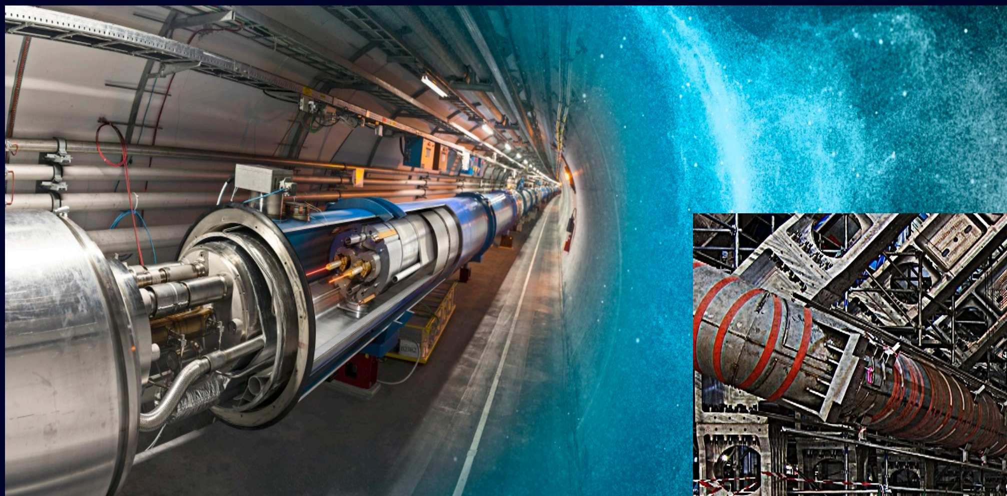
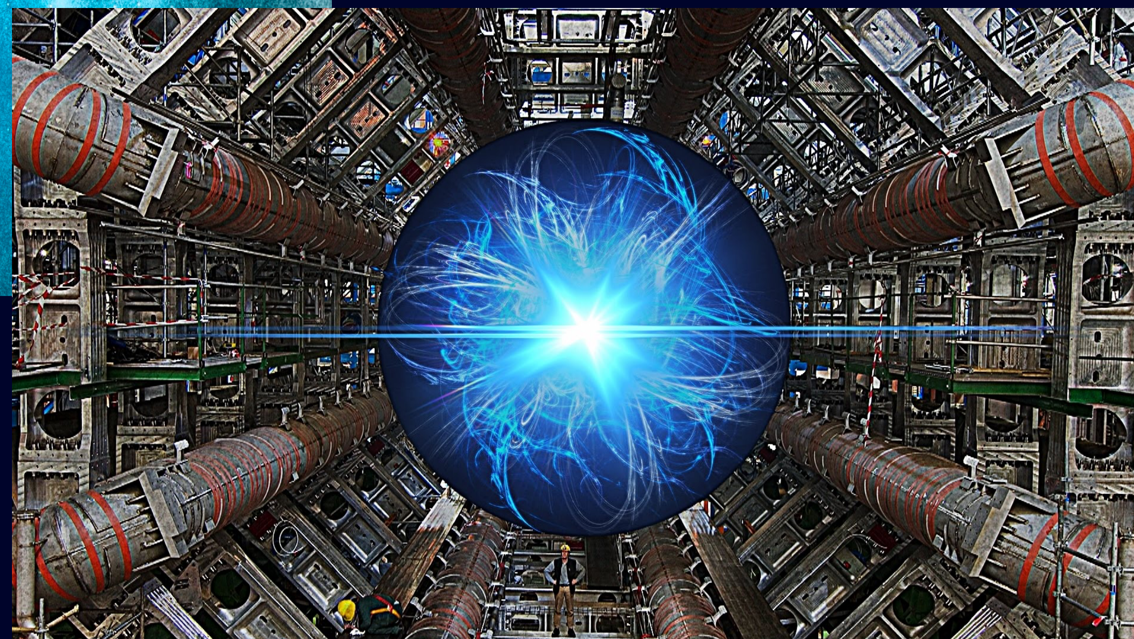
Higgs Portal to Dark Matter and Extra Dimensions





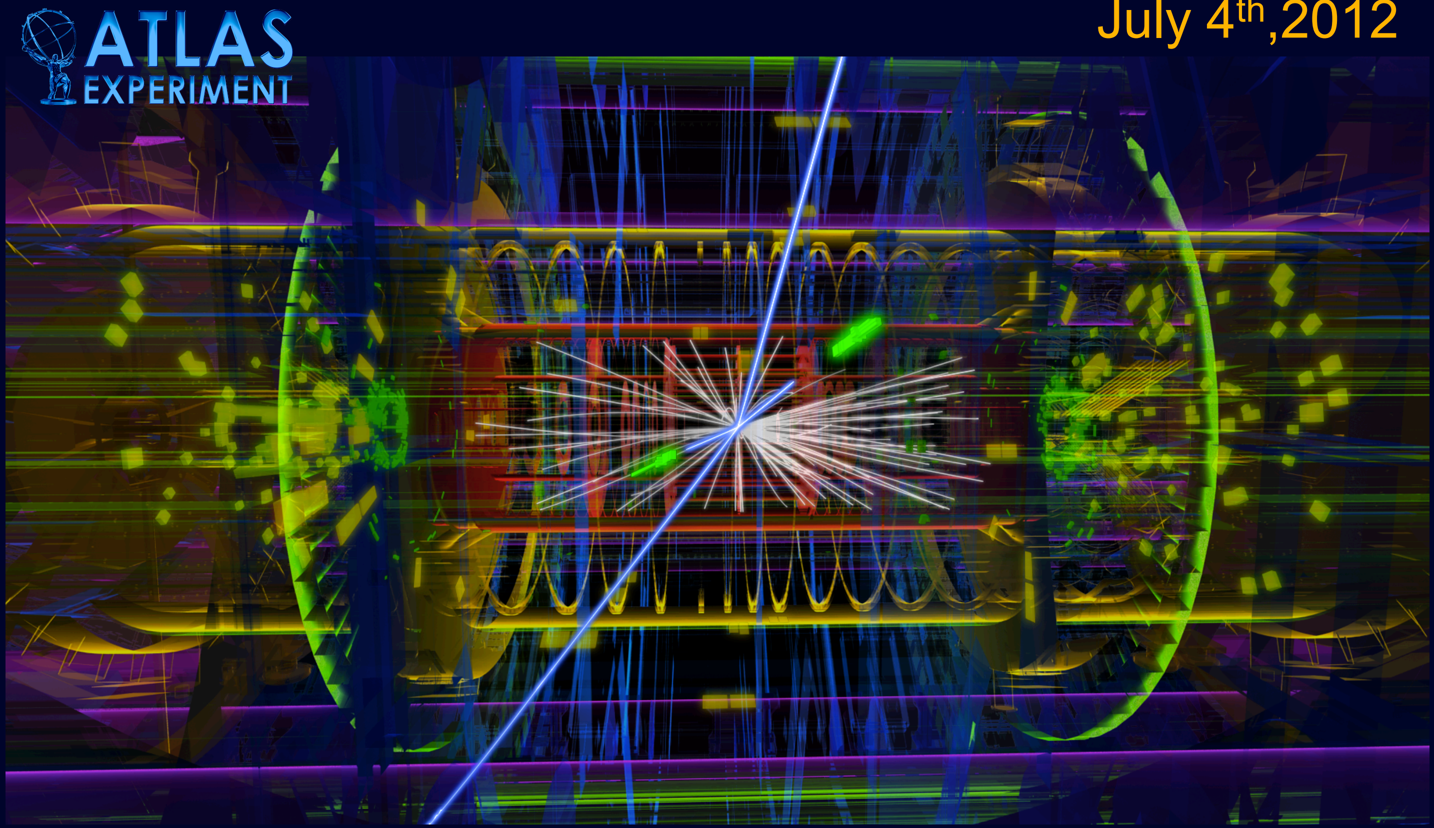
Marcela Carena

Fermilab & Uchicago

University of Toronto, February 2nd, 2017

The Higgs Boson at the Large Hadron Collider

July 4^{th},2012



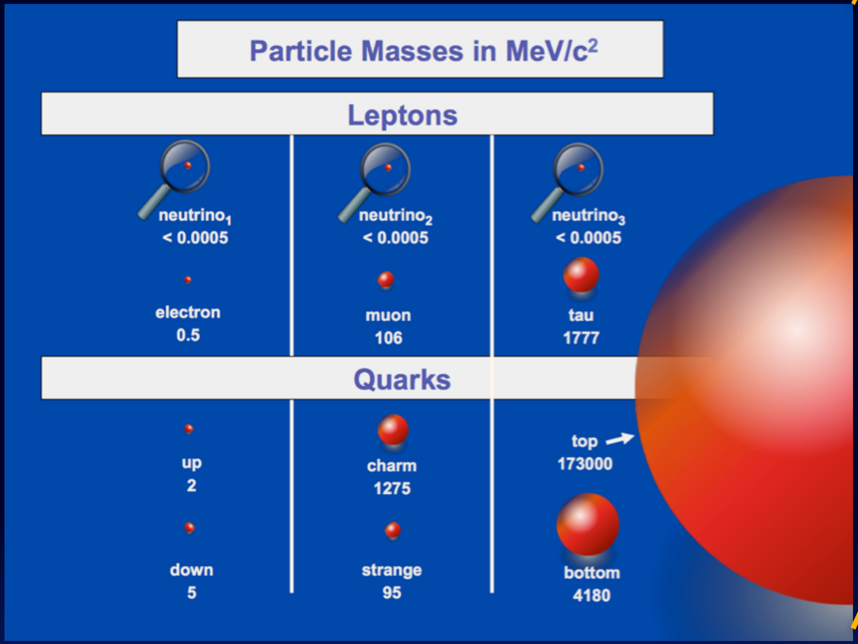
- Discovery of a new type of particle
- Discovery of a new type of force
- Start of a new era for particle physics and cosmology

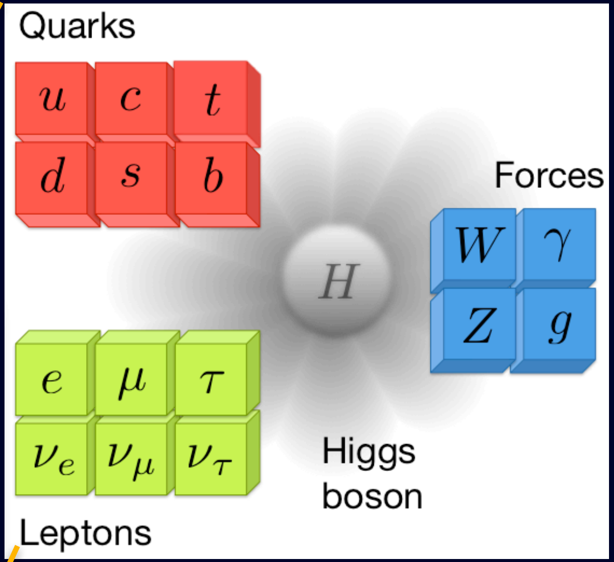
Why is the Higgs so important ?

Sub-atomic particles of the Standard Model

A gauge field theory
with a symmetry group

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$





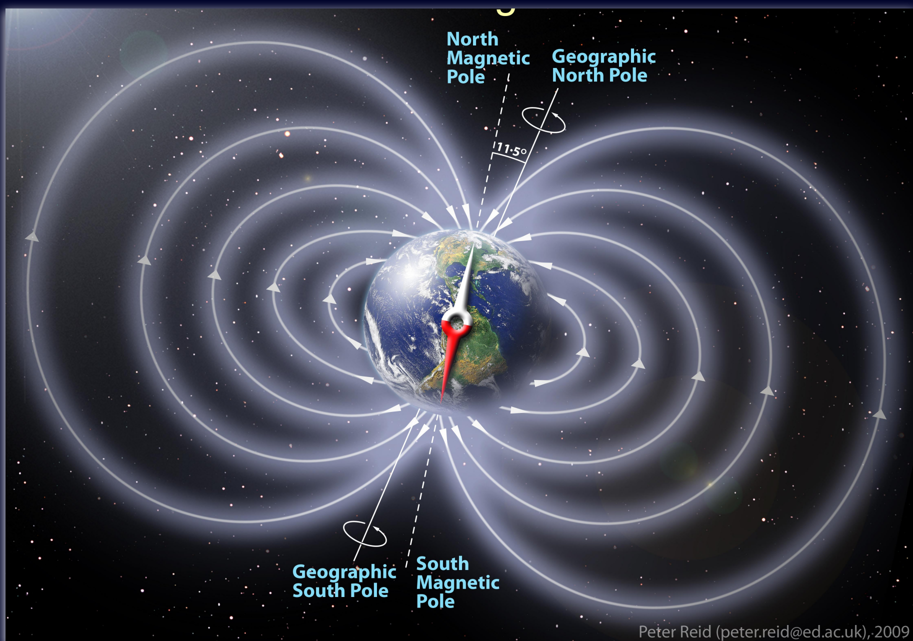
They have all been produced in the laboratory

They have very different masses

What causes fundamental particles to have mass?

A field of Energy that permeates all of the space

Invisible Force Fields



The Earth's Magnetic Field

sourced by the Earth permeates nearby space

The Higgs Field

sourced by itself permeates the entire universe

What turns the Higgs field on?

Spontaneous Symmetry Breaking (SSB)

There is a symmetry of the system that is not respected by the ground state

Nambu (1960)

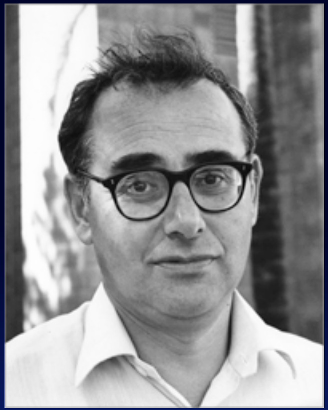
Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

Yoichiro Nambu

Physical system	Broken symmetry	Goldstone modes
Antiferromagnets	Rotational invariance	spin waves
Crystals	Translational and rotational	acoustic phonons
BCS Superconductors	U(1) phase symmetry	???

- **Apply condensed matter ideas to particle physics**

Now the quantum vacuum is the "medium"



Goldstone (1961)

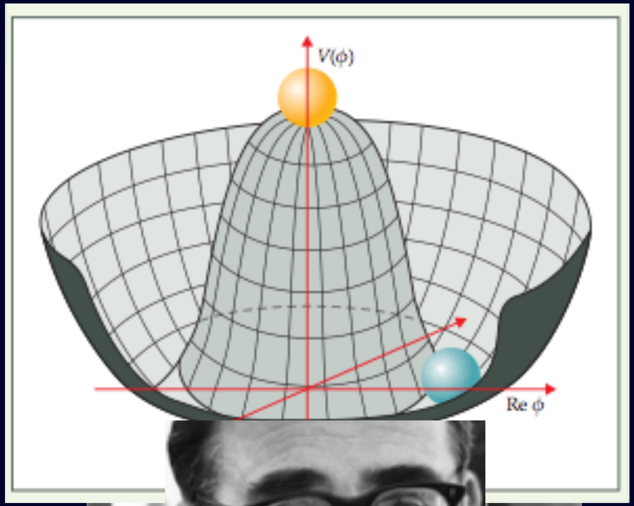
The Problem of the Massless Bosons:

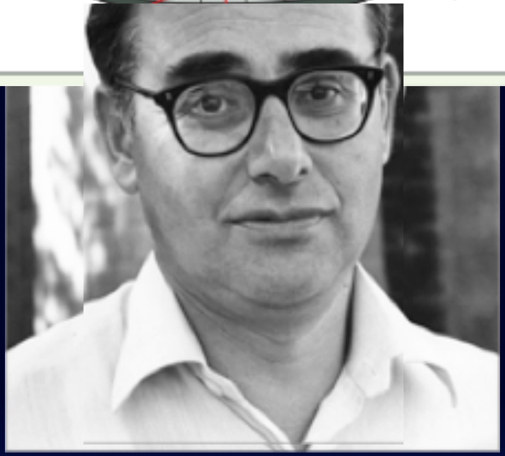
SSB implies a massless Goldstone boson per broken generator

What turns the Higgs field on?

Goldstone's Mexican Hat

$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$





- The Higgs field potential describes the energetics of turning on the Higgs field to a certain (complex) value
- The scalar field self-interactions may energetically favor a nonzero vev
- Because of the symmetry there are degenerate vacua

In quantum field theory it is difficult to transition from one degenerate ground state to another

"SSB is a property of large systems"

Anderson 1972

Still there are single particle excitations corresponding to locally deforming along the valley ➔ These are the massless Goldstone modes

Who invented the "Brout-Englert-Higgs" mechanism?

Nambu Goldstone Anderson
penned important early chapters in the story of the Higgs Boson

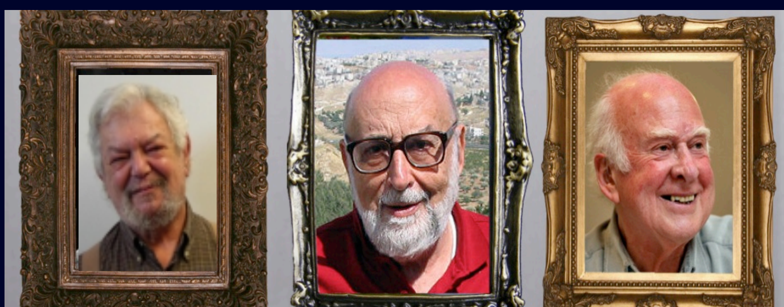
"It is likely, then, considering the superconducting analog, that the way is now open for a degenerate-vacuum theory of the Nambu type without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of 'canceling each other out' and leaving finite mass bosons only." **-- Phillip Anderson, 1962**

Englert Brout Higgs

"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**

The Brout-Englert-Higgs Mechanism & the Higgs Boson (1964)

A fundamental scalar field with self-interactions
can cause spontaneous symmetry breaking in the vacuum,
respecting the sophisticated choreography of gauge symmetries,
and can give gauge bosons mass

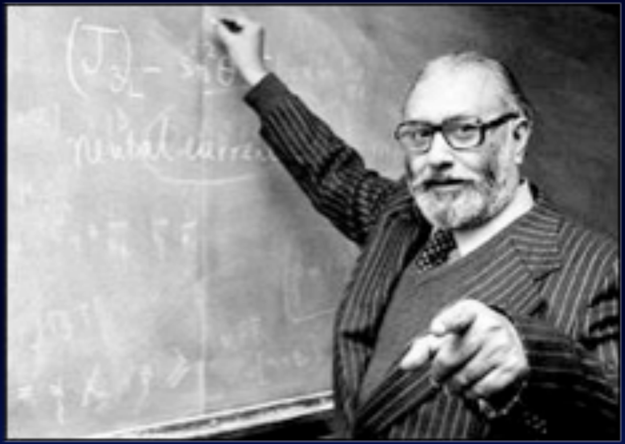


One particle left in the spectrum

Higgs explains: My first paper was rejected because it was not relevant for phenomenology

The Standard Model of Particle Physics

Weinberg-Salam: The electroweak SM (1967)



An $SU(2)_L \times U(1)_Y$ non-abelian gauge theory with chiral fermions

Spontaneously broken to $U(1)_{em}$ by a nonzero vacuum value of the Higgs field

Three of the four Higgs components (Goldstone bosons) are “eaten” to give mass to the W^+, W^-, and Z, leaving one neutral Higgs boson and a massless photon

The fermions also get mass from a new type of interactions (Yukawa int.) with the scalar field

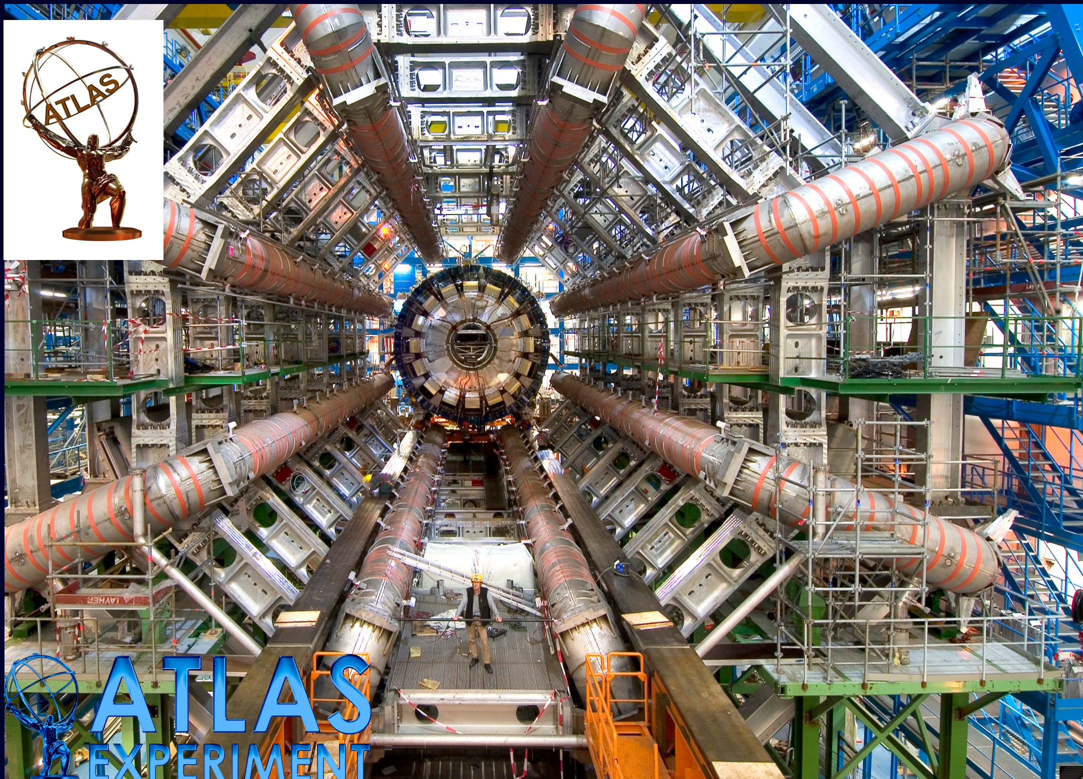
Heavier particles interact more with the Higgs

Half a century after the Higgs boson idea comes its discovery at the Large Hadron Collider (LHC)

proton-proton collisions
at E_{cm} = 8 TeV (13 TeV)

A 17 mile long vacuum pipe
300 feet below ground

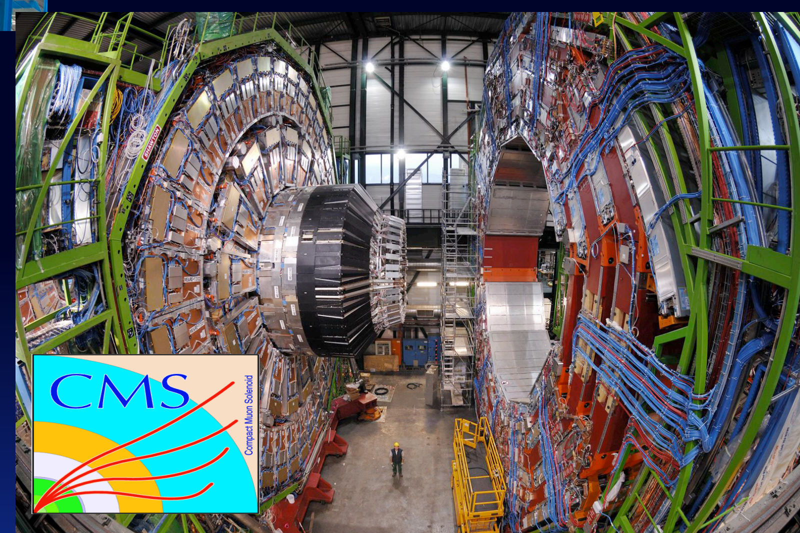
To look at the new particles we have powerful detectors



Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

Each experiment about
3000 physicists
180 Institutes
40 countries

Huge, complex objects with cutting-edge technology that take "pictures" of collisions



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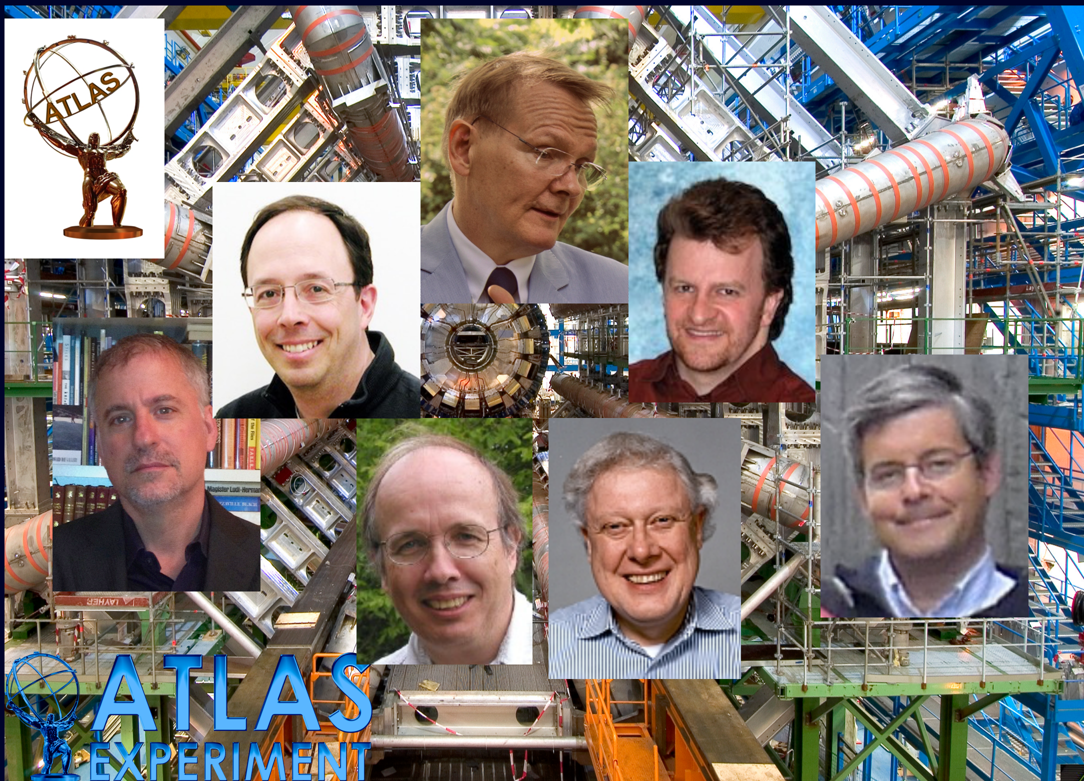

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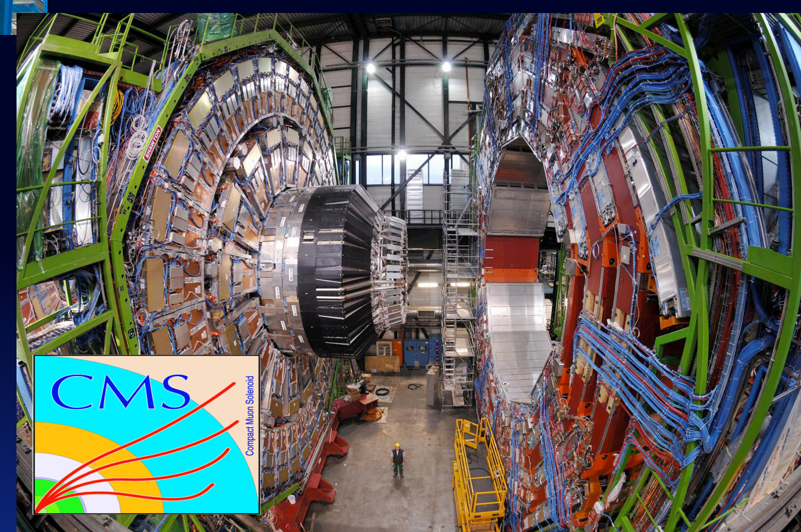
Huge, complex objects with cutting-edge technology that take "pictures" of collisions

10 Canadian institutions in ATLAS
Leading role in the Higgs discovery

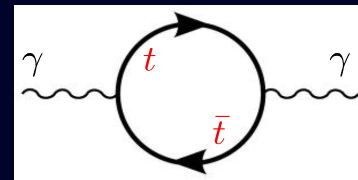


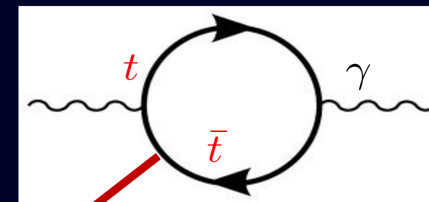
https://twiki.atlas-canada.ca/bin/view/AtlasCanada

Quantum Fluctuations can produce the Higgs at the LHC

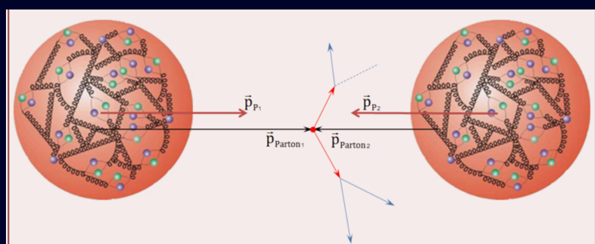
Photon propagates in quantum vacuum

Quantum fluctuations create and annihilate
"virtual particles" in the vacuum

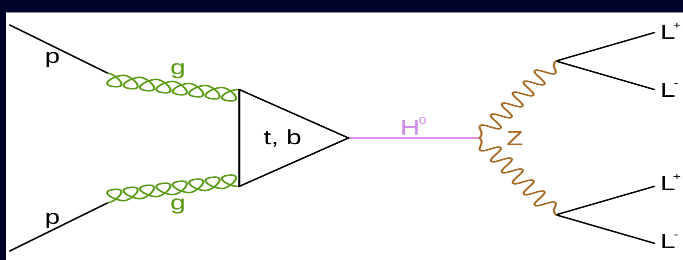


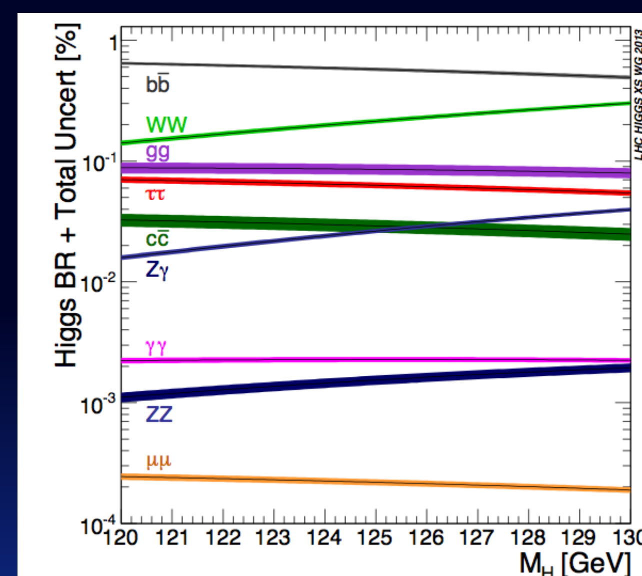


Higgs decays to two photons: H



Similarly, it is produced via gluons and decays in 4 leptons via virtual Z's



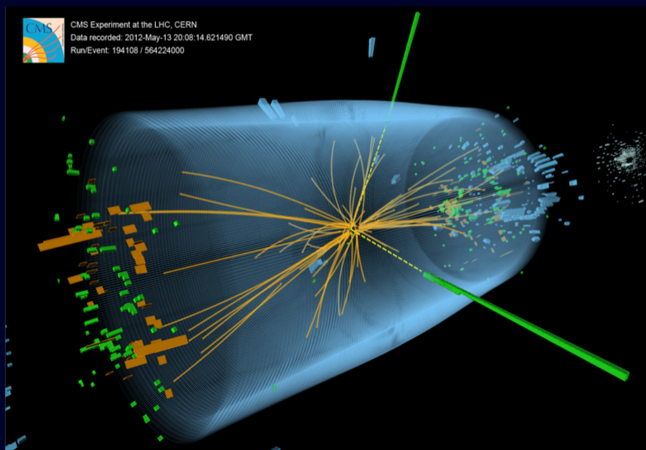


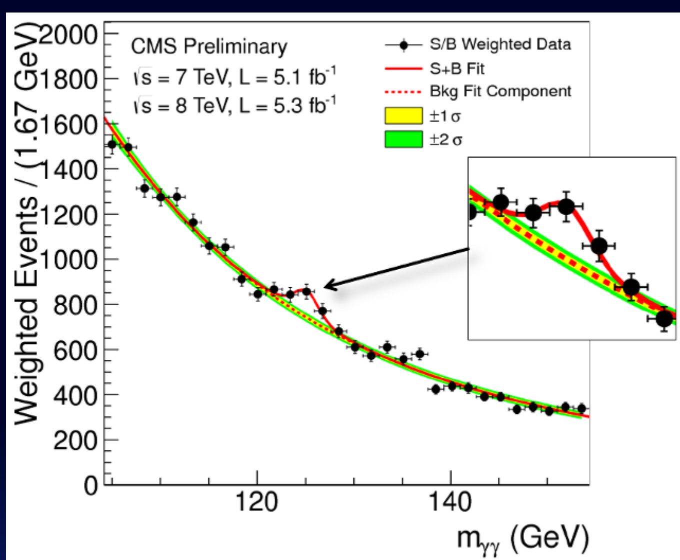
Higgs decay after about 100 yocktoseconds

into various pairs of lighter particles

The Higgs discovery channels at the LHC

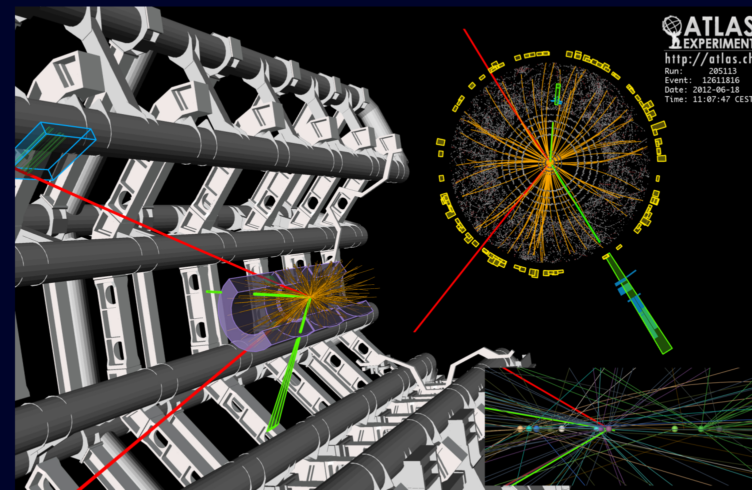
Higgs ➔ two photons

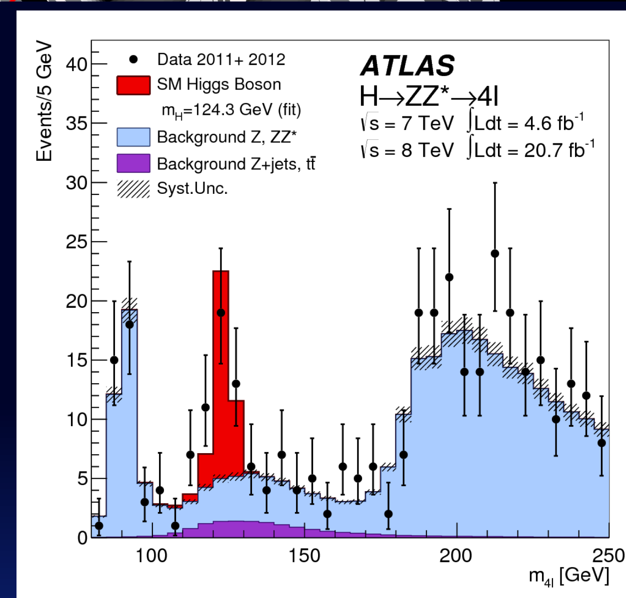




Search for a narrow mass peak with two isolated high E_T photons on a smoothly falling background

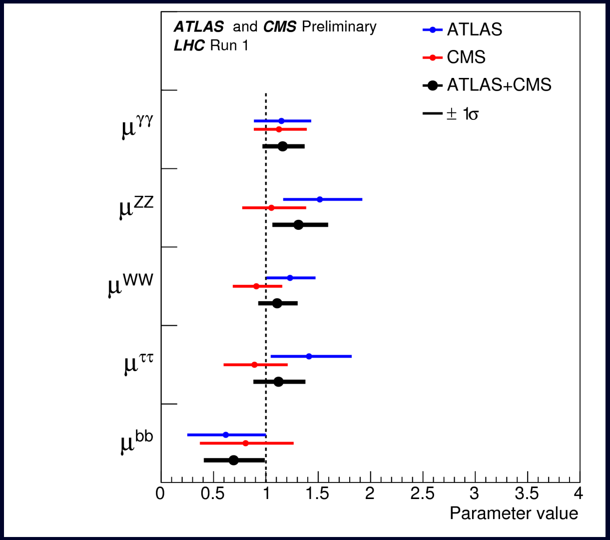
Higgs ➔ 4 Leptons (2e 2 μ)





with virtual Z bosons: The Golden Channel

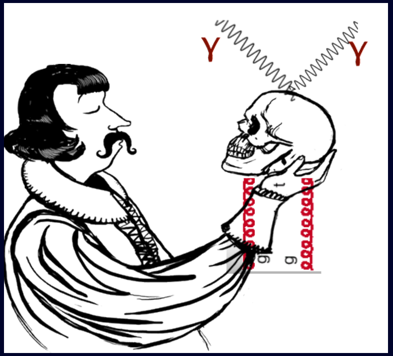
No doubt that a Higgs boson has been discovered



Signal compatible with SM Higgs

Also room for New Physics

How to quantify its SM-likeness



What kind of Higgs?

Could be a mixture of more than one Higgs

Could be a mixture of CP even and CP odd states

Could be a composite particle

Could have enhanced/suppressed couplings to photons or gluons

linked to the existence of new exotic charged or colored particles interacting with the Higgs

Could decay to exotic particles, e.g. dark matter

May not couple to matter particles proportional to their masses

Goal of current LHC run ➔ answer these questions and search for new physics

Are we Done? Not really, much to explain yet

Dark Matter, Baryogenesis, Dynamical Origin of Fermion Masses, Mixing, CP Violation, Tiny Neutrino Masses, ….

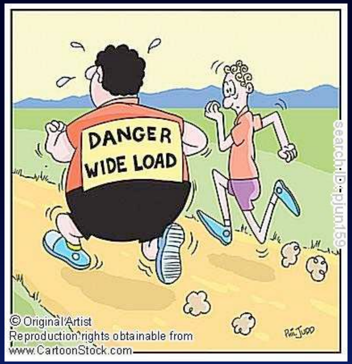
None of the above demands NP at the electroweak scale, but…

- **The Higgs is special : it is a scalar**

Scalar masses are not protected by gauge symmetries and at quantum level have quadratic sensitivity to the UV physics

$$\mathcal{L} \propto m^2 |\phi|^2 \qquad \delta \mathbf{m^2} = \sum_{\mathbf{B,F}} \mathbf{g_{B,F}} (-1)^{\mathbf{2S}} \frac{\lambda^2_{\mathbf{B,F}} \mathbf{m^2_{B,F}}}{\mathbf{32}\pi^{\mathbf{2}}} \log\left(\frac{\mathbf{Q^2}}{\mu^{\mathbf{2}}}\right)$$

Although the SM with the Higgs is a consistent theory, light scalars like the Higgs cannot survive in the presence of heavy states at GUT/String/Planck scales



Fine tuning ⟷ Naturalness problem

Supersymmetry:

A fermion-boson symmetry

The Higgs remains elementary but its mass is protected by SUSY ➔ $\delta m^2 = 0$

Composite Higgs Models

The Higgs does not exist above a certain scale,

at which some new strong dynamics takes place ➔ dynamical origin of EWSB

New strong resonance masses constrained by Precision Electroweak data and direct searches

Higgs ➔ scalar resonance much lighter that other ones

Flavor from the electroweak scale (Composite or SUSY extensions)

Flavor hierarchies arise from a Froggatt-Nielsen mechanism with two Higgs doublets jointly acting as a flavon

All options imply changes in the Higgs phenomenology and beyond

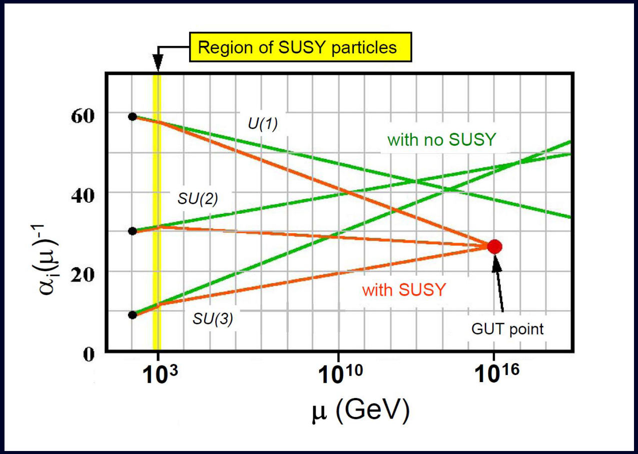
The Montreal Composites Vs the Toronto SUSY Leafs

Both teams have their strengths …

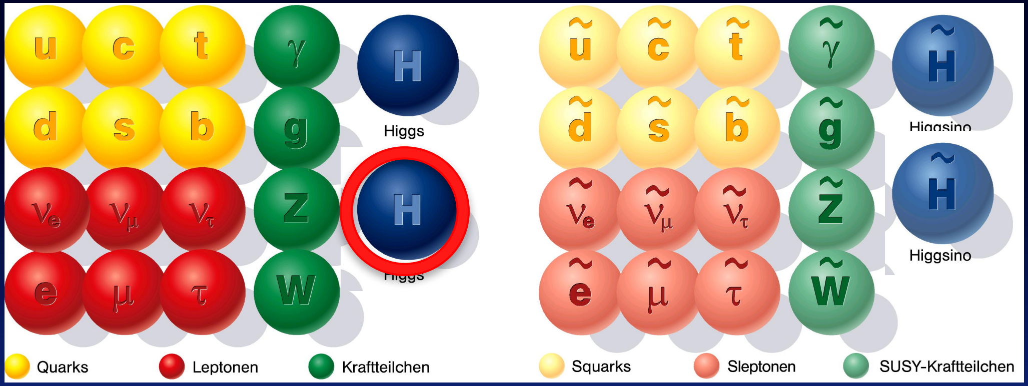
SUSY has many good properties

- **Allows a hierarchy between the electroweak scale and the Planck/unification scales**
- **Generates EWSB automatically from radiative corrections to the Higgs potential**
- Allows gauge coupling unification at ~10^{16} GeV
- Provides a good dark matter candidate:

  The Lightest SUSY Particle (LSP)



- Allows the possibility of electroweak baryogenesis
- String friendly



For every fermion there is a boson with equal mass & couplings

Extended Higgs sector

SUSY and Naturalness

- Higgs mass parameter protected by the fermion-boson symmetry: $\delta m^2 = 0$

In practice, no SUSY particles seen yet ➔ SUSY broken in nature:

$$\delta m^2 \propto M^2_{SUSY}$$

If $M_{SUSY} \sim M_{weak}$ ⟶ Natural SUSY

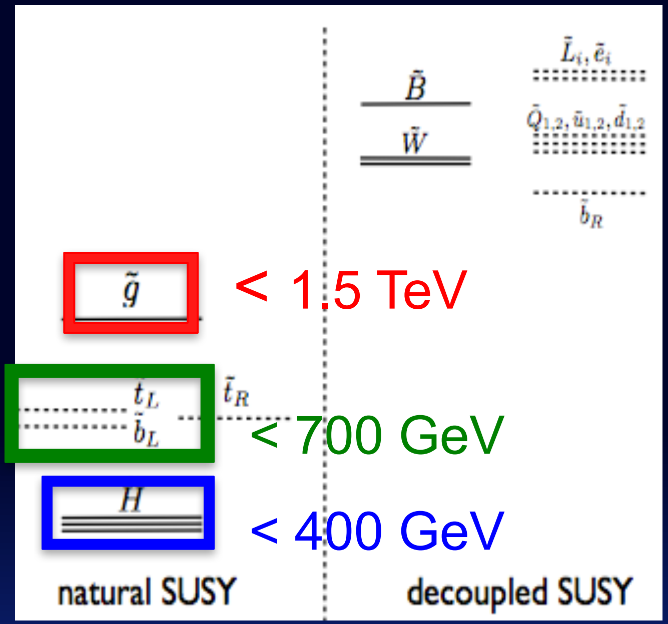
If $M_{SUSY} \ll M_{GUT}$ ⟶ big hierarchy problem solved

Where are the superpartners?

- **Not all SUSY particles play a role in the Higgs Naturalness issue**

Higgsinos, stops (sbottoms) and gluinos are special

- So why didn't we discover any SUSY particle already at LEP, Tevatron, LHC?

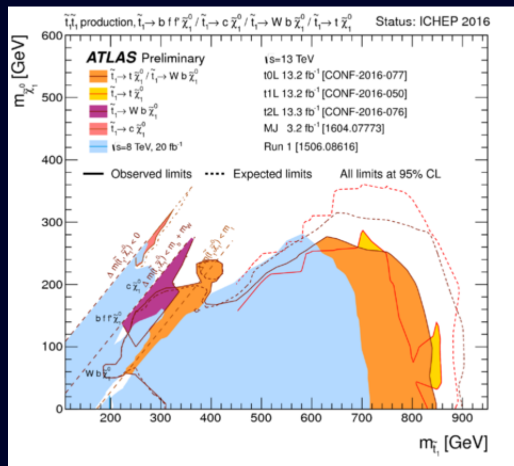


Papucci, Rudermann, Weiler '11

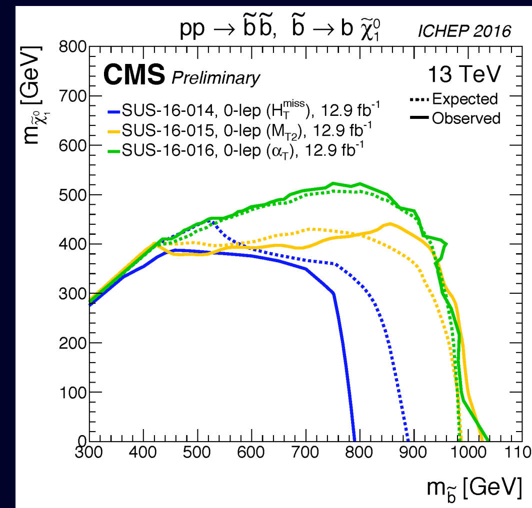
LHC Scientists, both at ATLAS and CMS

are incessantly pursuing the signatures of "naturalness".

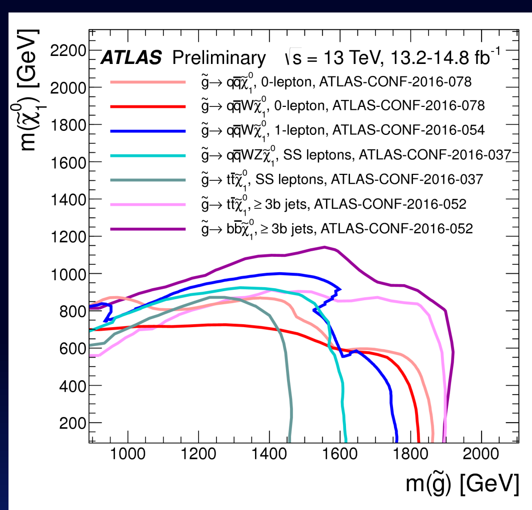
stops

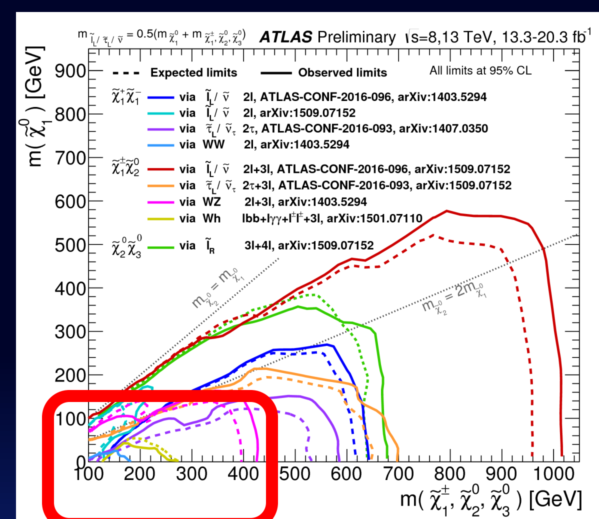


sbottoms



gluinos

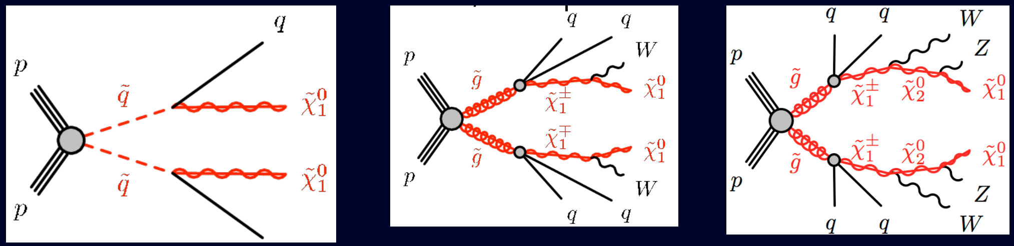




Partly Higgsinos

In the Hunt for SUSY

- Many searches in specific SUSY models: MSUGRA/CMSSM,GMSB, AMSB, RPV, mini-split SUSY, … and Simplified Models with many topologies



prompt decays,

long lived/detector-stable particles,

displaced vertices, disappearing tracks

It is possible to have SUSY models with super-partners well within LHC kinematic reach, but with *degraded* missing energy signatures or event activity

- Compressed spectra: e.g. stop mass ~ charm mass + LSP mass
- Stealth SUSY: long decay chains soften the observed particle spectrum from SUSY decays
- The LSP is not the dark matter, but decays

Still Many Opportunities for non-minimal "Natural" SUSY Models at the LHC

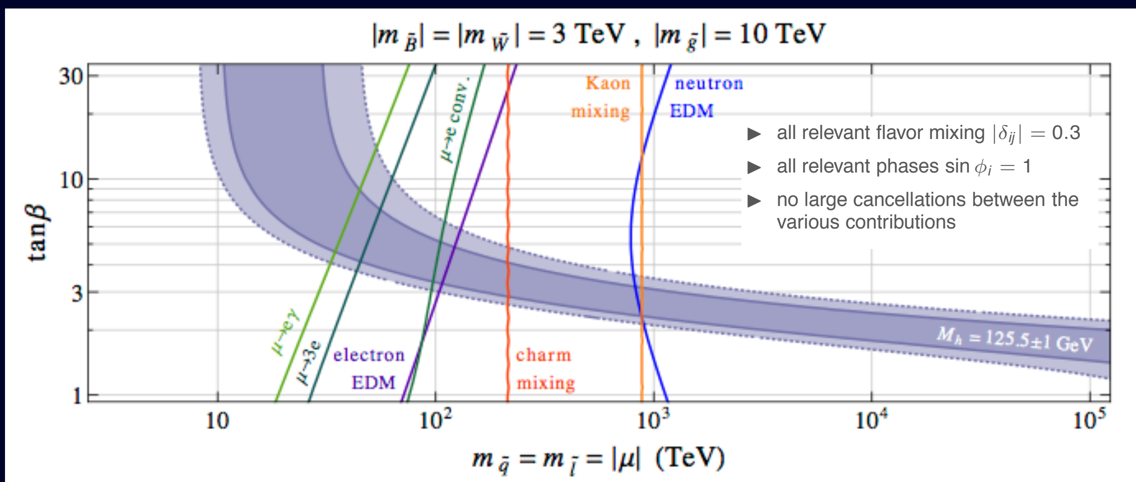
- address flavor as part of the SUSY breaking mechanism
- extend the SUSY sector to accommodate m_h ~ 125 GeV without large quantum corrections

- additional SM singlets or triplets or models with enhanced weak gauge symmetries -

SUSY may be at much higher energies?

[Unnatural SUSY]

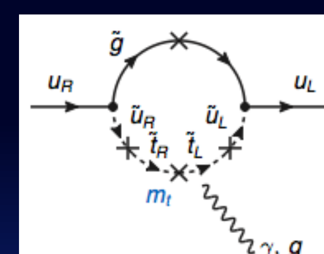
Low energy Probes of Flavor and CP violation with PeV Scale Sfermions



Altmannshofer, Harnik, Zupan'14

Heavy squarks, independent of the motivation, are good for the idea that flavor-violating effects may be intrinsically O(1), but with big mass suppression

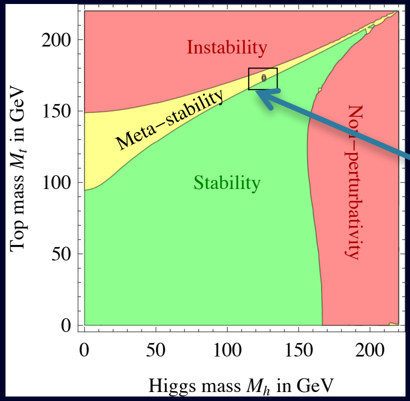
- PeV squarks already probed by CP violation in Kaon mixing
- CP violation in charm mixing and the neutron EDM reach up to O(100 TeV)
- EDMs particularly interesting:

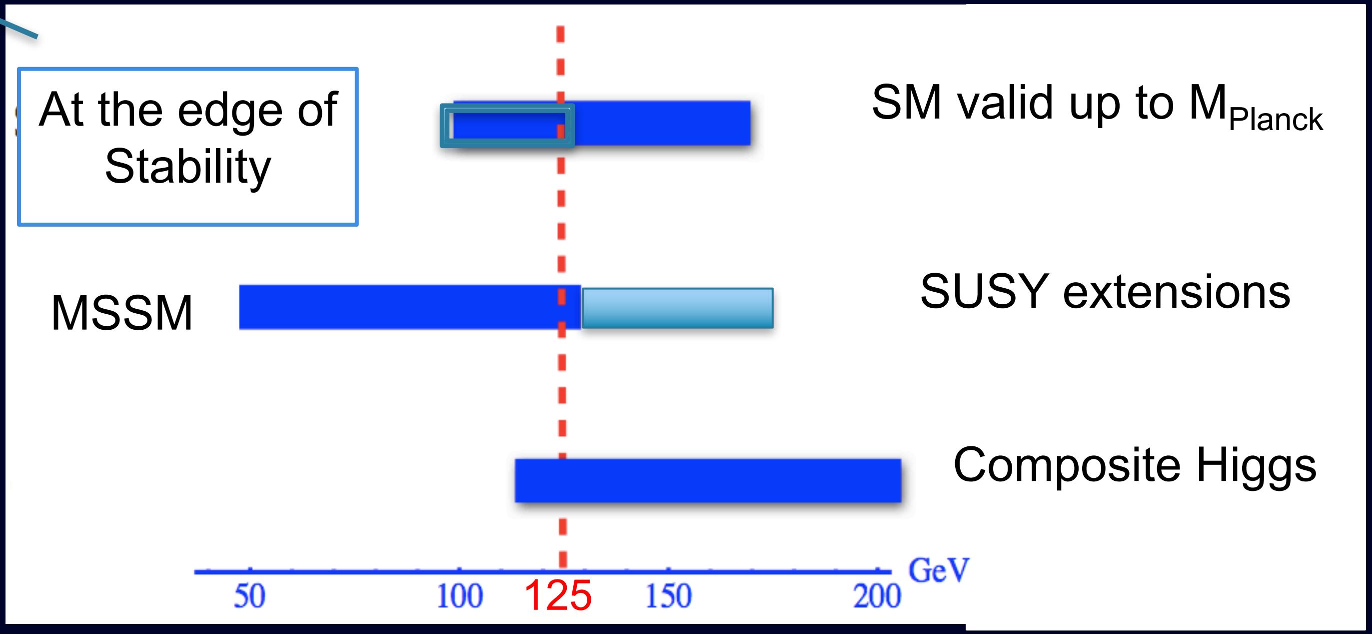


Not even a 100 TeV pp collider can probe this scales, so we need clues from rare processes

Looking under the Higgs lamp-post:

What type of Higgs have we seen?





125 GeV is suspiciously light for a composite Higgs

but it is suspiciously heavy for minimal SUSY

Also in fashion:

Twin Higgs and Mirror Worlds

- Demand a UV completion → Composite Higgs-

What does a 125 GeV Higgs implies in SUSY?

SUSY also predicts *at least* four kinds of Higgs bosons, differing in their masses and other properties

Minimal SUSY :

2 CP-even Higgs: h and H with mixing angle α

1 CP-odd Higgs A and 1 charged Higgs H^{+-}

$$\tan\beta = v_2/v_1$$

$$v = \sqrt{(v_1^2 + v_2^2)}$$

Quartic couplings given in terms of gauge couplings, hence lightest Higgs mass m_h naturally linked to Z boson mass

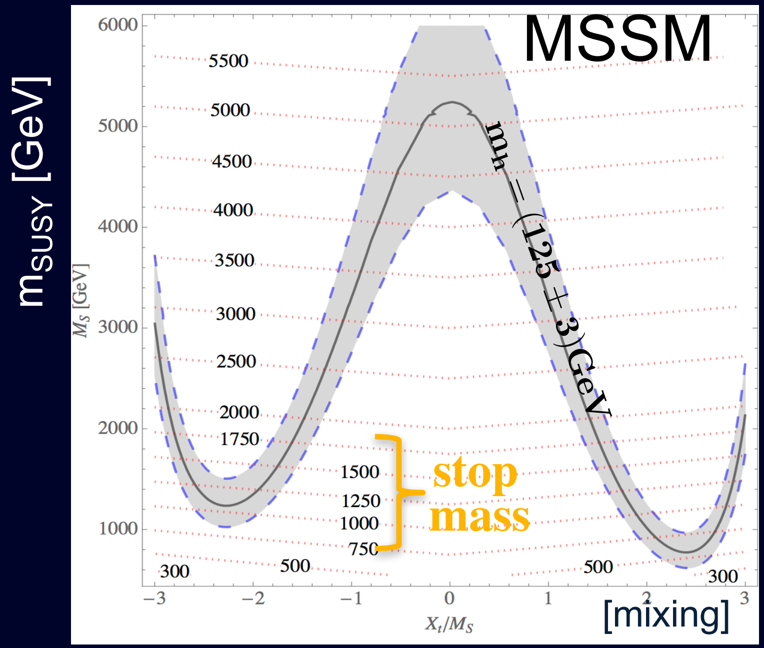
$$m_h^2 \leq \underbrace{M_Z^2}_{< (91\ \text{GeV})^2} \cos^2 2\beta + \Delta m_h^2$$

→ **Important radiative corrections with strong dependence on top/stop sector**

h may behave like the SM Higgs with $m_h \sim 125$ GeV

All other 3 Higgs bosons may be heavy [TeV range or above → Decoupling] or be as light as a few hundred GeV [Alignment]

The Higgs mass and the Stop Sector

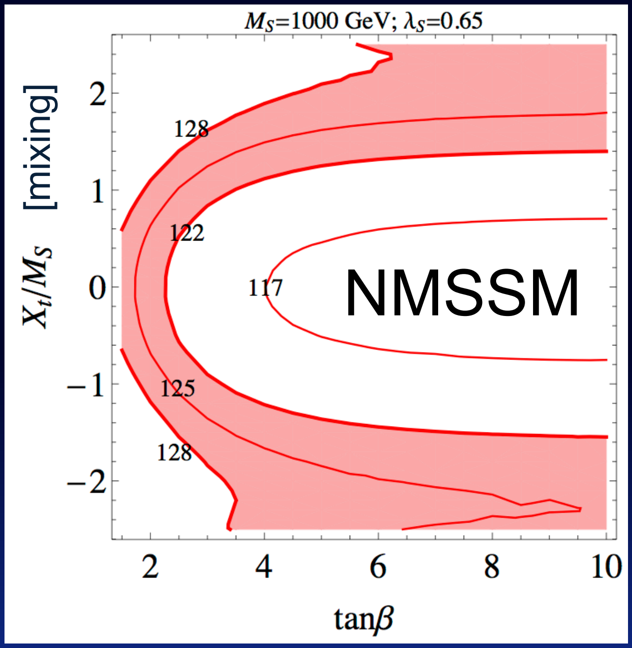


Higgs mass requires large stop mixing
[Unless stops above 5 TeV]
Small stop effects on gluon fusion Higgs production

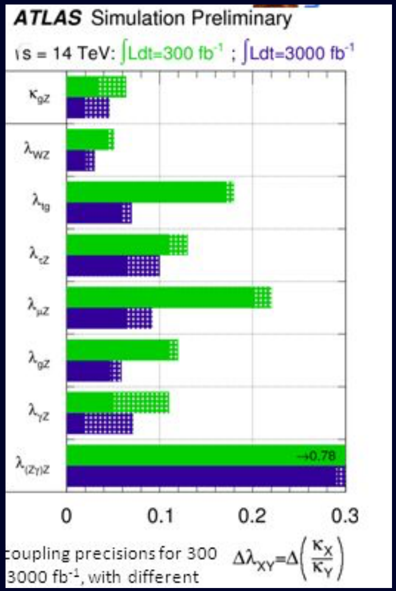
One stop can be light [a few hundred GeV]
and the other heavy [above a TeV]
or
both stops can be light [about 500 GeV]

M. C., Gori, Shah, Wagner '12 + Wang'12

MSSM with singlet extension + mh ~ 125 GeV : naturally compatible with stops at the electroweak scale, thereby reducing the degree of fine tuning to get EWSB



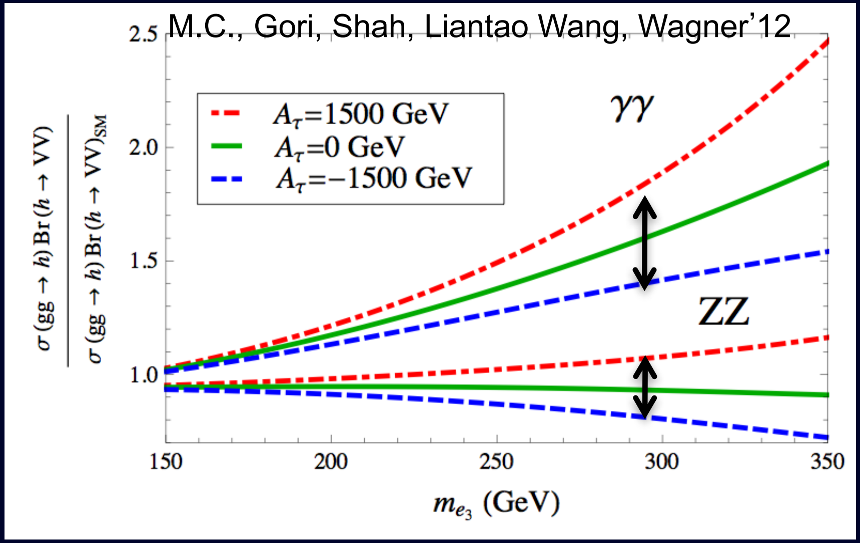
The new era of precision Higgs Physics



How close to Alignment or Decoupling?

There could be one or more "large" ~10% deviations in Higgs couplings versus the SM, detectable at LHC or HL-LHC running

ILC, CEPC,
100 TeV HC?

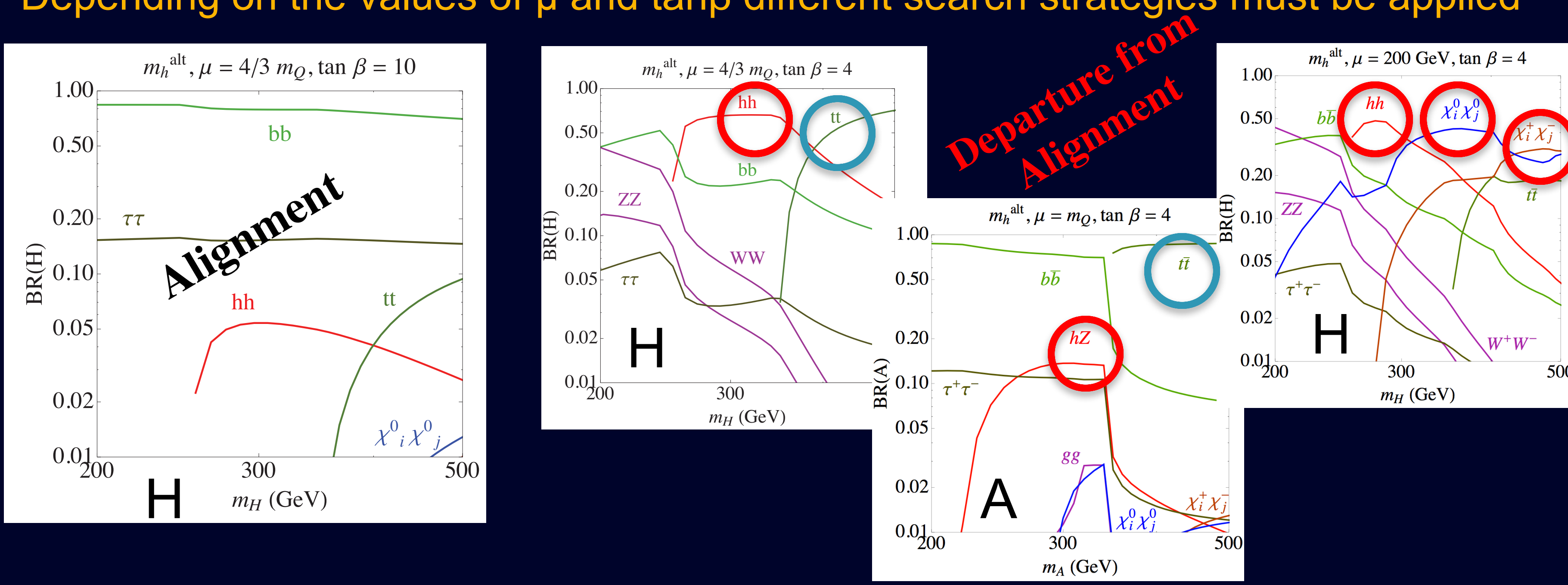


- New light charged or colored particles in loop-induced processes
- Modification of tree level couplings due to Higgs mixing effects → departures from alignment
- Through vertex corrections to Higgs-fermion couplings:

  This destroys SM relation BR(h →bb)/BR(h → ττ) ~ m_b^2/m_τ^2
- Decays to new or invisible particles, such as Dark Matter

Heavy Higgs Bosons: A variety of decay modes

Depending on the values of μ and tanβ different search strategies must be applied



If the discovered Higgs boson is qvery close to SM-like ➔ A/H dominant bottom & tau decays

If couplings deviate from SM values ➔ NEW, challenging decay modes require new techniques

H➔ hh, WW, ZZ and tt and A ➔ hZ, tt plus chargino and neutralino channels open up

Similar effects in Extensions of the MSSM (singlets, triplets, enhanced gauge symmetries)

~ Add new degrees of freedom that contribute at tree level to m_h,
improves on naturalness and opens new decay modes ~

Models of EWSB and Strong Interaction Dynamics

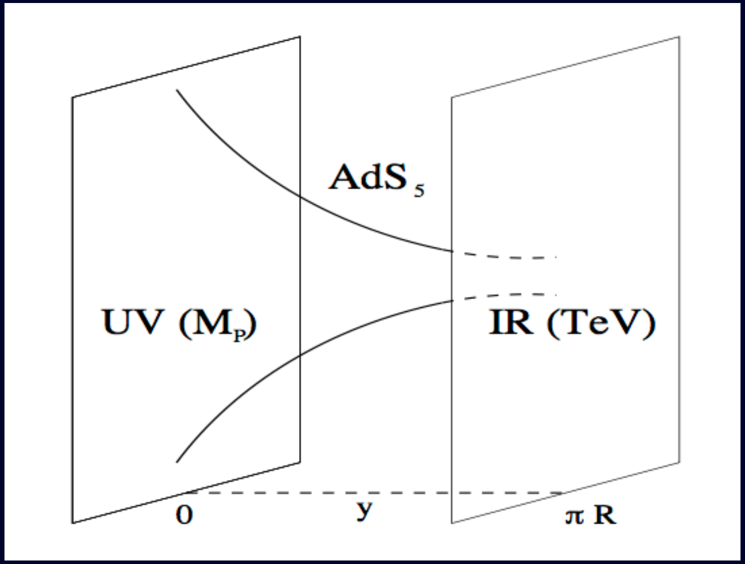
Electroweak Symmetry broken by critically strong new interactions

Analogy with QCD: EWSB scale exponentially separated from M_{planck} by running of coupling

What about the connection between theories of strong dynamics and the existence of extra dimensions of space?

Maldacena '97

Randall Sundrum Extra Dimensions



$$\mathbf{d}s^2 = \mathbf{e}^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

AdS space is highly curved, "warped"

k is the AdS curvature

AdS in 5D ⟷ CFT in 4D

In the 4-dim "holographic" description, the coordinate *y* has the interpretation of being the renormalization scale of the 4-dim theory:

UV (IR) brane is a UV (IR) cutoff in the 4-dim theory

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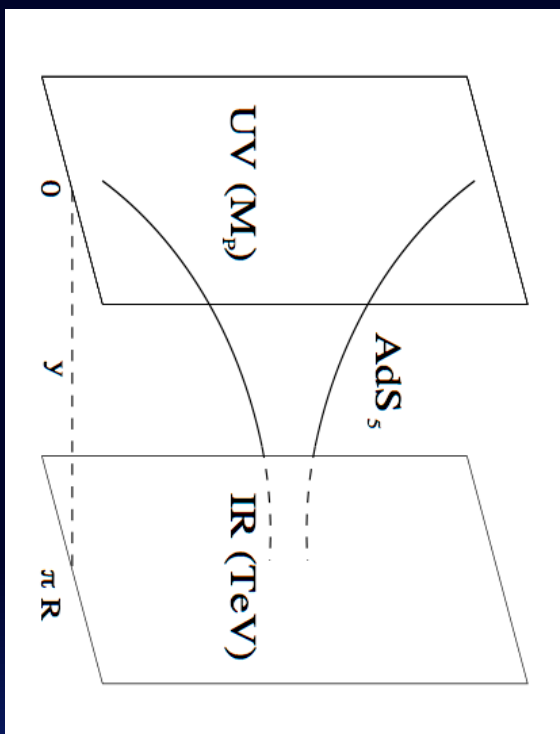
QCD Example



high energy theory is weakly coupled quarks and gluons

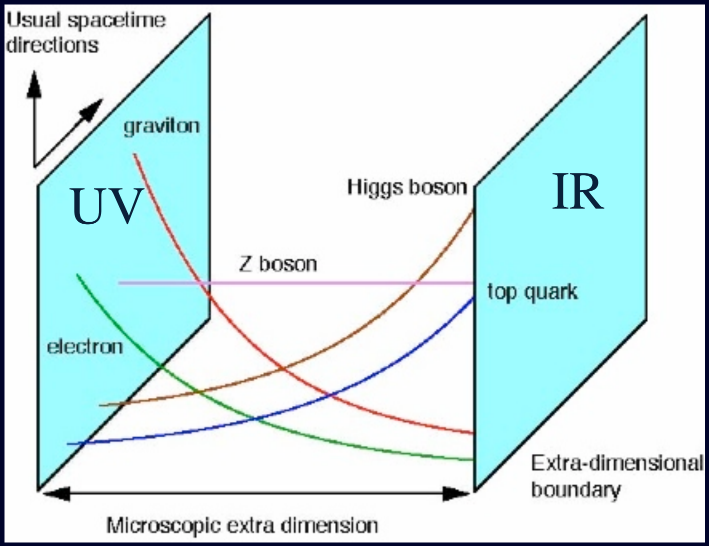
low energy theory is a tower of composite pions, baryons

AdS in 5D ⟷ CFT in 4D

- QCD has a dynamically generated mass scale from strong coupling that sets the mass scale for a tower of composite pion states
- The 5-dim field theory description in AdS thus describes both elementary quarks and composite pions
- In terms of the AdS curvature scale k, the pion mass scale is given by the IR brane cutoff scale

$$\mathbf{m_{gap}} = \pi k \, \mathbf{e}^{-\pi k R}$$

The Standard Model in Warped Extra Dimensions



- Elegant solution to the Hierarchy problem: it is possible that the otherwise mysterious mass scale of the Higgs boson is precisely an IR cutoff scale in a warped extra dimension

- The Higgs boson is really a pion-like composite

Hierarchical SM fermion masses from localization [masses and degree of compositeness depend on overlap with Higgs/TeV scale]

KK modes (weak bosons, gluons, fermions, gravitons) localized towards the IR with Masses ≥ 1 TeV from precision measurements (Higgs induced mixing with SM particles)

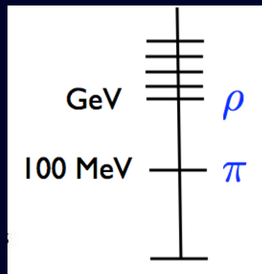
Gauge-Higgs Unification Models: A dynamical origin of the Higgs Field

Enlarge the SM gauge symmetry in the bulk such that additional zero mode/s of the 5D gauge field (scalars) are identified with the Higgs degrees of freedom

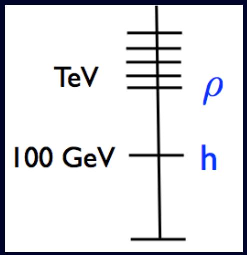
➔ No tree-level Higgs Potential ==> Induced at one-loop level

➔ Dynamical EWSB: driven by the top Yukawa

Composite Higgs Models
The Higgs as a pseudo Nambu-Goldstone Boson (pNGB)



Inspired by pions in QCD



QCD with 2 flavors: global symmetry $SU(2)_L \times SU(2)_R / SU(2)_V$.

π^{+-} π^0 are Goldstones associated to spontaneous breaking

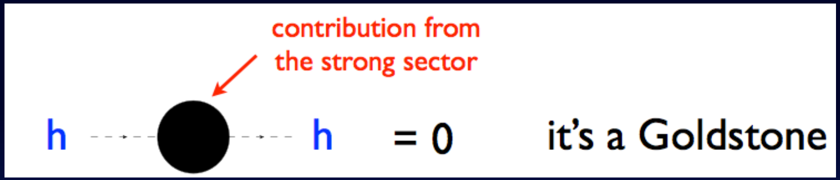
$$g, g' \to 0 \quad \& \quad m_q \to 0 \quad \Rightarrow m_\pi = 0$$

$$m_q \neq 0 \Rightarrow m_\pi^2 \simeq m_q B_0$$

$$e \neq 0 \Rightarrow \delta m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda_{QCD}^2$$

Higgs is light because is the pNGB
-- a kind of pion – of a new strong sector

Mass protected by the global symmetries



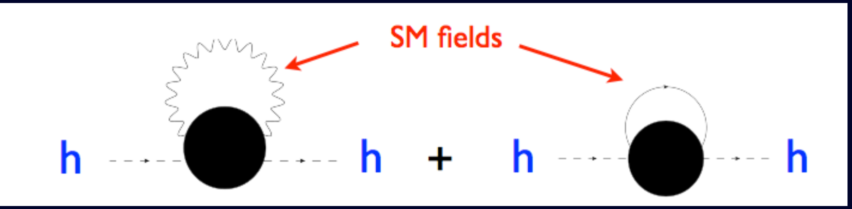
A tantalizing alternative to the strong dynamics realization of EWSB

Georgi,Kaplan'84

Higgs as a PNGB

Light Higgs since its mass arises from one loop

Mass generated at one loop: explicit breaking of global symmetry due to SM couplings



Dynamical EWSB: large set of vacua, some of them break $SU(2)_L \times U(1)_Y$

The Higgs potential depends on the chosen global symmetry
AND
on the fermion embedding in the representations of the symmetry group

Higgs mass challenging to compute due to strong dynamics behavior

$$m_H^2 \propto m_t^2 M_T^2 / f^2$$

Composite-sector characterized by a coupling $g_{cp} \gg g_{SM}$ and scale $f \sim$ TeV

New heavy resonances ➔ $m_\varrho \sim g_\varrho f$ and $M_{cp} \sim m_\varrho \cos_\psi$

New Heavy Resonances being sought for at the LHC

Minimal Composite Higgs models phenomenology

-- All About Symmetries --

Choosing the global symmetry [SO(5)] broken to a smaller symmetry group [SO(4)]
-- at an intermediate scale f larger the electroweak scale -- such that:
the Higgs can be a pNBG, the SM gauge group remains unbroken until the EW scale
and there is a custodial symmetry that protects the model from radiative corrections

Higgs couplings to W/Z determined by the gauge groups involved

SO(5) ➔ SO(4)

SO(5) ×U(1) smallest group: ⊃ G^{EW}_{SM} & cust. sym. & H = pNGB

Other symmetry patterns with additional Higgs Bosons

Model	Symmetry Pattern	Goldstone's
SM	SO(4)/SO(3)	W_L, Z_L
–	SU(3)/SU(2)×U(1)	W_L, Z_L, H
MCHM	SO(5)/SO(4)×U(1)	W_L, Z_L, H
NMCHM	SO(6)/SO(5)×U(1)	W_L, Z_L, H, a
MC2HM	SO(6)/SO(4)×SO(2) ×U(1)	$W_L, Z_L, h, H, H^{\pm}, a$

Higgs couplings to SM fermions depend on fermion embedding

With Notation $\mathrm{MCHM}_{\text{Q-U-D}}$

5, 10,
5-5-10, 5-10-10, 10-5-10
14-14-10, 14-1-10

SO(5) Representations

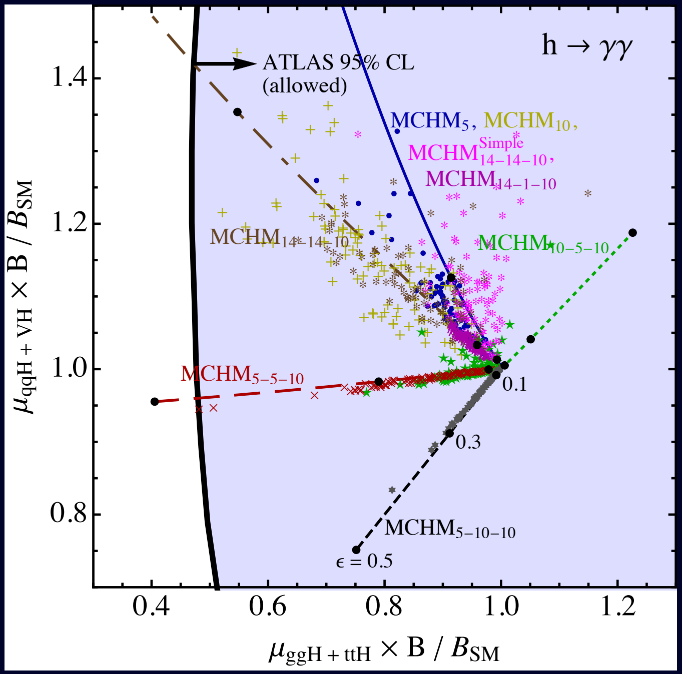
Generic features:

Suppression of all partial decay widths and all production modes

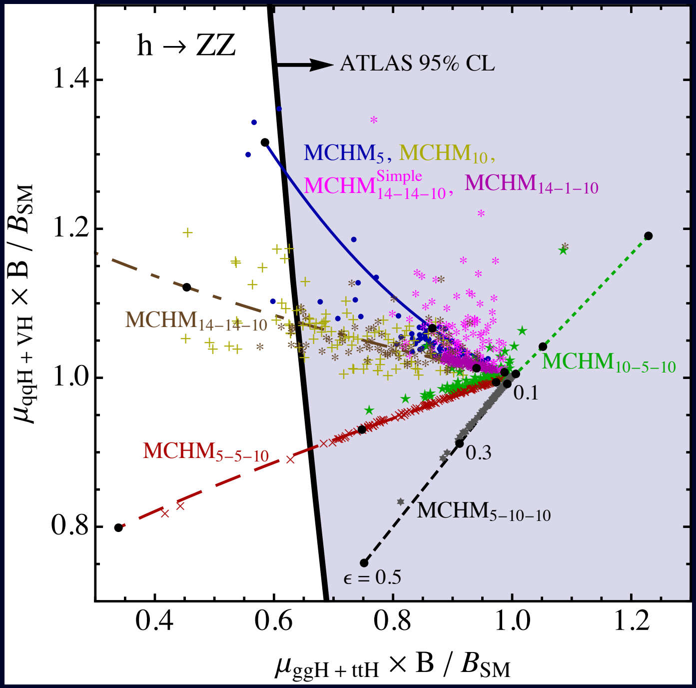
Enhancement/Suppression of BR's dep. on the effect of the total width suppression

Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ



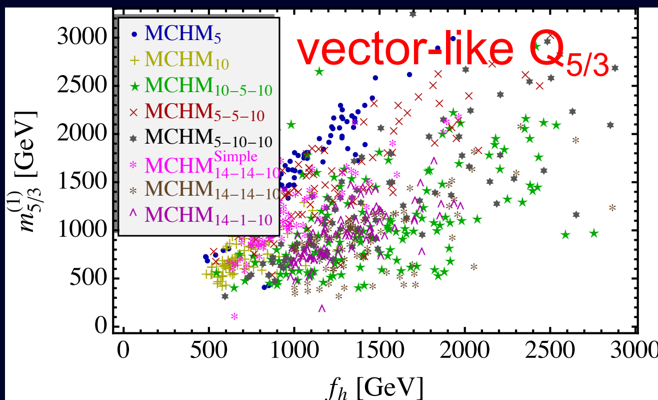
After EWSB: $\varepsilon = v_{SM}/f$ and precision data demands f > 500 GeV

M.C., Da Rold, Ponton'14

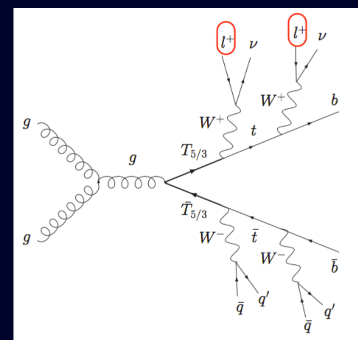
- More data on Higgs observables will distinguish between different realization in the fermionic sector, providing information on the nature of the UV dynamics
- Extended global gauge symmetries imply a heavy Higgs sector that may be strongly constrained by Higgs data: e.g. the inert 2HDM naturalness implies a light Higgs spectra
- Lots of model building underway to confront with LHC13 data

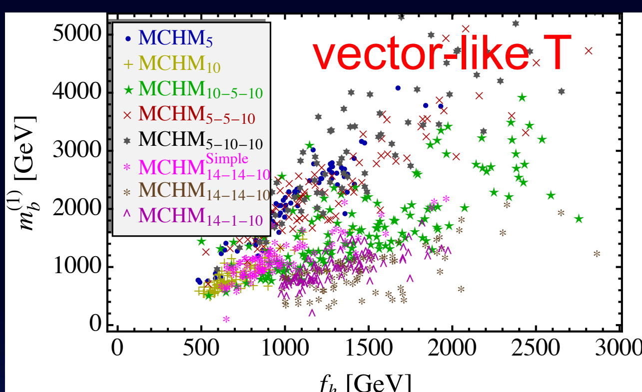
Composite pNGB Higgs Models predict light Fermions

Pair production, single production, or exotic Higgs production of vector-like fermions
[masses in the TeV range and possibly with exotic charges: Q = 2/3,−1/3, 5/3,8/3,−4/3]



SS di-leptons





M.C., Da Rold, Ponton'14

Large variety of signatures, many with energetic leptons

LHC exclusion for $M_f < 800$ GeV]

Deep Connections

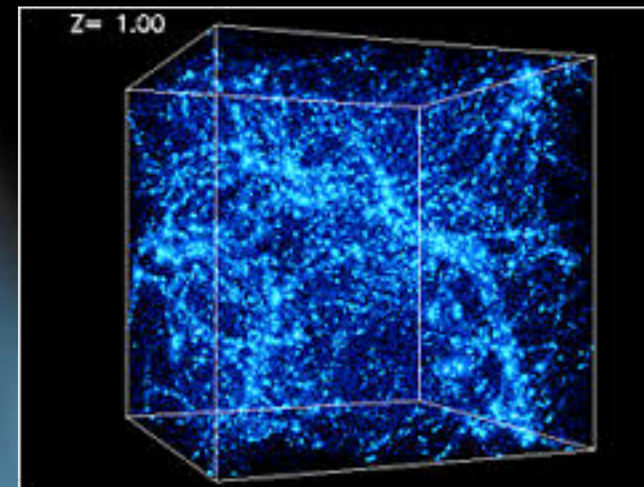
The Higgs

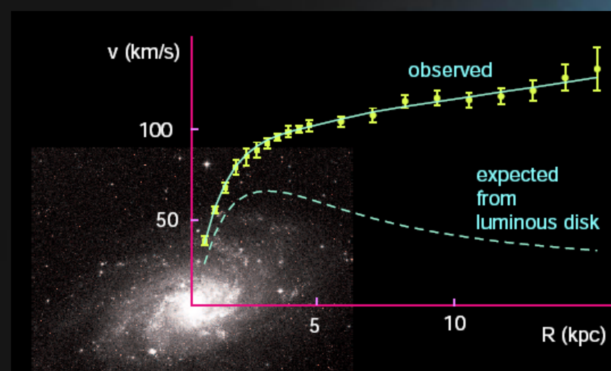
and the Mysteries of Matter

The power of the dark side

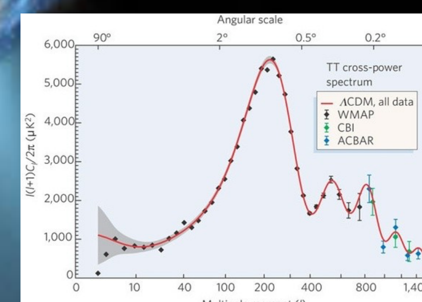
Holds the Universe together and makes ***85% of all the matter in it!***

What is it?
Which are its properties?
How to search for it?





M33 rotation curve
(fig. 1)



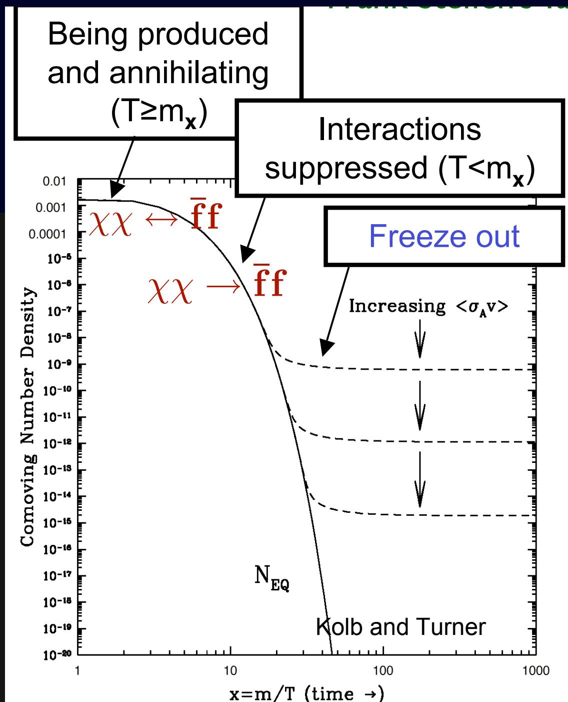
Interacts very weakly
(not charged)

→ **Gravity**

→ **Higgs-like Interactions ?**

Dark Matter as a Thermal Relic

WIMP Dark Matter ?



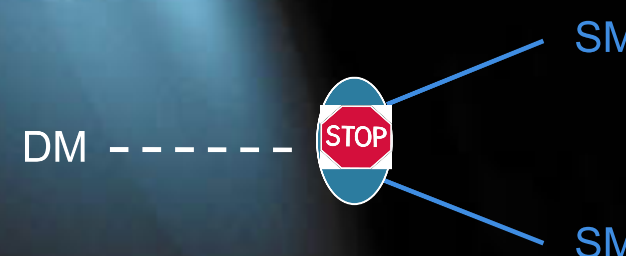
- DM = yet unknown, heavy, neutral elementary particle/s
- Mass estimate (model dependent) from observed relic dark matter abundance today set by weak scale interactions in the early universe

$$\Omega_{DM} h^2 \approx \; <\sigma_A v>^{-1}$$

$M_{DM} \sim 10 - 1000$ GeV

fits well with a weakly interacting particle = WIMP

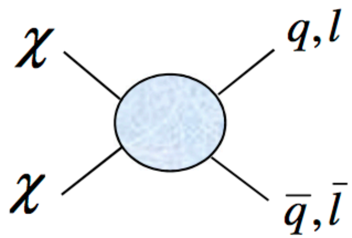
CAVEAT: To avoid decay of a WIMP to lighter visible matter, theorists invented a symmetry: "dark matter charge" such that



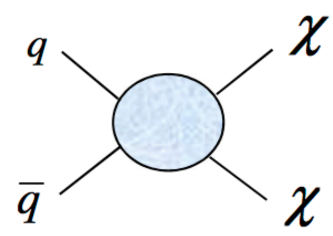
Typical example is SUSY. The symmetry is R-Parity

$$R_P = (-1)^{3B+L+2S}$$

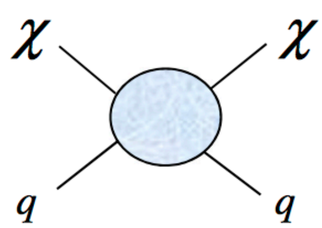
Dark Matter Detection Methods



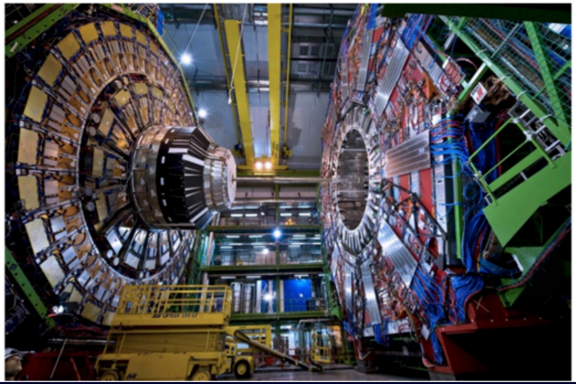
Above ground



Collider

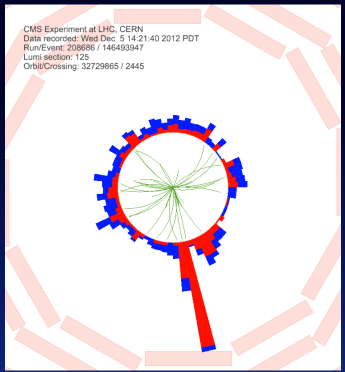


Underground

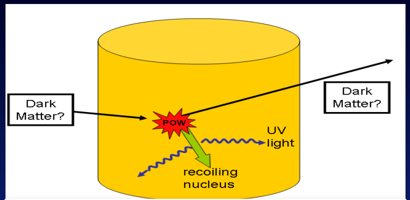


Thermal freeze out at early Universe, detect its annihilation products now:
gamma-rays, neutrinos and charged cosmic rays

Create DM at LHC



It can collide with a single nucleus in the detector and be observed



Underground detector

charg

SUSY and the WIMP Miracle

- If the LSP is the lightest neutralino it will behave as WIMP dark matter
- In the MSSM the lightest neutralino is generically a mixture of the Bino, Wino, and the two Higgsinos
- If you are more ambitious, you can try to require that the LSP is a thermal relic with the correct abundance to explain ALL dark matter

SUSY and the WIMP "Miracle"

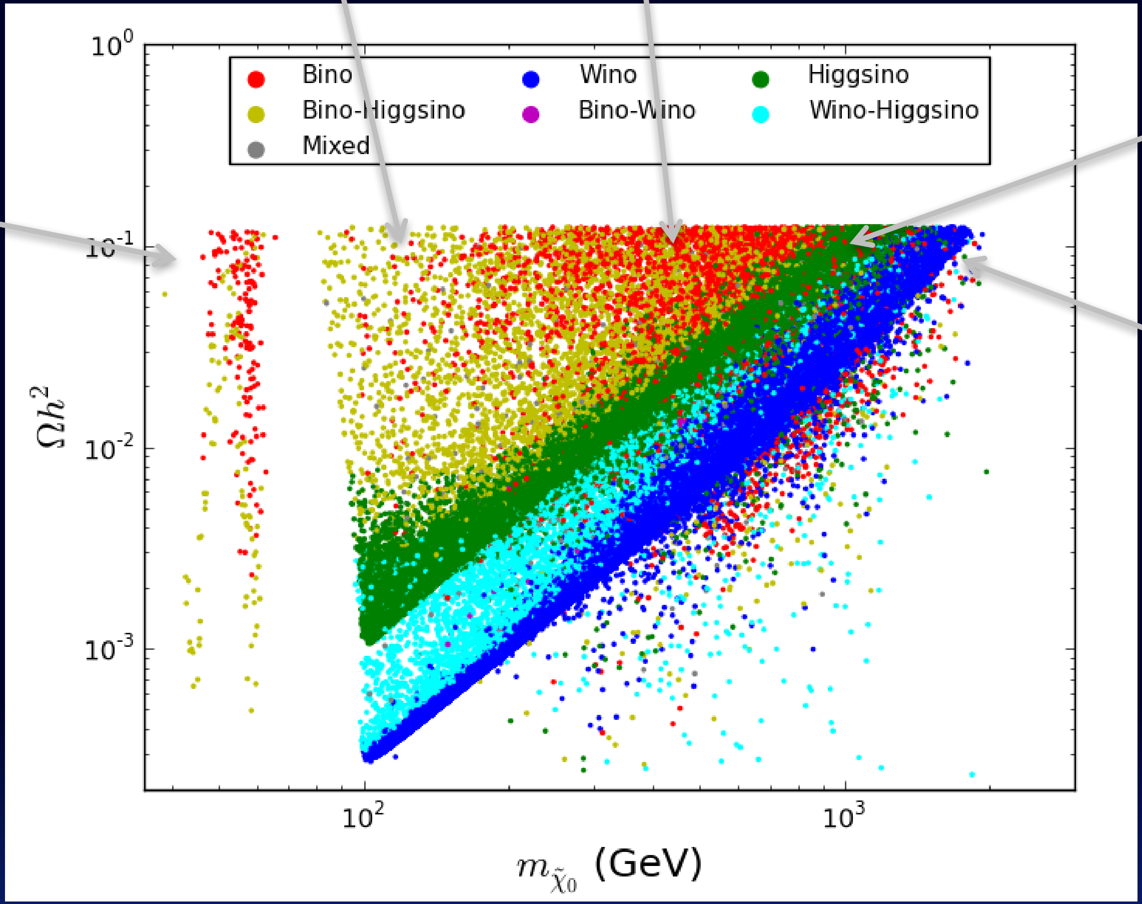
Bino-Higgsino mixture, closest case to the WIMP Miracle

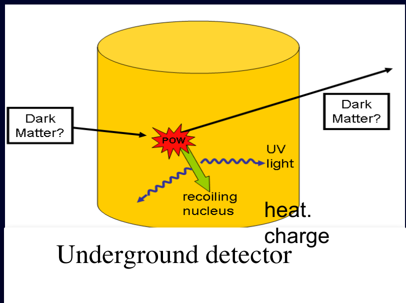
Pure Bino needs co-annihilation with other quasi-degenerate superpartners

Bino-like that can annihilate through the h or Z "funnels"

Higgsino, ~ 1.5 TeV

Wino, ~ 2 TeV

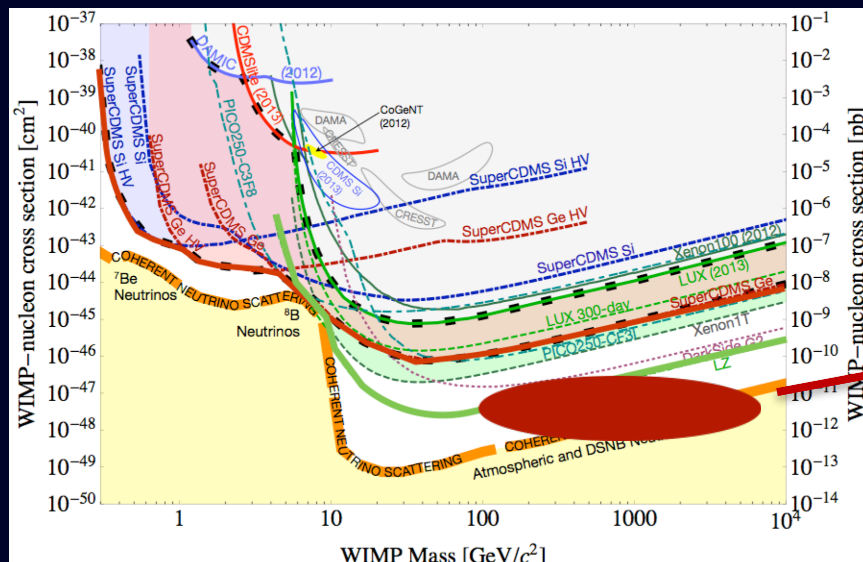


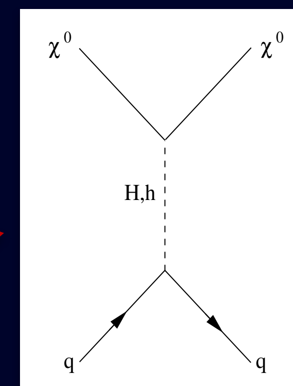


Dark Matter Direct Detection:

Starting to Probe the Higgs Portal

charg
e





- Mixed Wino-Higssino or Bino-Higgsino ➔ can have suppressed couplings with the Higgs bosons by tuning M_2 (M_1), tan β and μ
- Relevant destructive interference between h and H possible Huang, Wagner '14

Still room for a SUSY WIMP miracle but many other ideas flourishing

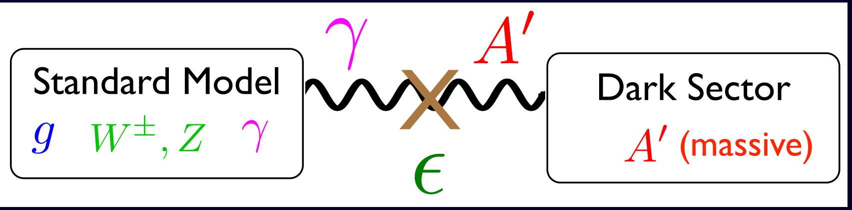
We are testing the outrageous idea of Dark Matter using accelerators, telescopes and specialized detectors!

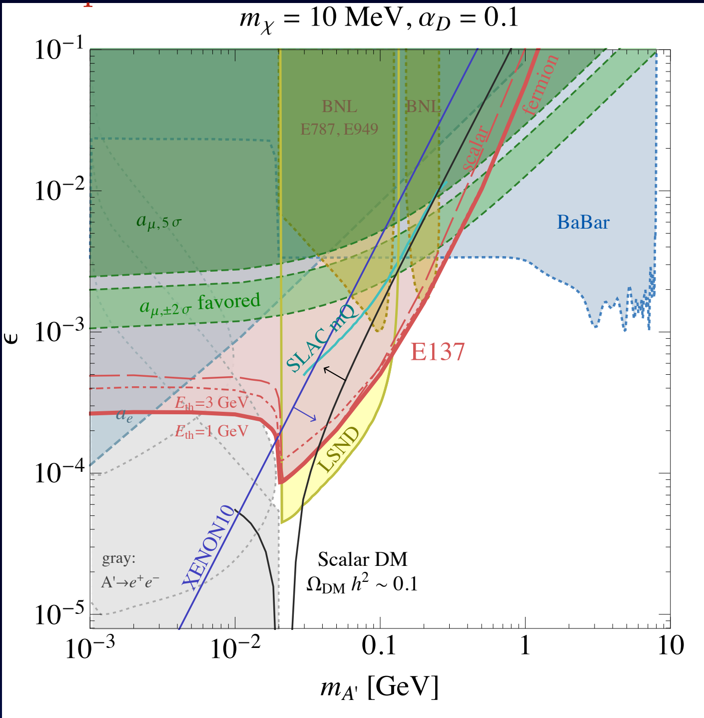
A priority for Particle Physics and Cosmology

DM does not need to be a WIMP at the weak scale! Many other Dark Sectors, e.g.

"Axion"	$\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$	axions & axion-like particles (ALPs)
"Vector"	$\epsilon\, F^{Y,\mu\nu} F'_{\mu\nu}$	dark photon A'

Holdom; Galison, Manohar





e.g. Sub-GeV DM searches at fixed target experiments.
Batell, Essig, Surujon, '14

- Astrophysical observations of structure may shed info on DM nature even if DM only interacts gravitationally with visible matter

Revolutionary advances in our understanding of the Universe are driven by powerful ideas and powerful instruments

Higgs Mechanism ⟷ LHC

What's Next?

We are probing the WIMP paradigm.
In addition, many novel DM ideas are starting to be tested

The Matter-Antimatter Imbalance implies new physics,
Some solutions may be accessible at the electroweak scale

The Higgs boson may play a key role in understanding both mysteries of matter and connecting with neutrinos