Rare Higgs Decays and TeV-scale "Type V" Neutrino Mass Model

Ivica Picek
University of Zagreb, Croatia

(with Branimir Radovčić and Krešimir Kumerički)

Portorož, 16 April 2013

New Particles
without new forces, motivated by

the evidence for a Dark Matter

&

the prominent SM's Landmarks:

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

Neutrino Mass

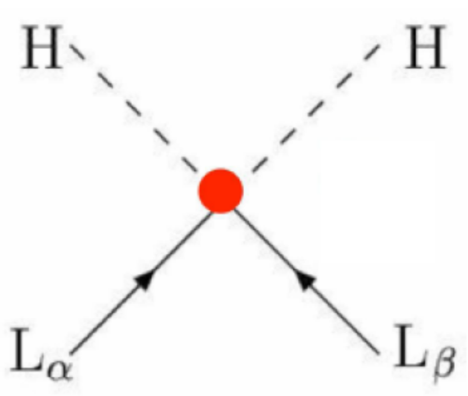
as most tangible BSM with new particles producing effective Dimension 5 neutrino-mass operator

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\lambda}{M}\underbrace{\bar{L}\tilde{H}\tilde{H}^T L^c}_{dim-5} + O(\frac{1}{M^2})$$

L_L — lepton doublet

H — Higgs boson doublet

M — heavy mass



$$\langle H\rangle_0 = v \quad \longrightarrow \quad m_\nu \sim \lambda v \left(\frac{v}{M}\right)$$

Dim-5 Seesaw Operator

Only 3 realizations at tree-level

- single BSM particle with SM charges

Type I — three heavy right-handed neutrinos

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

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

E. Ma, Phys. Rev. Lett. **81**, 1171 (1998)

Scale of New Physics for Type I, II and III Seesaw

- Type I [Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanović 79]
- Type II [Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al. 80; Mohapatra, Senjanović 80; Gelmini, Roncadelli 80]
- Type III [Foot, Lew, He, Joshi 89]

Taking empirical values $m_\nu \sim 0.1\,\mathrm{eV}$, $v = 246\,\mathrm{GeV}$ and natural value $\lambda = O(1)$ one gets

$$M \sim 10^{14}\,\mathrm{GeV}$$

But for such large M there is no hope of direct observation of either M-particles or $O(1/M^2)$ effects $\Rightarrow$ No new discoveries at LHC!

Lowering the seesaw scale
by going to Dim>5 operators

$$\mathcal{O}^{D=5} = \mathcal{O}_{\rm Weinberg} = LLHH$$
$$\mathcal{O}^{D=7} = (LLHH)(H^\dagger H)$$
$$\mathcal{O}^{D=9} = LLHH(H^\dagger H)(H^\dagger H)$$
$$\cdots$$

$$m_\nu \sim v \left(\frac{v}{M}\right)^{D-4}$$

D=9 and $M \sim \mathrm{TeV}$ is enough to get sub-eV neutrino mass

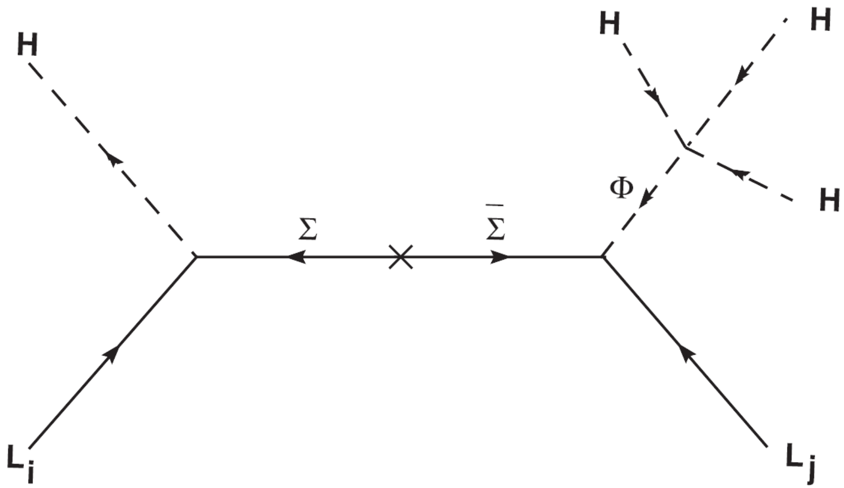
F. Bonnet, D. Hernandez, T. Ota and W. Winter, JHEP **0910**:076,2009 [0907.3143 [hep-ph]];

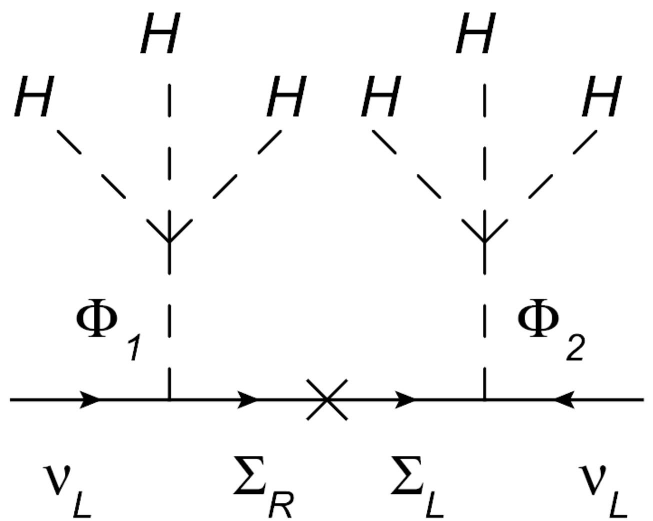
Only 2 realizations of dim>5 operator with Dirac fermion tree-level seesaw mediator

Seesaw Type	Exotic Fermion	Exotic Scalar	Scalar Coupling	m_ν at
Type I	$N_R \sim (1,0)$	-	-	dim 5
Type II	-	$\Delta \sim (3,2)$	$\mu \Delta H H$	dim 5
Type III	$N_R \sim (3,0)$	-	-	dim 5
Conjunct Mediator	Exotic Fermion Pair	Exotic Scalars $\Phi_1,\ \Phi_2$	Scalar - Higgs Couplings	m_ν at
doublet	$\Sigma_{L,R}\ (2,1)$	$(3,-2),\ (3,0)$	$\mu_{1,2}\Phi_{1,2}HH$	dim 5
triplet	$\Sigma_{L,R}\ (3,2)$	$(4,-3),\ (2,-1)$	$\lambda_1\Phi_1 HHH$	**dim 7**
quadruplet	$\Sigma_{L,R}\ (4,1)$	$(3,-2),\ (3,0)$	$\mu_{1,2}\Phi_{1,2}HH$	dim 5
quintuplet	$\Sigma_{L,R}\ (5,2)$	$(4,-3),\ (4,-1)$	$\lambda_{1,2}\Phi_{1,2}HHH$	**dim 9**

Two “TypeIV” Seesaw

dim 7 and dim 9 operators

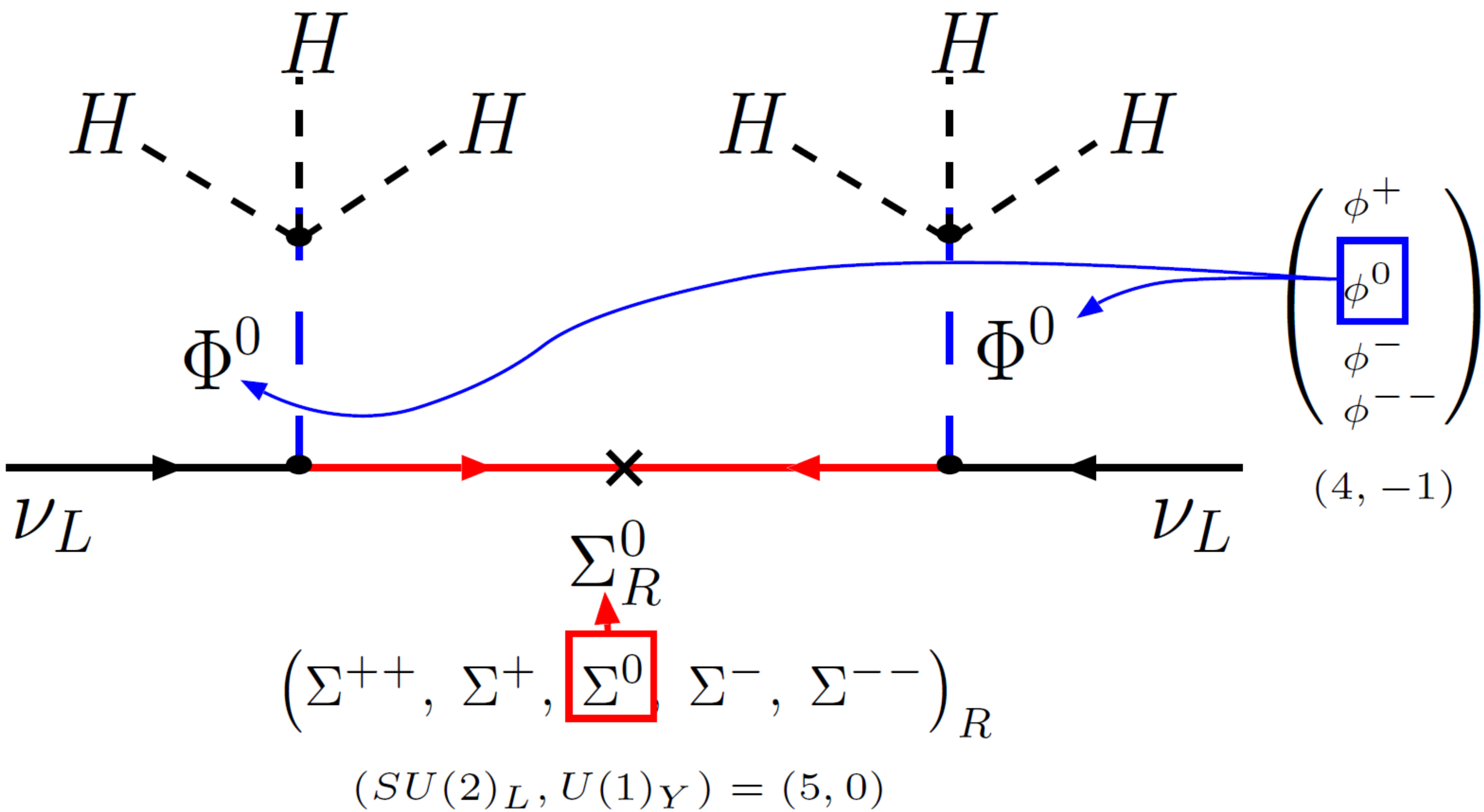




- **Dim 7 Operator,** Babu et al/0905.2710 (PRD)
- **Dim 9 Operator,** IP & BR/0911.1374 (PLB); KPR/1106.1069 (PRD)

"Type V" Seesaw

(5, 0) instead of (3, 0) in Type III



EWSB in usual way from the Higgs doublet

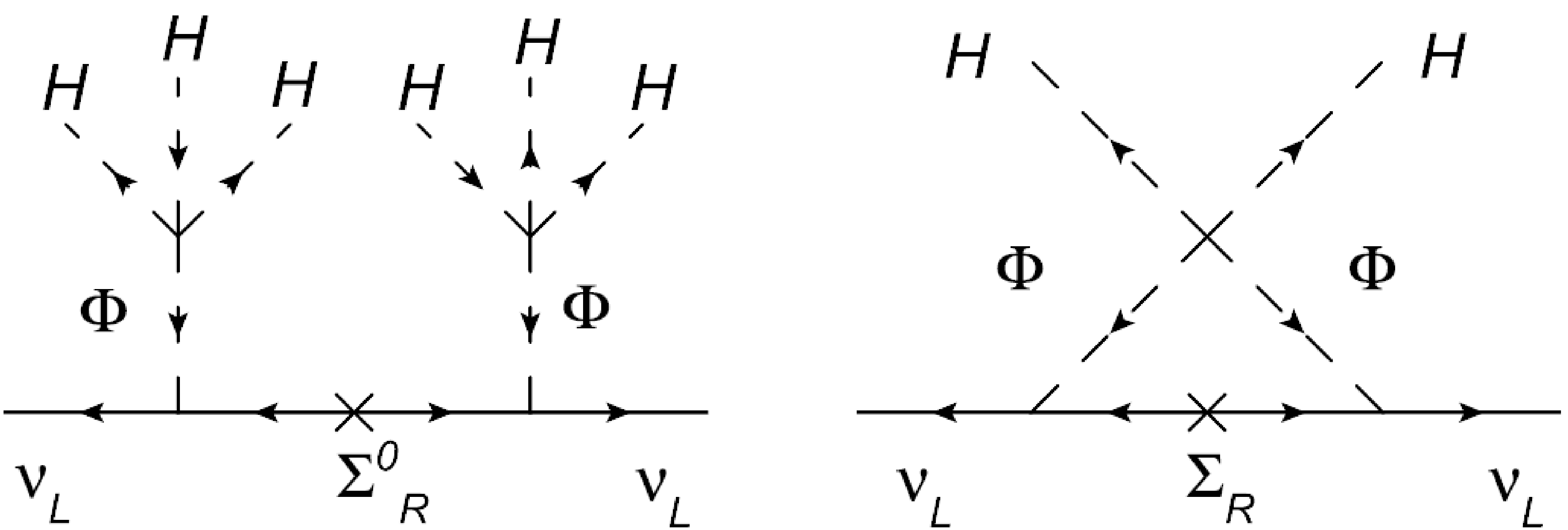
$$V(H,\Phi) = -\mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_1 \left(H^\dagger H\right)^2 + \lambda_2 H^\dagger H \Phi^\dagger \Phi$$
$$+ \lambda_3 H^* H \Phi^* \Phi + \left(\lambda_4 H^* H H \Phi + \text{H.c.}\right)$$
$$+ (\lambda_5 H H \Phi \Phi + \text{H.c.}) + \left(\lambda_6 H \Phi^* \Phi \Phi + \text{H.c.}\right)$$
$$+ \lambda_7 \left(\Phi^\dagger \Phi\right)^2 + \lambda_8 \Phi^* \Phi \Phi^* \Phi.$$

- Induced vev for quadruplet scalar Φ

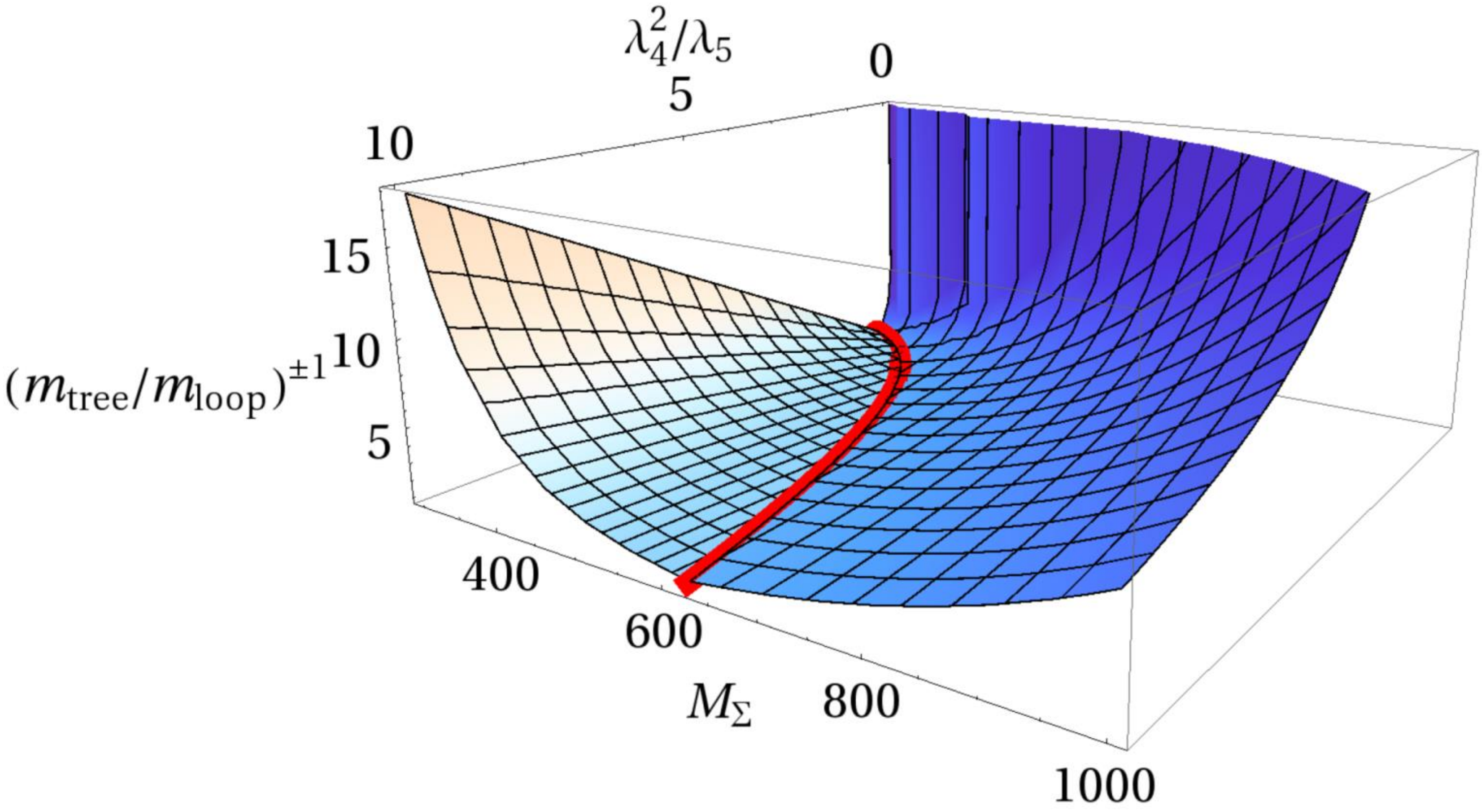
$$v_\Phi \simeq -\frac{1}{\sqrt{3}} \lambda_4^* \frac{v^3}{\mu_\Phi^2}$$

Seesaw w.r.t. Radiative

Mass ~ $$\frac{-1}{6}(\lambda_4^*)^2\frac{v^6}{\mu_\Phi^4}\sum_k \frac{Y_{ik}Y_{jk}}{M_k} + \frac{-5\lambda_5^* v^2}{24\pi^2}\sum_k \frac{Y_{ik}Y_{jk}M_k}{m_\Phi^2 - M_k^2}$$



Tree w.r.t. Radiative dominance



The options:

- **Real**
- **Virtual**
- **Scotogenic**

the loop contribution dominates for heavy masses and remains a sole contribution if additional discrete Z_2 symmetry forbids the λ_4 term

$$(m_\nu)^{\text{loop}}_{ij} = \frac{-5\lambda_5^* v^2}{24\pi^2} \sum_k \frac{Y_{ik} Y_{jk} M_k}{m_\Phi^2 - M_k^2} \left[1 - \frac{M_k^2}{m_\Phi^2 - M_k^2} \ln \frac{m_\Phi^2}{M_k^2} \right]$$

E. Ma, *Verifiable radiative seesaw mechanism of neutrino mass and dark matter*, Phys. Rev. D **73**, 077301 (2006) [hep-ph/0601225].

Real Heavy Leptons @LHC

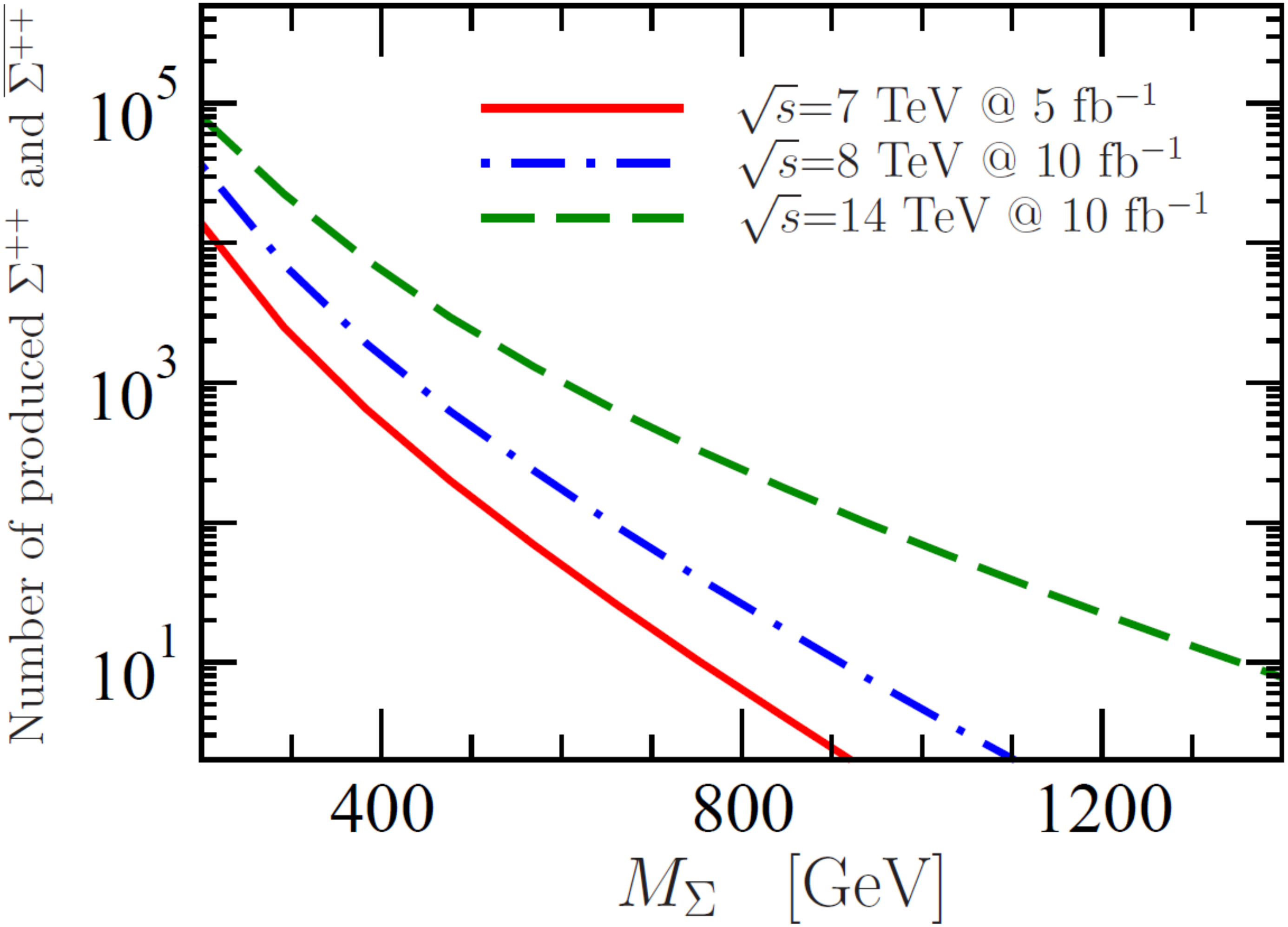
K. Kumerički, I. Picek, B. Radovčić, Phys. Rev. D 86 (2012) 013006, arXiv: 1204.6599 [hep-ph].

TABLE I. Production cross sections for Σ-$\bar{\Sigma}$ pairs for the LHC run at $\sqrt{s} = 7$ TeV, for three selected values of M_Σ.

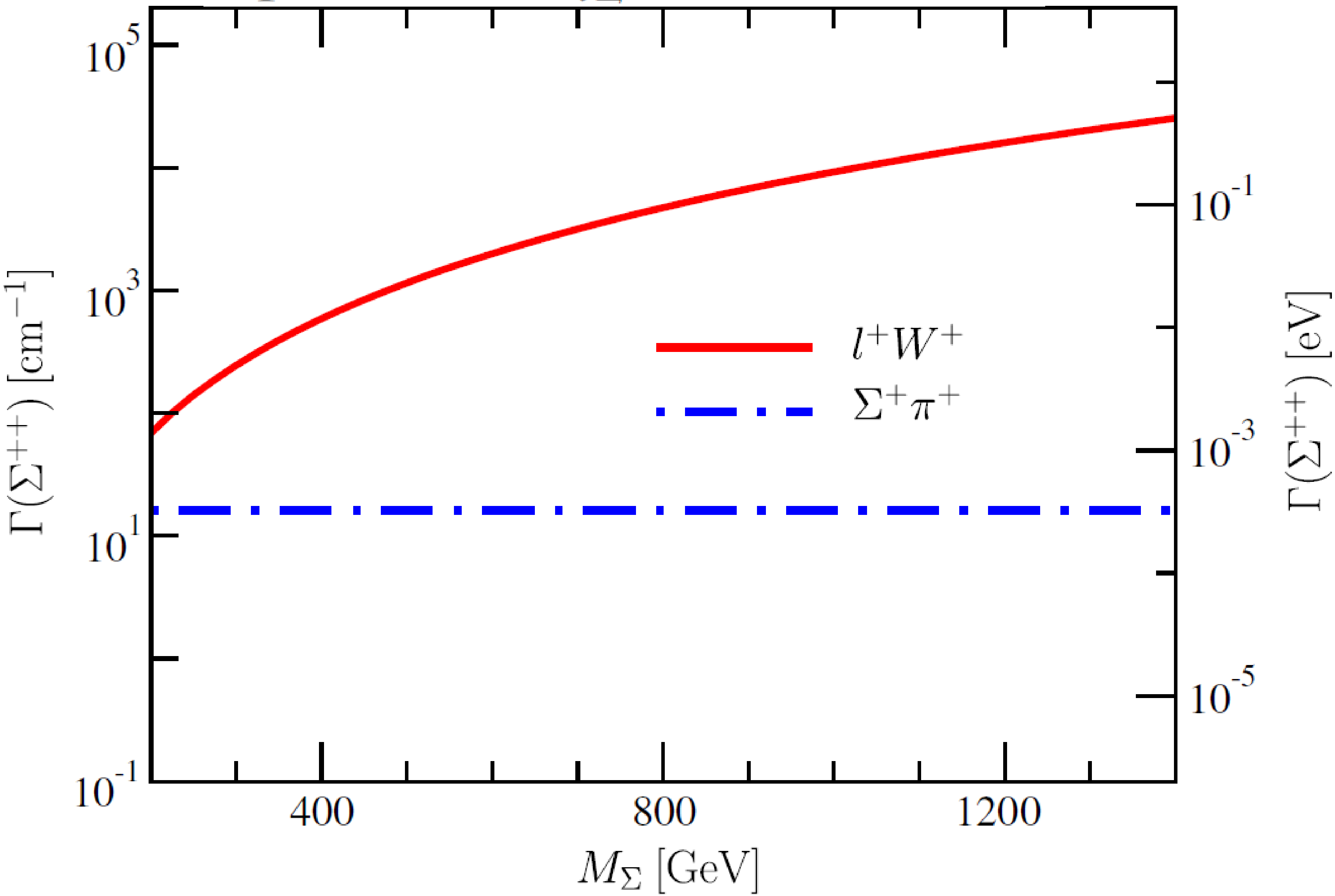
Produced pair	Cross section (fb) $M_\Sigma = 200$ GeV	$M_\Sigma = 400$ GeV	$M_\Sigma = 800$ GeV
$\Sigma^{++}\overline{\Sigma^{++}}$	924	34.4	0.43
$\Sigma^{+}\overline{\Sigma^{+}}$	231	8.6	0.11
$\Sigma^{++}\overline{\Sigma^{+}}$	641	26.5	0.32
$\Sigma^{+}\overline{\Sigma^{0}}$	961	39.8	0.49
$\Sigma^{+}\overline{\Sigma^{++}}$	276	9.1	0.10
$\Sigma^{0}\overline{\Sigma^{+}}$	414	13.6	0.15
Total	3447	132	1.6

Doubly-charged leptons @LHC

K. Kumerički, I. Picek, B. Radovčić, Phys. Rev. D 86 (2012) 013006, arXiv: 1204.6599 [hep-ph].



Partial decay widths of Σ^{++} lepton for $|V_{l\Sigma}| = 3.5 \times 10^{-7}$



The distinctive signatures good for the discovery

$$(i) \qquad p\,p \to \Sigma^+ \,\overline{\Sigma^0} \to (\ell^+ Z^0)\,(\ell^+ W^-)$$

the LNV event having 0.7 fb
with the same-sign dilepton state,

$$(ii) \qquad p\,p \to \Sigma^{++} \,\overline{\Sigma^+} \to (\ell^+ W^+)\,(\ell^- Z^0)$$

having relatively high signal rate of 1.1 fb
with respect to the SM background of 0.8 fb.

Virtual Physics in the LHC Era

Enhancement of $h \to \gamma\gamma$

$$\frac{[\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)]_{\mathrm{LHC}}}{[\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)]_{\mathrm{SM}}} = 1.71 \pm 0.33$$

even if this enhancement in $h \to \gamma\gamma$ disappears
it will still constrain the parameter space
of the extensions of the SM by new charged states

Actually, there is no consensus
between the ATLAS Collaboration 1.6 ± 0.3
and CMS Collaboration values 0.78 ± 0.27 and 1.11 ± 0.31

Virtual Charged Scalars @LHC

$$\Gamma(h \to \gamma\gamma) =$$

$$\frac{\alpha^2 m_h^3}{256\pi^3 v_H^2} \left| A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t) + N_{c,S} Q_S^2 \frac{c_S}{2} \frac{v_H^2}{m_S^2} A_0(\tau_S) \right|^2$$

to get an enhancement of the $h \to \gamma\gamma$ decay rate, requires negative couplings c_S, we assume $\lambda_{2,3} < 0$. For simplicity we assume $\lambda_2 = \lambda_3 = \lambda$, and restrict ourselves to the interval $\lambda \in [-2, 0]$.

$$\Gamma(h \to Z\gamma) = \frac{\alpha^2 m_h^3}{128\pi^3 v_H^2 \sin^2\theta_w} \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 |\mathcal{A}_{SM} + \mathcal{A}_S|^2$$

The couplings relevant for the diphoton decay

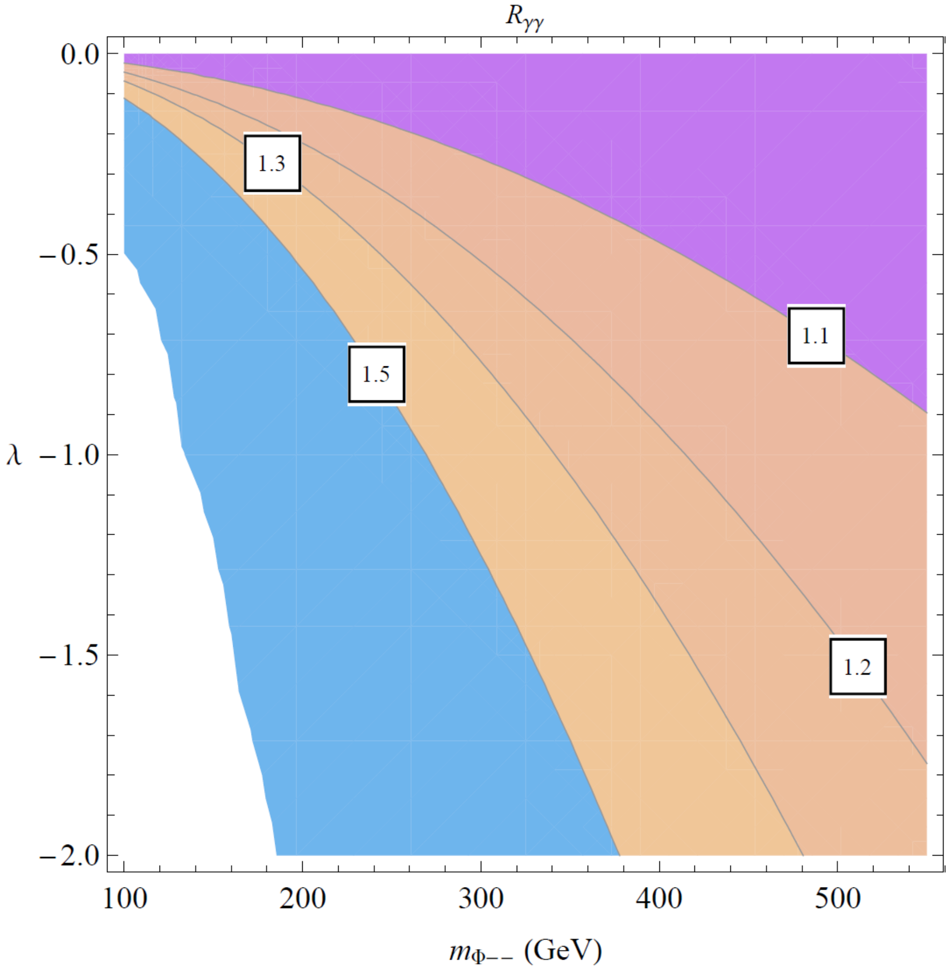
$$-\mathcal{L} = c_{\Phi^+} v_H h^0 \Phi^{+*} \Phi^+ + c_{\Phi^-} v_H h^0 \Phi^{-*} \Phi^-$$
$$+ c_{\Phi^{--}} v_H h^0 \Phi^{--*} \Phi^{--},$$

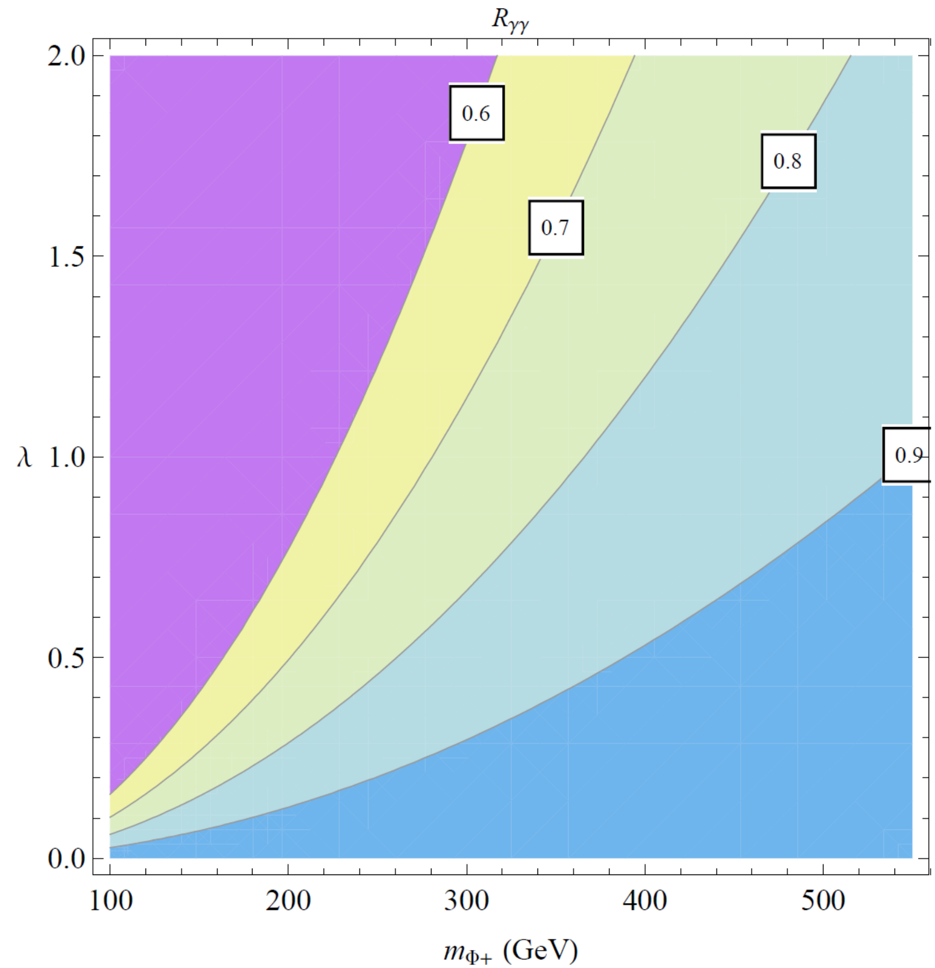
where the newly introduced couplings

$$c_{\Phi^+} = \lambda_2, \qquad c_{\Phi^-} = \lambda_2 + \frac{2}{3}\lambda_3, \qquad c_{\Phi^{--}} = \lambda_2 + \lambda_3,$$

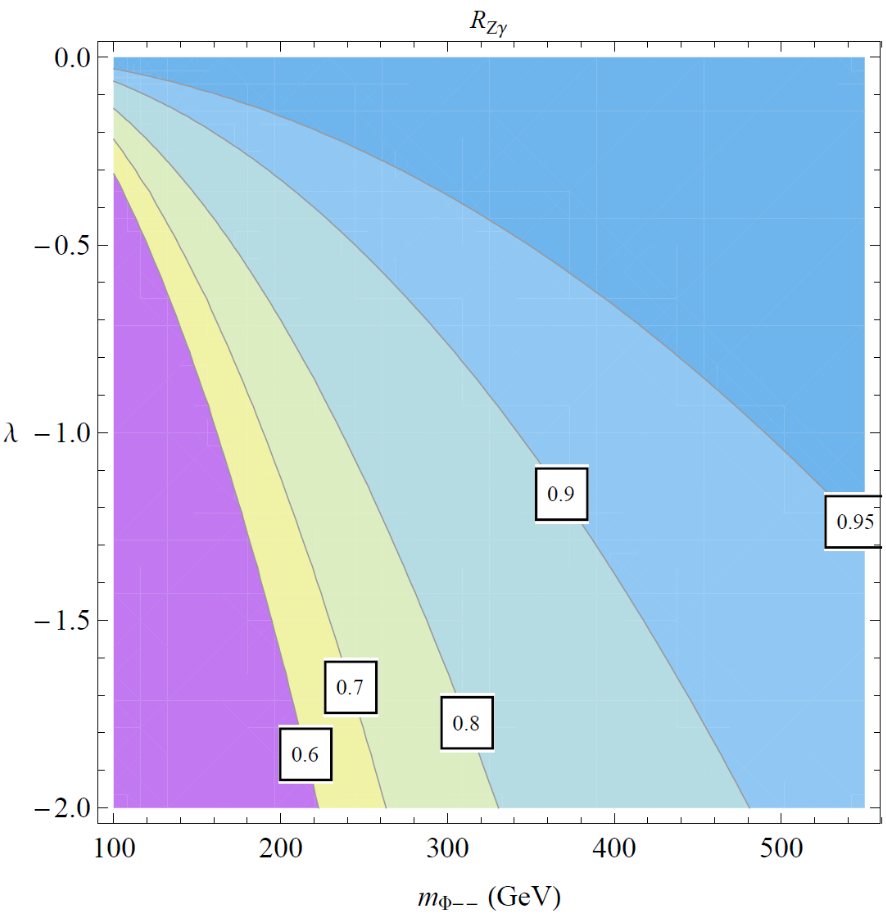
are expressed in terms of the quartic couplings λ_2 and λ_3

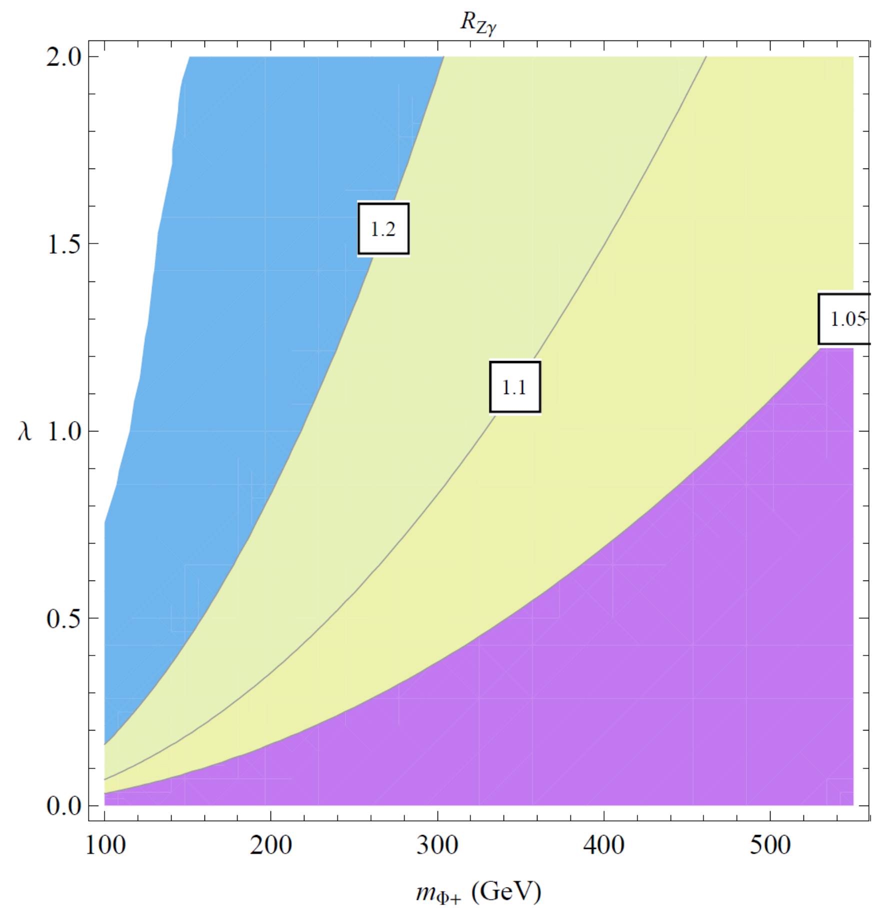
$$R_{\gamma\gamma} = \left| 1 + \sum_{S=\Phi^+,\Phi^-,\Phi^{--}} Q_S^2 \frac{c_S}{2} \frac{v_H^2}{m_S^2} \frac{A_0(\tau_S)}{A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)} \right|^2$$





$$R_{Z\gamma} = \left| 1 + \sum_{S=\Phi^+,\Phi^-,\Phi^{--}} \frac{\mathcal{A}_S}{\mathcal{A}_{SM}} \right|^2$$





Scotogenic Option

By exploring the conditions under which the quintuplets $\Sigma_R \sim (1,5,0)$
so-called minimal dark matter (MDM)

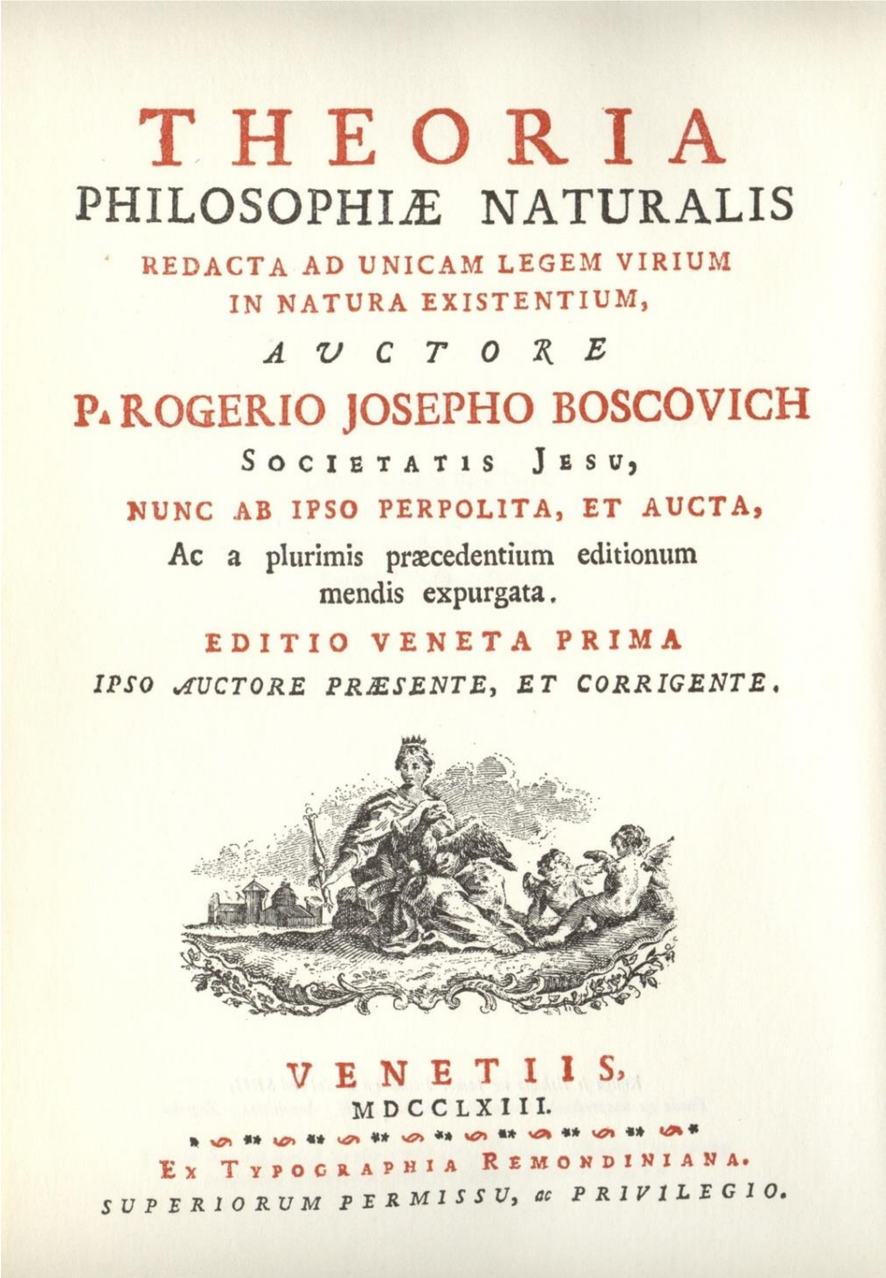
M. Cirelli, N. Fornengo and A. Strumia, *Minimal dark matter*, Nucl. Phys. B **753** (2006) 178

generate neutrino masses and provide a stable DM candidate

not possible without imposing the discrete Z_2 symmetry

K. Kumerički, I. Picek and B. Radovčić, *Critique of Fermionic RνMDM and its Scalar Variants*, JHEP **1207**, 039 (2012) [1204.6597 [hep-ph]].

250 anniversary of Bošković's "Theoria" & of the DM idea



Seems timely to recall thoughts in point # 518 therein

"It could be possible to imagine that there is no force between some of existing species. In this case, the substance of one kind might freely pass through that of another, without any collision.

In the same way, two of the species might have a common force law with third species, without any force between the first two".

Rogerio Josepho Boscovich, *Theoria Philosophiae Naturalis*, Venetiis, 1763; *A Theory of Natural Philosophy*, Chicago and London: Open Court Publishing Company, 1922 (Dual text in Latin and English).

3 Regimes of the “Type V” Seesaw

- Real – heavy lepton signals @LHC

Falsifiable dim 9 operator

- Virtual – charged scalars in loops

Measured rare decays of the higgs

- DM (Scotogenic)

Virtual Physics in the LHC-era