Testing electroweak scale seesaw models at $e^+e^-, pp, e^-\gamma$ and $\gamma\gamma$ collisions

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Talk is based on arXiv: 22xx:xxxx

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Outline

1. Brief Introduction to Type I, II and III seesaw

2. Collider search for Type I, II and III seesaw at e^+e^- and pp collider

3. Possible signatures for Type I, II and III seesaw at $e^-\gamma$ and $\gamma\gamma$ collider

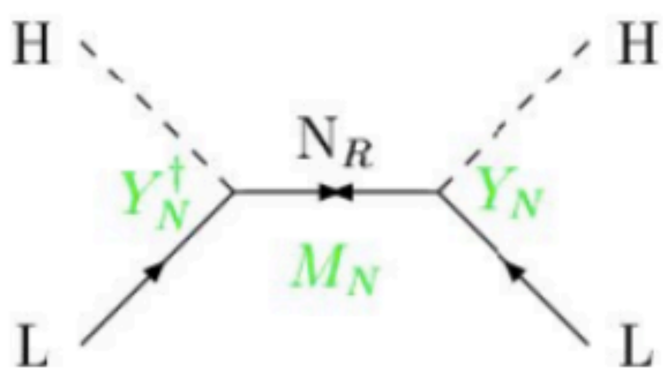
4. Conclusions

One of the most appealing framework to generate the light neutrino mass is through lepton number violating dimension five Wienberg operator,

$$\mathcal{O}_5 = \frac{c}{\Lambda} LLHH$$

PRL.43,1566(1979), S.Wienberg

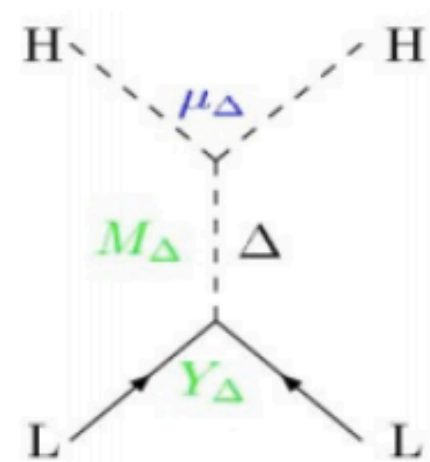
Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic

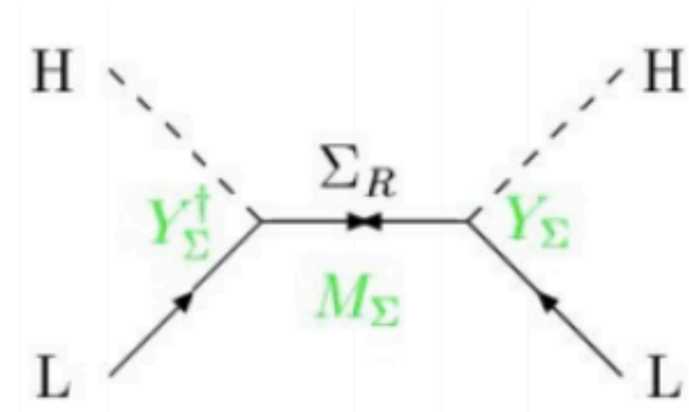
Scalar triplet: (type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet: (type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; Ma; Ma, Roy; T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

Type-I seesaw

Add three Right-handed neutrinos: $\mathcal{L}_{\text{int}} \supset - y_D^{\alpha\beta} \overline{\ell_L^\alpha} H N_R^\beta - \frac{1}{2} m_N^{\alpha\beta} \overline{N_R^{\alpha C}} N_R^\beta + H.c$

Neutrino Mass matrix: $M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \xrightarrow{M_D << M_N} m_\nu \simeq - M_D M_N^{-1} M_D^T$

This explains why light neutrino masses are so much lighter than charged leptons.

Light-heavy neutrino mixing: $\nu \simeq \mathcal{N} \nu_m + V N_m$, where $V = M_D M_N^{-1}$

For $m_\nu \sim \mathcal{O}(0.1 \text{ eV})$ and $y_D \sim \mathcal{O}(1)$, M_N must be large $\rightarrow$ Out of reach at colliders

Lowscale seesaw

Assumption: RHN mass and mixing elements are free parameters, constrained only by experimental conservations.

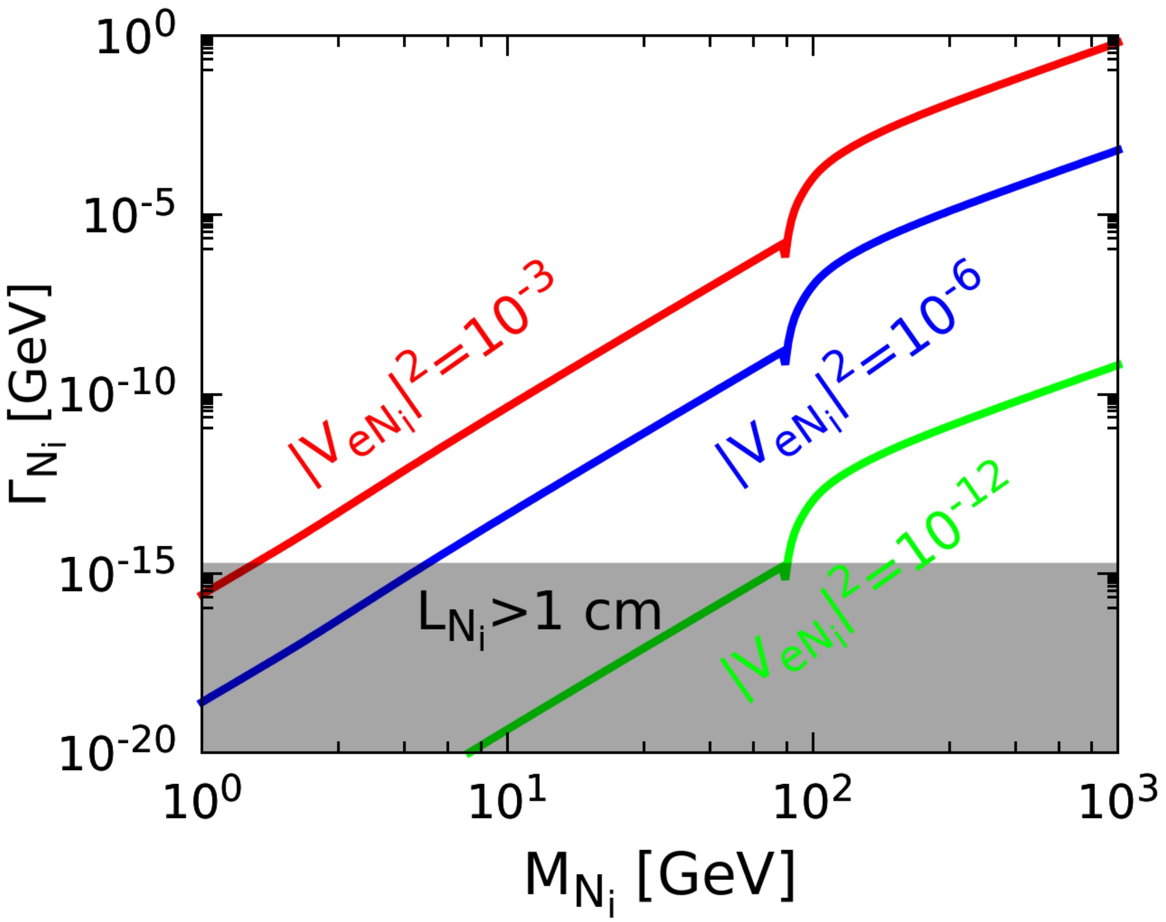
Modified Charged and neutral current Interactions:

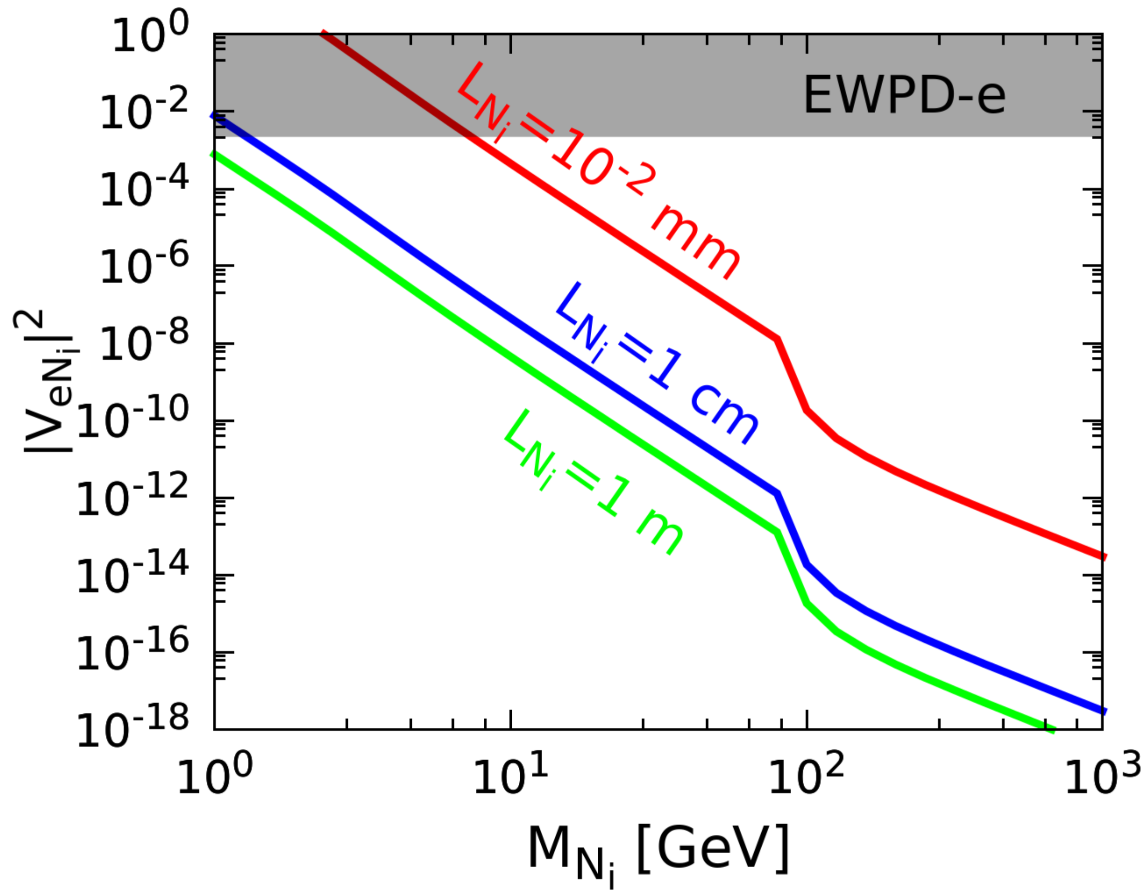
$$\mathcal{L}_{\text{CC}} = - \frac{g}{\sqrt{2}} W_\mu \bar{e} \gamma^\mu P_L \left(\mathcal{N} \nu_m + V N_m \right) + h.c.$$

$$\mathcal{L}_{\text{NC}} = - \frac{g}{2c_w} Z_\mu \left[\overline{\nu_m} \gamma^\mu P_L (\mathcal{N}^\dagger \mathcal{N}) \nu_m + \overline{N_m} \gamma^\mu P_L (V^\dagger V) N_m + \left\{ \overline{\nu_m} \gamma^\mu P_L (\mathcal{N}^\dagger V) N_m + h.c. \right\} \right]$$

Gives many interesting collider phenomenology, cLFV

RHN decay modes



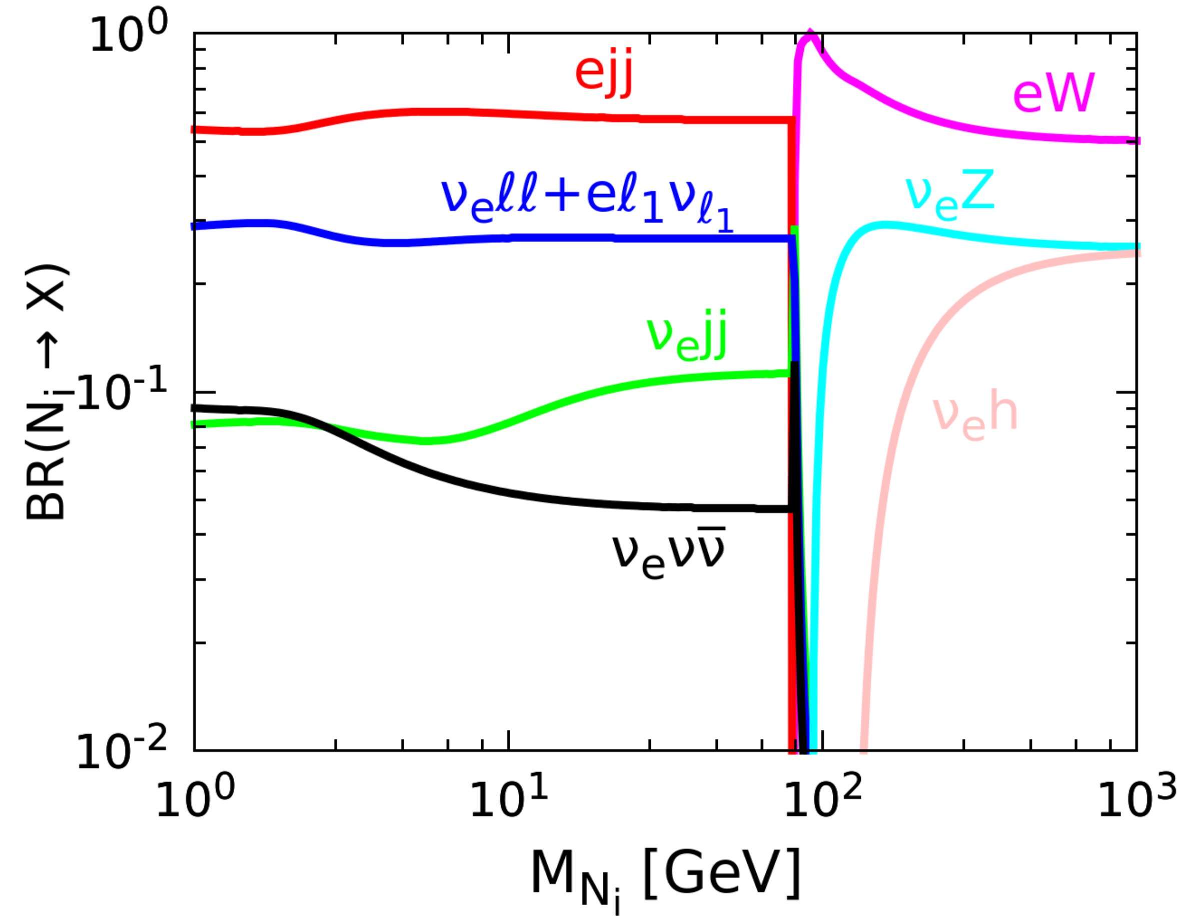


CC: $N_i \rightarrow \ell W^*$ NC: $N_i \rightarrow \nu_\ell Z^*$

Yukawa: $N_i \rightarrow \nu_\ell h^*$

Small M_N and small $V_{\ell N}$ implies small decay width:

Long-lived RHN ➡ Displaced vertex



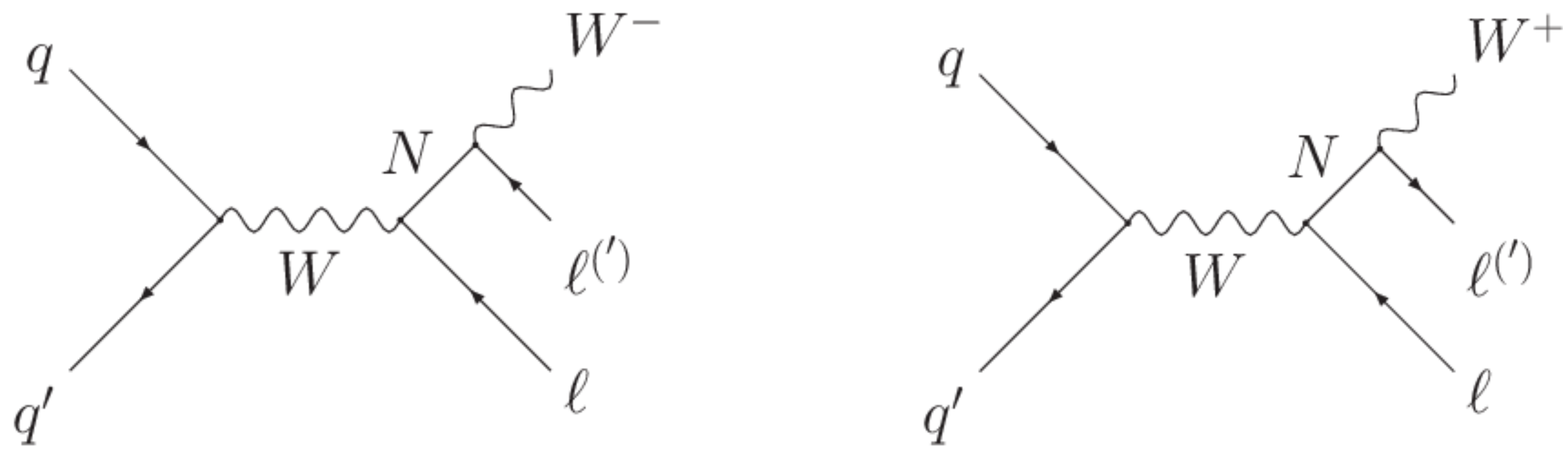
Stefan Antusch, Oliver Fischer, *JHEP* 12 (2016) 007

SM, Cottin, Chiang et al, arXiv: 1908.09838

Production of heavy neutrinos

pp collider:

HL-LHC, FCC-hh



(a) (b)

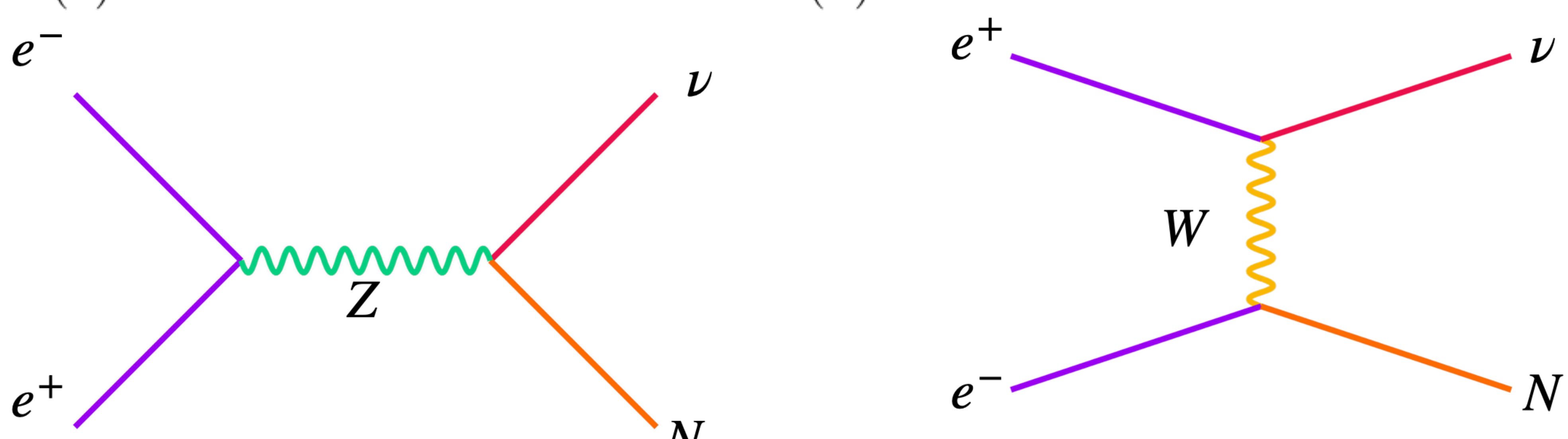
LNV final state?

LNV: $pp \to \ell^\pm \ell^\pm + jj$

LNC: $pp \to \ell^\pm \ell^\mp + jj$

Lepton collider:

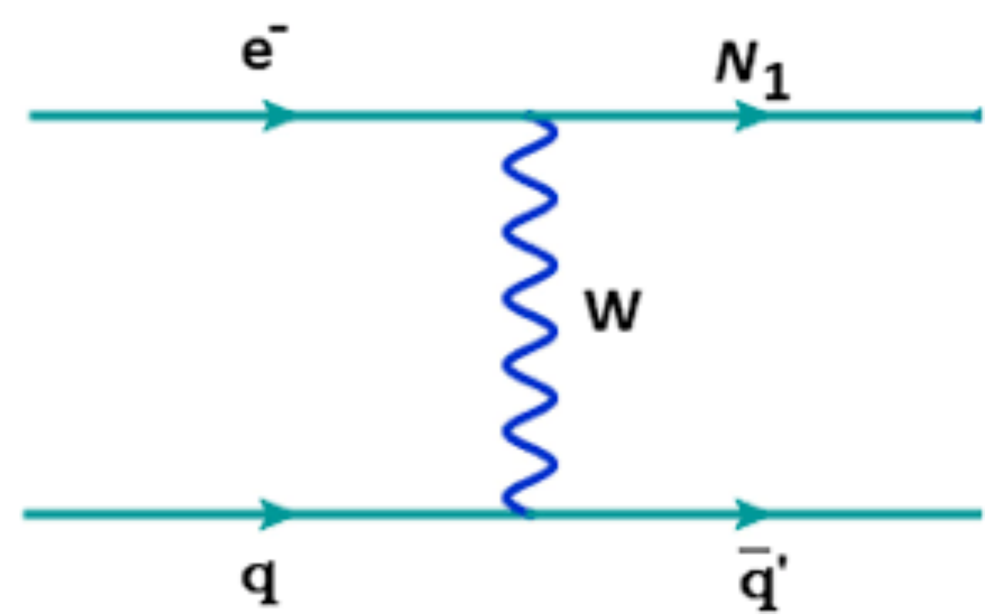
ILC,CLIC, CPEC, FCC-ee



(a) (b)

ep collider:

LHeC, FCC-eh



Stefan Antusch, Oliver Fischer, *Int.J.Mod.Phys.A* 30 (2015) 23, 1544004

Stefan Antusch, Oliver Fischer, arXiv: 1612.02728

Type III seesaw

Add one fermion field, isospin triplet, hypercharge 0: $\Psi = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \text{Tr}(\overline{\Psi} i\gamma^\mu D_\mu \Psi) - \frac{1}{2} M\, \text{Tr}(\overline{\Psi}\Psi^c + \overline{\Psi^c}\Psi) - \sqrt{2}(\overline{\ell_L} Y_D^\dagger \Psi H + H^\dagger \overline{\Psi} Y_D \ell_L)$$

Gauge interaction — Majorana mass term — Yukawa interactions

Mass term: $$-\mathscr{L}_{\text{mass}} = (\bar{e}_L \;\; \overline{\Sigma}_L) \begin{pmatrix} m_\ell & Y_D^\dagger v \\ 0 & M \end{pmatrix} \begin{pmatrix} e_R \\ \Sigma_R \end{pmatrix} + \frac{1}{2} (\overline{\nu_L^c} \;\; \overline{\Sigma_R^0}) \begin{pmatrix} 0 & Y_D^T \frac{v}{\sqrt{2}} \\ Y_D \frac{v}{\sqrt{2}} & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \Sigma_R^{0c} \end{pmatrix} + \text{h. c.}$$

Mass matrix is identical to type-I seesaw

Gives neutrino seesaw mass

$$m_\nu \simeq -\frac{v^2}{2} Y_D^T M^{-1} Y_D = M_D M^{-1} M_D^T$$

1. Neutral component Σ^0 mixes with ν_L :

$$\nu = \mathscr{A}\nu_m + V\Sigma_m^0, \quad \text{where } V = M_D M^{-1}$$

2. Charged components $\Sigma^\pm$ mix with charged leptons

3. Isospin fixes coupling strength to the gauge bosons

These give many interesting phenomenology

CC, NC and Higgs interactions

$$-\mathscr{L}_{\text{CC}} = \frac{g}{\sqrt{2}} (\overline{e} \quad \overline{\Sigma})\, \gamma^\mu W_\mu^- P_L \begin{pmatrix} (1+\frac{\epsilon}{2})U_{\text{PMNS}} & -\frac{Y_D^\dagger M^{-1} v}{\sqrt{2}} \\ 0 & \sqrt{2}(1-\frac{\epsilon'}{2}) \end{pmatrix} \begin{pmatrix} \nu \\ \Sigma^0 \end{pmatrix}$$

$$+ \frac{g}{\sqrt{2}} (\overline{e} \quad \overline{\Sigma})\, \gamma^\mu W_\mu^- P_R \begin{pmatrix} 0 & -\sqrt{2} m_\ell Y_D^\dagger M^{-2} v \\ -\sqrt{2} M^{-1} Y_D (1-\frac{\epsilon^*}{2}) V^*_{\text{PMNS}} & \sqrt{2}(1-\frac{\epsilon'^*}{2}) \end{pmatrix} \begin{pmatrix} \nu \\ \Sigma^0 \end{pmatrix}$$

New Vertices: $\ell^- - \Sigma^0 - W^-, \quad \Sigma^- - \Sigma^0 - W^-$

$$-\mathscr{L}_{\text{NC}} = \frac{g}{\cos\theta_W} (\overline{e} \quad \overline{\Sigma})\, \gamma^\mu Z_\mu P_L \begin{pmatrix} \frac{1}{2} - \cos^2\theta_W - \epsilon & \frac{Y_D^\dagger M^{-1} v}{2} \\ \frac{M^{-1} Y_D v}{2} & \epsilon' - \cos^2\theta_W \end{pmatrix} \begin{pmatrix} e \\ \Sigma \end{pmatrix} + \frac{g}{\cos\theta_W} (\overline{e} \quad \overline{\Sigma})\, \gamma^\mu Z_\mu P_R \begin{pmatrix} 1 - \cos^2\theta_W & m_\ell Y_D^\dagger M^{-2} v \\ M^{-2} Y_D m_\ell v & -\cos^2\theta_W \end{pmatrix} \begin{pmatrix} e \\ \Sigma \end{pmatrix}$$

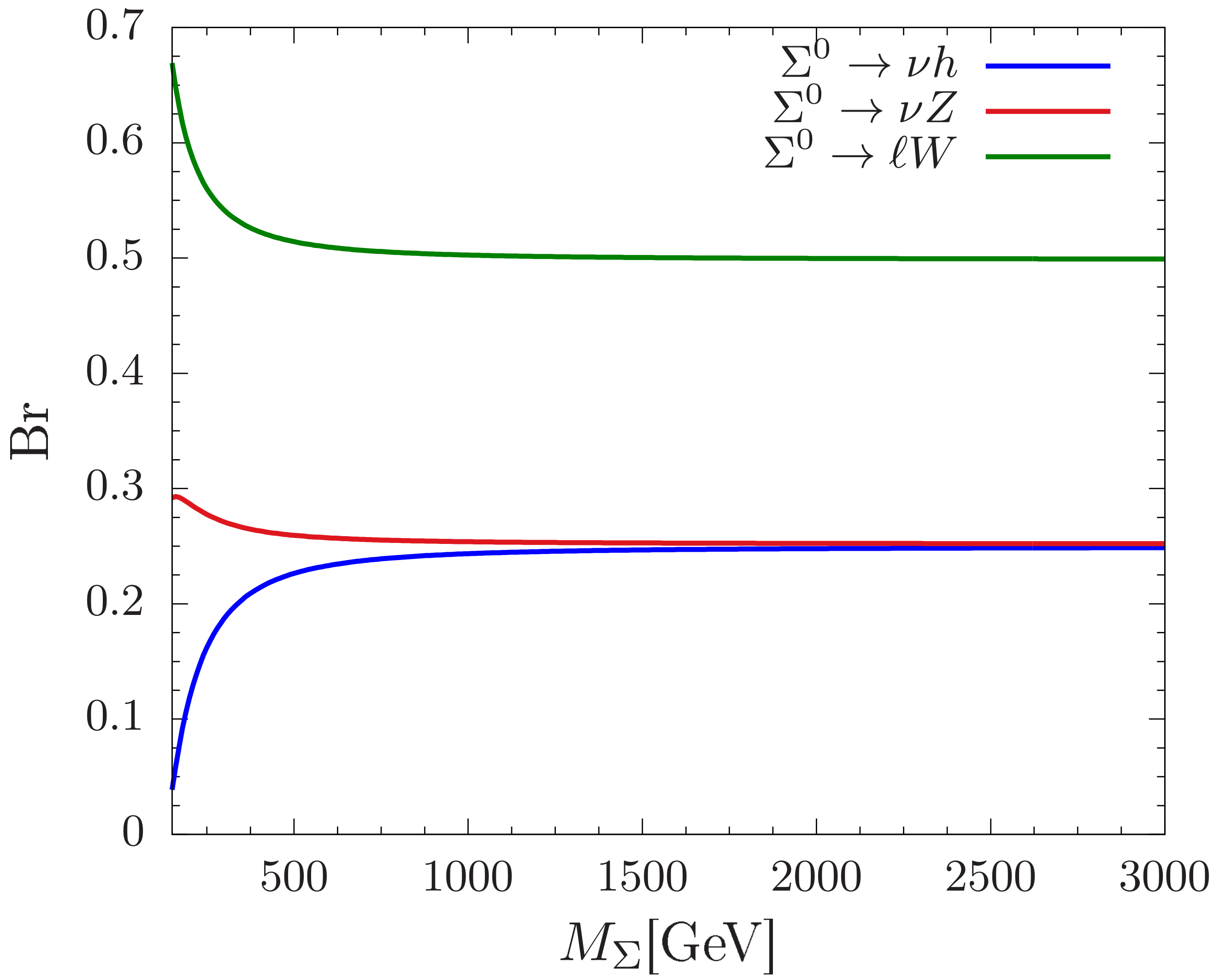
$$+ (\overline{\nu} \quad \overline{\Sigma^0})\, \gamma^\mu Z_\mu P_L \begin{pmatrix} 1 - U^\dagger_{\text{PMNS}} \epsilon U_{\text{PMNS}} & \frac{U^\dagger_{\text{PMNS}} Y_D^\dagger M^{-1} v}{\sqrt{2}} \\ \frac{M^{-1} Y_D U_{\text{PMNS}} v}{\sqrt{2}} & \epsilon' \end{pmatrix} \begin{pmatrix} \nu \\ \Sigma^0 \end{pmatrix}$$

New Vertices: $\Sigma^+ - \Sigma^- - Z, \ \ell^- - \Sigma^+ - Z, \ \nu - \Sigma^0 - Z$

$$-\mathscr{L}_H = \frac{g}{2M_W} (\overline{e} \quad \overline{\Sigma})\, h P_L \begin{pmatrix} -\frac{m_\ell}{v}(1-3\epsilon) & m_\ell Y_D^\dagger M^{-1} \\ Y_D(1-\epsilon) + M^{-2} Y_D m_\ell^2 & Y_D Y_D^\dagger M^{-1} v \end{pmatrix} \begin{pmatrix} e \\ \Sigma \end{pmatrix}$$

$$+ (\overline{\nu} \quad \overline{\Sigma^0})\, h P_L \begin{pmatrix} \frac{\sqrt{2} m_\nu}{v} & U^T_{\text{PMNS}} m_\nu Y_D^\dagger M^{-1} \\ (Y_D - \frac{Y_D \epsilon}{2} - \frac{\epsilon^T Y_D}{2}) U_{\text{PMNS}} & \frac{Y_D Y_D^\dagger M^{-1} v}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu \\ \Sigma^0 \end{pmatrix} + H.C$$

New Vertices: $\Sigma^+ - \Sigma^- - h, \ \Sigma^0 - \nu - h$


0.7
0.6
0.5
0.4
0.3
0.2
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0
Br
500
1000
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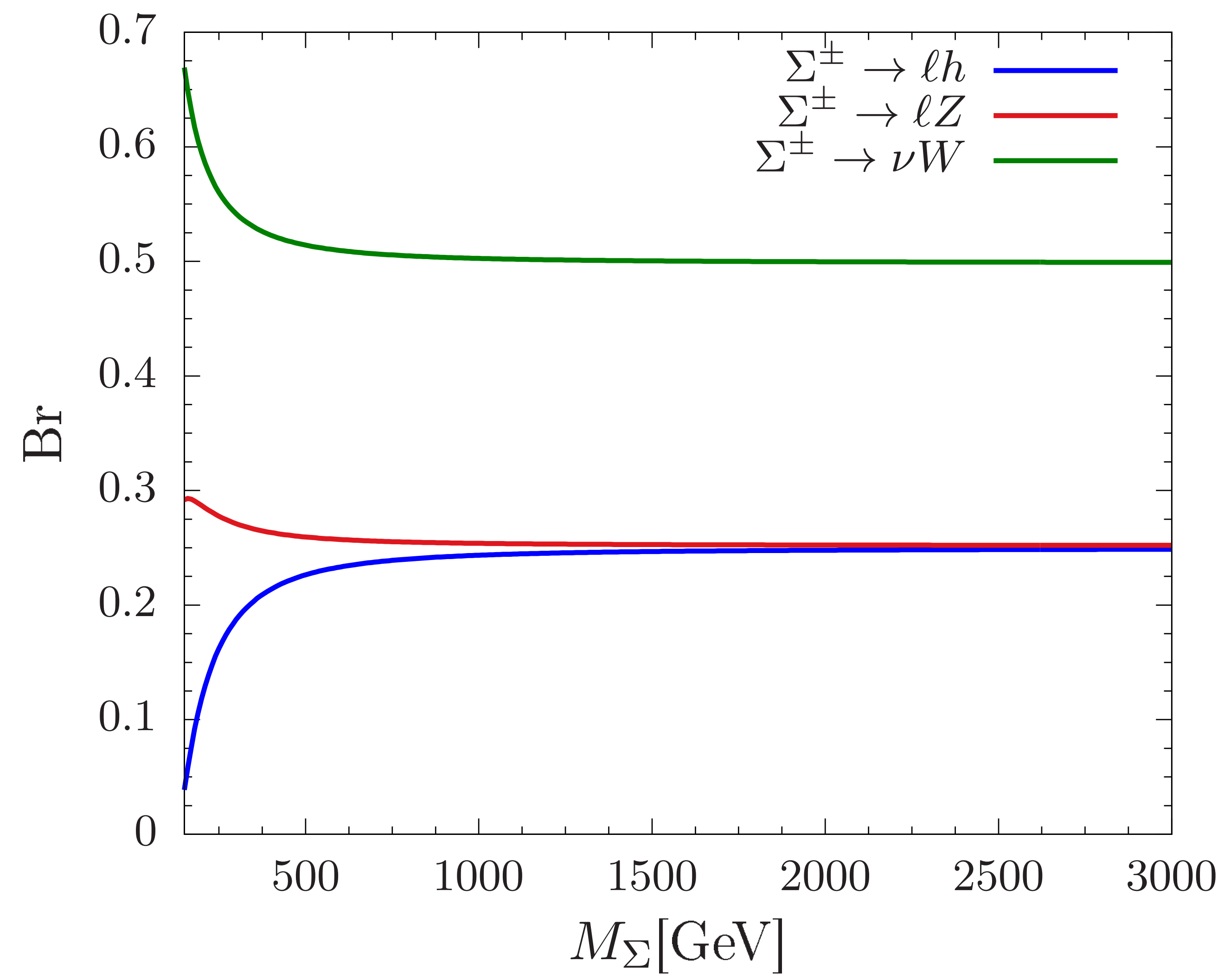
M_Σ[GeV]
$\Sigma^0 \to \nu h$
$\Sigma^0 \to \nu Z$
$\Sigma^0 \to \ell W$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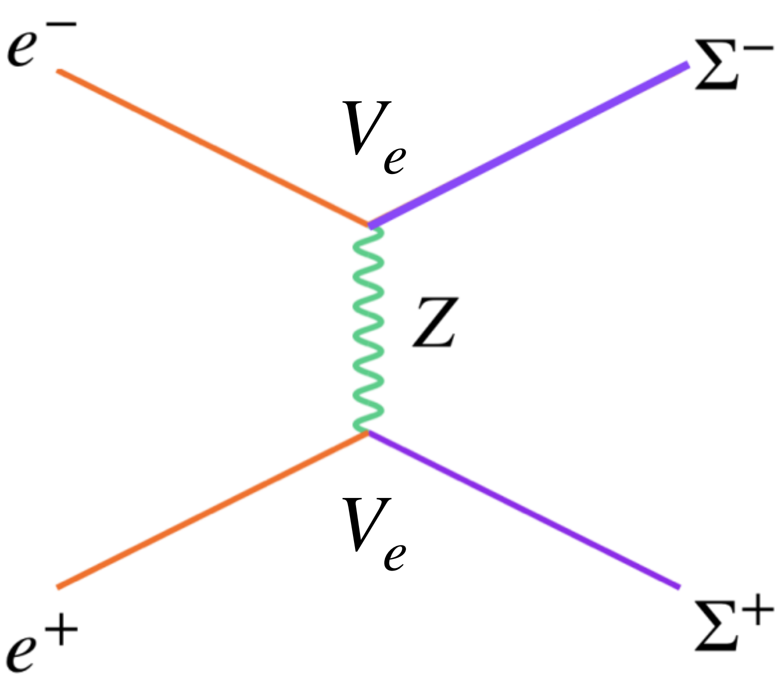
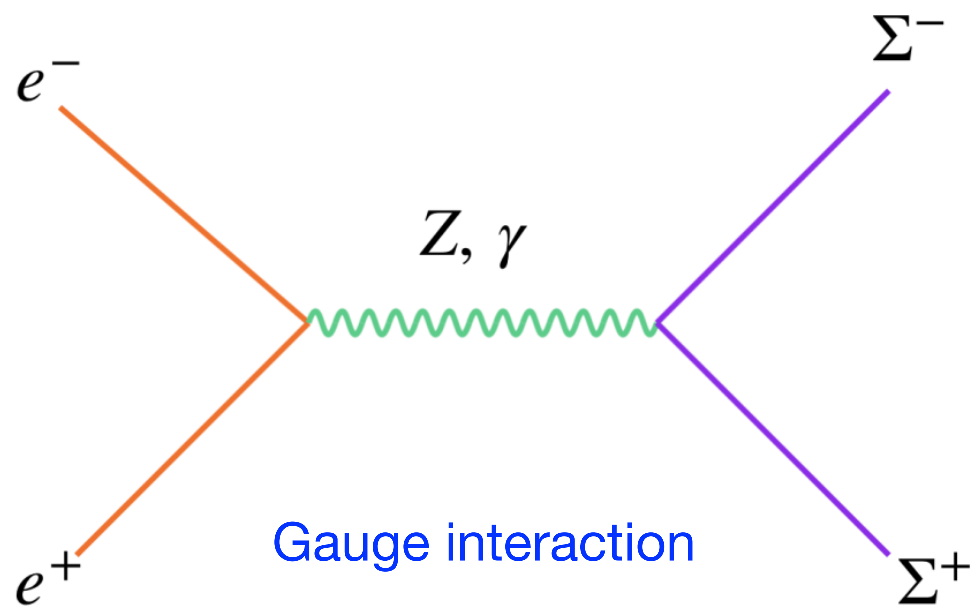
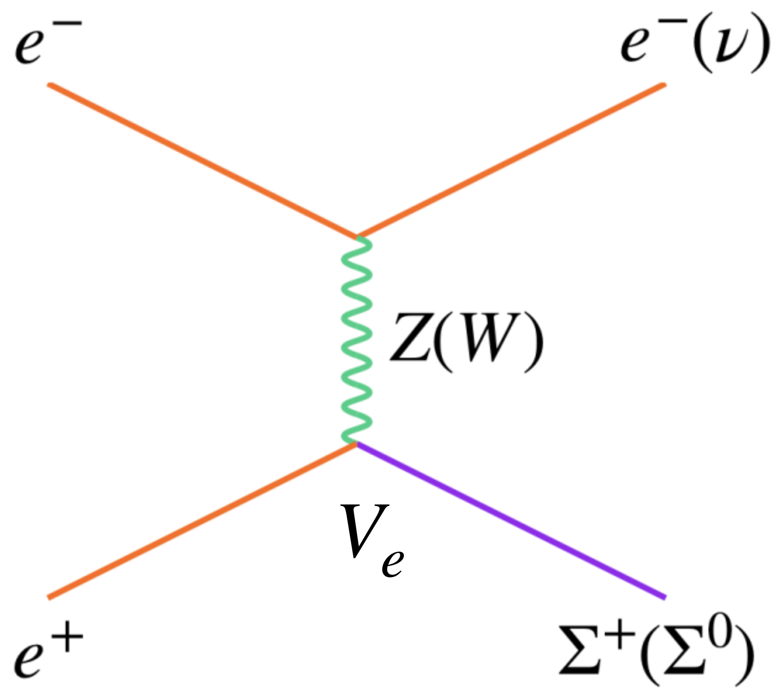
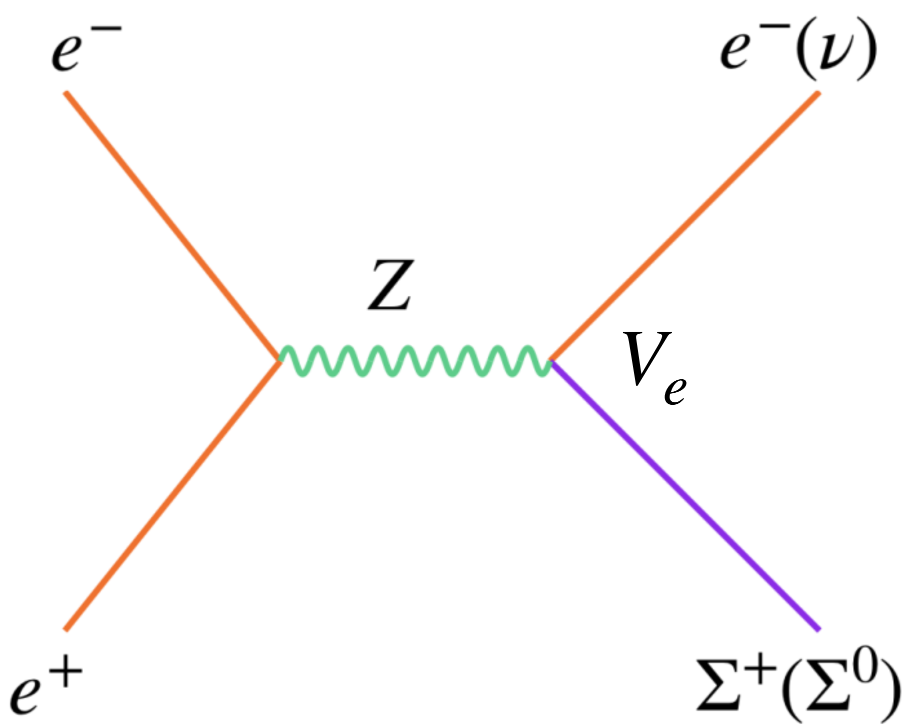
M_Σ[GeV]
$\Sigma^\pm \to \ell h$
$\Sigma^\pm \to \ell Z$
$\Sigma^\pm \to \nu W$

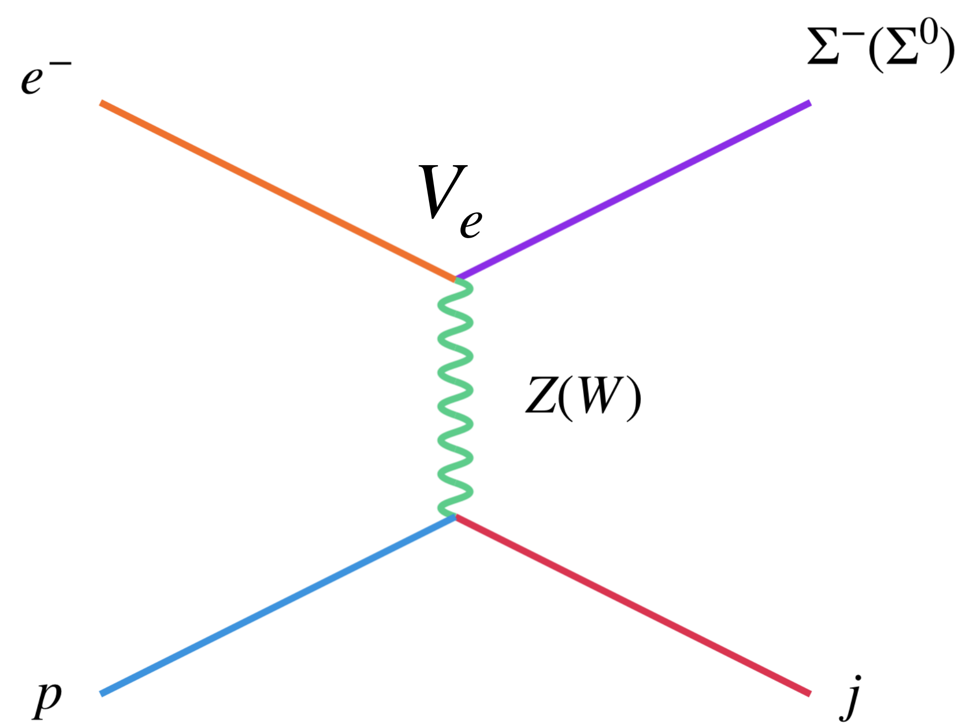
Triplet fermion production at Colliders











Thomas Hambye et al, arXiv: 0805.1613

SM, Das, Modak, arXiv: 2005.02267

Type II seesaw

One triplet scalar Δ with hypercharge Y=1 is included

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

$$\mathscr{L}_{\text{type II}} = \left[i Y_{\Delta\alpha\beta} L_\alpha^T C^{-1} \tau_2 \Delta L_\beta + \text{h.c.} \right] + \left(D_\mu \Phi \right)^\dagger (D^\mu \Phi) + \left(D_\mu \Delta \right)^\dagger (D^\mu \Delta)$$

Majorana mass term   Gauge interactions

Scalar potential is:

$$V(\Phi, \Delta) = -m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda}{4} (\Phi^\dagger \Phi)^2 + \tilde{M}_\Delta^2 \text{Tr} \left[\Delta^\dagger \Delta \right] + \lambda_2 \left[\text{Tr} \Delta^\dagger \Delta \right]^2 + \lambda_3 \text{Tr} \left[\Delta^\dagger \Delta \right]^2$$
$$+ \left[\mu \Phi^T i \sigma_2 \Delta^\dagger \Phi + \text{h.c.} \right] + \lambda_1 (\Phi^\dagger \Phi) \text{Tr} \left[\Delta^\dagger \Delta \right] + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi$$

μ term gives rise to the vev of the triplet $v_\Delta \approx \dfrac{\mu v_\Phi^2}{\sqrt{2} \tilde{M}_\Delta^2}$ (Induced vev)

Majorana mass term for light neutrinos $\mathscr{L}_\nu = \overline{\nu_L^c} m_\nu \nu_L + \text{H.c}$, with $m_\nu = \sqrt{2} Y_\Delta v_\Delta = Y_\Delta \dfrac{\mu v_\Phi^2}{\tilde{M}_\Delta^2}$

Need small v_Δ for large Y_Δ (small μ which can be viewed as a soft breaking lepton number)

Yukawa in terms of mass:

$$Y_\Delta = \frac{1}{\sqrt{2} v_\Delta} U_{\text{PMNS}}^\dagger m_\nu U_{\text{PMNS}}$$

Easy to deconstruct

$Y_D = \dfrac{\sqrt{2}}{v_\Phi} \sqrt{M_N} R \sqrt{m_\nu} U_{\text{PMNS}}$ with $R^T R = 1$ (TypeI, III seesaw)

Difficult to deconstruct

SM, Valle et al, arXiv: 2203.06362, 2202.04502

Upon EWSB, there are seven physical massive scalars: $H^{\pm\pm}, H^{\pm}, H, A$ and h

With small v_Δ, first four states are mainly from the triplet scalars and the last from SM doublet

$$(1).\ \lambda_4 = 0: \quad \Delta m \approx 0\, (m_{H^{\pm\pm}} \simeq m_{H^{\pm}} \simeq m_{H^0/A^0})$$

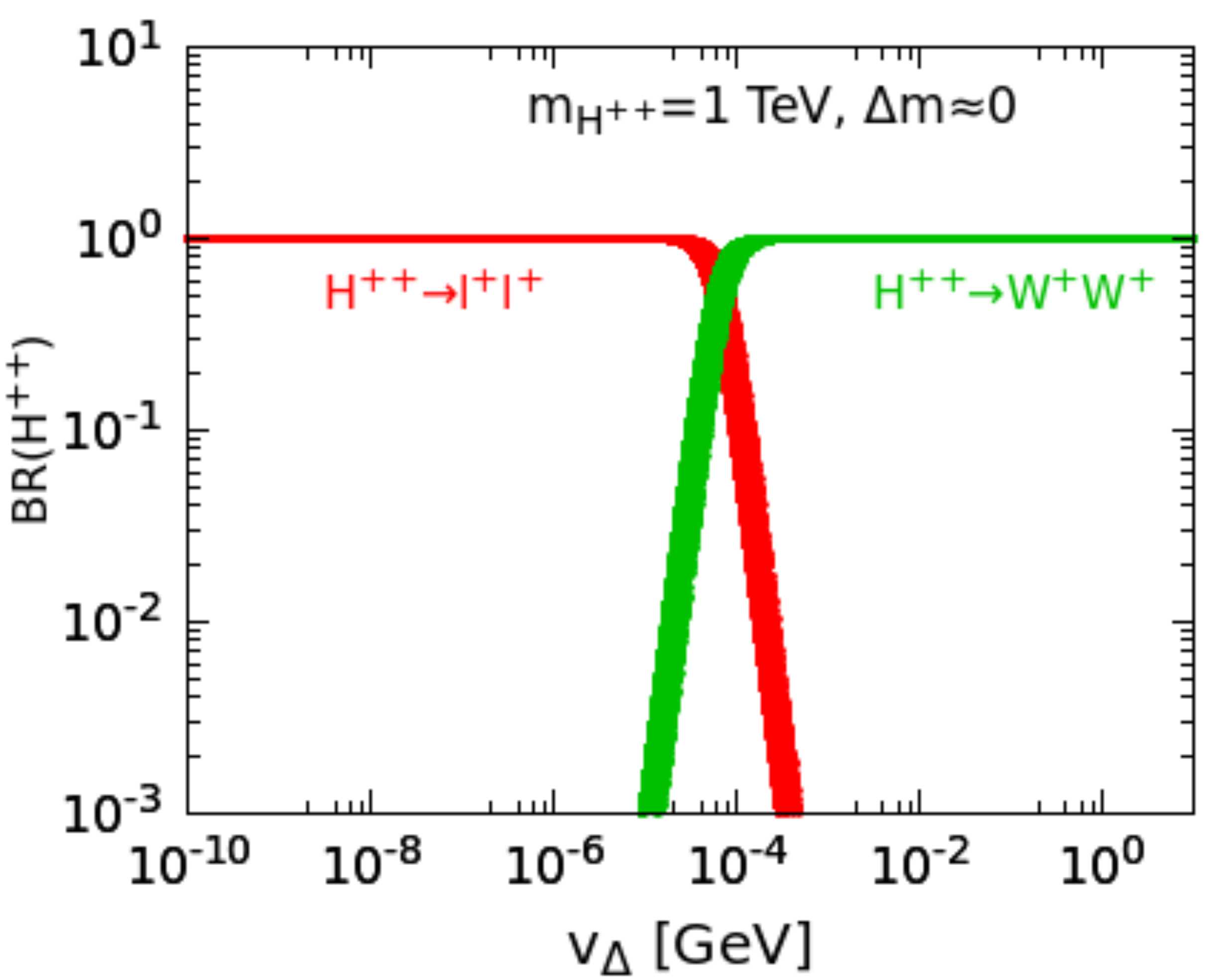
$$(2).\ \lambda_4 < 0: \quad \Delta m < 0\, (m_{H^{\pm\pm}} > m_{H^{\pm}} > m_{H^0/A^0})$$

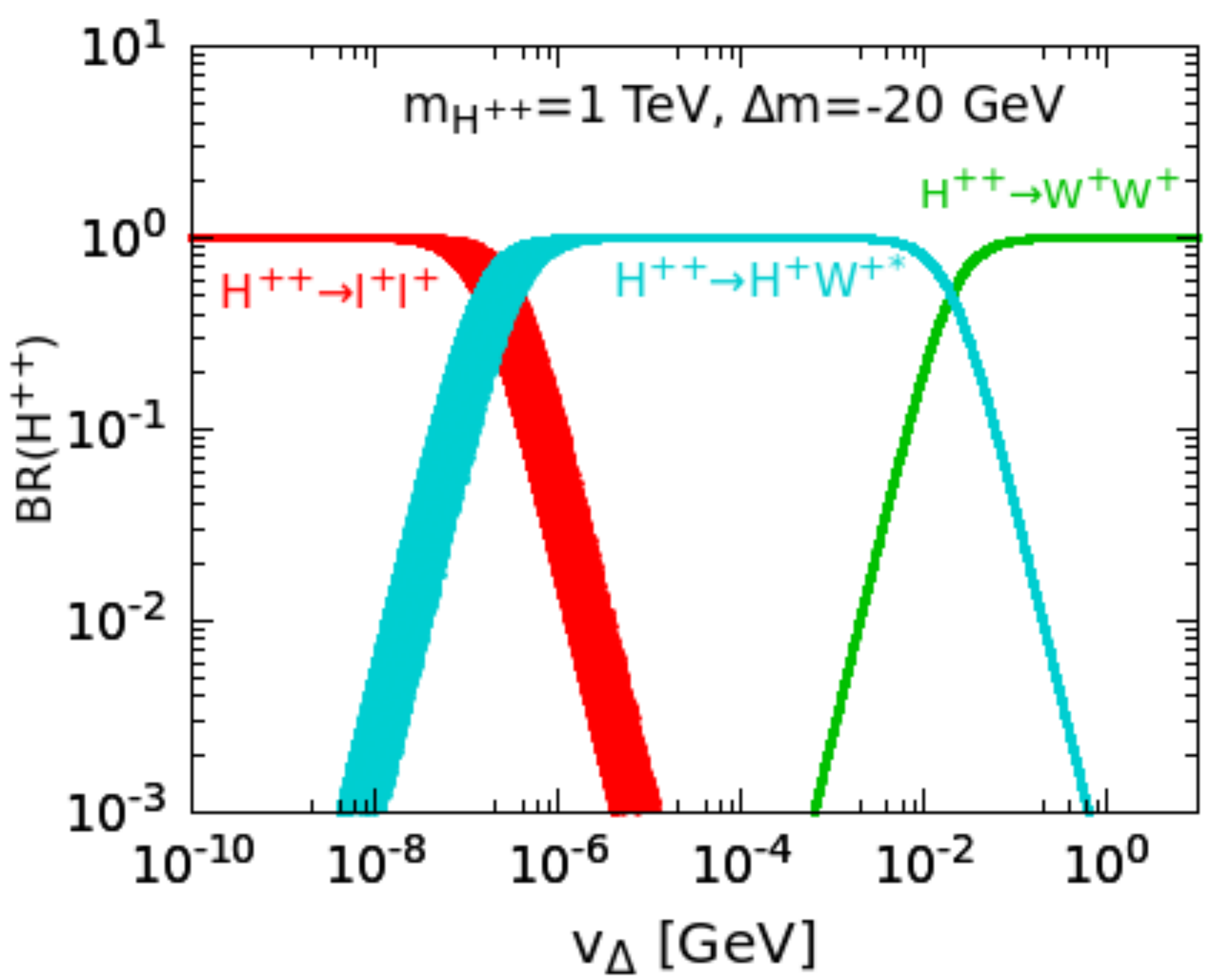
$$(3).\ \lambda_4 > 0: \quad \Delta m > 0\, (m_{H^{\pm\pm}} < m_{H^{\pm}} < m_{H^0/A^0})$$

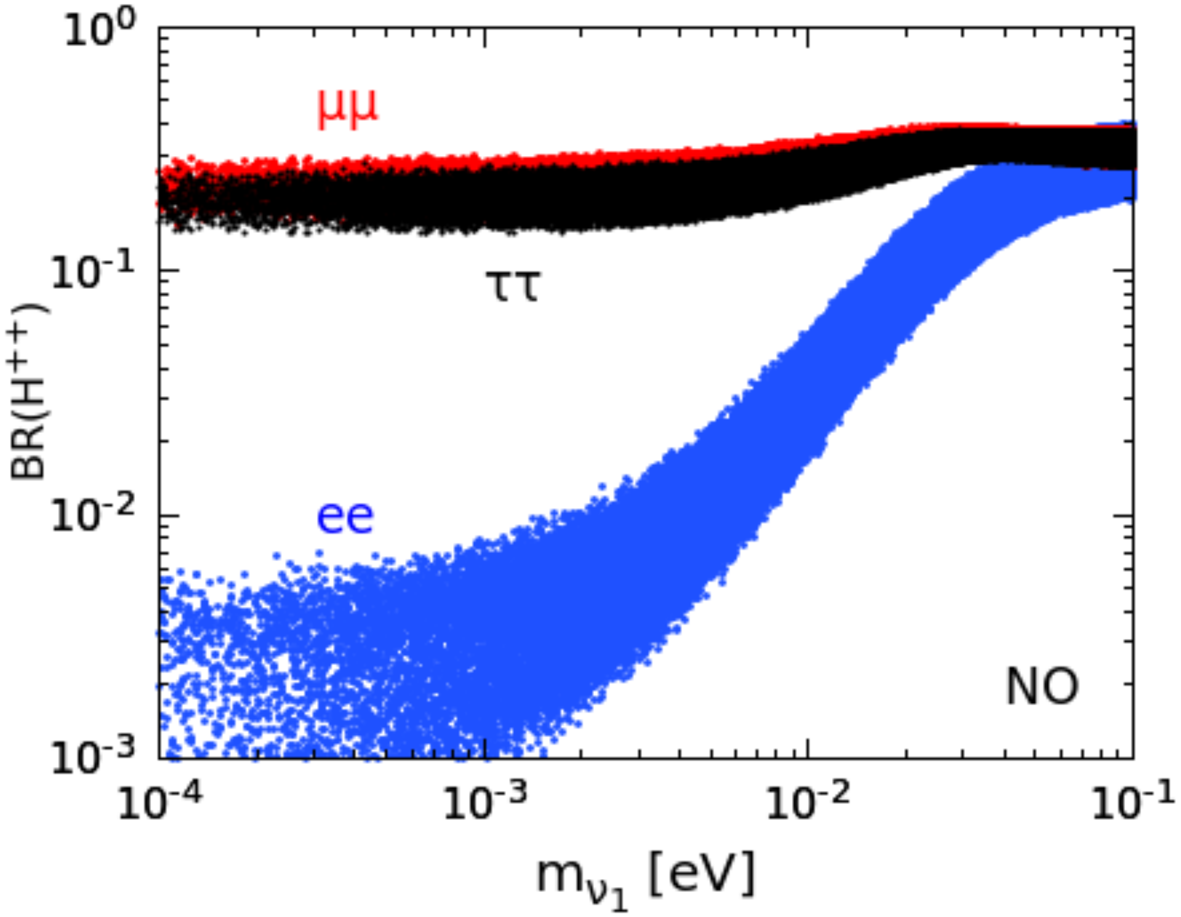
$$\Delta m = m_{H^{\pm}} - m_{H^{\pm\pm}}$$

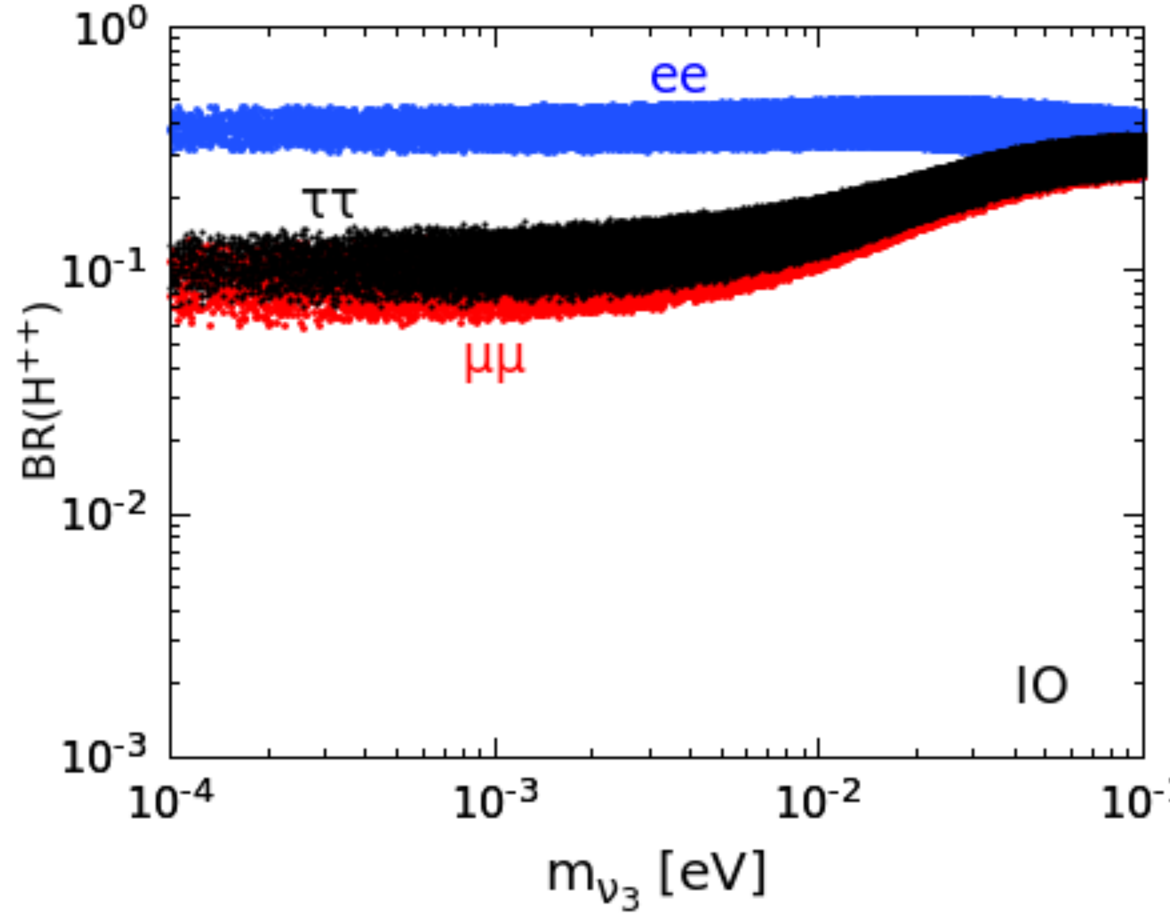
Three different mass spectra

$$\mathscr{L} = Y_{\Delta\alpha\beta} L_\alpha^T C^{-1} \tau_2 \Delta L_\beta \longrightarrow H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$$



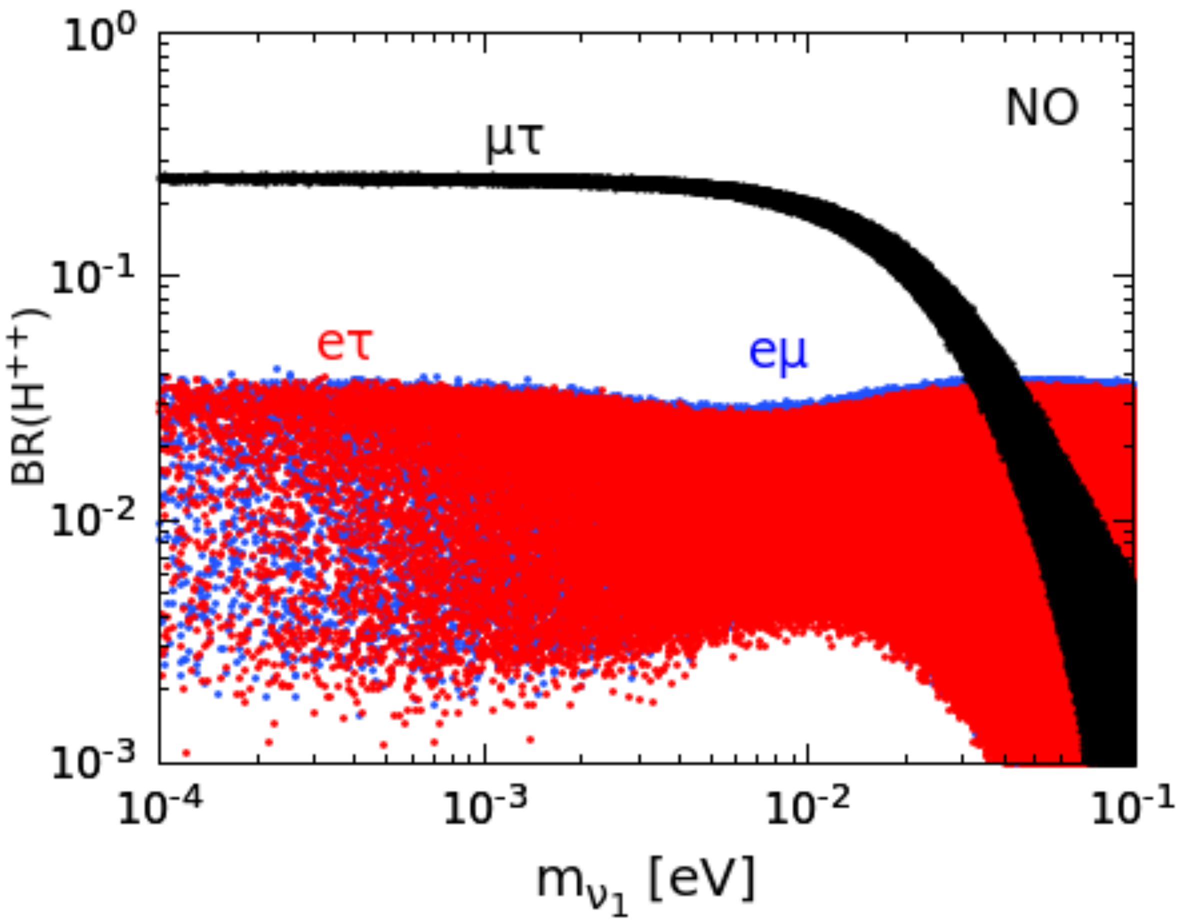


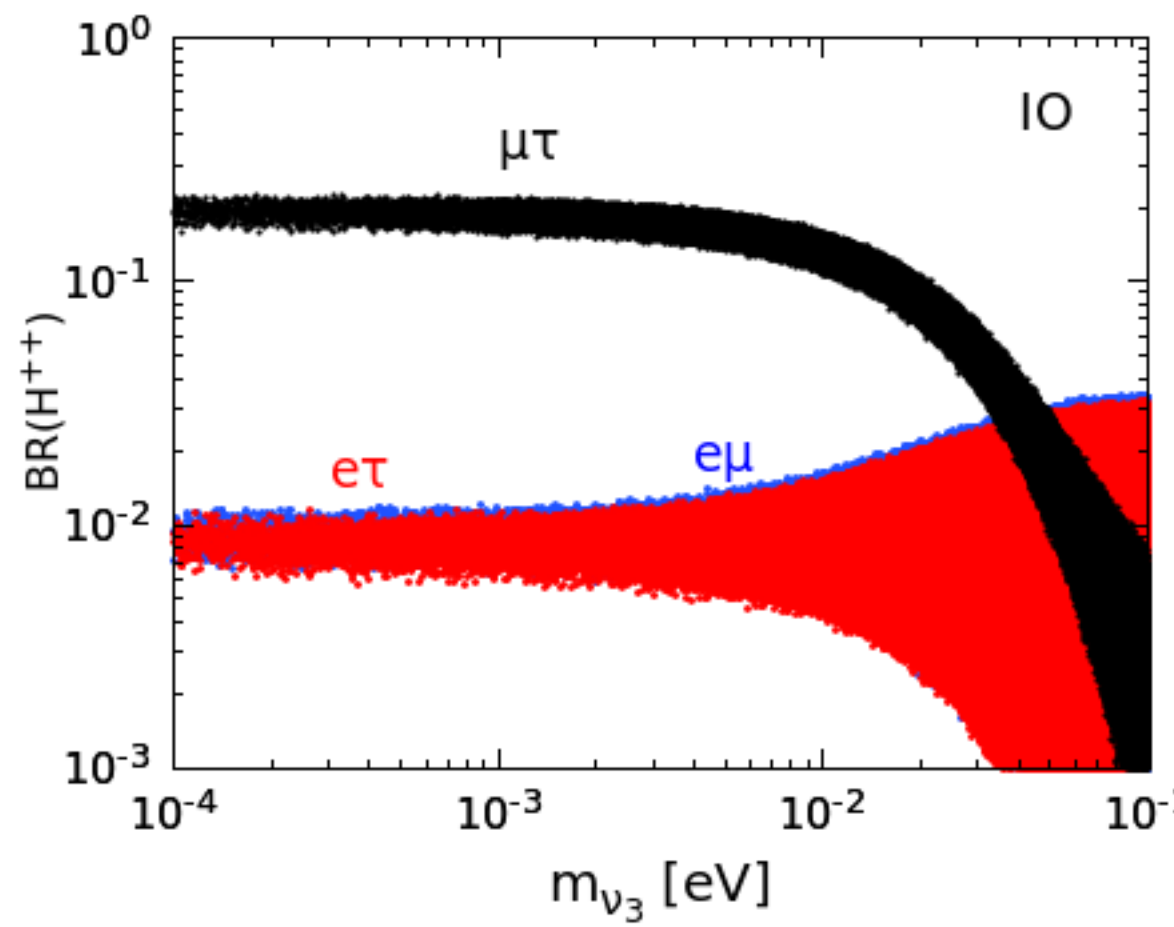




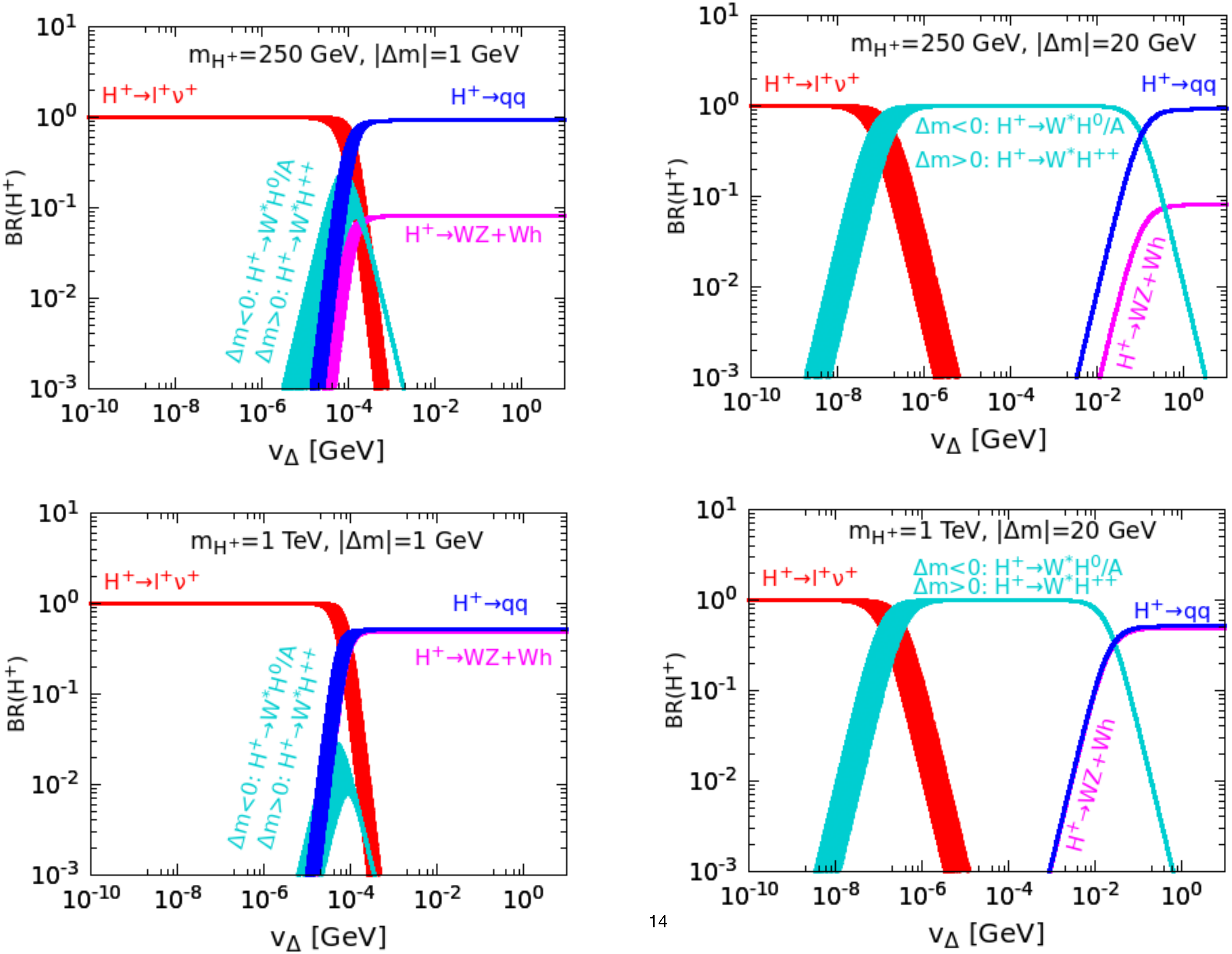
Assumption: v_Δ is very small

SM, Valle et al, arXiv: 2203.06362, 2202.04502





$H^{\pm}$ decay modes…

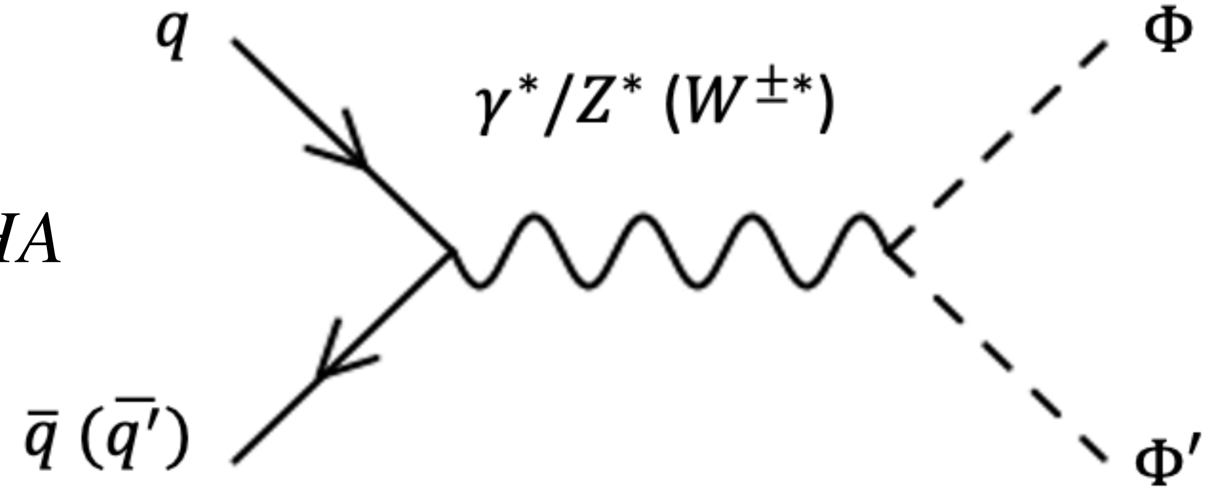


Triplert scalar productions

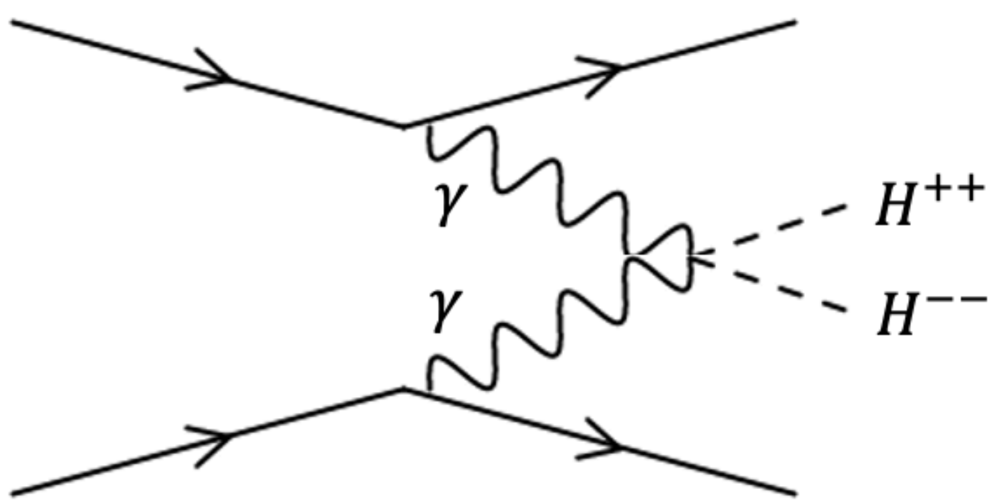
Drell-Yan production:

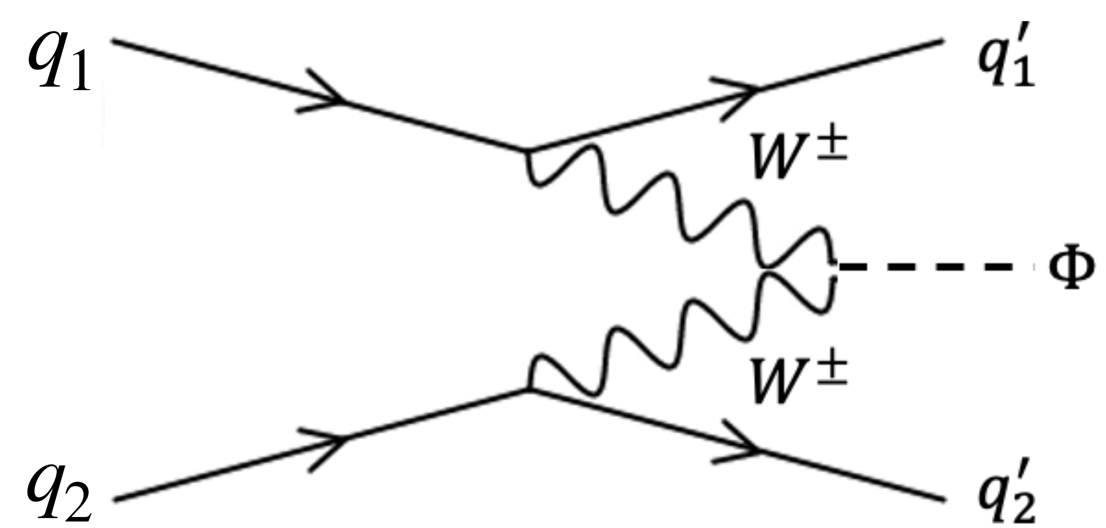
$$q\bar{q}, e^+e^- \to \gamma^*/Z^* \to H^{\pm\pm}H^{\mp\mp}, H^{\pm}H^{\mp}, HA$$

$$q\bar{q}' \to W^* \to H^{\pm\pm}H^{\mp}, H^{\pm}H, H^{\pm}A$$



Other possibilities:





Multi-leptonic final states:

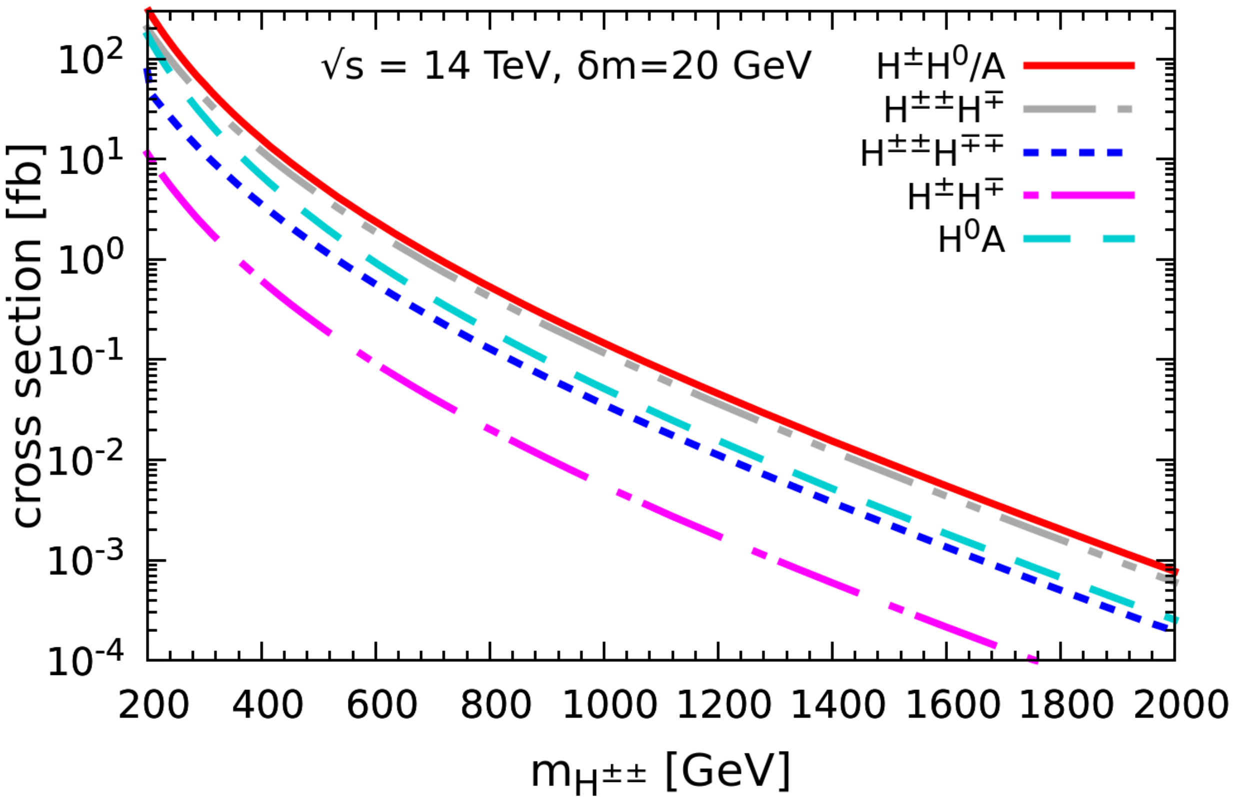
$$e^+e^-, pp \to H^{\pm\pm}H^{\mp\mp} \to \ell_i^{\pm}\ell_j^{\pm}\ell_k^{\mp}\ell_m^{\mp}$$

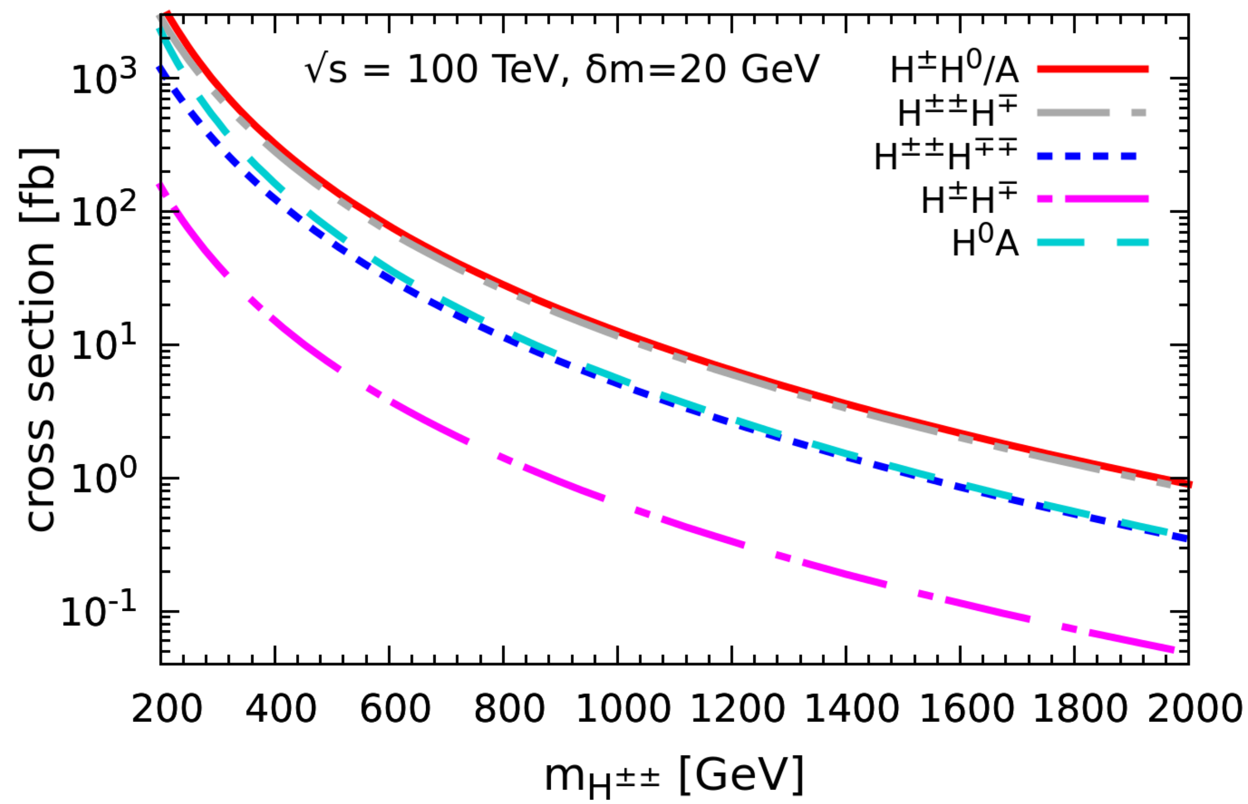
Can probe neutrino mass ordering

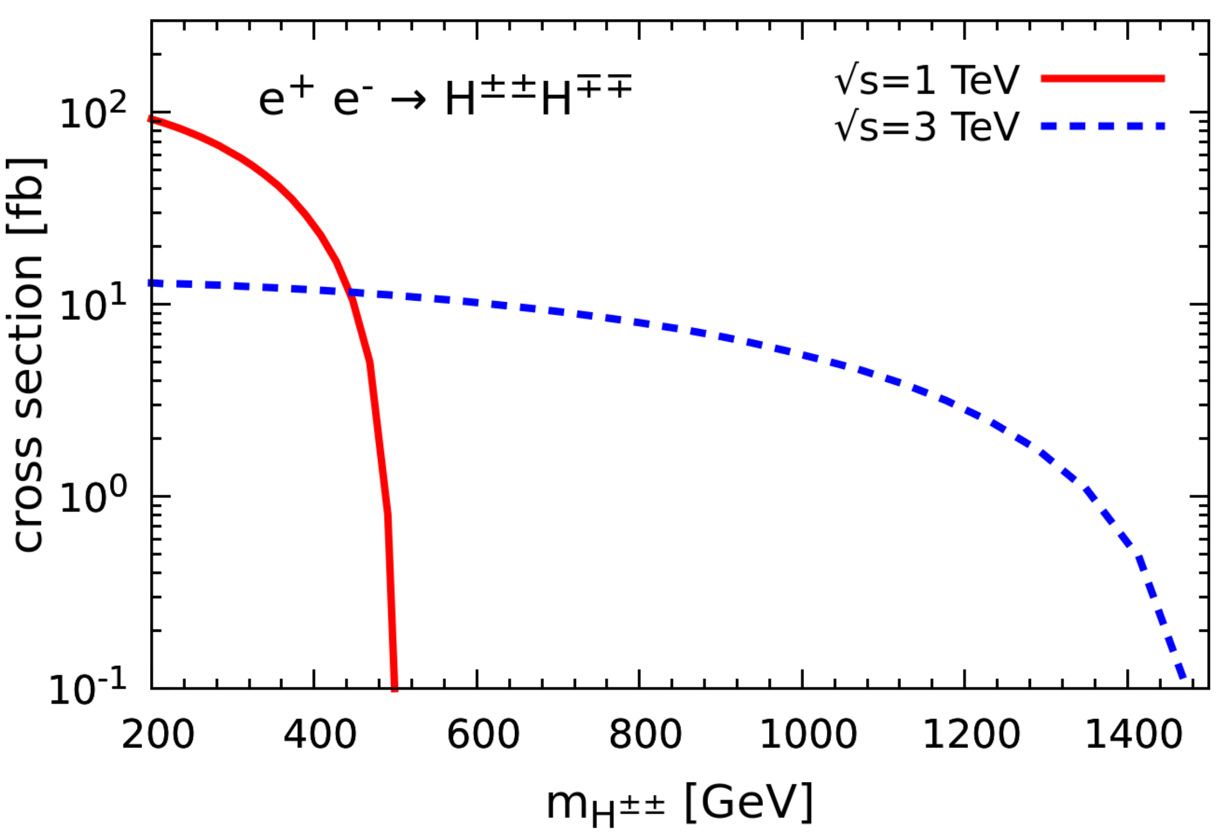
$$pp \to H^{\pm\pm}H^{\mp} \to \ell_i^{\pm}\ell_j^{\mp}\ell_k^{\mp}\nu$$

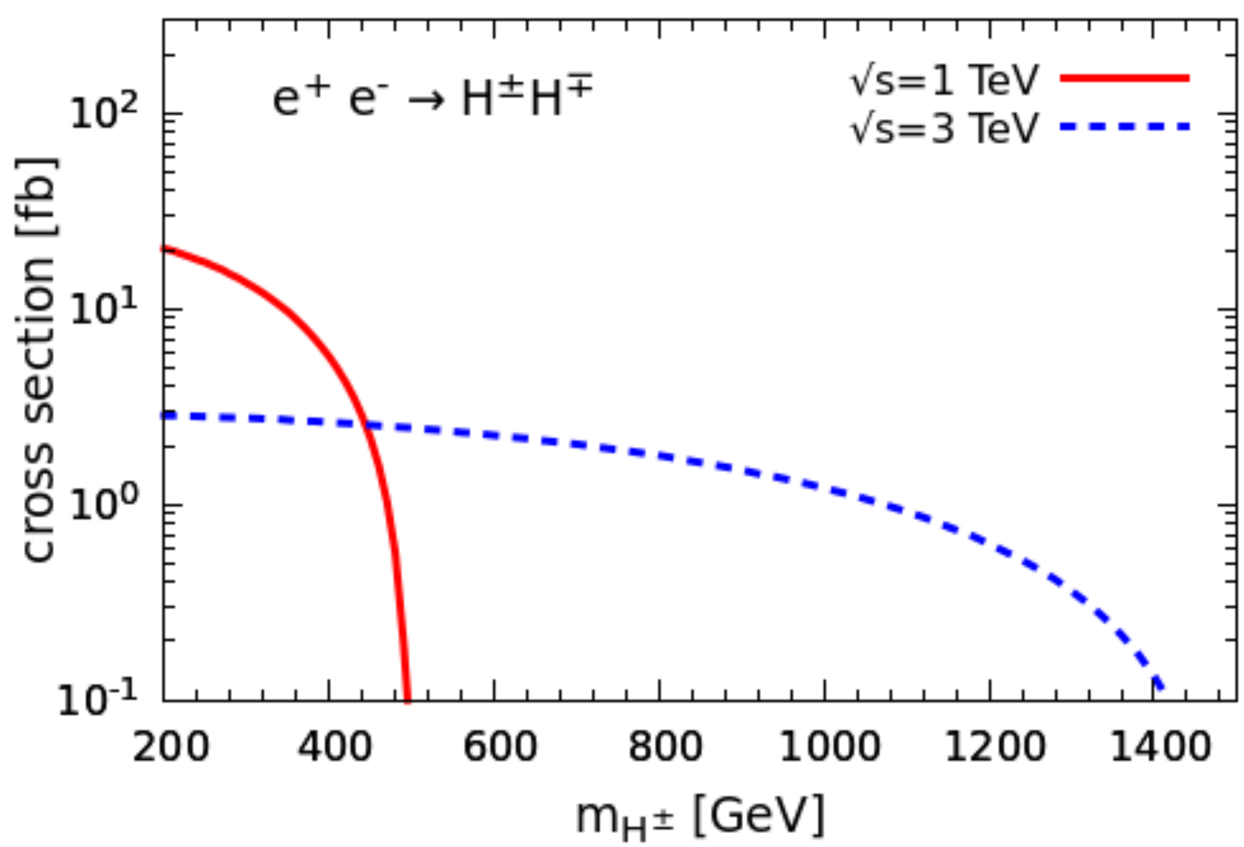
SM, Valle et al, arXiv: 2203.06362, 2202.04502

Triplert scalar productions cross sections

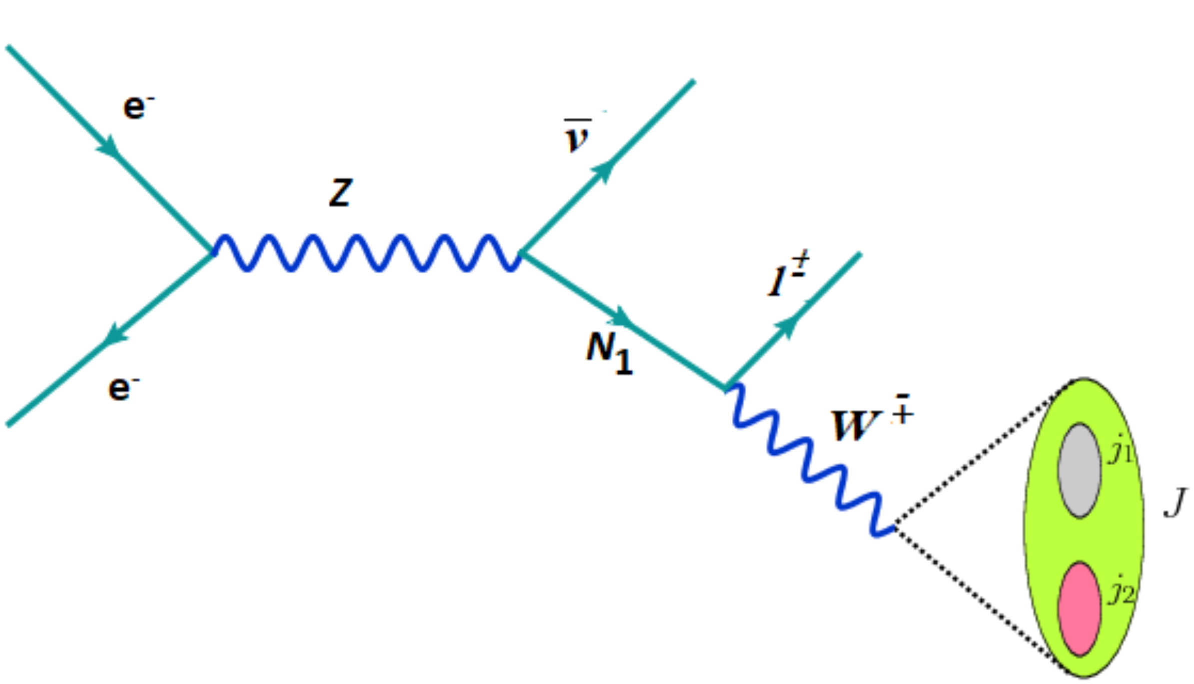


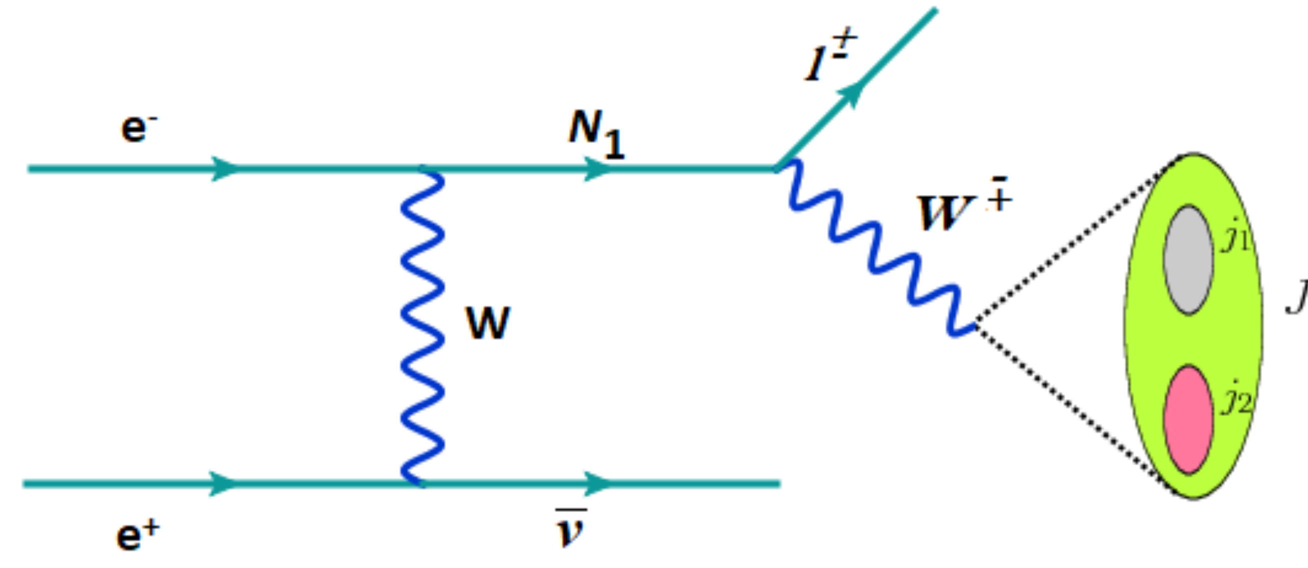






Type-I seesaw collider signatures at e^+e^- and e^-p collider: N is very heavy





SM, Jana, Das, Nandi, arXiv: 1811.04219

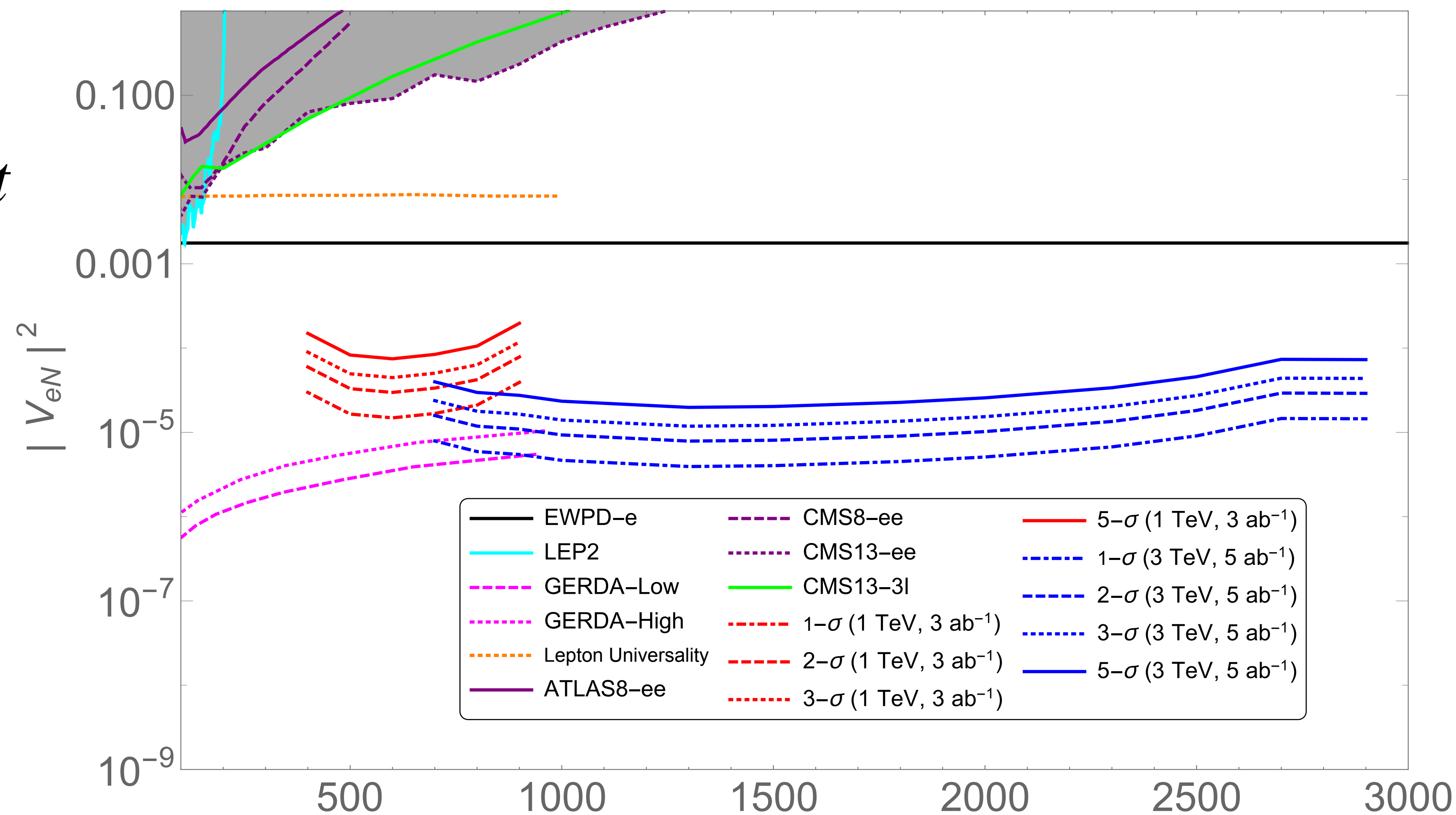
when $M_N \gg M_W$, W is highly boosted: Fatjet

Final state: $e^{\pm} + J + p_T^{\text{miss}}$

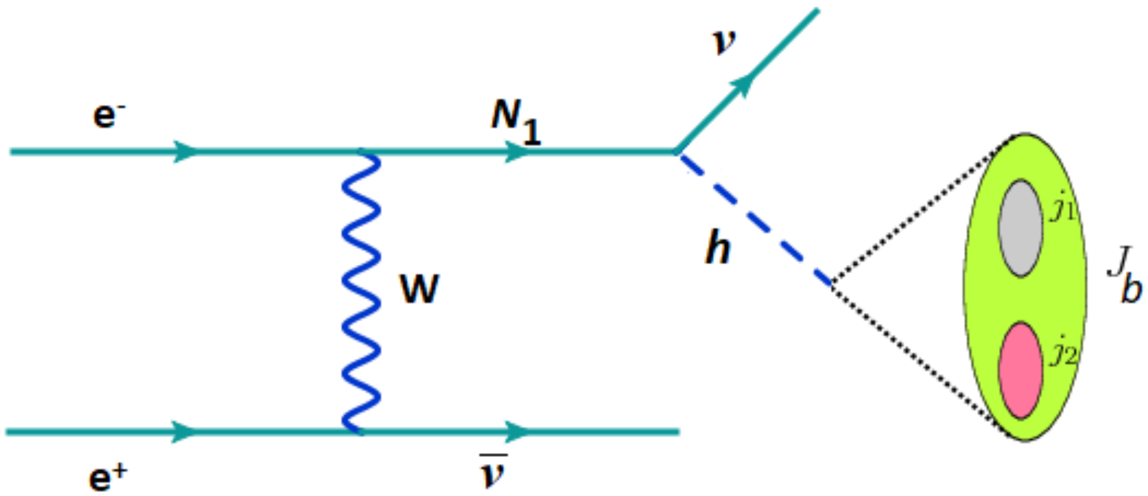
SM BKG: $\nu_e e W, WW, ZZ, \bar{t}t$

Important variables:

1. High p_T of Fatjet
2. Invariant mass of Fatjet M_J
3. Lepton polar angle cut



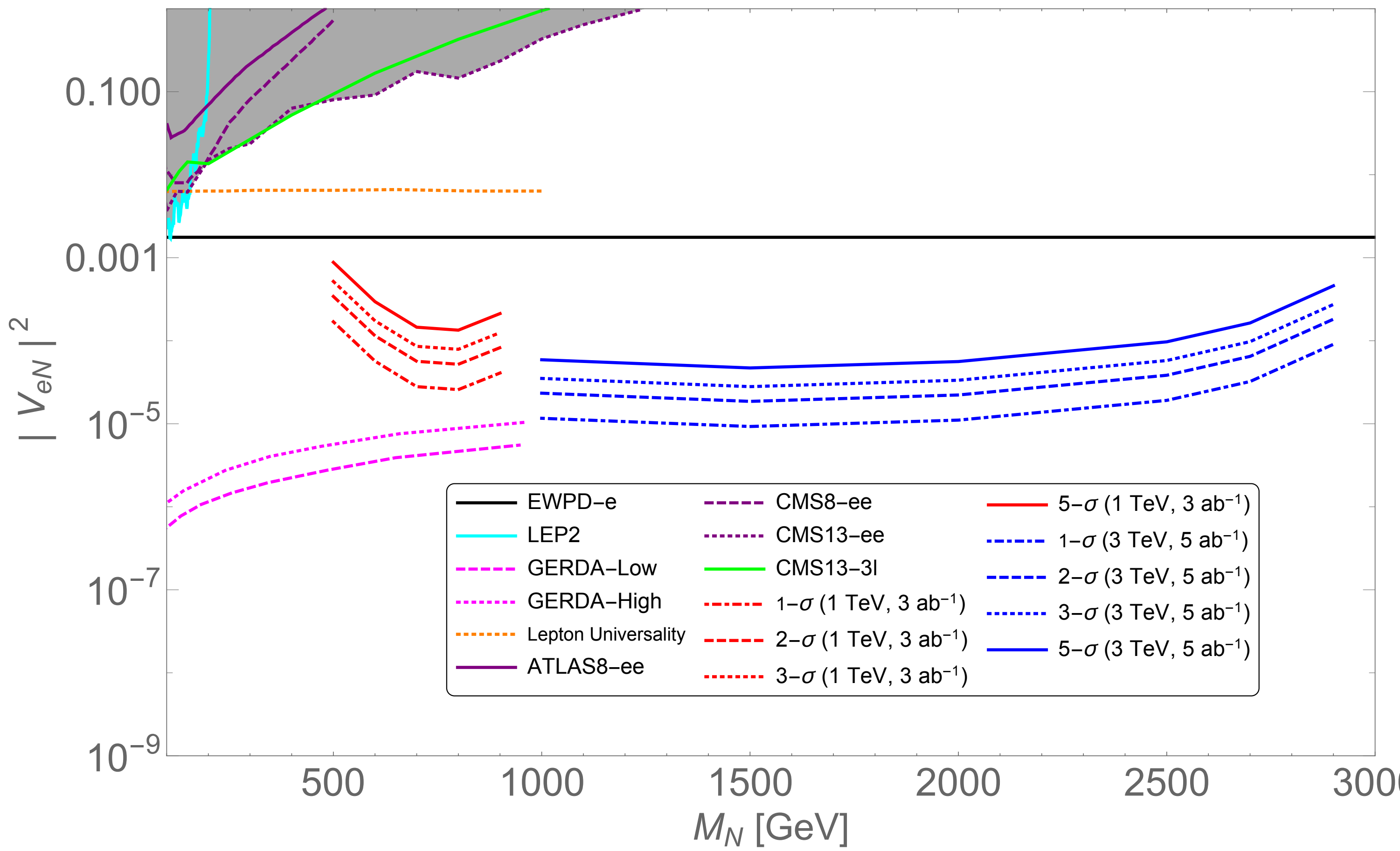
More possibilities…………..

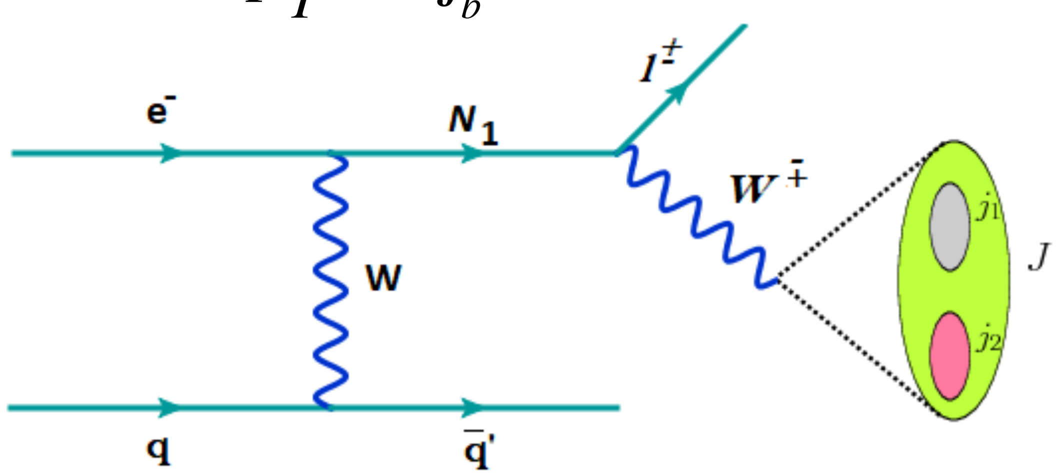


Final State: $J_b + p_T^{\rm miss}$

SM BKG: $h\nu\nu$, $Z\nu\nu$, ZZ and ZH

Cuts: $p_T^{J_b}, M_{J_b}$

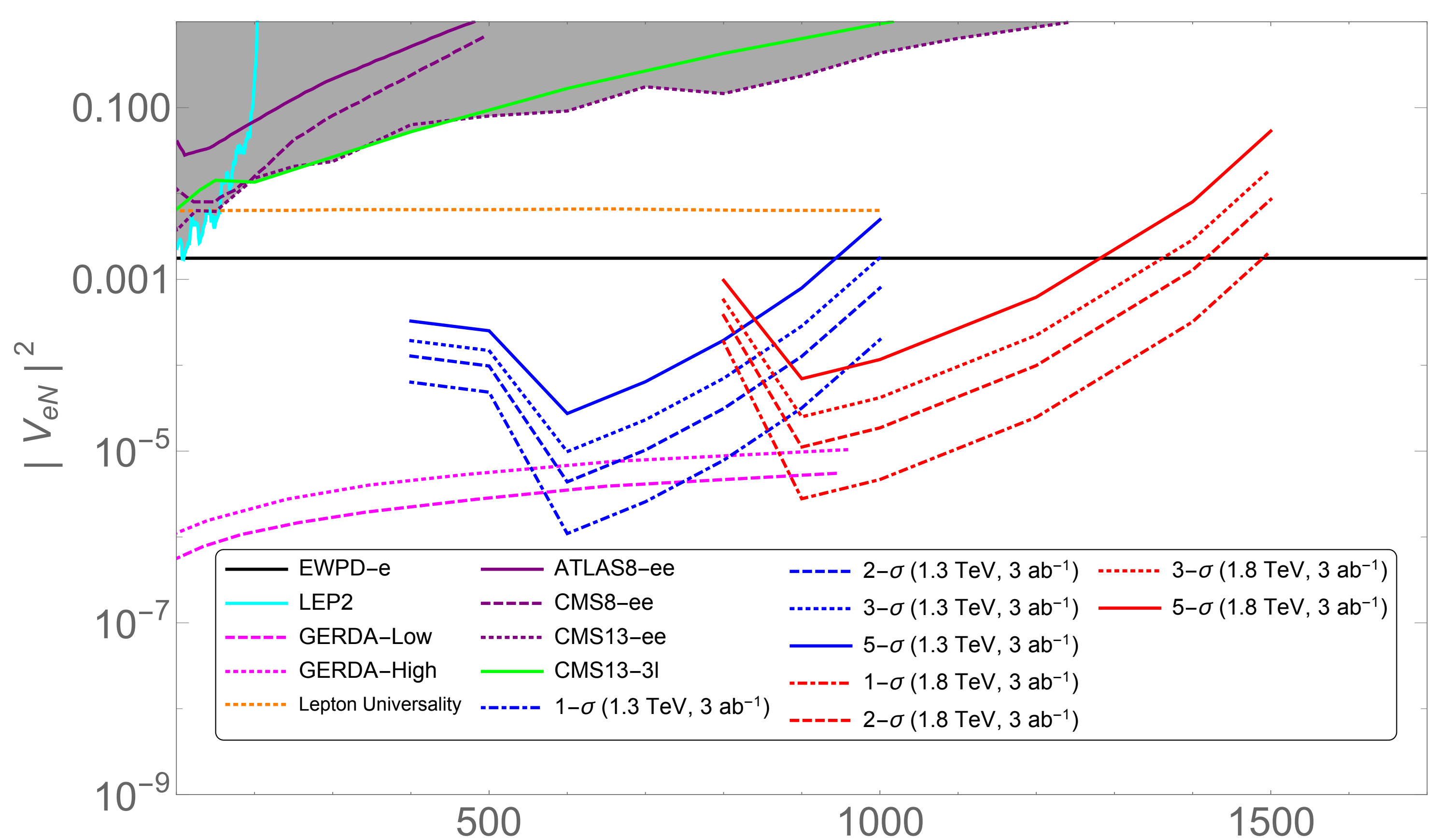




LNV Final State: $e^+ + J + j_1$

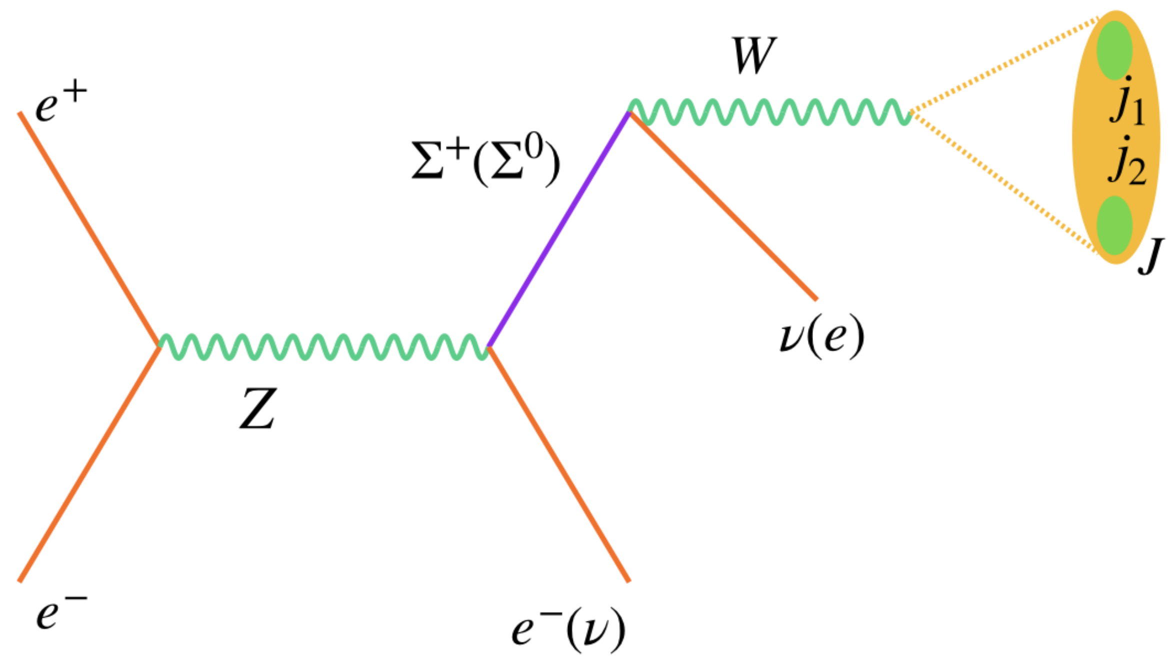
LNC Final State: $e^- + J + j_1$

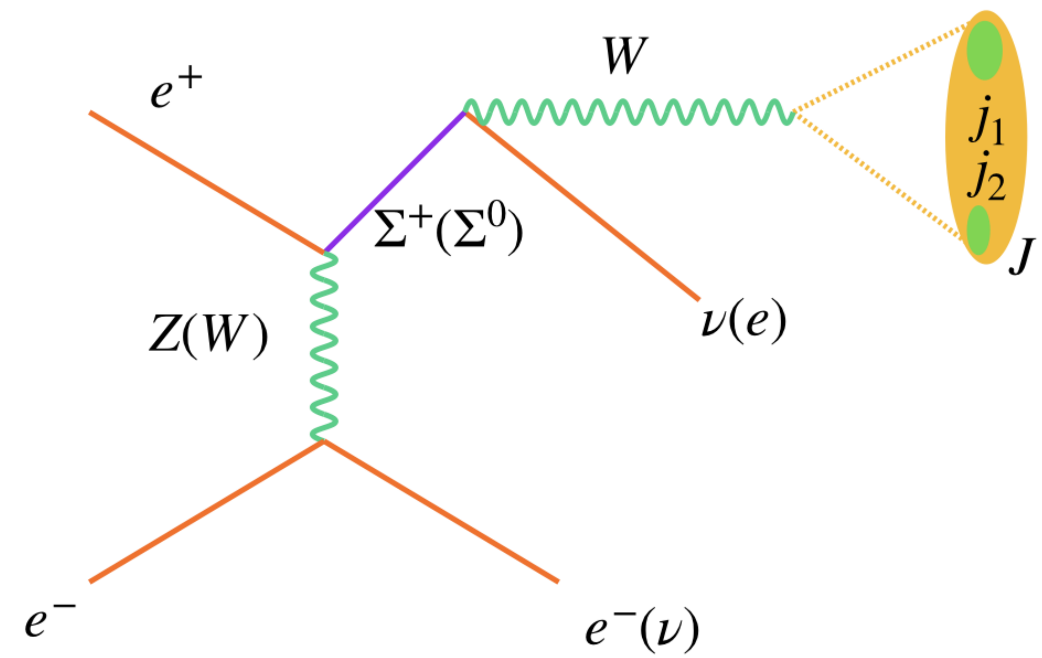
Cuts: p_T^J, M_{eJ}, M_J



Type-III seesaw collider signatures at e^+e^- and e^-p collider

SM, Das, Modak, arXiv: 2005.02267



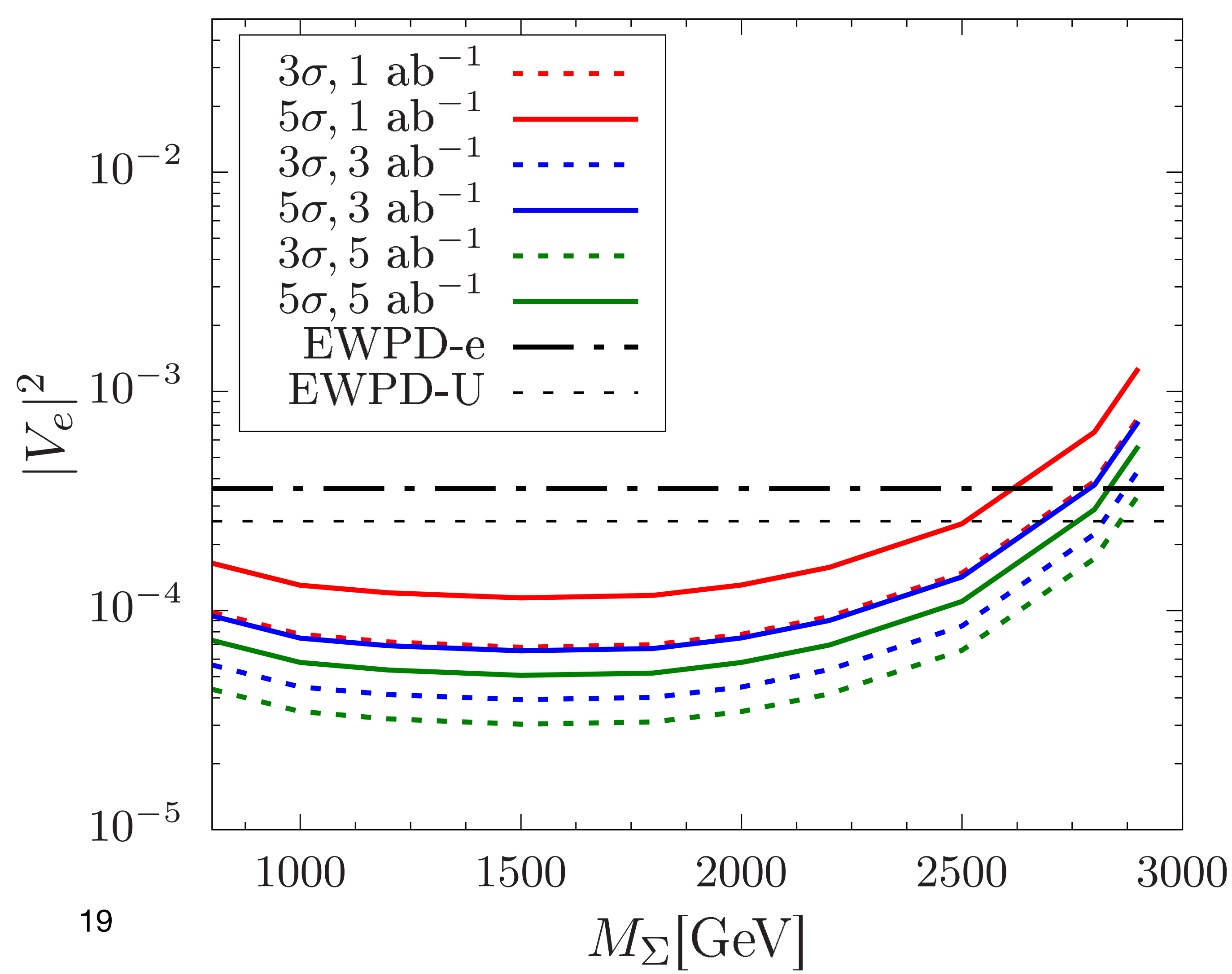


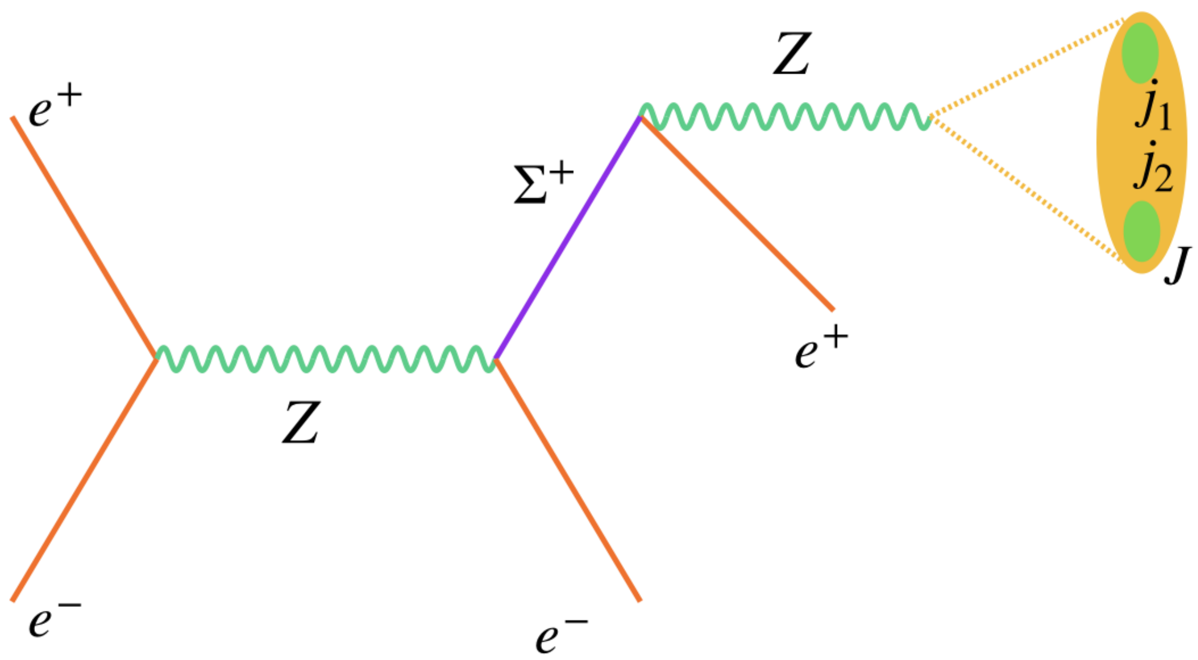
Final State: $e^{\pm} + J + p_T^{\mathrm{miss}}$

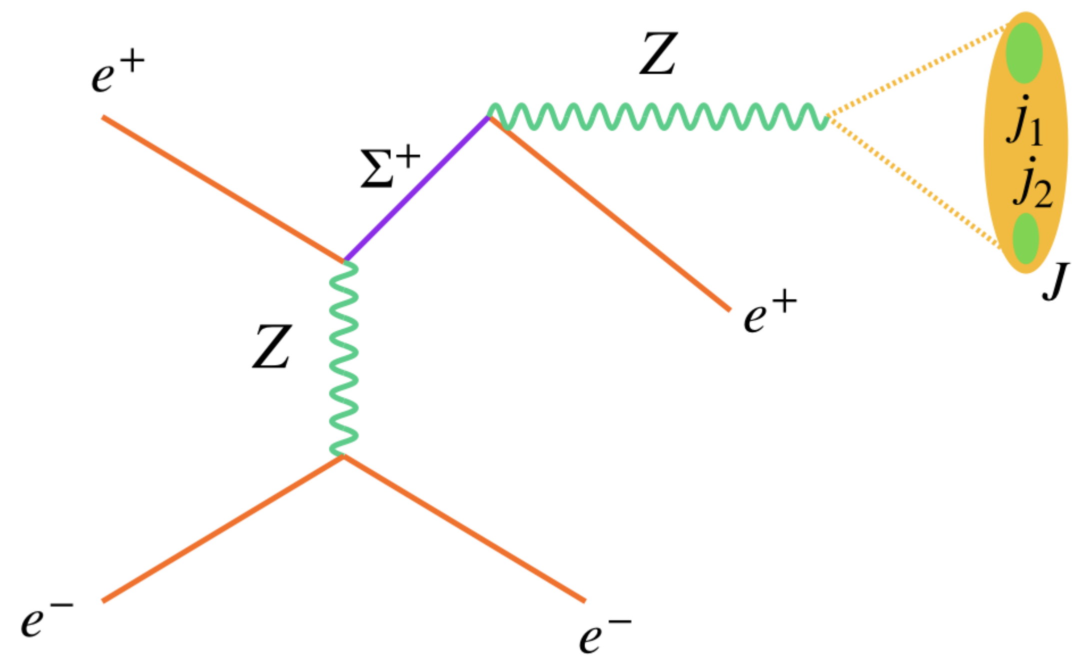
SM BKG: $\nu_e e W, WW, ZZ, \bar{t}t$

Σ is very heavy from multileptonic search

CMS, arXiv: 1911.04968

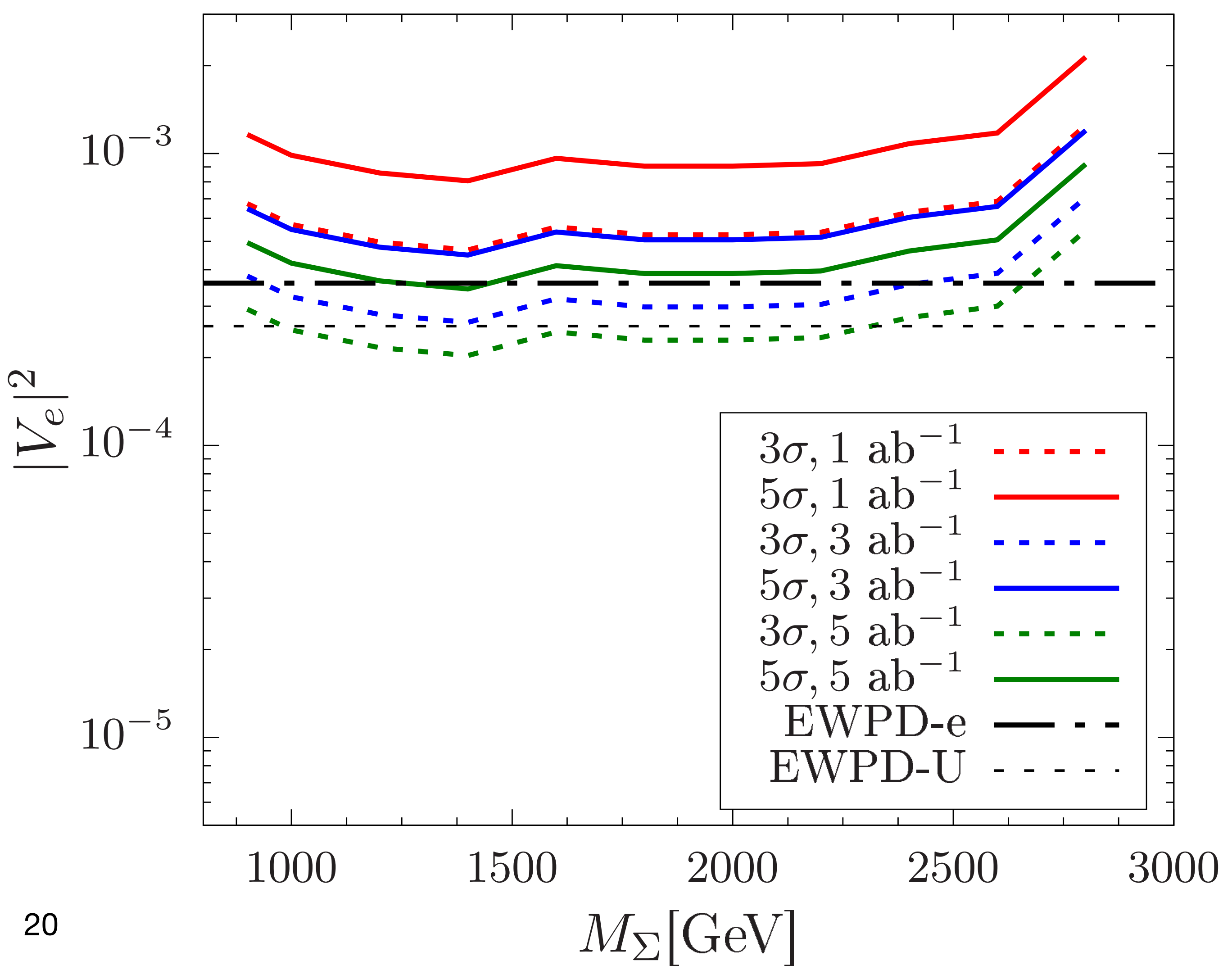


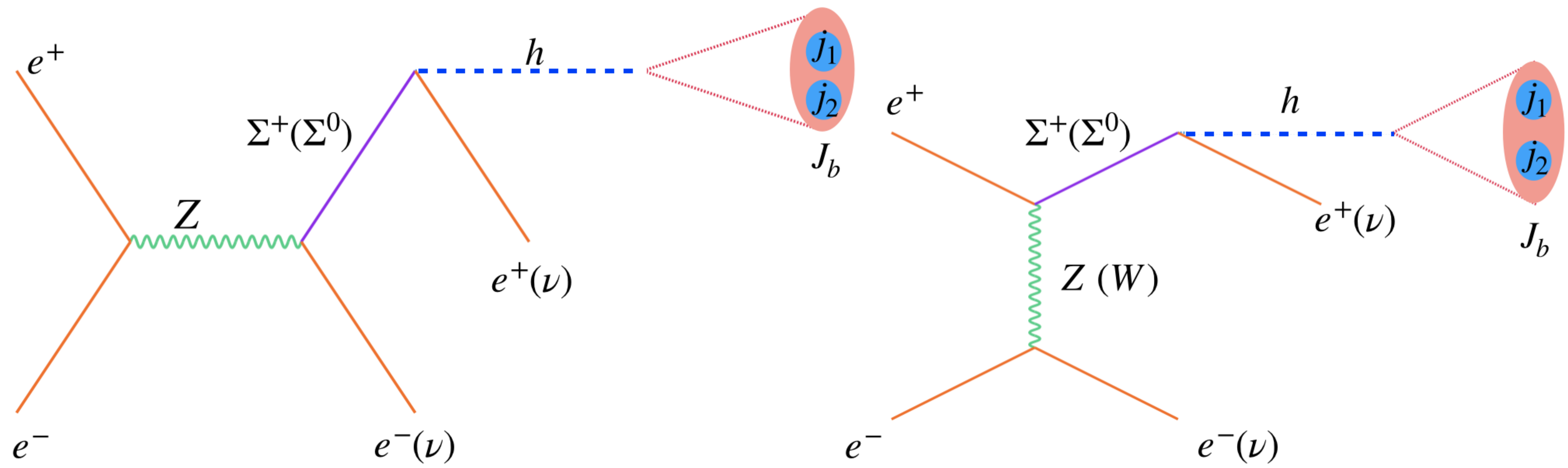




Final State: $e^+ + e^- + J$

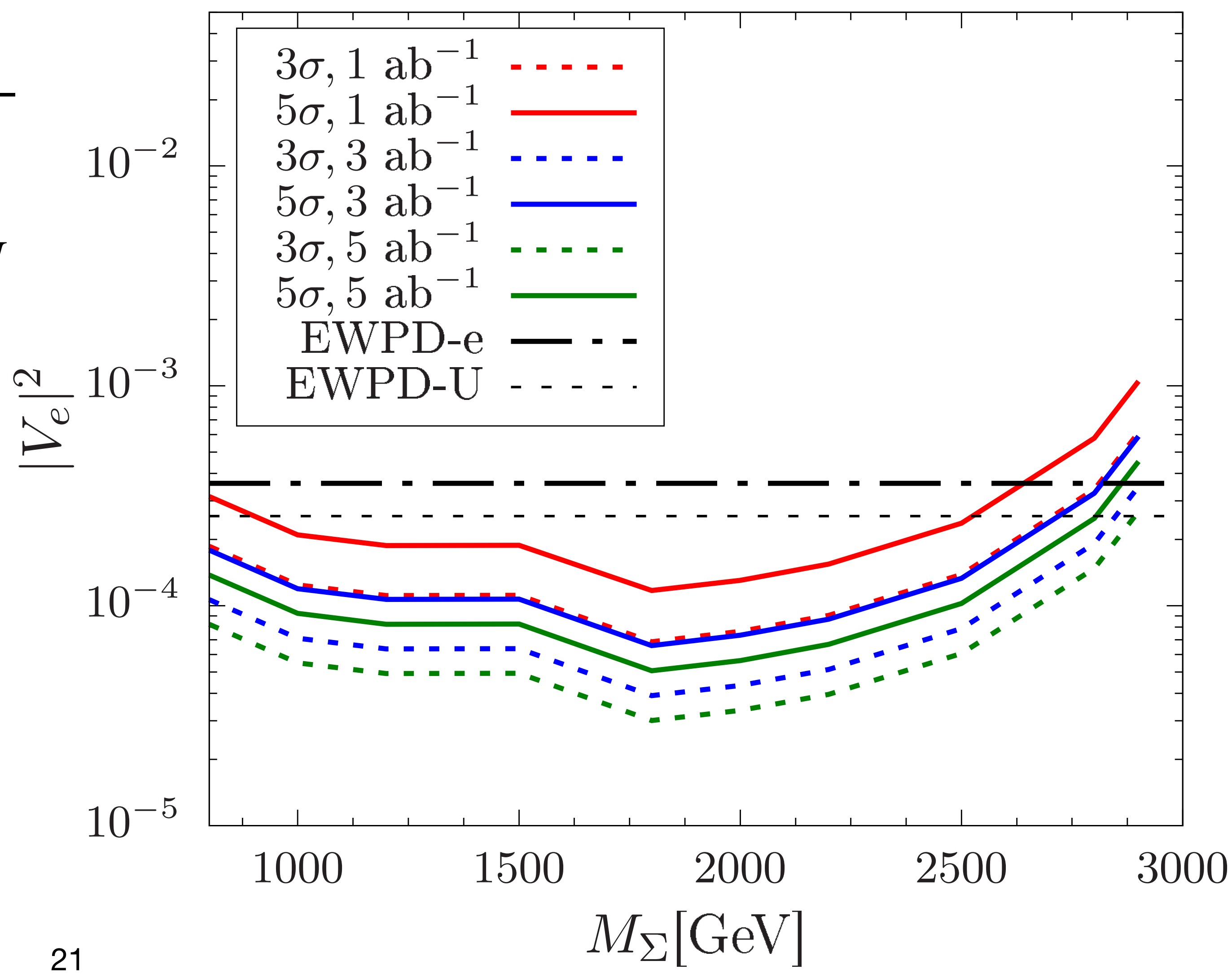
SM BKG: $Z/\gamma jj, WWZ, t\bar{t}$

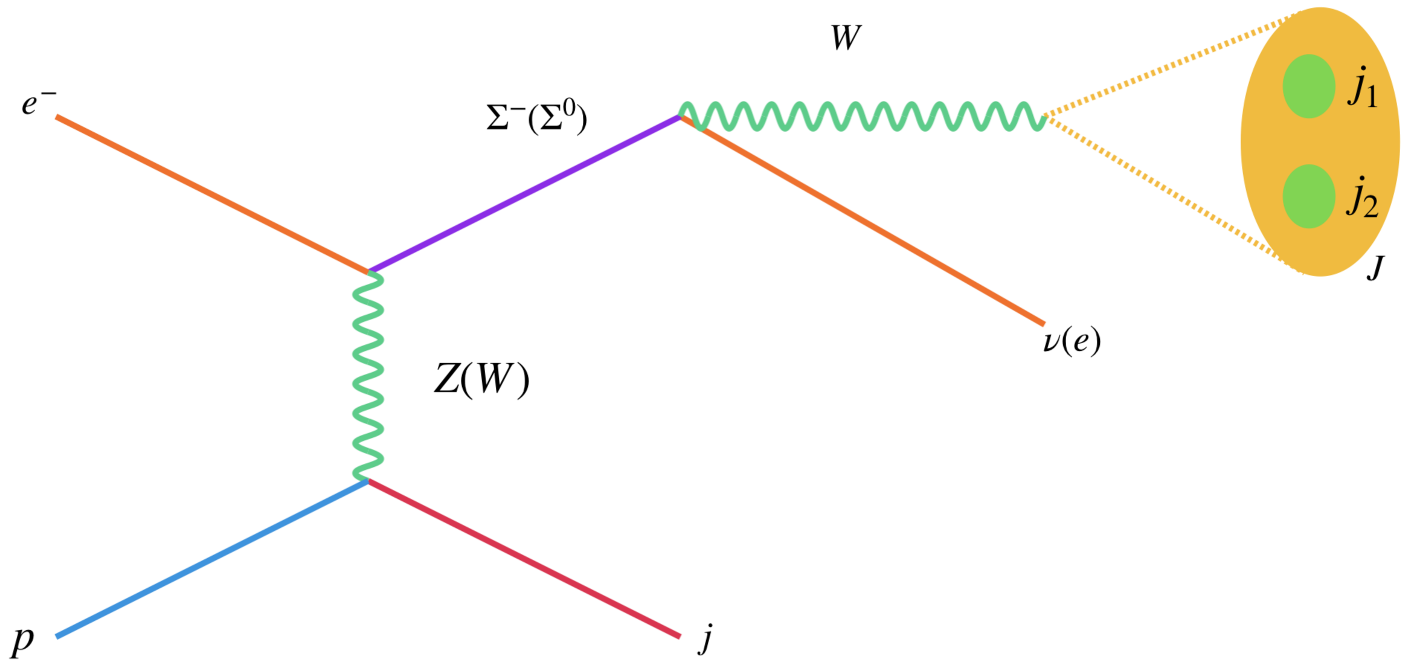


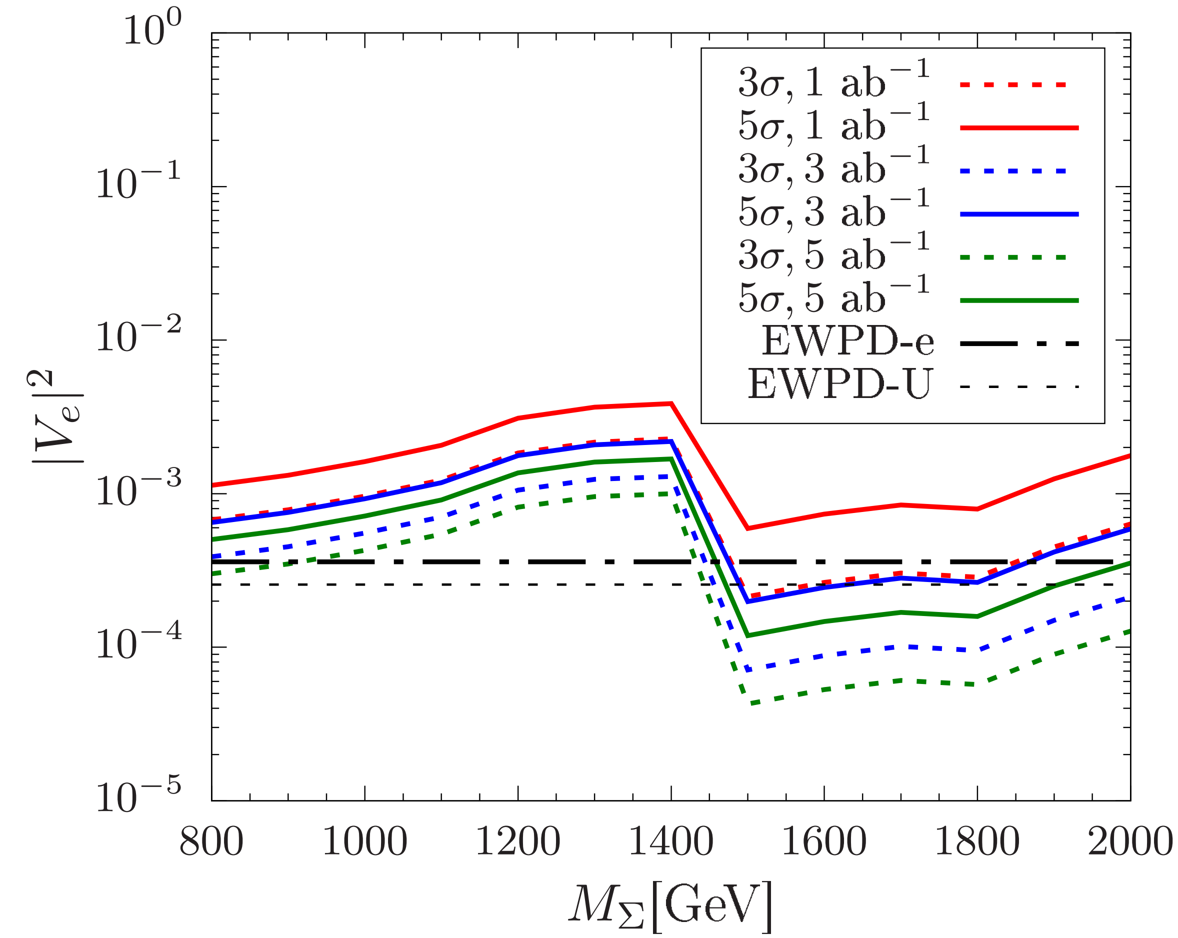


Final State: $J_b + p_T^{\rm miss}$ and $J_b + e^+ + e^-$

SM BKG for $J_b + p_T^{\rm miss}$: $h\nu\nu$, $Z\nu\nu$, ZZ and ZH



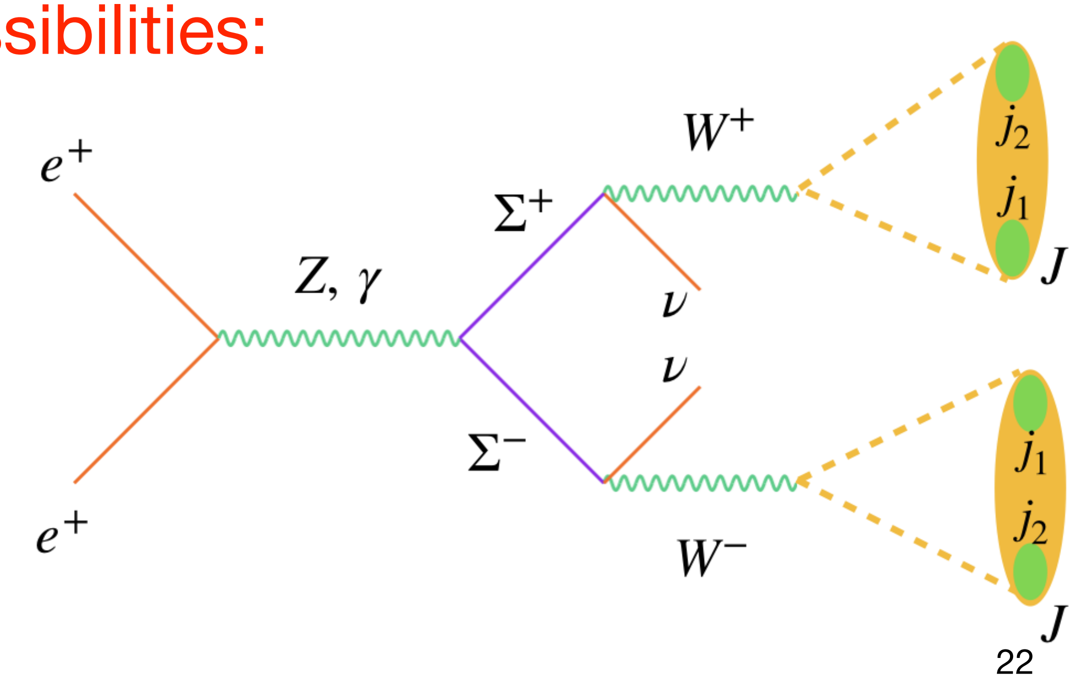


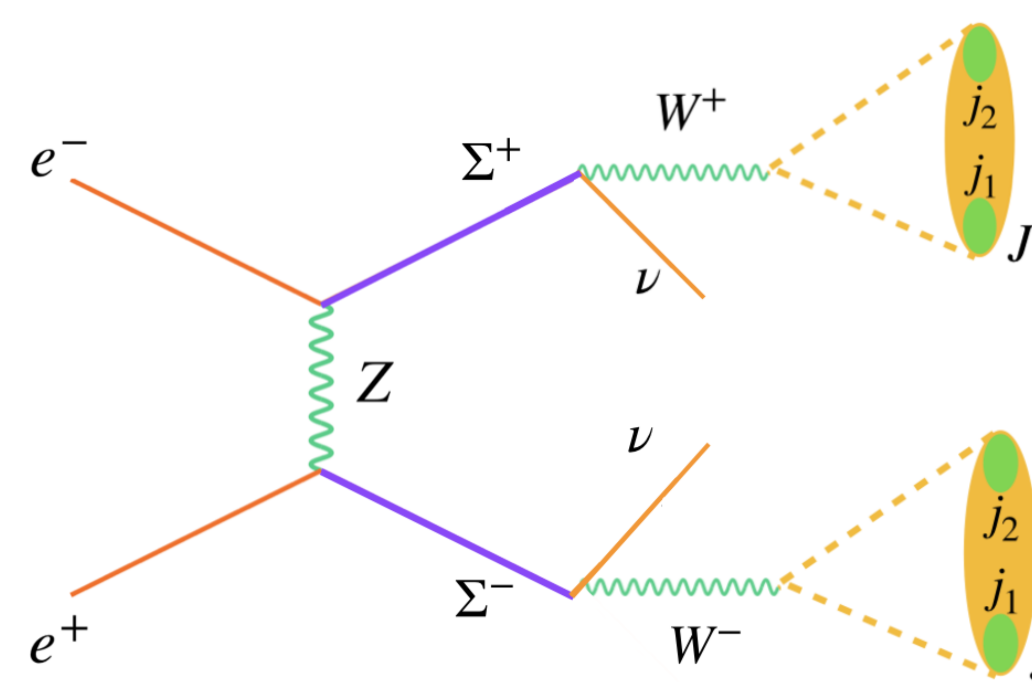


Final State: $e^\pm + J + j_1$

SM BKG: $e^- j + e^- jj + e^- jjj$

Other possibilities:

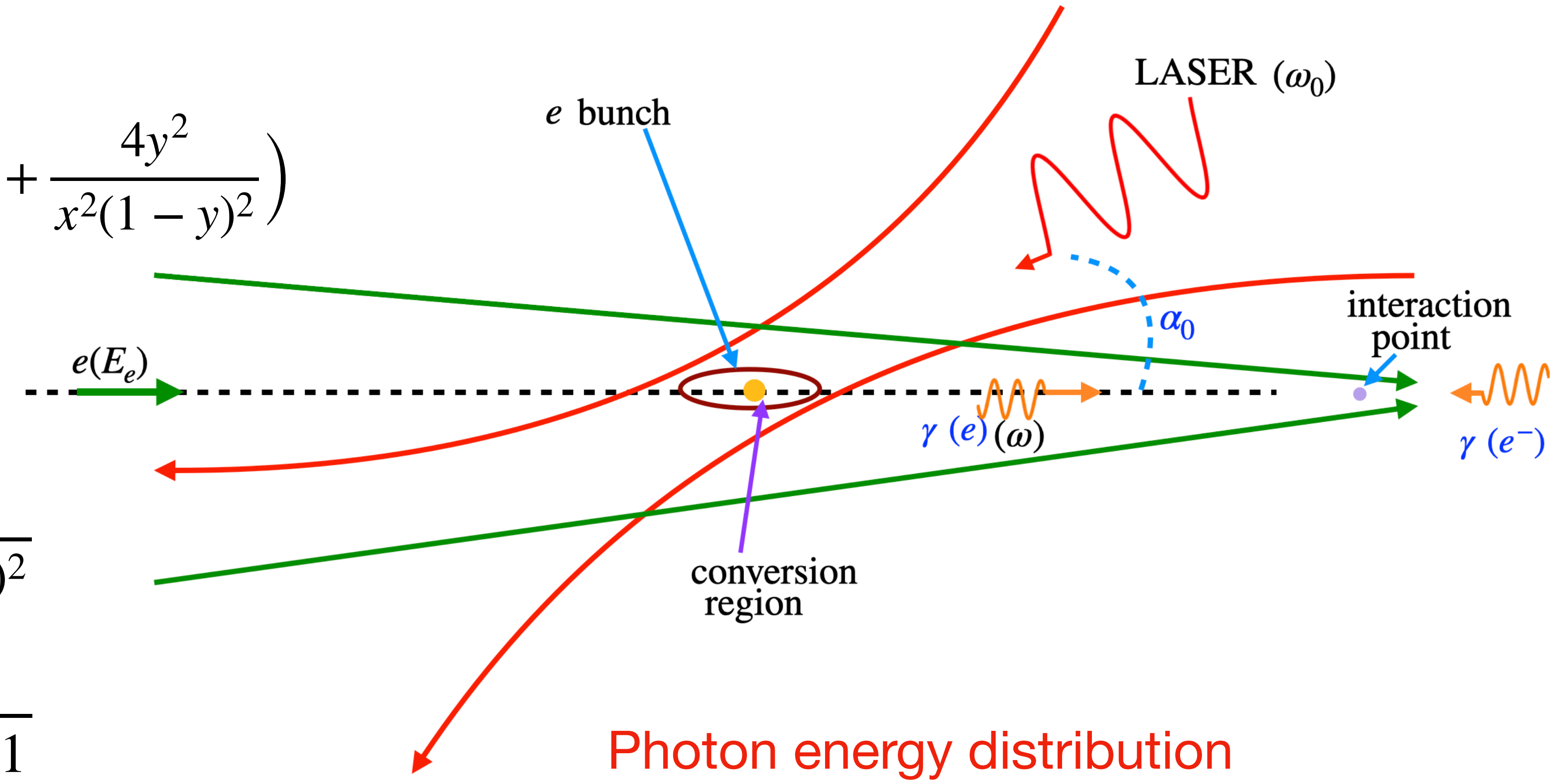




$e^-\gamma$ option at e^+e^- collider

Energy spectrum of the photon:

$$\frac{1}{N_\gamma}\frac{dN_\gamma}{dy} \equiv F_{\gamma/e}(x,y) = \frac{1}{D(x)}\left(\frac{1}{1-y}+1-y-\frac{4y}{x(1-y)}+\frac{4y^2}{x^2(1-y)^2}\right)$$



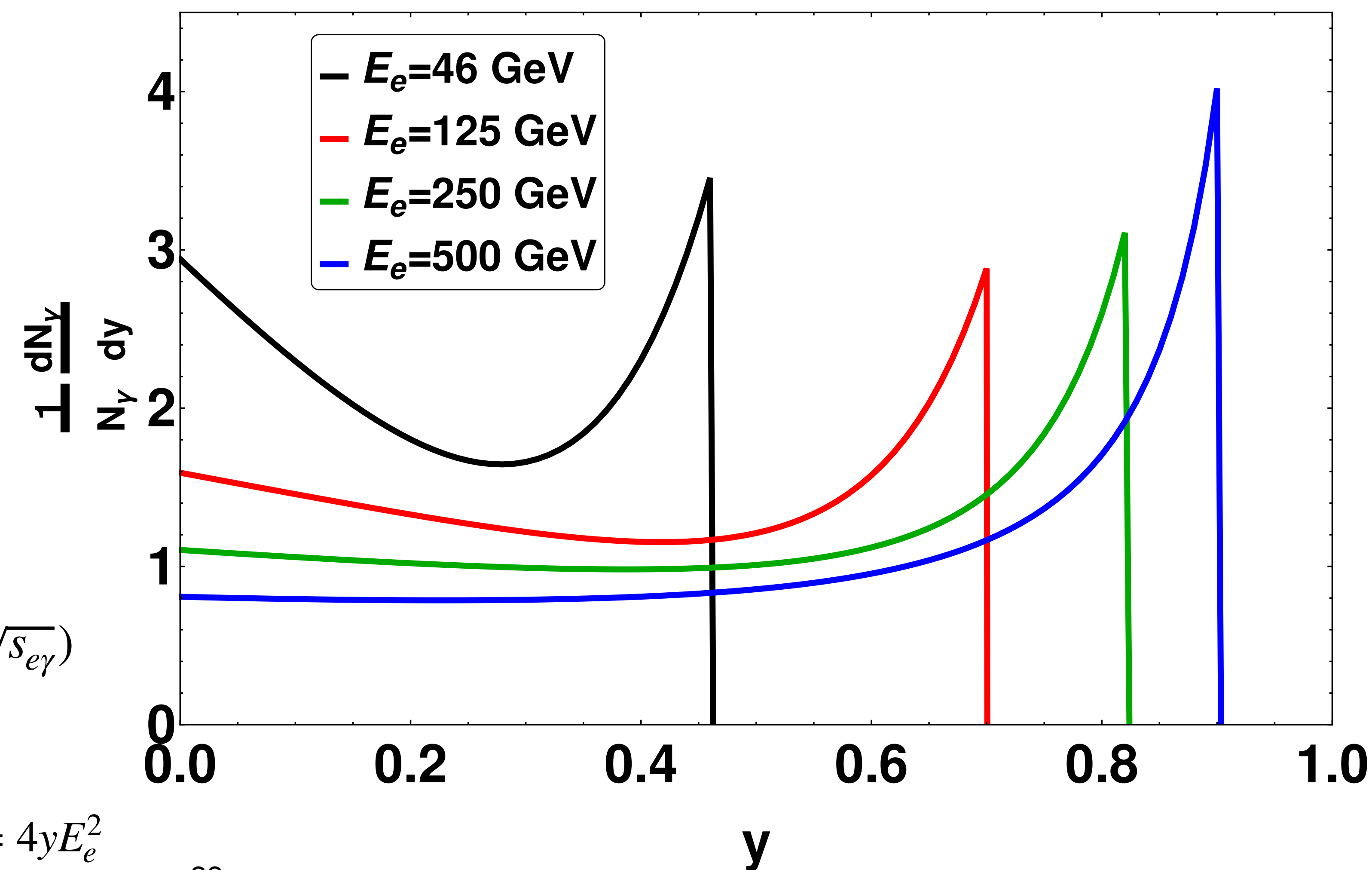
$$D(x) = \left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ln(1+x)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(1+x)^2}$$

$$x = \frac{4E_e\omega_0}{m_e^2}\cos^2\left(\frac{\alpha_0}{2}\right),\quad y = \frac{\omega}{E_e} \le y_m = \frac{\omega_m}{E_e} = \frac{x}{x+1}$$

ω_0 is the energy of the incident photon

α_0 is the collision angle and its small

Photon energy distribution

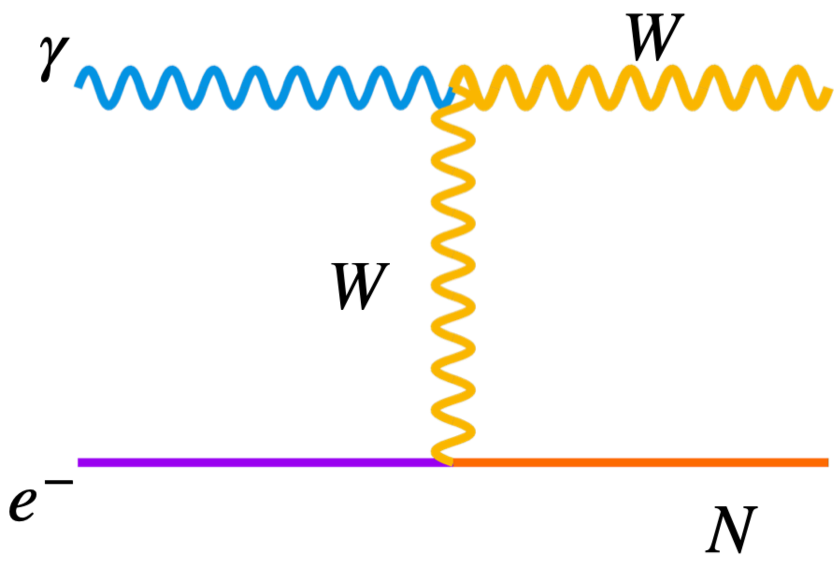


Cross section can be obtained being averaged over the photon spectrum:

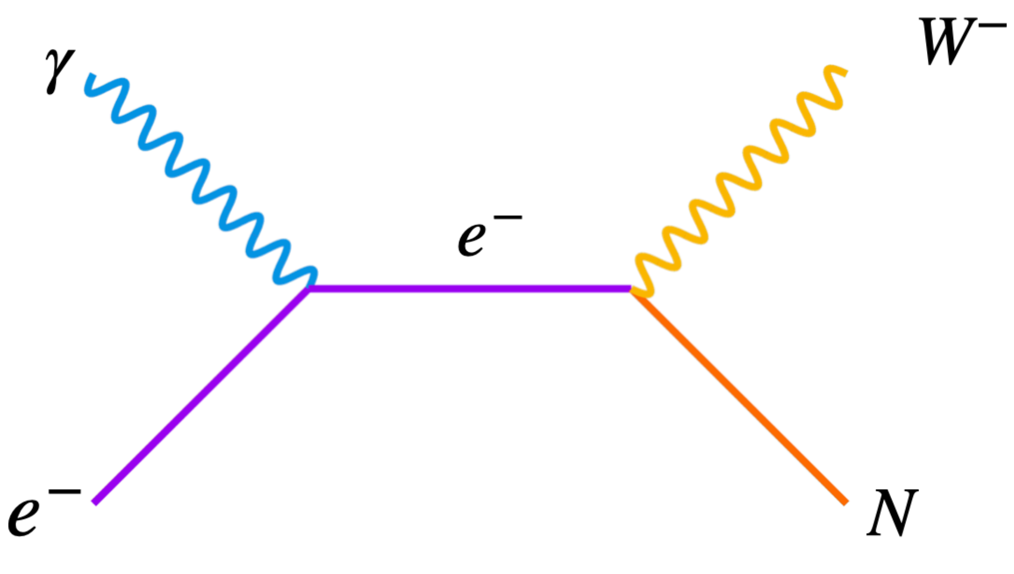
$$< \sigma_{\gamma e\to AB}(\sqrt{s_{ee}}) > = \int_{y_{\text{min}}}^{y_{\text{max}}} dy F_{\gamma/e}(x,y)\sigma_{\gamma e\to AB}(\sqrt{s_{e\gamma}})$$

$$s_{ee} = 4E_e^2, y_{\text{max}} = \frac{x}{1+x}, y_{\text{min}} = \frac{(M_A+M_B)^2}{s_{ee}},\ s_{e\gamma} = 4yE_e^2$$

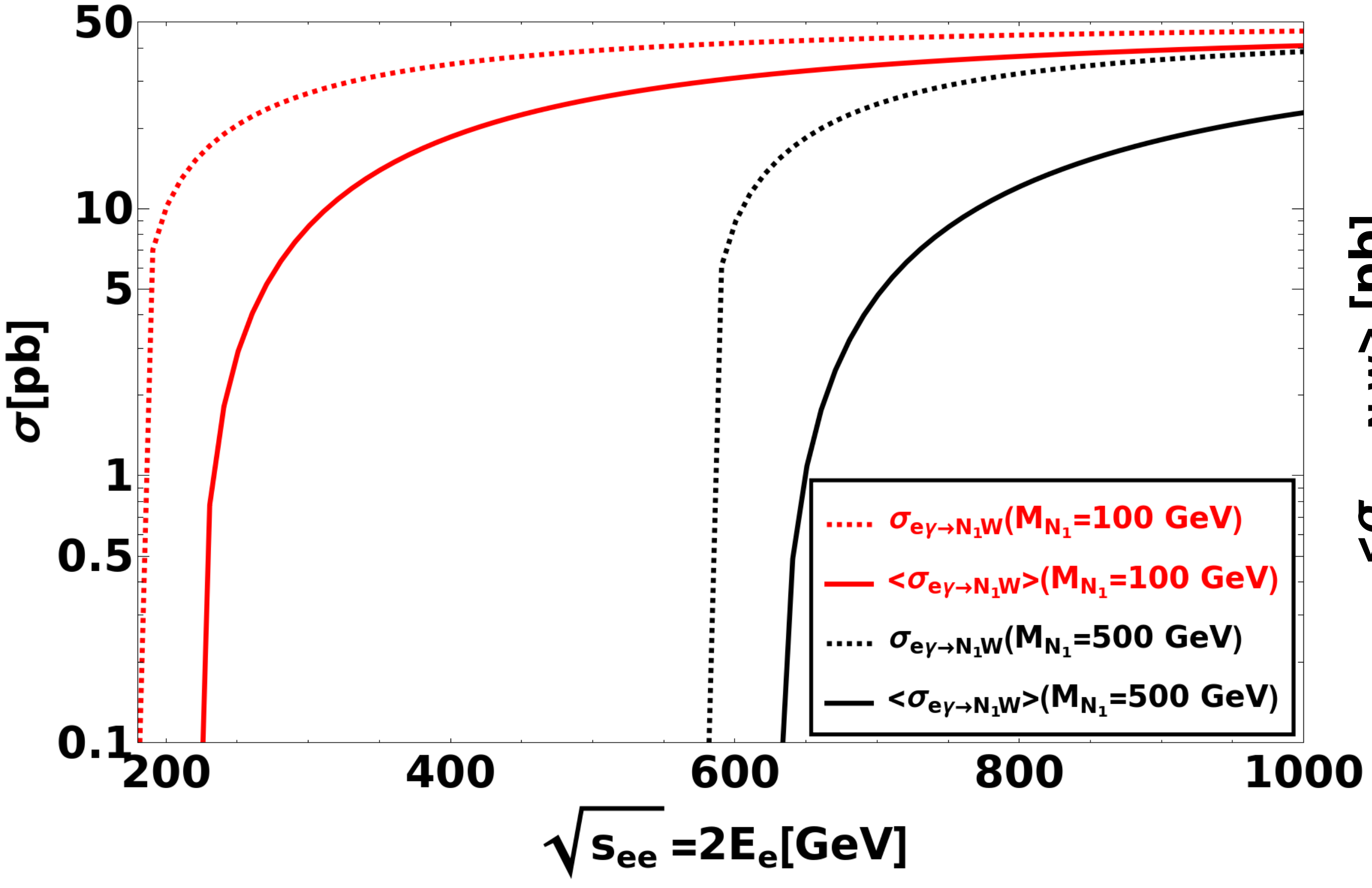
Heavy neutrino production at $e^-\gamma$ collider

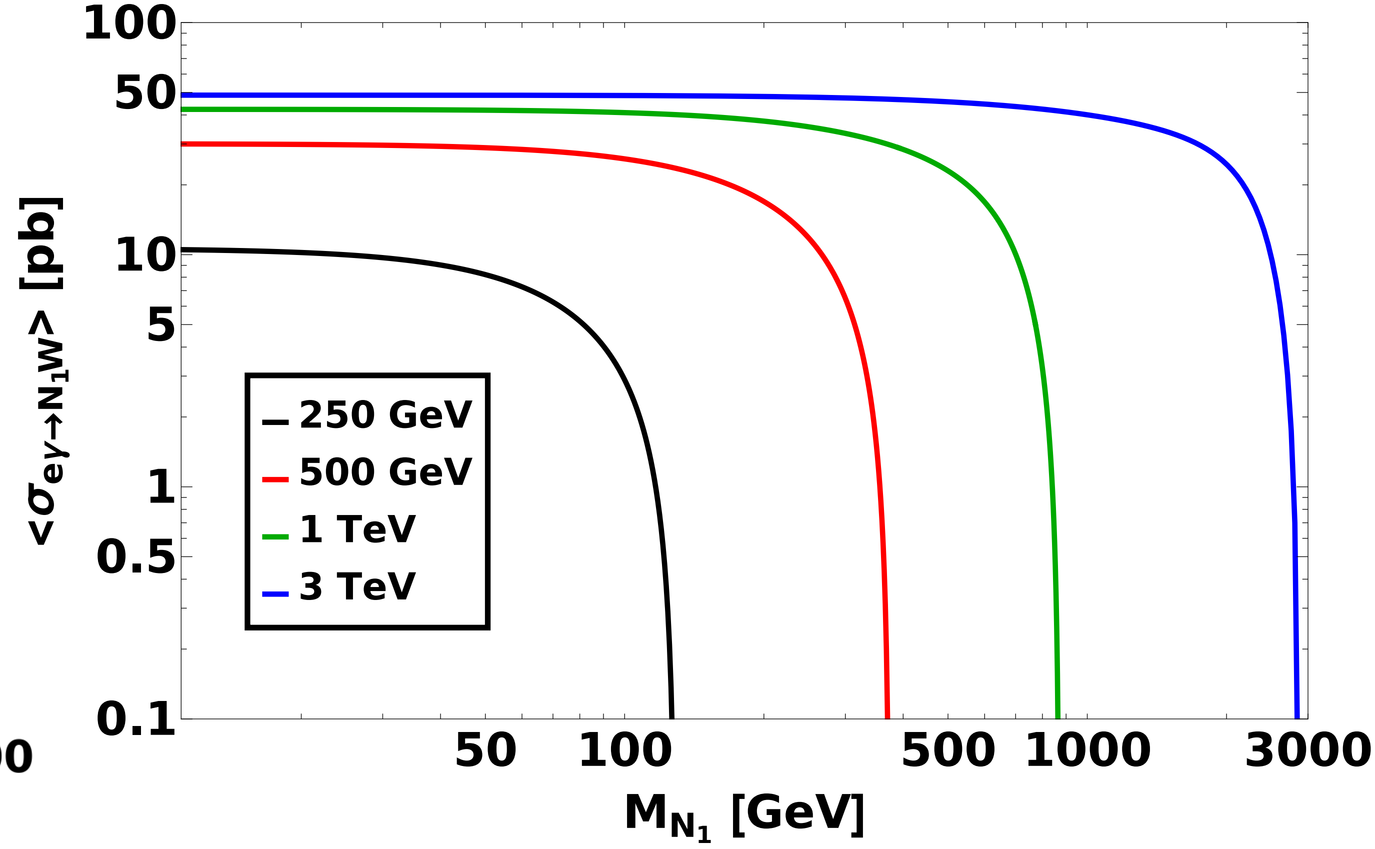


(a)

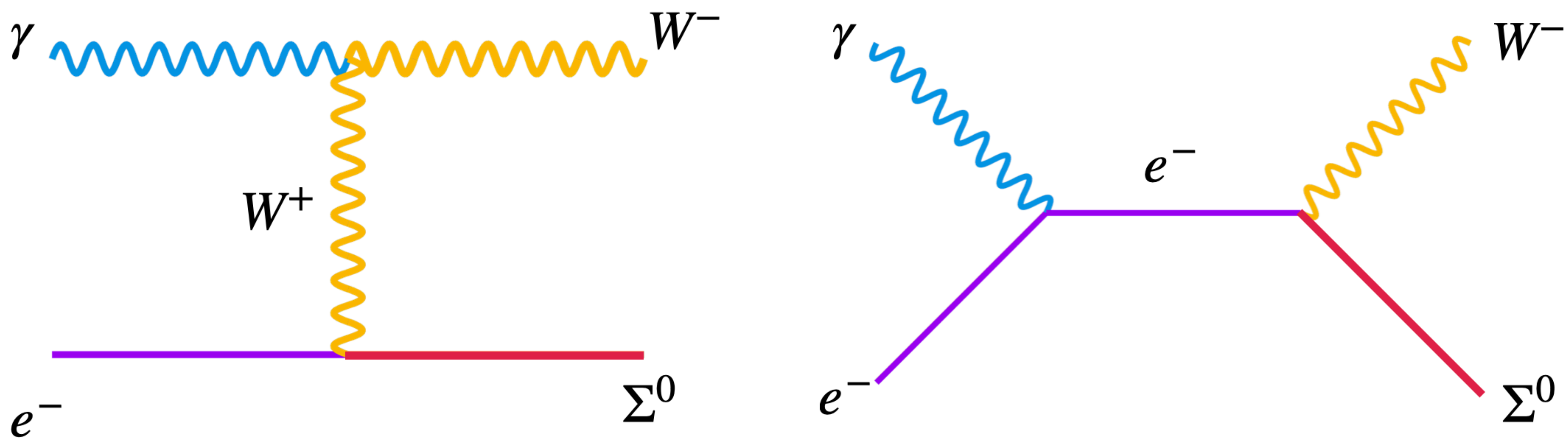


(b)

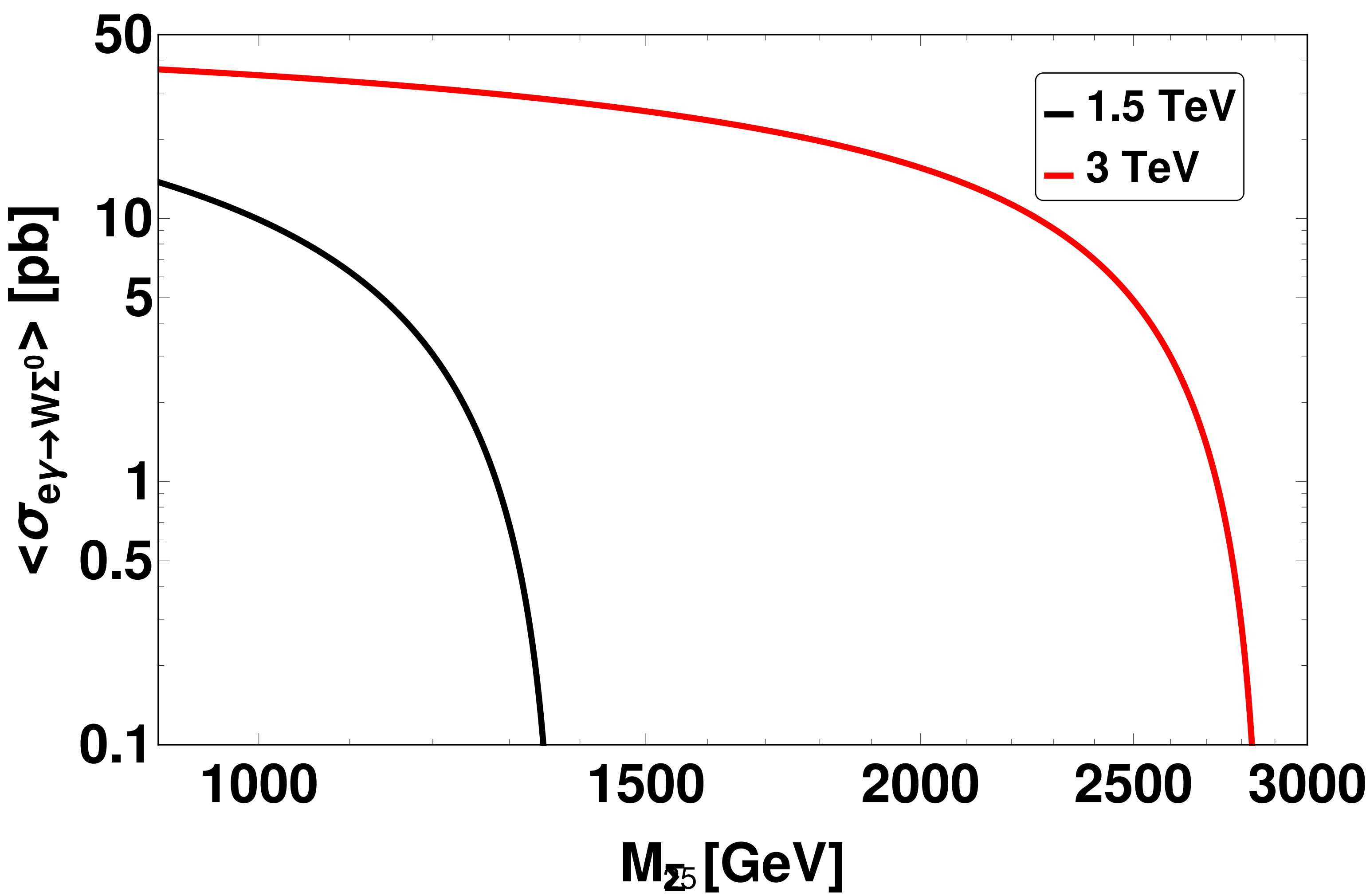




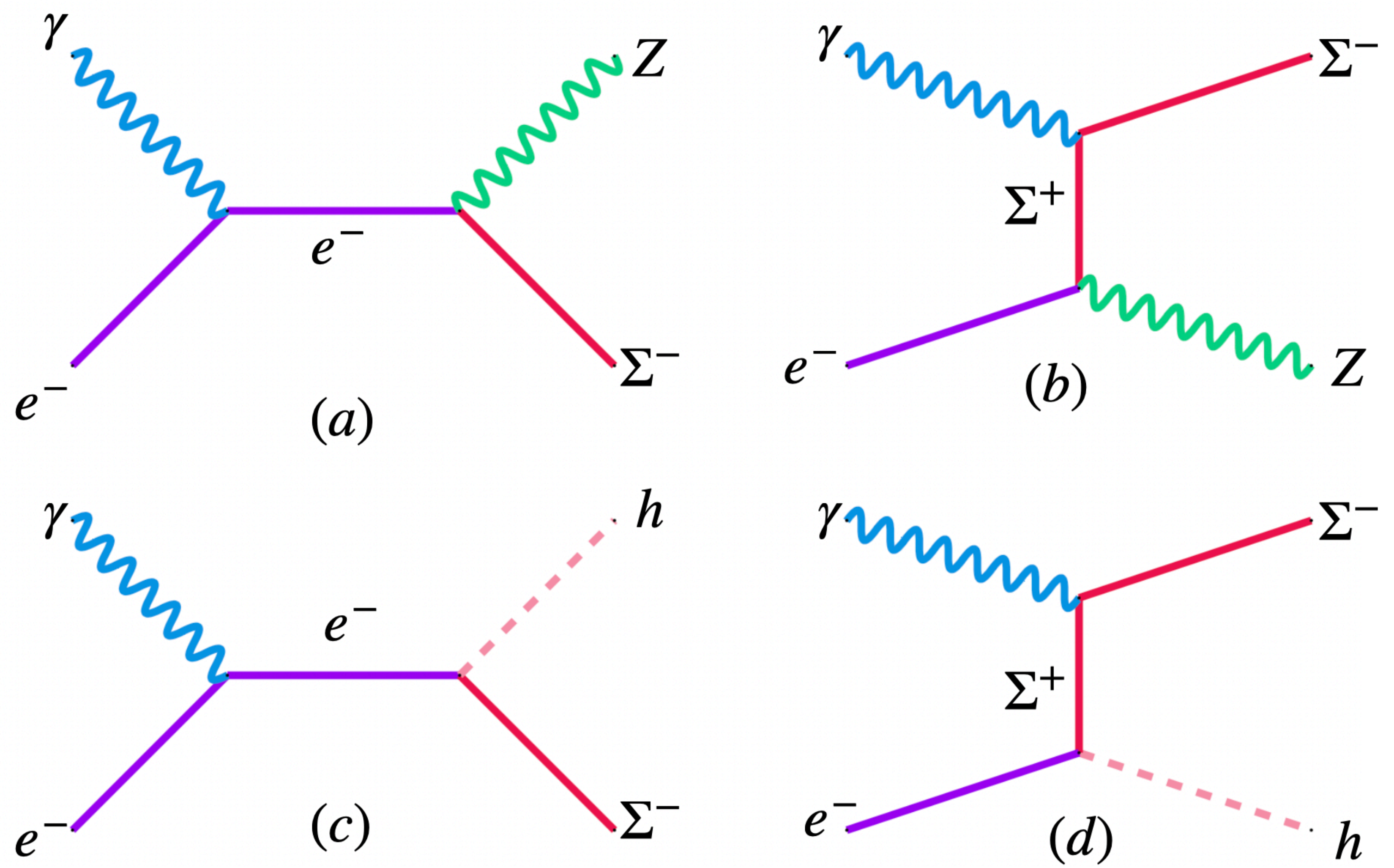
Heavy triplet fermion production at $e^-\gamma$ collider

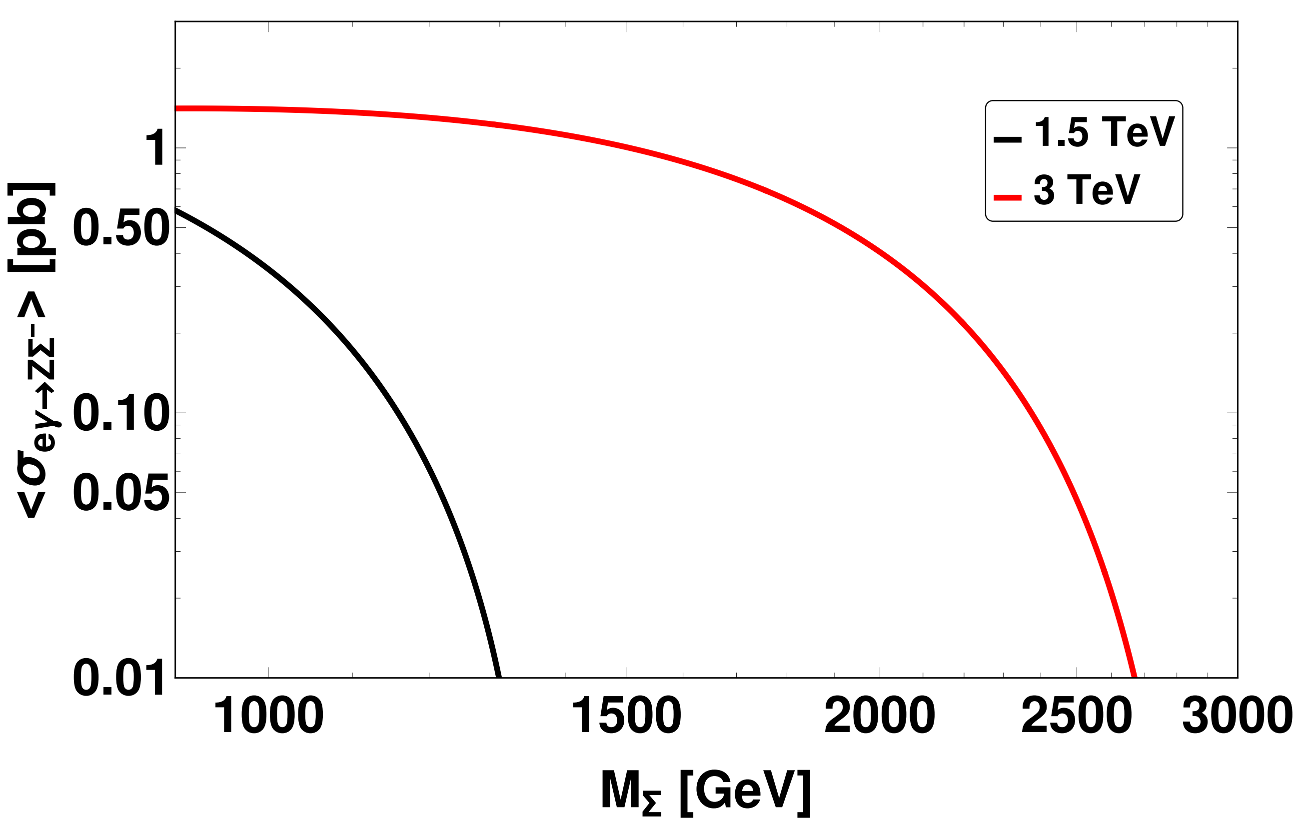


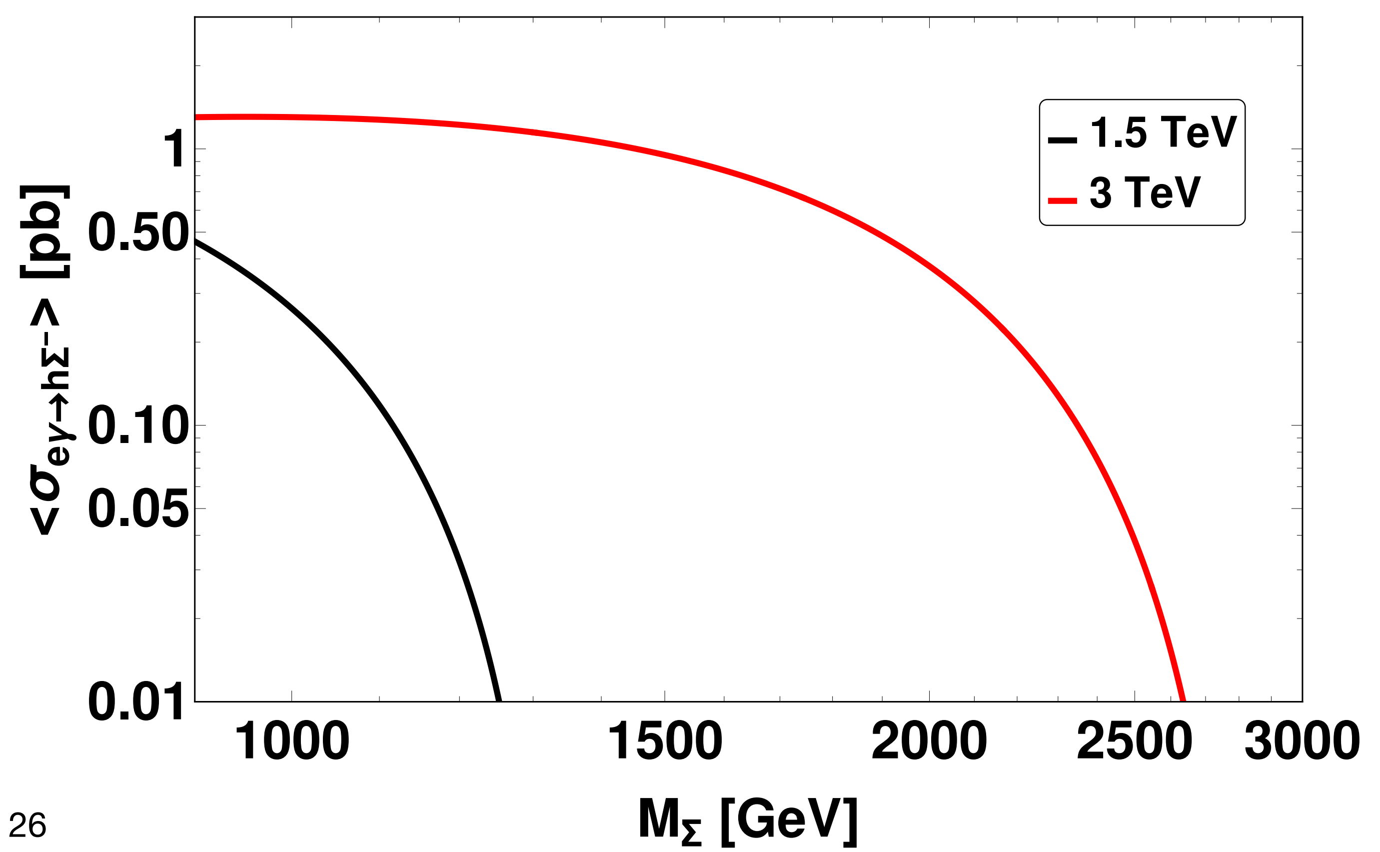
(a) (b)



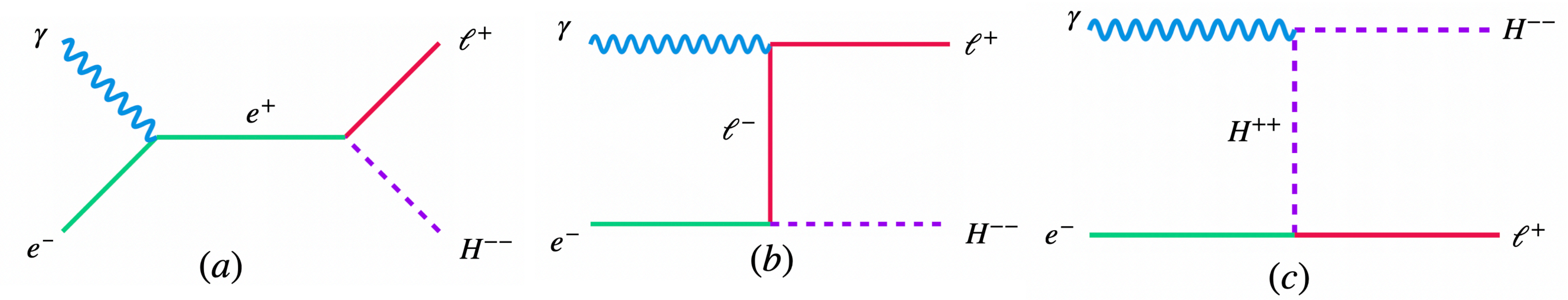
Charged triplet fermion production at $e^{-}\gamma$ collider

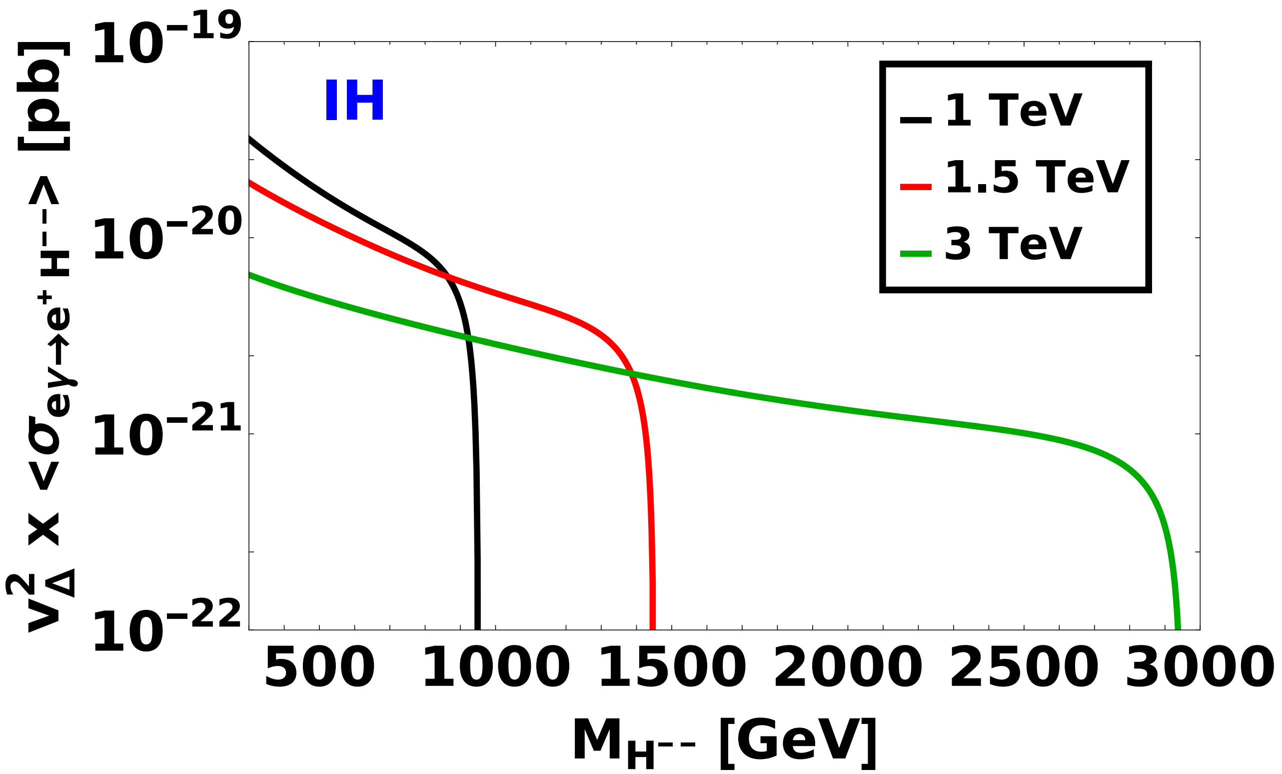




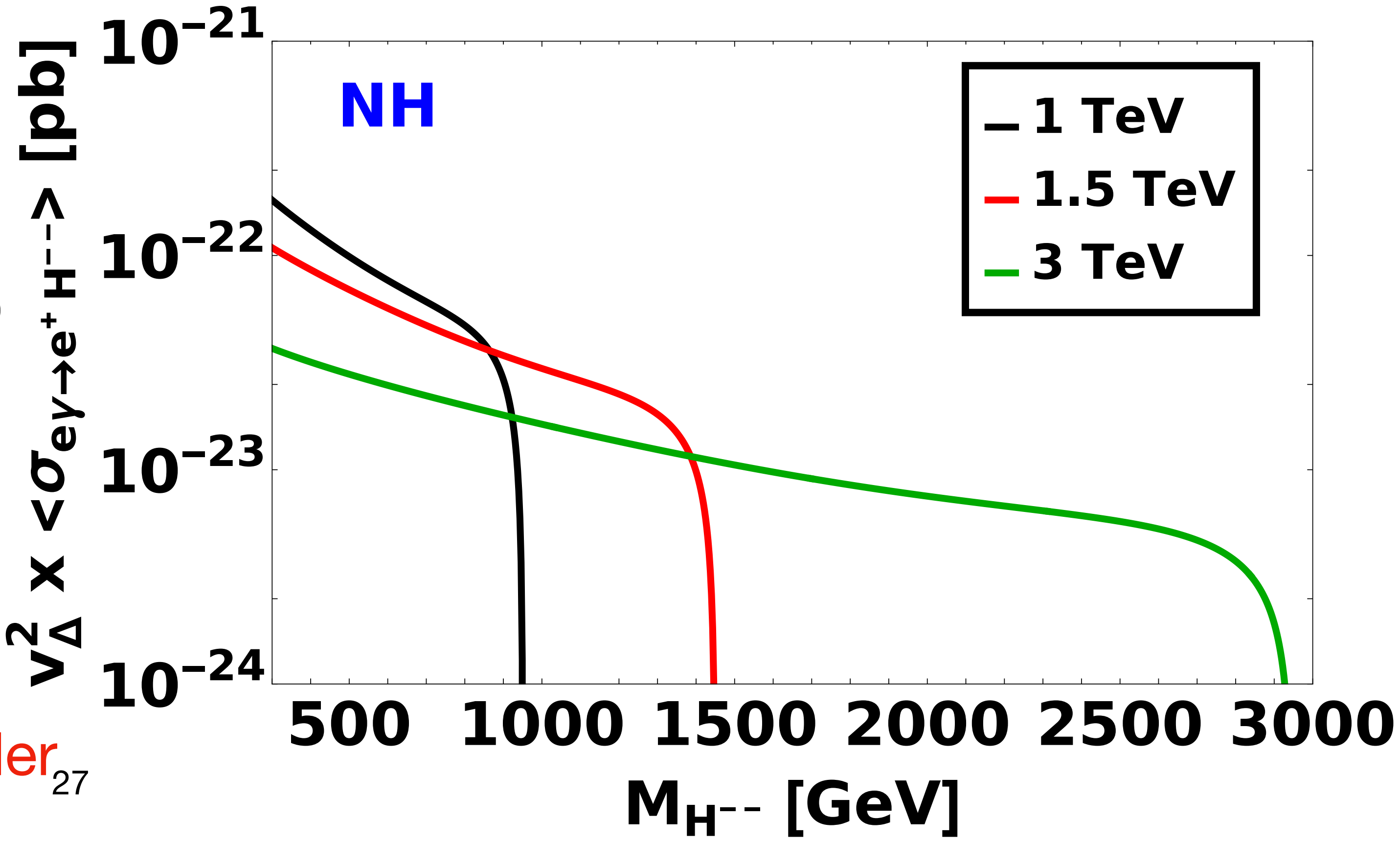


Triplet scalar production at $e^-\gamma$ collider



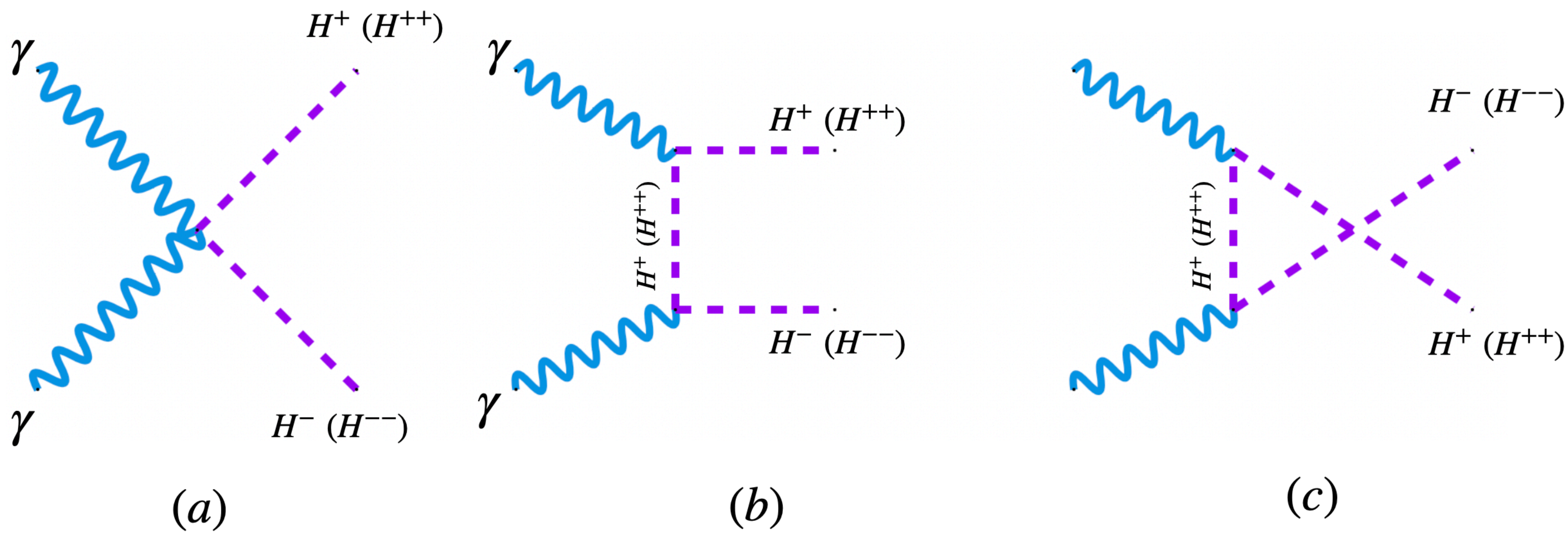


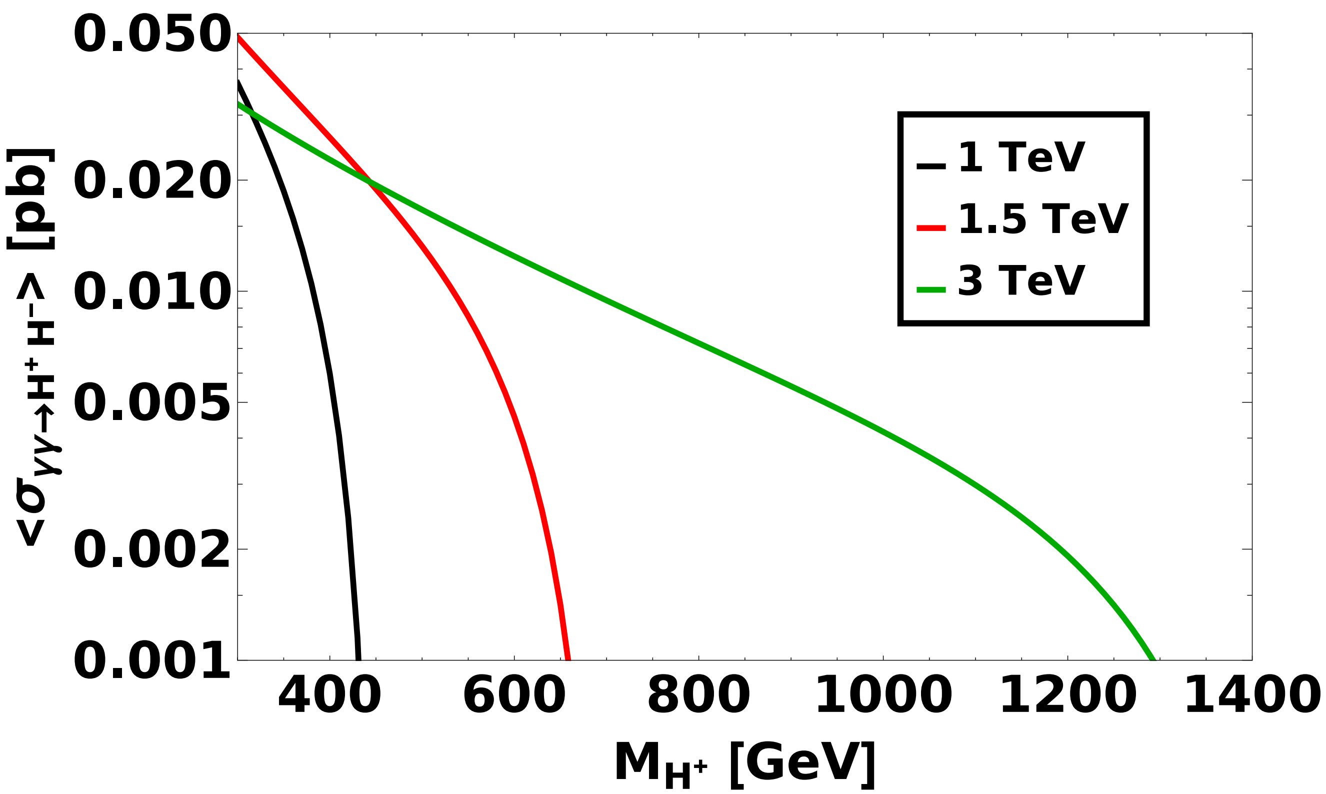
Not relevant

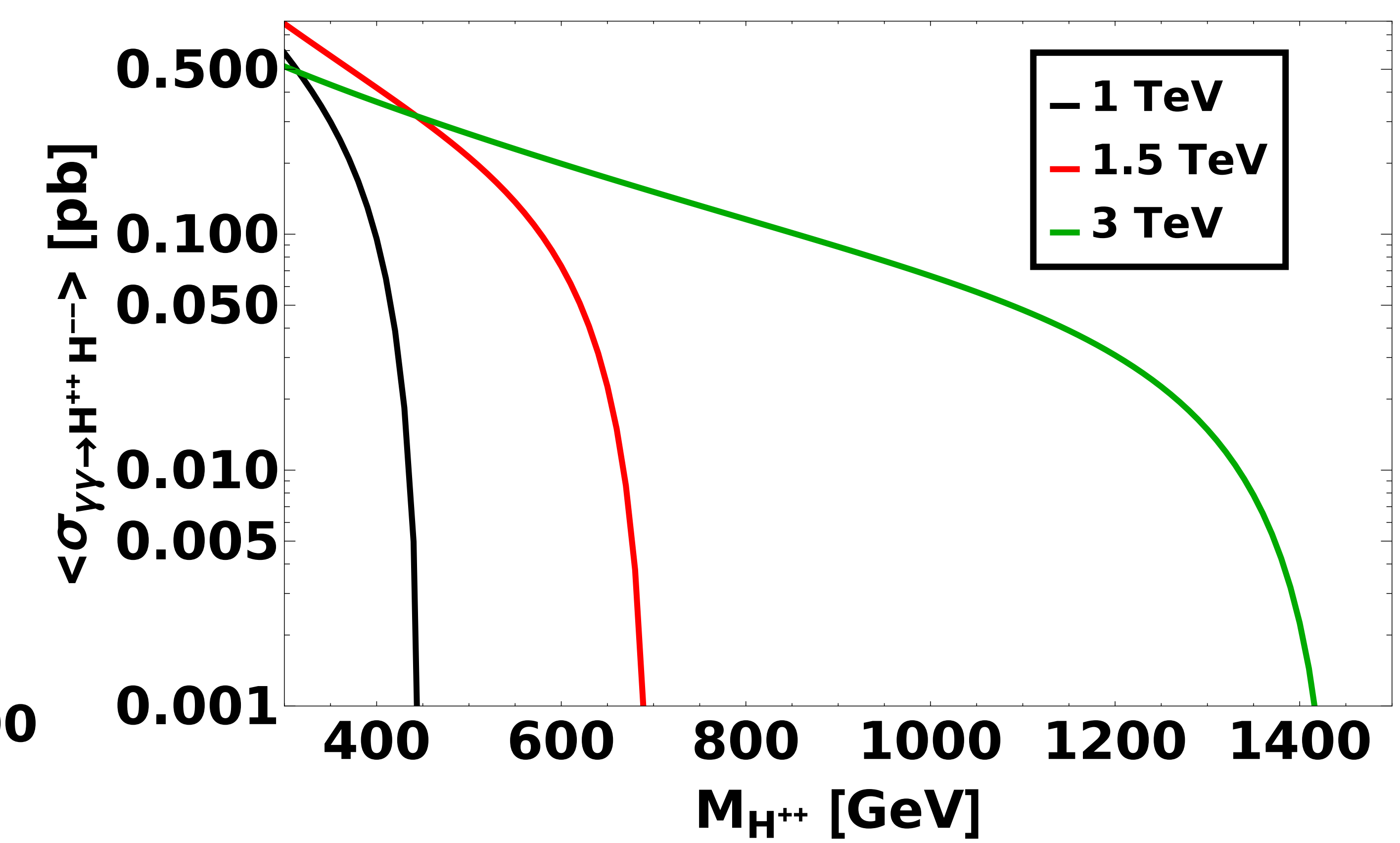


Not many interesting possibilities at $e^-\gamma$ collider

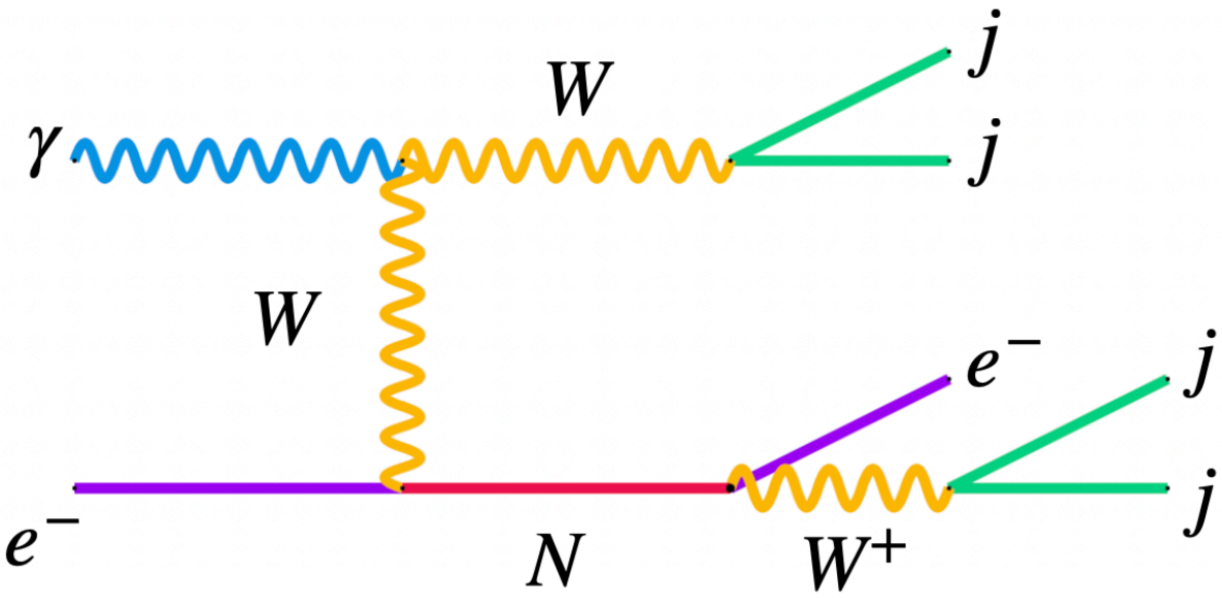
Triplet scalar production at $\gamma\gamma$ collider

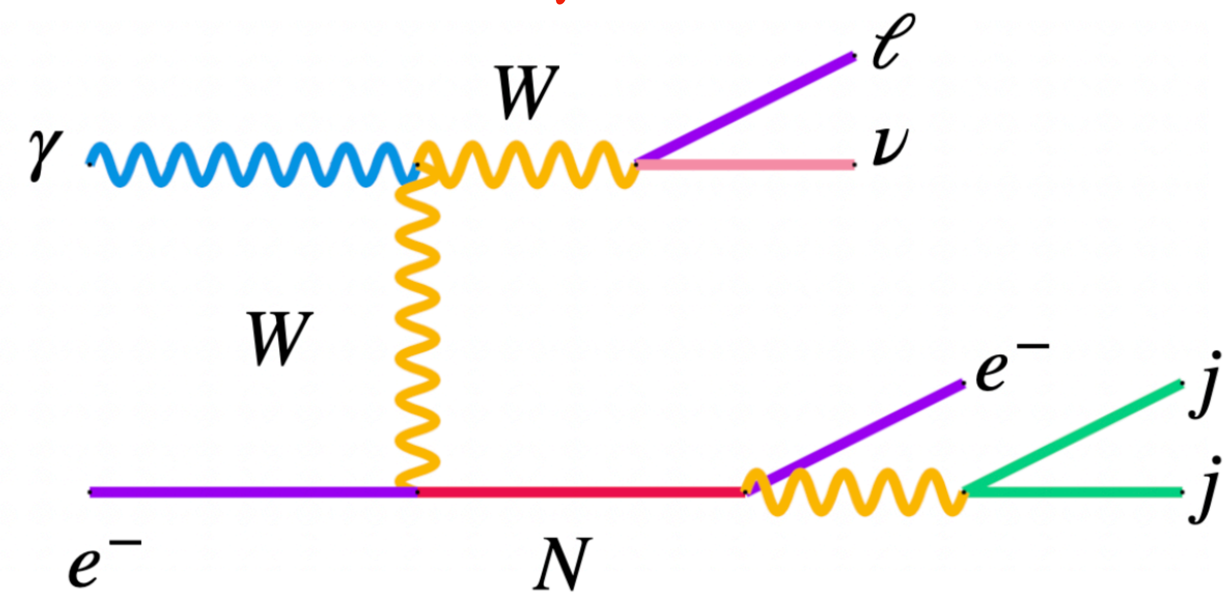






Collider signatures of Type-I seesaw at $e^-\gamma$ collider



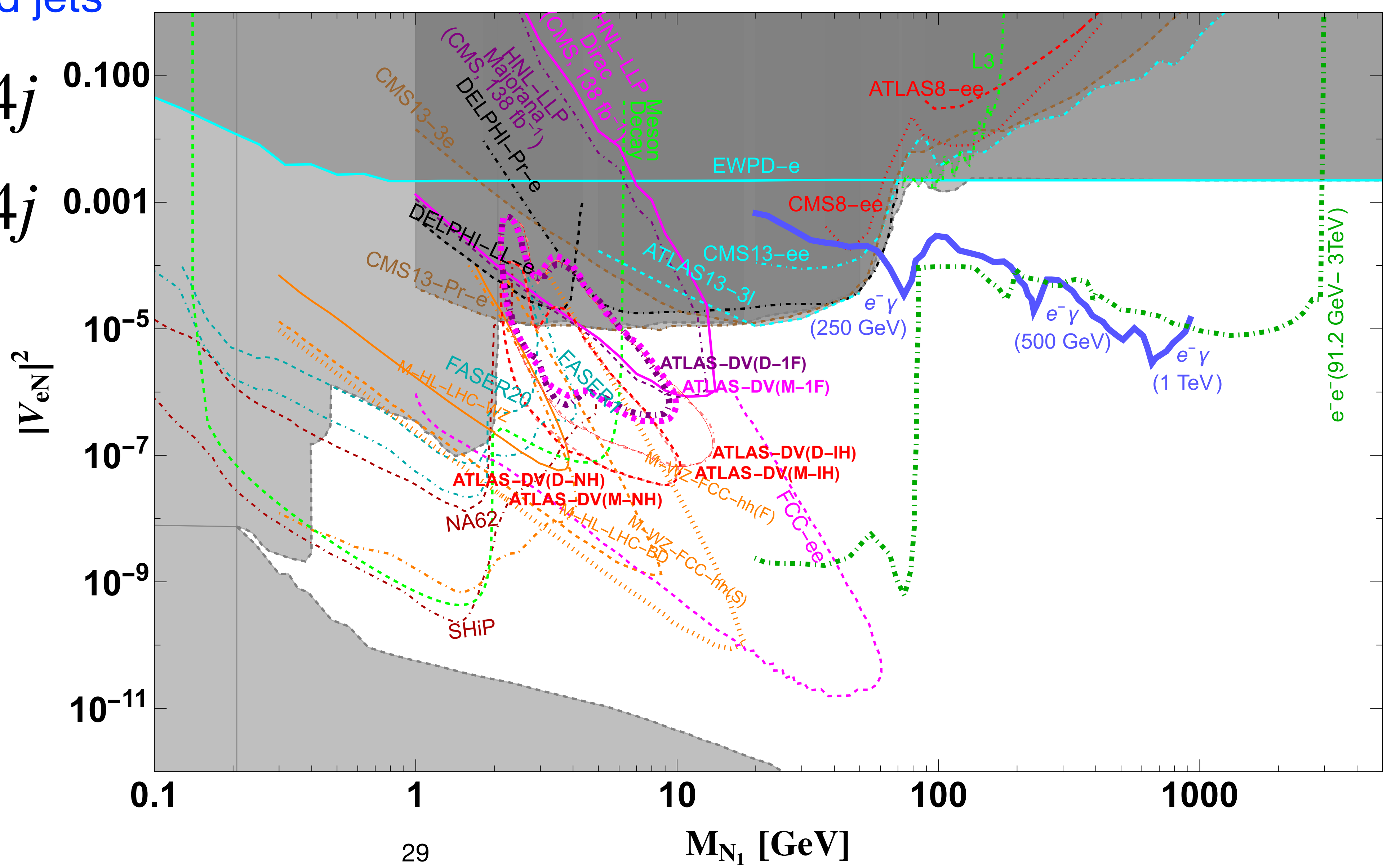


M_N is not too heavy: isolated jets

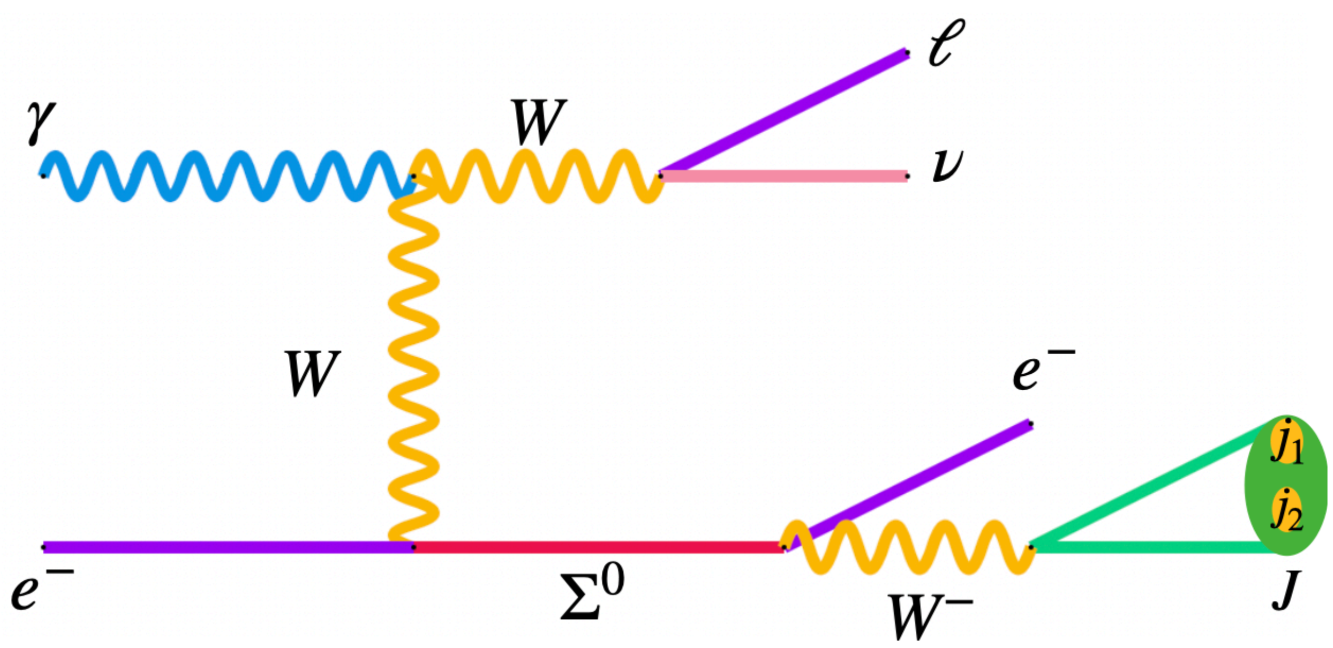
LNV Final State: $e^+ + 4j$

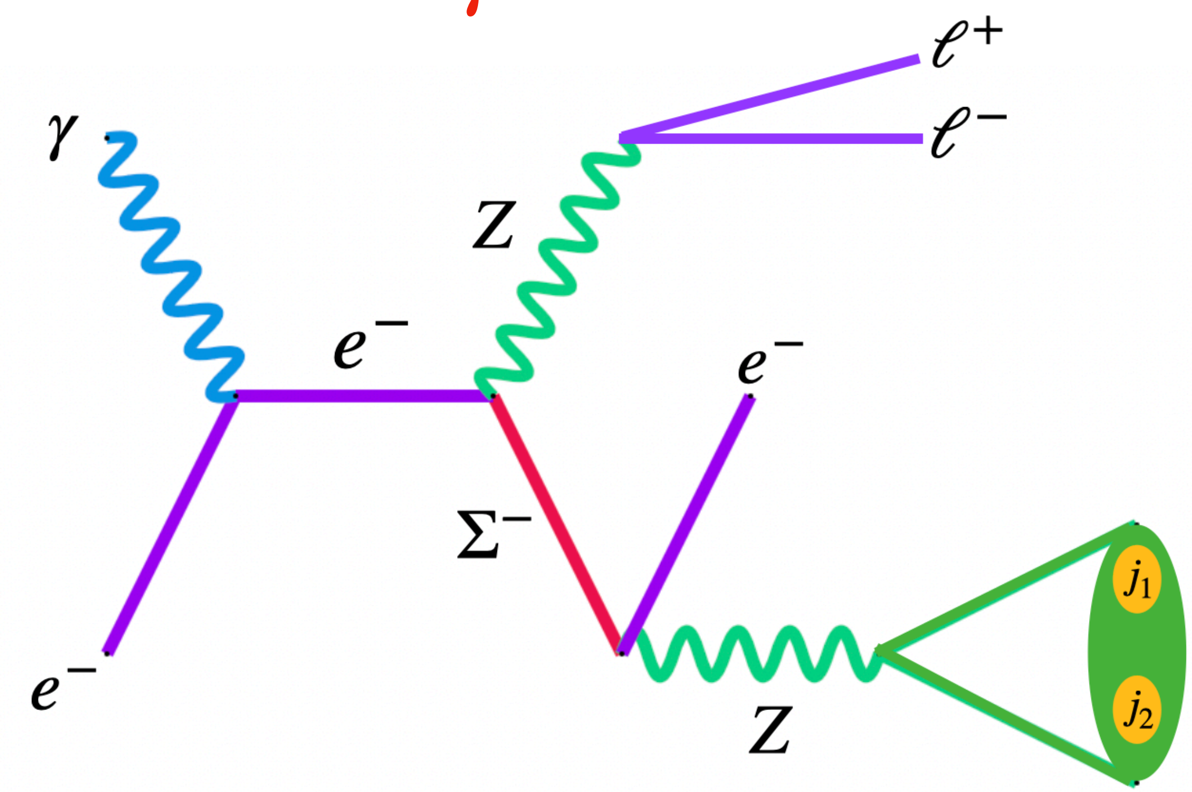
LNC Final State: $e^- + 4j$

SSDL: $e^-\ell^- jj\nu$



Collider signatures of Type-III seesaw at $e^-\gamma$ collider

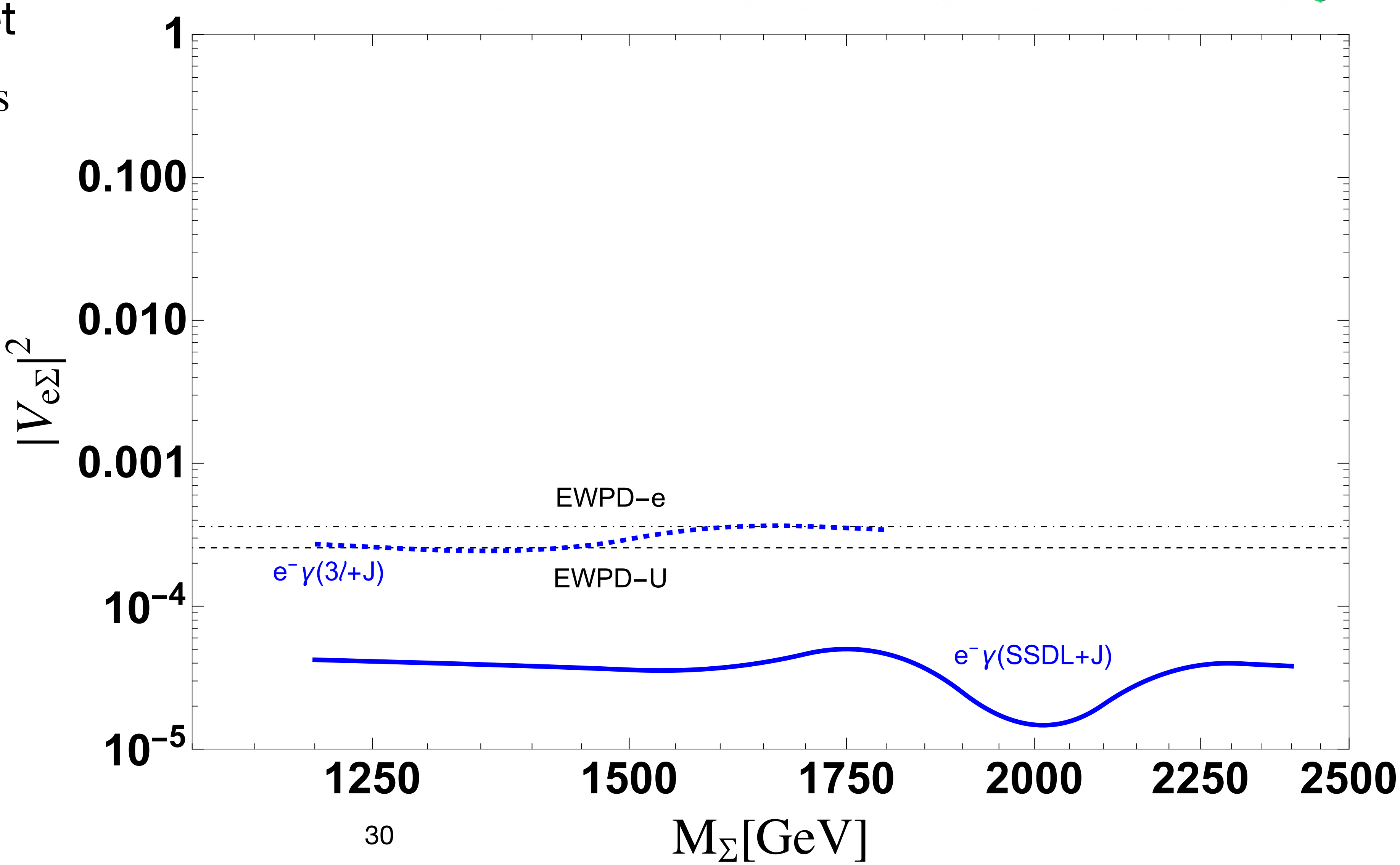




Triplet fermion is heavy: Fatjet

Final State: $e^{\pm}\ell^- J + p_T^{\rm miss}$

and $e^-\ell^-\ell^+ J$



Collider signatures of Type-II seesaw at $\gamma\gamma$ collider

$$\gamma\gamma \to H^{\pm\pm}H^{\mp\mp} \to \ell_i^{\pm}\ell_j^{\pm}\ell_k^{\mp}\ell_m^{\mp}$$

Three type of final states:

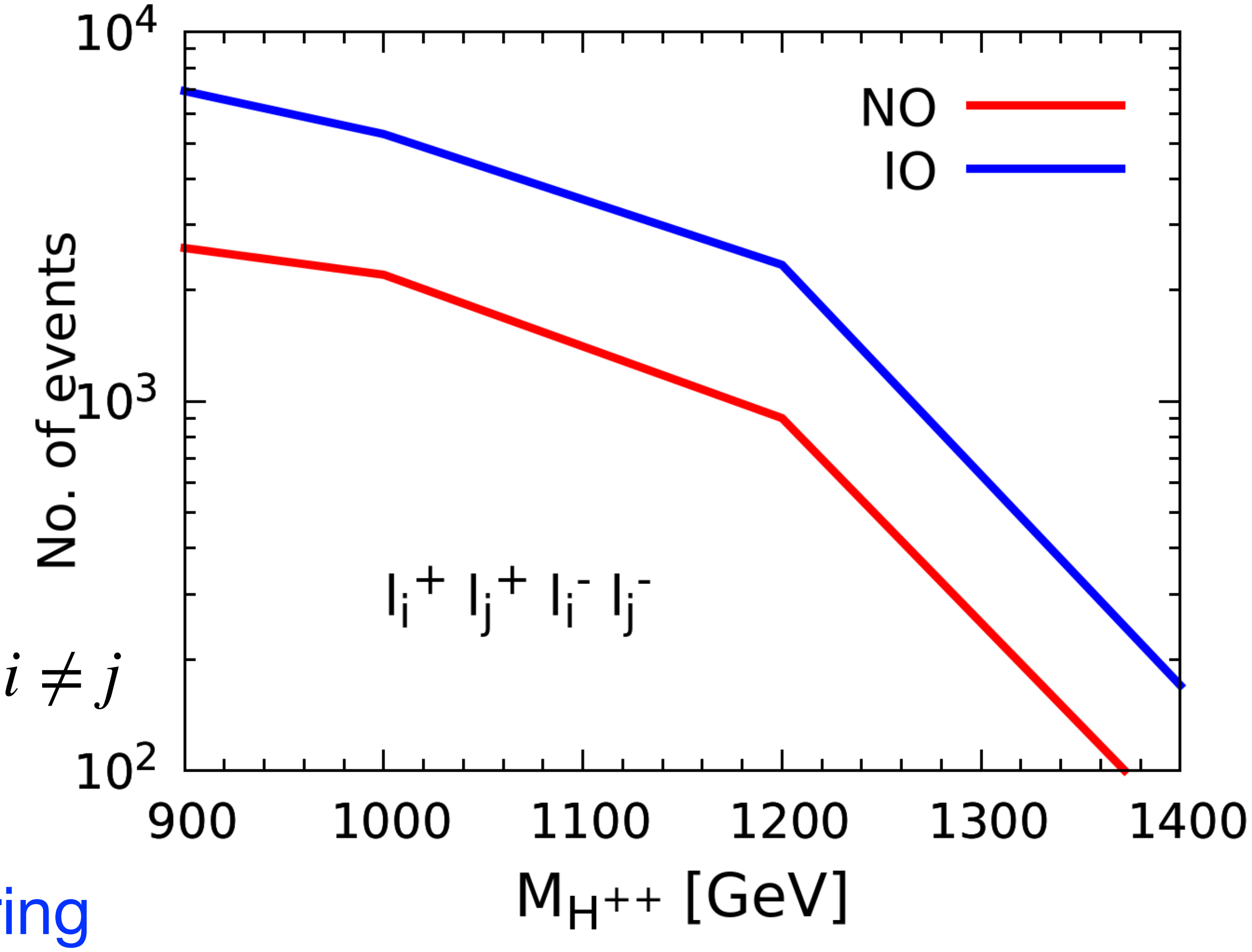
LFC: $\ell_i^+\ell_j^+\ell_i^-\ell_j^-$

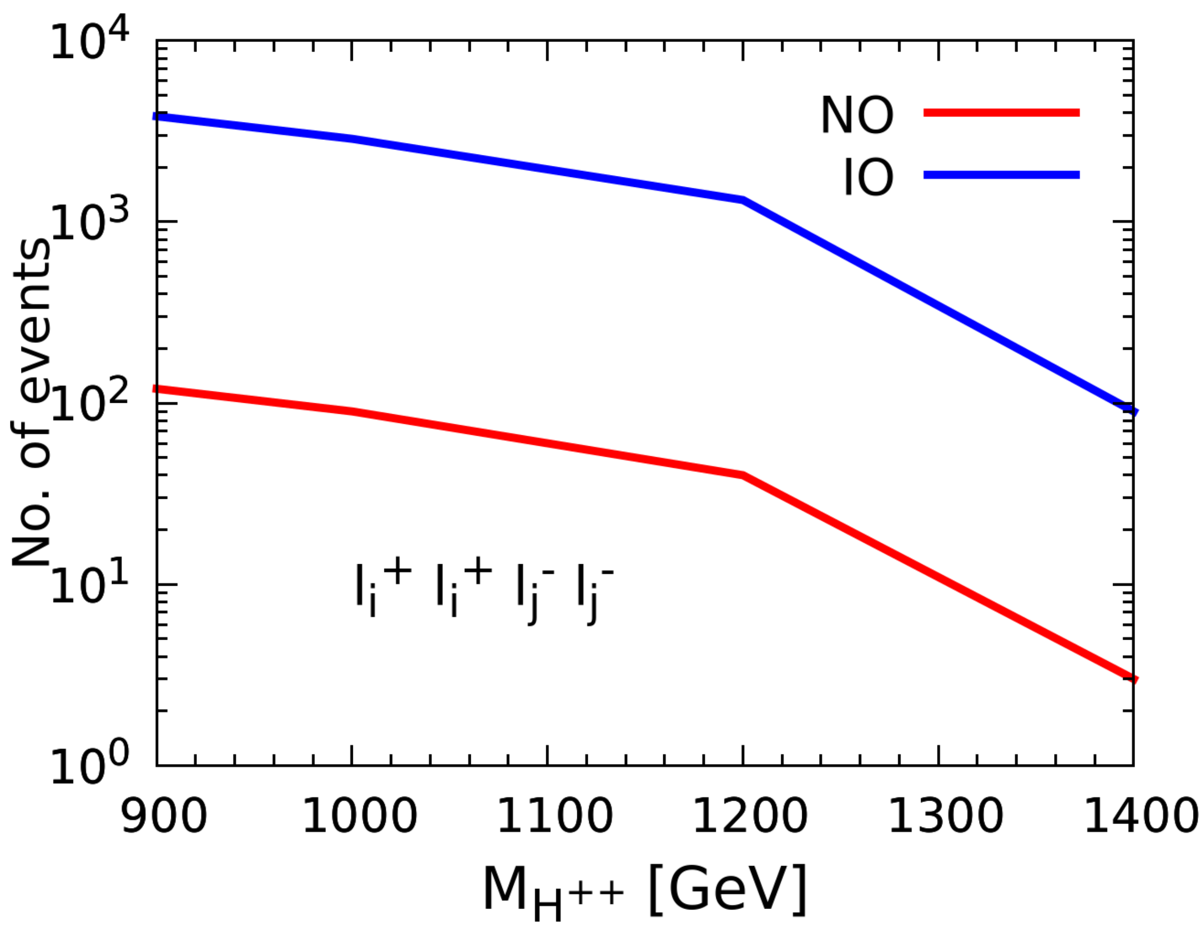
LFC$(\Delta F = 2)$: $\ell_i^+\ell_i^+\ell_j^-\ell_j^-$, where $i \neq j$

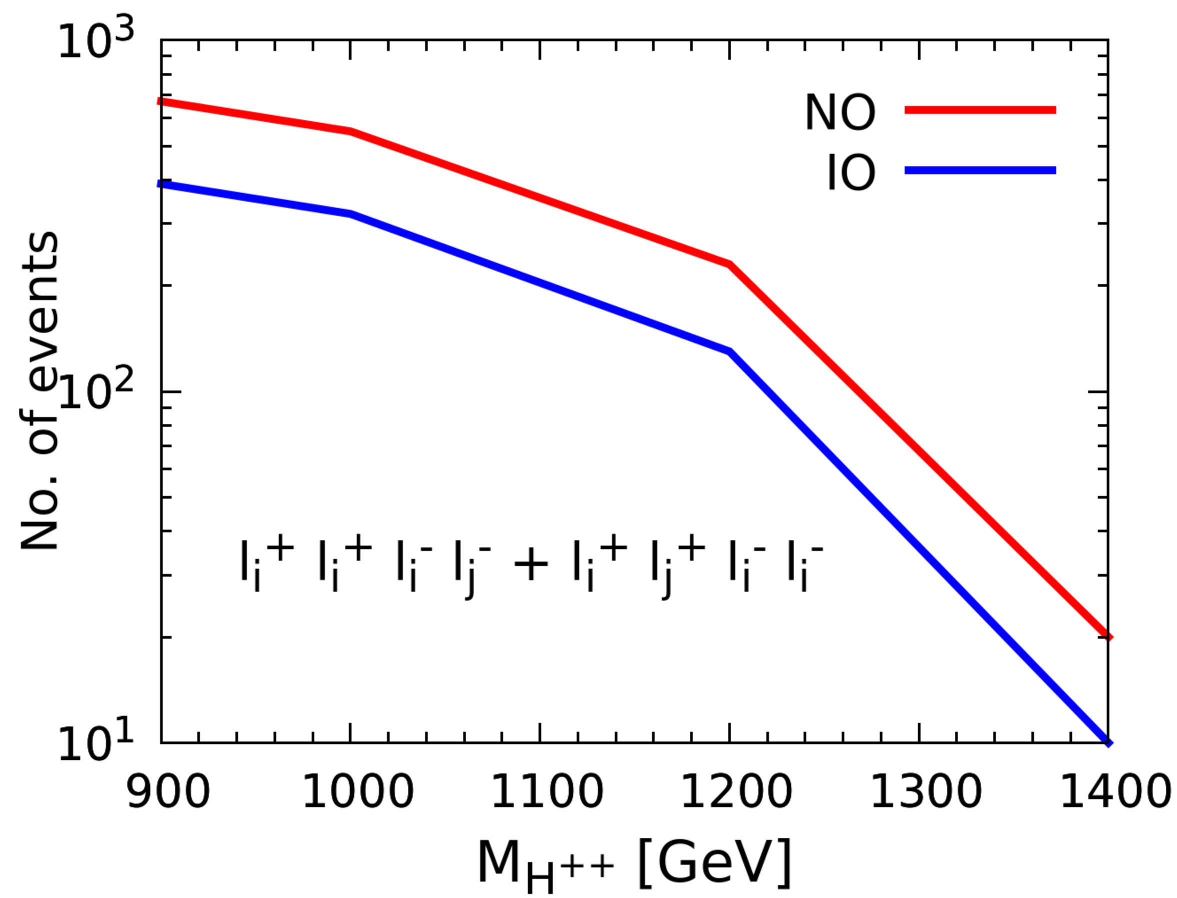
LFC$(\Delta F = 1)$: $\ell_i^+\ell_i^+\ell_i^-\ell_j^- + \ell_i^+\ell_j^+\ell_i^-\ell_i^-$, where $i \neq j$

Atleast with vanishing Majorana Phase

it is possible to probe ordering







Conclusions

Seesaw models are the most economical models to produce naturally small neutrino mass

TeV scale seesaw model is testable at colliders . At ongoing and future colliders one can easily produce them through the light-heavy neutrino mixing or can be produced through Drell-yan production

$e^-\gamma$ and $\gamma\gamma$ Collider are also very useful to probe seesaw models. For example one can hope to probe the neutrino mass ordering for type II seesaw at $\gamma\gamma$ collider

For high RH neutrino mass, fat jet technique can significantly reduce the SM background, hence effective to probe high neutrino mass.

Thank You………