

# 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  
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Now I've changed it more or less to:

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

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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

@iwaterippo reports: [iwate-ilc.jp/eng/news/the-f...](http://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  
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**2018**

ILC can be a  
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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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ILC can be a  
discovery machine!

*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...

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

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$\sqrt{s} = 8, 13 \text{ TeV}$

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	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	36.1	$Z'$ mass 4.5 TeV
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CI		CI $qq\bar{q}\bar{q}$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV $\eta_{LL}$
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	CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV	$ C_{4t}  = 4\pi$ CERN-EP-2018-174
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10<sup>-1</sup> 1 10 Mass scale [TeV]

\*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).

# HOW DO WE GO FROM HERE...

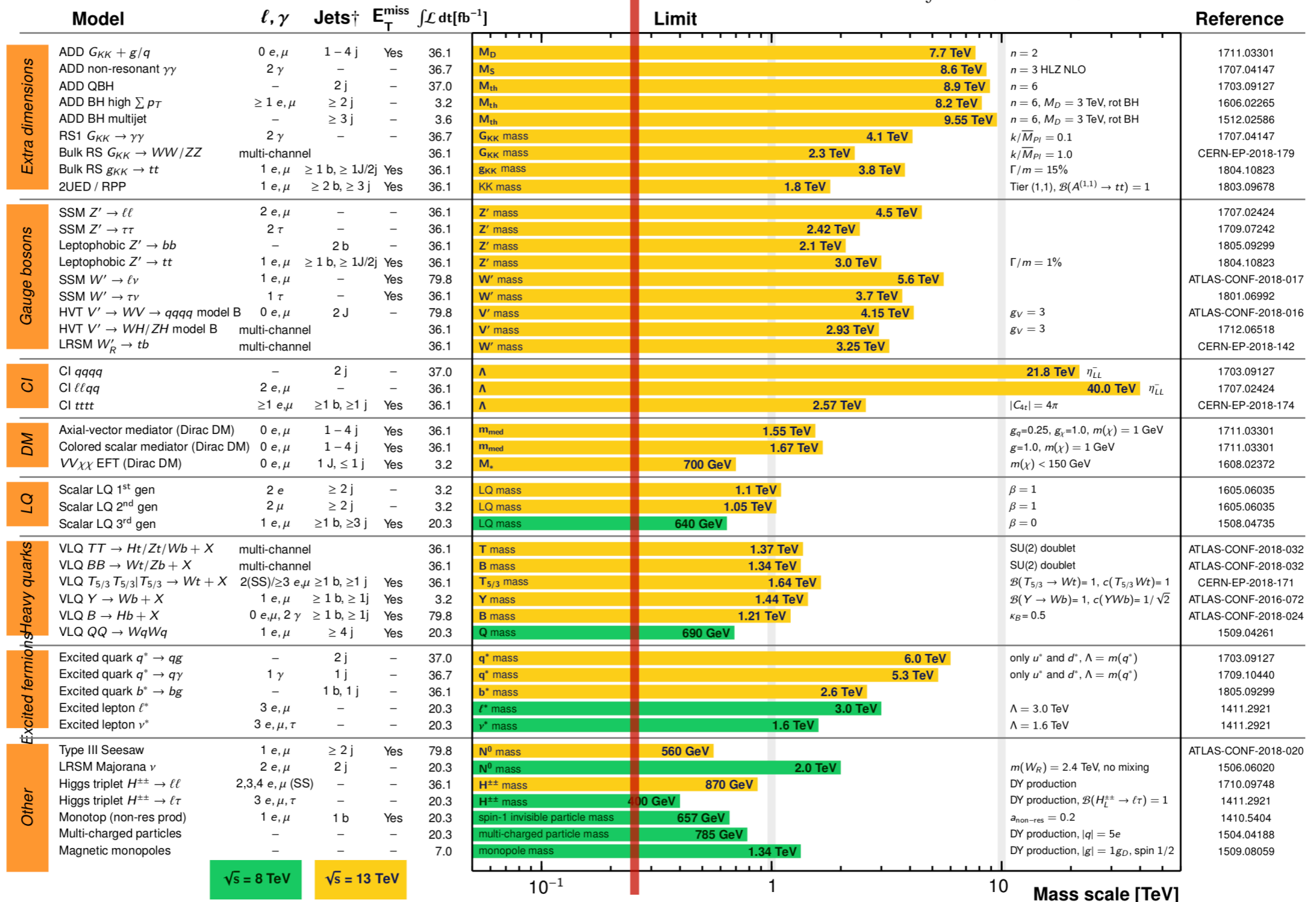
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ILC250

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\*



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- 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.

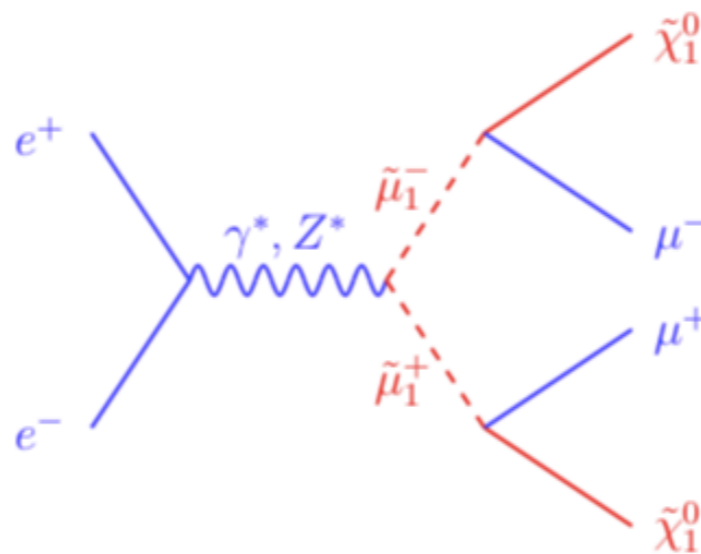


Figure 1: Smuon pair production and decay at an  $e^+e^-$  collider.

(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

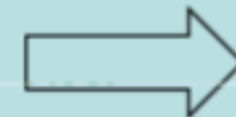
Jonathan Bagger

## Physics case

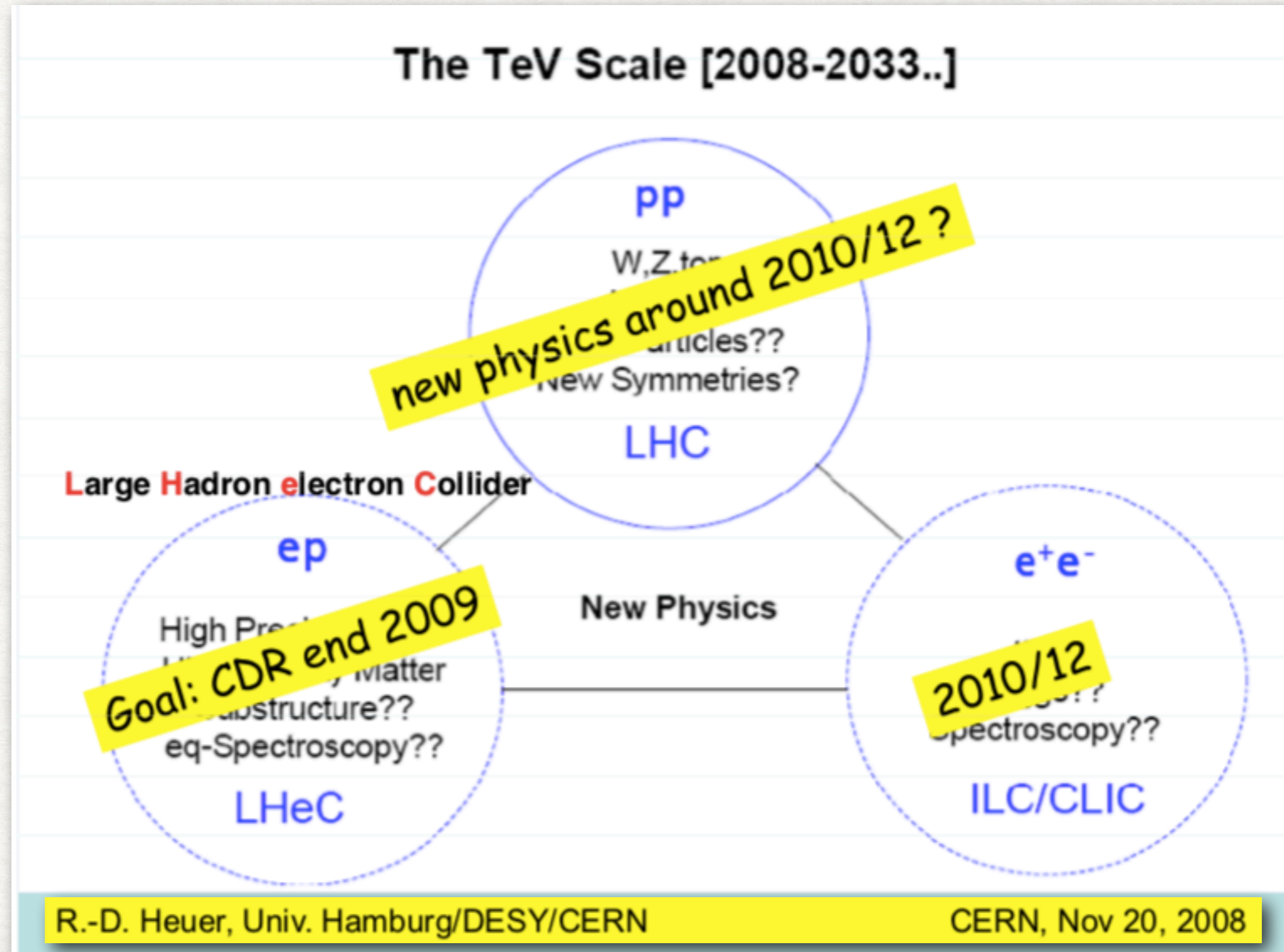


- The physics case must be built on the LHC
  - ◆ The LHC will open the Terascale ...
    - We need to celebrate its success!
- The case has not changed!
  - ◆ We have every expectation that the ILC will be the appropriate follow-on to the LHC ...

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?

Can it still exist?

NATURAL SUSY - ~~THEORY~~

Patrick Meade

Yang Institute for Theoretical Physics  
Stony Brook University

# BUT MAYBE NOT THE RIGHT CASE?

## TUNED MSSM

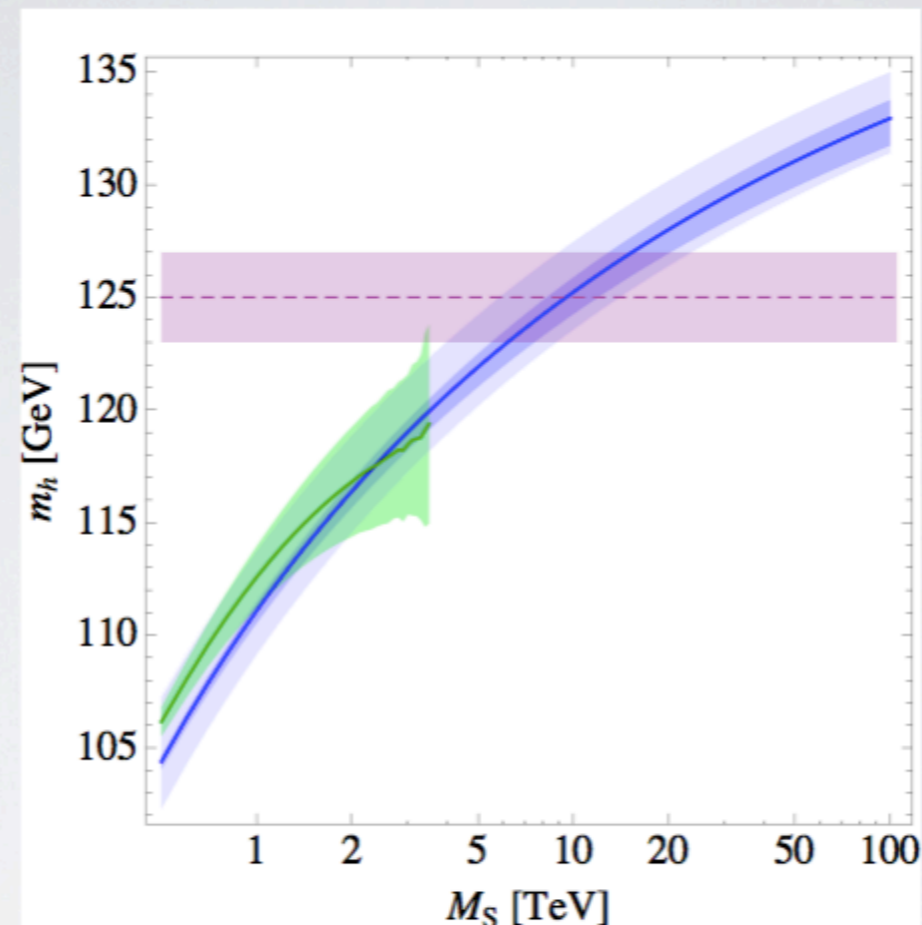


FIG. 6. Higgs mass as a function of  $M_S$ , with  $X_t = 0$ . The green band is the output of FeynHiggs together with its associated uncertainty. The blue line represents 1-loop renormalization group evolution in the Standard Model matched to the MSSM at  $M_S$ . The blue bands give estimates of errors 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...

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† Small-radius (large-radius) jets are denoted by the letter j (J).



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...

**OPTIMIST**

**HALF FULL**



**PESSIMIST**

**HALF EMPTY**



**REALIST**

**I NEED  
ANOTHER BEER**



Pessimistic Particle Physicists versus Optimistic Particle Physicists

# WHAT DO LHC RESULTS REALLY MEAN?

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

	Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1-4 j$	Yes	36.1	$M_D$ 7.7 TeV	$n = 2$ 1711.03301
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$ 8.6 TeV	$n = 3$ HLZ NLO 1707.04147
	ADD QBH	-	$2 j$	-	37.0	$M_{\text{th}}$ 8.9 TeV	$n = 6$ 1703.09127
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$ 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1606.02265
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	36.7	$G_{KK}$ mass 4.1 TeV	$k/\bar{M}_{Pl} = 0.1$ 1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV	$k/\bar{M}_{Pl} = 1.0$ CERN-EP-2018-179
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$g_{KK}$ mass 3.8 TeV	$\Gamma/m = 15\%$ 1804.10823
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1803.09678
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	36.1	$Z'$ mass 4.5 TeV
SSM $Z' \rightarrow \tau\tau$		$2 \tau$	-	-	36.1	$Z'$ mass 2.42 TeV	1709.07242
Leptophobic $Z' \rightarrow bb$		-	$2 b$	-	36.1	$Z'$ mass 2.1 TeV	1805.09299
Leptophobic $Z' \rightarrow tt$		$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$Z'$ mass 3.0 TeV	$\Gamma/m = 1\%$ 1804.10823
SSM $W' \rightarrow \ell\nu$		$1 e, \mu$	-	Yes	79.8	$W'$ mass 5.6 TeV	ATLAS-CONF-2018-017
SSM $W' \rightarrow \tau\nu$		$1 \tau$	-	Yes	36.1	$W'$ mass 3.7 TeV	1801.06992
HVT $V' \rightarrow WV \rightarrow qq\bar{q}\bar{q}$ model B		$0 e, \mu$	$2 J$	-	79.8	$V'$ mass 4.15 TeV	$g_V = 3$ ATLAS-CONF-2018-016
HVT $V' \rightarrow WH/ZH$ model B		multi-channel	-	-	36.1	$V'$ mass 2.93 TeV	$g_V = 3$ 1712.06518
LRSM $W'_R \rightarrow tb$		multi-channel	-	-	36.1	$W'$ mass 3.25 TeV	CERN-EP-2018-142
CI		CI $qqqq$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV $\eta_{LL}$
	CI $\ell\ell qq$	$2 e, \mu$	-	-	36.1	$\Lambda$ 40.0 TeV $\eta_{LL}$	1707.02424
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV	$ C_{4t}  = 4\pi$ CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	$m_{\text{med}}$ 1.55 TeV	$g_q=0.25, g_\nu=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	$m_{\text{med}}$ 1.67 TeV	$g=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	$M_s$ 700 GeV	$m(\chi) < 150 \text{ GeV}$ 1608.02372
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 3 <sup>rd</sup> gen	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$ 1508.04735
Excited fermions/heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV	SU(2) doublet ATLAS-CONF-2018-032
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet ATLAS-CONF-2018-032
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$ CERN-EP-2018-171	
	VLQ $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$ ATLAS-CONF-2016-072
	VLQ $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$ ATLAS-CONF-2018-024
	VLQ $QQ \rightarrow WqVWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	37.0	$q^*$ mass 6.0 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1703.09127
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	$q^*$ mass 5.3 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	36.1	$b^*$ mass 2.6 TeV	1805.09299
	Excited lepton $\ell^*$	$3 e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton $\nu^*$	$3 e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
Other	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	$N^0$ mass 560 GeV	ATLAS-CONF-2018-020
	LRSM Majorana $\nu$	$2 e, \mu$	$2 j$	-	20.3	$N^0$ mass 2.0 TeV	$m(W_R) = 2.4 \text{ TeV, no mixing}$ 1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production 1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_i^{\pm\pm} \rightarrow \ell\tau) = 1$ 1411.2921
	Monotop (non-res prod)	$1 e, \mu$	$1 b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$ 1410.5404
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ q  = 5e$ 1504.04188
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV	DY production, $ g  = 1g_D, \text{spin } 1/2$ 1509.08059

$\sqrt{s} = 8 \text{ TeV}$   $\sqrt{s} = 13 \text{ TeV}$

10<sup>-1</sup> 1 10 Mass scale [TeV]

\*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).

# 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

☰ SECTIONS



HOME



SEARCH

The New York Times

Securing Facebook during elections

See more

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

DID YOU SEE THE NEUTRINO SPEED OF LIGHT THING?

YUP! GOOD NEWS; I NEED THE CASH.  
HUH? CASH?



YEAH. WHEN THERE'S A NEWS STORY ABOUT A STUDY OVERTURNING ALL OF PHYSICS, I USED TO URGE CAUTION, REMIND PEOPLE THAT EXPERTS AREN'T ALL STUPID, AND END UP IN POINTLESS ARGUMENTS ABOUT GAUDED.

NO, THIS ISN'T ABOUT WHETHER RELATIVITY EXISTS. IF IT DIDN'T, YOUR GPS WOULDN'T WORK.

WHAT DO YOU MEAN, "SCIENCE THOUGHT POLICE"? HAVE YOU SEEN OUR BUDGET? WE COULDN'T BEGIN TO AFFORD OUR OWN THOUGHT POLICE.



THAT SOUNDS MISERABLE AND UNFULFILLING.

YUP. SO I GAVE UP, AND NOW I JUST FIND EXCITED BELIEVERS AND BET THEM \$200 EACH THAT THE NEW RESULT WON'T PAN OUT.



THAT'S MEAN.

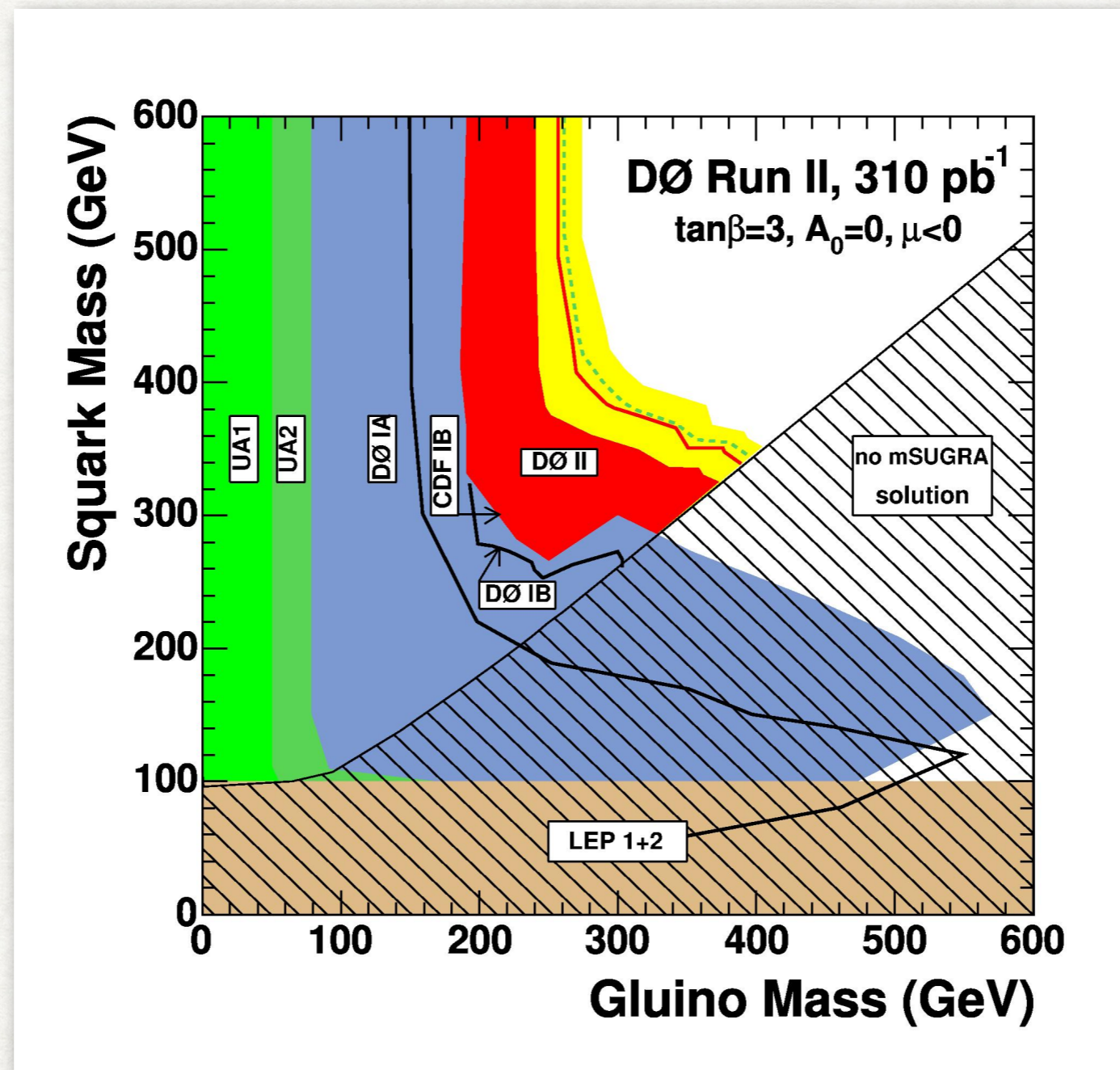
IT PROVIDES A GOOD INCOME, AND IF I'M EVER WRONG, I'LL BE TOO EXCITED ABOUT THE NEW PHYSICS TO NOTICE THE LOSS.



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 BAD



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

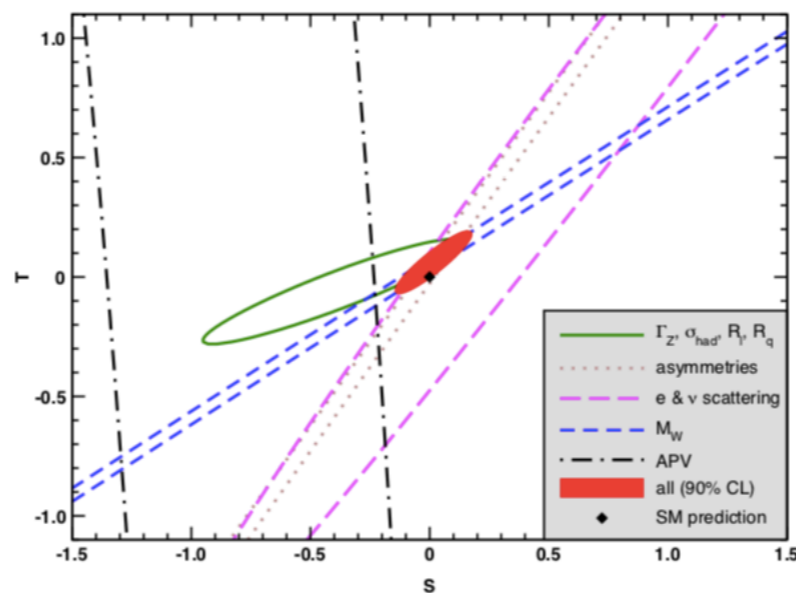


WE ALL DO IT,  
EVEN IF YOU INSIST YOU'RE NOT A BIASED  
PHYSICIST

- 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

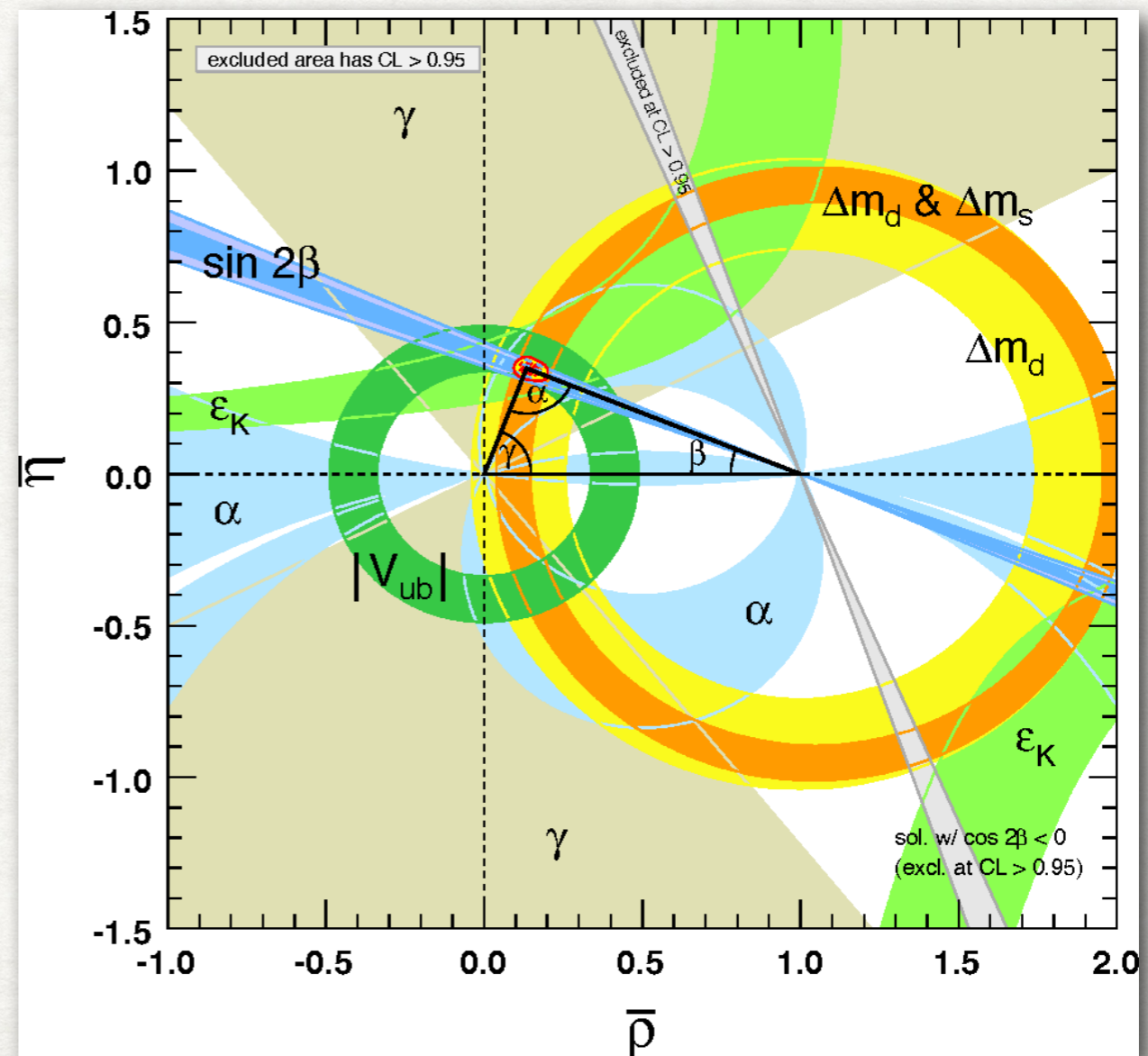
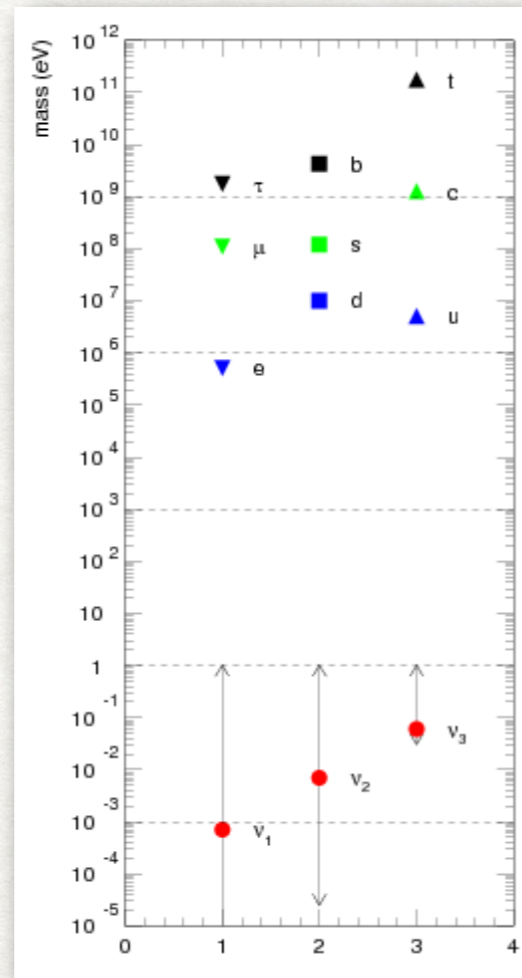


**Figure 10.6:**  $1\sigma$  constraints (39.35% for the closed contours and 68% for the others) on  $S$  and  $T$  (for  $U = 0$ ) from various inputs combined with  $M_Z$ .  $S$  and  $T$  represent the contributions of new physics only. Data sets not involving  $M_W$  or  $\Gamma_W$  are insensitive 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??

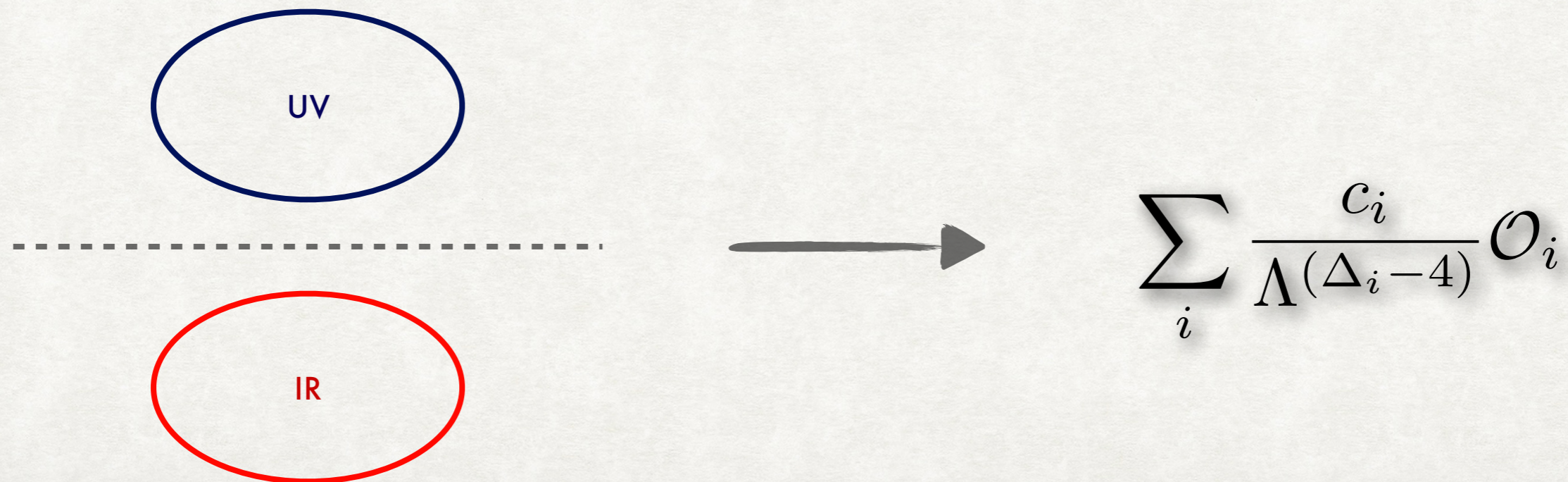
- These previous experiments are beautiful correct experiments...
- It's the *interpretation* of the results theoretically that matters when applying it to other experiments

# MODEL DEPENDENT VS MODEL INDEPENDENT

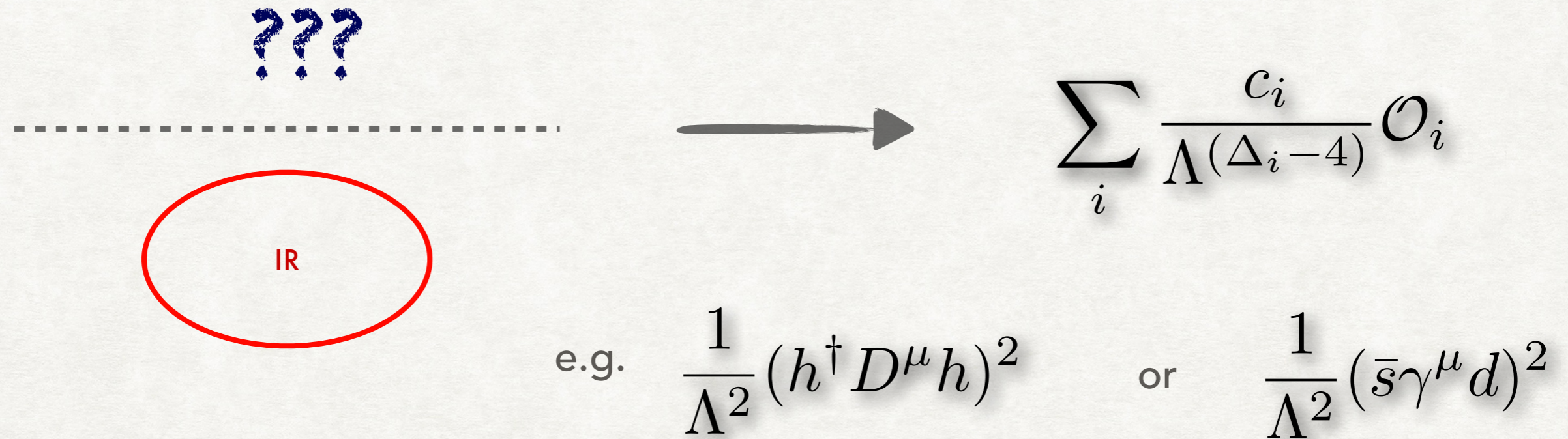
Most of you in the room will buy that a theorist  
can cook up a model (add an epicycle)  
which can evade a particular search

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



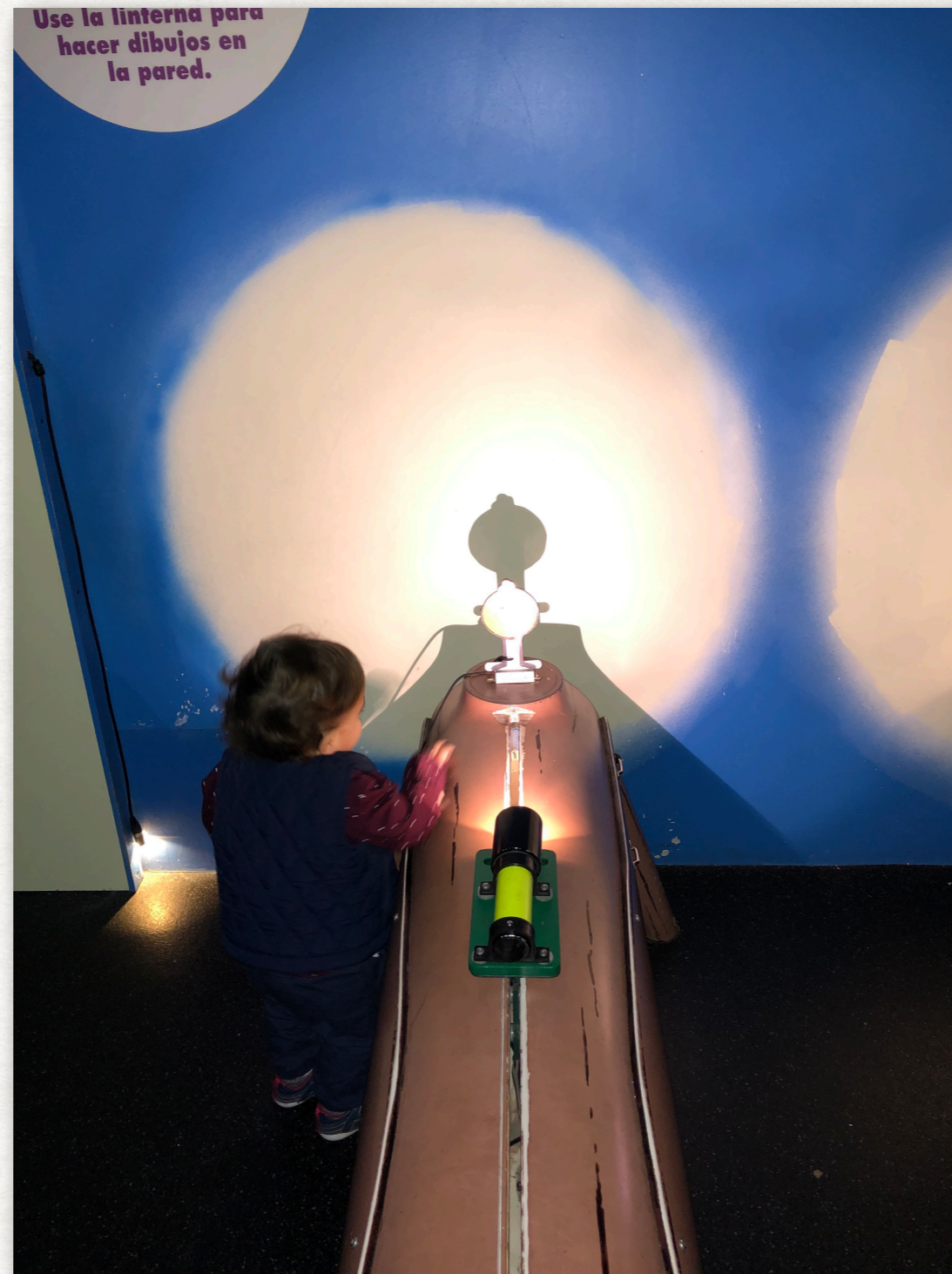
# EFFECTIVE FIELD THEORY BOUNDS



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

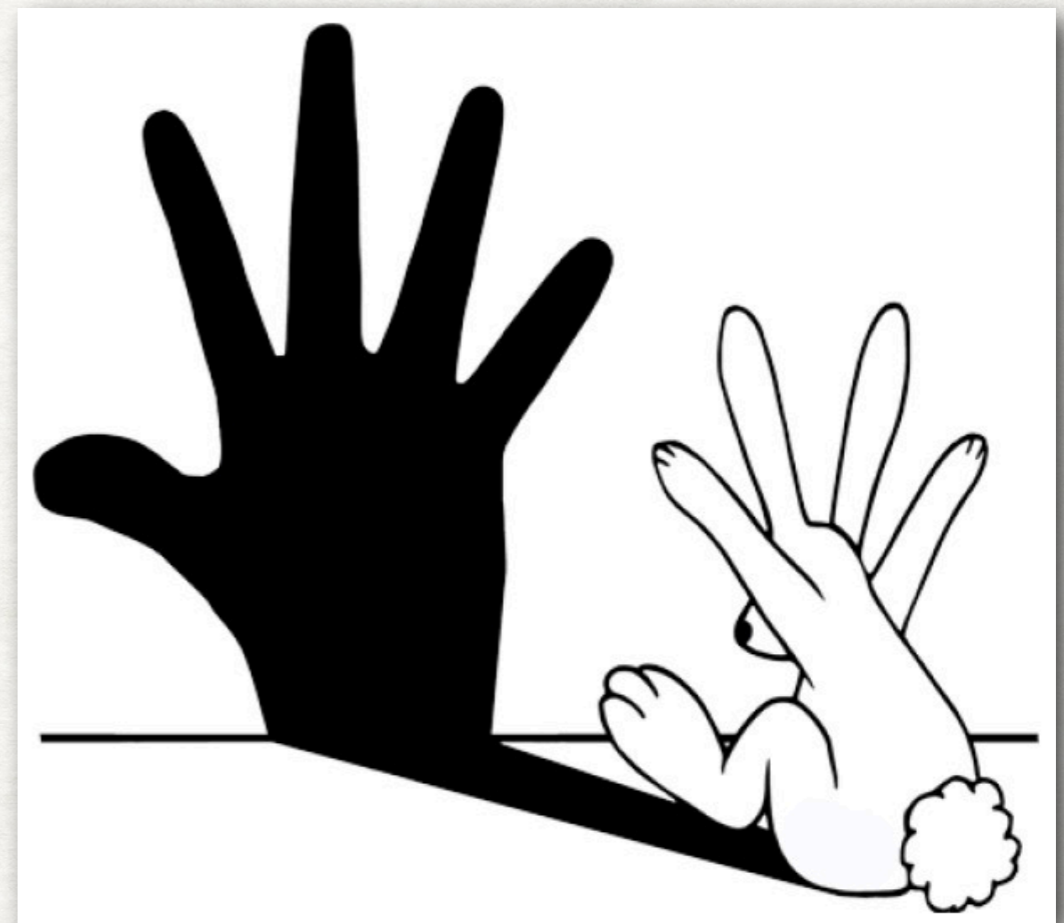
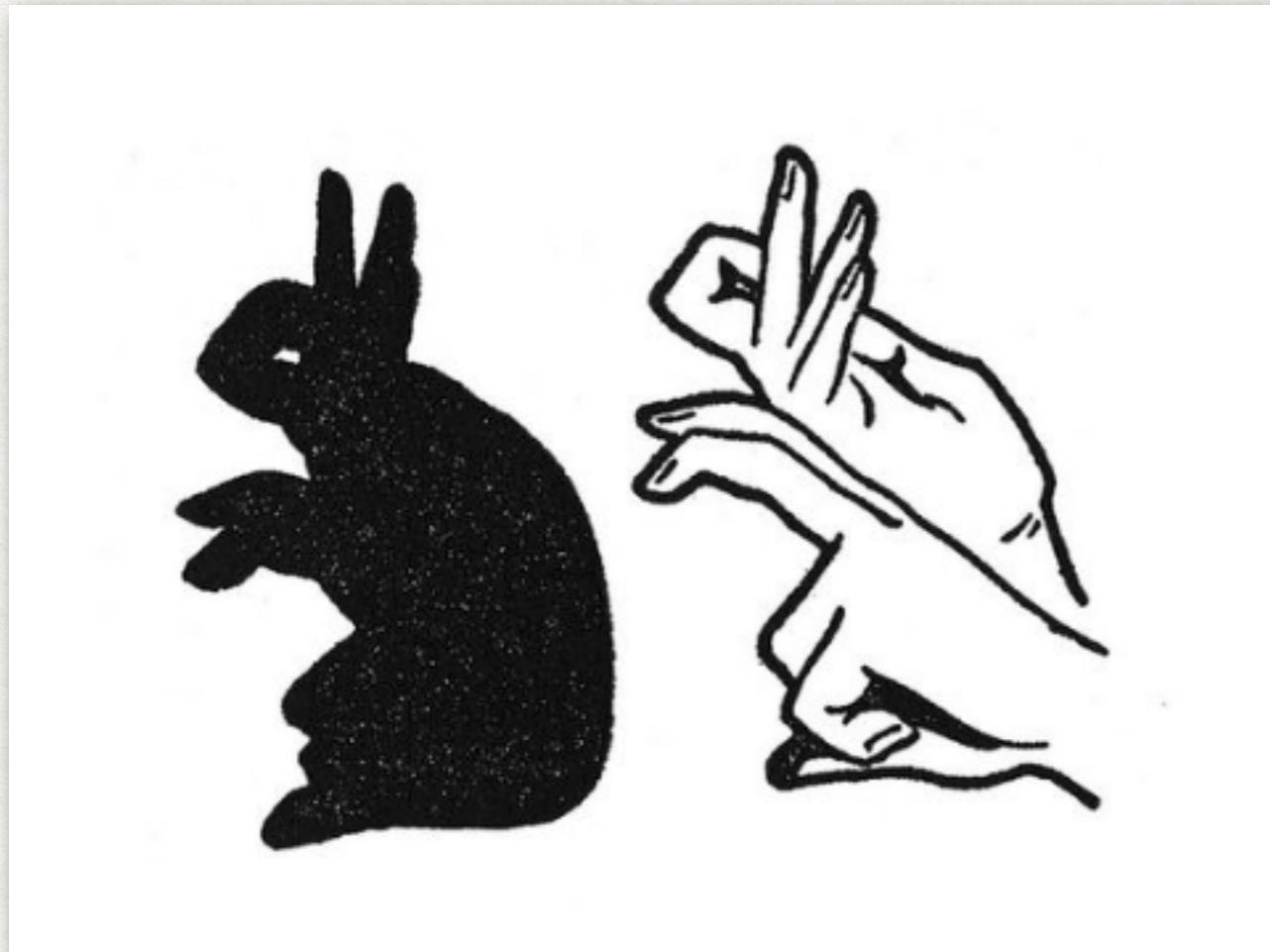


Trying to figure out what the object is by looking at it's projection

*Sometimes it's easy!*

# "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?

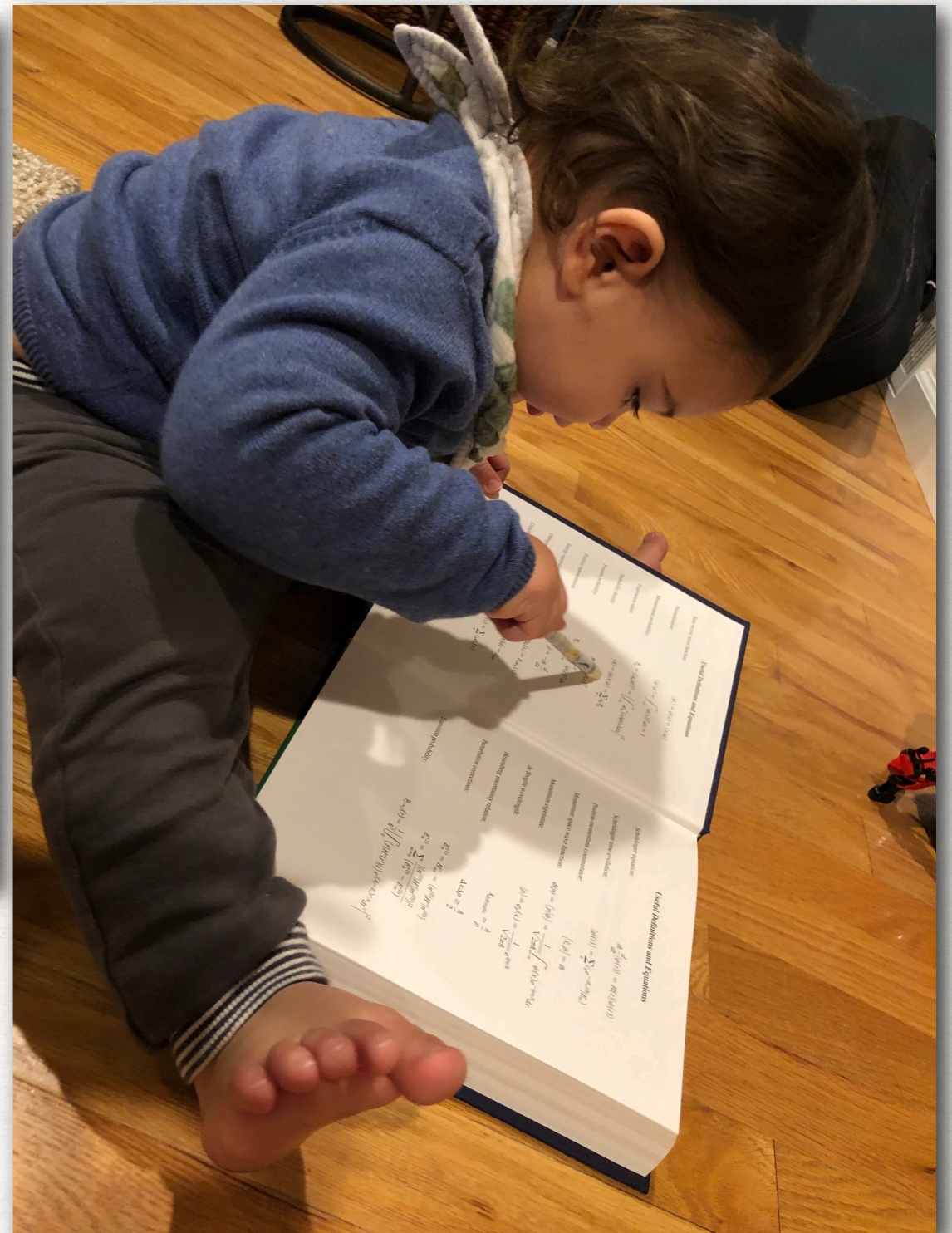
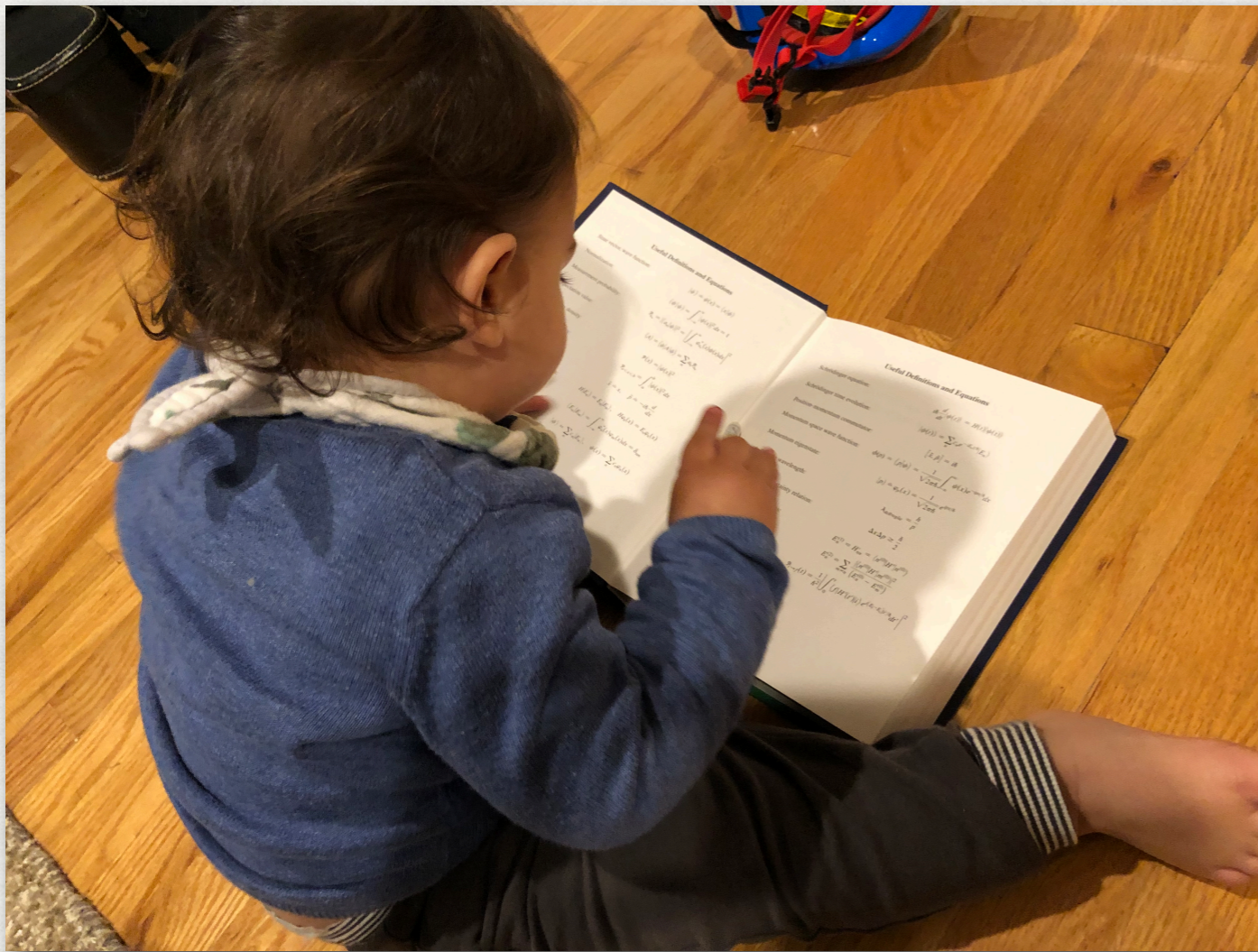
LET ALONE BUILDING A **LOWER** ENERGY ILC??

- 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 even 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!



# WHERE DOES MY OPTIMISM COME FROM?

- 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!

# WHERE DOES MY OPTIMISM COME FROM?

- 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!

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





# 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:

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

Wise professor tells entering graduate student 2017:

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

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**

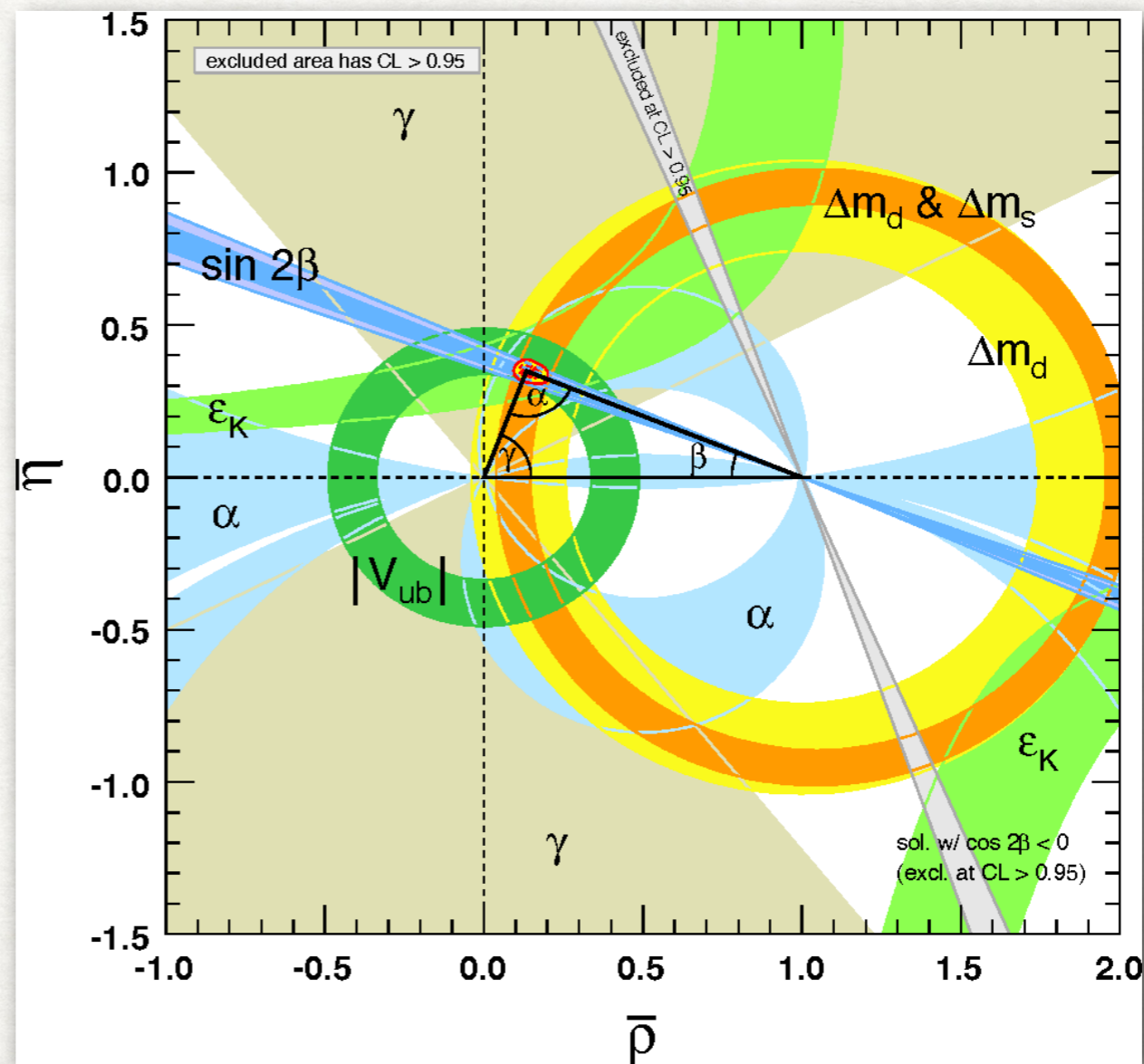
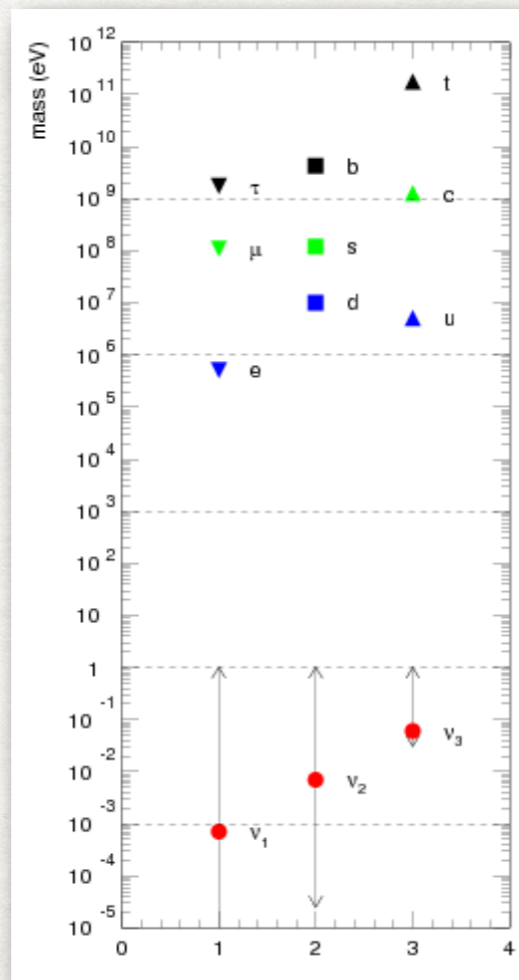


# HIGGS PHYSICS

- “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?

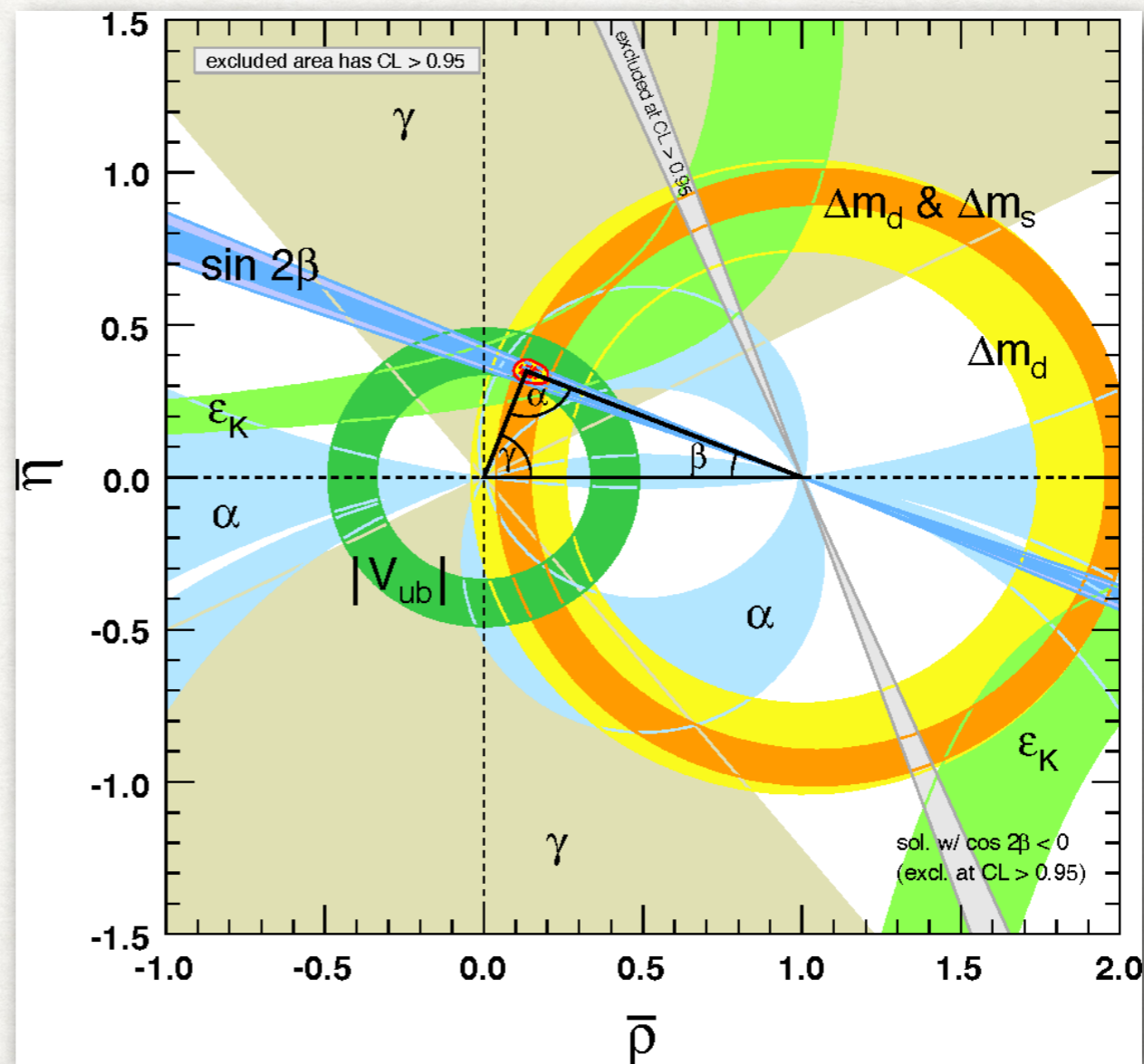
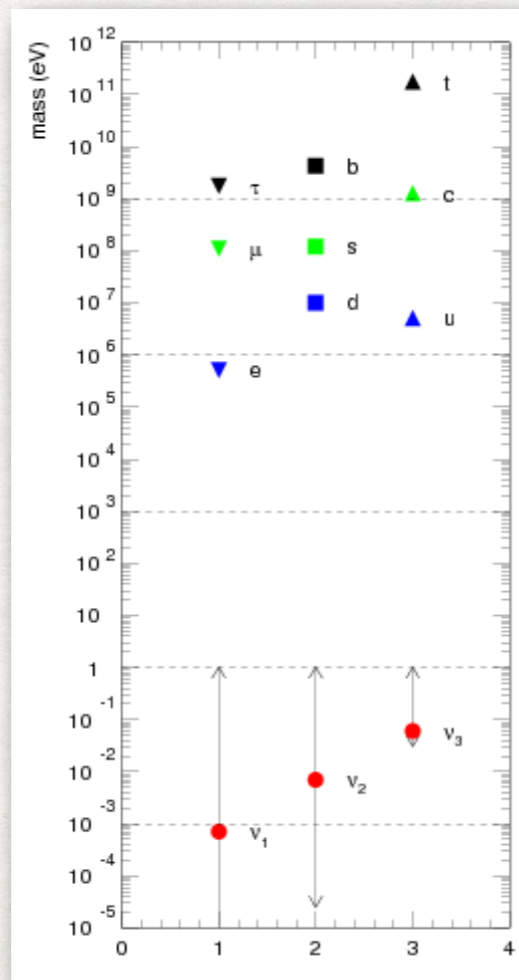
# INSIGHTS INTO THE ORIGIN OF MASS AND FLAVOR

- 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...

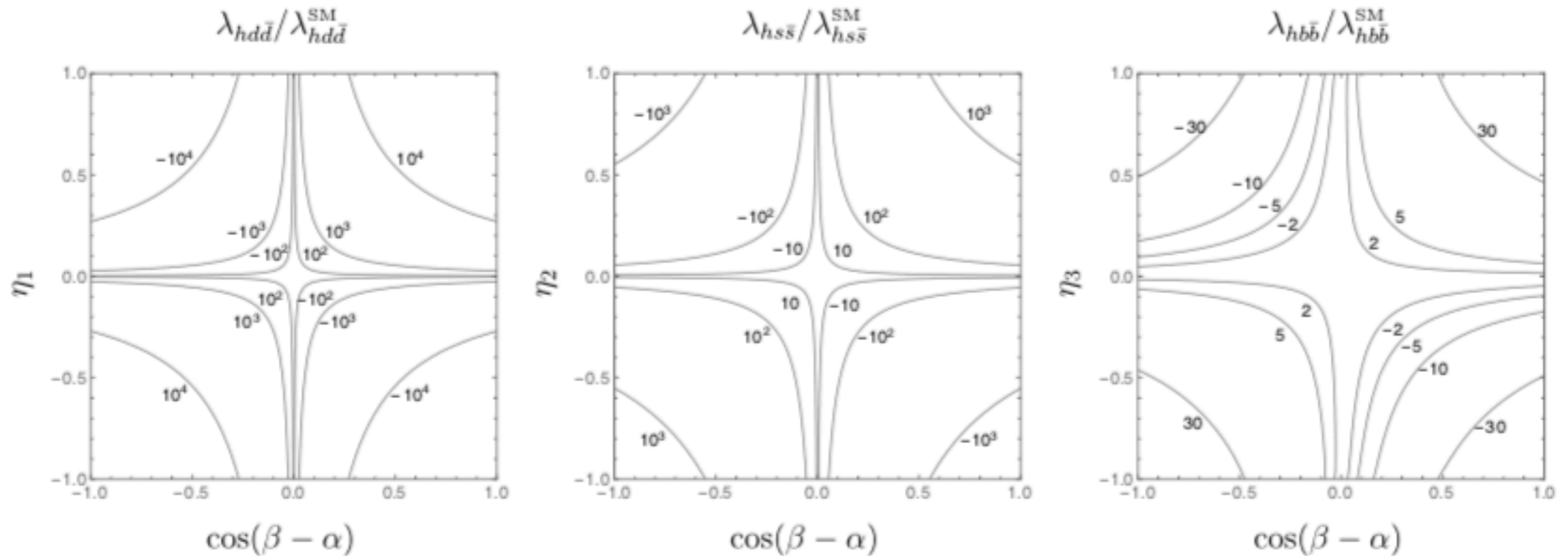


# INSIGHTS INTO THE ORIGIN OF MASS AND FLAVOR

- 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?



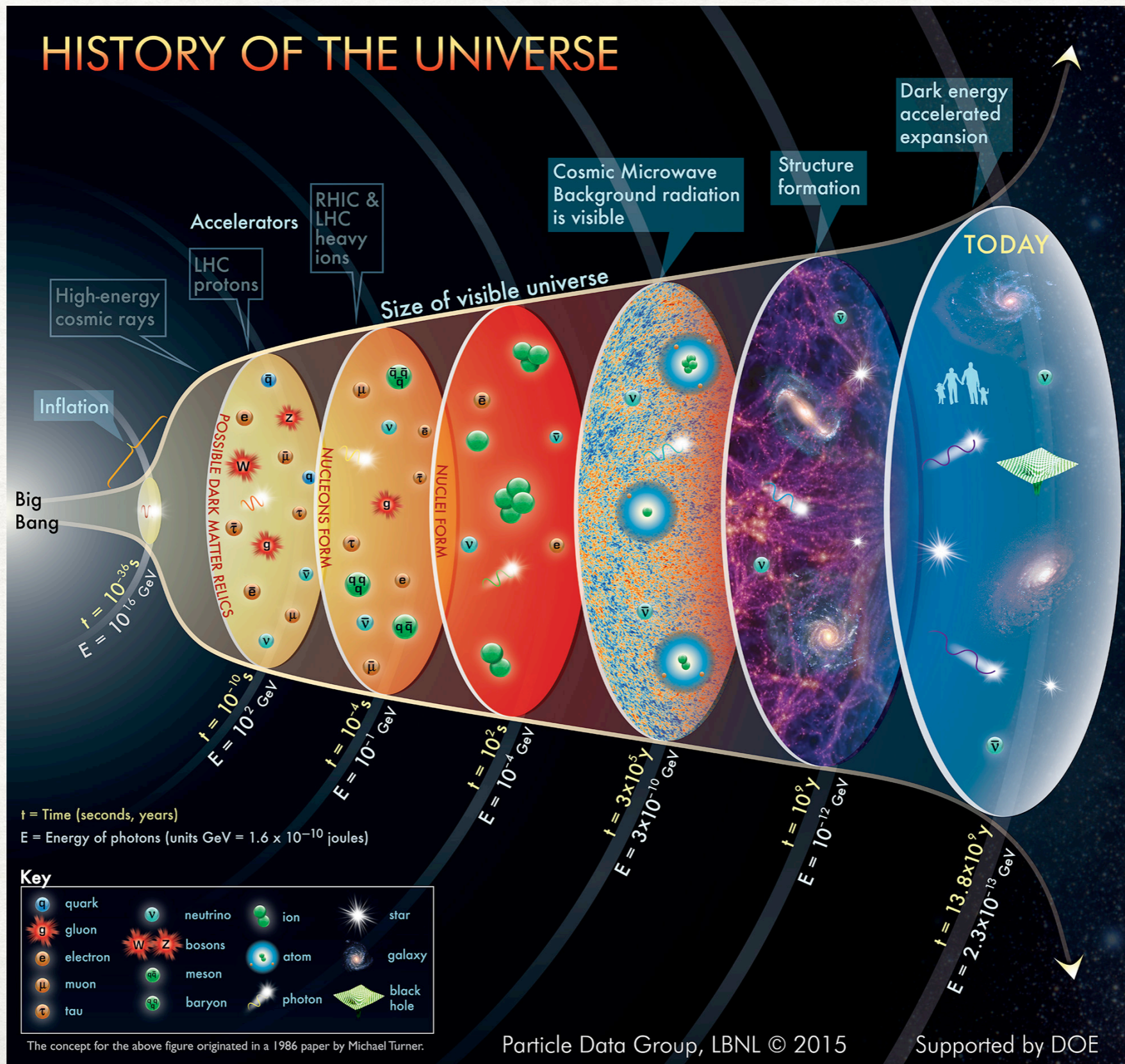
**Figure 1:** Yukawa enhancement

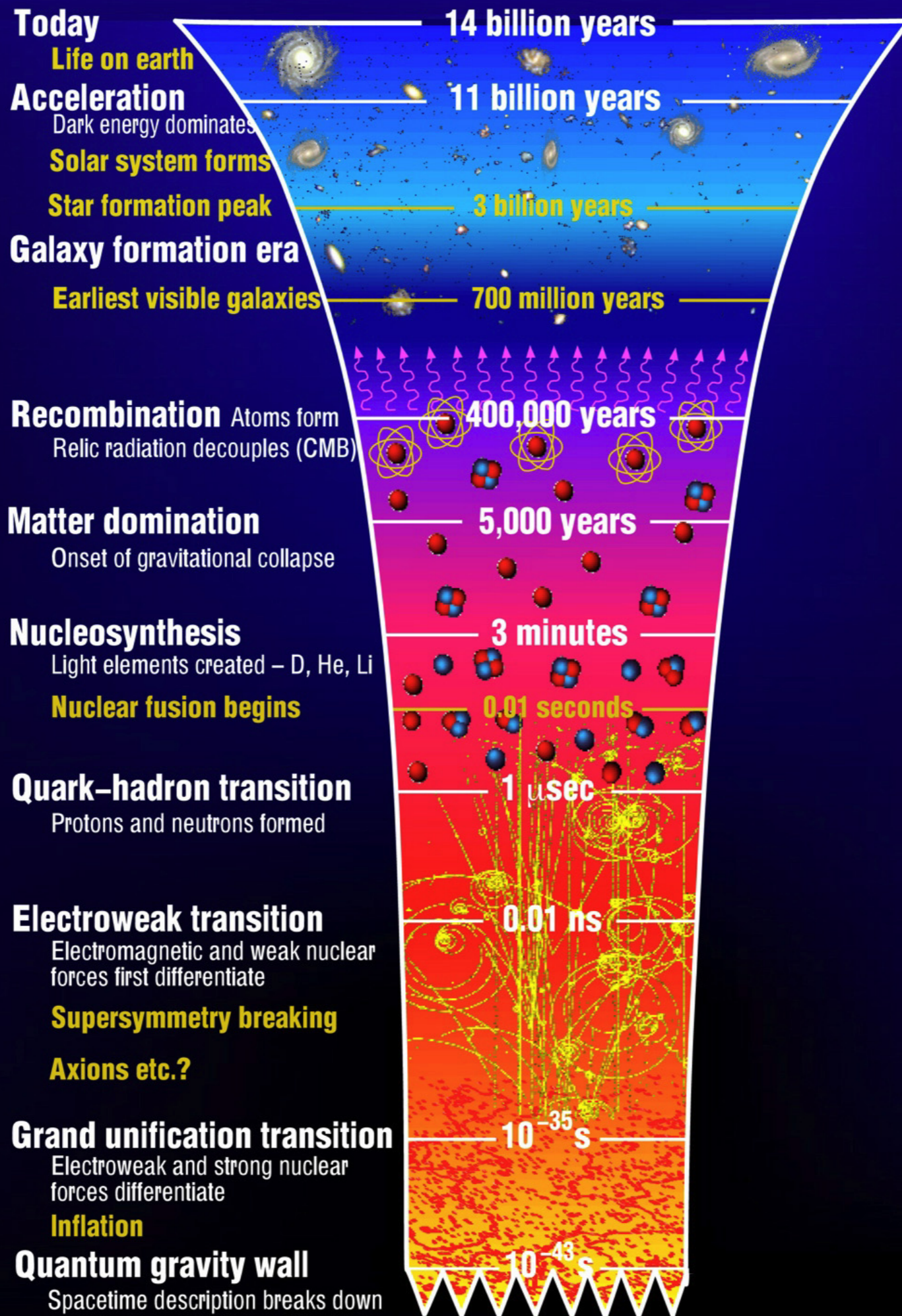
Aligned Flavor Violation (AFV) from Spontaneous Flavor Violation (SFV)

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

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

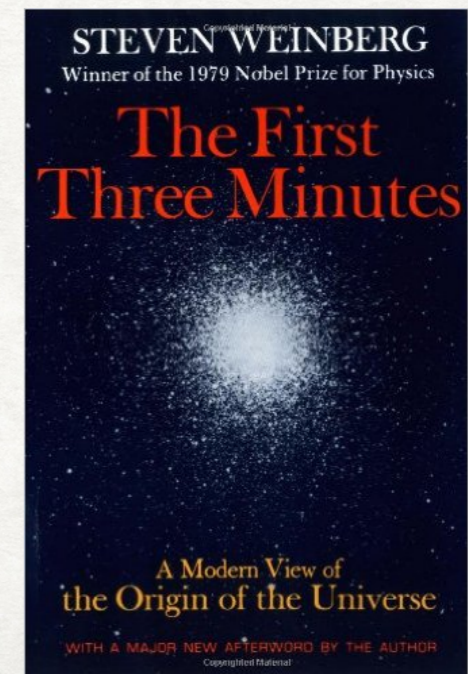
# THE HIGGS AND THE HISTORY OF OUR UNIVERSE?





**Cosmology  
stuck here**

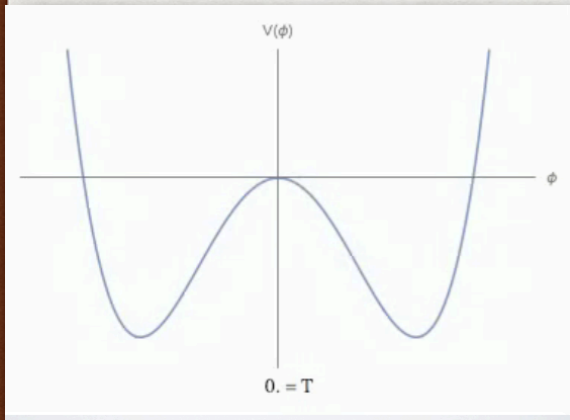
**Need particle  
physics to  
go further!**





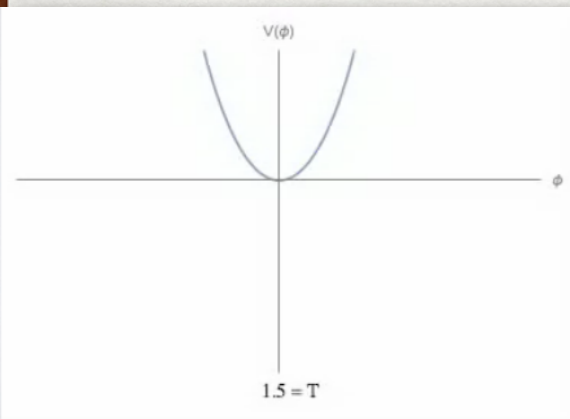
# FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION

Imperfect analogy:



Universe now

**Early universe  
was hotter!**



Early Universe

# BASIC CONCEPT IS INGRAINED IN TEXTBOOKS

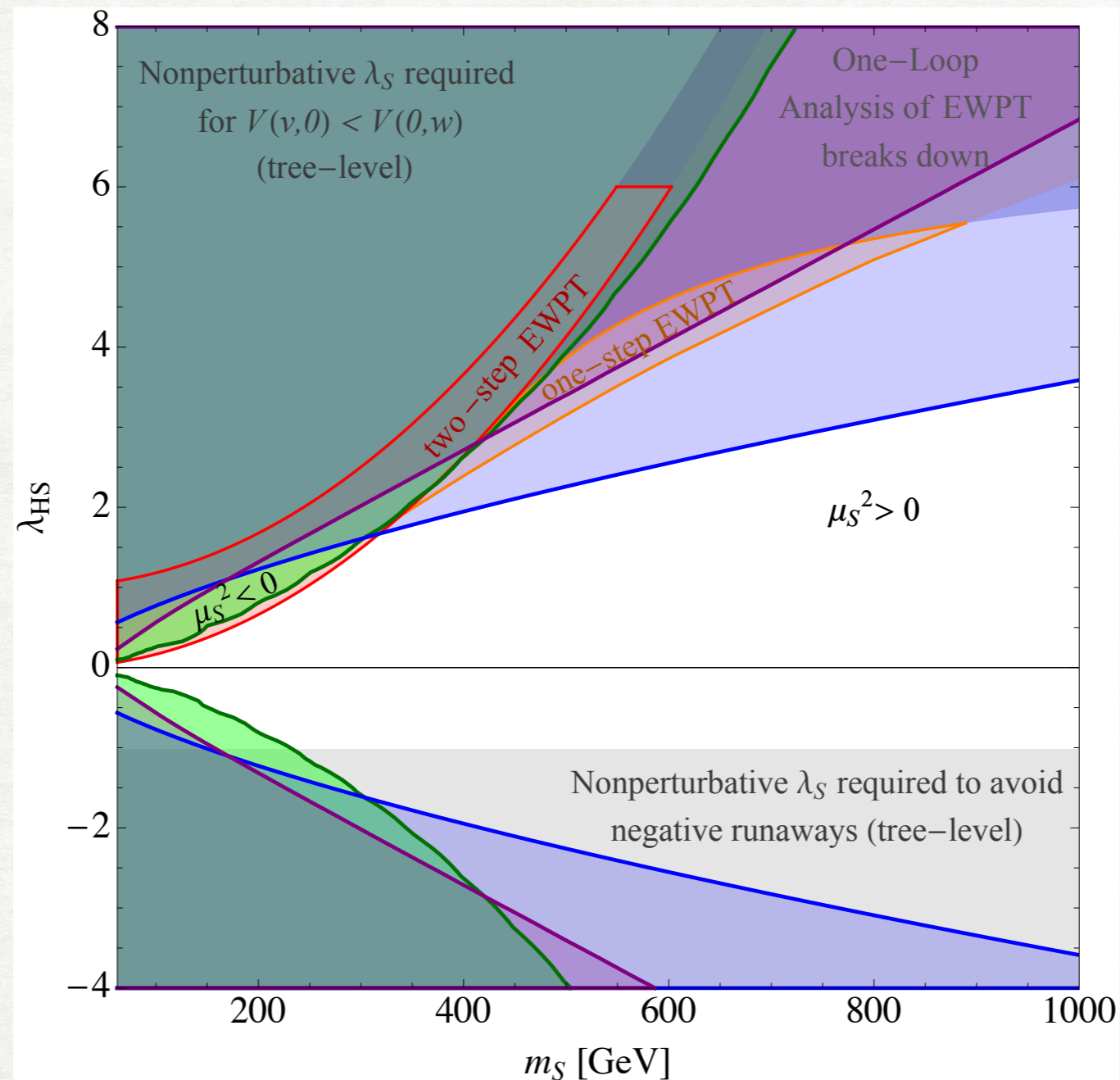
## PHASE TRANSITIONS

### 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 transition at a temperature of order 300 GeV and a time of order  $10^{-11}$  sec, associated with the breakdown of  $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$ . 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

# 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?

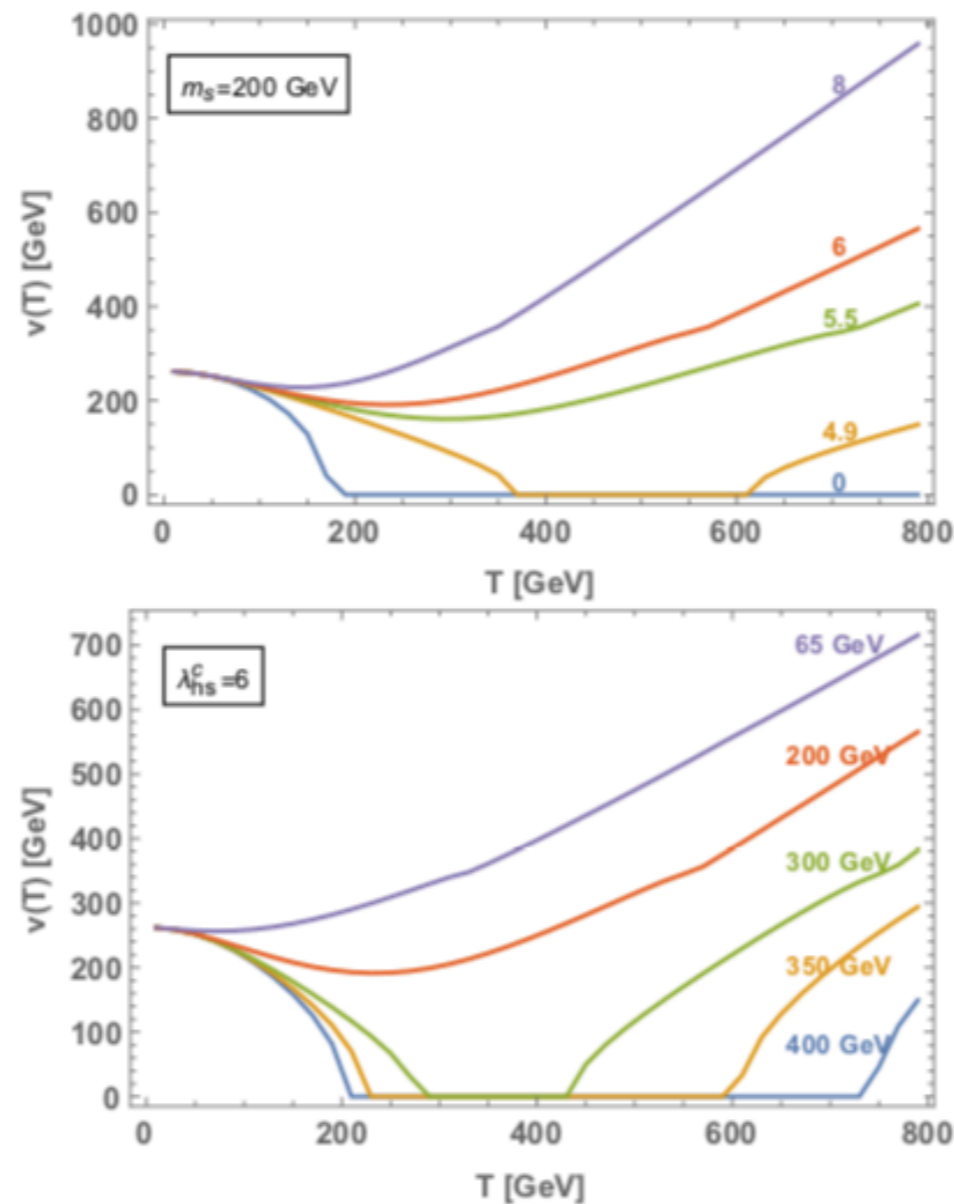


FIG. 2. Top: The temperature dependent VEV,  $v(T)$  for different values of  $\lambda_{hs}^c$  demonstrating different phase histories as a function of the temperature,  $T$ . Bottom: The temperature dependent VEV for a fixed  $\lambda_{hs}^c$  and different values of  $m_s$ .  $N_s = 600$  to exhibit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

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

PM, H. Ramani  
1807.07578

Unrestored Electroweak Symmetry

# ILC FOR DISCOVERY!

CERN-TH-2018-004

## Charged Fermions Below 100 GeV

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It was often thought LEP II 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!