Natural and Dynamical Neutrino Mass Mechanism at the LHC

Yuber F. Perez-Gonzalez

In collaboration with Julia Gehrlein,
Dorival Gonçalves and Pedro A. N. Machado

NuTheories: Beyond the 3 × 3 Paradigm
Pittsburgh, Nov 2018

Fermilab

Based on PRD 98 (2018) 3, 035045
arXiv:1804.09184

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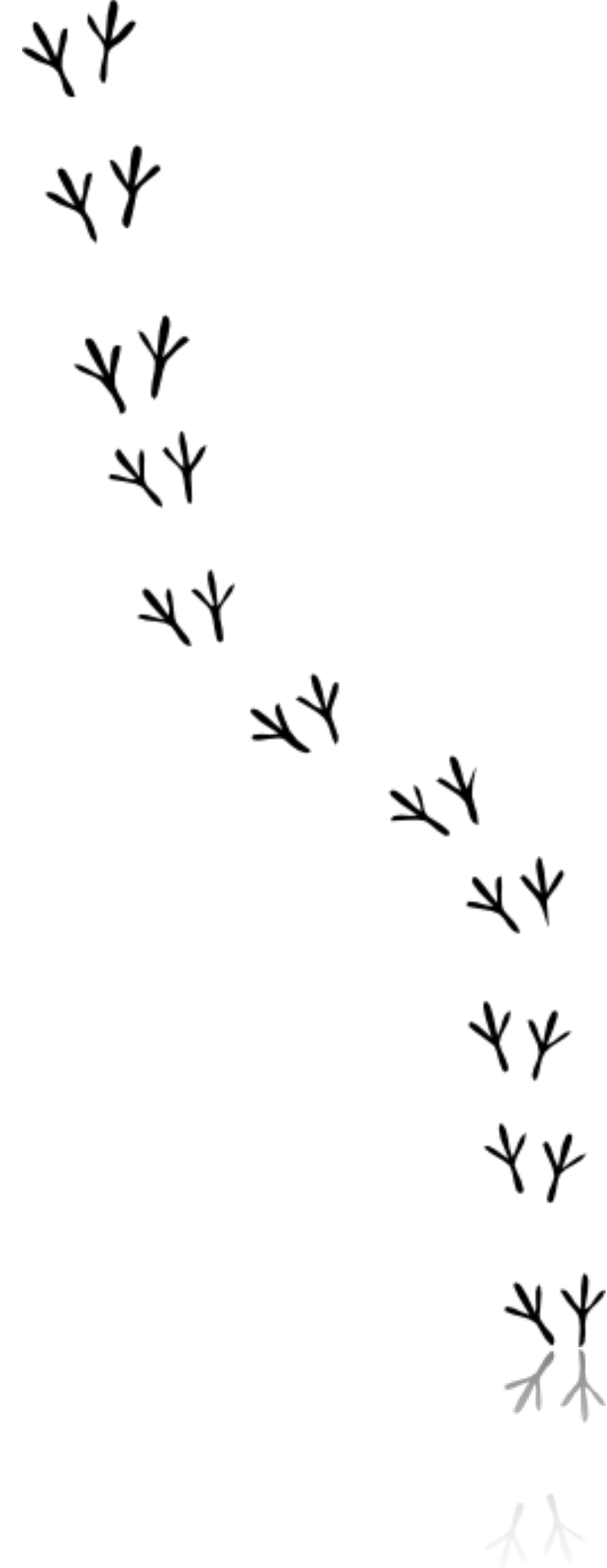
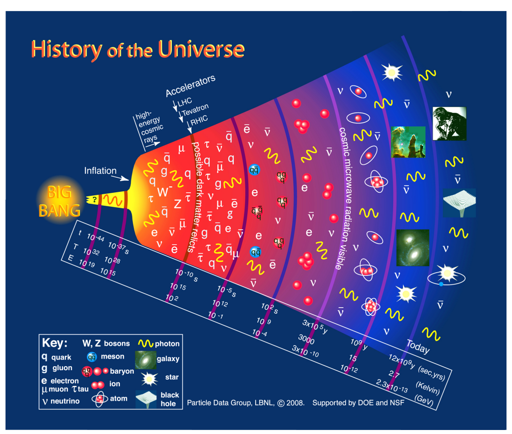
Outlook

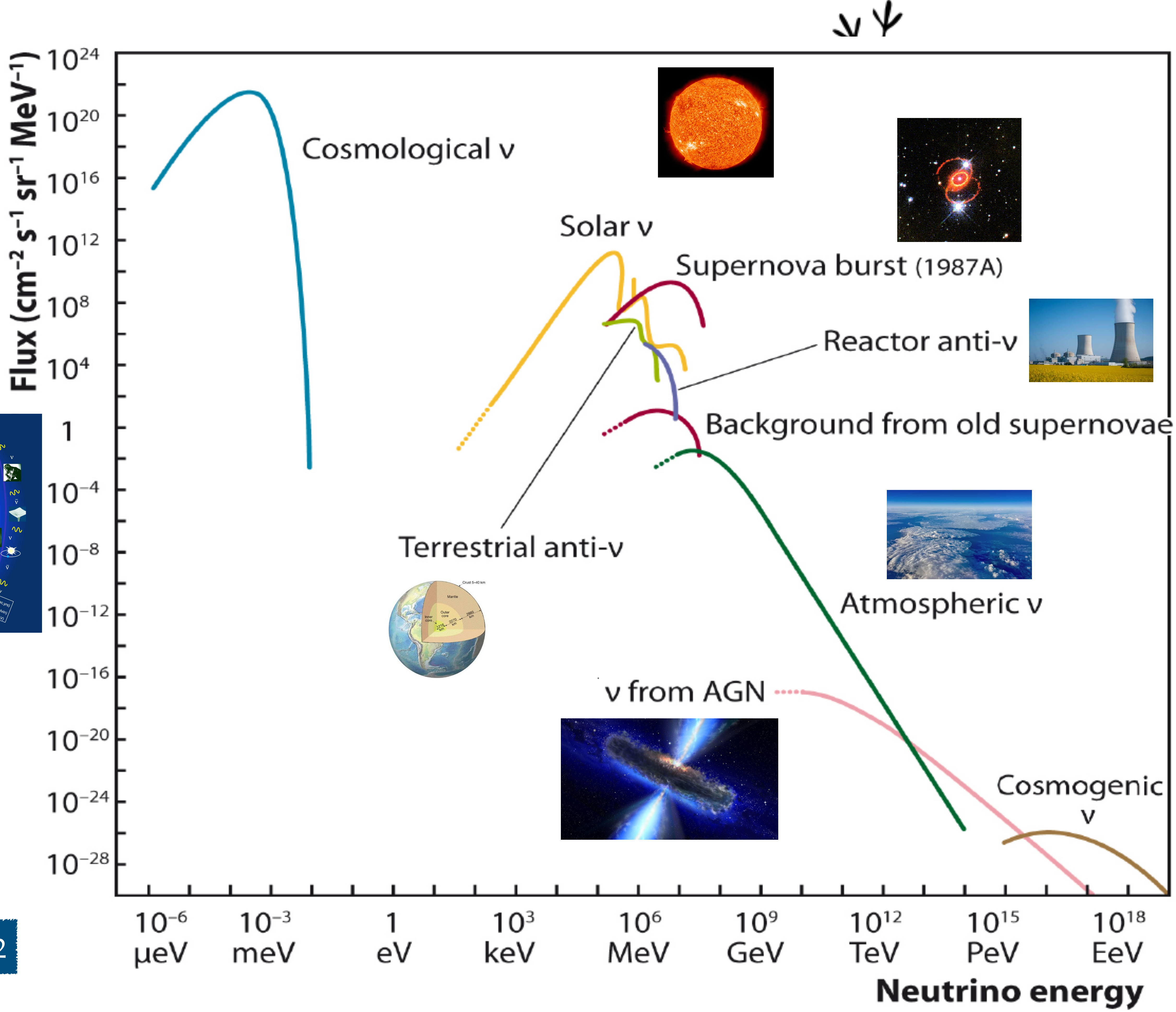
- Introduction
- The mechanism
- Phenomenology
- Conclusions



Introduction

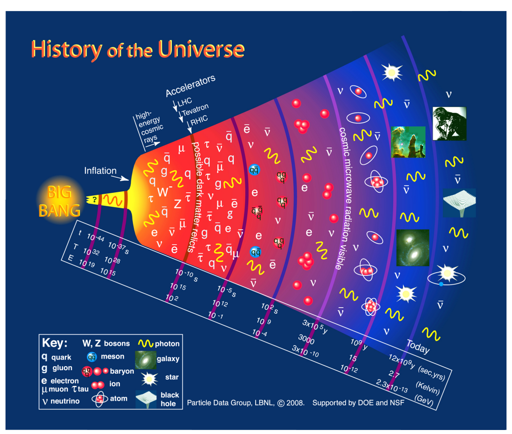
Neutrino Fluxes

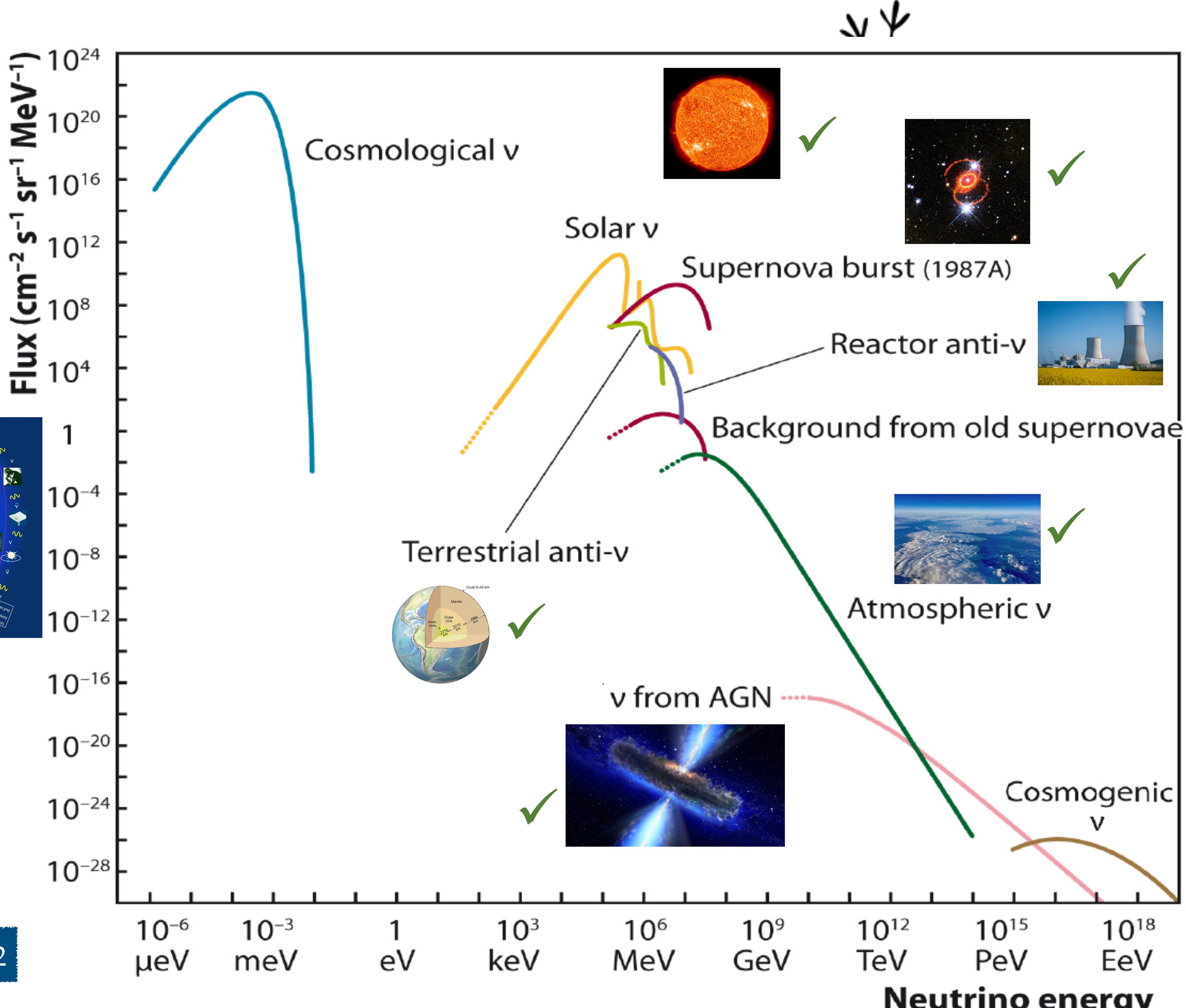




Katz et.al., 2012

Neutrino Fluxes





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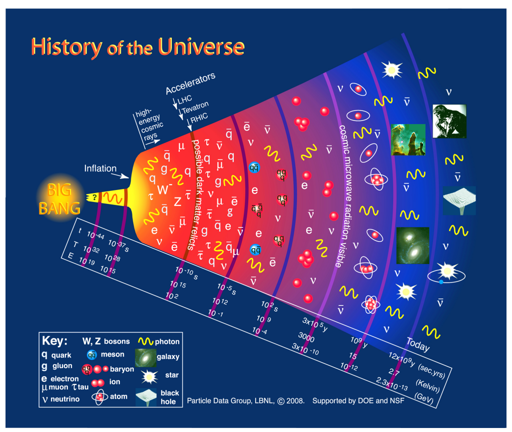
Neutrino Fluxes



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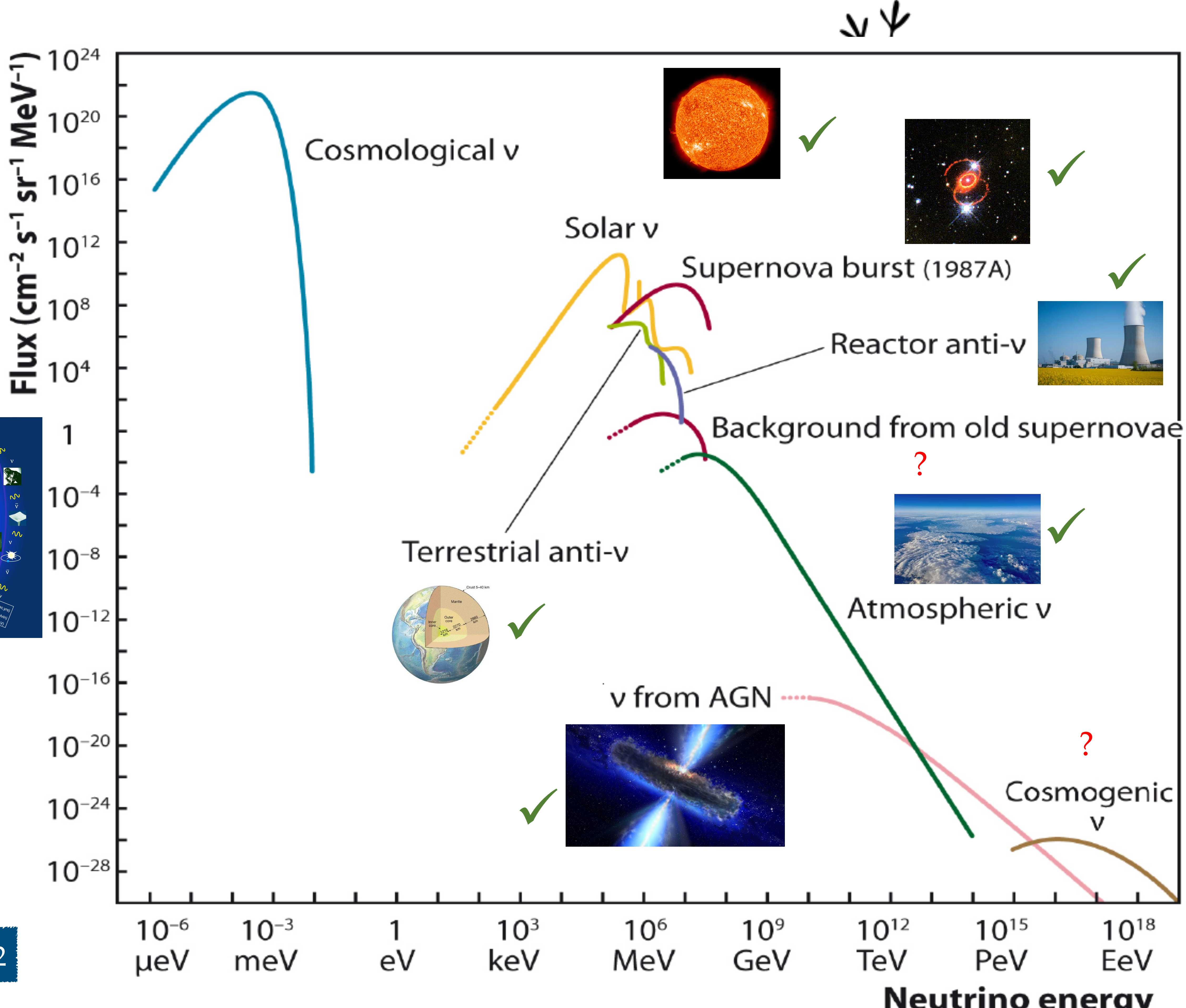

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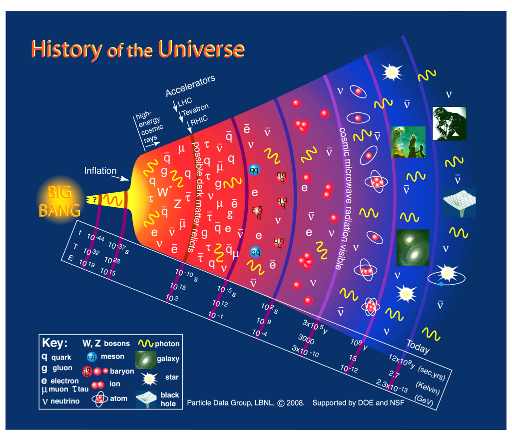
Neutrino Fluxes



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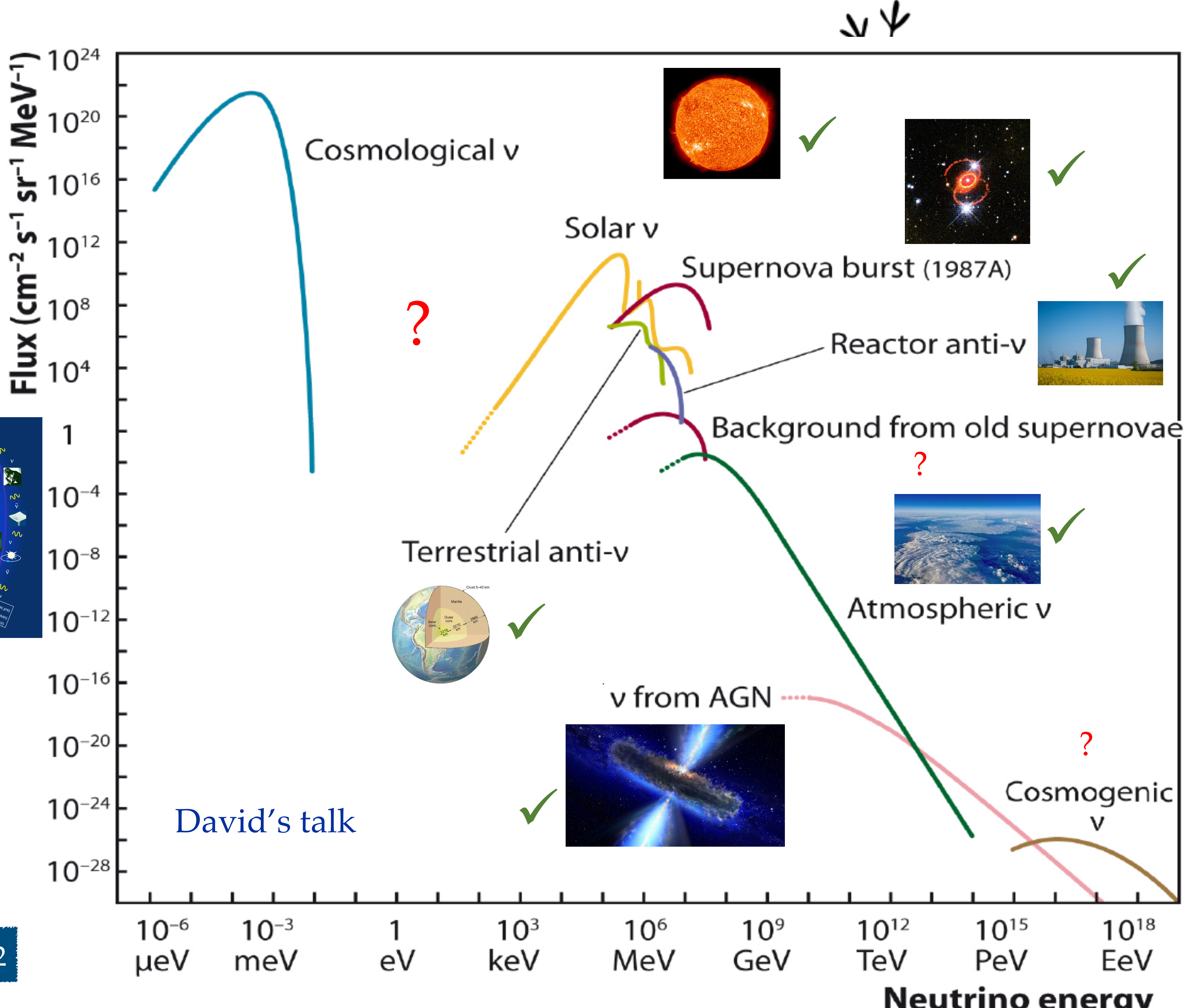

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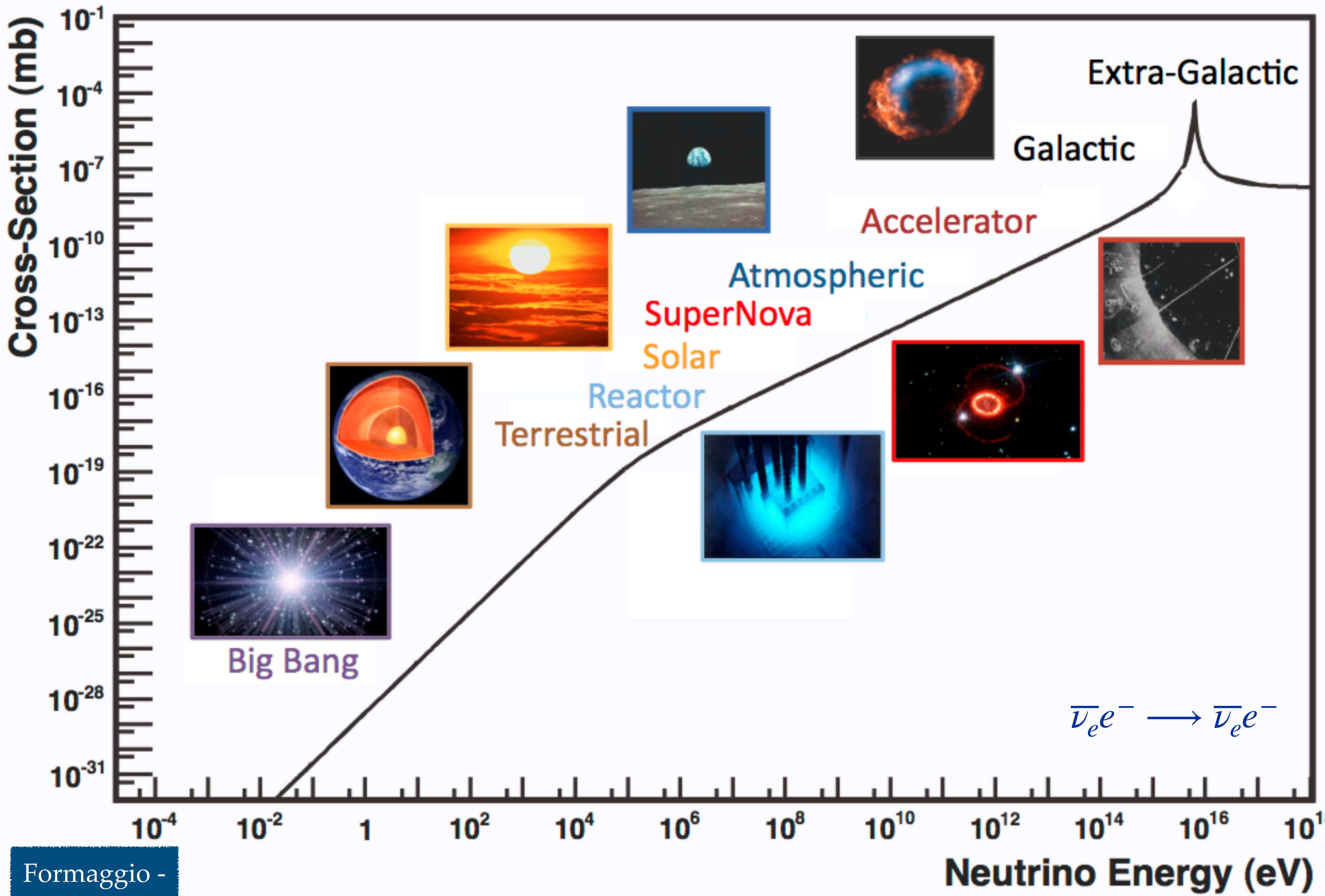
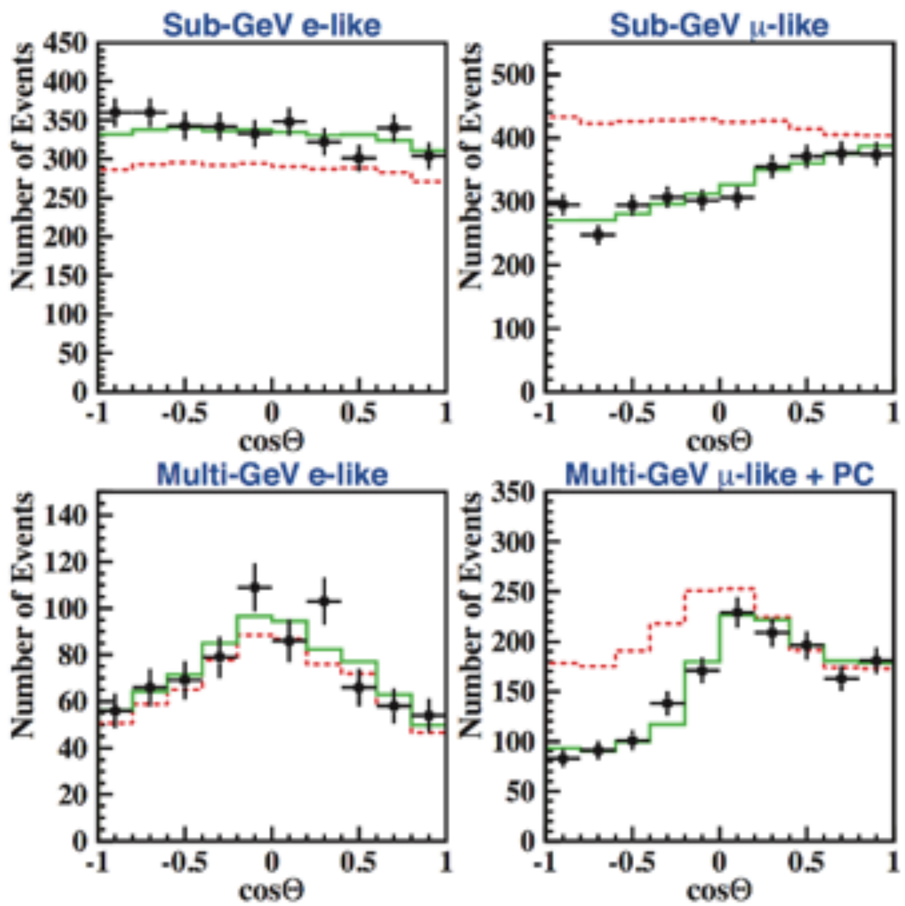


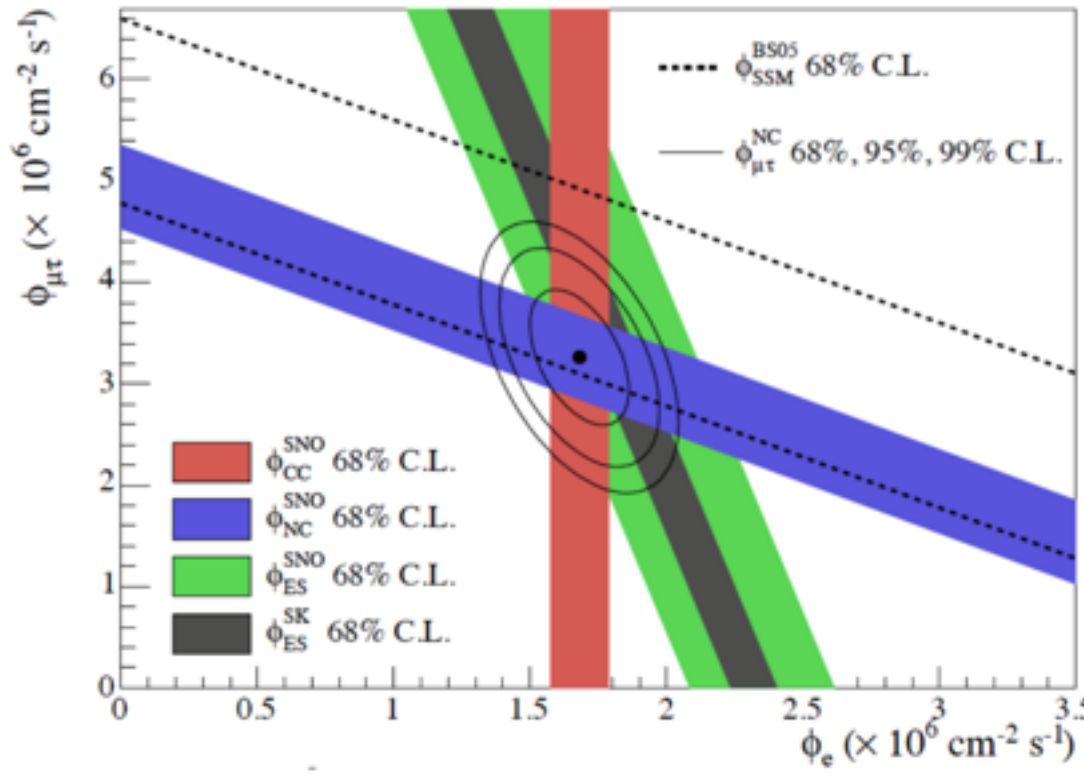
Formaggio - Zeller 2013

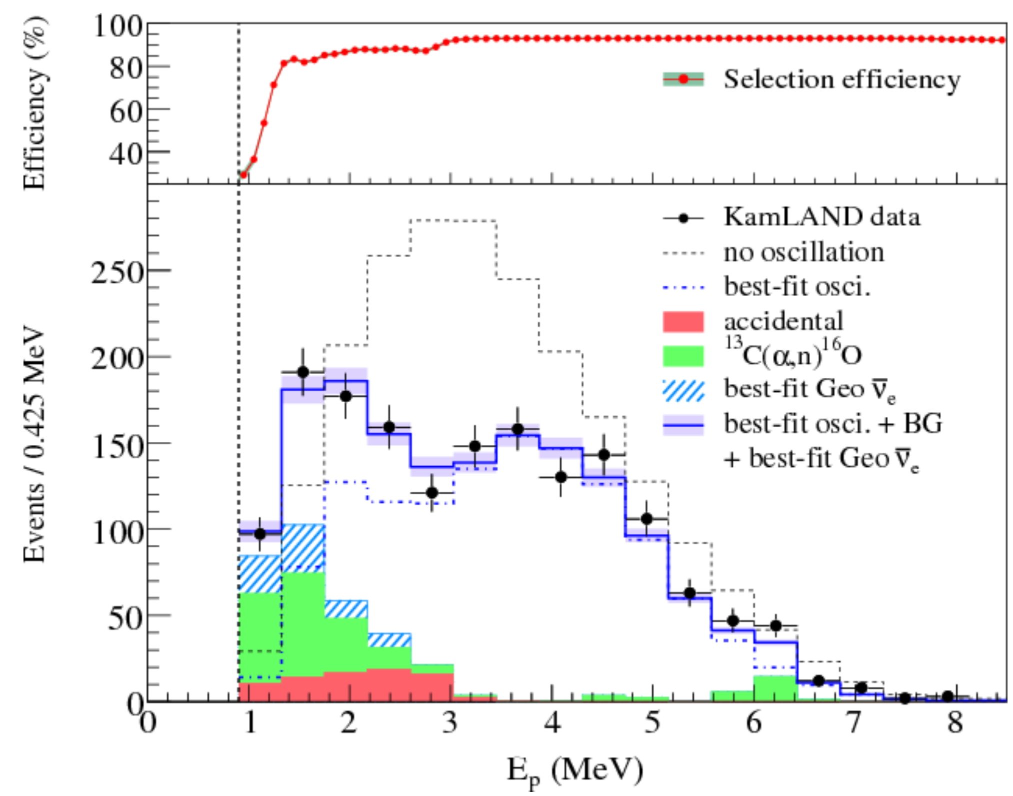
Neutrinos have mass!

SuperKamiokaNDE



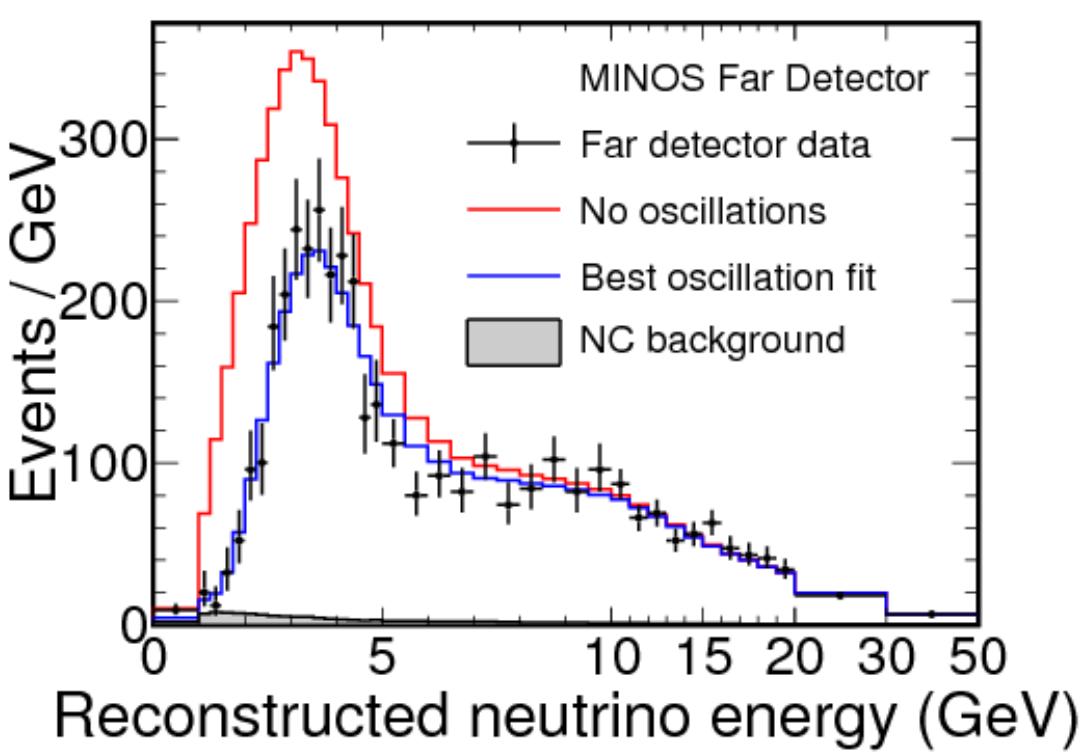
SNO





KamLAND

MINOS



T2K, Day Bay, and many others

What do we know about neutrino masses and mixing?

- 3 mixing angles
- 2 non-zero quadratic mass differences

$\Delta m^2_{21} > 0$

www.nu-fit.org

NuFIT 3.2 (2018)

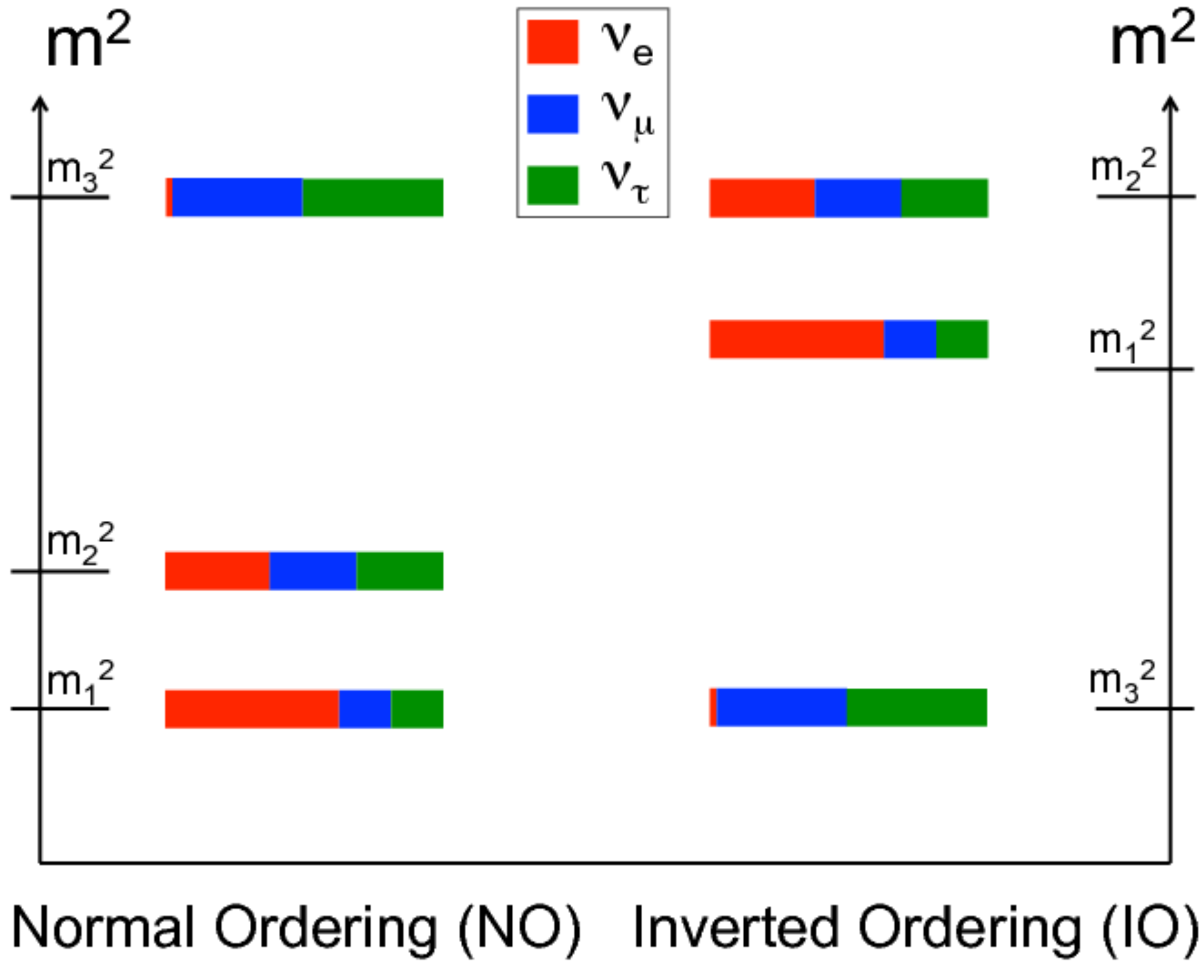
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix}+2.399 \to +2.593 \\ -2.536 \to -2.395\end{bmatrix}$

Ivan's talk

What do not we know about neutrino masses and mixing?

$$|\nu_a\rangle = \tilde{U}_{\alpha a}|\nu_\alpha\rangle$$

Mass ordering?



- CP phase – CP violation
- Absolute mass values
- Octant of θ_{23}

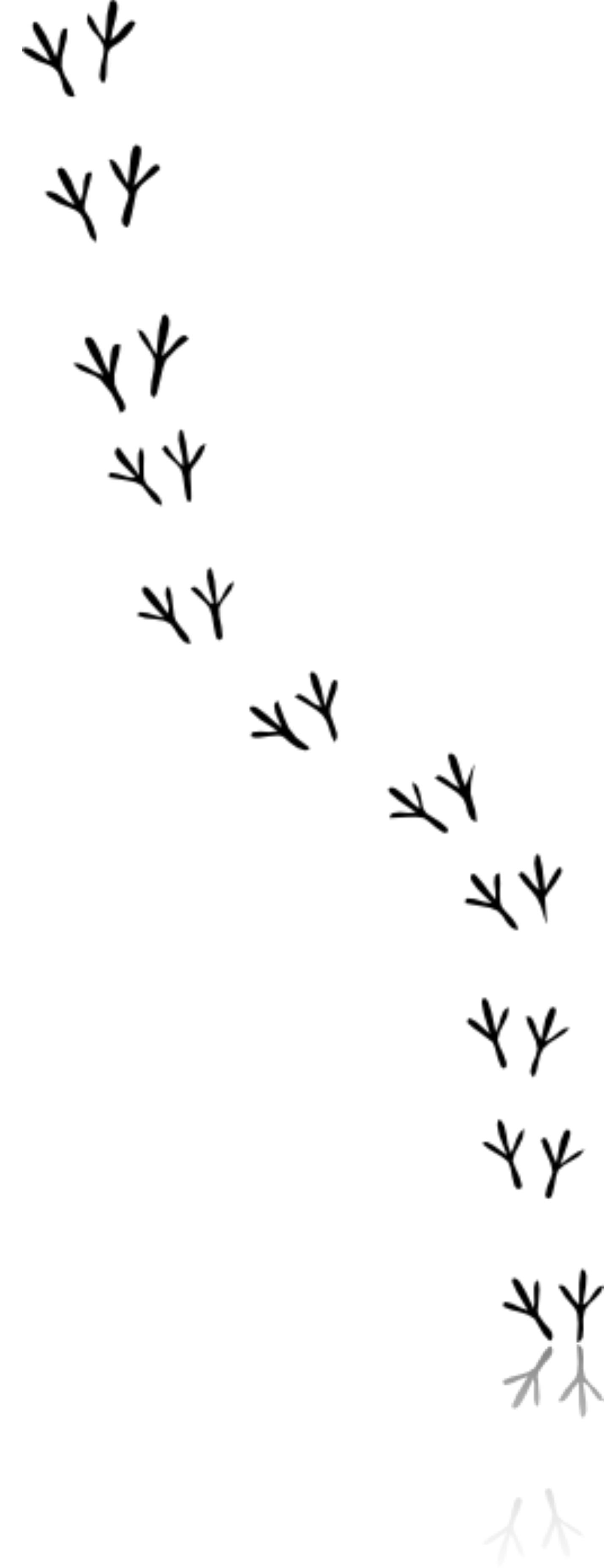
Dirac or Majorana nature

Origin of neutrino masses

Neutrinos are massive

↓

Only neutral fermion



P. A. M. Dirac

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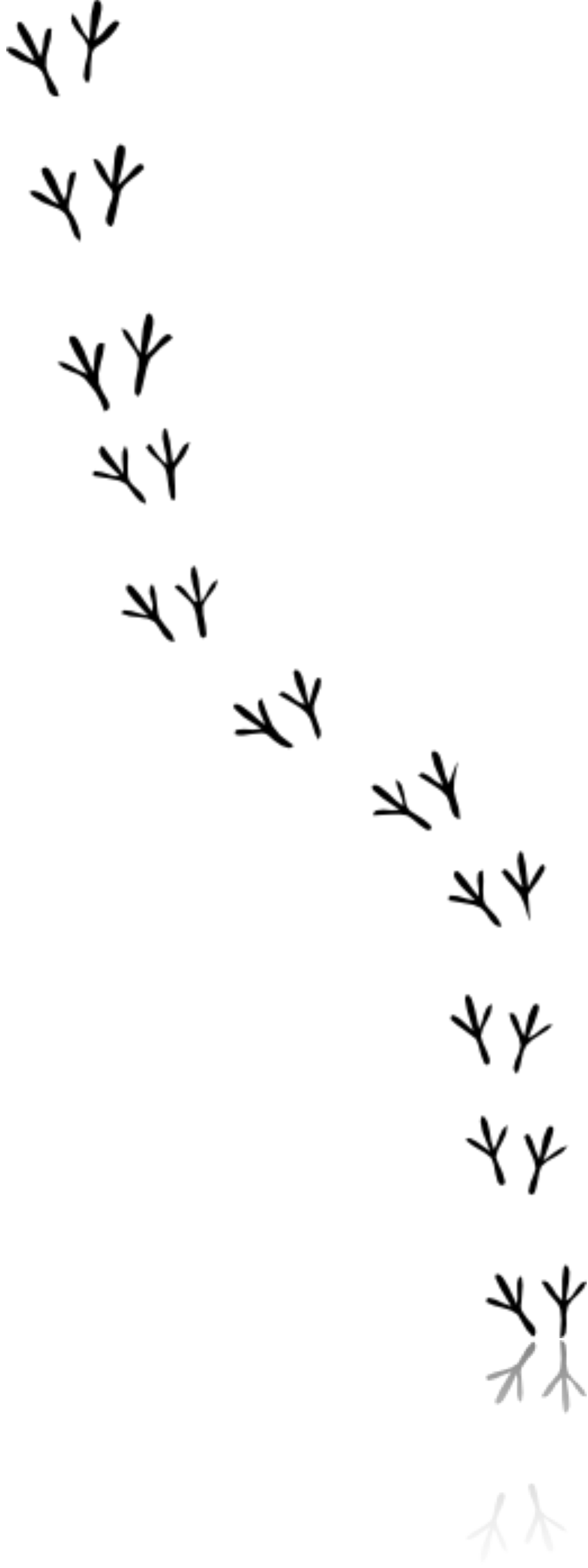
Dirac vs Majorana



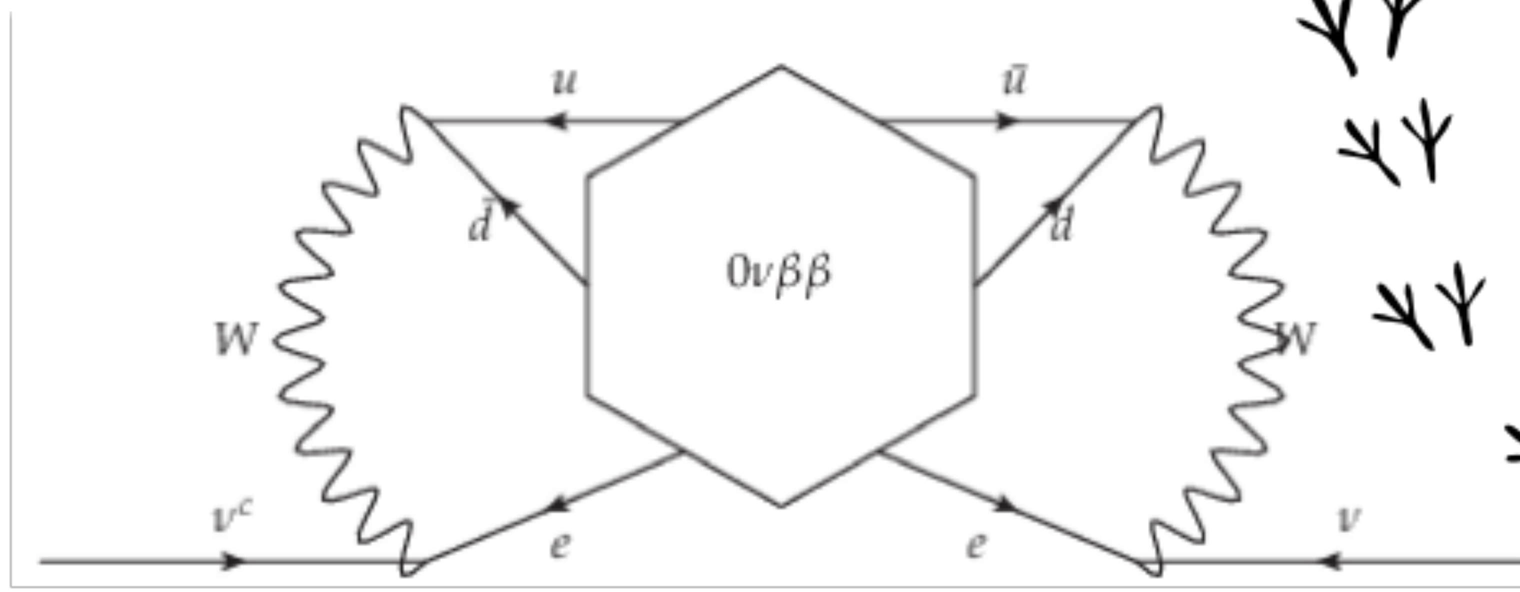
Dirac vs Majorana

- Neutrino-less double beta decay

Schechter Valle, 1982

$\tau_{1/2} > 10^{27} - 10^{28}$ y

nEXO, KamLAND2-Zen, Cupid..



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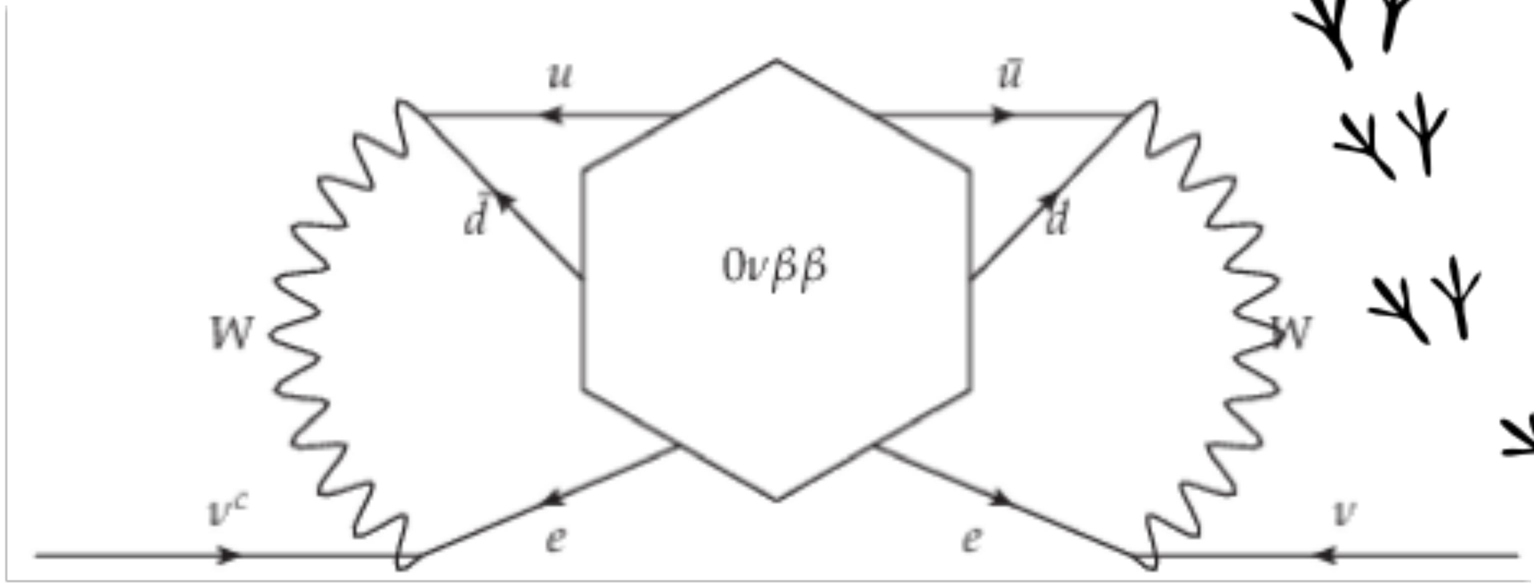


- Detect non-relativistic neutrinos

Dirac neutrinos	Majorana neutrinos
$\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} = N_T \bar{\sigma} n_0$	$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2 N_T \bar{\sigma} n_0$

$\bar{\sigma} \approx 4.05 \times 10^{-45}\ \mathrm{cm}^2$

$$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}}$$

Duda and Gelmini, 2001
Long et.al. 2014

Dirac vs Majorana

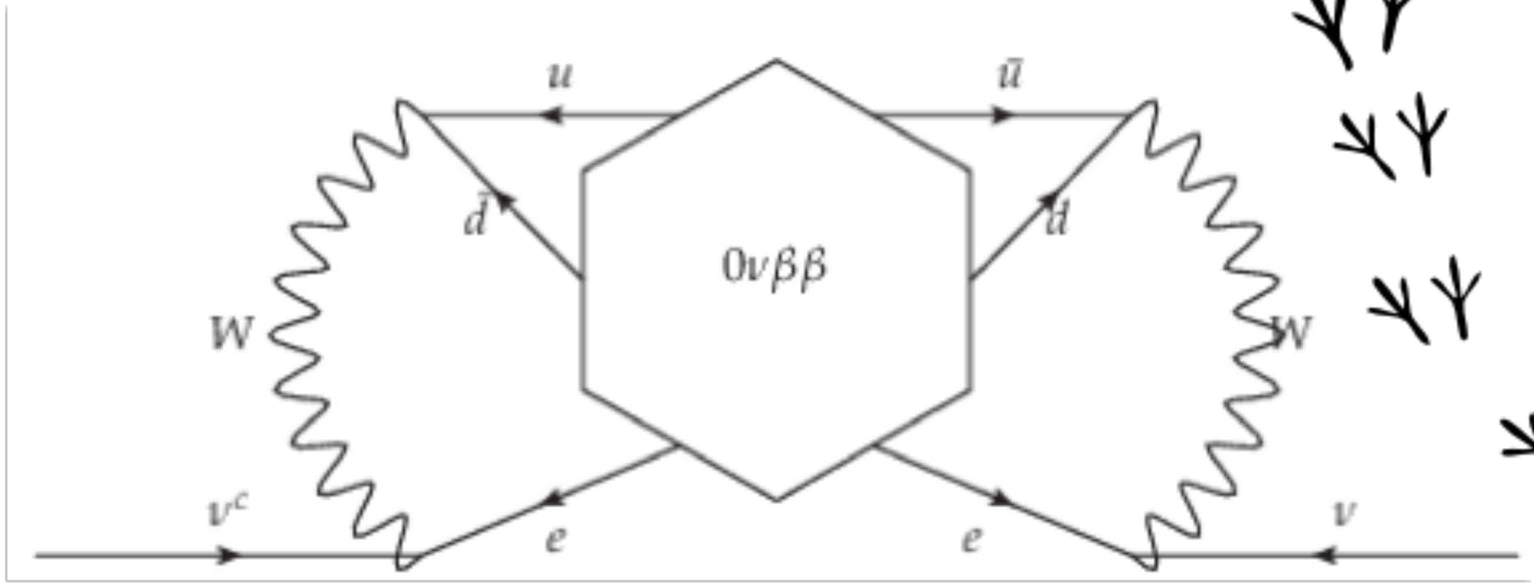
- Neutrino-less double beta decay

Schechter Valle, 1982

$\tau_{1/2} > 10^{27} - 10^{28}$ y

$m_{\beta\beta} < \sim 20$ meV

nEXO, KamLAND2-Zen, Cupid..



- Detect non-relativistic neutrinos

Dirac neutrinos

Cosmology prediction

Majorana neutrinos

$\Gamma^{\rm D}_{\rm C\nu B} = N_T \bar{\sigma} n_0$

$\Gamma^{\rm M}_{\rm C\nu B} = 2N_T \bar{\sigma} n_0$

$\bar{\sigma} \approx 4.05 \times 10^{-45}$ cm^2

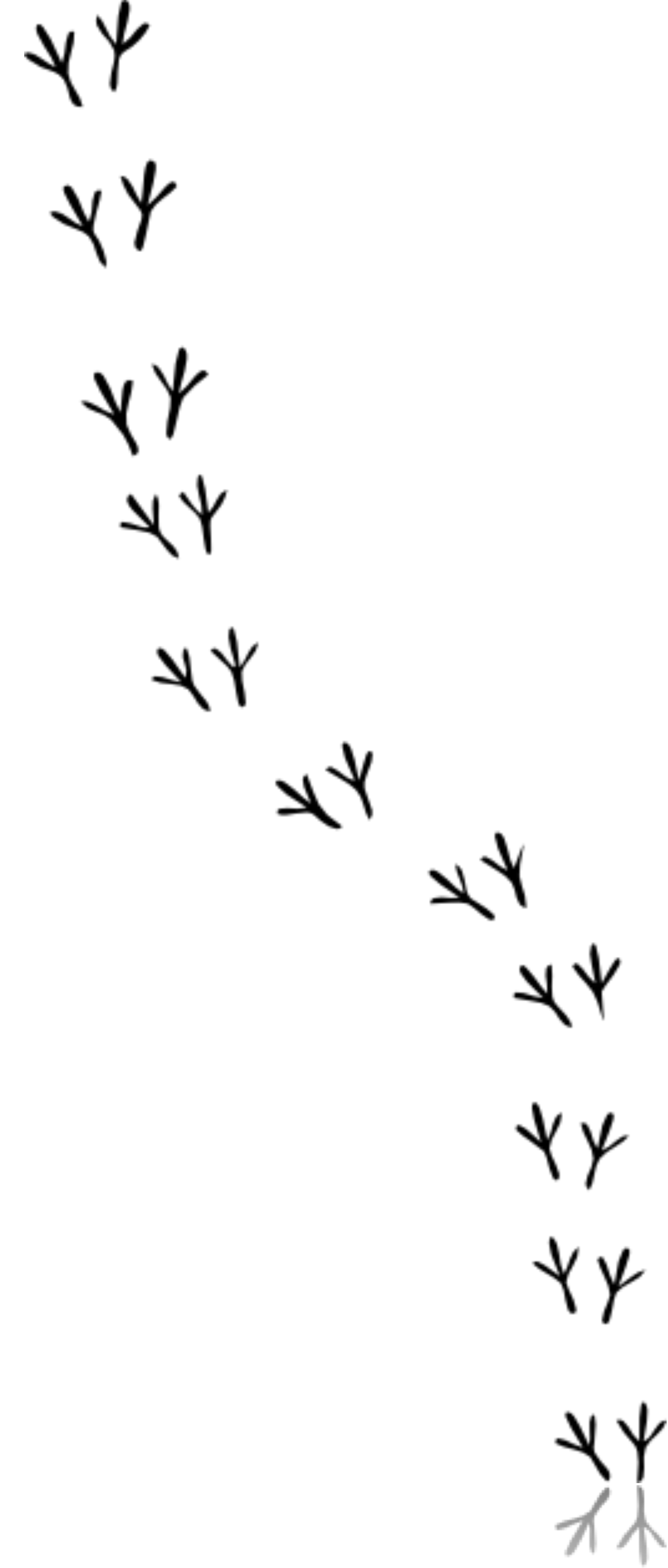
$\Gamma^{\rm M}_{\rm C\nu B} = 2\Gamma^{\rm D}_{\rm C\nu B}$

Duda and Gelmini, 2001
Long et.al. 2014

Dirac vs Majorana

How robust
is this result?

$$\mathscr{L}_{\rm BSM} = \mathscr{L}_{\rm SM} + \mathscr{L}_{d=5} + \frac{1}{\Lambda^2}\sum_{k=1} c_k^{(6)} Q_k^{(6)}$$



M. Arteaga, E. Bertuzzo, YFPG and R. Zukanovich Funchal, JHEP09 (2017) 160

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6-dimensional ops

Four-fermion Operators		Vertex Corrections
$Q^{(6)}_{\nu_L}$	$Q^{(6)}_{\nu_R}$	$Q^{(6)}_{\Phi}$
$Q_1 = (\overline{l_L} e_R)(\overline{d_R} q_L)$	$Q_5 = (\overline{l_L} \nu_R)\varepsilon(\overline{q_L} d_R)$	$Q_9 = i(\Phi^T \varepsilon D_\mu \Phi)(\overline{u_R}\gamma_\mu d_R)$
$Q_2 = (\overline{l_L} e_R)\varepsilon(\overline{q_L} u_R)$	$Q_6 = (\overline{\nu_R} l_L)(\overline{q_L} u_R)$	$Q_{10} = i(\Phi^T \varepsilon D_\mu \Phi)(\overline{\nu_R}\gamma^\mu e_R)$
$Q_3 = (\overline{l_L}\gamma^\mu \tau^A l_L)(\overline{q_L}\gamma_\mu \tau^A q_L)$	$Q_7 = (\overline{e_R}\gamma^\mu \nu_R)(\overline{u_R}\gamma_\mu d_R)$	$Q_{11} = (\Phi^\dagger i\overleftrightarrow{D}^a_\mu \Phi)(\overline{q_L}\gamma_\mu \tau^A q_L)$
$Q_4 = (\overline{l_L}\sigma^{\mu\rho} e_R)\varepsilon(\overline{q_L}\sigma_{\mu\rho} u_R)$	$Q_8 = (\overline{l_L}\sigma^{\mu\rho}\nu_R)\varepsilon(\overline{q_L}\sigma_{\mu\rho} d_R)$	$Q_{12} = (\Phi^\dagger i\overleftrightarrow{D}^a_\mu \Phi)(\overline{l_L}\gamma^\mu \tau^A l_L)$

M. Arteaga, E. Bertuzzo, YFPG
and R. Zukanovich Funchal,
JHEP09 (2017) 160

Dirac vs Majorana

How robust
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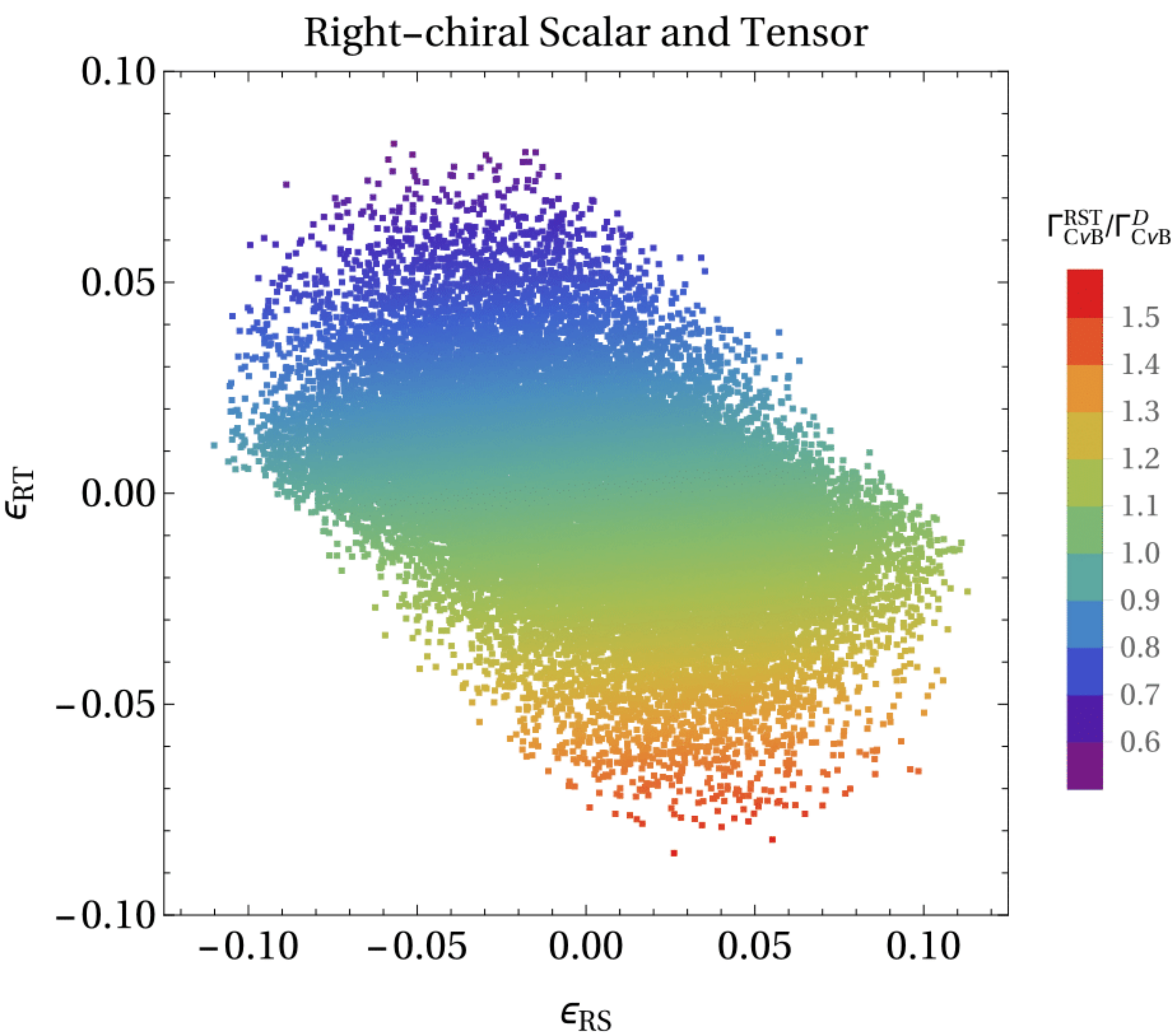

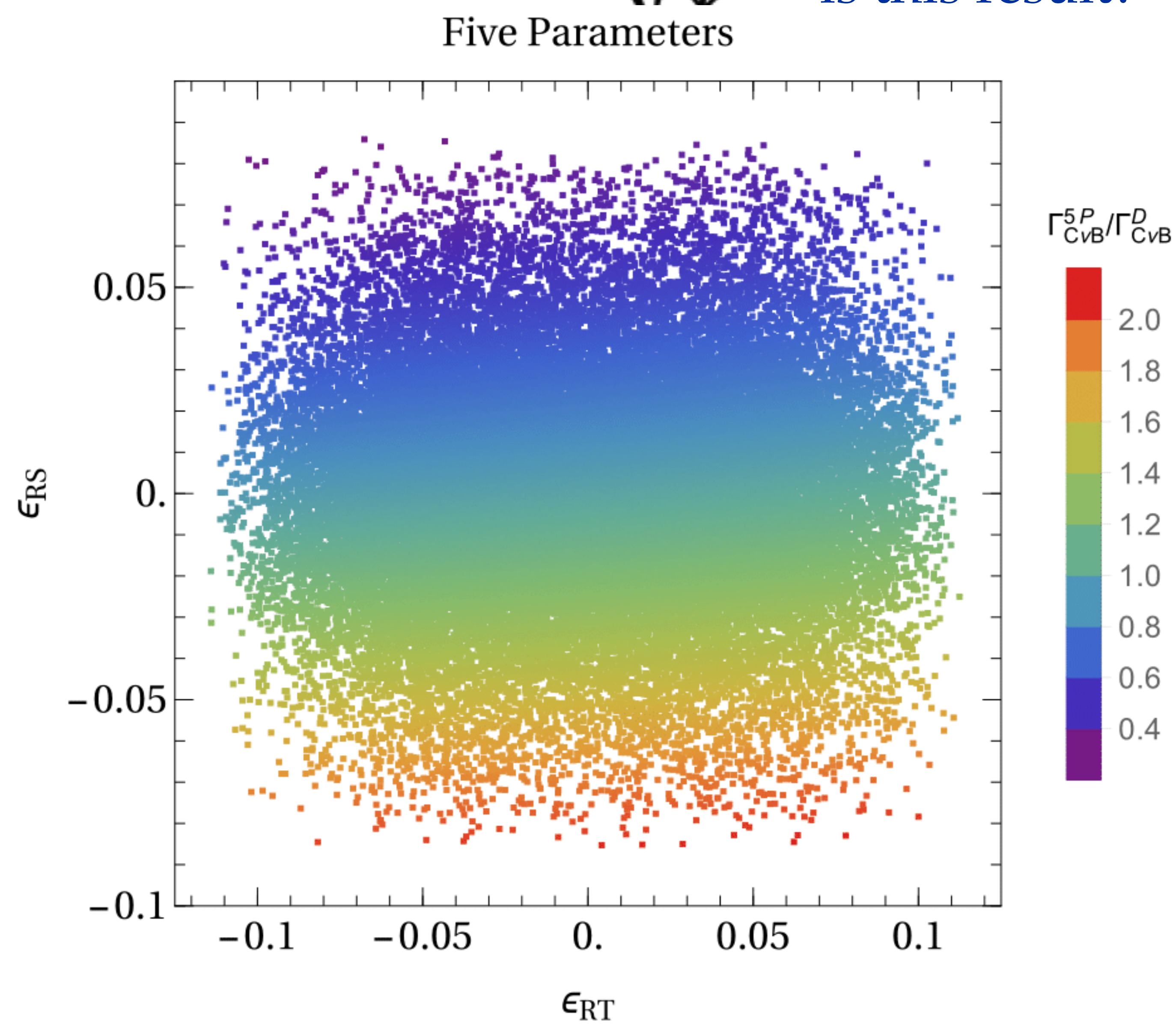

$$0.61\,\Gamma^{D}_{C\nu B} \lesssim \Gamma^{BSM}_{C\nu B} \lesssim 1.52\,\Gamma^{D}_{C\nu B}.$$

$$0.3\,\Gamma^{D}_{C\nu B} \lesssim \Gamma^{BSM}_{C\nu B} \lesssim 2.2\,\Gamma^{D}_{C\nu B}$$

Highly dependent of
right-handed couplings

M. Arteaga, E. Bertuzzo, YFPG
and R. Zukanovich Funchal,
JHEP09 (2017) 160

Dirac vs Majorana

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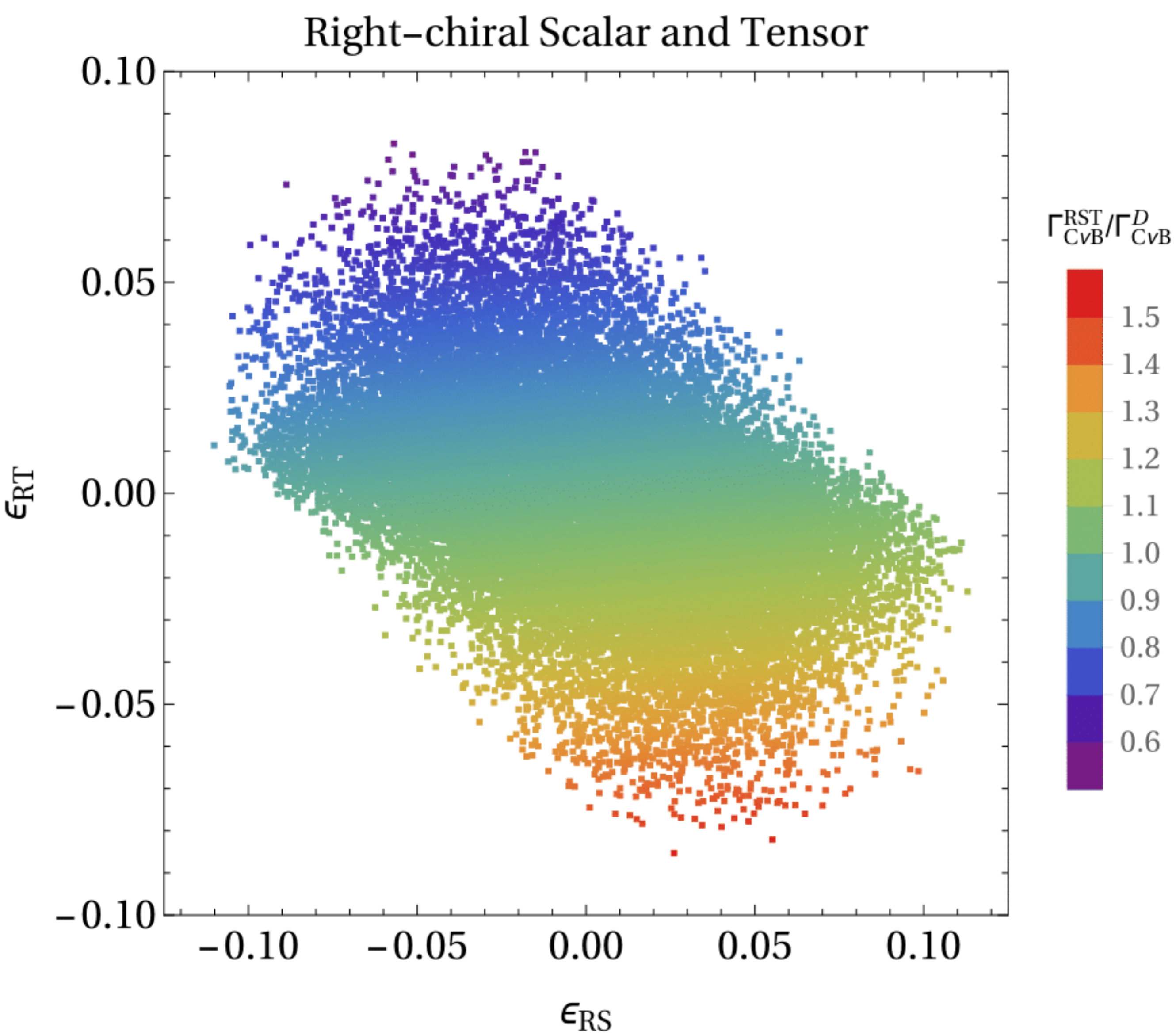

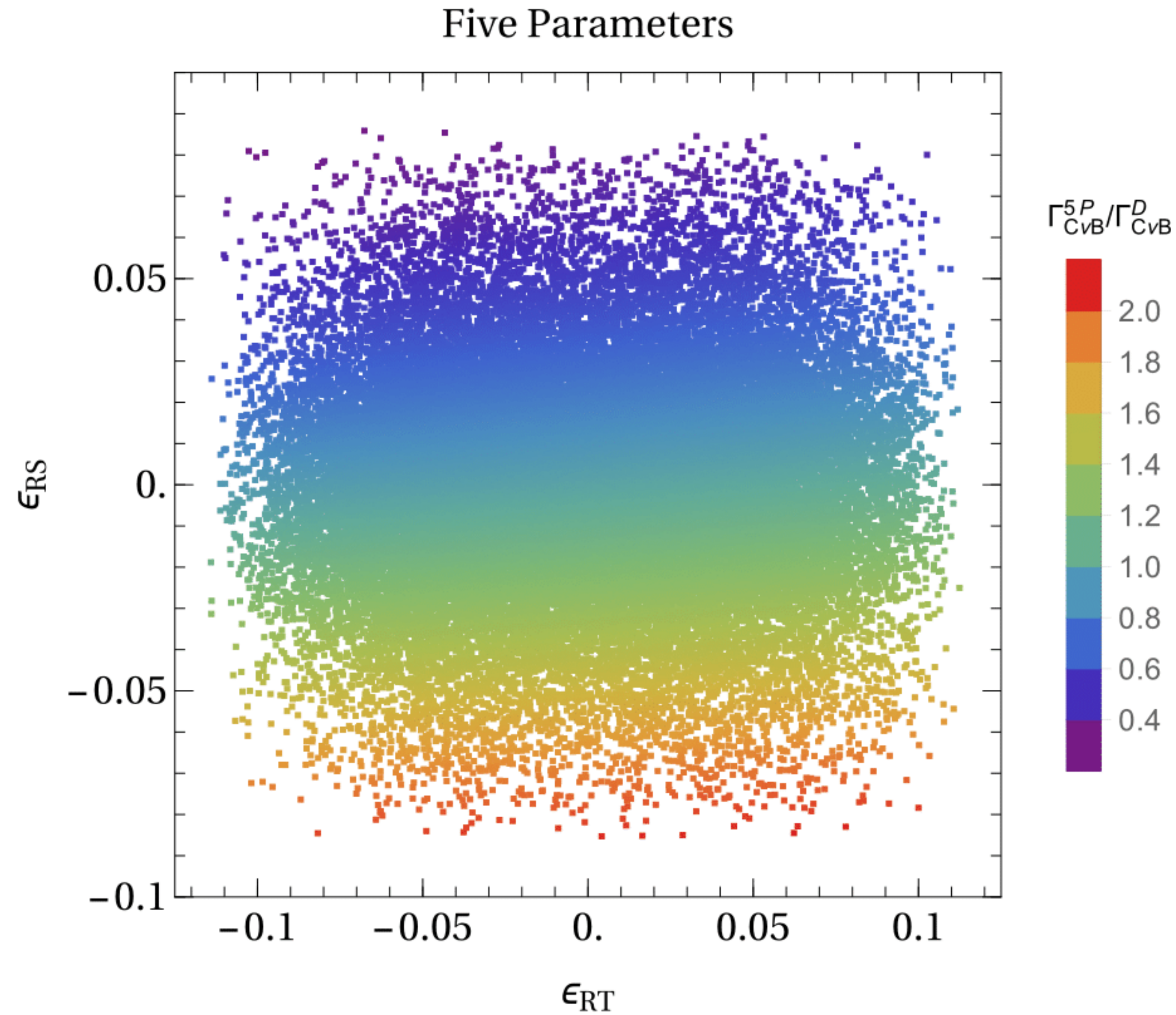

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Highly dependent of right-handed couplings

BSM can hinder the neutrino nature!

M. Arteaga, E. Bertuzzo, YFPG and R. Zukanovich Funchal, JHEP09 (2017) 160

P. A. M. Dirac

1930

Neutrinos are massive

1937

E. Majorana

$\nu \neq \nu^c$

Only neutral fermion

$\nu = \nu^c$

Are there other ways to differentiate between these two?

P. A. M. Dirac

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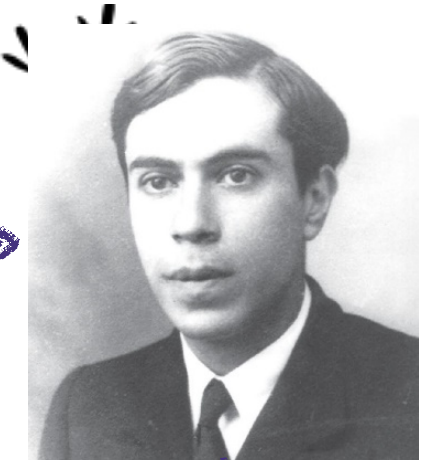

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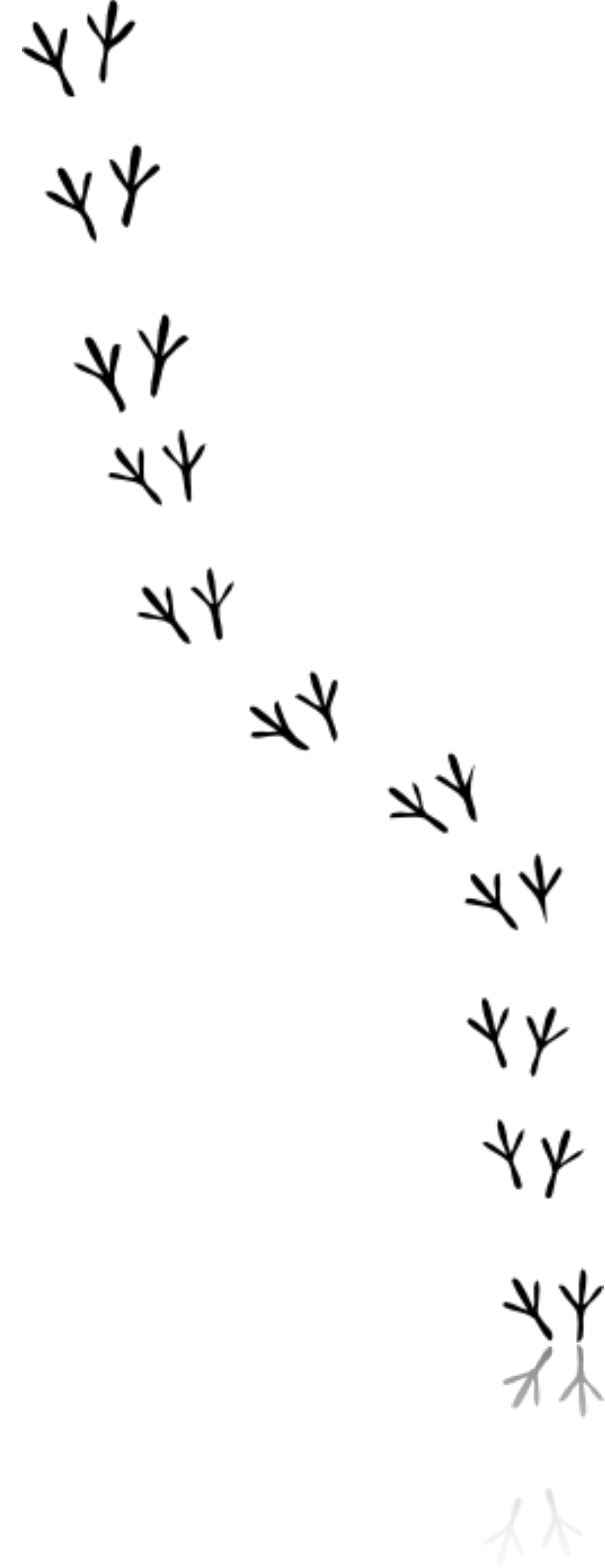
Are there other ways to differentiate between these two?

It is possible to have Dirac and Majorana neutrinos in extensions of the SM

Weinberg Operator

$$\mathscr{L}_{\text{BSM}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{d=5} + \frac{1}{\Lambda^2}\sum_{k=1} c_k^{(6)} Q_k^{(6)}$$



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$$\mathscr{L}_{d=5} = \frac{c^{(5)}}{\Lambda} LLHH$$

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$$m_\nu \propto \frac{c^{(5)} v^2}{\Lambda}$$

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To have neutrino masses of order $\mathcal{O}(\text{eV})$

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To have neutrino masses of order $\mathcal{O}(\text{eV})$

$\Lambda \gg v$ ⟶ $c \sim 1$ High scale seesaw

See Richard's talk

Weinberg Operator

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To have neutrino masses of order $\mathscr{O}$(eV)

$\Lambda \gg v$ → $c \sim 1$ High scale seesaw

$\Lambda \sim \mathscr{O}(\text{TeV})$ → $c \ll 1$ Low scale seesaw

See Richard's talk

Weinberg Operator

$$\mathscr{L}_5 = \frac{c}{\Lambda} LLHH$$

$$\Lambda \gg v \quad \longrightarrow \quad c \sim 1$$

$$\Lambda \sim \mathcal{O}(\text{TeV}) \quad \longrightarrow \quad c \ll 1$$

Without an underlying framework

Weinberg Operator

$$\mathscr{L}_5 = \frac{c}{\Lambda} LLHH$$

$\Lambda \gg v$ ⟶ $c \sim 1$

$\Lambda \sim \mathcal{O}(\text{TeV})$ ⟶ $c \ll 1$

Without an underlying framework

Large mass gap

Very small parameters

Weinberg Operator

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Without an underlying framework

Large mass gap

Very small parameters

Technically natural parameters

The Standard Type I See-saw

Minkowski, Mohapatra, Senjanovic, …

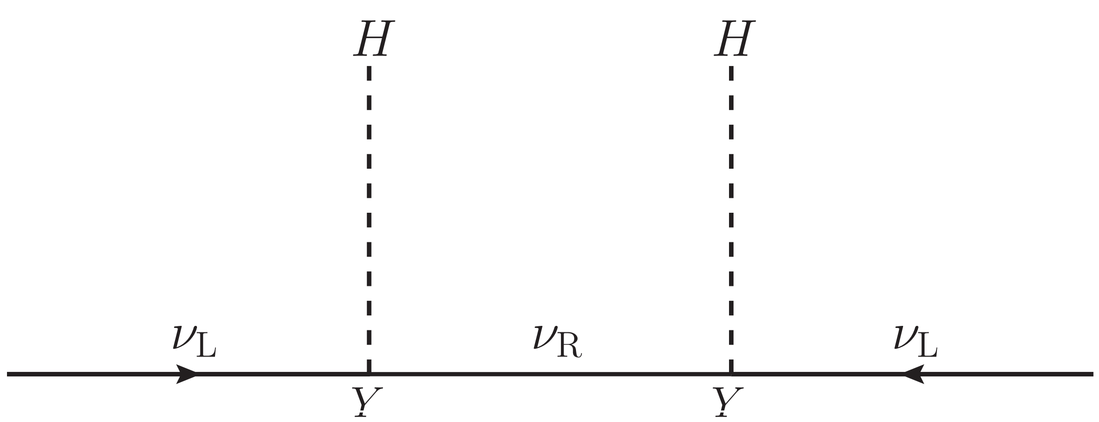
Weinberg Operator

$$\mathscr{L}_5 = \frac{c}{\Lambda} LLHH$$

$$\Lambda \gg v \longrightarrow c \sim 1$$

Standard Type I See-Saw

$$\mathscr{L}^{\nu}_{\mathrm{TI}} = \frac{1}{2}\overline{\nu^c_{\mathrm{R}}} M_{\mathrm{R}} \nu_{\mathrm{R}} - Y \overline{L_{\mathrm{L}}} \tilde{H} \nu_{\mathrm{R}}$$



$$\longrightarrow \quad m_\nu = \frac{Y^2 v^2}{M_{\mathrm{R}}}$$

See talks from Michael, Marco, Richard…

The Standard Type I See-saw

Weinberg Operator

$$\mathscr{L}_5 = \frac{c}{\Lambda} LLHH$$

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Standard Type I See-Saw

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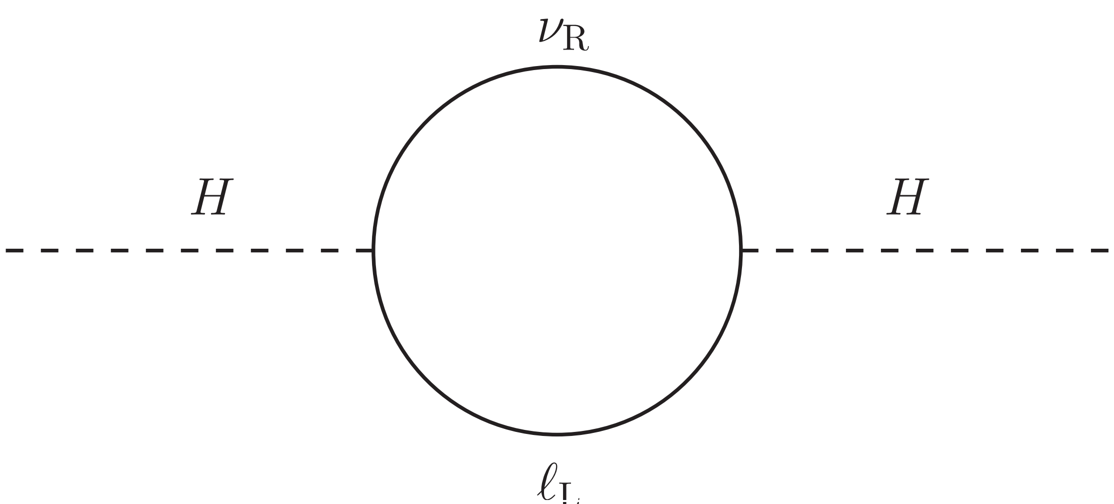

$$\ell_L = \{\nu_L, \alpha_L\}$$

Vissani, 1998

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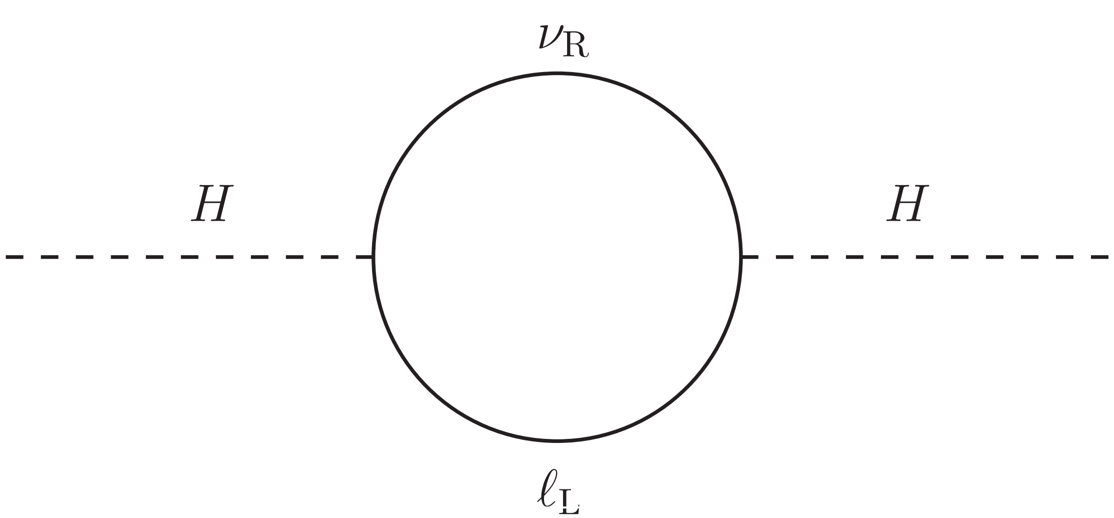

$\ell_L = \{\nu_L, \alpha_L\}$

$$\frac{\delta m_h^2}{m_h^2} \sim \frac{m_\nu \Lambda^3}{2\pi^2 v^2}$$

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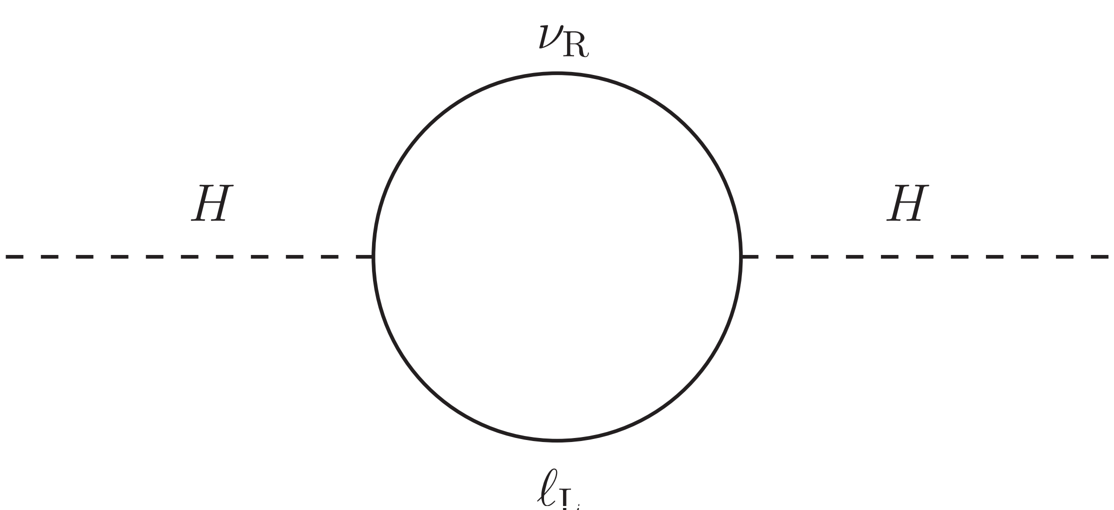

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$$\delta m_h^2 < 1\ \text{TeV}^2$$

$$m_\nu \sim 10^{-3}\ \text{eV} \longrightarrow \Lambda \lesssim 10^7\ \text{GeV}$$

Vissani, 1998

The Standard Type I See-saw

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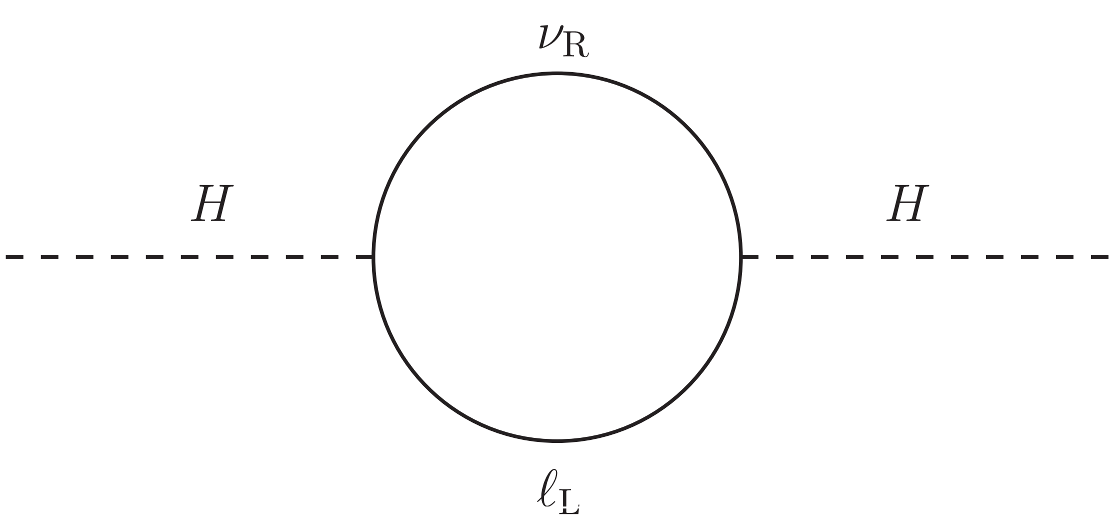
Standard Type I See-Saw



$\ell_L = \{\nu_L, \alpha_L\}$

$$\frac{\delta m_h^2}{m_h^2} \sim \frac{m_\nu \Lambda^3}{2\pi^2 v^2}$$

Multiple seesaws, Froggatt-Nielsen…

$$\delta m_h^2 < 1 \text{ TeV}^2$$

$$m_\nu \sim 10^{-3} \text{ eV} \longrightarrow \Lambda \lesssim 10^7 \text{ GeV}$$

Vissani, 1998

The Standard Type II See-saw

Weinberg Operator

$$\mathscr{L}_5 = \frac{c}{\Lambda} LLHH$$

$$\Lambda \gg v \longrightarrow c \sim 1$$

Standard Type II See-Saw

The Standard Type II See-saw

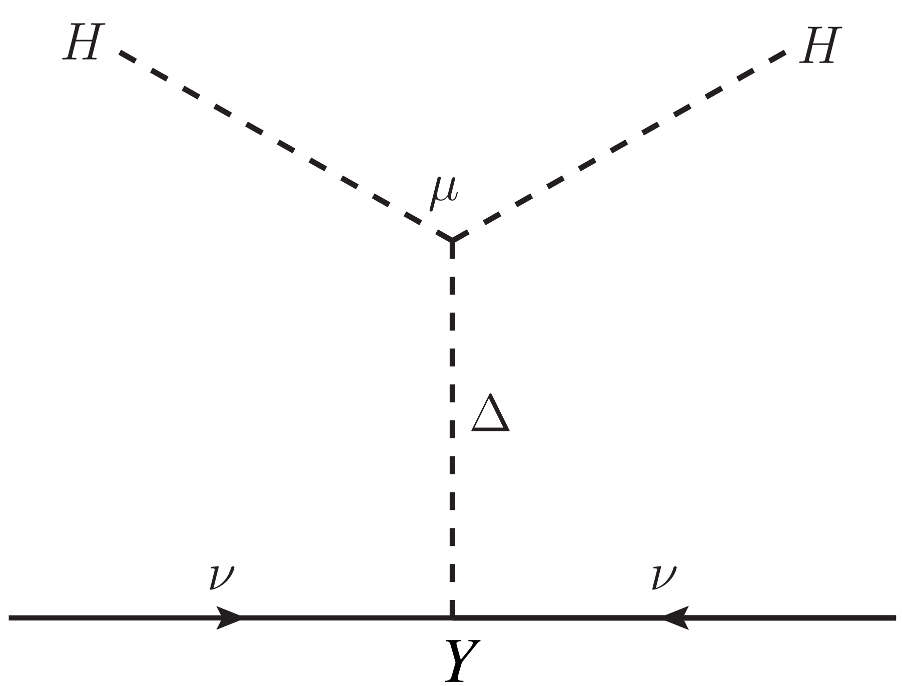
Weinberg Operator

$$\mathscr{L}_5 = \frac{c}{\Lambda} LLHH$$

$$\Lambda \gg v \longrightarrow c \sim 1$$

Standard Type II See-Saw

$$\mathscr{L}^{\nu}_{\rm TII} = -\, Y \overline{L^c_{\rm L}}\, i\sigma_2 \Delta\, L_{\rm L}$$



$$\longrightarrow m_\nu = \sqrt{2} Y v_\Delta$$

See Yongchao's talk

Konetschy, Kummer, Cheng, Li …

The Standard Type II See-saw

Weinberg Operator

$$\mathscr{L}_5 = \frac{c}{\Lambda} LLHH$$

$$\Lambda \gg v \longrightarrow c \sim 1$$

Standard Type II See-Saw

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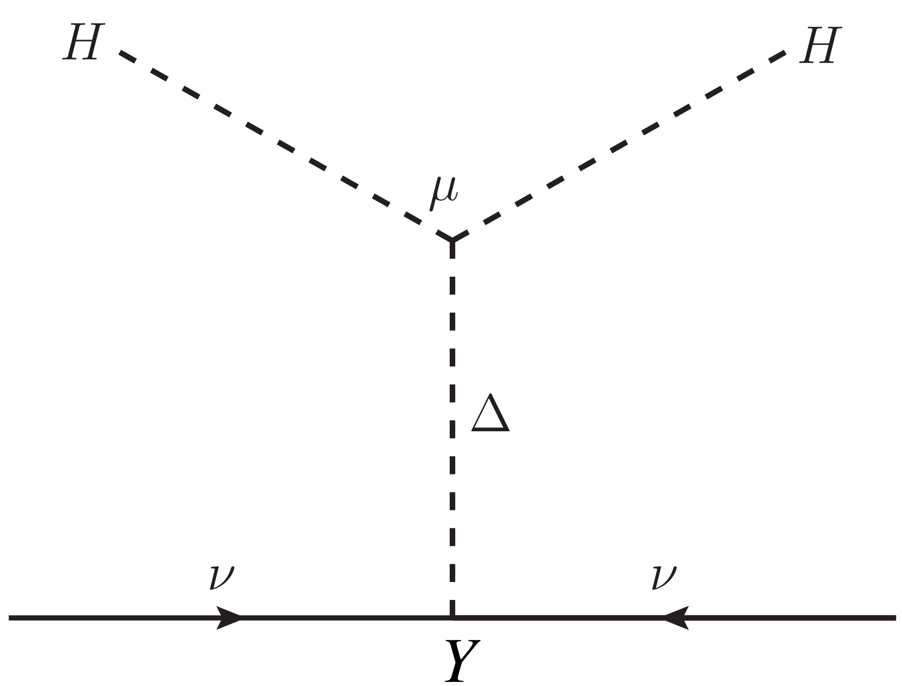
$\Delta \longrightarrow$ Gauge interactions



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How is the lepton number breaking?

Konetschy, Kummer, Cheng, Li …

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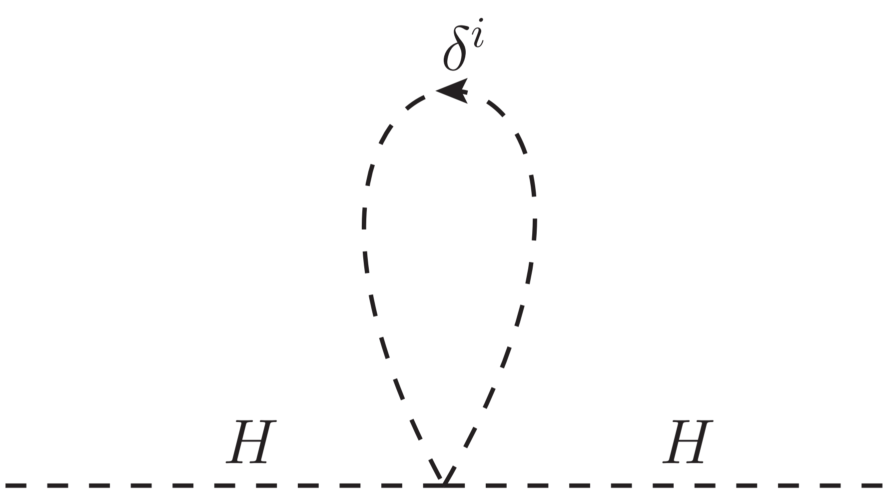

$$\frac{\delta m_h^2}{m_h^2} = -0.01 \lambda_{H\Delta} \left(\frac{M_\Delta}{100 \text{ GeV}} \right)^2 \qquad \lambda_{H\Delta} \ll 1$$

Bhupal Dev, Miralles Vila, Rodejohann, 2017

The Standard Type II See-saw

Weinberg Operator

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$$\mu \simeq 1.6 \text{ eV} \left(\frac{m_\nu}{0.1 \text{ eV}} \right)$$

$\mathcal{O}(M_\Delta) \sim \text{TeV}$

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Is it possible to generate dynamically this term?

$\mathcal{O}(M_\Delta) \sim \text{TeV}$

The Mechanism

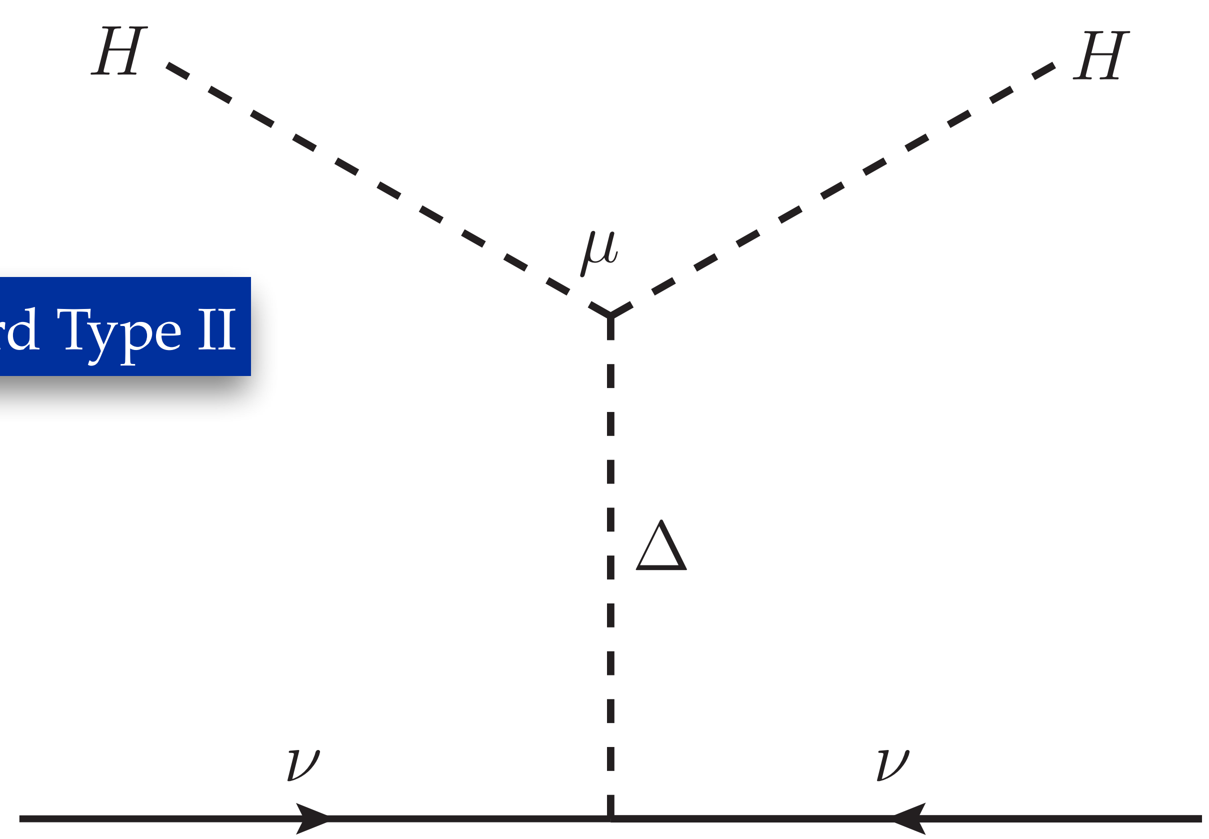
Our proposal

Generate small lepton number breaking dynamically

- At the weak scale
- Without fine tuning
- No arbitrary small couplings

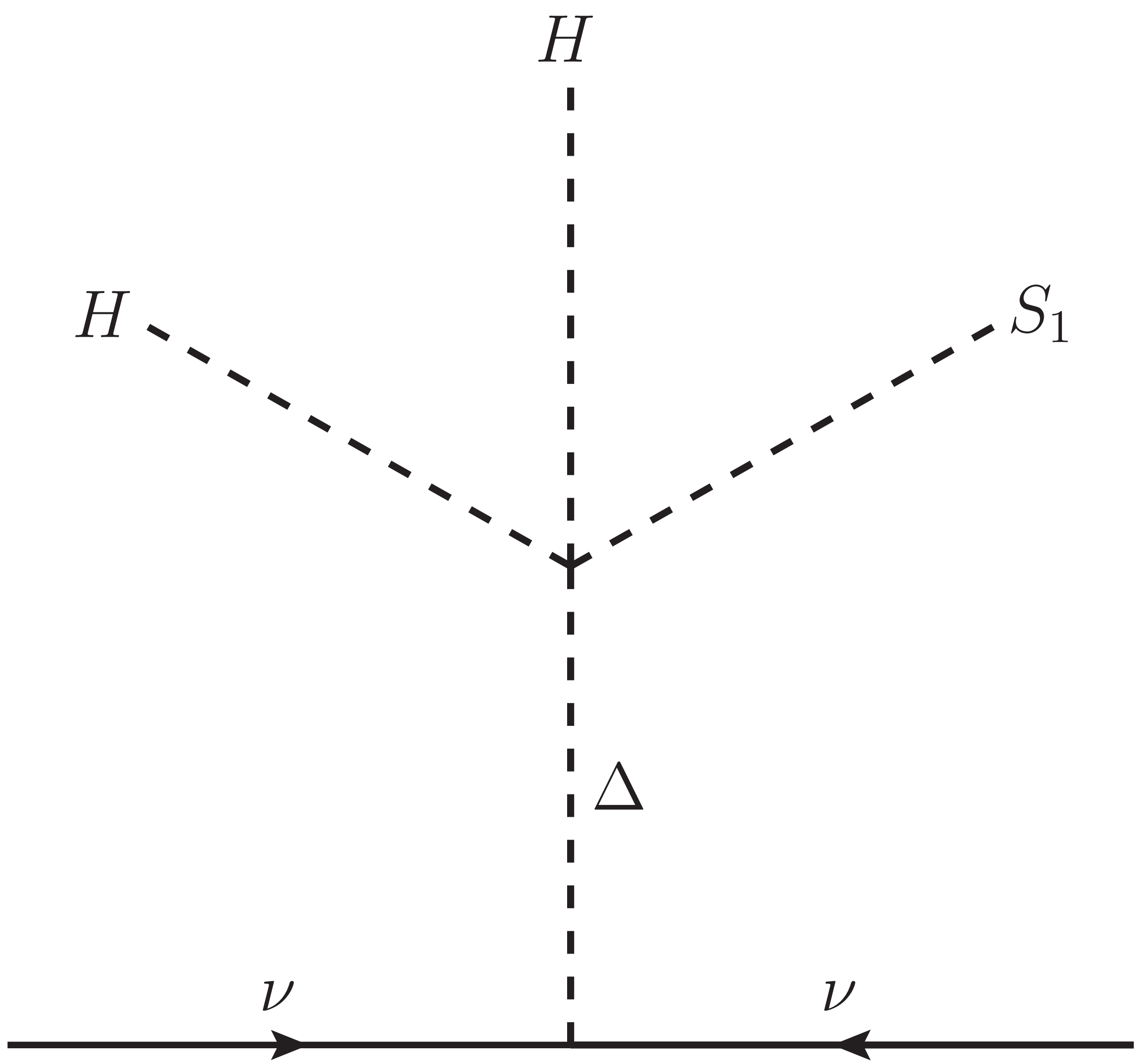
The Mechanism

Standard Type II

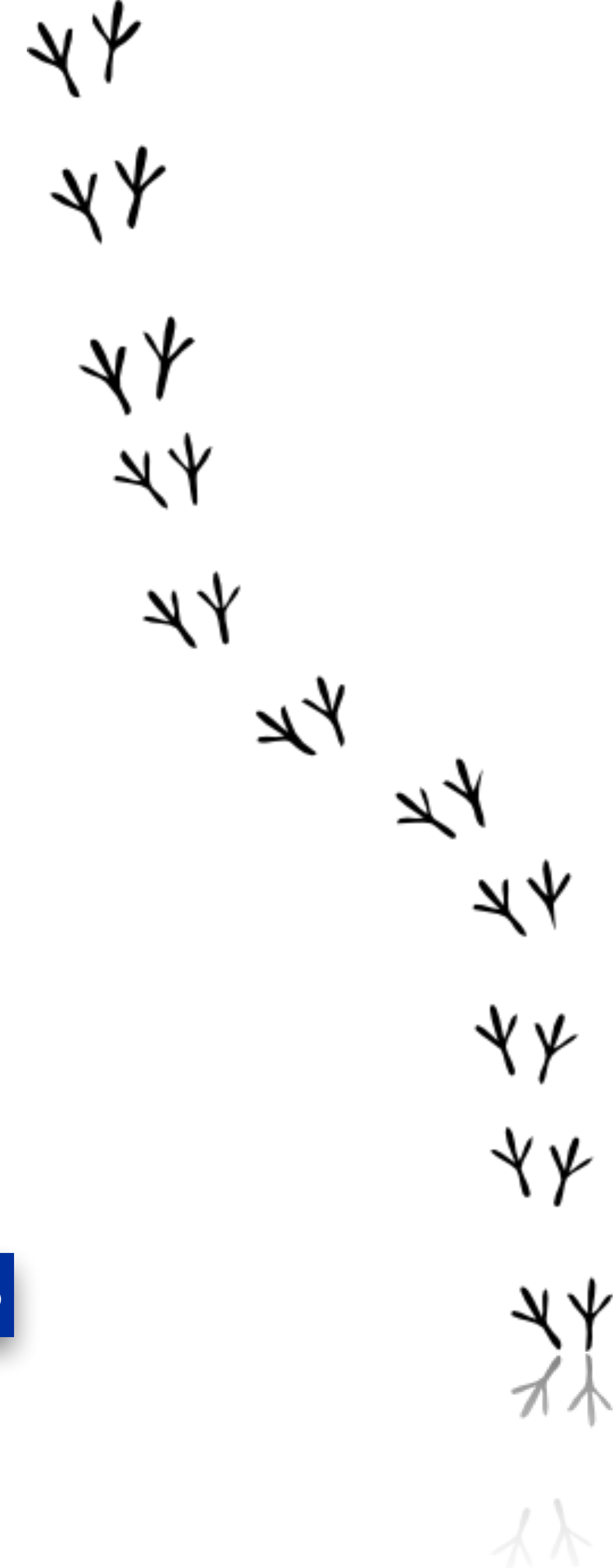


The Mechanism

Replicate seesaw n-times



1-Step



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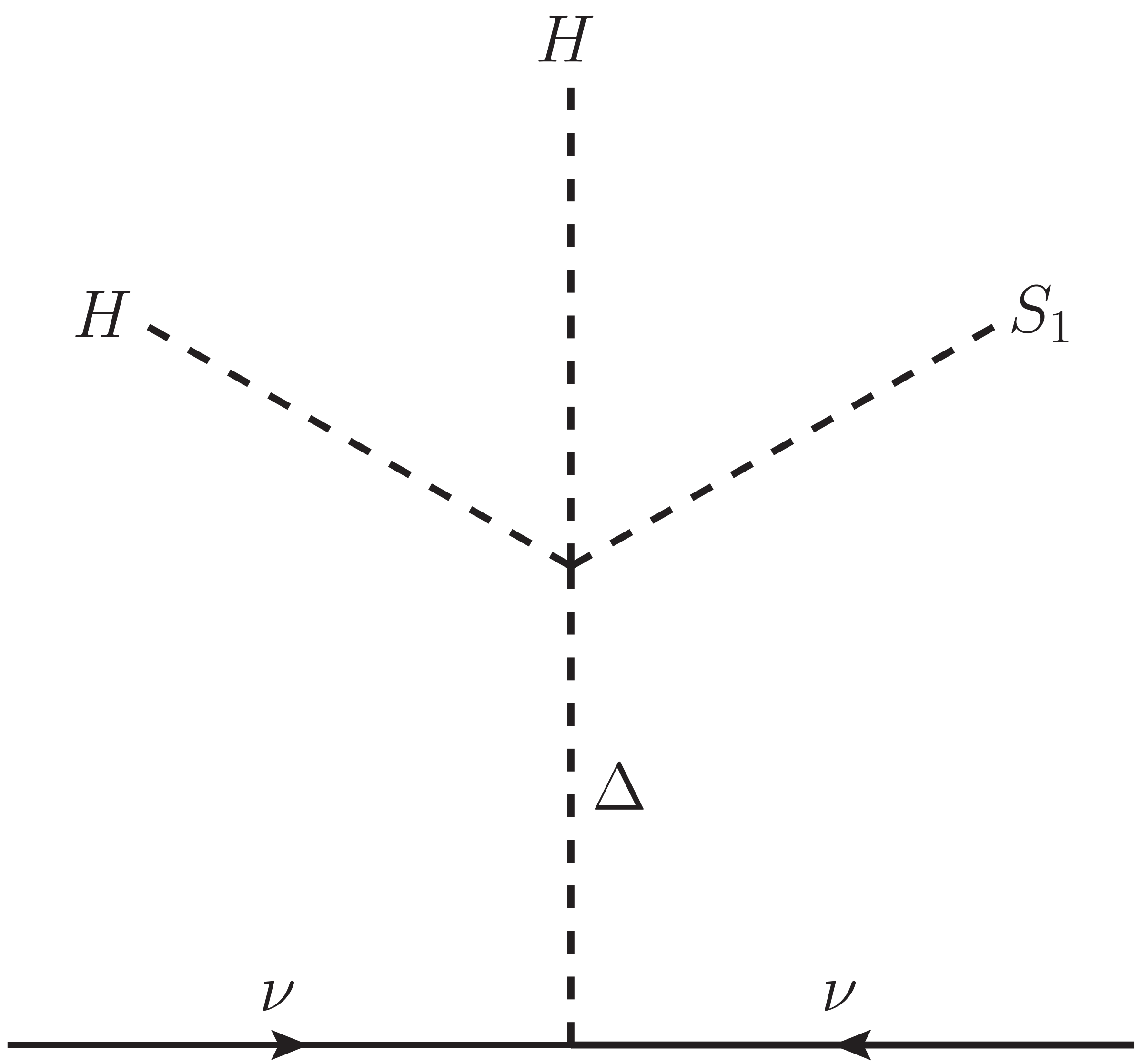

1-Step

Bonilla, Romão, Valle 2016

The Mechanism

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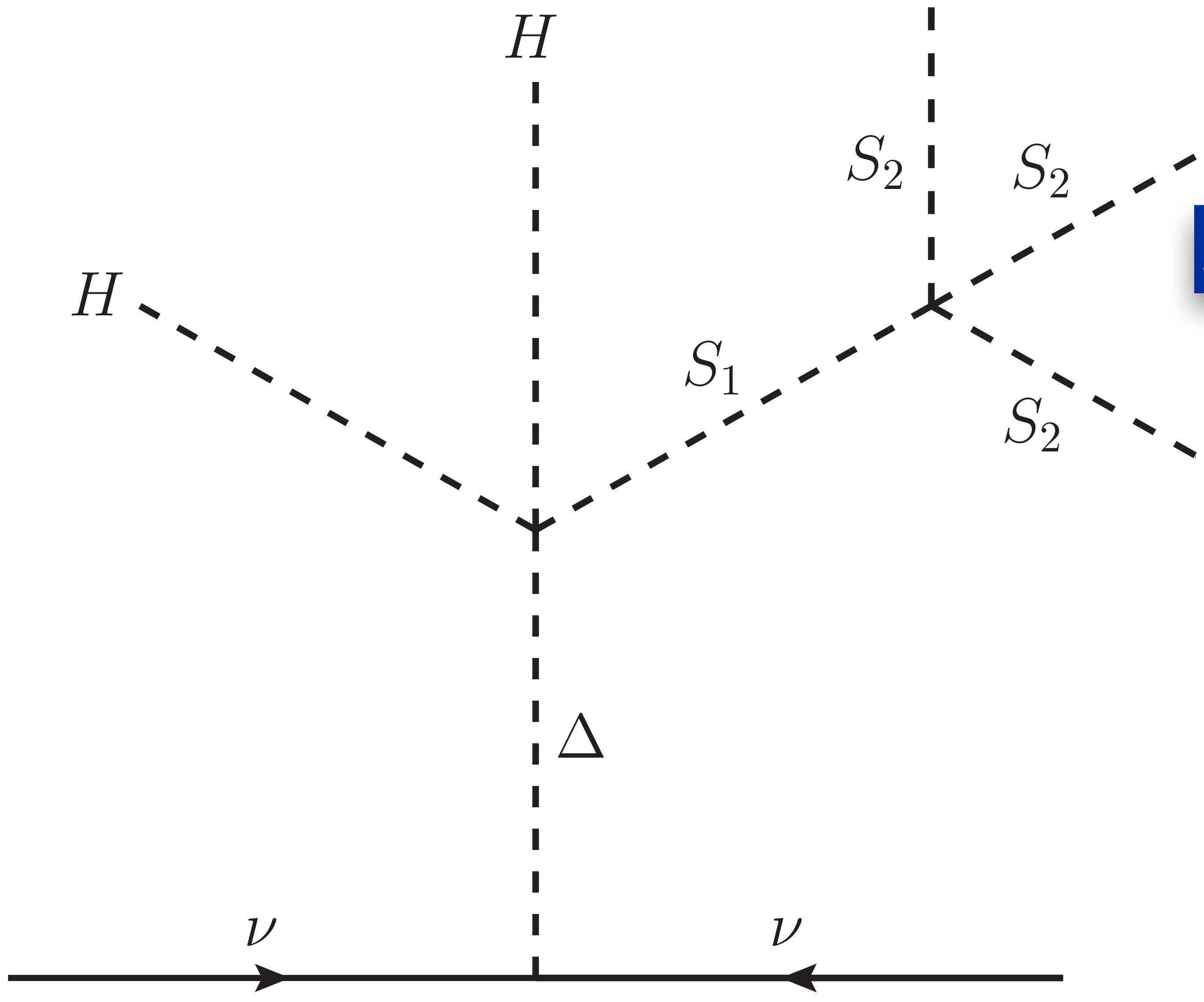
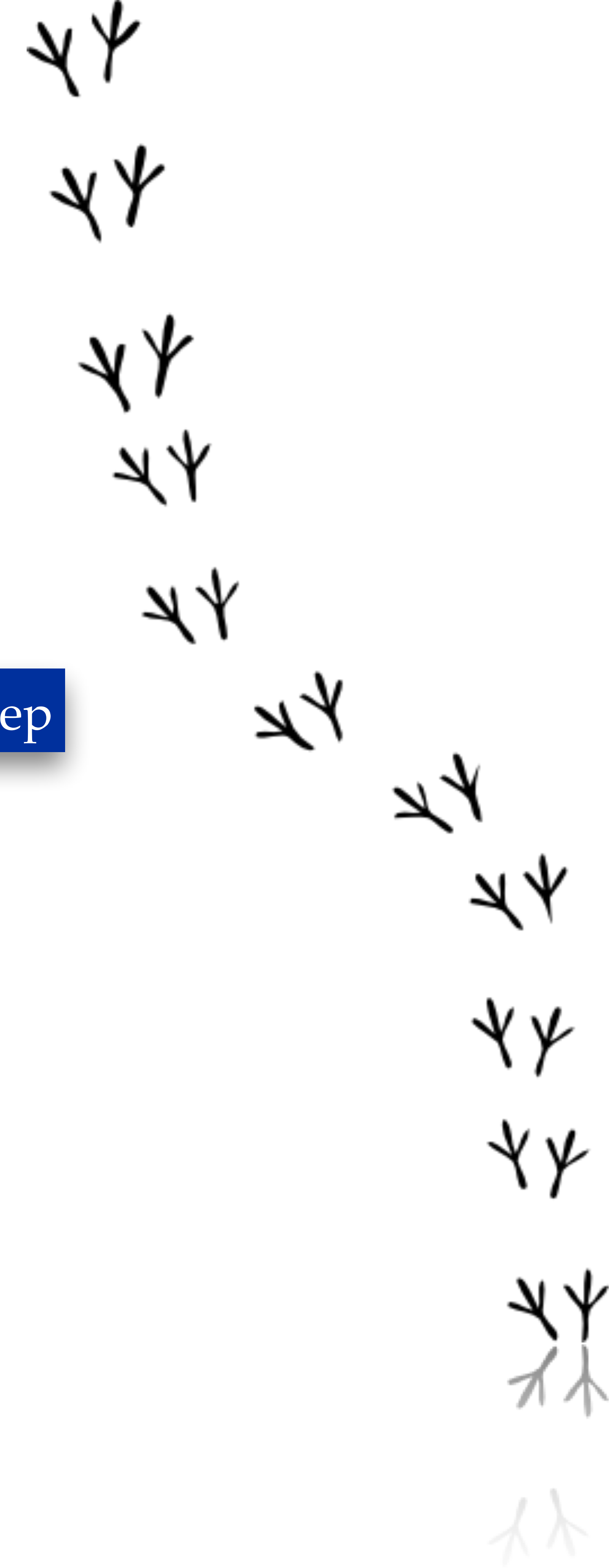
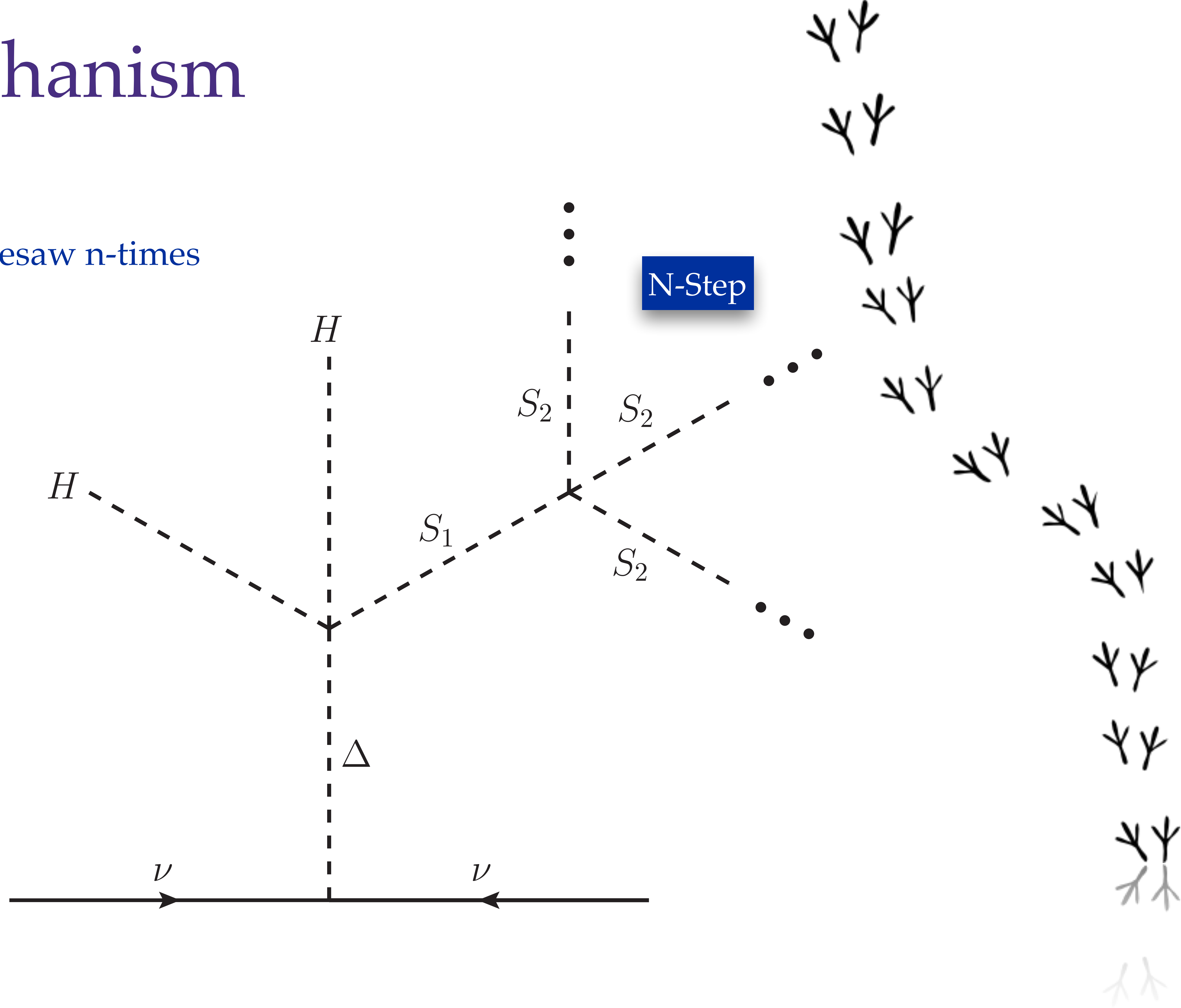


2-Step



The Mechanism

Replicate seesaw n-times



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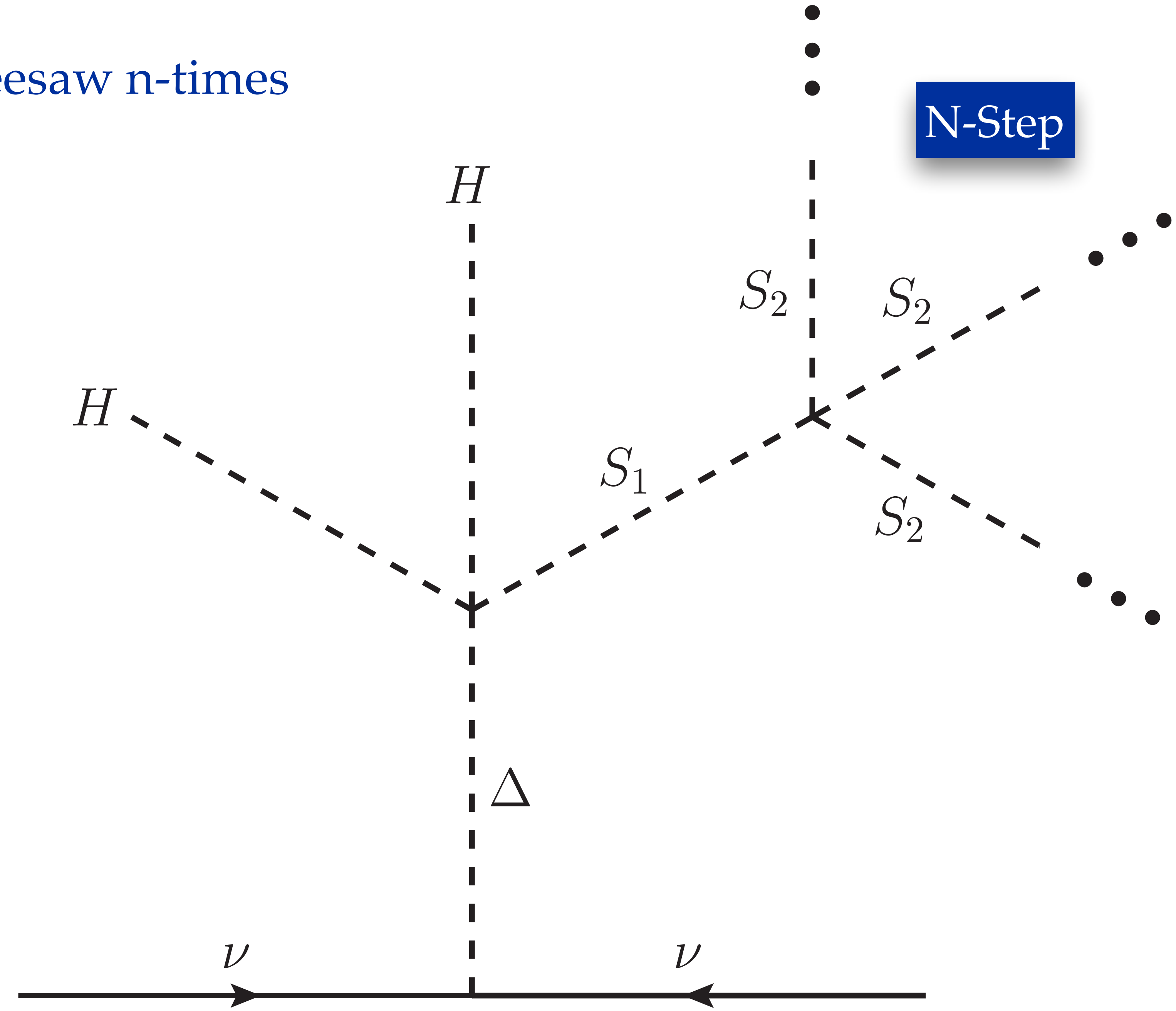
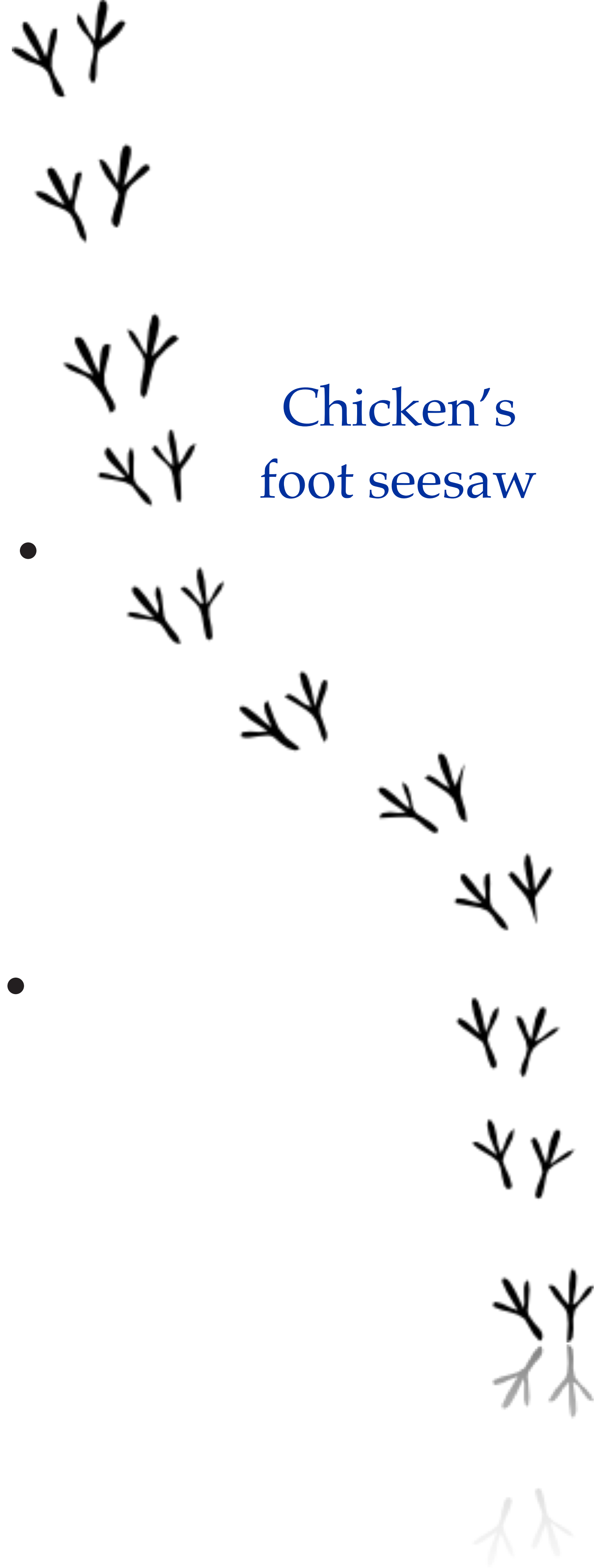
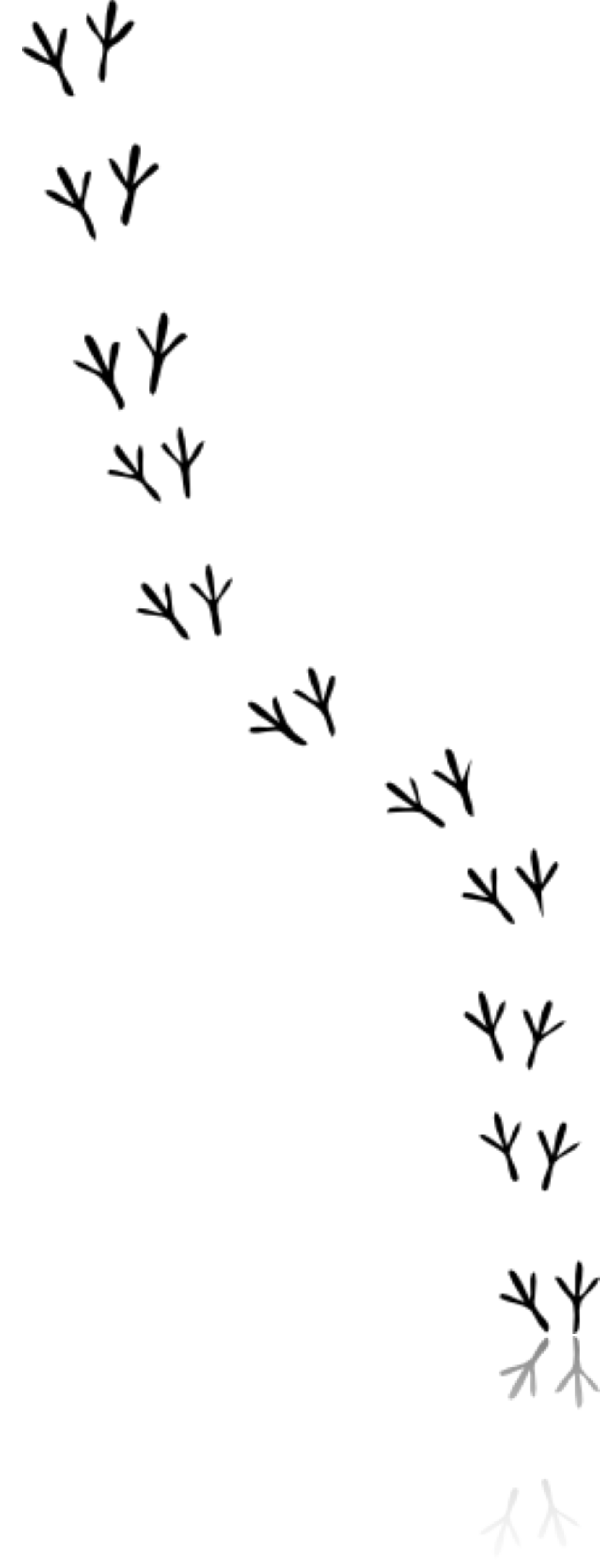




Chicken's
foot seesaw

The Mechanism

- All mass parameters near the EW scale
- All dimensionless parameters of the same order



The Mechanism

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We want to avoid ⟶ $\mu H^T i\sigma_2 \Delta^\dagger H$

The Mechanism

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We want to avoid → $\mu H^T i\sigma_2 \Delta^\dagger H$

Lepton number as a global symmetry

The Mechanism

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- All dimensionless parameters of the same order

We want to avoid → $\mu H^T i\sigma_2 \Delta^\dagger H$

Lepton number as a global symmetry

$$\mathcal{L}^{\nu}_{\text{Yuk}} = -\,Y\overline{L^c}\, i\sigma_2 \Delta\; L + \text{h.c.}$$

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L → $\ell_{\text{leptons}} = +1/2$

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Lepton number as a global symmetry

$$\mathcal{L}^{\nu}_{\rm Yuk} = - Y \overline{L^c}\, i\sigma_2 \Delta\, L + {\rm h.c.}$$

$\ell_{\Delta} = -1$ $\qquad$ $\ell_{\rm leptons} = +1/2$

The Mechanism

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Additional Scalars

The Mechanism

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We want to avoid $\longrightarrow$ $\mu H^T i\sigma_2 \Delta^\dagger H$

Lepton number as a global symmetry

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$\Delta \longrightarrow \ell_\Delta = -1$

$L \longrightarrow \ell_{\text{leptons}} = +1/2$

Additional Scalars: $S_1 \longrightarrow \ell_1 = +1$

The Mechanism

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Lepton number as a global symmetry

$$\mathscr{L}^{\nu}_{\text{Yuk}} = -\, Y \overline{L^c} i\sigma_2 \Delta L + \text{h.c.}$$

$$V \supset \lambda_A H^T i\sigma_2 \Delta^\dagger H S_1^* - \frac{2}{3} \lambda'_{12} S_1^* S_2^3 + \text{h.c.}$$

Additional Scalars

$S_1 \longrightarrow \ell_1 = +1$

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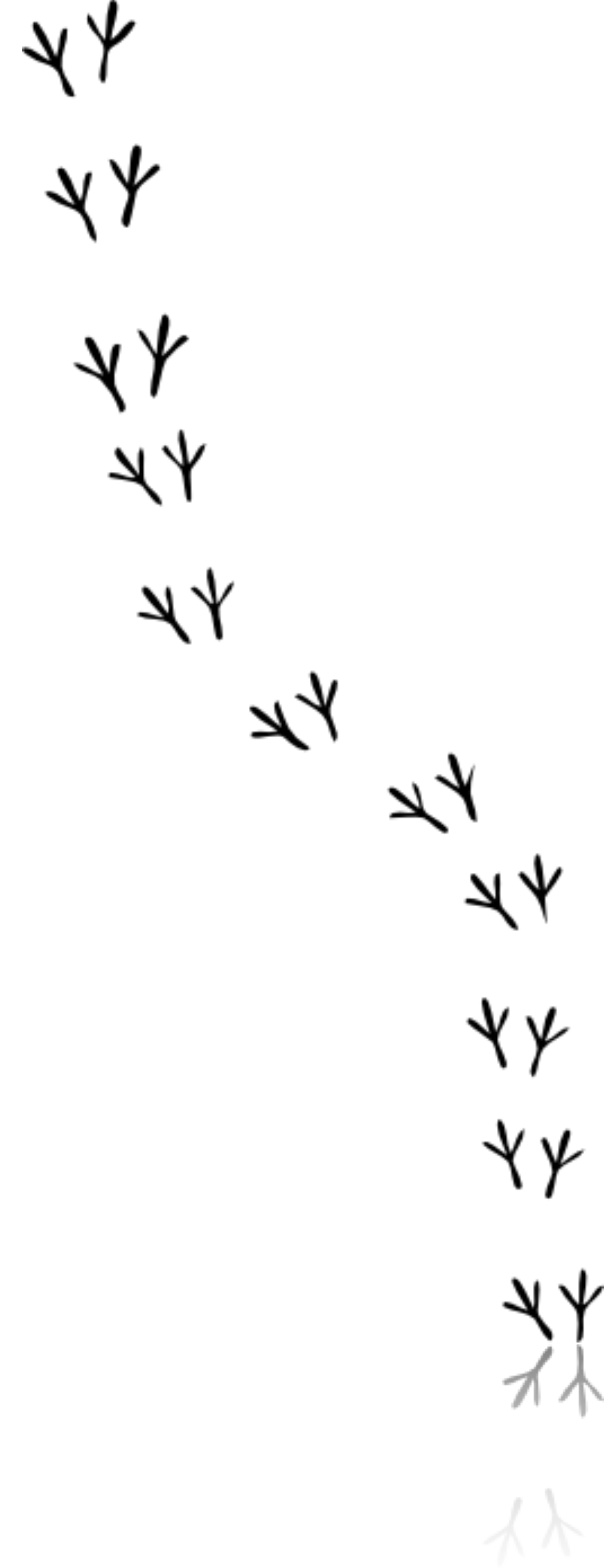
The Mechanism



The Mechanism

EWSB

$$m_H^2 = \frac{1}{2}\lambda_H v^2 + \lambda_{2H} v_2^2, \qquad m_2^2 = \frac{1}{2}\lambda_2 v_2^2 + \lambda_{2H} v^2 \,.$$

The Mechanism

EWSB

SM vev

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The Mechanism

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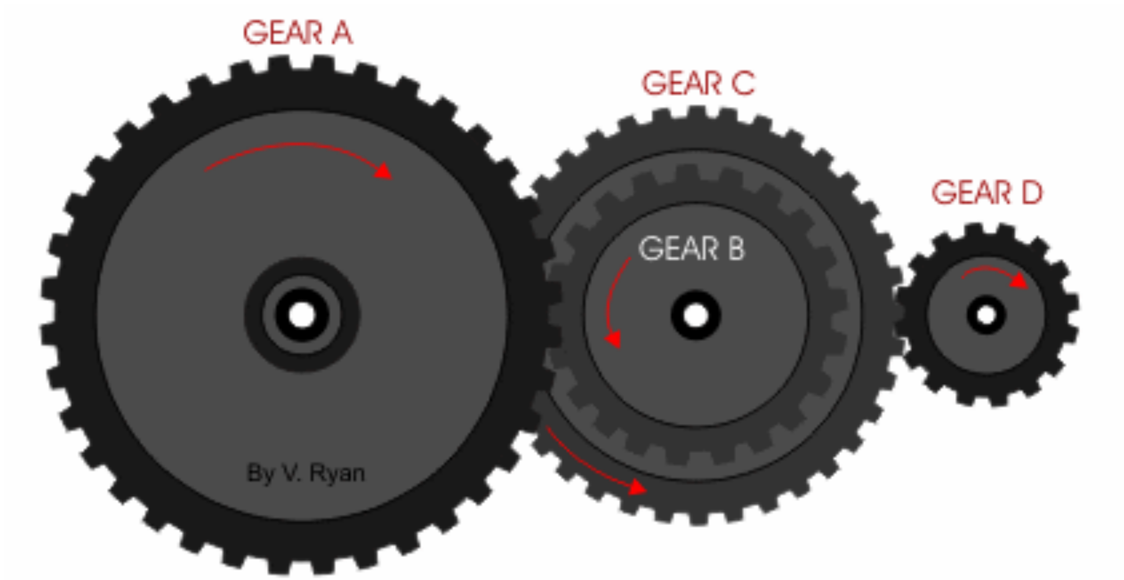
In a very schematically way



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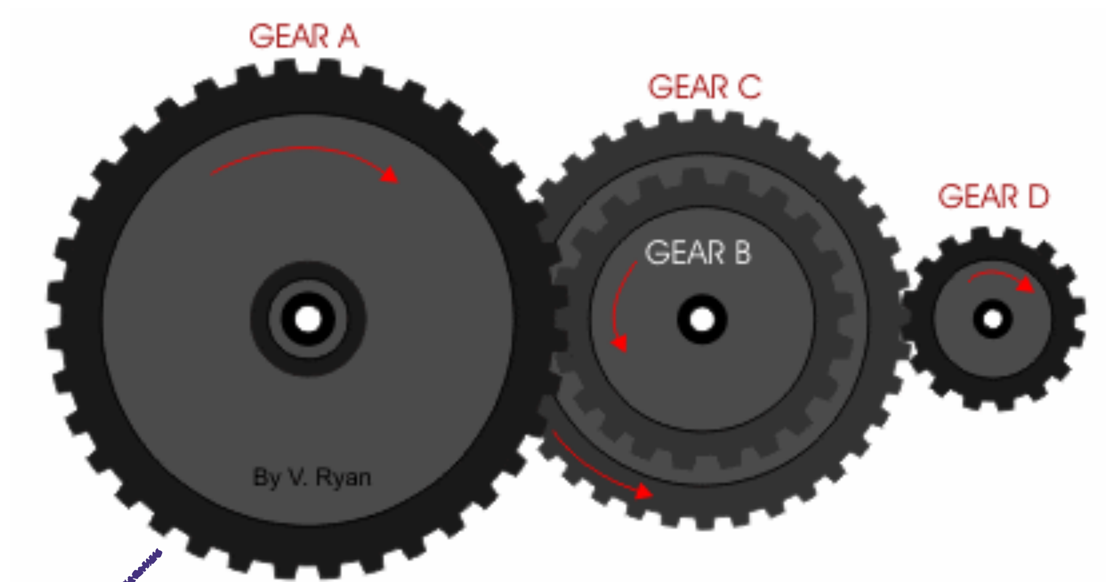
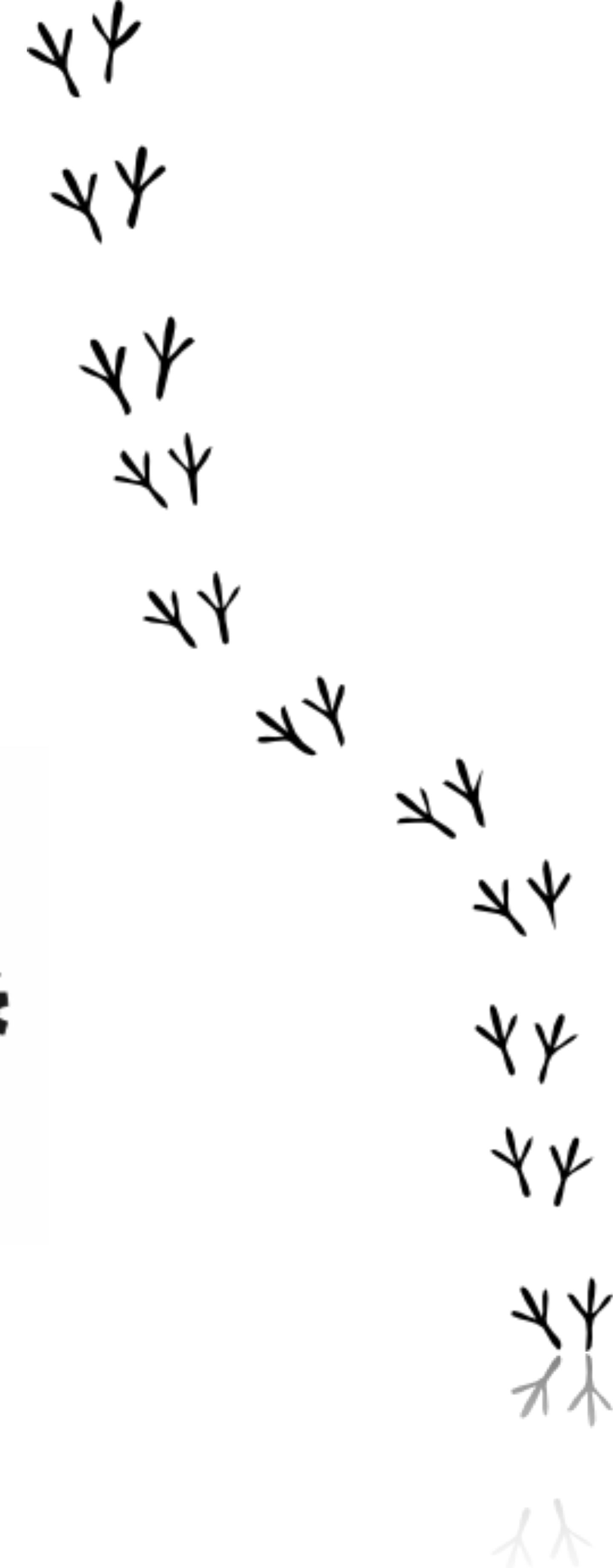


v_2



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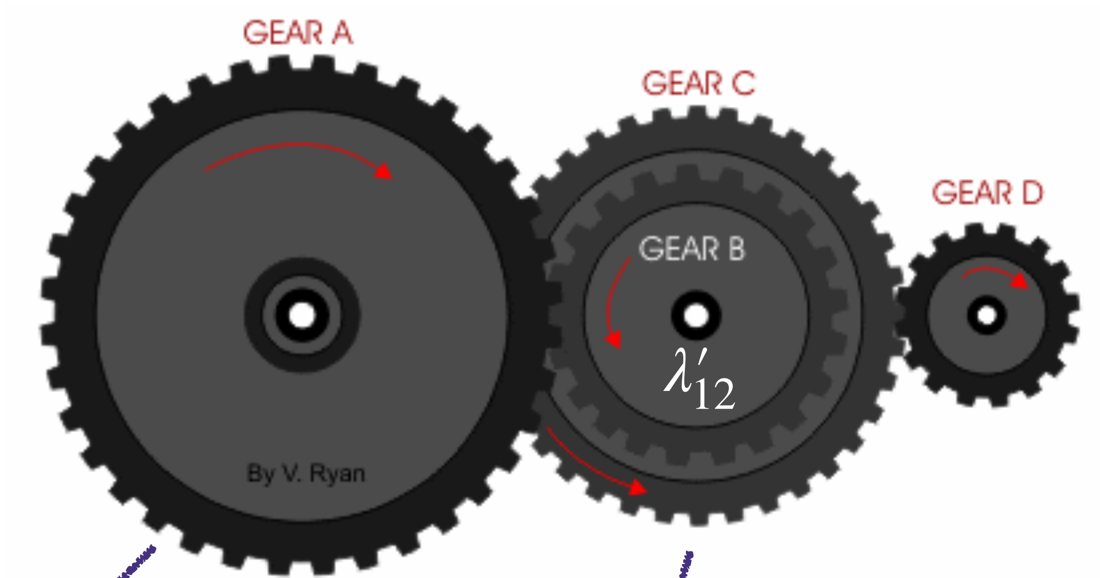

v_2

$$v_1 = \frac{\lambda'_{12} v_2^3}{3M_1^2}$$

The Mechanism

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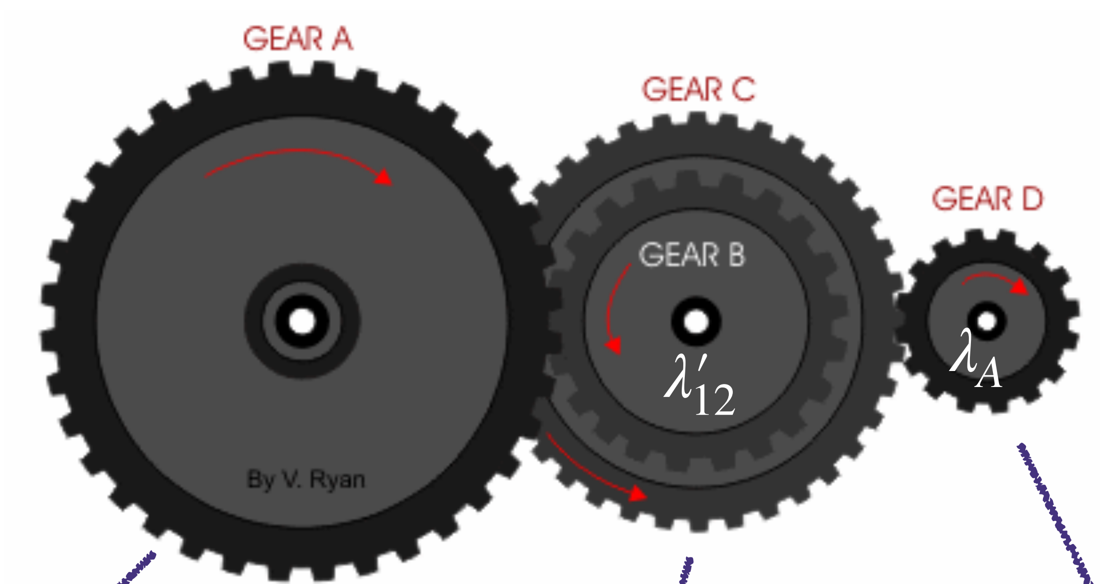


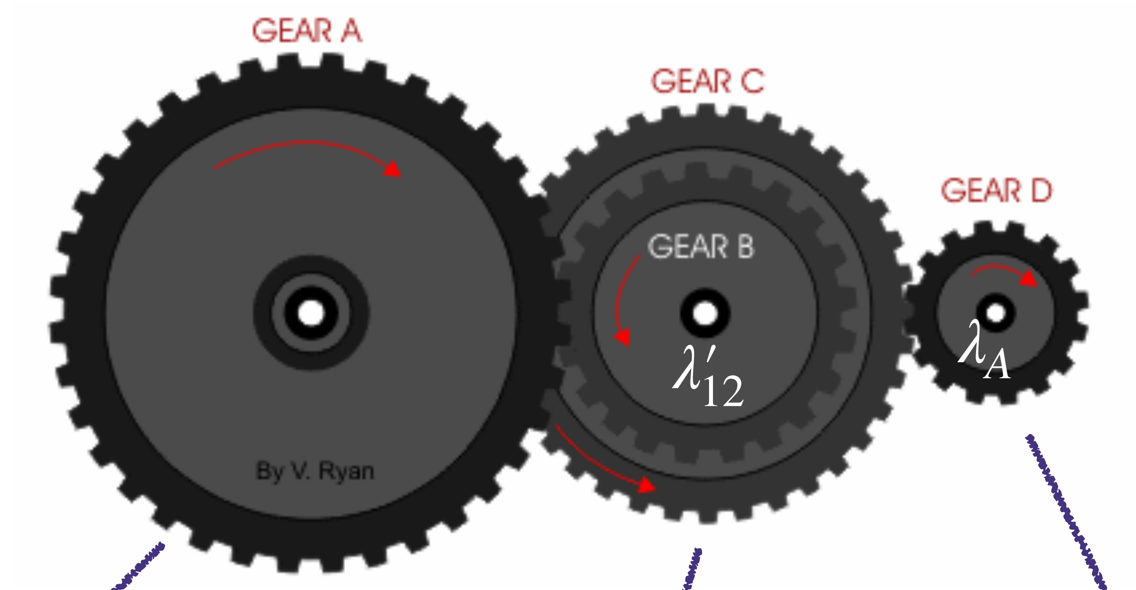
v_2

$$v_1 = \frac{\lambda'_{12} v_2^3}{3M_1^2}$$

$$v_\Delta = \frac{\lambda_A v^2 v_1}{2M_\Delta^2}$$

The Mechanism

In a very schematically way



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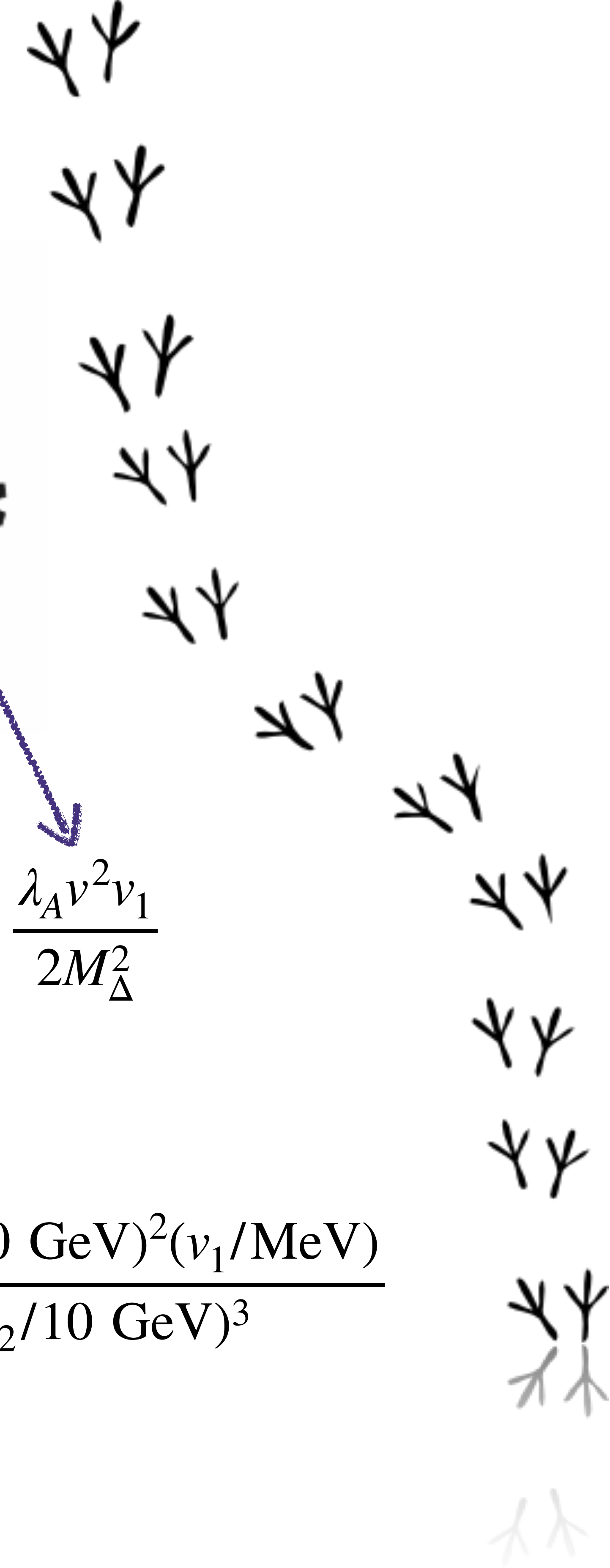


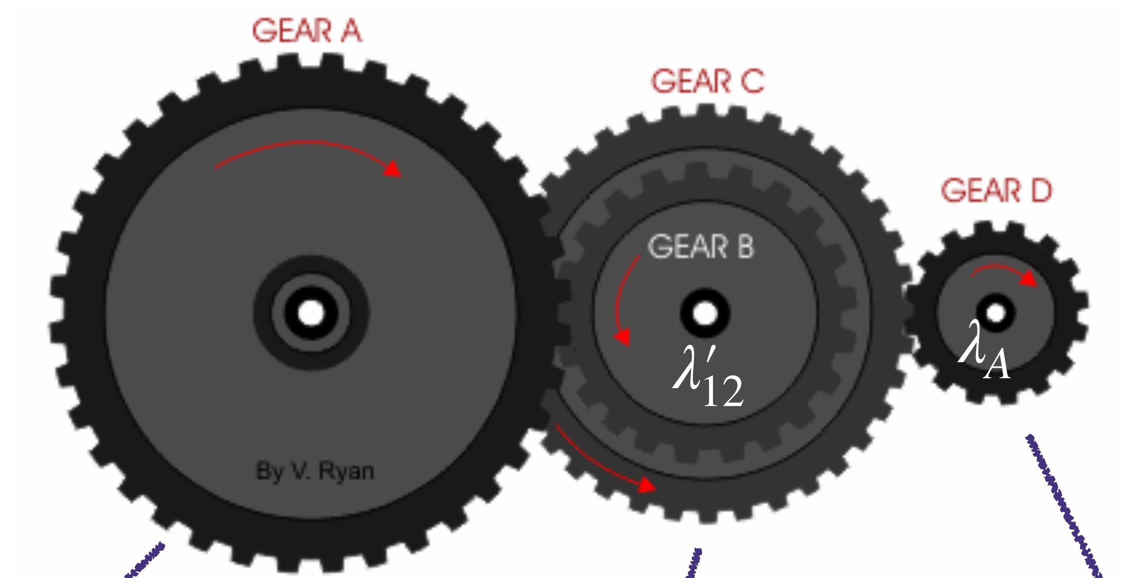
$$\lambda_A = 0.008 \left(\frac{M_\Delta}{500\ \text{GeV}}\right)^2 \left(\frac{v_\Delta/\ \text{keV}}{v_1/\ \text{MeV}}\right)$$

$$\lambda'_{12} = 0.03\, \frac{(M_1/100\ \text{GeV})^2 (v_1/\text{MeV})}{(v_2/10\ \text{GeV})^3}$$

Independent on the number of steps

The Mechanism

In a very schematically way



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Independent on the number of steps

Spectrum and Mixing

- 4 scalar particles h, δ, s_1, s_2
- Two charged particles δ^+, δ^{++}
- 2 massive pseudo scalars a_δ, a_1
- 1 massless Nambu-Goldstone boson J

Spectrum and Mixing

Higgs!

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As in SM TII

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New scalar degrees of freedom

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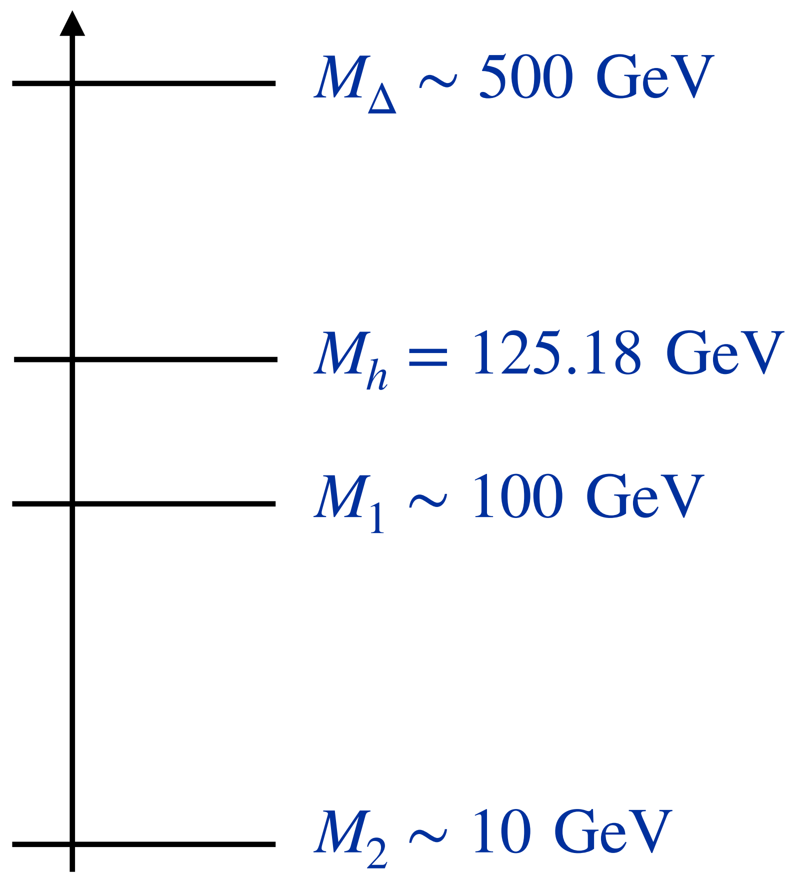
Majoron…

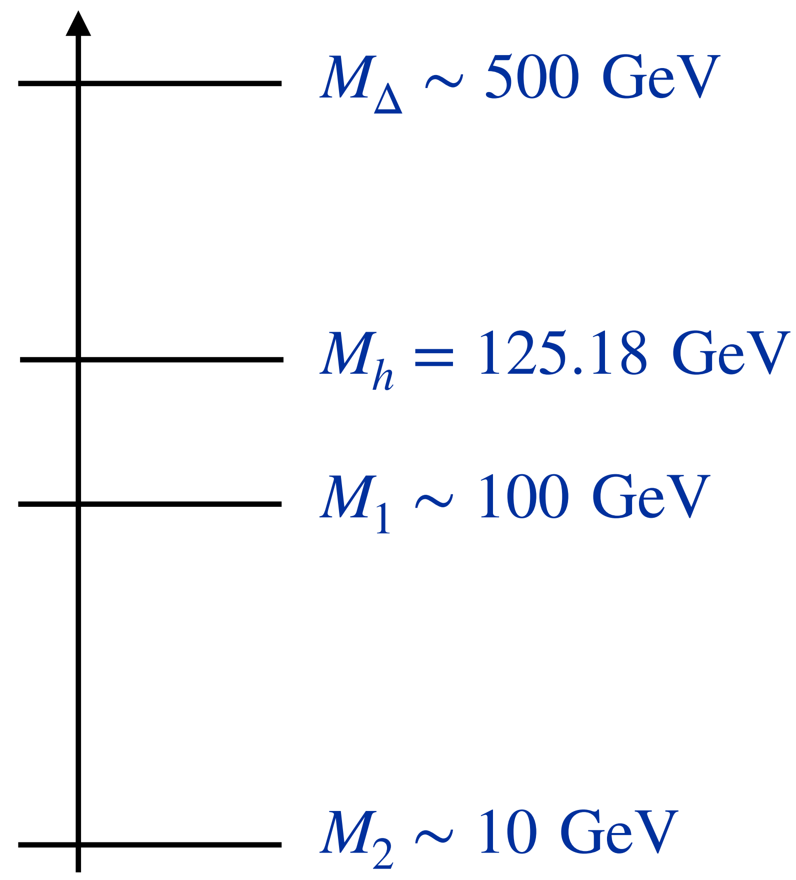
Spectrum and Mixing



At the same scale

Spectrum and Mixing

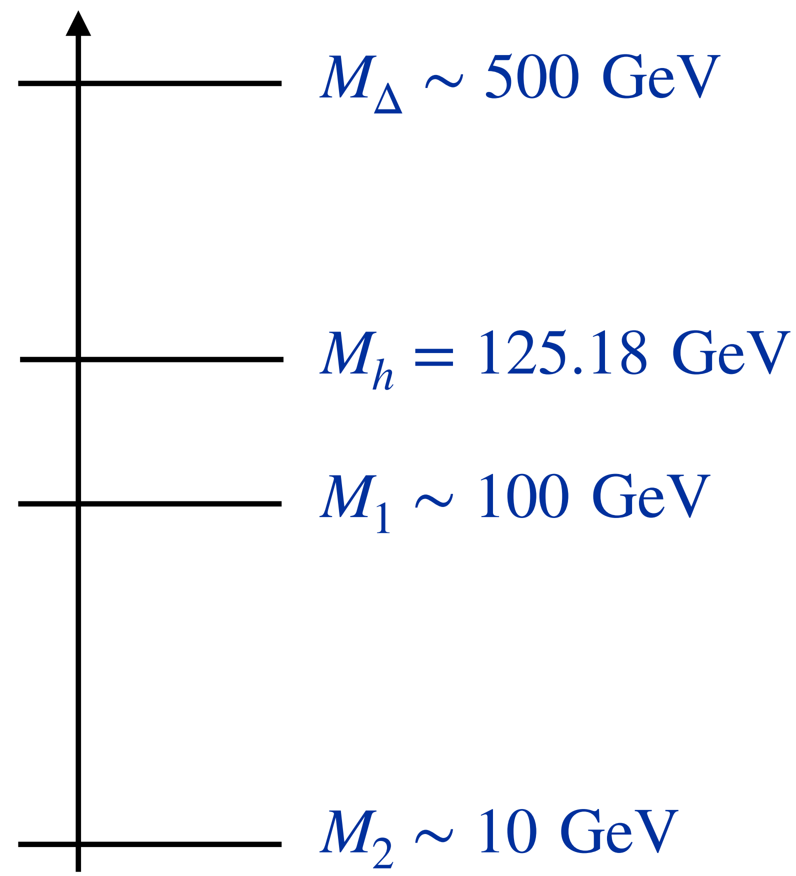
At the same scale



θ_{h2} $\theta_{\delta 1}$ θ_{h1}

Spectrum and Mixing

At the same scale

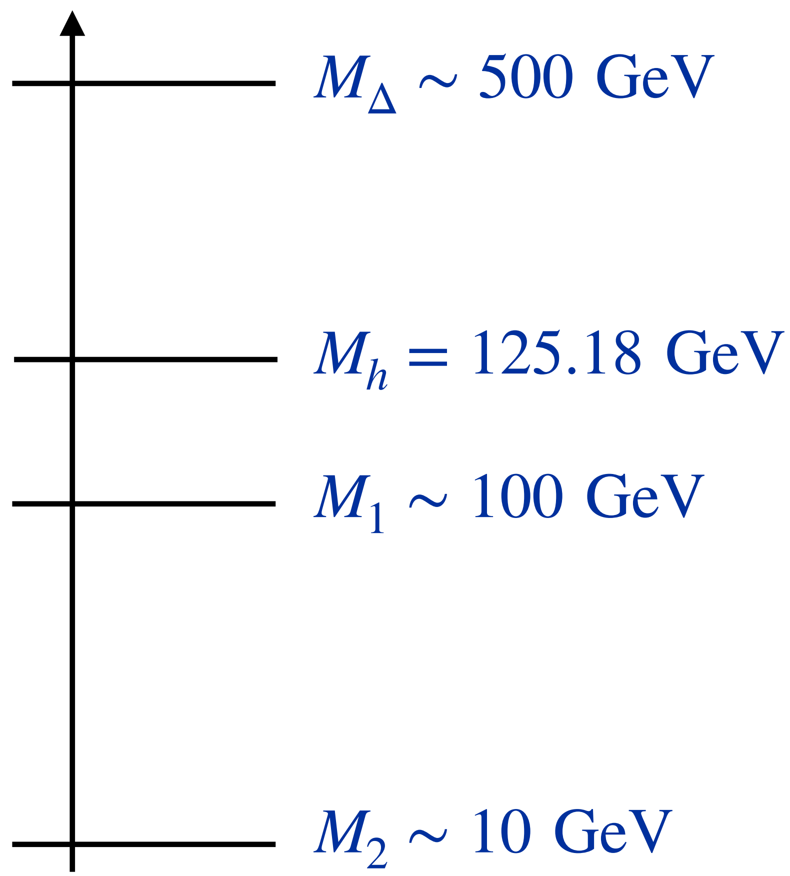


θ_{h2} $\theta_{\delta 1}$ θ_{h1}

Higgs observables,
direct s_2 production

Spectrum and Mixing

At the same scale



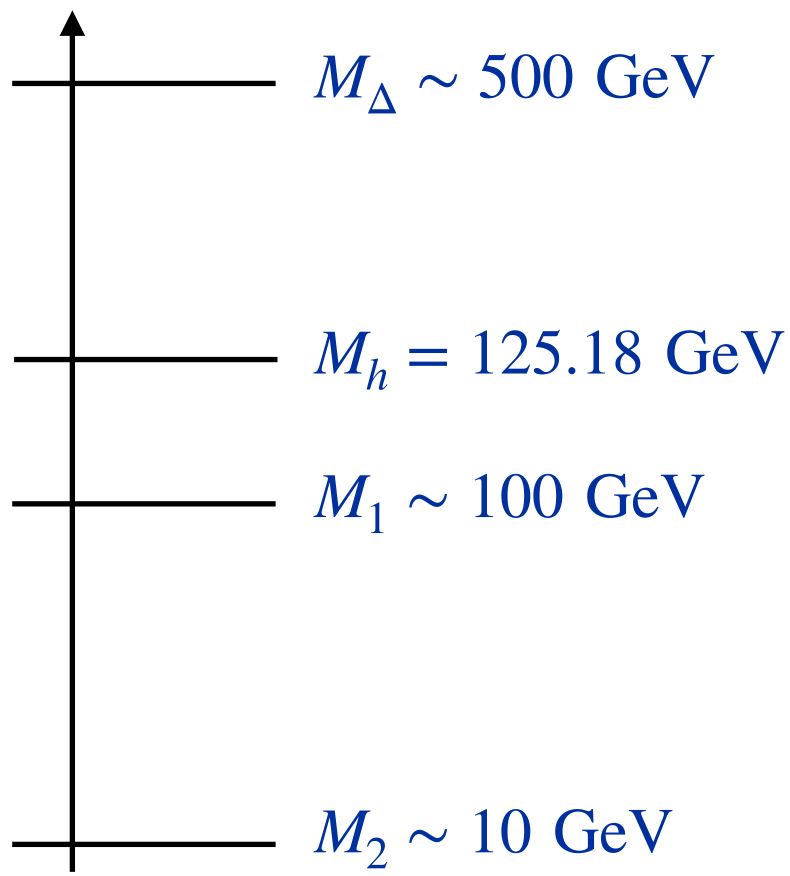
θ_{h2} $\theta_{\delta 1}$ θ_{h1}

Higgs observables,
direct s_2 production

LHC signatures
s_1 decay modes

Spectrum and Mixing

At the same scale



θ_{h2} → Higgs observables, direct s_2 production

$\theta_{\delta 1}$ → LHC signatures s_1 decay modes

θ_{h1} → s_1 decay modes

Phenomenology

Majoron

Purely massless Majoron

Compare with Julian's talk

Couplings

$$G_{Jff} = \frac{1.6 \cdot 10^{-18}}{\ell_2} \frac{(m_f/\text{GeV})(v_\Delta/\text{keV})^2}{(v_2/10\ \text{GeV})}$$

$$G_{J\nu\nu} = \frac{5 \cdot 10^{-12}}{\ell_2} \frac{(m_\nu/0.1\ \text{eV})}{(v_2/10\ \text{GeV})}$$

Majoron

Purely massless Majoron

Compare with Julian's talk

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Lepton number

Majoron

Purely massless Majoron

Compare with Julian's talk

Couplings

$$G_{Jff} = \frac{1.6 \cdot 10^{-18}}{\ell_2} \frac{(m_f/\text{GeV})(v_\Delta/\text{keV})^2}{(v_2/10\ \text{GeV})}$$

$$G_{J\nu\nu} = \frac{5 \cdot 10^{-12}}{\ell_2} \frac{(m_\nu/0.1\ \text{eV})}{(v_2/10\ \text{GeV})}$$

Lepton number

Astrophysical bounds

$$G_{Jee} < 4.3 \times 10^{-13}$$

Gando et.al., 2012

Majoron emission

$$G_{J\nu\nu} < (0.8 - 1.6) \times 10^{-5}$$

Patrignani et al, 2016

Majoron

Purely massless Majoron

Compare with Julian's talk

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ℓ_2 → Lepton number

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Higgs invisible decay

$$\theta_{h2} < 1.5 \cdot 10^{-3} \left[\frac{v_2}{10\ \text{GeV}}\right] \left[\frac{\Gamma_h}{4.2\ \text{MeV}} \frac{\text{BR}(\text{h} \to \text{inv})}{0.22}\right]^{1/2}$$

Majoron

Freeze in

$$\Gamma(\nu \to J\nu') = \frac{G_{J\nu\nu}^2}{32\pi} m_\nu$$

$$\tau = \approx 1 \cdot 10^{45} \frac{l_2^2 \cdot (v_2/10\ \mathrm{GeV})^2 \cdot (T/1\ \mathrm{GeV})}{(m_\nu/0.1\ \mathrm{eV})^4} \frac{1}{\mathrm{GeV}} \approx 10^{21}\ \mathrm{s} > \textbf{age universe}$$

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Compatible with CMB

$$G_{J\nu\nu}^{ii} < 1.2 \times 10^{-7}$$

$$G_{J\nu\nu}^{ij} < 2.3 \times 10^{-11} \left(\frac{0.05\ \text{eV}}{m} \right)^2$$

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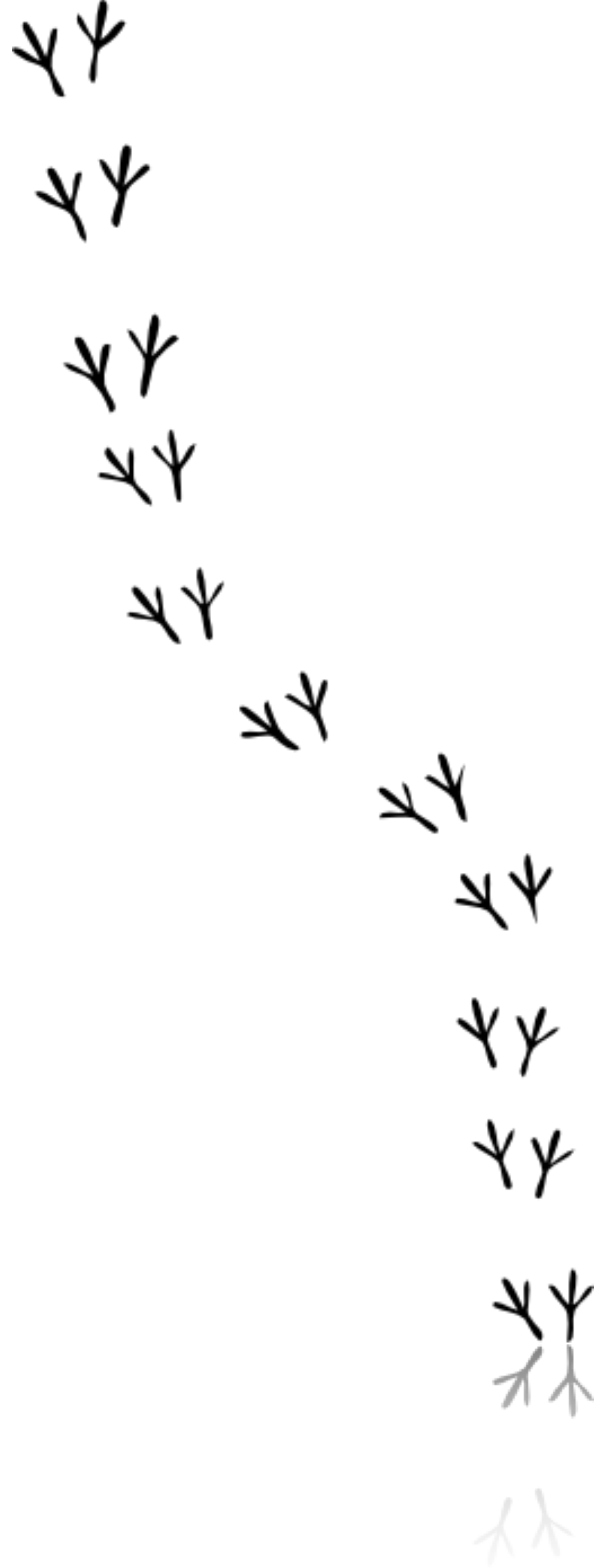
No problem with a massless majoron

Collider



Collider

- Identify Δ as a SU(2) triplet $pp \to \delta^{\pm\pm}\delta^{\mp}$

Perez, Han, Huang, Li, Wang, 2008

See also Melfo, Nemevšek, Nesti, Senjanović, Zhang 2011

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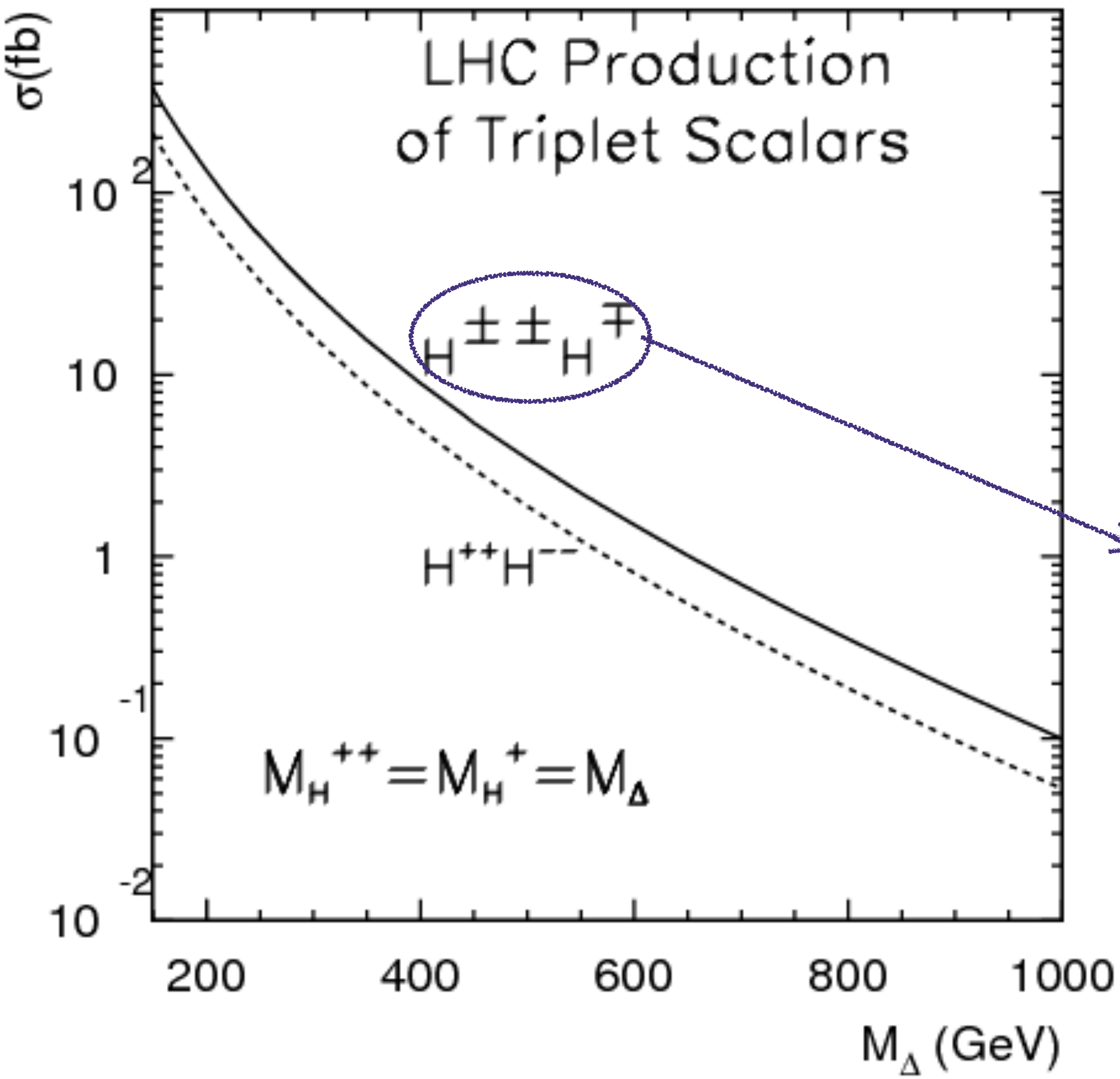
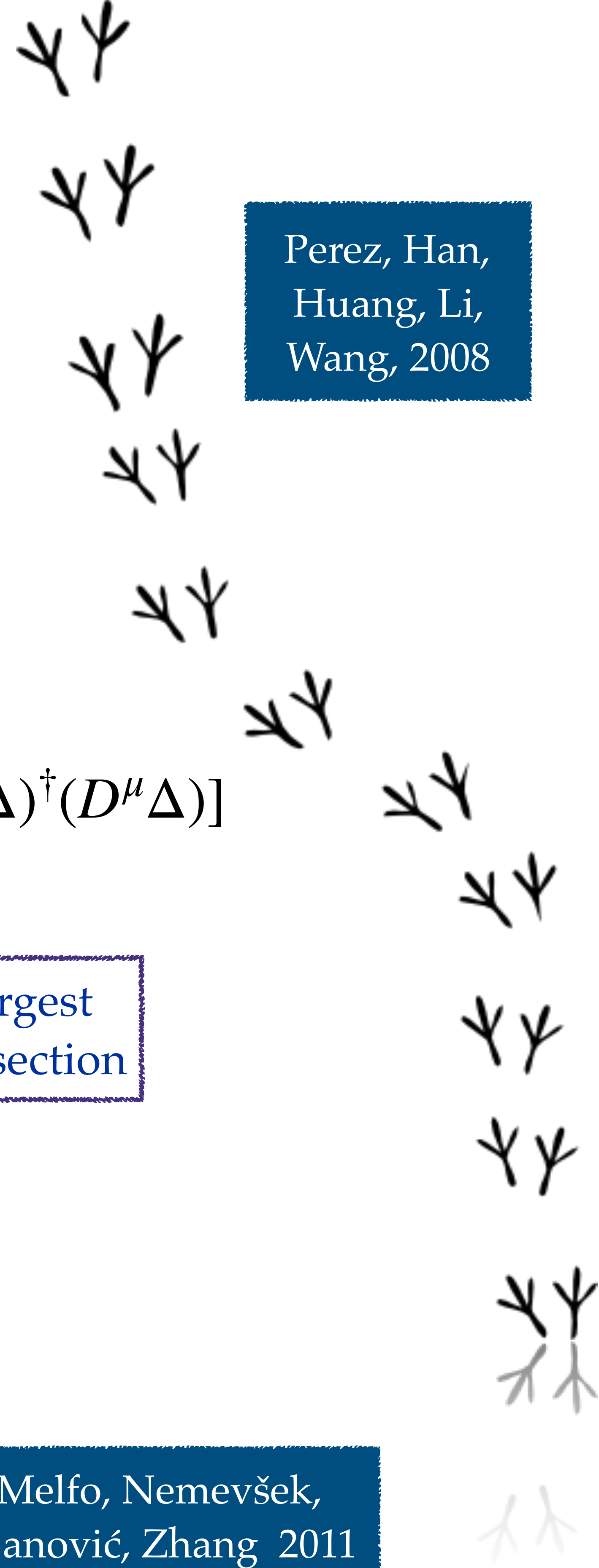


$$\mathscr{L} \supset \mathrm{Tr}[(D_\mu\Delta)^\dagger(D^\mu\Delta)]$$

Channel with largest Production cross-section



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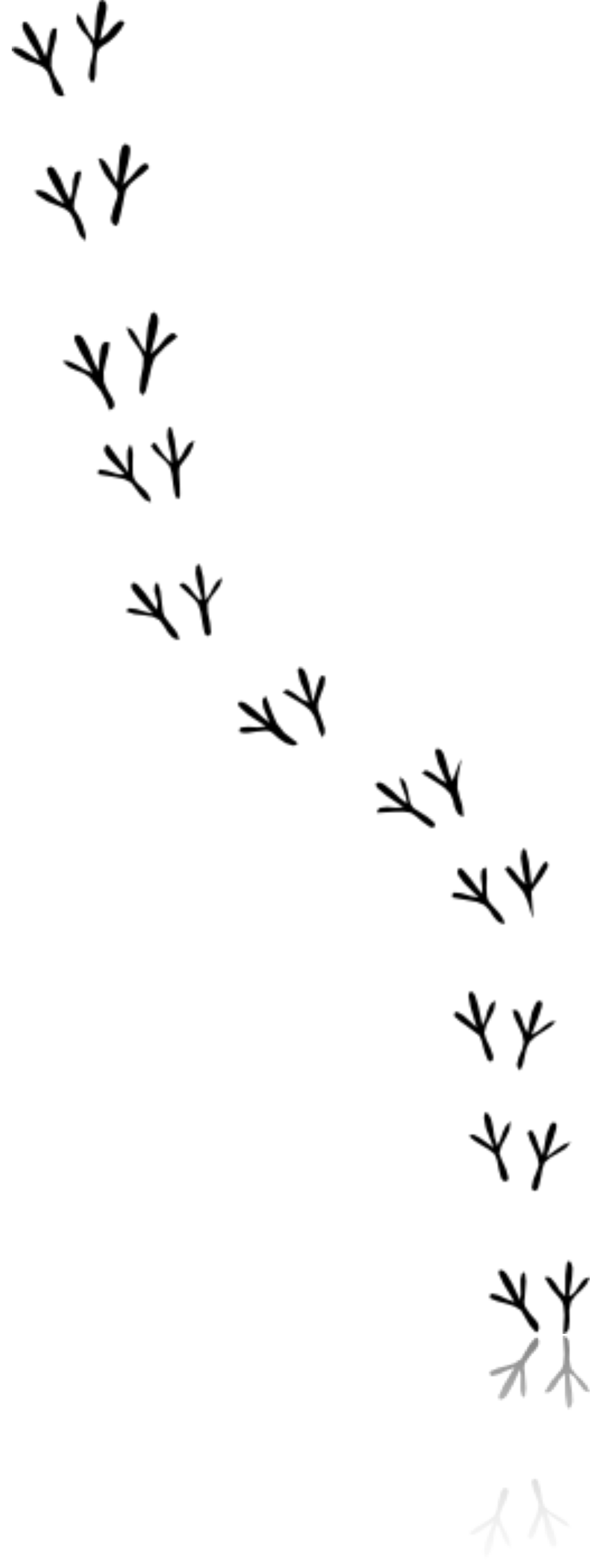
Collider



Collider

- Identify Δ as a SU(2) triplet $pp \to \delta^{\pm\pm}\delta^{\mp}$
- Understand the differences with the Standard TII

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Standard Type - II seesaw

$v_\Delta < 10^{-4}$ GeV

$\delta^{\pm} \to \ell^{\pm}\nu$ Independent of Majorana phases

$\delta^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ Dependent of Majorana phases

$$pp \longrightarrow \delta^{\pm\pm}\delta^{\mp} \to \ell^{\pm}\ell^{\pm}\ell^{\mp}\nu$$

Striking signature

See also Melfo, Nemevšek, Nesti, Senjanović, Zhang 2011

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Standard Type - II seesaw		Our scenario
$v_\Delta < 10^{-4}$ GeV		
$\delta^{\pm} \to \ell^{\pm}\nu$	Independent of Majorana phases	$\delta^{\pm} \to W^{\pm} s_1$
$\delta^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$	Dependent of Majorana phases	$\delta^{\pm\pm} \to W^{\pm}W^{\pm} s_1$
$pp \longrightarrow \delta^{\pm\pm}\delta^{\mp} \to \ell^{\pm}\ell^{\pm}\ell^{\mp}\nu$		Don't present v_Δ suppression
Striking signature		

Perez, Han, Huang, Li, Wang, 2008

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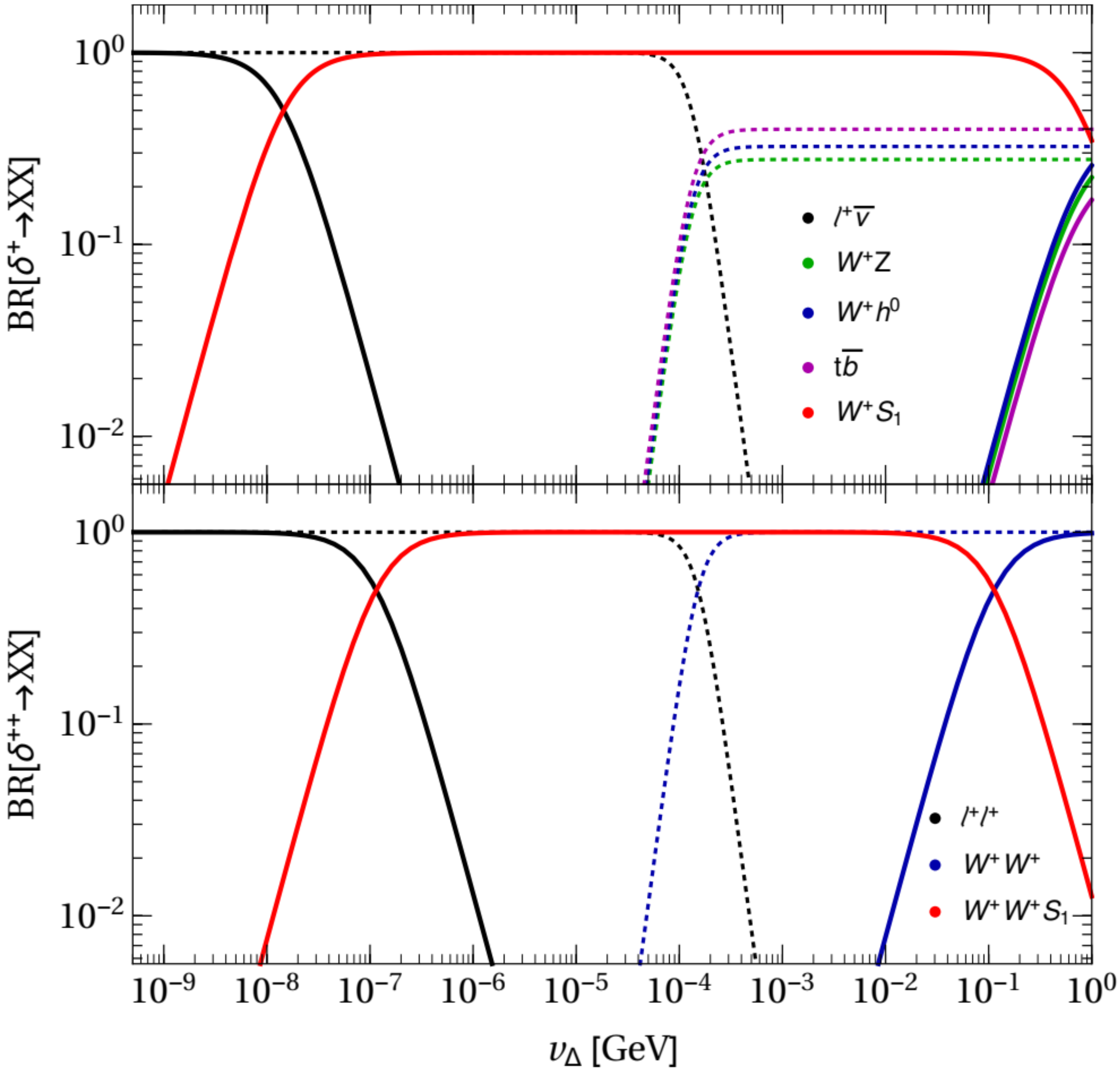
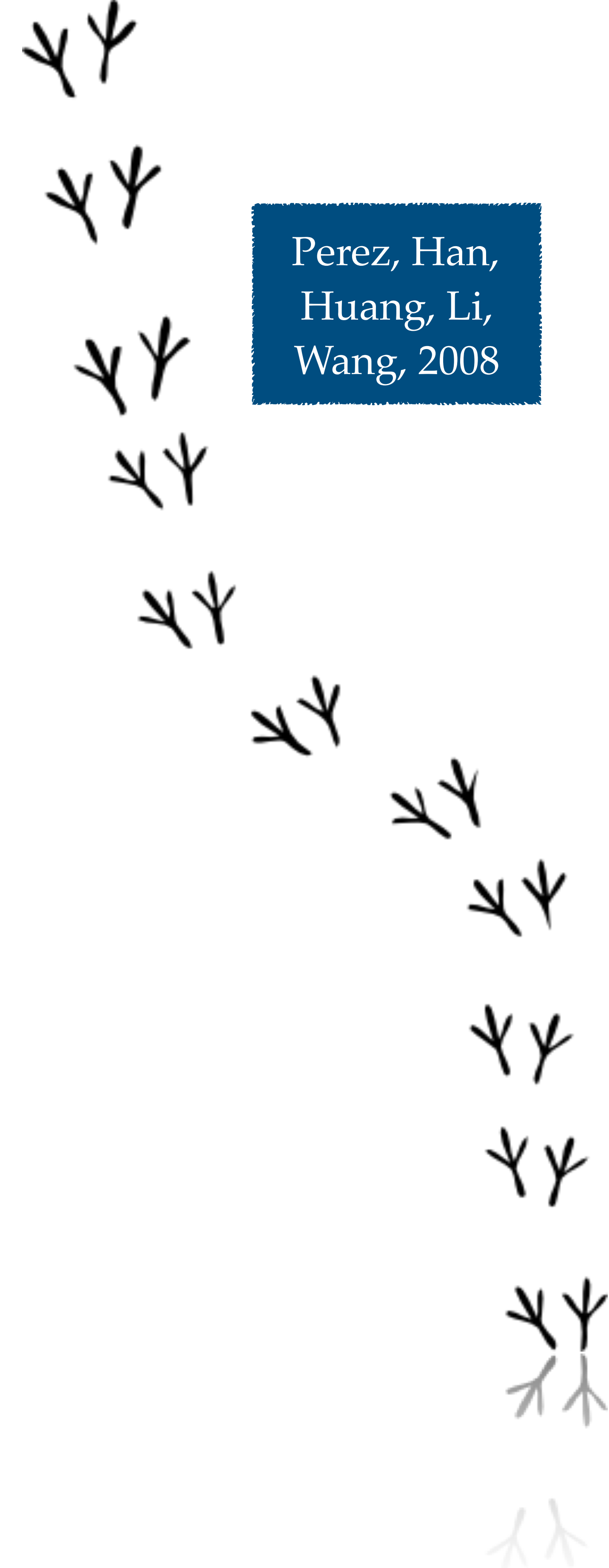
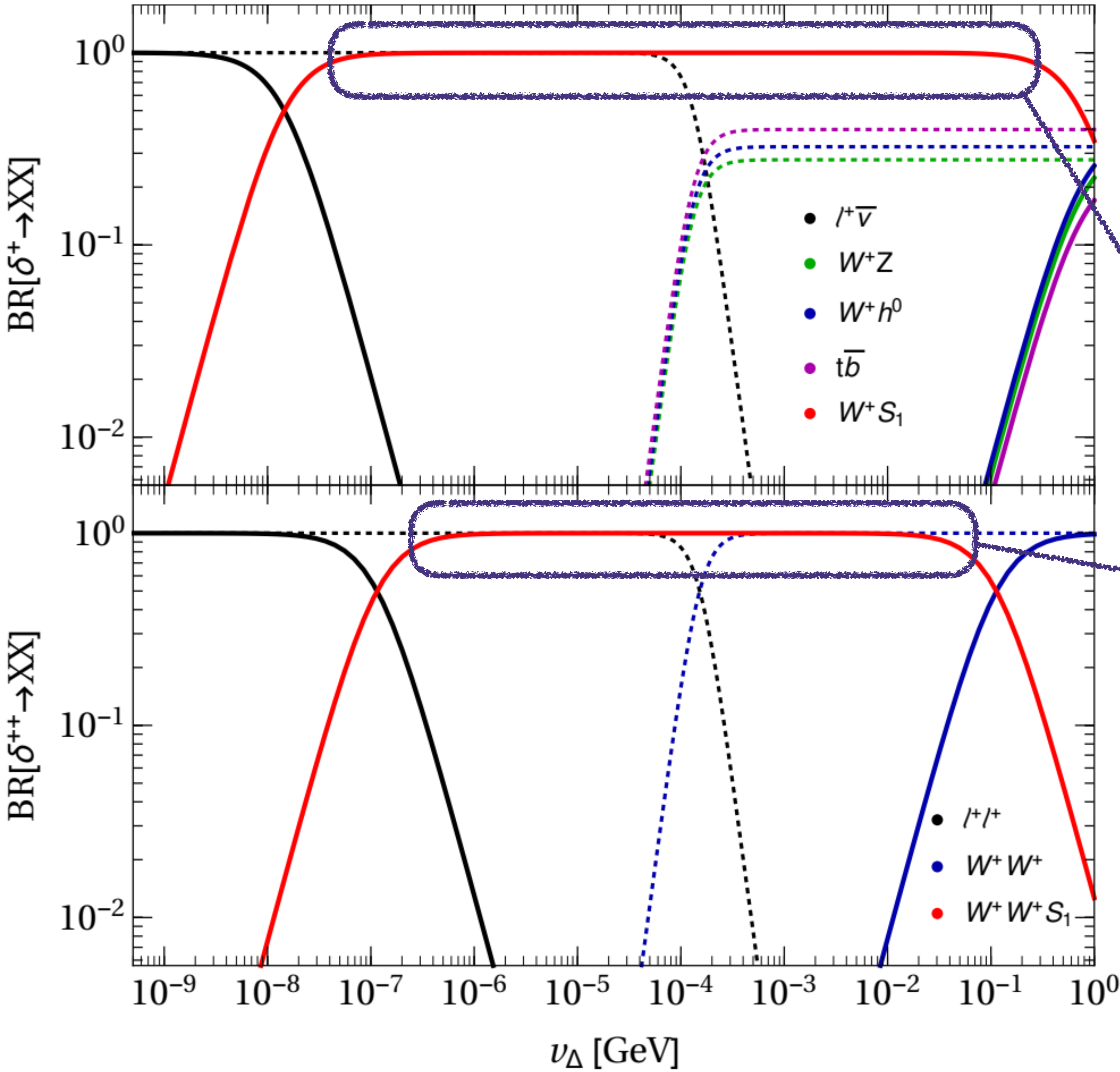
Collider

Perez, Han, Huang, Li, Wang, 2008





Collider

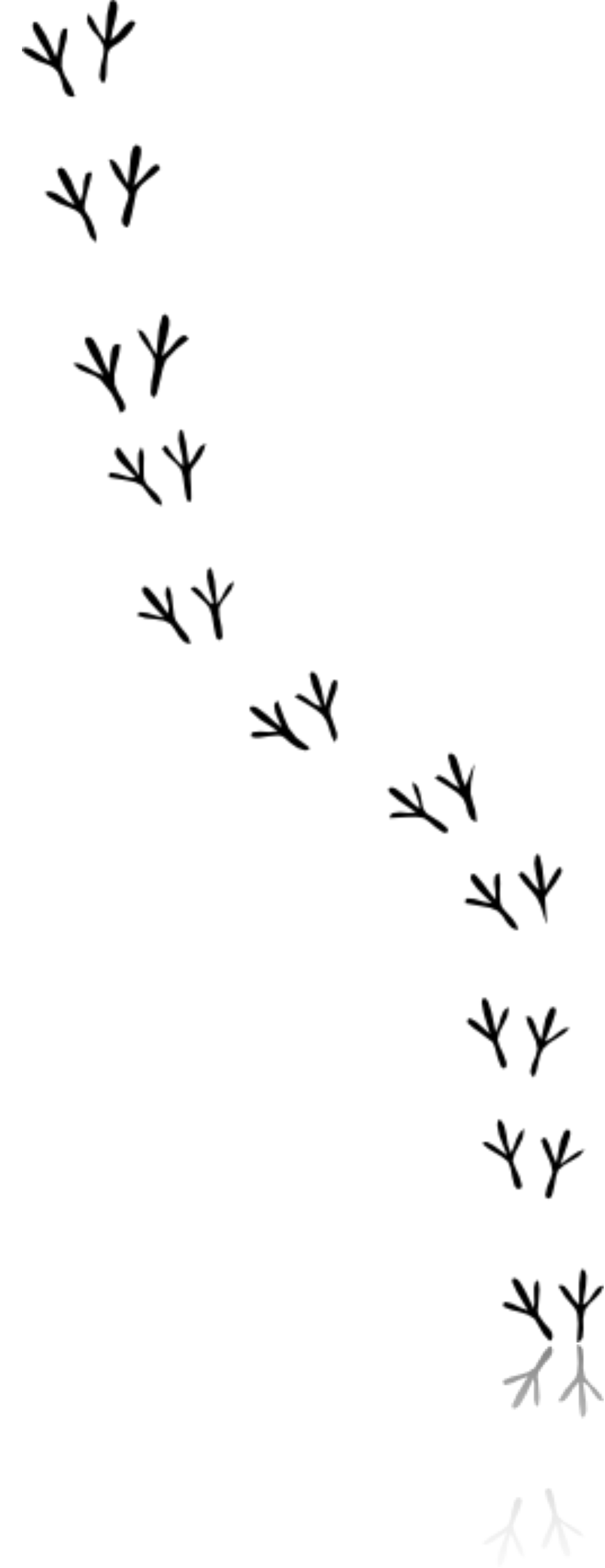


Perez, Han, Huang, Li, Wang, 2008

The decay into s1 dominates a large region

Collider

- Identify Δ as a SU(2) triplet
- Understand the differences with the Standard TII



Collider

- Identify Δ as a SU(2) triplet
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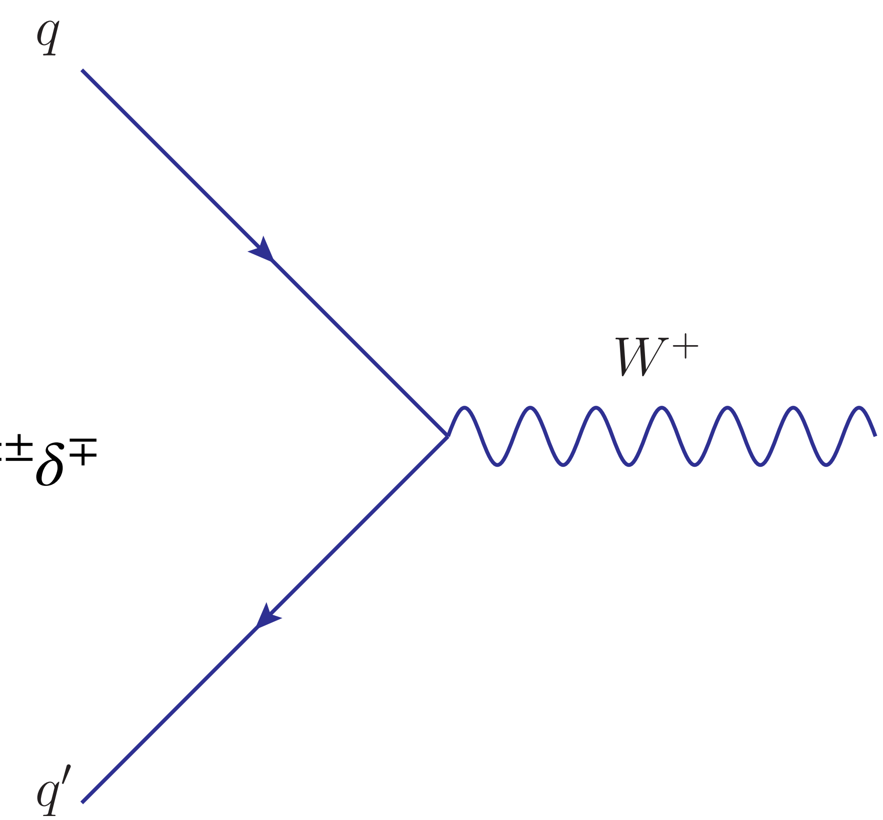
$pp \to \delta^{\pm\pm}\delta^{\mp}$



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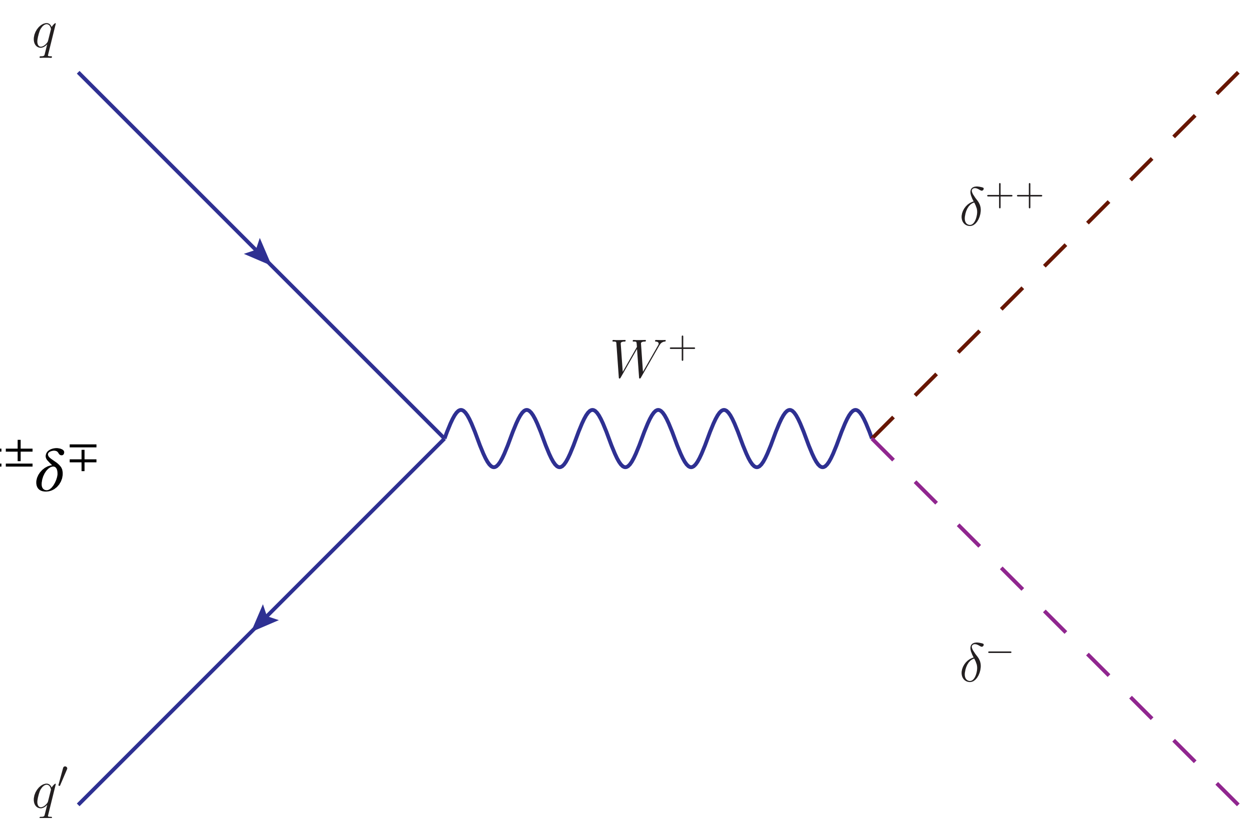

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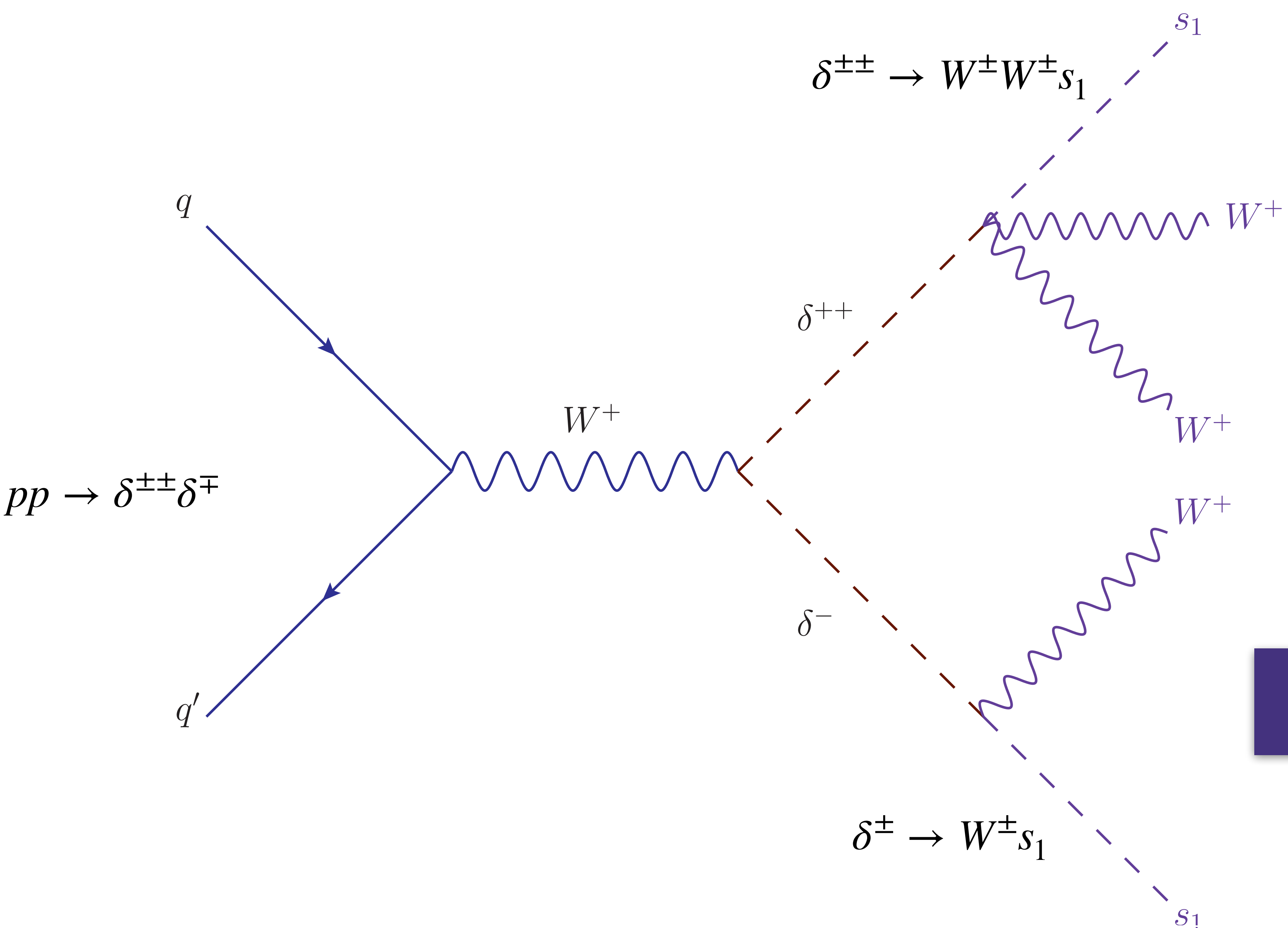
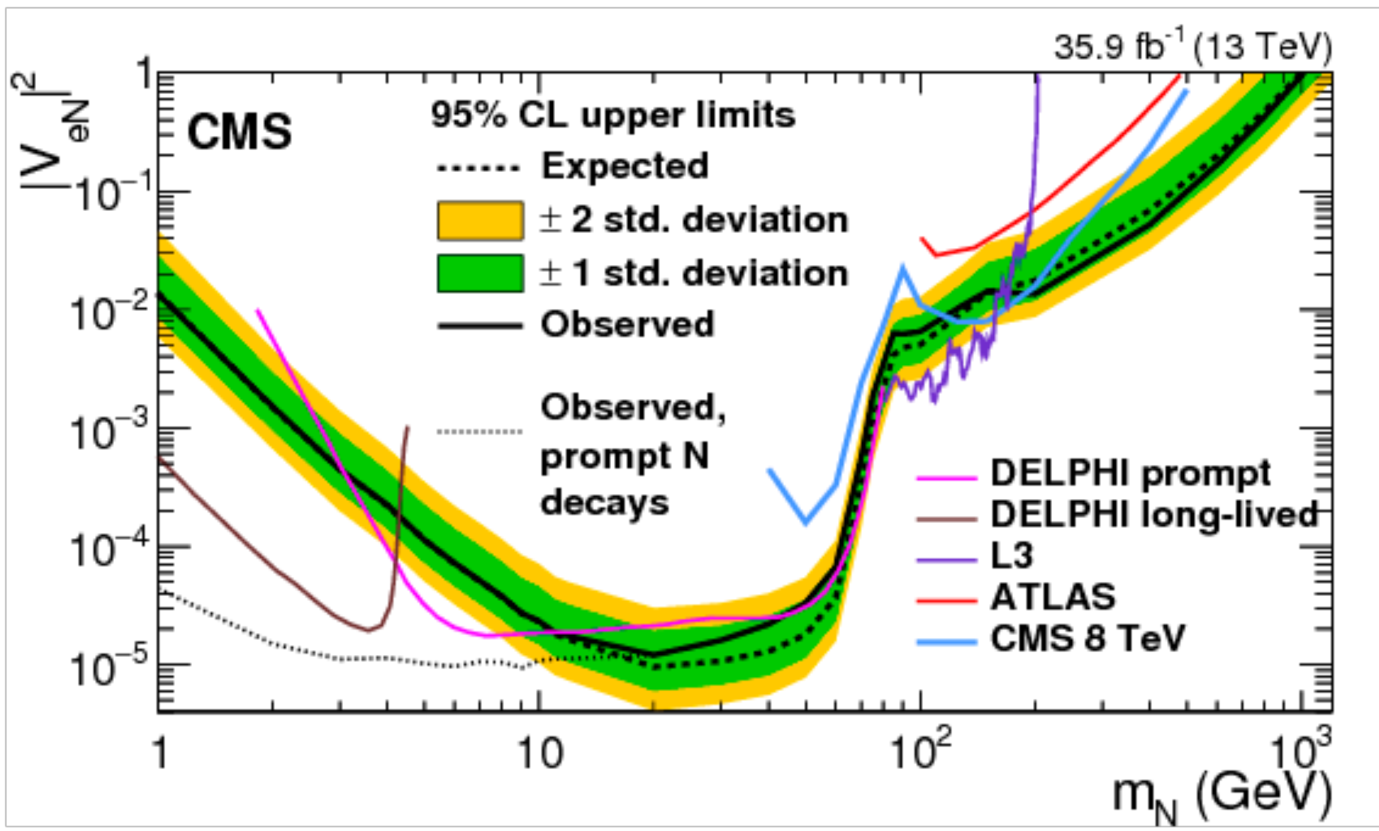
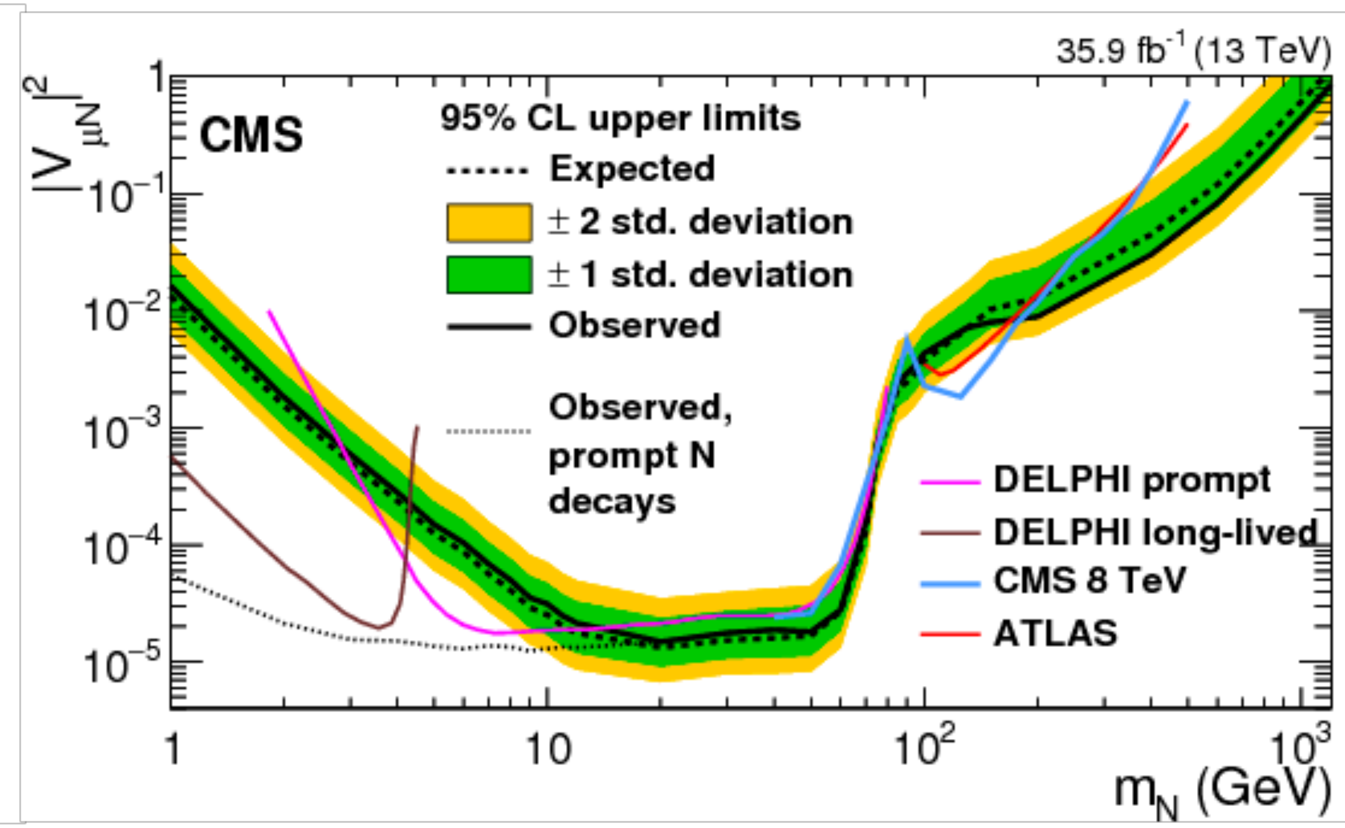


Two same flavor - same sign + MET

Collider Phenomenology

CMS - Heavy neutrino searches



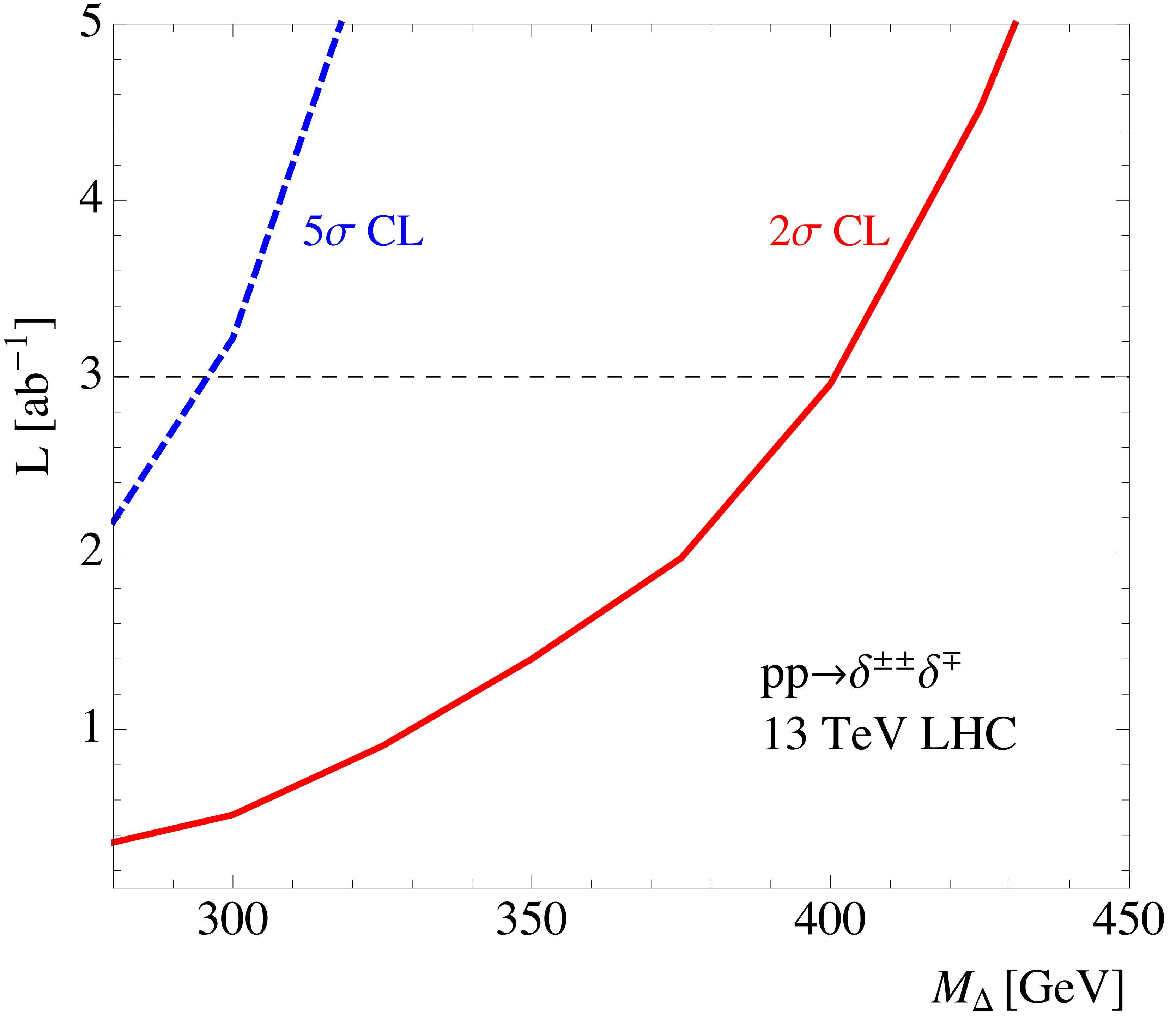


Two same flavor same sign + MET

1802.02965

Collider Phenomenology

Sensitivity

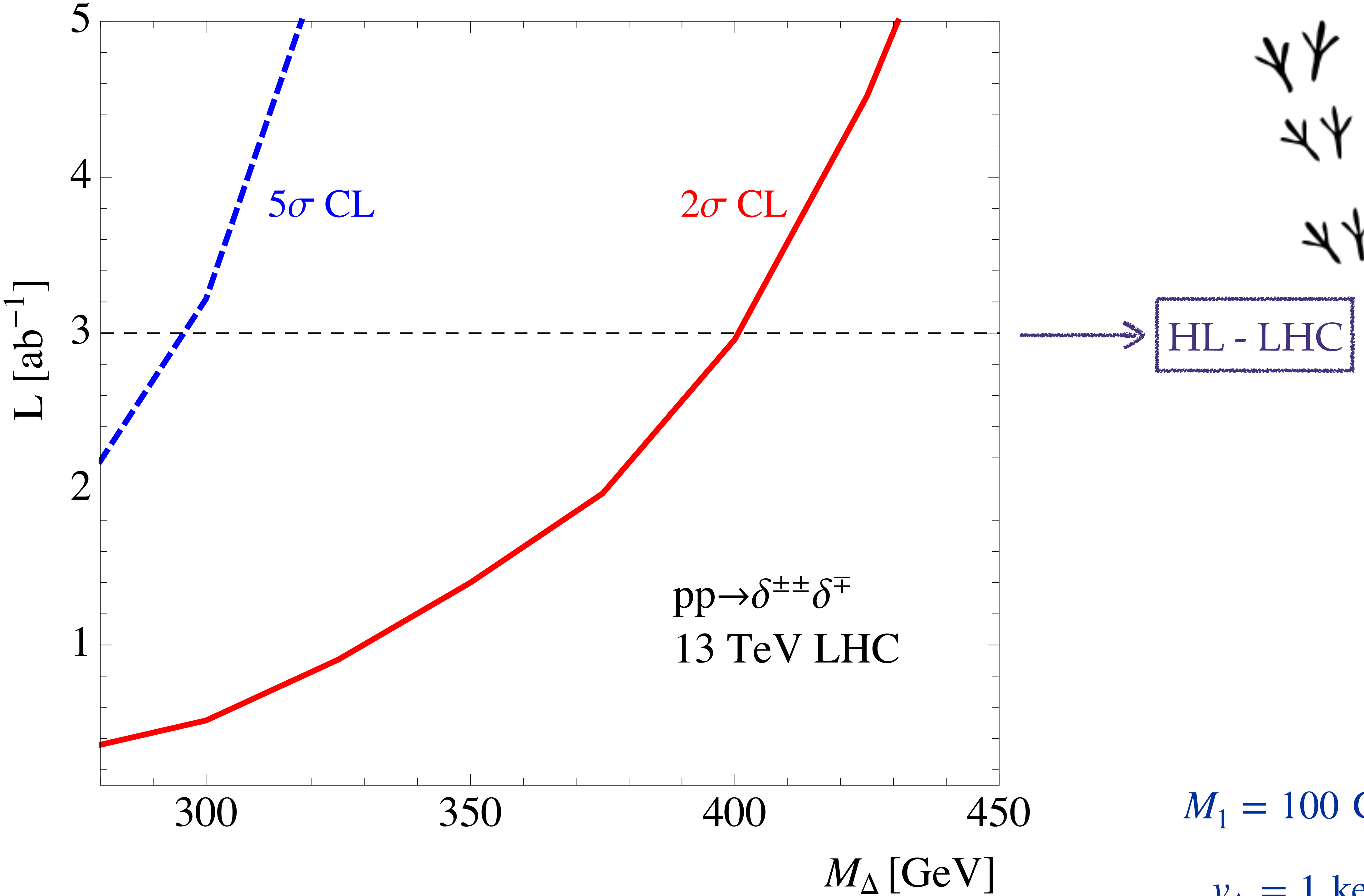


$M_1 = 100$ GeV

$v_\Delta = 1$ keV

Collider Phenomenology

Sensitivity



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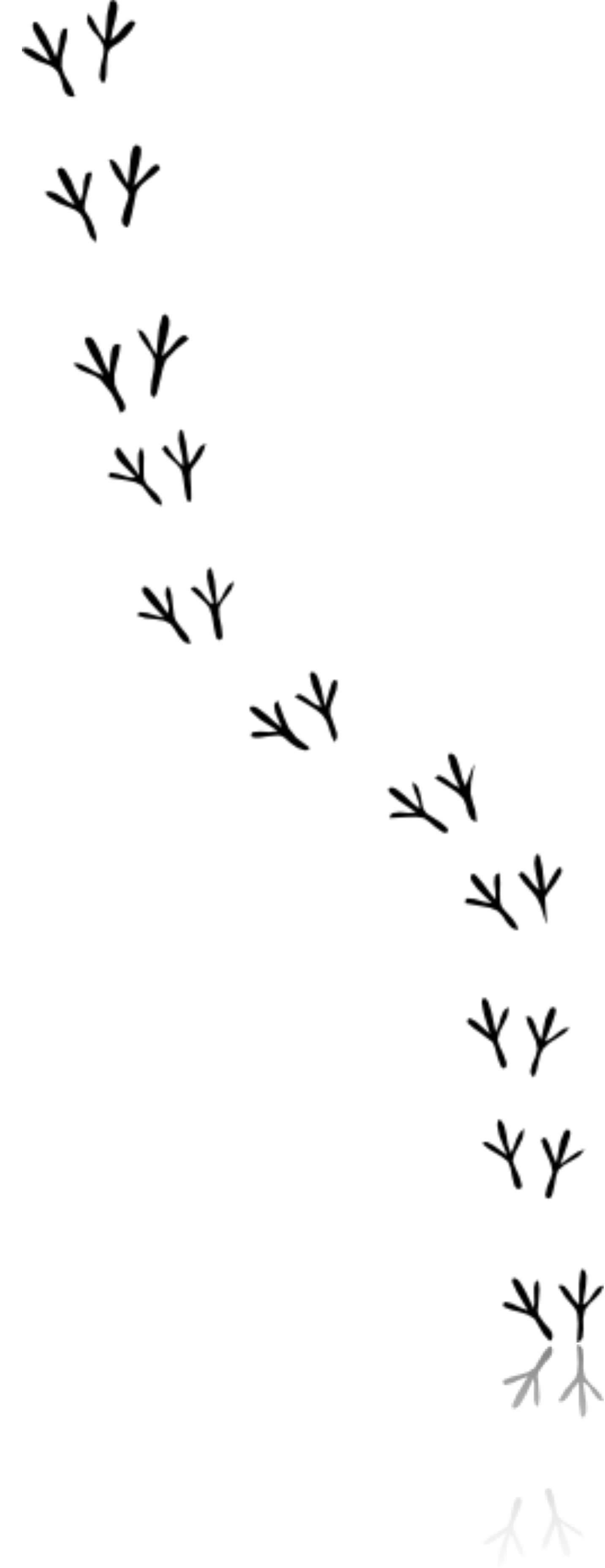
Other phenomenology?



Other phenomenology?

- Lepton Flavor Violation ⟶ As in the Standard TII

Perez, Han, Huang, Li, Wang, 2008

See Yongchao's talk

Other phenomenology?

- Lepton Flavor Violation → As in the Standard TII

Perez, Han, Huang, Li, Wang, 2008

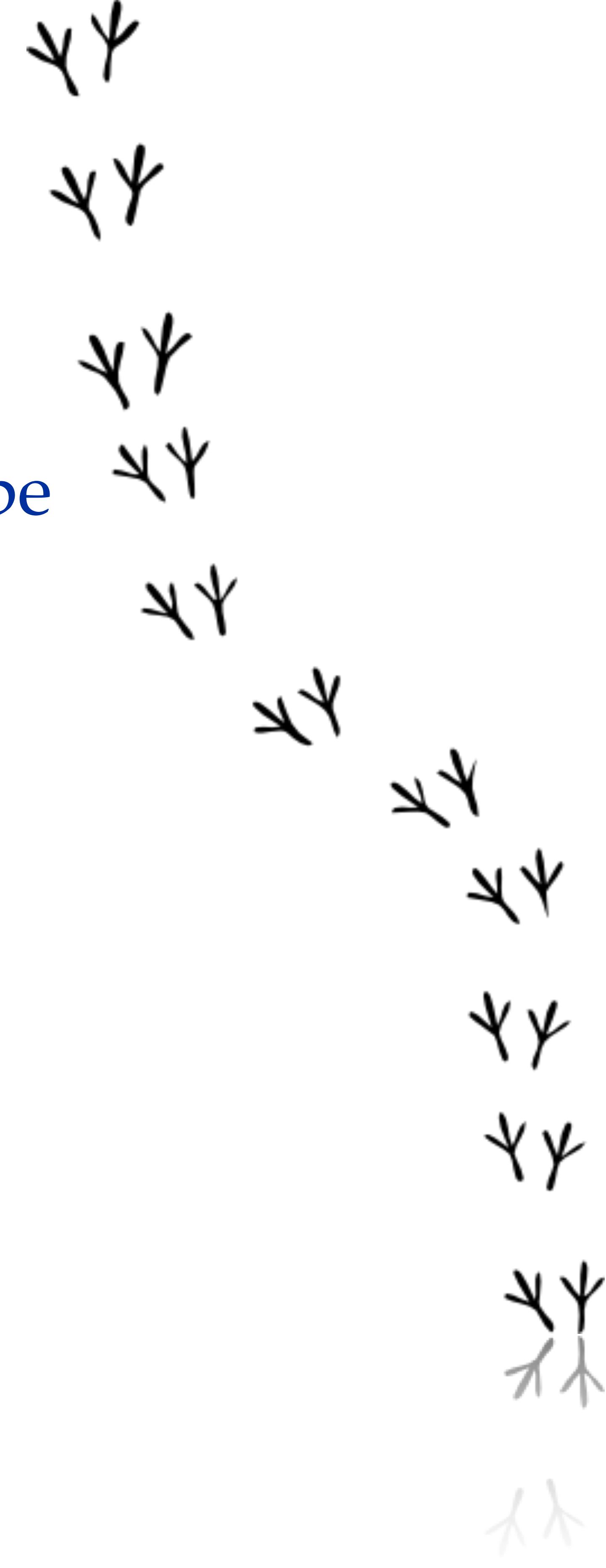
See Yongchao's talk

- Leptogenesis?

No Leptogenesis in this minimal setup

Need another scalar triplet to have CP violation

Conclusions



- We have proposed a natural generalization of type II see-saw
- It creates a dynamical small lepton number breaking
- It has a smoking gun at the LHC which allows to differentiate from the Standard TII
- Also has a rich phenomenology

Thank you!

Backup

$$v_j = \prod_{k=0}^{n-j-1} \left(\frac{\lambda'_{j+k,j+k+1}}{3} \frac{v_n^2}{M_{j+k}^2} \right)^{3^k} v_n$$

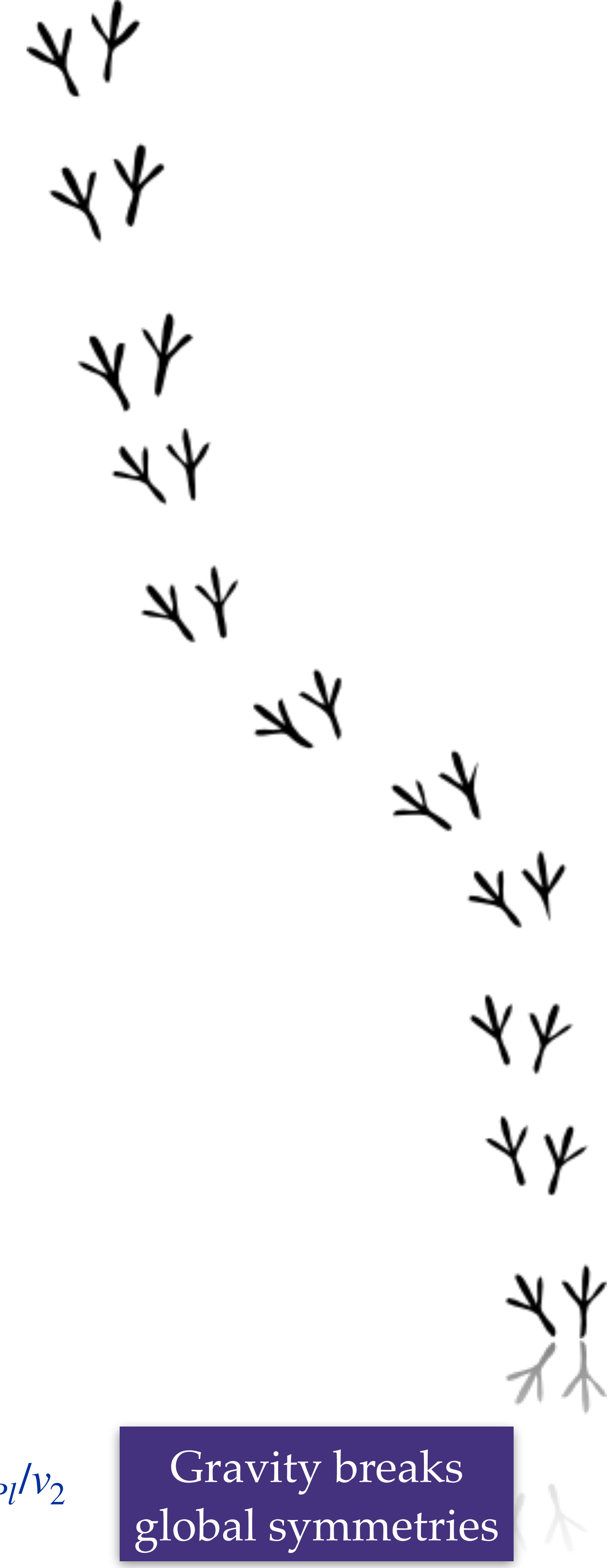
$$J \simeq \frac{1}{\ell_2 v_2} \left(\ell_1 v_1 a_1 + \ell_2 v_2 a_2 + \frac{1}{2} v_\Delta a_\delta - \frac{v_\Delta^2}{v} a \right)$$

$$M_h^2 = \frac{1}{2} \lambda_H v^2$$

$$M_1^2 = m_1^2 + \frac{1}{2} (\lambda_{1H} v^2 + \lambda_{12} v_2^2)$$

$$M_2^2 = \frac{1}{2} \lambda_2 v_2^2$$

$$M_\Delta^2 = m_\Delta^2 + \frac{1}{2} \left[\lambda_{2\Delta} v_2^2 + (\lambda_{H\Delta} + \lambda'_{H\Delta}) v^2 \right]$$



$$m_J \sim M_{Pl} \, \mathrm{e}^{-M_{Pl}/v_2}$$

Gravity breaks global symmetries

$$
\begin{aligned}
V =& -\frac{m_H^2}{2} H^\dagger H + m_\Delta^2 \langle \Delta^\dagger \Delta \rangle + m_1^2 S_1^* S_1 - \frac{m_2^2}{2} S_2^* S_2 + \frac{\lambda_H}{4} (H^\dagger H)^2 + \frac{\lambda_2}{4} (S_2^* S_2)^2 \\
&+ \lambda_{1H} (S_1^* S_1)(H^\dagger H) + \lambda_{2H} (S_2^* S_2)(H^\dagger H) + \left[\lambda_A H^T i\sigma_2 \Delta^\dagger H S_1^* - \frac{2}{3} \lambda'_{12} S_1^* S_2^3 + \text{h.c.} \right] \\
&+ \frac{\lambda_\Delta}{4} \langle \Delta^\dagger \Delta \rangle^2 + \frac{\lambda'_\Delta}{4} \langle \Delta^\dagger \Delta \Delta^\dagger \Delta \rangle + \frac{\lambda_1}{4} (S_1^* S_1)^2 + \lambda_{12} (S_1^* S_1)(S_2^* S_2) \\
&+ \lambda_{H\Delta} (H^\dagger H) \langle \Delta^\dagger \Delta \rangle + \lambda'_{H\Delta} \langle H^\dagger \Delta \Delta^\dagger H \rangle + \lambda_{1\Delta} \langle \Delta^\dagger \Delta \rangle (S_1^* S_1) + \lambda_{2\Delta} \langle \Delta^\dagger \Delta \rangle (S_2^* S_2),
\end{aligned}
$$

Spectrum and Mixing

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θ_{h2} $\theta_{\delta 1}$ θ_{h1}

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Higgs observables,
direct s_2 production

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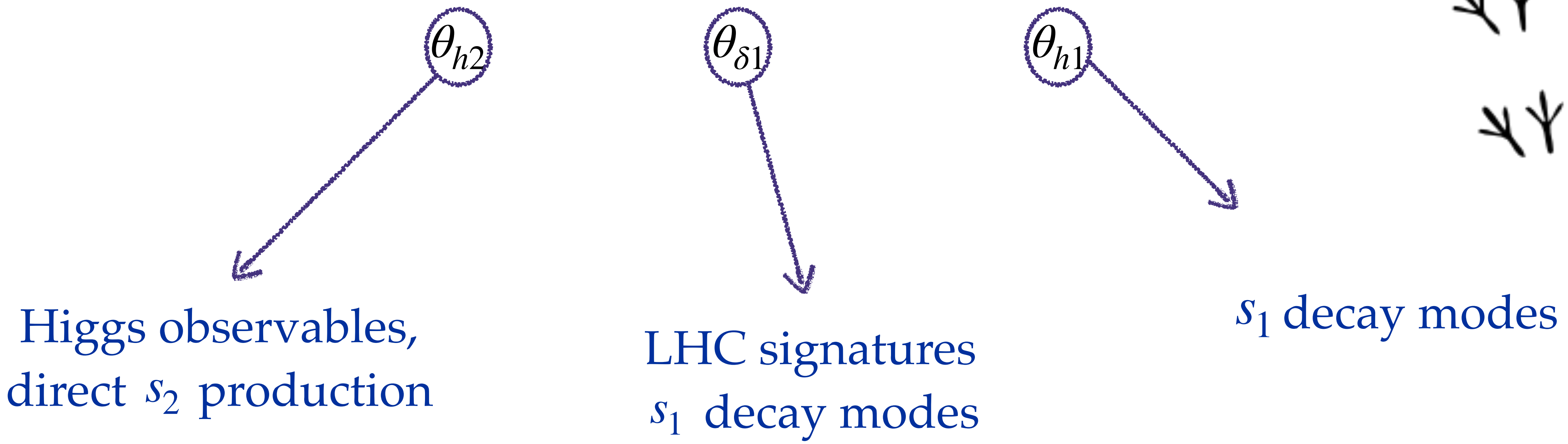
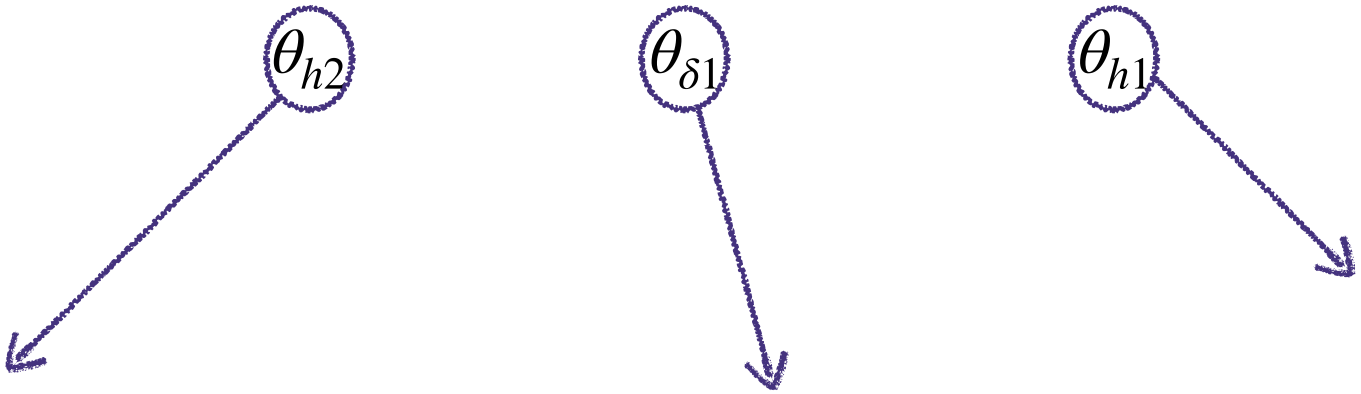
LHC signatures
s_1 decay modes

Spectrum and Mixing



Spectrum and Mixing

$$\frac{\lambda_A}{2} v^2 \delta^0 s_1^0$$



Higgs observables,
direct s_2 production

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s_1 decay modes

Spectrum and Mixing

$\beta_{ab} \equiv (1 - M_b^2/M_a^2)^{-1}$

$$\frac{\lambda_A}{2} v^2 \delta^0 s_1^0$$

θ_{h2} → Higgs observables, direct s_2 production

$\theta_{\delta 1}$ → LHC signatures s_1 decay modes

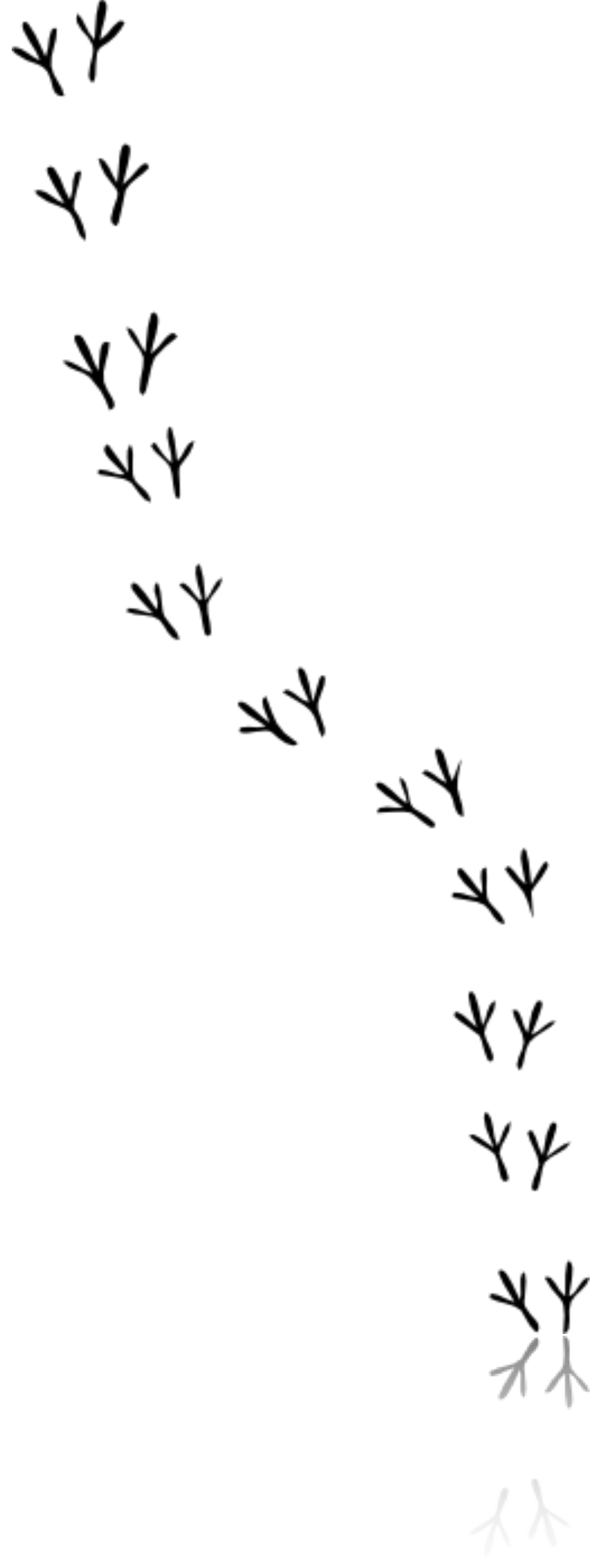
θ_{h1} → s_1 decay modes

$$\theta_{h1} \simeq 1.5 \cdot 10^{-5} \lambda_{1H} \left(\frac{v_1}{\text{MeV}} \right) \beta_{h1}$$

$$\theta_{h2} \simeq 0.16 \lambda_{2H} \left(\frac{v_2}{10\ \text{GeV}} \right) \beta_{h2}$$

$$\theta_{\delta 1} \simeq 10^{-3} \left(\frac{v_\Delta/\text{keV}}{v_1/\text{MeV}} \right) \beta_{1\delta}$$

Collider



Collider

CMS - 1802.02965

Heavy neutrino decay at $\sqrt{s} = 13$ TeV

$$W^{(*)} \longrightarrow N\ell$$

$$\quad \hookrightarrow W^{(*)}\ell$$

$$\qquad \hookrightarrow \ell\nu$$

Collider

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Three charged leptons + Missing E_T

$e^{\pm}e^{\pm}\mu^{\mp} + \not{E}_T$

$\mu^{\pm}\mu^{\pm}e^{\mp} + \not{E}_T$

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High mass region $\quad m_N > m_W$

High mass off-shell W → Three highly relativistic leptons + large missing energy

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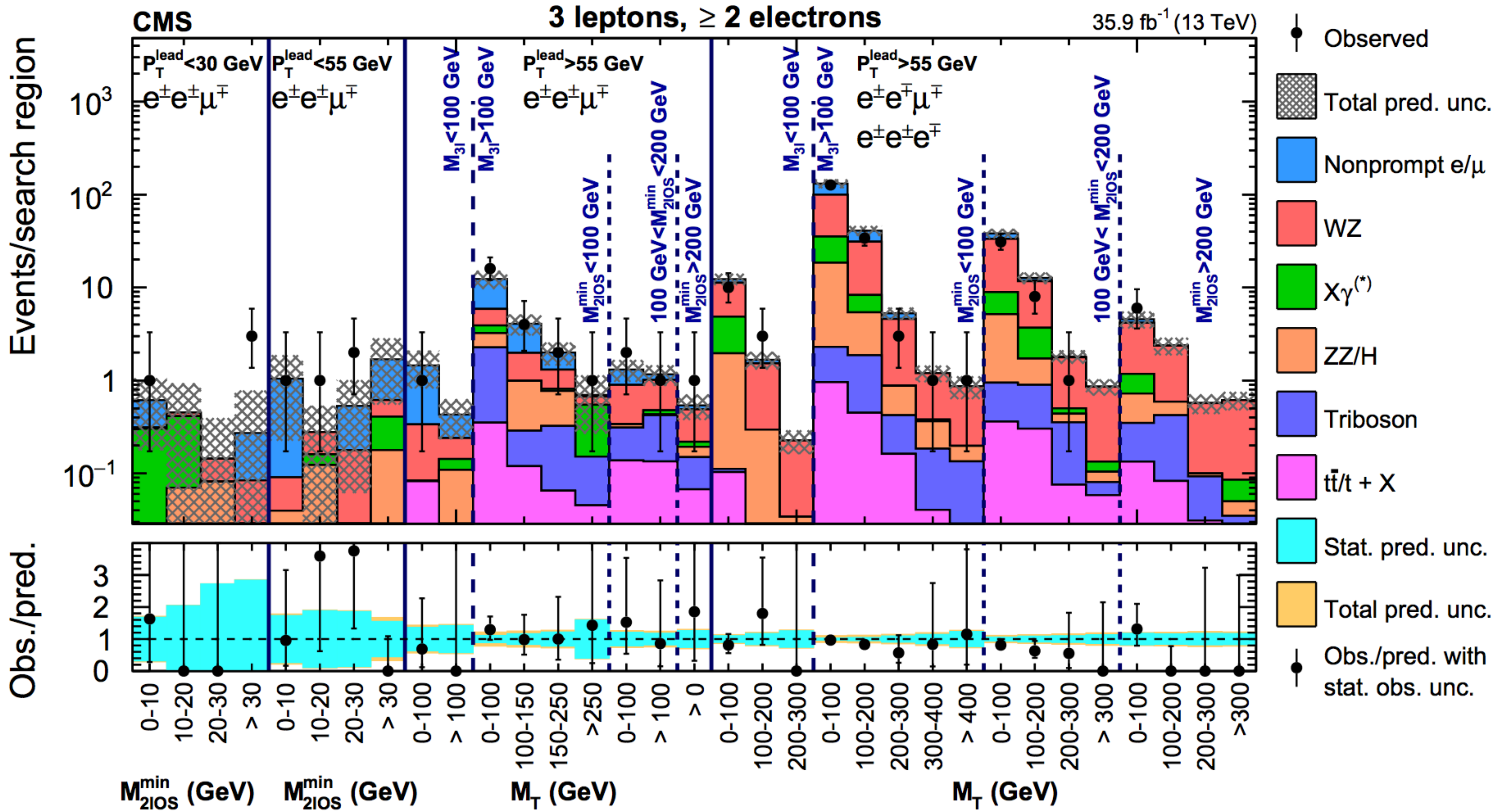
Background estimates for our scenario!

Collider



1802.02965