DISCOVERY AT THE ILC AND BEYOND

PATRICK MEADE
YANG INSTITUTE FOR THEORETICAL PHYSICS
STONY BROOK UNIVERSITY

This talk originally was the “physics summary” for the 2018 International Workshop for Future Linear Colliders

Michael Peskin et al made the brilliant or awful(yours to decide after this talk) decision to give me free rein to make an “interesting” talk rather than just a summary which resulted in:

A PERSONAL JOURNEY INTO DISCOVERING THE PHYSICS POTENTIAL OF A LC

PATRICK MEADE
YANG INSTITUTE FOR THEORETICAL PHYSICS
STONY BROOK UNIVERSITY

Now I’ve changed it more or less to:

A PERSONAL JOURNEY INTO DISCOVERING THE PHYSICS POTENTIAL OF AN ILC AND BEYOND*

PATRICK MEADE
YANG INSTITUTE FOR THEORETICAL PHYSICS
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The “beyond" is just my caveat to say that
the questions I’ll address can be attacked at the ILC, but
can also be addressed at other future collider projects.

Nevertheless, the ILC is the first and possibly most important
step that I’ll be talking about today

I’m a theorist, so this effectively means I have no knowledge of anything substantive about the ILC (or anything else), my current info comes from Twitter

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Patrick Meade Retweeted

Iwate & the ILC @IwateILC · 21h

The final deadline for a decision is March 7th – Scientists urge the national government to voice their intent at an FDMILC assembly

@iwatenippo reports: iwate-ilc.jp/eng/news/the-f…

5 8

The final deadline for a decision is March 7th – Scientists urge the national government to voice their intent at an FDMILC assembly

TRANSLATED BY **AMANDA WAYAMA** | DECEMBER 12, 2018

The original article was published in the Iwate Nippo (December 8th edition). Read the original here.

TIMELINE

December 7th – The Science Council of Japan (SCJ) begins reviewing the draft from the ILC Committee

December 19th – SCJ Board of Directors meeting

-2019-

January 31st – SCJ Board of Directors meeting

February 28th – SCJ Board of Directors meeting

(Sometime within January-February, the national government will make its intentions clear?)

March 7th – Meeting held in Tokyo by International Committee for Future Accelerators (ICFA) and the Linear Collider Board (LCB) (→this is the final deadline)

MY PERSONAL JOURNEY

Early 2000's grad school

ILC is a precision machine
only useful after LHC
discovered something

2012 Higgs Discovery

ILC probably won't
see anything based
on LHC data

2018

ILC can be a
discovery machine!

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*I'll **attempt** to make this journey accessible to all, this talk by no means covers all the interesting things the ILC can do and is heavily influenced by my personal opinions*

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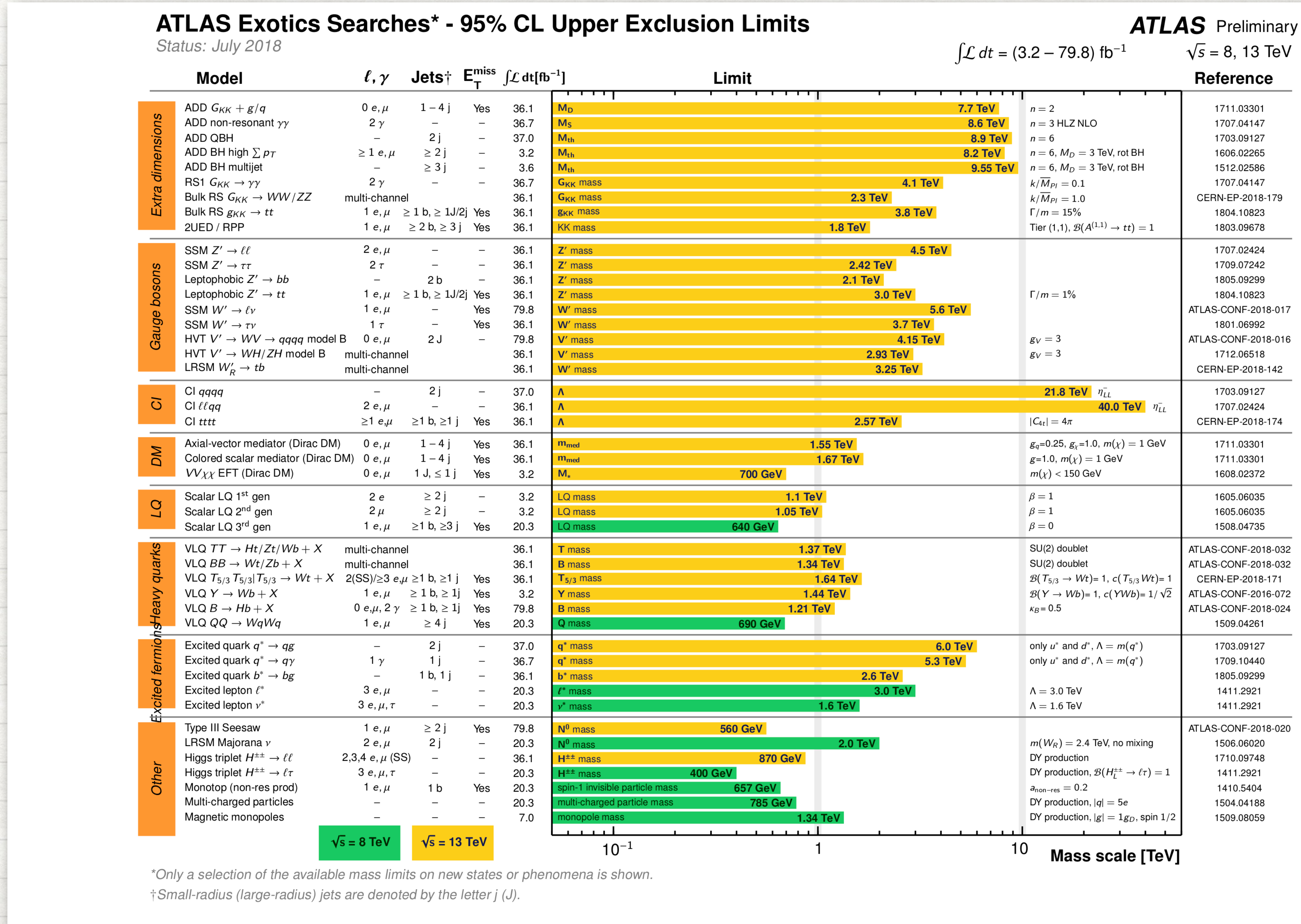
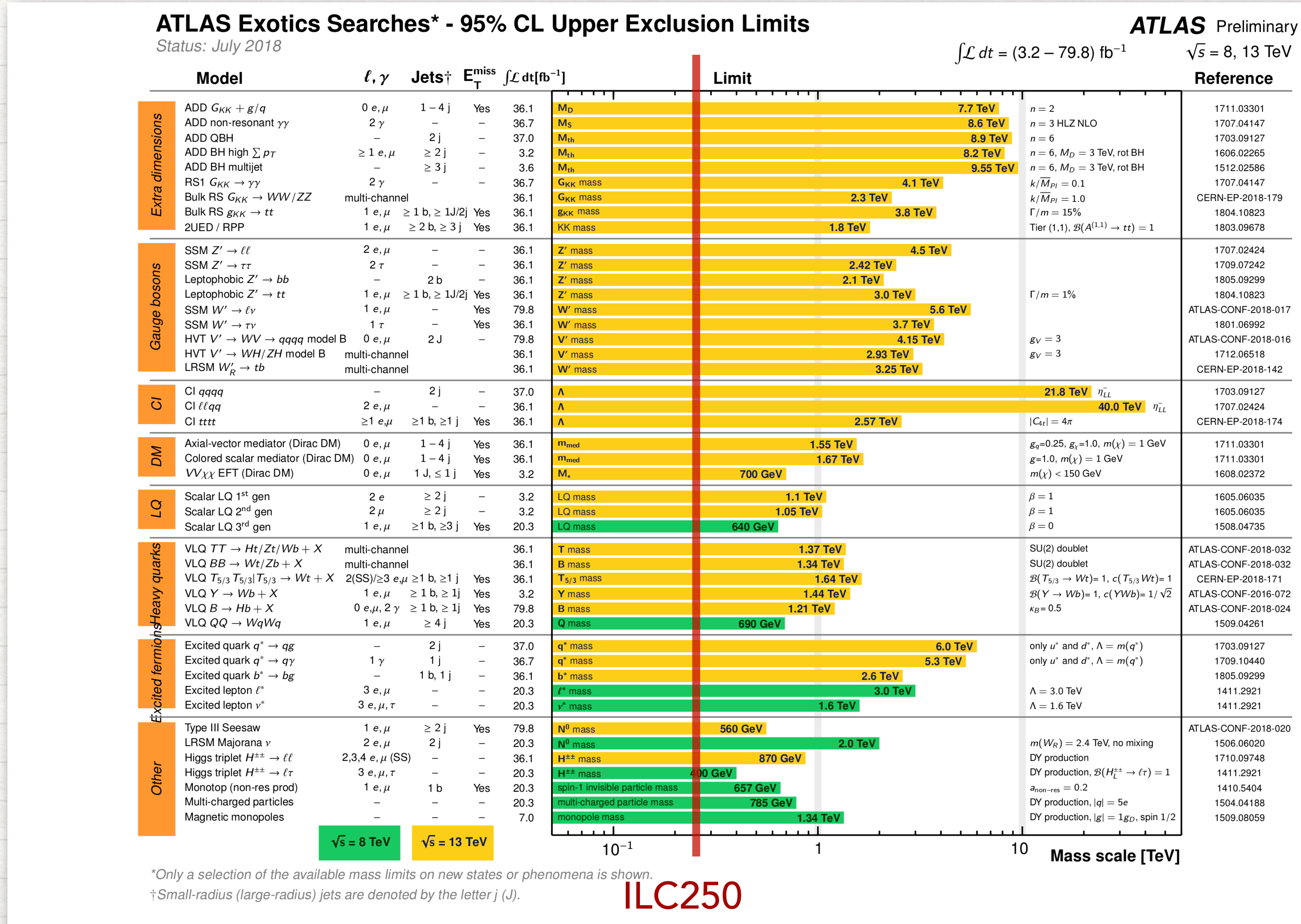
You could also already take from this you should never listen to me…
However, like most people I'm guided by my understanding (of QFT) which evolves over time

HOW DO WE GO FROM HERE...



HOW DO WE GO FROM HERE...



HOW DO WE GO FROM HERE...

WHERE IS THE NEW PHYSICS??

DOES AN ILC HAVE ANY PHYSICS POTENTIAL??

TO HERE???

THE PHYSICS POTENTIAL NEVER TASTED SO GOOD!!

HAVE TO UNDERSTAND THE HISTORY*

HAVE TO UNDERSTAND THE HISTORY*

- When I was a graduate student, the ILC was “pitched” as a precision machine that would follow the LHC and determine the underlying scale of SUSY breaking and mediation mechanism…

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Problem 2. Slepton production at a Lepton Collider. Consider pair-production of the lightest smuon $\tilde{\mu}_1$ (of mass $M_{\tilde{\mu}_1}$) at a future Linear Collider of center-of-mass energy $E_{CM} > 2M_{\tilde{\mu}_1}$. Assume that the smuons decay directly to the LSP, which is the lightest neutralino $\tilde{\chi}_1^0$ of mass $M_{\tilde{\chi}_1^0}$. The diagram for this process is shown in Fig. 1.

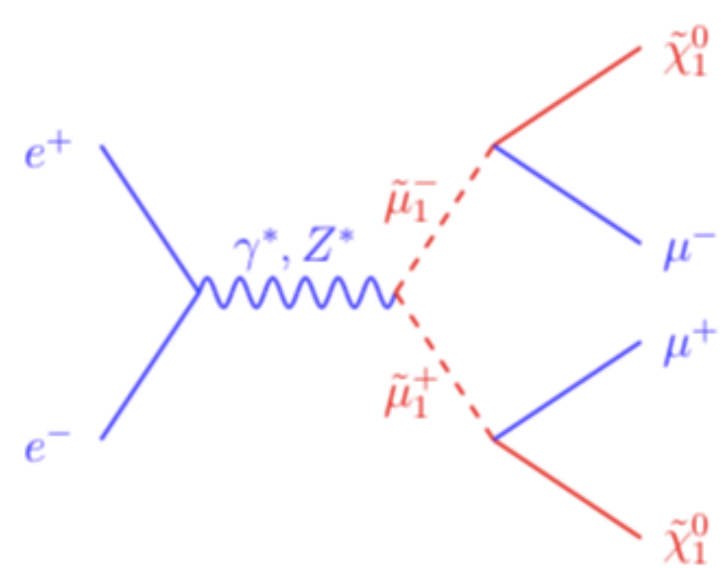


Figure 1: Smuon pair production and decay at an e^+e^- collider.

(b) Make a histogram of the muon energy distribution. Notice the box-like shape of the distribution. Record the values of the two endpoints, E_{min} and E_{max}, of the muon energy distribution and use them to calculate the slepton and neutralino masses $M_{\tilde{\mu}_1}$ and $M_{\tilde{\chi}_1^0}$. How close did you get to the real answer?

SO MUCH SO IF WE GO BACK TO 2008 PHYSICS SUMMARIES

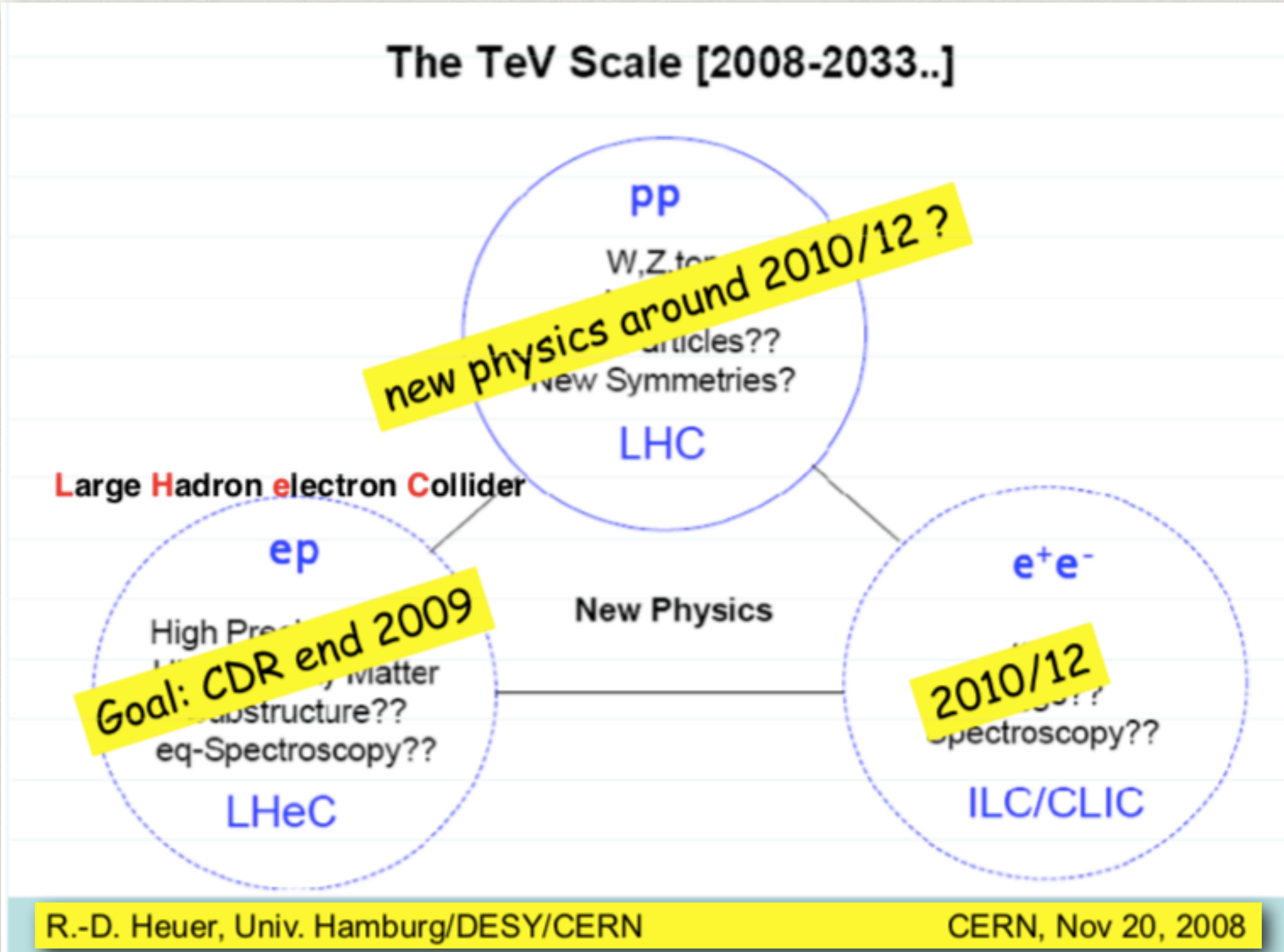
Jonathan Bagger

Physics case

- The physics case must be built on the LHC
  - The LHC will open the Terascale …
    - We need to celebrate its success!
- The case has not changed!
  - We have every expectation that the ILC will be the appropriate follow-on to the LHC …

Two striking examples of LHC-ILC synergy

SO MUCH SO IF WE GO BACK TO 2008 PHYSICS SUMMARIES

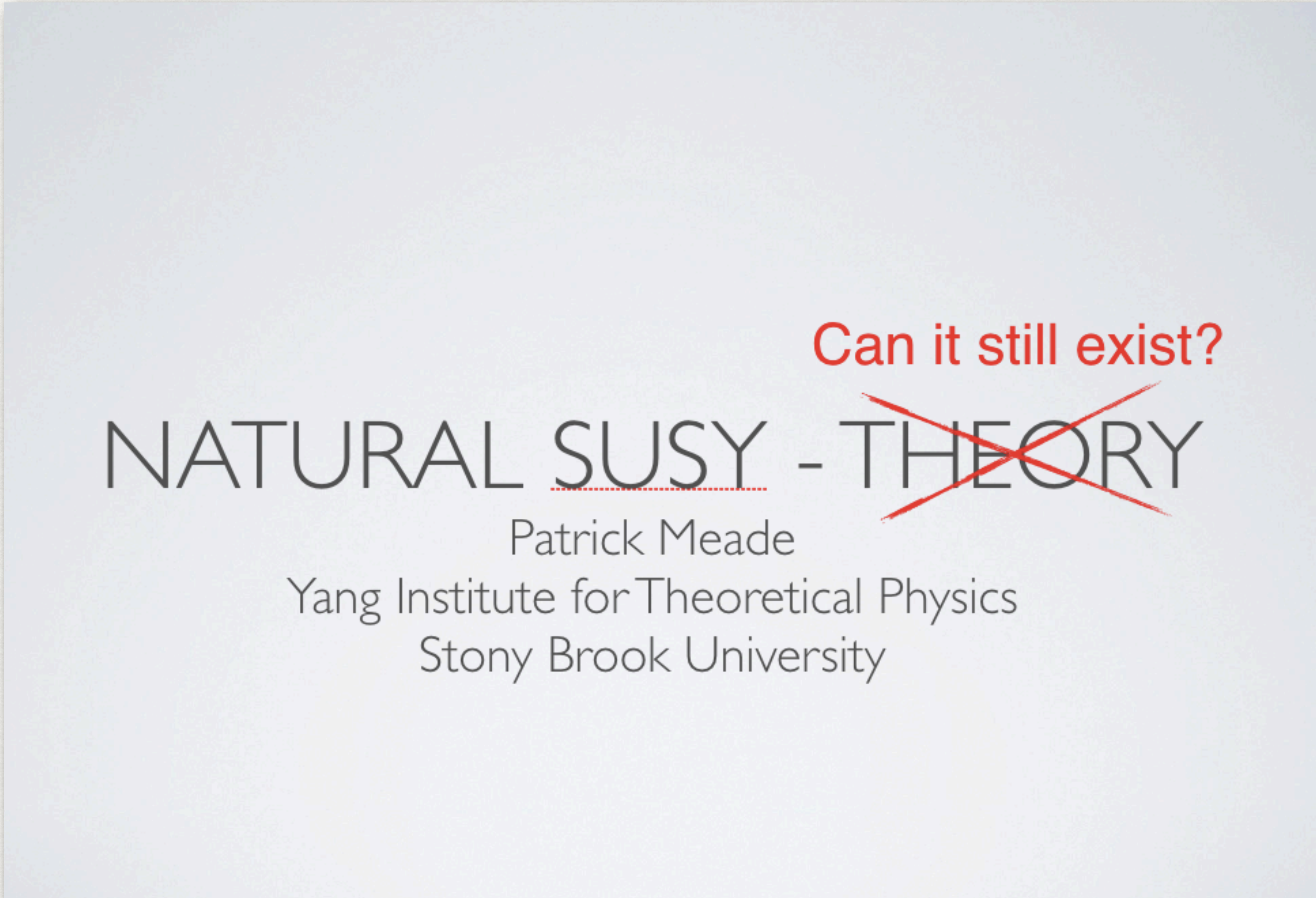


Everyone waiting eagerly for the LHC to make the physics case!

WELL THE LHC MADE A CASE...

Higgs discovery!

BUT MAYBE NOT THE RIGHT CASE?



Patrick Meade LCWS2012 Natural SUSY talk

BUT MAYBE NOT THE RIGHT CASE?

TUNED MSSM

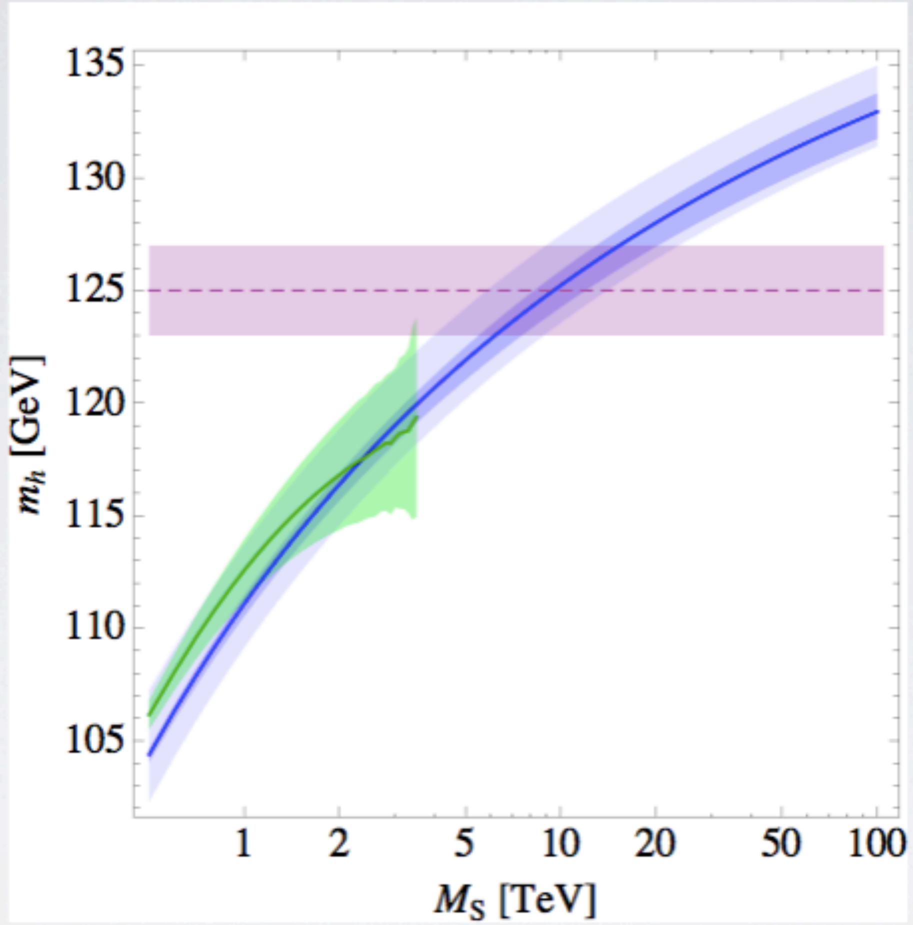
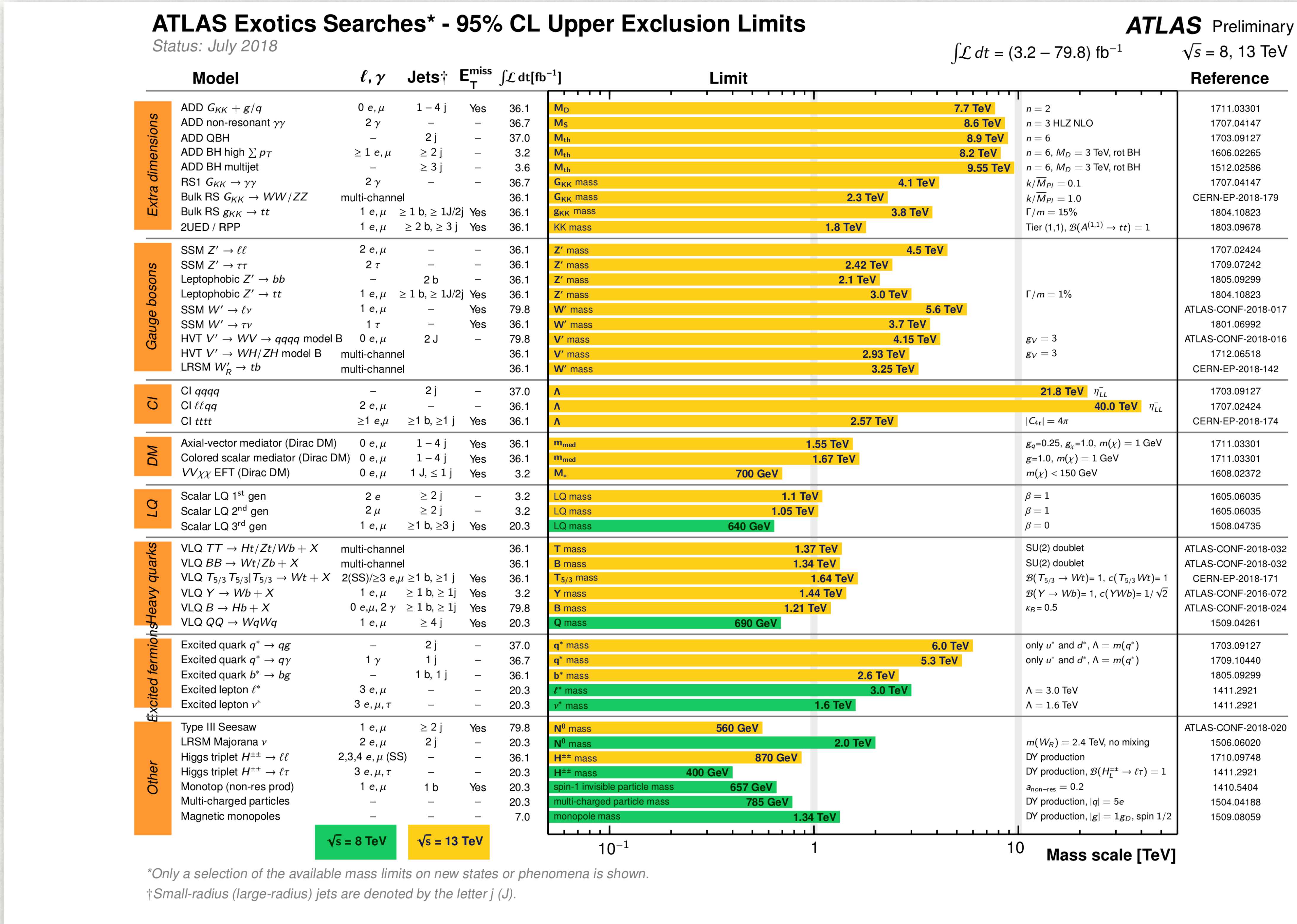


FIG. 6. Higgs mass as a function of M_S, with $X_t = 0$. The green band is the output of FeynHiggs together with its associated uncertainty. The blue line represents 1-loop renormalization group evolution in the Standard Model matched to the MSSM at M_S. The blue bands give estimates of errors from varying the top mass between 172 and 174 GeV (darker band) and the renormalization scale between $m_t/2$ and $2m_t$ (lighter band).

We understood early on that what we thought things would look like pre LHC would probably look different than originally anticipated

THEN THE LHC CONTINUED TO MAKE A CASE…



THEN FOR SOME, A MORE FATEFUL TIME AROSE...

Does an ILC have any chance at seeing new physics if the LHC doesn't?

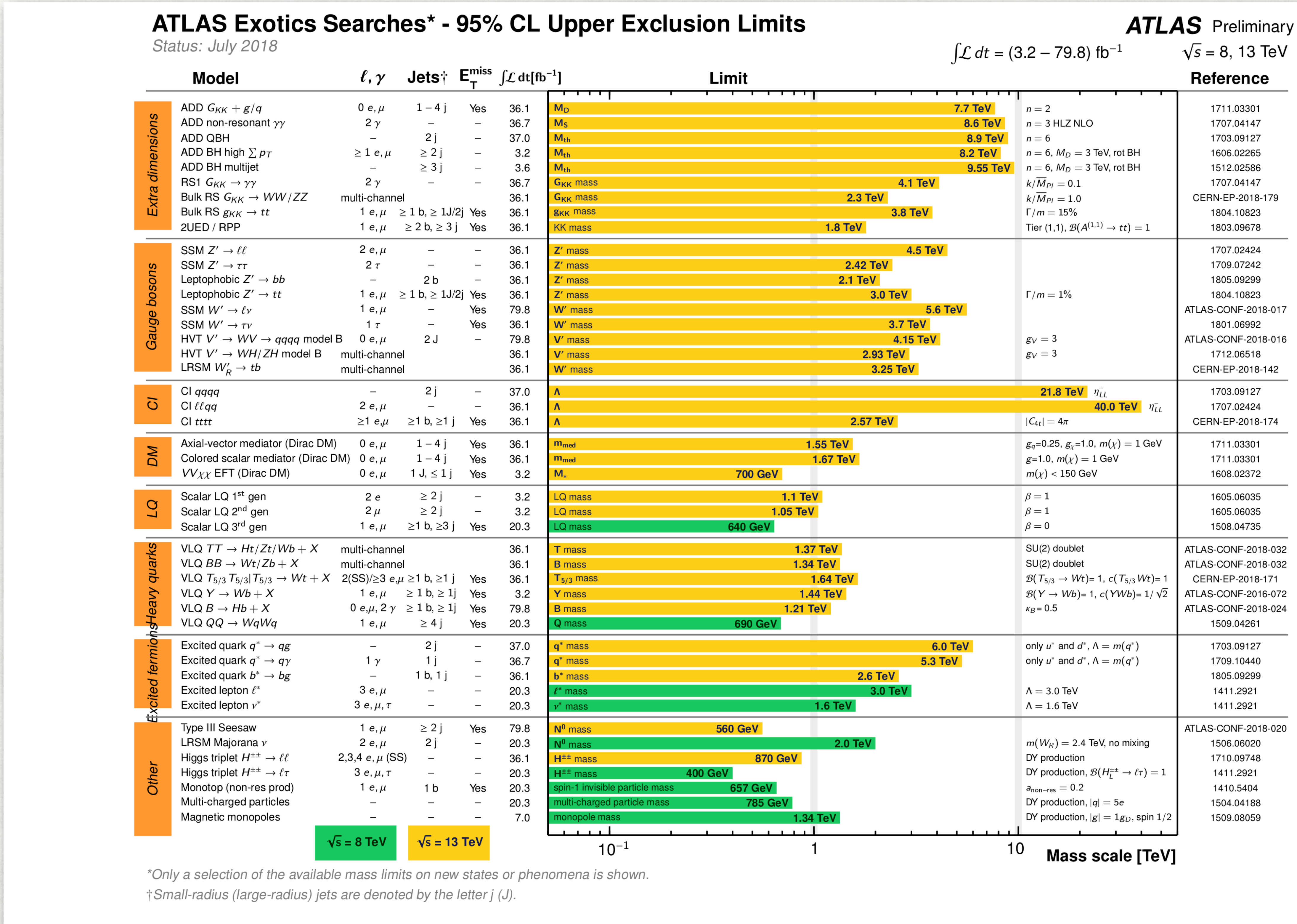
AT THIS POINT A BIFURCATION OCCURRED…

Pessimistic Physicists versus Optimistic Physicists

AT THIS POINT A BIFURCATION OCCURRED...

Pessimistic Particle Physicists versus Optimistic Particle Physicists

WHAT DO LHC RESULTS *REALLY* MEAN?



IMPLICIT/EXPLICIT THEORY BIAS

- Many times LHC results mean exactly what they say
- Often they can be recast in many other ways too, making them even more powerful
- Nevertheless there can often be strong biases based on what we "think" new physics should look like, or the hope that it will show up where the Standard Model isn't to let us have sensitivity
- Have to examine our biases to understand what really could be the physics models describing our universe

SOMETIMES THEORY BIAS IS **GOOD**

SCIENCE

Tiny Neutrinos May Have Broken Cosmic Speed Limit

By DENNIS OVERBYE SEPT. 22, 2011

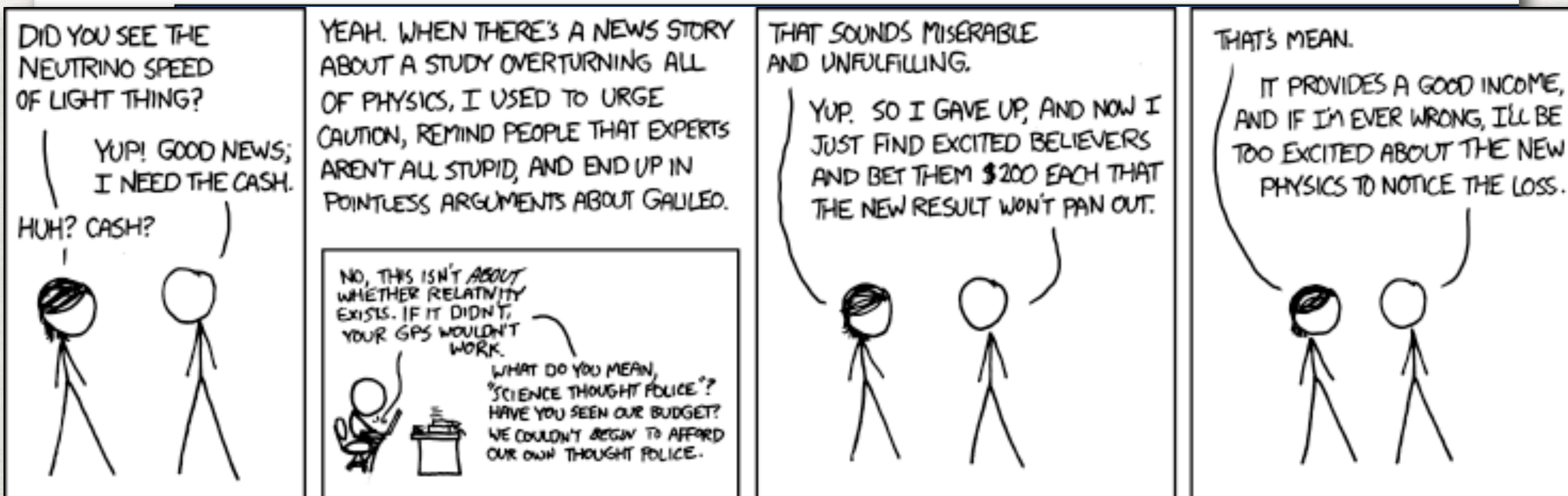
Roll over, Einstein?

The physics world is abuzz with news that a group of European physicists plans to announce Friday that it has clocked a burst of subatomic particles known as neutrinos breaking the cosmic speed limit — the speed of light — that was set by Albert Einstein in 1905.

If true, it is a result that would change the world. But that "if" is enormous.

SOMETIMES THEORY BIAS IS **GOOD**

SECTIONS HOME SEARCH The New York Times



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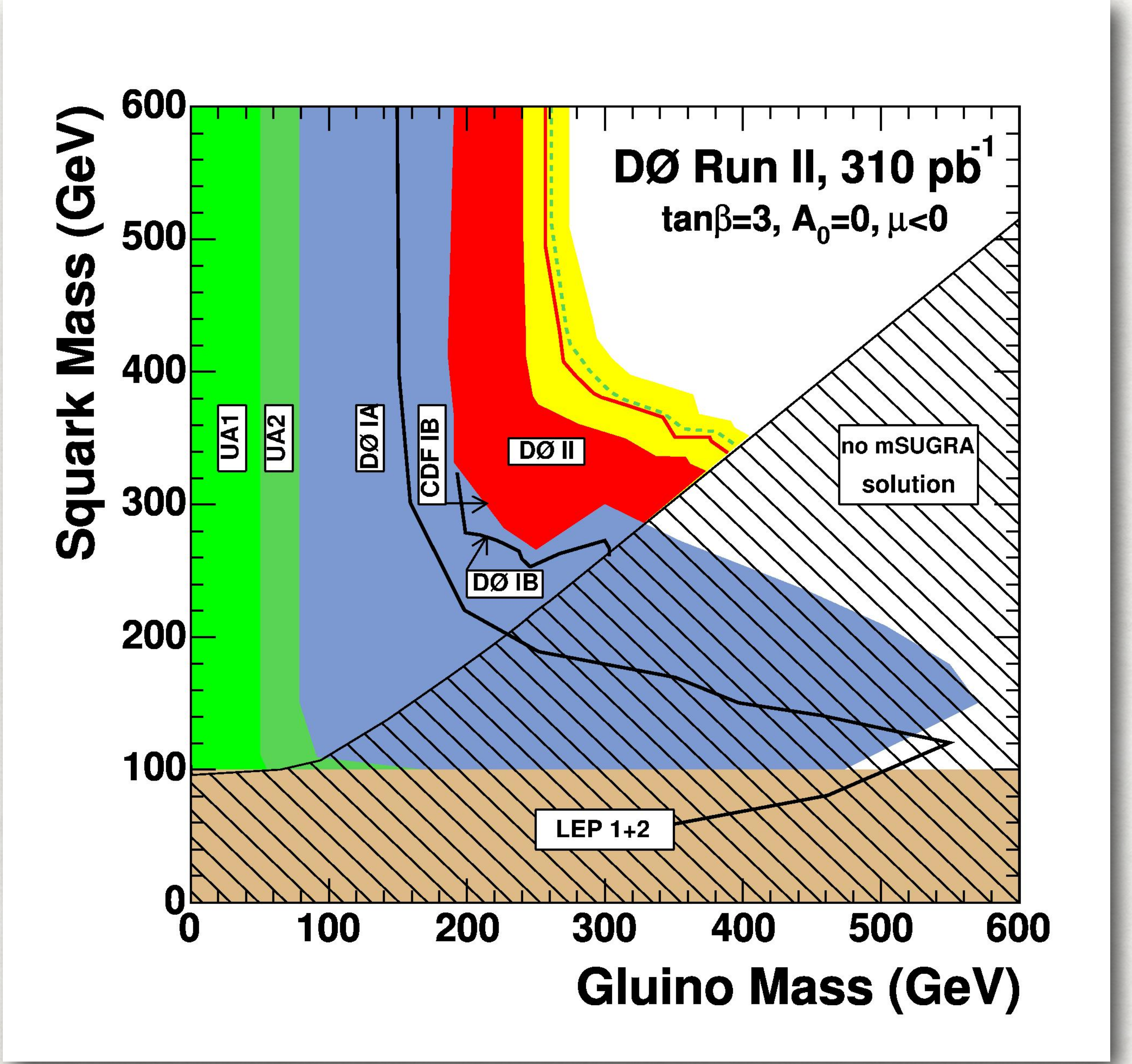
SOMETIMES THEORY BIAS IS **BAD**



These plots were much more frequent in the past, but just for illustration purposes I've used this… Bias still persists though!

WE ALL DO IT, EVEN IF YOU INSIST YOU’RE NOT A BIASED PHYSICIST

- Many experiments before the LHC!

WE ALL DO IT,
EVEN IF YOU INSIST YOU'RE NOT A BIASED PHYSICIST

- Many experiments before the LHC!

- Electroweak Precision - previous e^+e^- colliders

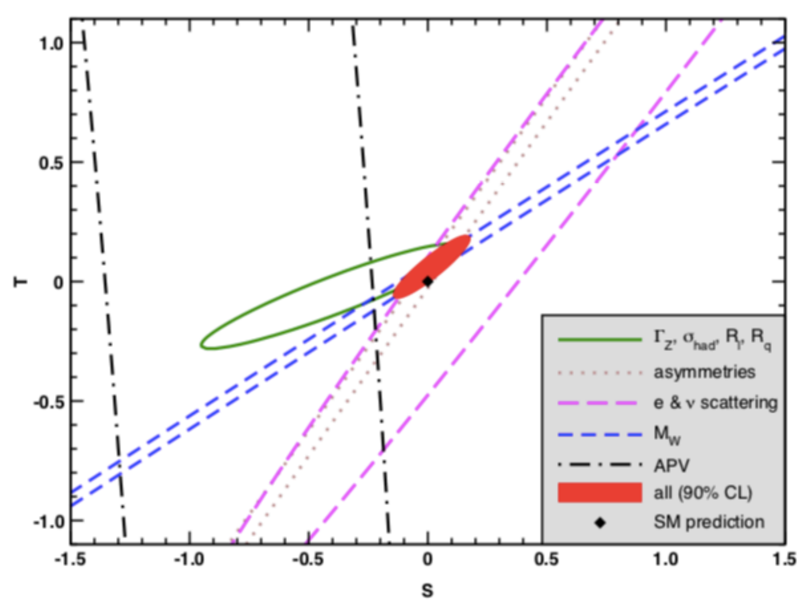
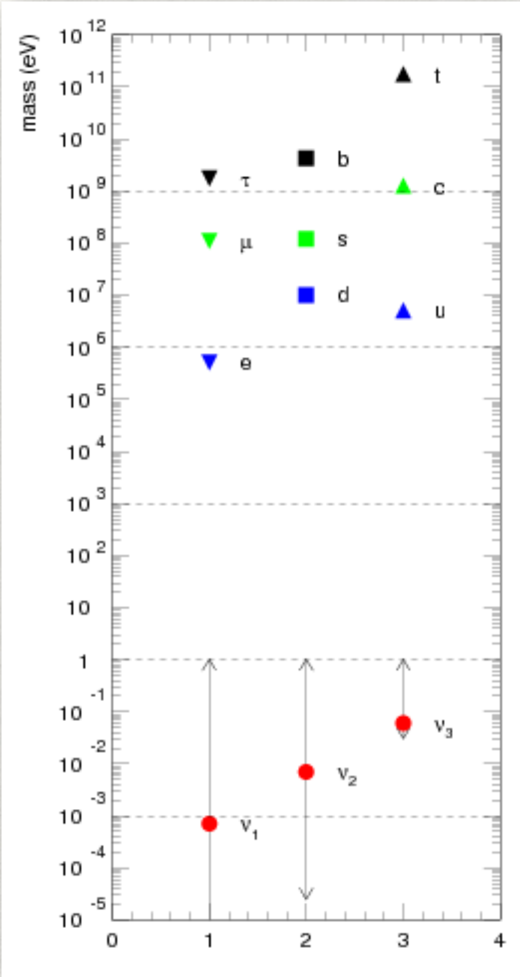


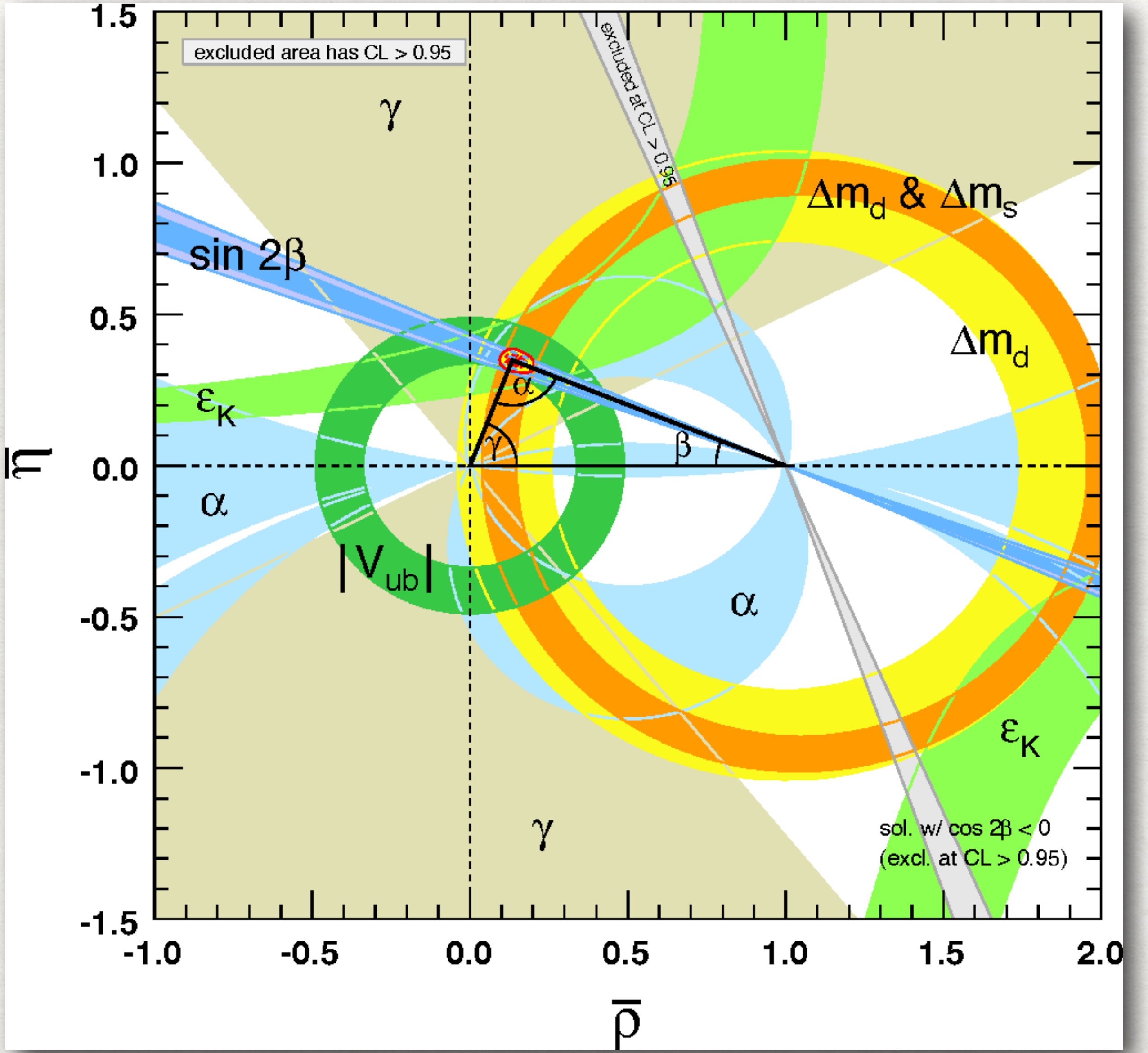
Figure 10.6: 1 σ constraints (39.35% for the closed contours and 68% for the others) on S and T (for $U = 0$) from various inputs combined with M_Z. S and T represent the contributions of new physics only. Data sets not involving M_W or Γ_W are insensitive to U. With the exception of the fit to all data, we fix $\alpha_s = 0.1187$. The black dot indicates the Standard Model values $S = T = 0$.

Generic new physics contributing to Electroweak Symmetry Breaking should be above ***10 TeV***!

WE ALL DO IT, EVEN IF YOU INSIST YOU'RE NOT A BIASED PHYSICIST

- Many experiments before the LHC!
- Flavor physics experiments





Generic new physics contributing to Flavor physics should be above ***100,000 TeV***!

WHY ARE WE **CONTINUING** THE LHC PROGRAM?

LET ALONE BUILDING A **LOWER** ENERGY ILC??

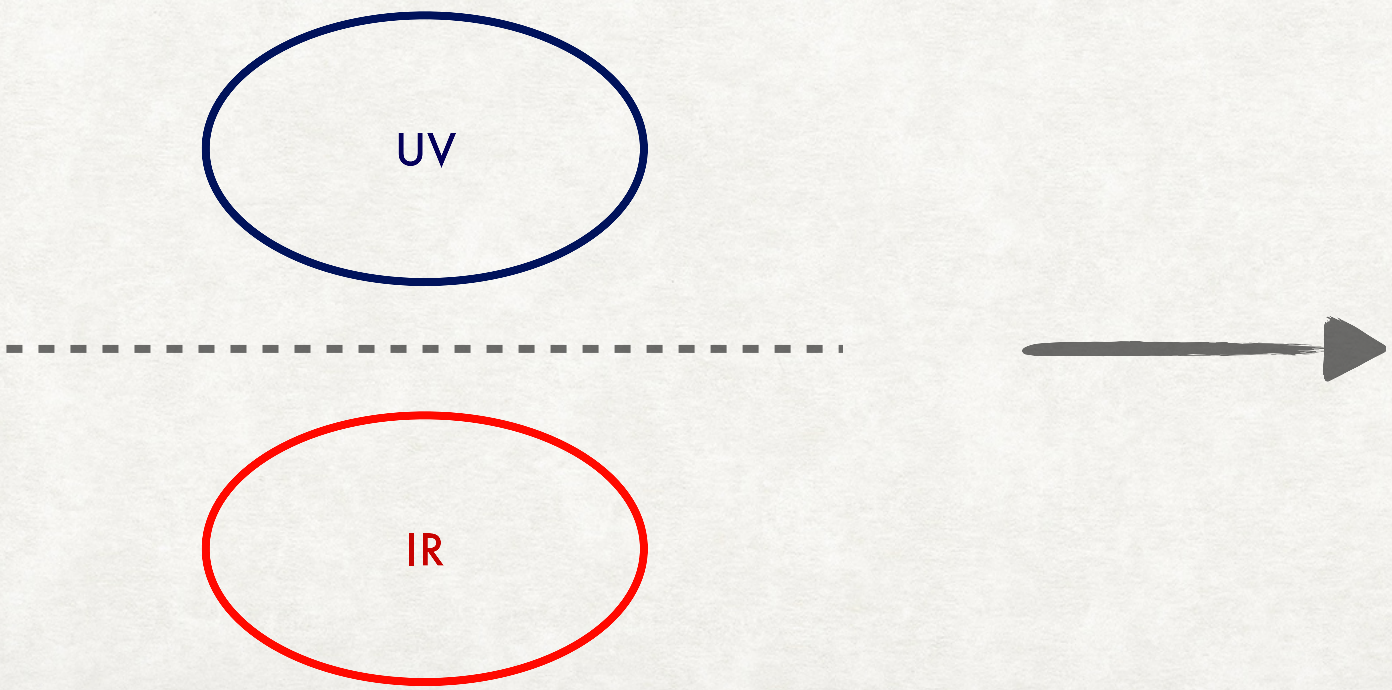
- These previous experiments are beautiful correct experiments…
- It's the ***interpretation*** of the results theoretically that matters when applying it to other experiments

MODEL DEPENDENT VS MODEL INDEPENDENT

<u>Most of you in the room will buy that a theorist can cook up a model (add an epicycle) which can evade a particular search</u>

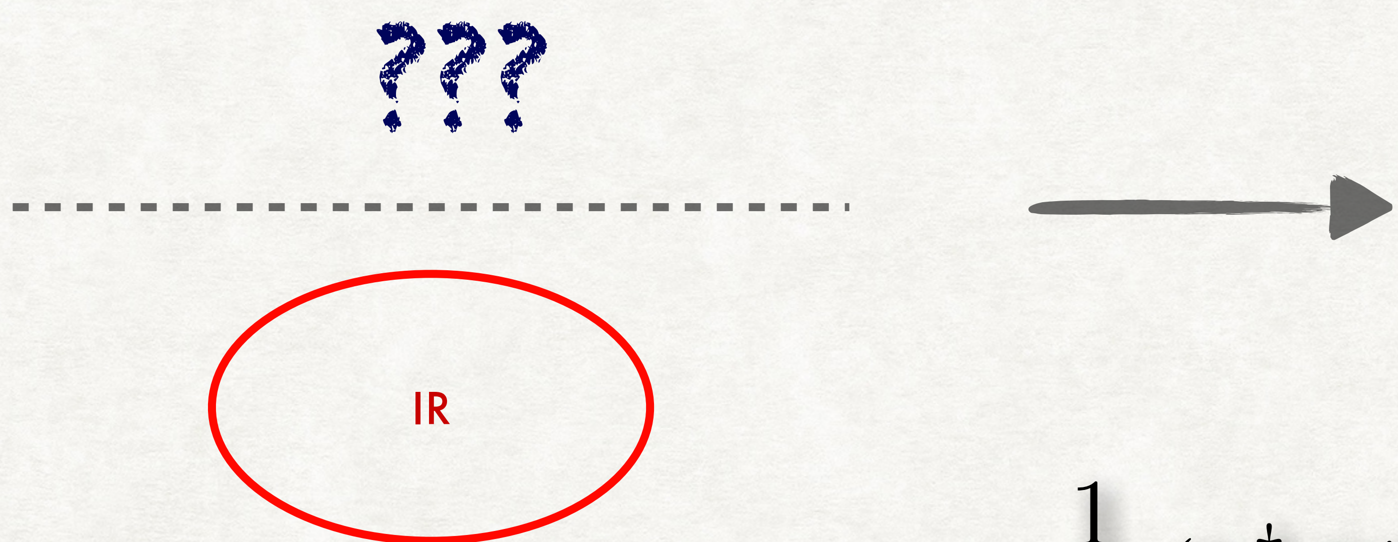
What about model "independent" bounds, Effective Field Theories (EFT)?

Astute observers already realize these are just as model dependent from my two previous examples, but I want to emphasize this point here to a broader audience



$$\sum_i \frac{c_i}{\Lambda^{(\Delta_i - 4)}} \mathcal{O}_i$$

EFFECTIVE FIELD THEORY BOUNDS



$$\sum_i \frac{c_i}{\Lambda^{(\Delta_i - 4)}} \mathcal{O}_i$$

e.g. $\frac{1}{\Lambda^2}(h^\dagger D^\mu h)^2$ or $\frac{1}{\Lambda^2}(\bar{s}\gamma^\mu d)^2$

Basic concept is simple, we're replacing our knowledge of the UV theory with some template of what we ***could*** see

New physics has a mass scale but the coefficient matters too

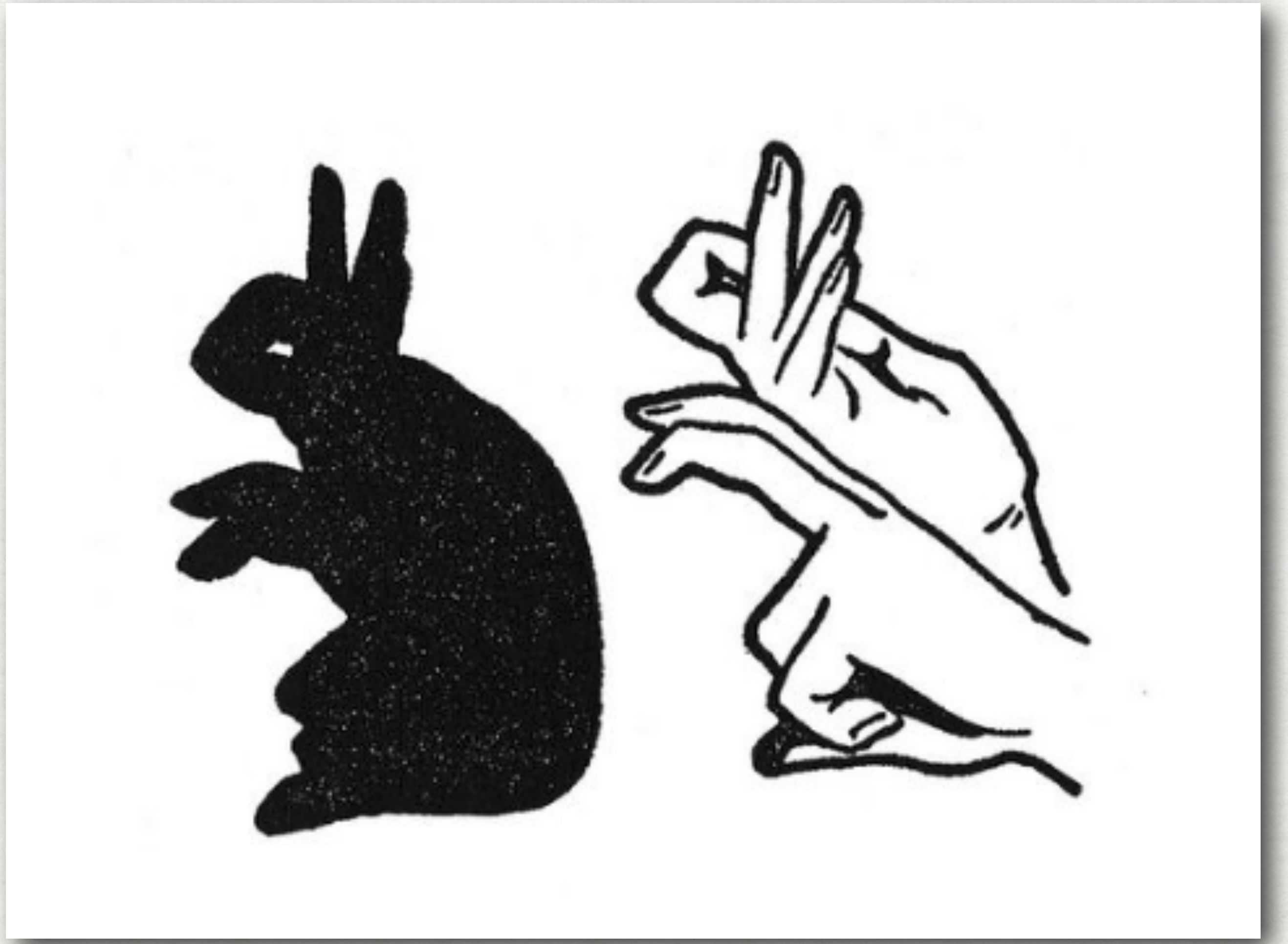
EFFECTIVE FIELD THEORY BOUNDS

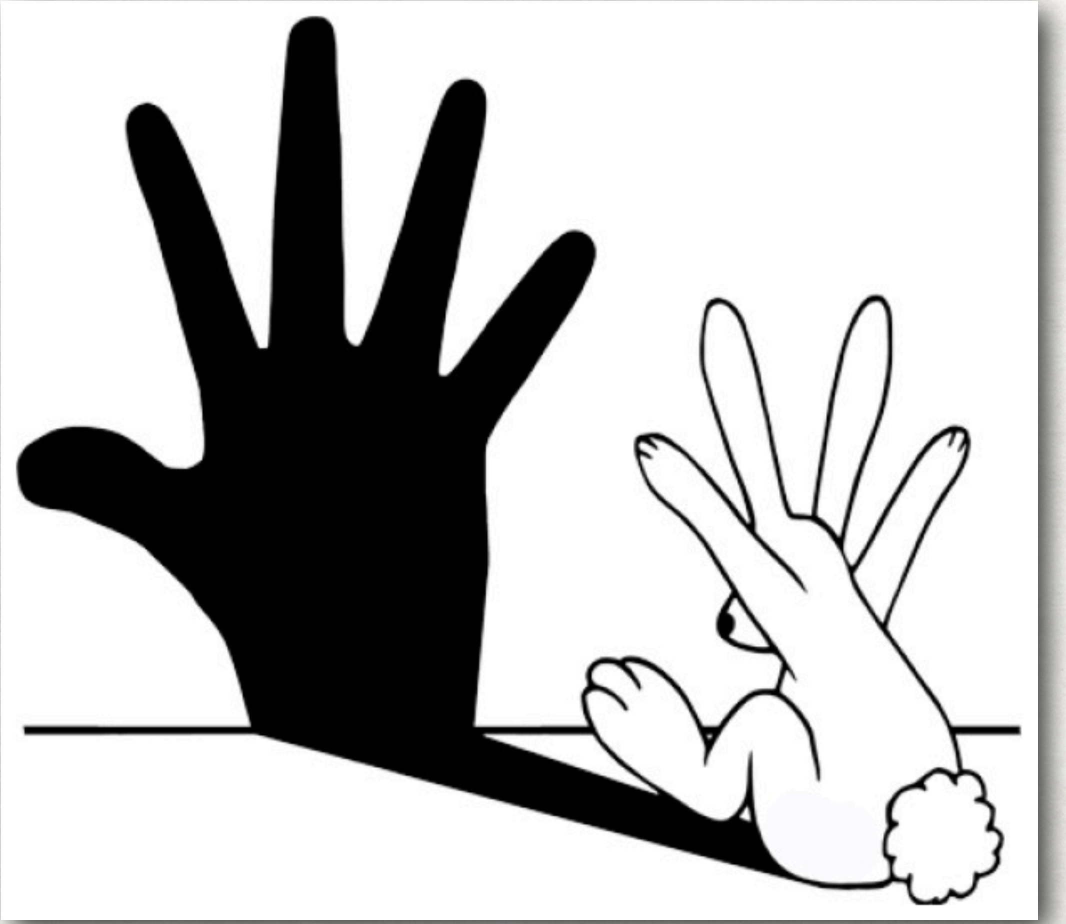
Trying to figure out what the object is by looking at it's projection

<u>Sometimes it's easy!</u>

"MODEL INDEPENDENT BOUNDS"

However we can definitely get confused as well!





See RMP with
D. Green, PM, M. Pleier
1610.07572
for more comments

WHY ARE WE **CONTINUING** THE LHC PROGRAM?

LET ALONE BUILDING A **LOWER** ENERGY ILC??

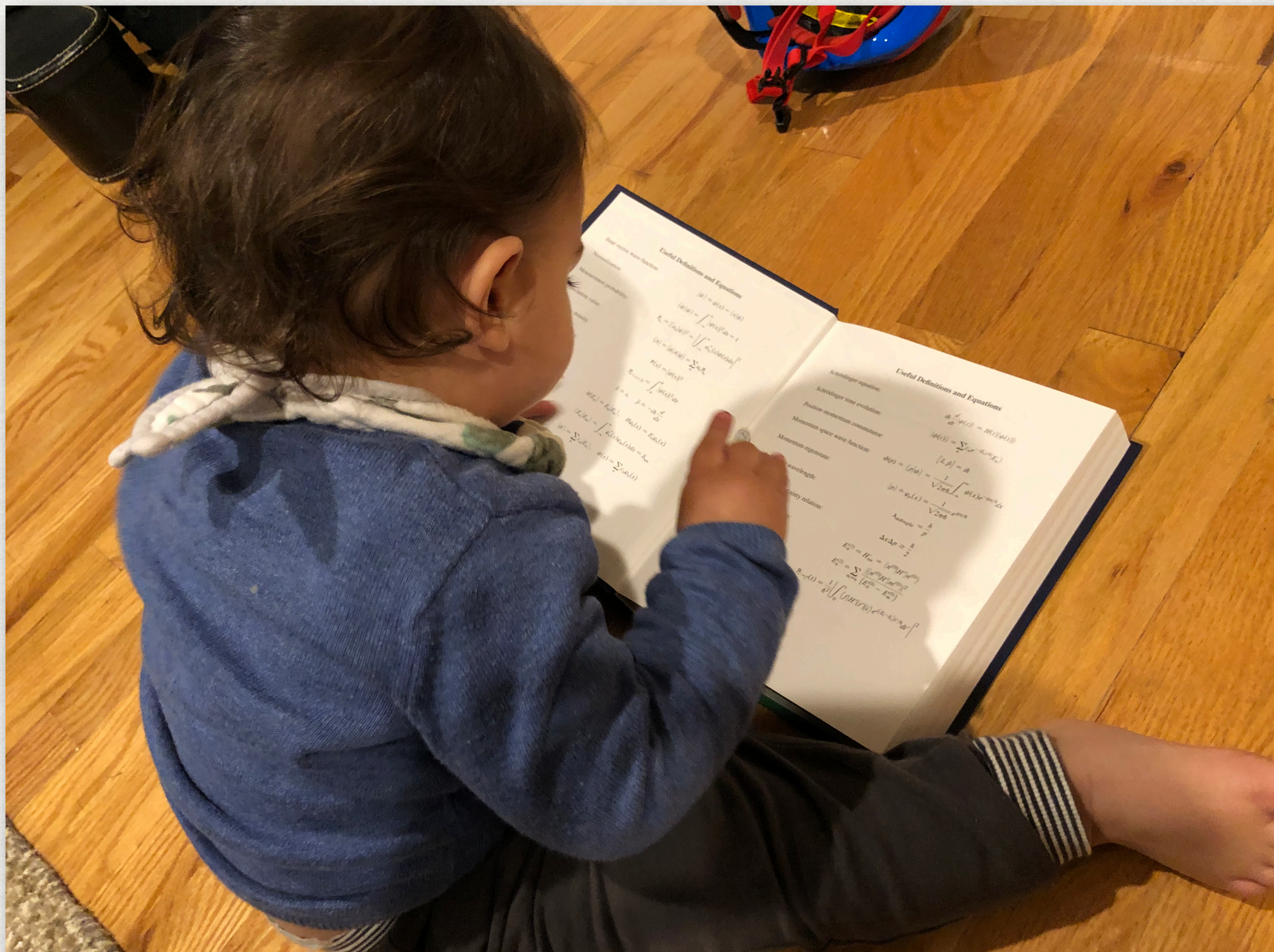
- These previous experiments are beautiful correct experiments…
- It's the ***interpretation*** of the results theoretically that matters when applying it to other experiments
  - ***Potentially*** we can always work around model dependent and model independent bounds
- The LHC can still discover new physics **and** the ILC can discover new physics ***<u>even</u>*** if the LHC doesn't!

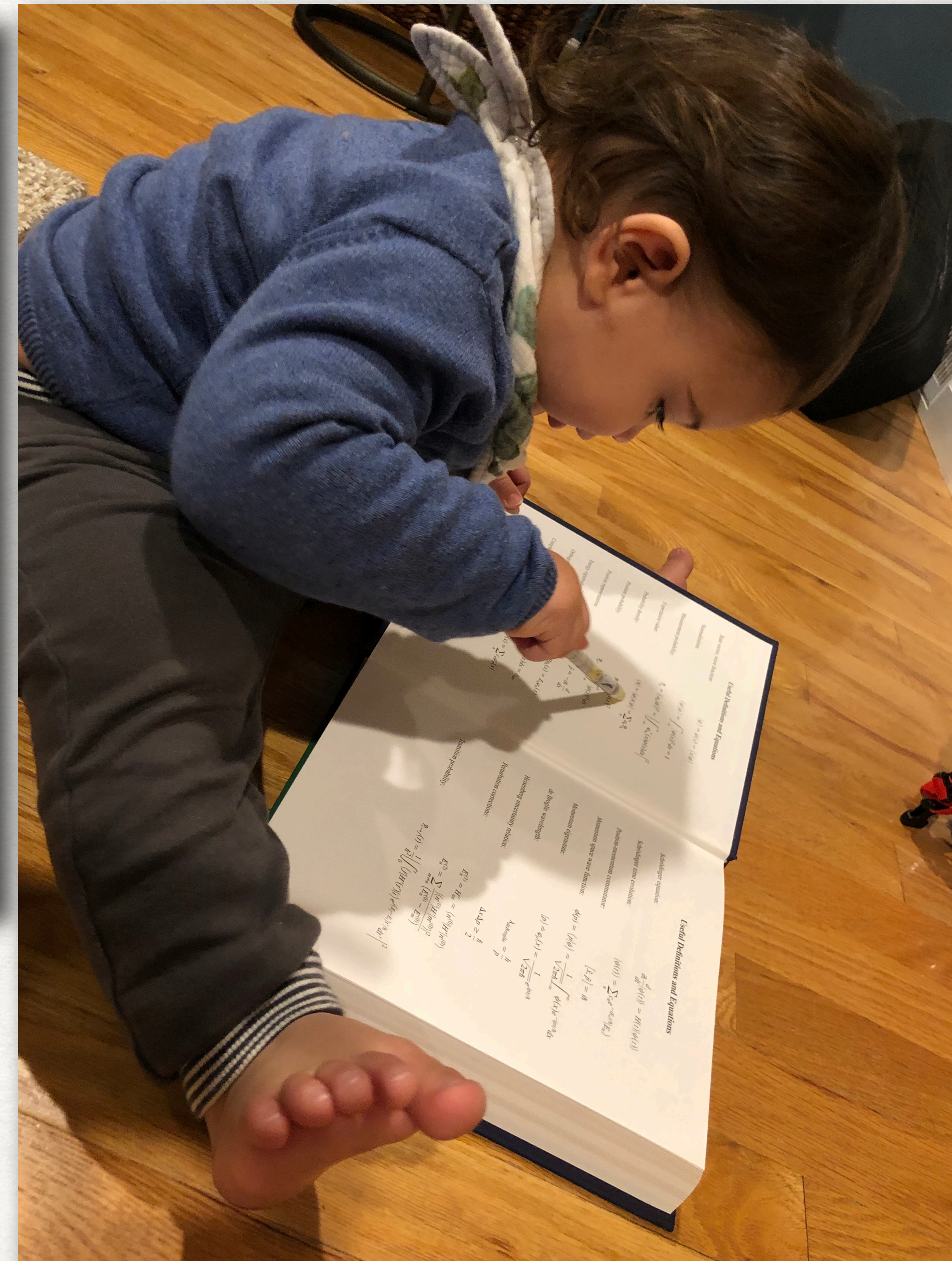
WHERE DOES MY OPTIMISM COME FROM?

- Realizing theory bias is important but it only gets you so far

OFTEN REQUIRES A LOT OF HARD WORK

WE HAVE TO GO BACK TO EARLY STAGES AND CHALLENGE OUR ASSUMPTIONS!





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- Realizing theory bias is important but it only gets you so far

- Theorists still work hard even if the LHC doesn't find anything!
  - Major theoretical advances in both phenomenological and formal theory!

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- Theorists still work hard even if the LHC doesn't find anything!
    - Major theoretical advances in both phenomenological and formal theory!

Amplitudes, Bootstrap, NNLO revolution, boundaries and QFTs, …

ON THE PHENO SIDE

Famous H. Murayama Slide from a decade or so ago

EVOLUTION IN PHENO IDEAS

Space of ideas since then!!

EVOLUTION IN PHENO IDEAS

Space of ideas since then!!

(alas I have much less artistic flair than Hitoshi)

NOT **JUST** IN COLLIDER PHYSICS, BUT DARK MATTER TOO!

"Wise" professor tells entering graduate student 2002:

$$m_{DM} \sim \mathcal{O}(100)\,\mathrm{GeV}$$

Wise professor tells entering graduate student 2017:

could be $m_{DM} \sim 10^{-22}\,\mathrm{eV}$

but… also could be **50** to **90** orders of magnitude heavier depending on assumptions of course

EVOLUTION IN PHENO IDEAS

Space of ideas since then!!

(alas I have much less artistic flair than Hitoshi)

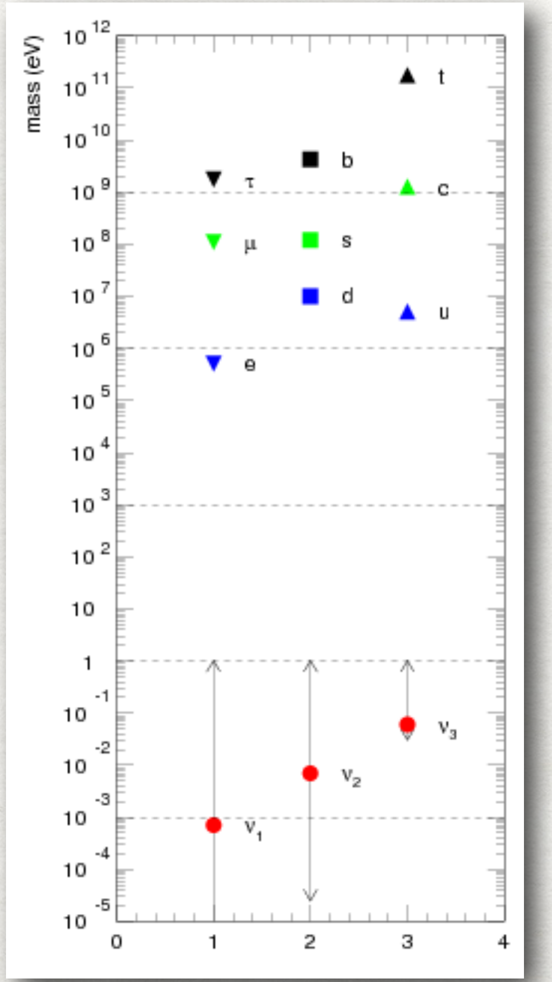
RATHER THAN LIST EVERYTHING, I'LL PICK A FEW INTERESTING* IDEAS FOR A LC WITH QUALITATIVE CONSEQUENCES

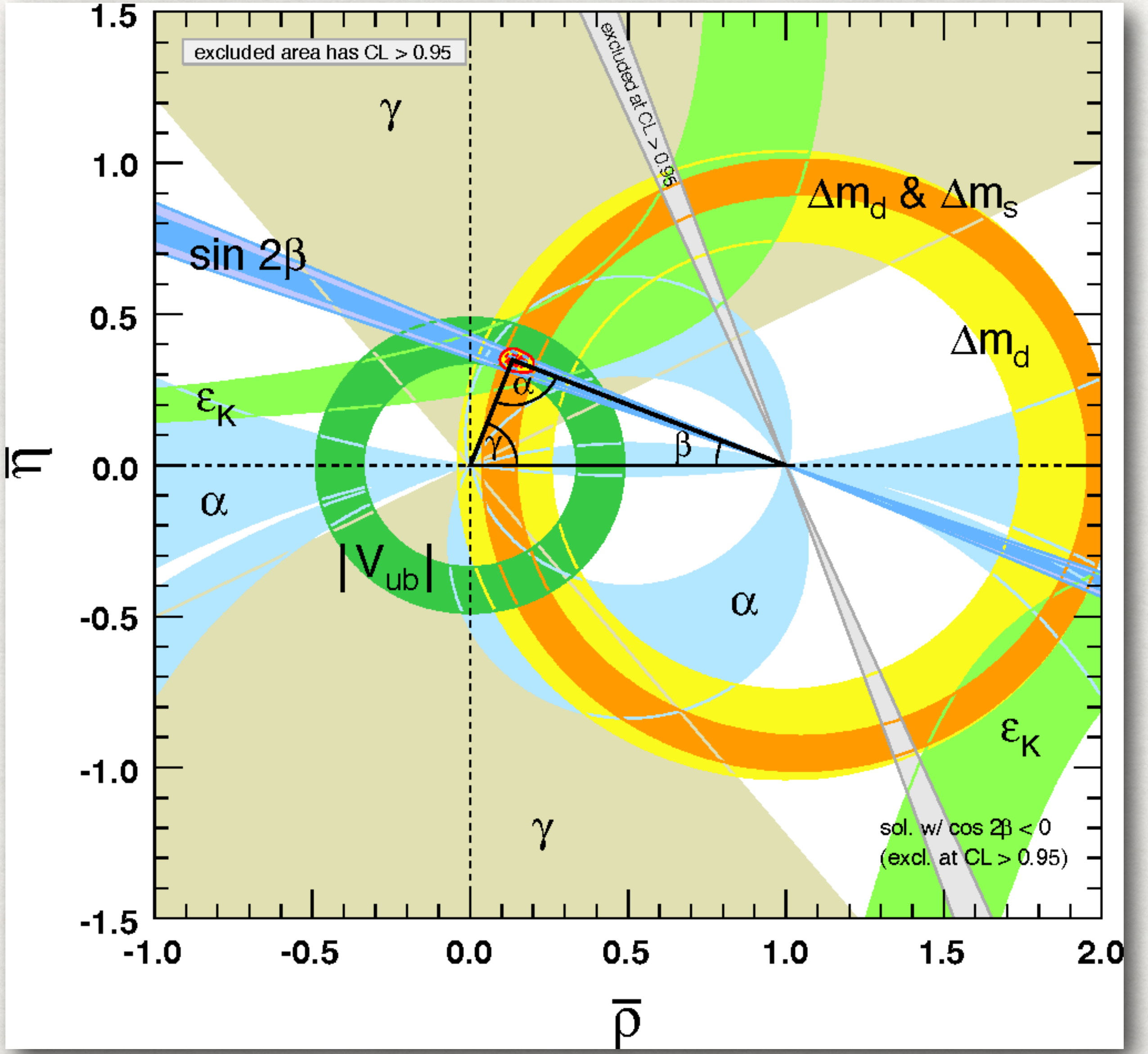
HIGGS PHYSICS

- “Everyone” already knows the ILC has incredible potential as a Higgs factory
- What’s not always expressed is what does this really get you other than better precision?
    - When can ***quantitative*** differences lead to huge changes in our ***qualitative*** understanding?

INSIGHTS INTO THE ORIGIN OF MASS AND FLAVOR

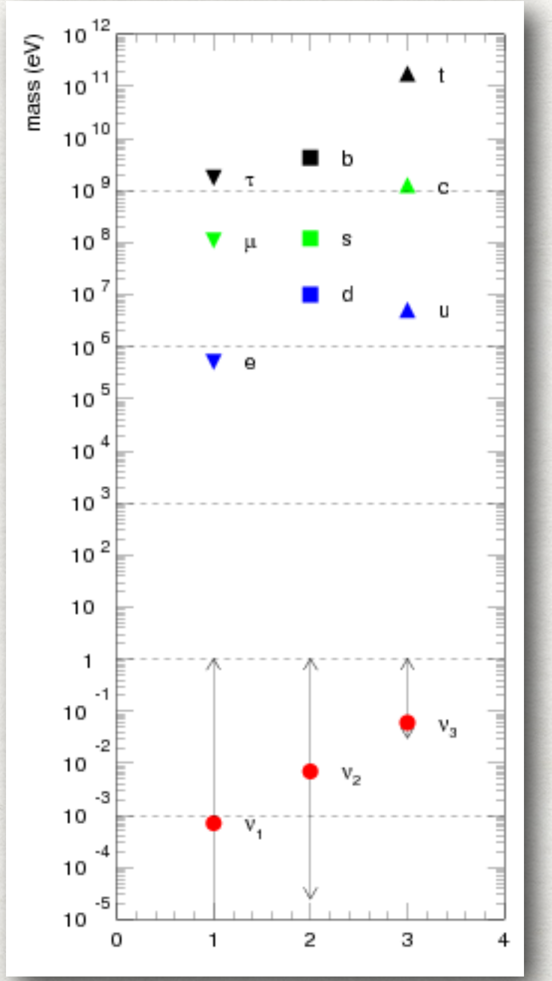
- The Higgs gives elementary particles their mass, and yes there could be slight deviations, but we normally don't address the bigger elephant in the room with it...

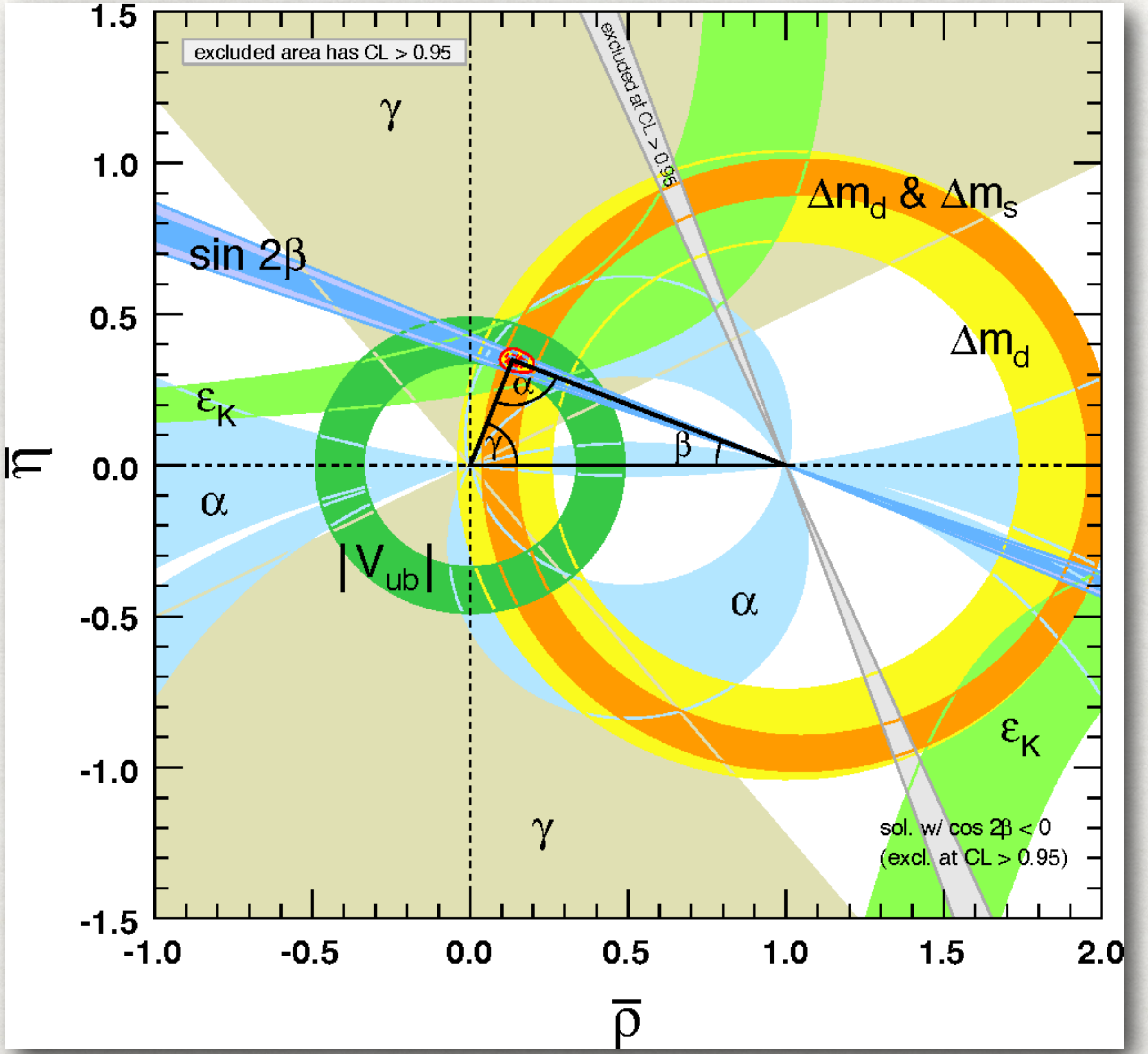




INSIGHTS INTO THE ORIGIN OF MASS AND FLAVOR

- The Higgs gives elementary particles their mass, and yes there could be slight deviations, but we normally don't address the bigger elephant in the room with it… we normally run from it!





WHAT IF THERE WAS A WAY WHERE FLAVOR WAS VISIBLE?

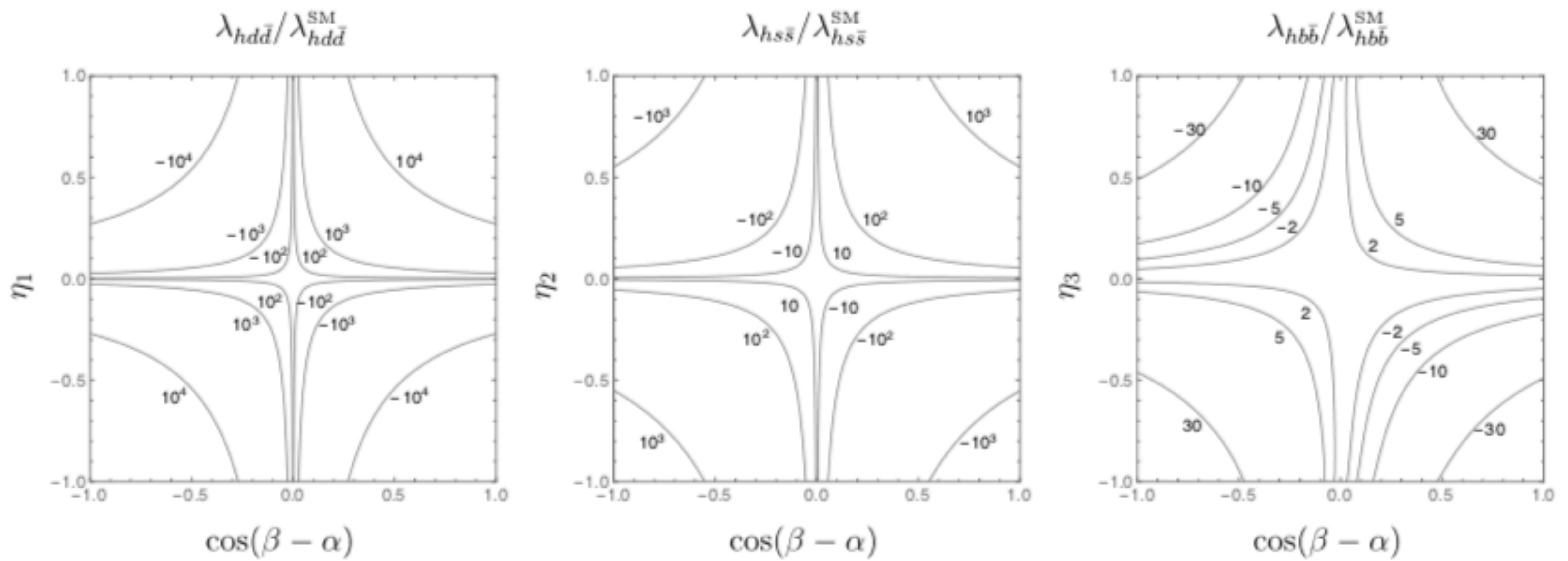


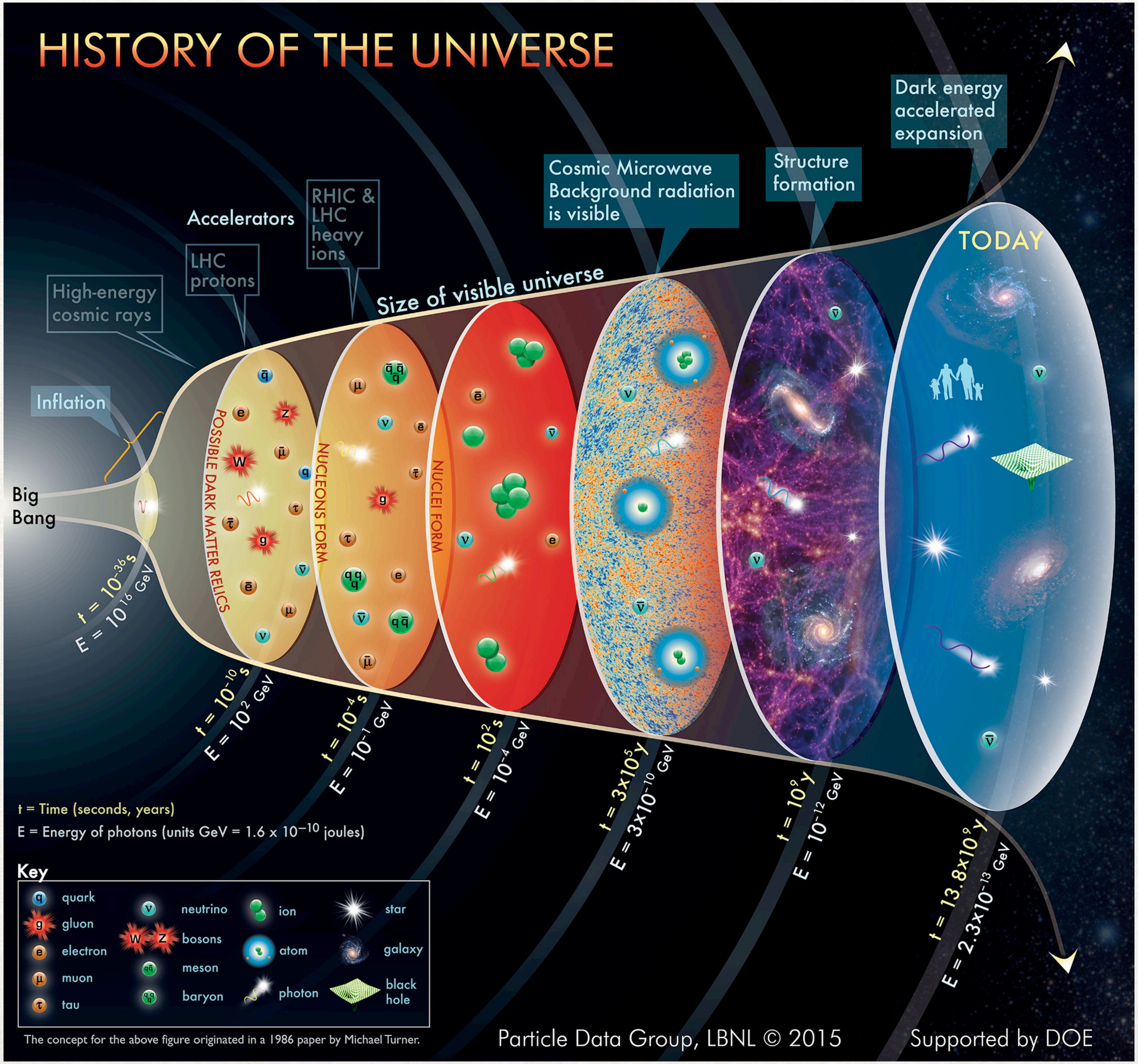
Figure 1: Yukawa enhancement

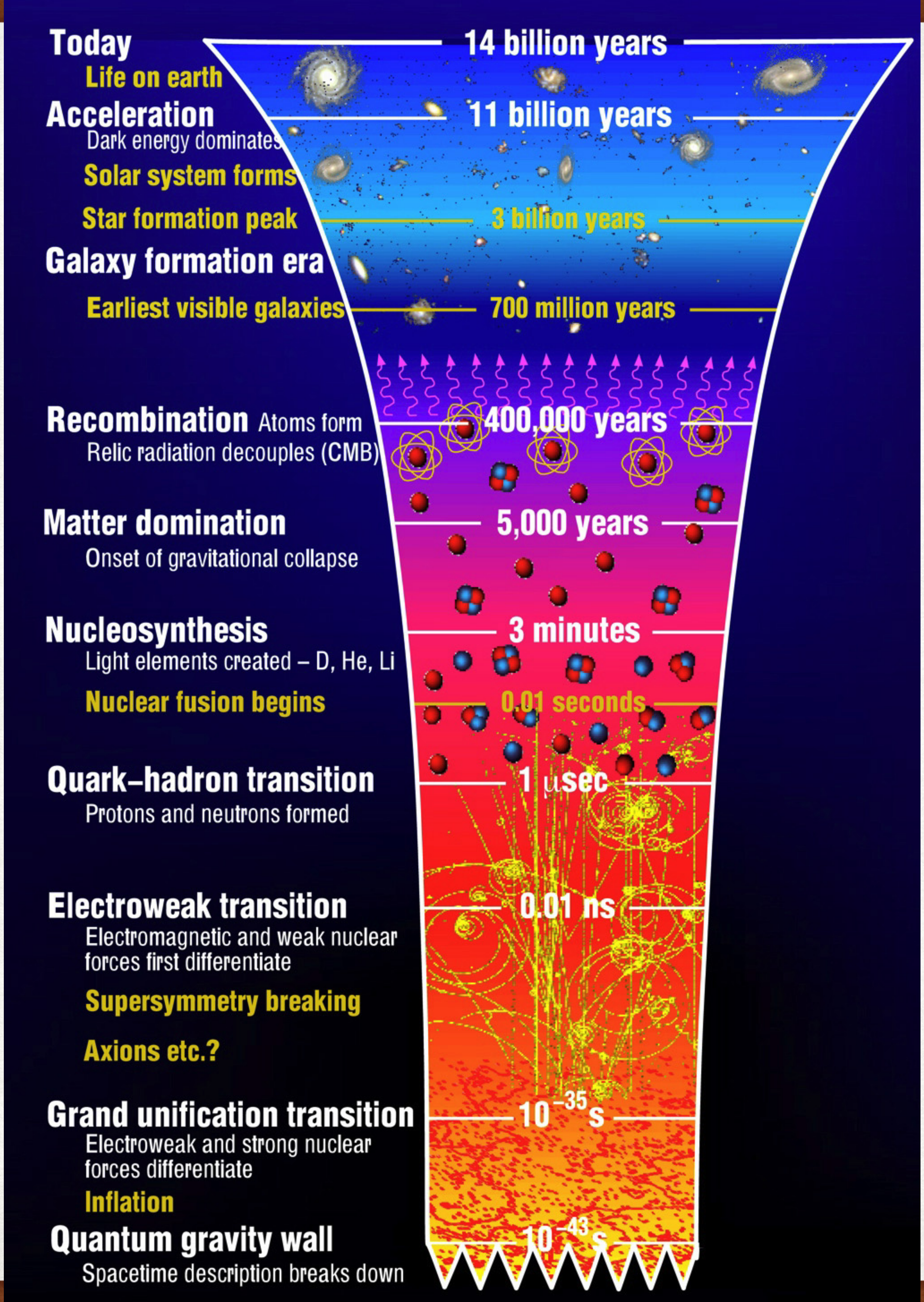
Aligned Flavor Violation (AFV) from Spontaneous Flavor Violation (SFV)

D. Egana-Ugrinovic, PM, S. Homiller 1811.00017 and 1812.xxxxx

How well can we do light flavor tagging at the pristine ILC environment?

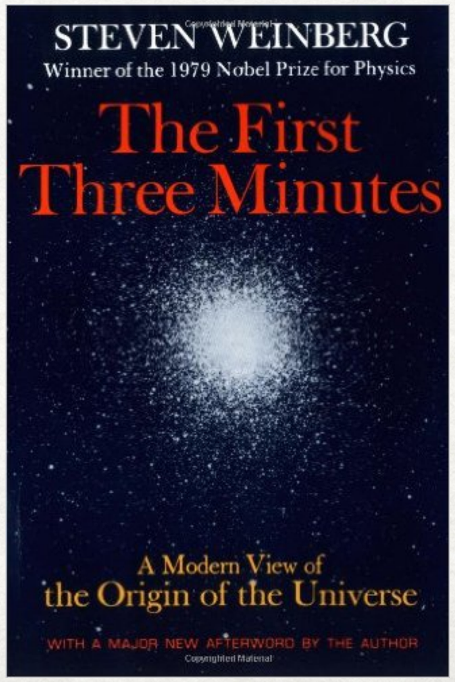
THE HIGGS AND THE HISTORY OF OUR UNIVERSE?





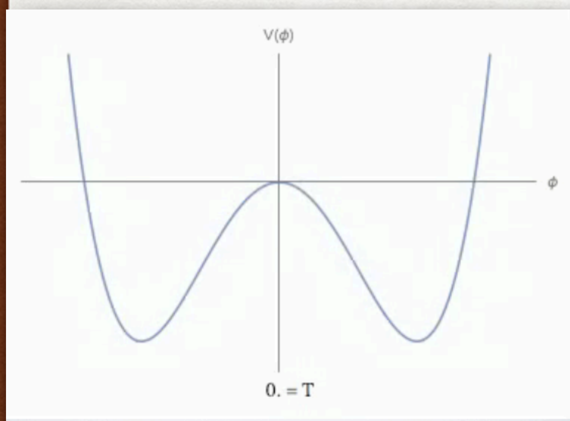
Cosmology stuck here

Need particle physics to go further!



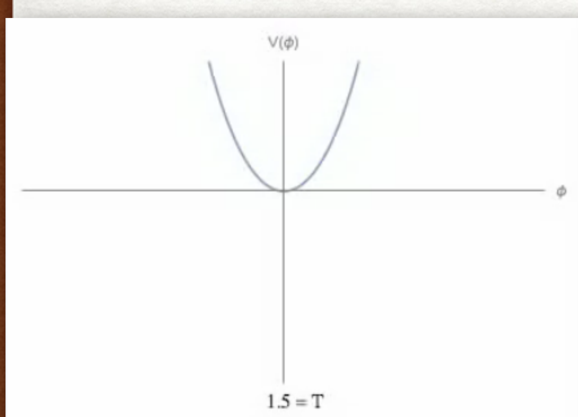
FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION

Imperfect analogy:



Universe now

Early universe
was hotter!



Early Universe

BASIC CONCEPT IS INGRAINED IN TEXTBOOKS

PHASE TRANSITIONS

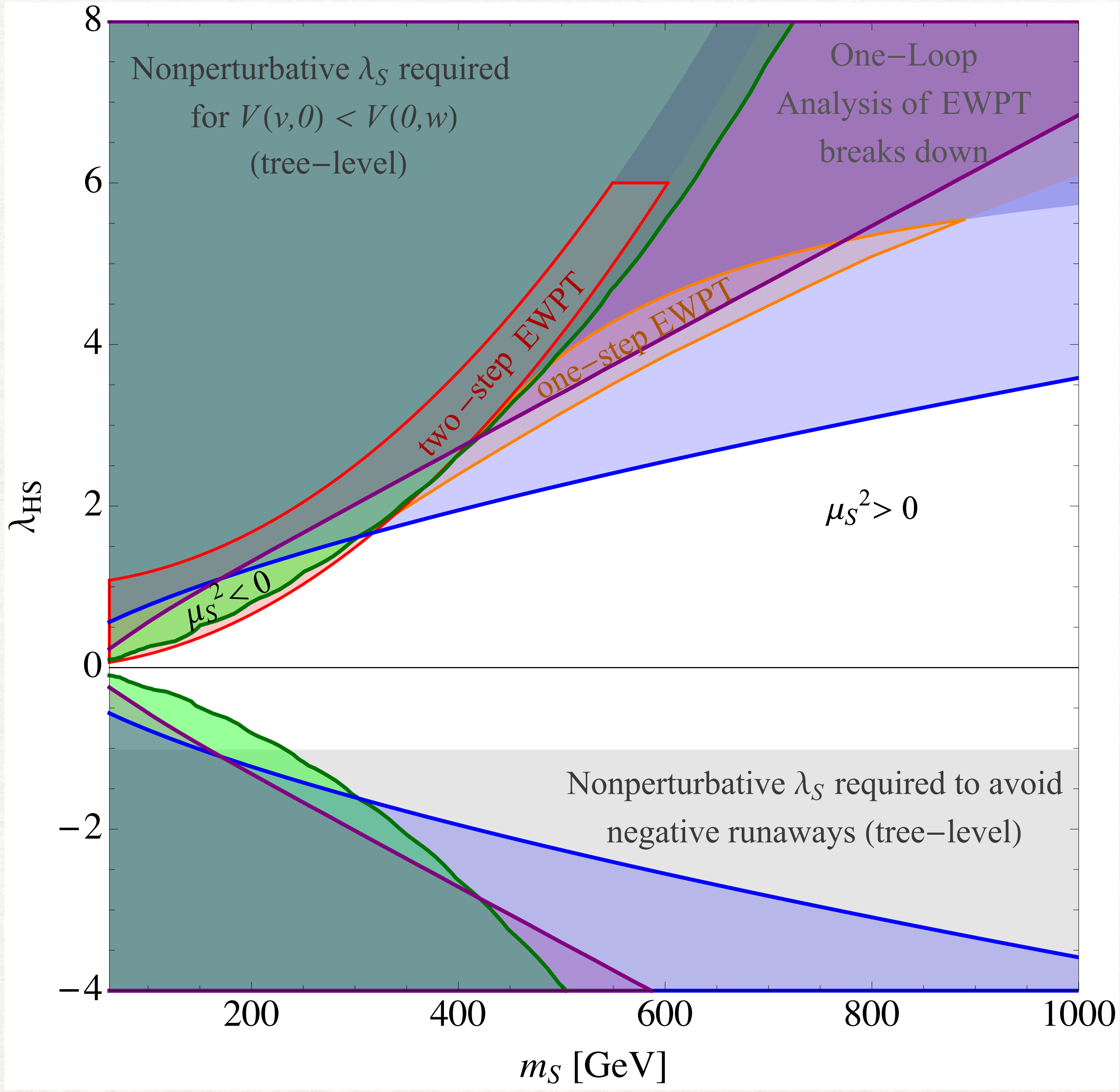
7.1 High-Temperature Symmetry Restoration

One of the most important concepts in modern particle theory is that of spontaneous symmetry breaking (SSB). The idea that there are underlying symmetries of Nature that are not manifest in the structure of the vacuum appears to play a crucial role in the unification of the forces. In all unified gauge theories—including the standard model of particle physics—the underlying gauge symmetry is larger than that of our vacuum, whose symmetry is that of $SU(3)_C \otimes U(1)_{EM}$. Of particular interest for cosmology is the theoretical expectation that at high temperatures, symmetries that are spontaneously broken today were restored [1], and that during the evolution of the Universe there were phase transitions, perhaps many, associated with the spontaneous breakdown of gauge (and perhaps global) symmetries. In particular, we can be reasonably confident that there was such a phase transistion at a temperature of order 300 GeV and a time of order 10^{-11} sec, associated with the breakdown of $SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$. Moreover, the vacuum structure in many spontaneously broken gauge theories is very rich: Topologically stable configurations of gauge and Higgs fields exist as domain walls, cosmic strings, and monopoles. In addition, classical configurations that are not topologically stable, so-called nontopological solitons, may exist and be stable for dynamical reasons. Interesting examples include soliton stars, Q-balls, nontopological cosmic strings, and so on [2].

The cosmological production, and subsequent implications, of such topological defects will occupy much of this Chapter. The possibility that the Universe undergoes inflation during a phase transition will be the subject of the next Chapter. Before discussing topological defects and their production in cosmological phase transitions, we will review some general

Kolb & Turner

FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION



D. Curtin, PM, T. Yu
1409.0005

We can test the nature of the phase transition through Higgs properties!

Can be applied more generally to the concept of Electroweak Baryogenesis

FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION

Imperfect analogy:

Universe now

Early universe was hotter!

Early Universe????????????

PM, H. Ramani
1807.07578

Unrestored Electroweak Symmetry

WAS THERE EVEN AN ELECTROWEAK PHASE TRANSITION?

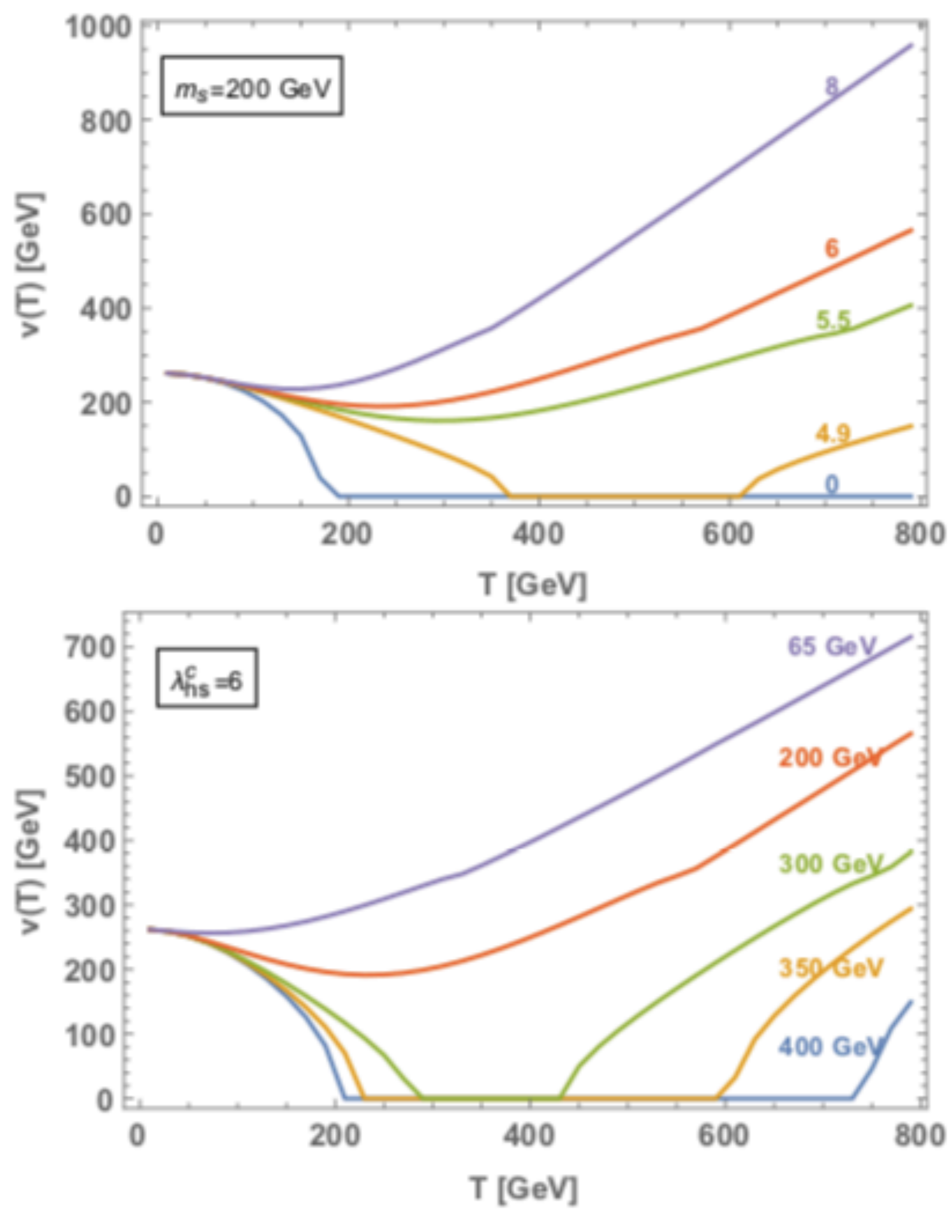


FIG. 2. Top: The temperature dependent VEV, $v(T)$ for different values of λ^c_{hs} demonstrating different phase histories as a function of the temperature, T. Bottom: The temperature dependent VEV for a fixed λ^c_{hs} and different values of m_s. $N_s = 600$ to exhibit the large N_s limit.

Unrestored Electroweak Symmetry

Can look for new physics *directly*, not just Higgs couplings

PM, H. Ramani
1807.07578

ILC FOR DISCOVERY!

CERN-TH-2018-004

Charged Fermions Below 100 GeV

Daniel Egana-Ugrinovic[1], Matthew Low[2], and Joshua T. Ruderman[3,4]

[1] C. N. Yang Institute for Theoretical Physics, Stony Brook, NY 11794, USA

[2] School of Natural Sciences, Institute for Advanced Study,
Einstein Drive, Princeton, NJ 08540, USA

[3] Center for Cosmology and Particle Physics, Department of Physics,
New York University, New York, NY 10003, USA

[4] Theoretical Physics Department, CERN, Geneva, Switzerland

It was often thought LEPII cleaned up below 100 GeV, and the LHC surely could cover this range. This isn't true always, EW states are very interesting for ILC

ILC FOR DISCOVERY!

- There is still room to miss lots of things at the LHC at low energies that the ILC is poised to jump on immediately!
- There are many possibilities and we are just starting to scratch the surface as we remove our biases and think harder!
  - Precision Higgs, Naturalness, Exotic Higgs Decays, SM measurements, new EW states, etc. (look at the talks from LCWS18)

CONCLUSIONS

MY PERSONAL JOURNEY

Early 2000's grad school

LC is a precision machine only useful after LHC discovered something

2012 Higgs Discovery

LC probably won't see anything based on LHC data

2018

LC can be a discovery machine!

So I've given you a reason why I've changed my views and am now optimistic, but remember:

LAMPPOST EFFECT

I've just given you the ***THEORY*** lamppost argument so far!

CONCLUSIONS (2)

ENLARGING THE SPACE OF THEORETICAL POSSIBILITIES

- We're stuck with *only* theories without experiment to guide us further

- More importantly the space of ideas we haven't thought of is incredibly hard to quantify…

- We ***need*** an experimental lamppost if we ever want to understand some of the deepest questions about our universe

  - The ILC is an amazing lamppost, full of possibilities, let's hope it happens soon!