The View Ahead

Joseph Lykken
Fermilab

40th SLAC Summer Institute, Aug 3, 2012

Caveats and Disclaimers

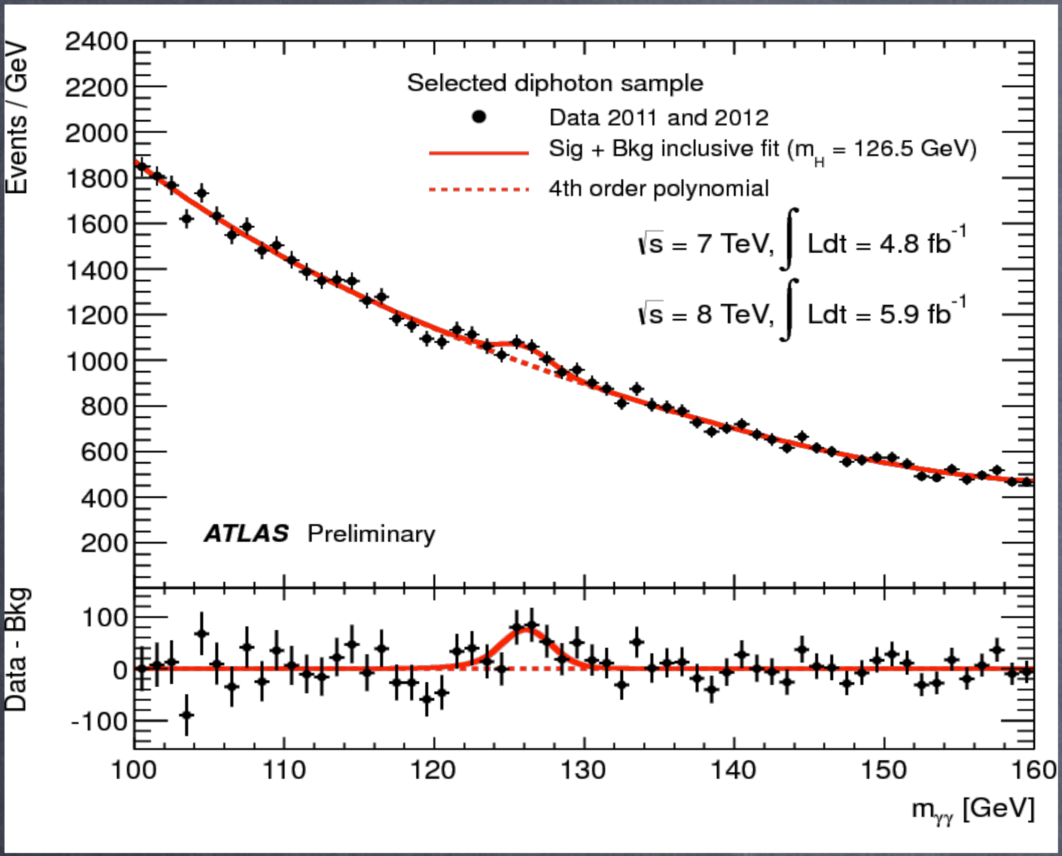
- This talk is addressed to the young people in the audience
- It reflects my theory biases
- Also I am a lapsed string theorist who joined the CMS collaboration, so there must be something seriously wrong with me

This is a great time to be entering the field of particle physics

History is not just a thing of the past!

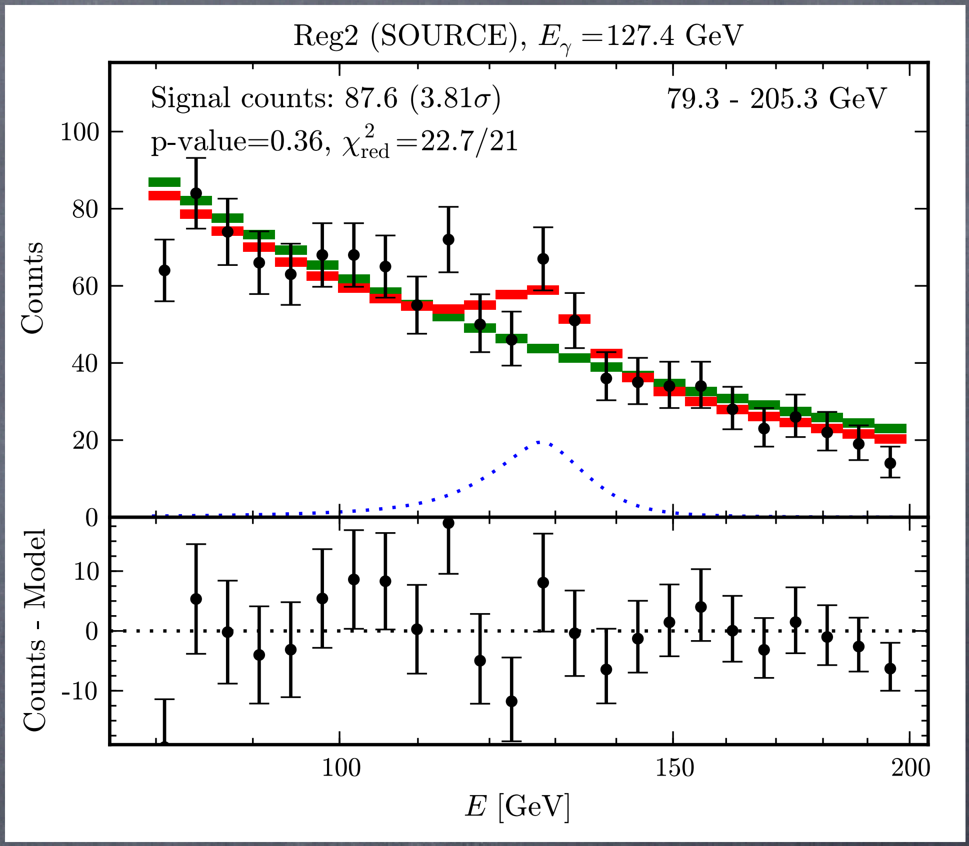
Chris Quigg

photon bumps at the LHC



Sau Lan Wu

photon bumps from the Milky Way



Tim Tait, Patrick Fox

How little we know

Maybe it happens this way
Maybe we really belong together
But after all, how little we know

Maybe it's just for a day
Love is as changeable as the weather
And after all, how little we know

Who knows why an April breeze never remains
Why stars in the trees hide when it rains
Love comes along, casting a spell
Will it sing you a song
Will it say a farewell
Who can tell

Maybe you're meant to be mine
Maybe I'm only supposed to stay in your arms a while
As others have done

Is this what I've waited for, am I the one
Oh, I hope in my heart that it's so
In spite of how little we know

Is this what I've waited for, am I the one
Oh, I hope in my heart that it's so
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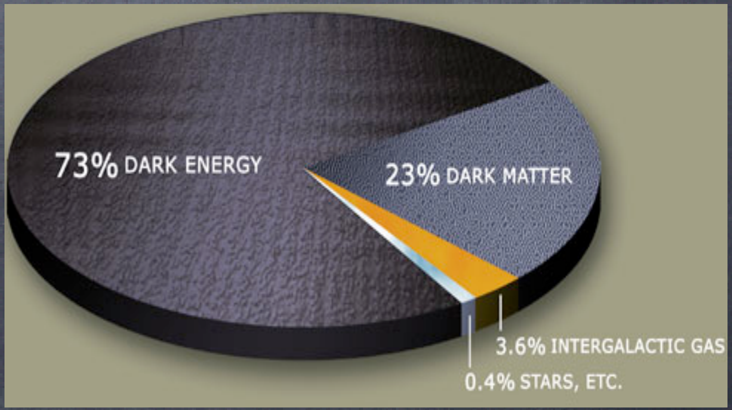
Hoagy Carmichael



How little we know: EWSB

- Wait a minute, "everybody" knows that the July 4 discovery is the Higgs boson of the Standard Model
- So aren't we doomed to spend the next 20 years just confirming the Standard Model to ever-greater precision?

"if it quacks like a gun and smokes like a duck..."

Current status of "the particle"

It's not a mirage, but who is it?

2013 status of “the particle”

It’s not a mirage, but who is it?

Future status of “the particle”

It’s Omar Sharif!

Lots of questions about the connection between the July 4 discovery and EWSB

The key questions looking forward

- Does the new boson discovered at the LHC exhibit the expected properties of the SM Higgs boson (spin? parity? couplings?)
- Will further study of the properties of this new state yield significant deviations from the SM Higgs boson expectations?
- How accurately can one measure the Higgs prope we need a dedicated precision Higgs factory?
- Will new BSM physics be discovered at the LHC t the origin of EWSB?

Howard Haber

- Is it a Higgs or an impostor? Does it participate in EWSB?
- If it is an Higgs, is it fundamental or composite?
- Implications for specific models?

Michele Papucci

From "Unanswered Questions in EW Theory"

1. What is the agent that hides the electroweak symmetry? Specifically, is there a Higgs boson? Might there be several?
2. Is the Higgs boson elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
4. What stabilizes the Higgs boson mass below 1 TeV?
5. Do the different behaviors of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?
6. What will be the next symmetry recognized in nature? Is nature supersymmetric? Is the electroweak theory part of some larger edifice?
7. Are there additional generations of quarks and leptons?
8. What resolves the vacuum energy problem?
9. Is electroweak symmetry breaking an emergent phenomenon connected with strong dynamics? Is electroweak symmetry breaking related to gravity through extra spacetime dimensions?
10. What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

Chris Quigg

the roadblock to physics beyond the SM

- For decades we claimed that the big roadblock to arriving at the promised land of total enlightenment was not understanding the mechanism of EWSB

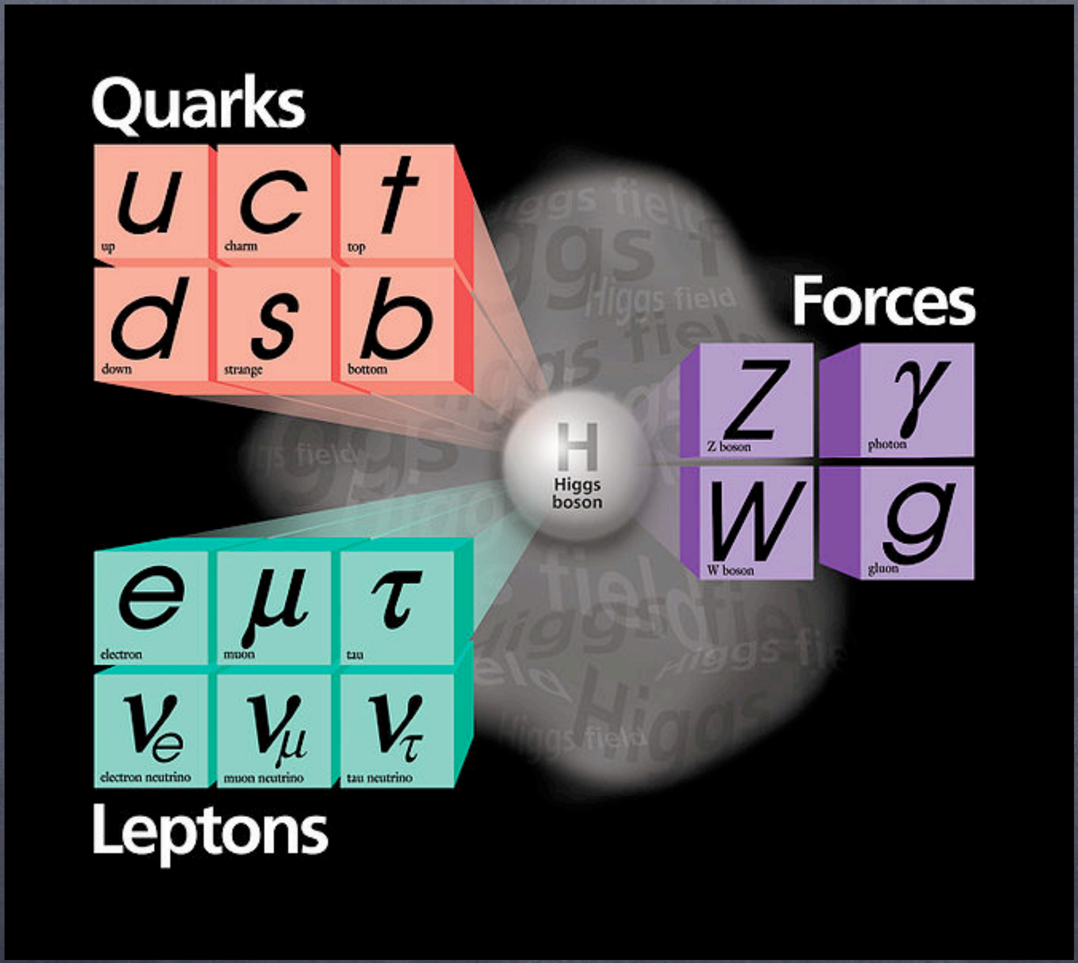
- Now we hope to make progress on a much broader front

some big questions

0. What is the origin of mass for fundamental particles?
1. Are there undiscovered principles of nature: new symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

Based on "The Quantum Universe," *HEPAP 2004*

BQ#0: what is the origin of mass for fundamental particles?



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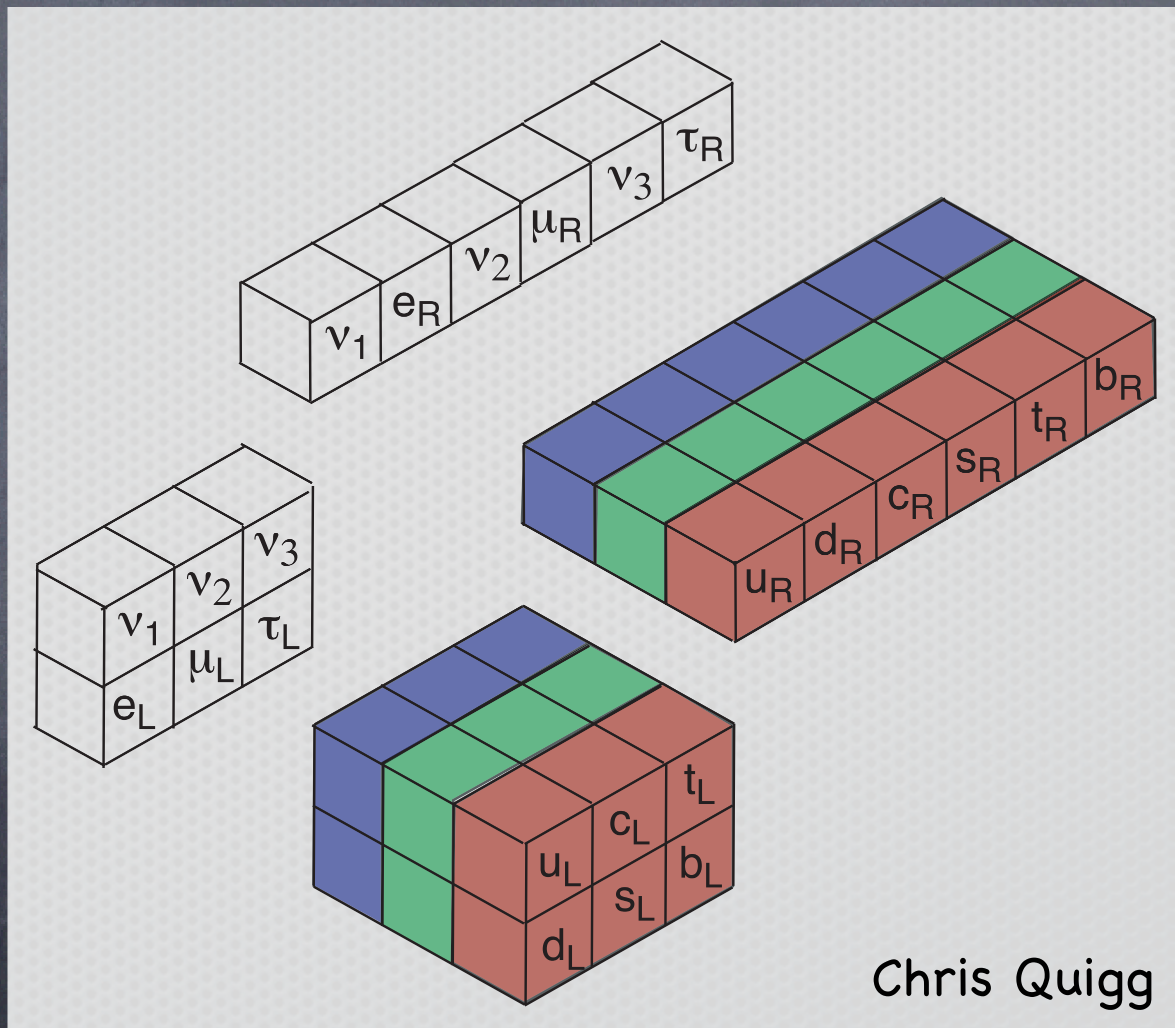

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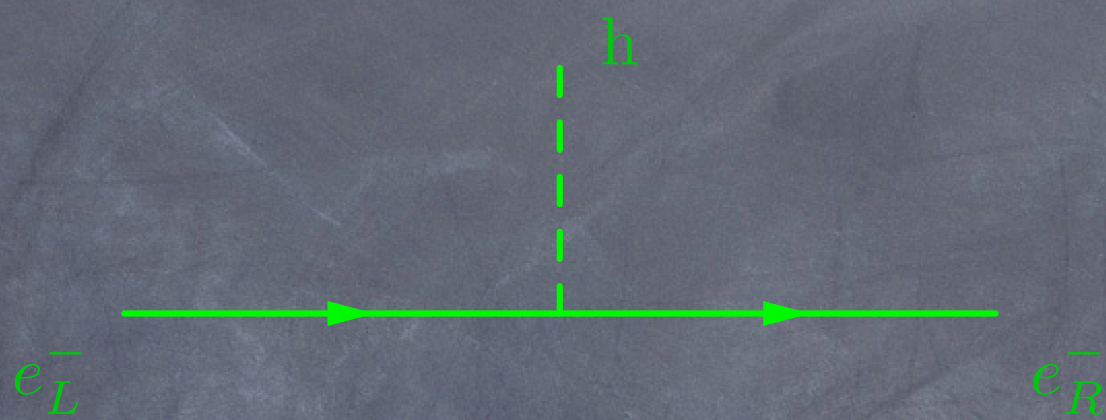
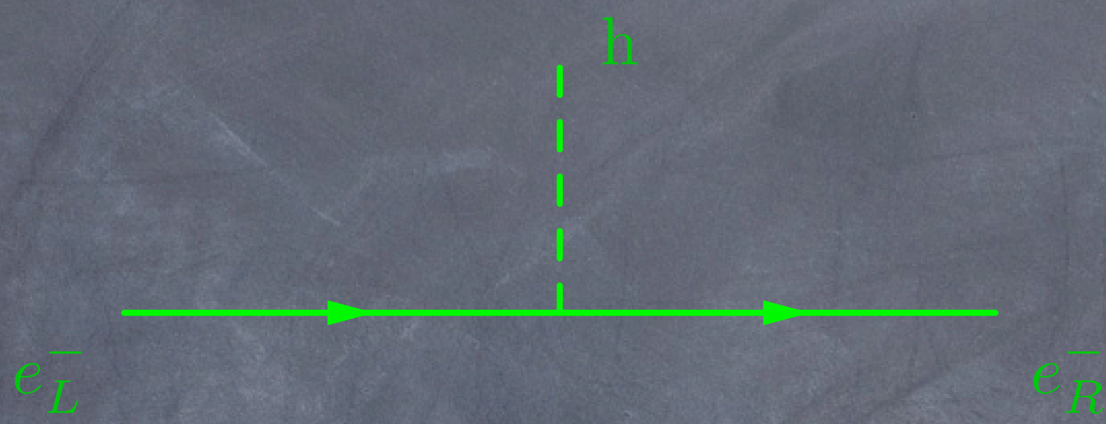


- In Weinberg's theory the new interaction is a weakly coupled Yukawa interaction with a fundamental Higgs scalar

virtues of the Higgs as mass giver



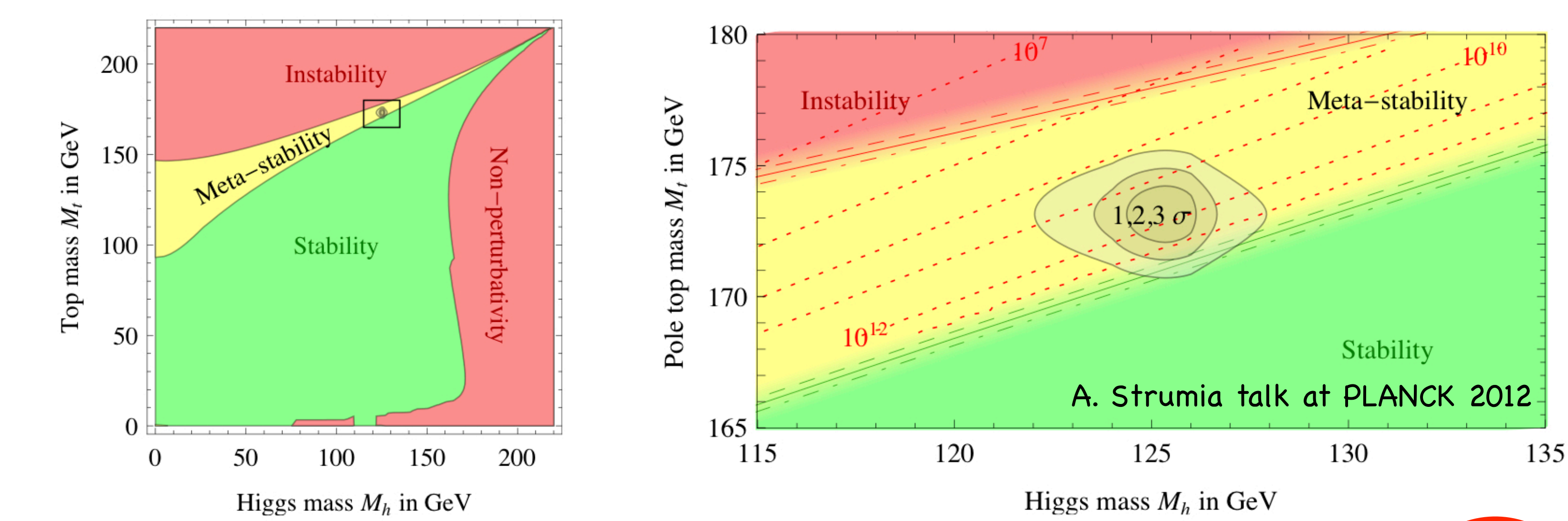
- The interactions are weakly coupled and simple
- Works for W, Z, quarks, and leptons
- Flavor-changing neutral currents suppressed

caveats of the Higgs as mass giver

- Why weakly coupled?
- Why should all fermions and gauge bosons get mass from the same source?
- Why a fundamental scalar?
- How a fundamental scalar?

One GeV differences that destroy the universe

A 126 GeV Higgs in the SM means you are just barely on the wrong side of the vacuum stability bound:



$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

we need to know both the Higgs mass AND the top mass to high precision to know if the universe is stable

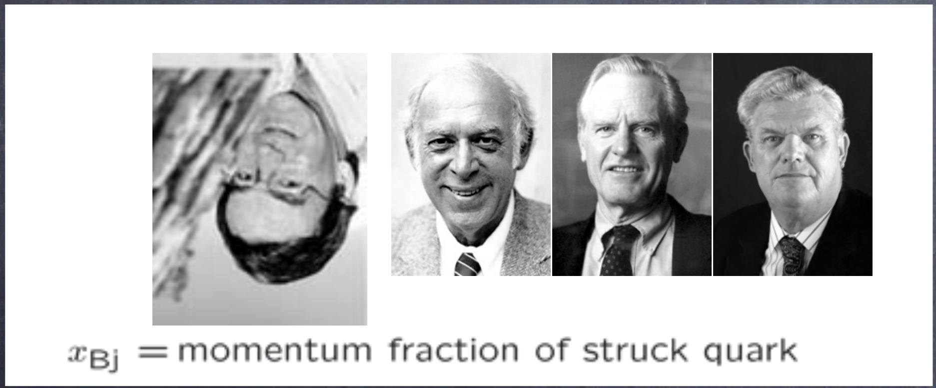
a suspiciously round number

How little we know: QCD

- It is often claimed that we understand 99% the mass of the proton from QCD
- While it is true that most of this mass comes from QCD, it is NOT true that we understand it
- Ask your local CM theorist if writing down the Lagrangian of a system means you understand all the physics...

what is inside the proton?

- Naive picture: a simple mixture of valence quarks, gluons, and virtual quark pairs.
- This is ONLY true if you are probing the proton with large Q and large Bjorken x, at zero temperature and zero chemical potential

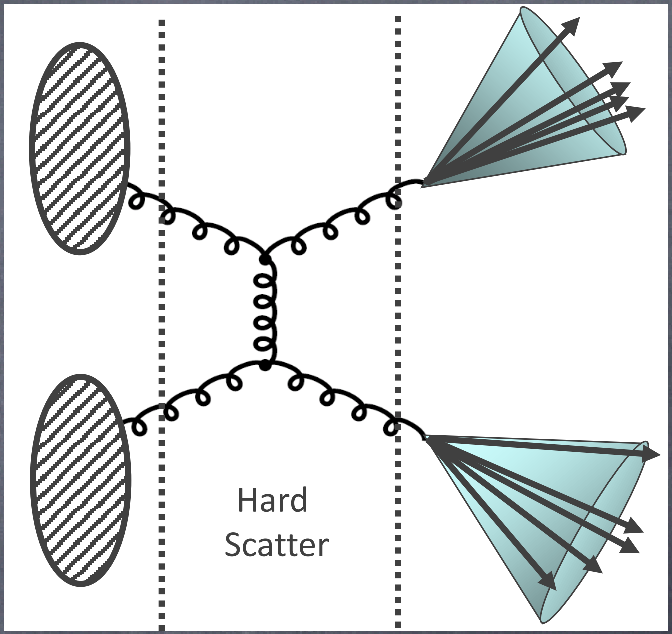


Lance Dixon

what is inside the proton?

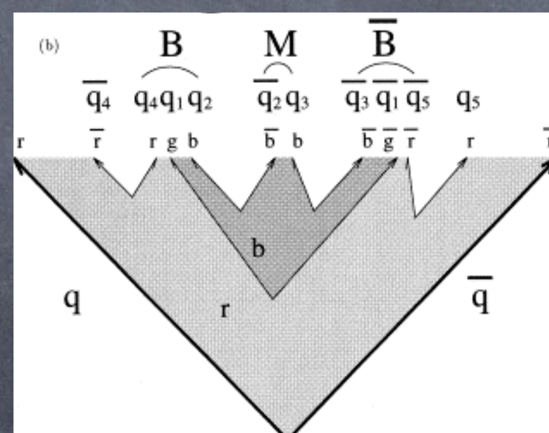
- Even for high pT processes at the LHC, the proton INITIAL state is described in terms of parton distribution functions parametrizing our ignorance

Tom LeCompte



- But we could also ask how FINAL state quarks and gluons at the LHC assemble themselves back into hadrons

- Pythia and Herwig do this, but they do NOT use QCD -- they use (different) phenomenological models
- Pythia uses "string fragmentation", an idea based on the original string theory of the 1970s
- Is this picture "correct"? What does that mean? How would we know?

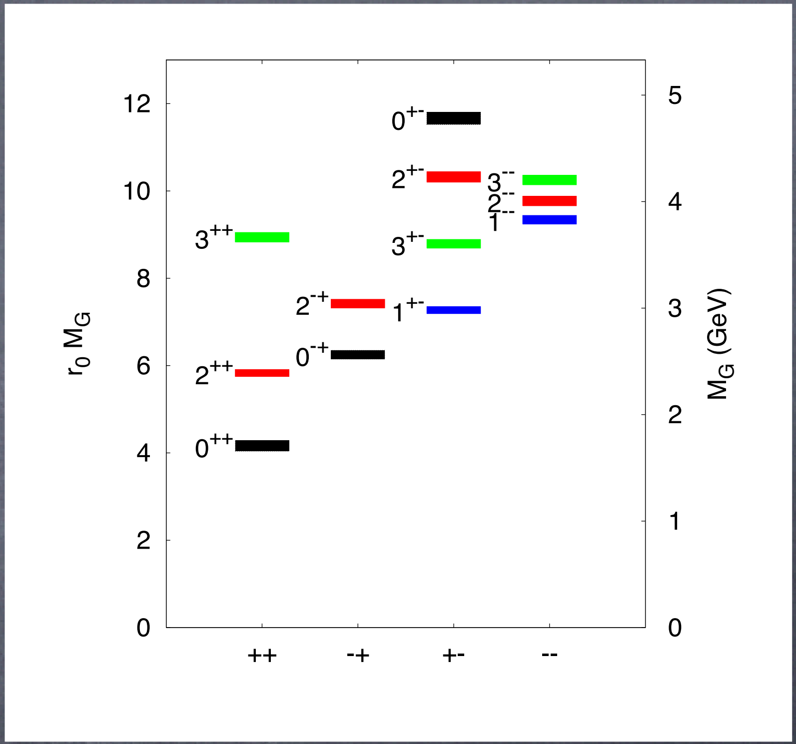


QCD: how little we know

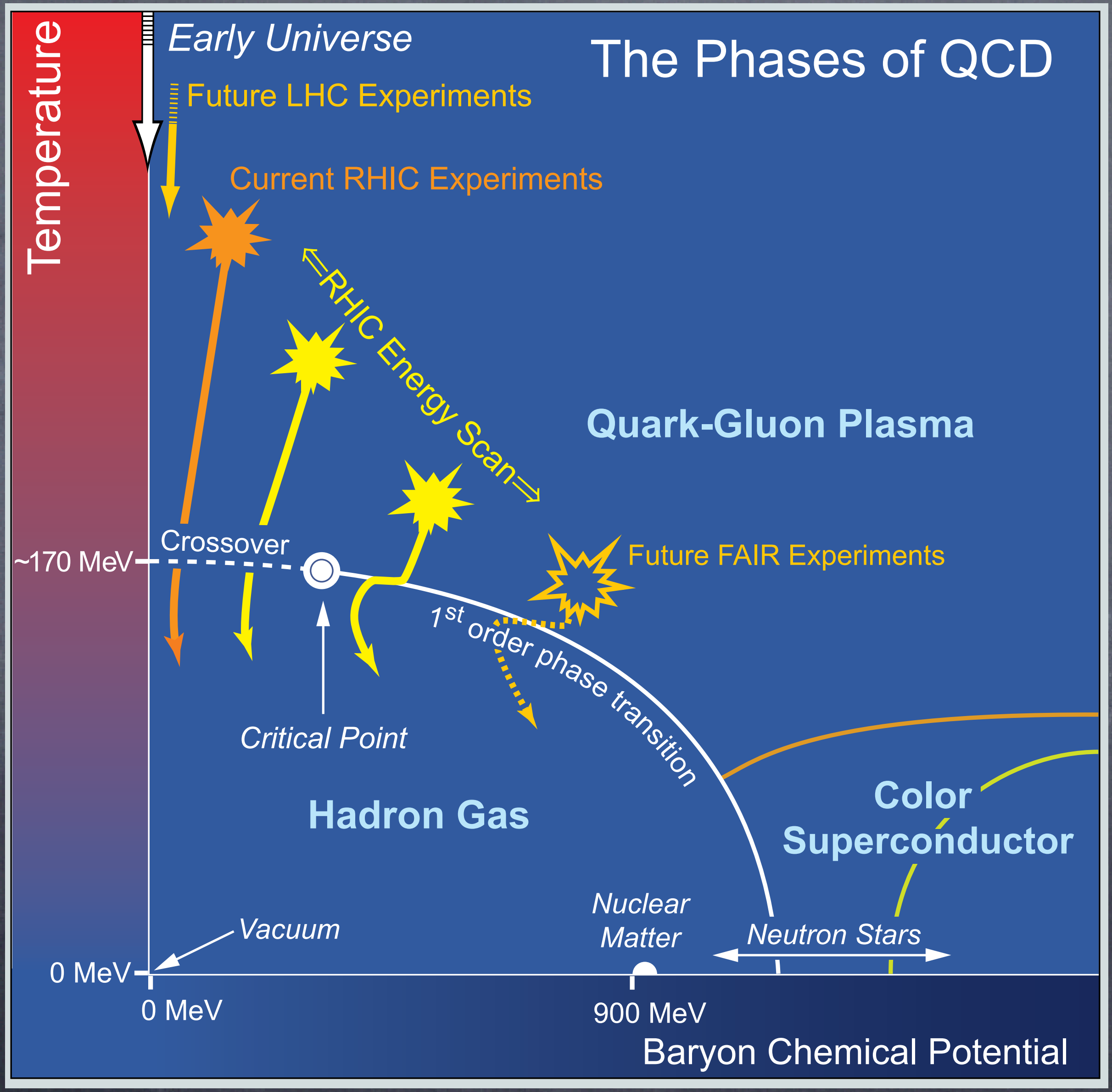
- Question: Doesn't lattice QCD allow is to compute all this nonperturbative stuff?
- Answer: Modern LQCD does make many important contributions, with real error bars, including computation of hadron masses from first principles
- But even for **heavy** quark spectroscopy BaBar and Belle have found unexpected states with unexpected masses

QCD: how little we know

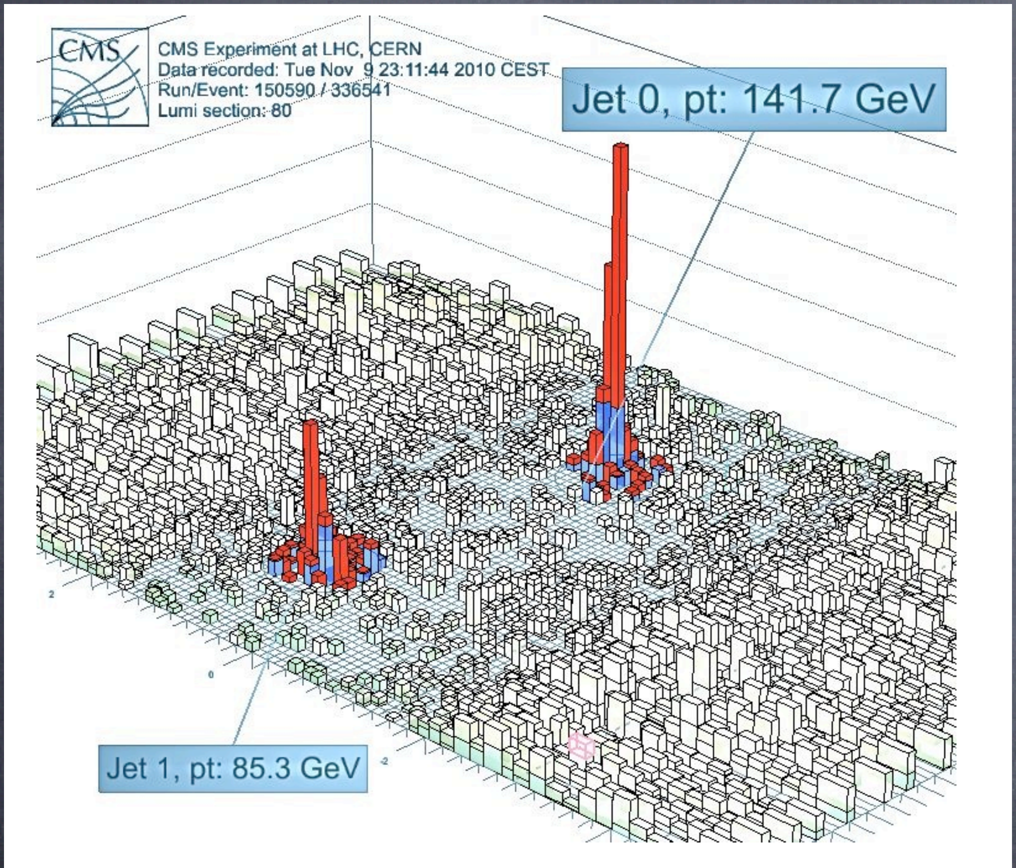
- Do quark-gluon hybrids exist?
- How many glueballs have we identified?
- In AdS/CFT duality, the 2^{++} glueball is a massive graviton
- What does this duality teach us about confinement? (Stan Brodsky)

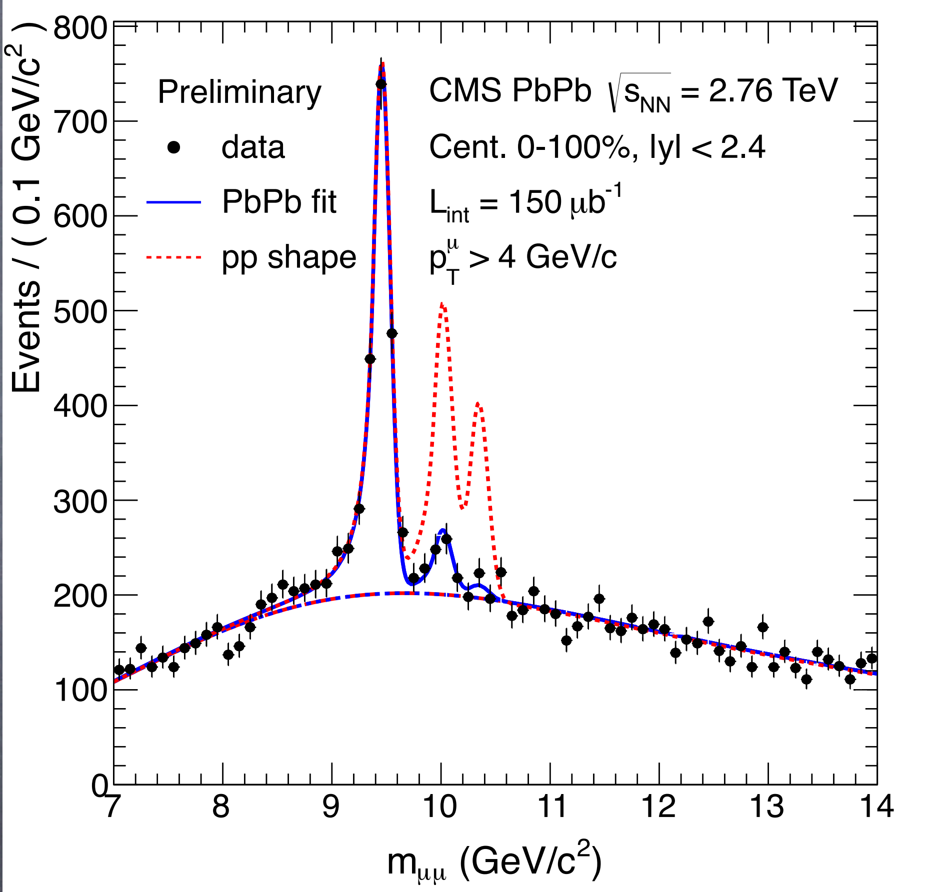


QCD at nonzero temperature or nonzero densities = terra incognita



QCD: how little we know





what kind of medium did this?

is this deconfinement?

where is the CP violation from the theta angle of QCD?

The $\theta_{\rm QCD}$ puzzle

- $\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\theta_{\rm QCD} G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}$
- $d_n \sim 3.6 \times 10^{-16}\ \theta_{\rm QCD}\ e\ {\rm cm}$
- $d_n^{\rm exp} < 2.9 \times 10^{-26}\ e\ {\rm cm}$
- $\Longrightarrow\ \ \theta_{\rm QCD} < 10^{-10}$

Yossi Nir

Can we detect a nonzero value of theta_QCD from EDMs?

How little we know: BSM

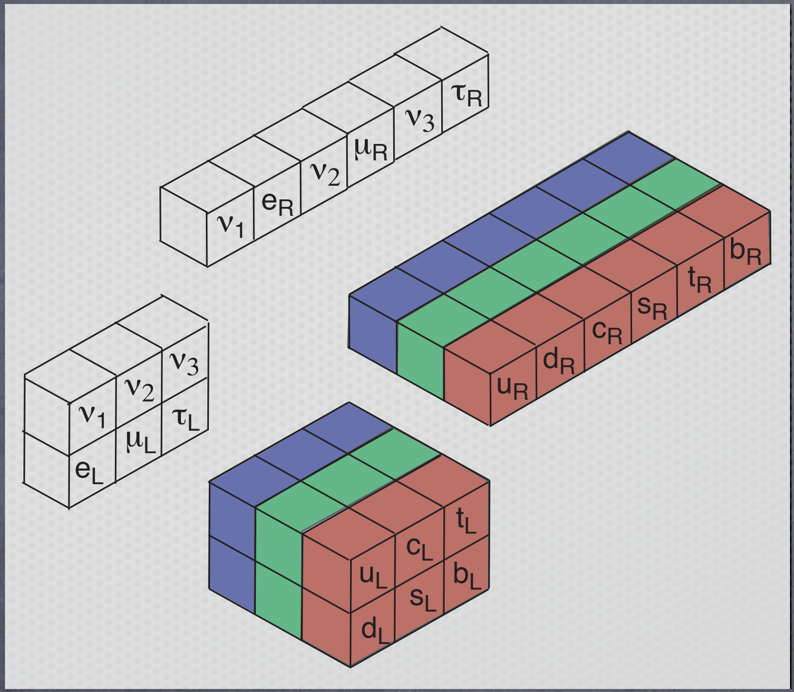
BQ#1: are there undiscovered principles of nature: new symmetries, new physical laws?

BQ#3: are there extra dimensions of space?

BQ#4: do all the forces become one?

why are there so many "elementary" particles?

Let's count:



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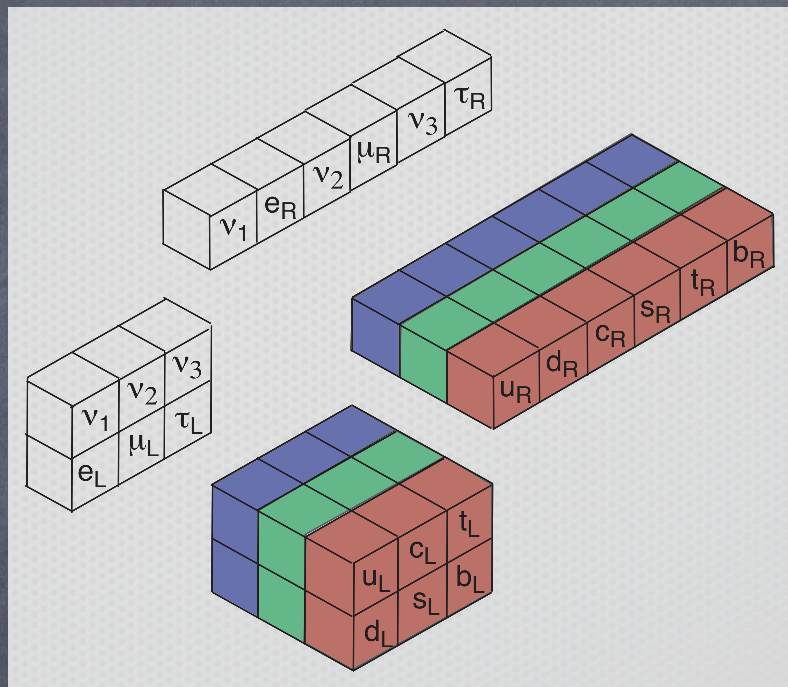
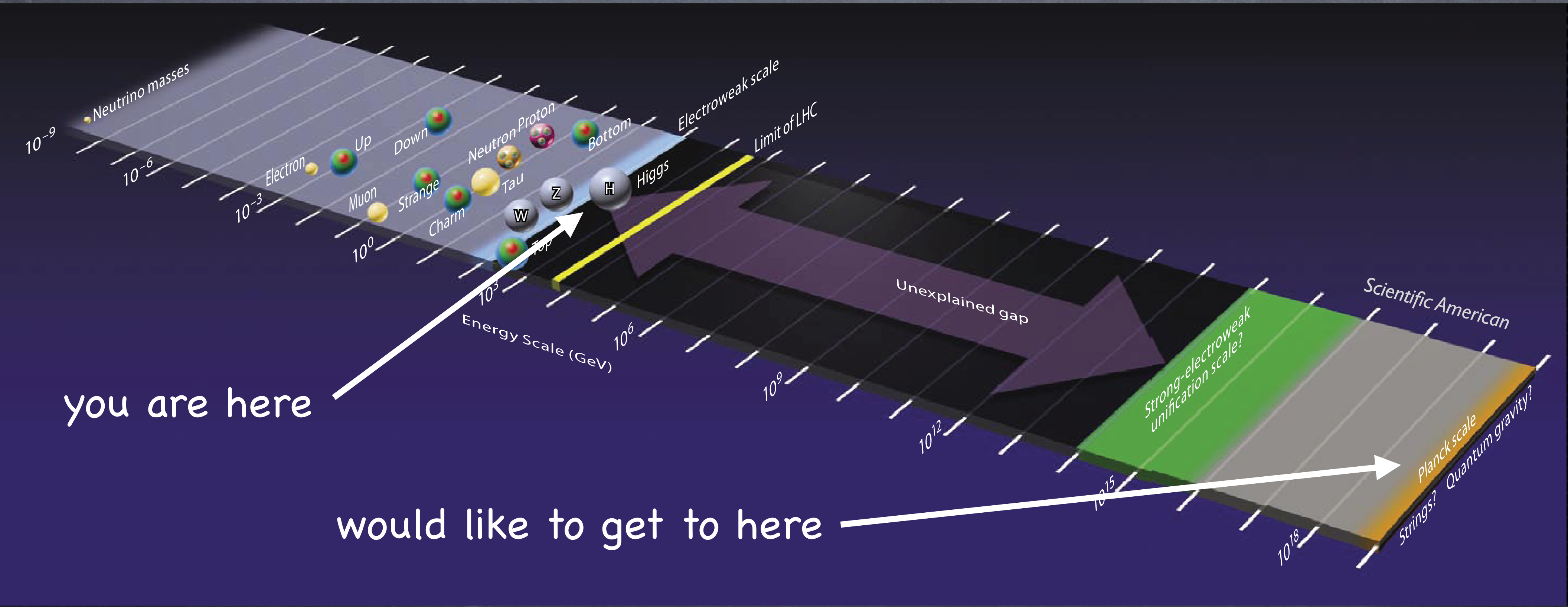


So (not including the Higgs, graviton, and RH neutrinos) there are 3*15 + 12 = 57 known "elementary" particles

why are there so many "elementary" particles?

- Is there a unifying principle (e.g. GUTs) or we should abandon the idea of elementary particles (e.g. string theory)
- We certainly have some good hints:

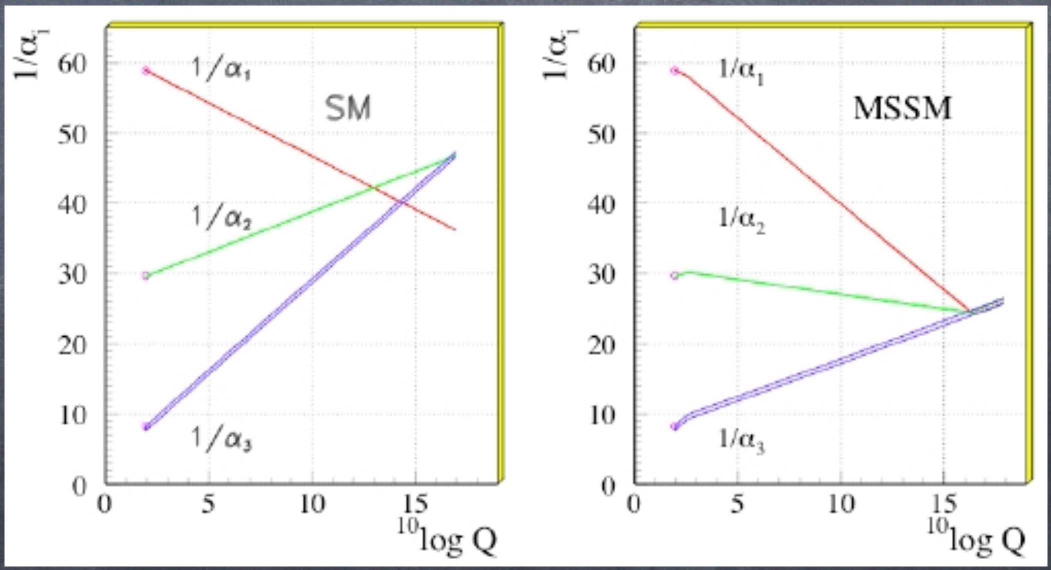


hints of unification?

- Both hypercharge and the approximate custodial symmetry of the SM seem to hint at a gauged SU(2)_L x SU(2)_R
- 15 quanta per generation matches a 5bar + 10 of SU(5), the smallest gauge group containing the SM gauge interactions
- with RH neutrinos we have 16 quanta, matching a 16 of SO(10), and suggesting that neutrinos may be different at the high scale

hints of unification?

- The rough "coming together" of the SM gauge couplings run up to super-high energies is already suggestive
- Even better when assisted by SUSY (both in the running and in allowing a hierarchy of scales)
- Why would Nature tease us like this?



the supersymmetry nonrenormalization theorem

Available on CMS information server **CMS NOTE 2008/018**

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

6 December 2008

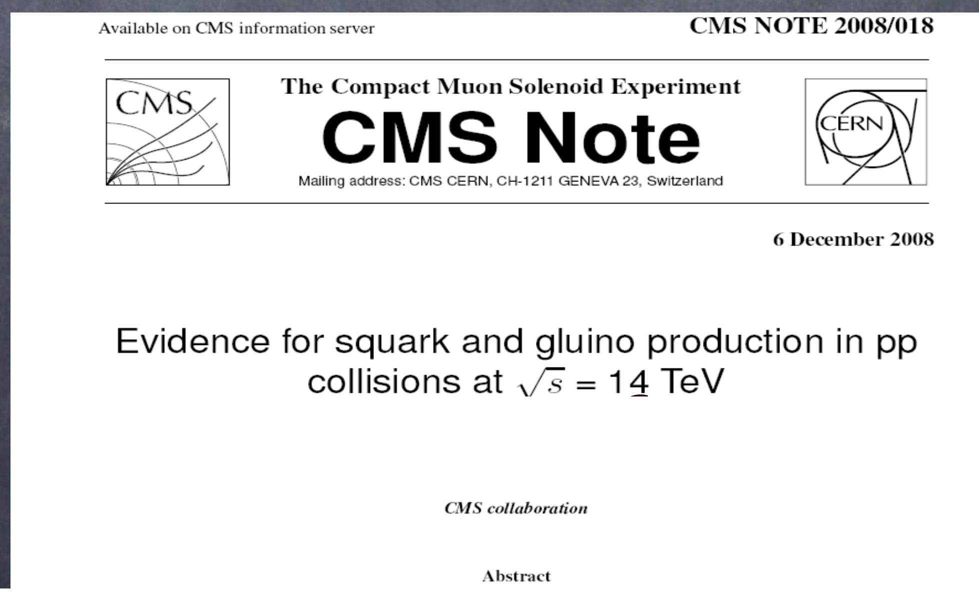
Evidence for squark and gluino production in pp collisions at $\sqrt{s}$ = 14 TeV

CMS collaboration

Abstract

the supersymmetry nonrenormalization theorem

- Supersymmetry was a good idea 30 years ago



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- Supersymmetry was a good idea 30 years ago
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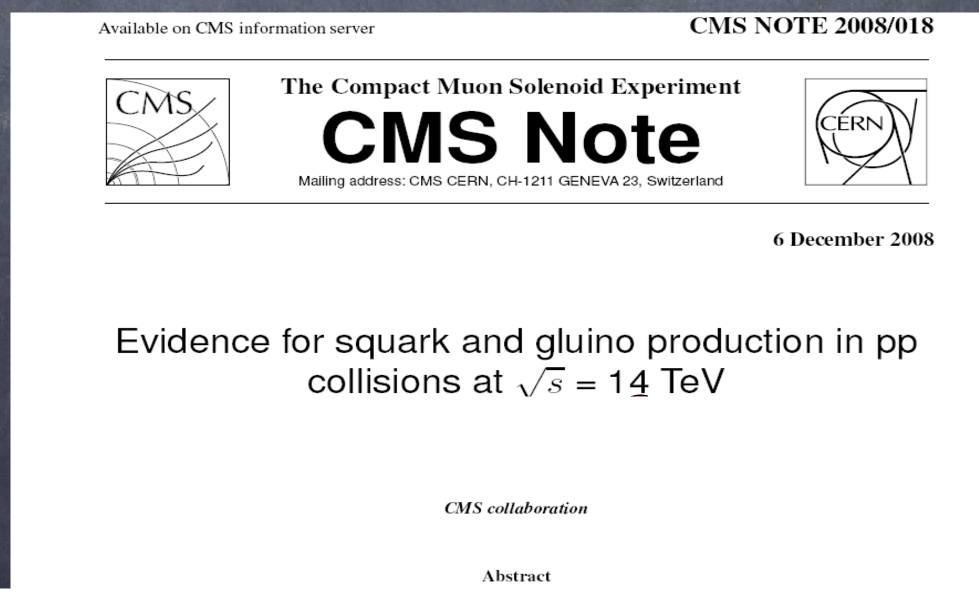

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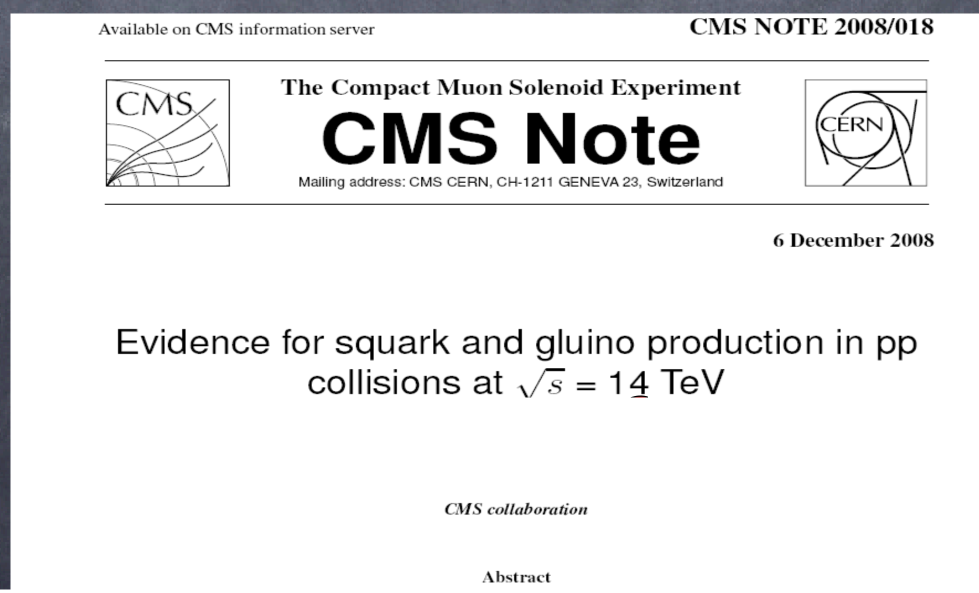
the supersymmetry nonrenormalization theorem

- Supersymmetry was a good idea 30 years ago
- Supersymmetry was a good idea 20 years ago
- Supersymmetry is a good idea now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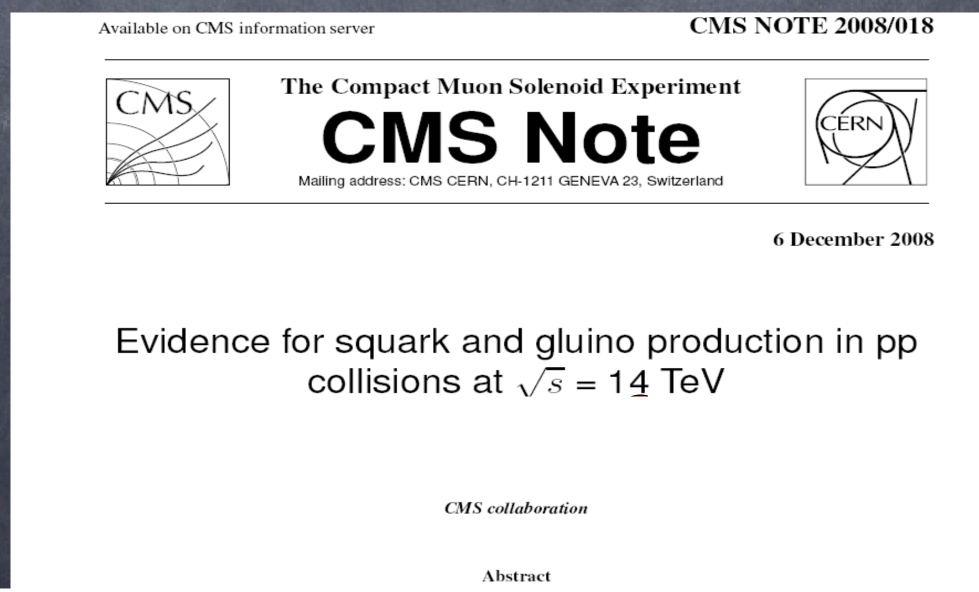
Abstract

the supersymmetry nonrenormalization theorem

- Supersymmetry was a good idea 30 years ago
- Supersymmetry was a good idea 20 years ago
- Supersymmetry is a good idea now
- Supersymmetry will be a good idea 20 years from now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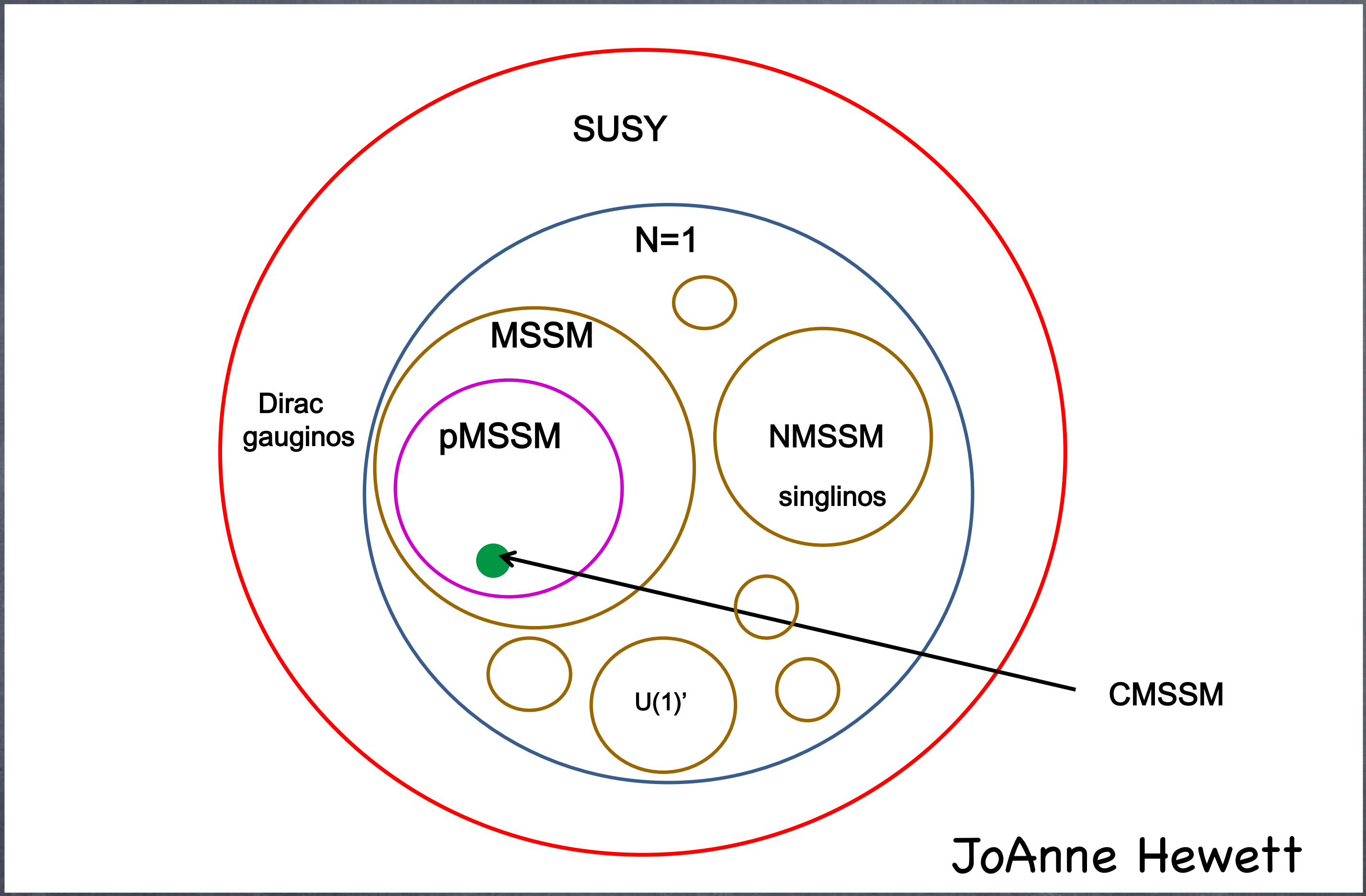
Abstract

which SUSY?



LHC searches are narrowing it down

string unification?

- String theory provides a more complex picture of unification
- In addition to SUSY, there are extra dimensions, membranes, extra gauge interactions, etc etc
- Perhaps this is more realistic and complete than GUTs, but it also more mysterious

How little we know: Flavor

- Why are there so many "elementary" particles?
- Why are there so many fermion mass hierarchies?
- Why are there flavor-violating hierarchies?
- How many sources are there of flavor and CP violation?

Why are there so many fermion mass hierarchies?

- There are a few nice relations, e.g. $\mathbf{m_s \simeq m_\mu, \quad m_c \simeq m_\tau}$

$$\mathbf{m_t = 172 \ \mathrm{GeV} = \frac{\mathit{v}}{\sqrt{2}}}$$

- But then there are intergenerational hierarchies:

$$\mathbf{\frac{m_\tau}{m_e} = 3600} \qquad \mathbf{\frac{(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)}{\mathit{v}^8} = 10^{-15}}$$

- And there are big hierarchies within an SU(2)L doublet:

$$\mathbf{\frac{m_t}{m_b} = 37}$$

- And the first generation masses are ridiculously light:

$$\mathbf{\frac{\mathit{v}}{m_e} = 492000}$$

- And with neutrino masses it is much worse:

$$\mathbf{\frac{m_t}{m_{\nu_i}} > 10^8}$$

Why are there so many fermion mass hierarchies?

These hierarchies are not naturalness problems, because setting the SM Yukawa couplings to zero restores a large global "flavor" symmetry:

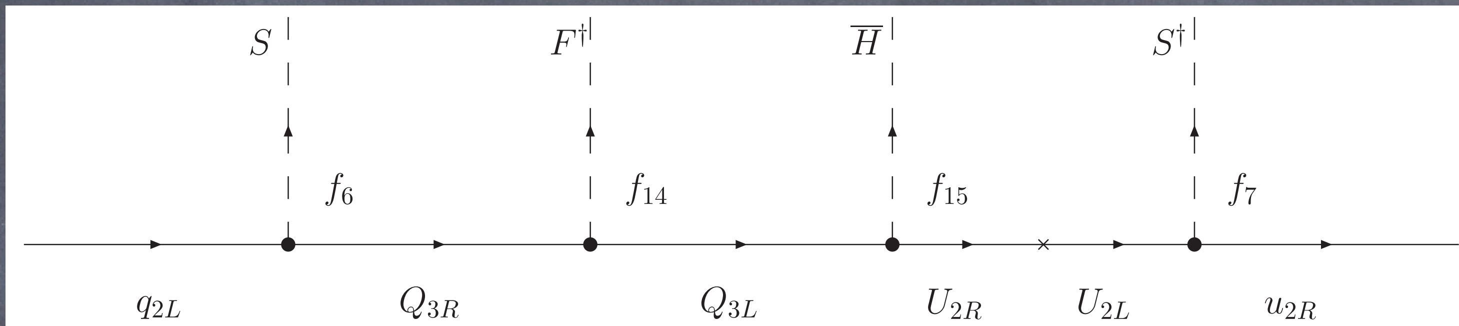
$$\mathbf{U(3)_Q \times U(3)_U \times U(3)_D}$$

How to generate all these different small numbers?
Many sorts of mechanisms are partially successful:

- Froggatt-Nielsen
- Loops
- Tumbling Extended technicolor
- Warped geography
- M-theory

Froggatt-Nielsen

Basic Idea: Lighter fermions do not couple to Higgs directly, but indirectly through a chain of Yukawa couplings to heavy vectorlike fermions and "flavon" scalars



Where do the small numbers come from: powers of $\epsilon = \dfrac{v_{\text{flavon}}}{\mathbf{M}_{\text{heavy}}}$

$$
\begin{aligned}
(m_t,\ m_c\ ,m_u) &\simeq (|h^u_{33}|,\ |h^u_{22}|\epsilon^2,\ |h^u_{11} - h^u_{12}h^u_{21}/h^u_{22}|\epsilon^6)\, v\ ,\\
(m_b,\ m_s,\ m_d) &\simeq (|h^d_{33}|\epsilon^2,\ |h^d_{22}|\epsilon^4,\ |h^d_{11}|\epsilon^6)\, v\ ,\\
(m_\tau,\ m_\mu,\ m_e) &\simeq (|h^\ell_{33}|\epsilon^2,\ |h^\ell_{22}|\epsilon^4,\ |h^\ell_{11}|\epsilon^6)\, v\ ,
\end{aligned}
$$

JL, Z. Murdoch, S. Nandi hep-ph/0812.1826

Froggatt-Nielsen

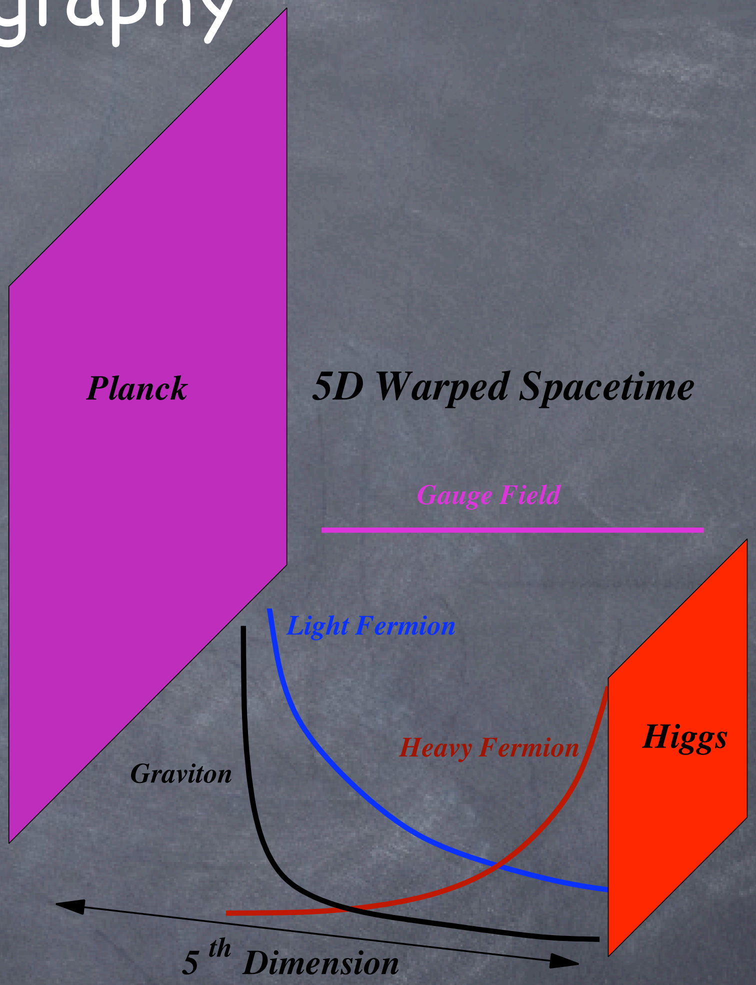
- Advantage: Could all be happening at the GUT scale
- Advantage: Might mesh with SUSY-like unification
- Advantage: If happening at the TeV scale, we will know soon

Why it cannot be the complete explanation: too complicated

Warped Geography

~~Randall-Sundrum models~~

Davoudiasl-Hewett-Rizzo models



Basic Idea: Higgs is localized at the IR brane of an RS type warped geometry. SM fermions live in the 5D bulk, have different wave function overlaps with Higgs

Where do the small numbers come from: 5D wave function overlaps

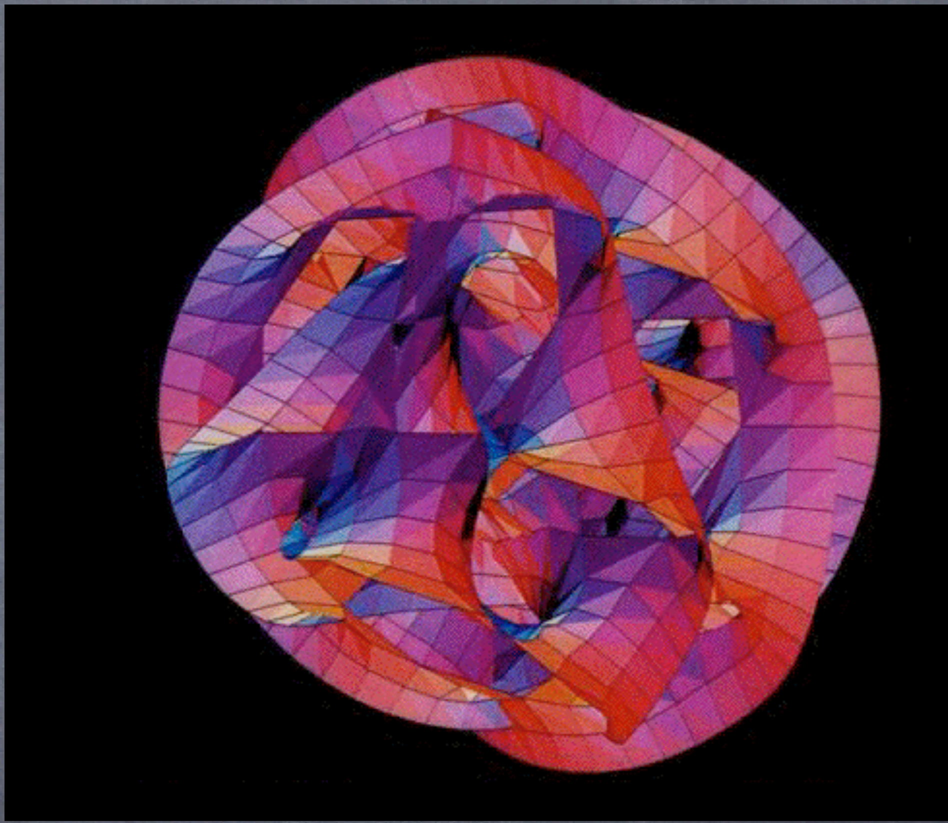
Warped Geography

- Advantage: Simple geometrical mechanism
- Advantage: Could give SM Yukawa couplings starting from random order 1 inputs

Why it cannot be the complete explanation: maybe it can! - but still need to explain/stabilize the warped geography, and avoid all the EW precision constraints

M theory

Basic Idea: In the 7 compactified dimensions of 11D M theory, different SM fermions are related to different brane wrappings and singularities in the 7D compact space



B. Acharya et al, hep-ph/0801.0478

Where do the small numbers come from: warp factors, flux factors, topological/cohomological indices

M theory

- Advantage: It's all at the Planck scale
- Advantage: Geometrical mechanism

Note: there are no actual models, just proof-of-principle

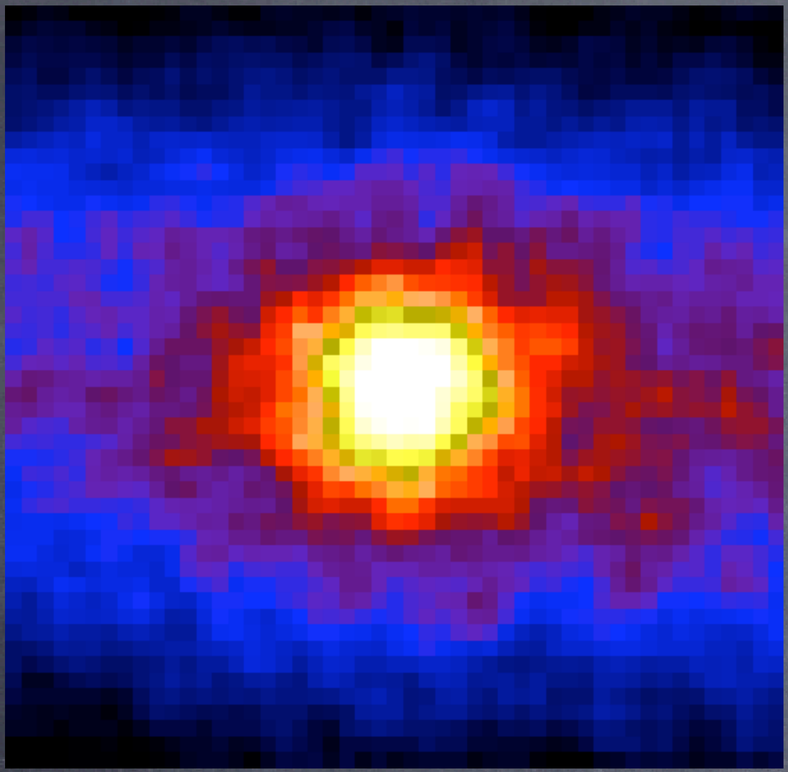
Why it cannot be the complete explanation: can't motivate the necessarily complicated compactification without getting anthropic

Why are there so many fermion mass hierarchies?

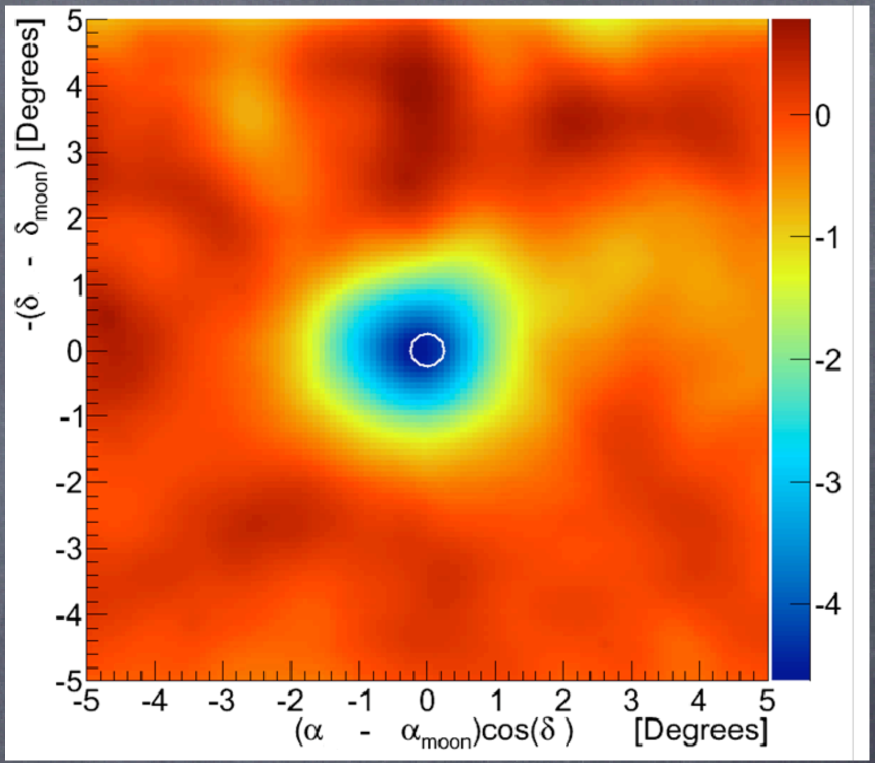
The bottom line:

- With the exception of the warped case, hardly anybody is working on this, so it is a big opportunity
- However it is a hard problem, partly because we don't know the relevant energy scales
- If the answer is all at the Planck scale it will be hard to get verification from experiment
- And beware the Dirac fallacy: "the most important problem in physics is to figure out why 1/alpha is 137"

How little we know: neutrinos



the Sun as seen by the Super-K water Cherenkov neutrino detector



the Moon as seen by the IceCube neutrino detector in ice at the South Pole

Neutrinos are Messengers of New Physics

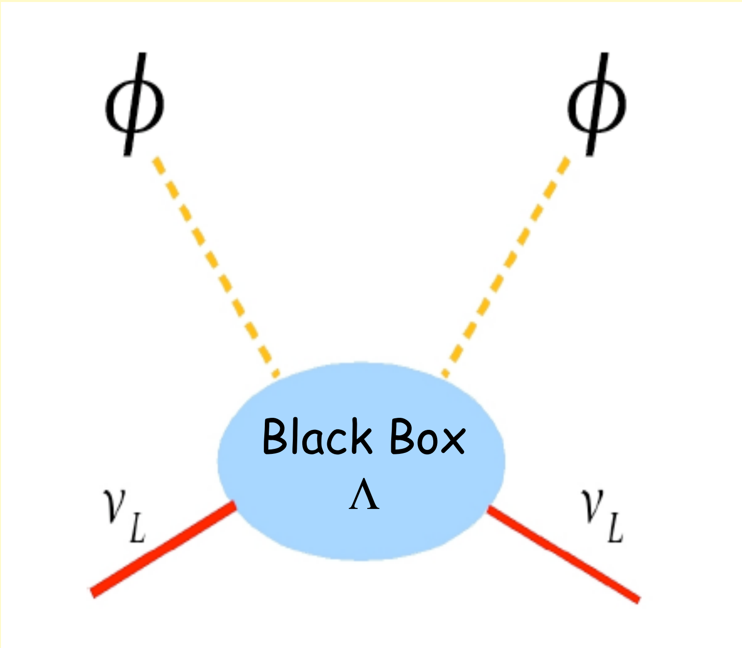
Neutrinos, unlike quarks:

- Have tiny masses
- May have "inverted" mass splittings
- Have large mixings
- Might be mixed with additional light fermions ("steriles")
- Might be their own antiparticles ("Majorana")
  - thus violating L and B - L
  - and having extra CP phases
  - and having superheavy partners

Furthermore:

- Their oscillation phase is sensitive to the medium (matter effects)
- They are part of the dark matter and may be related to dark energy
- They may experience new interactions or exotic effects

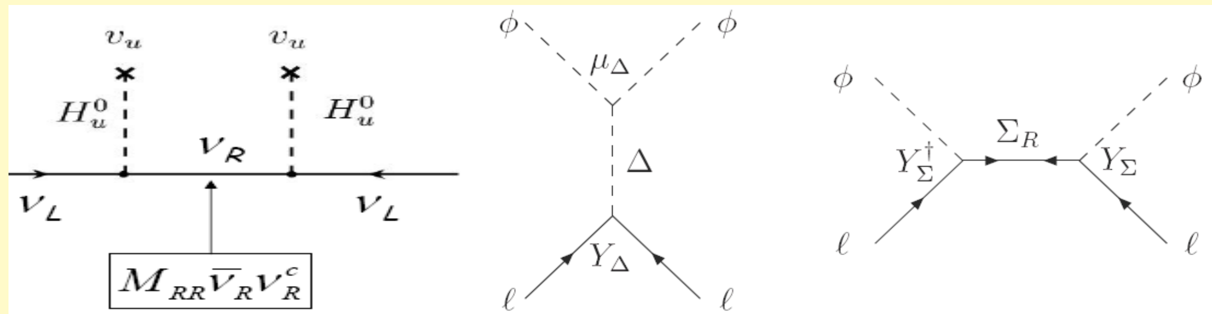
How do neutrinos talk to the Higgs?



Type I, fermion singlet N, charge 0

Type II, scalar triplet Δ, charge 0, 1, 2

Type III, fermion triplet Σ, charge 0, 1



+ variants (inverse, +SUSY, +LR, +radiative,...)

- Either neutrinos couple to the Higgs via superheavy partners, or via new TeV particles accessible at the LHC (connected to EWSB?)
- Need to nail down the neutrino masses, mixings, and possible CP phases
- Even more so if neutrinos have one or more sterile components

three ideas for baryogenesis

1. GUT inflation: baryogenesis happened very very early, and is mixed up with the details of primordial inflation.

   ➡Good theory motivation but may be impossible to prove.

2. Electroweak baryogenesis: the phase transition of electroweak symmetry breaking was sufficiently first order, and there was some new source of CP violation

   ➡If true, LHC experiments will see a nonstandard Higgs plus supersymmetry or other new particles

three ideas for baryogenesis

3. Leptogenesis: the baryon excess began as a lepton excess, from the CP violating decays of superheavy Majorana neutrinos

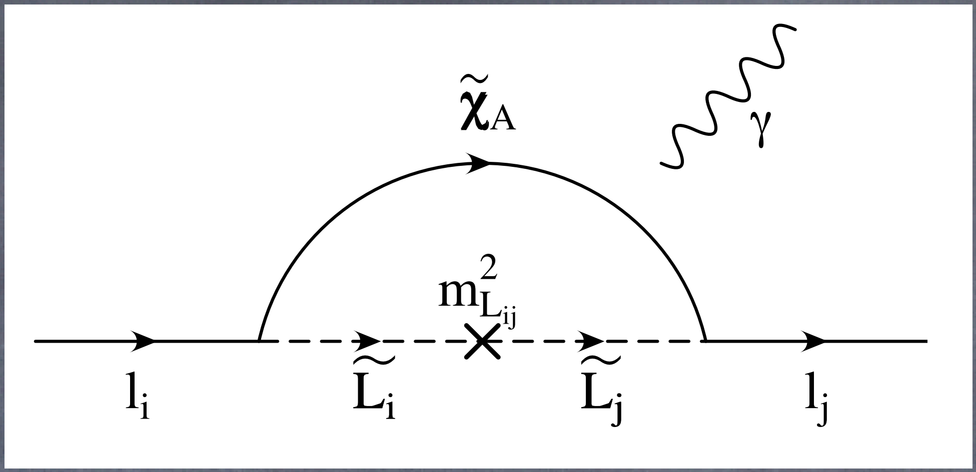
- If true, the "see-saw" mass mixing with these superheavy guys implies three properties of the observed neutrinos:

    ✓ they should have tiny masses

    – they should be Majorana

    – they should violate CP

new physics with muons

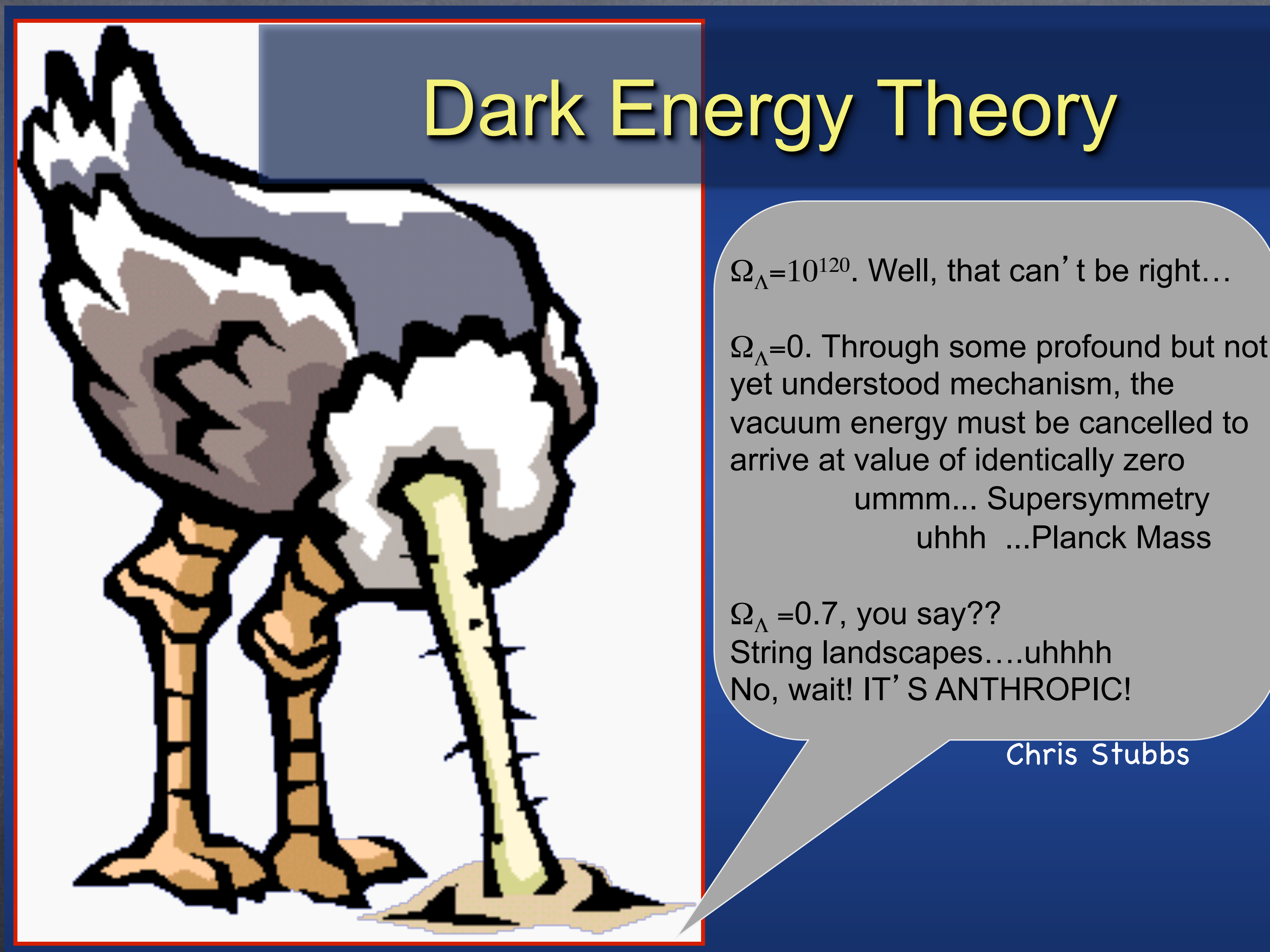


W. Altmannshofer, A. Buras, S. Gori, P. Paradisi, D. Straub, arXiv:0909.1333

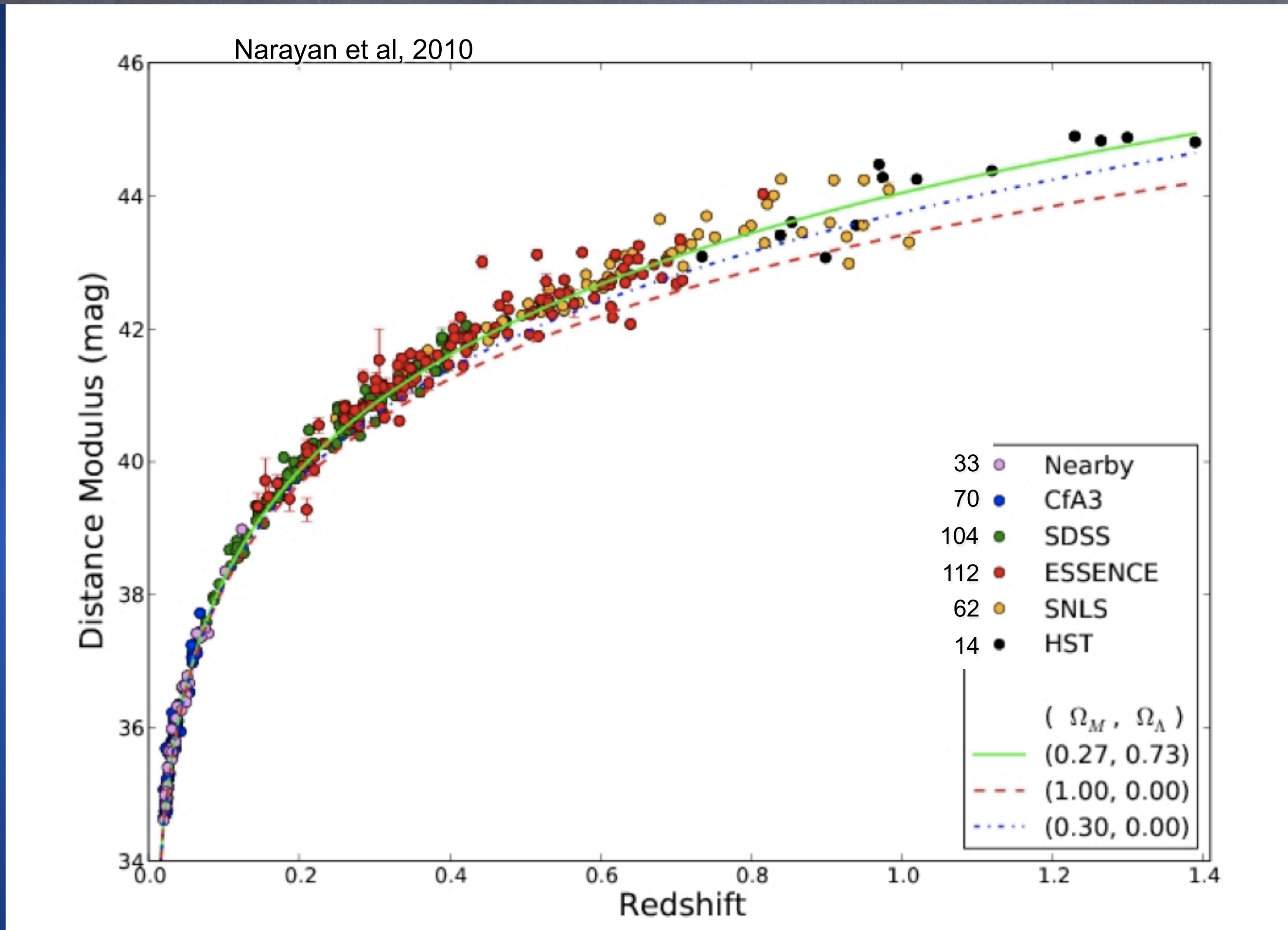
New heavy particles could affect charged leptons via loops

- The lepton flavor conserving, CP conserving part of this contributes to muon g-2
- The lepton flavor conserving, CP violating part creates an EDM
- The lepton flavor violating part induces mu to e conversion. Note that a heavy Majorana neutrino sector will induce this automatically

How little we know: dark energy



dark energy looks like vacuum energy



$$(1 + w) = 0.008 \pm 0.07(stat) \pm 0.13(syst)$$

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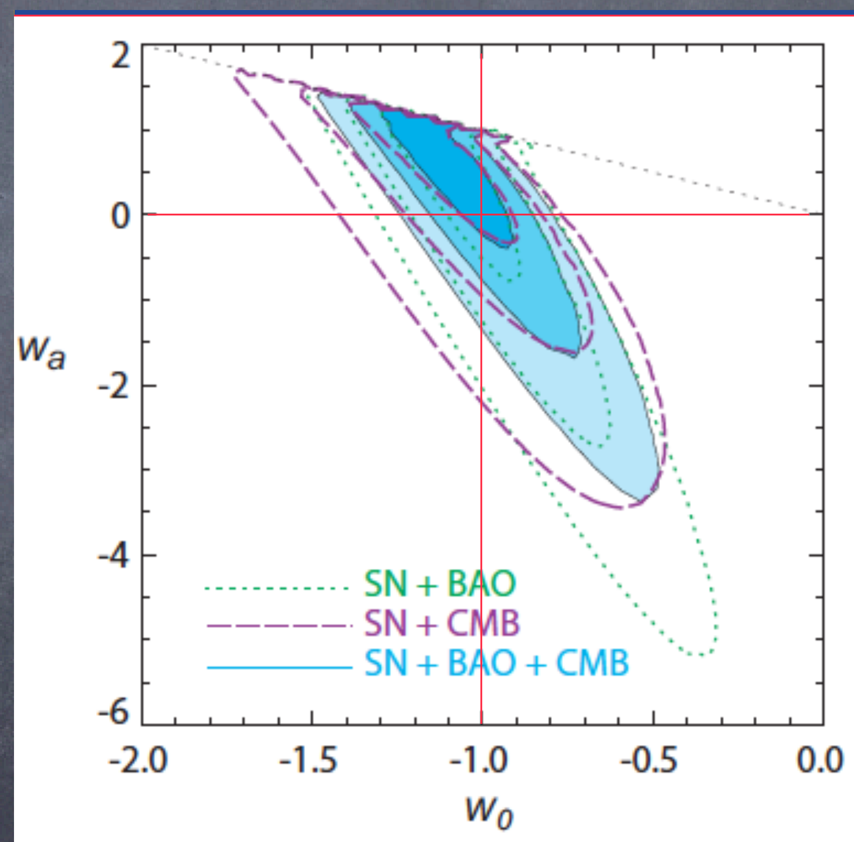
dynamical dark energy?

- OK can we tell if the equation of state of dark energy varies with time (i.e. billions of years)?
- Not yet

$$\mathbf{w = w_0 + w_a(1 - a(t))}$$

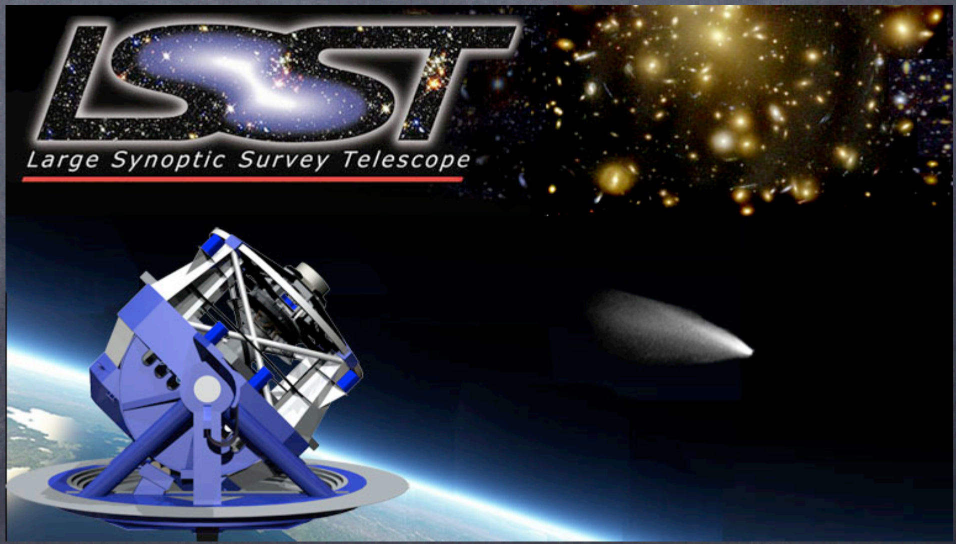


no dark energy?

- accelerated expansion of the universe does NOT necessarily imply that there is a new kind of source term for the Einstein equations of GR

- maybe the problem is with the Einstein equations themselves (modified GR? extra-dimensional gravity with branes?)

- maybe the problem is that the universe is not really homogenous on large scales



theorists: what good are they?

Question: of living theorists, which two made the most essential contributions to the "Higgs" discovery?

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explained why it should be there

Steven Weinberg

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explained why it should be there

Steven Weinberg

senior (living) author of PYTHIA, which (along with HERWIG and SHERPA) makes it possible to make discoveries at hadron colliders

Torbjorn Sjostrand

beware the myth of the solitary genius

- Science is a social enterprise
- Experiments require collaboration, specialization, coordination, and a lot of patience
- Theory advances emerge from the Zeitgeist of a whole community exchanging and criticizing ideas

The LHC era: looking ahead

- The LHC era (with HL and perhaps HE upgrades) will last for a long time
- We should therefore be very ambitious about the physics goals of this program

CMS Workshop. "Perspectives on Physics and on CMS at Very Very High Luminosity"

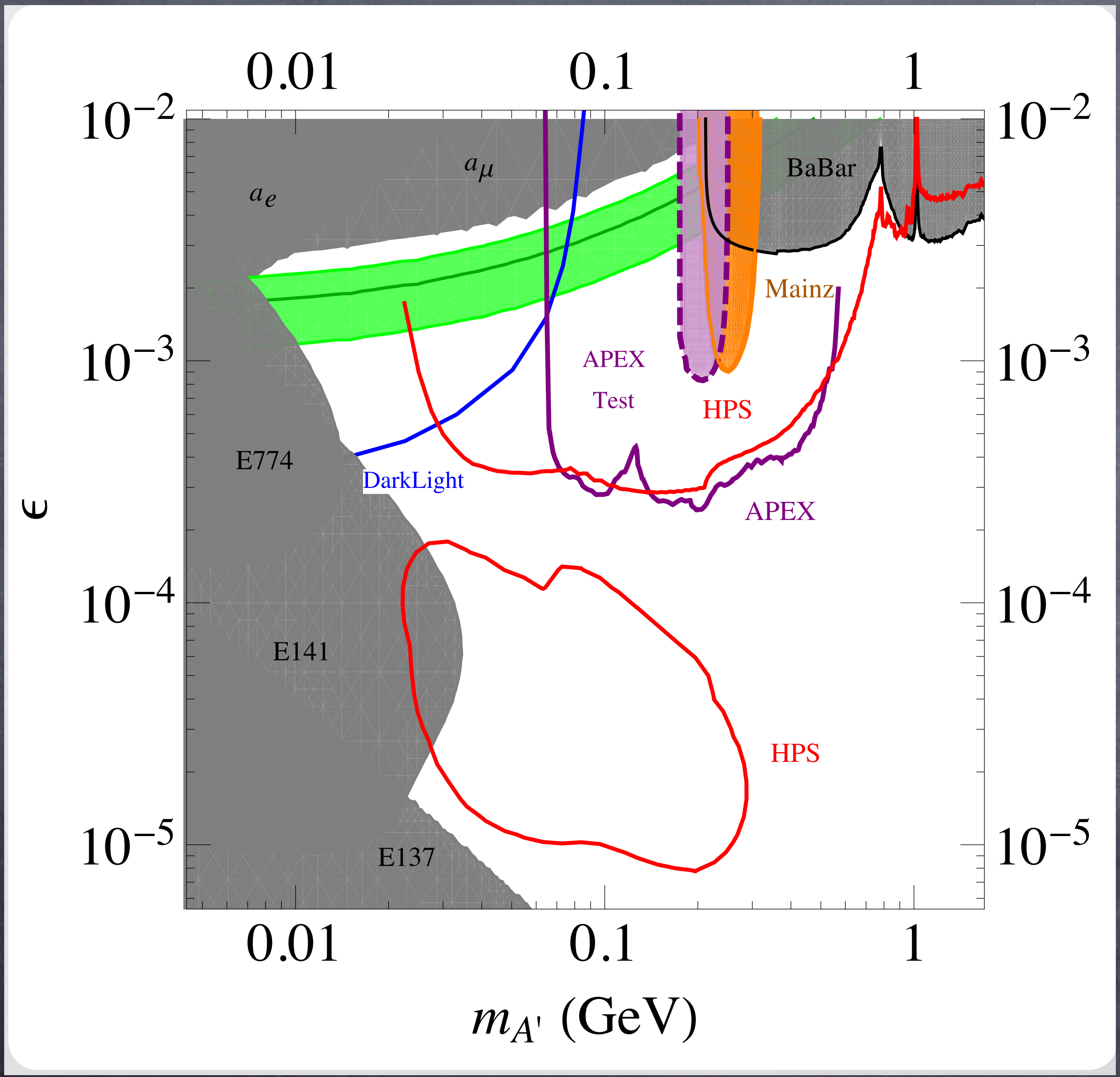
Alushta,Crimea,Ukraine, 28-31 May, 2022

The LHC era: looking ahead

- We should push for a Next Lepton Collider
- And push for a variety of experiments at lower energies
- Not everything that has strong physics motivation will actually happen (funding), but that's OK
- A lot of it won't happen in the USA (not so OK)

"Throw deep!"

Can we connect to the dark sector?



Matthew Graham
Dan Hooper
Patrick Fox
Tim Tait

(NOT) THE END

stolen from A. De Roeck