Higgs Physics and Beyond the Standard Model

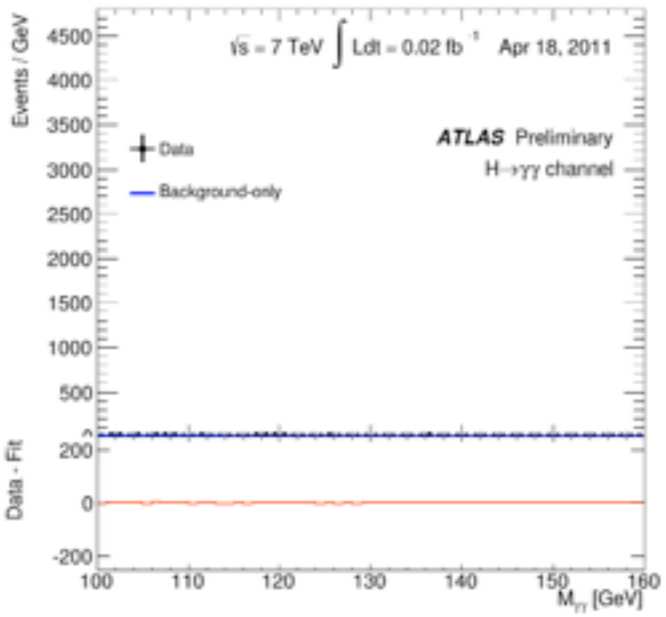
(mainly SUSY)

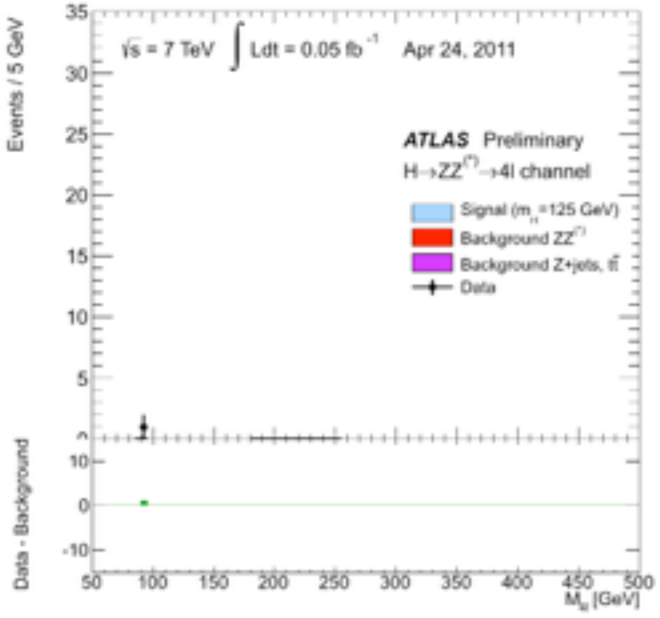
Koichi Hamaguchi (University of Tokyo)

@AEPSHEP2014, Puri,
November 11-16, 2014

Discovery of the Higgs boson

2012. July 4





2013. October 8

2013 NOBEL PRIZE IN PHYSICS

François Englert

Peter W. Higgs

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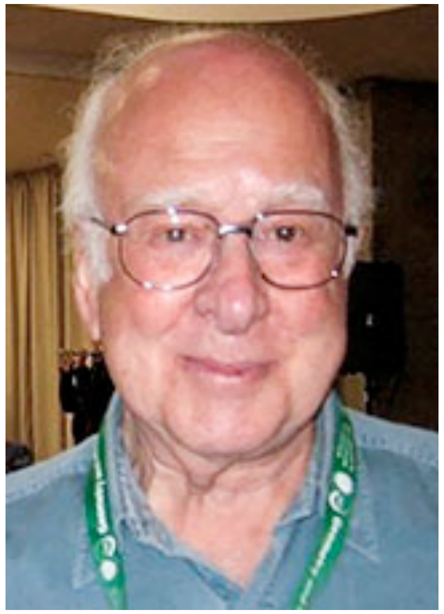
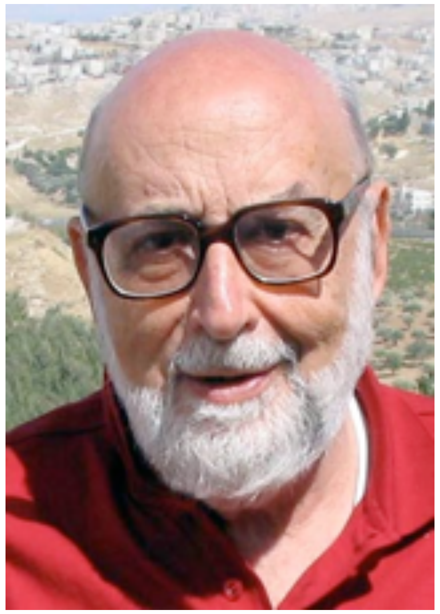
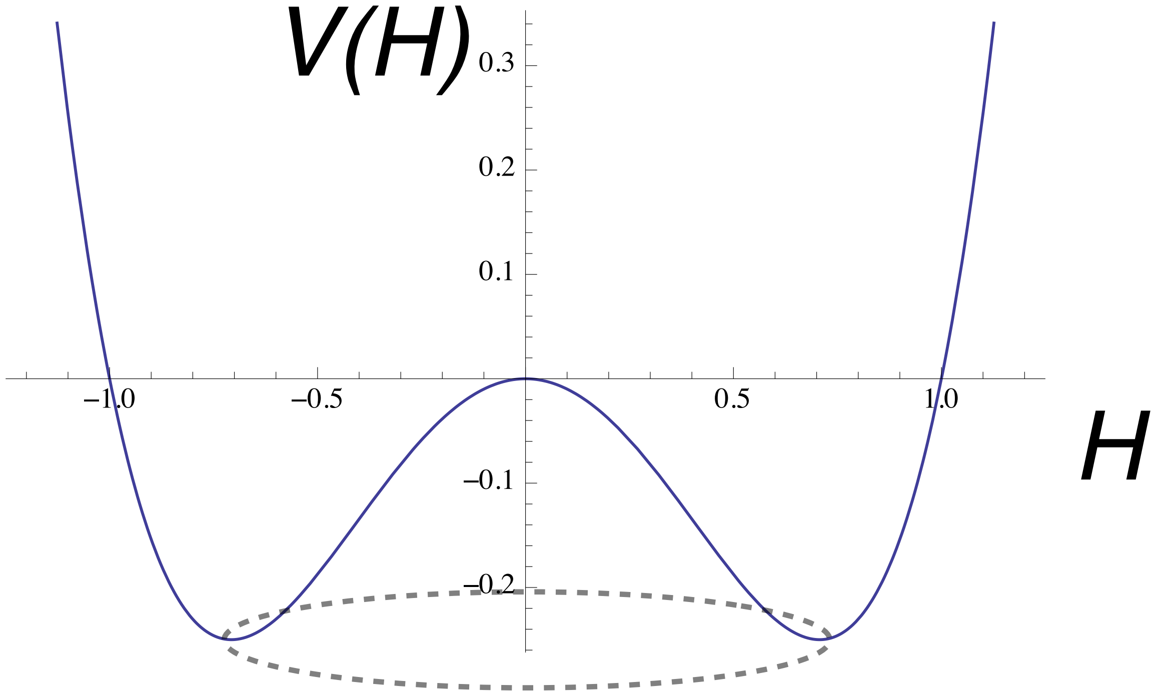




R. Brout (1928-2011)

126 GeV Higgs

$$V(H) = -{\color{blue}m^2}(H^\dagger H) + {\color{red}\lambda_{\mathrm{H}}}(H^\dagger H)^2$$



126 GeV Higgs

$$V(H) = -m^2 (H^\dagger H) + \lambda_{\mathrm{H}} (H^\dagger H)^2$$

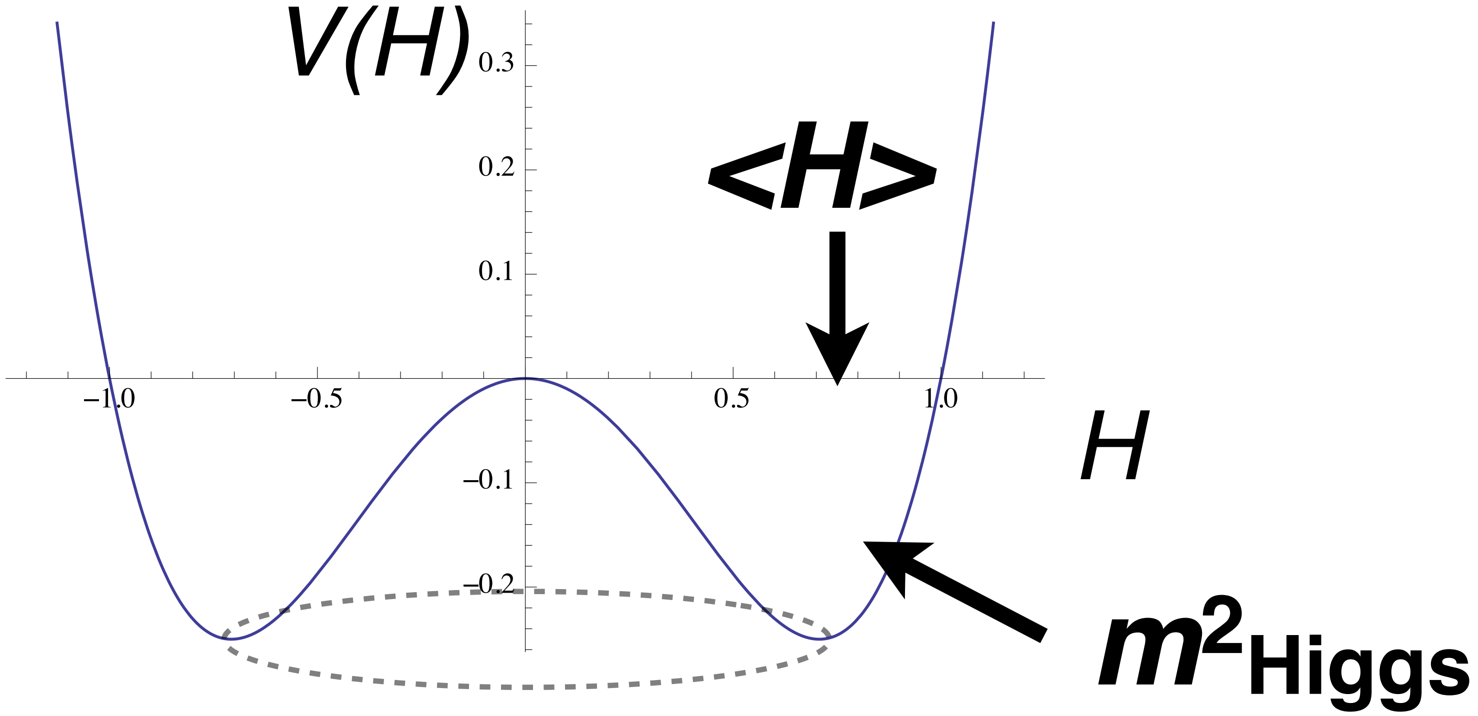
We knew...

Now we also know

$$\rightarrow \begin{cases} \langle H \rangle^2 = \dfrac{m^2}{2\,\lambda_{\mathrm{H}}} = \dfrac{1}{2\sqrt{2}\,G_F} \simeq (174\ \mathrm{GeV})^2 \\ m^2_{\mathrm{Higgs}} = 2\,m^2 \simeq \mathbf{(126\ GeV)^2} \end{cases}$$

Fermi constant

$G_F \simeq 1.17 \times 10^{-5} \mathrm{GeV}^{-2}$



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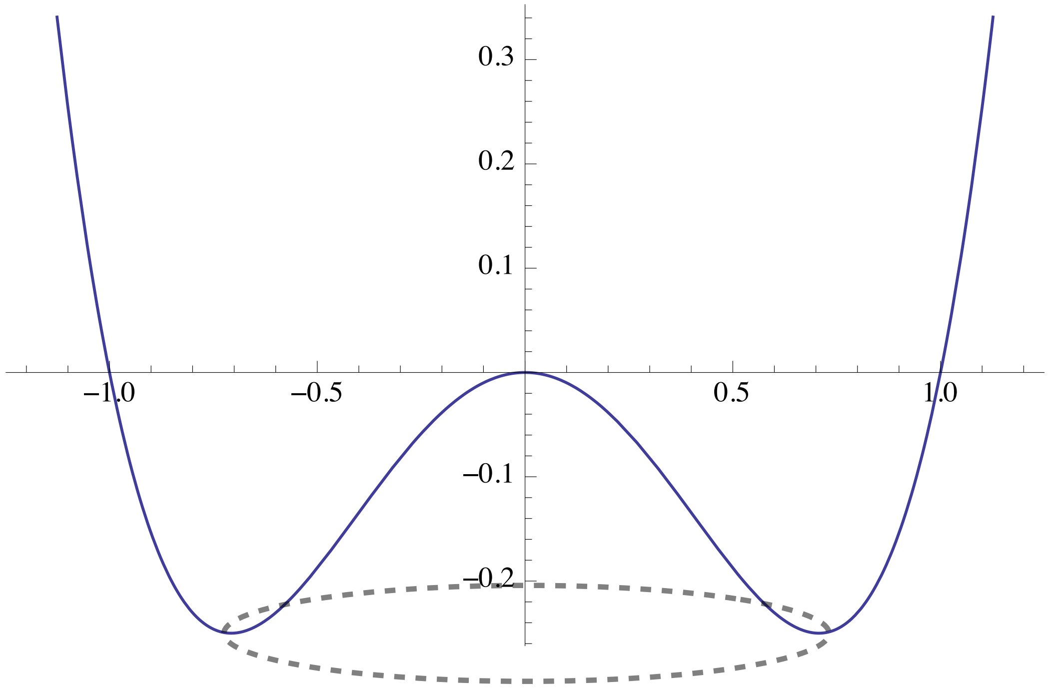


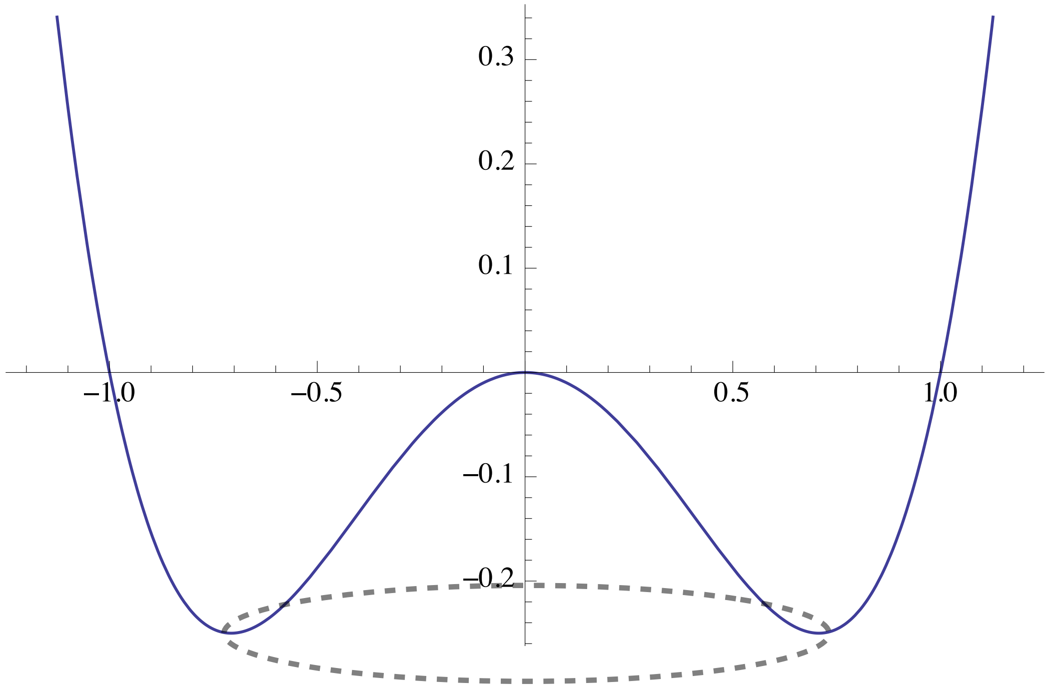
$$\rightarrow \begin{cases} m^2 = \dfrac{m_{\rm Higgs}^2}{2} \simeq (\mathbf{89\ GeV})^2 \\ \lambda_{\rm H} = \dfrac{m_{\rm Higgs}^2}{4\langle H \rangle^2} \simeq \mathbf{0.13} \end{cases}$$

126 GeV Higgs

$$V(H) = -m^2(H^\dagger H) + \lambda_{\rm H}(H^\dagger H)^2$$

$$(\mathbf{89\ GeV})^2 \qquad \mathbf{0.13}$$

completely determined !



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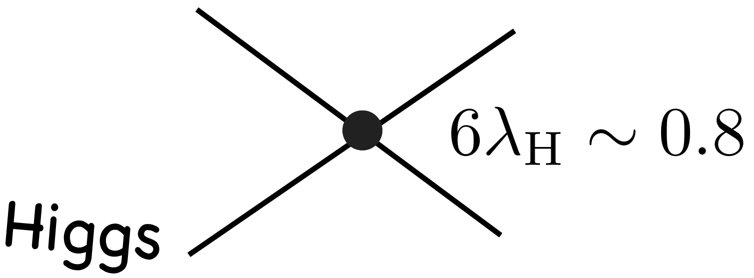
126 GeV Higgs

$$V(H) = -m^2(H^\dagger H) + \lambda_{\mathrm{H}}(H^\dagger H)^2$$

$$(89\ \mathbf{GeV})^2 \qquad 0.13$$

It seems... Higgs sector is also described by weakly coupled, perturbative QFT.
(at least no sign of strong interaction etc, so far...)



Imlications for BSM

(in my opinion.....)

This is compatible with....

- **GUT and coupling unification** in perturbative QFT. ☞ §2
- **heavy right-handed neutrinos** (Seesaw + Leptogenesis)

☞ §2 and Lectures by Prof. Rubakov and Prof. Xing.

- **Supersymmetry** ☞ §3

Supersymmetry

boson ⇔ fermion

Supersymmetry (SUSY)

		spin		
quarks q	$\frac{1}{2}$	⟷	0	squarks $\tilde{q}$
leptons ℓ	$\frac{1}{2}$	⟷	0	sleptons $\tilde{\ell}$
gauge bosons A_μ	1	⟷	$\frac{1}{2}$	gauginos λ
Higgs bosons H	0	⟷	$\frac{1}{2}$	higgsinos $\tilde{h}$

Standard Model

naturalness

fine-tuning problem

$$m_H^2 = m_{H,0}^2 + \Lambda^2 \qquad (\Lambda \gg m_H)$$

(fine tuning like 1.0000000000000001 - 1)

→ solved by the supersymmetry !

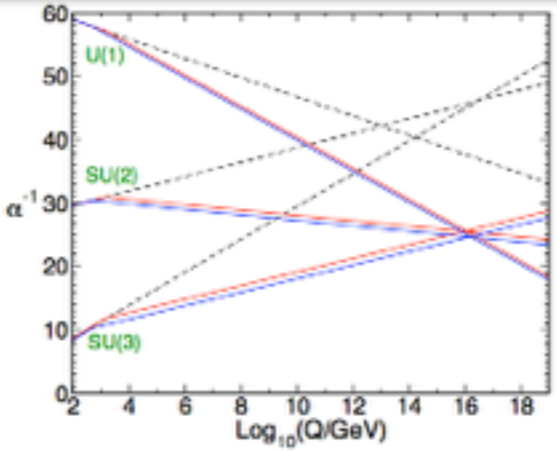
$$m_H^2 = m_{H,0}^2 + (\Lambda^2 - \Lambda^2)$$

fermion

boson

coupling unification

Grand Unified Theory



without SUSY

with SUSY

Dark Matter = Lightest SUSY particle

OK, then,....

What's the implications of 126 GeV Higgs for

Supersymmetry (SUSY) ??

126 GeV Higgs and SUSY

$$V(H) = -\underbrace{m^2}_{(89\ \mathrm{GeV})^2}(H^\dagger H) + \underbrace{\lambda_H}_{0.13}(H^\dagger H)^2$$

in SUSY…

$$= \lambda_H^{\mathrm{tree}} + \delta\lambda_H^{\mathrm{loop}}$$

$$\frac{g^2 \cos^2 2\beta}{8 \cos^2 \theta_W} \simeq \mathbf{0.069}\ \cos^2 2\beta$$

too small…

parameters
in Standard Model
(known)

126 GeV Higgs and SUSY

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$(89\ \mathrm{GeV})^2$

0.13

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$$\frac{g^2 \cos^2 2\beta}{8 \cos^2 \theta_W} \simeq \mathbf{0.069} \cos^2 2\beta$$

$$\frac{3 y_t^4}{16\pi^2} \left(\log \left(\frac{m_{\mathrm{stop}}^2}{m_t^2} \right) + \alpha^2 - \frac{\alpha^4}{12} \right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t / m_{\mathrm{stop}})$

...requires **heavy stop**

and/or **large A-term**

126 GeV Higgs and SUSY

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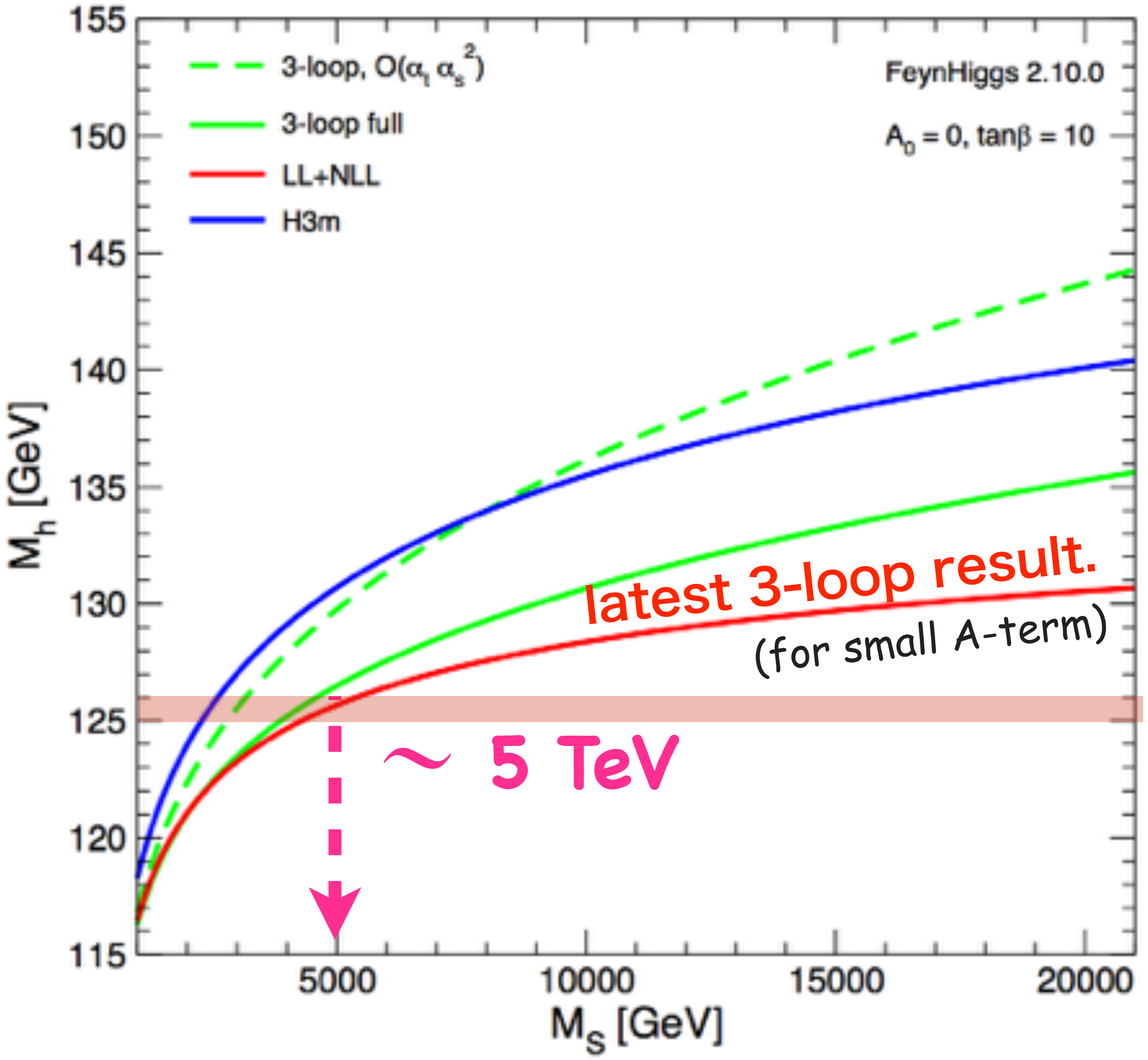

latest 3-loop result.

(for small A-term)

$\sim$ 5 TeV

1404.0186 Hahn et.al.

126 GeV Higgs and SUSY

$$V(H) = -m^2(H^\dagger H) + \lambda_{\rm H}(H^\dagger H)^2$$

$(89\ \mathbf{GeV})^2$

0.13

$$= \lambda_H^{\rm tree} + \delta\lambda_H^{\rm loop}$$

on the other hand

$$-m^2 \simeq |\mu|^2 + m_{H_u}^{2\,(\rm tree)} + \delta m_{H_u}^{2\,(\rm loop)}$$

up to $\mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$

Higgsino mass

soft mass for
up-type Higgs

$$\frac{g^2\cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\ \cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\rm stop}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

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up to $\mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$

large μ -----> fine-tuning.

e.g., $\simeq (1000\ \mathrm{GeV})^2 - (1004\ \mathrm{GeV})^2$

for $|\mu| \simeq 1\ \mathrm{TeV}$

requires **Light Higgsino**
to avoid a fine-tuning.

$$\frac{g^2 \cos^2 2\beta}{8 \cos^2\theta_W} \simeq \mathbf{0.069} \cos^2 2\beta$$

$$\frac{3y_t^4}{16\pi^2}\left(\log\left(\frac{m_{\text{stop}}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

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126 GeV Higgs and SUSY

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$$(\mathbf{89\ GeV})^2 \qquad \mathbf{0.13}$$

$$= \lambda_H^{\mathrm{tree}} + \delta\lambda_H^{\mathrm{loop}}$$

on the other hand

$$-m^2 \simeq |\mu|^2 + m_{H_u}^{2\,(\mathrm{tree})} + \delta m_{H_u}^{2\,(\mathrm{loop})}$$

Moreover,

$$\delta m_{H_u}^{2\,(\mathrm{loop})} \sim \frac{-3y_t^2}{8\pi^2}\left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2\right)\log\left(\frac{M_{\mathrm{mess}}}{m_{\tilde{}}}\right) + \cdot\cdot$$

inconsistent !!

requires **Light stop and small A-term** to avoid a fine-tuning.

$$\frac{g^2\cos^2 2\beta}{8\cos^2\theta_W} \simeq \mathbf{0.069}\,\cos^2 2\beta$$

$$\frac{3y_t^4}{\pi^2}\left(\log\left(\frac{m_{\mathrm{stop}}^2}{m_t^2}\right) + \alpha^2 - \frac{\alpha^4}{12}\right) + \cdots$$

for large $\tan\beta$. $(\alpha \simeq A_t/m_{\mathrm{stop}})$

...requires **heavy stop** and/or **large A-term**

126 GeV Higgs and SUSY

Fine-tuning worse than 1% seems unavoidable in MSSM.

(MSSM =Minimal SUSY Standard Model)

What does it imply ??

1. **No SUSY ?**

2. (It's anyway fine-tuned, then….)

Very heavy SUSY ? (10-100 TeV, or even higher…)

3. (still…..)

O(0.1-1) TeV SUSY ? (fine-tuned, but less than 2 and 3…)

Plan

0. Introduction (… done)
1. **Higgs**
2. Beyond the Standard Model
3. SUSY
4. SUSY after Higgs discovery

will be discussed again on the last day.

Please interrupt and ask questions at any time!

Any questions so far?

1. Higgs

Now we know the Higgs properties very well.

For a review, see

Review of Particle Physics

(K.A. Olive et al. (PDG), Chin. Phys. C38, 090001 (2014), http://pdg.lbl.gov)

"11. Status of Higgs Boson Physics,"

by M. Carena, C. Grojean, M. Kado, and V. Sharma

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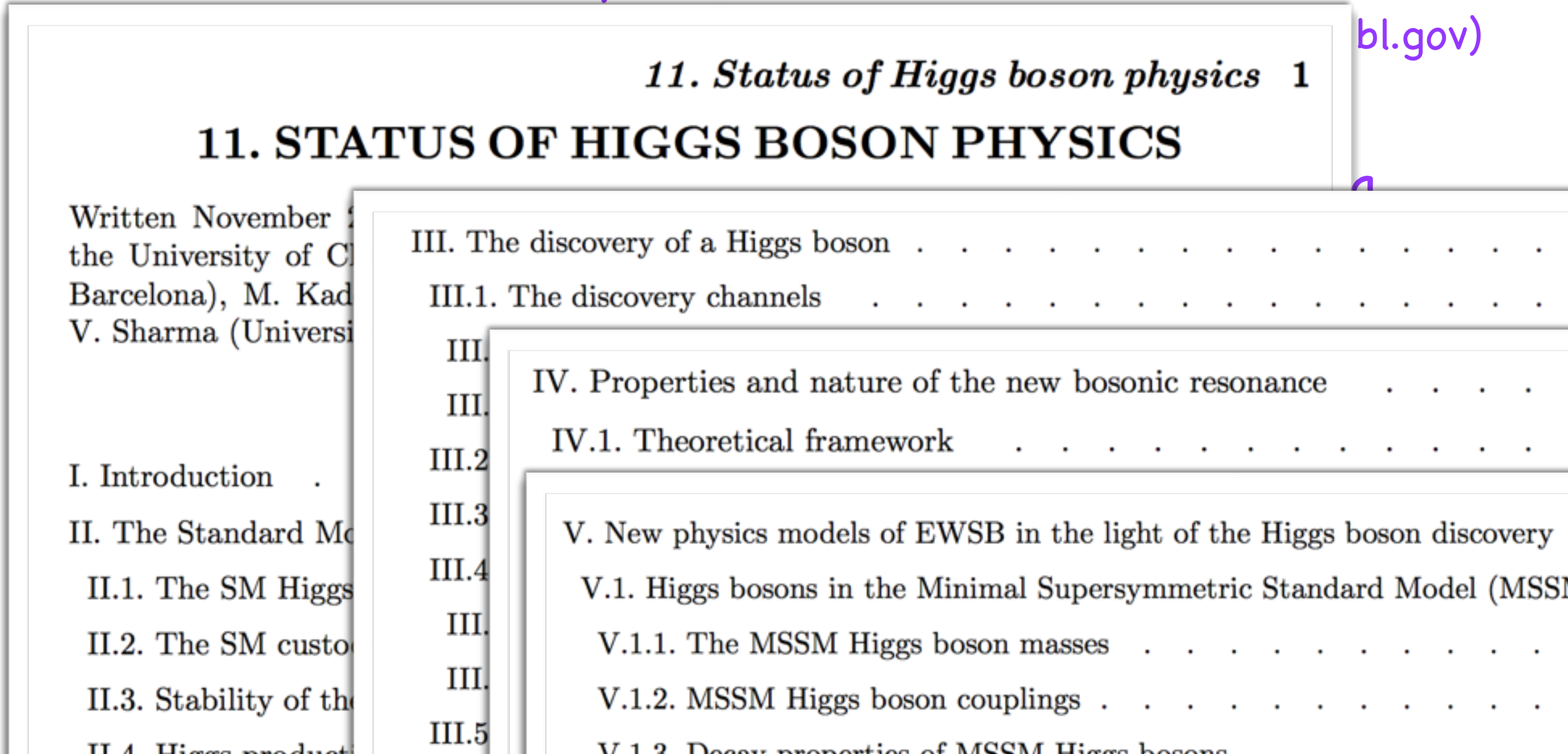
bl.gov)



11. Status of Higgs boson physics 1

11. STATUS OF HIGGS BOSON PHYSICS

Written November
the University of C
Barcelona), M. Kad
V. Sharma (Universi

1. Higgs

Before the Higgs discovery, we already knew its couplings very well (**assuming** that there is no deviation from the SM).
..... Only the mass was unknown.

$$(\text{mass of a SM particle } \mathbf{X}) = (\text{its coupling to Higgs}) \times (\text{Higgs VEV})$$

$$\Longrightarrow \quad \underbrace{(\mathbf{X}\text{'s coupling with Higgs})}_{\text{known}} = \frac{(\mathbf{X}\text{'s mass})}{(\text{Higgs VEV})} \begin{array}{l} \longleftarrow \text{known} \\ \\ \longleftarrow \text{known} \end{array}$$

1. Higgs

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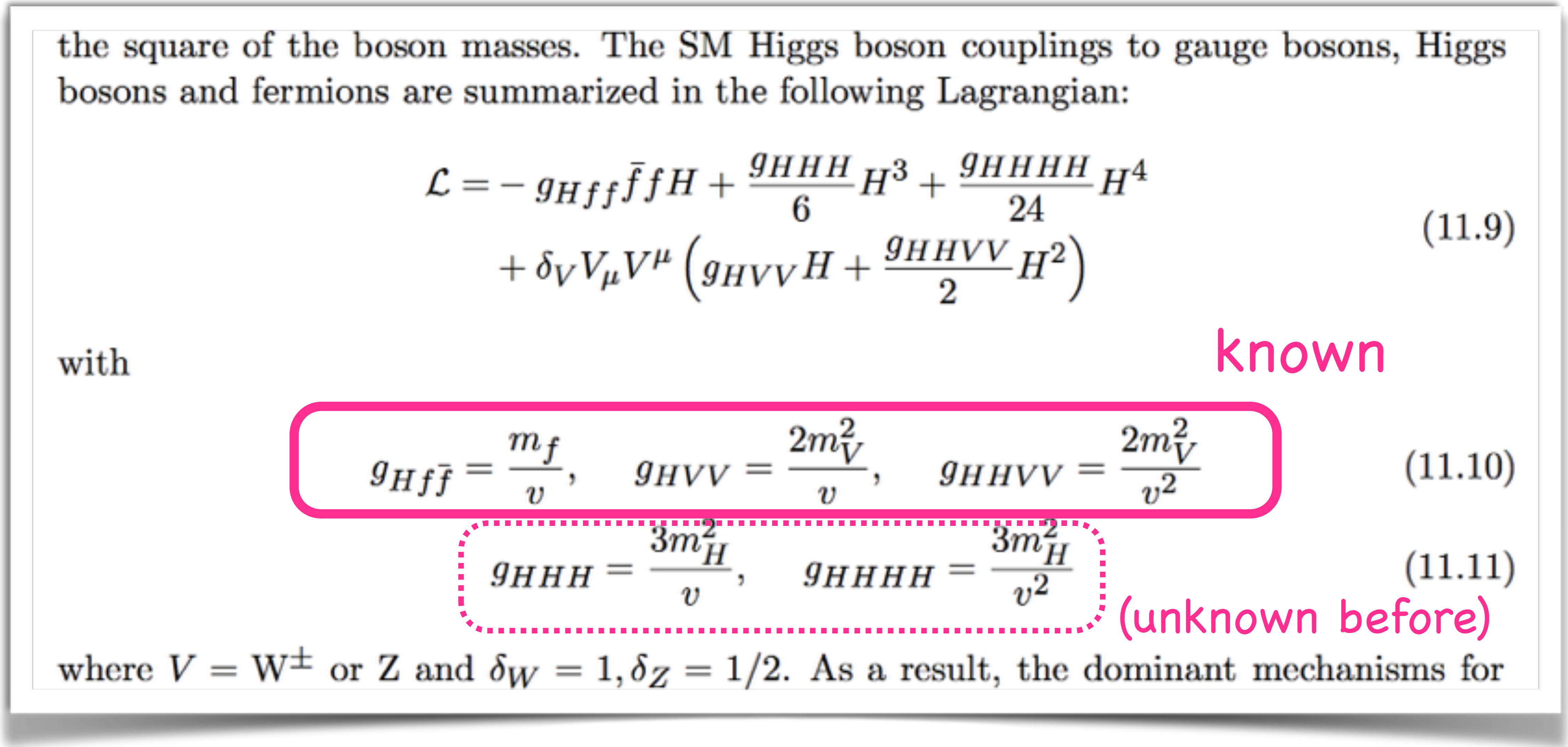
….. Only the mass was unknown.

(from RPP, "11. Status of Higgs Boson Physics.")



the square of the boson masses. The SM Higgs boson couplings to gauge bosons, Higgs bosons and fermions are summarized in the following Lagrangian:

$$\mathcal{L} = - g_{Hff}\bar{f}fH + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right) \qquad (11.9)$$

with

known

$$g_{Hf\bar{f}} = \frac{m_f}{v}, \quad g_{HVV} = \frac{2m_V^2}{v}, \quad g_{HHVV} = \frac{2m_V^2}{v^2} \qquad (11.10)$$

$$g_{HHH} = \frac{3m_H^2}{v}, \quad g_{HHHH} = \frac{3m_H^2}{v^2} \qquad (11.11)$$

(unknown before)

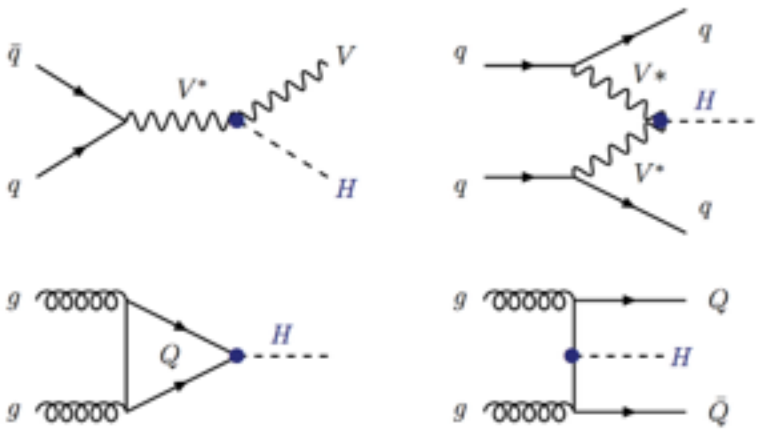
where $V = W^\pm$ or Z and $\delta_W = 1, \delta_Z = 1/2$. As a result, the dominant mechanisms for

1. Higgs

Before the Higgs discovery, we already knew its couplings very well (**assuming** that there is no deviation from the SM). ….. Only the mass was unknown.

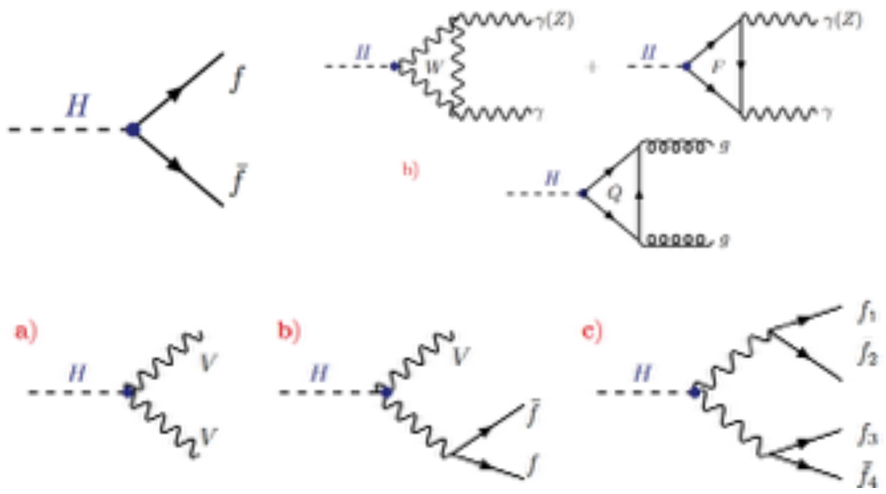
Thus, both the **production cross section** and the **decay rates** of the Higgs were also calculated (as a function of Higgs mass) very precisely.

production



+ higher order diagrams…

decay



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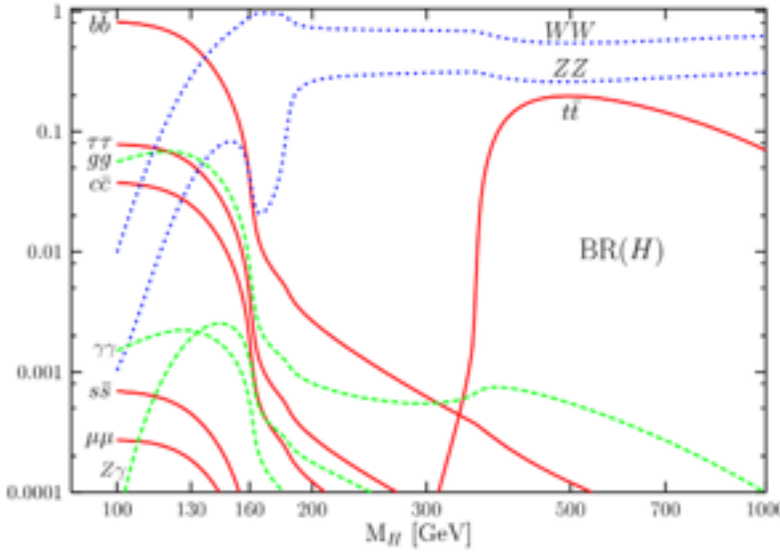


Figure 2.25: The SM Higgs boson decay branching ratios as a function of M_H

(figures are A.Djouadi, hep-ph/0503172)

1. Higgs

(figures are from RPP,
"11. Status of Higgs Boson Physics.")

Now the Higgs mass is also well measured.

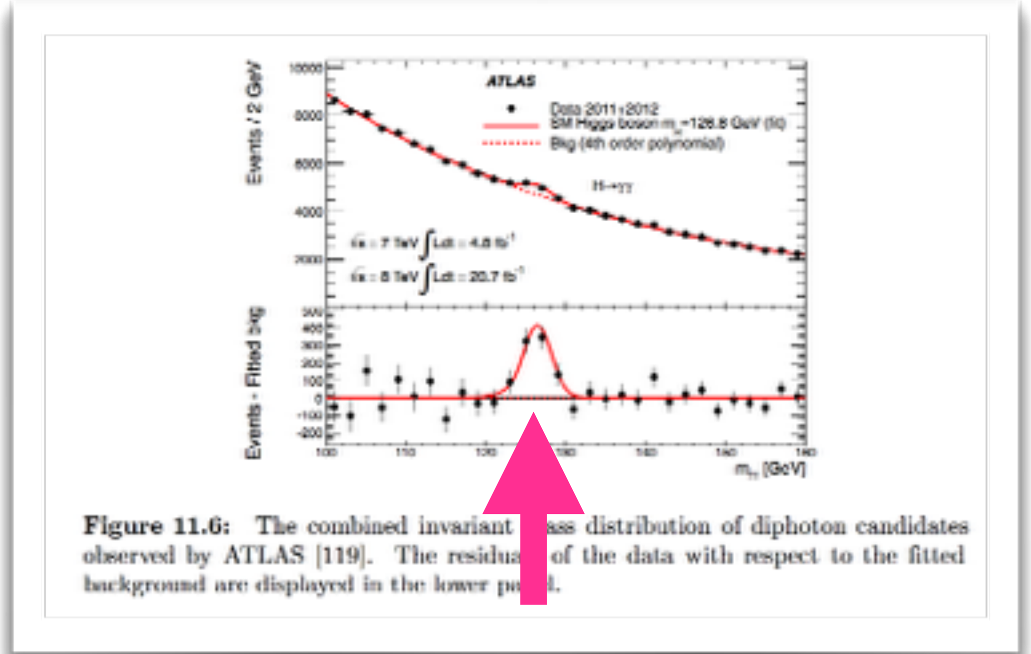


Figure 11.6: The combined invariant mass distribution of diphoton candidates observed by ATLAS [119]. The residuals of the data with respect to the fitted background are displayed in the lower panel.

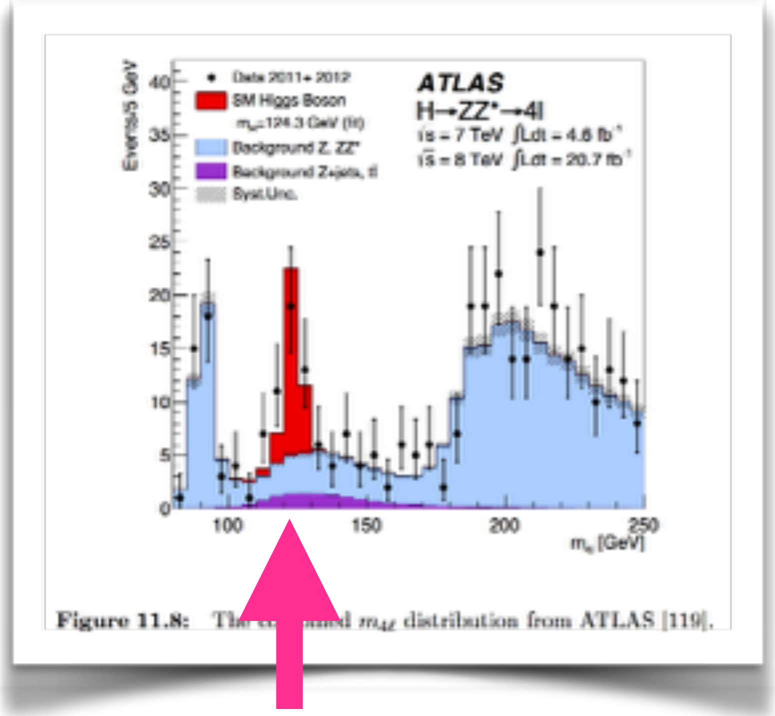


Figure 11.8: The combined $m_{4\ell}$ distribution from ATLAS [119].

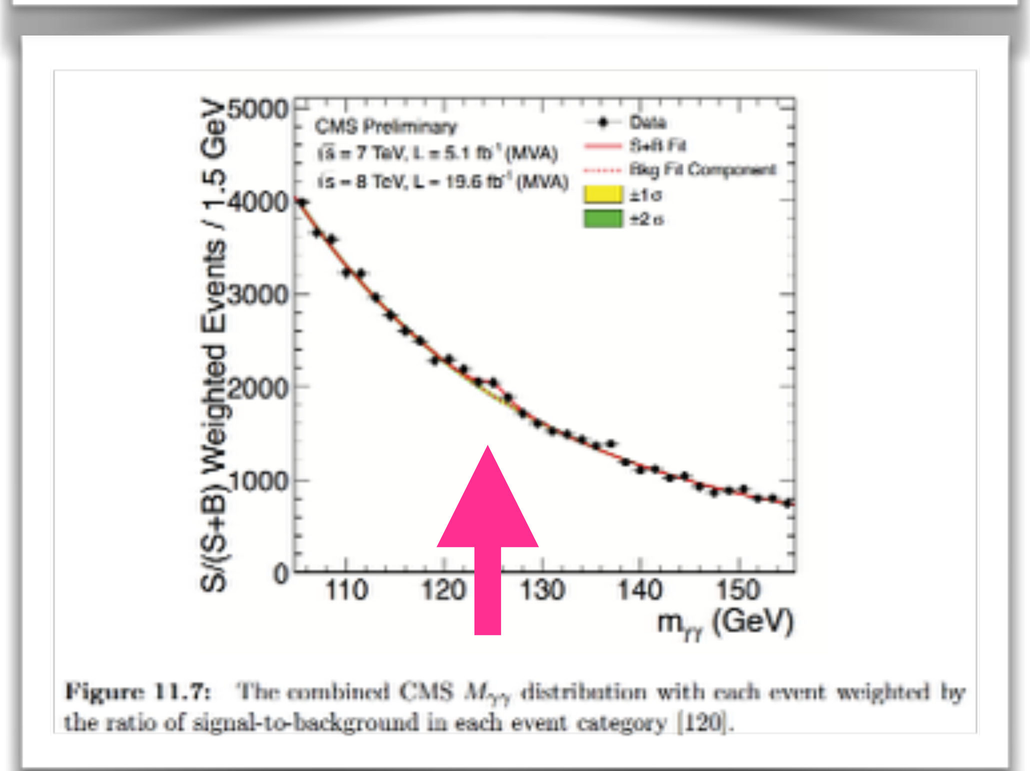


Figure 11.7: The combined CMS $M_{\gamma\gamma}$ distribution with each event weighted by the ratio of signal-to-background in each event category [120].

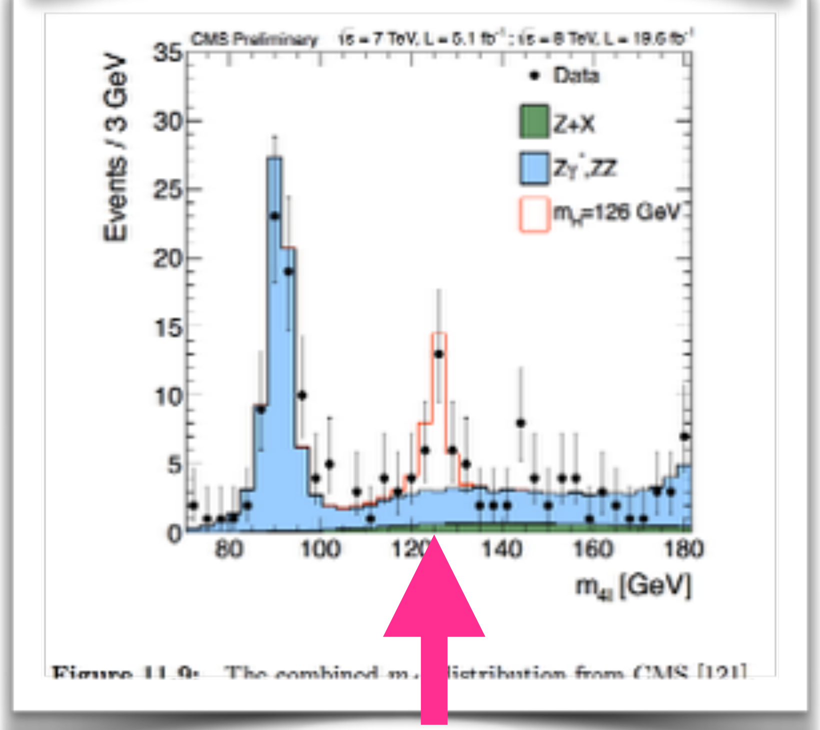


Figure 11.9: The combined $m_{4\ell}$ distribution from CMS [121].

1. Higgs

Now the Higgs mass is also well measured.

(from RPP, Particle Listings, "Gauge and Higgs Bosons")

(from RPP, "11. Status of Higgs Boson Physics.")

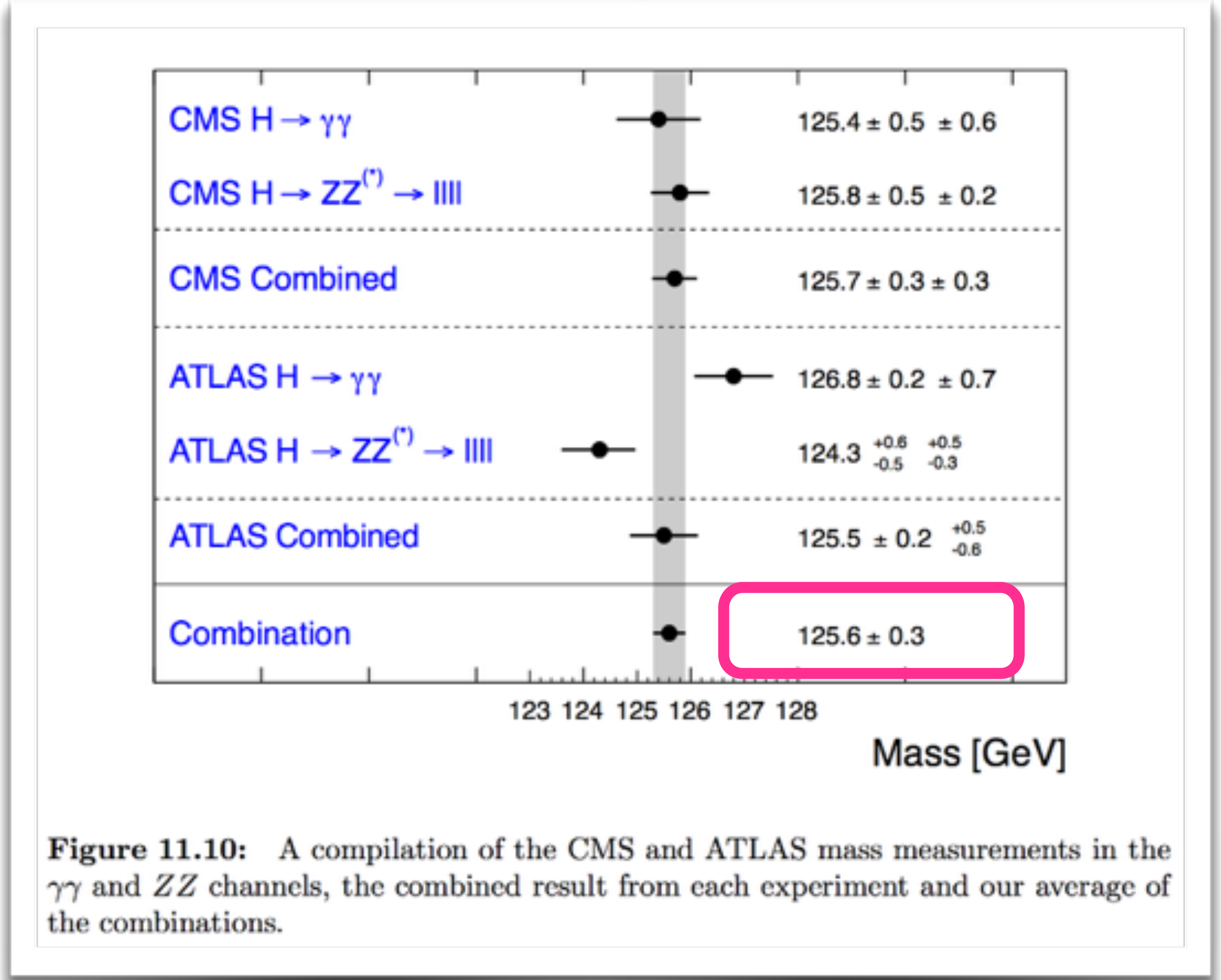
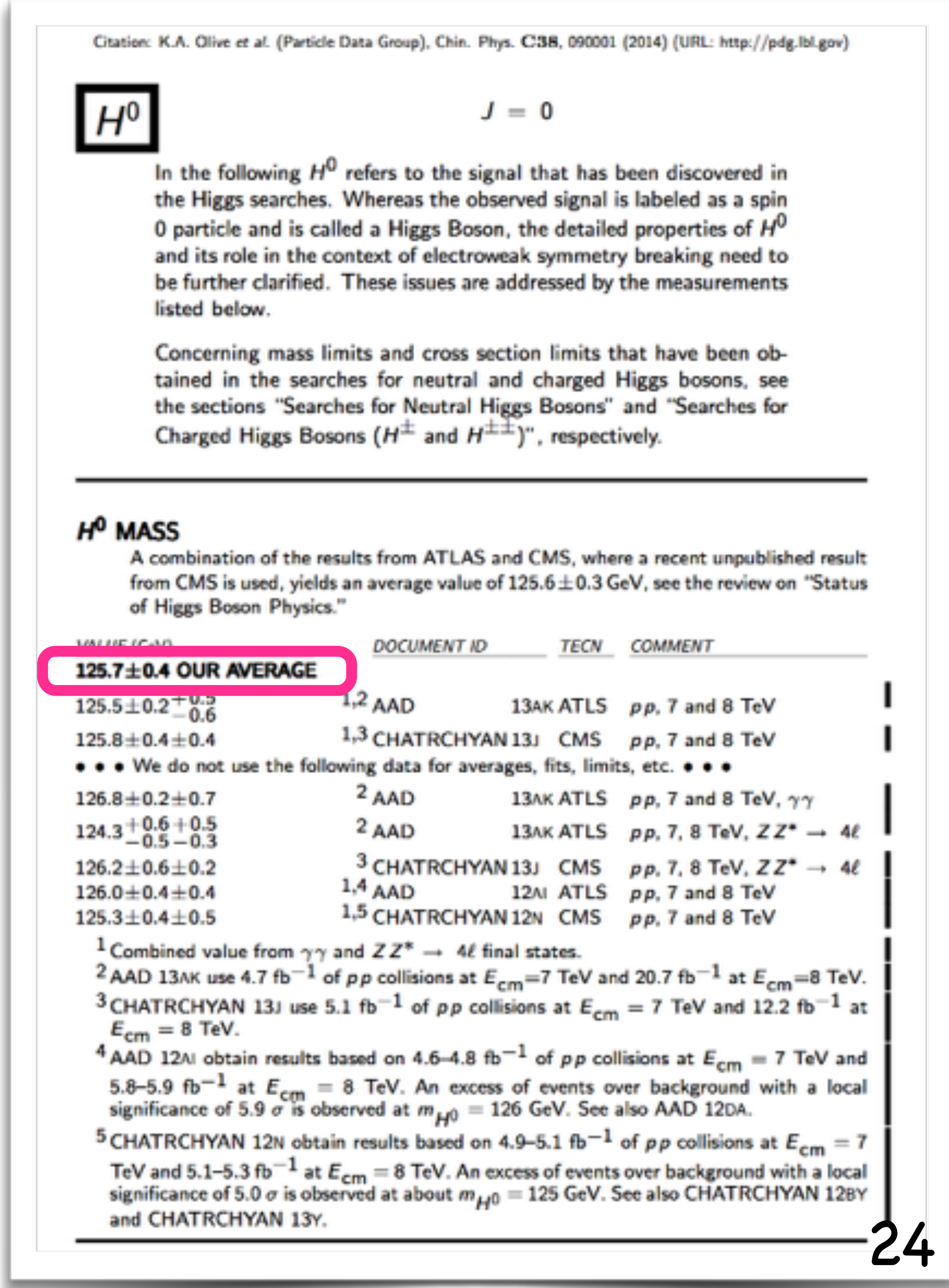


Figure 11.10: A compilation of the CMS and ATLAS mass measurements in the $\gamma\gamma$ and ZZ channels, the combined result from each experiment and our average of the combinations.



Citation: K.A. Olive et al. (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

H^0 $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

H^0 MASS

A combination of the results from ATLAS and CMS, where a recent unpublished result from CMS is used, yields an average value of 125.6±0.3 GeV, see the review on "Status of Higgs Boson Physics."

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125.7±0.4 OUR AVERAGE			
$125.5 \pm 0.2 ^{+0.5}_{-0.6}$	[1,2] AAD 13AK	ATLS	pp, 7 and 8 TeV
$125.8 \pm 0.4 \pm 0.4$	[1,3] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$126.8 \pm 0.2 \pm 0.7$	[2] AAD	13AK ATLS	pp, 7 and 8 TeV, $\gamma\gamma$
$124.3 ^{+0.6}_{-0.5} {}^{+0.5}_{-0.3}$	[2] AAD	13AK ATLS	pp, 7, 8 TeV, $ZZ^* \rightarrow 4\ell$
$126.2 \pm 0.6 \pm 0.2$	[3] CHATRCHYAN 13J	CMS	pp, 7, 8 TeV, $ZZ^* \rightarrow 4\ell$
$126.0 \pm 0.4 \pm 0.4$	[1,4] AAD 12AI	ATLS	pp, 7 and 8 TeV
$125.3 \pm 0.4 \pm 0.5$	[1,5] CHATRCHYAN 12N	CMS	pp, 7 and 8 TeV

[1] Combined value from $\gamma\gamma$ and $ZZ^* \rightarrow 4\ell$ final states.

[2] AAD 13AK use 4.7 fb^{-1} of pp collisions at E_{cm}=7 TeV and 20.7 fb^{-1} at E_{cm}=8 TeV.

[3] CHATRCHYAN 13J use 5.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 12.2 fb^{-1} at $E_{\text{cm}} = 8$ TeV.

[4] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 5.8–5.9 fb^{-1} at $E_{\text{cm}} = 8$ TeV. An excess of events over background with a local significance of 5.9 σ is observed at $m_{H^0} = 126$ GeV. See also AAD 12DA.

[5] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ TeV and 5.1–5.3 fb^{-1} at $E_{\text{cm}} = 8$ TeV. An excess of events over background with a local significance of 5.0 σ is observed at about $m_{H^0} = 125$ GeV. See also CHATRCHYAN 12BY and CHATRCHYAN 13Y.

1. Higgs

Now the Higgs mass is also well measured.

==> No free parameter within the SM.

==> One can compare the predictions and measurements to see if there is any deviation.

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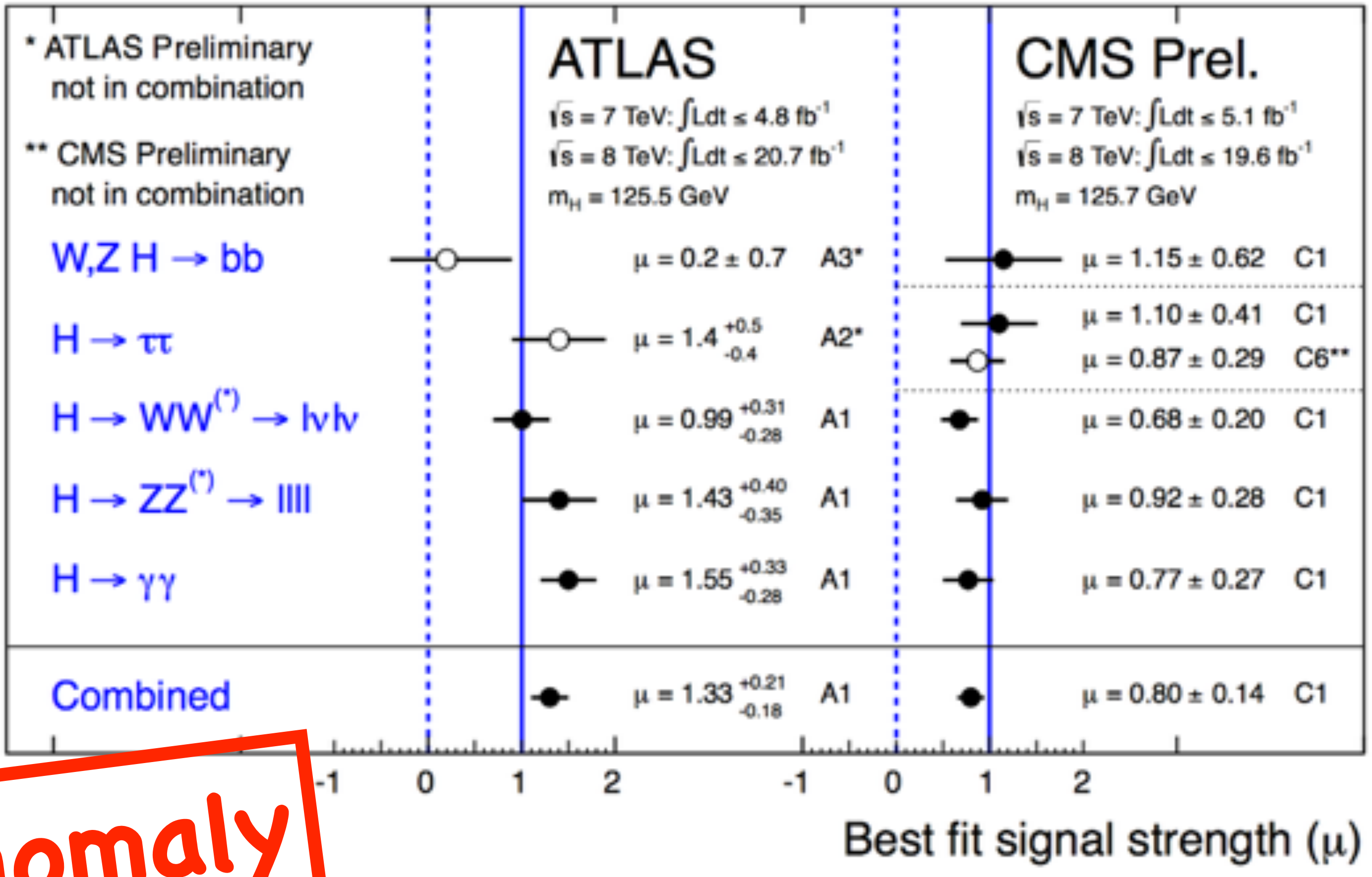
(from RPP, "11. Status of Higgs Boson Physics.")

$$\mu = \frac{(\sigma \cdot \mathcal{B})_{\text{observed}}}{(\sigma \cdot \mathcal{B})_{\text{SM prediction}}}$$

σ : Higgs production cross section

$\mathcal{B}$: Higgs decay branching ratio



no anomaly

Figure 11.16: The signal strengths μ measured by the ATLAS experiment from Refs. A1 [119], A2 [133] and A3 [138], and CMS experiment from Ref. C1 [124] and C6 [132] in the five principal channels and their combination. It should be noted that the ATLAS combination only includes the bosonic $\gamma\gamma$, ZZ and WW channels.

1. Higgs

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==> One can compare the predictions and measurements to see if there is any deviation.

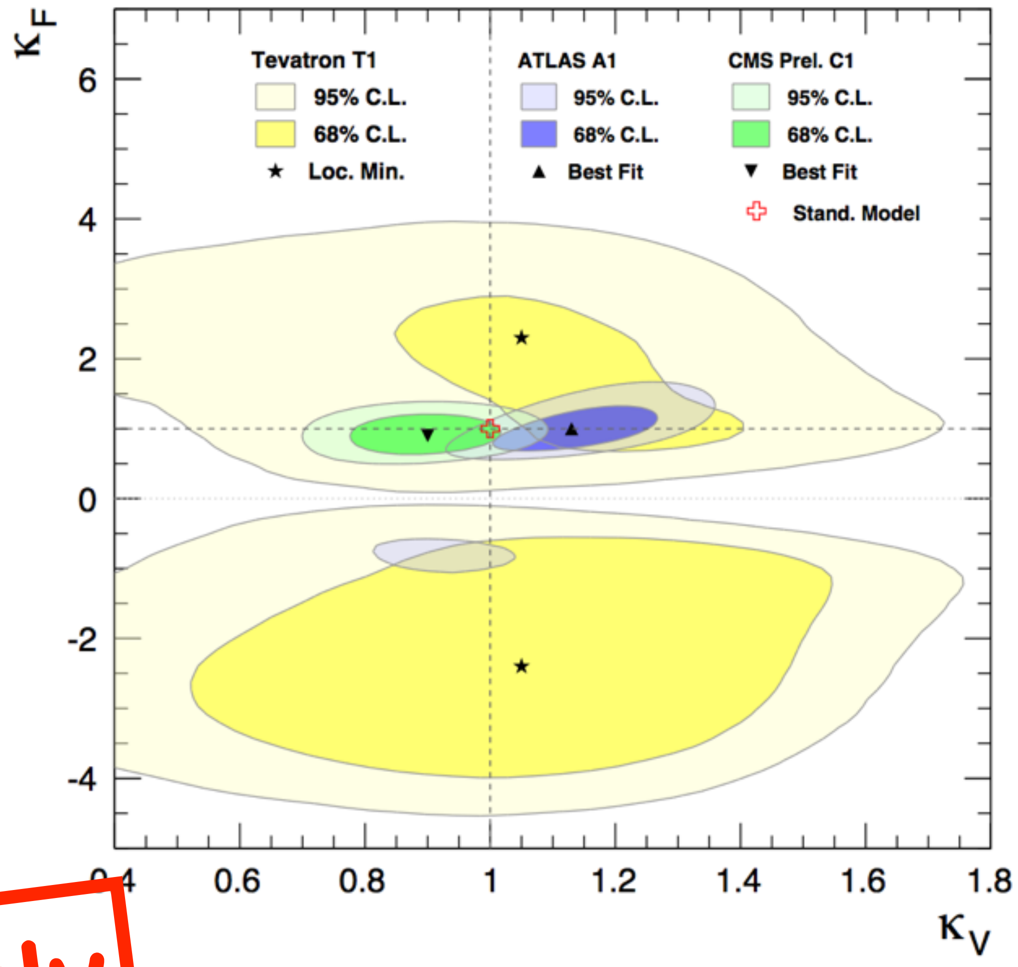
Using effective Lagrangian...

$$\begin{aligned}\mathcal{L} = {}& \boxed{\kappa_3}\frac{m_H^2}{2v}H^3 + \boxed{\kappa_Z}\frac{m_Z^2}{v}Z_\mu Z^\mu H + \boxed{\kappa_W}\frac{2m_W^2}{v}W_\mu^+ W^{-\mu} H \\ & + \boxed{\kappa_g}\frac{\alpha_s}{12\pi v}G^a_{\mu\nu}G^{a\mu\nu}H + \boxed{\kappa_\gamma}\frac{\alpha}{2\pi v}A_{\mu\nu}A^{\mu\nu}H + \boxed{\kappa_{Z\gamma}}\frac{\alpha}{\pi v}A_{\mu\nu}Z^{\mu\nu}H \\ & + \boxed{\kappa_{VV}}\frac{\alpha}{2\pi v}\left(\cos^2\theta_W Z_{\mu\nu}Z^{\mu\nu} + 2\,W^+_{\mu\nu}W^{-\mu\nu}\right)H \\ & - \left(\boxed{\kappa_t}\sum_{f=u,c,t}\frac{m_f}{v}f\bar{f} + \boxed{\kappa_b}\sum_{f=d,s,b}\frac{m_f}{v}f\bar{f} + \boxed{\kappa_\tau}\sum_{f=e,\mu,\tau}\frac{m_f}{v}f\bar{f}\right)H.\end{aligned}$$

$\kappa_X = 1$ in SM $_{(\kappa_{Z\gamma}=0)}$

$\Longrightarrow \kappa_X \neq 0$

(modified "by hand")



no anomaly

Figure 11.18: Likelihood contours of the global fit in the (κ_F, κ_V) plane for the ATLAS A1 [119], the CMS C1 [120] and the D0 and CDF combined T1 [108] results.

(from RPP, "11. Status of Higgs Boson Physics.")

1. Higgs

Now the Higgs mass is also well measured.

==> No free parameter within the SM.

==> One can compare the predictions and measurements to see if there is any deviation.

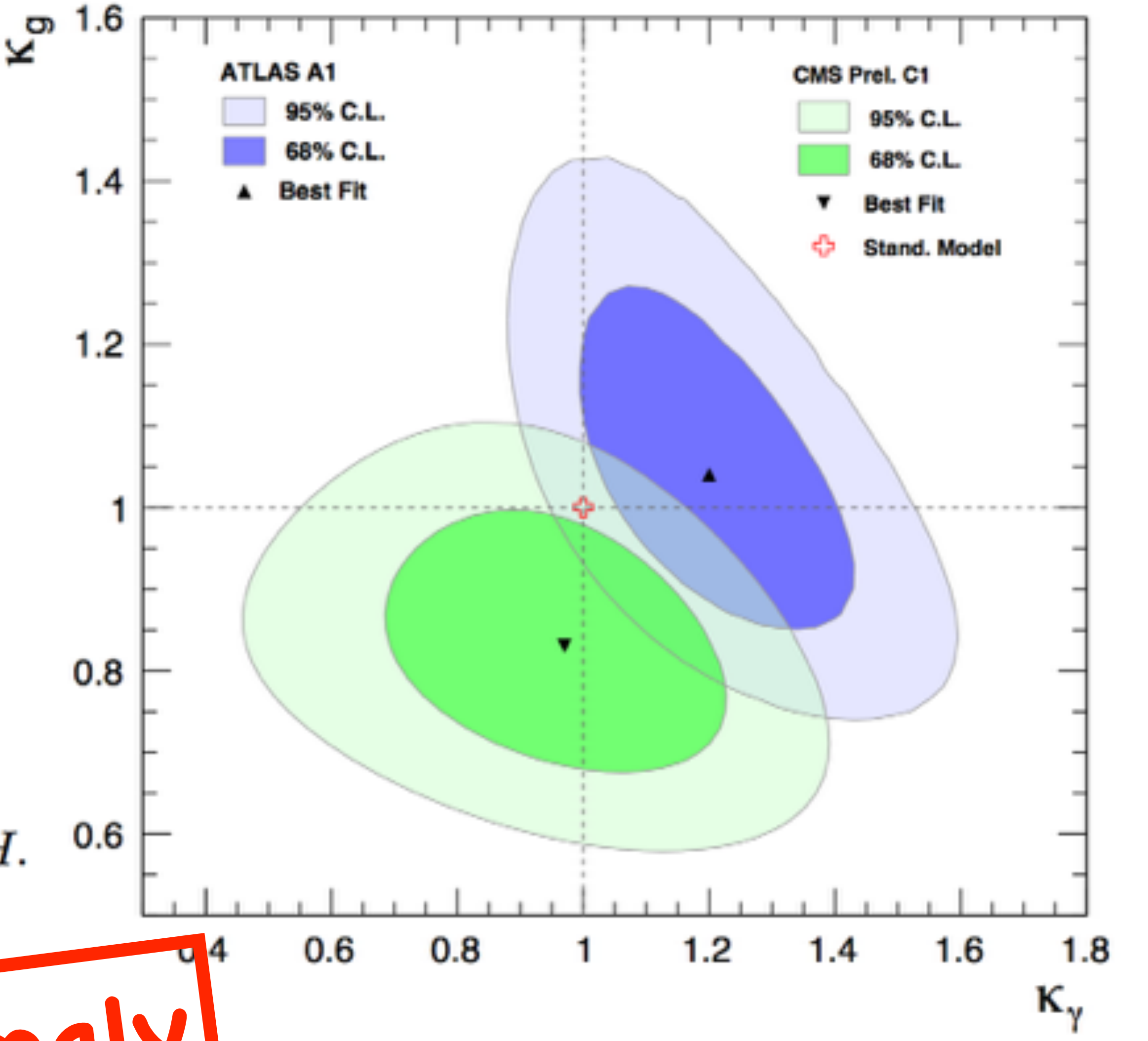
Using effective Lagrangian...

$$\mathcal{L} = \boxed{\kappa_3}\frac{m_H^2}{2v}H^3 + \boxed{\kappa_Z}\frac{m_Z^2}{v}Z_\mu Z^\mu H + \boxed{\kappa_W}\frac{2m_W^2}{v}W_\mu^+ W^{-\mu} H$$
$$+\boxed{\kappa_g}\frac{\alpha_s}{12\pi v}G_{\mu\nu}^a G^{a\mu\nu}H + \boxed{\kappa_\gamma}\frac{\alpha}{2\pi v}A_{\mu\nu}A^{\mu\nu}H + \boxed{\kappa_{Z\gamma}}\frac{\alpha}{\pi v}A_{\mu\nu}Z^{\mu\nu}H$$
$$+\boxed{\kappa_{VV}}\frac{\alpha}{2\pi v}\left(\cos^2\theta_W Z_{\mu\nu}Z^{\mu\nu} + 2\,W_{\mu\nu}^+ W^{-\mu\nu}\right)H$$
$$-\left(\boxed{\kappa_t}\sum_{f=u,c,t}\frac{m_f}{v}f\bar{f} + \boxed{\kappa_b}\sum_{f=d,s,b}\frac{m_f}{v}f\bar{f} + \boxed{\kappa_\tau}\sum_{f=e,\mu,\tau}\frac{m_f}{v}f\bar{f}\right)H.$$

$\kappa_X = 1$ in SM $(\kappa_{Z\gamma}=0)$

$\Longrightarrow$ $\kappa_X \neq 0$

(modified "by hand")



no anomaly

Figure 11.19: ikelihood contours of the global fit in the $(\kappa_g, \kappa_\gamma)$ plane for the TLAS experiment A1 [119] and the CMS experiment C1 [120] results.

(from RPP, "11. Status of Higgs Boson Physics.")

1. Higgs

SUMMARY

Higgs was discovered,
and everything seems consistent with the SM.

…… any hint of physics **beyond the SM** ??

👉 §2

Plan

0. Introduction
1. Higgs

done

2. **Beyond the Standard Model**
3. SUSY
4. SUSY after Higgs discovery

Any questions so far?

Plan

0. **Introduction**
1. **Higgs**
2. **Beyond the Standard Model**
   - 2.1. puzzles in SM = hints of BSM.
   - 2.2. renormalization and naturalness

The purpose of this section is:

to introduce some of

Motivations for BSM physics

and

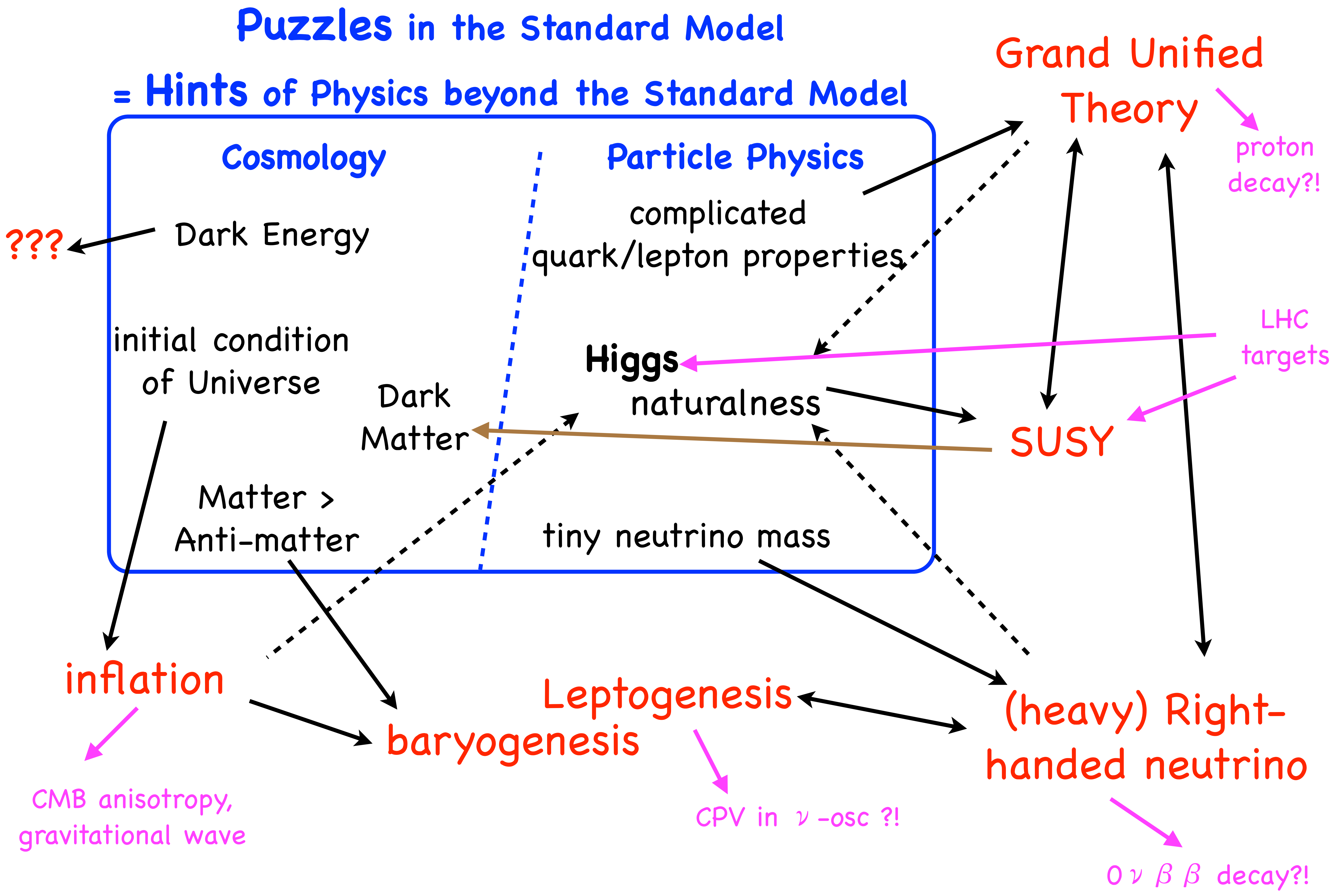
Candidates for BSM physics.

(NOTE: biased!)

2.1. puzzles in SM = hints of BSM.

Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model



Cosmology

Particle Physics

???

Dark Energy

complicated quark/lepton properties

initial condition of Universe

Higgs naturalness

Dark Matter

Matter > Anti-matter

tiny neutrino mass

Grand Unified Theory

proton decay?!

LHC targets

SUSY

inflation

CMB anisotropy, gravitational wave

baryogenesis

Leptogenesis

CPV in ν -osc ?!

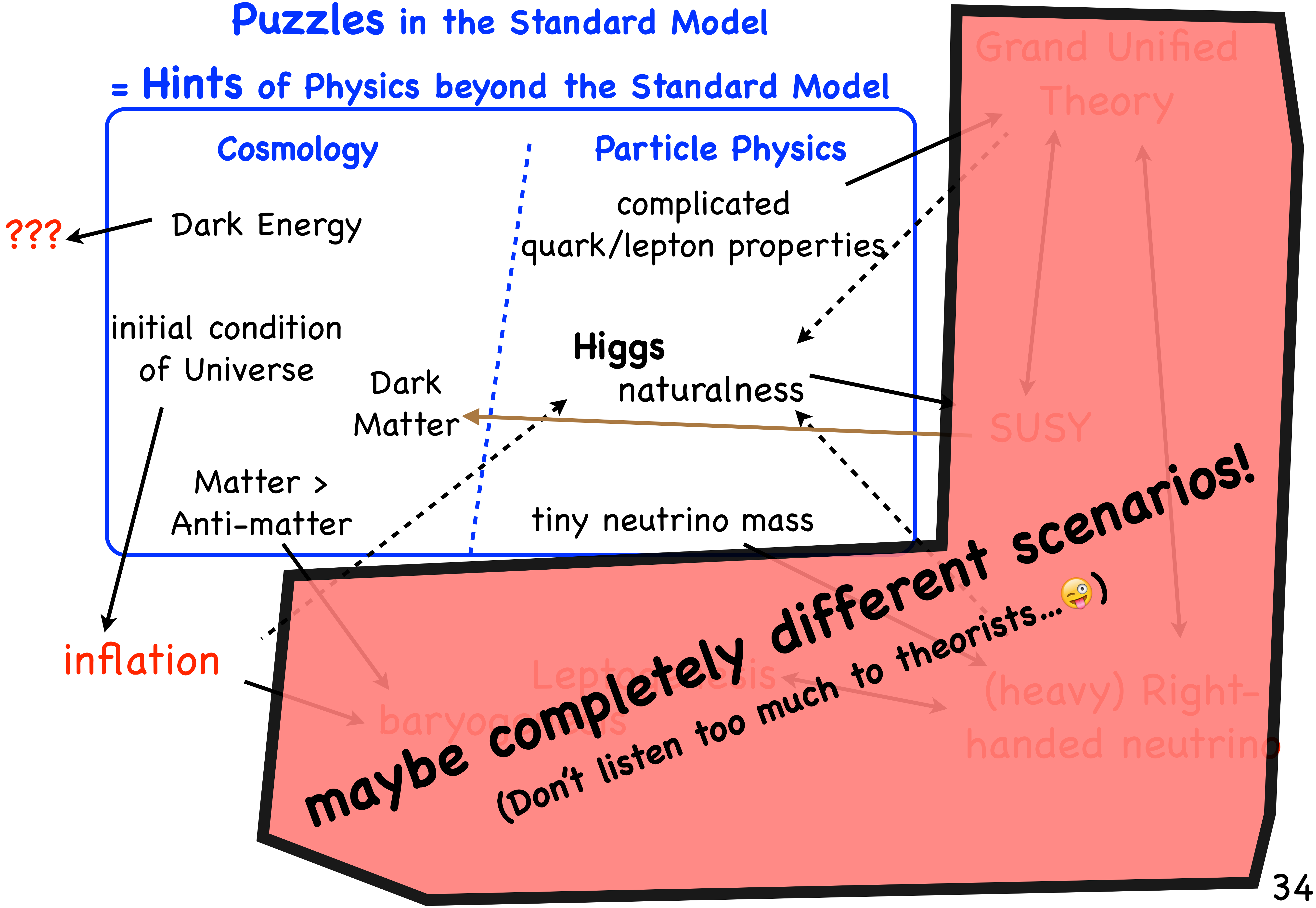
(heavy) Right-handed neutrino

$0\nu\beta\beta$ decay?!

2.1. puzzles in SM = hints of BSM.

Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model



Cosmology

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initial condition of Universe

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Higgs naturalness

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tiny neutrino mass

inflation

Grand Unified Theory

SUSY

Leptogenesis

baryogenesis

(heavy) Right-handed neutrino

maybe completely different scenarios!

(Don't listen too much to theorists...😜)

comment:

perturbative 4d QFT up to high scale?

YES

▷ compatible with

- perturbative GUT,
- seesaw and leptogenesis with heavy right-handed neutrino.

▷ cosmology can be discussed within perturbative QFT.
(inflation, baryogenesis,...)

this lecture

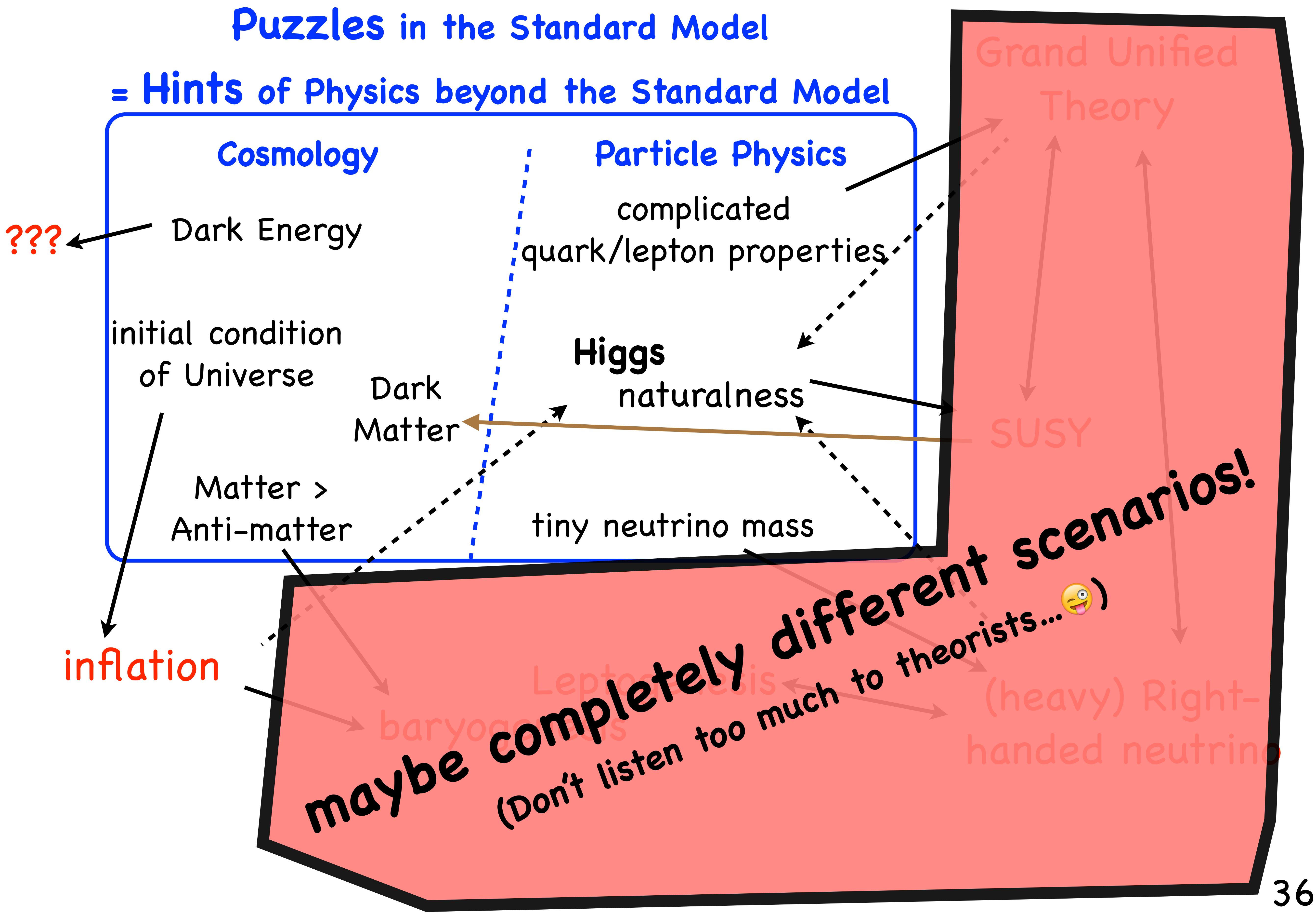
NO

example

- extra-dimension (large, warped,...)
- composite Higgs
- ……

=> maybe we can discuss in discussion session.....

2.1. puzzles in SM = hints of BSM.



Puzzles in the Standard Model = Hints of Physics beyond the Standard Model

Cosmology

Particle Physics

??? ← Dark Energy

complicated quark/lepton properties

initial condition of Universe

Dark Matter

Higgs naturalness

Matter > Anti-matter

tiny neutrino mass

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SUSY

Leptogenesis

baryogenesis

(heavy) Right-handed neutrino

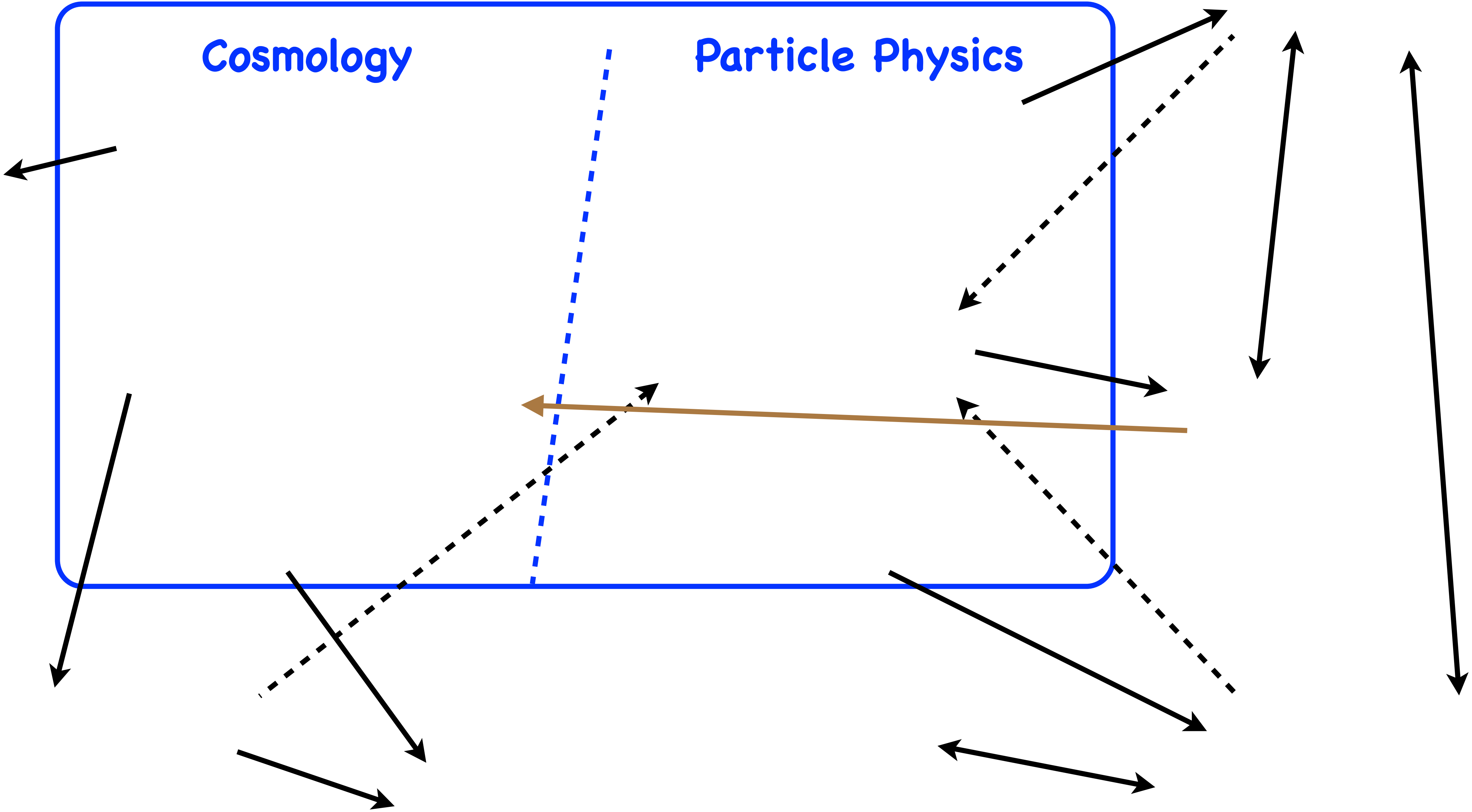
maybe completely different scenarios!

(Don't listen too much to theorists...😜)

2.1. puzzles in SM = hints of BSM.

Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model

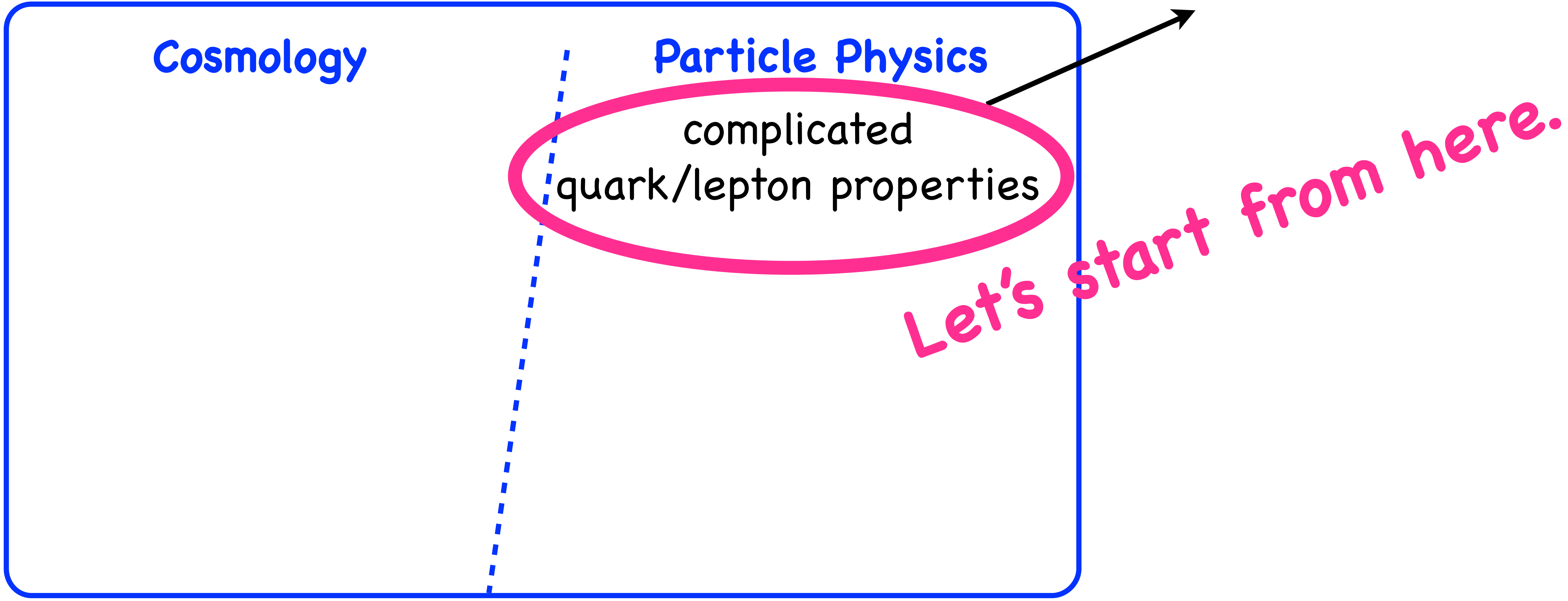


Where shall we start…?

2.1. puzzles in SM = hints of BSM.

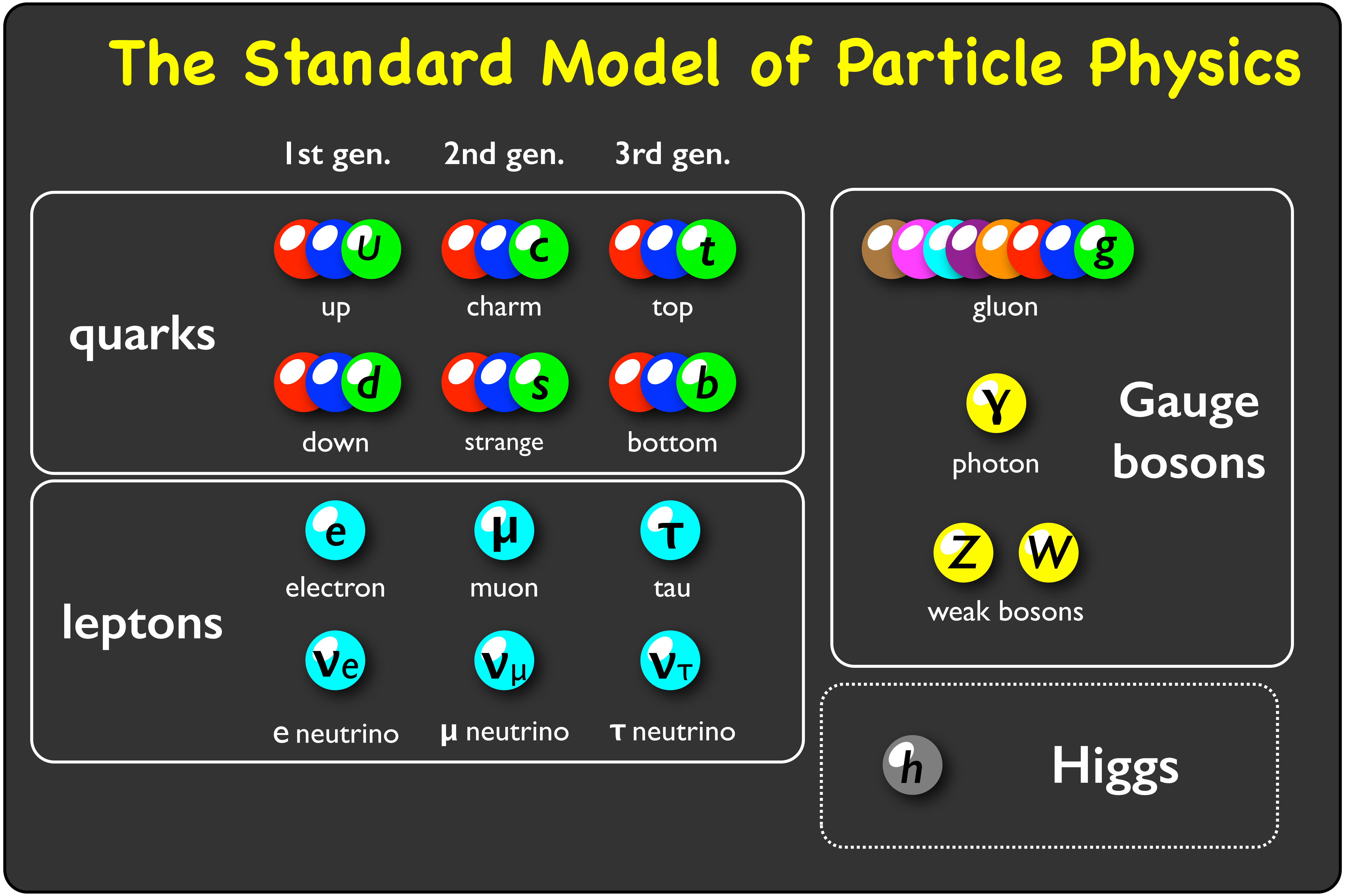
Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model



Let's start from here.

Where shall we start…?



The Standard Model of Particle Physics

	1st gen.	2nd gen.	3rd gen.
quarks	up	charm	top
	down	strange	bottom
leptons	electron	muon	tau
	e neutrino	μ neutrino	τ neutrino

Gauge bosons

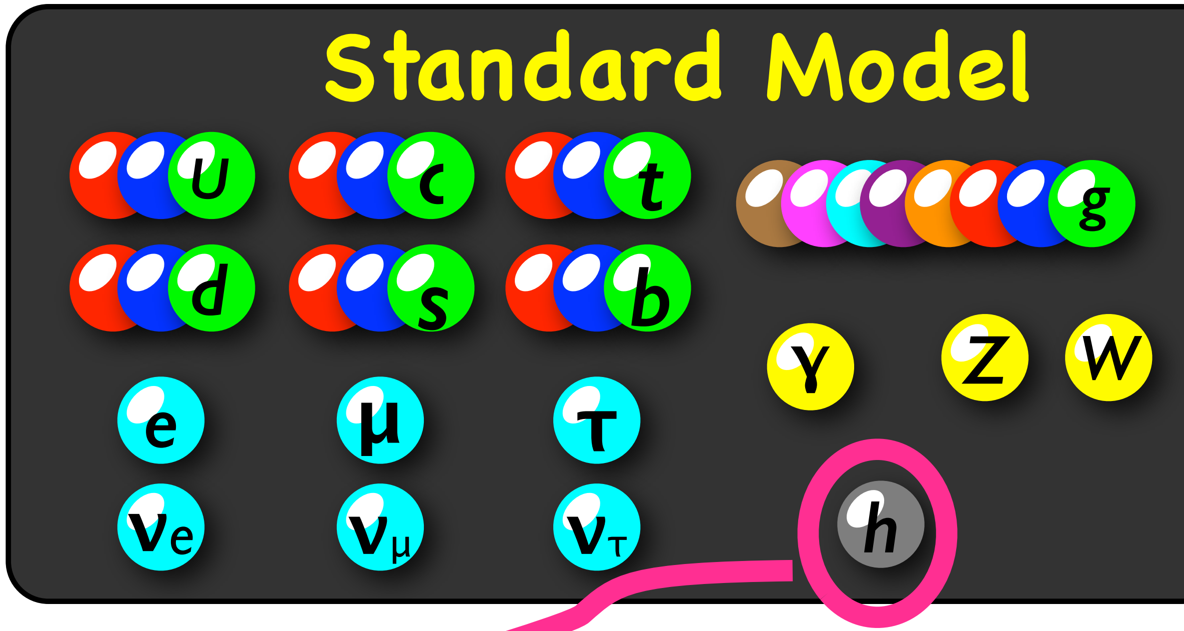
gluon

photon

weak bosons

Higgs

2.1. puzzles in SM = hints of BSM.

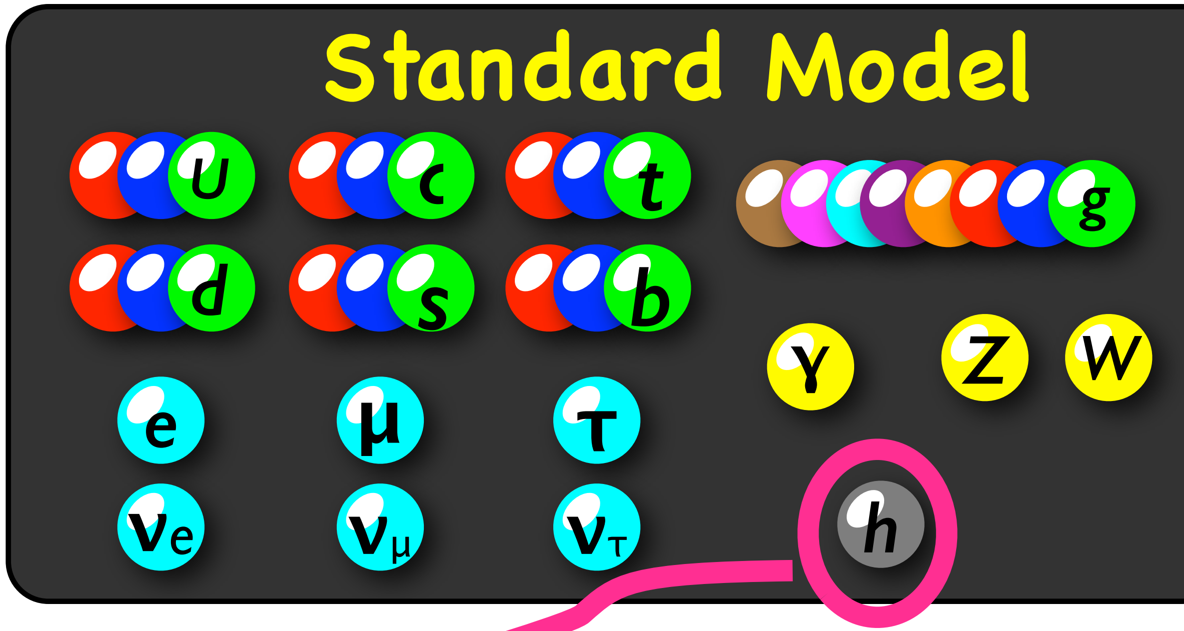


First of all,

Let's recall how Higgs gives masses to fermions.

☞ cf. Lecture by Prof. Godbole.

e.g. electron:



First of all,

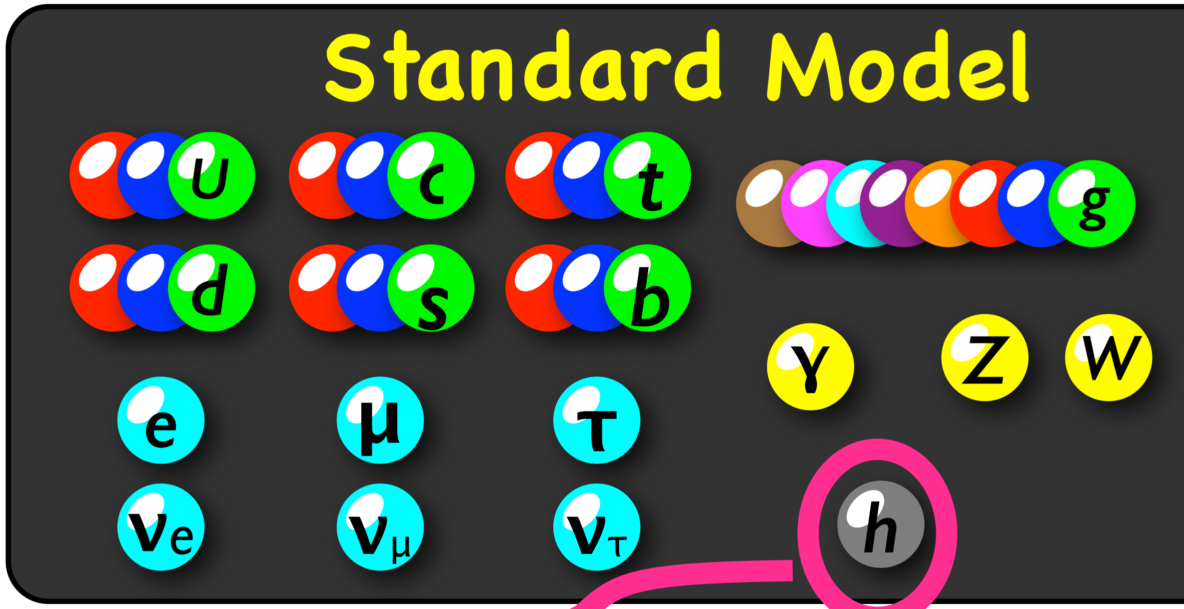
Let's recall how Higgs gives masses to fermions.

👉 cf. Lecture by Prof. Godbole.

e.g. electron:

e = right-handed e_R + left-handed e_L

(not weakly interacting) (weakly interacting)



First of all,

Let's recall how Higgs gives masses to fermions.

👉 cf. Lecture by Prof. Godbole.

e.g. electron: **without Higgs,.....**

(not weakly interacting)

right-handed e_R

left-handed e_L

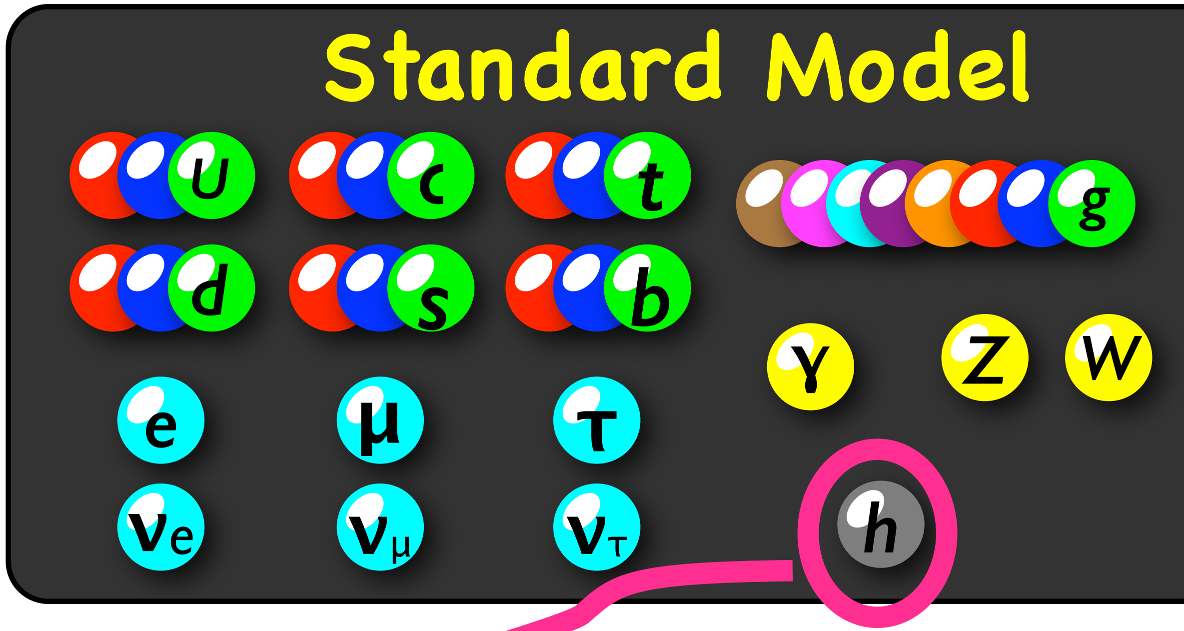
(weakly interacting)

different particles !!

zero masses !

(moving with a speed of light)

2.1. puzzles in SM = hints of BSM.

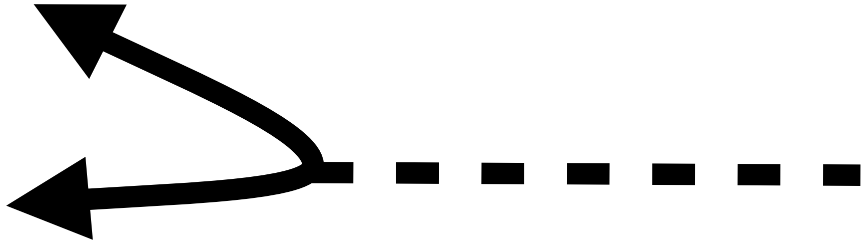


First of all,

Let's recall how Higgs gives masses to fermions.

☞ cf. Lecture by Prof. Godbole.

e.g. electron: the **Higgs** connects the two components.



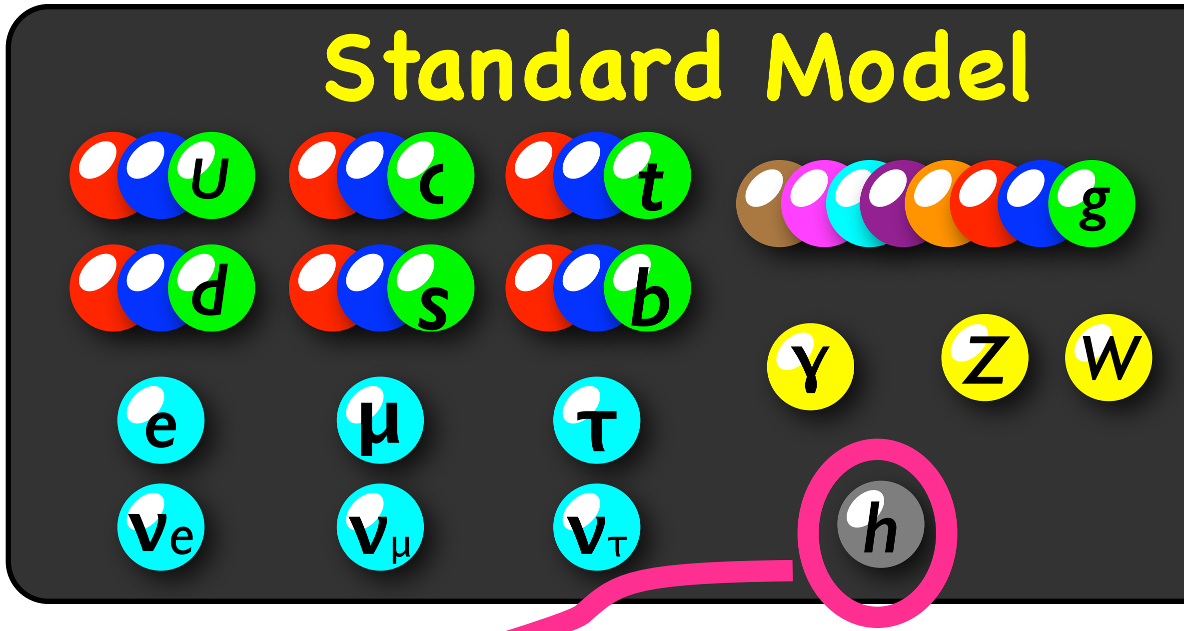
(not weakly interacting)
right-handed e_R

left-handed e_L
(weakly interacting)

Higgs

Yukawa
interaction

2.1. puzzles in SM = hints of BSM.



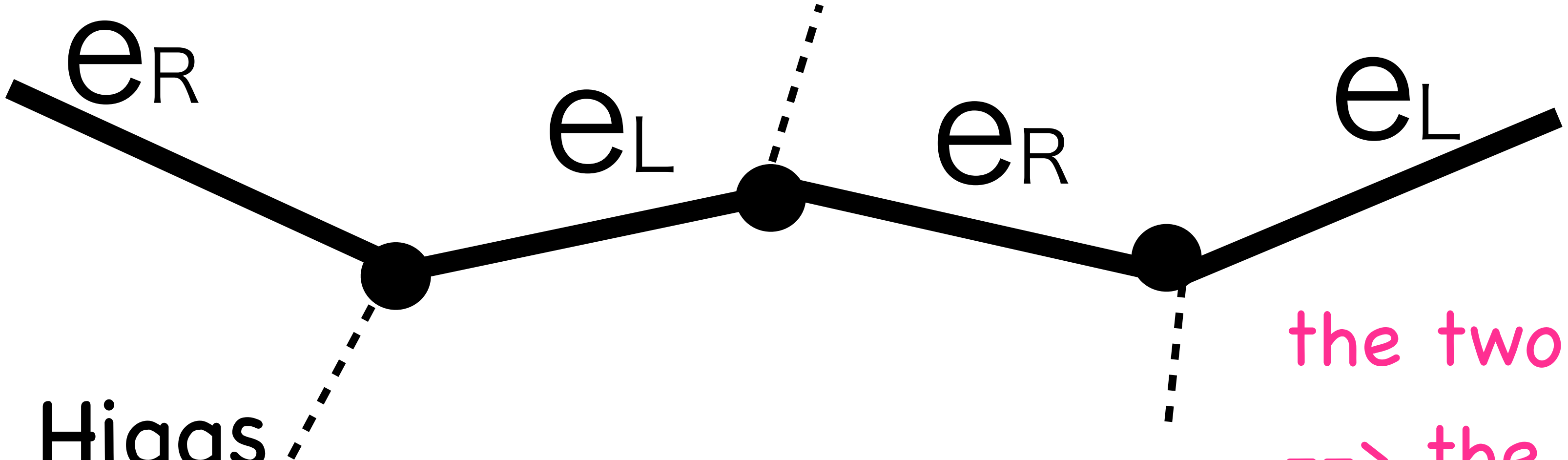
First of all,

Let's recall how Higgs gives masses to fermions.

👉 cf. Lecture by Prof. Godbole.

e.g. electron:

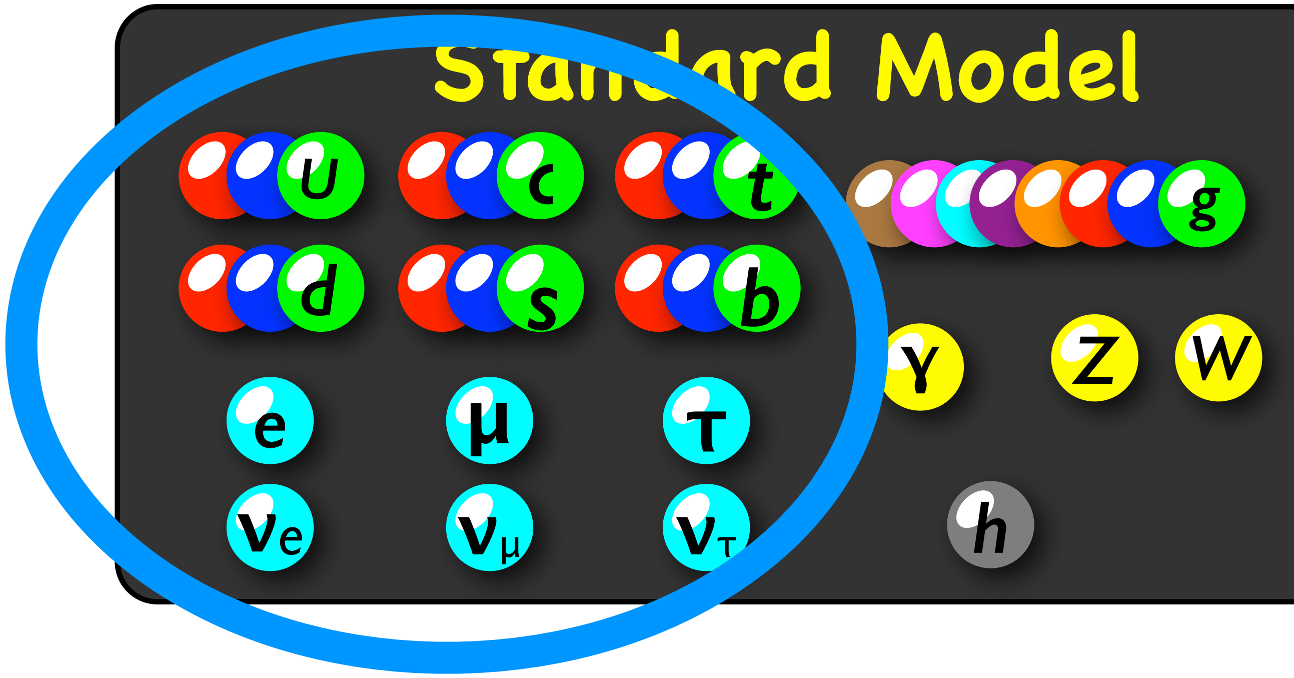
thanks to the "Higgs condensation" in vacuum....



the two components are exchanged

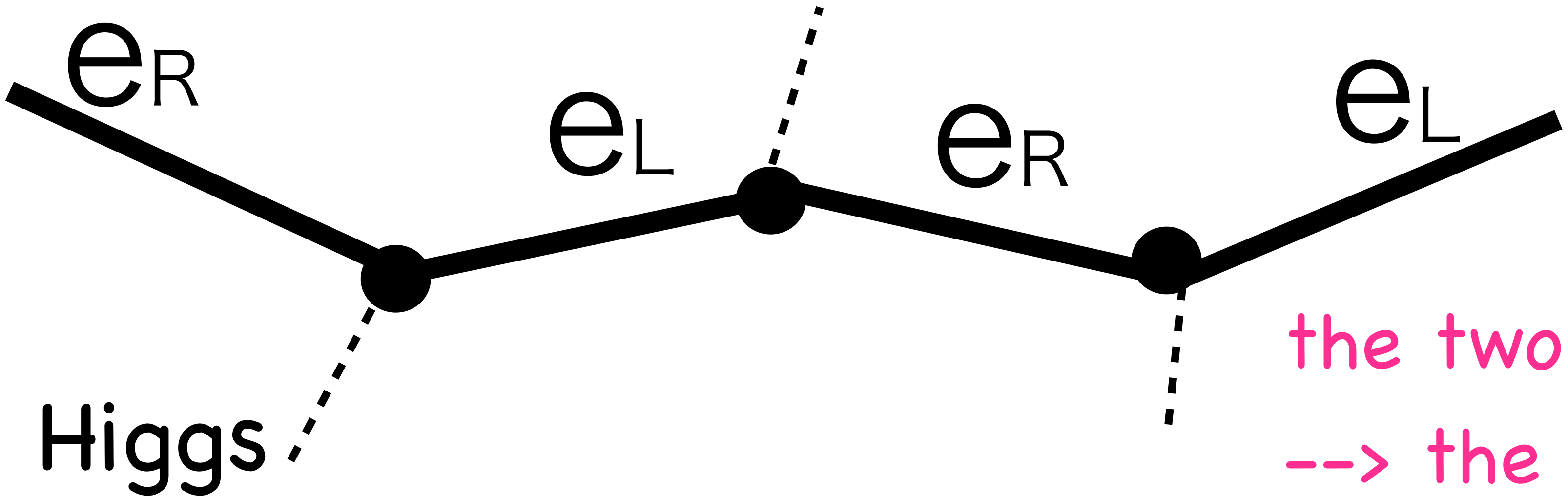
--> the electron gets a **mass** !!

2.1. puzzles in SM = hints of BSM.



Other quarks and leptons get masses in similar ways.

"Left + Right"

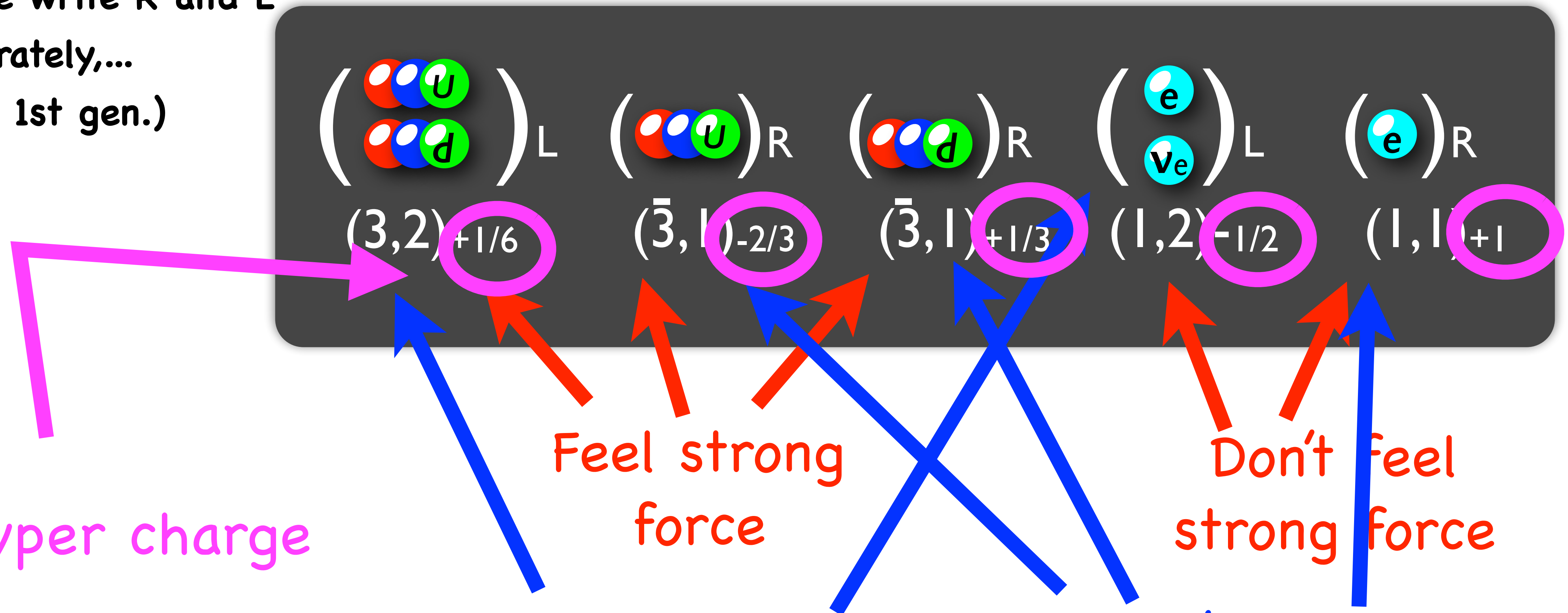


the two components are exchanged

--> the electron gets a **mass** !!

2.1. puzzles in SM = hints of BSM.

If we write R and L separately,...
(only 1st gen.)



left-handed quark

right-handed up quark

right-handed down quark

left-handed lepton

right-handed lepton

$(3,2)_{+1/6}$ $(\bar{3},1)_{-2/3}$ $(\bar{3},1)_{+1/3}$ $(1,2)_{-1/2}$ $(1,1)_{+1}$

hyper charge

Feel strong force

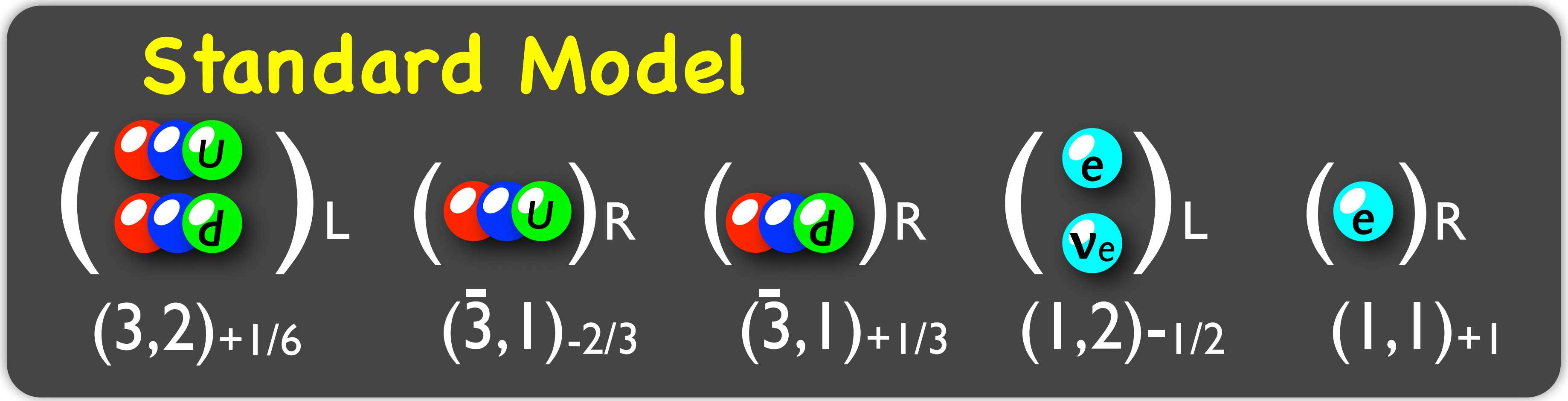
Don't feel strong force

Feel weak force

Don't feel weak force

... very complicated !!

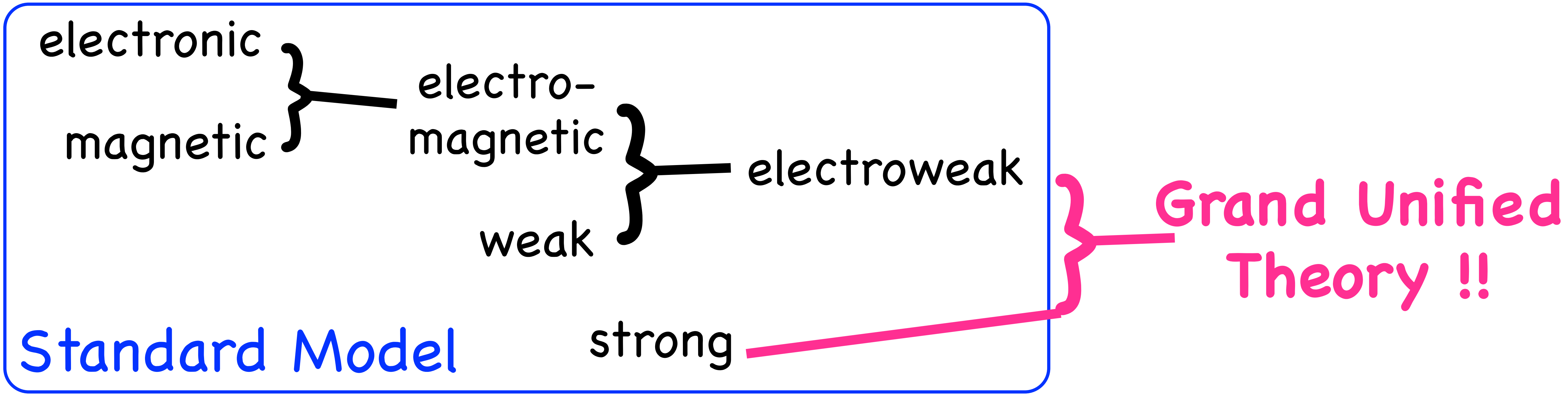
Q: any simple, unified theory to explain it?



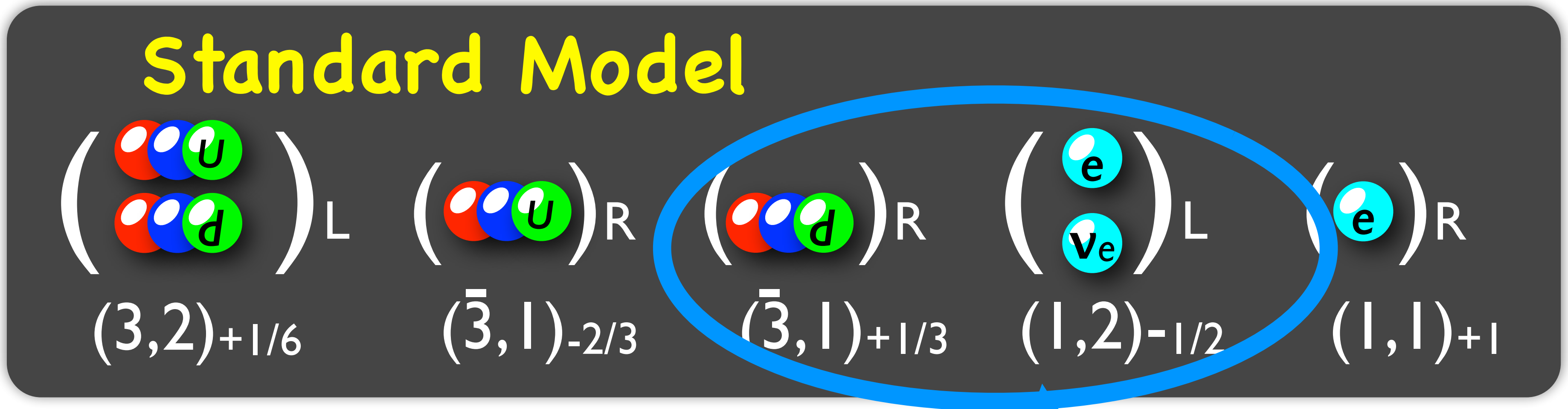
Standard Model

$(3,2)_{+1/6}$ $(\bar{3},1)_{-2/3}$ $(\bar{3},1)_{+1/3}$ $(1,2)_{-1/2}$ $(1,1)_{+1}$

Q: any simple, unified theory to explain it?



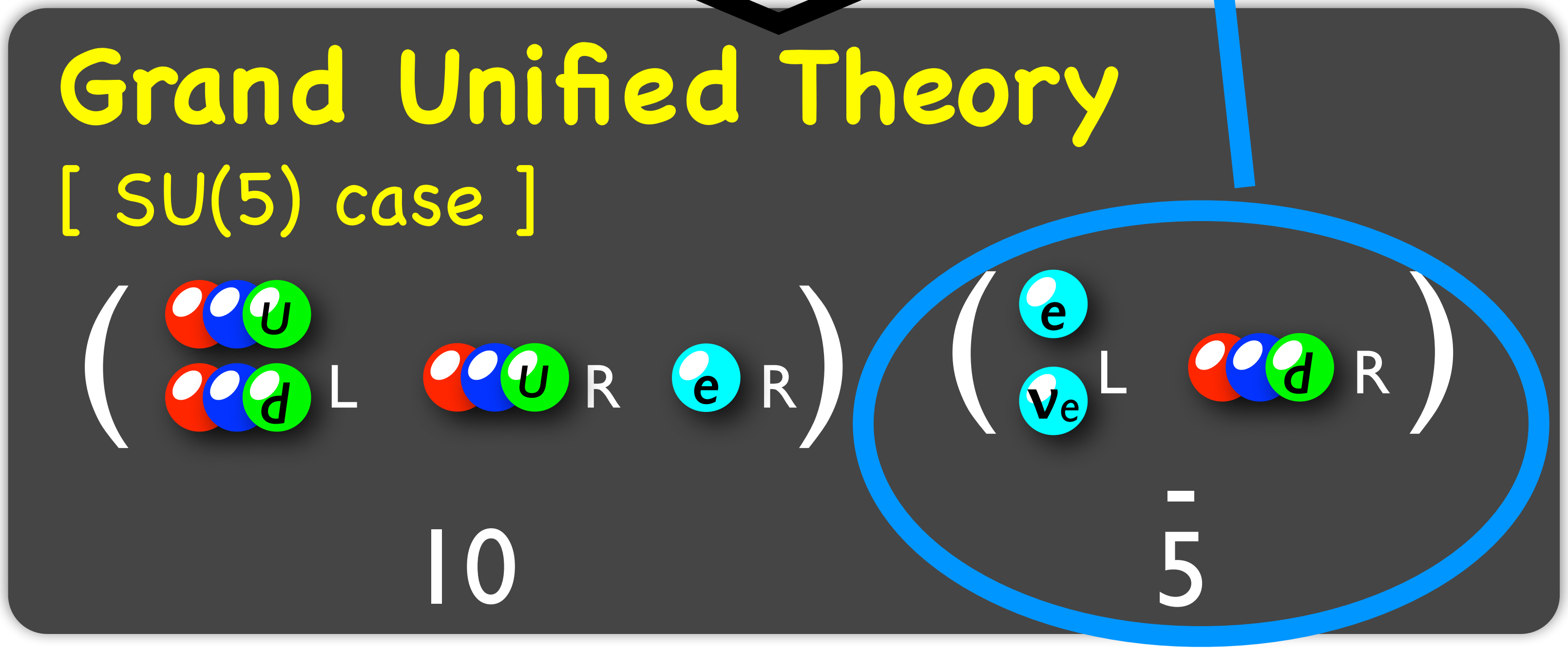
electronic
magnetic
electro-magnetic
weak
electroweak
strong
Standard Model
Grand Unified Theory !!



Q: any simple, unified theory to explain it?

1/3 + 1/3 + 1/3 − 1/2 − 1/2 = 0

Complicated numbers are naturally explained !



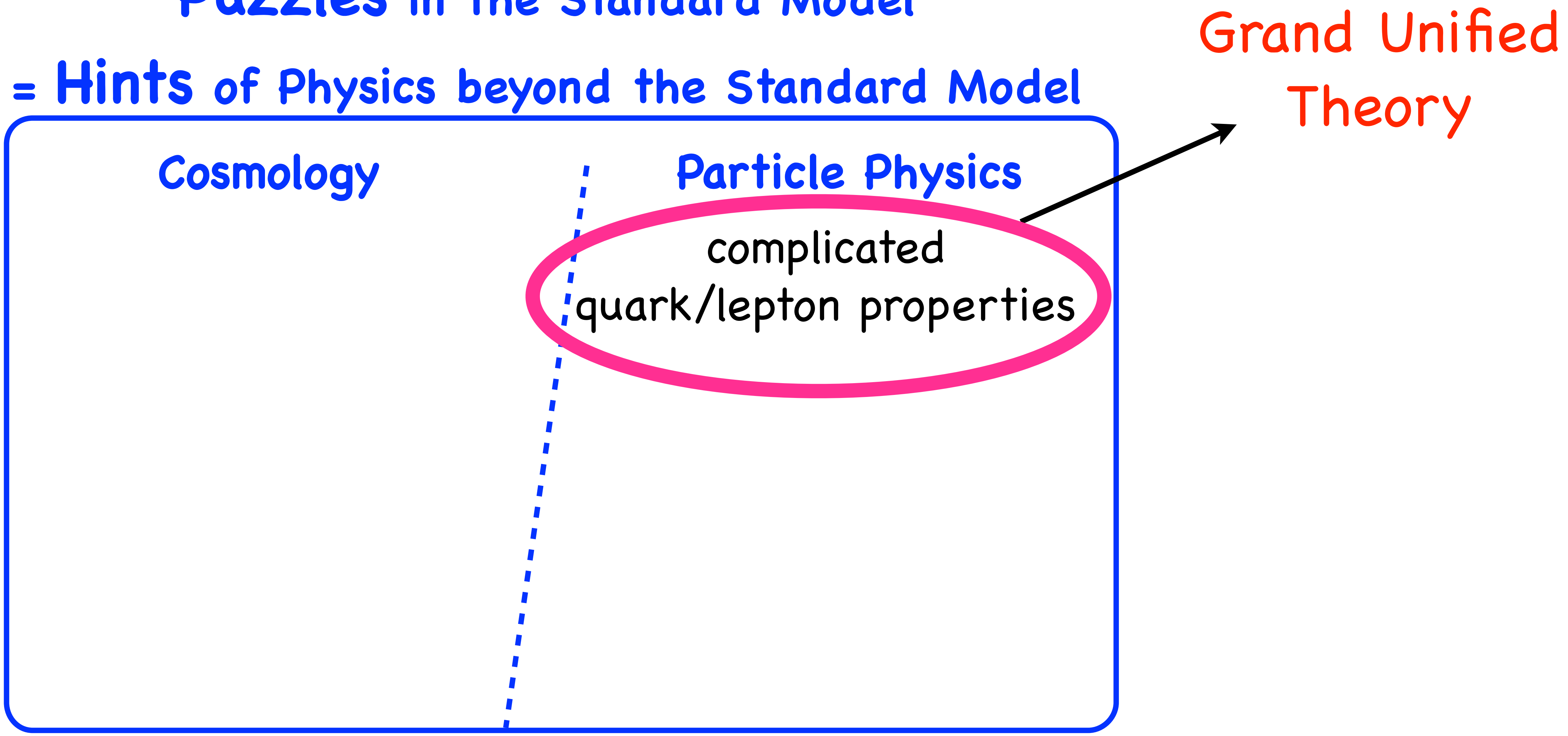
… beautifully unified into simple SU(5) representations !

[Georgi, Glashow 1974]

2.1. puzzles in SM = hints of BSM.

Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model



Cosmology

Particle Physics

complicated
quark/lepton properties

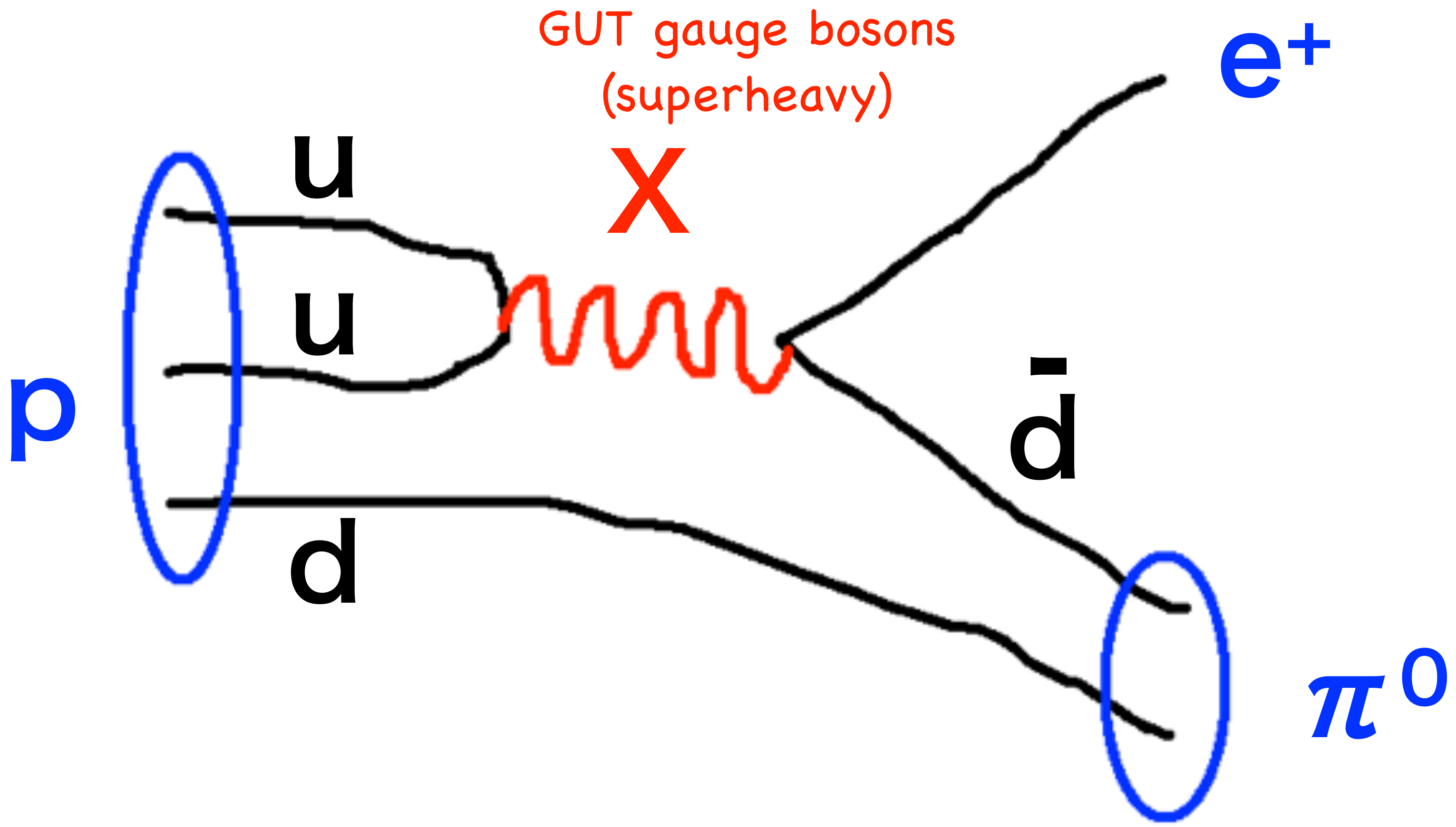
Grand Unified
Theory

Any prediction by Grand Unified Theorie (GUT) ?

Any prediction by Grand Unified Theorie (GUT) ?

prediction 1. If GUT is correct,.....

protons decay!



But the proton lifetime strongly depends on the GUT model.

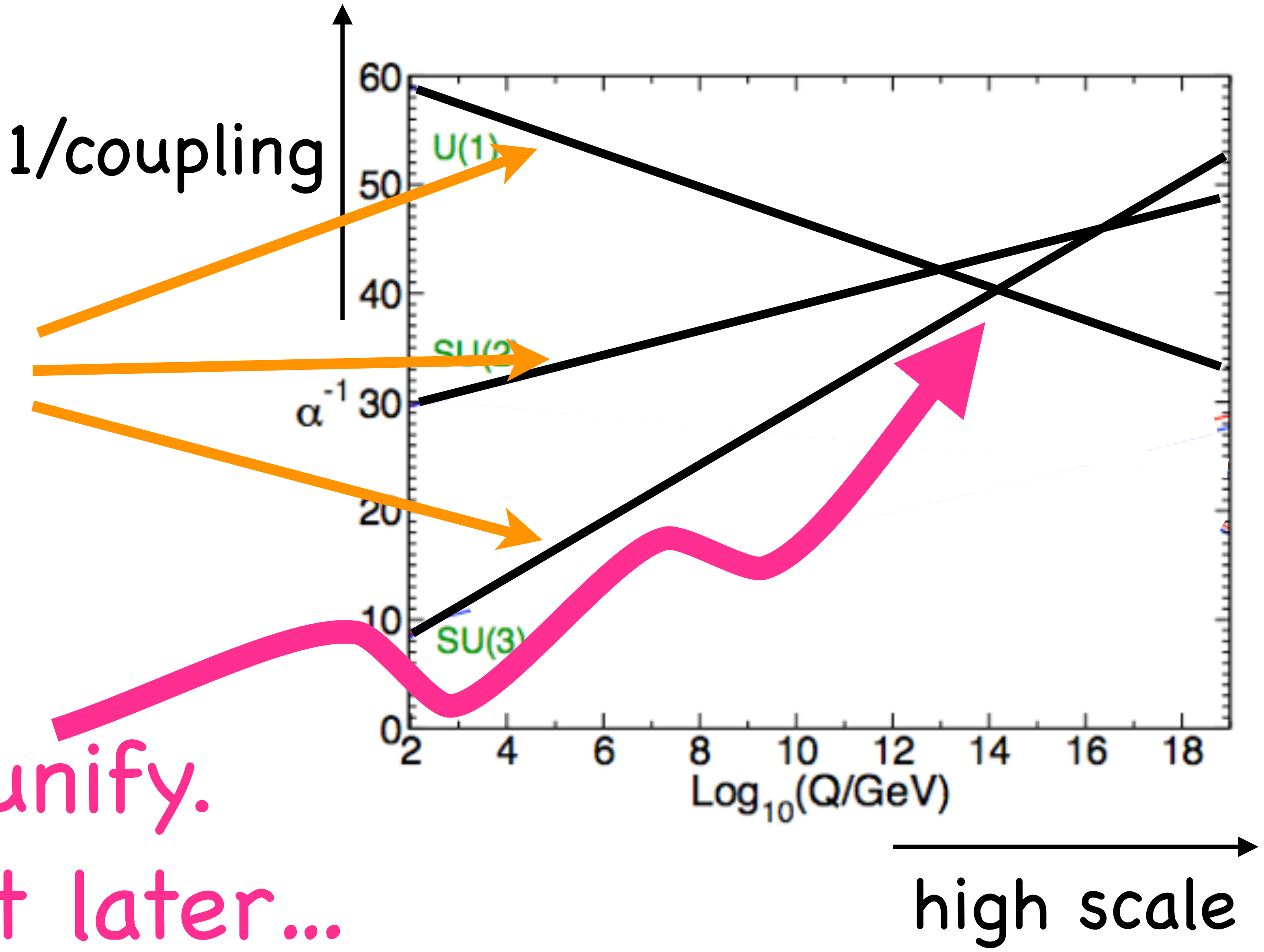
(Don't listen too much to theorists...😜)

Any prediction by Grand Unified Theorie (GUT) ?

prediction 2. If GUT is correct,.....

the three gauge couplings unify at high scale.

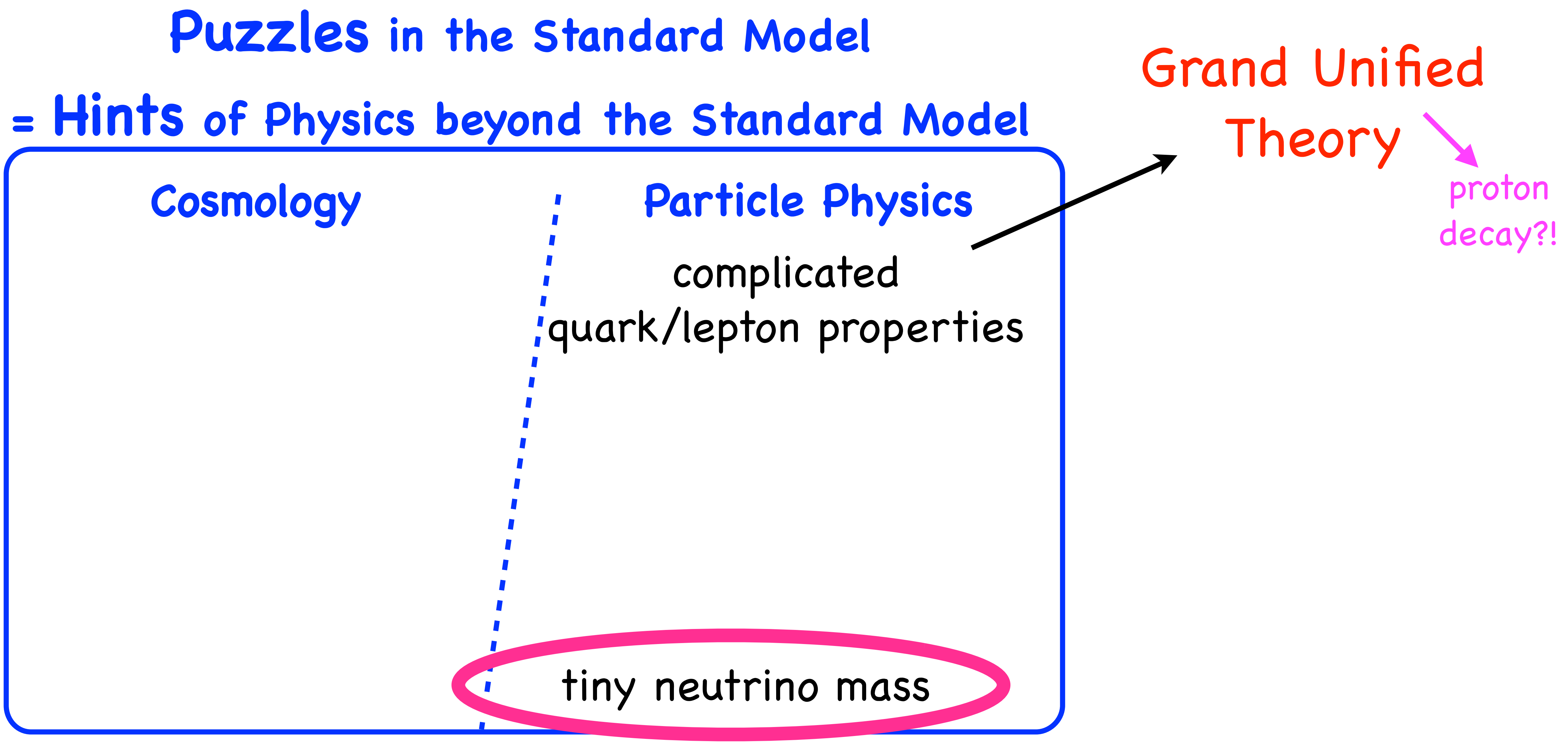
3 couplings



They don't really unify.

More on this point later...

2.1. puzzles in SM = hints of BSM.



Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model

Cosmology

Particle Physics

complicated
quark/lepton properties

tiny neutrino mass

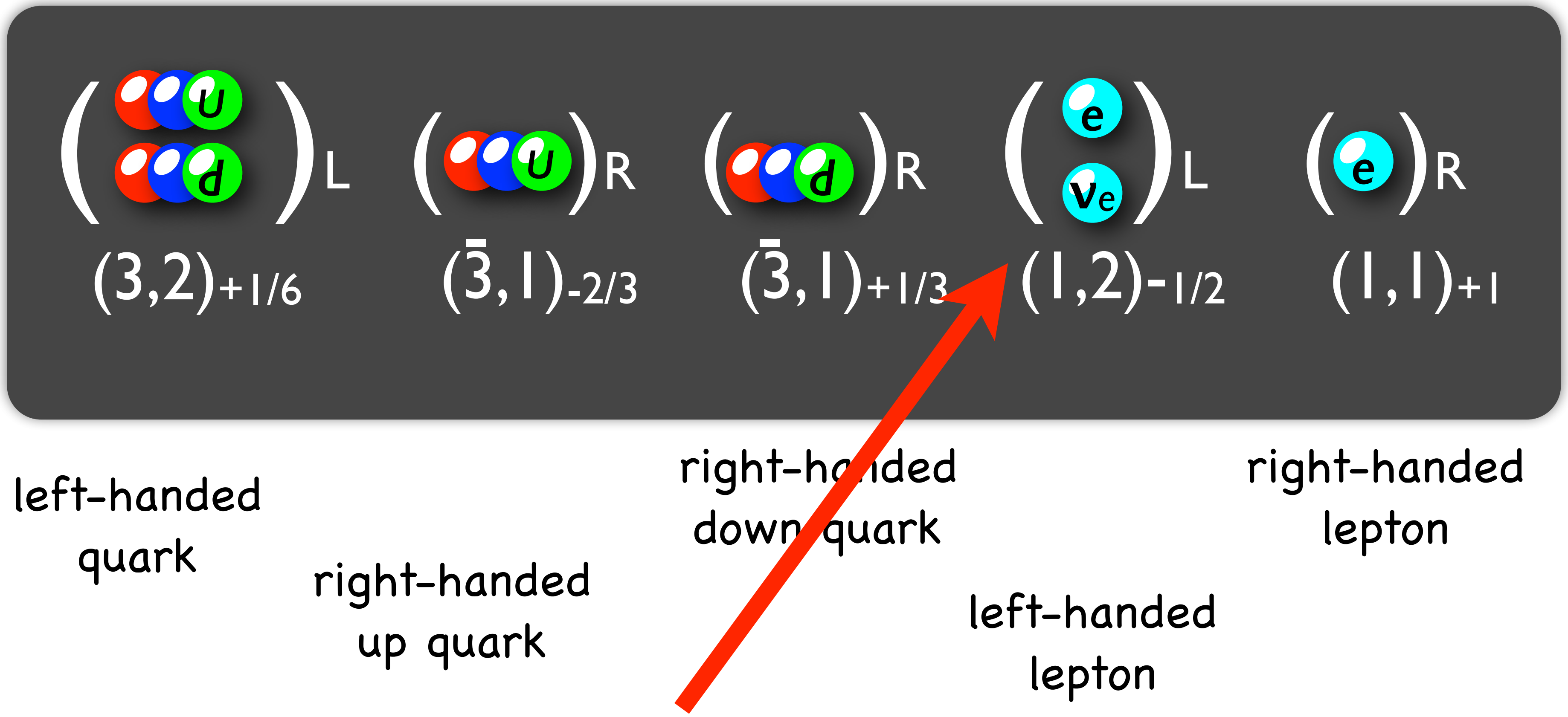
Grand Unified
Theory

proton
decay?!

Next,...

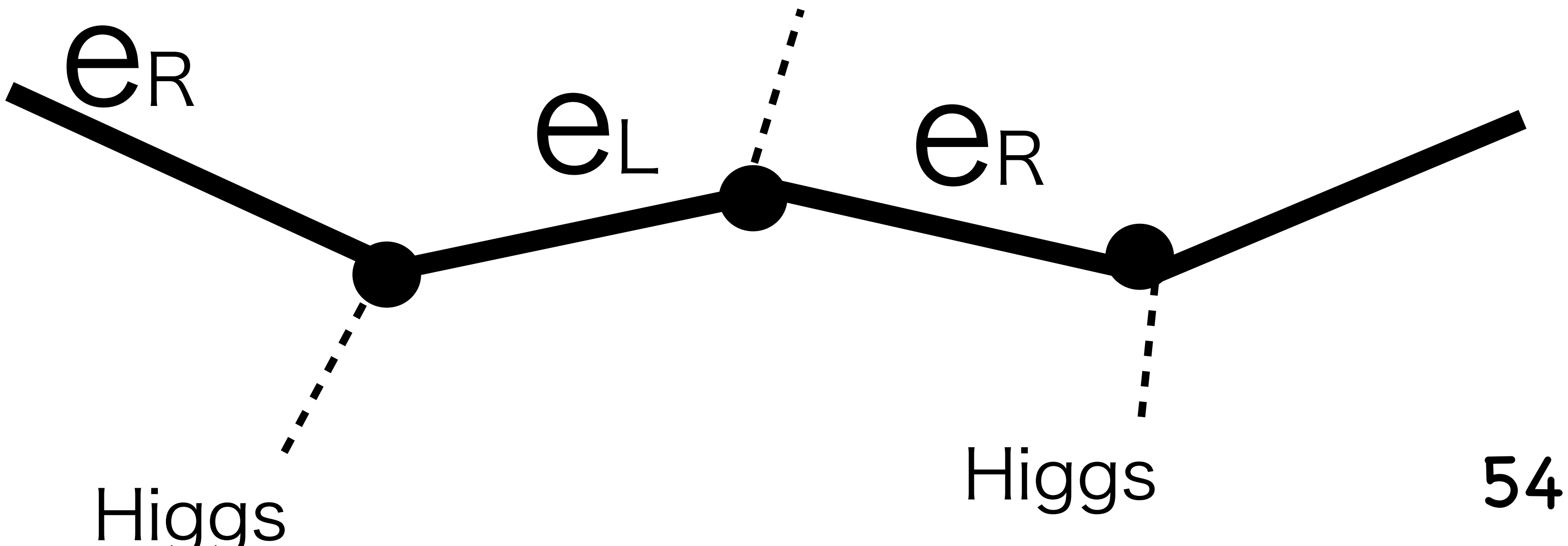
puzzle: neutrino masses

👉 cf. Lecture by Prof. Xing.



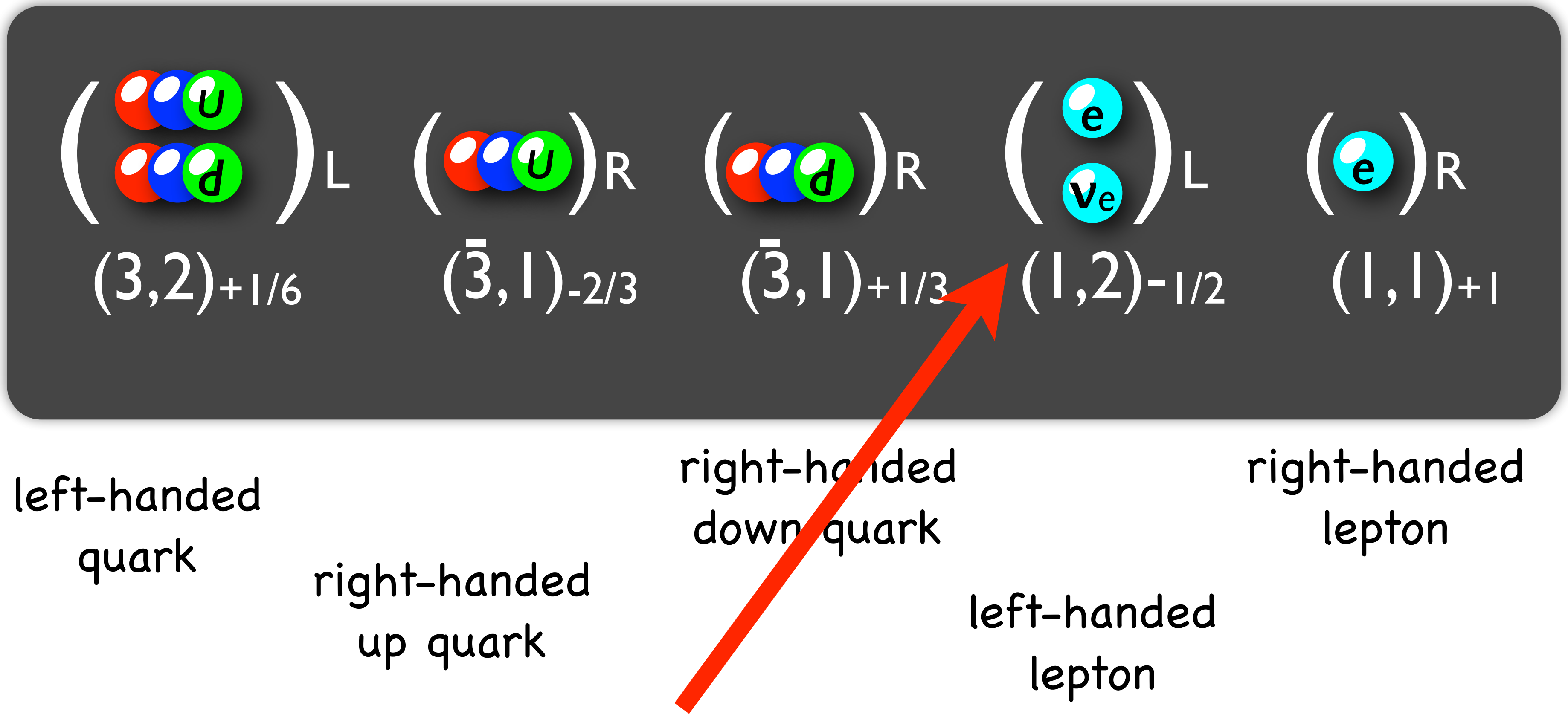
The neutrino has only left-handed component.

recall the case of electron...



puzzle: neutrino masses

☞ cf. Lecture by Prof. Xing.



left-handed quark

right-handed up quark

right-handed down quark

left-handed lepton

right-handed lepton

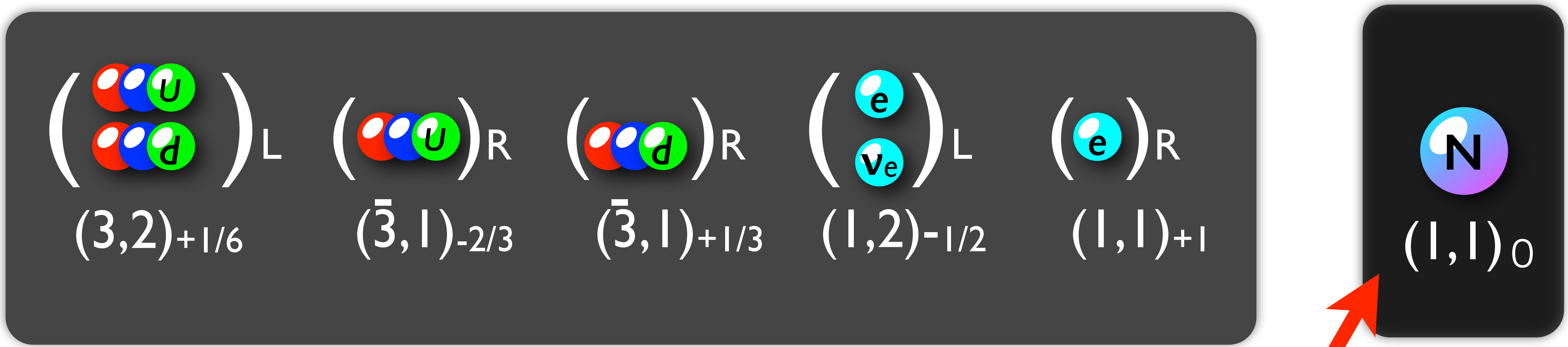
The neutrino has only left-handed component.

===> Massless !!

But the neutrino masses are confirmed by neutrino oscillations!

puzzle: neutrino masses

☞ cf. Lecture by Prof. Xing.



left-handed quark

right-handed up quark

right-handed down quark

left-handed lepton

right-handed lepton

right-handed neutrino

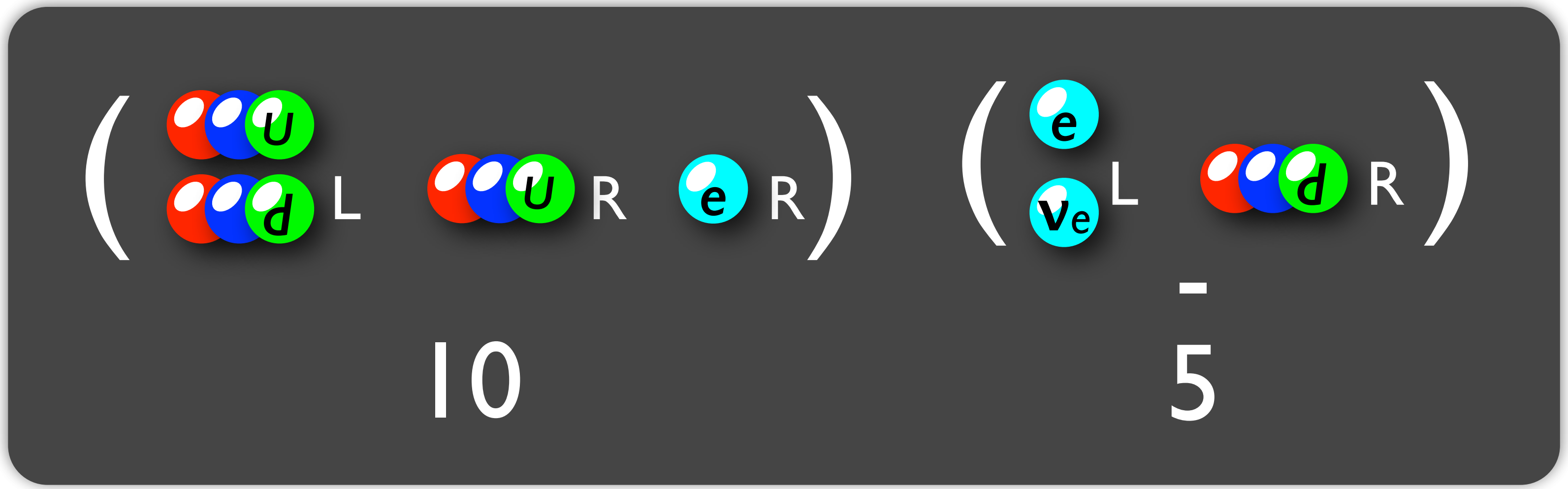
a solution is ...

To add a right-handed neutrino !!

The right-handed neutrino N plays a triple role.

The right-handed neutrino plays a triple role.

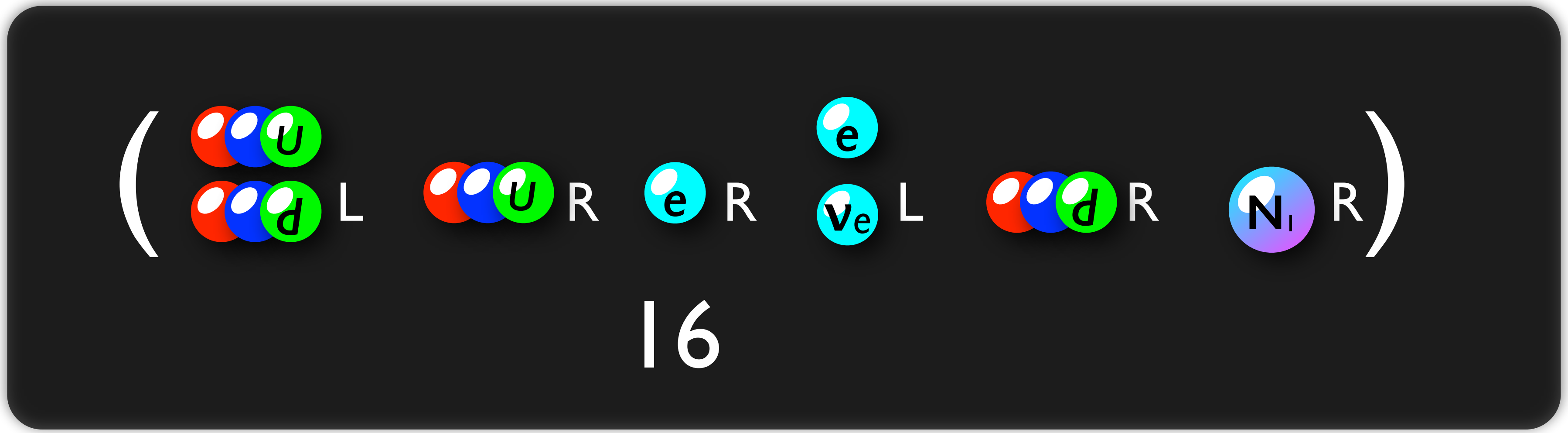
① quarks and leptons completely unified



SU(5)
GUT

+

=

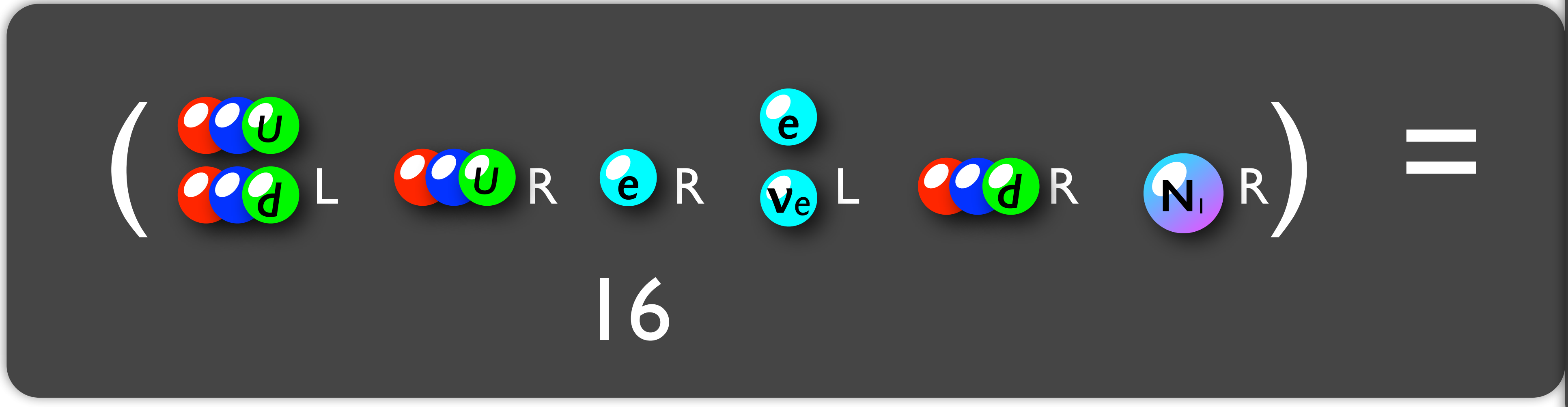


SO(10)
GUT

All quarks and leptons unified !

The right-handed neutrino N plays a triple role.

① quarks and leptons completely unified



$$= \left(\begin{matrix} u \\ d \end{matrix} \right)_L \quad u_R \quad e_R \quad \left(\begin{matrix} e \\ \nu_e \end{matrix} \right)_L \quad d_R \quad N_{I\,R} \Bigg) =$$

16

(↑↓ ↓↓↑)
(↑↓ ↓↑↓)
(↑↓ ↑↓↓)
(↓↑ ↓↓↑)
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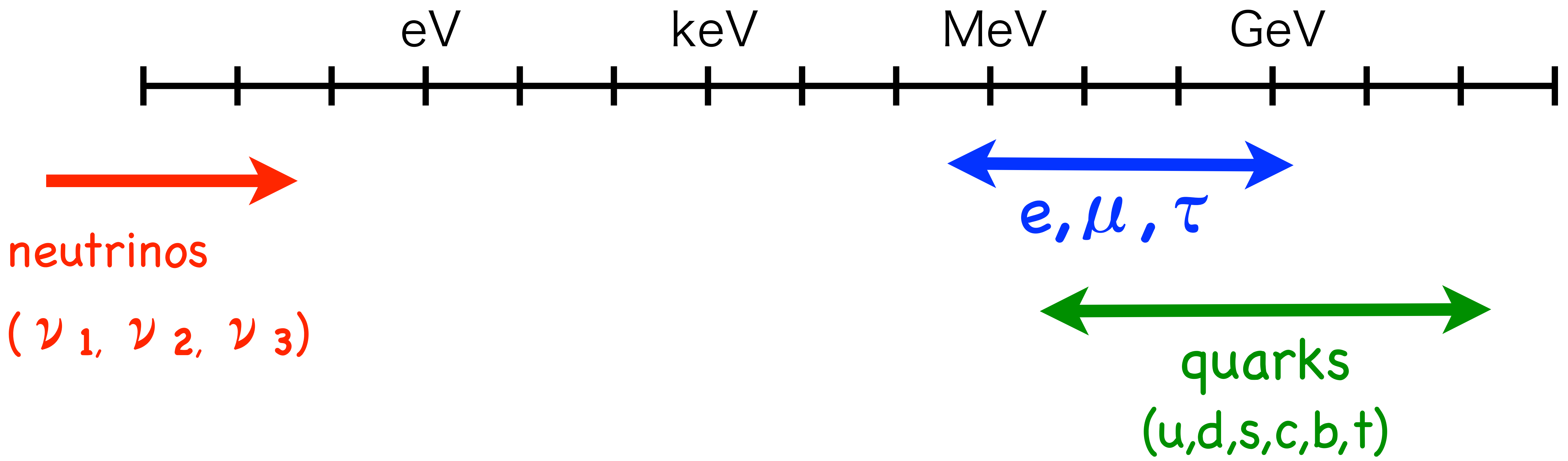
The right-handed neutrino plays a triple role.

② explains tiny neutrino mass

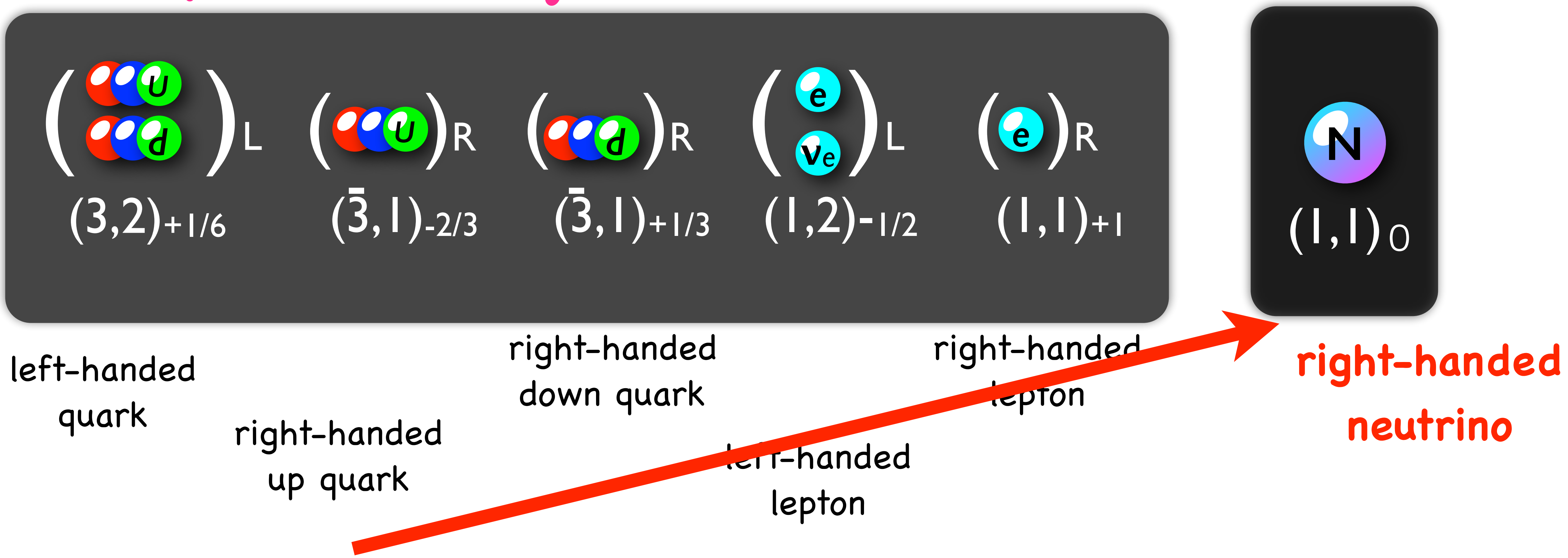
masses of quarks and leptons



・・・why neutrino masses are so small??

The right-handed neutrino plays a triple role.

② explains tiny neutrino mass



$(3,2)_{+1/6}$
left-handed quark

$(\bar{3},1)_{-2/3}$
right-handed up quark

$(\bar{3},1)_{+1/3}$
right-handed down quark

$(1,2)_{-1/2}$
left-handed lepton

$(1,1)_{+1}$
right-handed lepton

$(1,1)_0$
right-handed neutrino

This guy is special ..... singlet (feels none of three (EM, weak, and strong) forces.)

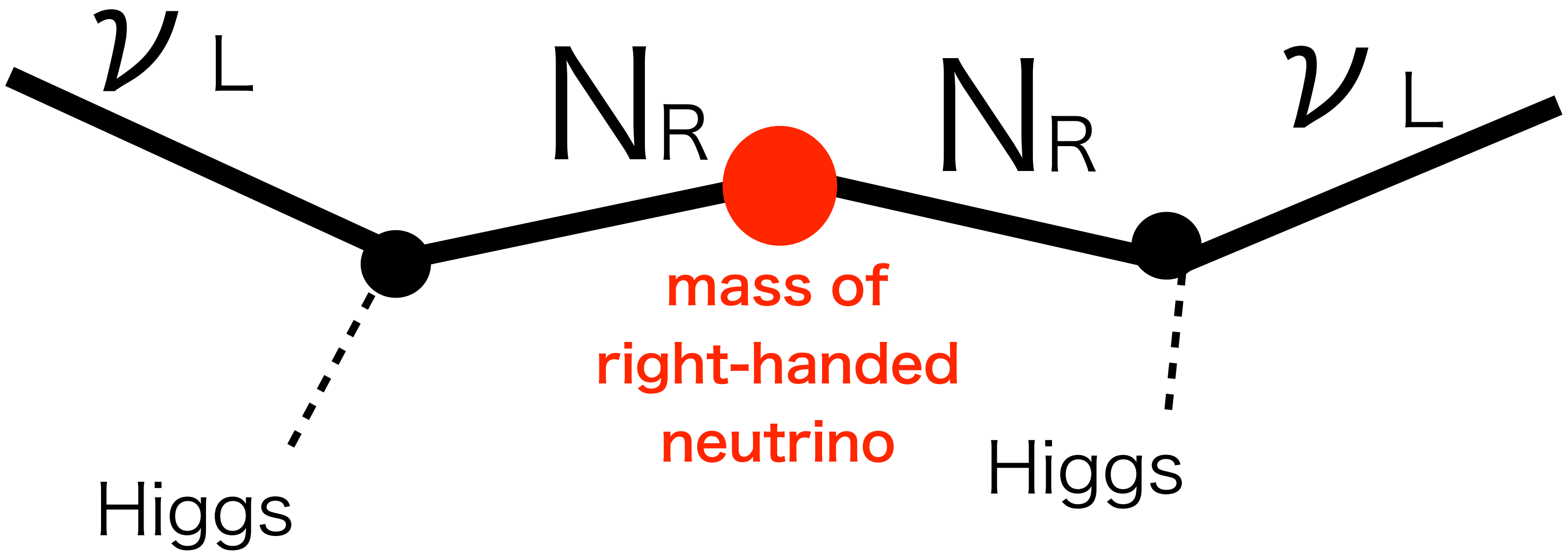
→ **it has no charge.**

→ **it can be its own anti-particle.**

→ **it can have a mass without Higgs.**

The right-handed neutrino N plays a triple role.

② explains tiny neutrino mass



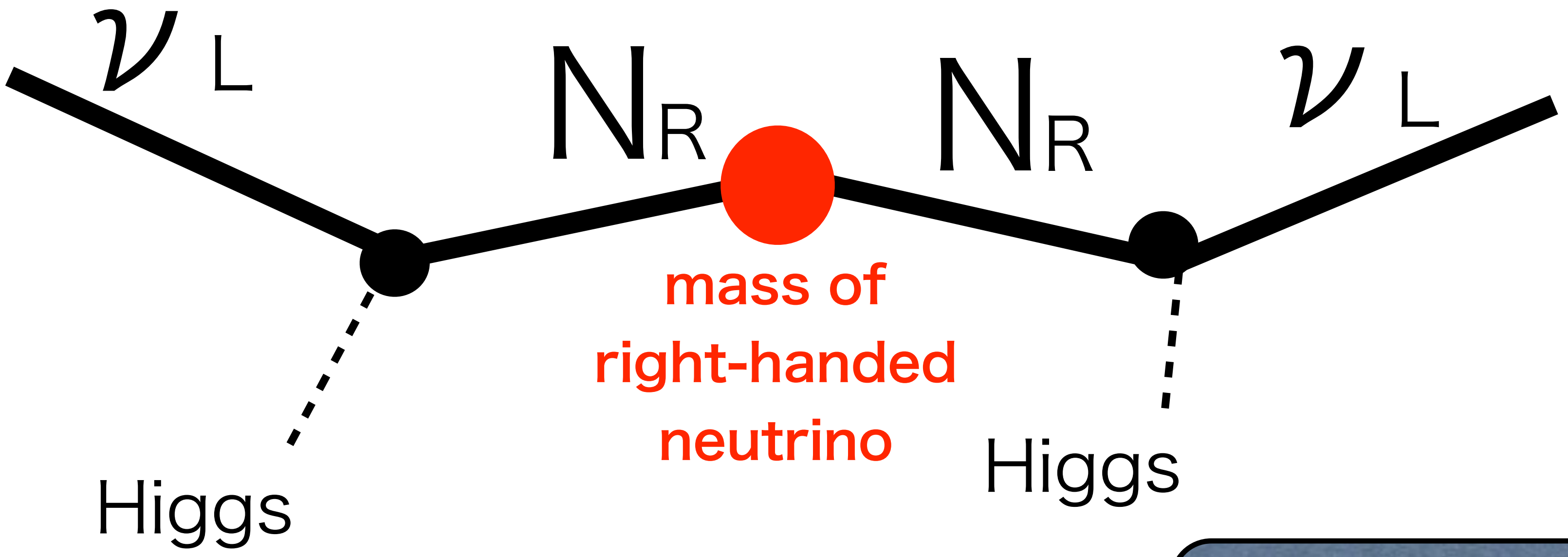
$$\text{Neutrino mass} = \frac{(\sim \text{other quark/lepton mass})^2}{\text{mass of right-handed neutrino}}$$

(seen e.g., by oscillation exp.)

heavy R.H. ν → small neutrino masses (“see-saw mechanism”)

The right-handed neutrino plays a **triple role.**

② explains **tiny** neutrino mass



$$\text{Neutrino mass} = \frac{(\sim \text{other quark/lepton mass})^2}{\text{mass of right-handed neutrino}}$$

0.01 eV

e.g. 100 GeV

e.g. 10^{15} GeV

heavy R.H. ν → small neutrino masses (“see-saw mechanism”)

The right-handed neutrino N plays a triple role.

③ explains matter > anti-matter

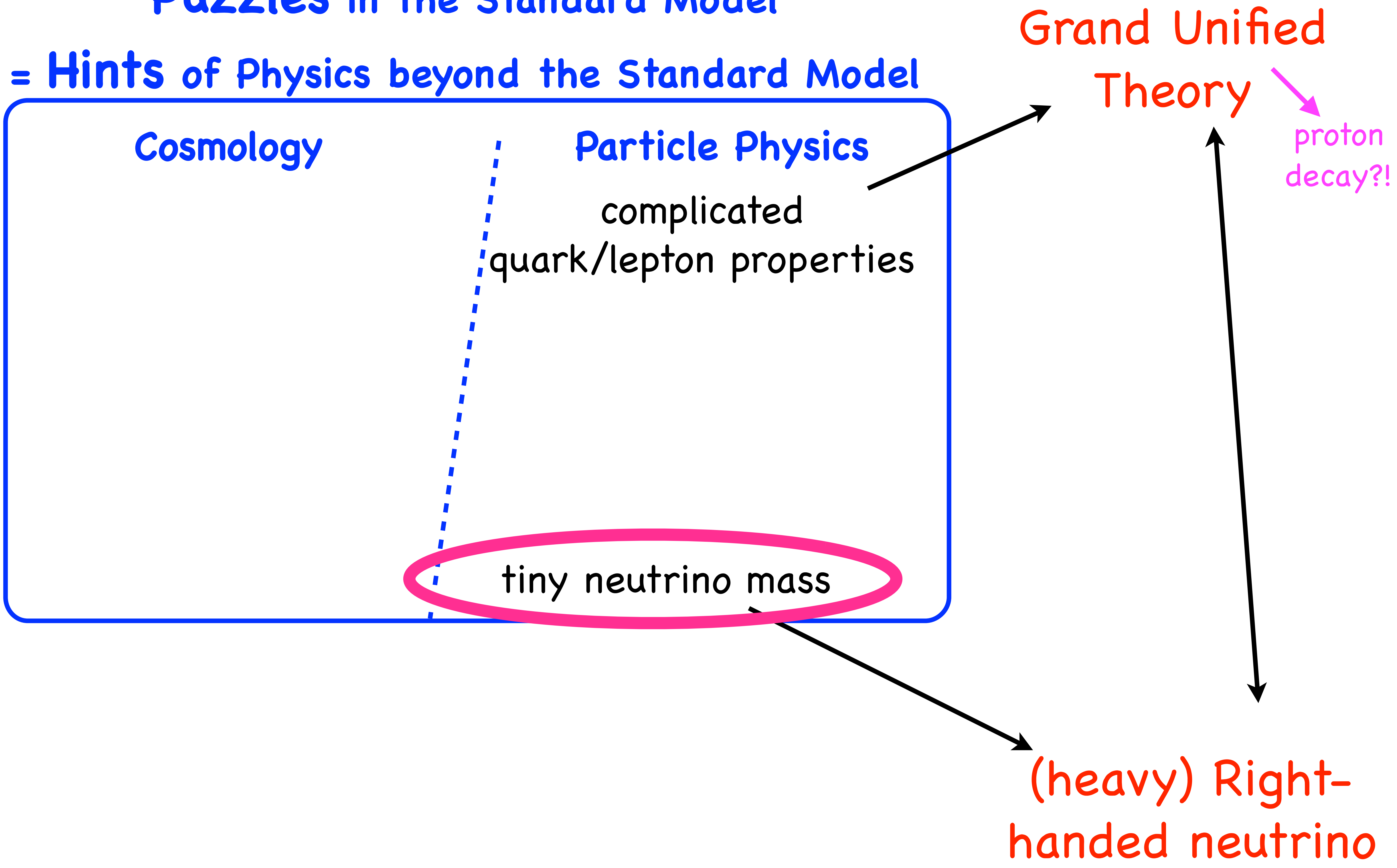
asymmetry of the universe.

-----> **Leptogenesis !!**

more on this later ...

Puzzles in the Standard Model

= **Hints** of Physics beyond the Standard Model



Cosmology

Particle Physics

complicated
quark/lepton properties

tiny neutrino mass

Grand Unified Theory

proton decay?!

(heavy) Right-handed neutrino

- to be continued…