Seesaw-predicted Heavy Leptons at the LHC

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The contents:

1. Advocate **vectorlike TeV-scale fermions** beyond the 3rd SM generation

2. Conventional **GUT-scale Seesaw**:
Majorana Neutrinos with
GUT-scale Majorana Mediators

3. Novel **TeV-scale Seesaw** Model:

Majorana Neutrinos with
TeV-scale Dirac Mediators

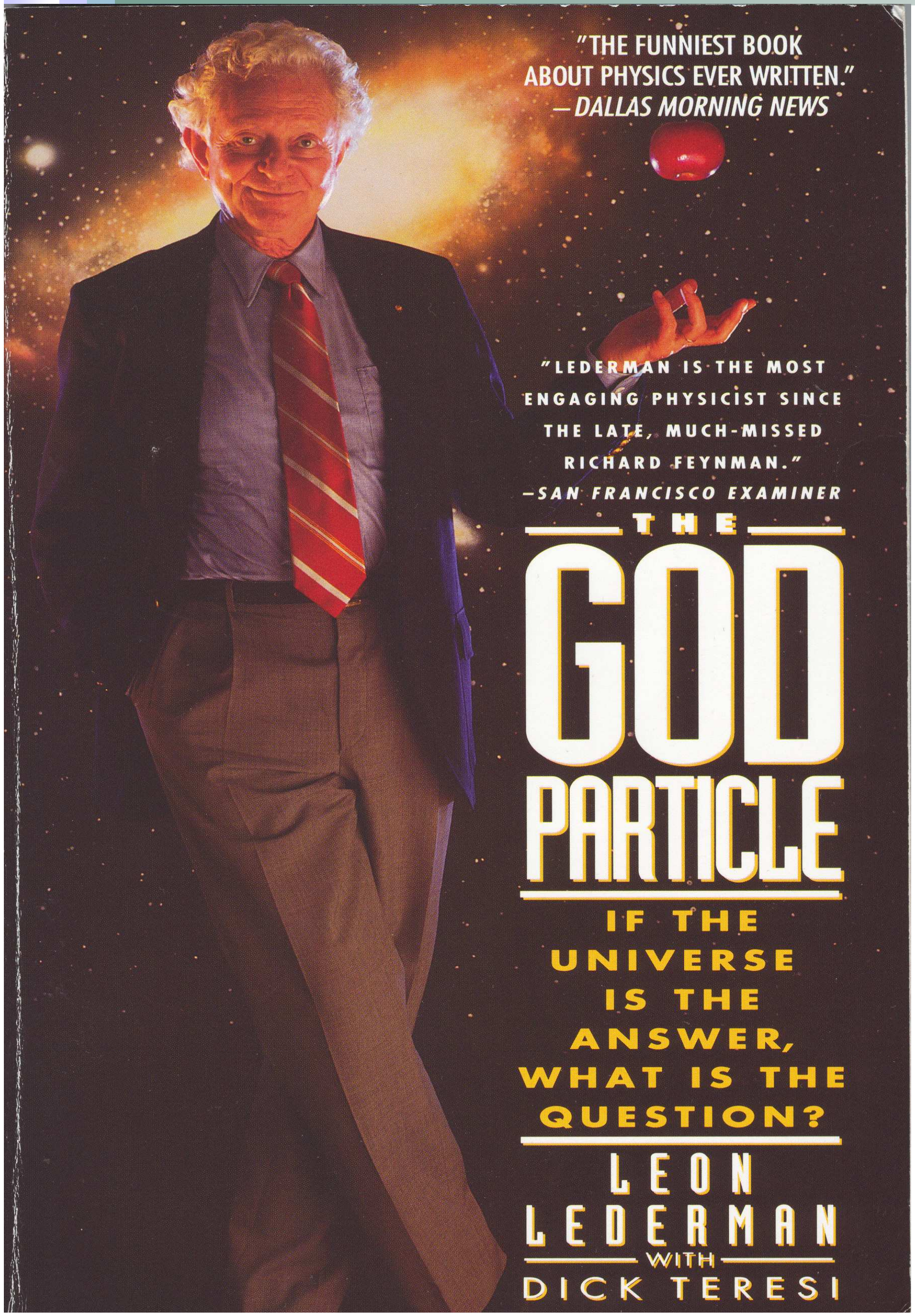
I. Introduction

Q:Where are we coming from?

Figure 1. Gauguin's questions: D'où venons-nous? Que sommes-nous? Où allons-nous? Where are we coming from? What are we? Where are we going?

A: "Bošković's 300 anniversary"

(answering 1st Gauguin's/Ellis'0710.5590 question)



THE DALMATIAN PROPHET R. Bošković

A final note on this first stage, the age of mechanics, the great era of classical physics. The phrase "ahead of his time" is overused. I'm going to use it anyway. I'm not referring to Galileo or Newton. Both were definitely right on time, neither late nor early. Gravity, experimentation, measurement, mathematical proofs . . . all these things were in the air. Galileo, Kepler, Brahe, and Newton were accepted — heralded! — in their own time, because they came up with ideas that the scientific community was ready to accept. Not everyone is so fortunate.

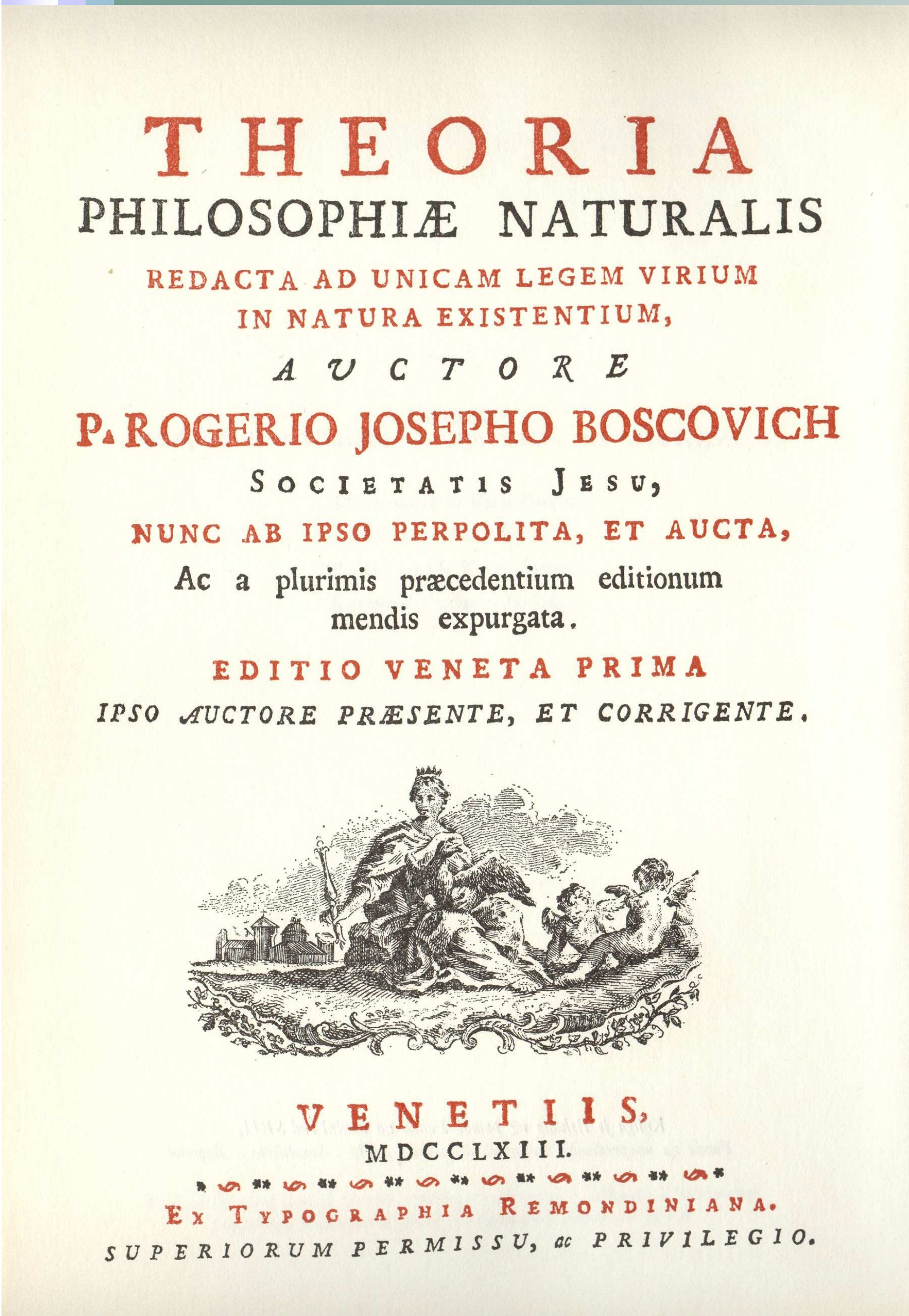
Roger Joseph Boscovich, a native of Dubrovnik who spent much of his career in Rome, was born in 1711, sixteen years before Newton's death. Boscovich was a great supporter of Newton's theories, but he had some problems with the law of gravitation. He called it a "classical limit," an adequate approximation where distances are large. He said that it was "very nearly correct but that differences from the law of inverse squares do exist even though they are very slight." He speculated that this classical law must break down altogether at the atomic scale, where the forces of attraction are replaced by an oscillation between attractive and repulsive forces. An amazing thought for a scientist in the eighteenth century.

Boscovich also struggled with the old action-at-a-distance problem. Being a geometer more than anything else, he came up with the idea of *fields of force* to explain how forces exert control over objects at a distance. But wait, there's more!

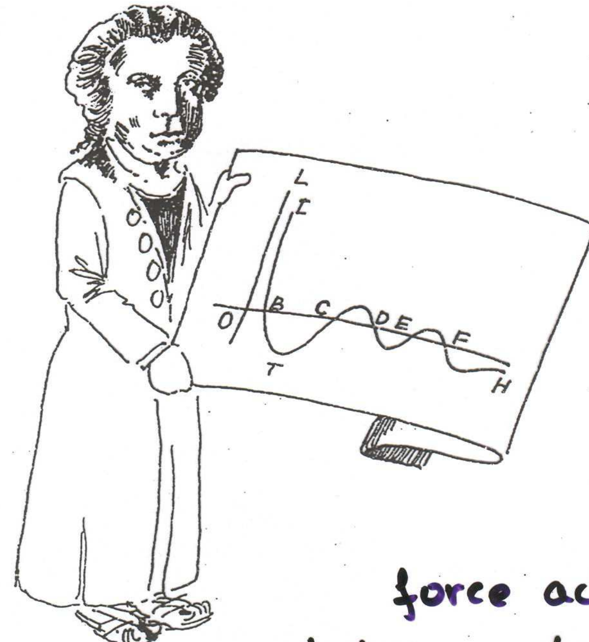
Boscovich had this other idea, one that was real crazy for the eighteenth century (or perhaps any century). Matter is composed of invisible, indivisible a-toms, he said. Nothing particularly new there. Leucippus, Democritus, Galileo, Newton, and others would have agreed with him. Here's the good part: Boscovich said these particles had no size; that is, they were geometrical points. Clearly, as with so many ideas in science, there were precursors to this — probably in ancient Greece, not to mention hints in Galileo's works. As you may recall from high school geometry, a point is just a place; it has no dimensions. And here's Boscovich putting forth the proposition that matter is composed of particles that have no dimensions! We found a particle just a couple of decades ago that fits such a description. It's called a quark.

We'll get back to Mr. Boscovich later.

GAUGE-THEORY PREHISTORY


THEORIA
PHILOSOPHIÆ NATURALIS
REDACTA AD UNICAM LEGEM VIRIUM
IN NATURA EXISTENTIUM,
AUCTORE
P. ROGERIO JOSEPHO BOSCOVICH
SOCIETATIS JESU,
NUNC AB IPSO PERPOLITA, ET AUCTA,
Ac a plurimis præcedentium editionum
mendis expurgata.
EDITIO VENETA PRIMA
IPSO AUCTORE PRÆSENTE, ET CORRIGENTE.
VENETIIS,
MDCCLXIII.
EX TYPOGRAPHIA REMONDINIANA.
SUPERIORUM PERMISSU, ac PRIVILEGIO.

- **Rudjer Bošković** (1711 - 1787) — " Theoria Philosophiae Naturalis " (1763)



force acting
- between particles of matter

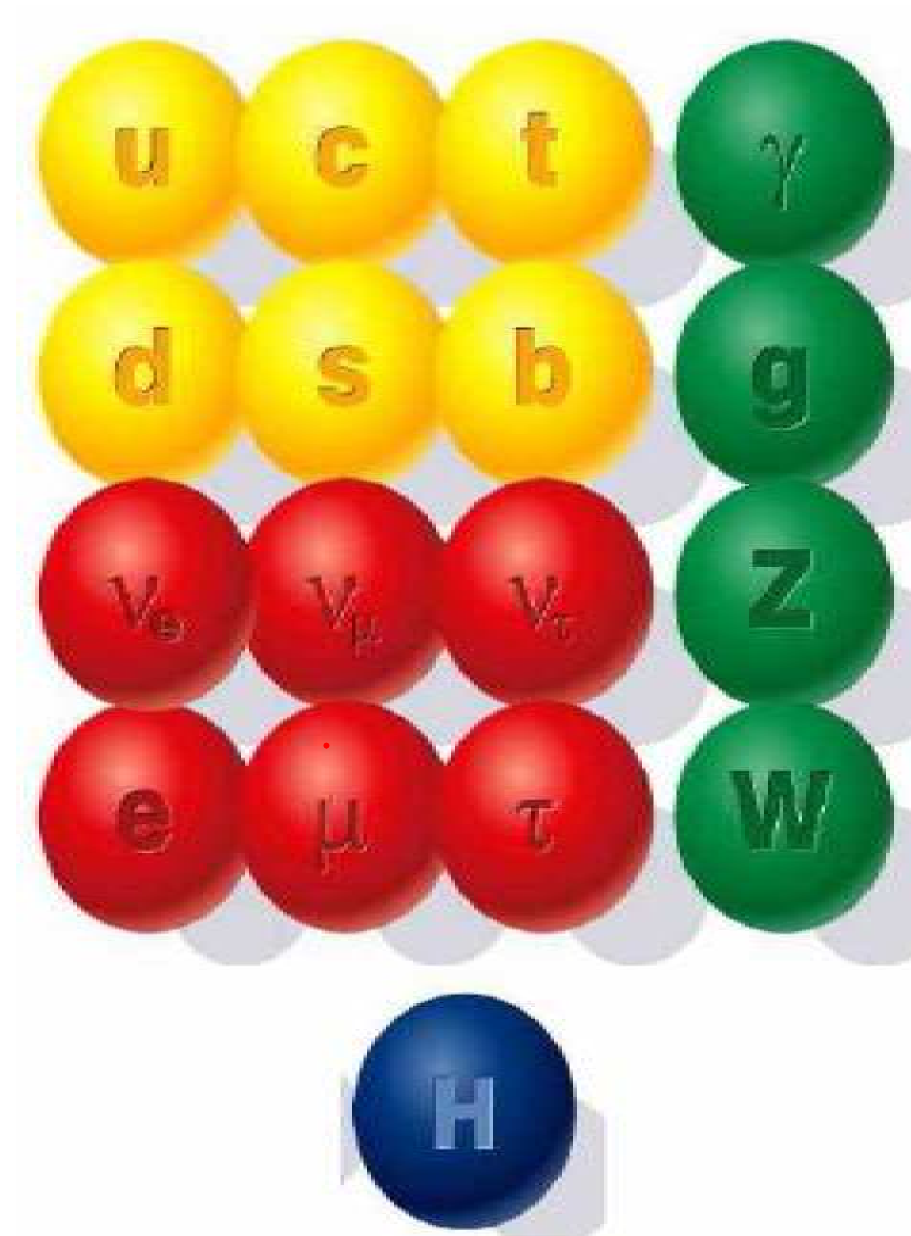
- **John Lesslie** (Edinburgh) — besides lecturing from 1785 on Bošković's theory

introduced separate forces acting
- between two particles of light
- between particle of matter and particle of light

basic ingredients in the SM of forces !

Q: Where are we?

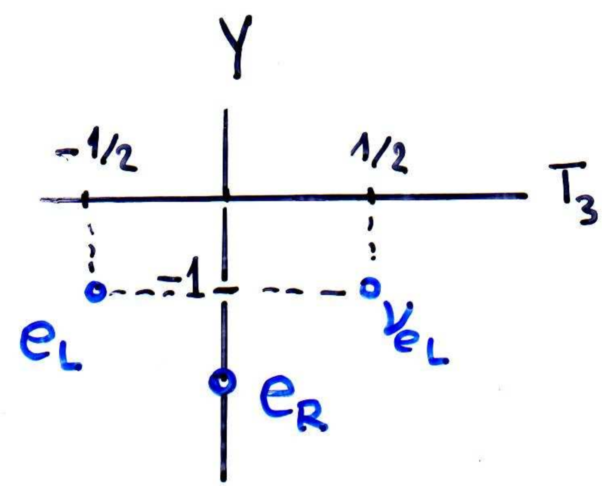
A: Present day Bošković’s “atoms” identified as sources of colour, weak isospin, and weak hypercharge forces ($Q=T_3+Y/2$)

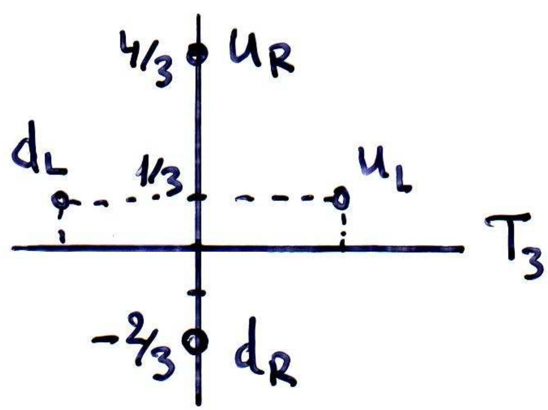


Gauge Theory History

- Particle physics "as a modern name for the long quest to understand the laws of nature" (E.Witten), born in 1897, now evolved to the
- STANDARD MODEL, based on SU(3)xSU(2)xU(1) gauge symmetry
- Bošković's message: Let's talk about new (BSM) forces only if there are new (BSM) charges

SM charges assignment in terms of 5 lowest reprezentations of the SMG for 15 helicity states

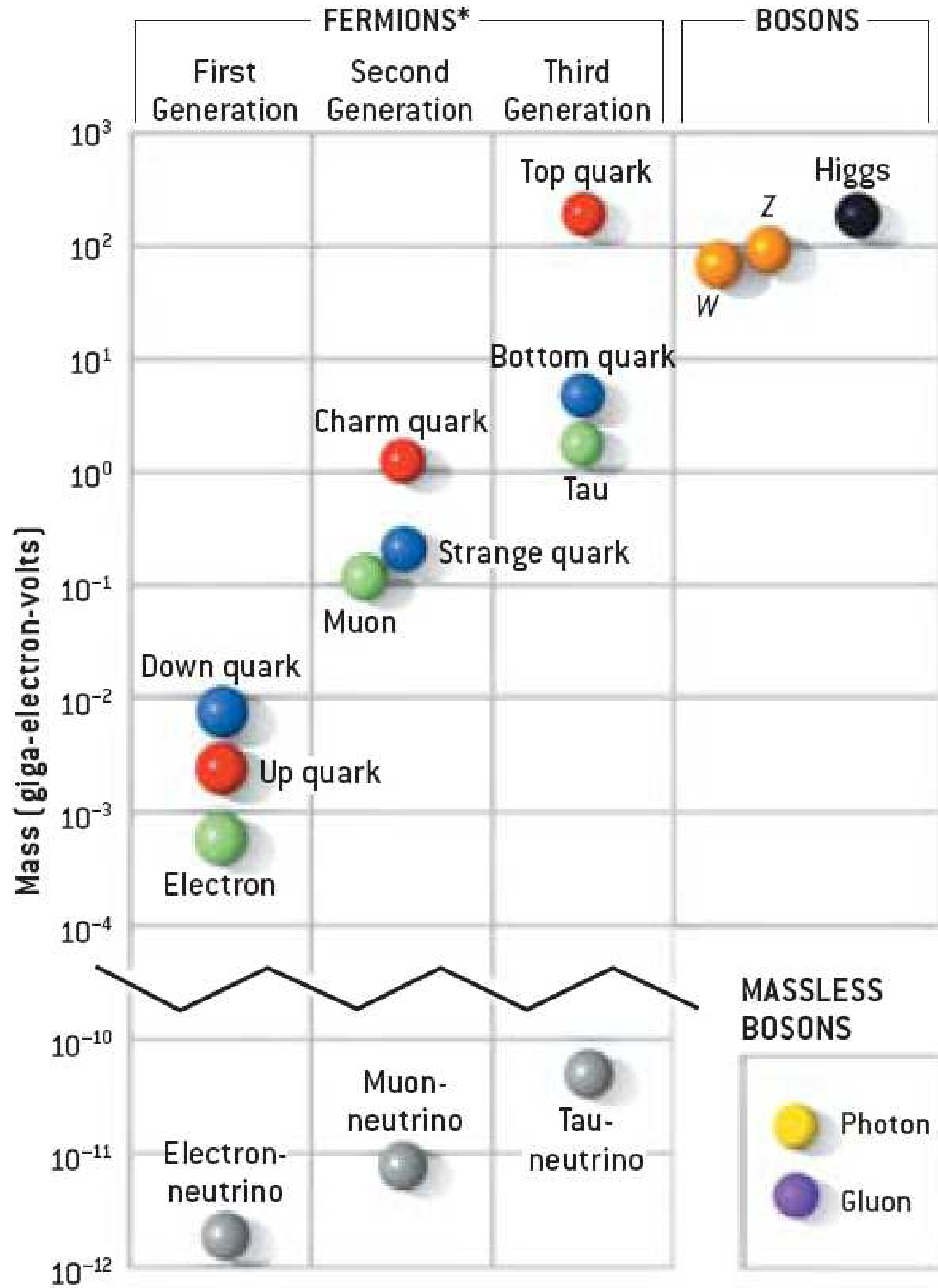




	$SU(3)_{boje} \times SU(2) \times U(1)$
$L \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$(1, 2, -1)$
e_R	$(1, 1, -2)$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$(3, 2, 1/3)$
u_R	$(3, 1, 4/3)$
d_R	$(3, 1, -2/3)$

All 12 SM fermions are discovered!

What about possible BSM d.o.f.? (w.r.t. 3rd Gauguin's question)



Q3: Where are we going?

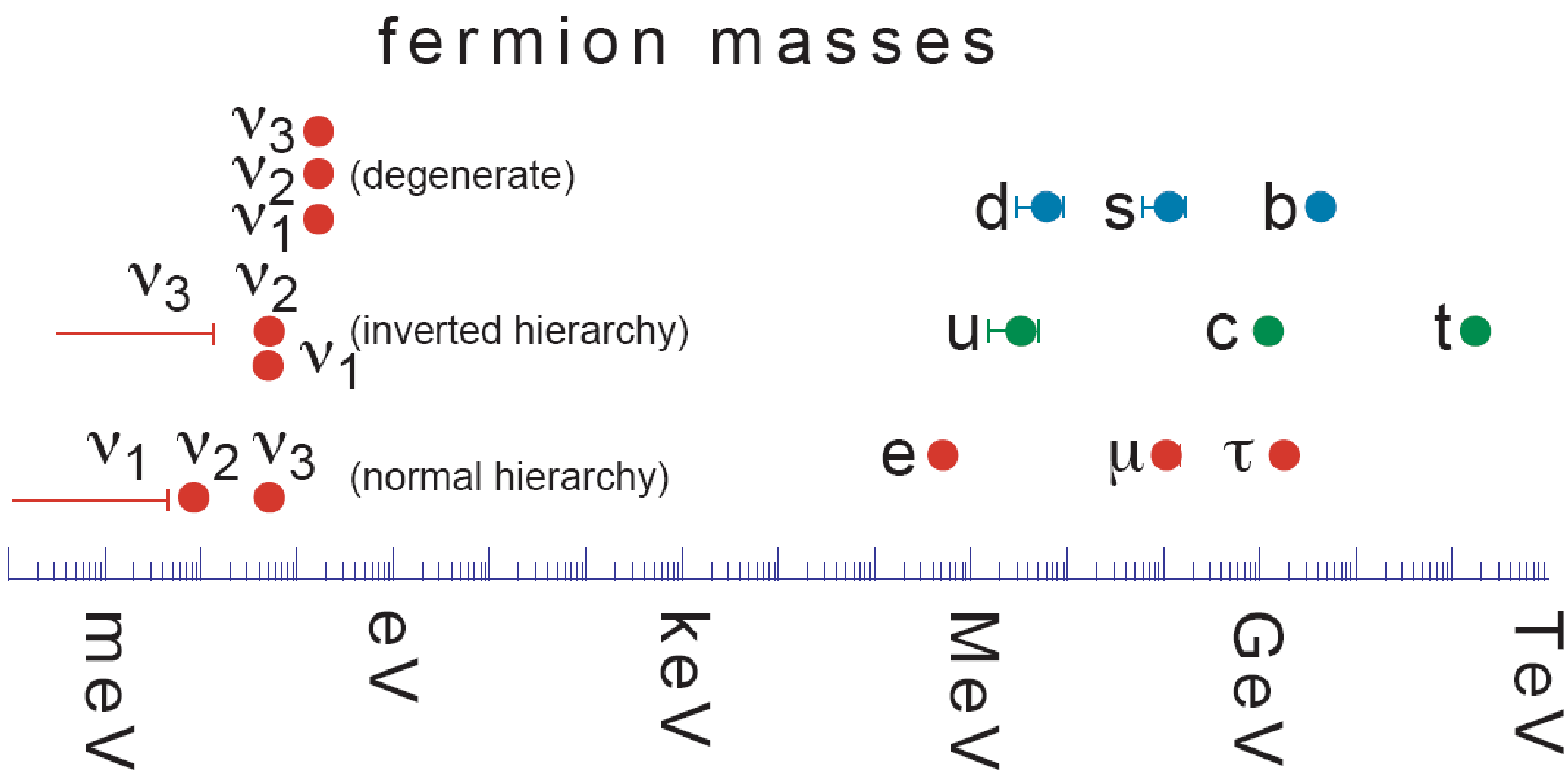
A: Introduce new particles without new forces, as suggested by prominent SM's Landmarks:

- Heavyness of top
- Lightness of neutrinos
- Lightness of the SM Higgs

The first two Landmarks:

Lightness of ν's & Heavyness of top

(Fig.Murayama'08)



The 3rd Landmark: Lightness of SM Higgs doublets

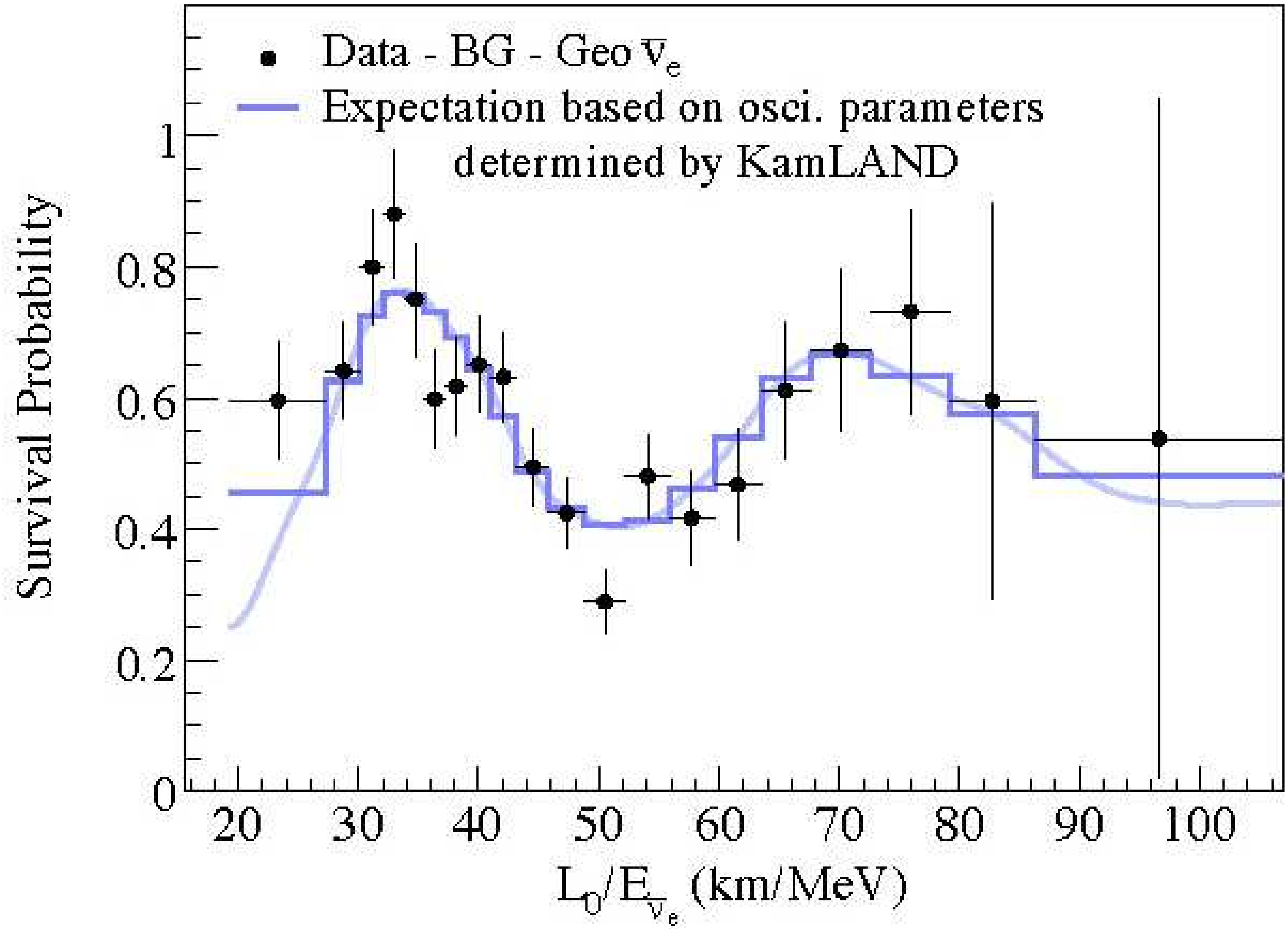
known as the Hierarchy Problem

- Introducing the top-partner T to cancel the largest contribution to Higgs mass quadratic divergence → suggests:
- such Seesaw Mediators which explain small neutrino masses without introducing extra Hierarchy Problem
- while keeping the renormalizability

II. New Heavy Leptons motivated by lightness of ν's

Neutrino Masses beyond doubt -

KamLAND evidence of ν-masses



The seesaw picture -ascribes the lightness of ν's to the existence of some heavy-scale d.o.f.

- **Light sterile neutrinos** – lacking motivation?
- **Heavy Majorana neutrinos** – conventional fermionic Type I & III seesaws
- **Vectorlike Dirac fermions** - beyond Type I & III seesaw

Only 3 realizations of dim 5 operator at the tree-level

Type I — three heavy right-handed neutrinos

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2} \overline{N_{\rm R}^{\rm c}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

Type II — one heavy Higgs triplet $\Delta \equiv \begin{pmatrix} \Delta^- & -\sqrt{2}\,\Delta^0 \\ \sqrt{2}\,\Delta^{--} & -\Delta^- \end{pmatrix}$

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \frac{1}{2} \overline{l_{\rm L}} Y_\Delta \Delta i\sigma_2 l^{\rm c}_{\rm L} - \lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + {\rm h.c.}$$

Type III — three heavy triplet fermions $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} \sqrt{2} Y_\Sigma \Sigma^{\rm c} \tilde{H} + \frac{1}{2} {\rm Tr}\left(\overline{\Sigma} M_\Sigma \Sigma^{\rm c}\right) + {\rm h.c.}$$

Conventional Seesaw Mediators

- single additional particle with SM charges

Type I — three heavy right-handed neutrinos

$N_R \sim (1,1,0)$

Type II — one heavy Higgs triplet $\Delta \equiv \begin{pmatrix} \Delta^- & -\sqrt{2}\,\Delta^0 \\ \sqrt{2}\,\Delta^{--} & -\Delta^- \end{pmatrix}$

$\Delta \sim (1,3,-2)$

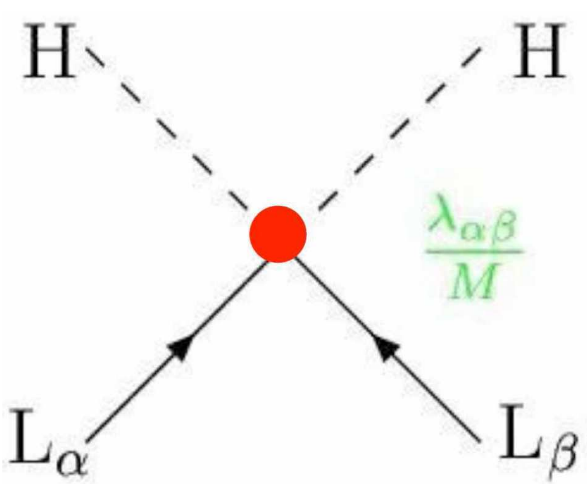
Type III — three heavy triplet fermions $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

$\Sigma \sim (1,3,0)$

Dim 5 Weinberg's op. ~LLHH by integrating out heavy d.o.f.

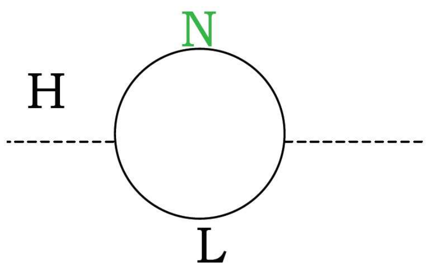
$$\frac{\mathcal{L}_{\rm d=5}}{\Lambda} = \begin{cases} \frac{1}{2}\left(Y_\nu M_{\rm R}^{-1} Y_\nu^T\right)_{\alpha\beta} \overline{l_{\alpha \rm L}} \tilde{H} \tilde{H}^T l^{\rm c}_{\beta \rm L} + {\rm h.c.} & \text{(Type I)} , \\ -\frac{\lambda_\Delta}{M_\Delta}\left(Y_\Delta\right)_{\alpha\beta} \overline{l_{\alpha \rm L}} \tilde{H} \tilde{H}^T l^{\rm c}_{\beta \rm L} + {\rm h.c.} & \text{(Type II)} , \\ \frac{1}{2}\left(Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T\right)_{\alpha\beta} \overline{l_{\alpha \rm L}} \tilde{H} \tilde{H}^T l^{\rm c}_{\beta \rm L} + {\rm h.c.} & \text{(Type III)} \end{cases}$$

SSB->Majorana mass



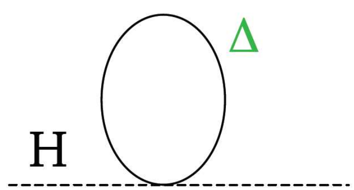
$$M_\nu = \begin{cases} -\frac{1}{2} Y_\nu \frac{v^2}{M_{\rm R}} Y_\nu^T & \text{(Type I)} , \\ \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} & \text{(Type II)} , \\ -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T & \text{(Type III)} \end{cases}$$

TeV-seesaw scale awoids hierarchy problem (Fig.B.Gavela'09)



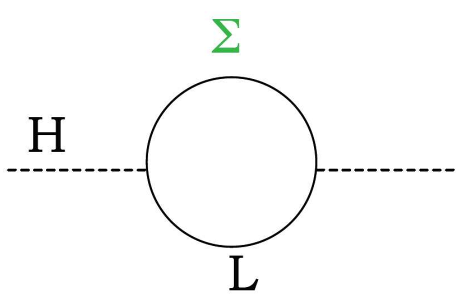
$$\delta m_H^2 = -\frac{Y_N^\dagger Y_N}{16\pi^2}\left[2\Lambda^2 + 2M_N^2 \log\frac{M_N^2}{\Lambda^2}\right]$$

(Vissani)



$$\delta m_H^2 = -3\frac{\lambda_3}{16\pi^2}\left[\Lambda^2 + M_\Delta^2\left(\log\frac{M_\Delta^2}{\Lambda^2} - 1\right)\right] - \frac{\mu_\Delta^2}{2\pi^2}\log\left(\left|\frac{M_\Delta^2 - \Lambda^2}{M_\Delta^2}\right|\right)$$

(Abada, Biggio, Bonnet, Hambye, M.B.G.)



$$\delta m_H{}^2 = -3\frac{Y_\Sigma^\dagger Y_\Sigma}{16\pi^2}\left[2\Lambda^2 + 2M_\Sigma^2 \log\frac{M_\Sigma^2}{\Lambda^2}\right]$$

Lowering seesaw scale by going to dim>5 operators:

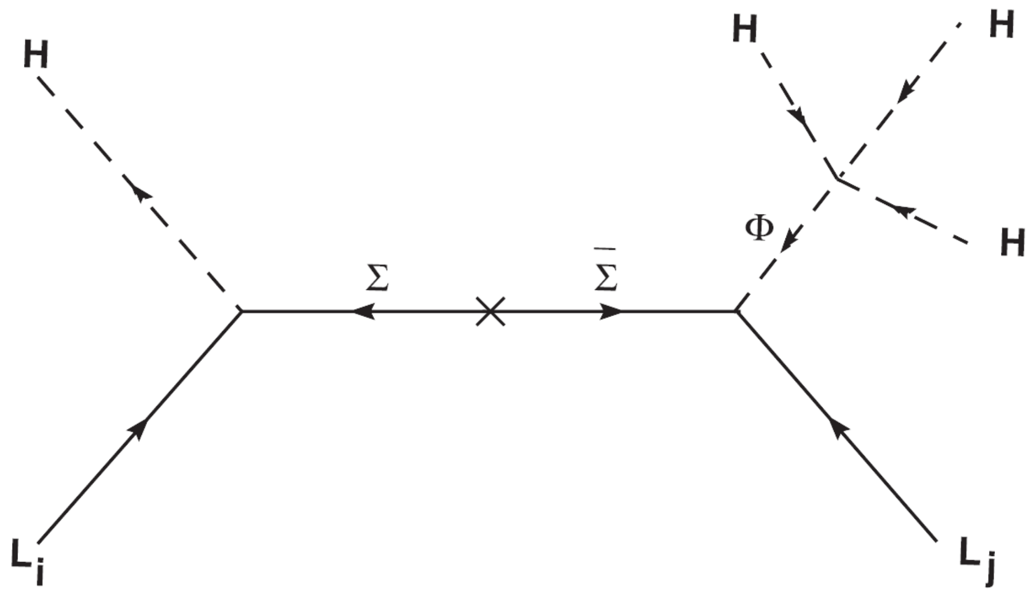
$$
\begin{aligned}
\mathcal{O}^5 &= \mathcal{O}_W = LLHH \\
\mathcal{O}^7 &= (LLHH)(H^\dagger H) \\
\mathcal{O}^9 &= (LLHH)(H^\dagger H)(H^\dagger H) \\
&\vdots
\end{aligned}
$$

$$
m_\nu \sim v \left(\frac{v}{\Lambda_{\mathrm{NP}}} \right)^{d-4}
$$

F. Bonnet, D. Hernandez, T. Ota and W. Winter, JHEP **0910**:076,2009 [0907.3143 [hep-ph]];

- NP scale 1-10 TeV with d=9 is enough for sub-eV neutrino mass
- Operators are studied for singlet, doublet and triplet mediators

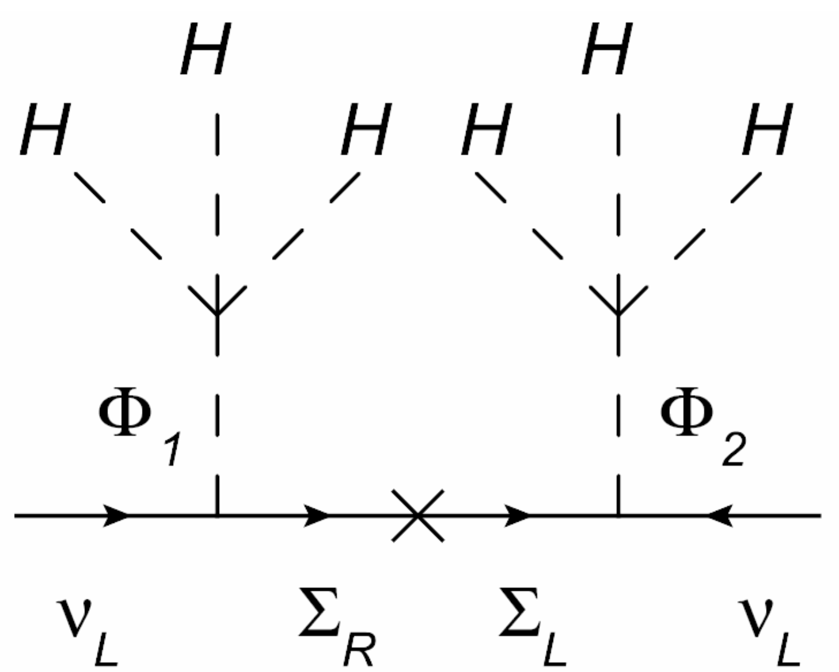
TwoTree-level Seesaw Options:
dim 7 and dim 9 operators



$$m_\nu \sim v^4/M^3$$

- **Dim 7 Operator** Babu et al' 09, PRD 80, 071702(R)
- **Dim 9 Operator** **I.P. and B.Radovčić, PLB 687 ('10) 338**

Dim-9 ~ LLHH(H†H)(H†H) tree-level op. -integrating out heavy d.o.f.



$$m_\nu \sim \frac{Y_1 Y_2\ \lambda_1 \lambda_2\ v^6}{M_\Sigma\ \mu^2_{\Phi_1}\ \mu^2_{\Phi_2}}$$

$$\sim v^6/M^5$$

- **Light Majorana neutrino naturally in sub-eV range with TeV-scale heavy d.o.f.**

Novel Tree-level Seesaw Model

based on vectorlike Dirac fermion 5-plet Σ (I=2, Y=2) mediators

$$\Sigma_L = (\Sigma_L^{+++}, \Sigma_L^{++}, \Sigma_L^{+}, \Sigma_L^{0}, \Sigma_L^{-})$$
$$\Sigma_R = (\Sigma_R^{+++}, \Sigma_R^{++}, \Sigma_R^{+}, \Sigma_R^{0}, \Sigma_R^{-})$$

both transforming as $(1, 5, 2)$

- In conjunction with isospin 3/2 scalar fields Φ_1 and Φ_2:

$$\Phi_1 = (\Phi_1^0, \Phi_1^-, \Phi_1^{--}, \Phi_1^{---}) \qquad \Phi_2 = (\Phi_2^+, \Phi_2^0, \Phi_2^-, \Phi_2^{--})$$

transforming as $(1, 4, -3)$ and $(1, 4, -1)$, respectively.

SM gauge invariant terms

Dirac mass term
for new seesaw mediator

$$\mathcal{L}_{\rm M} = -\, M_\Sigma\, \overline{\Sigma}_L \Sigma_R + {\rm H.c.}$$

Yukawa term includes
Lepton Number Violation

$$\mathcal{L}_{\rm Y} = Y_1\, \bar{l}_L \Sigma_R\, \Phi_1 + Y_2\, \overline{\Sigma}_L (l_L)^c\, \Phi_2^* + {\rm H.c.}$$

Dirac seesaw by diagonalizing the mass matrix

$$\left(\bar{\nu}_L\ \overline{\Sigma^0_L}\ \overline{(\Sigma^0_R)^c}\right)\begin{pmatrix} 0 & m_2 & m_1 \\ m_2 & 0 & M_\Sigma \\ m_1 & M_\Sigma & 0 \end{pmatrix}\begin{pmatrix} (\nu_L)^c \\ (\Sigma^0_L)^c \\ \Sigma^0_R \end{pmatrix}$$

- representing the mixing between neutral components of the SM lepton doublet and the Σ 5-plets

Mass eigenvalues:

- Two nearly degenerate Heavy neutral states $m_{\nu_H} \sim M_\Sigma$
- Light Majorana neutrinos

$$m_\nu \sim \frac{m_1 m_2}{M_\Sigma} \sim \frac{Y_1 Y_2 v_{\Phi_1} v_{\Phi_2}}{M_\Sigma}$$

From the EW precision: $\rho = 1.0004^{+0.0008}_{-0.0004}$

$$\rho \simeq 1 - 6v_{\Phi_1}^2/v^2 + 6v_{\Phi_2}^2/v^2$$

an upper bound on v_{Φ_1} and v_{Φ_2} of a few GeV.

EWSB in usual way from Higgs doublet $\mu_H^2 < 0$

$$V(H,\Phi_1,\Phi_2)$$

$$\begin{aligned} &\sim \mu_H^2 H^\dagger H + \mu_{\Phi_1}^2 \Phi_1^\dagger \Phi_1 + \mu_{\Phi_2}^2 \Phi_2^\dagger \Phi_2 + \lambda_H (H^\dagger H)^2 \\ &+ \{\lambda_1 \Phi_1^* H^* H^* H^* + \text{H.c.}\} + \{\lambda_2 \Phi_2^* H H^* H^* + \text{H.c.}\} \\ &+ \{\lambda_3 \Phi_1^* \Phi_2 H^* H^* + \text{H.c.}\} \ . \end{aligned}$$

- Induced vev for Φ_1 and Φ_2, scalars with $\mu_{\Phi_1}^2, \mu_{\Phi_2}^2 > 0$

$$v_{\Phi_1} \simeq -\lambda_1 \frac{v^3}{\mu_{\Phi_1}^2} \ , \ v_{\Phi_2} \simeq -\lambda_2 \frac{v^3}{\mu_{\Phi_2}^2}$$

Operators of dim 7 and 5 are generated at loop level from dim 9 op. - smaller than dim 9 tree level if

$$\Lambda_{NP} < 4\pi v \simeq 2 \text{ TeV}$$

- The operator of dim 5 generated at loop level from λ_3 term – for $\lambda_1 \lambda_2 = \lambda_3$ is smaller than dim 9 tree level if

$$\Lambda_{NP} < \sqrt{4\pi} v \simeq 620 \text{ GeV}$$

NP scale splitting dim 5 loop & dim 9 tree-level contributions

For simplicity, $\mu_\Phi = M_\Sigma = \Lambda_{NP}$

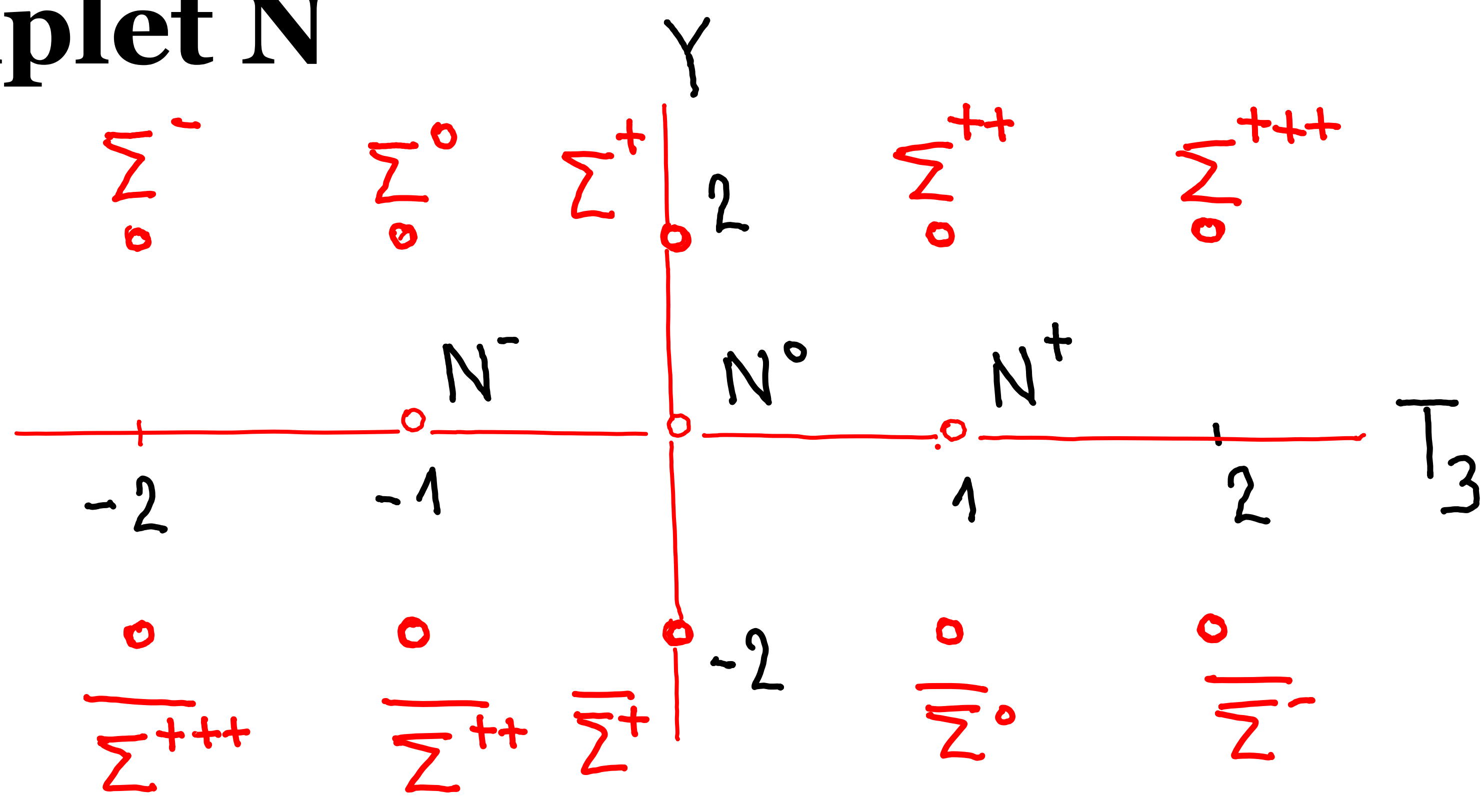
the values $v = 174$ GeV and $m_\nu \sim 0.1$ eV

& moderate $Y \sim Y' \sim \lambda_2 \sim 10^{-2}$ result in

$\Lambda_{NP} \simeq 580$ GeV and $v_{\Phi_1} \simeq 80$ MeV and $v_{\Phi_2} \simeq 60$ MeV.

- There is a part of the parameter space where tree-level dim 9 operator dominates over loop generated dim 5 and dim 7 contributions!

III. Signatures of 5-plet Σ at the LHC - and distinguishing it from type III triplet N

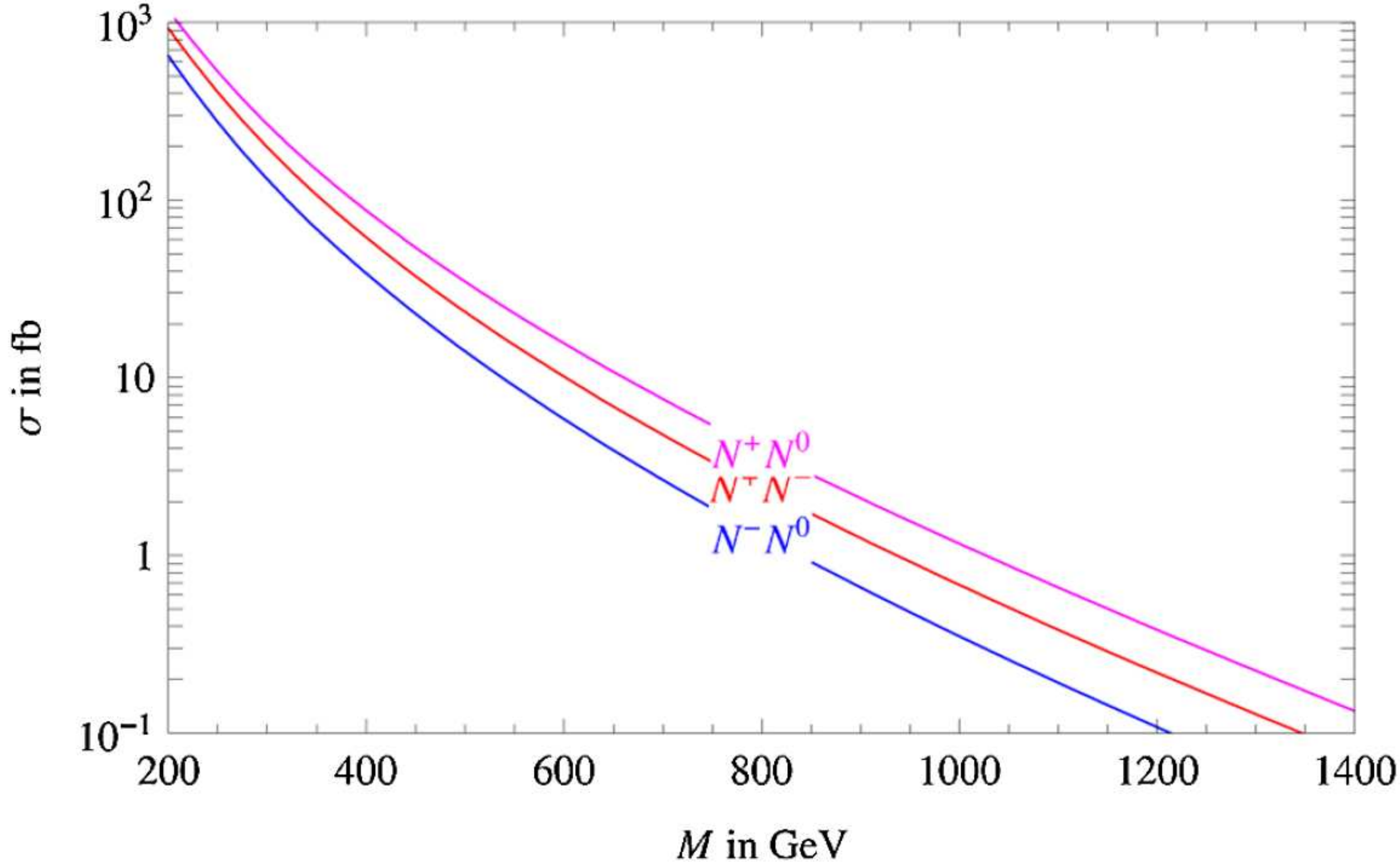


Production of 5-plet States by Drell-Yan fusion

- Via CC associated production of pairs
- Via NC direct pair prodiction
- Using CTEQ6.6 PDFs via LHAPDF
- Check by MadGraph via FeynRules

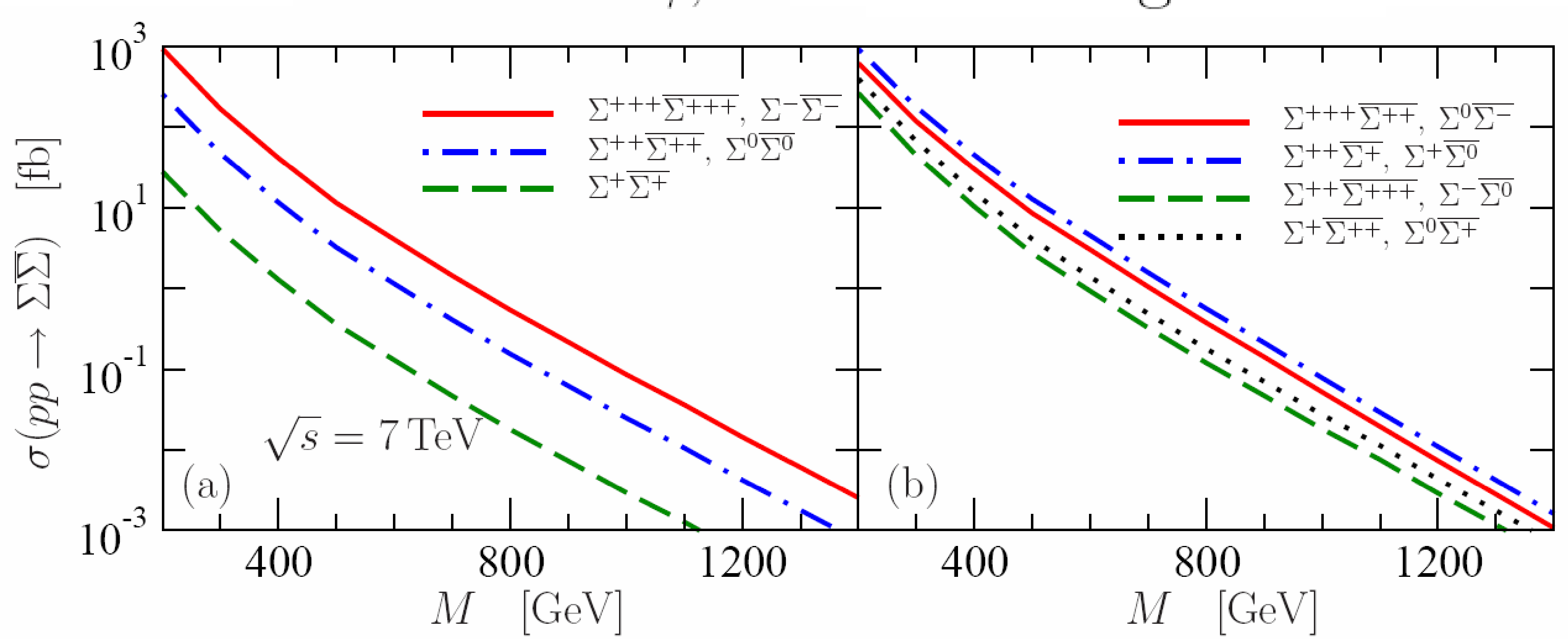
Check on production cross section for type-III triplets at LHC

(Franceschini,Hambye,Strumia, PRD78, 2008)



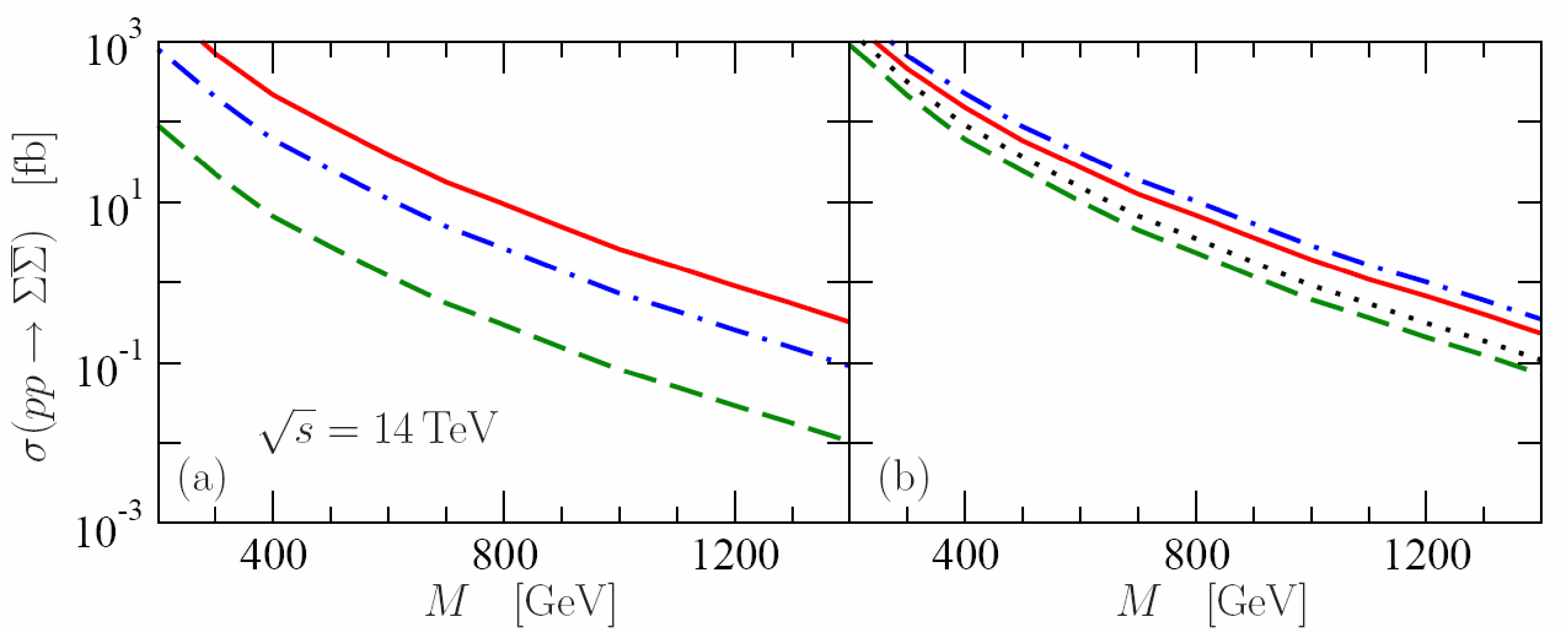
Production cross section for 5-plets at 2010-run LHC energy

via neutral γ, Z and charged $W^{\pm}$



Production cross section for 5-plets for designed LHC energy

via neutral γ, Z and charged $W^{\pm}$



Two classes of decay-processes - like those for Type III triplet

$$\Gamma(N^\pm \to N^0\pi^\pm) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi}\sqrt{1 - \frac{m_\pi^2}{\Delta M^2}},$$

ΔM suppressed

$$\Gamma(N^\pm \to N^0 e^\pm \overset{(-)}{\nu}_e) = \frac{2G_F^2 \Delta M^5}{15\pi^3},$$

$$\Gamma(N^\pm \to \ell^\pm Z) = \frac{1}{4}\frac{\lambda^2 M}{8\pi}\left(1 - \frac{M_Z^2}{M^2}\right)^2\left(1 + 2\frac{M_Z^2}{M^2}\right),$$

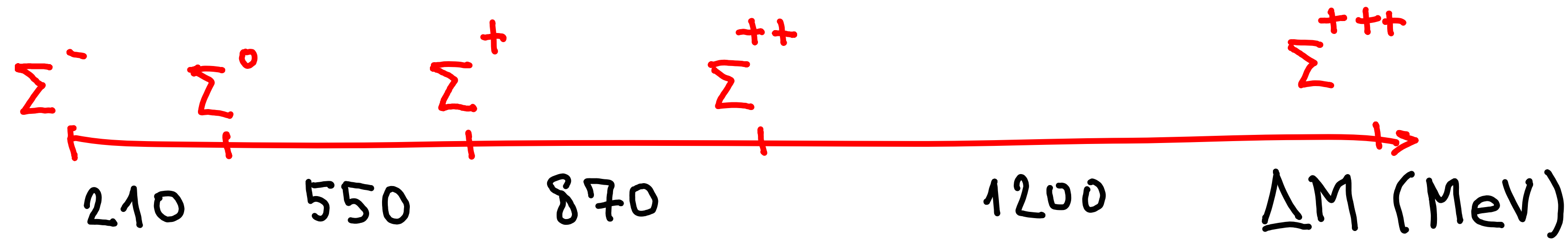
$$\Gamma(N^\pm \to \overset{(-)}{\nu}_\ell W^\pm) = \frac{1}{2}\frac{\lambda^2 M}{8\pi}\left(1 - \frac{M_W^2}{M^2}\right)^2\left(1 + 2\frac{M_W^2}{M^2}\right).$$

Suppression by small mass splittings within a multiplet

$$M_Q - M_0 \simeq Q(Q + Y/\cos\theta_W)\Delta M$$

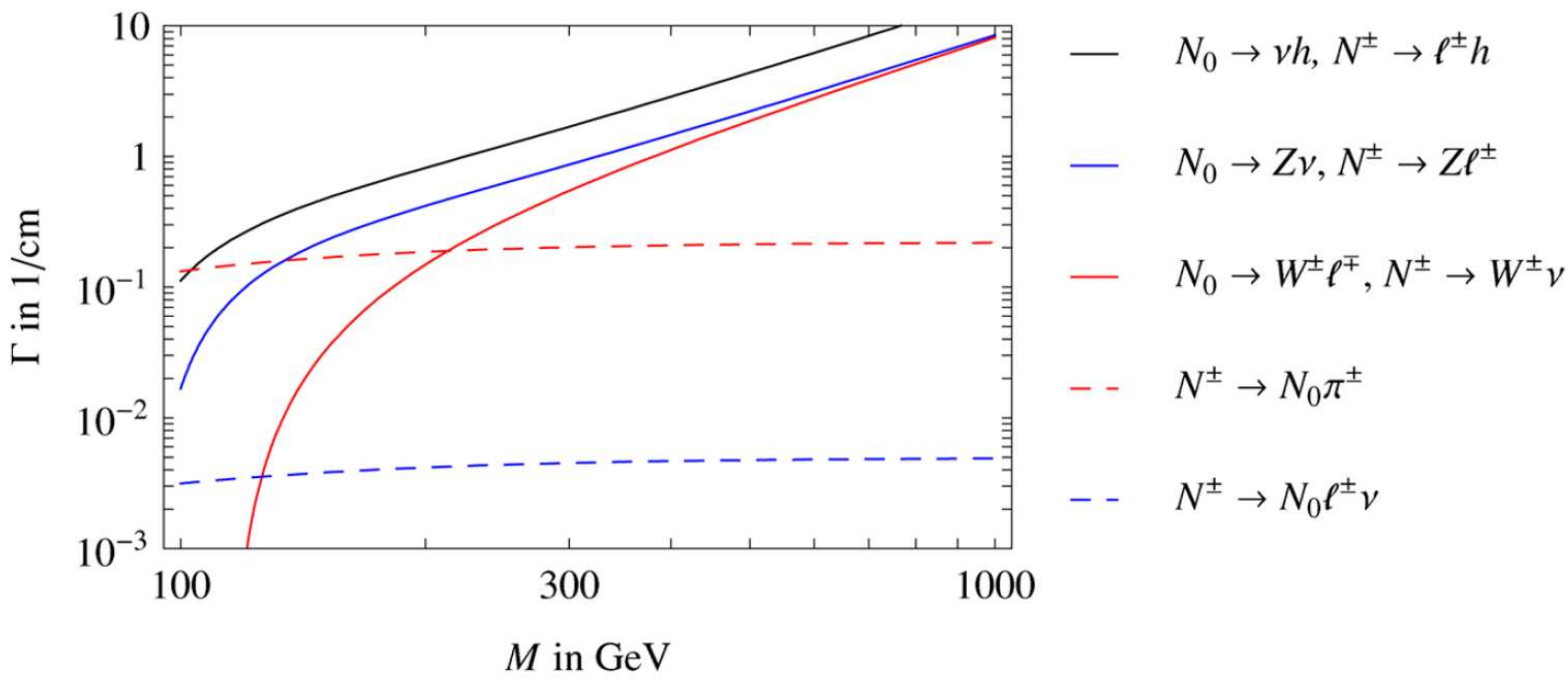
$$\Delta M = \alpha_2 M_W \sin^2\frac{\theta_W}{2} = (166 \pm 1) MeV.$$

- **Suppression for Type III triplet**
- **Still, there is larger splitting among higher states within a Σ multiplet**

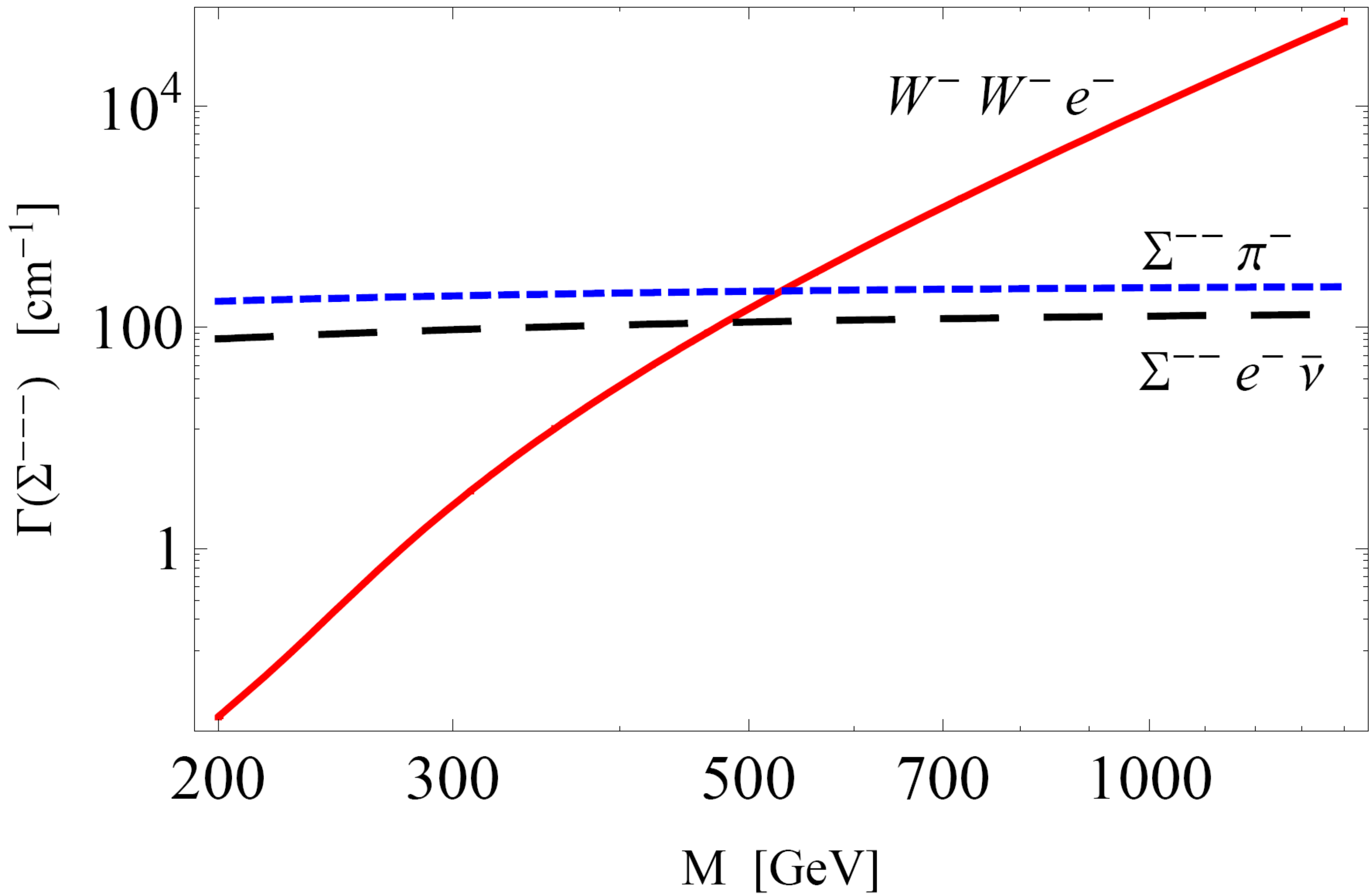


Type-III triplet decay widths

(Franceschini, Hambye, Strumia, PRD78, 2008)



Decay widths of triply-charged Σ



Signatures from LNC & LNV decays

$$\Sigma^{+++} \rightarrow W^+ W^+ l^+ \qquad \Sigma^{++} \rightarrow W^+ l^+$$

$$\Sigma^{+} \rightarrow W^+ \nu, Z l^+, H^0 l^+$$

$$\Sigma^{-} \rightarrow W^- \nu, Z l^-, H^0 l^-$$

$$\Sigma^{0} \rightarrow W^\pm l^\mp, Z \nu, H^0 \nu$$

- **Two types of decays with same sign dileptons and the jets as a signature**

$$q\bar{q}' \rightarrow W^* \rightarrow \Sigma^+ \overline{\Sigma^0} \rightarrow l^+ Z l^+ W^- \rightarrow l^+ l^+ j j \ ,$$

$$q\bar{q} \rightarrow Z^* \rightarrow \Sigma^0 \overline{\Sigma^0} \rightarrow l^\pm W^\mp l^\pm W^\mp \rightarrow l^\pm l^\pm j j$$

Conclusions: Falsifiable dim 9 tree-level seesaw

i) Sizable production at the LHC (already 1000 pairs at present 7 TeV)

States too heavy to be produced may be revealed through virtual loop effects

ii) Characteristic triply charged 5-plet state decay as a link between collider phenomenology and the origin of neutrino masses