In quest of parity symmetry restoration at the LHC

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work in progress

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Parity restoration

gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ [1973-1974: Pati, Salam, Senjanovic, Mohapatra]

(i) restores left-right symmetry to electroweak interactions

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}, \qquad \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

(ii) hypercharge interpreted as a difference of baryon and lepton numbers

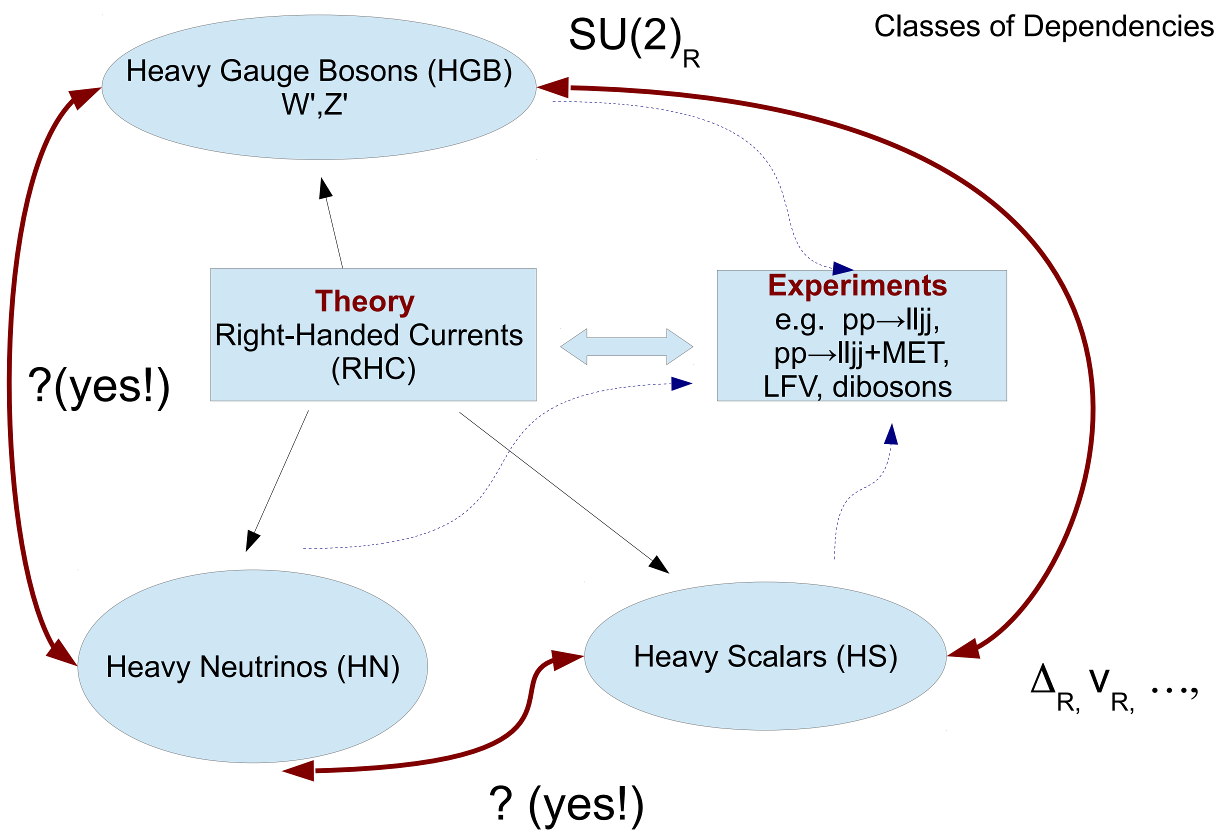
$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

Symmetry breaking:

$$\begin{matrix} W_L^{\pm}, W_L^0 \\ W_R^{\pm}, W_R^0 \\ B^0 \end{matrix} \;\rightarrow\; [SSB] \;\rightarrow\; \begin{matrix} W_1^{\pm}, W_2^{\pm} \\ Z_1, Z_2 \\ \gamma \end{matrix}$$

Test right handed currents at the LHC!

RHC includes plenty of connected issues



RHC & LHC excess data

A few deviations from the SM reported by the ATLAS and CMS in invariant mass distributions:

- Run 1, 8 TeV
  - ...
  - $eejj$ and dibosons excesses in invariant masses around 1.8-2.2 TeV
  - interpreted in the context of L-R models as originating from heavy gauge bosons [Brehmer et al. arXiv: 1507.00013, Deppisch et al., arXiv:1508.05940, Dev and Mohapatra, arXiv:1508.02277, Gluza and Jelinski arXiv:1504.05568, Coloma et al. arXiv:1508.04129. . .]
- Run 2, 13 TeV
  - diboson excess not confirmed
  - $eejj(?)$
  - diphoton $\to$ huge interest in explaning this excess, also within L-R models [Deppisch et al. arXiv:1601.00952, Dasgupta et al. arXiv:1512.09202]

We shall focus on $pp \to lljj$.

Why $pp \to lljj$?

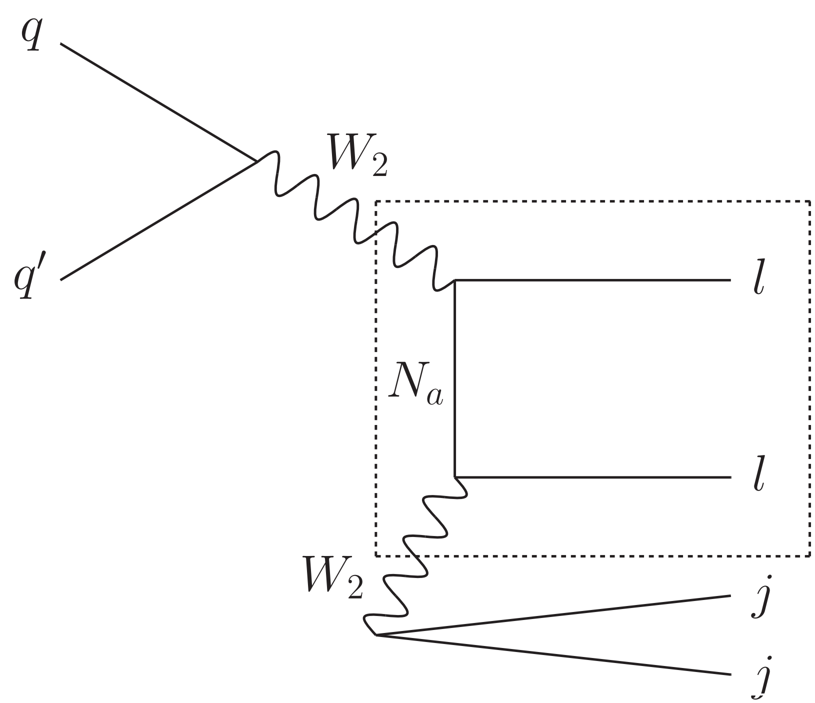
- golden channel for Majorana heavy neutrinos $\to$ SS and OS content of the dilepton signal, LFV

- heavy neutrino masses and mixings are crucial for interferences effects $\to$ more careful treatment of $pp \to eejj$ is needed; rough analyses can lead to overconstraining parameter space.

- provide effective approach for quick estimation of cross-sections in more complex/realistic scenarios

What is important for $\sigma(pp \to lljj)$?

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}} \overline{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W^+_{2\mu} + \text{h.c.}$$



What is important for $\sigma(pp \to lljj)$?

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}} \overline{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W^+_{2\mu} + \mathrm{h.c.}$$

- $U^R_{CKM} \approx U^L_{CKM}$, PDFs
- K_R is heavy neutrino mixing matrix
- heavy gauge boson $W_2^\pm$, $M_{W_2} \sim 2$ TeV

$$\frac{\Gamma(W_2)}{M_{W_2}} = \frac{g_L^2}{96\pi}\left[\sum_a F_W(x_a) + 18\right] \sim 10^{-2}, \quad x_a = \frac{M^2_{N_a}}{M^2_{W_2}},$$

$$F_W(x) = (2 - 3x + x^3)\theta(1-x)$$

- heavy neutrinos N_a, usually $M_{N_a} < M_{W_2}$

$$\frac{\Gamma(N_a)}{M_{N_a}} = \frac{9 g_L^4}{1024\pi^3} F(x_a) \sim 10^{-5}, \quad F(x) = \frac{12}{x}\left[1 - \frac{x}{2} - \frac{x^2}{6} + \frac{1-x}{x}\ln(1-x)\right]$$

Non-degenerate heavy neutrinos & $pp \to lljj$

- non-degenerate i.e. $\min_{a\neq b} |M_{N_a} - M_{N_b}| \gg \max_a \Gamma(N_a)$
- negligible interferences between diagrams with different N_a
- $\sigma_{ij} \equiv \sigma(pp \to W_2 \to N_a l_i \to l_i l_j jj)$

Factor out dependence on mixing angles:

$$\sigma_{ij}^{\pm\pm} = \sum_a \widehat{\sigma}_a^{\pm\pm} |(K_R^\dagger)_{ia}(K_R^*)_{aj}|^2 + (\text{small INT})$$

$$\sigma_{ij}^{\pm\mp} = \sum_a \widehat{\sigma}_a^{\pm\mp} |(K_R^\dagger)_{ia}(K_R)_{aj}|^2 + (\text{small INT})$$

Due to $\Gamma \ll M$ 'bare' cross section $\widehat{\sigma}(pp \to lljj)$ can be approximated by

$$\widehat{\sigma}_a = \sigma(pp \to W_2)\text{BR}(W_2 \to N_a l_1)\text{BR}(N_a \to l_1 jj)$$

what leads to

$$r_{ij} = \left(\frac{N_{SS}}{N_{OS}}\right)_{ij} = \frac{\sigma_{ij}^{++} + \sigma_{ij}^{--}}{\sigma_{ij}^{+-}} \approx 1$$

Degenerate heavy neutrinos & $pp \to lljj$

- degenerate i.e. $M_{N_a} = M_N$ or $\max_{a \neq b} |M_{N_a} - M_{N_b}| \ll \min_a \Gamma(N_a)$
- important interferences between diagrams with different N_a
- $\sigma_{ij} \equiv \sigma(pp \to W_2 \to N_a l_i \to l_i l_j jj)$

Factor out dependence on mixing angles:

$$\sigma_{ij}^{\pm\pm} = \widehat{\sigma}^{\pm\pm} |\sum_a (K_R^\dagger)_{ia} (K_R^*)_{aj}|^2$$

$$\sigma_{ij}^{\pm\mp} = \widehat{\sigma}^{\pm\mp} |\sum_a (K_R^\dagger)_{ia} (K_R)_{aj}|^2 = \widehat{\sigma}^{\pm\mp}, \quad \text{if } K_R \text{ is unitary}$$

Due to $\Gamma \ll M$ 'bare' cross section $\widehat{\sigma}(pp \to lljj)$ can be approximated by

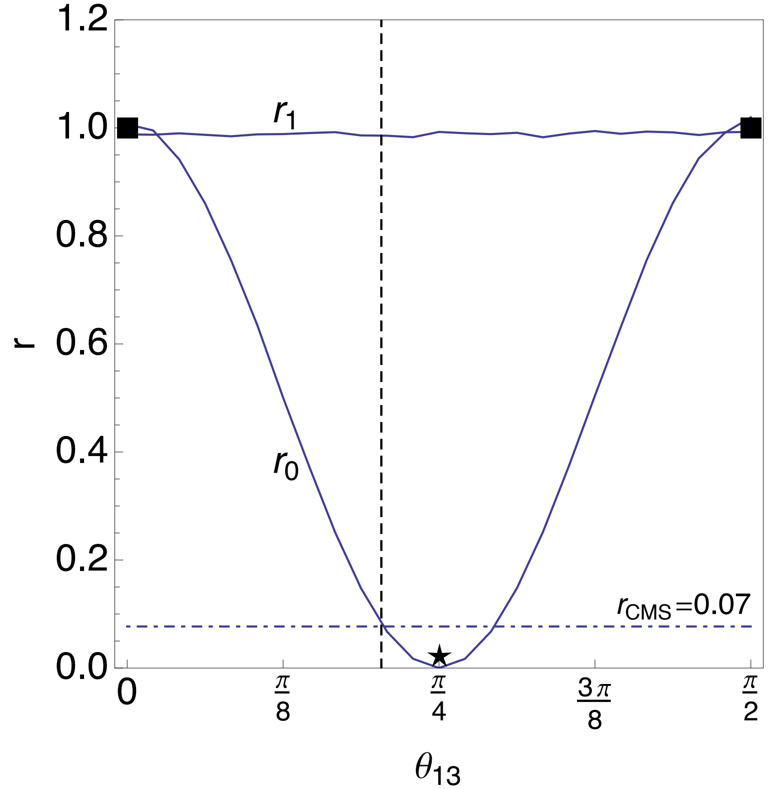
$$\widehat{\sigma} = \sigma(pp \to W_2) \mathrm{BR}(W_2 \to N_1 l_1) \mathrm{BR}(N_1 \to l_1 jj)$$

what leads to

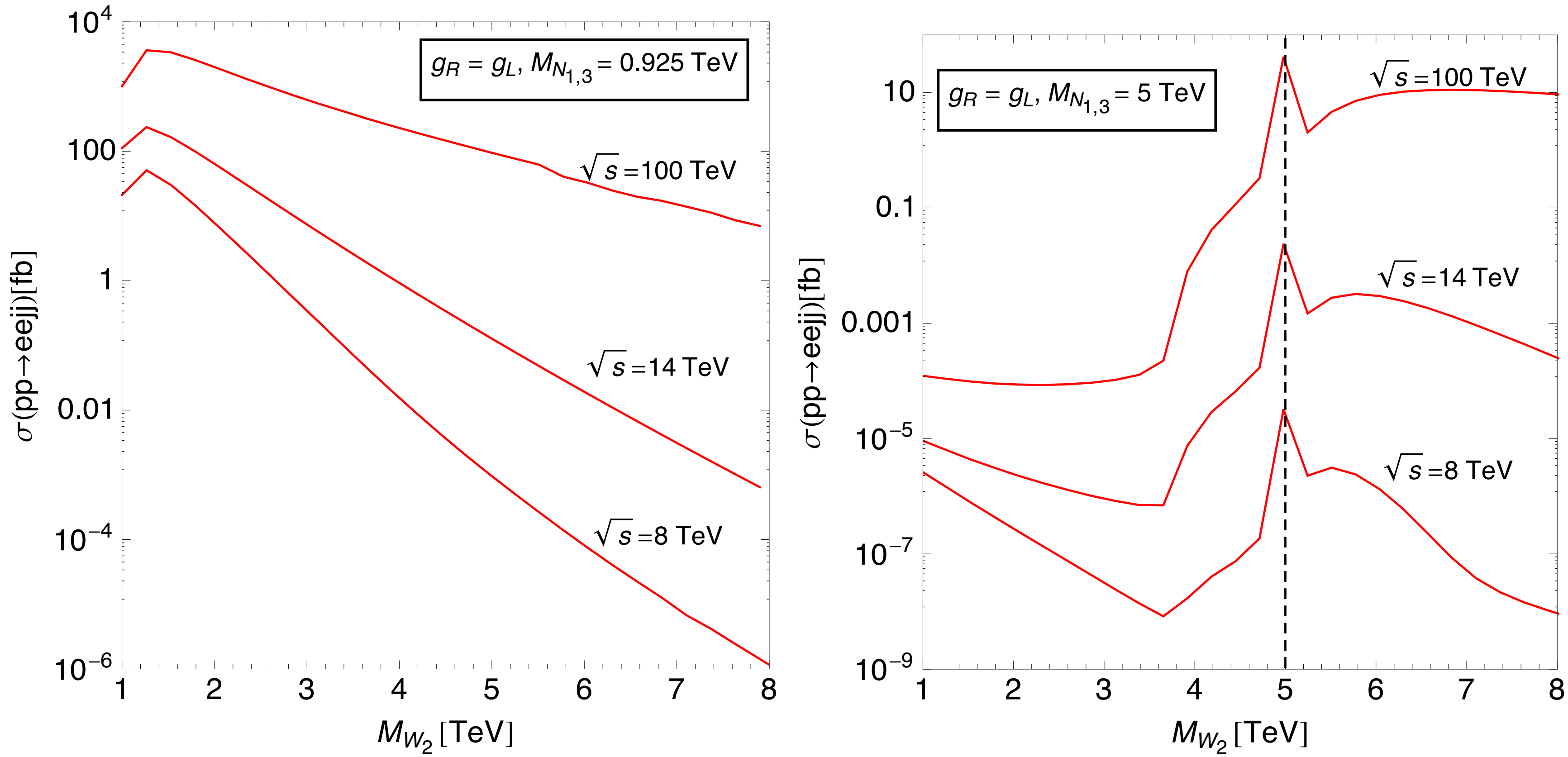
$$r_{ij} = \left(\frac{N_{SS}}{N_{OS}}\right)_{ij} = \frac{\sigma_{ij}^{++} + \sigma_{ij}^{--}}{\sigma_{ij}^{+-}} \approx |\sum_a (K_R^\dagger)_{ia} (K_R^*)_{aj}|^2$$

An example

$$M_{N_{1,3}} = 0.925\,\mathrm{TeV}, \quad M_{N_2} = 10\,\mathrm{TeV}, \quad K_R = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -i\sin\theta_{13} & 0 & i\cos\theta_{13} \end{pmatrix}$$

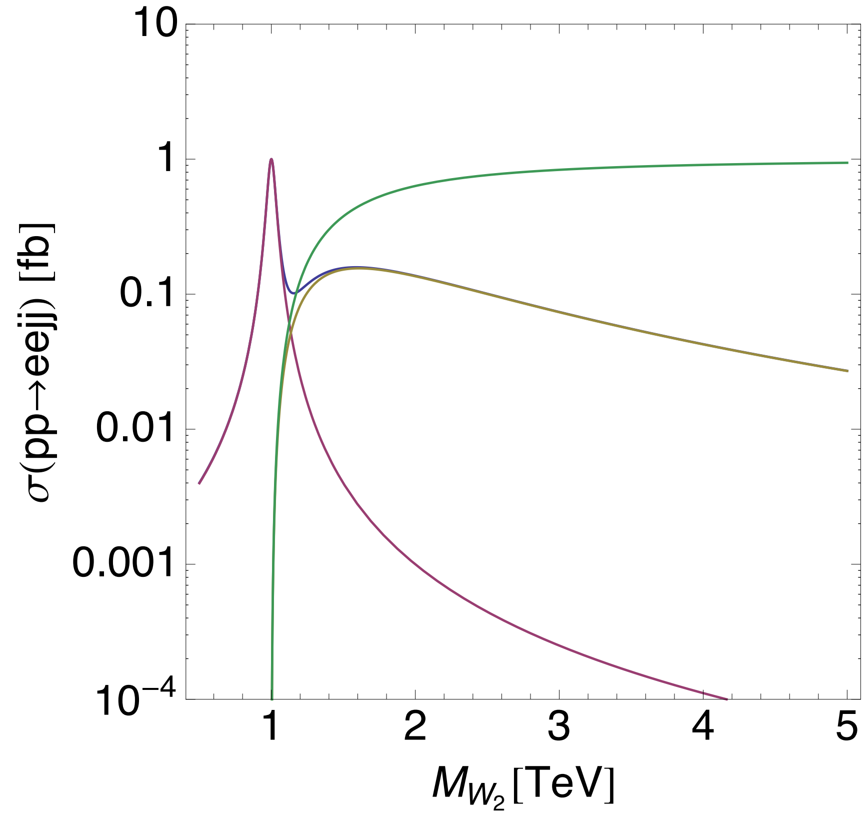


MadGraph & $\widehat{\sigma}(pp \to eejj)$



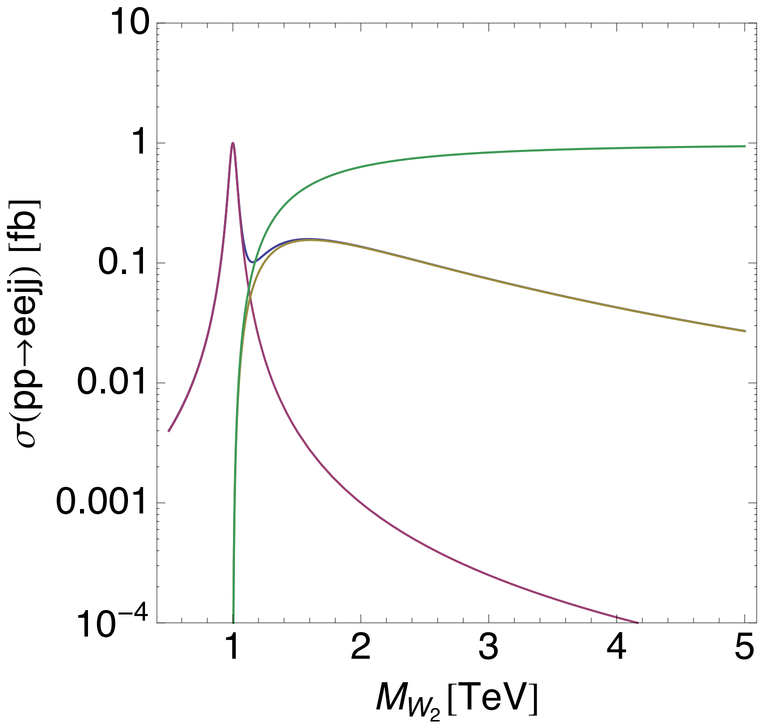
NWA valid only for $M_N < M_{W_2} < \sqrt{s}$

Why $\widehat{\sigma}(pp \to eejj)$ has such shape?



$$\widehat{\sigma} = \int_{M_N^2/s}^{1} dx \int_{M_N^2/xs}^{1} dy \sum_{\alpha\beta} f_\alpha(x, Q^2) f_\beta(x, Q^2) \widehat{\sigma}_{\alpha\beta}(xys)$$

Why $\widehat{\sigma}(pp \to eejj)$ has such shape?

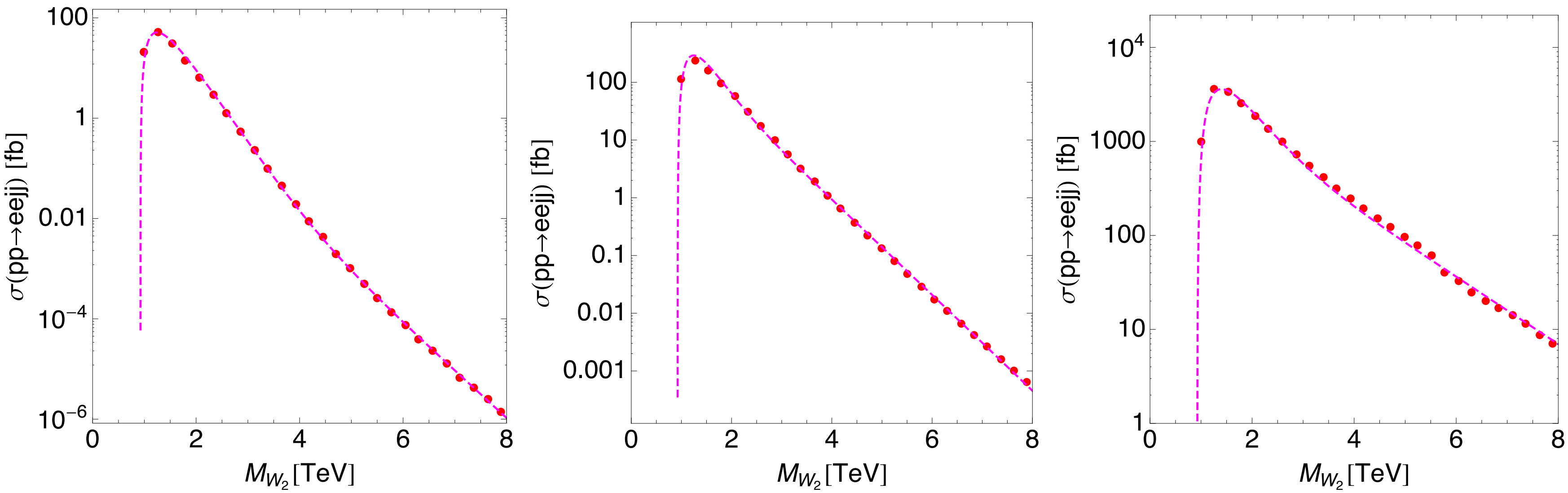


Use NWA:

$$\widehat{\sigma} = \frac{g_L^2 \pi}{6s[18 + 2F_W(x_1)]} \left(1 - \frac{M_N^2}{M_{W_2}^2}\right)^2 \left(1 + \frac{M_N^2}{2M_{W_2}^2}\right) P\left(\frac{M_{W_2}^2}{s}\right)$$

Fitting $P\left(M_{W_2}^2/s\right)$ dependence on M_{W_2}

$$P\left(\frac{M_{W_2}^2}{s}\right) = \int_{M_{W_2}^2/s}^{1} \frac{dx}{x} \sum_{\alpha\beta} f_\alpha\left(x, M_{W_2}^2\right) f_\beta\left(\frac{M_{W_2}^2}{xs}, M_{W_2}^2\right)$$



Naive approximation: $P(x) = a(e^{-bx} + ce^{-dx})$. E.g. for $\sqrt{s} = 14$ TeV: $a = 6.73 \times 10^3$, $b = 3.97$, $c = 0.016$, $d = 1.92$

More systematic approach to fitting $P\left(M_{W_2}^2/s\right)$

$$P\left(\frac{M_{W_2}^2}{s}\right) = \int_{M_{W_2}^2/s}^{1} \frac{dx}{x} \sum_{\alpha\beta} f_\alpha\left(x, M_{W_2}^2\right) f_\beta\left(\frac{M_{W_2}^2}{xs}, M_{W_2}^2\right)$$

Use analytic parametization of PDFs:

$$f(x, Q_0^2) = Ax^\delta (1-x)^\eta \left[\sum_{i=1}^{4} a_i T_i\left(1 - 2\sqrt{x}\right)\right]$$

Then $P\left(M_{W_2}^2/s\right)$ can be expressed in terms of hypergeometric functions.

Summary

- Details of heavy neutrinos sector are really important for interpreting experimental data

- There is a handy and quick way to estimate $\widehat{\sigma}(pp \to lljj)$ what can help to better explore parameter space of heavy neutrinos

- Dependence on mixing angles can be easily incorporated once $\widehat{\sigma}(pp \to lljj)$ is derived