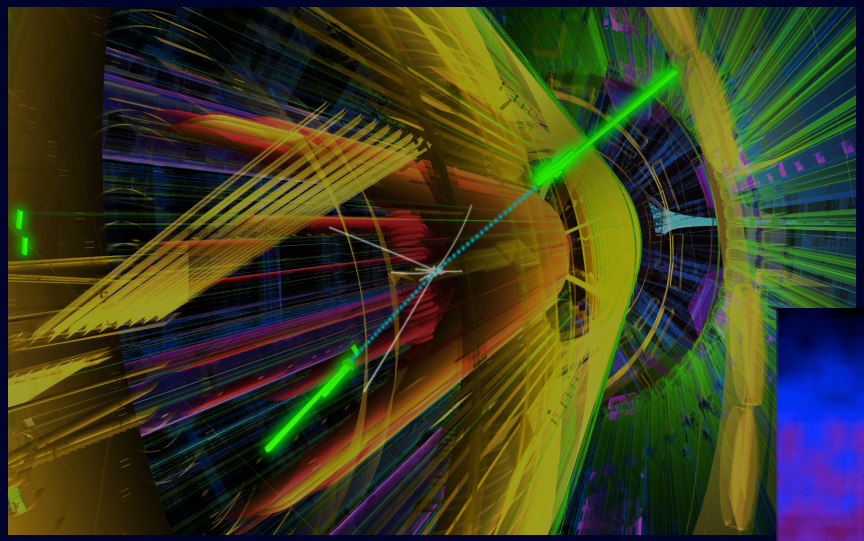
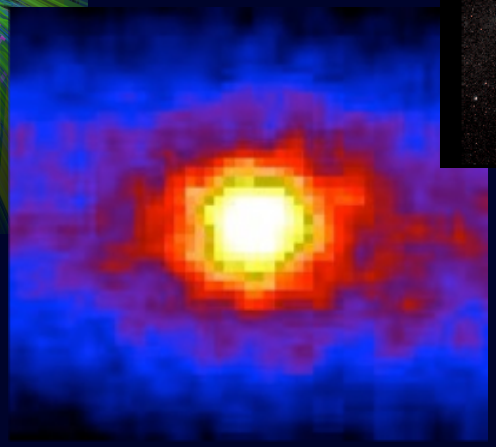
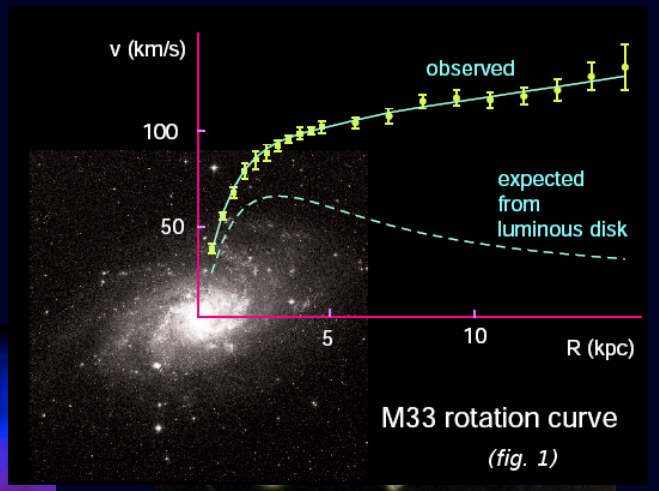
Particle Physics beyond the Higgs



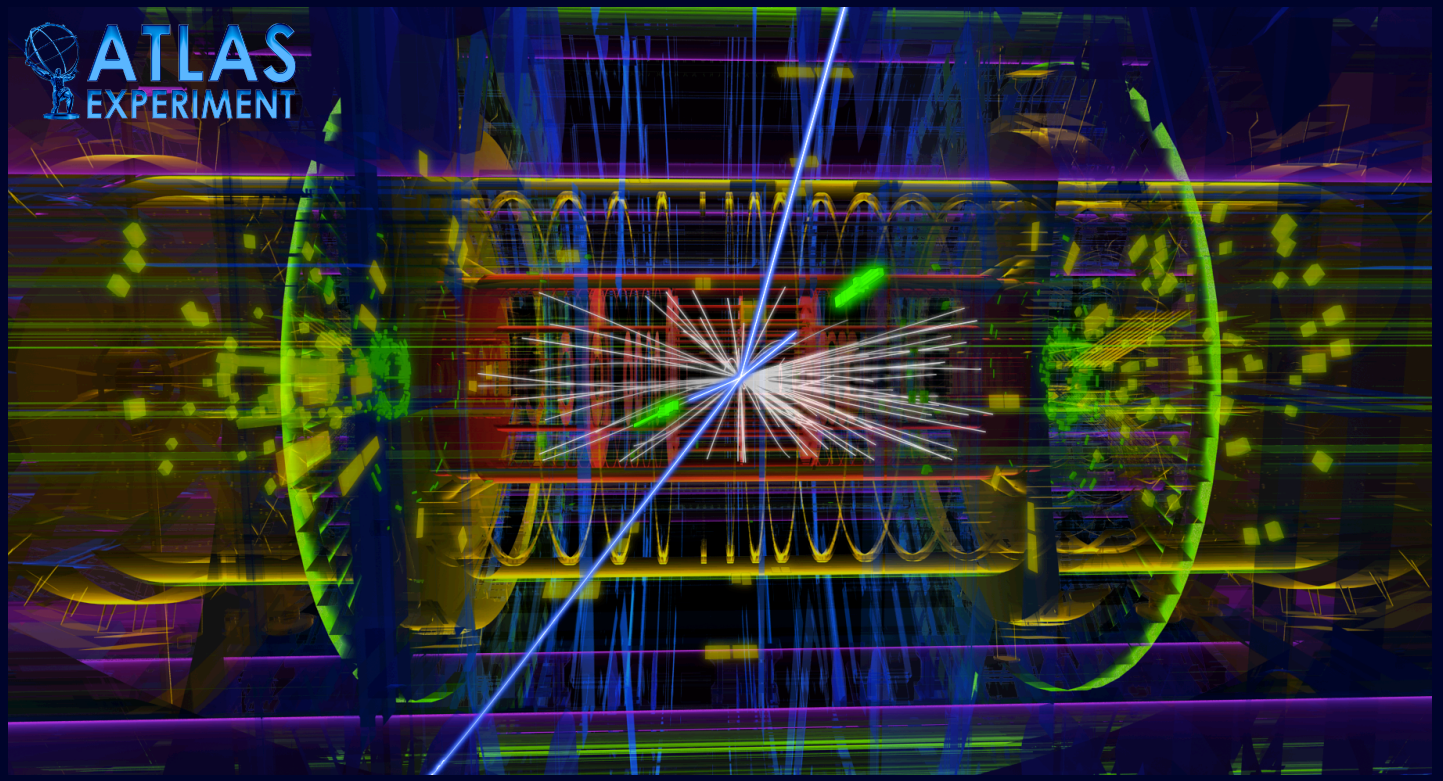




Marcela Carena
Fermilab and U. of Chicago

University of Chicago, January 15, 2015

Fireworks on 4th July 2012

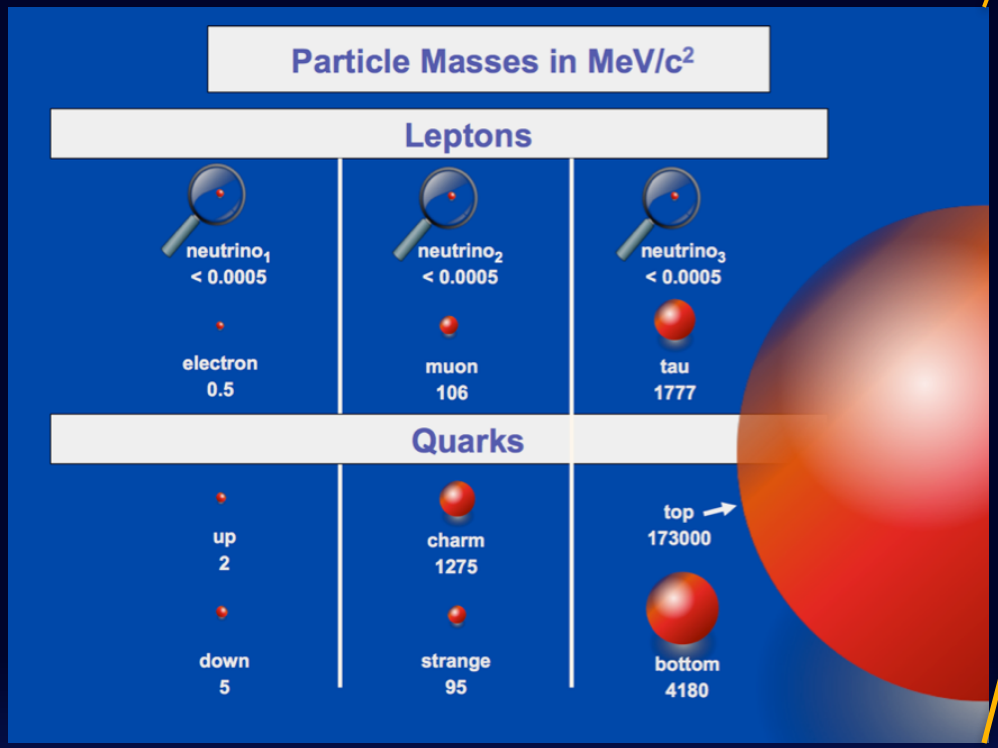


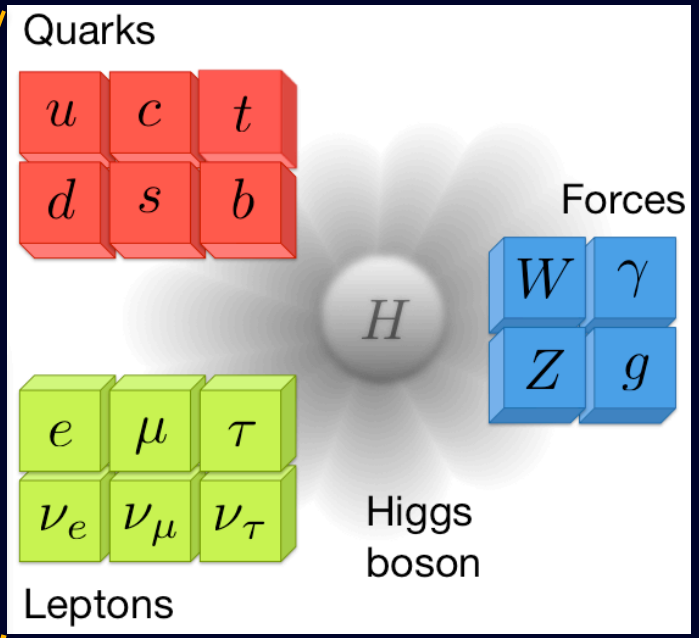
- Discovery of a new type of particle
- Discovery of a new type of force
- Start of a new era for particle physics and cosmology

The first time that the entire NYT Science section is devoted to a single story

Why is the Higgs so important ?

Sub-atomic particles of the Standard Model of Particle Physics





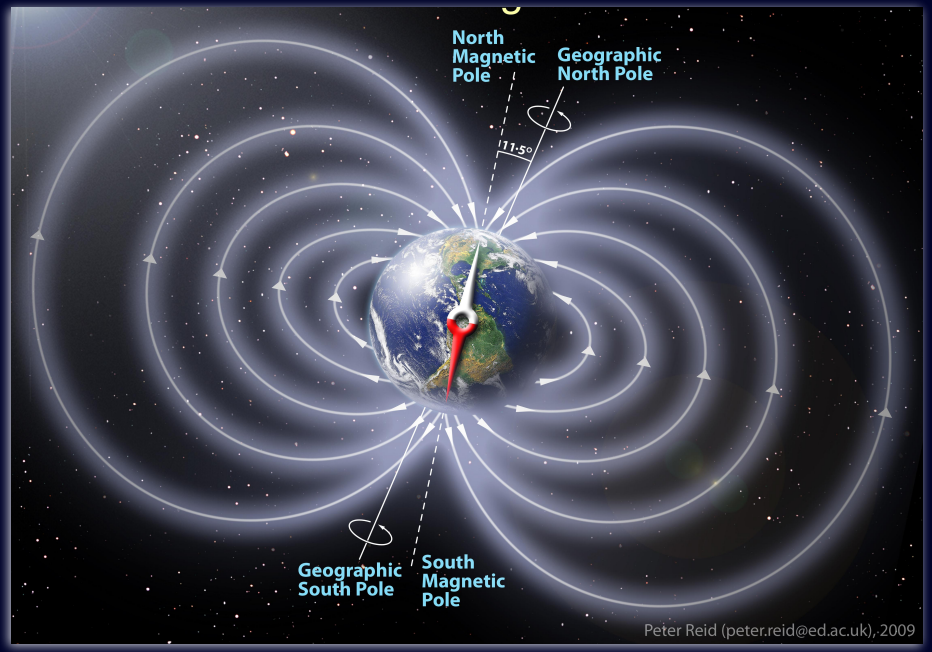
They have all been produced in the laboratory

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)

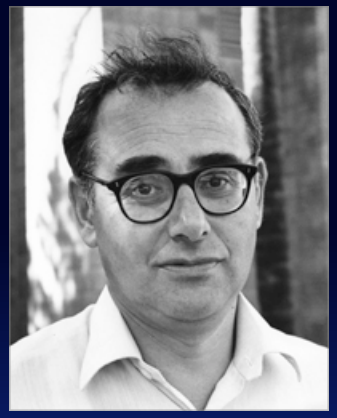
Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

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)

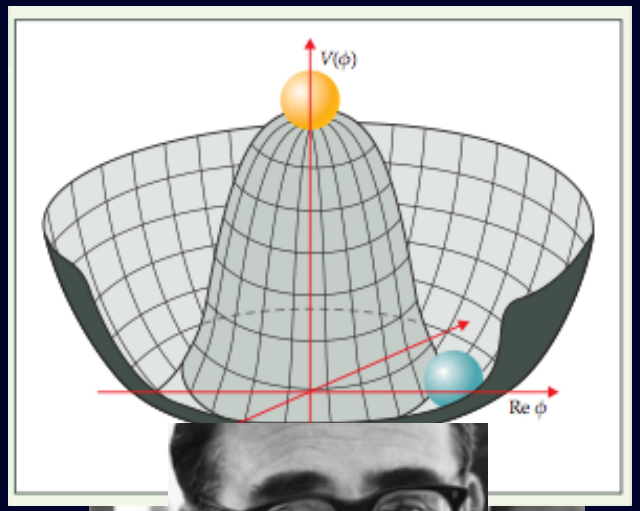
The Problem of the Massless Bosons:

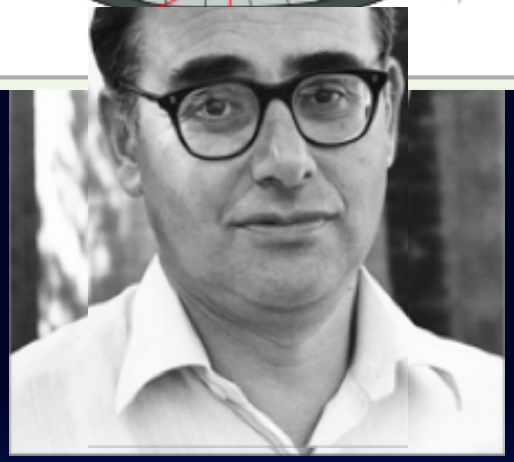
SSB implies a massless Goldstone boson per broken generator

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"

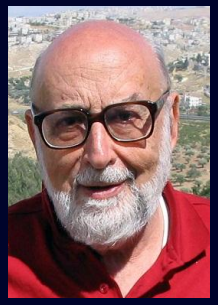
Anderson 1972

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

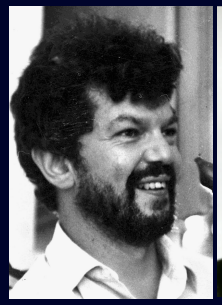
Who invented the "Brout-Englert-Higgs" mechanism?

Nambu, Goldstone and 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

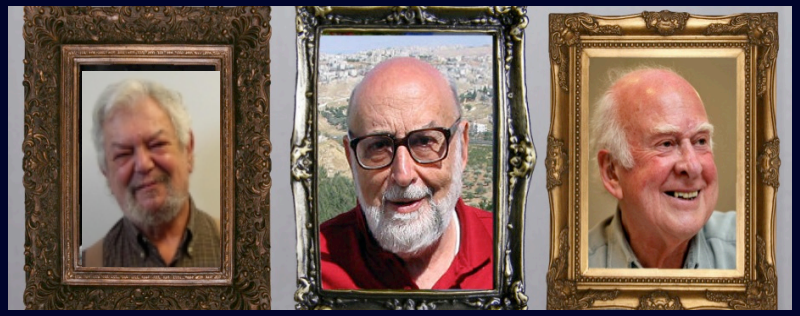
"The purpose of the present note is to report that...the spin-one quanta of some of the gauge fields acquire mass...This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson has drawn attention" **-- Peter Higgs, 1964**

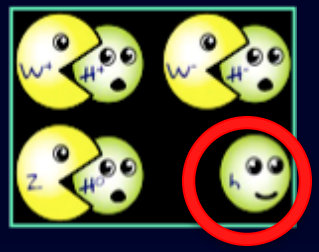
" I couldn't have imagined 50 years ago, when I was working with my colleagues Gerald Guralnik and Tom Kibble on our paper, that society would spend billions of dollars and that thousands of scientists worldwide would be involved in the search for a particle and a mechanism that stem from those three papers published in 1964". **-- Carl Hagen, 2013**

Kibble Hagen Guralnik

The BEH + GHK 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



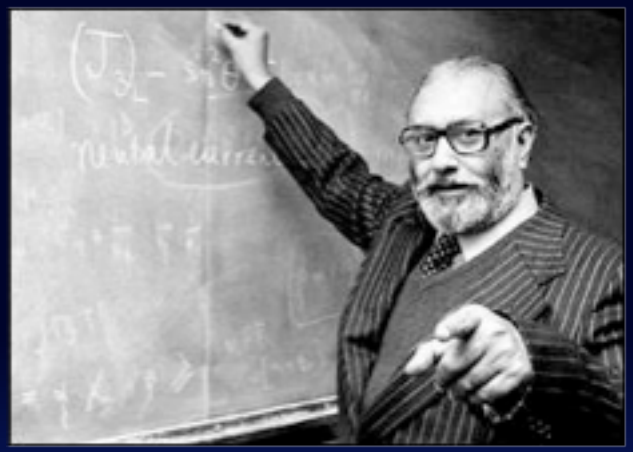


One particle left in the spectrum

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

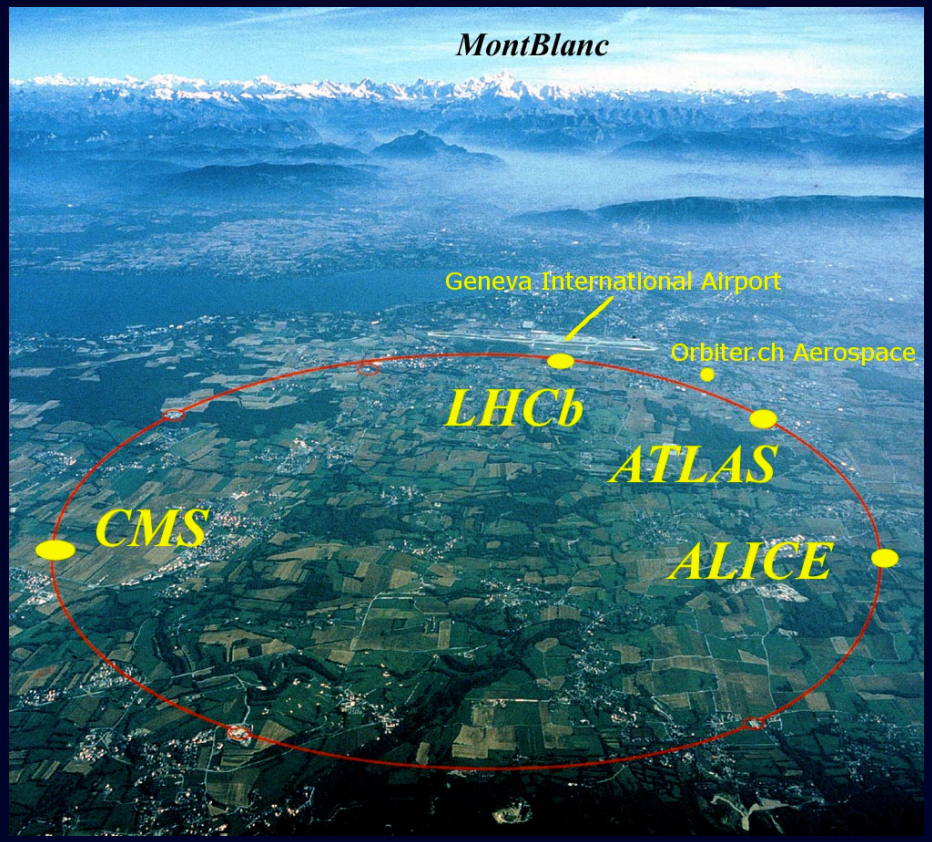
Spontaneously broken to $U(1)_{em}$ by a nonzero vacuum value of the Higgs field

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

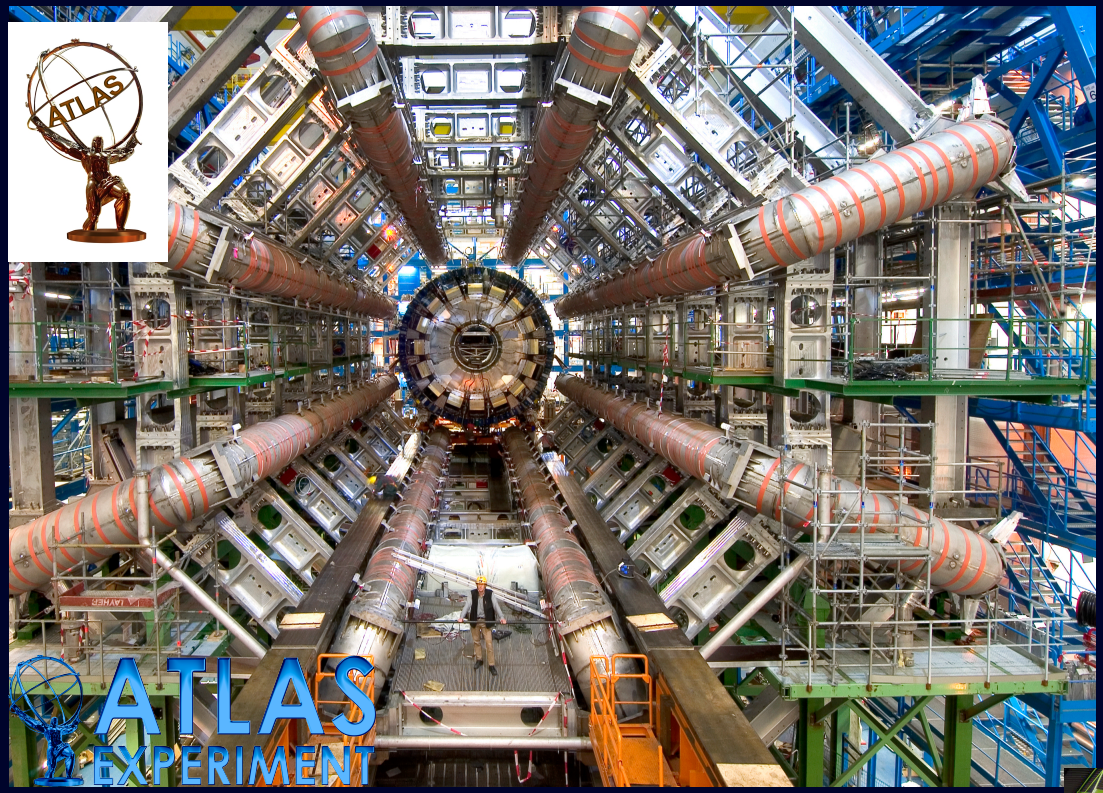
Half a century later: The Higgs boson discovery at the Large Hadron Collider (LHC)



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

A 17 mile long vacuum pipe
300 ft 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

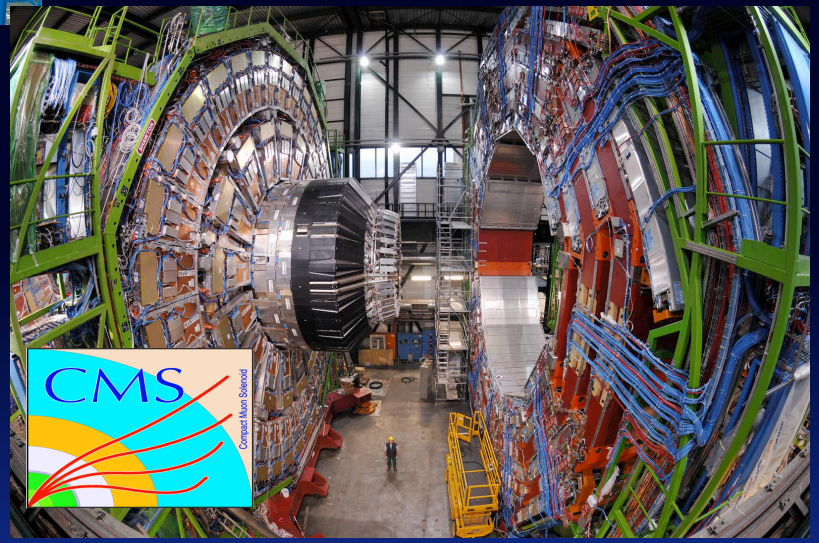
Each experiment about

3000 physicists

180 Institutes

40 countries

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



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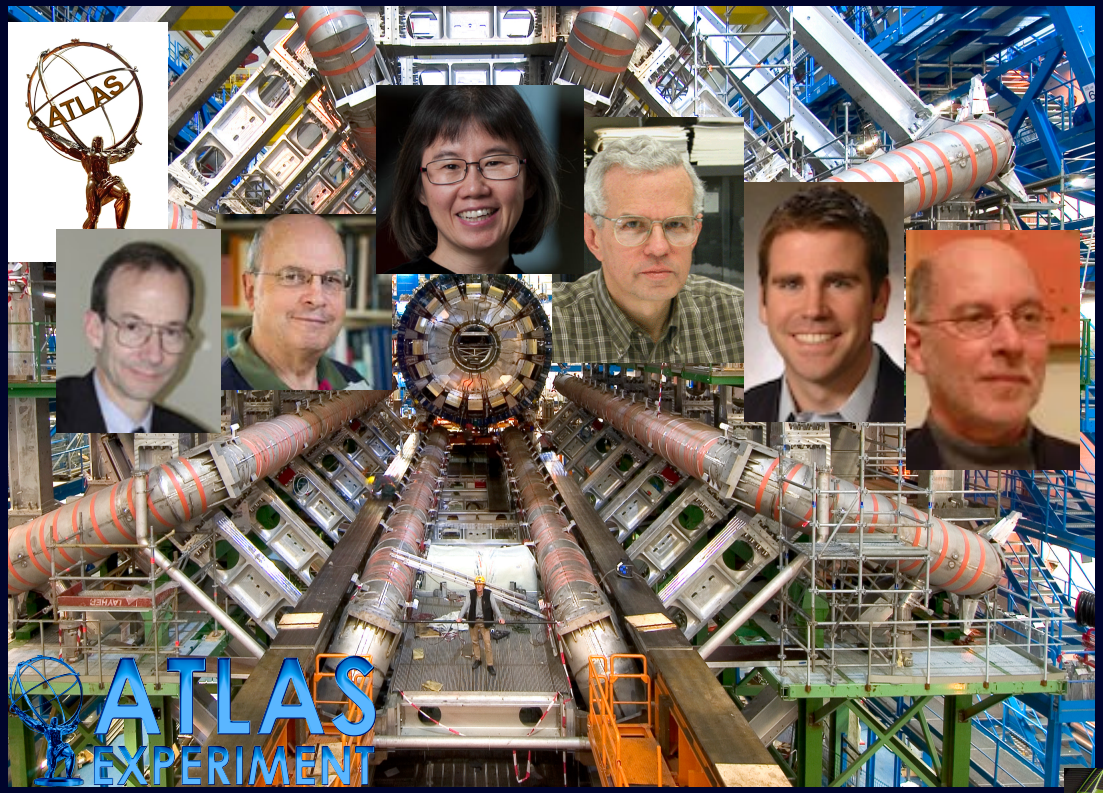

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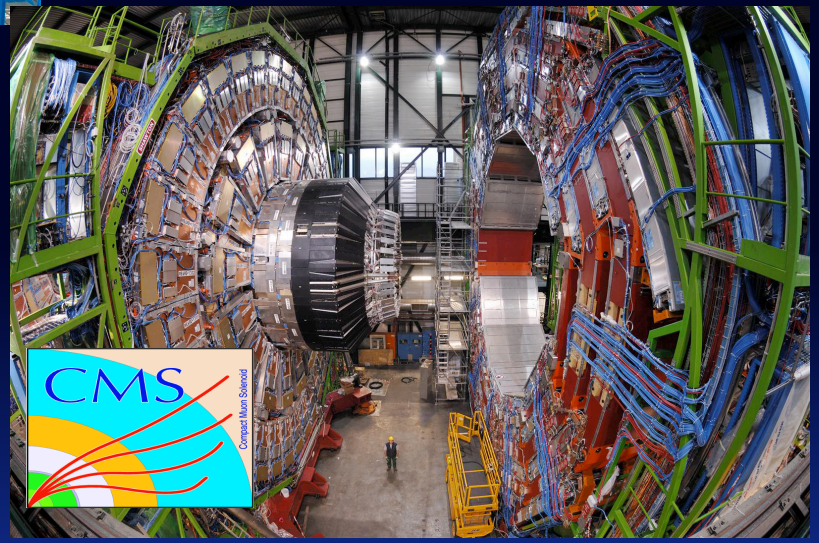
Huge, complex objects with cutting-edge technology that take "pictures" of collisions

U.S. played a leading role in the Higgs discovery

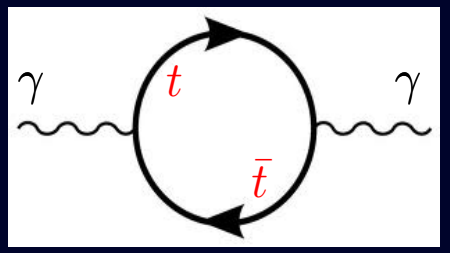
U.S. = 1/3 of CMS; U.S. = 1/5 of ATLAS



Quantum Fluctuations can produce the Higgs at the LHC

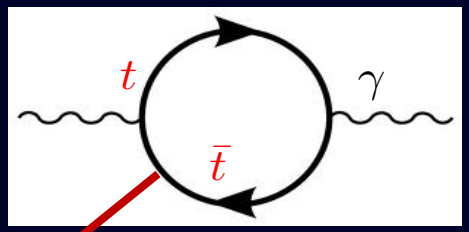
"Nothingness" is the most exciting medium in the cosmos!

Photon propagates in Quantum Vacuum

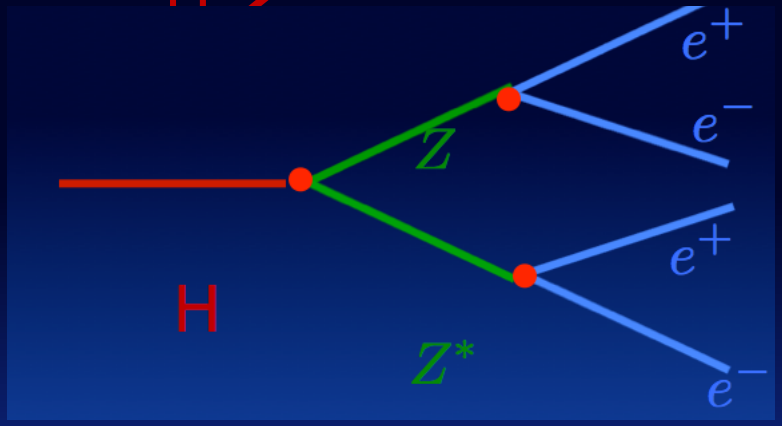


Quantum fluctuations create and annihilate "virtual particles" in the vacuum

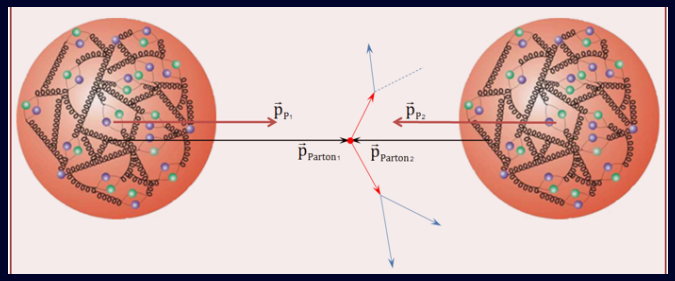
Higgs decays into 2 Photons

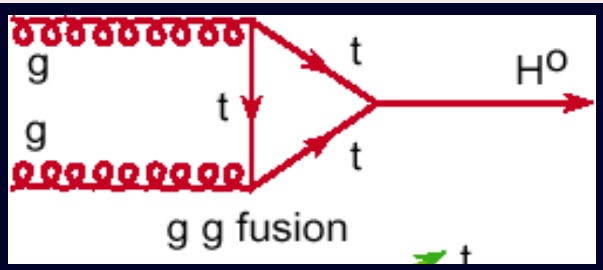


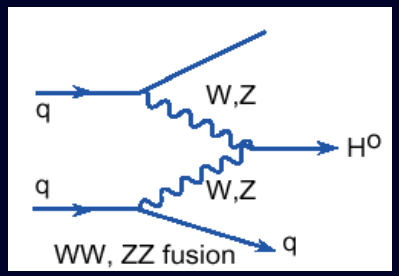
Higgs decay into 4 leptons via virtual Z bosons

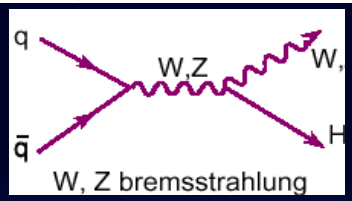


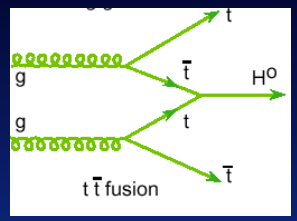
The SM Higgs at the LHC



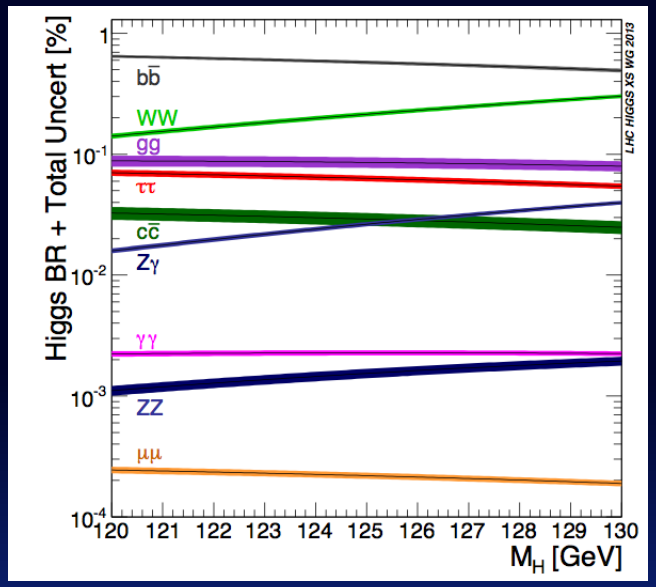


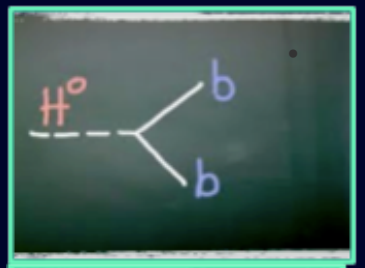




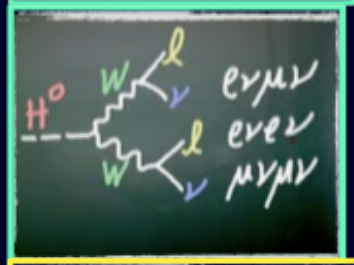


Higgs decays after about 100 yocktoseconds into various pairs of lighter particles





Lots of background

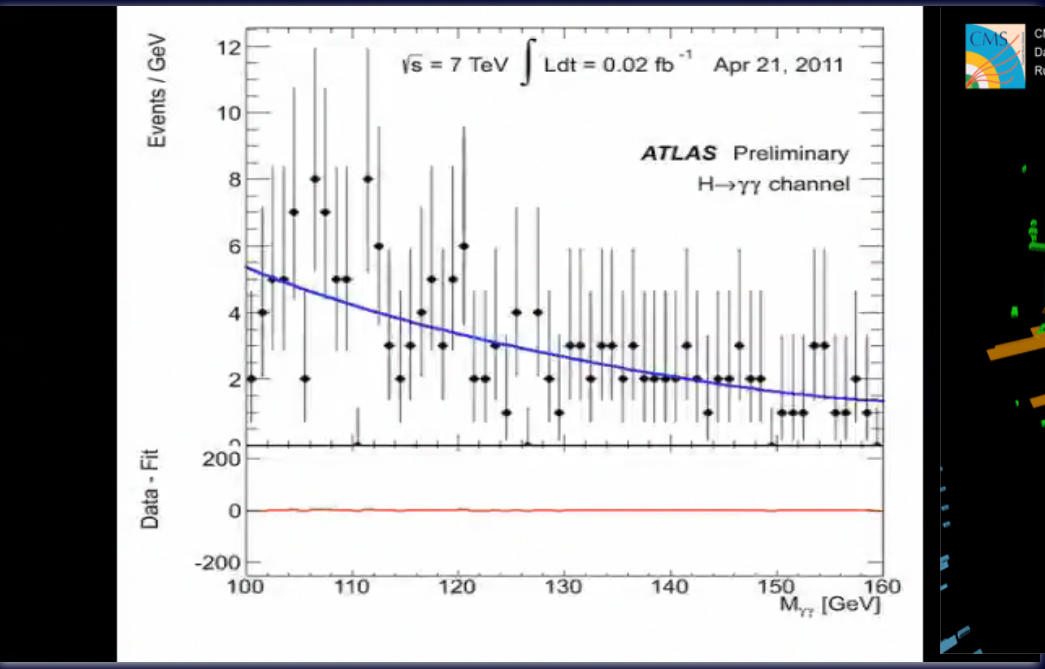


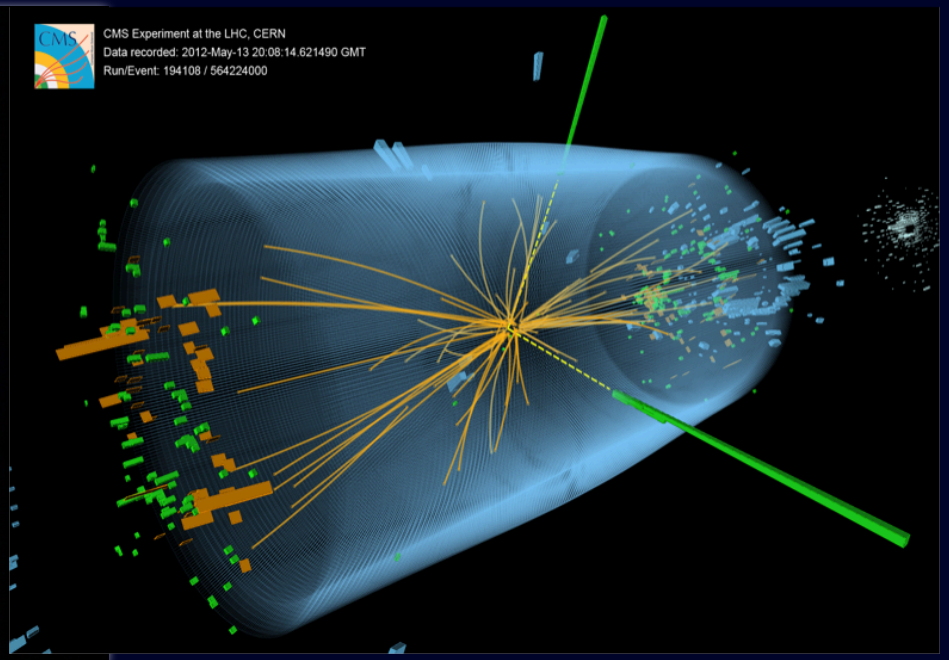
Neutrinos not detected

Rare but "Golden" channel

Rare but relatively clean

The Discovery: Higgs ➔ two photons

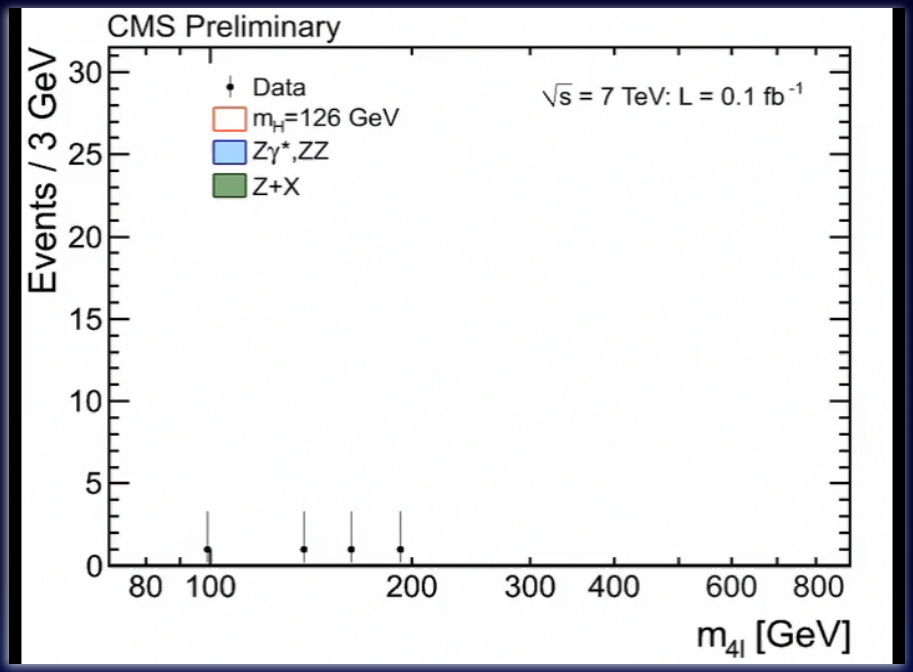


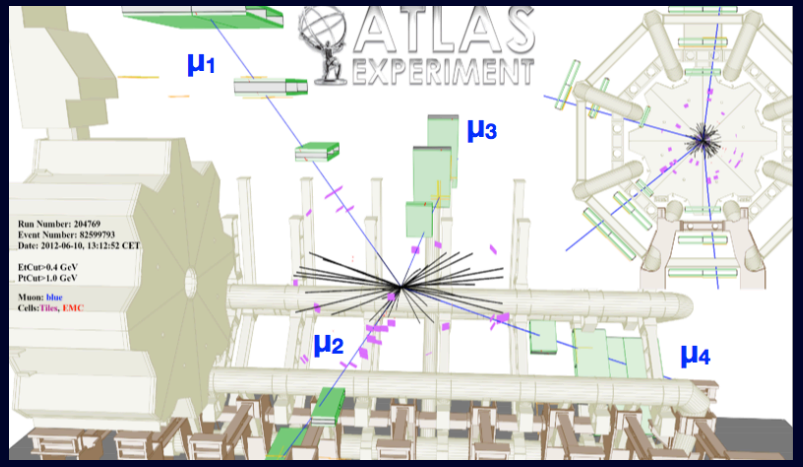


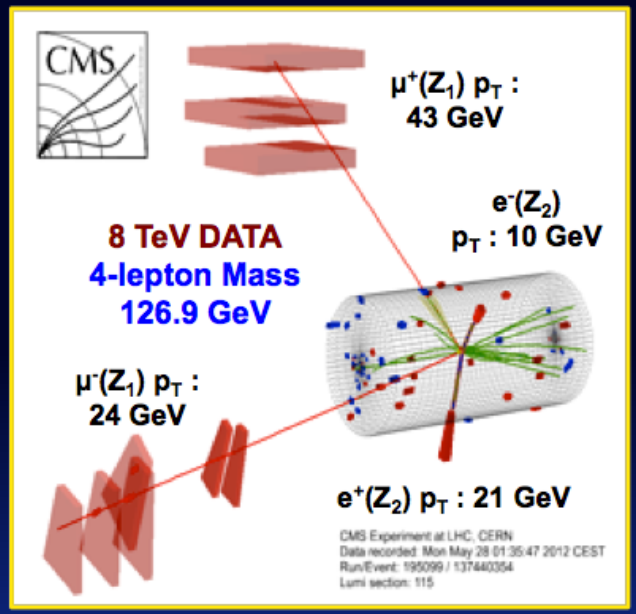
Search for a narrow mass peak with two isolated high E_T photons on a smoothly falling background

The Discovery: Higgs ➔ 4 Leptons

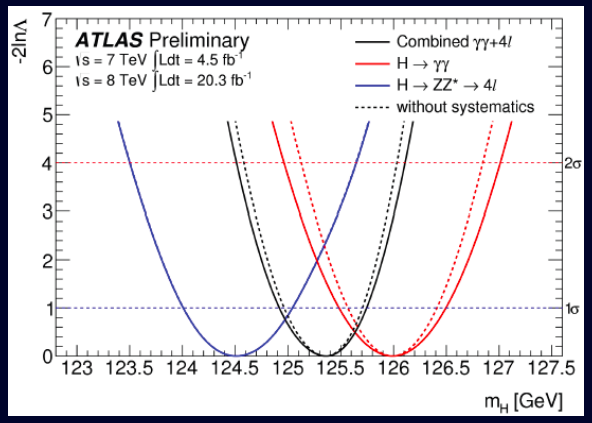
with virtual Z bosons: The Golden Channel







No doubt that a Higgs boson has been discovered

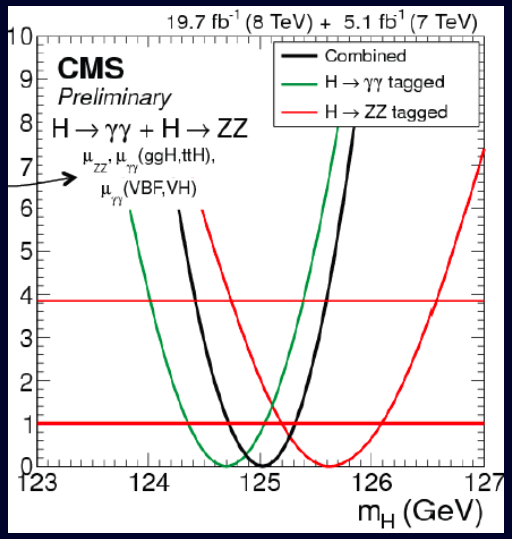


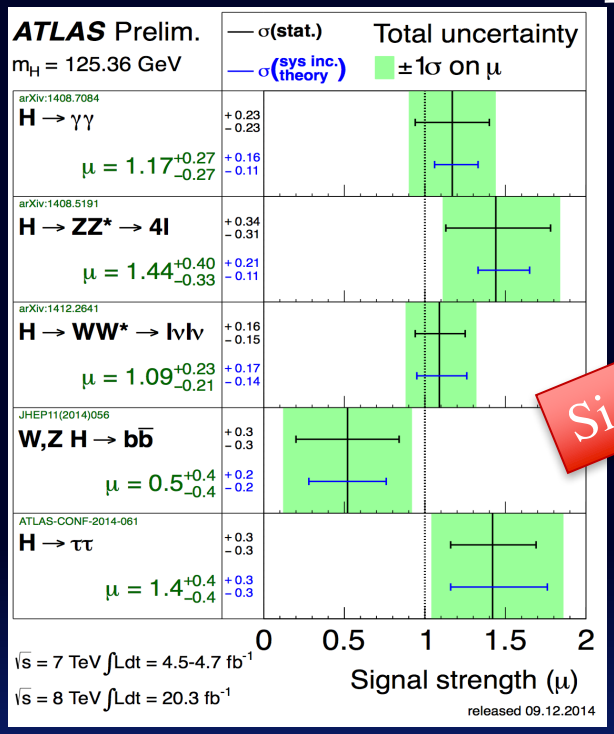
ATLAS:

$$\mathbf{m_H = [125.36 \pm 0.41]GeV}$$

CMS:

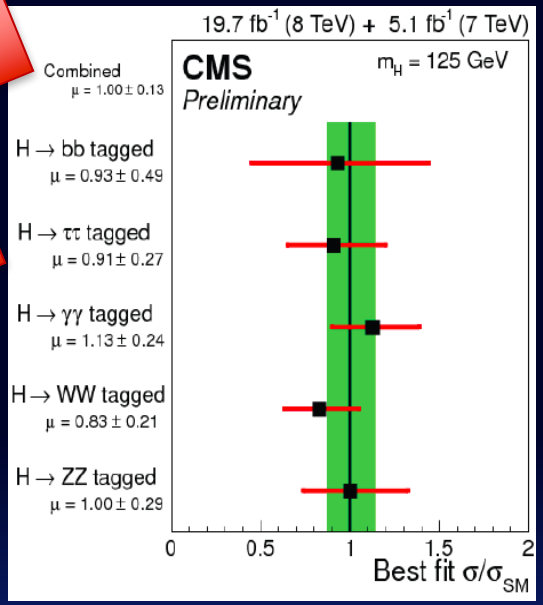
$$\mathbf{m_H = [125.03 \pm 0.30]GeV}$$





Signal compatible with SM Higgs

Also room for New Physics



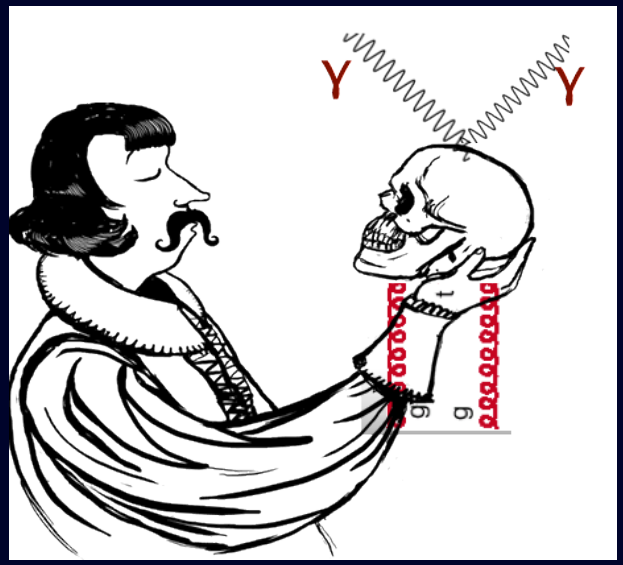
$$\sigma/\sigma_{\rm SM} = 1.00 \pm 0.13 \left[\pm 0.09({\rm stat.})^{+0.08}_{-0.07}({\rm theo.}) \pm 0.07({\rm syst.})\right]$$

What kind of Higgs?

- Is it THE Higgs boson that explains the mass of fundamental particles?

  ~1% of all the visible mass

" The" Standard Model Scalar Boson, or not ....



- Is it just THE STANDARD MODEL HIGGS ?

- **Spin 0**
- **Neutral CP even component of a complex $SU(2)_L$ doublet**
- **Couples to weak gauge bosons as**

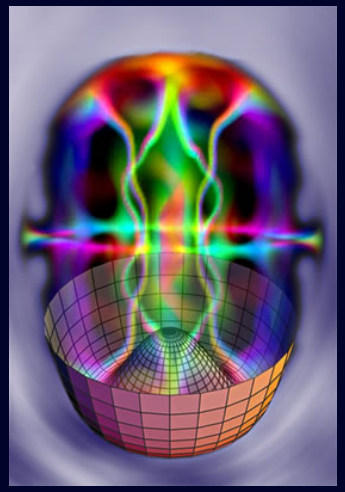
$$g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$$

- **Couplings to SM fermions proportional to their masses**
- **Self-coupling strength determines its mass (and v = 246 GeV)**

- or just a close relative, or an impostor?

It could look SM-like but have some non-Standard properties and still partially do the job

- 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

The goal of the next LHC phase, starting in May 2015,
is to answer these questions and
search for new physics

Why to expect New Physics?

To explain dark matter, baryogenesis, dynamical origin of fermion properties, tiny neutrino masses…

None of the above demands NP at the electroweak scale

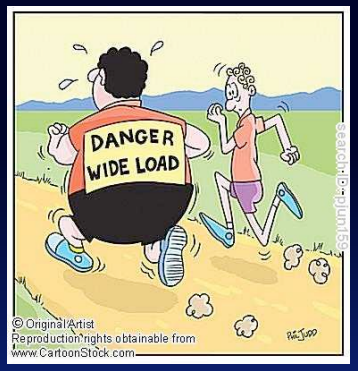
- **The Higgs restores the calculability power of the SM**
- **The Higgs is special : it is a scalar**

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

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

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 the 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

Both options imply changes in the Higgs phenomenology and beyond

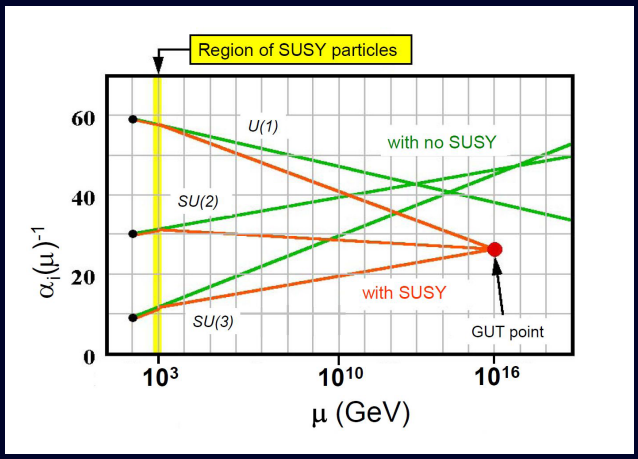
COMPOSITE Cubs Vs SUSY White Sox

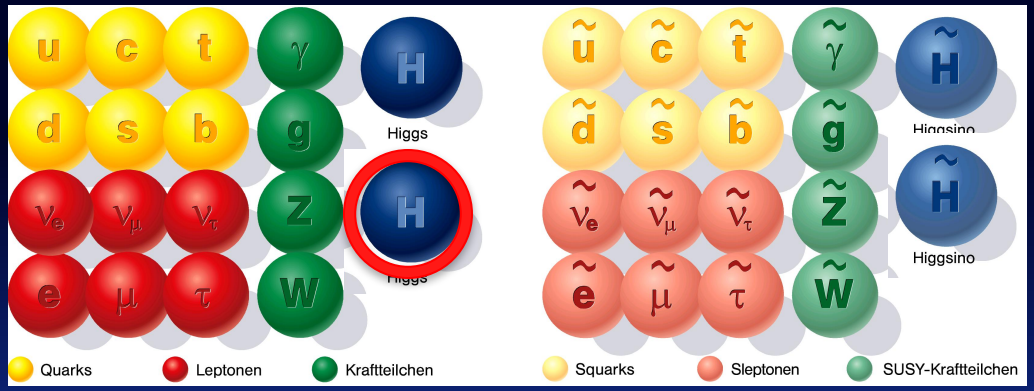
Will the 2015 season restore former glory?

SUSY has many good properties

- **Allows a hierarchy between the electroweak scale and the Planck/unification scales**
- **Generates EWSB automatically from 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

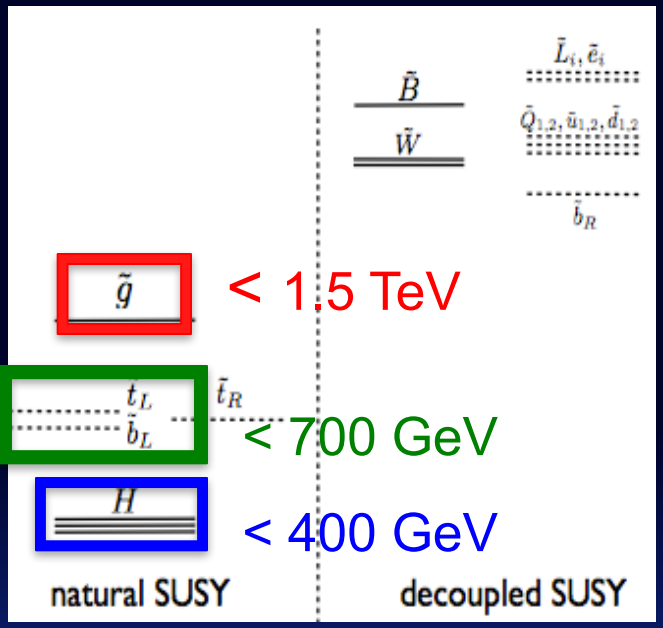
If $M_{SUSY} \ll M_{GUT}$ ⟶ big hierarchy problem solved

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, or LHC8?

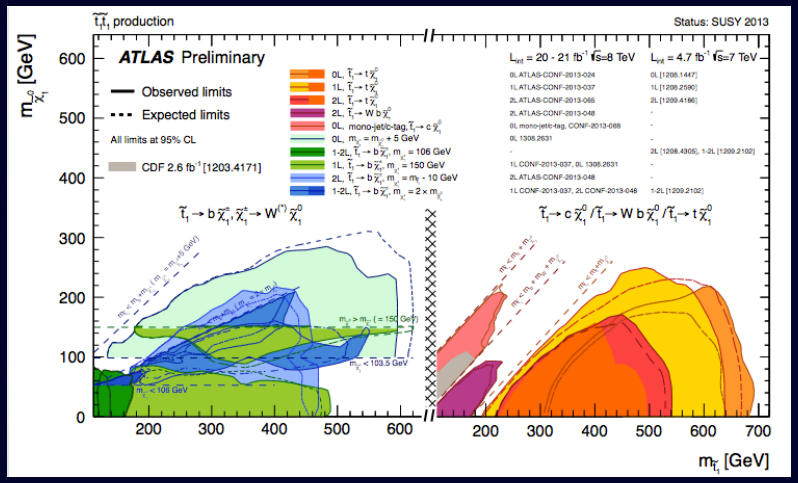


Papucci, Rudermann, Weiler '11

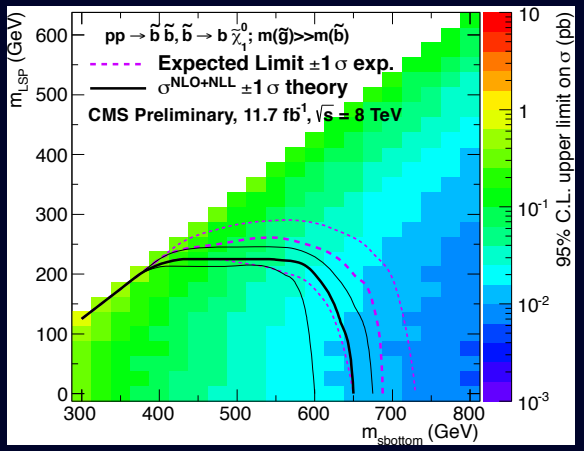
SUSY Weltschmerz*?

ATLAS/CMS are aggressively pursuing the signatures of "naturalness".

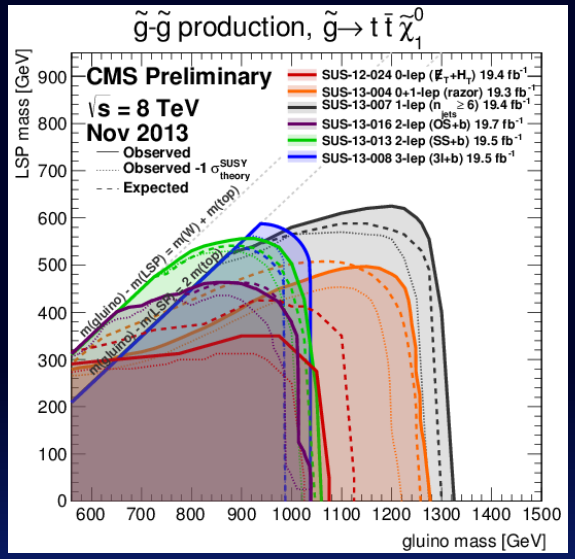
stops



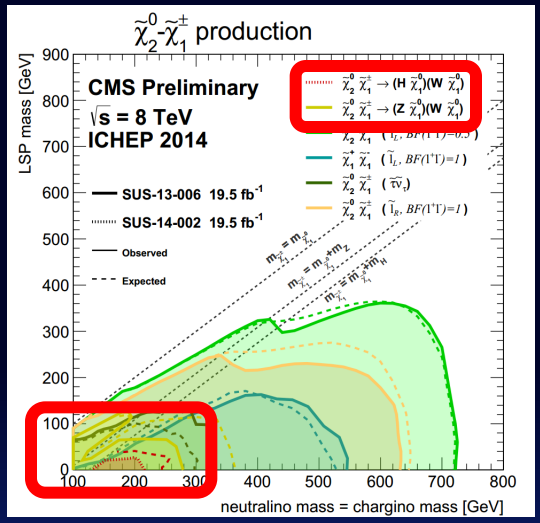
sbottoms



gluinos



Higgsinos



*The feeling experienced by someone who understands that physical reality can never satisfy the demands of the mind

Is SUSY hiding?

It is possible to have SUSY models with super-partners well within LHC8 kinematic reach, but with ***degraded*** missing energy signatures or event activity

- Compressed spectra: e.g. stop mass ~ charm mass + LSP mass

M.C., Freitas, Wagner '08

- Stealth SUSY: long decay chains soften the spectrum of observed particles from SUSY decays
- The LSP is not the dark matter, but decays

ATLAS/CMS closing the gaps

Still many opportunities for non-minimal "Natural" SUSY models, not yet badly threaten by LHC:

- address flavor as part of the SUSY breaking mechanism

connect lightness of 3rd generation sfermions to heaviness of 3rd generation fermions

- alleviate the tension of a Higgs mass that needs sizeable radiative corrections from stop contributions, by raising its tree level value

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

In the Hunt for SUSY

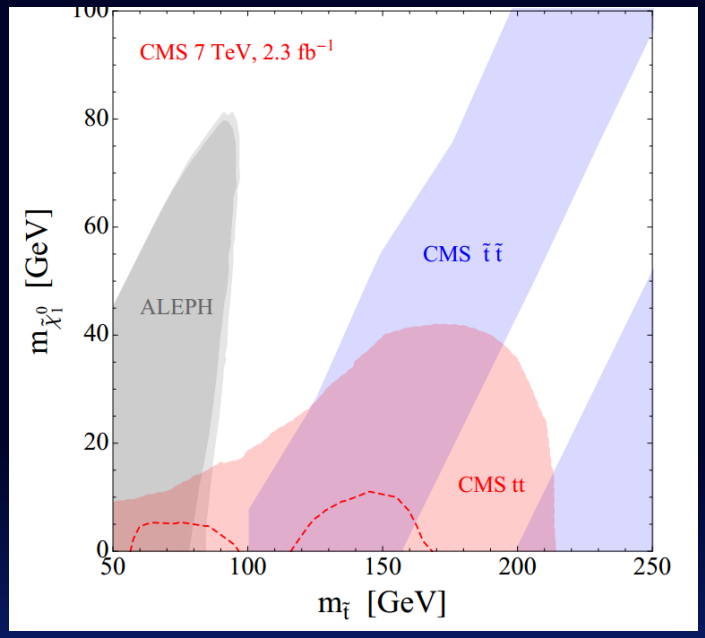
- **ATLAS and CMS are doing a great job**

  Specific SUSY models: MSUGRA/CMSSM,GMSB, AMSB, RPV, mini-split SUSY, …
  and Simplified Models

  prompt decays, long lived/detector-stable particles, displaced vertices, disappearing tracks

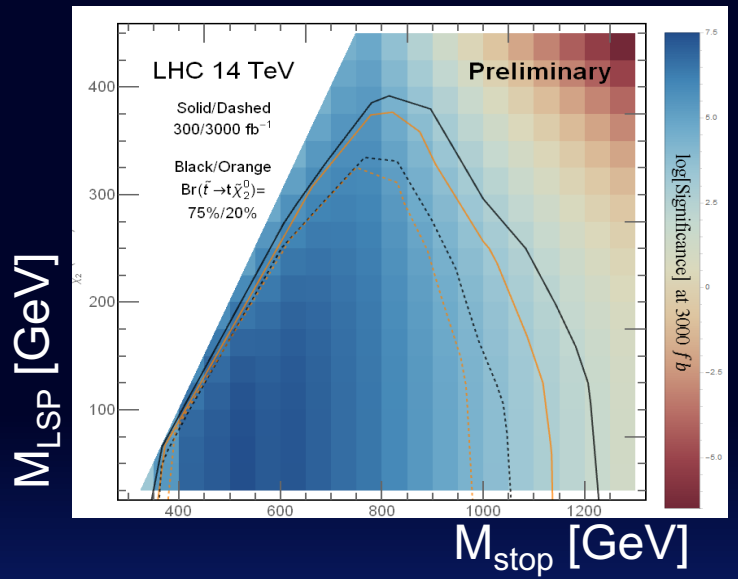
- **Theorists are helping**

  Close gaps in stop searches from limits on stop contamination in SM top pair production



Czakon, Mitov, Papucci, Ruderman, Weiler '14

Recast ttH projections for Stop-Electroweakino searches via Higgs decay channels

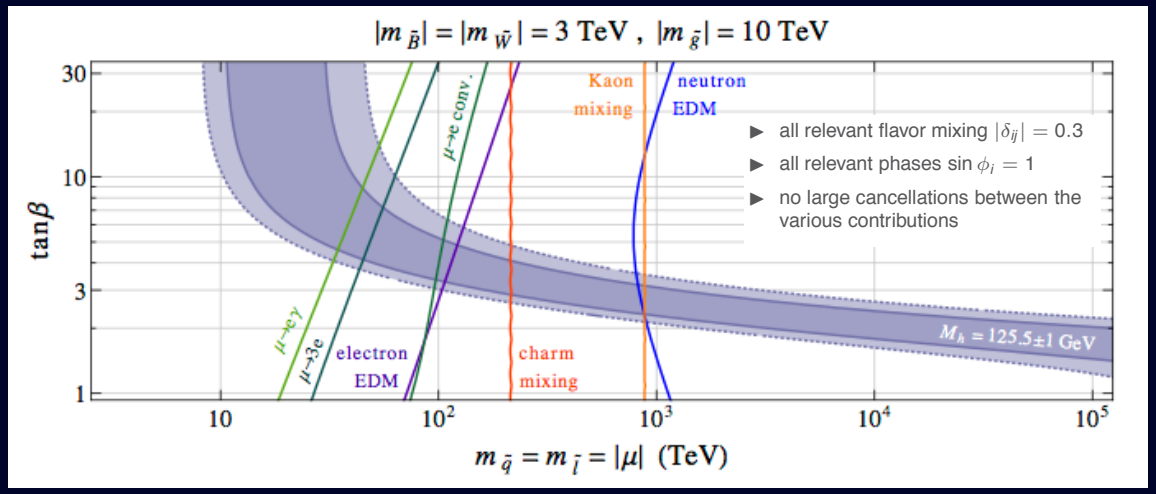


M.C. Zhen Liu, in prep.

SUSY may be at much higher energies?

[Unnatural SUSY]

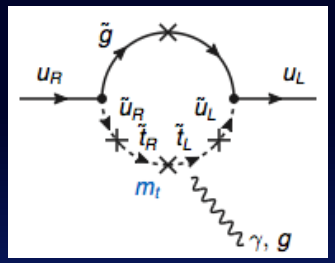
Low energy Probes of Flavor and CP violation with PeV Scale Sfermions



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

SUSY2215

SUSY: THE NEW HOPE

- QUANTUM MECHANICS AND QFT STILL HOLD
- THE ORBITAL COLLIDER STILL SEES NOTHING

THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!

The seasonal trends
Extremely-weeny constrained SUSY
NSFWMSSM
FF3C10ACBA9-MSSM
MSSM retrograde
Anthropic landscaping and trimming it down
The problem of condensed matter: They still don't get it
Strings - The Perpetual Revolution
Number of free parameters: P or NP complete?

Invited seminar
How to ensure your model remains predictability-free

Forum
Is choice moral?
"Every time you choose a path of action, a multiverse is killed"

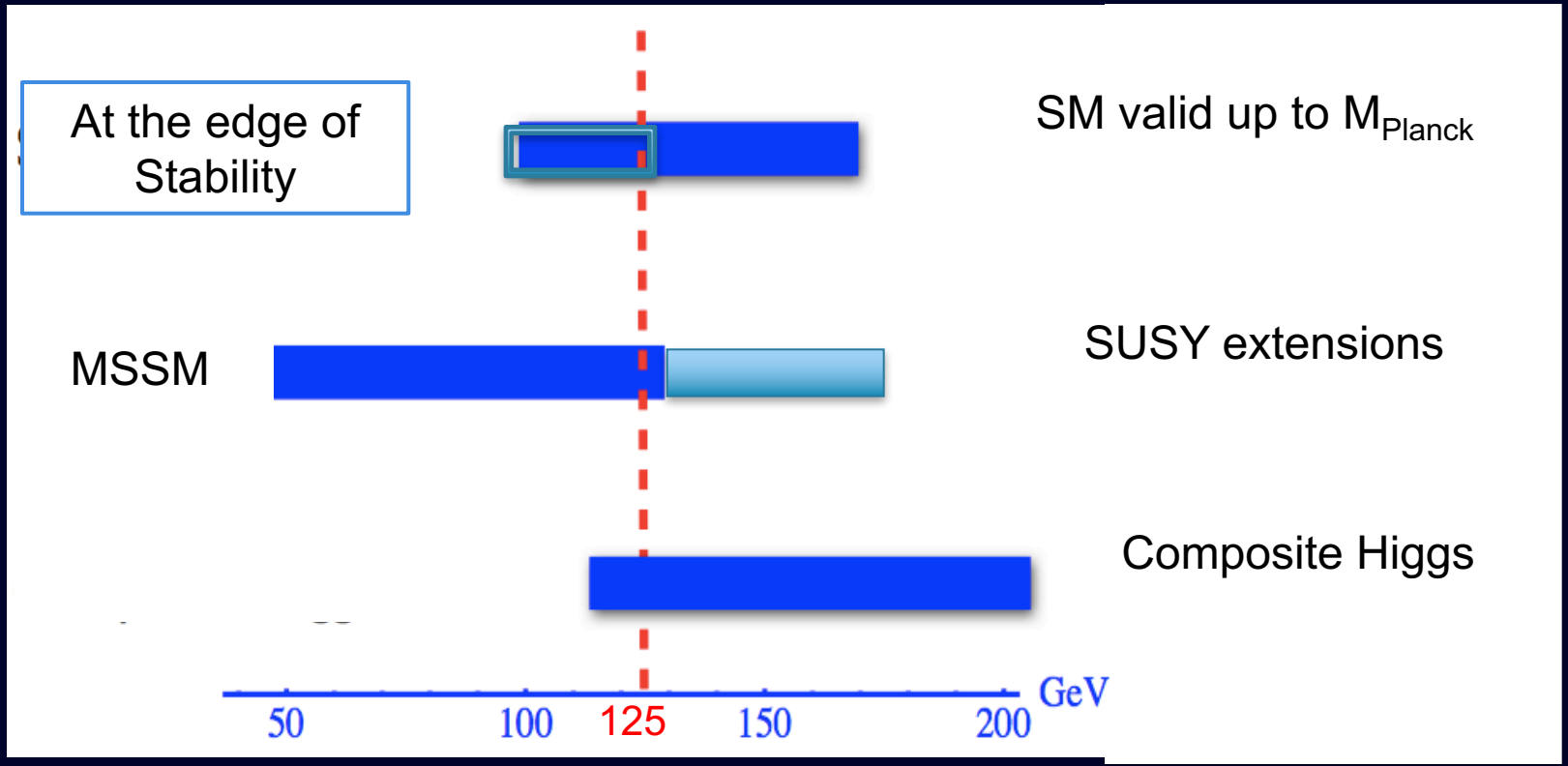
Special topic
If the universe is not supersymmetric is it necessarily existing?

The perpetual conference

5 Jan - 5 Mar: Chamonix
15 Mar - 30 June: Hainan Island
1 July - 15 Sep: Wailea, Maui
15 Sep - 20 Nov: Jumeirah 1
21 Nov - 24 Dec: Hainan Island

Sponsored by:
The Milner-Zuckerberg Institution

What does a 125 GeV Higgs tell us?

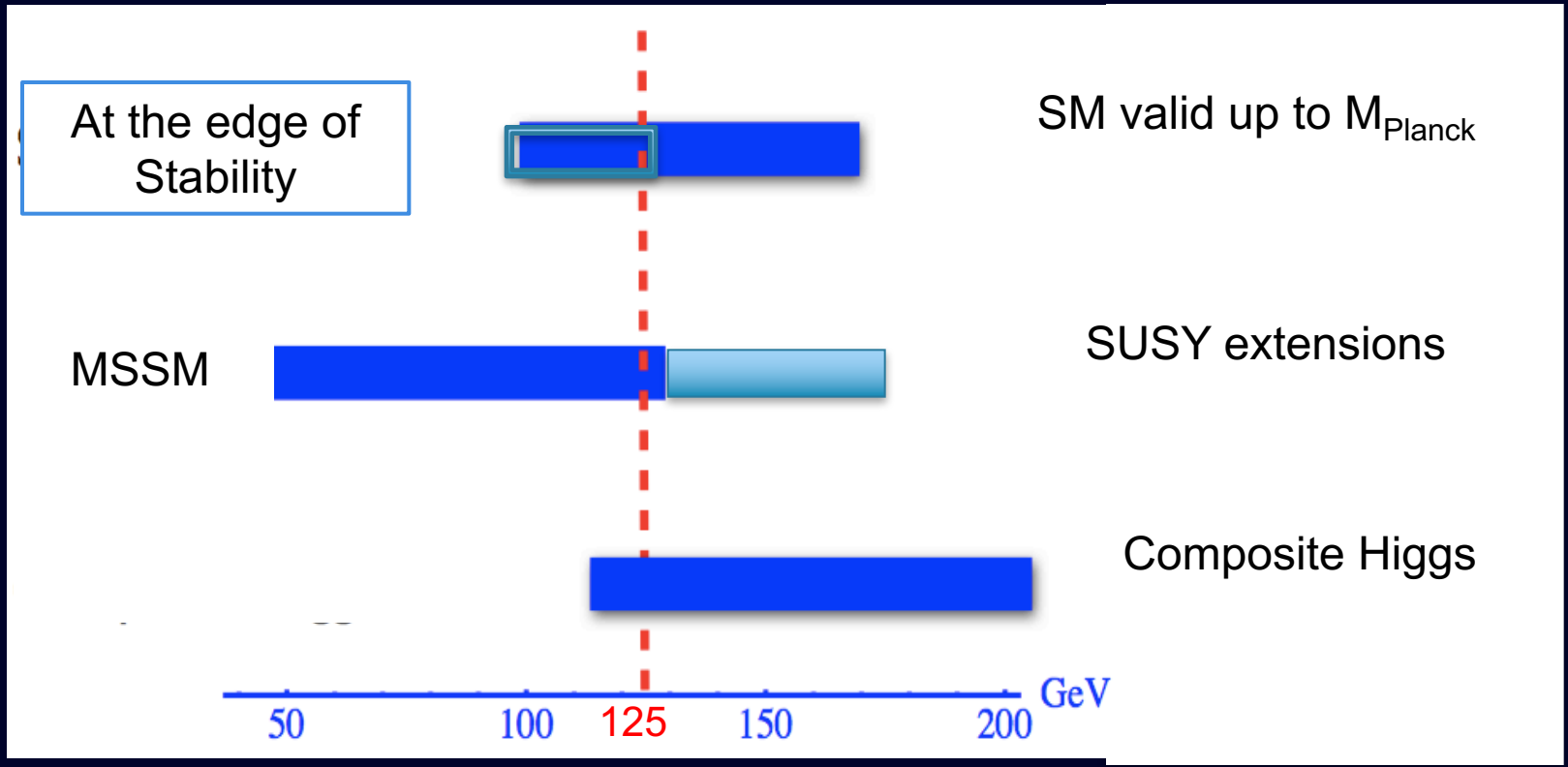


125 GeV is suspiciously light for a composite Higgs boson

but it is suspiciously heavy for minimal SUSY

What does a 125 GeV Higgs tell us?

Theorists must be humble



125 GeV is suspiciously light for a composite Higgs boson

but it is suspiciously heavy for minimal SUSY

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

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

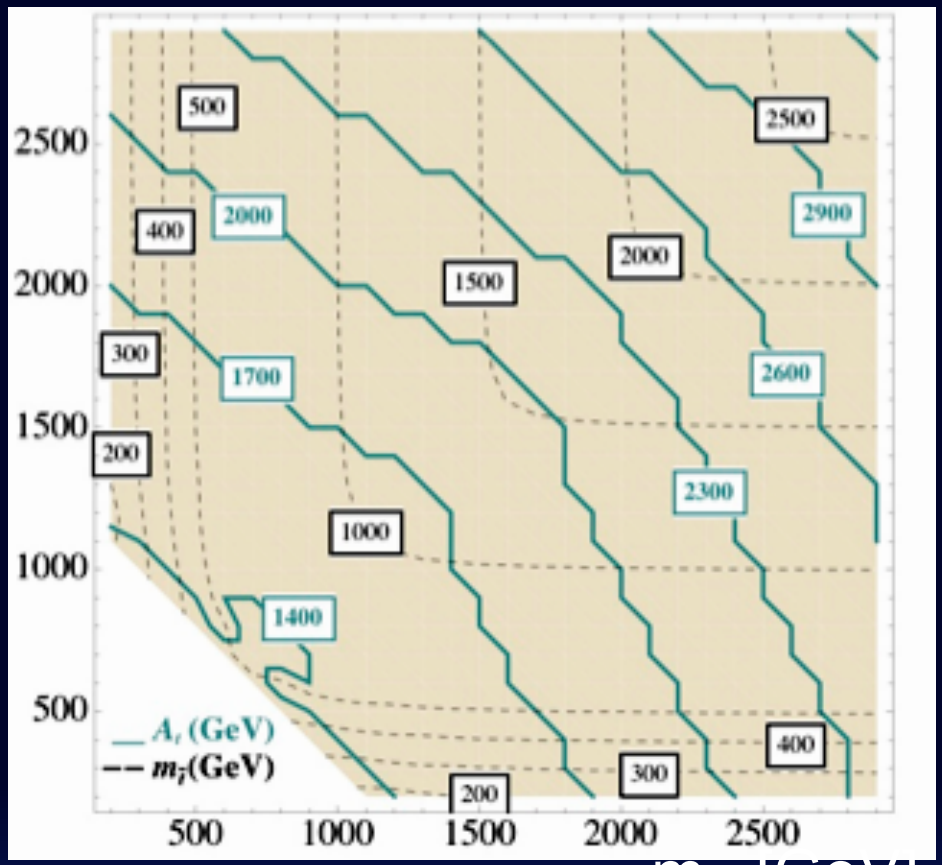
Important radiative corrections with strong dependence on top/stop sector

h may behave like the SM Higgs with m_h ~ 125 GeV

All other 3 Higgs bosons may be heavy (TeV range)
Or as light as a few hundred GeV (Alignment)

The minimal SUSY Higgs mass and the Stop Sector

$m_h \sim 125.5$ GeV



Large Mixing in the stop sector

[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]

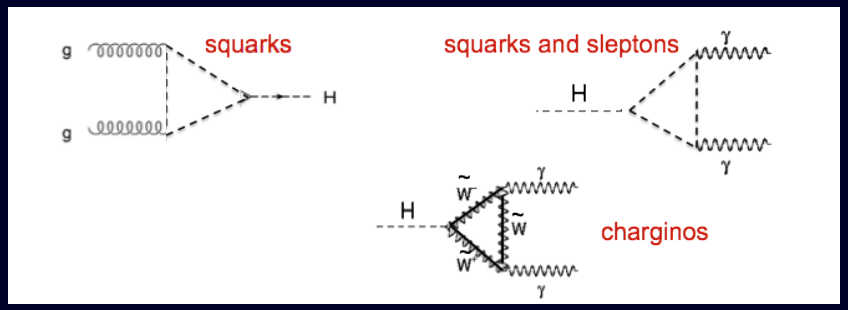
M. C., Gori, Shah, Wagner '12 + Liantao Wang'12

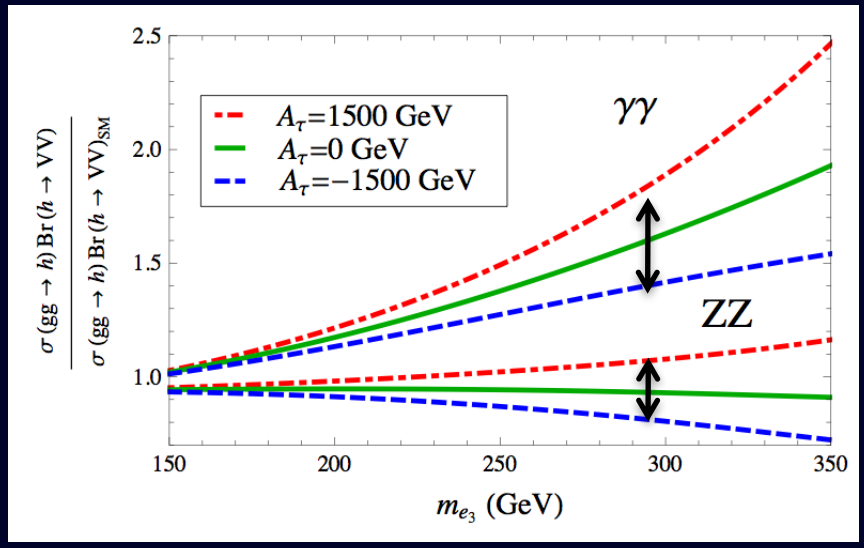
The new era of precision Higgs Physics

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

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

- 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

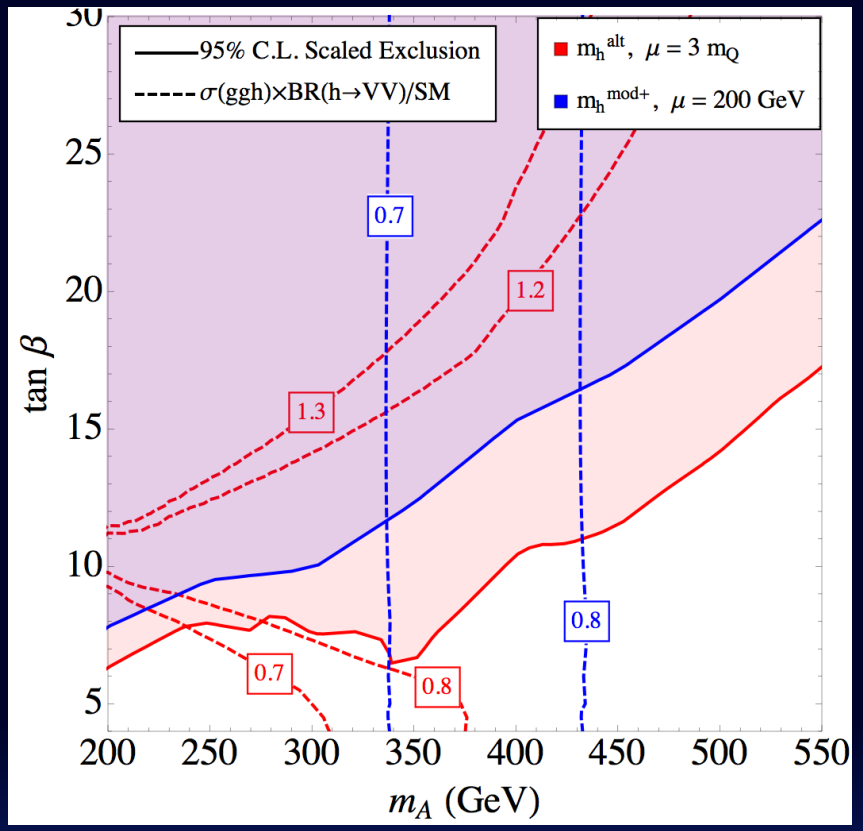
The new era of precision Higgs Physics

Additional Higgs Bosons Searches: A/H → ττ
Vs Precision Higgs Physics: h → WW/ZZ

— σ(bbH/A+ggH/A) × BR(H/A → $\tau\,\tau$) (8 TeV)
--- σ(bbh+ggh) × BR(h → WW)/SM

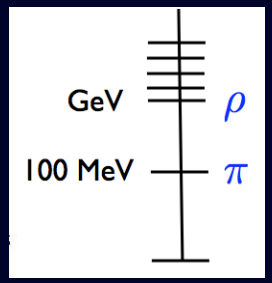
Complementarity crucial to probe SUSY Higgs sector

Correlations between deviations may reveal underlying physics

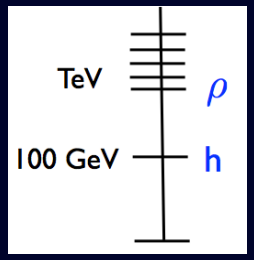


M.C., Haber, Low, Shah, Wagner'14

Composite Higgs Models
The Higgs as a pseudo Nambu-Goldstone Bosons (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

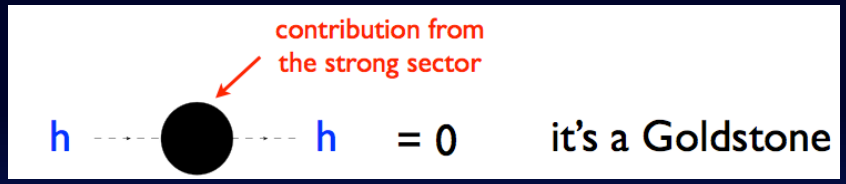
$$g, g' \to 0 \quad \& \quad m_q \to 0 \Rightarrow m_\pi = 0$$

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

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

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

Mass protected by the global symmetries



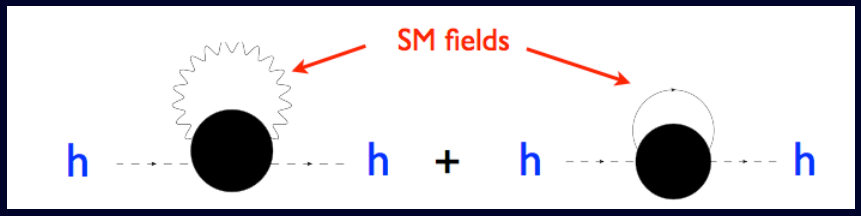
A tantalizing alternative to the strong dynamics realization of EWSB

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

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

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)

Higgs couplings to SM fermions depend on fermion embedding

With Notation $MCHM_{Q\text{-}U\text{-}D}$

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

Representations of SO(5)

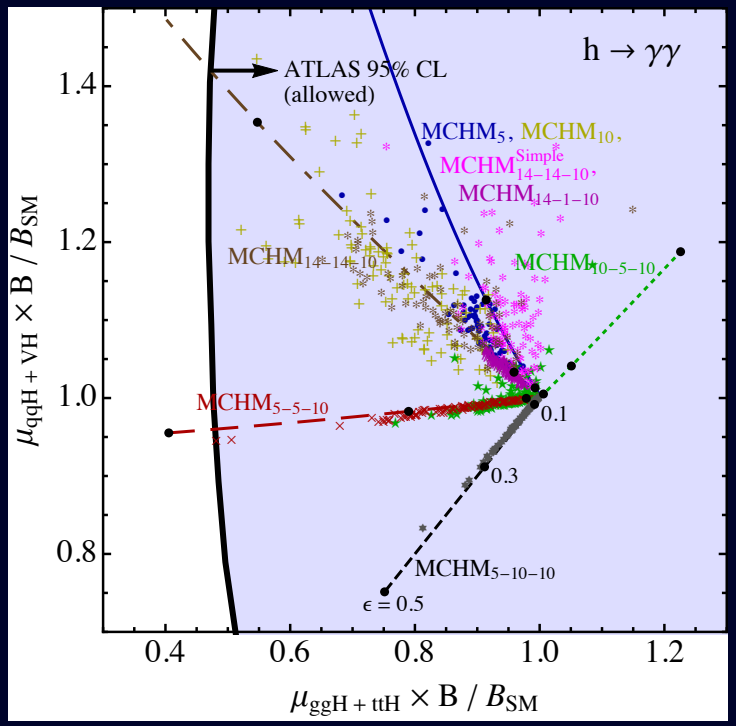
Generic features:

Suppression of all partial decay widths
Suppression of all production modes
Enhancement/Suppression of BR's dep. on the effect of the total width suppression

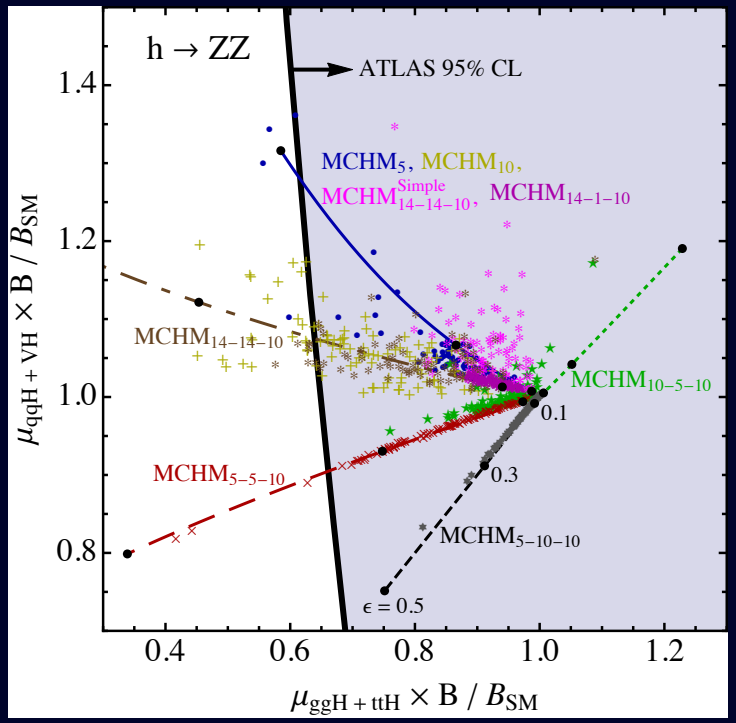
Driven by the idea that heavy SM fermions are a mixture of elementary and composite states

Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ



M.C., Da Rold, Ponton'14

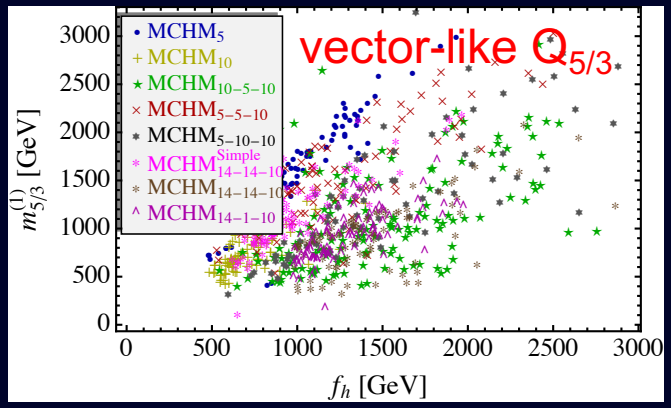
After EWSB: $\varepsilon = v_{SM}/f$ and precision data demands $f > 500$ GeV

More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

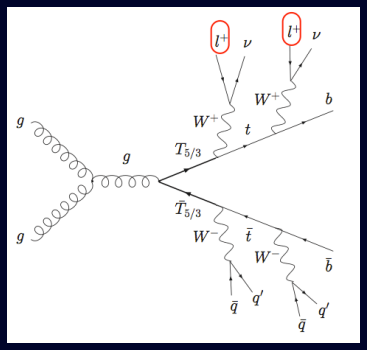
Composite pNGB Higgs Models predict light Fermions

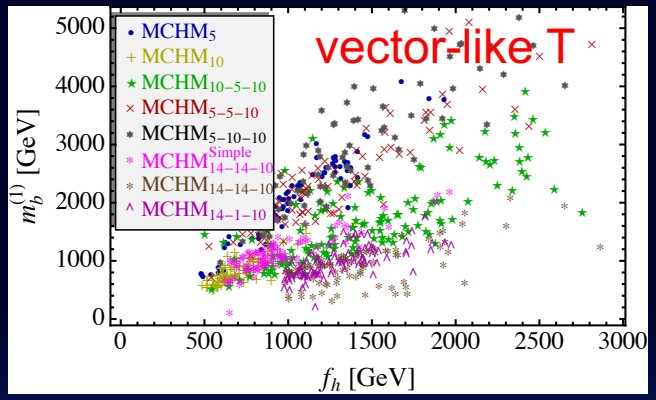
Pair production, single production, or exotic Higgs production of vector-like fermions

[masses in the TeV range and possibly with exotic charges: Q = 2/3,−1/3, 5/3,8/3,−4/3]



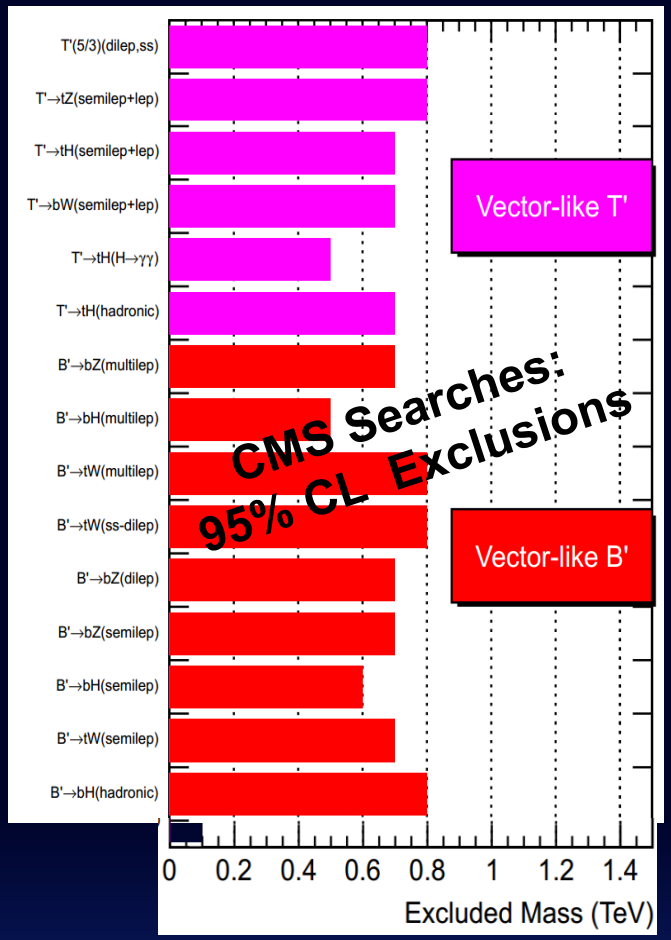
SS di-leptons



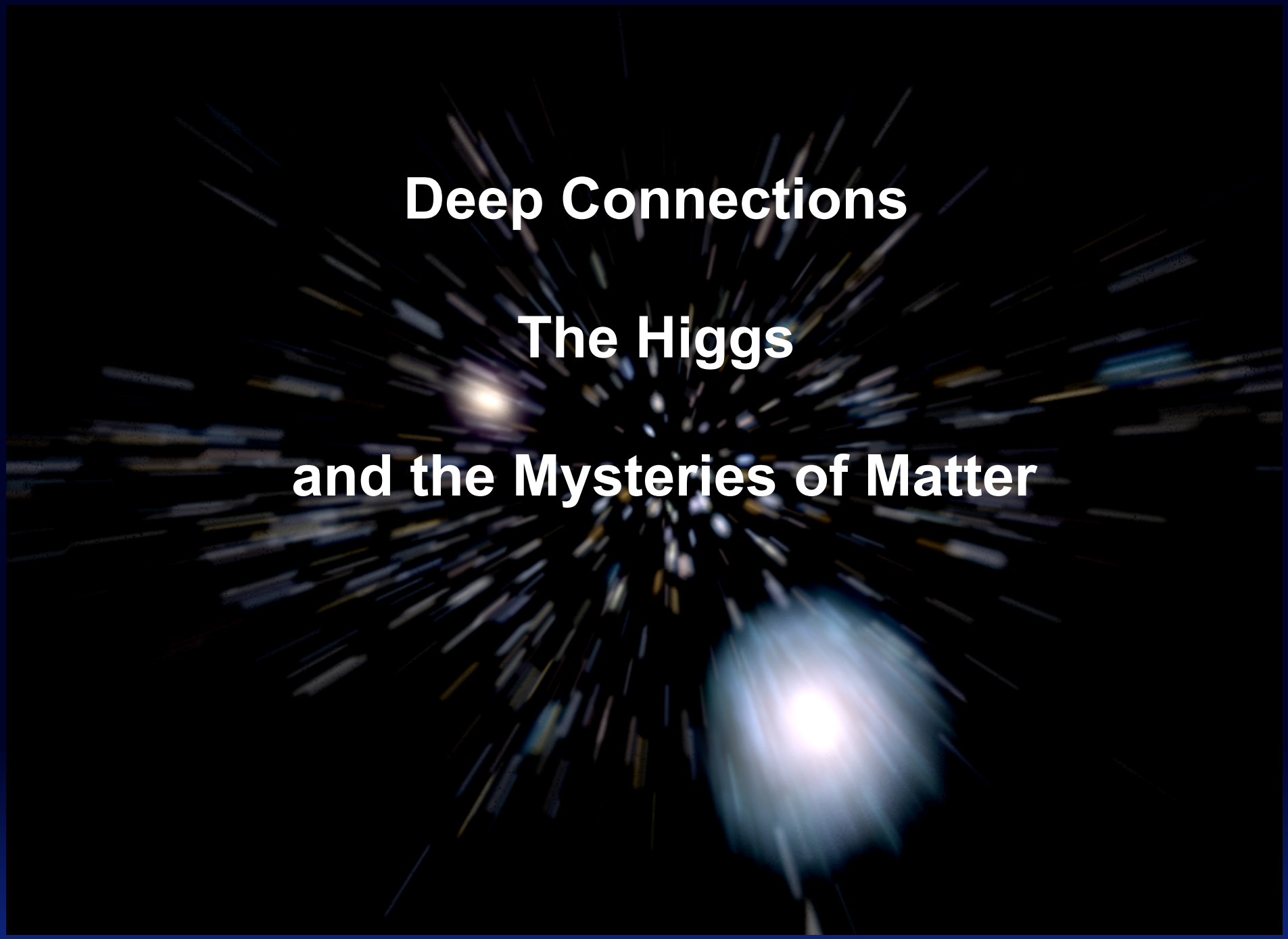


M.C., Da Rold, Ponton'14

Large variety of signatures, many with energetic leptons



LHC exclusion for $M_f < 800$ GeV]


Deep Connections
The Higgs
and the Mysteries of Matter

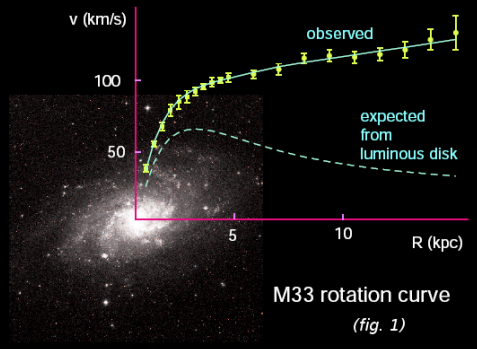
The power of the dark side

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

Interacts very weakly
(not charged)

→ **Gravity**

→ **Higgs-like Interactions ?**



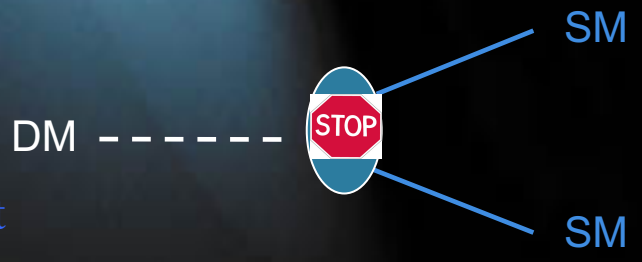
WIMP Dark Matter ?

- DM = yet unknown, heavy, neutral elementary particle/s
- Mass estimate (model dependent) from observed dark matter abundance:

$$M_{DM} \sim 100 - 1000 \text{ GeV}$$

and 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



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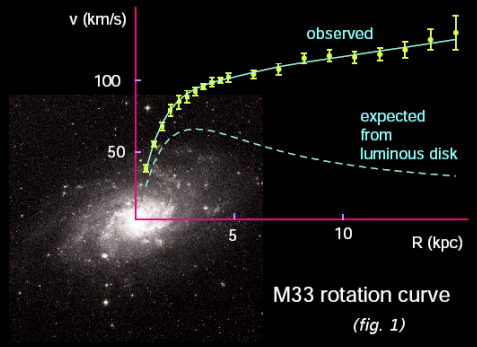


M33 rotation curve
(fig. 1)

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"

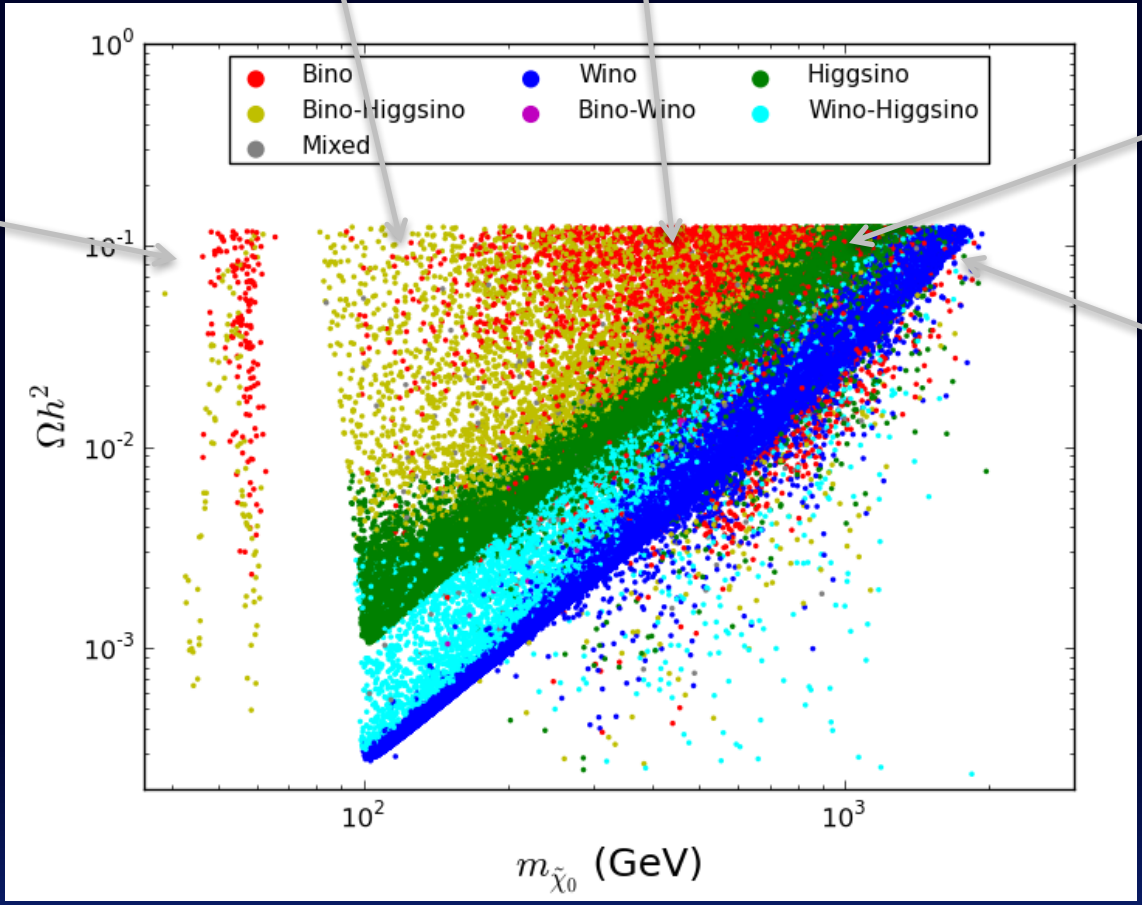
Bino-Higgsino mixture, closest case to the WIMP Miracle

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

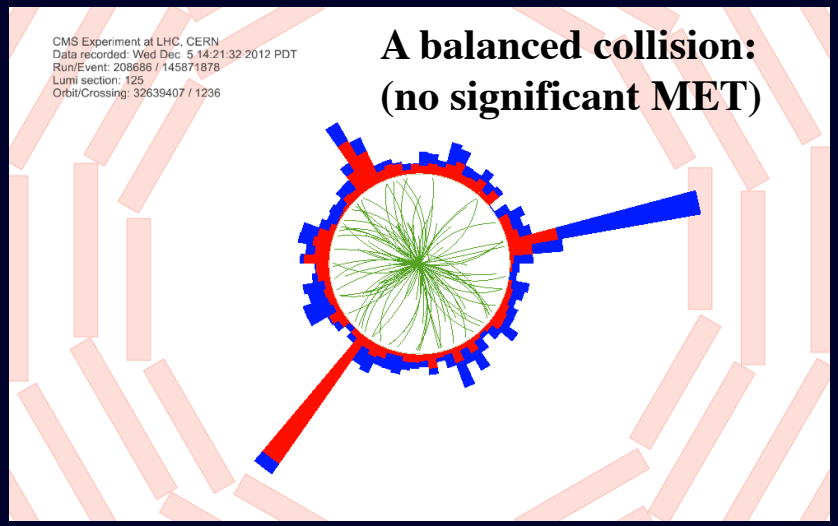
Bino-like that can annihilate through the h or Z "funnels"

Higgsino, ~ 1.5 TeV

Wino, ~ 3 TeV

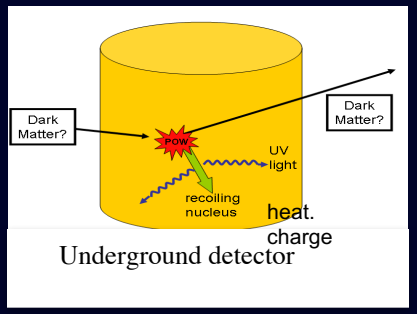


We can create Dark Matter at the LHC



Counting the energy we put in and the energy that comes out
if a lot is missing we created Dark Matter

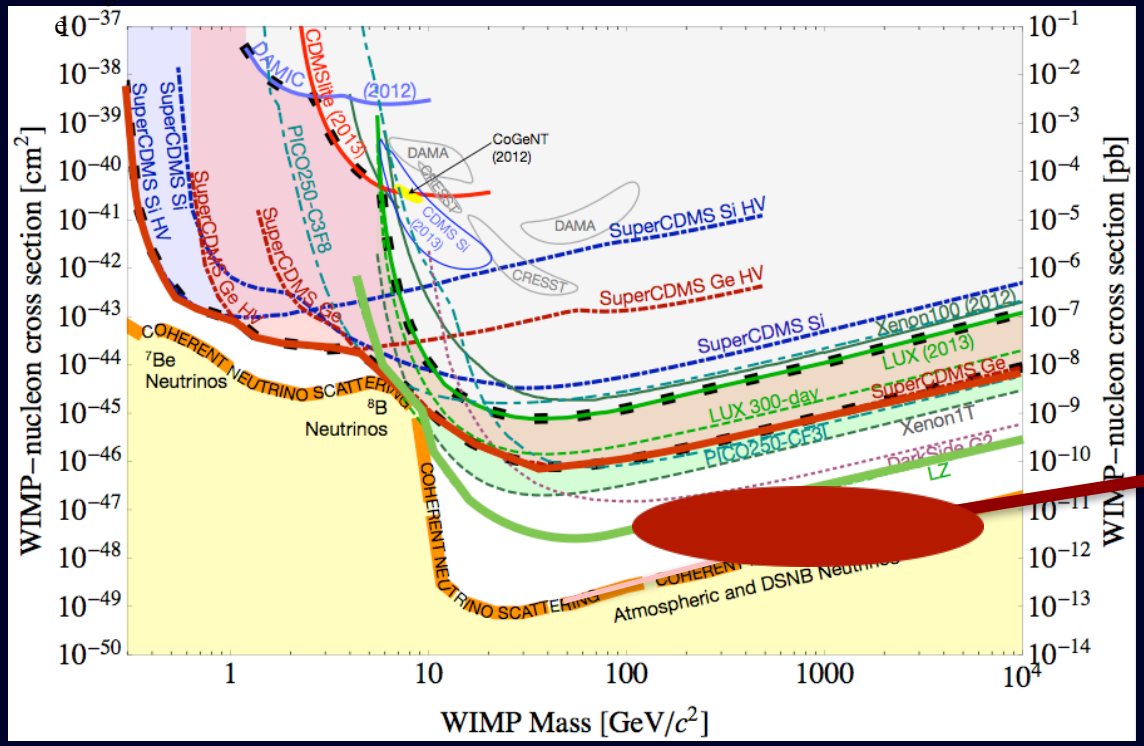
We can also produce dark matter in the decay of other new particles charged under the dark sector,
e.g. in the decays of stops, sbottoms and gluinos

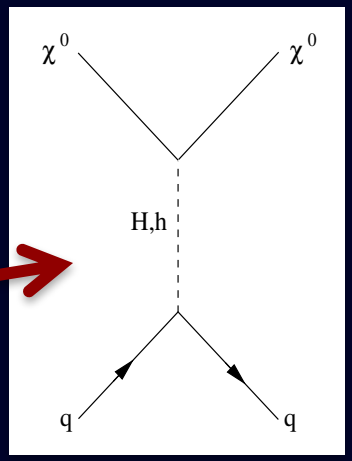


Dark Matter Direct Detection:

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

Starting to Probe the Higgs Portal





- 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

We are testing the outrageous idea

of Dark Matter using

accelerators, telescopes and specialized detectors!

A priority for Particle Physics and Cosmology

- Still room for a WIMP miracle

but many other ideas flourishing

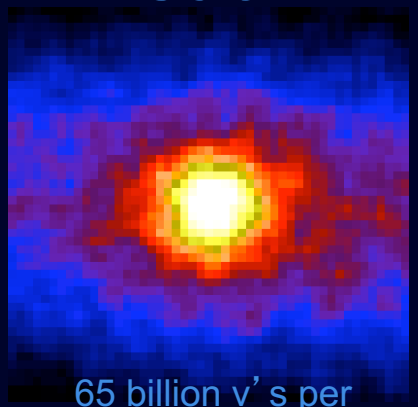
- Astrophysical observations of structure may shed info on DM nature
  even if DM only interacts gravitationally with visible matter

The Omnipresent Neutrinos

Key actors in important physical processes on Earth and out in the Universe

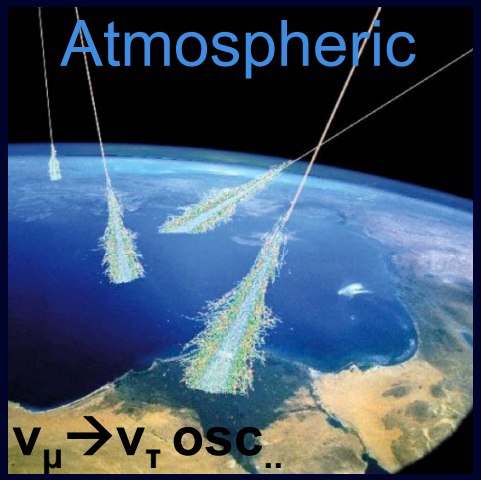
Neutrinos from many sources

Solar



65 billion ν's per cm^2 of Earth surface facing the Sun

Atmospheric

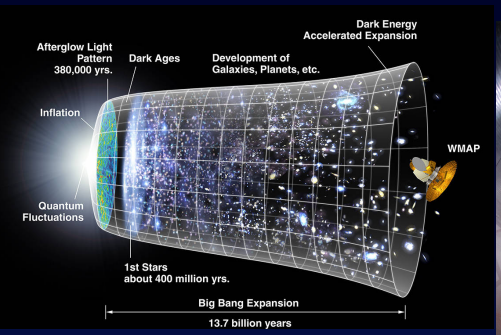


Supernovae

99% of the energy of a supernova explosion is carried off by neutrinos

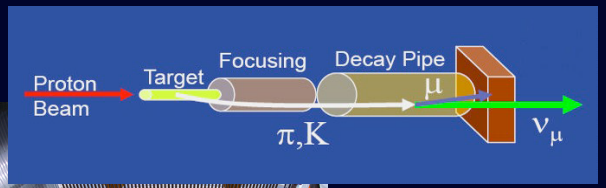
Geo

Relic



10 million ν's left over per cubic foot of space

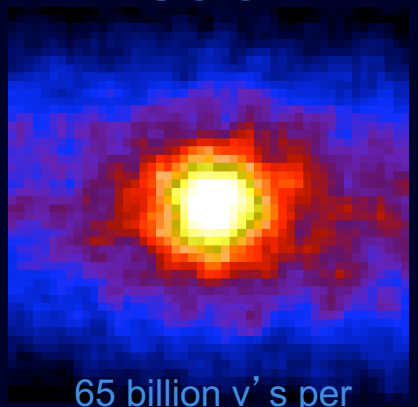
Accelerators



Reactors

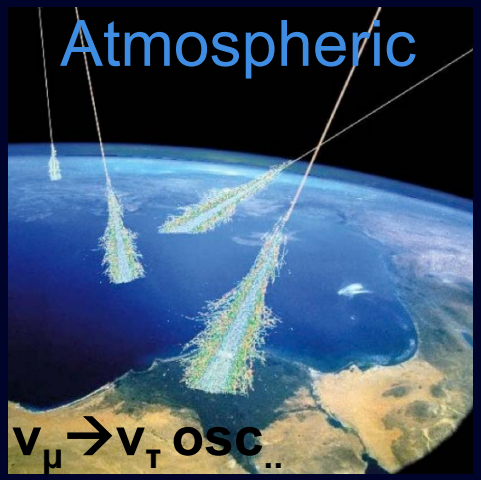
Neutrinos from many sources

Solar



65 billion ν's per cm^2 of Earth surface facing the Sun

Atmospheric



Supernovae

99% of the energy of a supernova explosion is carried off by neutrinos

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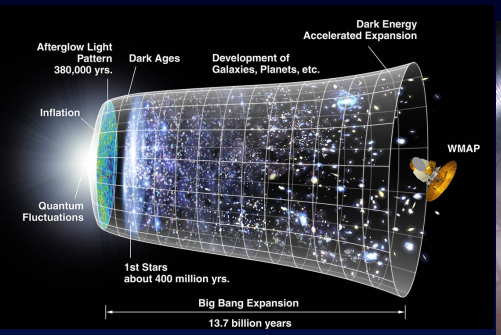
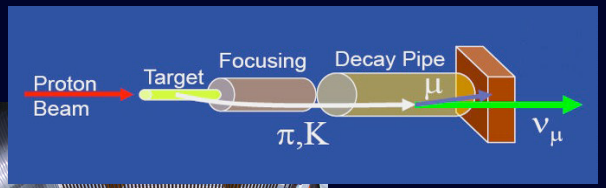


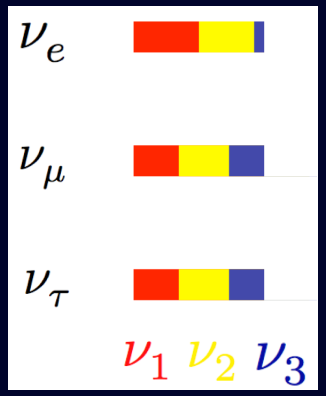
10 million ν's left over per cubic foot of space

Accelarators



Reactors

Neutrinos Oscillate



Neutrino oscillations are like many other systems in QM, in which the initial state is a coherent superposition of eigenstates of a Hamiltonian

Neutrinos have mass ➔ the different massive components of the initial flavor state need to propagate with different phases

Neutrinos mix , otherwise, the flavor eigenstates would also be eigenstates of the Hamiltonian and not evolve.

What we know :

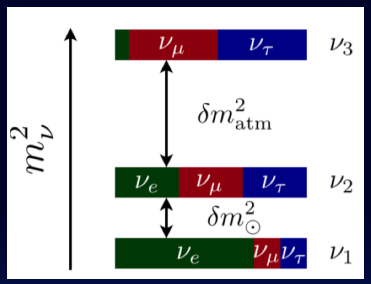
2 squared mass differences

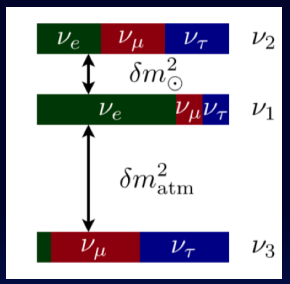
$\Delta^2_{sol} \sim 7.5 \times 10^{-5}\ eV^2$ $\Delta^2_{atm} \sim 2.4 \times 10^{-3}\ eV^2$

3 mixing angles (much larger than in the quark sector)

What we don't know :

The ordering ➔





How much above zero is the whole pattern ?

Are there new sources of CP violation? Do Neutrinos violate Lepton Number ?

Neutrino Future

- A very large number of experiments in particle physics will cornered the neutrinos unknowns in the coming years

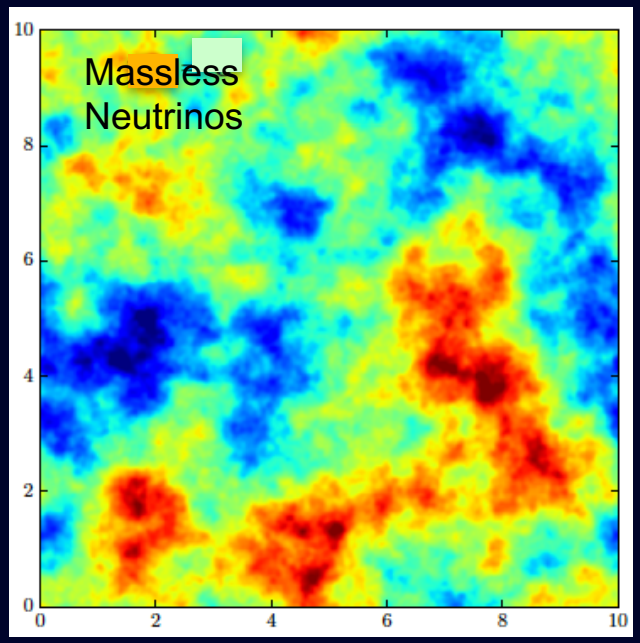
  this will demand: strong use of powerful controlled beams of neutrinos and large, rmore sensitive neutrino detectors

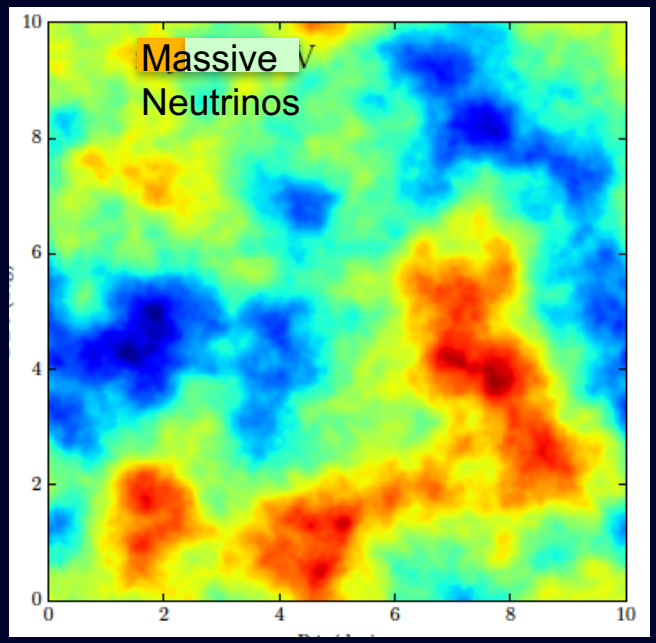
- Information on neutrino masses will also come from cosmology

Simulated maps of distortions produced by CMB gravitational lensing

Massive neutrinos produce a universe with shallower gravitational potential wells

Manzotti, Dodelson'14



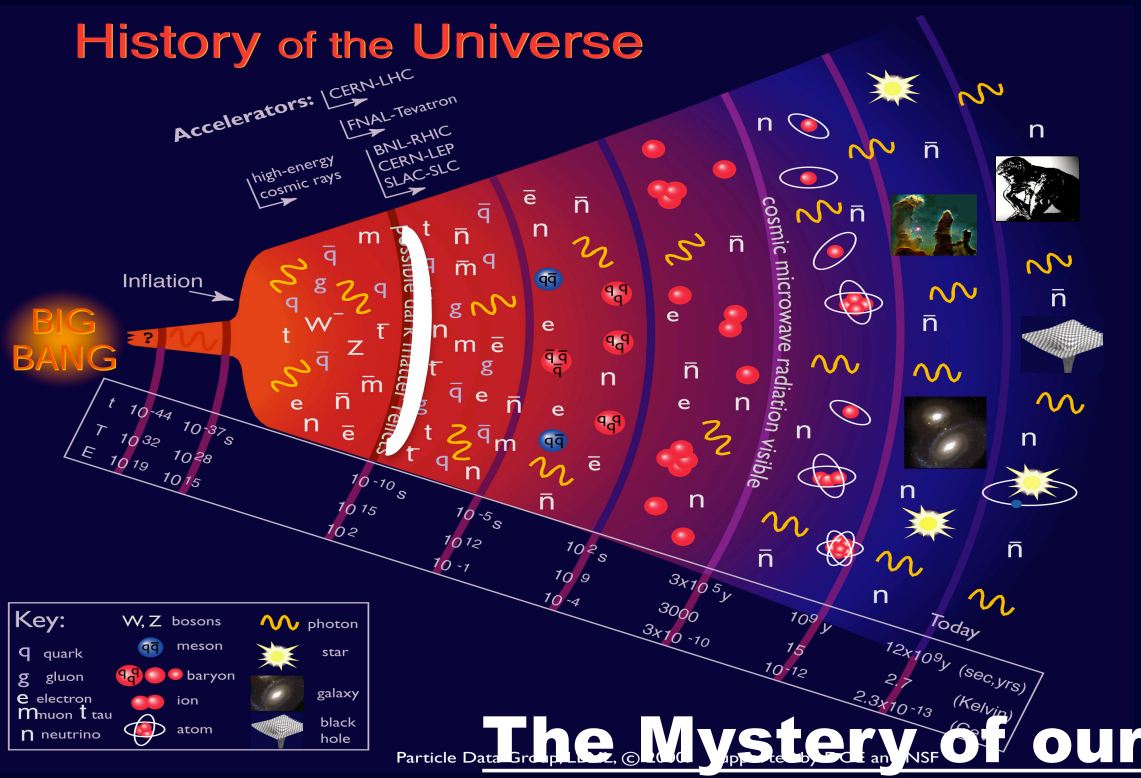


Relic neutrinos contribute to the total matter density of the universe and have an impact on structure on small scales.

Standard Cosmological Model sets stringent limits on Neutrino masses $\Sigma m_i < 0.3$- 1.3 eV

Deep Neutrino Connections

- How are tiny neutrino masses related to the origin of particle masses in general?
- How does the Higgs boson talk to neutrinos?
- Are neutrinos responsible for the dominance of matter over antimatter “leptogenesis”?
- Are neutrinos related to the unification of all matter and forces?
- How are neutrinos related to dark matter?
- Extra credit: are neutrinos related to dark energy?



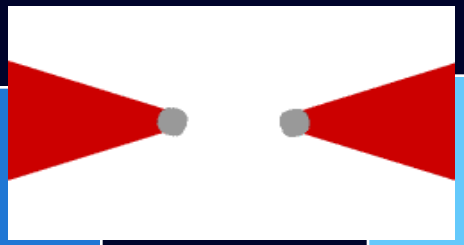
At the BIG BANG :

Equal amounts of Matter and Anti-matter

The Mystery of our Existence

There was a big matter-antimatter battle…

A tiny amount of matter survived …



Matter	Antimatter
10,000,000,001	10,000,000,000

Baryogenesis

What generated the small imbalance between matter and antimatter?
How did it happen? When?

Sakharov's 3 principles for an asymmetry to develop:

- **Out of Equilibrium processes**
- **Violation of CP Symmetry that relates matter with antimatter**
- **Baryon (or Lepton) number violation**

Electroweak Baryogenesis

- Start with B=L= 0 above the EW scale
- CP phases generate chiral baryonic asymmetry in the symmetric phase
- Sphalerons create net Baryon number that diffuse in the broken phase

In the SM the Higgs is too heavy and the CP violation is too small

Leptogenesis

The decays of heavy out of equilibrium neutrinos produce an asymmetry in the light leptons

Sphalerons transform lepton into baryon number, while in equilibrium up to the EW scale

[B & L violated but B-L conserved]

Falsibiable Electroweak Baryogenesis at colliders

- **Baryogenesis at the Electroweak Scale can explain our existence and can be tested at the LHC or beyond**
- **New particles that couple strongly to the Higgs can make this work**
- **It requires going beyond Minimal SUSY with additional CP violation sources or extending the SM with additional scalars**
- **CP violation may be observed at LHC and or other experiments e.g. Electric Dipole Moment**

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

Higgs Mechanism  **LHC**

What's Next?

The existence of Dark Matter and the Matter-Antimatter Imbalance implies new physics which may be accessible to experiment in this decade

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