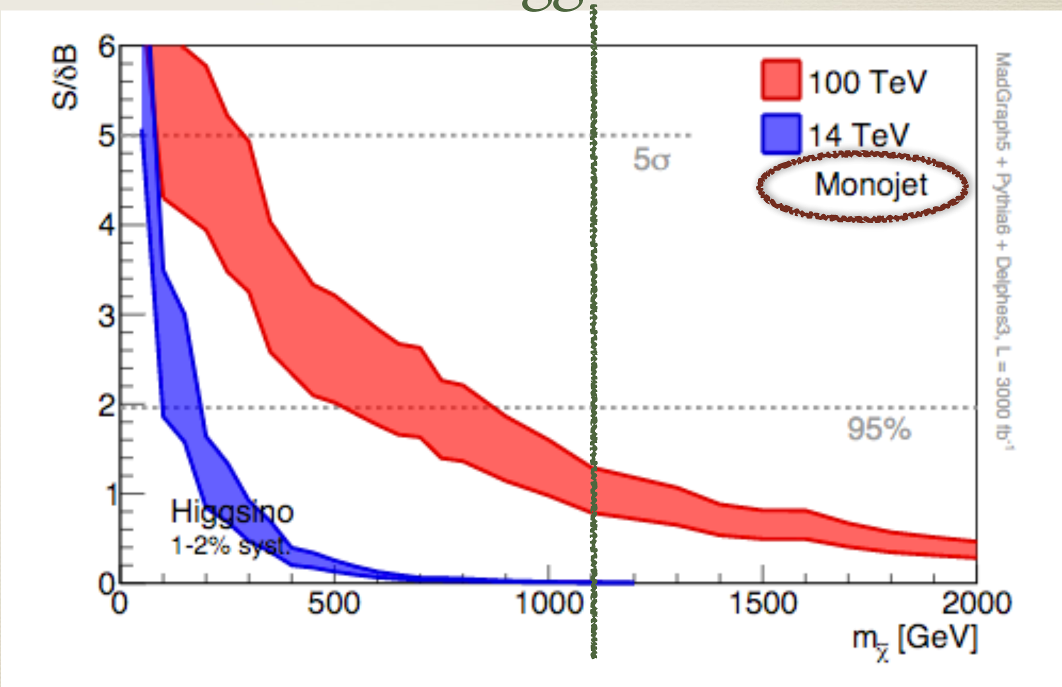
Simple WIMP at large: Higgsino DM

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.



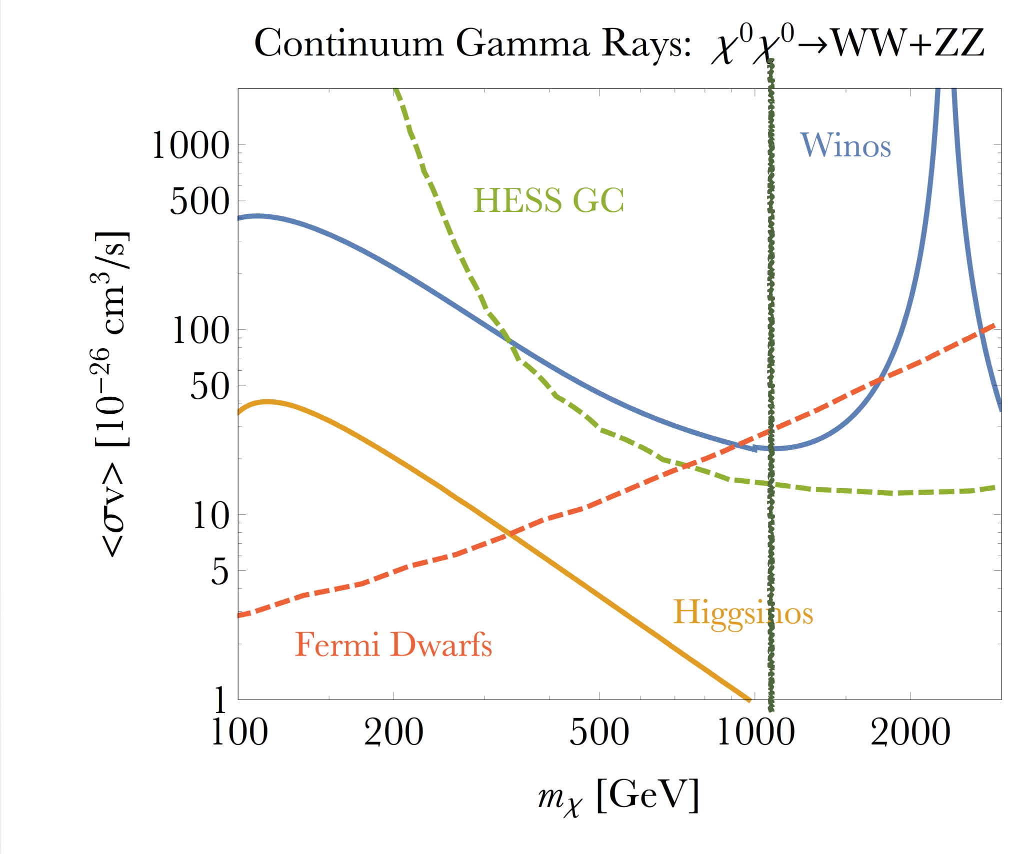
Low, Wang: 2014

Thermal higgsino benchmark



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.



Krall, Reece 1705.04843

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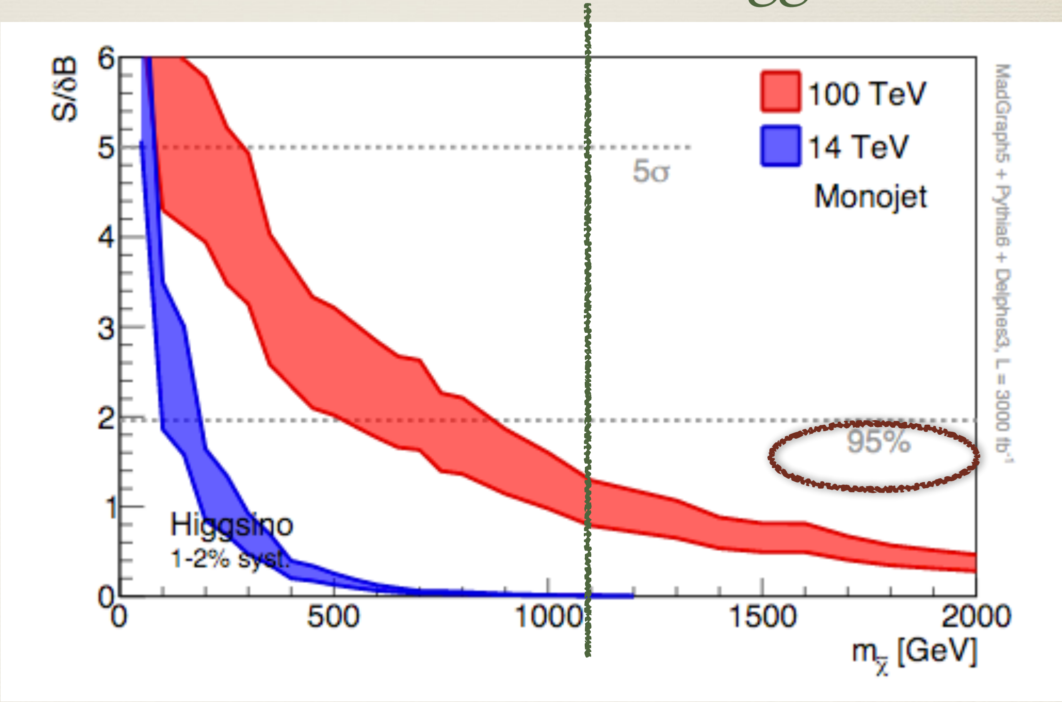


Notice **wide bands**: varying background systematics 1-2%. Big experimental challenge is well-characterized background!

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, cτ~ **6.6 mm**

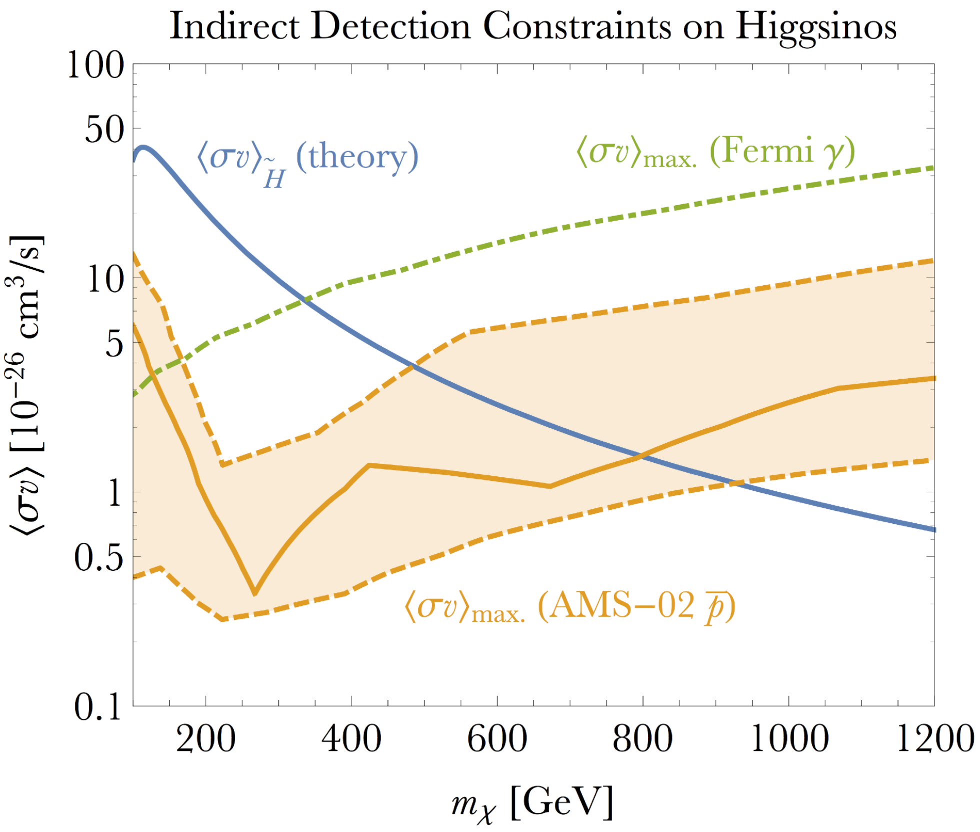
Disappearing charged track: need large boost (~ 100) (more easy to get large forward than transverse boost)

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

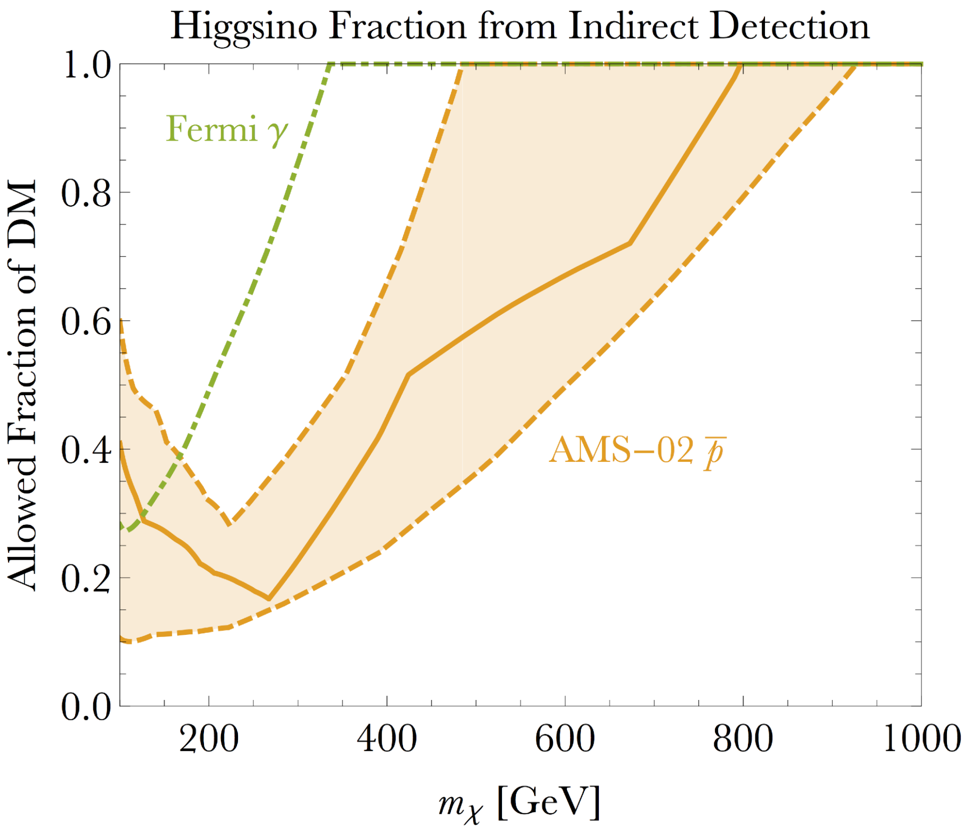
In the future, may consider having a forward tracker covering
$2 \leq |\eta| \leq 4$,

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

AMS anti-proton constraint on higgsino



Indirect Detection Constraints on Higgsinos



Higgsino Fraction from Indirect Detection

Krall, Reece 2017