

Title: Physics beyond the standard model from Higgs Parity

Speakers: Keisuke Harigaya

Series: Cosmology & Gravitation

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Abstract: The discovery of the Higgs boson has revealed that the quartic Higgs self-coupling becomes small at very high energy scales. Guided by this observation, I introduce Higgs Parity, which is a spontaneously broken symmetry exchanging the standard model Higgs with its parity partner. In addition to explaining the small Higgs quartic coupling, Higgs Parity can provide a dark matter candidate, solve the strong CP problem, and arise from an SO(10) grand unified gauge symmetry. I will show that the Higgs Parity symmetry breaking scale is determined by standard model parameters and predicts experimental signals such as the proton decay rate and the warmness of dark matter. As a result, Higgs Parity provides a tight correlation between future precision measurements of standard model parameters and these experimental signals.

05/19/2020

Perimeter Institute

# Physics beyond the standard model from Higgs Parity

Keisuke Harigaya

(Institute for Advanced Study)

Hall and KH

: [1803.08119](#), [1905.12722](#)

Dror, Dunsky, Hall and KH: [2004.09511](#)

# Particle physics

is trying to answer questions such as

\* What are **the fundamental laws** of physics?

Particles, interactions among them, ...

\* How did our **universe** begin and evolve?

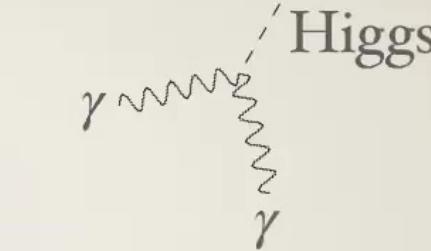
Inflation, cosmic perturbations,  
baryon asymmetry, dark matter, ...

# Standard Model

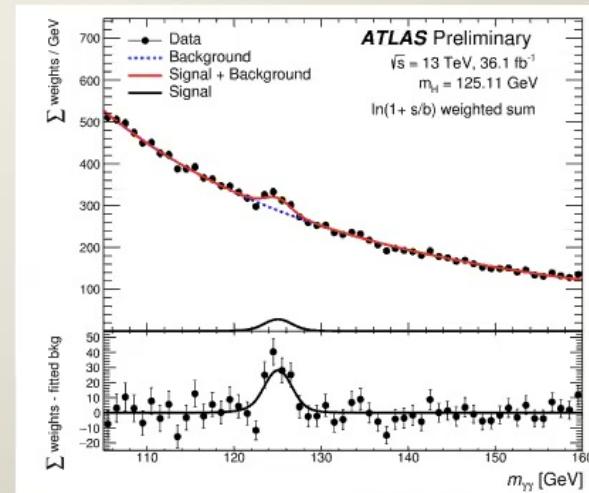
(of particle physics)

	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>		
Quarks	$u$ up	$c$ charm	$t$ top	$\gamma$ photon	$H$ Higgs Boson
	$d$ down	$s$ strange	$b$ beauty	$W^\pm$ W boson	
Leptons	$e$ electron	$\mu$ muon	$\tau$ tau	$Z^0$ Z boson	
	$\nu_e$ neutrino electron	$\nu_\mu$ neutrino muon	$\nu_\tau$ neutrino tau	$g$ gluon	Gauge Bosons

figure from [www.physik.uzh.ch](http://www.physik.uzh.ch)



Events



Invariant mass

# Precise measurements

- \* Higgs mass     $m_h = 125.18 \pm 0.16$  GeV
- \* Top quark mass     $m_t = 173.1 \pm 0.4$  GeV
- \* Strong coupling constant     $\alpha_s(m_Z) = 0.1184 \pm 0.0011$
- \* ...

Can we learn something beyond the Standard Model ?

nature of dark matter, mass of new particles, rare decays, etc.

# Precise measurement and new physics

Hall and KH (2018, 2019)  
Dunsky, Hall and KH (2019)

New symmetry  
**Higgs Parity**

- \* gives a dark matter candidate
- \* is part of a grand unified gauge symmetry
- \* solves the strong CP problem

# Precise measurement and new physics

Hall and KH (2018, 2019)  
Dunsky, Hall and KH (2019)

top quark mass

Higgs mass

strong coupling constant



Higgs Parity  
symmetry  
breaking scale

# Outline

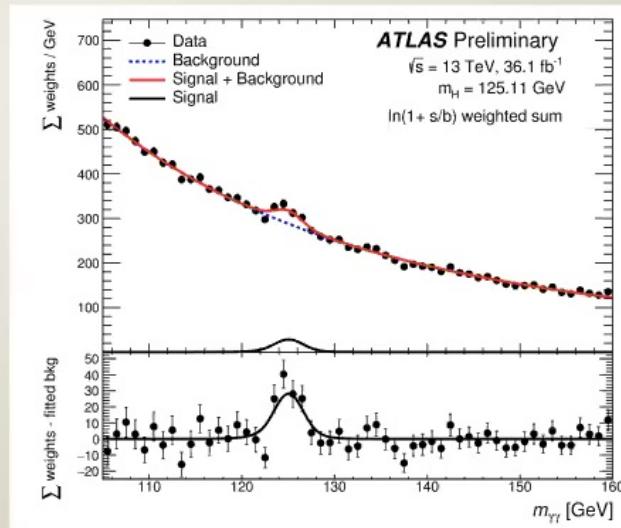
- \* Introduction (continued)
- \* Higgs Parity
- \* Left-Right Higgs Parity and the strong CP problem
- \* Grand unification and proton decay
- \* Warm right-handed neutrino dark matter
- \* Summary and outlook

# Introduction

# Standard Model

quarks	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>		
	$u$ up	$c$ charm	$t$ top	$\gamma$ photon	$H$ Higgs Boson
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figure from [www.physik.uzh.ch](http://www.physik.uzh.ch)



CERN, 2013



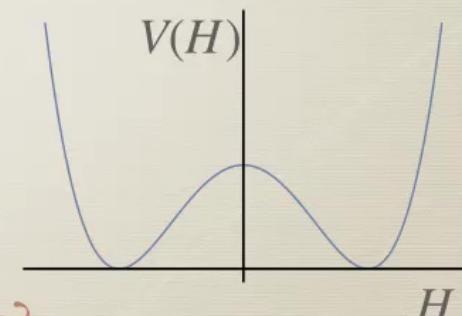
Picture from Recondito.org

# We are far away from the goal

- \* What is dark matter?
- \* How did cosmic inflation occur?
- \* How was the baryon asymmetry of the universe created?
- \* Why does QCD preserve CP symmetry?
- \* What sets the Higgs potential parameters?

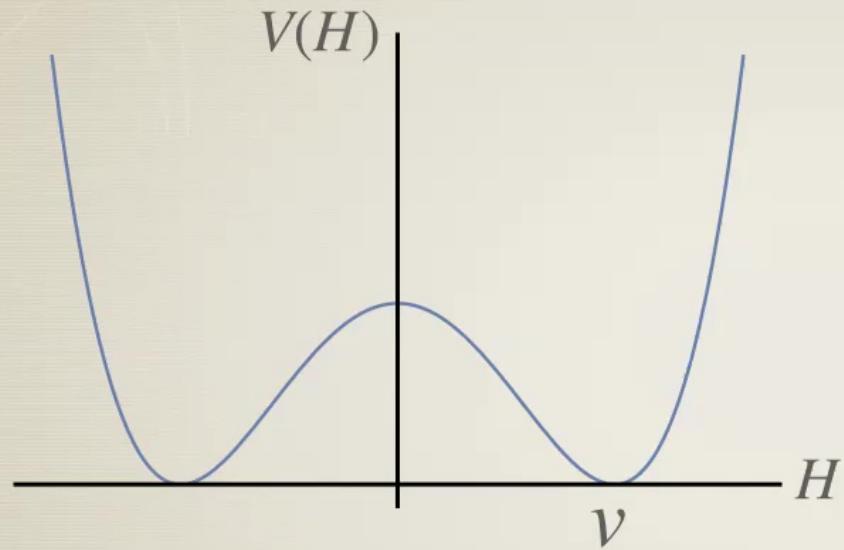
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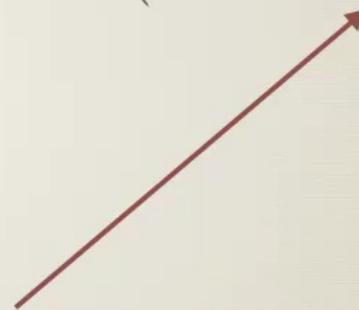


$$V(H) = \lambda_{\text{SM}} \left( |H|^2 - v^2 \right)^2$$

# Higgs potential



$$V(H) = \lambda_{\text{SM}} (|H|^2 - v^2)^2$$



A question of few decades:  
What sets the mass scale of Higgs?

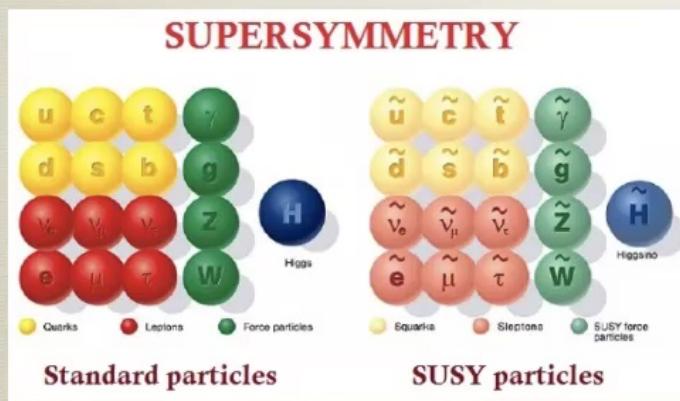
$v = 173 \text{ GeV} \ll (\text{Planck scale, GUT scale})$

**Hierarchy problem**

# Higgs potential

What sets the small mass scale of Higgs?

Ex. Supersymmetry



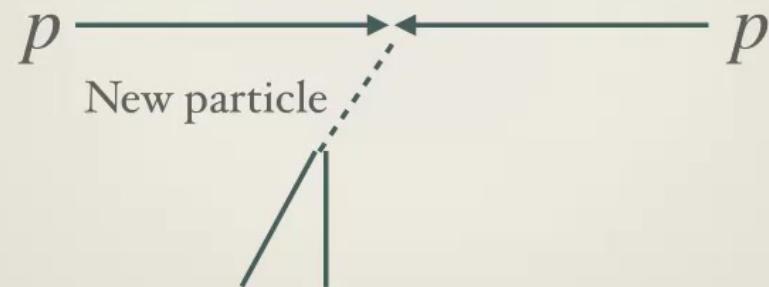
Higgs mass scale is naturally much smaller than the Planck scale

Maiani (1979), Veltman (1979), Witten (1981)

**predict new particles with masses around 100 GeV**

# 100 GeV scale new physics

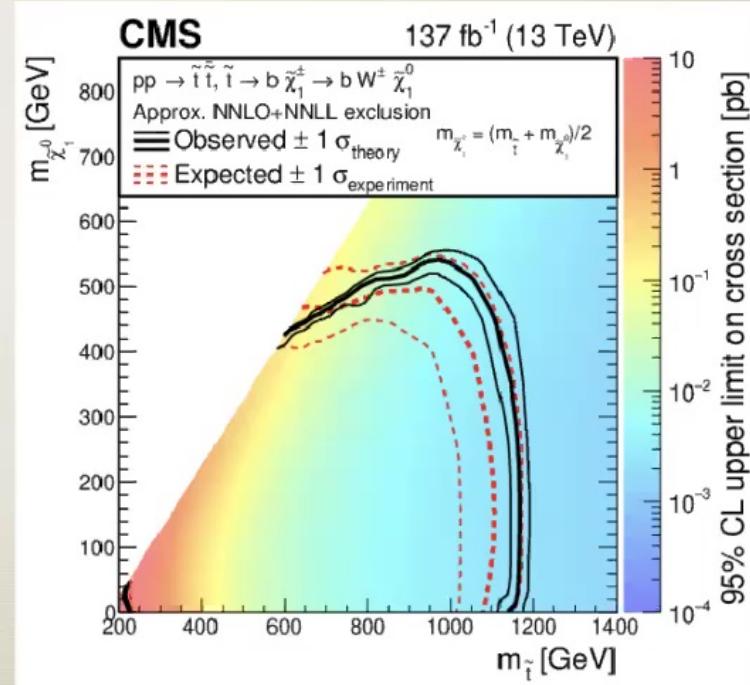
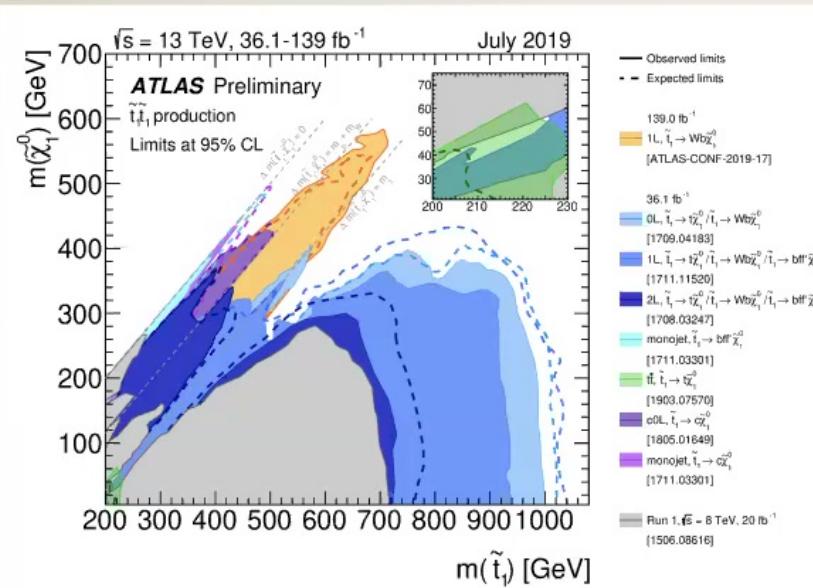
Searches for new particles at colliders



# 100 GeV scale new physics

New particles have not been found so far

Ex. Constraints on the masses of new particles  
in supersymmetric theories



# What to do?

$$V(H) = \lambda_{\text{SM}} \left( |H|^2 - v^2 \right)^2$$

We should keep trying to explain the small Higgs mass and seek experimental signatures of the explanation.

Recent effort includes, for example,

- \* Twin Higgs

Chacko, Goh and Harnik (2006), Falkowski, Pokorski and Schmaltz (2006),  
Chang, Hall and Weiner (2006), KH and Badziak (2017,2018), Barbieri, Hall and KH (2017,2018),

- \* Relaxion

Graham, Kaplan and Rajendran (2015), Espinosa et.al. (2015), Hook and Marques-Tavares (2016),  
Evans, Gherghetta, Nagata and Thomas (2016), Ibe, Shoji and Suzuki (2019), ...

We should also pursue complementary directions

# Fine-tuned Higgs mass?

$$V(H) = \lambda_{\text{SM}} \left( |H|^2 - v^2 \right)^2$$

We are not sure if the small Higgs mass is a guiding principle to look for new physics

The small Higgs mass may be explained by theoretical ideas which are difficult to probe experimentally

## Ex. Multiverse and anthropic selection

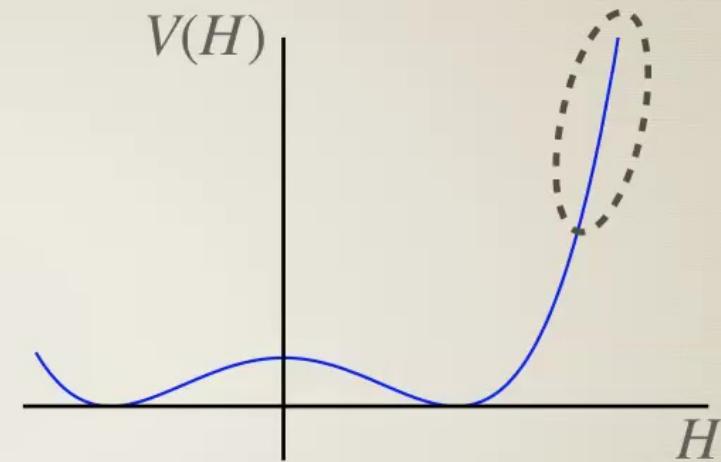
Weinberg (1987), Susskind (2003), Agrawal, Barr, Donoghue and Seckel (1998), Clavelli and White (2006), Hall, Pinner and Ruderman (2014), ...

# Higgs self-interaction?

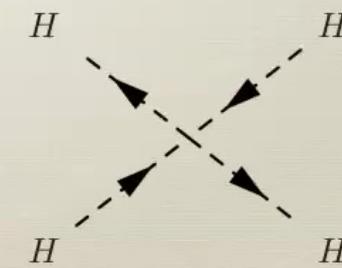
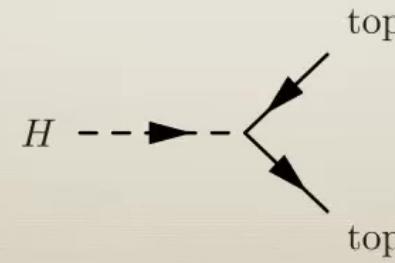
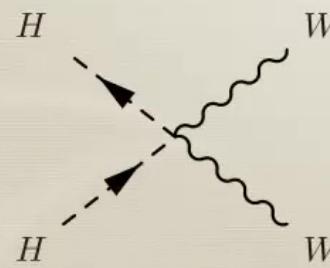
$$V(H) = \lambda_{\text{SM}} (|H|^2 - v^2)^2$$



$$m_h^2/(4v^2) \simeq 0.13$$



Let us examine the quartic coupling,  
assuming that the standard model is valid up to high energy scales,  
including quantum corrections

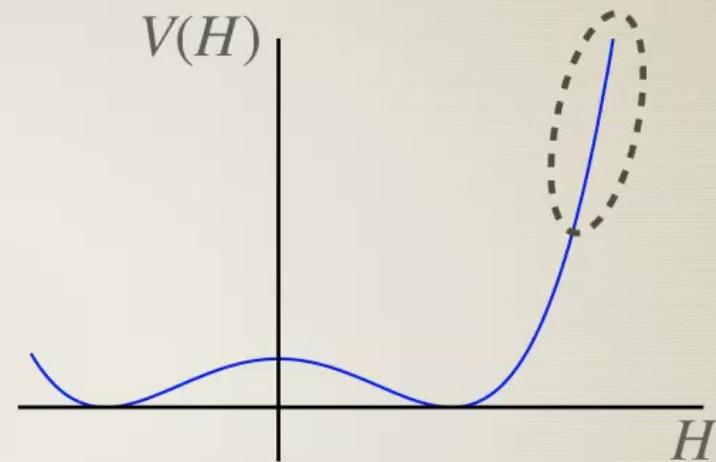
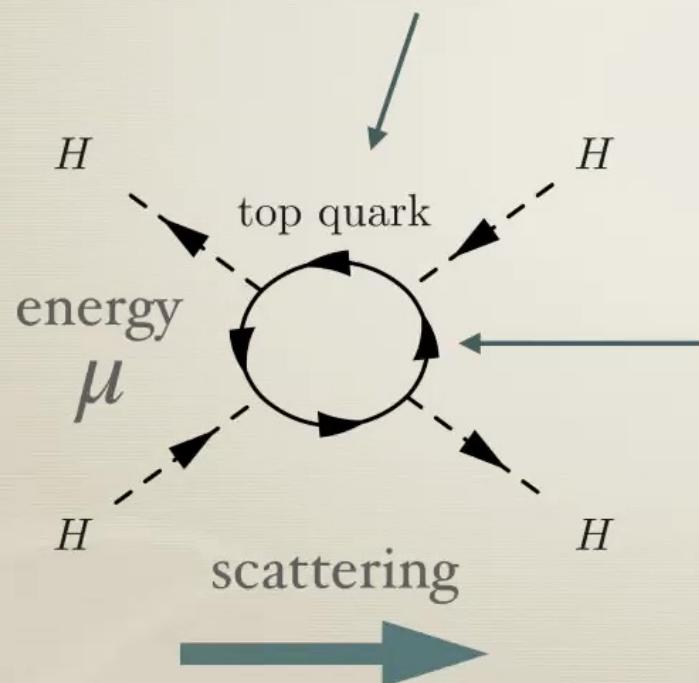


# Energy-dependent quartic coupling

perturbation theory

$$\Delta\lambda_{\text{SM}} \sim \sum_i \langle HH | i \rangle \langle i | HH \rangle$$

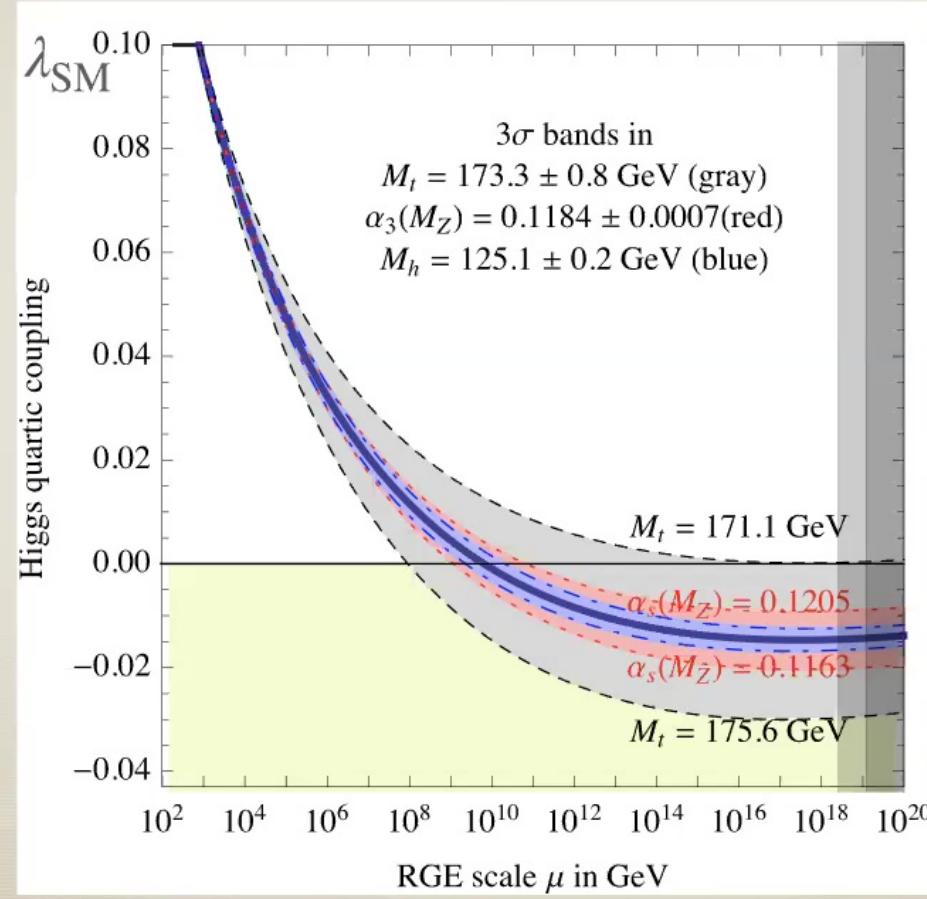
sum over intermediate states



Intermediate states  
depend on energy  $\mu$

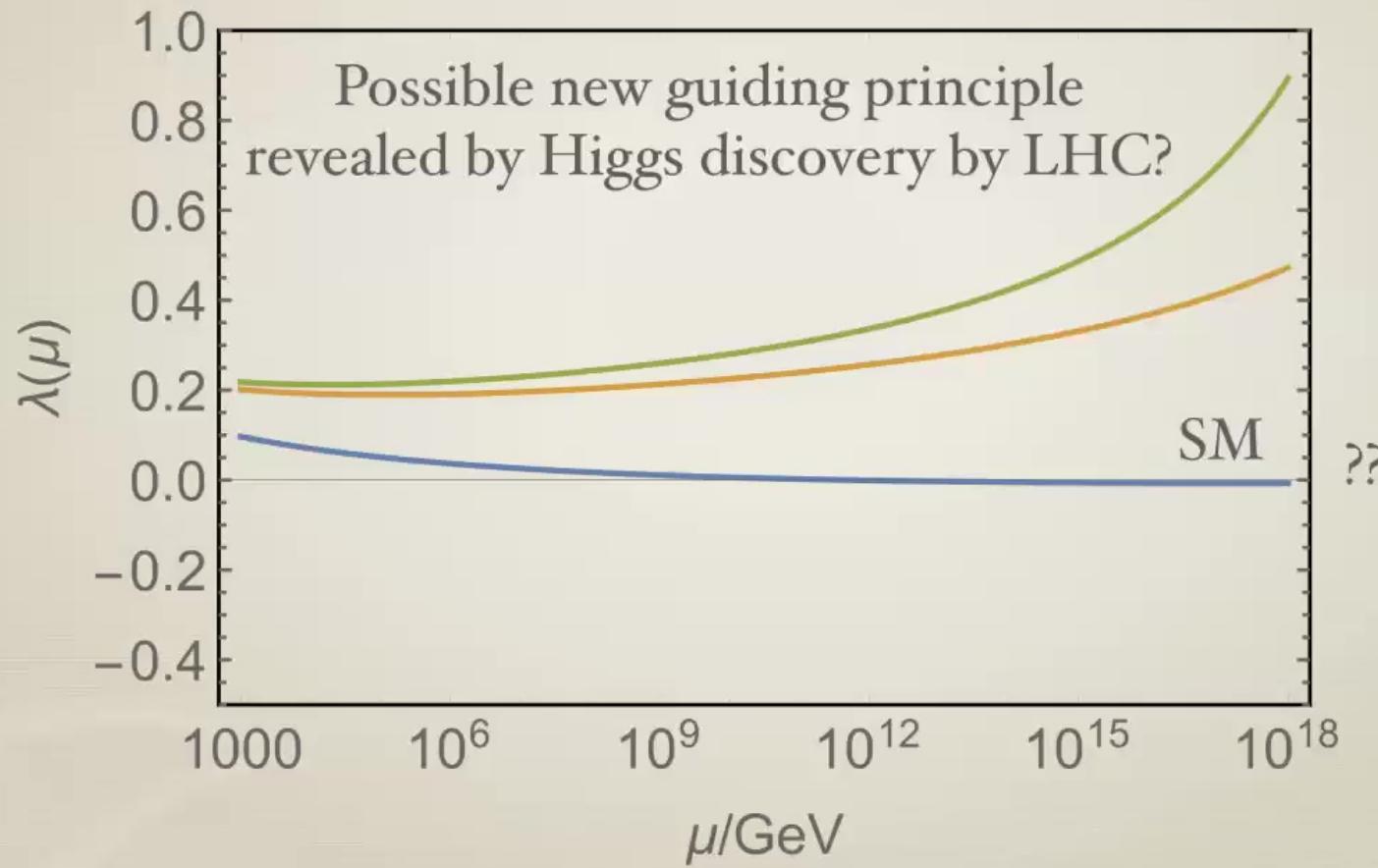
energy-dependent coupling

# Small quartic coupling



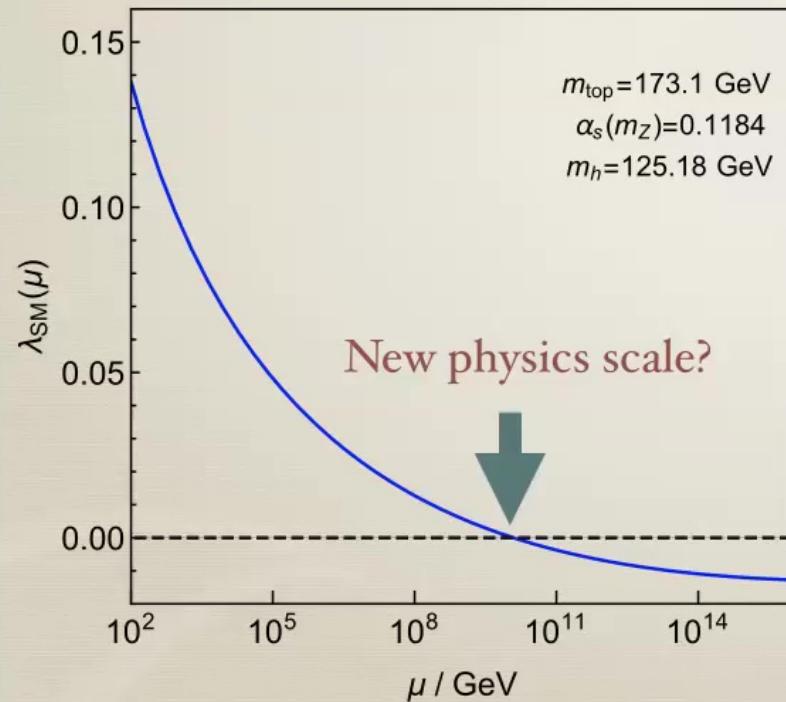
Buttazzo et.al (2013)

# Small quartic coupling



# New physics?

Conjecture : some new physics which couples to Higgs  
sets  $\lambda_{\text{SM}} \simeq 0$  at a high energy scale



PQ symmetry? Redi and Strumia (2012)  
Supersymmetry? Hall and Nomura (2013),  
Ibe, Matsumoto and Yanagida (2013)

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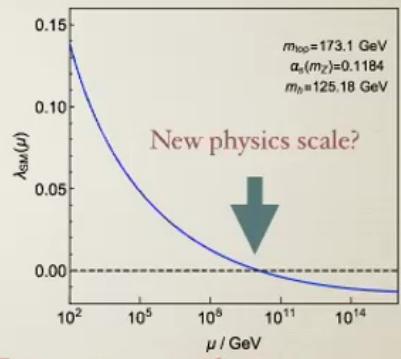
# Precise measurement and new physics?

top quark mass  
Higgs mass  
strong coupling constant



scale of the new physics  $\longleftrightarrow$  Experimental signatures?

Hall and KH (2018, 2019)  
Dunsky, Hall and KH (2019)



$\lambda_{EM}(\mu)$

$\mu / \text{GeV}$

$m_{\text{top}} = 173.1 \text{ GeV}$   
 $\alpha_s(m_Z) = 0.1184$   
 $m_h = 125.18 \text{ GeV}$

New physics scale?

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Precise measurement and new physics

Hall and KH (2018, 2019)  
Dunsky, Hall and KH (2019)

top quark mass  
Higgs mass  
strong coupling constant

New symmetry (Higgs Parity) breaking scale

New physics scale

$\lambda_{SM}(\mu)$

$m_{top}=173.1 \text{ GeV}$   
 $\alpha_s(m_Z)=0.1184$   
 $m_h=125.18 \text{ GeV}$

$\mu / \text{GeV}$

Experimental signatures

Proton decay, warm dark matter, dark matter detection, dark radiation, gravitational waves, neutron EDM, ...

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- \* Introduction
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- \* Summary and outlook

Outline

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# Symmetry

Symmetry has been playing the central role in physics

Dictate **relations** among masses and interaction rates of particles

- \* Symmetry of hadrons

Explain why the proton mass is similar to the neutron mass

938.27 MeV	939.57 MeV
------------	------------

- \* Symmetry of crystals

Relation between phonon excitations

Z<sub>2</sub> symmetry  
 $x \leftrightarrow y$

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Z<sub>2</sub> symmetry

Higgs       $\longleftrightarrow$       Higgs'  
 $H$                            $H'$

Weak gauge boson       $\longleftrightarrow$       Weak gauge boson'  
 $W$                            $W'$   
 $SU(2)$                            $SU(2)'$

$H$        $W$   
 $H$        $W$

$W'$        $H'$   
 $W'$        $H'$

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Small gauge coupling

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New physics?

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Note physics?

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Precise measurement and new physics?

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Precise measurement and new physics?

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Quarks

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Neutral

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Stability

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$Z_2$  symmetry

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$Z_2$  symmetry

# $Z_2$ symmetry

Higgs       $\longleftrightarrow$       Higgs'  
 $H$                            $H'$

Weak gauge boson       $\longleftrightarrow$       Weak gauge boson'  
 $W$                            $W'$   
 $SU(2)$                            $SU(2)'$

quark, lepton       $\longleftrightarrow$       quark', lepton'  
 $q, L$                            $q', L'$

(photon, gluon : several options)

- \* solves the strong CP problem
- \* is part of a grand unified gauge symmetry
- \* gives a dark matter candidate

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Outline

Symmetry

$H$

$H'$

$W$

$W'$

$q, L$

$q', L'$

mass  $\propto \langle H \rangle$

mass  $\propto \langle H' \rangle$

$\longleftrightarrow$

In well-motivated theories (explained later),  
 $W', q'$  or  $L'$  interact with Standard Model particles with  
 $O(1)$  couplings

unbroken  $Z_2 \langle H \rangle = \langle H' \rangle$  is experimentally excluded

$\langle H \rangle \ll \langle H' \rangle$  is required

Spontaneously Broken Higgs Parity

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Z<sub>2</sub> symmetry

Higgs       $\longleftrightarrow$       Higgs'  
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# Higgs potential

$$V = (\lambda |H|^4 - m^2 |H|^2) + (\lambda |H'|^4 - m^2 |H'|^2) + \tilde{y} |H|^2 |H'|^2$$

$$= \lambda (|H|^2 + |H'|^2 - v'^2)^2 + y |H|^2 |H'|^2$$

Let us consider the parameters such that  $\langle H \rangle \ll \langle H' \rangle$

Style Arrange

Back Front Backward Forward

Align Distribute

Size 296 pt Width 66 pt Height Constrain proportions

Position 463 pt X 339 pt Y

Rotate Angle 0° Flip

Lock Unlock

Group Ungroup

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# Small quartic

Hall, KH (2018)

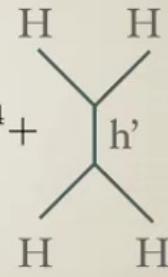
$$V(H, H') = \lambda(|H|^2 + |H'|^2)^2 + y|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$$

$$\langle H' \rangle^2 = \frac{m^2}{2\lambda} \equiv v'^2$$

Integrate out heavy d.o.f.

$$V_{\text{eff}} \simeq \frac{y v'^2 |H|^2}{|y| \ll 1} - \frac{y(1 + \frac{y}{4\lambda}) |H|^4}{\lambda_{\text{SM}}(v')} = 0$$

Threshold correction:  $\lambda_{\text{SM}}(v') \sim -\frac{y_t^4}{16\pi^2} \sim -10^{-3}$



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Small quartic

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Symmetry

$Z_2$  symmetry

$Z_2$  symmetry

$Z_2$  symmetry

Higgs Potential

Spontaneous Broken Symmetry

Higgs potential

Small quarks

pseudo-NGB Higgs

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# pseudo-NGB Higgs

Hall, KH (2018)

$$V(H, H') = \lambda(|H|^2 + |H'|^2)^2 + \cancel{y|H|^2|H'|^2} - m^2(|H|^2 + |H'|^2)$$

Accidentally U(4) symmetric  $4 = (H, H')$

$U(4) \rightarrow U(3)$  by  $H'$

$$16 - 9 = 7 = 4 + 3$$

SM Higgs is a pseudo Nambu-Goldstone boson

$$\lambda_{\text{SM}}(v') = 0$$

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31 Symmetry breaking scale

32 Z quarks

33 Z quarks

34 Z quarks

35 Z quarks

36 Higgs potential

37 Small square

38 pseudo-NGB Higgs

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# Prediction on symmetry breaking scale

Hall, KH (2018)

$m_{\text{top}}=173.1 \text{ GeV}$   
 $\alpha_s(m_Z)=0.1184$   
 $m_h=125.18 \text{ GeV}$

$\lambda_{\text{SSM}}(\mu)$

$\mu / \text{GeV}$

symmetry breaking scale

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Quiz 1  
 (20 seconds)

If the Higgs mass is larger,  $v'$  is

A : Larger  
 B : Smaller

Hint: Higgs mass

$m_h \propto \lambda_{SM}^{1/2}(\mu = \text{EW scale})$

$\lambda_{SM}(\mu)$

$m_{top}=173.1 \text{ GeV}$   
 $\alpha_s(m_Z)=0.1184$   
 $m_h=125.18 \text{ GeV}$

symmetry breaking scale

$\mu / \text{GeV}$

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$\mu / \text{GeV}$

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Quiz 2  
 (20 seconds)

If the top quark mass is larger,  $v'$  is

A : Larger  
 B : Smaller

Hint: the quartic coupling becomes smaller because of the top quark yukawa

$\lambda_{\text{SM}}(\mu)$

$m_{\text{top}}=173.1 \text{ GeV}$   
 $\alpha_s(m_Z)=0.1184$   
 $m_h=125.18 \text{ GeV}$

symmetry breaking scale

$\mu / \text{GeV}$

$V'$

$H$  top quark  $H$

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symmetry breaking scale

$\lambda_{\text{SM}}(\mu)$

$\mu / \text{GeV}$

$H$  top quark  $H$

Quark 1  
Quark 2  
Quark 3  
Quark 4  
Quark 5  
Quark 6  
Quark 7

Quiz 2  
Quiz 3  
Quiz 4  
Quiz 5  
Quiz 6  
Quiz 7  
Quiz 8  
Quiz 9  
Quiz 10  
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Quiz 44

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39 pseudo-NGGB Higgs

40 Predictive measure breaking scale

41 Quark 1

42 Quark 2

43 Quark 2

44 Quark 2

45 Precise measurement and new physics

46 Ocular

47 Left Right symmetry

# Precise measurement and new physics

Hall and KH (2018, 2019)  
Dunsky, Hall and KH (2019)

top quark mass  
Higgs mass  
strong coupling constant

Higgs Parity (HP)  
symmetry breaking scale

Experimental signatures

$m_{\text{top}} = 173.1 \text{ GeV}$   
 $\alpha_s(m_Z) = 0.1184$   
 $m_h = 125.18 \text{ GeV}$

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Outline

- \* Introduction
- \* Higgs Parity
- \* Left-Right Higgs Parity and the strong CP problem
- \* Grand unification and proton decay
- \* Warm right-handed neutrino dark matter
- \* Summary and outlook

A blue arrow points from the text "Left-Right Higgs Parity and the strong CP problem" to the bullet point "Left-Right Higgs Parity and the strong CP problem".

The sidebar on the left shows thumbnails of slides 38 through 46, and slide 47 is currently selected.

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# Left-Right symmetry

momentum

L R

spin

$u_L, d_L$

$QED$

$u_R, d_R$

$u_L, d_L$

$QCD$

$u_R, d_R$

$g$

$u_L, d_L$

$u_R, d_R$

$u_R, d_R$

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Left-Right symmetry

Weak interaction

Lee and Yang (1956), Wu (1957)

Left-Right symmetry

Spontaneously broken Left-Right symmetry

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# Spontaneously broken Left-Right symmetry

$u_L$   $d_L$   $\nu_L$   $W$   $SU(2)_L$   $\leftrightarrow$   $SU(2)_R$   $d_R$   $\nu_R$

$e_L$   $W$   $m_W \ll m_{W'}$   $e_R$   $W'$   $u_R$

Lee (1973), Pati and Salam (1975),  
Mohapatra and Pati (1975), Senjanovic and Mohapatra (1975)

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The strong CP problem

Neutron Electric Dipole Moment

$$H = d_n \vec{E} \cdot \vec{S}$$

$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm ?}$$

$$d_n/e < 2.9 \times 10^{-26} \text{ cm} \quad \text{Baker et.al (2006)}$$

Suggests CP symmetry forbidding  $H = d_n \vec{E} \cdot \vec{S}$

But CP violation from quark masses is essential for CKM phase

Strong CP problem  
't Hooft (1976)

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# Spontaneously broken Left-Right symmetry

Motivated by the Strong CP problem in the standard model

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The strong CP problem

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Suggests CP symmetry forbidding  $H = d_n \vec{E} \cdot \vec{S}$

But CP violation from quark masses is essential for CKM phase

Strong CP problem  
't Hooft (1976)

Outline

Left-Right symmetry

Spontaneously broken Left-Right symmetry

Spontaneously broken Left-Right symmetry

The strong CP problem

Left-Right symmetry relates to strong CP problem

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# Left-Right symmetry solves the strong CP problem

Mohapatra and Senjanovic (1978), Beg and Tsao (1978), Babu and Mohapatra (1989), Hall and KH (2018)

We can combine the LR symmetry with space-time parity

$$H = d_n \vec{E} \cdot \vec{S}$$

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Left-Right symmetry solves the strong CP problem

Mohapatra and Senjanovic (1978), Beg and Tsao (1978), Babu and Mohapatra (1989), Hall and KH (2018)

At the quantum field theory level,

$$q_L(x, t) \leftrightarrow q_R(-x, t)$$

$$\cancel{\mathcal{L} = \theta G\tilde{G} + m_{ij}q_L^i\bar{q}_R^j + m_{ij}^* \bar{q}_L^i q_R^j}$$

The quark mass matrix is Hermitian

$$\theta_{CP} = \theta + \arg(\det m) = 0$$

## Left-Right Higgs Parity

$$\text{Higgs} \quad \longleftrightarrow \quad \text{Higgs}$$

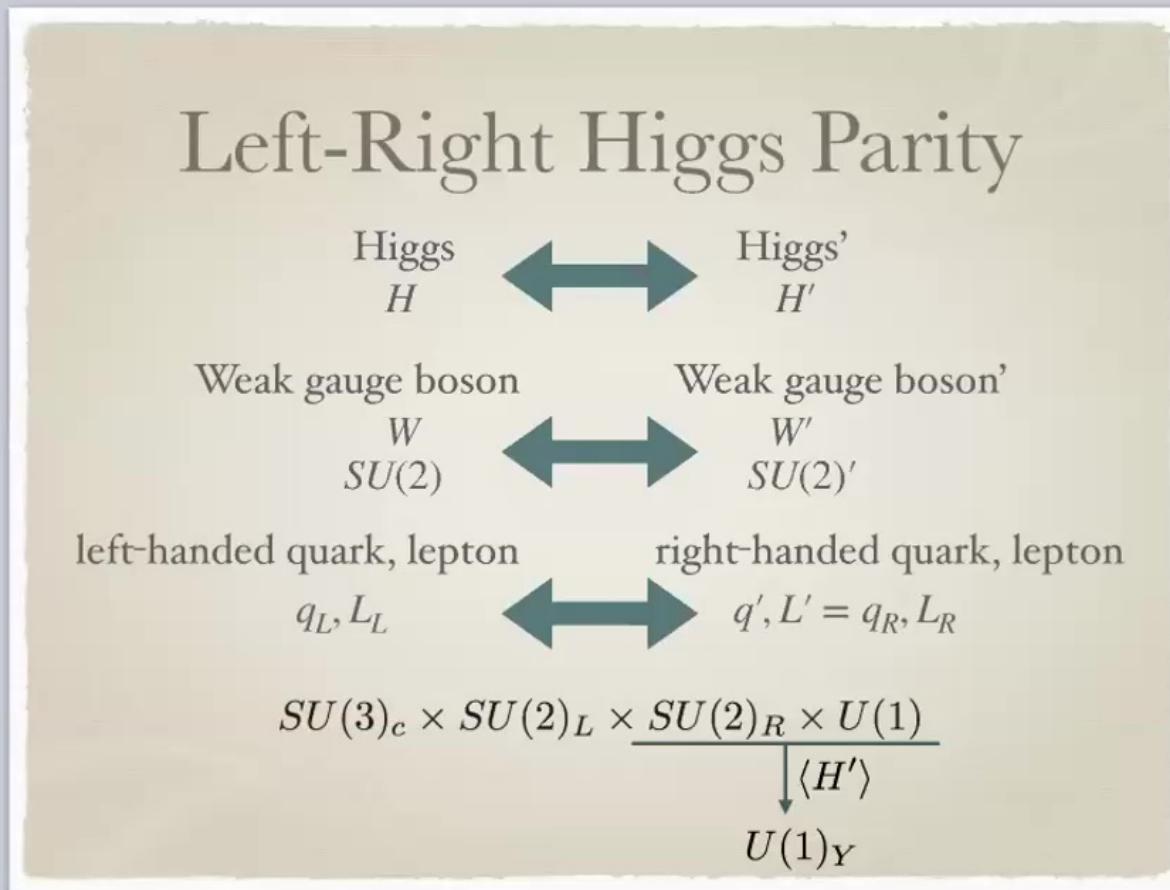
$$H \qquad \qquad H'$$

The diagram illustrates the equivalence between two different representations of weak gauge bosons. On the left, a double-headed arrow connects two boxes. The top box is labeled "Weak gauge boson" above "W" and below "SU(2)". The bottom box is labeled "Weak gauge boson" above "W'" and below "SU(2)'".

left-handed quark, lepton      right-handed quark, lepton

$q_L, L_L \quad \longleftrightarrow \quad q', L' = q_R, L_R$

$$\begin{array}{c} SU(3)_c \times SU(2)_L \times \frac{SU(2)_R \times U(1)}{\downarrow \langle H' \rangle} \\ U(1)_Y \end{array}$$



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46 Left-Right symmetry

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48 Spontaneously broken Left-Right symmetry

49 Spontaneously broken Left-Right symmetry

50 The strong CP problem

51 Left-Right symmetry solution for strong CP problem

52 Left-Right symmetry solves the strong CP problem

53 Left-Right Higgs Parity

54 Left-Right Higgs Parity

55 Left-Right Higgs Parity

# Left-Right Higgs Parity

Higgs  $\longleftrightarrow$  Higgs'  $H \longleftrightarrow H'$

$m_{top}=173.1 \text{ GeV}$   
 $\alpha_s(m_Z)=0.1184$   
 $m_h=125.18 \text{ GeV}$

$\lambda_{SM}(\mu)$

$\mu / \text{GeV}$

$v_R$

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# Left-Right Higgs Parity

$v_R = 10^9 - 10^{12}$  GeV

λ<sub>SR</sub>(μ)

LR-HP symmetry breaking scale

$m_{top} = 173.1$  GeV  
 $\alpha_s(m_Z) = 0.1184$   
 $m_h = 125.18$  GeV

μ / GeV

How can we possibly probe such high scale physics??

# Left-Right Higgs Parity

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# Precise measurement and new physics

Hall and KH (2018, 2019)  
Dunsky, Hall and KH (2019)

top quark mass  
Higgs mass  
strong coupling constant

Left-Right Higgs Parity symmetry breaking scale

Proton decay  
warm dark matter

$\lambda_{SM}(\mu)$

$m_{top} = 173.1 \text{ GeV}$   
 $\alpha_s(m_Z) = 0.1184$   
 $m_h = 125.18 \text{ GeV}$

$v_R$

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- \* Grand unification and proton decay ←
- \* Warm right-handed neutrino dark matter
- \* Summary and outlook

Outline

Left-Right symmetry and Grand Unified Theory

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# Left-Right symmetry and Grand Unified Theory

Grand Unification  $SO(10)$

Left-Right Symmetry  $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$

$\langle H' \rangle \neq 0$

Standard Model  $SU(3)_c \times SU(2)_L \times U(1)_Y$

Single gauge group, single type of fermions

Fritzsch and Minkowski (1975), Georgi (1975)

$\psi_{16}$

$q_L, L_L, q_R, L_R$

$q_L = (u_L, d_L), L_L = (\nu_L, e_L), u_R, d_R, e_R$

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# Coupling unification

Hall, KH (2018, 2019)

energy-dependent couplings

couplings

RGE scale  $\mu / \text{GeV}$

$m_h = 125.18 \text{ GeV}$   
 $\alpha_s(m_Z) = 0.1181$   
 $m_t = 173.0 \text{ GeV}$

$g_3$

$g_2$

$g_Y$

$5 \lambda_{\text{SM}}$

$g_{B-L}$

$\frac{1}{g_1^2} = \frac{2}{5} \frac{1}{g_{B-L}^2} + \frac{3}{5} \frac{1}{g_2^2}$

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# Coupling unification

Hall, KH (2018, 2019)

Other  $v_R$

$v_R$  determined by Higgs Parity

$m_h = 125.18 \text{ GeV}$   
 $\alpha_s(m_Z) = 0.1181$   
 $m_t = 173.0 \text{ GeV}$

$100 \quad 10^5 \quad 10^8 \quad 10^{11} \quad 10^{14} \quad 10^{17}$

$1.2 \quad 1.0 \quad 0.8 \quad 0.6 \quad 0.4 \quad 0.2 \quad 0.0$

$\mu / \text{GeV}$

$g_3$   
 $g_2$   
 $g_Y$   
 $g_{B-L}$   
 $5\lambda_{SM}$

$v_R = 10^9 \text{ GeV}$

$10^2 \quad 10^5 \quad 10^8 \quad 10^{11} \quad 10^{14} \quad 10^{17}$

$1.2 \quad 1.0 \quad 0.8 \quad 0.6 \quad 0.4 \quad 0.2 \quad 0.0$

$\mu / \text{GeV}$

$g_3$   
 $g_2$   
 $g_Y$   
 $g_{B-L}$

$v_R = 10^{13} \text{ GeV}$

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# Higgs Parity GUT

Hall, KH (2018, 2019)

energy-dependent couplings

couplings

RGE scale  $\mu / \text{GeV}$

$m_h = 125.18 \text{ GeV}$   
 $\alpha_s(m_Z) = 0.1181$   
 $m_t = 173.0 \text{ GeV}$

$g_3$   
 $g_2$   
 $g_Y$   
 $g_{B-L}$   
 $5\lambda_{SM}$

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# Proton decay

Diagram illustrating the decay of a proton ( $p \rightarrow e^+ \pi^0$ ) via the exchange of a New heavy gauge boson between a  $u$  quark and a  $d$  quark.

$p \rightarrow e^+ \pi^0$

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# Proton decay

Hall, KH (2019)

Suppose proton decay is observed at Hyper-K (2027-)

$M_{XY}=10^{16}$  GeV  
 $\Delta<10$ ,  $b/\tau$  fixed  
45 GUT Higgs

$\alpha_s(m_Z)$

$m_t / \text{GeV}$

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# Proton decay

Hall, KH (2019)

Suppose proton decay is observed at Hyper-K (2027-)

$M_{XY}=10^{16} \text{ GeV}$

$\Delta<10, b/\tau \text{ fixed}$

45 GUT Higgs

$\alpha_s(m_Z)$

$m_t / \text{GeV}$

$\Delta \alpha_s(m_Z) = 0.0001$  by lattice  
Lepage, Mackenzie and Peskin (2014)

lepton colliders e.g. ILC  
Kiyo, Mishima and Sumino (2015)

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Leptogenesis

$m_{\text{top}} = 173.1 \pm 0.4 \text{ GeV}$

$M_1 [\text{keV}]$

$m_{\text{top}} [\text{GeV}]$

Dunsky, Hall and KH (in prep.)

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Quantify unification

Hall, KH (2019)

mass of new gauge boson mediating proton decay

$M_{XY} / \text{GeV}$

$v' / \text{GeV}$

$X_{45}, r_{XY}=2$

$\Delta = 10, 5$

Hyper-K

$\tau(p \rightarrow e^+ \pi^0) < 1.6 \times 10^{34} \text{ years}$

There can be quantum corrections from heavy particles around the GUT scale

$$\Delta = \max_{i,j} \left| \frac{8\pi^2}{g_i^2} - \frac{8\pi^2}{g_j^2} \right|$$

typically

$\Delta = \text{few} - 10$

(smaller than SUSY GUT)

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64 Proton decay  $p \rightarrow e^+ \pi^0$

65 Proton decay

66 Proton decay

67 Outfit

68 Right-handed neutrino DM

69 Right-handed neutrino DM

70 Right-handed neutrino DM

71 Production of DM

72 Production of DM

73 Production of DM

# Proton decay

Hall, KH (2019)

Suppose proton decay is observed at Hyper-K (2027-)

$M_{XY}=10^{16} \text{ GeV}$   
 $\Delta<10, b/\tau \text{ fixed}$   
45 GUT Higgs

$\alpha_s(m_Z)$

$m_t / \text{GeV}$

$\Delta\alpha_s(m_Z) = 0.0001$  by lattice  
Lepage, Mackenzie and Peskin (2014)

lepton colliders e.g. ILC  
Kiyo, Mishima and Sumino (2015)

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\* Left-Right Higgs Parity and the strong CP problem

\* Grand unification and proton decay

\* Warm right-handed neutrino dark matter ←

(I do not impose unified gauge symmetry)

\* Summary and outlook

Outline

Right-handed neutrino DM

Right-handed neutrino DM

Right-handed neutrino DM

Production of DM

Production of DM

Production of DM

64 Proton decay  $p \rightarrow e^+ \pi^0$

65 Proton decay

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67 Outline

68 Right-handed neutrino DM

69 Right-handed neutrino DM

70 Right-handed neutrino DM

71 Production of DM

72 Production of DM

73 Production of DM

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64 Proton decay  $p \rightarrow e^+ \pi^0$

65 Proton decay

66 Proton decay

67 Online

68 Right-handed neutrino DM

69 Right-handed neutrino DM

70 Right-handed neutrino DM

71 Production of DM

72 Production of DM

73 Production of DM

# Right-handed neutrino DM

```

graph TD
    H[H] <--> HHp[H'']
    W[SU(2)] <--> WWp[SU(2)']
    L[uL, dL, eL, nuL] <--> RRp[uR, dR, eR, nuR]
    
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64 Proton decay  $p \rightarrow e^+ \pi^0$

65 Proton decay

66 Proton decay

67 Online

68 Right-handed neutrino DM

69 Right-handed neutrino DM

70 Right-handed neutrino DM

71 Production of DM

72 Production of DM

73 Production of DM

# Right-handed neutrino DM

Higgs  $H$   $\longleftrightarrow$  Higgs'  $H'$

Weak gauge boson  $W_{SU(2)}$   $\longleftrightarrow$  Weak gauge boson'  $W'_{SU(2)'}^{}$

left-handed quark, lepton  $u_L, d_L, e_L, \nu_L$   $\longleftrightarrow$  right-handed quark, lepton  $u_R, d_R, e_R, \nu_R \equiv N$

New particle without electromagnetic and color charge  
Dark Matter??  $N_1$

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64 Production of DM

65 Production of DM

66 Production of DM

67 Chiral

68 Right-handed neutrino DM

69 Right-handed neutrino DM

70 Right-handed neutrino DM

71 Production of DM

72 Production of DM

73 Production of DM

# Production of DM

If the temperature of the universe is large enough that  $N$  is thermalized,

$$\frac{\Omega_{N_1}}{\Omega_{\text{DM}}} \simeq \frac{M_1}{100 \text{ eV}}$$

DM is too warm:  $\lambda_{\text{Free-streaming}} \simeq 10 \text{ Mpc}$

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67 Outline

68 Right-handed neutrino DM

69 Right-handed neutrino DM

70 Right-handed neutrino DM

71 Production of DM

72 Production of DM

73 Production of DM

# Production of DM

- \* Larger DM mass with dilution by another long-lived right-handed neutrino  $N_2$

Bezrukov, Hettmansperger and Lindner (2009)

- \* Low reheating temperature

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# Production of DM

- \* Larger DM mass with dilution by another long-lived right-handed neutrino  $N_2$

Let us see how the parameter space is constrained

- \* Low reheating temperature

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73 Production of DM

74 Dilution for  $N_2$

# Dilution by $N_2$

$$n_{N_1} = n_{N_2}$$

$$\left( \frac{\rho_{N_1}}{s} \right) = \frac{\rho_{N_1}}{\rho_{N_2}} \left( \frac{\rho_{N_2}}{s} \right)_{N_2 \text{ decay}} = \frac{M_1}{M_2} \frac{3}{4} T_{\text{RH}}$$

$$= 0.4 \text{ eV} \frac{M_1}{10 \text{ keV}} \frac{300 \text{ GeV}}{M_2} \frac{T_{\text{RH}}}{10 \text{ MeV}} \quad T_{\text{RH}} \sim \sqrt{\Gamma_{N_2} M_{\text{pl}}}$$

$N_2$  must be heavy enough while long-lived

Strong constraints on the parameter space

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Right-handed neutrino DM

Right-handed neutrino DM

Right-handed neutrino DM

Production of DM

Production of DM

Production of DM

Dilution for  $N_e$

Neutrino mass

Neutrino mass

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# Neutrino mass

$$L = (\nu_L, e_L), \bar{L} = (N, \bar{e}_R)$$

$$\mathcal{L} = \frac{c_i}{2\Lambda} L_i L_i H_L H_L + \frac{c_i}{2\Lambda} \bar{L}_i \bar{L}_i H_R H_R + \frac{d_{ij}}{\Lambda} L_i \bar{L}_j H_L H_R$$

$$\mathcal{L} = \frac{c_i}{2\Lambda} L_i L_i H_L H_L + \frac{1}{2} M_i N_i N_i + y_{ij} L_i N_j H_L \quad M_i = \frac{c_i}{\Lambda} v_R^2 \quad y_{ij} = \frac{v_R}{\Lambda} d_{ij}$$

$$m_{\nu,ij} = \delta_{ij} M_i \left( \frac{v}{v_R} \right)^2 - \frac{y_{ik} y_{jk} v^2}{M_k}$$

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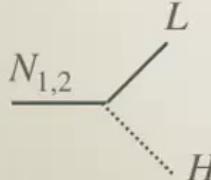
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# Neutrino mass

$$m_{\nu,ij} = \delta_{ij} M_i \left( \frac{v}{v_R} \right)^2 - \frac{y_{ik} y_{jk} v^2}{M_k}$$

The second term is strongly constrained from the stability of  $N_{1,2}$



$y_{i1}, y_{i2}$  are required to be small

$$y_{ij} L_i N_j H$$

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Right-handed neutrino mass

$$m_{\nu,22} = M_2 \left( \frac{v}{v_R} \right)^2 - \frac{y_{2k} y_{2k} v^2}{M_k}$$

From enough stability of  $N_1$  and  $N_2$ , one can show that the first term is significant

$$M_2 = \left( \frac{v_R}{v} \right)^2 \times (\text{observed SM neutrino mass})$$

$$\equiv \left( \frac{v_R}{v} \right)^2 \times m_2$$

Dror, Dunsky, Hall and KH (2020)

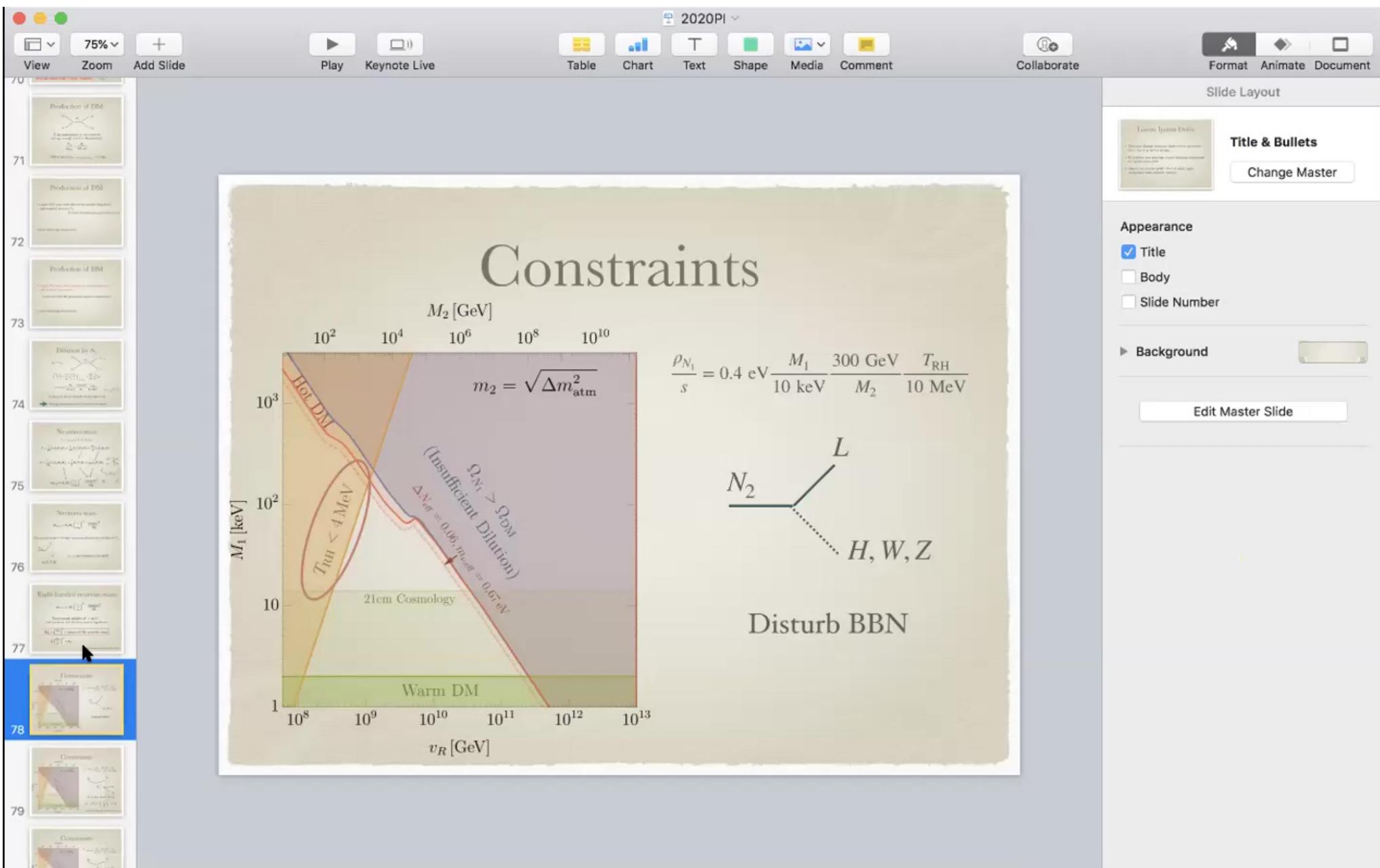
Right-handed neutrino mass

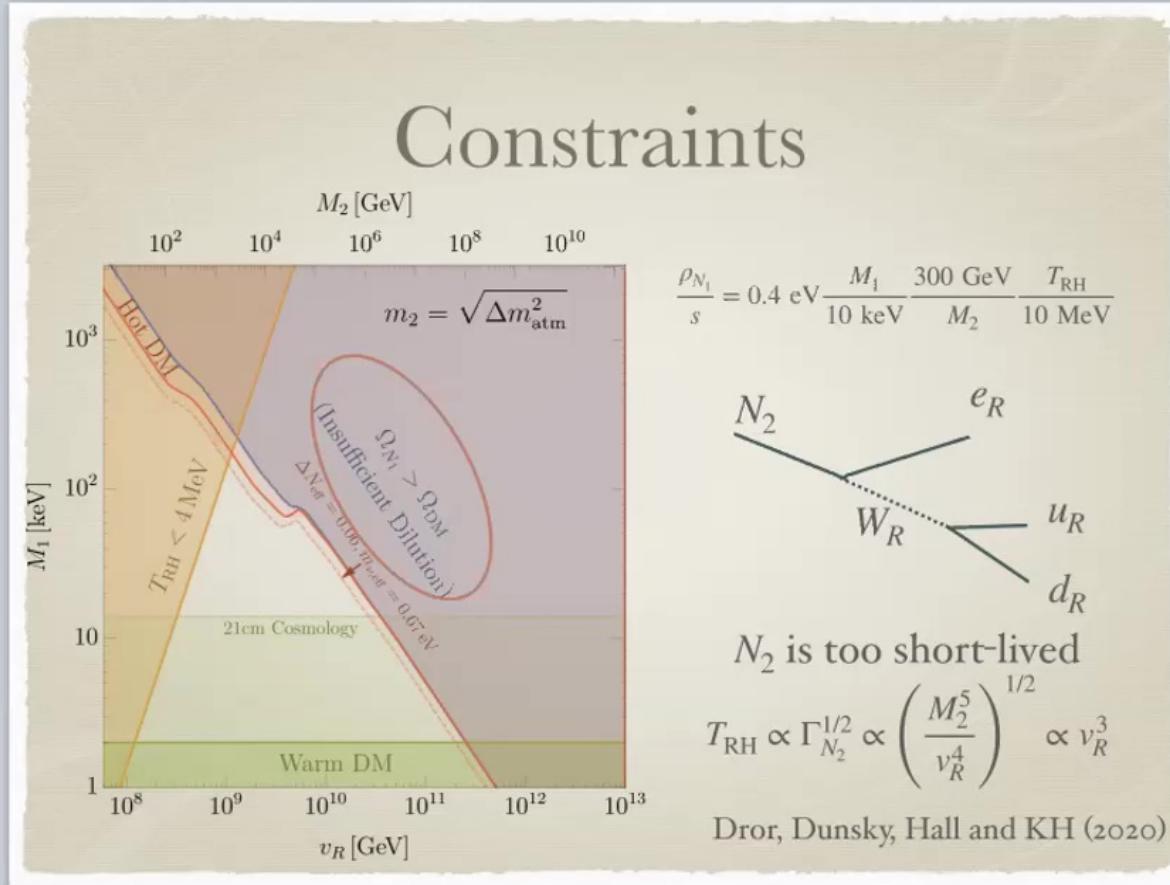
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Production of DM

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Production of DM

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Dilution in  $N_1$

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Neutrino mass

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Neutrino mass

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Right-handed neutrino mass

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Constraints

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Constraints

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Constraints

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Constraints

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# Constraints

$$\frac{\rho_{N_1}}{s} = 0.4 \text{ eV} \frac{M_1}{10 \text{ keV}} \frac{300 \text{ GeV}}{M_2} \frac{T_{\text{RH}}}{10 \text{ MeV}}$$

$N_2 \rightarrow W_R \rightarrow e_R + e_R$

Significant amount of hot  $N_1$  is produced

Dror, Dunsky, Hall and KH (2020)

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Production of DM

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Dilution by  $N_1$

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Neutrino mass

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No neutrino mass

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Right-handed neutrino mass

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Electron mass

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Electron mass

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Electron mass

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Electron mass

# Constraints

$$\lambda_{FS} \simeq 0.5 \text{ Mpc} \times \left( \frac{\text{keV}}{m_{N_1}} \right)^{1.15}$$

$\delta\rho/\rho$

$X$

$\delta\rho/\rho$

$X$

e.g. Viel, Becker, Bolton and Haehnelt

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# Future prospect

$M_2 [\text{GeV}]$

$m_2 = \sqrt{\Delta m_{\text{atm}}^2}$

$T_{\text{RH}} < 4 \text{ MeV}$

$\Omega_{N_1} > \Omega_{\text{DM}}$

$\Delta m_{\text{eff}} = 0.06, m_{\text{DM}} = 0.07 \text{ eV}$

$21\text{cm Cosmology}$

$M_1 [\text{keV}]$

$v_R [\text{GeV}]$

$\lambda_{\text{FS}} \simeq 0.5 \text{ Mpc} \times \left( \frac{\text{keV}}{m_{N_1}} \right)^{1.15}$

$\delta\rho/\rho$

$X$

$\delta\rho/\rho$

$X$

Muoz, Dvorkin and Cyr-Racine (2019)

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# LR symmetry breaking scale

$M_2 [\text{GeV}]$

$m_2 = \sqrt{\Delta m_{\text{atm}}^2}$

$v_R = 10^8 - 10^{12} \text{ GeV}$

$\lambda_{SM}(\mu)$

$\mu / \text{GeV}$

$m_{\text{top}} = 173.1 \text{ GeV}$   
 $\alpha_s(m_Z) = 0.1184$   
 $m_h = 125.18 \text{ GeV}$

LR-HP symmetry breaking scale

$v_R$

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Higgs Parity

$m_2 = \sqrt{\Delta m_{\text{atm}}^2}$

$\Omega_{N_1} > \Omega_{\text{DM}}$   
(Insufficient Dilution)

$M_1 [\text{keV}]$

$m_{\text{top}} [\text{GeV}]$

Hot DM

Warm DM

Warm DM

Dunsky, Hall and KH (in prep.)

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# Higgs Parity

$m_{\text{top}} = 173.1 \pm 0.4 \text{ GeV}$

$m_2 = \sqrt{\Delta m_{\text{atm}}^2}$

$(\mu_c - D) > \Omega_{\text{DM}}$  (labeled  $\mu_c > \Omega_{\text{DM}}$ )

$\mu_c > 2 \Omega_{\text{DM}}$

$\mu_c > 3 \Omega_{\text{DM}}$

Warm DM

Dunsky, Hall and KH (in prep.)

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Lepton asymmetry

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Leptogenesis  
Fukugita and Yanagida (1986)

anti-lepton

lepton

$N_2$

$H$

$\neq$

$N_2$

$H^\dagger$

Lepton asymmetry

weak interaction  
(quantum anomaly)

Baryon asymmetry

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Leptogenesis

Fukugita and Yanagida (1986)

The diagram shows three Feynman diagrams representing different loop corrections to the Yukawa coupling. The first diagram shows a loop with two Higgs bosons (H) and two neutrinos (N<sub>2</sub>, N<sub>3</sub>). The second diagram shows a loop with one Higgs boson (H) and two neutrinos (N<sub>2</sub>, N<sub>3</sub>). The third diagram shows a loop with two Higgs bosons (H) and two neutrinos (N<sub>2</sub>, N<sub>3</sub>). All diagrams include vertices labeled with y.

(asymmetry)  $\propto y^2 < \frac{m_\nu M_{2,3}}{v^2} < \frac{m_\nu^2 v_R^2}{v^4}$

$$m_{\nu,ij} = -\frac{y_{ik}y_{jk}v^2}{M_j} + \delta_{ij}M_i \left(\frac{v}{v_R}\right)^2$$

Leptogenesis favors large  $v_R$ , which is however disfavored by DM production

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# Enhancement?

$$(\text{asymmetry}) \propto y^2 < \frac{m_\nu M_{2,3}}{v^2} < \frac{m_\nu^2 v_R^2}{v^4}$$

$$m_{\nu,ij} = -\frac{y_{ik} y_{jk} v^2}{M_j} + \delta_{ij} M_i \left( \frac{v}{v_R} \right)^2$$

- \* Cancellation between the two terms in  $m_\nu$
- \* Resonant enhancement

Flanz, Paschos and Sarkar (1995)

$$\frac{M_{2,3}}{M_2 - M_3}$$

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**Enhancement?**

We can naturally achieve them by imposing a neutrino flavor structure, which is however destabilized by quantum corrections (e.g. by charged lepton yukawa)

→ Lower bound on  $v_R$

- \* Cancellation between the two terms in  $m_\nu$
- \* Resonant enhancement

Flanz, Paschos and Sarkar (1995)

$$\frac{M_{2,3}}{M_2 - M_3}$$

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Levens Ipsum Dicitur

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Leptogenesis

Dunsky, Hall and KH (in prep.)

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Leptogenesis

$m_2 < m_3$  (IH)  
 $\alpha_s(M_Z) = 0.1181$

$\Omega_{N1} > \Omega_M$   
(Insufficient Dilution)

$T_{DM} > 1$  MeV

Leptogenesis

Warm DM

$M_1$  [keV]

$m_{top}$  [GeV]

Dunsky, Hall and KH (in prep.)

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Summary and outlook

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The screenshot shows the Keynote application window on a Mac OS X system. The main canvas displays a slide with the title 'Summary and outlook' in a large serif font. The slide has a light beige background with a subtle paper texture. On the left, a vertical stack of thumbnail previews for other slides is visible, numbered from 84 to 93. The slide at index 93 is highlighted with a blue border. The top menu bar includes options like View, Zoom, Add Slide, Play, Keynote Live, Table, Chart, Text, Shape, Media, Comment, Collaborate, Format, Animate, and Document. The right side features a 'Slide Layout' sidebar with a preview of the current slide's design, labeled 'Title - Center'. Below this are sections for Appearance (with checkboxes for Title, Body, and Slide Number), Background, and an 'Edit Master Slide' button.

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# Other models with Higgs Parity

- \*  $SU(3)_c \times SU(2)_L \times SU(2)' \times U(1)_Y \times U(1)'_Y$

Dunsky, Hall and KH, [1902.07726](#)

Strong CP problem is solved via parity. [backup slides](#)

Dark matter direct detection rate is predicted from the SM parameters [plot](#)

- \* A model with a mirror copy of the SM

Dunsky, Hall and KH, [1908.02756](#)

Dark radiation and gravitational wave abundance are predicted from the SM parameters [plot](#)

Other models with Higgs Parity

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Enhancement?

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Enhancement?

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Lepnogenesis

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Summary and outlook

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Higgs Party

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Other particle with Higgs Party

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Future of colliders

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# Future of colliders

We should maximize the impact of future colliders

- \* Searches for new particles
- \* Searches for deviation from the standard model predictions
- \* Precise measurement of the standard model parameters
  - top quark mass,
  - strong coupling constant,
  - Higgs mass, etc.

Any other new physics models impacted by precise measurements?

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# Higgs Parity

Hall and KH (2018, 2019)  
Dunsky, Hall and KH (2019)

top quark mass  
Higgs mass  
strong coupling constant

$\uparrow$

Higgs Parity symmetry breaking scale  $\leftrightarrow$  Proton decay, warm dark matter

(gravitational waves, dark radiation, direct detection, neutron EDM)

$u$   $d$   $e^+$   $\delta\rho/\rho$   $x$