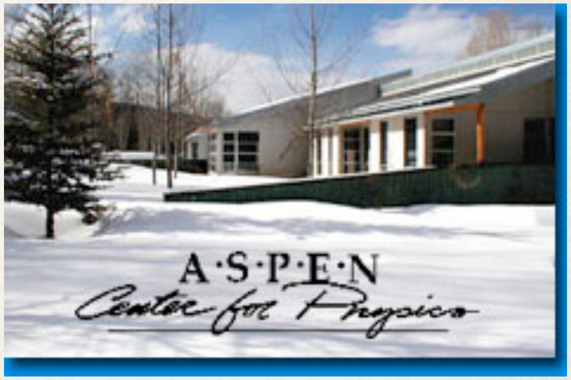
Theory Overview

Joseph Lykken

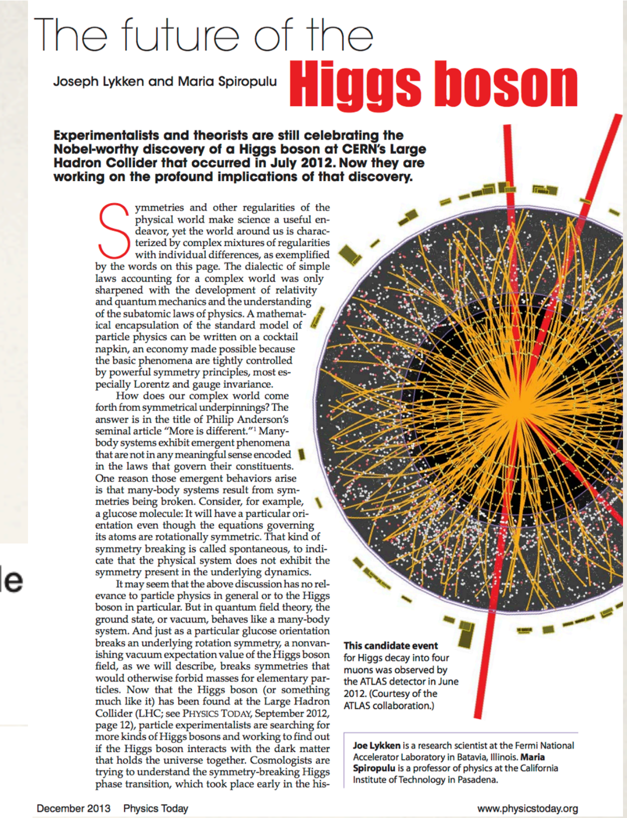
Fermilab



Higgs discovery!

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

Big Ideas: a little history



The future of the **Higgs boson**

Joseph Lykken and Maria Spiropulu

Experimentalists and theorists are still celebrating the Nobel-worthy discovery of a Higgs boson at CERN's Large Hadron Collider that occurred in July 2012. Now they are working on the profound implications of that discovery.

Symmetries and other regularities of the physical world make science a useful endeavor, yet the world around us is characterized by complex mixtures of regularities with individual differences, as exemplified by the words on this page. The dialectic of simple laws accounting for a complex world was only sharpened with the development of relativity and quantum mechanics and the understanding of the subatomic laws of physics. A mathematical encapsulation of the standard model of particle physics can be written on a cocktail napkin, an economy made possible because the basic phenomena are tightly controlled by powerful symmetry principles, most especially Lorentz and gauge invariance.

How does our complex world come forth from symmetrical underpinnings? The answer is in the title of Philip Anderson's seminal article "More is different."[1] Many-body systems exhibit emergent phenomena that are not in any meaningful sense encoded in the laws that govern their constituents. One reason those emergent behaviors arise is that many-body systems result from symmetries being broken. Consider, for example, a glucose molecule: It will have a particular orientation even though the equations governing its atoms are rotationally symmetric. That kind of symmetry breaking is called spontaneous, to indicate that the physical system does not exhibit the symmetry present in the underlying dynamics.

It may seem that the above discussion has no relevance to particle physics in general or to the Higgs boson in particular. But in quantum field theory, the ground state, or vacuum, behaves like a many-body system. And just as a particular glucose orientation breaks an underlying rotation symmetry, a nonvanishing vacuum expectation value of the Higgs boson field, as we will describe, breaks symmetries that would otherwise forbid masses for elementary particles. Now that the Higgs boson (or something much like it) has been found at the Large Hadron Collider (LHC; see PHYSICS TODAY, September 2012, page 12), particle experimentalists are searching for more kinds of Higgs bosons and working to find out if the Higgs boson interacts with the dark matter that holds the universe together. Cosmologists are trying to understand the symmetry-breaking Higgs phase transition, which took place early in the his-

This candidate event for Higgs decay into four muons was observed by the ATLAS detector in June 2012. (Courtesy of the ATLAS collaboration.)

Joe Lykken is a research scientist at the Fermi National Accelerator Laboratory in Batavia, Illinois. **Maria Spiropulu** is a professor of physics at the California Institute of Technology in Pasadena.

December 2013 Physics Today www.physicstoday.org

Nambu (1960)
the importance of Spontaneous Symmetry Breaking

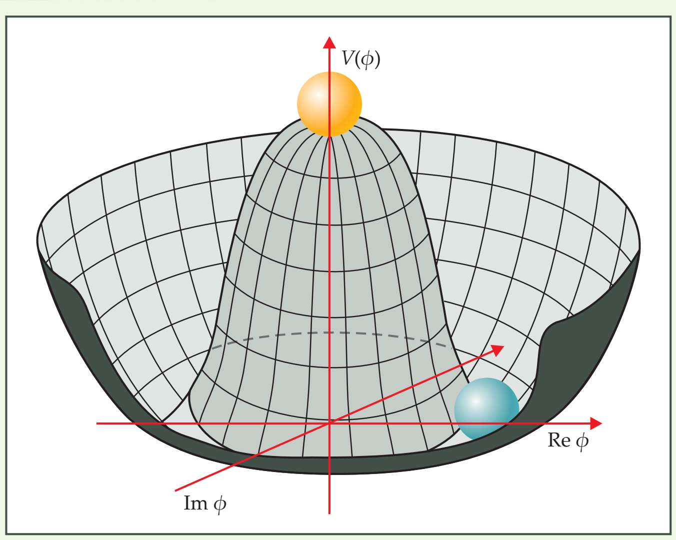
Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

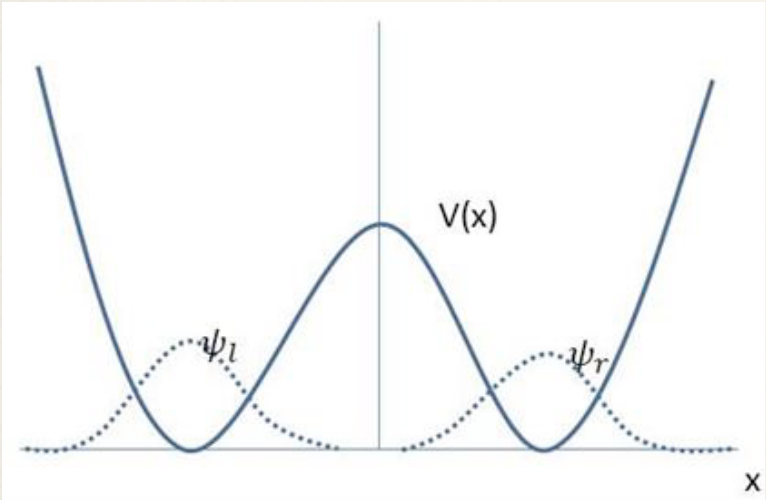
Yoichiro Nambu

Physical system	Broken symmetry
Ferromagnets	Rotational invariance (with respect to spin)
Crystals	Translational and rotational invariance (modulo discrete values)
Superconductors	Local gauge invariance (particle number)

- Apply condensed matter ideas to **particle physics**
- **Now the quantum vacuum is the "medium"**

Goldstone's Mexican Hat (1961)





- At this point it is usually claimed that spontaneous symmetry breaking is obvious, but this is not so
- For example in the double well quantum mechanics problem, there is a degeneracy associated with a Z_2 symmetry
- But the ground state is a superposition that preserves the symmetry!

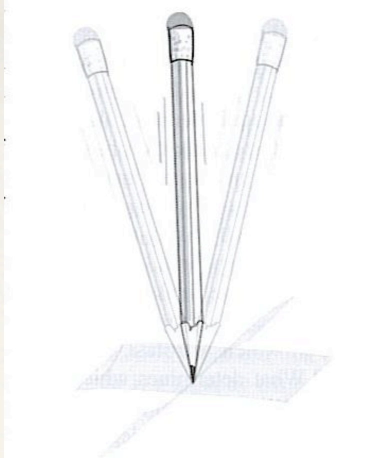
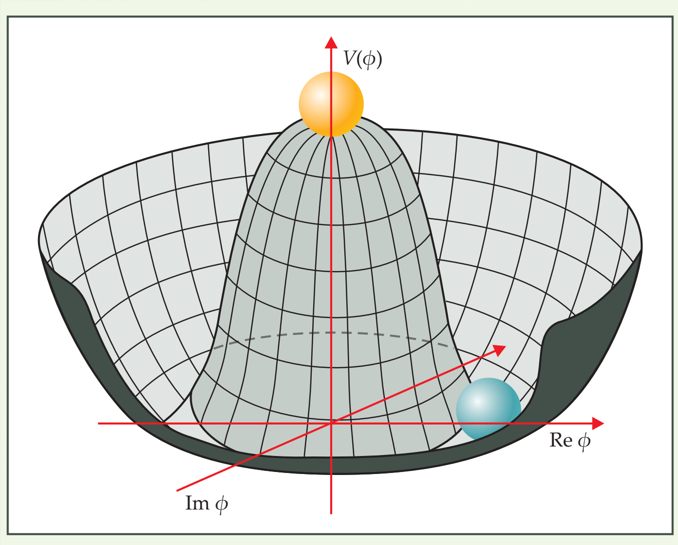
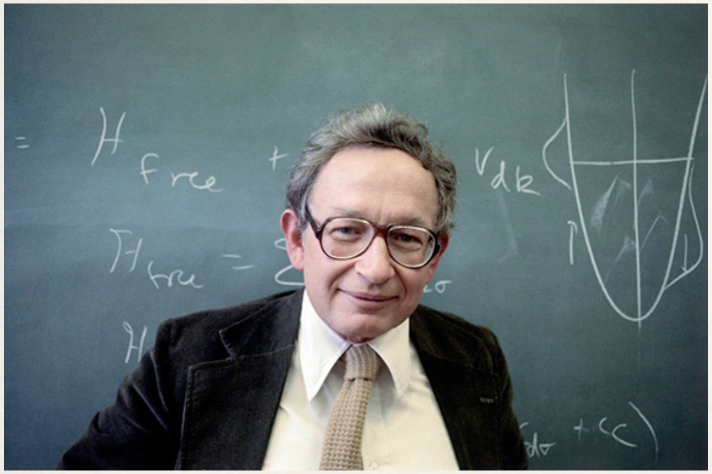


Figure 20. Pencil on its lead tip. The system (including gravity) has rotational symmetry about the vertical axis when the pencil is balanced on its tip, but this configuration is unstable. The pencil falls in a random direction, spontaneously breaking the symmetry. (Illustration by Shea Ferrell.)

More is Different





- The key difference is that in quantum field theory it is much more difficult to transition from one one degenerate ground state to another
- The quantum vacuum is like a many-body system in this sense
- As Phillip Anderson emphasized in his 1972 article “More is Different”, spontaneous symmetry breaking is a property of “large” systems

Who invented the BEH mechanism?

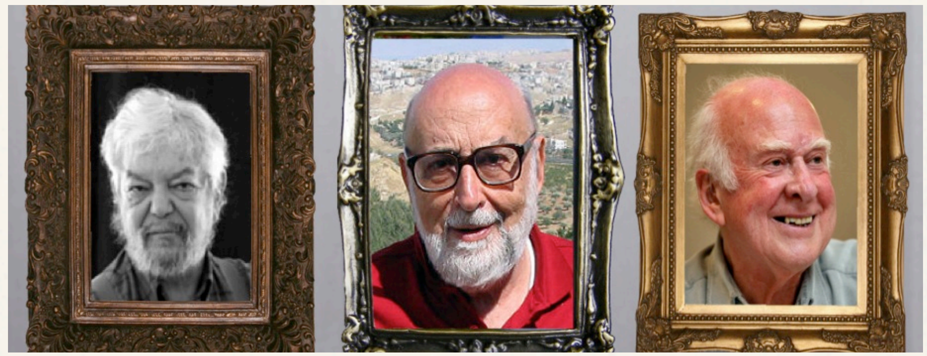
Figure 1. Yoichiro Nambu, Jeffrey Goldstone, and Philip Anderson penned important early chapters in the story of the Higgs boson. Beginning in 1960, particle physicists Nambu **(left)** and Goldstone **(center)** adapted ideas from condensed-matter physics to explore the relationship of symmetry breaking to the generation of massive particles. Two years later, condensed-matter physicist Anderson **(right)** argued that two types of troubling massless particles—Goldstone bosons and gauge bosons—could together yield a massive particle. (Nambu photo courtesy of the AIP Emilio Segrè Visual Archives, Marshak Collection. Goldstone and Anderson photos courtesy of the AIP Emilio Segrè Visual Archives, PHYSICS TODAY Collection.)

"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**

"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**

Higgs + BEGHK (1964)

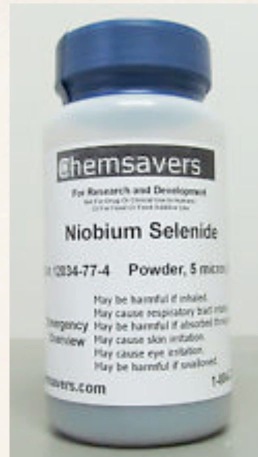
- a fundamental scalar field with self-interactions
- can cause spontaneous (global) symmetry-breaking in the vacuum
- and give gauge bosons mass
- while respecting the delicate choreography of gauge symmetry with Lorentz invariance

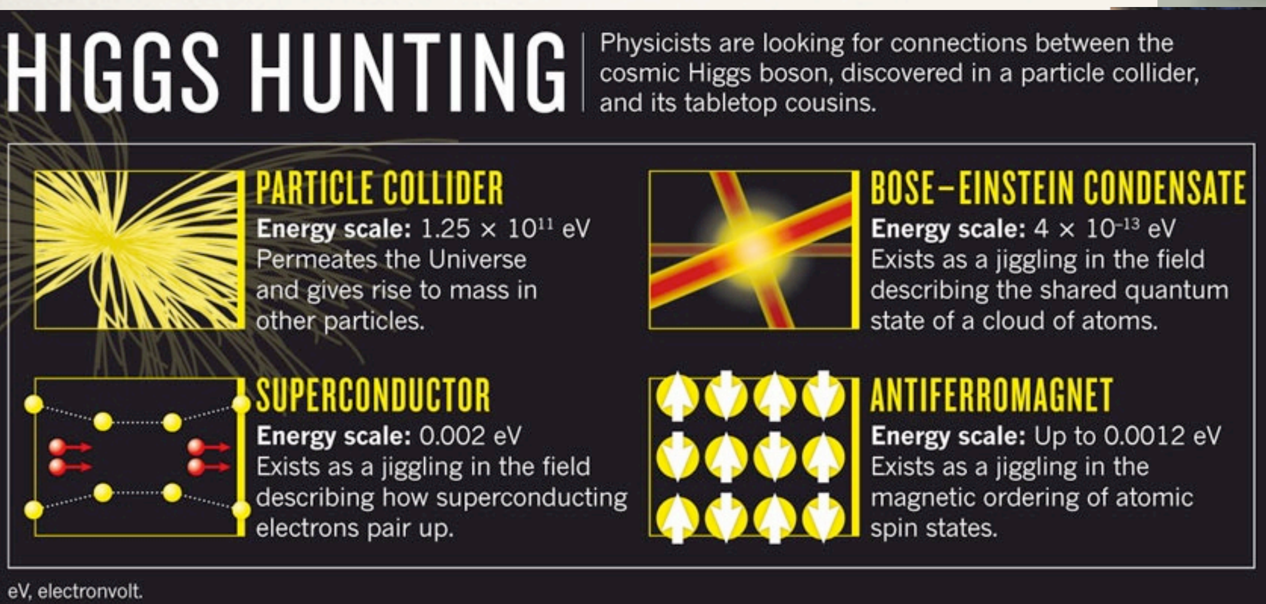


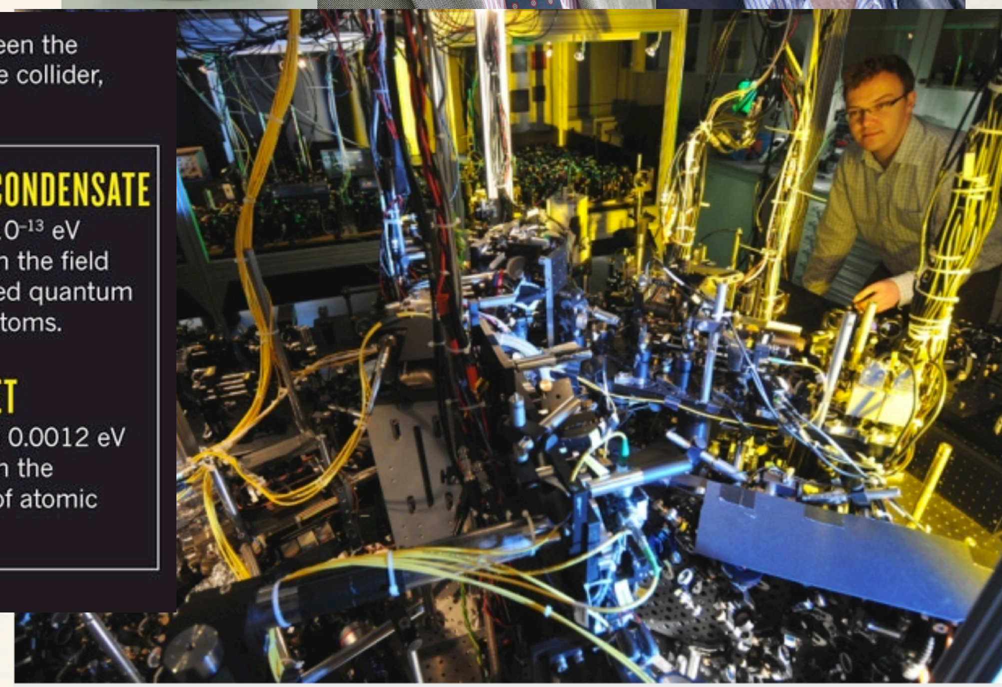
Higgs explains: and if you started with a complex scalar field, there will be a neutral massive boson left over, and eventually you get a trip to Stockholm

Who discovered the Higgs boson?

Peter Littlewood and Chandra Varma discovered "light" Higgs bosons in niobium-selenide superconductors, 1981



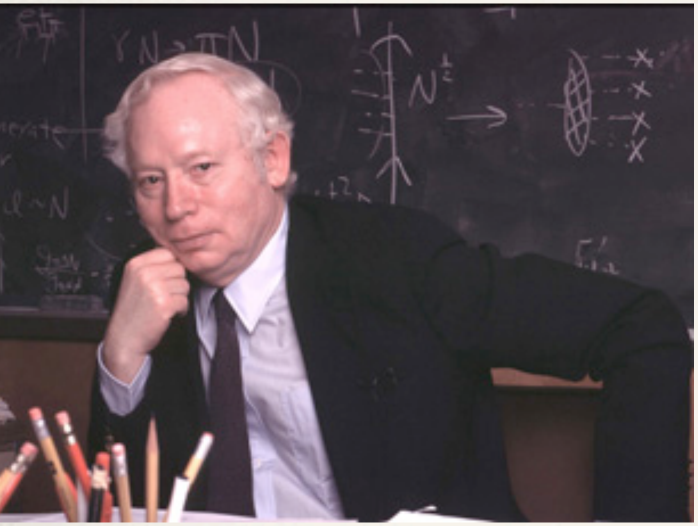




Physicists have found Higgs-like particles in a superfluid at the Max Planck Institute in Munich, Germany.

THORSTEN NAESER/MPQ

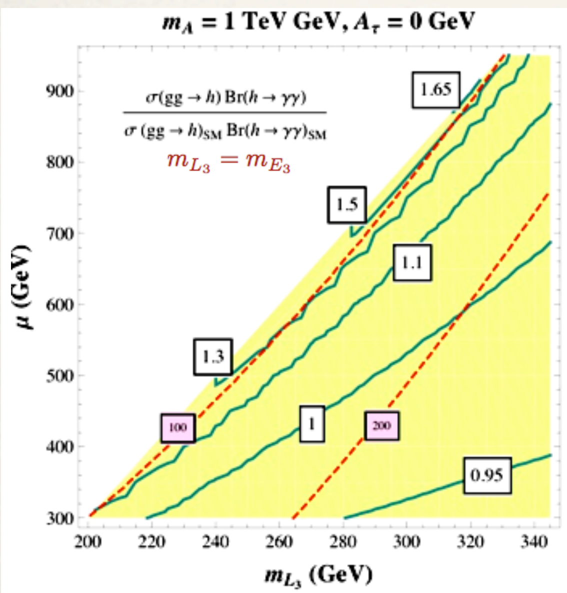
What is the 126 GeV Higgs?



- Could be a mixture from more than one Higgs SU(2) doublet, singlets or SU(2) triplets
- Could be a mixture of CP even and CP odd
- Could have enhanced/suppressed couplings to photons or gluons if there are exotic heavy charged or colored particles
- Could decay to exotic particles, e.g. dark matter
- May not couple to quarks and leptons precisely proportional to their masses
- Could be composite, by itself does not unitarize VV scattering

What Higgs precision do we need?

- There could be one or more "large" ~10% deviations in Higgs couplings versus the SM
- Many of these would then be detectable at LHC
- Typically this implies other smaller deviations -> ILC
- Large deviations typically imply lighter new particles, within reach of LHC direct detection or perhaps an ILC



Note it is the correlations between deviations that will reveal the underlying physics

M. Carena et al, arXiv:1205.5842

EWPO constrain Higgs couplings

Assumption:

Giudice et al;Contino et al;Azatov et al;Contino et al

- the main effect in EWPO is due to a possibly modified Higgs coupling a to vectors (GB's):

$$S = \frac{1}{12\pi}(1-a^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right), \quad T = -\frac{3}{16\pi c_W^2}(1-a^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right),$$

LHCP 2013 Barcelona — L. Silvestrini

$$\Lambda = 4\pi v/\sqrt{|1-a^2|}$$

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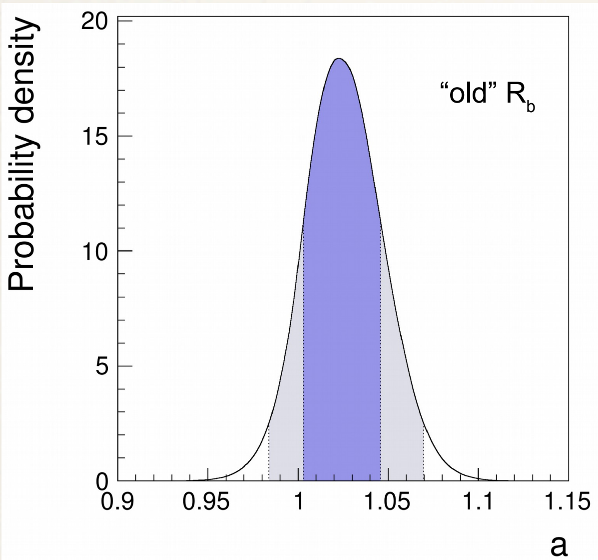
Talk by Luca Silvestrini at LHCP 2013



See also Falkowski,Riva&Urbano; Contino et al.;Pich et al

Strongly constrains simplest composite Higgs models

Strong bound from EW fit

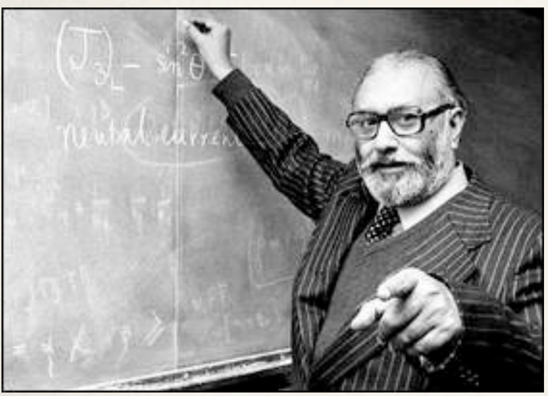
- $a = 1.02 \pm 0.02$
- $a \in [0.98, 1.07]$@95%
- Composite Higgs models typically generate $a < 1$ (Falkowski,Rychkov&Urbano)
- for $a < 1$, $\Lambda > 15$ TeV
- need additional light states to fix EW fit!

Higgs connections

- Is there a Higgs portal to dark matter
- Electroweak baryogenesis
- What is the origin of the electroweak scale
- How does the Higgs talk to neutrinos
- What are the dynamical origins of fermion masses, mixings and CP violation
- Extra credit: is the Higgs related to inflation or dark energy

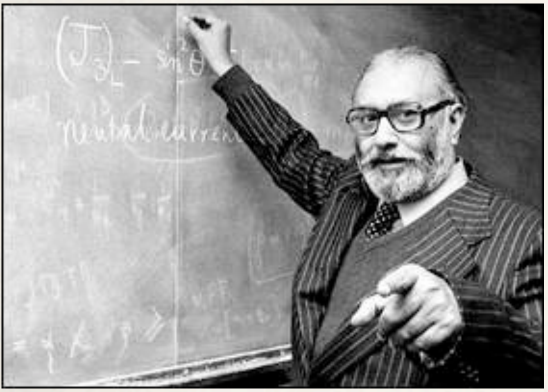
→ Motivates a multi-decade global experimental effort on all three “frontiers” of HEP

the dynamical origins of mass



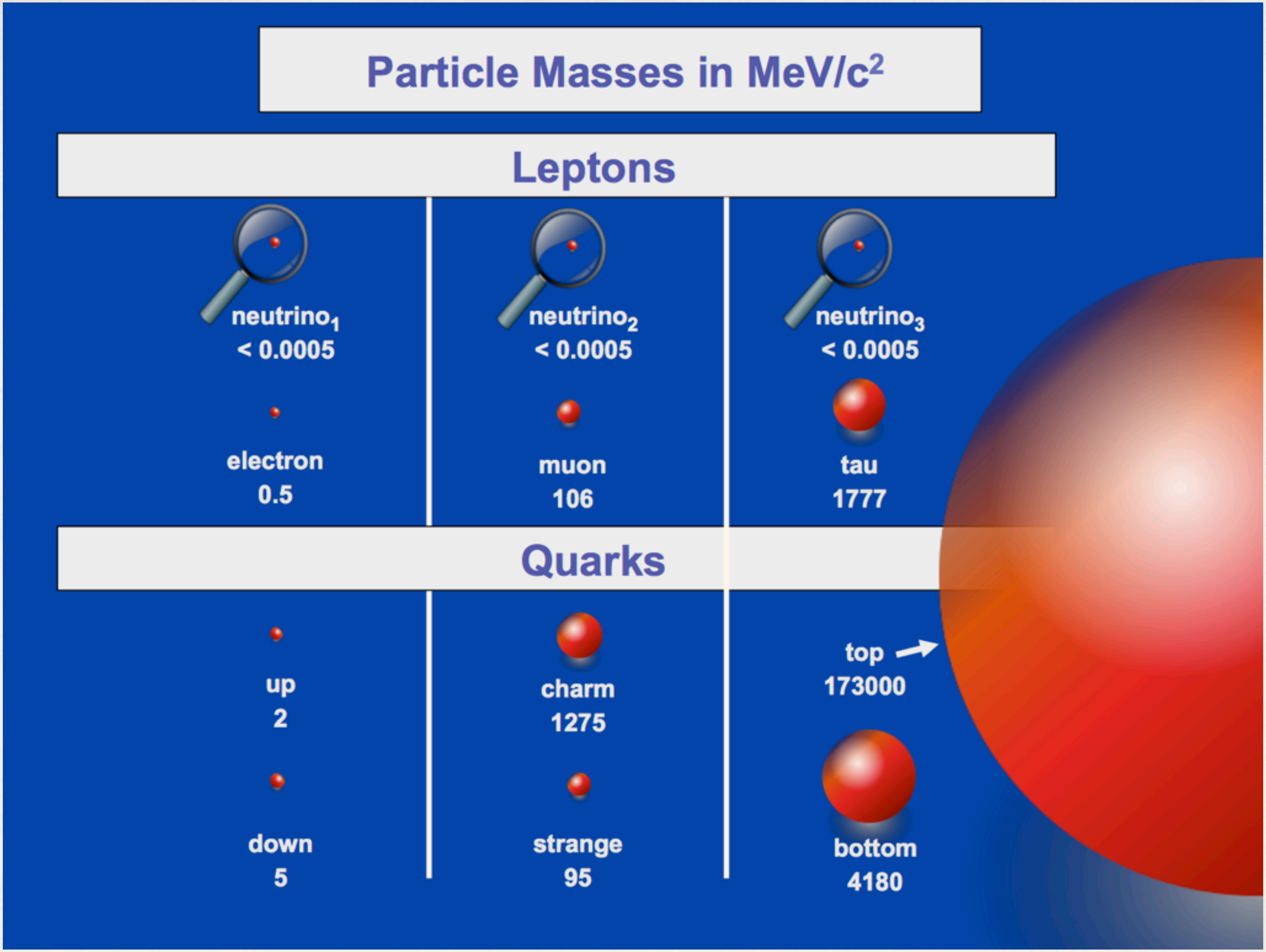
- A headline of this long story is that **elementary particles do not naturally have mass**,
- But they can acquire mass through dynamics
- In stark contrast to spin, the other conserved quantum number of Poincare invariance

the dynamical origins of mass

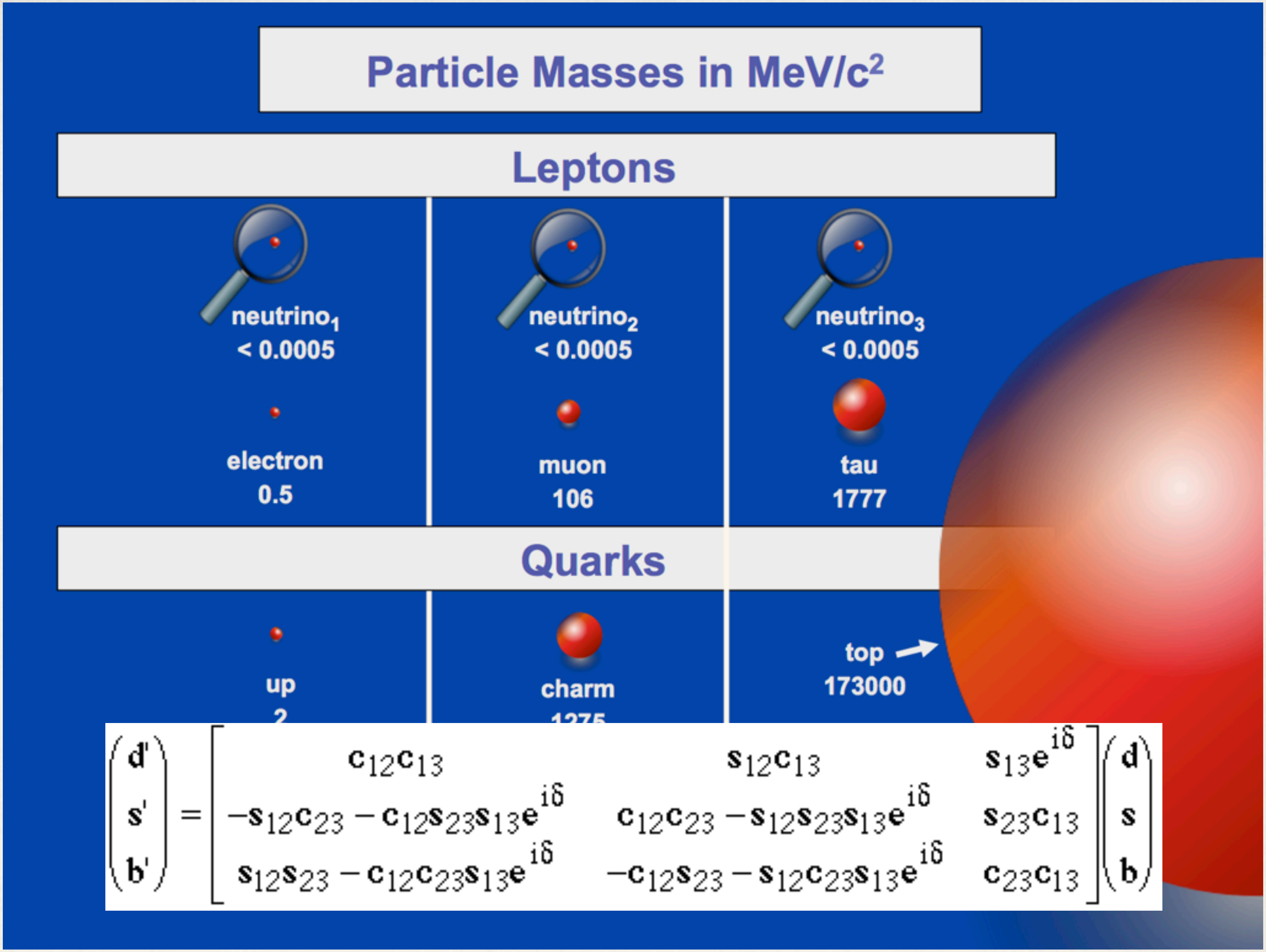


- ATLAS and CMS seem to have discovered a rather weakly self-coupled boson that couples to other heavy particles proportionally to their masses
- If this holds up, then we do in fact understand mass generation for the W and Z bosons
- **But for fermions we are just getting started...**

$$y_e \, \bar{L} \, H \, e_R + h.c. \to y_e \frac{v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L)$$



Particle Masses in MeV/c²
Leptons
neutrino1
< 0.0005
neutrino2
< 0.0005
neutrino3
< 0.0005
electron
0.5
muon
106
tau
1777
Quarks
up
2
charm
1275
top
173000
down
5
strange
95
bottom
4180



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

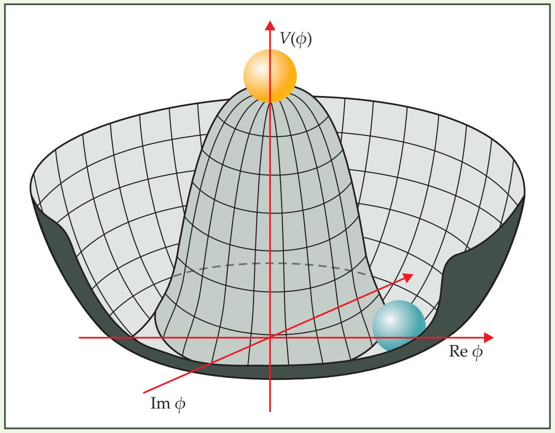
Flavor is the big over-arching challenge of particle physics for this half of the 21st century

- What are the dynamical origins of fermion masses, mixings, and CP violation?
- What are the scales associated with this dynamics?
- What are the symmetries and symmetry-breakings?
- What is the full Higgs sector and how does it work?
- How are quark and lepton flavor related?
- What other flavor sectors are accessible, e.g.
  - superpartners?
  - dark matter?

Gathering clues from many directions

- Look for new sources of flavor-breaking/CPV in the quark sector
- Determine the flavor structure of the neutrino sector
- Determine the full Higgs sector and its flavor implications
- Look for nonconservation of lepton number, baryon number, and charged lepton flavor violation
- Find the portals to the dark sector and the dark particle content
- Any new physics and any new scales could be relevant

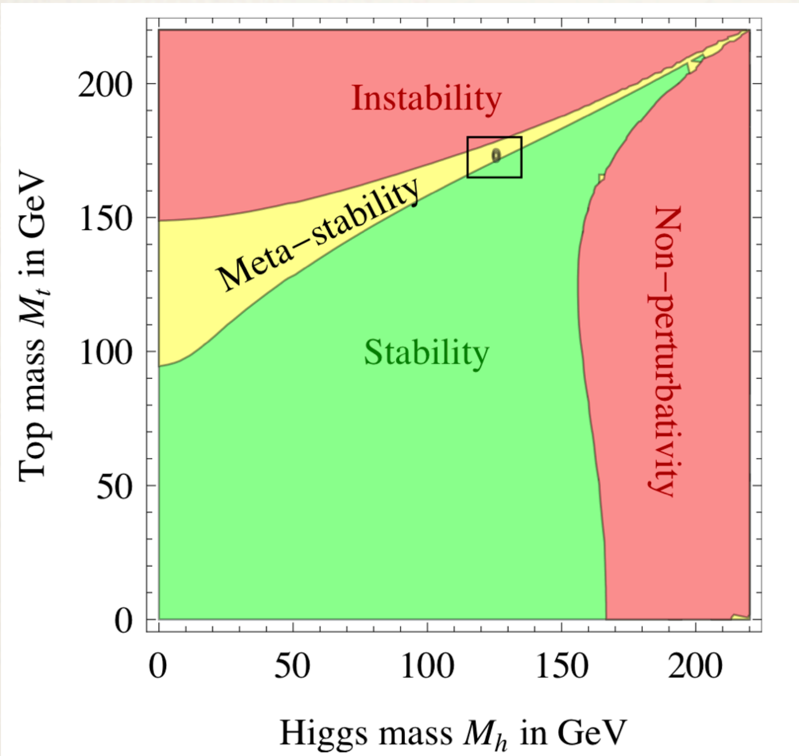
Higgs Naturalness in Crisis



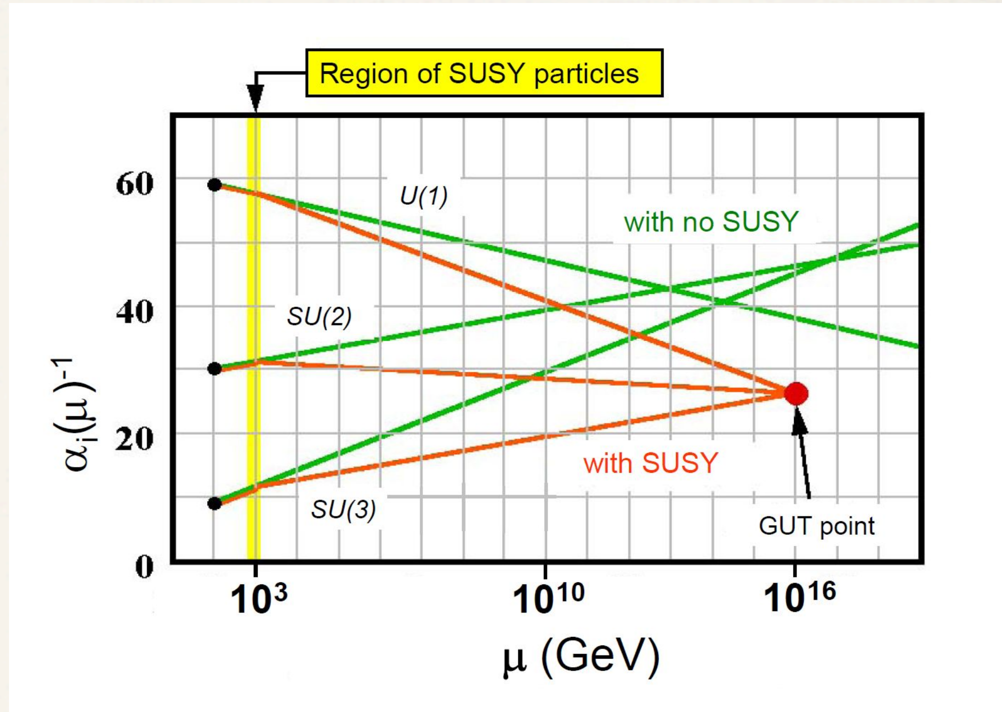
- Many particle theorists have chosen to ignore these rather dramatic mysteries of mass in the Standard Model, probably because the problems look too hard
- Instead we have 20,000 papers related to ``Higgs Naturalness", a problem of the Standard Model that, until recently, looked like it had an obvious solution
- This problem has to do with the one **explicit** mass scale of the Standard Model, a mass-squared parameter defining the leading order shape of the Mexican Hat

$$V_0 = m_0^2 |H|^2 + \frac{1}{2}\lambda |H|^4$$

why do we live on the ragged edge of doom?

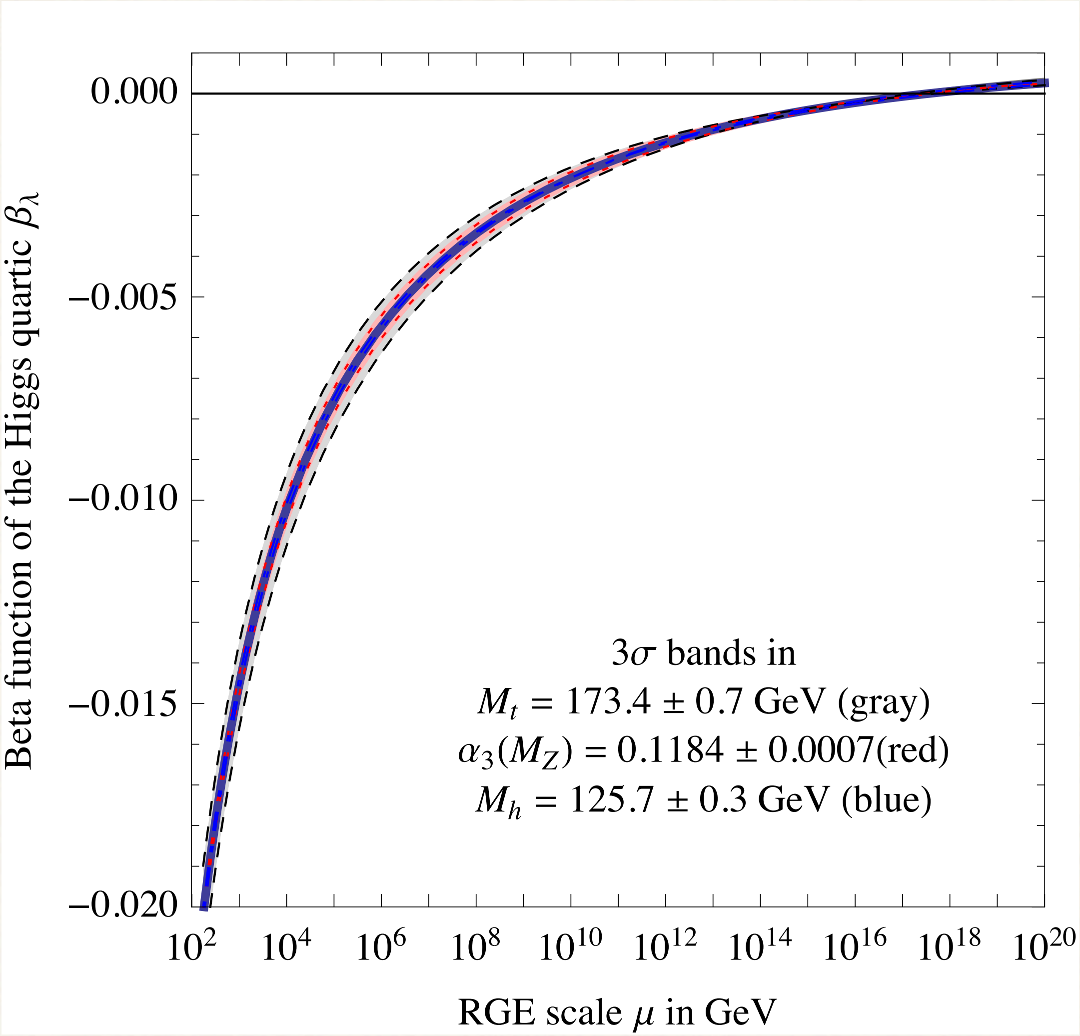


or does supersymmetry save us?



- Maybe one or both of these is just a coincidence at the few % level
- But dismissing striking features of the data as coincidence has historically not been a winning strategy in science...

SM Higgs and the Planck scale?



D. Buttazzo et al, arXiv:1307.3536

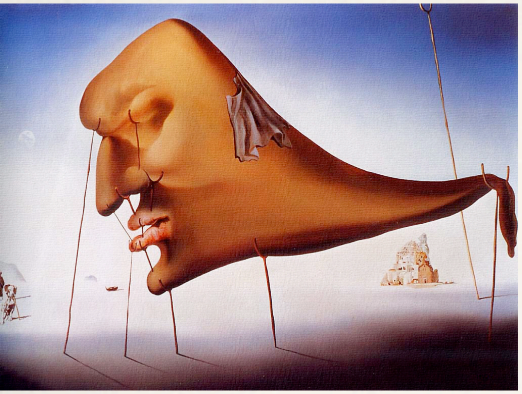
What does this mean?

A hint about physics at the Planck scale?

M. Shaposhnikov, C. Wetterich

BUT: What about the Higgs naturalness problem and resulting fine-tuning?

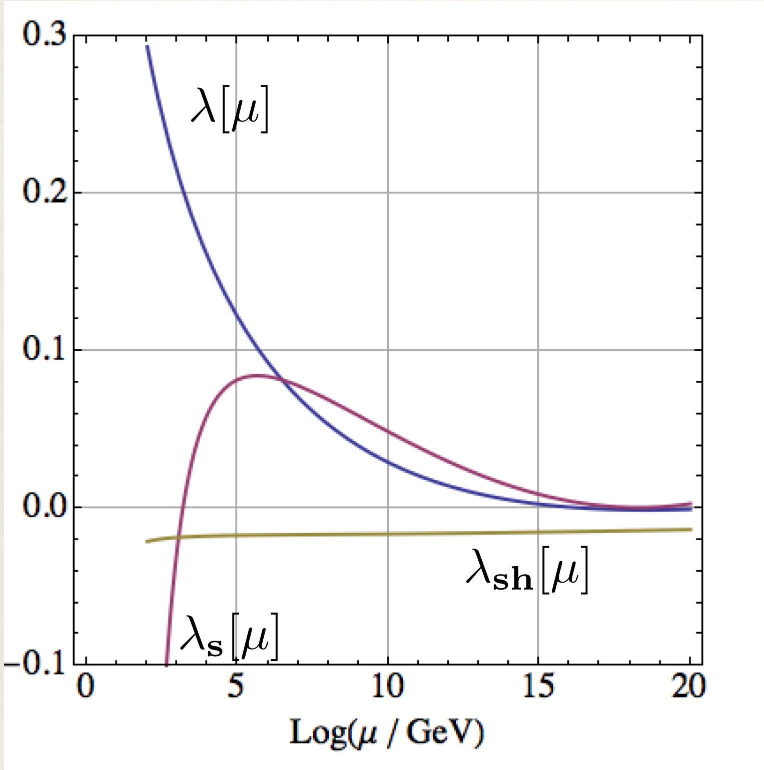
The Standard Model is (almost) all that there is?



Maybe the naturalness argument applied to the Higgs is just wrong (well, it was also wrong for the vacuum energy...)

- The SM plus some renormalizable TeV scale additions (like dark matter) is all that there is
- Renormalizable theories don't have naturalness problems, because (at the end of the day) they don't have cutoffs
- Usual counterargument that at least there is a physical cutoff at M_{Planck} is speculative
- The SM hypercharge coupling has a Landau pole at 10^{27} GeV, but who cares?

generating the electroweak scale radiatively from dark matter



$$\mathbf{V_0(H,S)} = \frac{\mathbf{1}}{\mathbf{2}}\lambda|\mathbf{H}|^\mathbf{4} + \lambda_\mathbf{sh}|\mathbf{H}|^\mathbf{2}|\mathbf{S}|^\mathbf{2} + \frac{\mathbf{1}}{\mathbf{2}}\lambda_\mathbf{s}|\mathbf{S}|^\mathbf{4}$$

- Using the Higgs portal coupling, can make many simple viable models of dark matter
- The “dark matter scale” can be generated radiatively
- Triggering also EWSB at a nearby scale
- Are all mass scales generated from some kind of dimensional transmutation?

Altmannshofer, Bardeen, Carena, JL
see also Hambye, Strumia

FERMILAB-CONF-05/482-T

Conjecture on the Physical Implications of the Scale Anomaly

Christopher T. Hill
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia,
Illinois 60510, USA

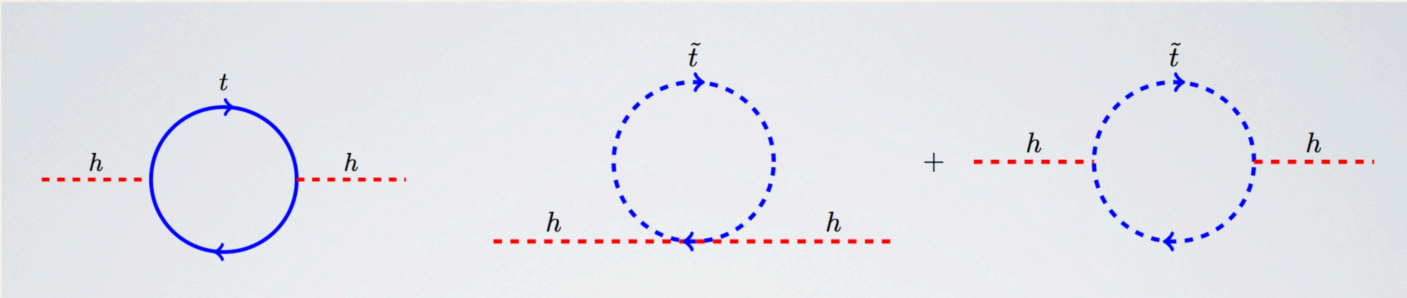
Invited Talk delivered at the Santa Fe Institute
on the Occasion of the Celebration of the
75th Birthday of Murray Gell-Mann.
July 23, 2005

- There is something very appealing about the idea that **all** mass is quantum phenomenon
- As Chris Hill has pointed out, this conjecture has a number of dramatic consequences, such as:

- The Planck scale (i.e. Newton's gravitational constant) must be generated as a quantum effect (~ the "induced gravity" of Adler and Zee)
- Grand unification is wrong
- String theory is (probably) wrong

can we start to test these ideas in experiments?

SUSY or other partners?



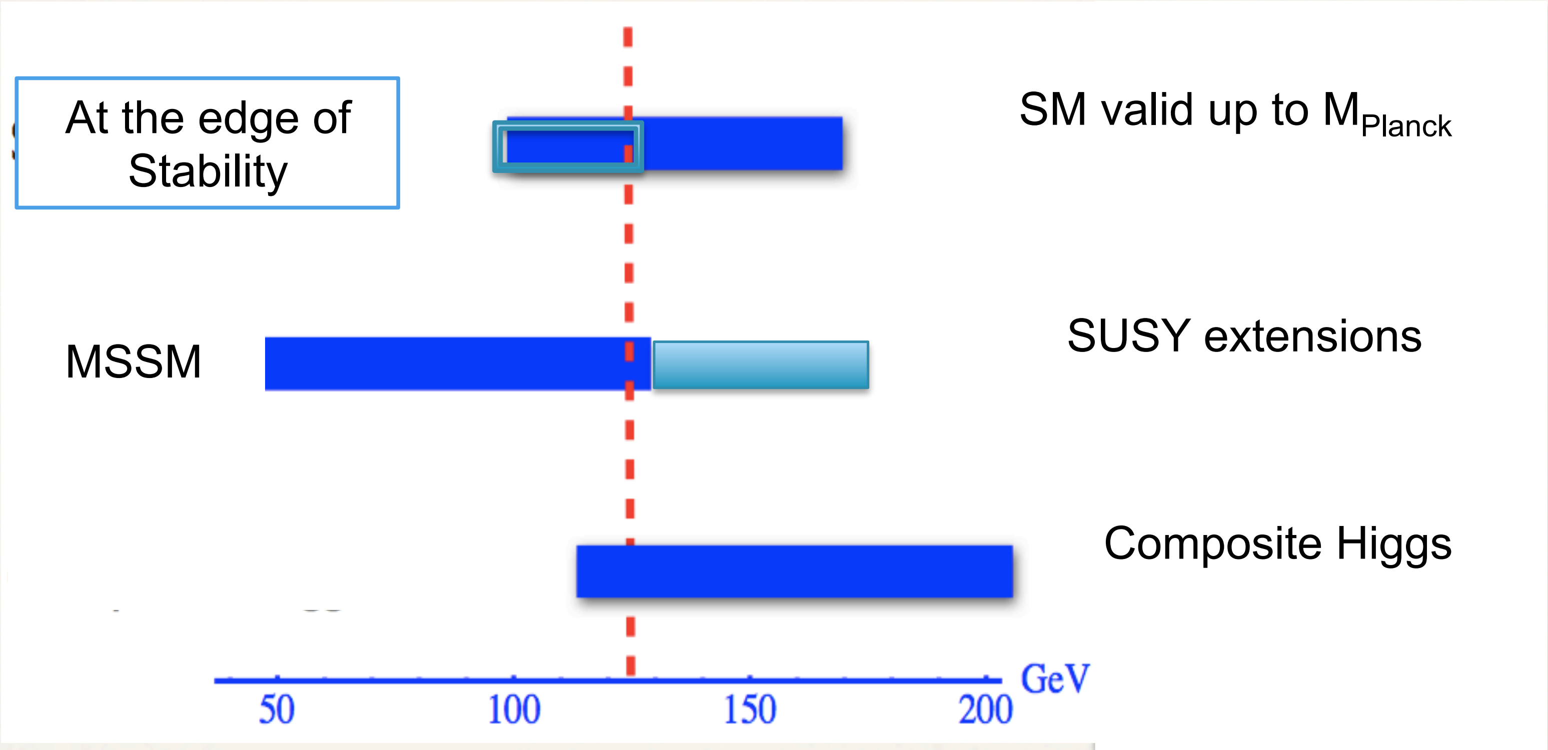
- Supersymmetry is the most robust fix to the Higgs naturalness problem
- It cancels all the quadratic divergences, even when we break SUSY softly to get realistic models
- There are other ways to cancel these divergences, involving other kinds of partners
- Examples are Lee-Wick theory, and Little Higgs models
- But SUSY models have many other nice features, and give a more complete picture, in principle up to the Planck scale

the canonical BSM paradigm

- Natural + ~MFV SUSY at the weak scale
- Neutralino dark matter
- A grand desert populated at the high end by a hidden sector for dynamical SUSY breaking, some heavy Majorana neutrinos, maybe PQ axions, inflatons
- Gauge coupling unification circa 10^{16} GeV accompanied by GUT or stringy unification of matter and gauge forces
- Planck scale stringiness with lots of extra structure to explain flavor etc.

there were lots of good arguments for this picture

What does a 126 GeV Higgs mean for minimal supersymmetry?



- 126 GeV is suspiciously light for a composite Higgs boson
- but it is suspiciously heavy for minimal SUSY

The Naturalness Dogma: caveat emptor

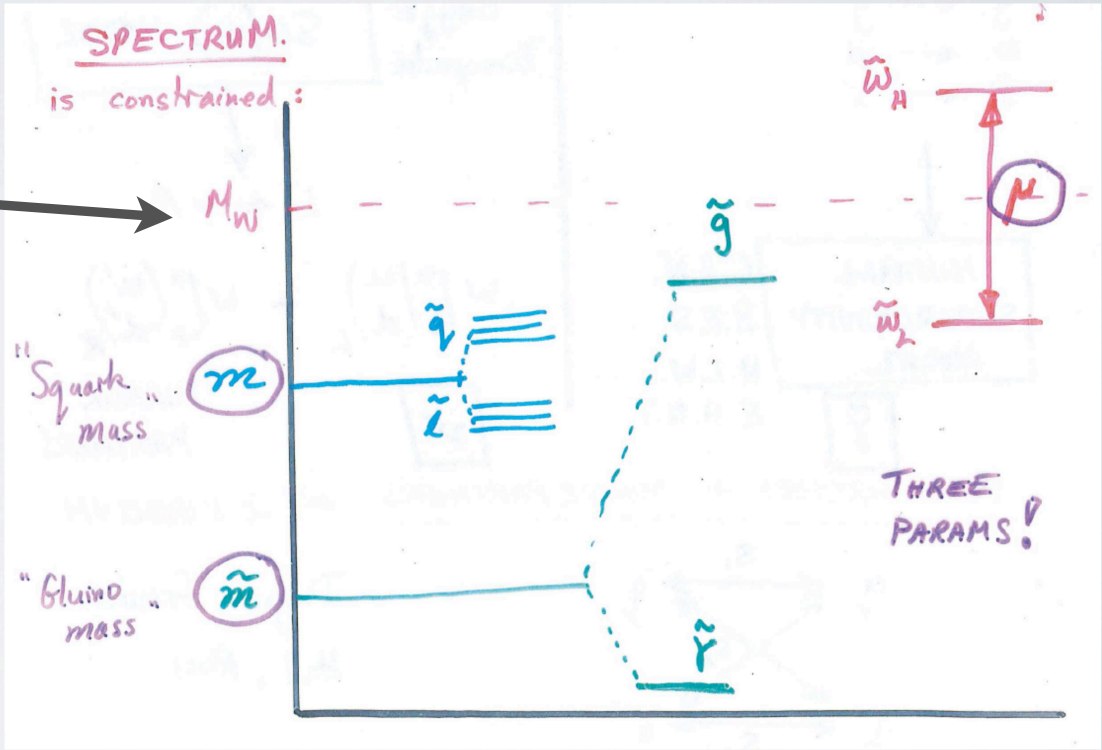
NATURAL SUSY, 1984

From Lawrence Hall's talk at SavasFest

W boson near the top of the spectrum....

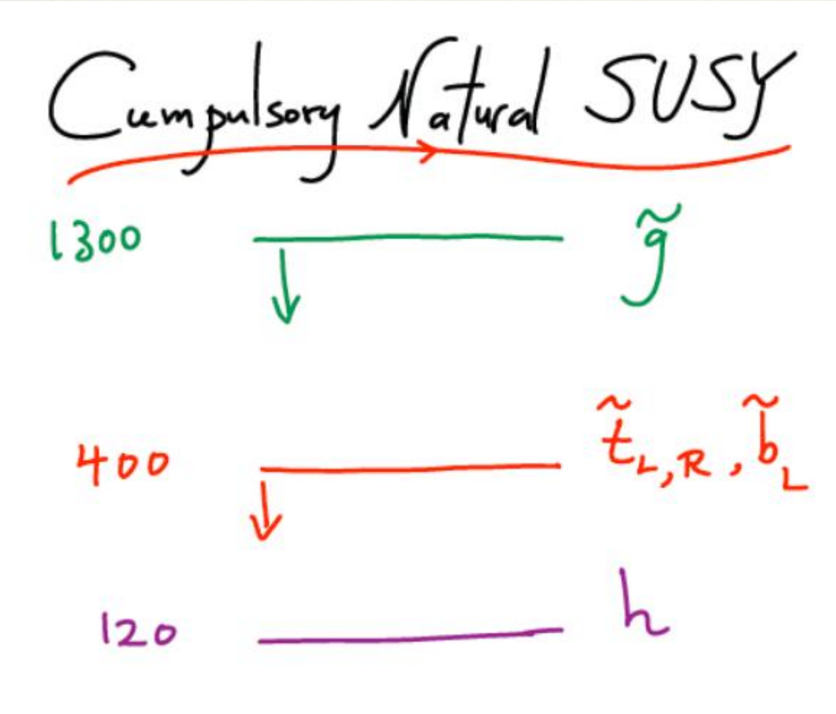
1984 was a utopian year for SUSY.

Times have changed!

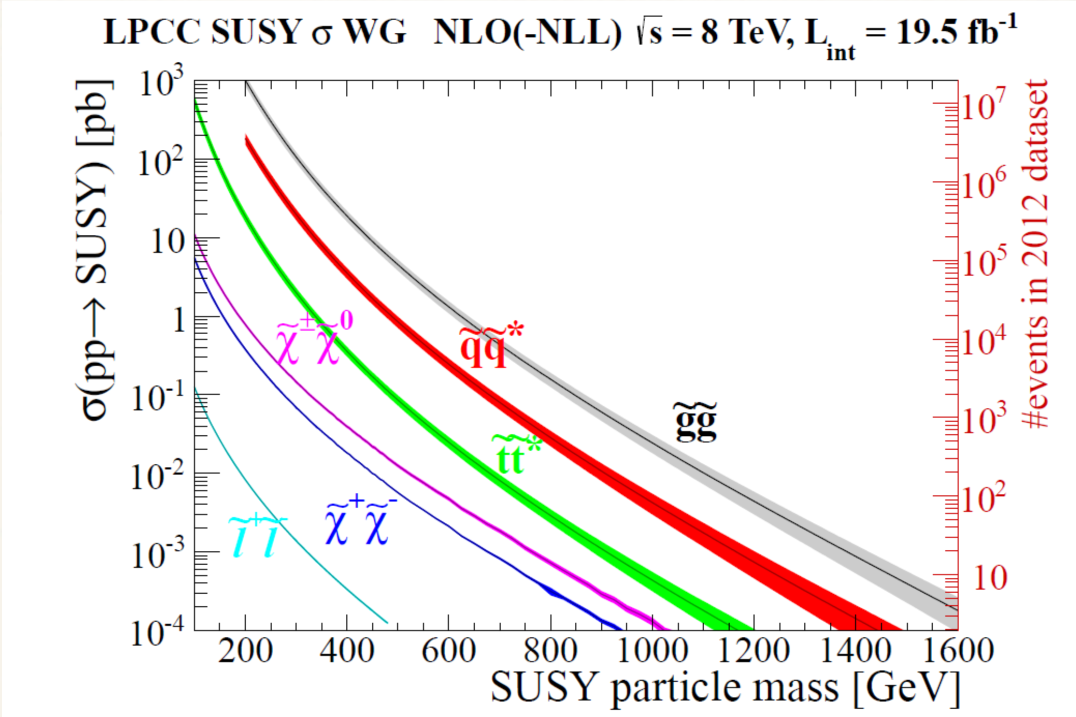


Talk by Matt Reece at LHCP 2013

SUSY agonistes



N. Arkani-Hamed



- If you really believe in a strong naturalness argument, then we should have seen gluinos and stops already at the LHC

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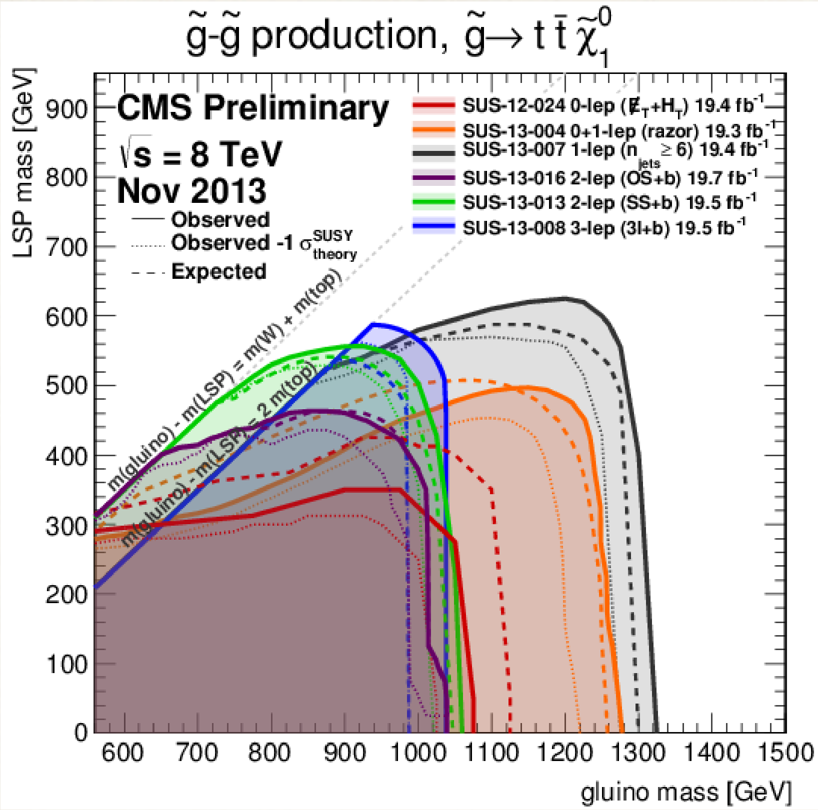
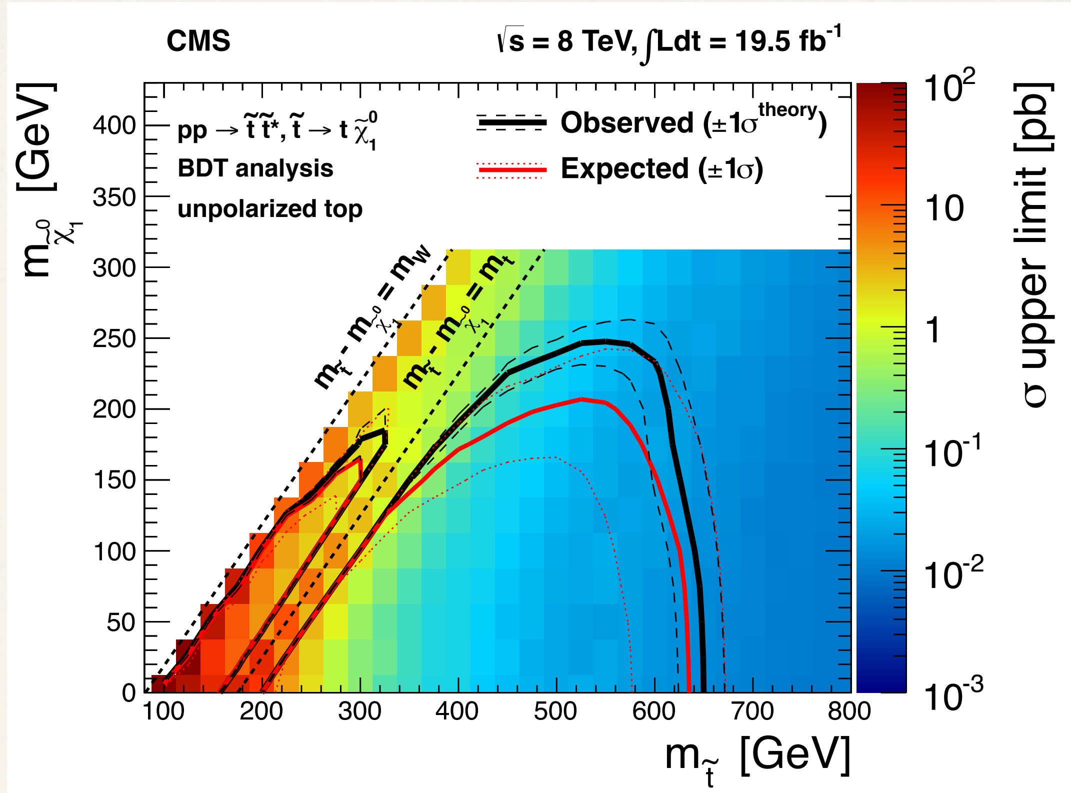
SUSY agonistes





- Of course it is possible that we just missed the superpartners in the last LHC runs at 7 and 8 TeV, and they will show up quickly in the new run at 13 TeV
- Stranger things have happened: both the LEP and Tevatron collider experiments just missed discovering the Higgs boson

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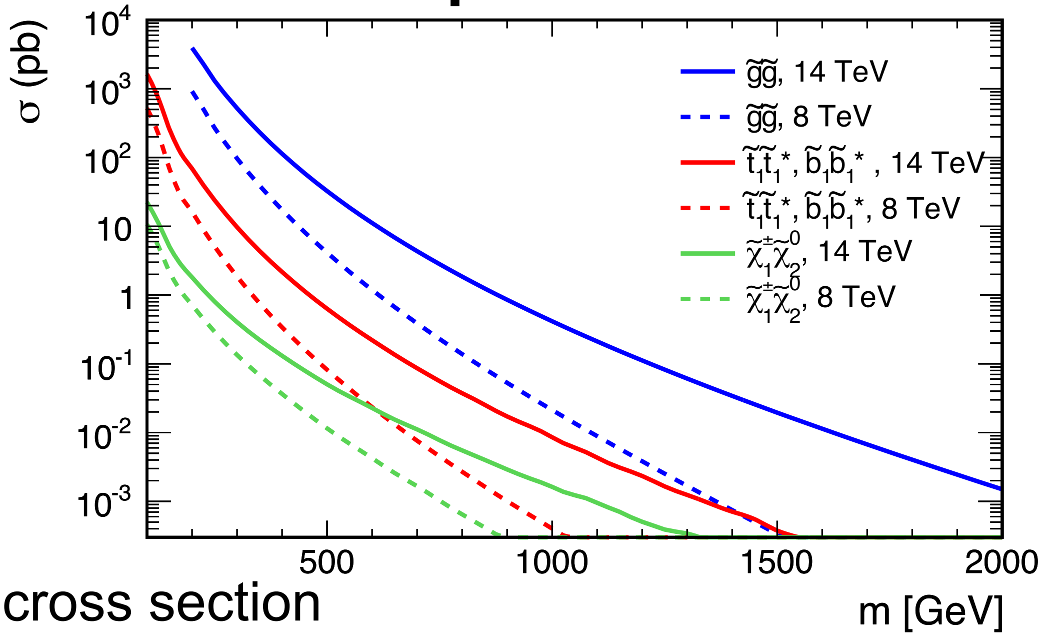
What to expect at 13TeV



increase in cross section

1350GeV gluinos: x30
1000GeV gluinos: x20
750GeV squarks: x9
350GeV $X^{+-}X^0$: x3
top pairs: x4

Reach new territory with 1-6/fb of 13TeV luminosity

Signal grow much faster than SM bkg
-> will need data driven techniques.

11/12/13 LPC 2013 12

Frank Wurthwein

Moderate tuning doesn't mean your theory is wrong

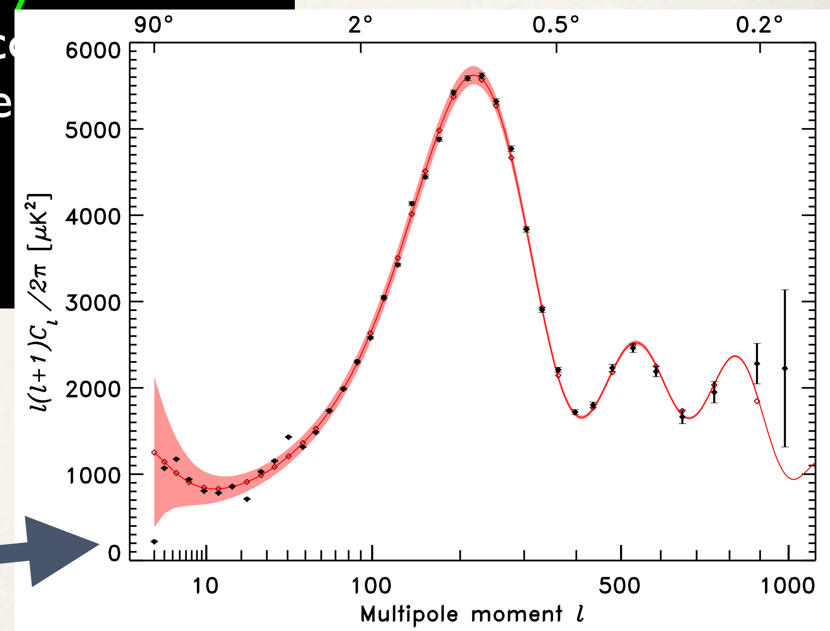
- Before COBE, upper limit on CMB anisotropy kept getting better and better
- Before 1998, the universe appeared younger than oldest stars
- cosmologists got antsy
- "crisis in standard cosmology"
- it turned out a little "fine-tuned"
  - low quadrupole
  - dark energy

"Big Bang not yet dead but in decline"
Nature 377, 14 (1995)

"Bang! A Big Theory May Be Shot"
A new study of the stars c
the history of the universe
Times, Jan 14 (1991)

Talk by Hitoshi Murayama at Lepton-Photon 2013

worse than 1% tuning

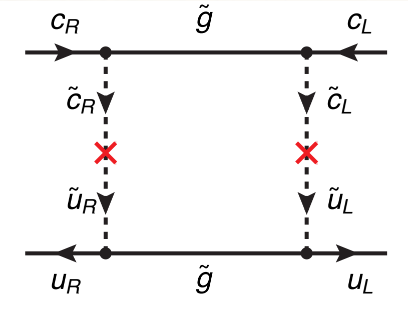


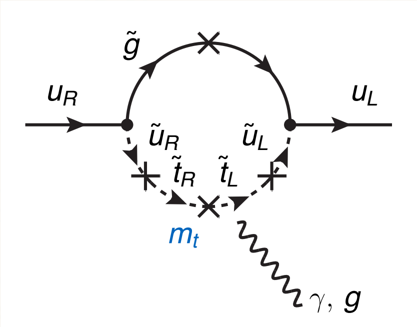
moving SUSY to higher ground?

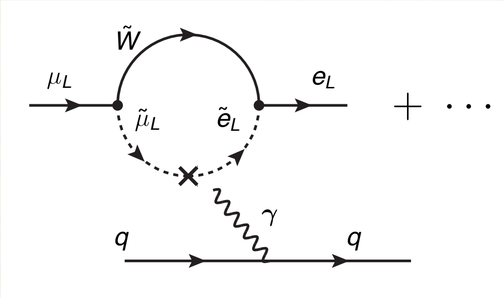
- Just in case, many theorists are busy making arguments for why it was obvious all along that superpartners should not be within reach of the LHC
- 10 TeV, 100 TeV, even 1 PeV are becoming popular mass scales for superpartners
- As on Red Mountain, moving to higher ground is very expensive...

the scales of flavor?

- putting squark masses at 100 TeV, whatever the motivation, is a good playground for the idea that flavor-violating effects may be intrinsically O(1), but with a big mass suppression
- in such a regime it is also easier to make dynamical models of SM fermion mass hierarchies, without getting sunk by large FCNCs
- even a VLHC cannot probe this scale directly, so you will have to get clues from rare processes:

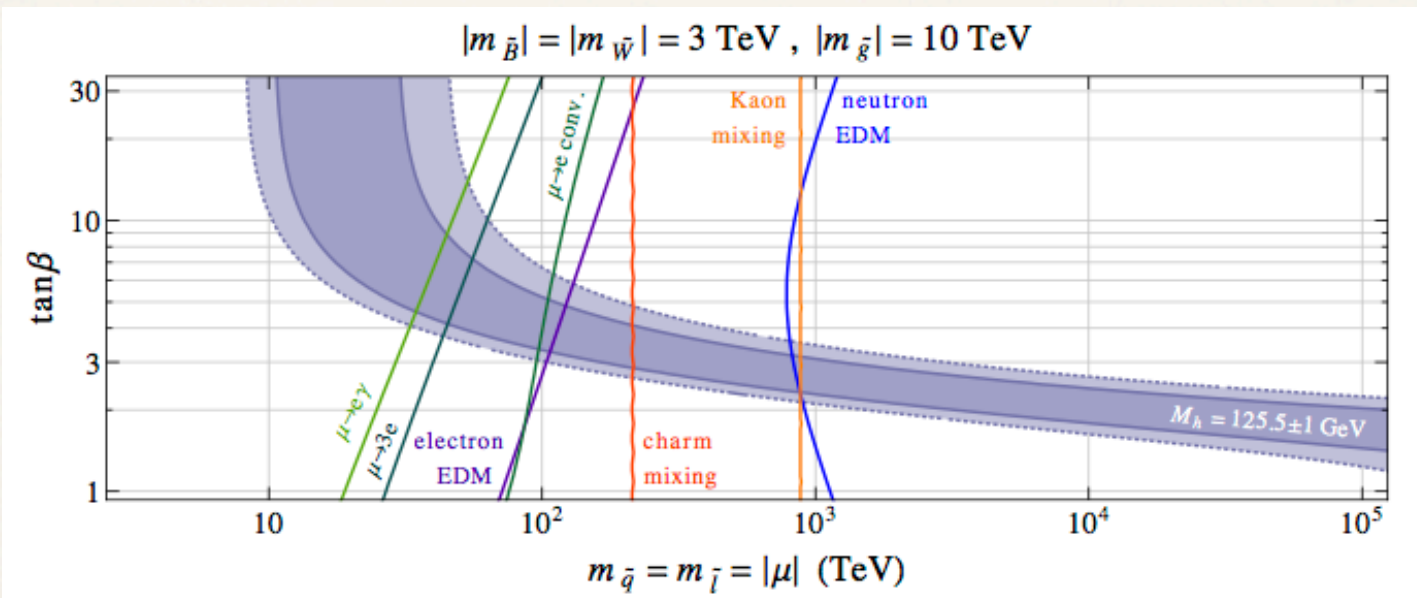






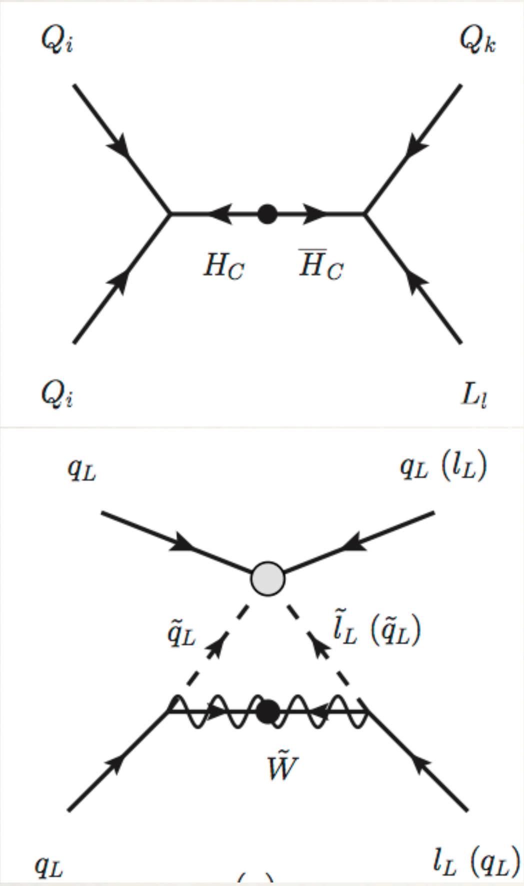
the scales of flavor?

- Heavy flavor probes up to 50 TeV (LHCb and Belle II)
- EDMs can probe up to 100 to 1000 TeV
- Kaons probe up to 1000 TeV
- Mu2e can probe 100 to 1000 TeV

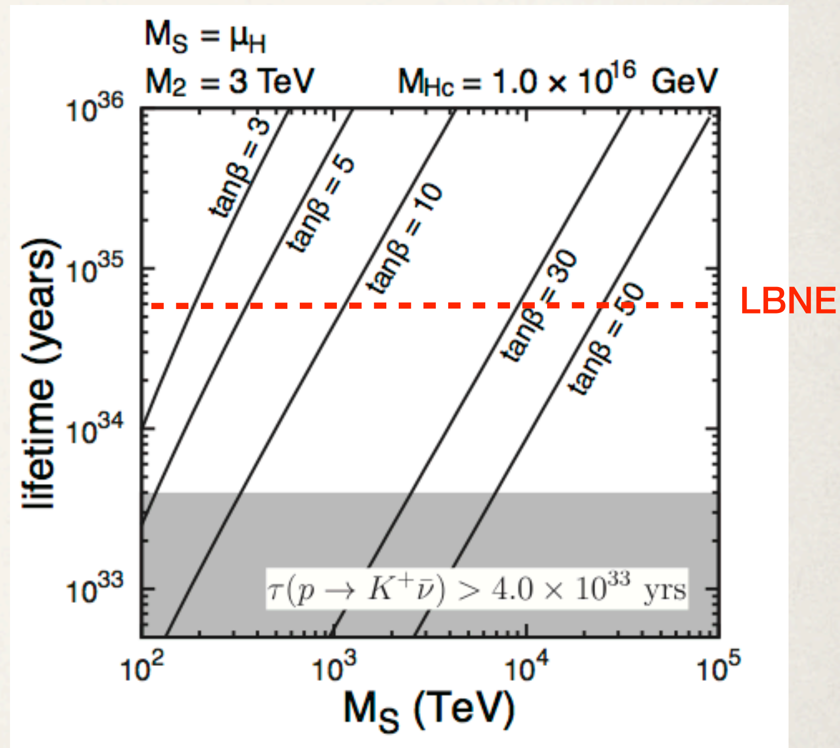


W. Altmannshofer, R. Harnik, J. Zupan, arXiv:1308.3653

minimal SUSY SU(5) revived

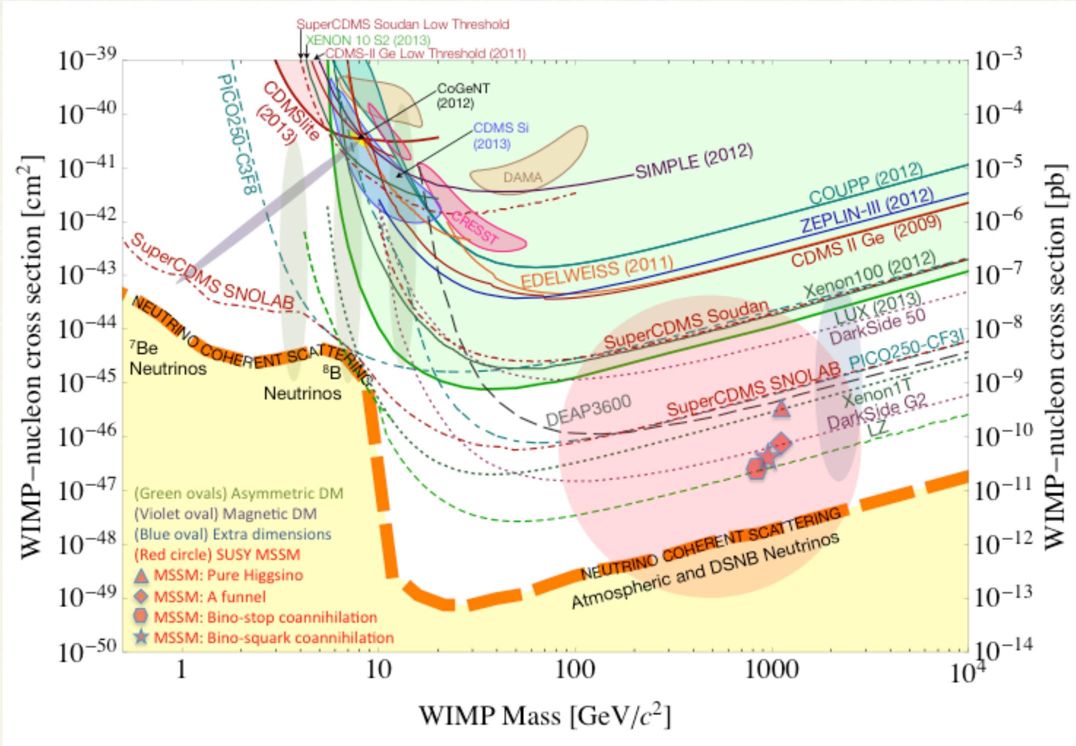


- color-triplet scalars that live in the Higgs 5-plet induce dimension five proton decay in SUSY SU(5)
- seemed to rule out the minimal scenario, since the proton lifetime was $\tau(p \to K^+\bar{\nu}) \lesssim 10^{30}$ yrs
- but with squark masses lifted to ~100 TeV, there is an extra suppression
- predicts that LBNE will see proton decay



J. Hisano et al, arXiv:1304.3651

WIMPs getting wimpier



- the WIMP miracle is starting to look like the WIMP fairytale
- theorists may soon have to stop saying “it’s a 100 GeV neutralino, stupid”
- good news: already DAMA, CoGeNT, etc have inspired the theory community to start taking a much broader view of the dark sector

dark matter bestiary

- SUSY LSP, extra dimensions LKP, Little Higgs LTP
- axions
- sterile neutrinos
- WIMPzillas
- other nonthermal relics from decays of moduli, or Q-balls, or ...
- asymmetric dark matter
- self-interacting dark matter, partially interacting dark matter, dissipative DM

possible portals to the dark sector:

- Z boson (not looking good)
- Higgs boson direct coupling to dark sector scalar or fermion
- Exotic light force carriers

is dark matter like visible matter?

- Why should the dark sector be any simpler than the visible sector?
- The visible sector has 5 stable massive particles (6 if you count the neutron), and a bunch of long and short range force carriers
- baryonic matter abundance is not a thermal relic abundance
- leave out seemingly small details, e.g. neutrinos, and you get the whole picture wrong

my guess:

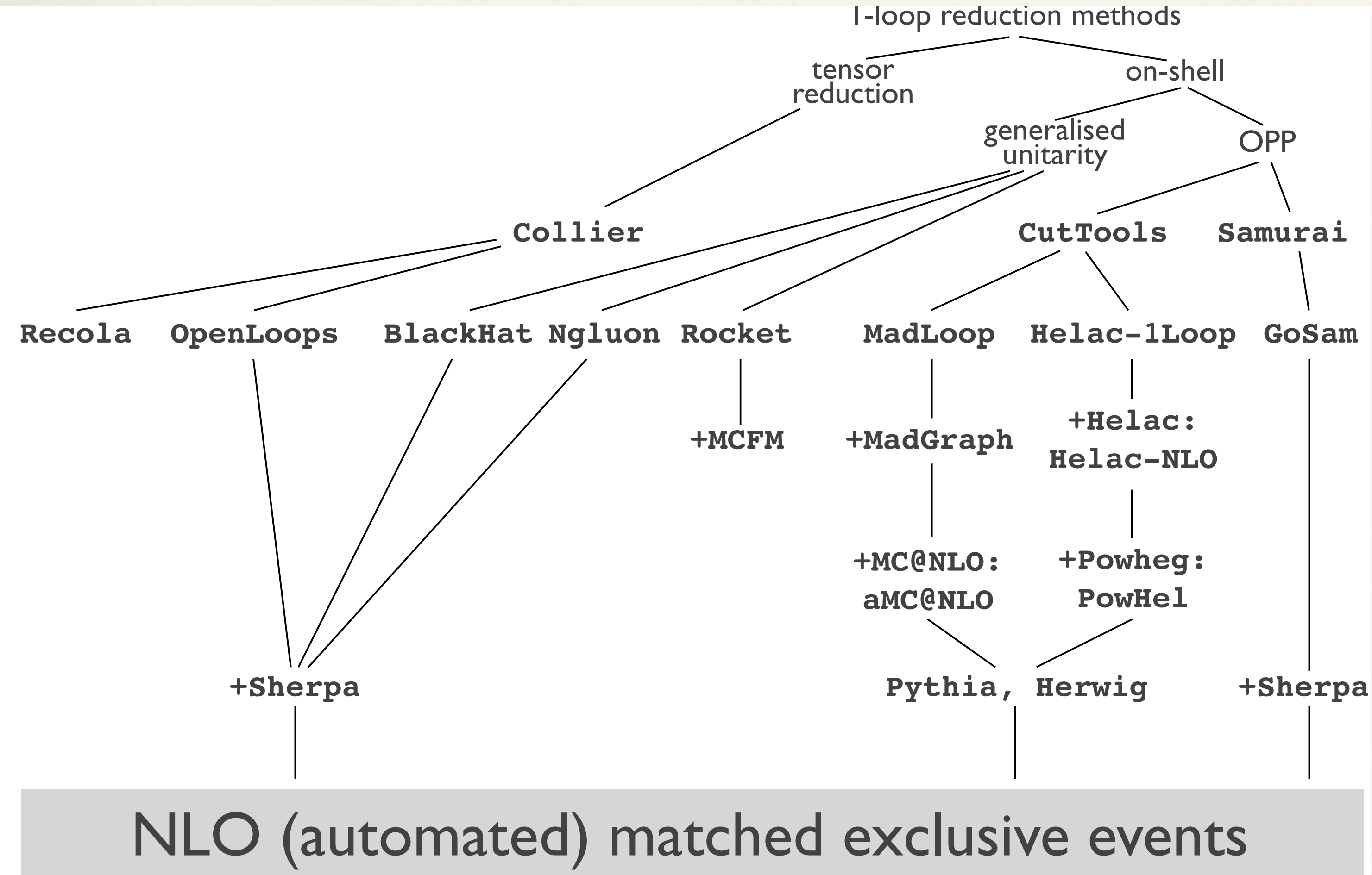
- dark matter has several stable components
- some of them have mass and abundance linked to those of baryons, as per asymmetric dark matter
- some of them have significant interactions among themselves

QCD: hic sunt dracones

Just when you thought QCD was becoming tame, LHC data reminds us that QCD is full of surprises and new/old challenges

- pQCD for the masses
- parton distributions (need to) grow up
- QCD hydrodynamics
- The revenge of quarkonia?

pQCD for the masses



The NLO revolution continues, will be of increasing importance for LHC

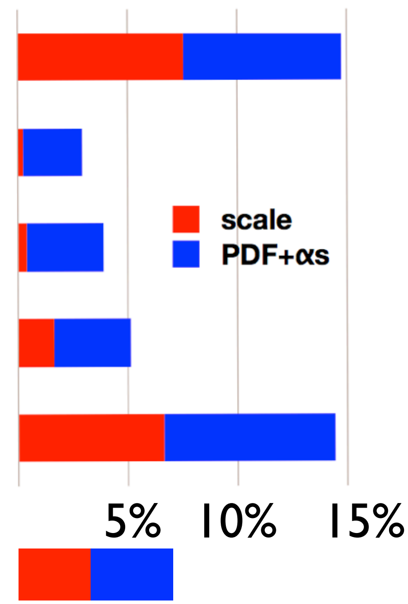
Increasing power of public automated tools for SM and BSM

parton distributions (need to) grow up

Impact of PDFs uncertainties

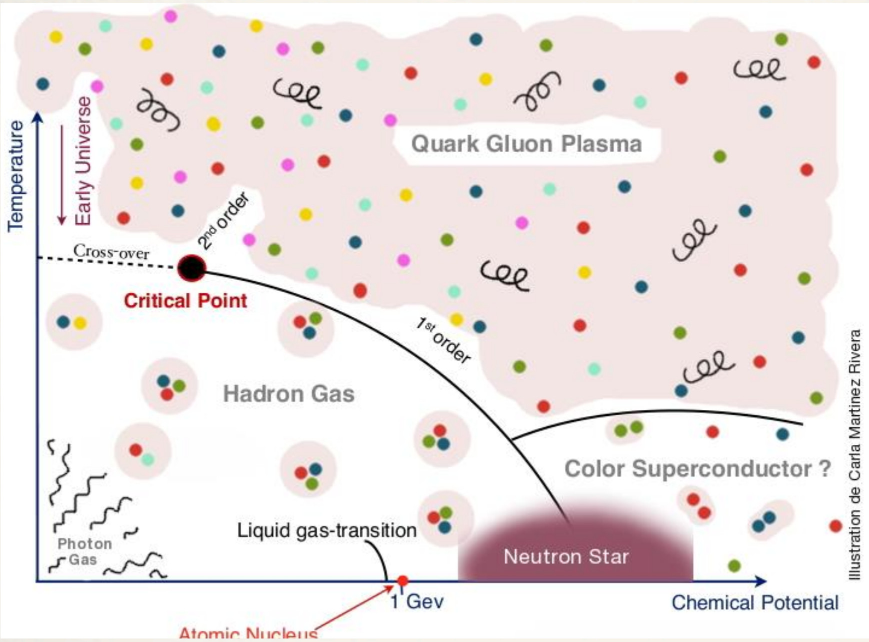
J. Campbell, ICHEP'12

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%
NNLO QCD	tt	245.8 pb	7%



- PDF uncertainties at least comparable to missing higher orders ones

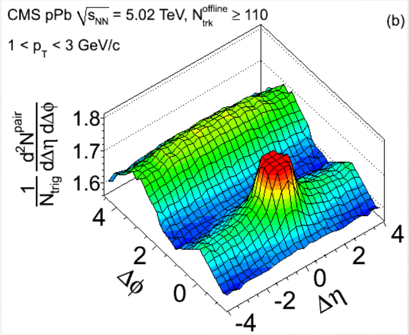
QCD hydrodynamics



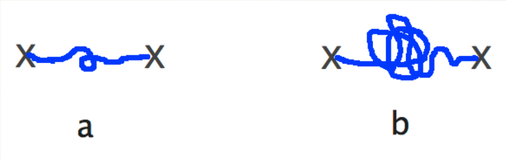
- Heavy ion collisions at LHC produce an excited nonequilibrium strongly-interacting extended state
- It isotropizes extremely rapidly, time scale ~ 1 fermi/c
- Shows flow characteristics of relativistic hydrodynamics
- Quenches jets and melts quarkonia
- This is the Quark Gluon Plasma!

The Golden Age of Heavy Ion physics is now

from strings to QGP to black holes



- At LHC, we see QGP-like features in p-Pb collisions, and even in high multiplicity p-p collisions ("the ridge")!
- An experimental opportunity and a theoretical challenge
- Can we understand the transition from scattering described in terms of gluons and QCD strings, to relativistic hydrodynamics?



E. Shuryak and I. Zahed arXiv:1301.4470

- AdS/CFT duality allows to use perturbed black holes as toy models for strongly-coupled out-of-equilibrium plasmas: how much can we learn from this about QCD?

a quarkonia polarization crisis?

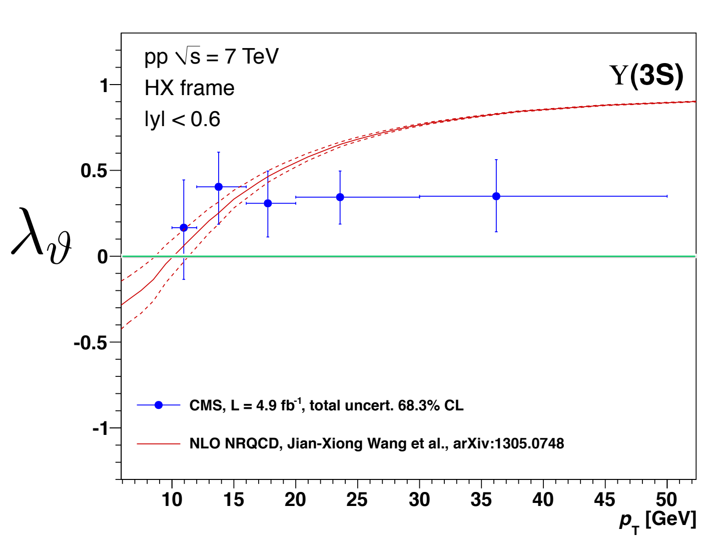
NRQCD factorization [Bodwin Braaten Lepage 95]

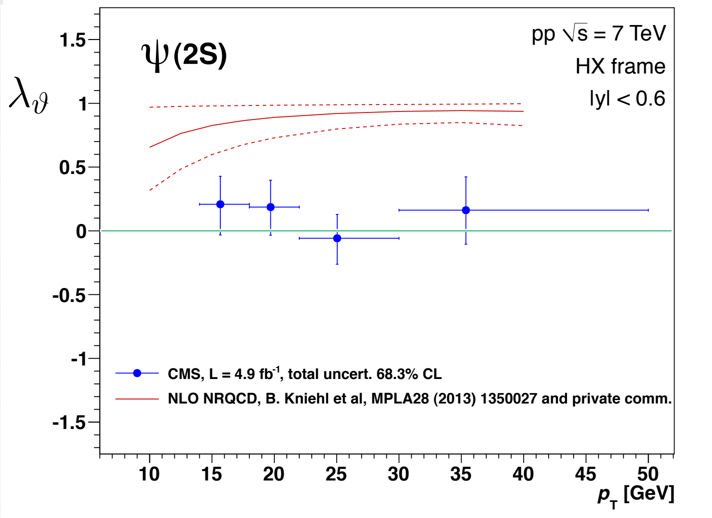
- Rigorous effective field theory
- Based on factorization of soft and hard scales
  (Scale hierarchy: $Mv^2, Mv \ll \Lambda_{QCD} \ll M$)
- Theoretically consistent: no leftover singularities.
- NNLO proof of factorization [Nayak Qiu Sterman 05]
- Can explain hadroproduction at Tevatron.

Talk by Bernd Kniehl

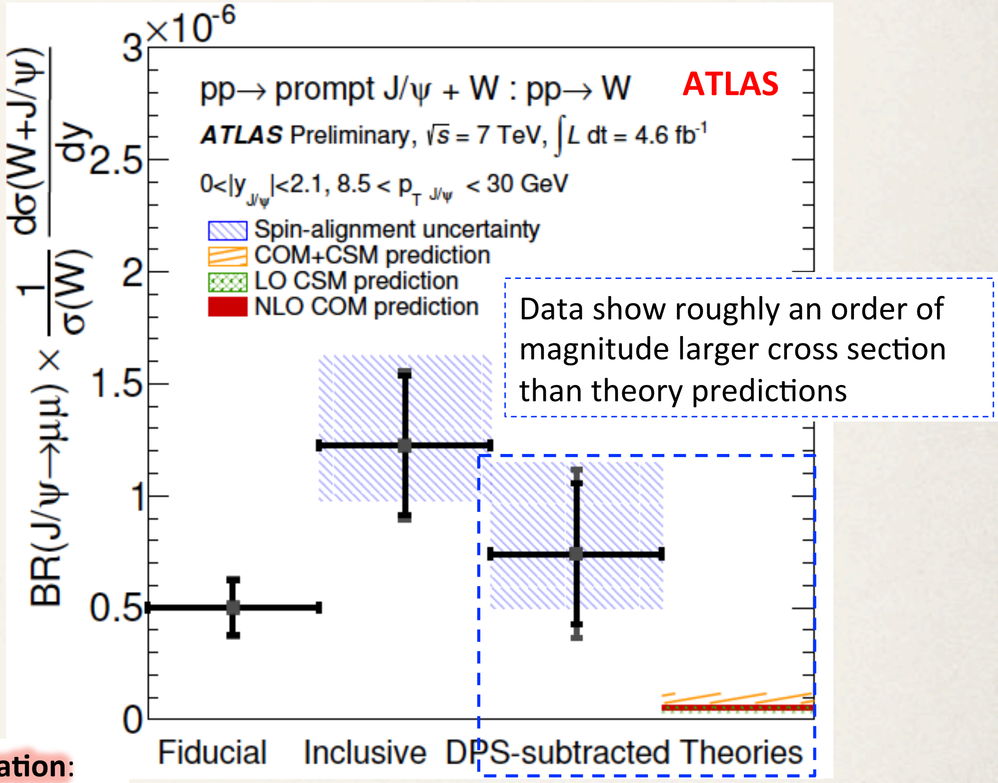
- **NRQCD *is* QCD, in an unambiguous expansion in powers of both $\alpha_{\mathbf{s}}$ and the heavy quark velocity v**
- **However the factorization introduces a number of long distance matrix elements that have to be fit to data (like pdfs)...**
- **And it is assumed that these LDMEs are universal...**
- **And for charmonium and bottomonium, v is not especially small...**

a quarkonia polarization crisis?





"We have been comparing our beautiful data to too many bad theories"
-- Carlos Lourenco at LHCP2014



- **NRQCD factorization**: quarkonia also produced as ***coloured*** *Q-Q*bar pairs *of any possible quantum numbers*

Outlook

- The Higgs discovery is only the beginning of a story that will bridge all the frontiers of particle physics
- The challenge of understanding the dynamical origins of fermion masses and mixings will require probing higher scales directly and indirectly
- Dark matter may be a game changer in the next few years, but the story will be more complicated than just picking a winner form the current laundry list
- Whether canonical BSM thinking is correct or incorrect, we have entered a New Age

Not the End