Phenomenology of Seesaw-Motivated Heavy Leptons at the LHC

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The contents:

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

2. Mission in **TeV-scale Seesaw** Model:
Light Majorana Neutrinos with
(sub)TeV-scale Dirac Mediators

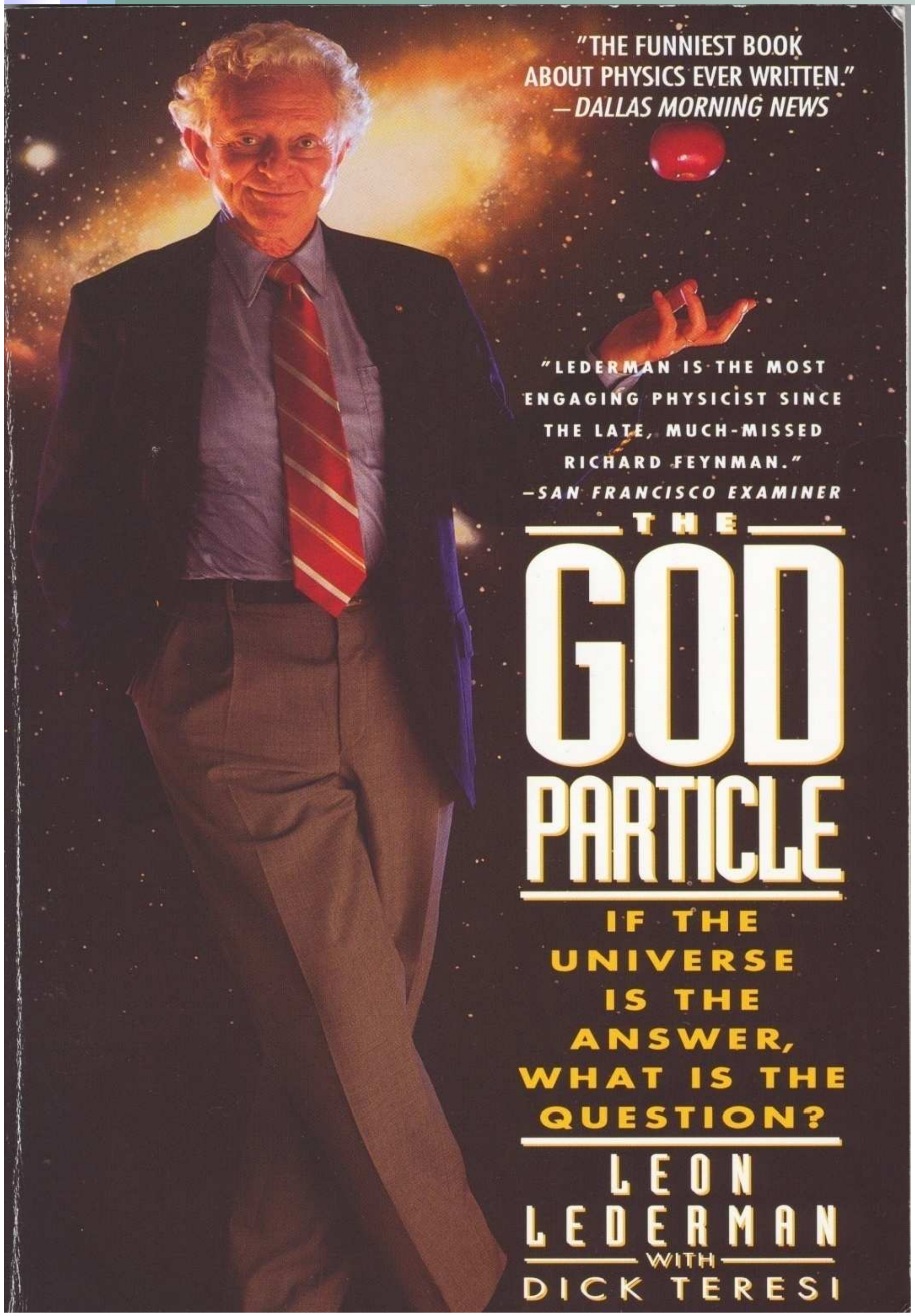
3. Phenomenology of **weak 5-plets** Σ:
Drell-Yan production @LHC
Distinguished triply-charged Σ decays

I. Introduction
to Additional Exotic States

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?

In light of Bošković's 300 anniversary

answering Gauguin's questions (Ellis'0710.5590)



R. Bošković

THE DALMATIAN PROPHET

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.

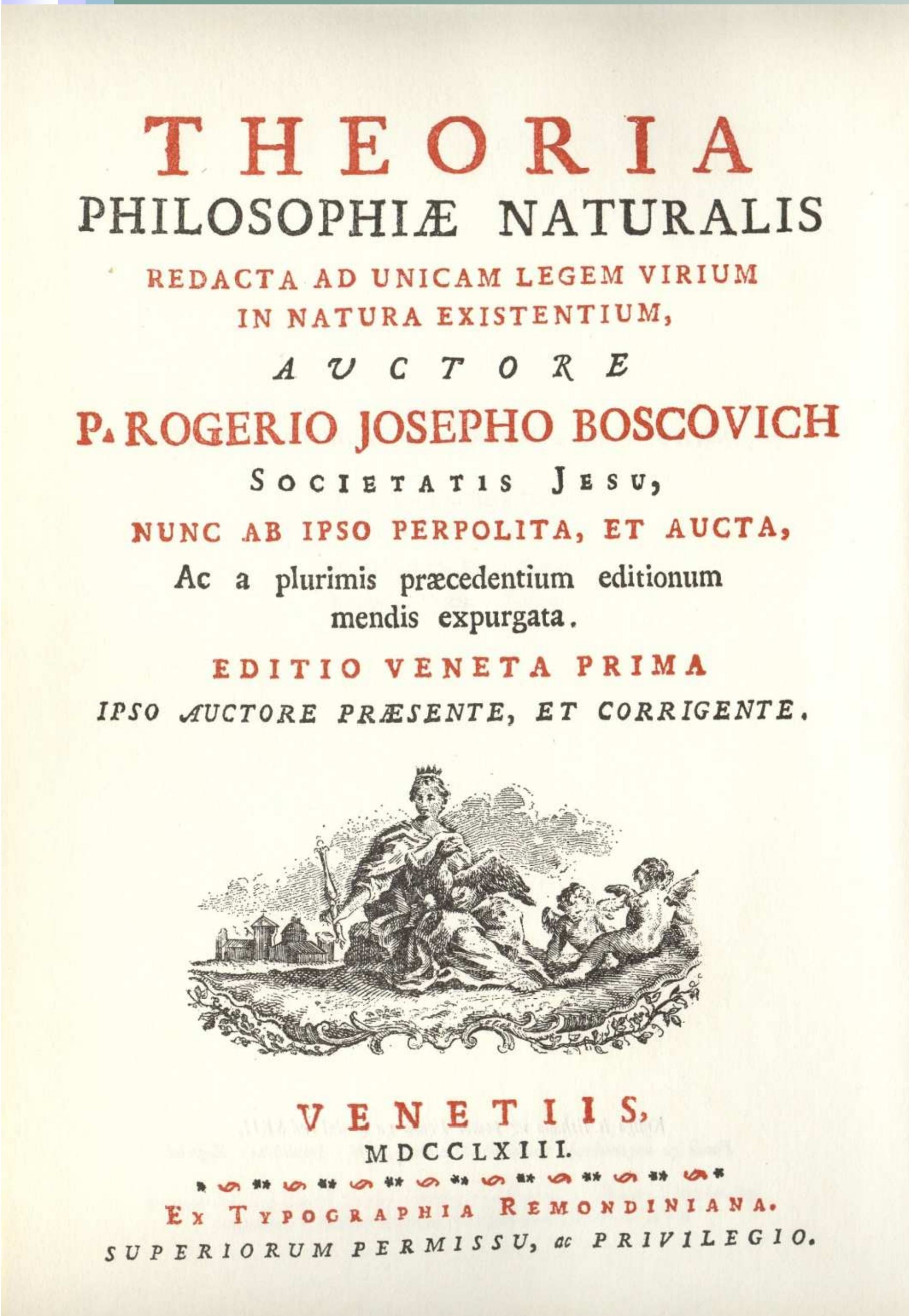
Roger Joseph Boscovich, a native of Dubrovnik who spent much of his career in Rome, was born in 1711, sixteen years before Newton's death. Boscovich was a great supporter of Newton's theories, but he had some problems with the law of gravitation. He called it a "classical limit," an adequate approximation 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.

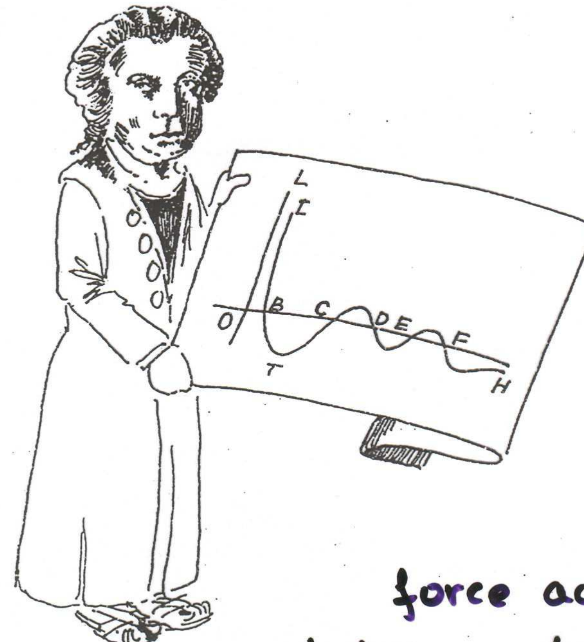
GAUGE-THEORY PREHISTORY



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

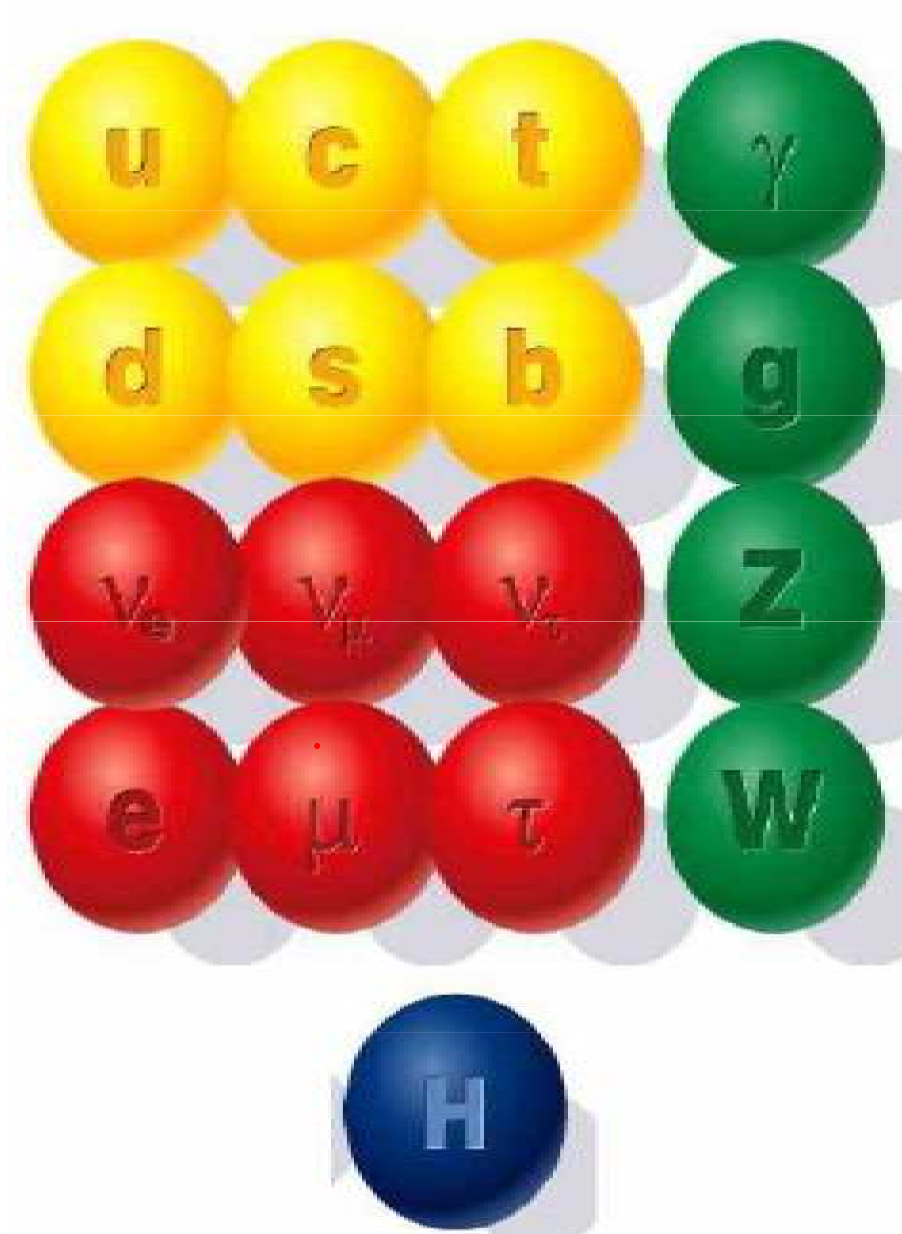
- **John Lesslie** (Edinburgh) besides lecturing from 1785 on Bošković's theory

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

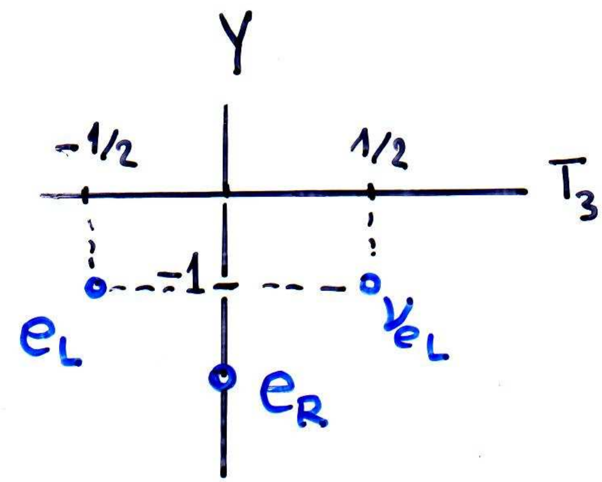
basic ingredients in the SM of forces !

In Gauge History

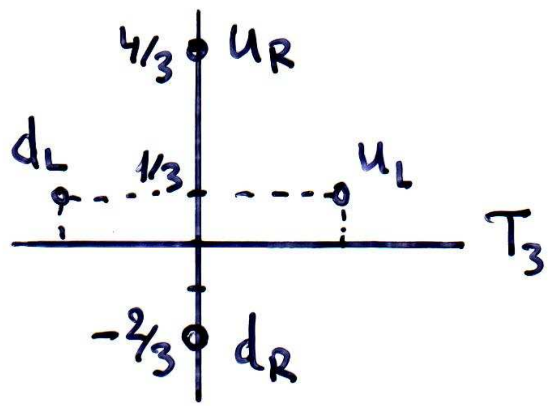
the present day "Bošković's atoms" identified as sources of **colour, weak isospin, and weak hypercharge** forces ($Q=T_3+Y/2$)



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)



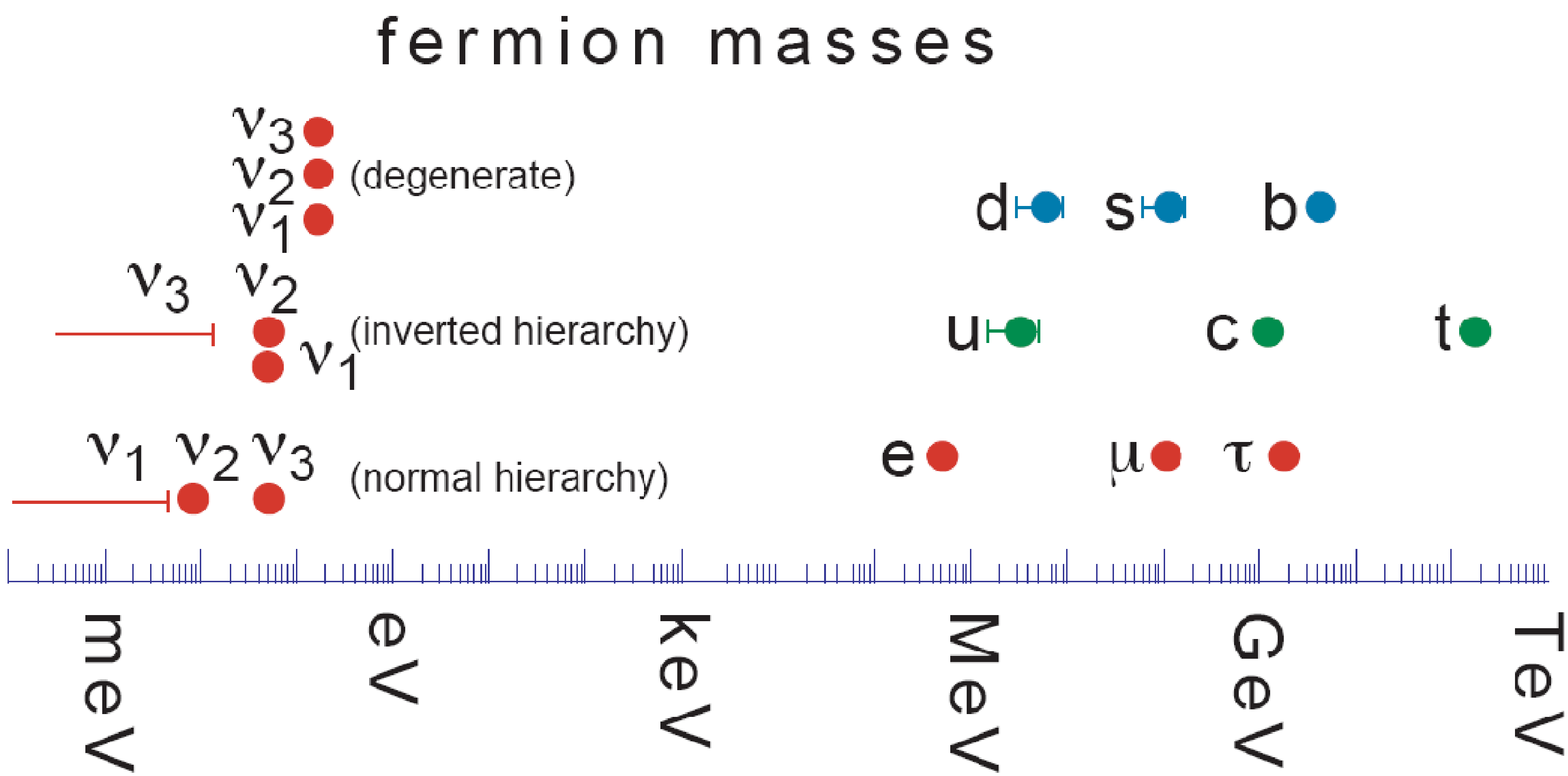
Introducing new particles without new forces, following prominent SM's Landmarks:

- 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

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

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

Type II — one heavy Higgs triplet $\Delta \sim (1,3,-2)$

$$\Delta \equiv \begin{pmatrix} \Delta^- & -\sqrt{2}\,\Delta^0 \\ \sqrt{2}\,\Delta^{--} & -\Delta^- \end{pmatrix}$$

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

Type III — three heavy triplet fermions $\Sigma \sim (1,3,0)$

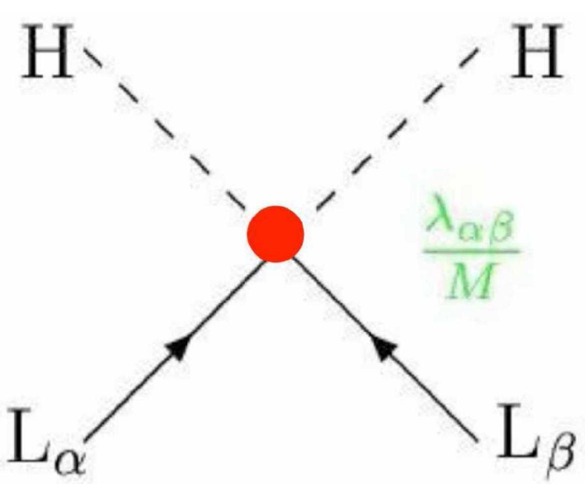
$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$

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

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

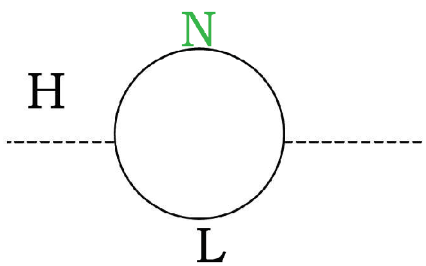
$$\frac{\mathcal{L}_{\rm d=5}}{\Lambda} = \begin{cases} \frac{1}{2}\left(Y_\nu M_{\rm R}^{-1} Y_\nu^T\right)_{\alpha\beta} \overline{l_{\alpha \rm L}} \tilde{H} \tilde{H}^T l^{\rm c}_{\beta \rm L} + {\rm h.c.} & ({\rm Type\ I}) \ , \\ -\frac{\lambda_\Delta}{M_\Delta} \left(Y_\Delta\right)_{\alpha\beta}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

SSB->Majorana mass



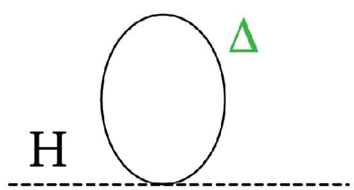
$$M_\nu = \begin{cases} -\frac{1}{2} Y_\nu \frac{v^2}{M_{\rm R}} Y_\nu^T & ({\rm Type\ I}) \ , \\ \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} & ({\rm Type\ II}) \ , \\ -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T & ({\rm Type\ III}) \end{cases}$$

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



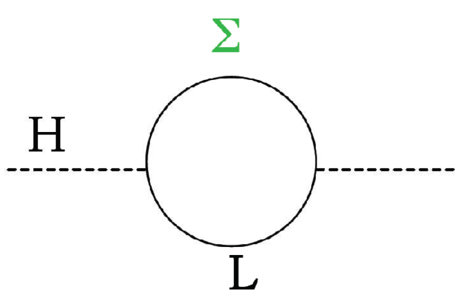
$$\delta m_H^2 = -\frac{Y_N^\dagger Y_N}{16\pi^2}\left[2\Lambda^2 + 2M_N^2 \log\frac{M_N^2}{\Lambda^2}\right]$$

(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:

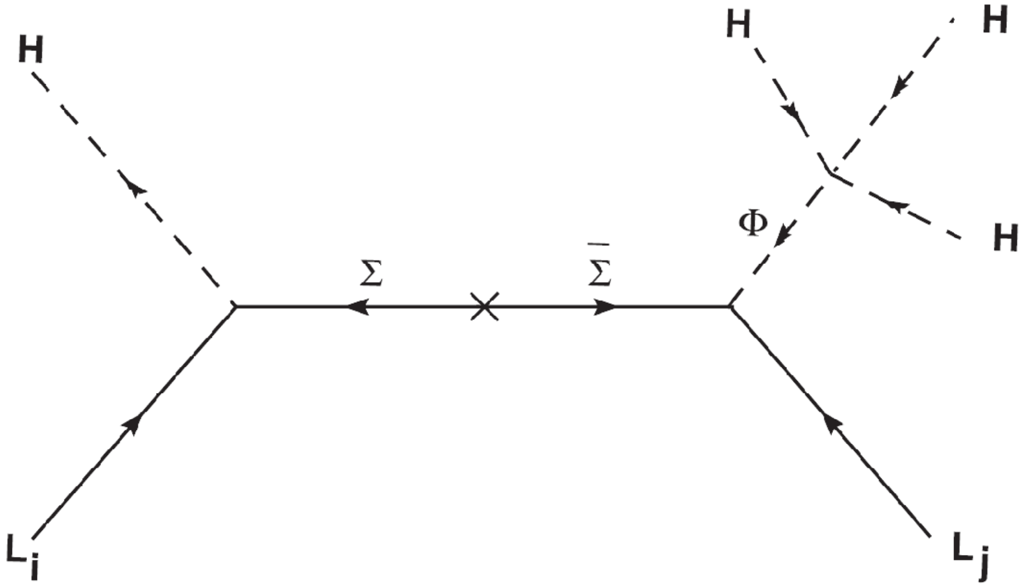
$$\begin{aligned} \mathcal{O}^5 &= \mathcal{O}_W = LLHH \\ \mathcal{O}^7 &= (LLHH)(H^\dagger H) \\ \mathcal{O}^9 &= (LLHH)(H^\dagger H)(H^\dagger H) \\ &\vdots \end{aligned}$$

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

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

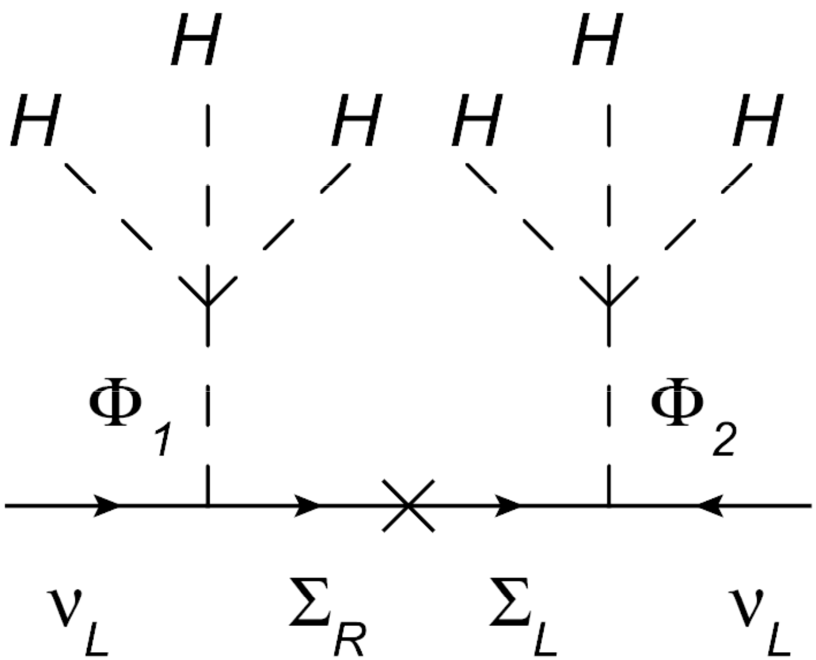
TwoTree-level Seesaw Options:
dim 7 and dim 9 operators



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

- **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 (T=2, Y=2) mediators

$$\Sigma_L = (\Sigma_L^{+++}, \Sigma_L^{++}, \Sigma_L^{+}, \Sigma_L^{0}, \Sigma_L^{-})$$
$$\Sigma_R = (\Sigma_R^{+++}, \Sigma_R^{++}, \Sigma_R^{+}, \Sigma_R^{0}, \Sigma_R^{-})$$
$$\text{both transforming as } (1,5,2)$$

- **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

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

Yukawa term includes
Lepton Number Violation

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

Dirac seesaw by diagonalizing the mass matrix

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

- 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 $\mu_H^2 < 0$

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

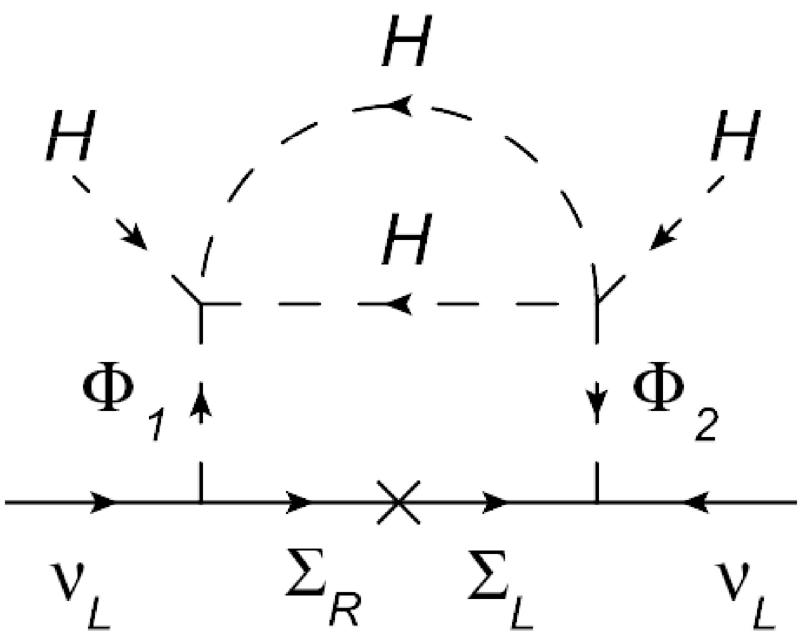
$$\begin{aligned}
&\sim \quad \mu_H^2 H^\dagger H + \mu_{\Phi_1}^2 \Phi_1^\dagger \Phi_1 + \mu_{\Phi_2}^2 \Phi_2^\dagger \Phi_2 + \lambda_H (H^\dagger H)^2 \\
&+ \quad \{\lambda_1 \Phi_1^* H^* H^* H^* + \text{H.c.}\} + \{\lambda_2 \Phi_2^* H H^* H^* + \text{H.c.}\} \\
&+ \quad \{\lambda_3 \Phi_1^* \Phi_2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

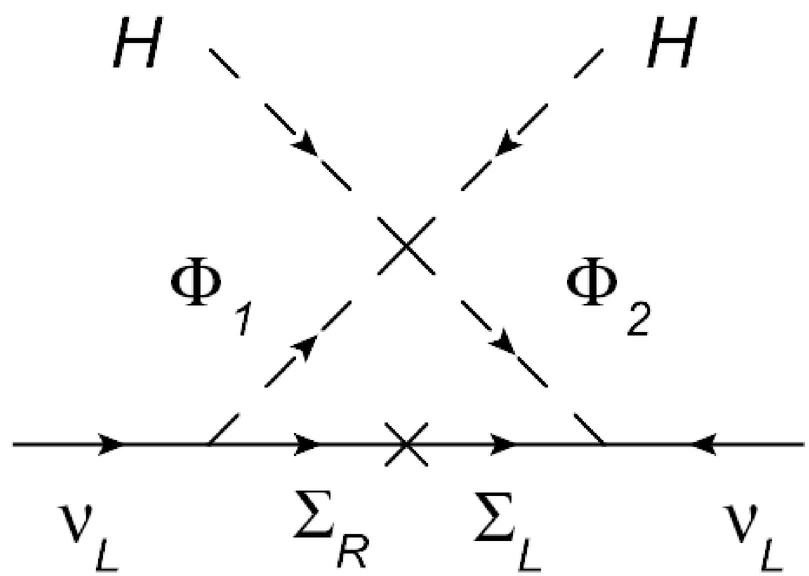
- Induced vev for Φ_1 and Φ_2, scalars with $\mu_{\Phi_1}^2, \mu_{\Phi_2}^2 > 0$

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

Operators of dim 5 generated at the loop level

suppressed by loop factors





Operator of dim 5 generated at two-loop level from dim 9 op.
- smaller than dim 9 tree level if

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

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

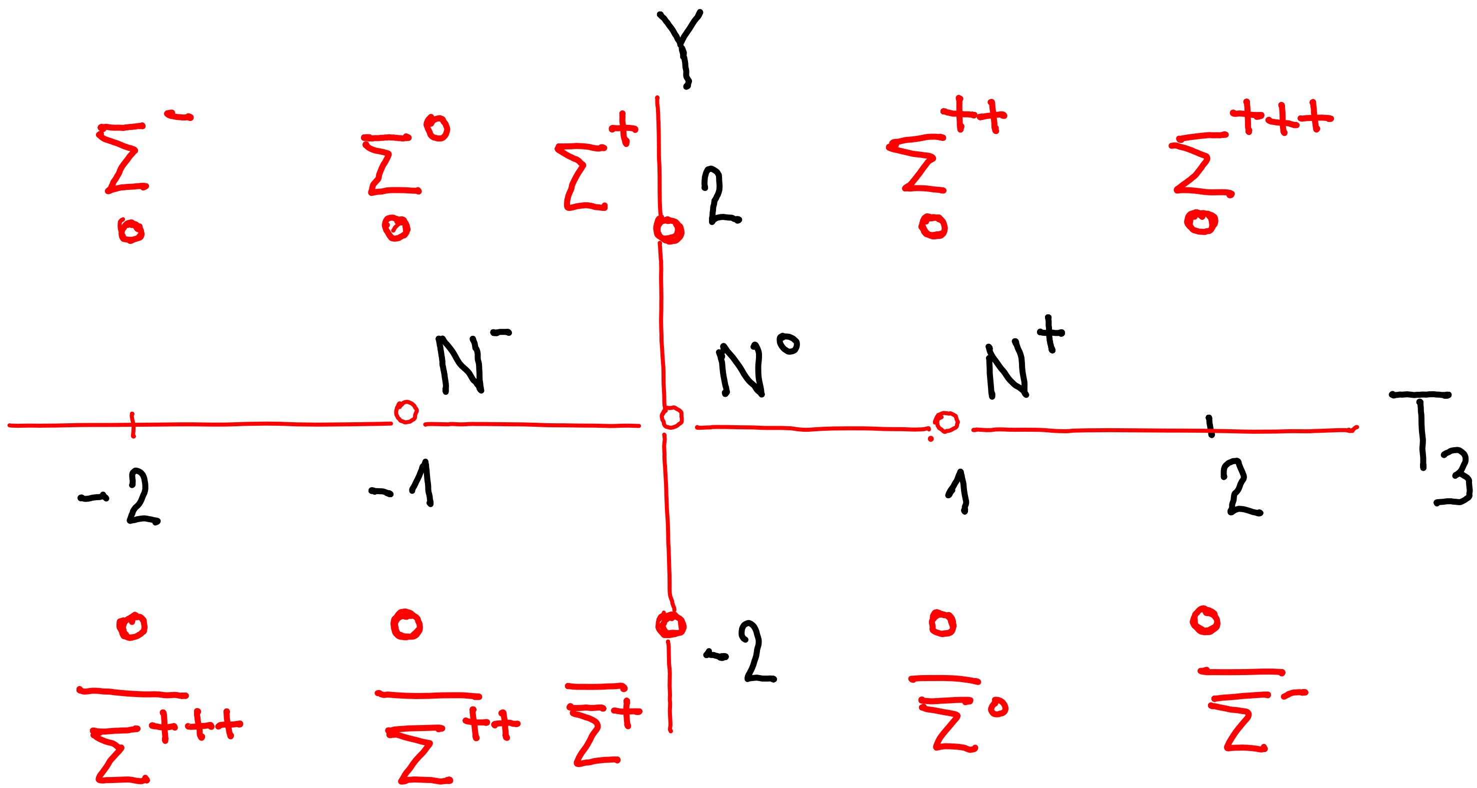
the values $v = 174$ GeV and $m_\nu \sim 0.1$ eV

& 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 contributions - **testable at the LHC**

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



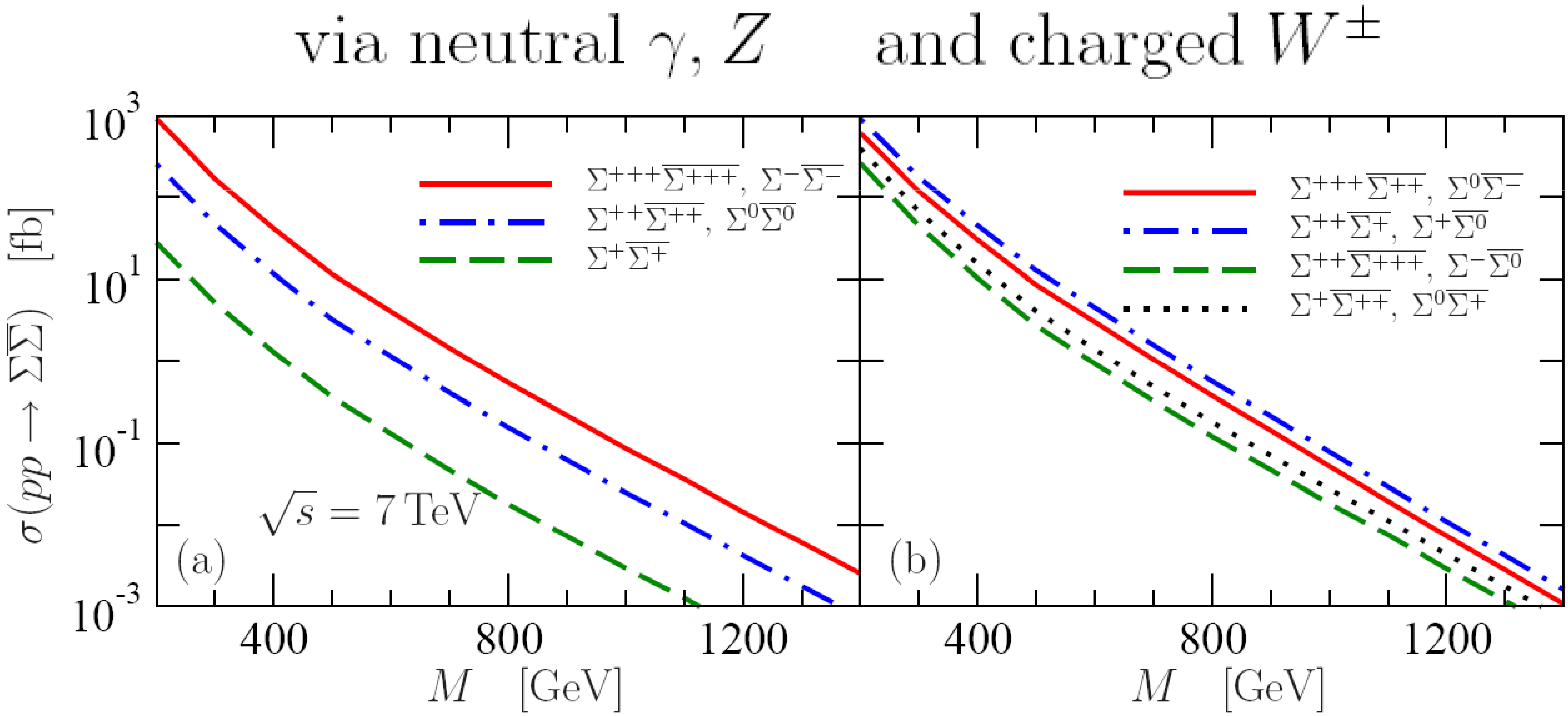
Drell-Yan production

- **Using CTEQ6.6 PDFs via LHAPDF**
- **Check by MadGraph via FeynRules**

Leading production rates for 400 GeV mass of new fermions

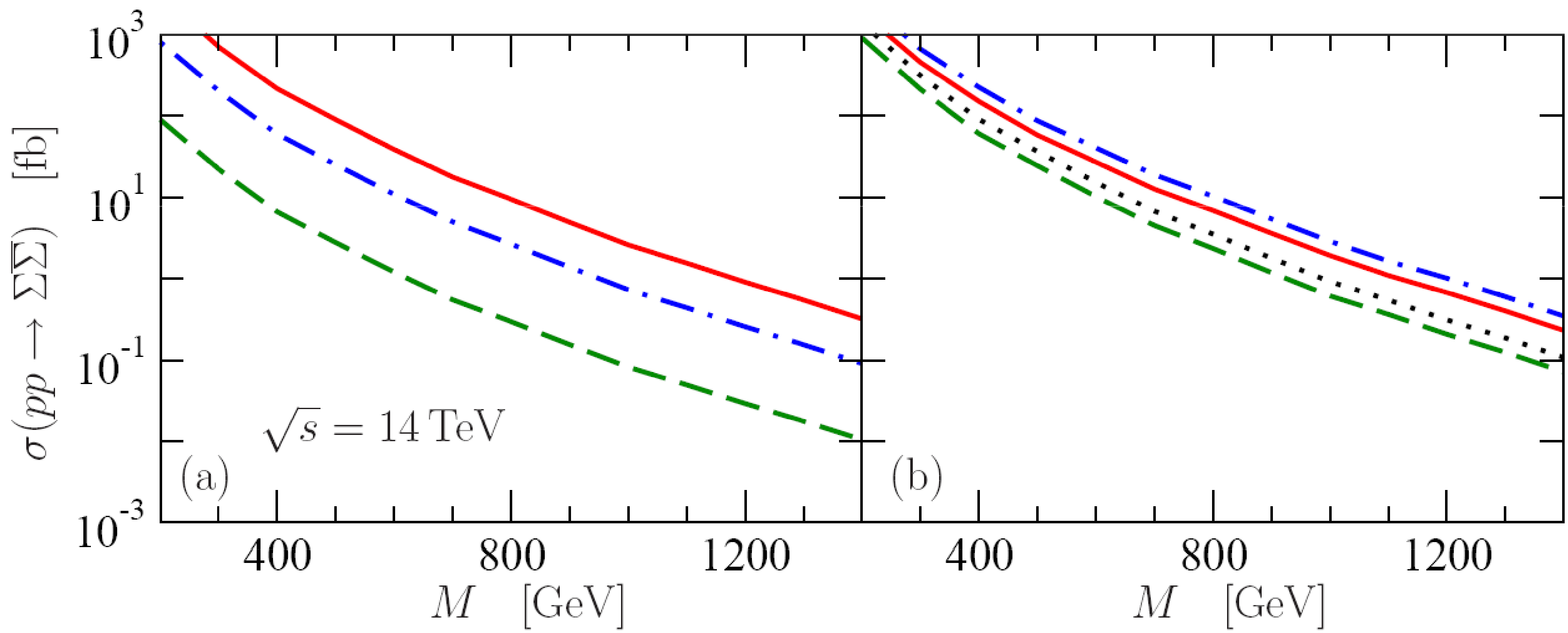
	Produced pair	σ/fb
Type III mediators	N^+N^0	90
5-plet mediators	$\Sigma^{+++}\overline{\Sigma^{++}}$	180
	$\Sigma^{++}\overline{\Sigma^{+}}$	270
	$\Sigma^{+}\overline{\Sigma^{0}}$	270
	$\Sigma^{+++}\overline{\Sigma^{+++}}$	230
	$\Sigma^{-}\overline{\Sigma^{-}}$	210
All 5-plet productions	Total	2000

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



Production cross section for 5-plets for designed LHC energy

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



$\sqrt{s} = 7$ TeV

Produced pair	σ/fb		
	M=300 GeV	M=500 GeV	M = 700 GeV
$\Sigma^{+++}\overline{\Sigma^{+++}}$, $\Sigma^{-}\overline{\Sigma^{-}}$	184	15	2
$\Sigma^{++}\overline{\Sigma^{++}}$, $\Sigma^{0}\overline{\Sigma^{0}}$	51	4	1
$\Sigma^{+}\overline{\Sigma^{+}}$	6	0	0
$\Sigma^{+++}\overline{\Sigma^{++}}$, $\Sigma^{0}\overline{\Sigma^{-}}$	129	11	2
$\Sigma^{++}\overline{\Sigma^{+}}$, $\Sigma^{+}\overline{\Sigma^{0}}$	194	17	2
$\Sigma^{++}\overline{\Sigma^{+++}}$, $\Sigma^{-}\overline{\Sigma^{0}}$	49	4	0
$\Sigma^{+}\overline{\Sigma^{++}}$, $\Sigma^{0}\overline{\Sigma^{+}}$	73	5	1

$\sqrt{s} = 14$ TeV

Produced pair	σ/fb		
	M=300 GeV	M=500 GeV	M = 700 GeV
$\Sigma^{+++}\overline{\Sigma^{+++}}$, $\Sigma^{-}\overline{\Sigma^{-}}$	709	98	23
$\Sigma^{++}\overline{\Sigma^{++}}$, $\Sigma^{0}\overline{\Sigma^{0}}$	197	27	6
$\Sigma^{+}\overline{\Sigma^{+}}$	21	3	1
$\Sigma^{+++}\overline{\Sigma^{++}}$, $\Sigma^{0}\overline{\Sigma^{-}}$	453	66	16
$\Sigma^{++}\overline{\Sigma^{+}}$, $\Sigma^{+}\overline{\Sigma^{0}}$	679	100	24
$\Sigma^{++}\overline{\Sigma^{+++}}$, $\Sigma^{-}\overline{\Sigma^{0}}$	209	27	6
$\Sigma^{+}\overline{\Sigma^{++}}$, $\Sigma^{0}\overline{\Sigma^{+}}$	314	40	9

The decays of Dim 9 states generalize those for Type III triplet states

$$\Gamma(\Sigma^+ \to \Sigma^0 \pi^+) = \Gamma(\overline{\Sigma^+} \to \overline{\Sigma^0} \pi^-) = $$

$$= \frac{6 G_F^2 |V_{ud}|^2 (\Delta M_0)^3 f_\pi^2}{\pi} \sqrt{1 - \frac{m_\pi^2}{(\Delta M_0)^2}}$$

$$\Gamma(\Sigma^{+++} \to \Sigma^{++} \pi^+) = \Gamma(\overline{\Sigma^{+++}} \to \overline{\Sigma^{++}} \pi^-) = $$

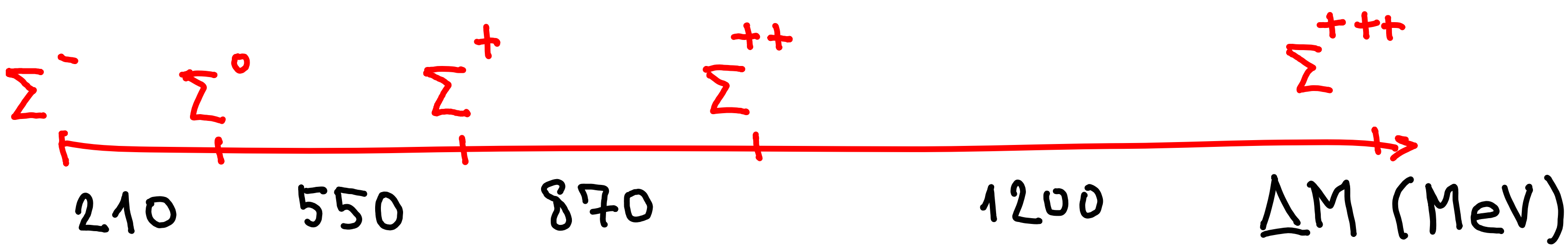
$$= \frac{4 G_F^2 |V_{ud}|^2 (\Delta M_2)^3 f_\pi^2}{\pi} \sqrt{1 - \frac{m_\pi^2}{(\Delta M_2)^2}}$$

Suppression by small mass splittings within a multiplet

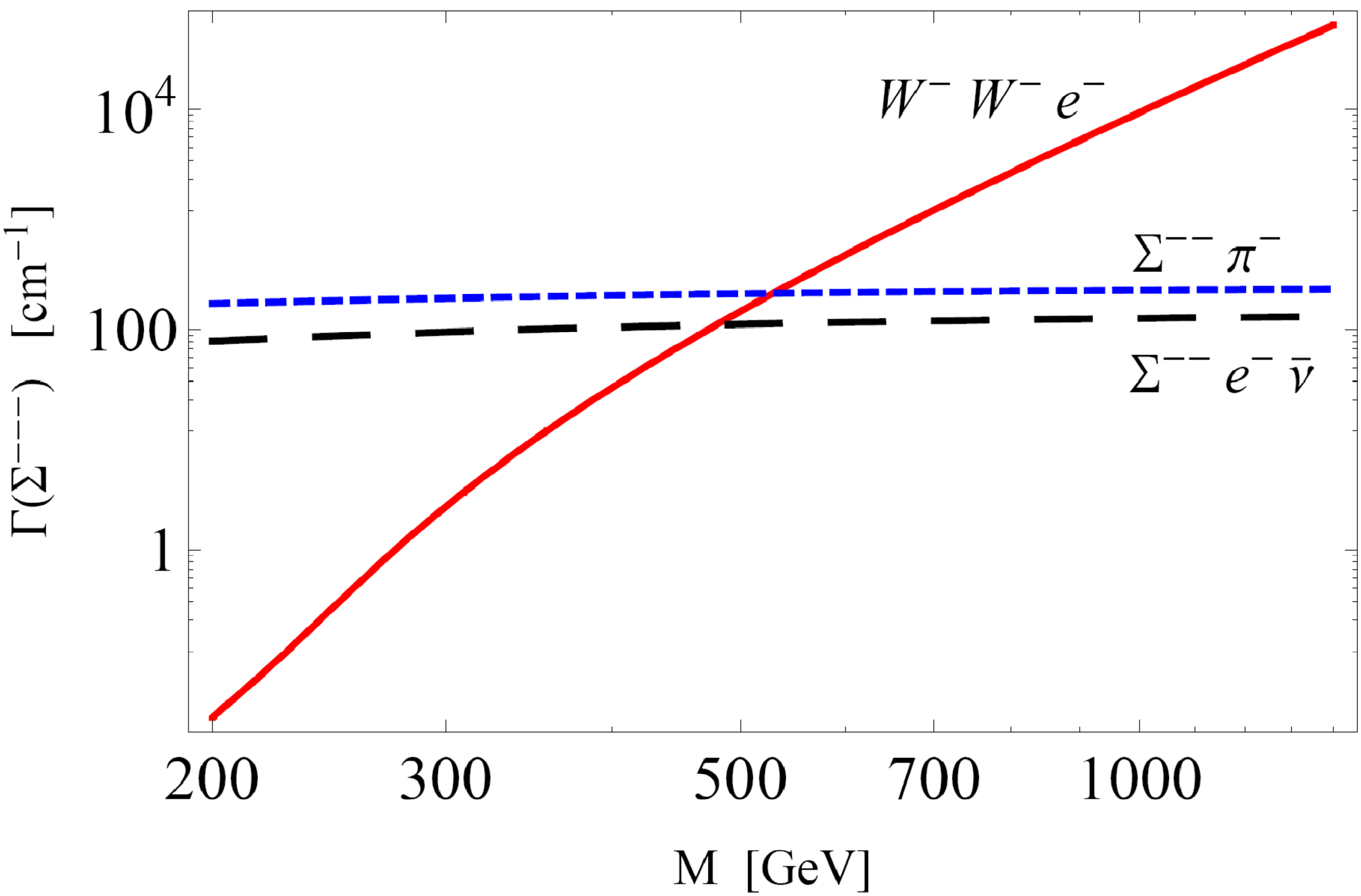
$$M_Q - M_0 \simeq Q(Q + Y/\cos\theta_W)\Delta M$$

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

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



Decay widths of triply-charged Σ



Signatures from LNC & LNV decays

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

$$\Sigma^+ \to W^+\nu, Zl^+, H^0l^+$$

$$\Sigma^- \to W^-\nu, Zl^-, H^0l^-$$

$$\Sigma^0 \to W^\pm l^\mp, Z\nu, H^0\nu$$

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

$$q\bar{q}' \to W^* \to \Sigma^+\overline{\Sigma^0} \to l^+Zl^+W^- \to l^+l^+jj \ ,$$

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

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