Particle physics: vision

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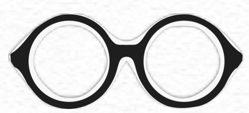
LHC days in Split, 2022

Talking about vision



Quantum Mechanics days:

Max Born to Heisenberg:
too bad we finished physics

Sixties:

Regge poles and bootstrap
end of fundamental physics
end of QFT

Today
Physics alive and kicking
SM = QFT in full glory

No idea what
future will bring

Critical essay of SM
(and BSM)

SM: Problems?

The only problem:
no real problem

SM - gauge theory of weak interaction

Glashow ‘61

Weinberg ‘67

Salam ‘68

’t Hooft ‘72

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SM - theory of the origin of mass

Brout, Englert ‘64

Higgs ‘64

Weinberg ‘67

GIM ‘69

Today a high precision theory

SM as QFT

Masses from Higgs mechanism

Gauge bosons: $M_W = \frac{g}{2} v$ g= gauge coupling

Fermions: $m_f = y_f\, v$ y_f = Yukawa coupling

Higgs: $m_h = \lambda\, v$ λ = quartic self-coupling

v = Higgs field vev

Often argued: fermion mass protected - Higgs mass not -
against large scales (cut-off)

After all, fermion mass ~ chiral symmetry

Wrong

Renormalisation:

$$y_f = y_f^0 \left[1 + \left(\frac{\alpha}{4\pi} + \frac{(y_f^0)^2}{16\pi^2} \right) \ln \frac{\Lambda}{v} \right]$$

$$\lambda = \lambda^0 + \frac{g^4}{16\pi^2} \ln \frac{\Lambda}{v} + \ldots$$

Yukawa protected more - but nothing to do with large scales

small Yukawa = stable against loops
small λ not - but λ is not small ($m_h \simeq M_W$)

You could worry about instability at astronomical scales
- but these are LHC days: don't worry, be happy :)

Predictions

Work with y_f, λ

↓

$$\Gamma(h \to \bar{f} f) \propto y_f^2 \, m_h \propto \left(\frac{m_f}{M_W} \right)^2 \; m_h$$

$$A(h + h \to h + h) \propto \lambda^2 \propto \left(\frac{m_h}{M_W} \right)^2$$

SM perfectly consistent predictive theory -
up to powers of M_W/Λ

Higgs mass equally `predicted' as other masses

Hierarchy problem = problem of scale?

$$v^2 = (v^0)^2 + \Lambda^2$$

- Why is weak scale much smaller than Planck scale?

$$G_N = \frac{1}{M_{Pl}^2} = \frac{g^2}{M_F^2} \qquad g \ll 1 \Longrightarrow M_F \ll M_{Pl}$$

Glashow '85

ADD '98

- How to keep v small in perturbation theory?

Low E supersymmetry -> makes first question far more dramatic: now another scale too much smaller than Planck scale?

Questions - **not problems -** just renormalise v

Argument → new physics around the corner

Problem: corner not well defined

Strong CP violation in SM

QCD - extra interaction $\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a} \propto \theta \vec{E}\vec{B}$

violates both P and T(CP)

CP violating physical term

$$\bar{\theta} = \theta + \arg\det M_q$$

neutron electric dipole moment $(\bar{\theta})_{exp} \lesssim 10^{-10}$

Again, perfectly consistent in SM:
experiments decides

In perfect analogy with CKM determined by experiment

Question of naturalness?

perturbation theory
of the strong CP parameter

Ellis, Gaillard '79

$$(\bar{\theta})_{loop} \simeq 10^{-19}$$

$$(\bar{\theta})_{inf} \simeq (\frac{\alpha}{2\pi}\frac{m_q}{M_W})^6 \ln\frac{\Lambda_{cutoff}}{\Lambda_{QCD}}$$

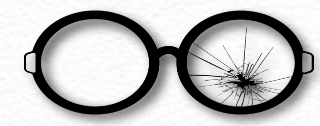
$$\Lambda_{cutoff} = M_{Pl} \Rightarrow (\bar{\theta})_{inf} \simeq 10^{-19}$$

No strong CP problem whatsoever in SM

Experiment - as usual - will decide the fate

Simple: measure as many dipole moments.
If agree with the value of $\bar{\theta}$ - SM is complete

Personal belief (vision?)



Study nature through theories of natural phenomena

If no true problem, follow a fundamental theory
with clear predictions of new physics

Example: SM arose from a desire to have a more
fundamental theory of weak interaction

BSM theories

- LR symmetric theory
- grand unified theory

True theory in a sense of Feynman

Make a guess

say, gauge principle

↓

Minimal formulation

based on guess

↓

Leave it

so we can compute predictions

↓

Experiment

Unambiguous predictions = self-contained theory

The crux of it all

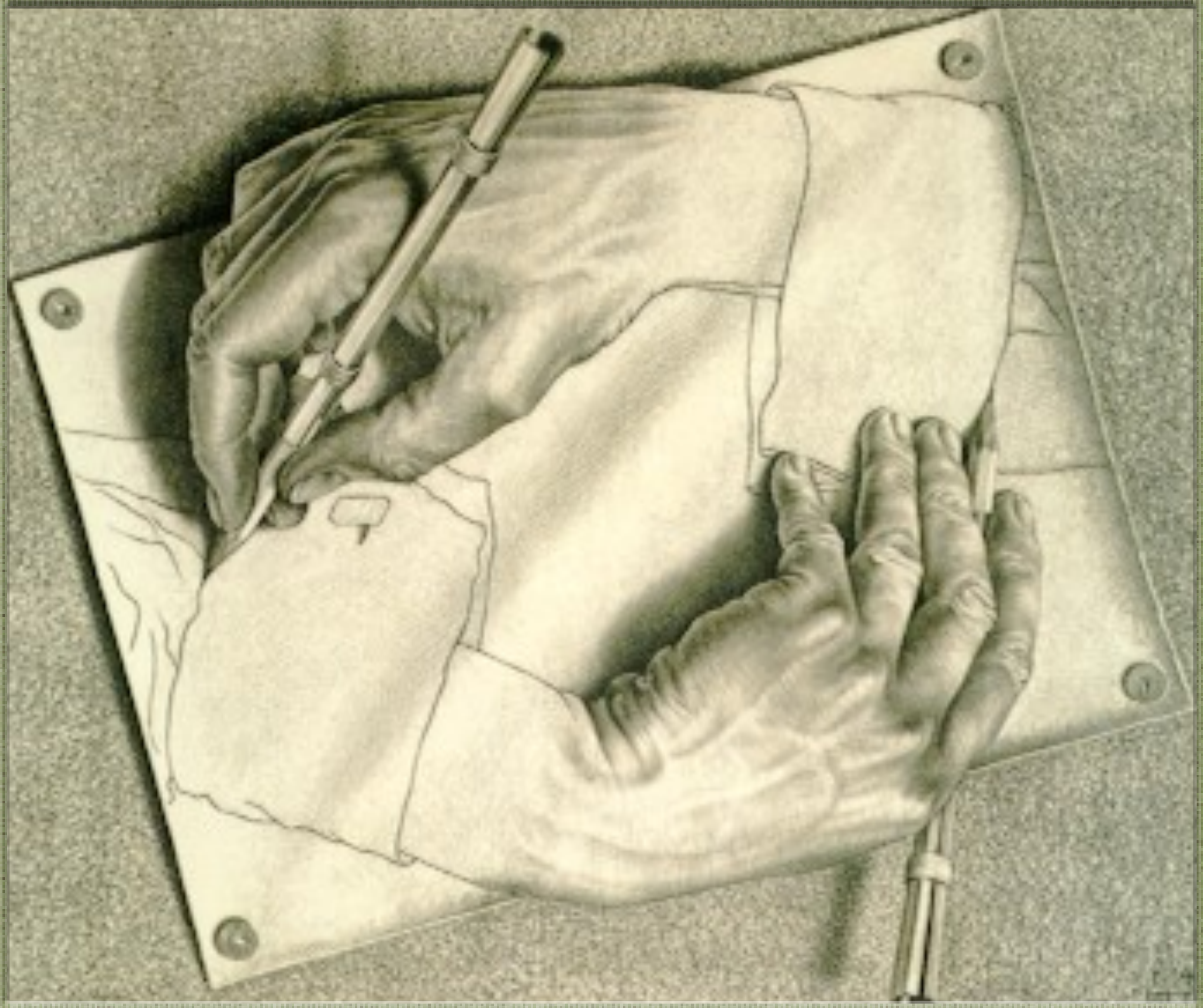
What is at the essence of the SM?

- Gauge principle + SSB
- Parity violation

} Deeply connected

Parity and SM

- and beyond



Maximal parity violation -> SM

Lee, Yang '56

Wu et al '56

↓

V-A — Marshak, Sudarshan '57

↓

"V-A was the key" — Weinberg '09

Gauge ew theory

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \qquad d_R$$

↓

fermions (and gauge bosons) massless

need a Higgs doublet - and it suffices → gives mass to all: W, Z, Higgs, charged fermions

but, neutrino massless

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

P violation: blessing or curse?

LR symmetry → massive neutrino

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

Left-Right Symmetric Model

Mohapatra, Pati, Salam '74

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Mohapatra, GS '75

GS '79

neutrino is massive

$$q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \ell_L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \longleftrightarrow \quad \ell_R \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_R \quad q_R \equiv \begin{pmatrix} u \\ d \end{pmatrix}_R$$

W_L W_R

$$M_{W_R} \gg M_{W_L}$$

Neutrino mass long before experiment

Neutrino = Majorana

Minkowski '77

Mohapatra, GS '79

N = ν_R

$$M_\nu = -M_D^T \frac{1}{M_N} M_D$$

$$M_N \propto M_{W_R}$$

small neutrino mass related to
near maximal parity violation

Neutrino = anti neutrino?

Majorana '37

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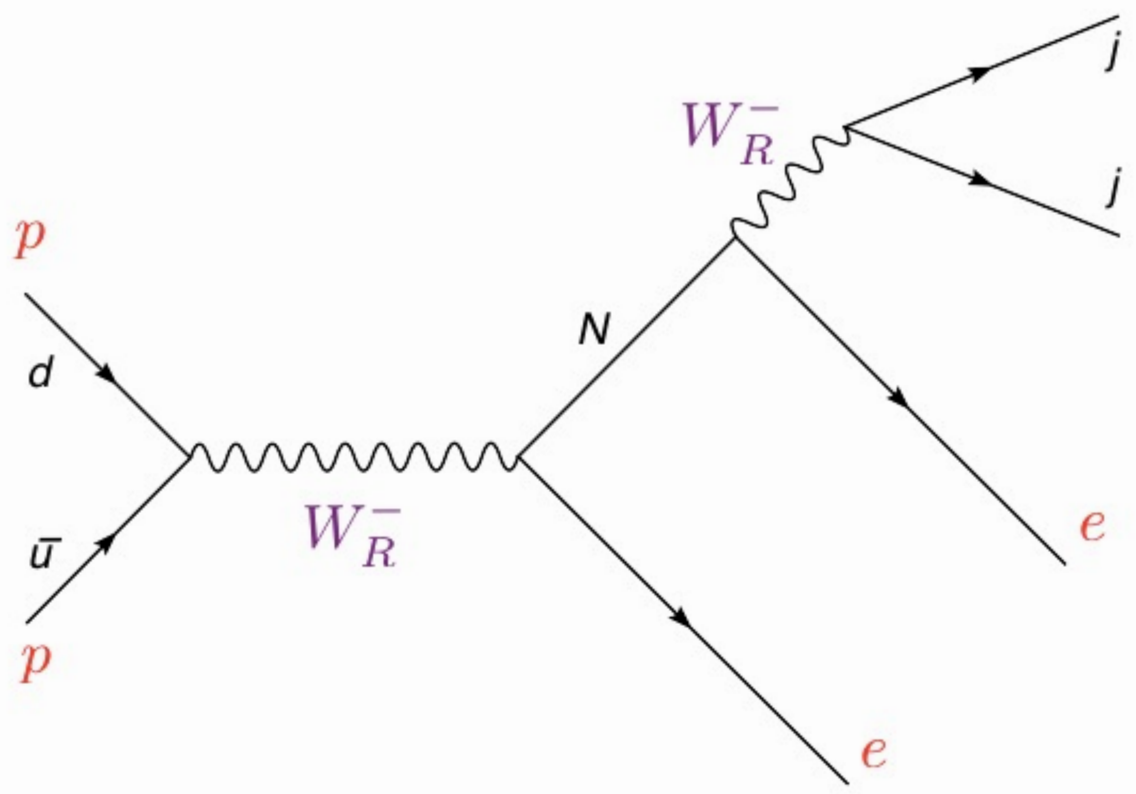
Lepton Number Violation (LNV)

- neutrinoless double beta decay — Furry '38
- hadron colliders — Keung, GS '83

From Majorana to LHC

Keung, GS 1983

- direct probe of Majorana nature:



50% lepton
50 % anti-leptons

- Parity restoration

- Lepton Number Violation: same sign leptons

Untangling seesaw

Nemevsek, GS, Tello '12

GS, Tello '16 -'20

$$M_\nu = -M_D^T \frac{1}{M_N} M_D$$

LR = C $\quad M_D^T = M_D \quad \Rightarrow \quad M_D = i M_N \sqrt{M_N^{-1} M_\nu}.$

$$Y_D = M_D / v$$

compare with naive seesaw:

$$M_D = \sqrt{m_N}\, \mathcal{O} \sqrt{M_\nu}$$

O-arbitrary complex orthogonal

Minimal theory

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\Gamma(N_i \to W \ell_j) \propto V_{ij}^2 m_{\nu_i} \frac{m_{N_i}^2}{M_W^2} \quad \Longleftrightarrow \quad \Gamma(h \to f\bar{f}) \propto m_h (m_f/M_W)^2$$

Weinberg ’67

Nemevsek, GS, Tello ‘12 GS, Tello ’16- ‘20

plethora of other processes, all depend on M_D and/or M_N

GS, Tello ’18

Maiezza, Nemevsek, Nesti, Tello, Vasquez,…

LRSM
self-contained, predictive theory of neutrino mass

- Provides rationale for RH neutrino N

- N - physical particle produced through gauge interactions

- Seesaw untangled

LRSM -> seesaw

- understanding P violation
- gauge structure: new currents
- LNV@colliders, direct `Majoranity'
- see-saw: ν_R

SM -> neutral current

- Electroweak unification
- gauge structure
- W-Z mass ratio
- neutral currents: Z boson

Just in order not to have predictions

Scale of LR?

Need input from experiment: CDF?

↓

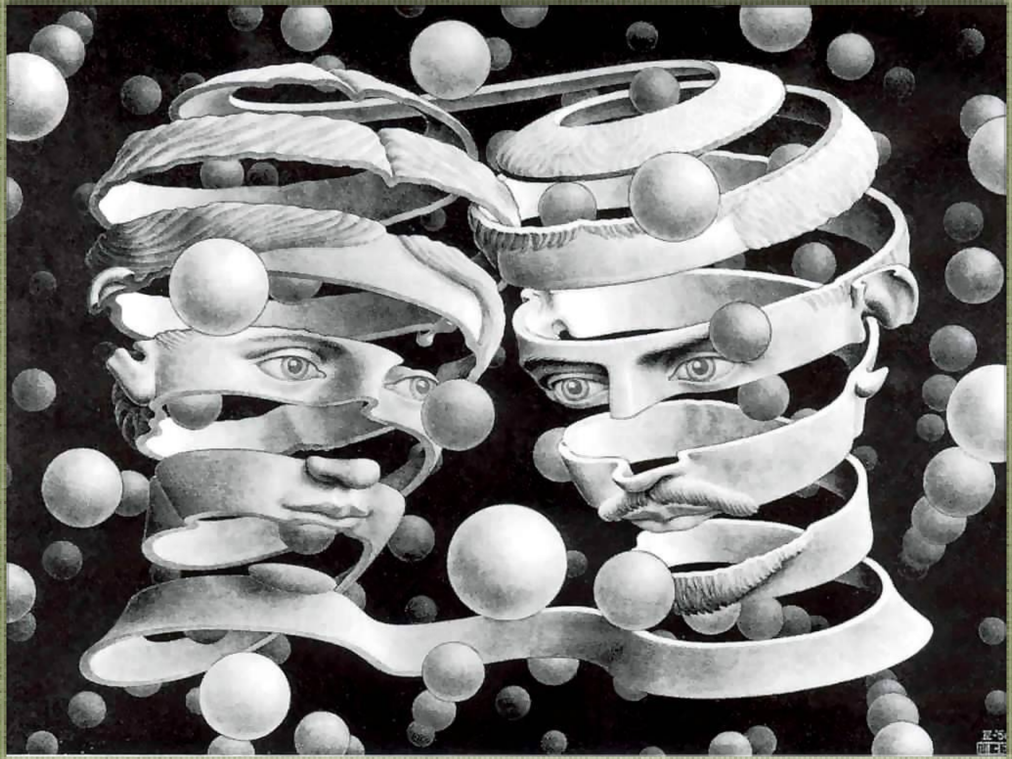
$$M_R \lesssim 10\, TeV$$

Neutrinoless double beta: e = RH

↓

$$M_R \lesssim 10\, TeV$$

Grand unification



Unification of SM forces + charge quantisation

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- Magnetic monopoles

- Proton decay

Minimal SU(5)

Georgi, Glashow '74

Double failure:

Talk by Zantedeschi

- Gauge couplings do not unify
- Neutrino massless

Minimal SU(5): proton decay

Quark - lepton unification: $M_d = M_e^T$ wrong

↓

All p decay branching ratios given by: V_{CKM}

Mohapatra '79

Beautiful theory killed by ugly facts of nature?

Realistic extensions -> new `light' states, LHC?

Dorsner, Fileviez Perez '05

Bajc, GS '06

Talk by Zantedeschi

p decay rates not predictable

Minimal SO(10)

Georgi '74

Fritzsch, Minkowski '74

$$\Psi_{16} = \begin{pmatrix} u \\ u \\ u \\ \nu \\ d \\ d \\ d \\ e \\ e^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ u^c \\ u^c \\ u^c \end{pmatrix}$$

Generation unified ➔ (heavy) RH neutrino

C = finite SO(10) transformation

> 40 years of gospel:
desert all the way to $M_I \simeq 10^{11}\,GeV$

del Aguila, Ibanez '80

Rizzo, GS '80

SO(10)@LHC?

Preda GS, Zantedeschi ‘22

↓

Talk by Zantedeschi

New light states, possibly at LHC

↓

Light weak triplets, modify W-mass: CDF?

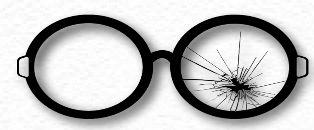
But no theory of proton decay - no true GUT

GUT -> proton decay

- unification of forces
- charge quantization: monopoles
- fermion mass relations
- proton decay: X boson

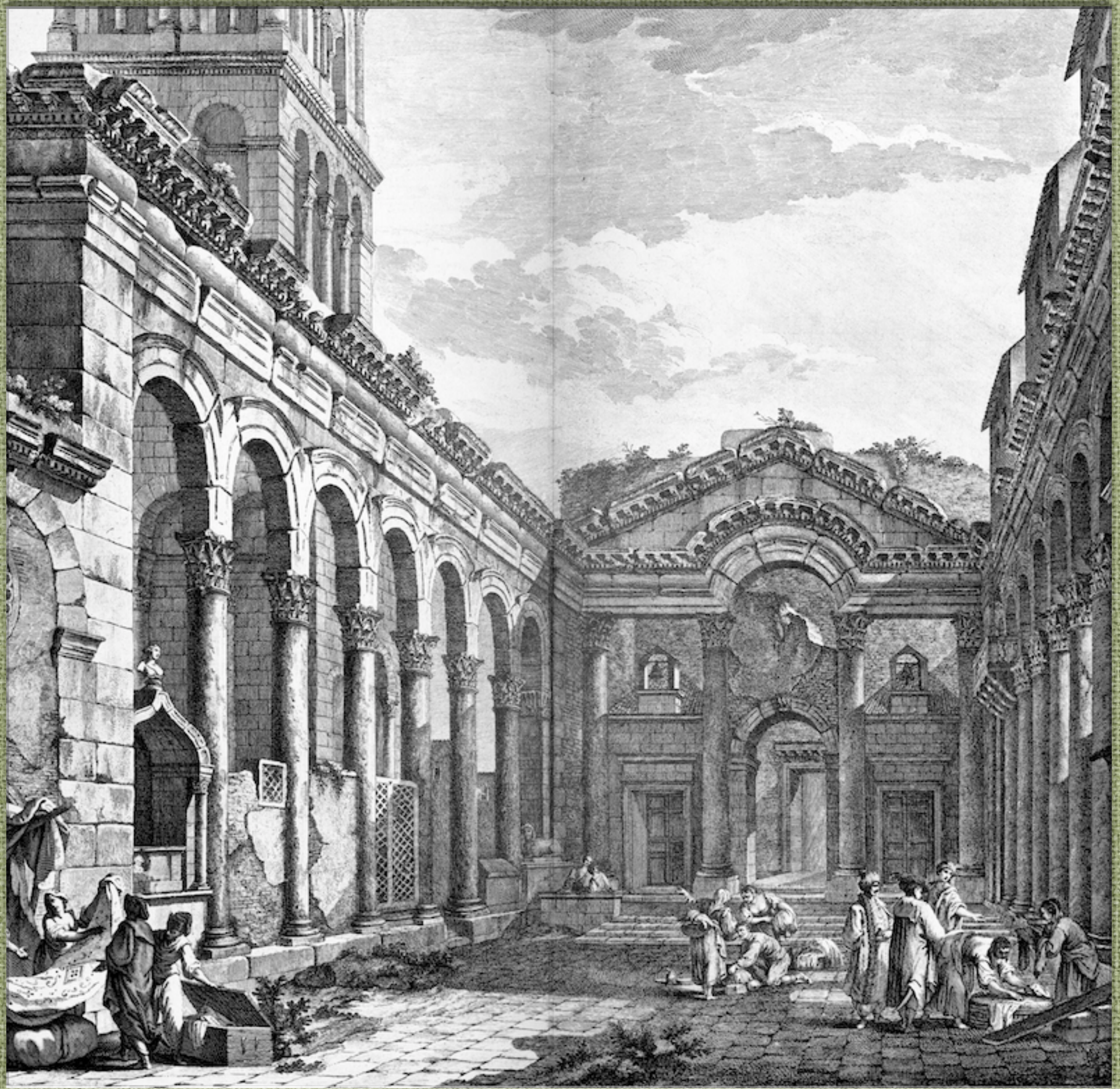
Message

No idea what future will bring



Keep testing SM

Study & probe motivated physical theories



Thank you

SM: incomplete?

- Lacks DM candidate?

Not the task of SM. In principle even BH.
Could come from high energy $E \gg M_W$

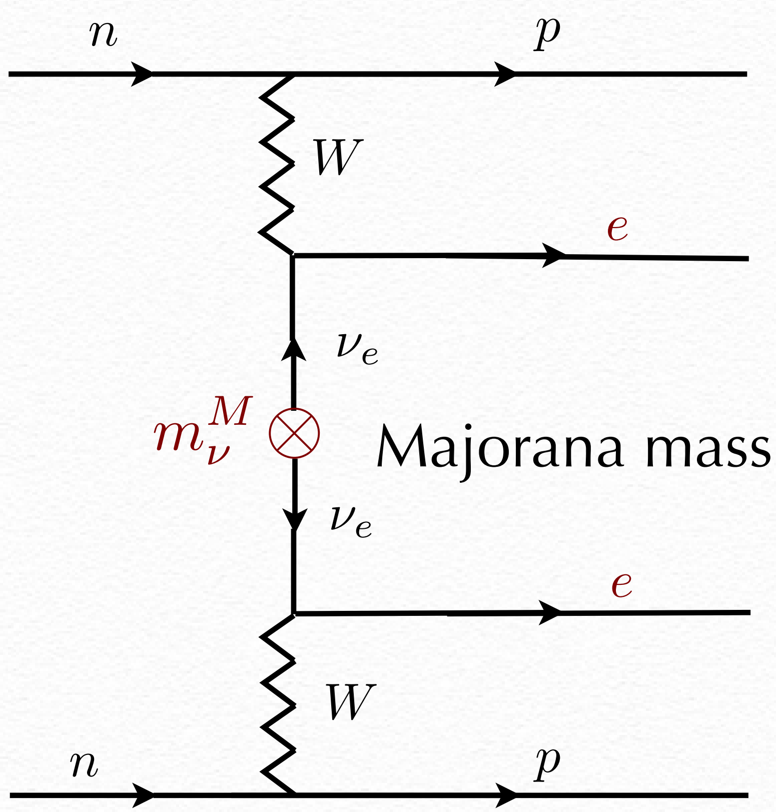
- Genesis not explained?

Baryo and lepto genesis.
Inflation itself could generate B&L.
Could come from $E \gg M_W$

- Neutrino mass

The only true incompleteness.
Could come from $E \gg M_W$

Neutrino-less double beta decay



$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \simeq G_F^2\ 10^{-8}\, GeV^{-1}$$

$$(p \simeq 100\, MeV)$$

$$\tau_{0\nu 2\beta} \gtrsim 10^{26} yr \quad \rightarrow \quad m_\nu^M \lesssim 0.3\, eV$$

GERDA 2021

Both e = LH

New physics involved?

Feinberg, Goldhaber '59

Pontecorvo '64

Mohapatra, GS '79

d=9 operator

$$\tau_{0\nu 2\beta} \gtrsim 10^{26} yr$$

$$\frac{1}{\Lambda^5}\, n\, n\, p\, p\, e\, e \quad \rightarrow \quad \Lambda \gtrsim 3\, TeV$$ LHC energies

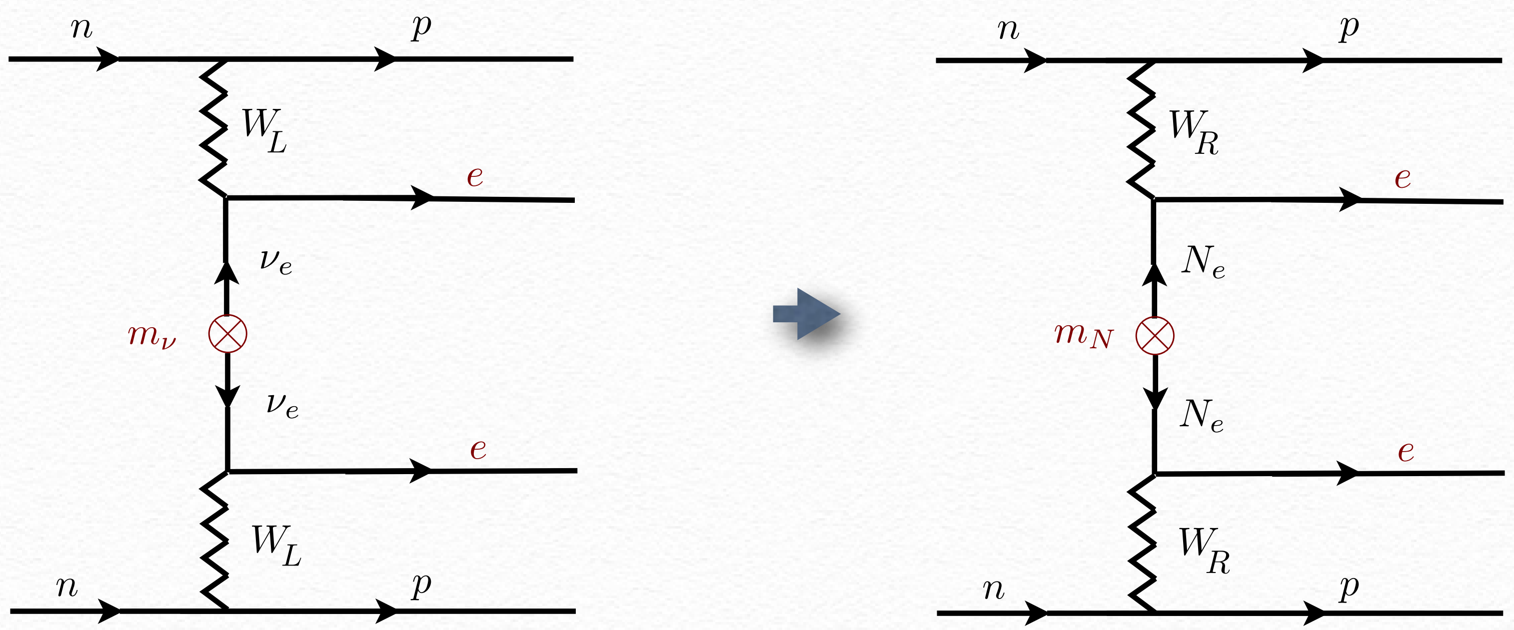
If e = RH → New physics at accessible energies

Compare with p decay

$$\frac{1}{\Lambda^2}\, q\, q\, q\, e \quad \rightarrow \quad \Lambda \gtrsim 10^{15} GeV$$

$$\tau_p \gtrsim 10^{34} yr$$

Neutrinoless double beta decay



Mohapatra, GS '79

Tello et al '11

Quark sector

Determine RH mixings ~ 40 years challenge

$$(V_R)_{ij} \simeq (V_L)_{ij} - i\epsilon \frac{(V_L)_{ik}(V_L^\dagger m_u V_L)_{kj}}{m_{d_k} + m_{d_j}}$$

GS, Tello 1408.3835 (hep-ph)

GS, Tello 1502.05704 (hep-ph)

$\epsilon \ll 1$ - not predicted

⬇

$$\theta_R \simeq \theta_L$$

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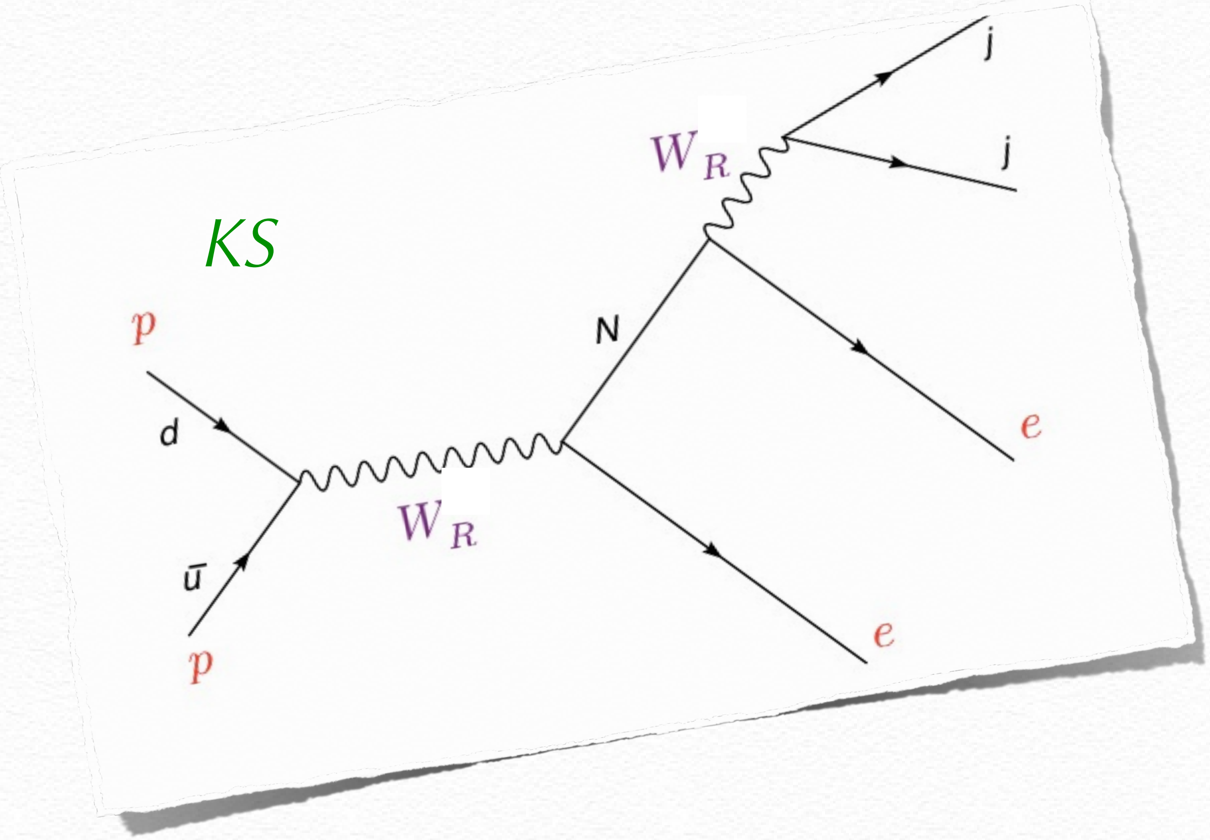
justifies quoted limits on M_R
- assume same L & R mixings

LR@LHC

ATLAS. CMS

$$M_{W_R} \gtrsim 5\, TeV$$



neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than

Also $M_{W_R} \gtrsim 5\, TeV$ from $W_R \to j + j$

LHC reach

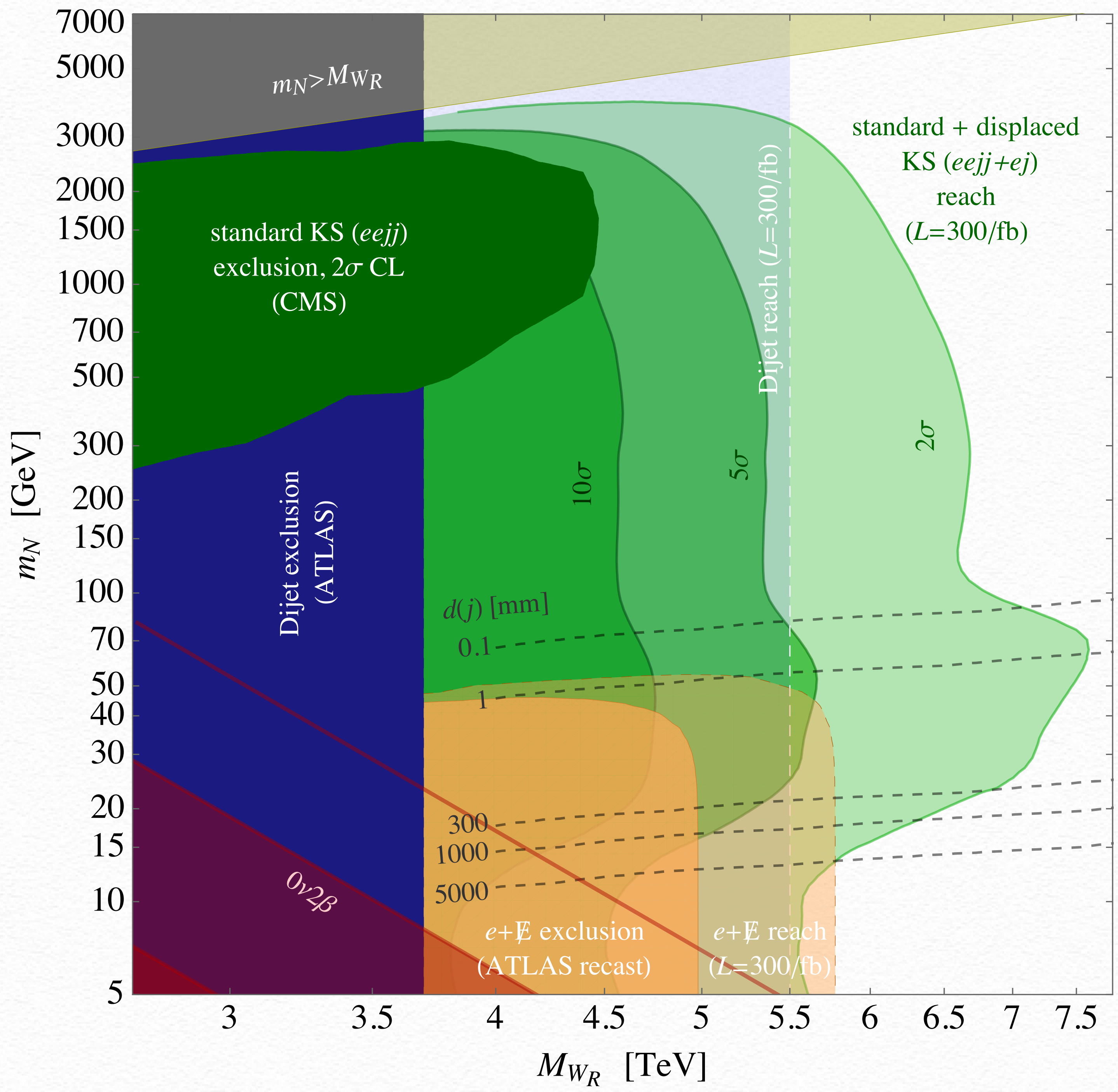
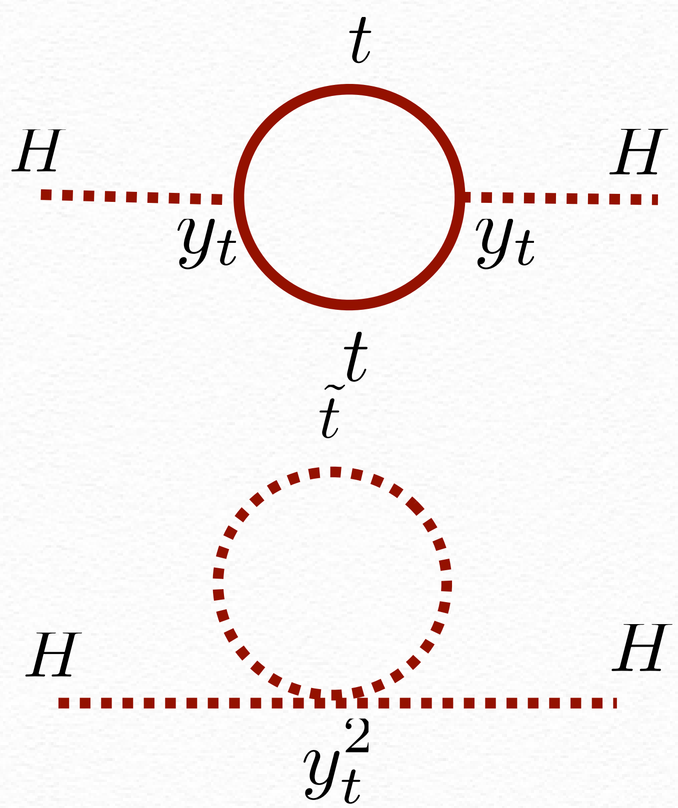


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet displacement.

Nemevsek, Nesti, Popara 1801.05813 (hep-ph)

Low energy supersymmetry



$$\delta m_H^2 = \frac{y_t^2}{16\pi^2}\left(\Lambda^2 + m_t^2\right)$$

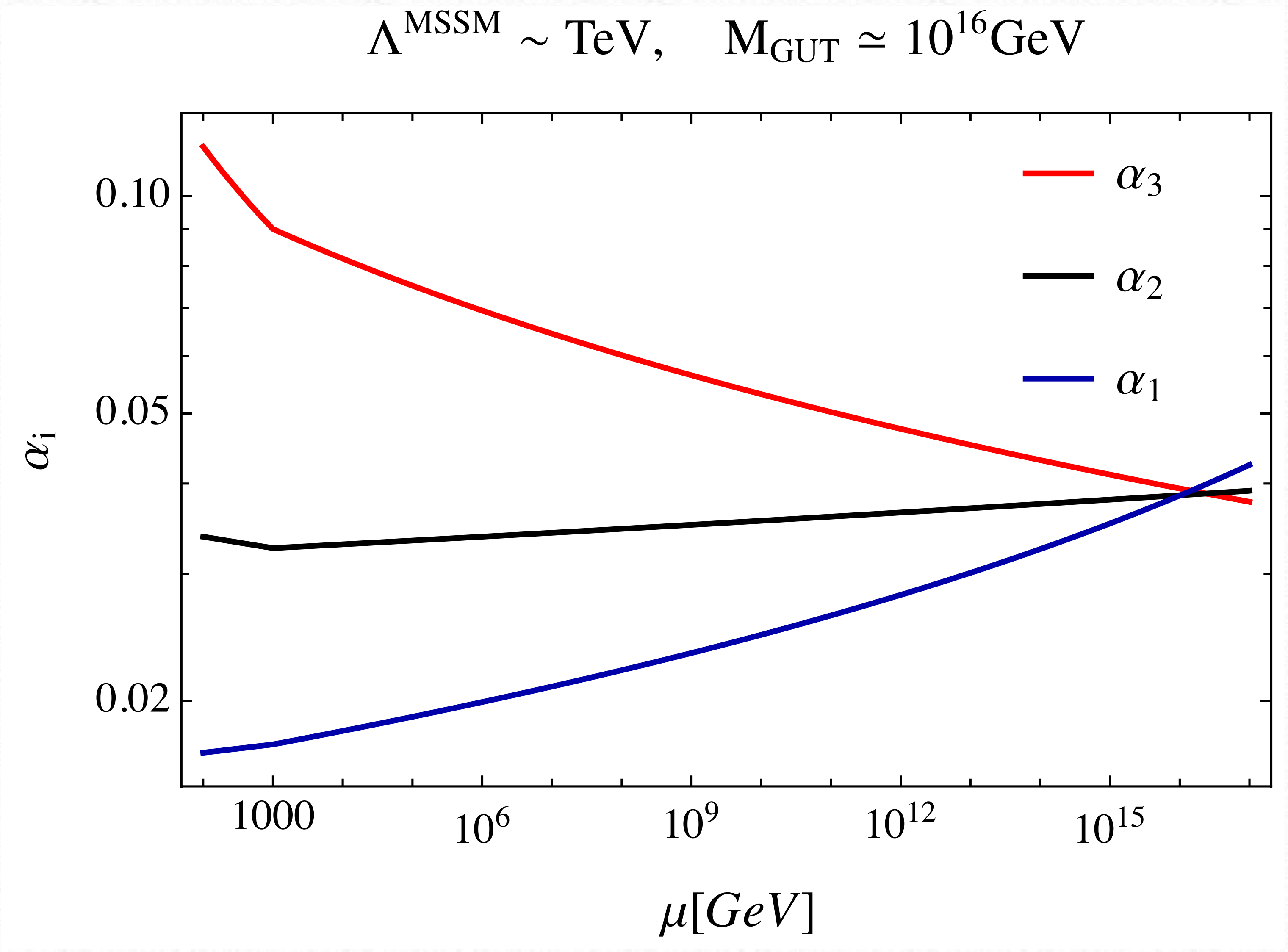
$$\delta m_H^2 = -\frac{y_t^2}{16\pi^2}\left(\Lambda^2 + m_{\tilde{t}}^2\right)$$

$$\Rightarrow \quad \delta m_H^2 = -\frac{y_t^2}{16\pi^2}\left(m_{\tilde{t}}^2 - m_t^2\right)$$

$$m_{\tilde{t}} \leq TeV$$

vague - how can you quantify fine-tuning?

old claim: @LEP



$m_{\tilde{p}} \simeq TeV$

Ibanez, Ross '81

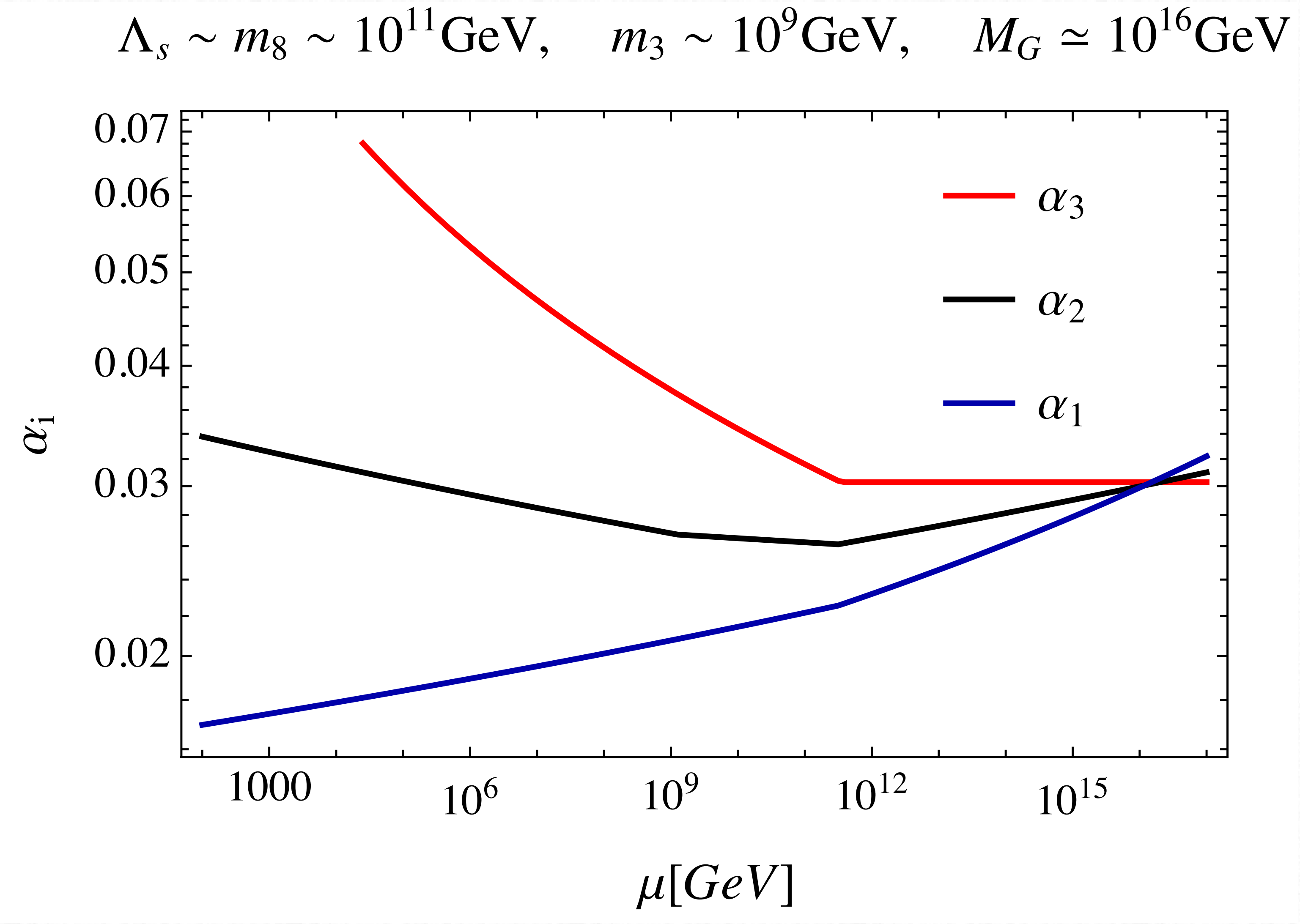
Dimpopoulos et al '81

Einhorn, Jones '81

Marciano, GS '81

Needs naturalness, otherwise: $$\Lambda = \Lambda^{\rm MSSM}\left(\frac{M_{\rm GUT}^2}{m_3 m_8}\right)^{3/4}.$$

GS, Zantedeschi '22



vague - how can you quantify fine-tuning?

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