Seesaw Searches at a Lepton Collider

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Neutrino Mass Models at Collider?

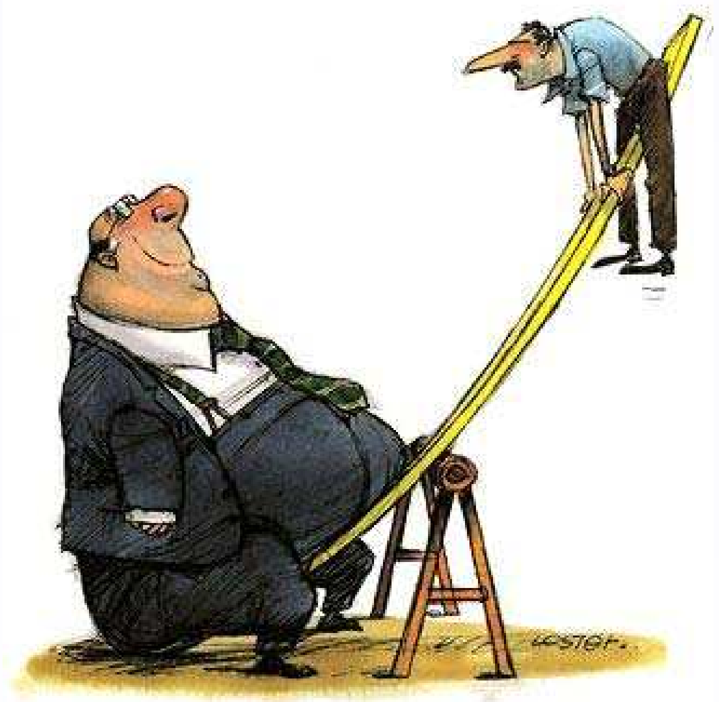
↓

Heavy Neutrino, Higgs triplet

Seesaw:

From neutrino oscillation and bound from cosmology

eV mass of Neutrinos



Seesaw

Minkowski, 1977;Gell-mann, Raymond, Slansky 1977

Yanagida, 1979; Mohapatra, Senjanovic, 1980

Lepton Number Violating →

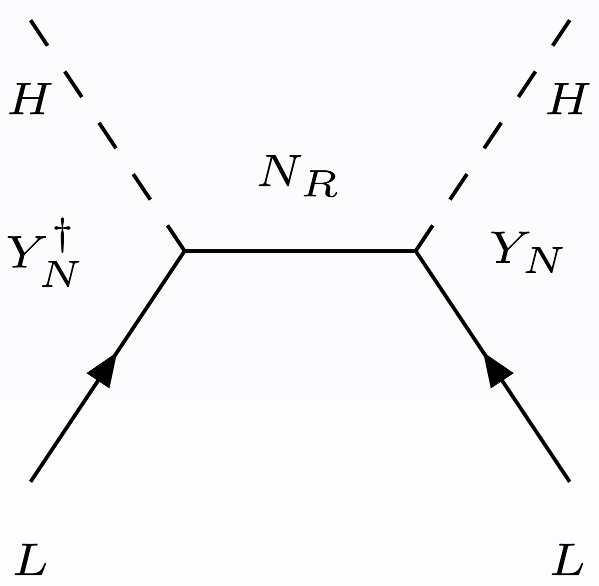
$$\hat{O} = \frac{LLHH}{\Lambda}$$

Different UV completed models

Contd:

Type-I

SM gauge singlet



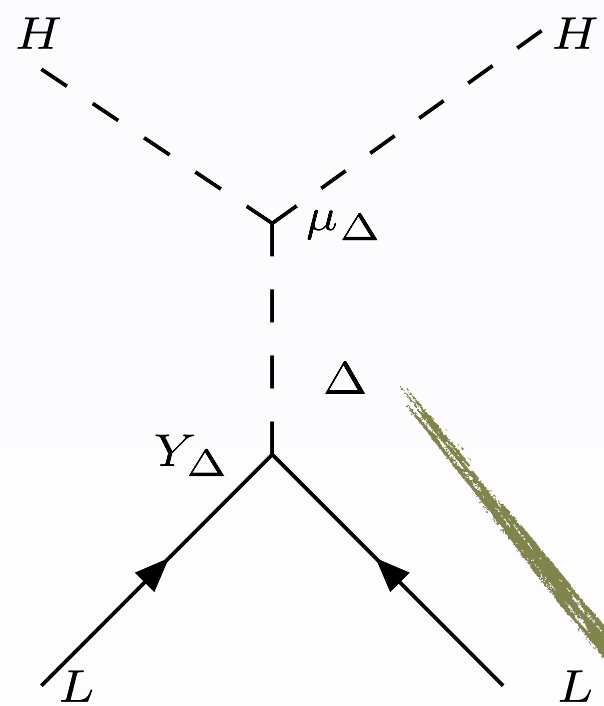
interaction of N with other SM particles is proportional to the active-sterile mixing

V_{lN} → $\frac{m_D}{M}$

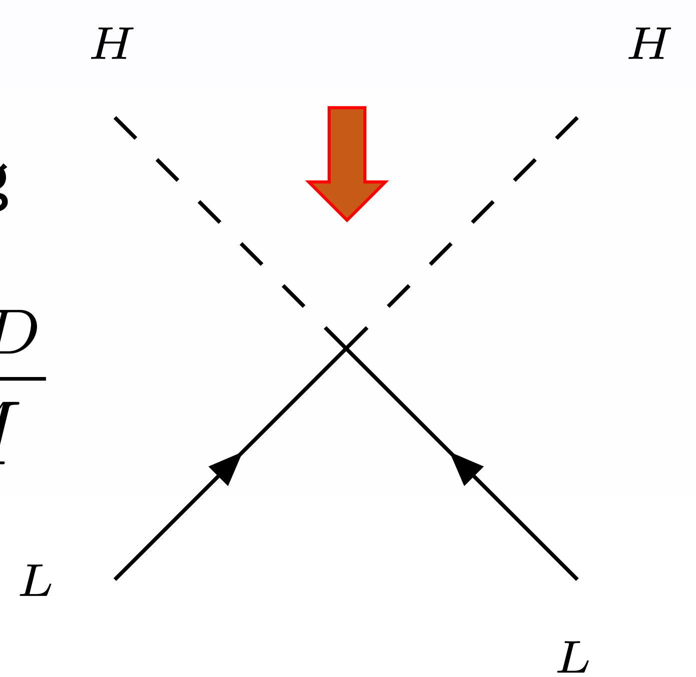
Suppressed

Type-II

$SU(2)$ Triplet, $Y = 2$



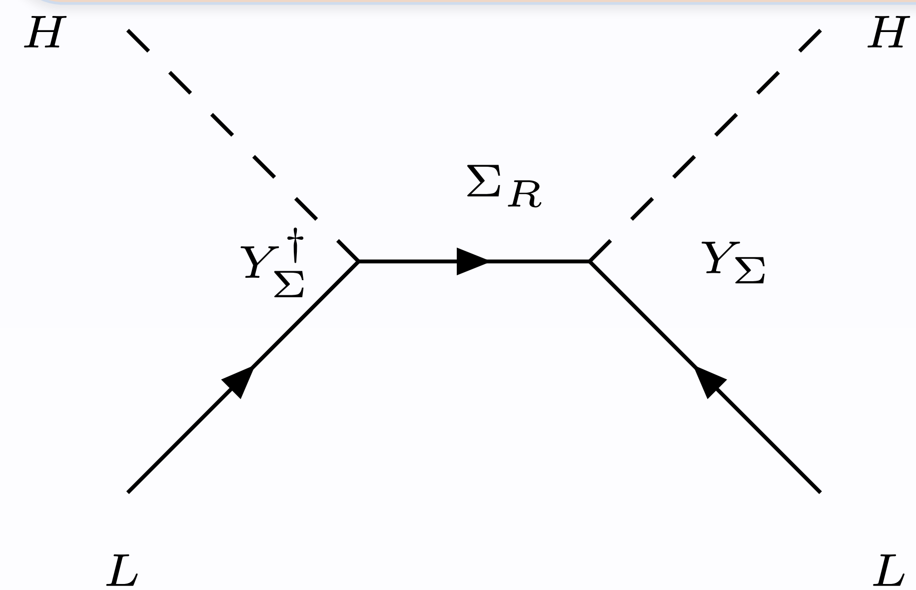
H^{++} **Doubly charged Higgs**



Type-III

$SU(2)$ Triplet, $Y = 0$

Σ_R → Gauge interaction



Heavy modes integrate out

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979, Yanagida 1979, Mohapatra, Senjanovic 1980; Magg, Wetterich, 1980; Foot et al., 1989

Quasi-degenerate neutrinos

Inverse Seesaw

$M_{N_{1,2}} = M \pm \mu$

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

Unsuppressed mixing $\frac{m_D}{M} \to \sigma$ large

Mohapatra, Valle, 1986

- For $\mu \ll m_D < M \to$ $m_\nu \sim \mu \frac{m_D}{M}^2$

$\mu \sim 0$

enhances lepton number symmetry

- R-parity violating supersymmetry-(Masiero, 1982; Santamaria, Valle, 1987; Romao, Valle, 1992; Borzumati, 1996; B. Mukhopadhyaya, S Roy, F Vissani, PLB 1998, Anjan S Joshipura, Sudhir K Vempati, PRD 60, 1999...)

- Loop generated mass? Radiative inverse seesaw (A. Zee, 1980; A. Zee, K. S. Babu 1988; D, Choudhury et al., PRD 1994; Dev, Pilaftsis, 2012...)

- Others—dimension 7 $\frac{(LLHH)HH}{\Lambda^3}$ operators etc (K.S. Babu et al.,, 2009)

Left-Right symmetric theory

Type-I and Type-II

Pati; Salam; Mohapatra, Senjanović, 74, 75

Enlarged gauge sector $\rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Parity symmetric theory $\rightarrow$ parity violating SM

- Two Higgs triplet $\Delta_L = (3,1,2)$, $\Delta_R = (1,3,2)$.

  $\langle \Delta_R \rangle$ **breaks the** $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$
- Sterile neutrino N is part of the gauge multiplet $\begin{pmatrix} N \\ e \end{pmatrix}_R$
- Additional gauge bosons W_R and Z'. $M_{W_R} \propto \langle \Delta_R \rangle$

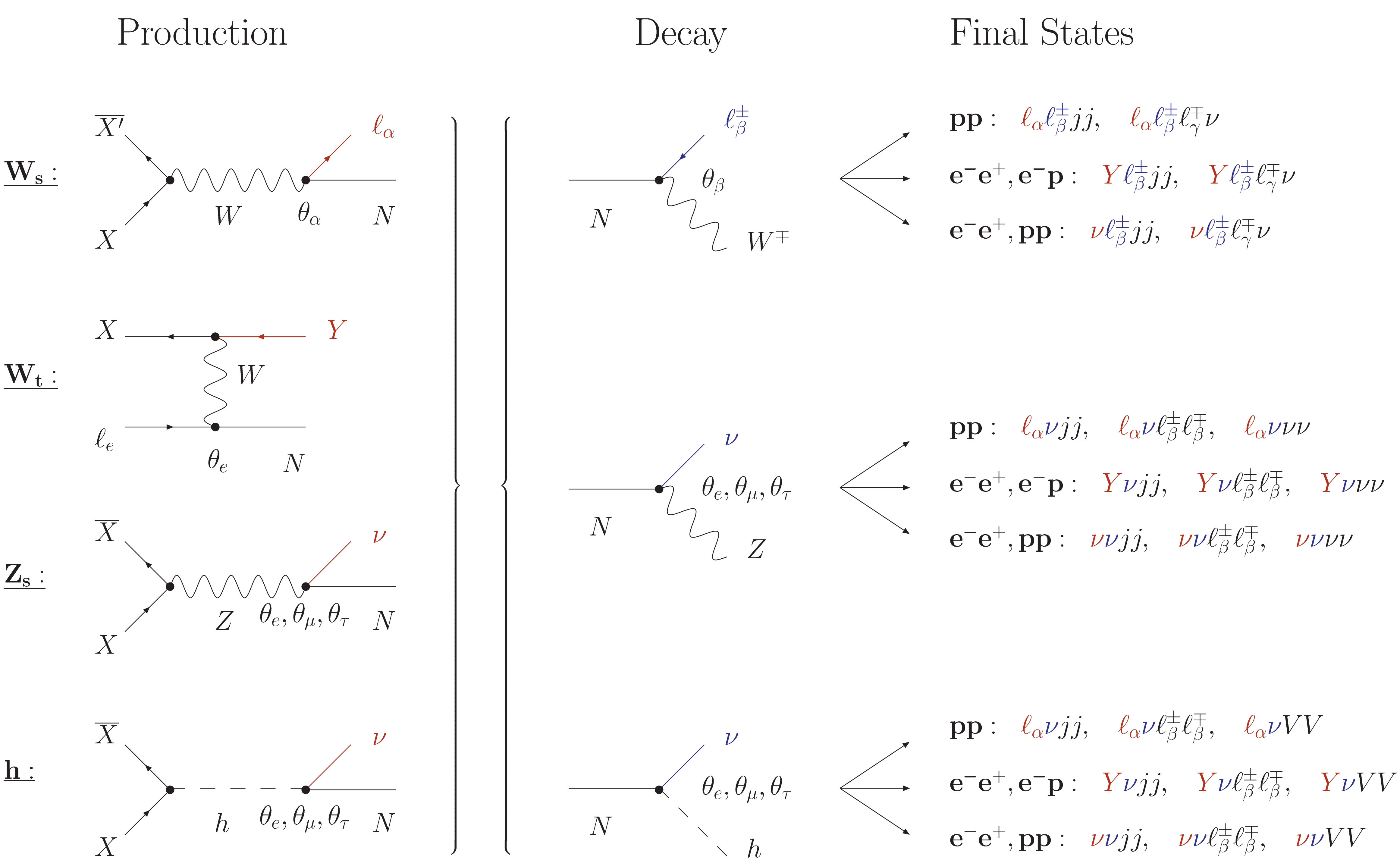
Natural way to embed the sterile neutrinos

N, W', Z', Δ^{++} $\longrightarrow$ Phenomenology

Sterile Neutrinos

Charged current $-\frac{g}{\sqrt{2}}\bar{l}\gamma^\mu W_\mu \theta_\alpha N_R$; N.C $-\frac{g}{2c_w}\bar{\nu}\gamma^\mu Z_\mu \theta_\alpha N_R$; Higgs $\frac{gM}{2M_w}\bar{\nu}\theta_\alpha N_R H$

Interaction depends on the mass M and mixing θ_α → $\frac{m_D}{M}$



Multilepton, multijet final states

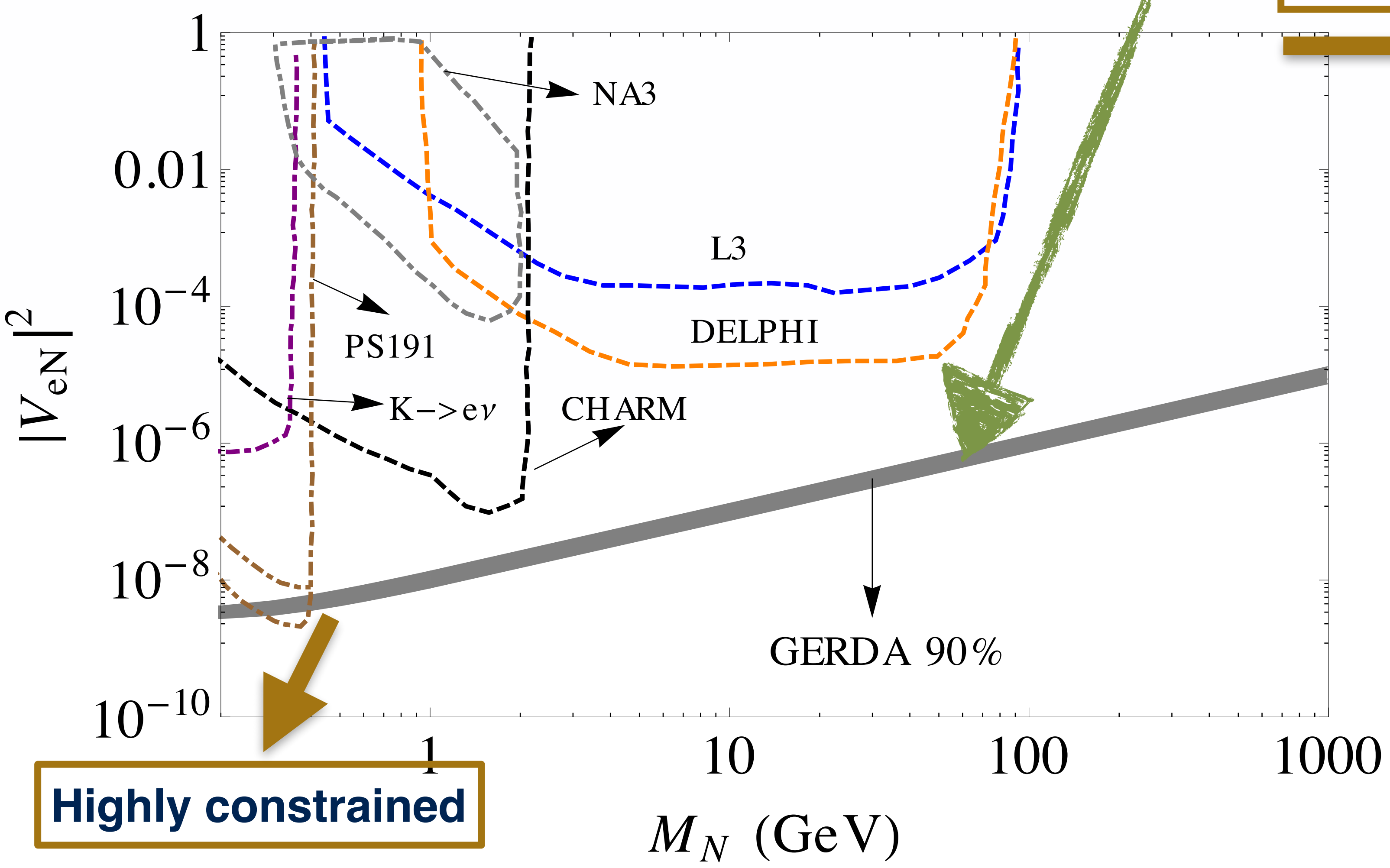
From arXiv: 1612.02728, S. Antusch et al.,

Bounds

Limits on active-sterile neutrino mixing V from neutrino mass, $(\beta\beta)_{0\nu}$-decay, beam dump experiments and others...

- Light neutrino mass $V \sim 10^{-5}/\sqrt{M}$.
- For $M = 100$ GeV, $V \sim 10^{-6} \rightarrow$ extremely small
- Experimental constraints $\rightarrow$ $(\beta\beta)_{0\nu}$-decay, beam dump experiments. $(\beta\beta)_{0\nu}$-decay $\rightarrow$ stringent.

$M_N \rightarrow TeV$ **less constrained**



Highly constrained

Mitra, Pascoli, Wong, 2013 ;

Atre et al., JHEP **0905**, 030 (2009);

Mitra at el, , NPB **856**, 26 (2012)

Direct vs Indirect

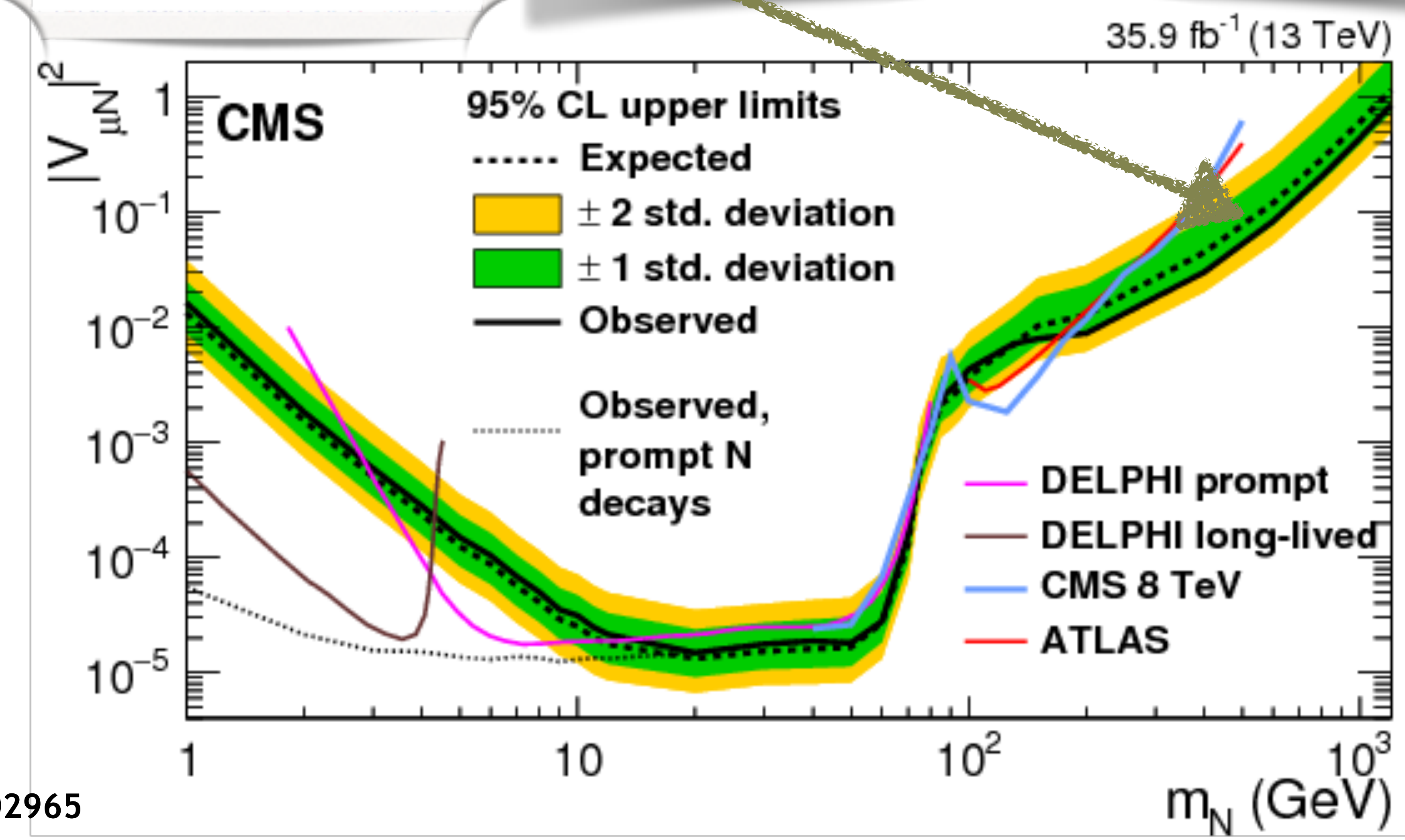
Collider signatures → lepton channels

- Like sign/ different flavor diliptons $l^{\pm}l^{\pm}/l^{\pm}l'^{\mp}+2j$
- Trilepton channels $l^{\pm}l^{\mp}l^{\pm}$ → For Dirac neutrinos N_R
- Lepton number violating $l^{\pm}l^{\pm}$ → Proof of heavy Majorana neutrinos N_R

Atre et al., JHEP **0905**, 030 (2009); Aguila et al., NPB **813**, 2009; Aguila et al., 2007; Aguila et al., PLB **672**, 2009; Arhib et al., 2010, ...

3l+X search

Low sensitivity in high mass regime



CMS collaboration, arXiv 1802.02965

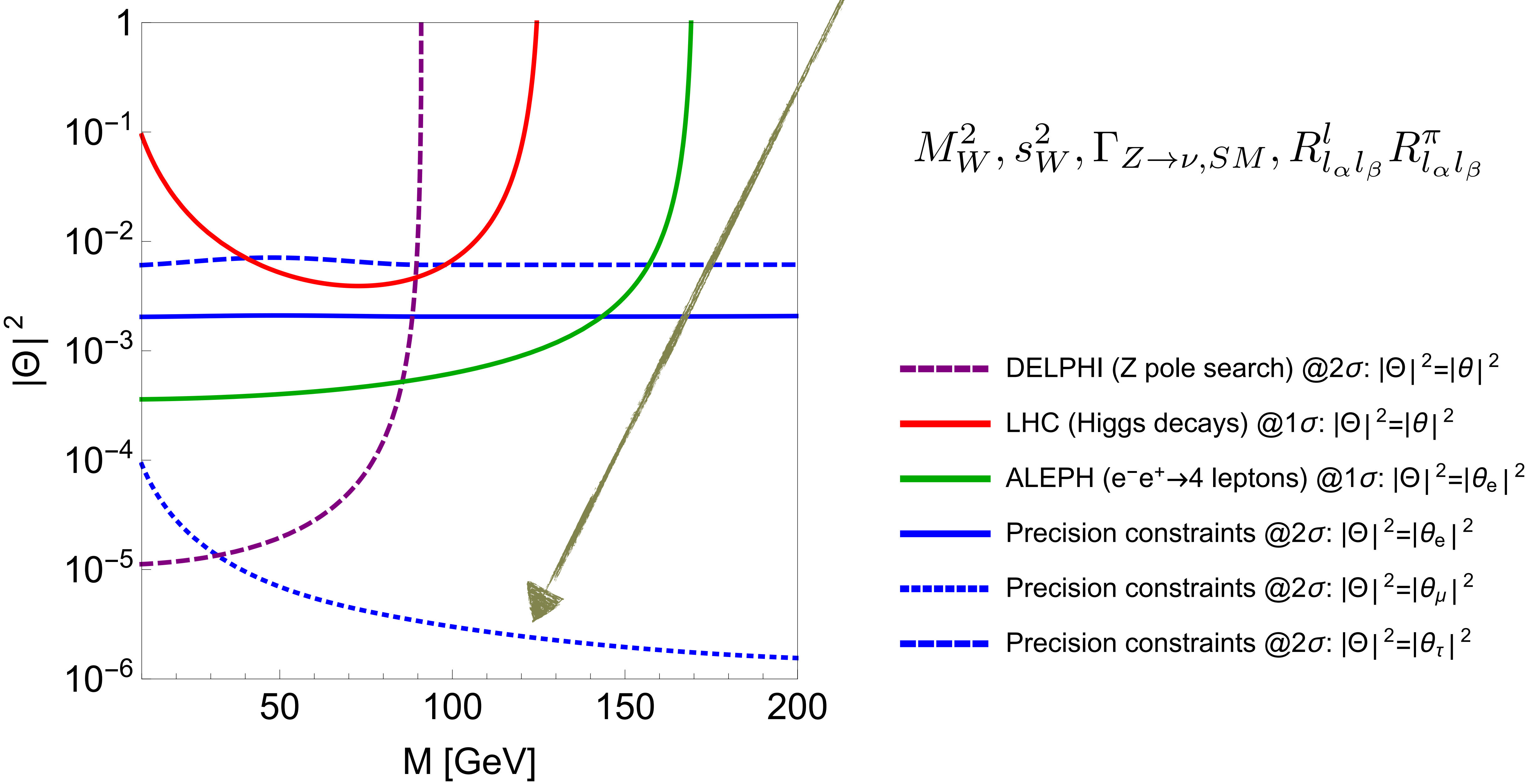
Indirect constraint from electroweak precision

Modified weak current →

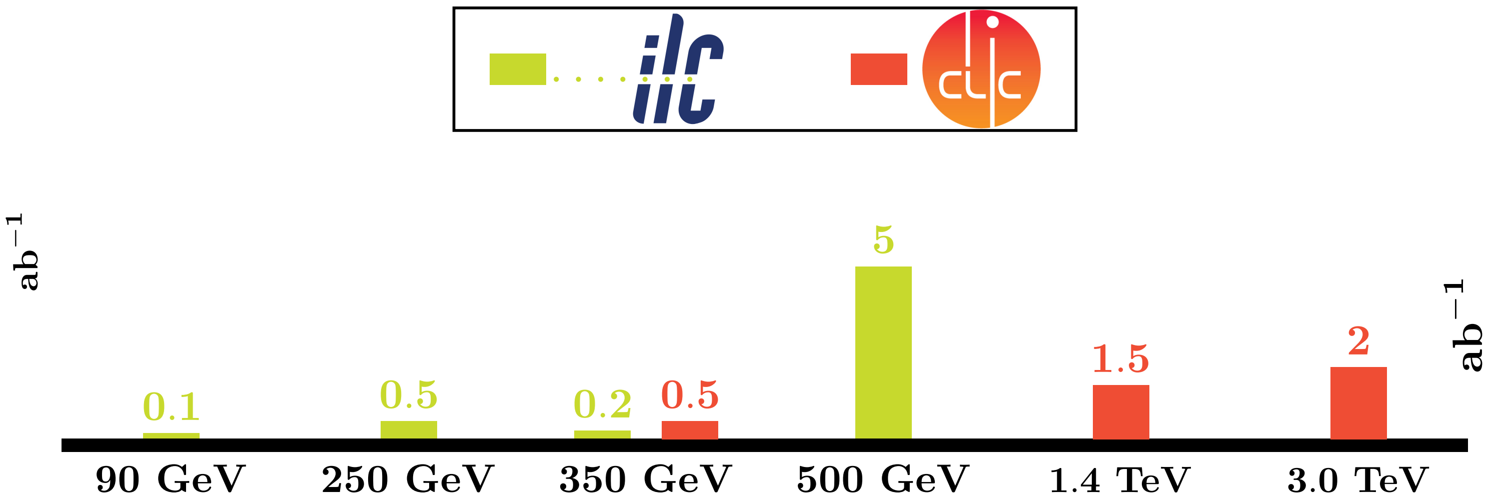
$$\sigma_{\mu^- \to e^- \bar{\nu}\nu} = (NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}\sigma_{\mu^- \to e^- \bar{\nu}\nu}(SM)$$

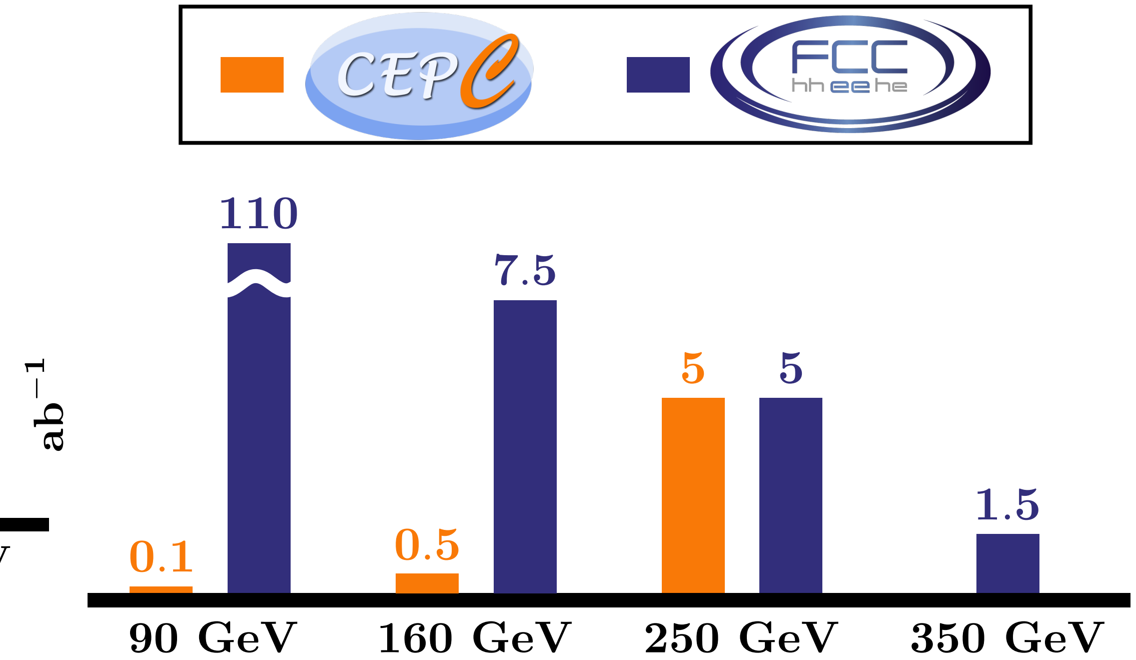
$$G_F^2 \to G_F^2 (NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}$$

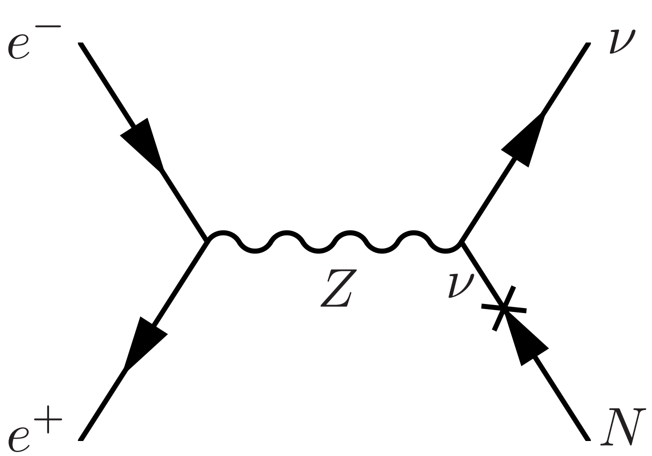
$$M_W^2, s_W^2, \Gamma_{Z\to\nu,SM}, R^l_{l_\alpha l_\beta} R^\pi_{l_\alpha l_\beta}$$



Future Lepton Collider

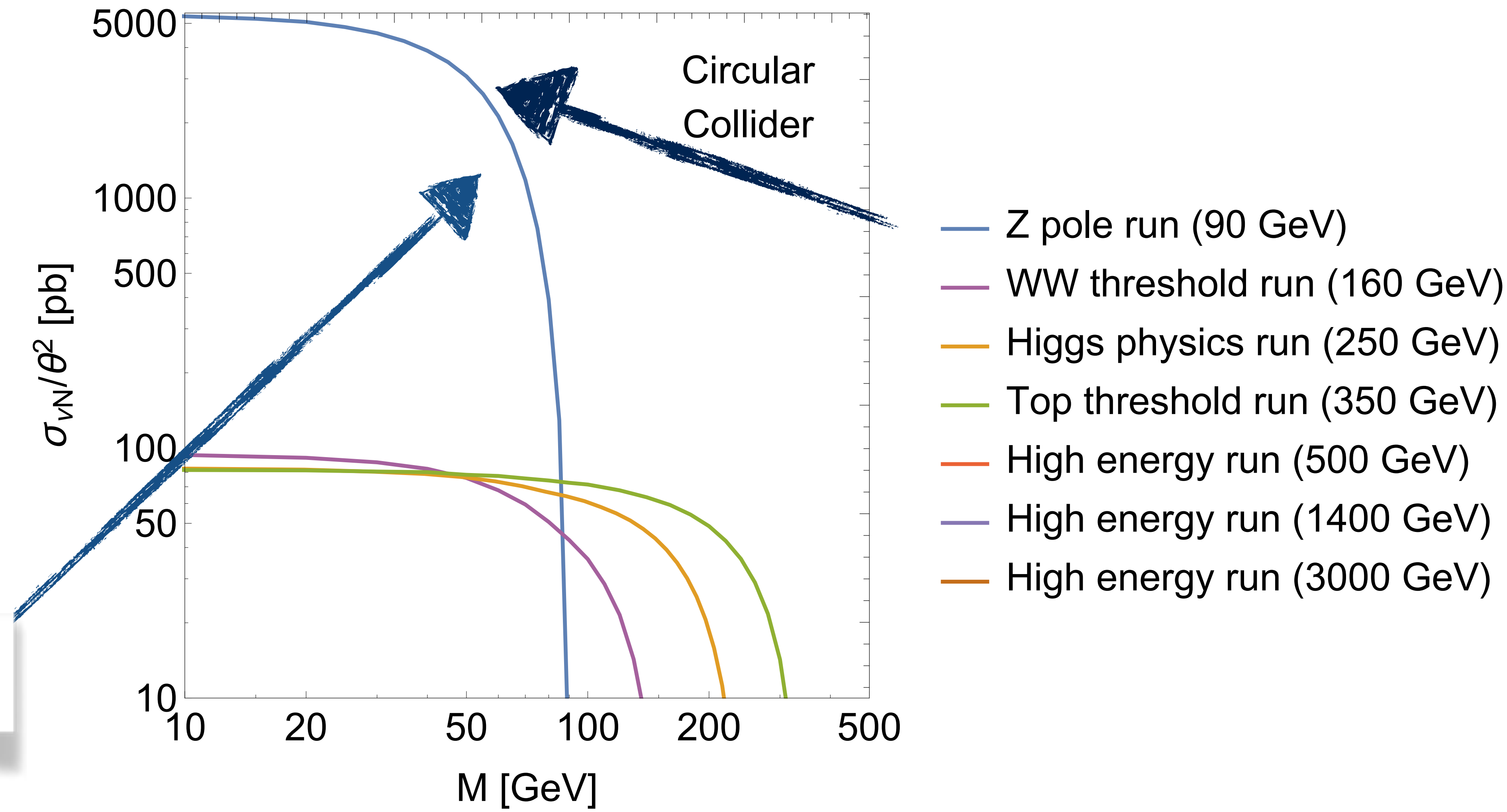




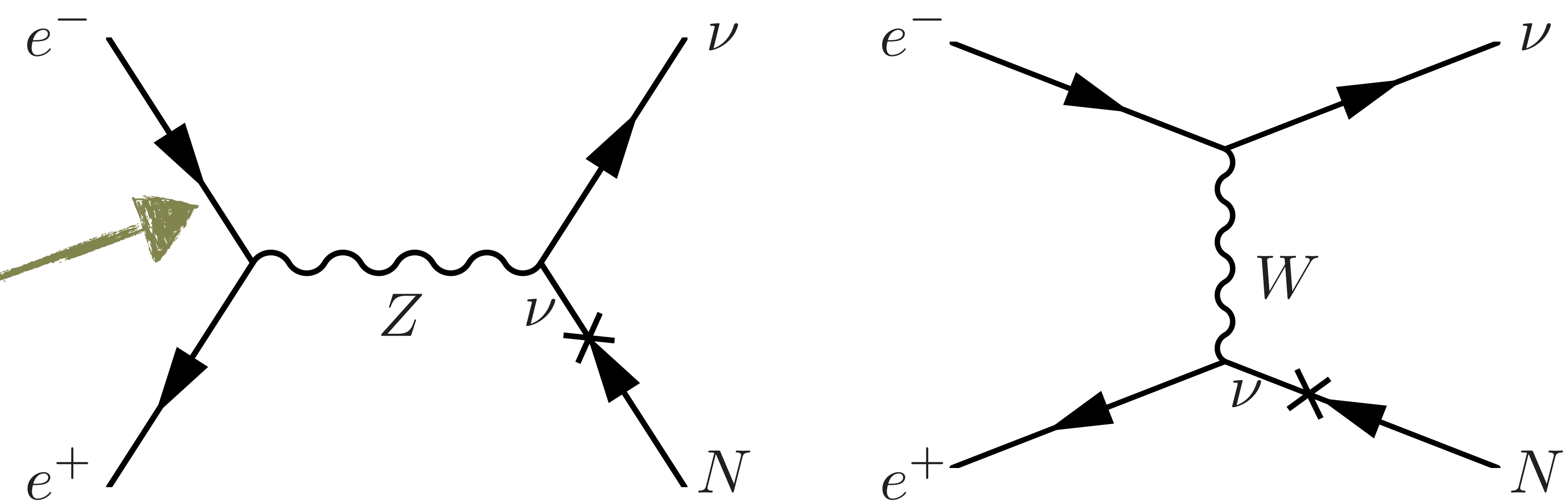


Limited by kinematics

$M_N < M_Z$



Antusch et al., Int.J.Mod.Phys. A32 (2017) no.14, 1750078



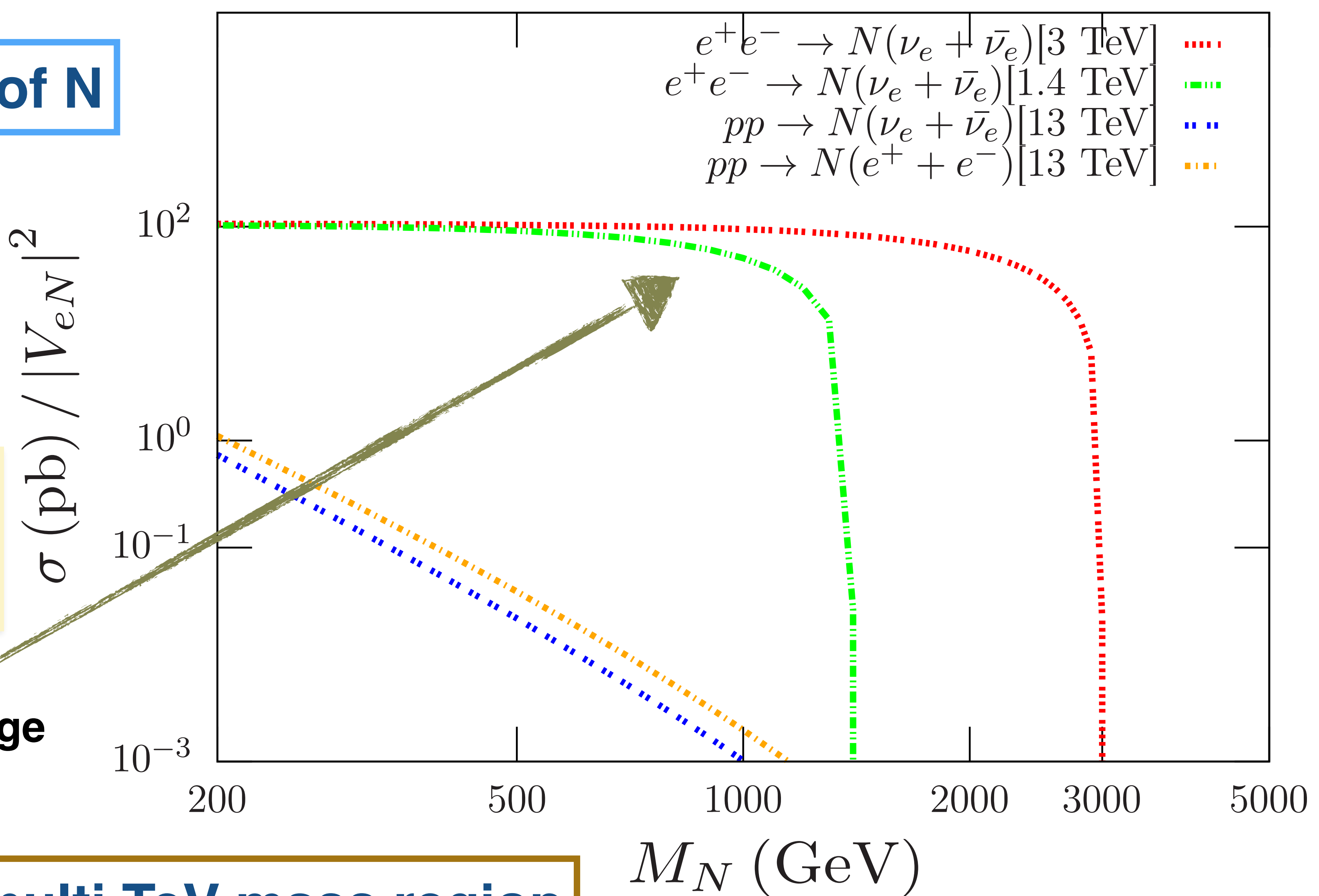
$e^+e^- \rightarrow \nu N$

Followed by decay of N

$N \rightarrow lW, \nu Z, \nu h$

$$\frac{\sigma}{|V_{eN}|^2} \sim 10^2$$

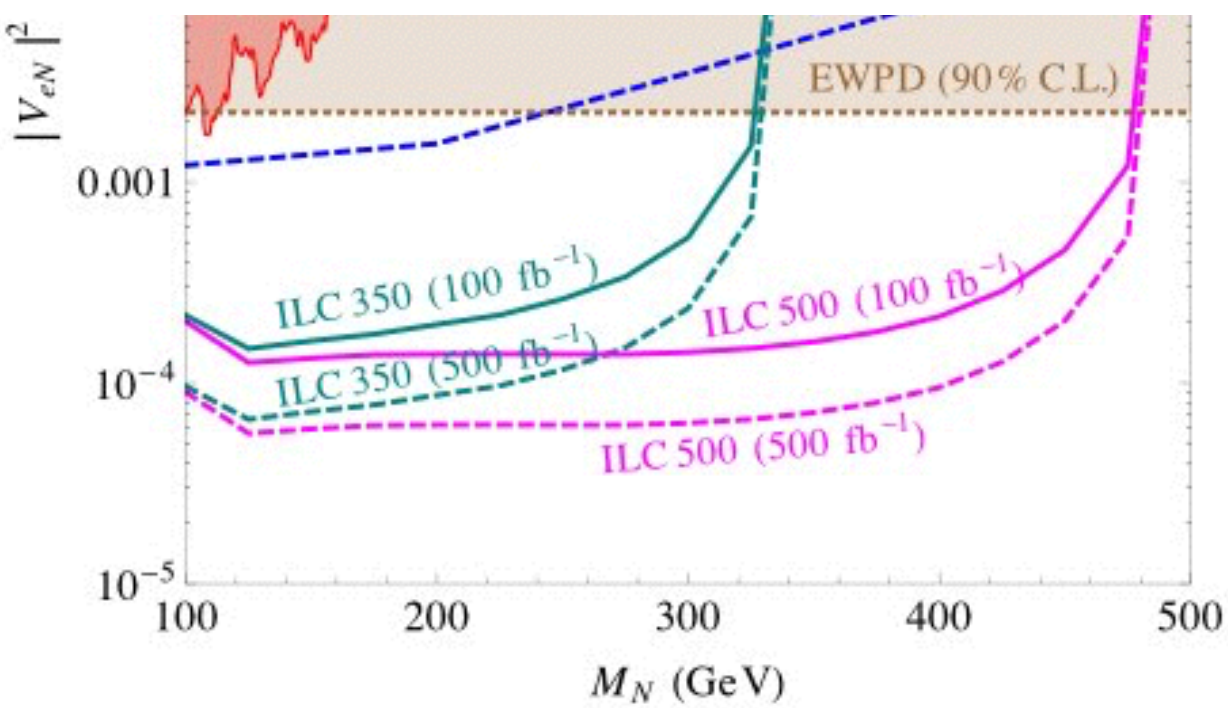
Cross-section is large



Large cross section in multi TeV mass region

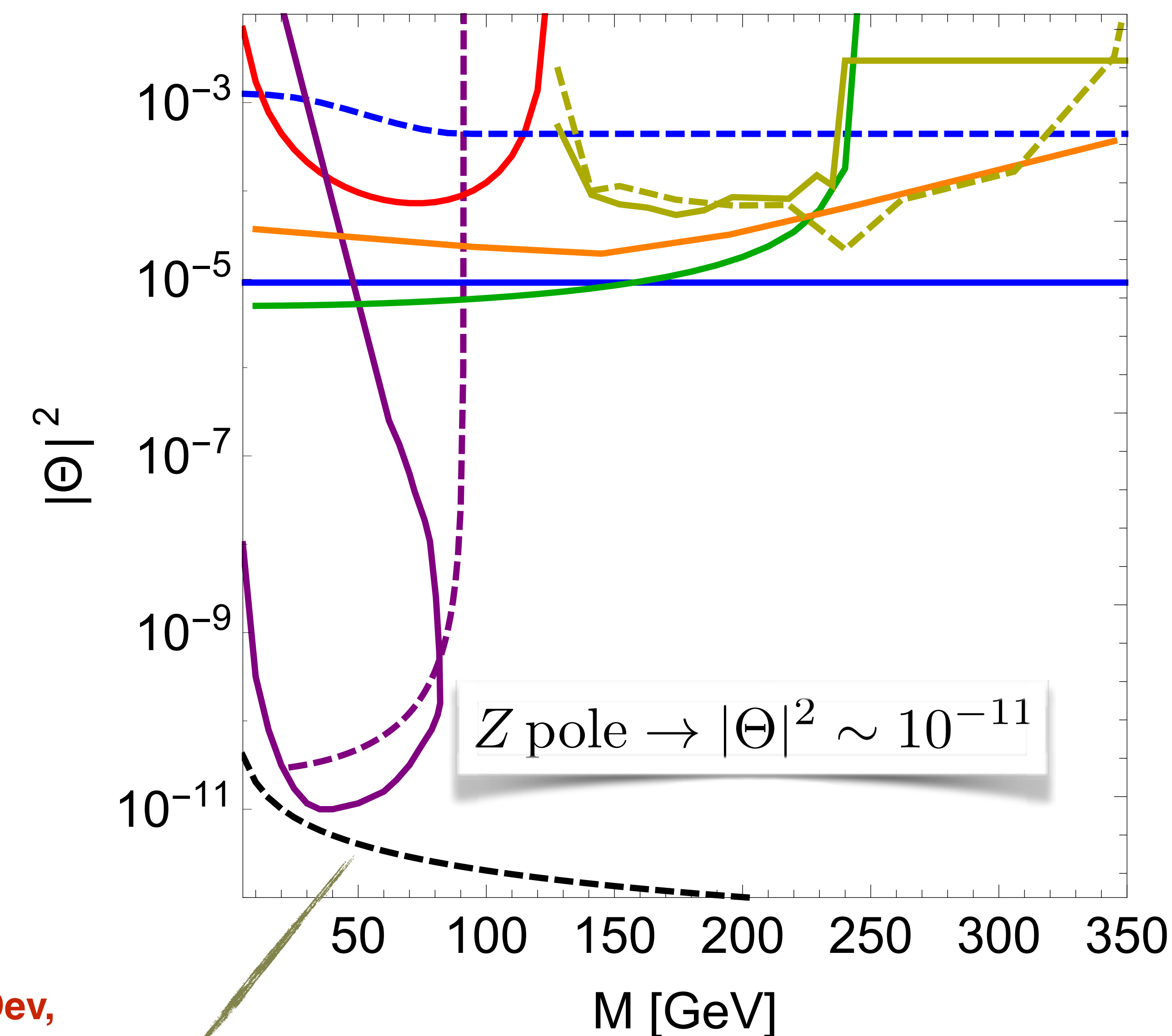
ILC Sensitivity

$$e^+e^- \to \nu N \to e + 2j + \not{p}$$



Phys.Rev. D92 (2015) 075002 , S. Banerjee, A. Ibarra, P.S.B. Dev, T. Mandal, M. Mitra

CEPC/FCC-ee Sensitivity



Conventional Z pole search @2σ: $|\Theta|^2=|\theta|^2$

Displaced vertex search @2σ: $|\Theta|^2=|\theta|^2$

Higgs branching ratios @1σ: $|\Theta|^2=|\theta|^2$

Mono−Higgs @1σ: $\Theta^2=|\theta_e|^2$

WW production cross section @1σ: $|\Theta|^2=|\theta_e|^2$

Lepton−dijet @1σ: $|\Theta|^2=|\theta_e|^2$

EWPOs @2σ: $|\Theta|^2=|\theta_e|^2+|\theta_\mu|^2$

EWPOs @2σ: $|\Theta|^2=|\theta_\tau|^2$

"Unprotected" type−I seesaw

light neutrino mass constraint

S. Antusch et al., Int.J.Mod.Phys. A32 (2017) no.14, 1750078

LHC and 100 TeV → **S. Pascoli et al., arXiv:1812.08750; M. Hirsch at al., arXiv:1806.05191; M. Drews et al., arXiv:1903.06100, A. Abada et al., arXiv:1807.10024, and others**

EFT description → **F. Del Aguila et al., arXiv: 0806.0876; Julien Alcaide et al., arXiv: 1905.11375**

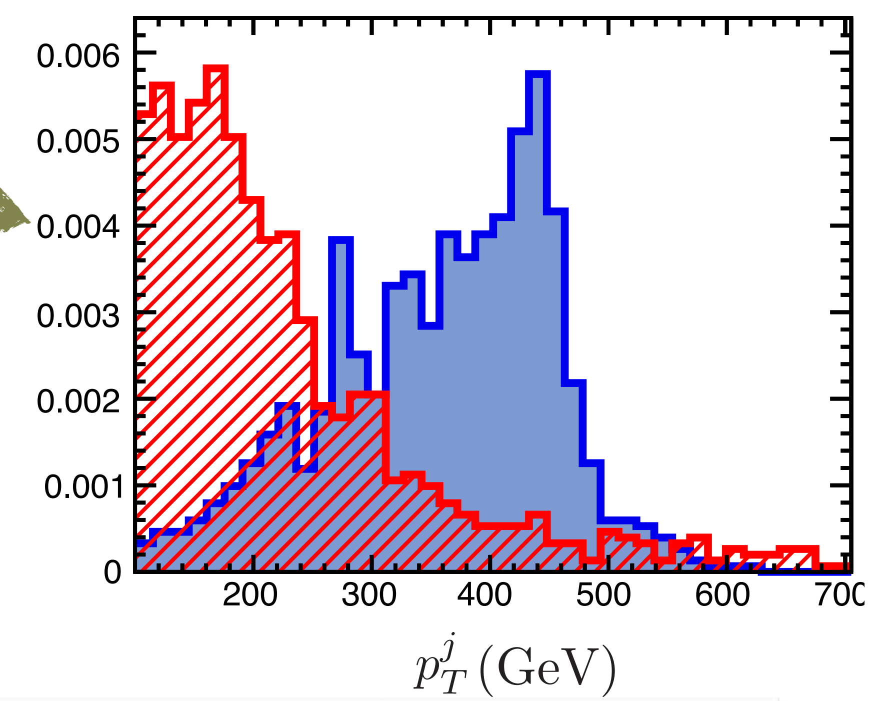
Even more massive N $M_N \sim TeV$

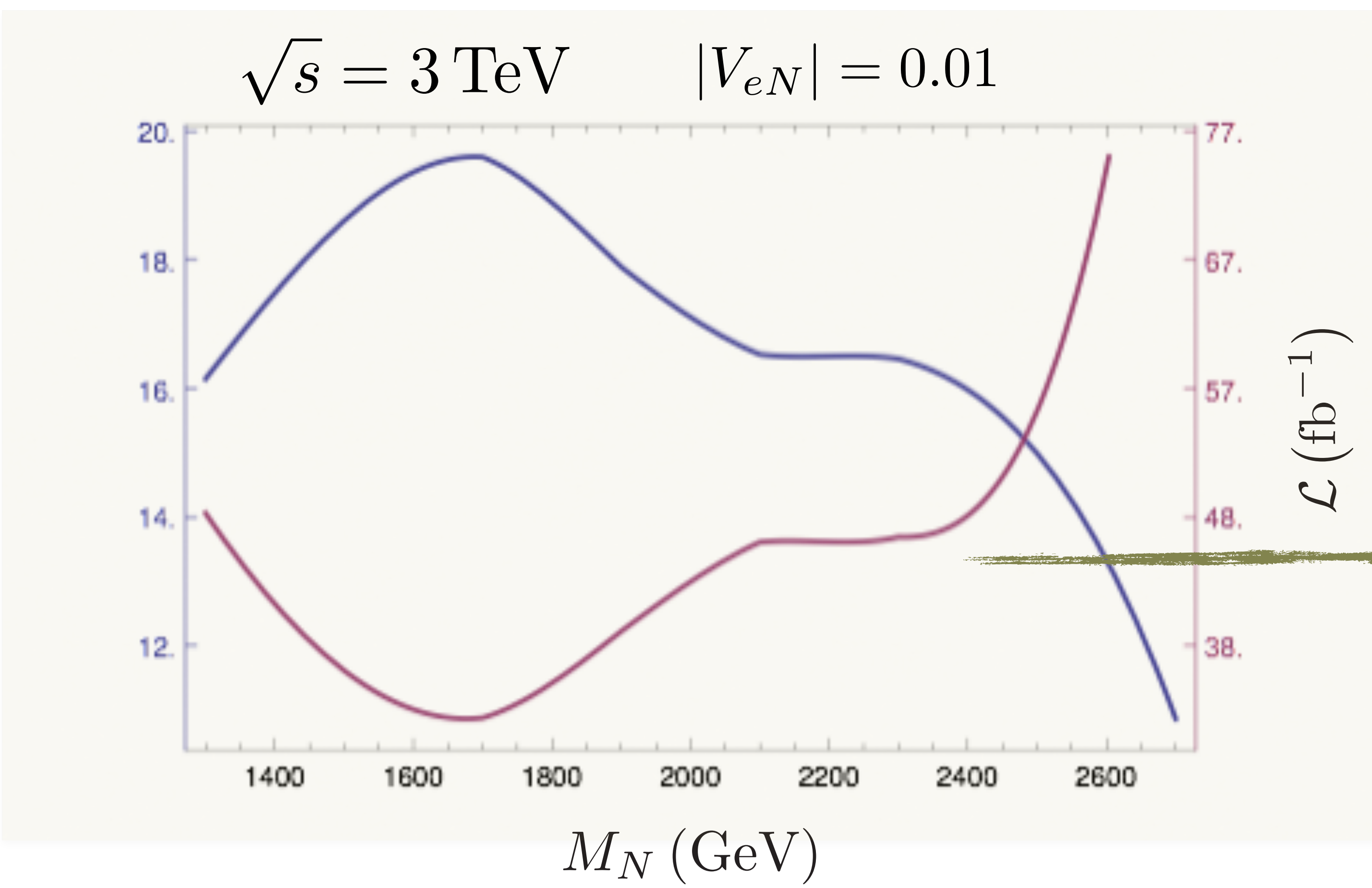
Model signature → $e^+e^- \to \nu N \to lW\nu \to lJ_{Fat} + \not{E}$

Boosted W → Collimated decay products

High Mass of N=900 GeV

High p_T





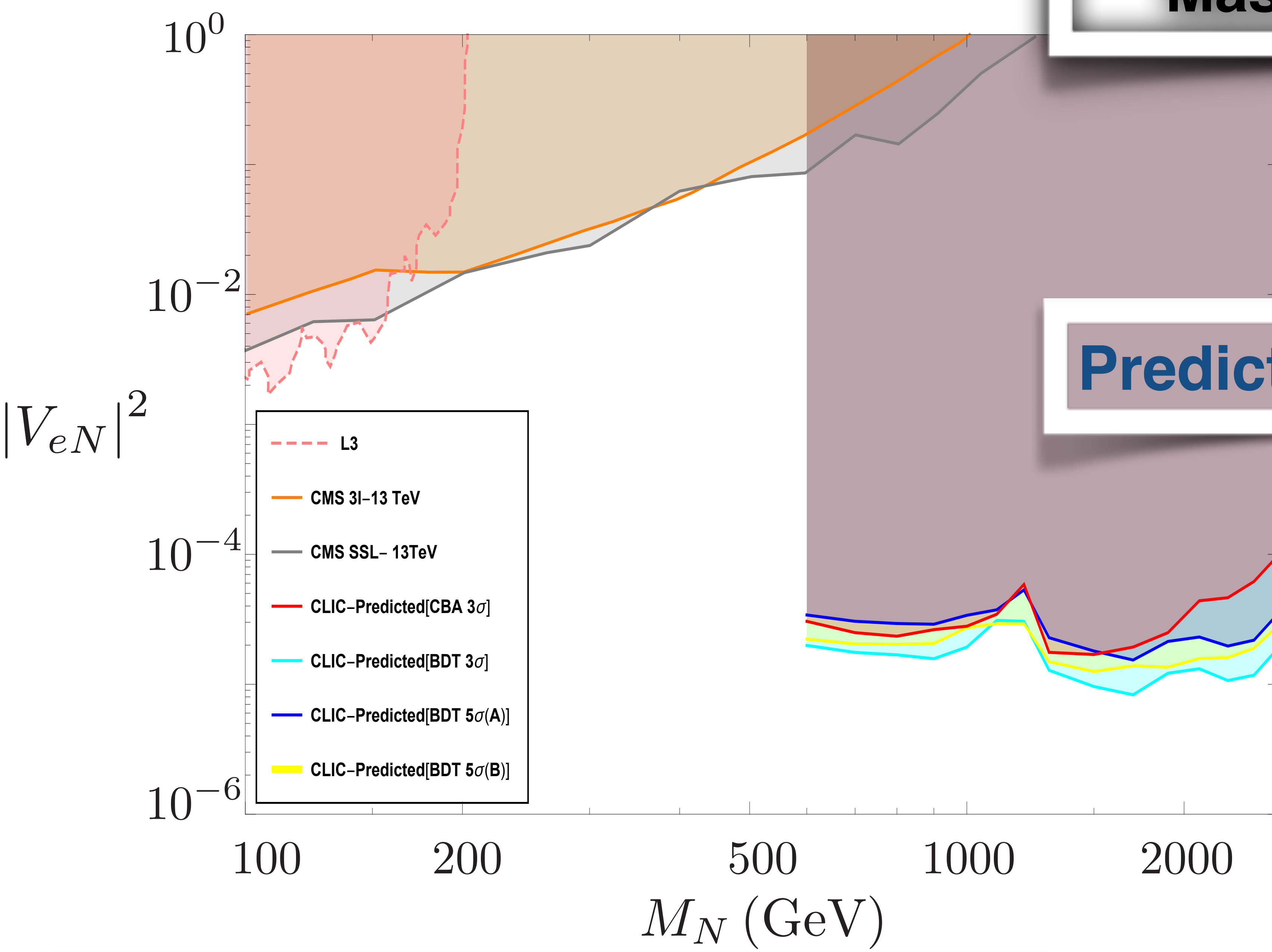
Required luminosity

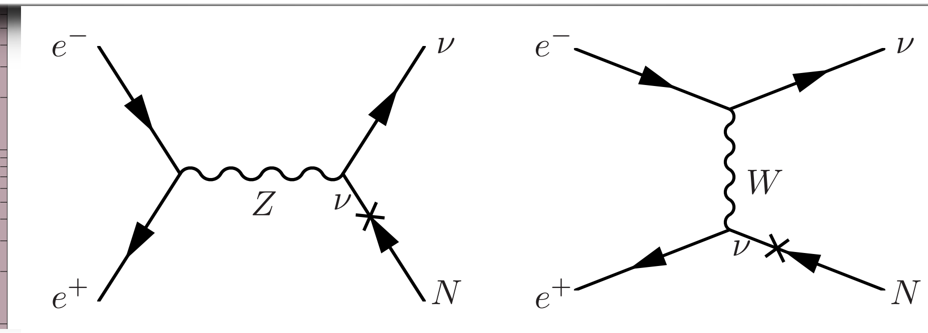
$$\mathcal{L} < 38\,\text{fb}^{-1}$$

arXiv:1810.08970, Sabyasachi Chakraborty, Sujay Shil and M. Mitra

arXiv:1810.08970, S. Chakraborty, S. Shil and M. Mitra

Mass vs active-sterile mixing

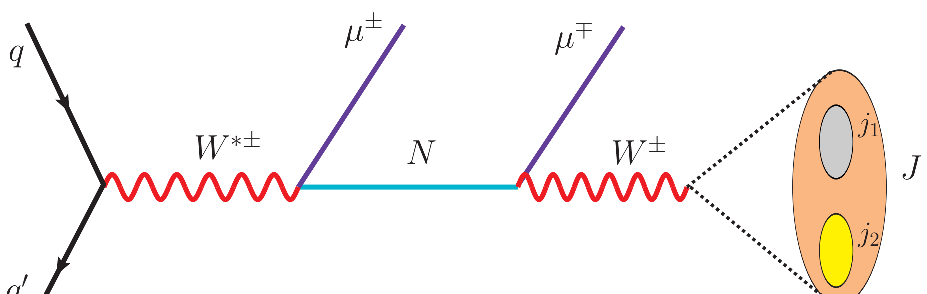




Prediction for CLIC

$$|V_{eN}|^2 \sim 10^{-5}$$

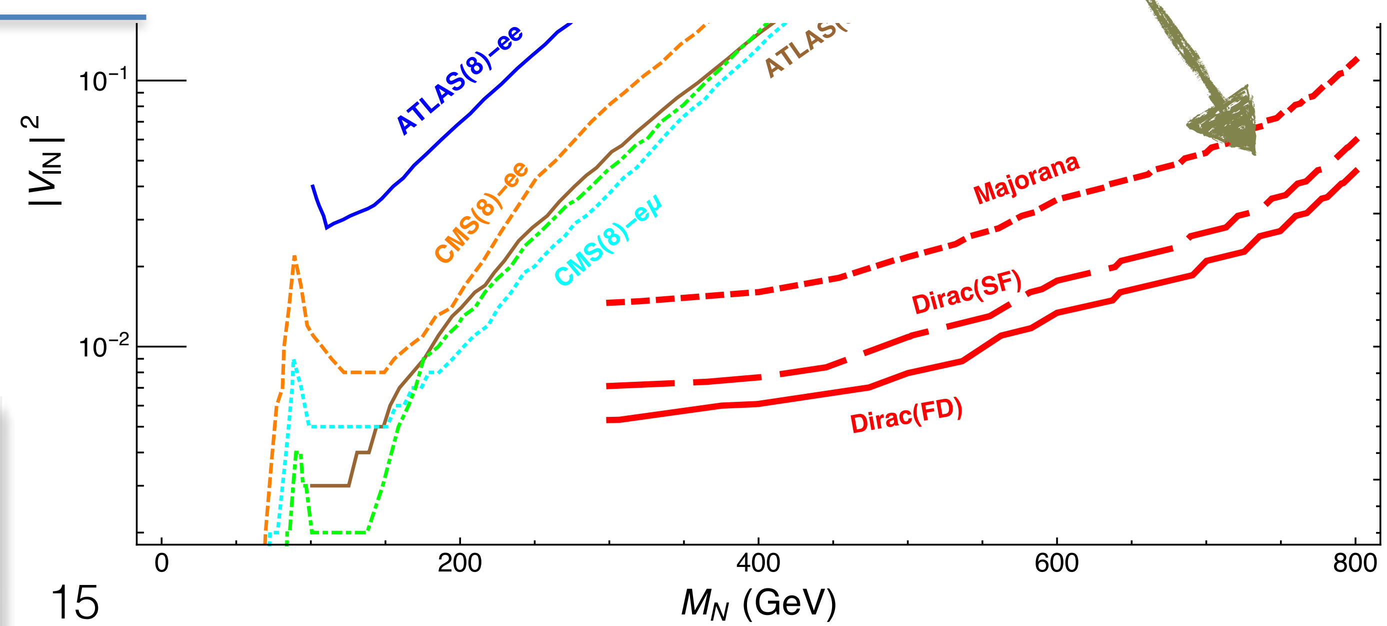
- Competitive to neutrinoless double beta decay
- order of magnitude improvement compared to HL-LHC



Bharadwaj et al., arXiv 1801.00797

High sensitivity for active-sterile mixing in large mass regime at e+ e-

HL-LHC



Higgs triplet:

Higgs triplet, Δ (3,2)

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

The gauge invariant Lagrangian

$$-\mathcal{L}_Y = y_\Delta L_L^T C i\tau_2 \Delta L_L + \mu_\Delta H^T i\tau_2 \Delta^\dagger H + \quad M_\Delta Tr(\Delta^\dagger \Delta) + \mathrm{h.c} + \ldots$$

Magg, Wetterich, PLB 94, 61, 1980

- **Light neutrino mass** $M_\nu \propto y_\Delta v_\Delta$
- $v_\Delta = v^2 \frac{\mu_\Delta}{M_\Delta^2}$.
- **Lepton number violation** $\rightarrow y_\Delta, \mu_\Delta$
- eV light neutrino mass $\rightarrow y_\Delta \sim \mathcal{O}(1)$, $v_\Delta = 1$ eV

$\mu_\Delta \rightarrow 0 \rightarrow v_\Delta \rightarrow 0$

Massless neutrino

$\downarrow$

y_Δ, μ_Δ

The Yukawa $y_\Delta = M_\nu / v_\Delta = U_{PMNS}^T M_d^\nu U_{PMNS}^* / v_\Delta$

$$y_\Delta = f(\theta_{12}, \theta_{13}, \theta_{23}, m_i, \delta, \alpha_1, \alpha_2, v_\Delta)$$

fixed from the PMNS mixing and neutrino mass

Large y_Δ $\Rightarrow$ lepton flavor violation

$$H^{\pm\pm} \to l^{\pm} l^{\pm} \quad \text{for} \quad v_{\Delta} < 10^{-4}\,\text{GeV}$$

Decays of doubly charged Higgs →

$$H^{\pm\pm} \to W^{\pm} W^{\pm} \quad \text{for} \quad v_{\Delta} > 10^{-4}\,\text{GeV}$$

- **CMS search for same sign di-lepton** $pp \to H^{\pm\pm} H^{\mp\mp} \to l^{\pm\pm} l^{\mp\mp}$

HIG-PAS-16-036

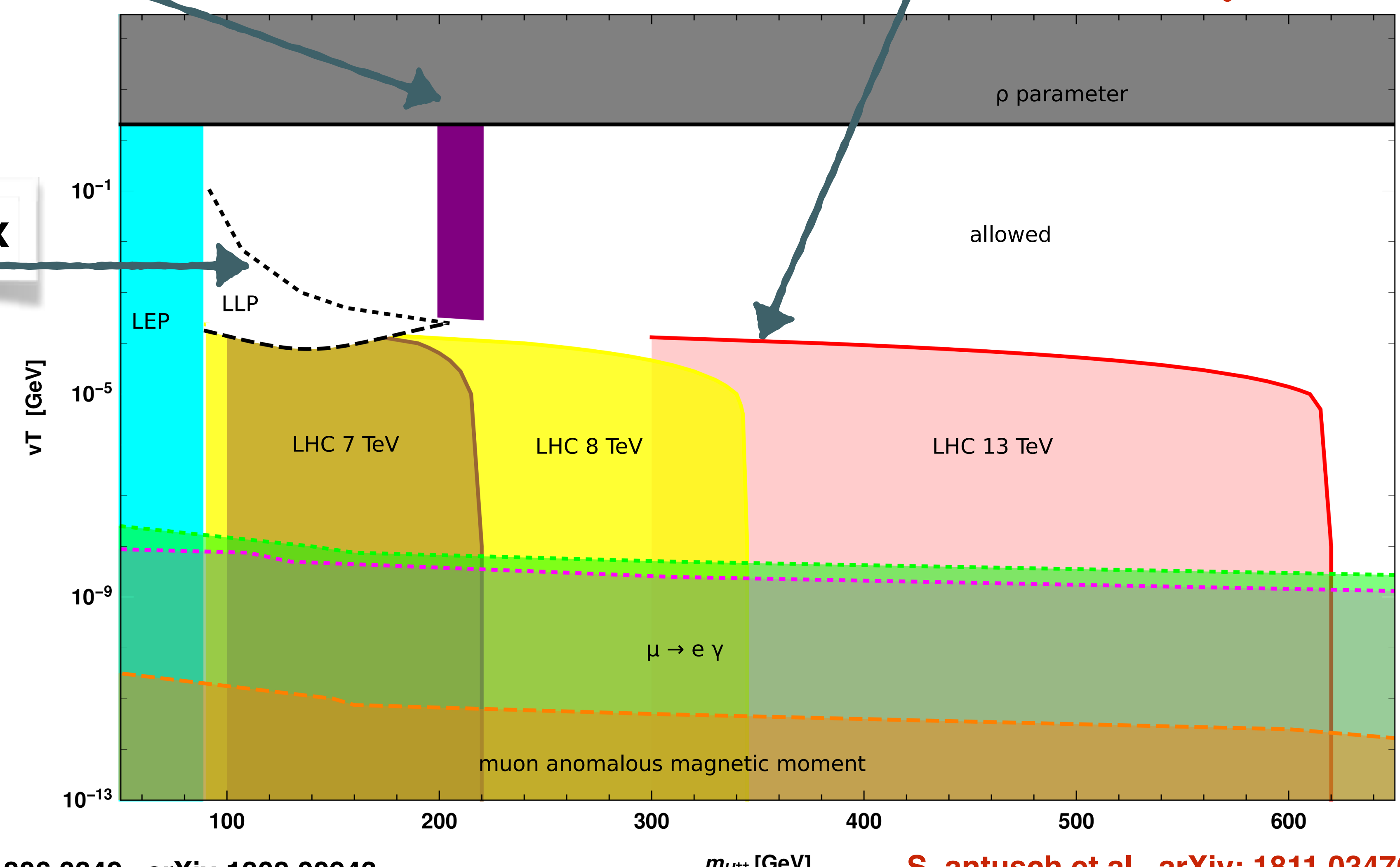
- **ATLAS search for same sign W** $pp \to H^{\pm\pm} H^{\mp\mp} \to W^{+} W^{+} W^{-} W^{-}$

arXiv: 1808.01899

- **200-220 GeV excluded**

Unconstrained →

Long lived → **Displaced vertex**



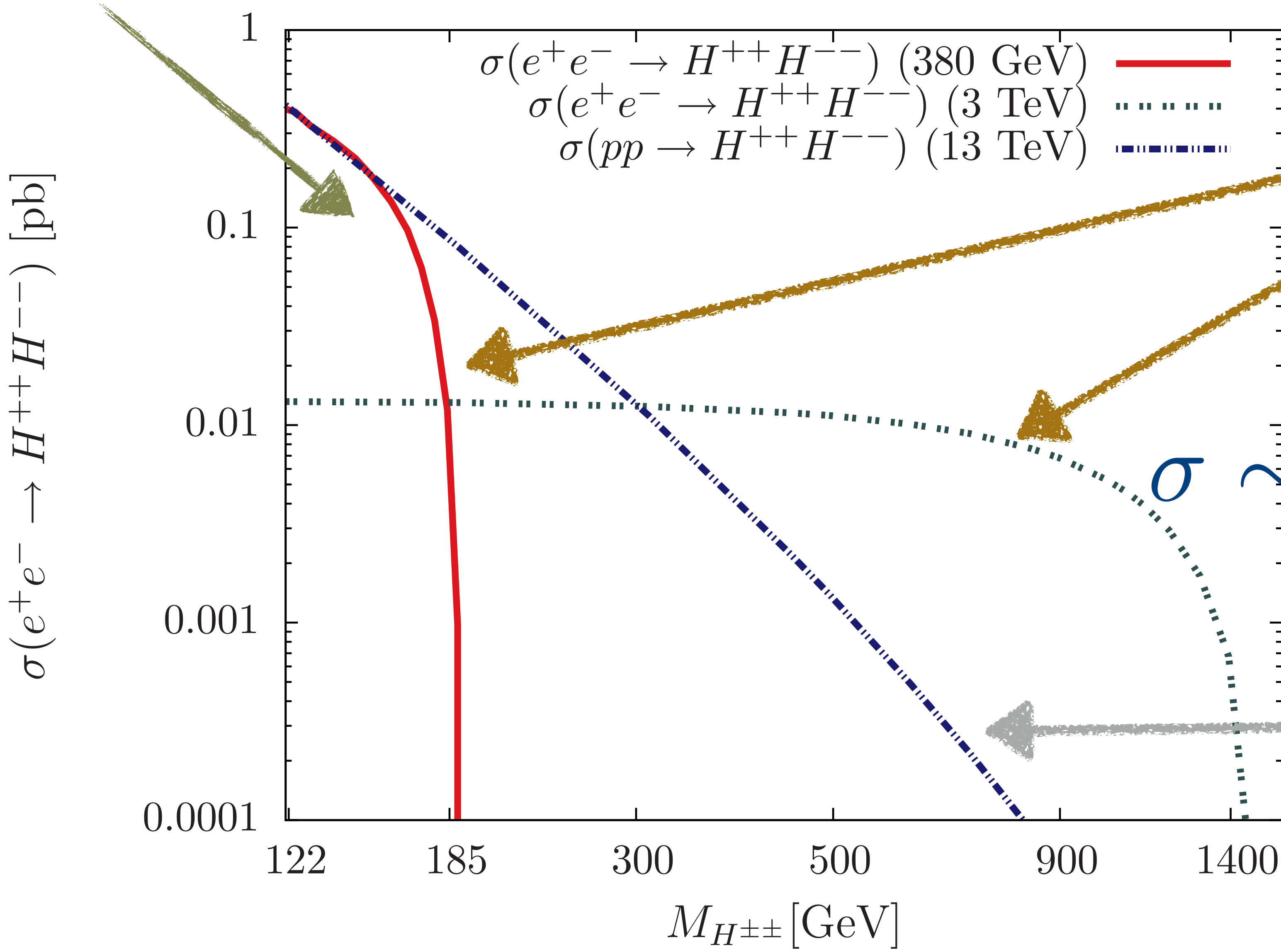
High mass and large vev is unconstrained

LHC and 100 TeV -> P.S.Bhupal Dev et al., arXiv:1806.0849, arXiv:1808.00943, Yong Du et al., arXiv:1810.09450

S. antusch et al., arXiv: 1811.03476

Cross-sections:

$\sigma \sim 100 - 400\,\mathrm{fb}$



CLIC

380 GeV, 3 TeV

$\sigma \sim 10\,\mathrm{fb}$

LHC 13 TeV

LHC cross-section is low for higher masses $\sigma \sim 0.004\,\mathrm{fb}$ for $\mathrm{M_{H^{\pm\pm}}} = 1.3\,\mathrm{TeV}$

For high mass and large vev, lepton collider is more suitable

Two mass ranges

Light Higgs, large vev (CLIC with 380 GeV c.m.energy)
Heavy Higgs, large vev (CLIC with 3 TeV c.m.energy)

Phys.Rev. D98 (2018) no.1, 015024 , P. Agrawal, M. Mitra, S. Shil, S. Niyogi and M. Spannowsky

Heavy Higgs at 3 TeV:

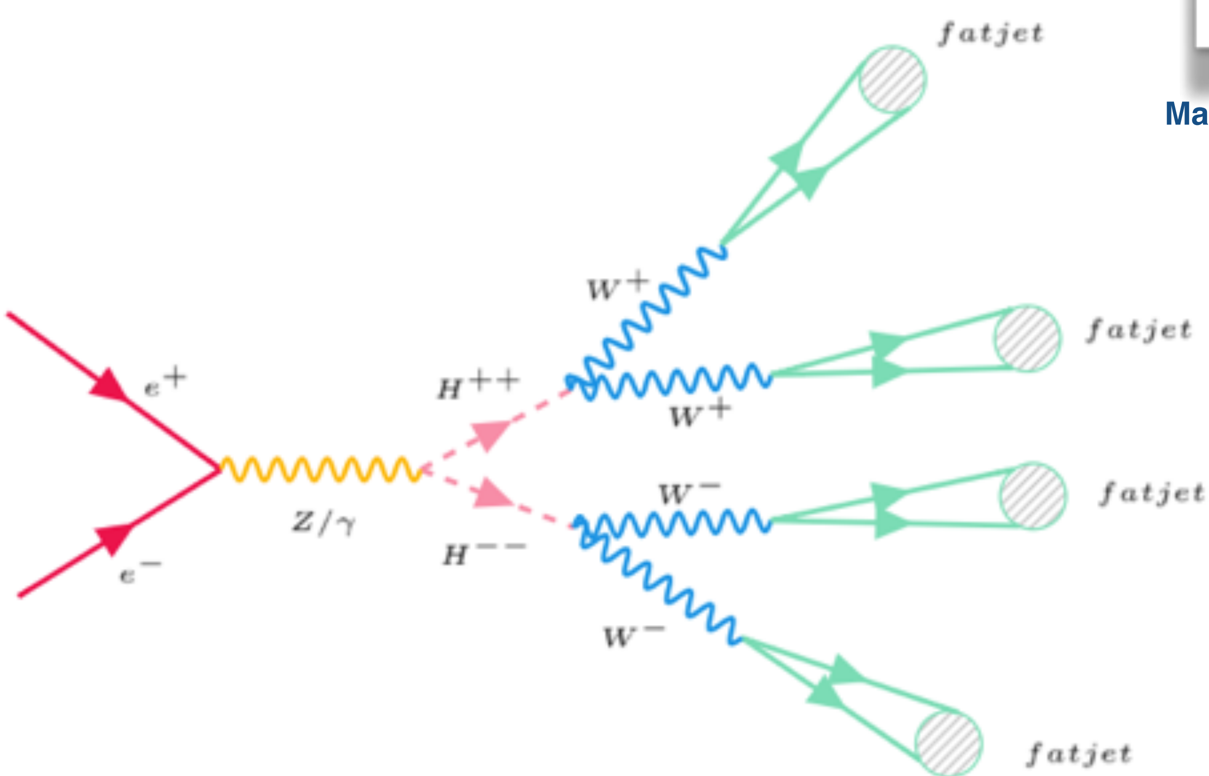
Higher c.m.energy → 3 TeV

Heavy Higgs upto 1.5 TeV

Boosted W → **Fat jets**

- $e^+e^- \to H^{\pm\pm}H^{\mp\mp} \to W^\pm W^\mp W^\pm W^\mp \to 4\,\mathrm{fat-jet}.$

MadGraph5_aMC@NLO, Pythia8, Cambridge-Achen algorithm in FastJet-3.0.0, jet radius R=1.0



$e^+e^- \to H^{++}H^{--} \to W^+W^+W^-W^- \to N j_{\mathrm{fat}}$		
Masses (GeV)	n_s (2, 3-tagged $\mathcal{L} = 500\,\mathrm{fb}^{-1}$)	$\mathcal{L}(\mathrm{fb}^{-1})$(with 2,3-tagged)
800	17.96(2-tag)	38.75
1000	13.95(2-tag)	64.23
1120	11.49(2-tag)	94.68
1350	5.48(3-tag)	416.24
1400	3.95(3-tag)	801.15

$M_{H^{\pm\pm}} =$ 800 GeV-1120 GeV discovery with $\mathcal{L} = 39 - 94\,\mathrm{fb}^{-1}$

Summary

Sterile Neutrino, Higgs Triplet

↓

Electroweak Production

Multi TeV mass range, challenging final states can be tested at lepton collider

Higher Dimensional Probe of Seesaw

Babu-Nandi-Tavartkiladze (BNT) Model

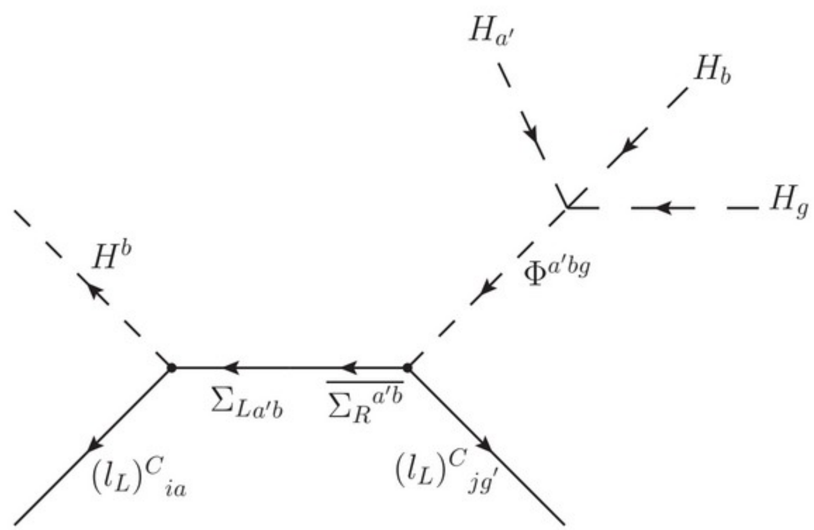
Scalar isospin 3/2 quadruplet (Φ)

$$\Phi = \begin{pmatrix} \Phi^{+++} & \Phi^{++} & \Phi^{+} & \Phi^{0} \end{pmatrix}_{Y=3}$$

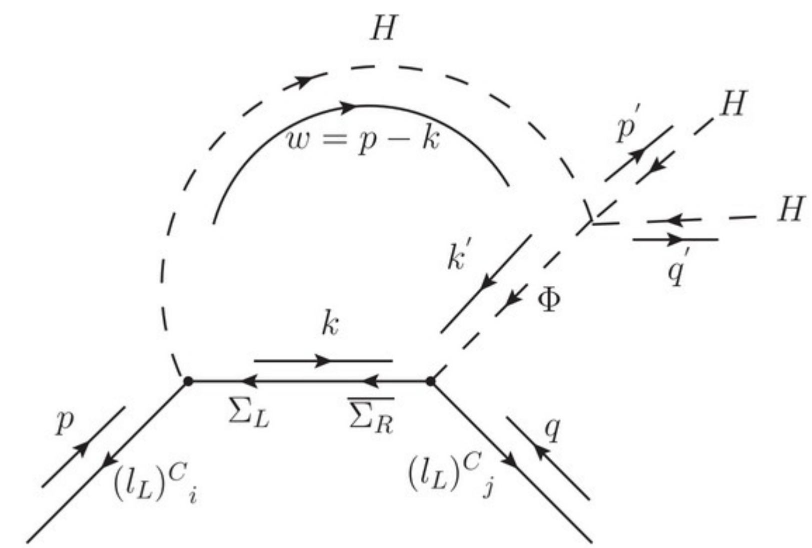
Vecor like triplet (Σ)

$$\Sigma_{R,L} = \begin{pmatrix} \Sigma^{++}_{R,L} & \Sigma^{+}_{R,L} & \Sigma^{0}_{R,L} \end{pmatrix}_{Y=2}$$

Tree level (d=7)



1-loop level (d=5)



$$V = \mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Phi^\dagger \Phi)^2$$
$$+ \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \tau_a H)(\Phi^\dagger T_a \Phi)$$
$$+ \{\lambda_5 H^3 \Phi^* + \text{H.c.}\},$$

$$(m_\nu)_{ij} = -\frac{\lambda_5 (Y_i Y_j' + Y_i' Y_j) v^4}{(M_\Sigma M_{\Phi^0}^2)}$$

Slide courtesy: Tanmoy Mondal

Rich Phenomenology with **"Multi-lepton"** final states

$$pp \xrightarrow{Z/\gamma} \Phi^{\pm\pm\pm}\Phi^{\mp\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm}\Phi^{\mp};$$
$$pp \xrightarrow{W^\pm} \Phi^{\pm\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp},\ \Phi^{\pm}\Phi^{0}.$$

3ℓ, 4ℓ, 5ℓ and 6ℓ events

Same-sign-tri-lepton events

Lepton flavour violating (LFV) 4 lepton events

Small v_Φ

K. S. Babu, S. Nandi, and Zurab Tavartkiladze, PRD (Rap Comm) 80, 071702(R) (2009)

Gulab Bambhaniya, Joydeep Chakrabortty, Srubabati Goswami, and Partha Konar, PRD, 88, 075006 (2013)

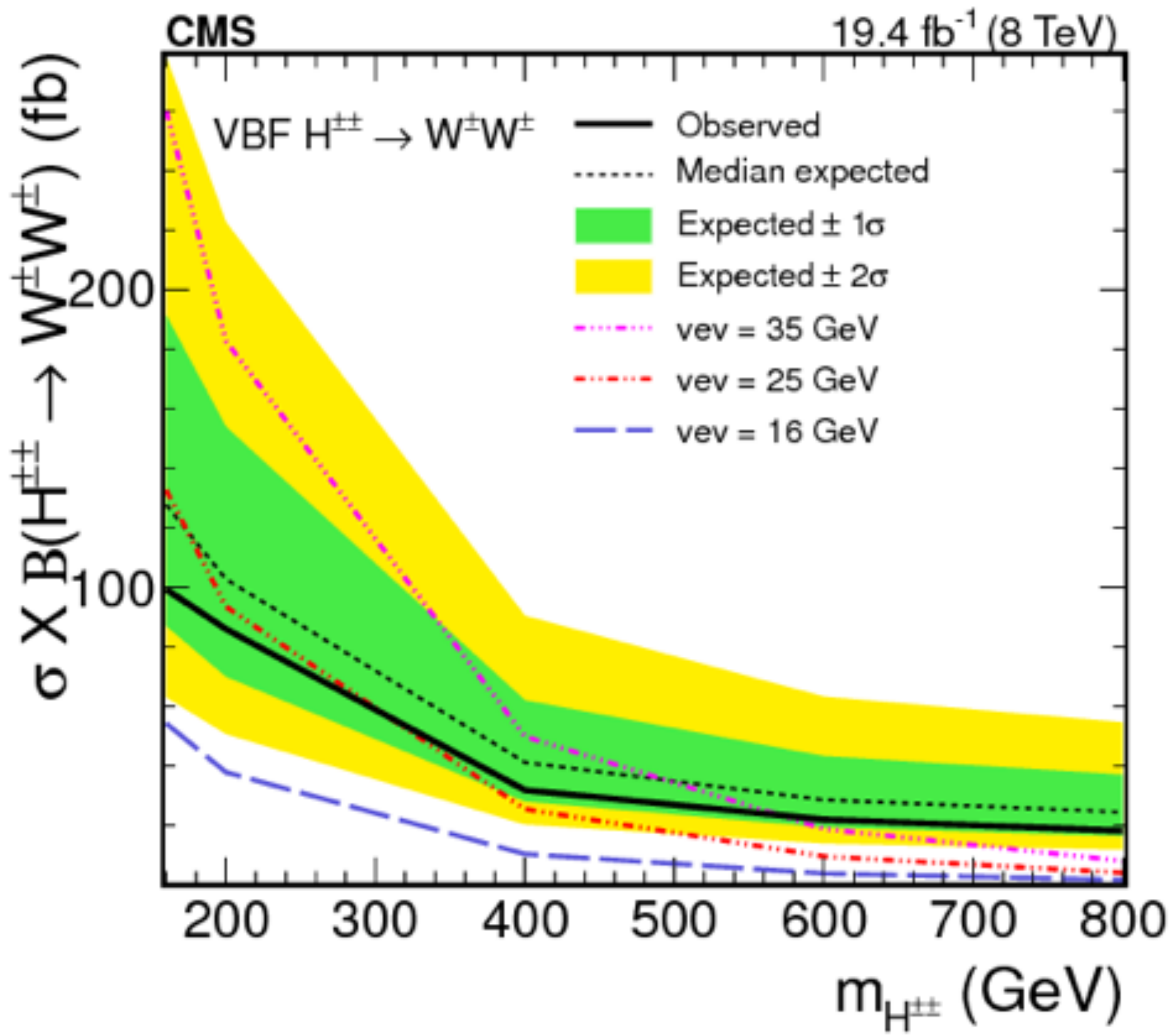
Other Searches

LEP-II limit (pair-production) on $M_{H^{\pm\pm}} > 97.3\,\text{GeV}$ **(hep-ex/0303026)**

VBF at LHC - same sign gauge boson **(arXiv: 1410.6315, 1709.05822)**

Sensitive to large triplet vev

$pp \to H^{\pm\pm} jj$



similar result for 13 TeV search

$v_\Delta = 0.0001 - 1$ GeV

Difficult to probe in VBF

Signal reduces by factor 2

$e^+e^- \to H^{++}H^{--} \to W^+W^+W^-W^- \to N j_{\text{fat}}$

Masses (GeV)	σ_p (ab)	$4j_{\text{fat}}$ (> 120 GeV)	4 MD	1 tagged	2 tagged	3-tagged	4-tagged
800	1250	812.9	758.0	757.9	748.9	671.8	389.0
1000	850.6	527.0	492.5	492.3	486.1	436.6	258.9
1120	670.0	380.0	358.4	358.3	354.2	321.9	193.1
1350	167.1	80.4	75.54	75.52	74.88	68.2	42.0
1400	94.36	45.54	42.85	42.84	42.42	38.6	24.0

Backgrounds

Processes	σ_p (ab)	$4j$ (> 120 GeV)	4 MD	1 tagged	2 tagged	3-tagged	4-tagged
$4j$	6900.0	1310.0	895.0	360.0	68.0	5.5	0.0
W^+3j & W^-3j	1900.0	320.0	220.0	166.0	44.0	4.8	1.52×10^{-1}
W^+W^-2j	190.0	25.6	17.7	15.6	8.3	1.23	5.7×10^{-2}
W^+W^-Zjj	4.23	-	-	-	-	-	-
$t\bar{t}$	42	-	-	-	-	-	-

Largest

Huge background reduction

$e^+e^- \to H^{++}H^{--} \to W^+W^+W^-W^- \to N j_{\text{fat}}$

Masses (GeV)	n_s (2, 3-tagged $\mathcal{L} = 500\,\text{fb}^{-1}$)	$\mathcal{L}(\text{fb}^{-1})$(with 2,3-tagged)
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>=2 tagged jet

>=3 tagging

$M_{H^{\pm\pm}} =$ 800 GeV-1120 GeV discovery with $\mathcal{L} = 39 - 94\,\text{fb}^{-1}$

arXiv:1803.00677

Type-II seesaw

$$\Delta(3,2) \to H^{++}, H^{+}, A^0, H_2^0, H_1^0$$

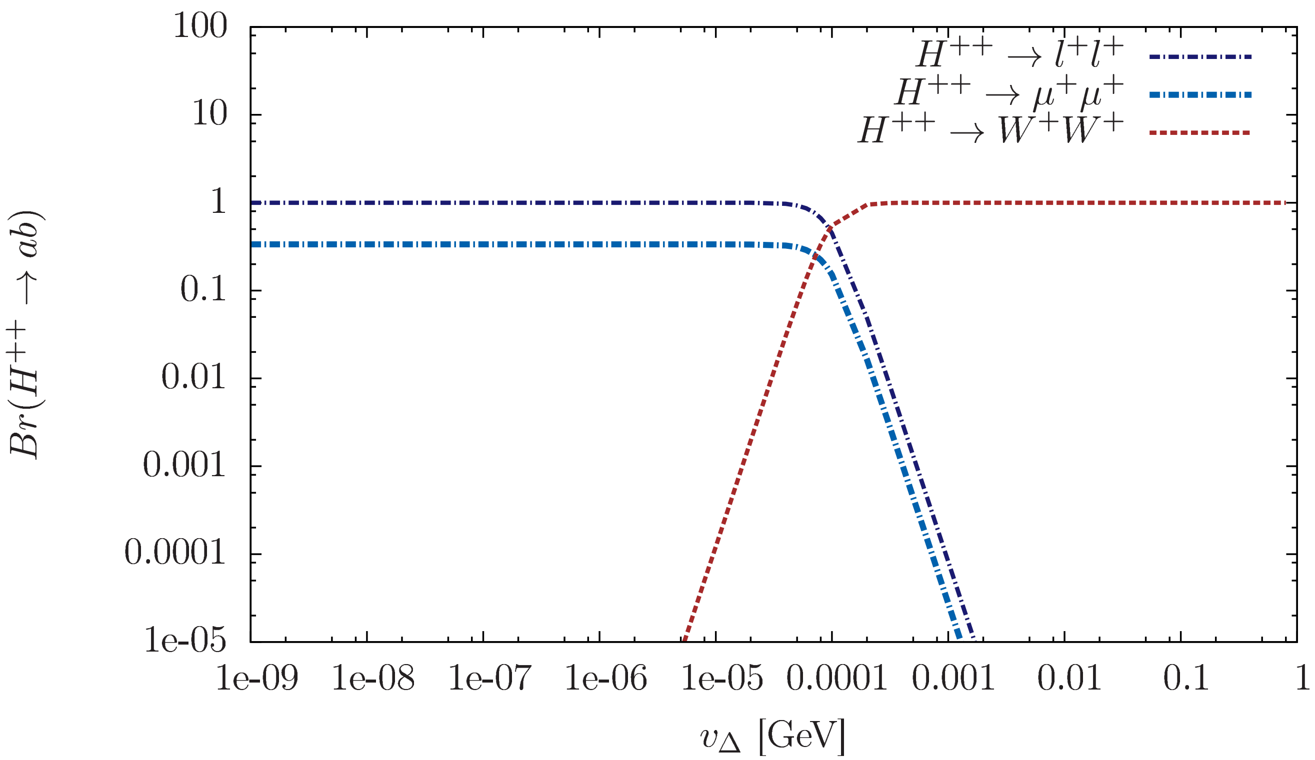
$LL\Delta \to$ Light neutrino mass $M_\nu = y_\Delta v_\Delta$. $\boxed{H^{++}l^-l^- \sim M_\nu/v_\Delta}$.

$$\Gamma\left(H^{++} \to e_i^+ e_j^+\right) = \frac{|M_\nu^{ij}|^2}{8\pi(1 + \delta_{ij})v_\Delta^2} M_{H^{++}}$$

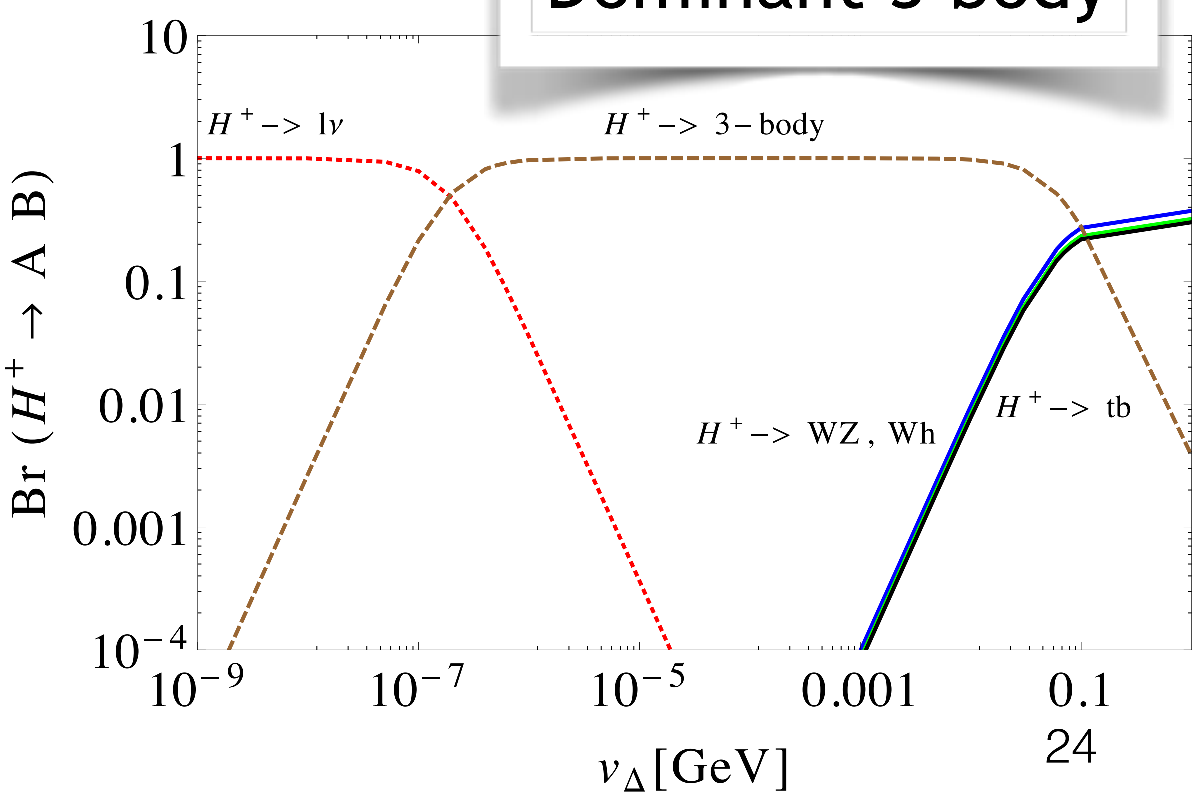
$$\Gamma\left(H^{++} \to W^+ W^+\right) = \frac{v_\Delta^2 M_{H^{++}}^3}{4\pi v_0^4}\left(1 - \frac{4M_W^2}{M_{H^{++}}^2}\right)^{1/2}\left(1 - \frac{2M_W^2}{M_{H^{++}}^2}\right)^2$$

Different $v_\Delta \to$ distinctive H^{++}, H^+ branching

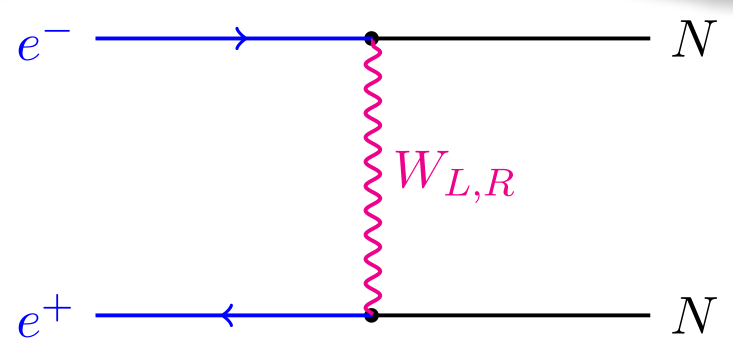
$v_\Delta \geq 10^{-4}$ **GeV** $\to H^{++} \to W^+W^+ \to$ **evading LHC bound**



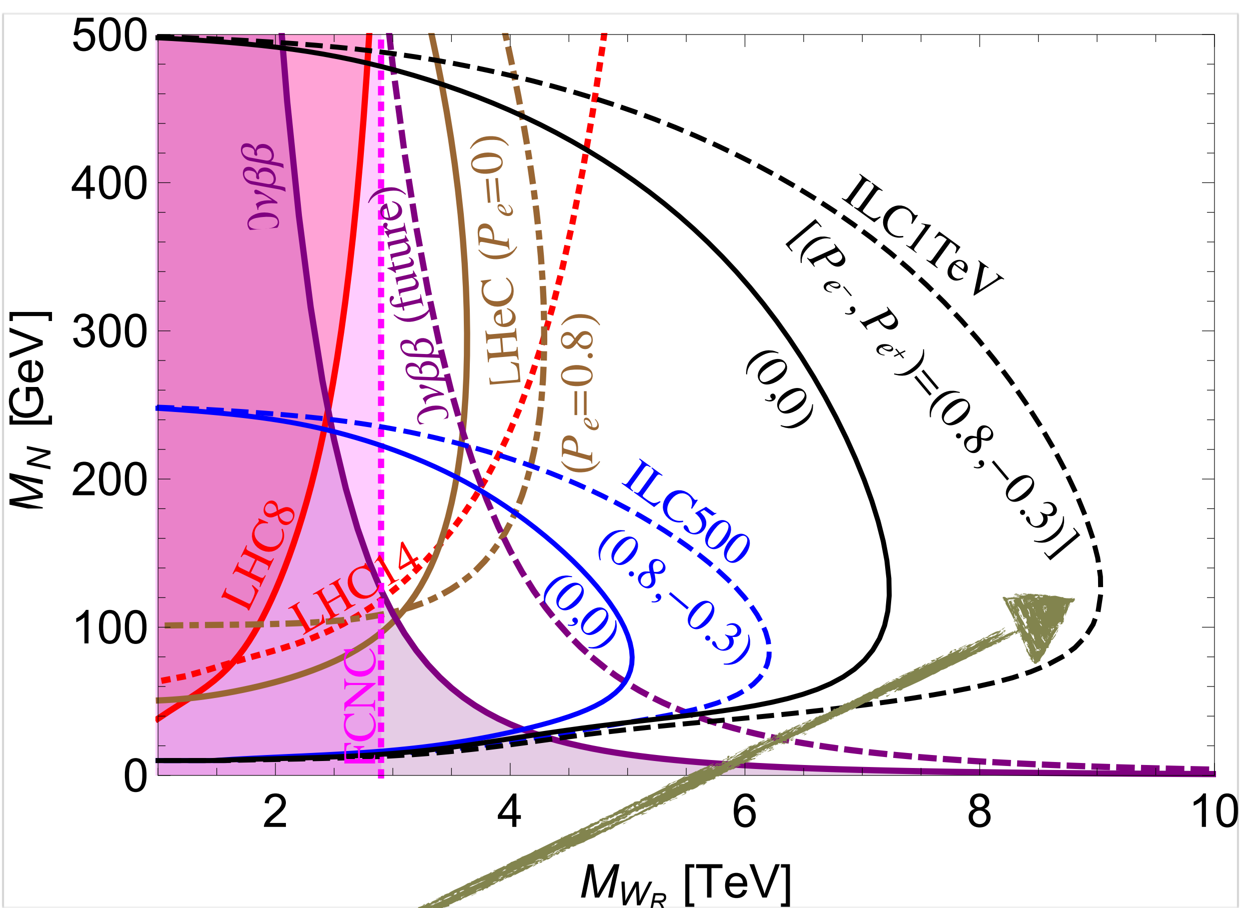
Dominant 3 body



Minimal Left-Right



(a) t-channel production



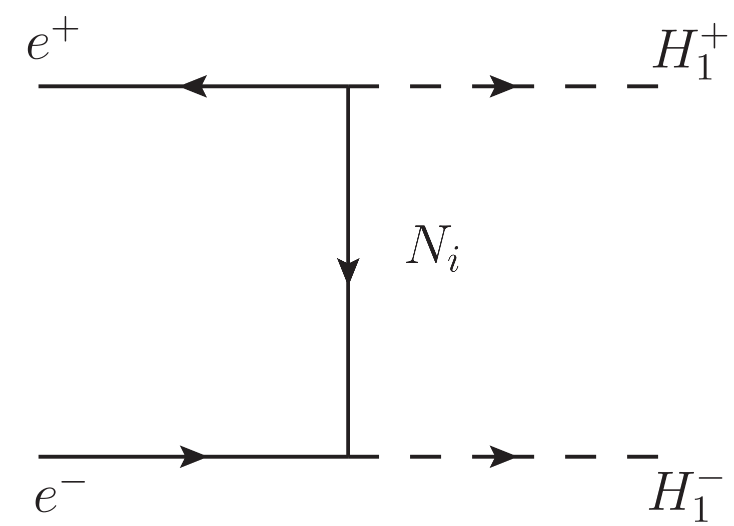
arXiv: 1701.01851, Bhupal Dev et al.,

Larger mass to probe

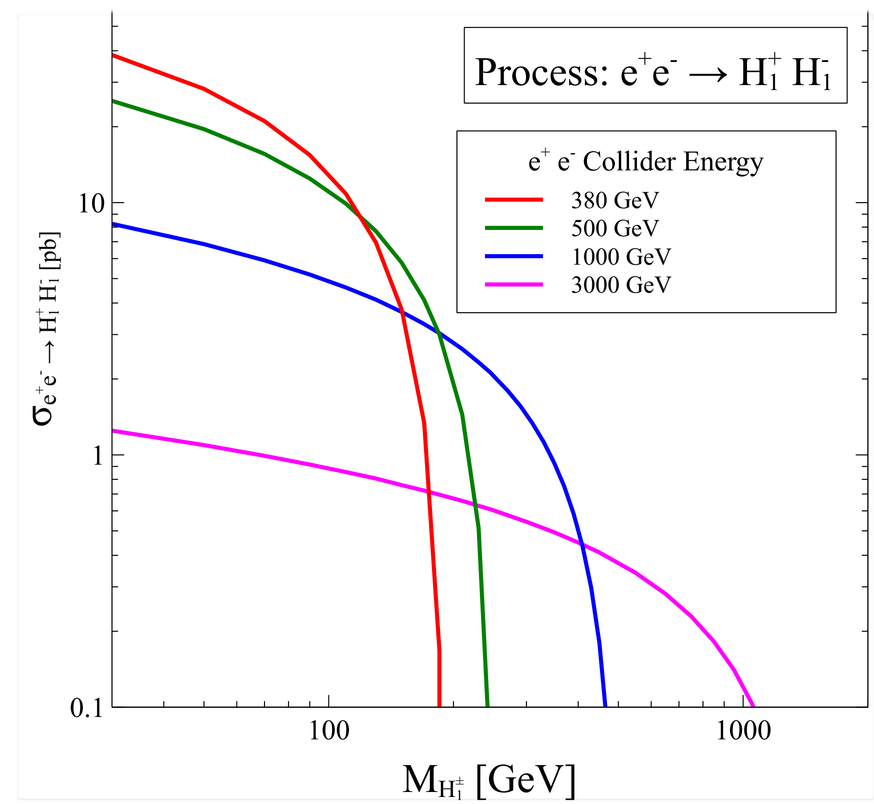
Left-Right Extended Zee Babu

- **Dirac, Majorana Mass at loop level**
- **eV-MeV scale right handed neutrino**

P. Fileviez Perez et al., [arXiv:1607.00246,1701.06801]



Large charged Higgs pair-production in pb



arXiv: 1805.09844, S. Khan, M. Mitra and A. Patra

$M_{H^{\pm\pm}} = 159 - 172\,\text{GeV} \rightarrow \sigma \sim 5.0 - 5.45\,\text{fb} \rightarrow$ Partonic

final cuts and detector effect $\rightarrow \sigma^d_{max} \sim 2.58 fb$

$e^+e^- \to H^{++}H^{--} \to N_j \geq 7j$			
Mass (GeV)	σ_p (fb)	$\sigma_d(N_j \geq 7j)$ (fb)	$\sigma_d(N_j \geq 7j + b\,\text{veto})$ (fb)
121	0.80	0.30	0.20
137	2.08	0.94	0.66
159	5.45	2.58	1.82
172	5.04	2.48	1.74
184	1.11	0.53	0.38

Backgrounds			
Processes	σ_p (fb) $\times 10^{-2}$	$\sigma_d(N_j \geq 7j)$ (fb)$\times 10^{-2}$	$\sigma_d(N_j \geq 7j + b\,\text{veto})$ (fb) $\times 10^{-2}$
$e^+e^- \to t\bar{t} \to 6j$	10341.0	338.0	36.0
$W^+W^-3j, W^\pm \to 2j$	8.89	1.18	0.88
$ZZ + 3j, Z \to 2j$	0.98	0.13	0.10
$7j$	30.32	1.13	0.88
$W^\pm + 5j, W^\pm \to jj$	30.18	4.64	3.54
$Z + 5j, Z \to jj$	18.32	2.15	1.61

Drop in background

Significance

$\mathcal{L} = 100\,\text{fb}^{-1}$

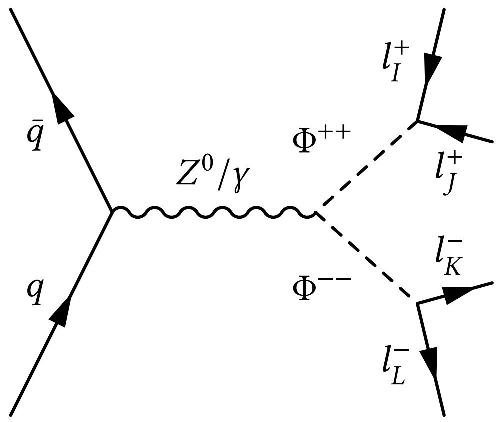
$e^+e^- \to H^{++}H^{--} \to N_j \geq 7j$		
Mass (GeV)	n_s	$\mathcal{L}\,(\text{fb}^{-1})$
121	1.54	1054.14
137	4.48	124.56
159	10.48	22.76
172	10.15	24.26
184	2.69	345.48

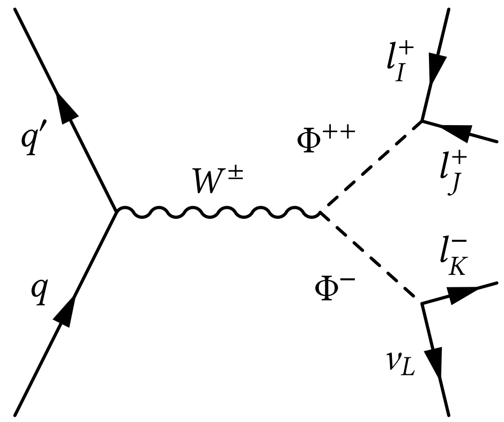
159-172 GeV can be detected in the early run

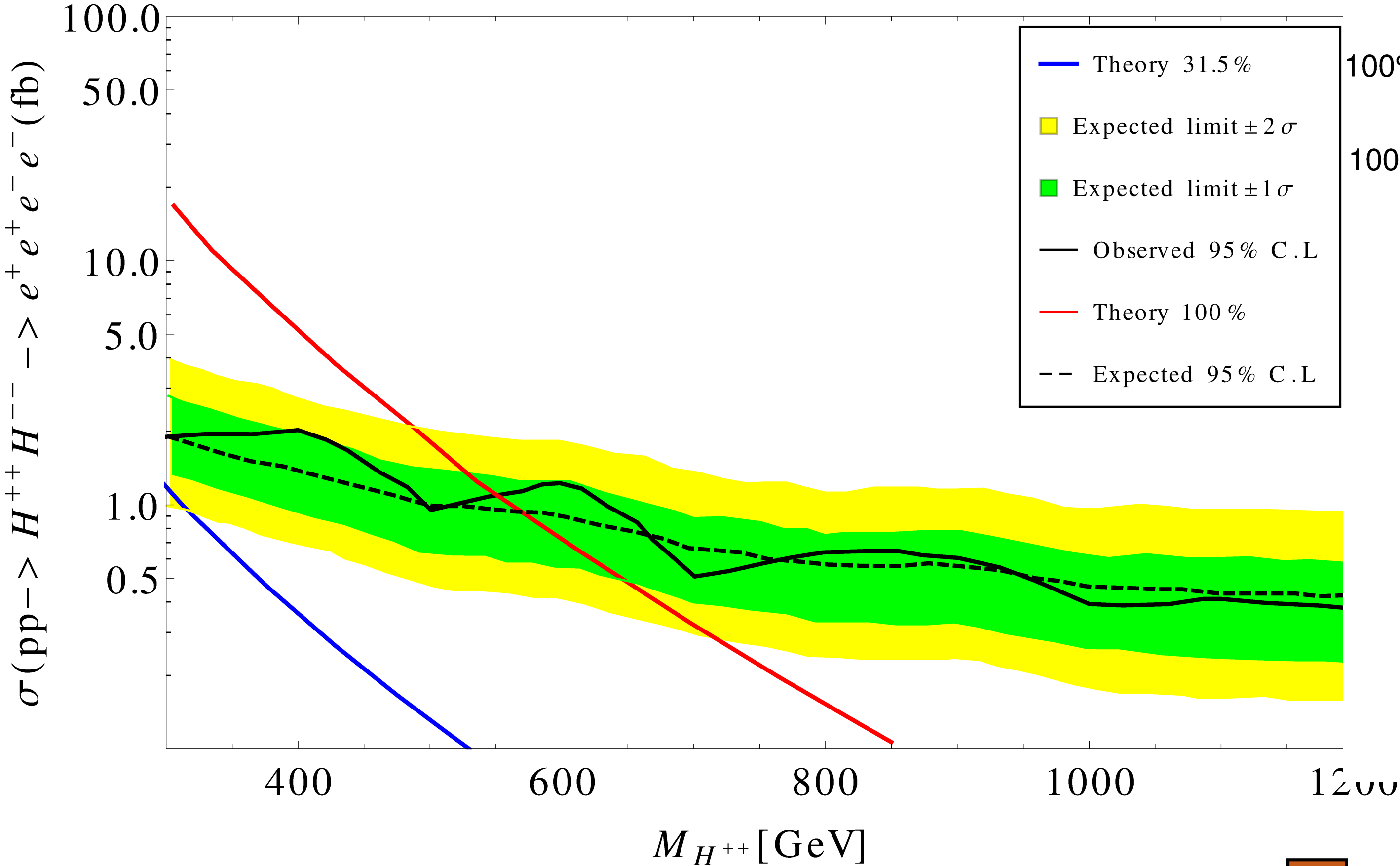
Required luminosity

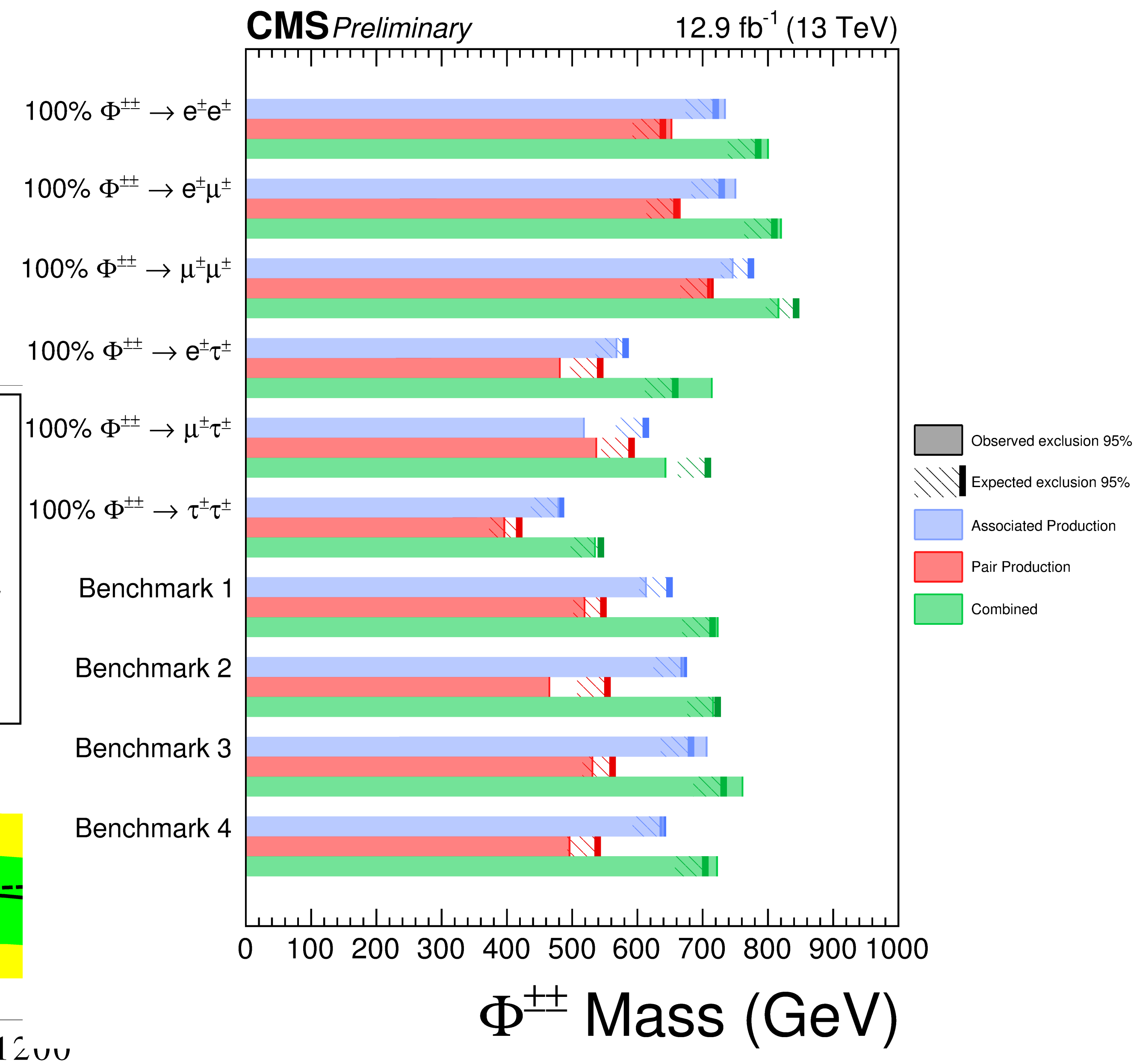
arXiv:1803.00677

Limit from LHC









$M_{H++} \geq 580$ GeV in the $4e$ channel ATLAS-CONF-2016-051

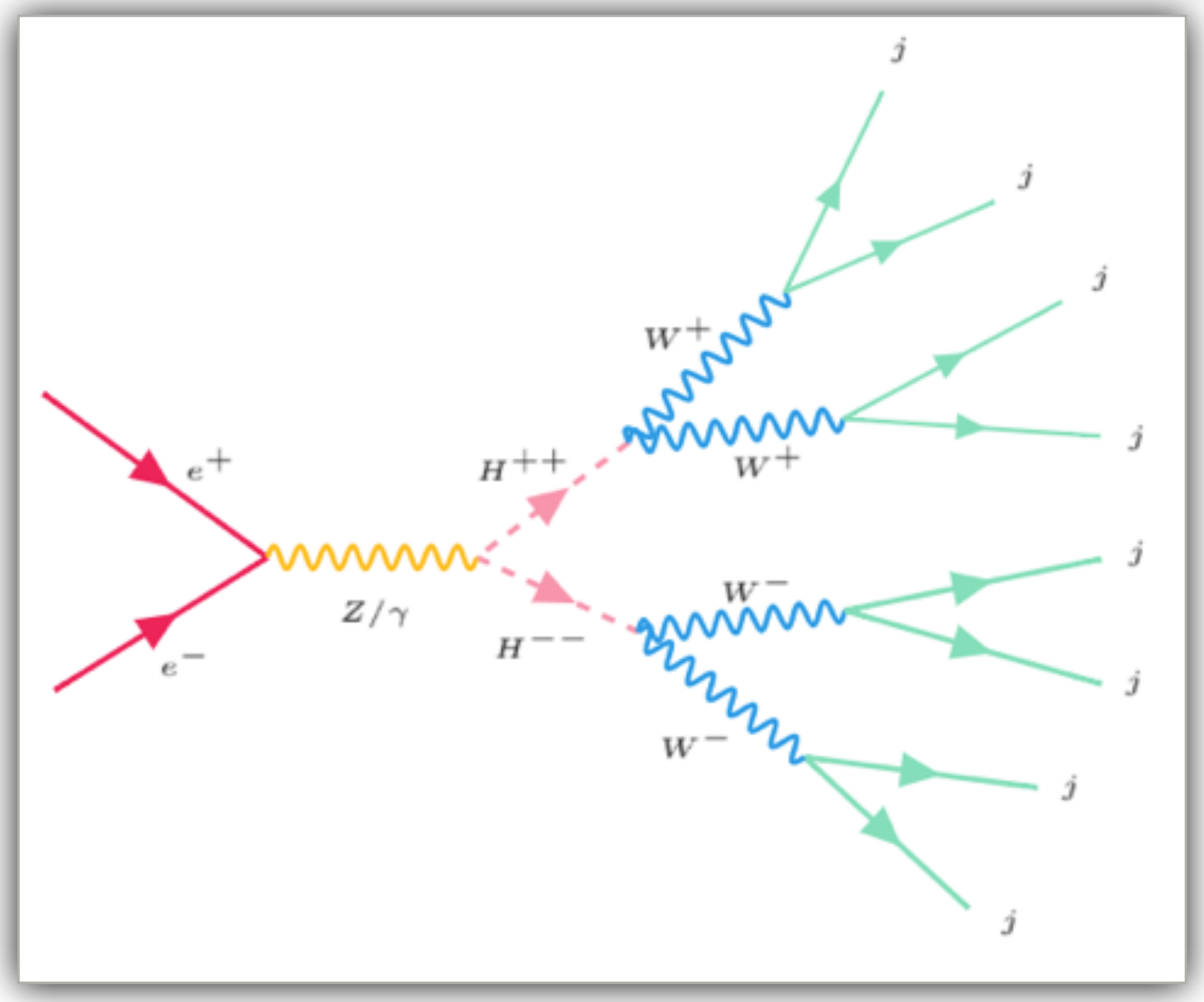
Combined bound $\rightarrow M_{H++} \geq 820$ (100% Br)-small v_Δ HIG-16-036-pas

Lighter Higgs at 380 GeV:

$$e^+e^- \to H^{\pm\pm}H^{\mp\mp} \to W^+W^+W^-W^- \geq 7j$$

Model Signatures → All hadronic

- $e^+e^- \to H^{\pm\pm}H^{\mp\mp} \to 4W \geq 7j$ for $M_{H^{\pm\pm}} \gtrsim 2M_W$ → **On-shell W decay**
- $e^+e^- \to H^{\pm\pm}H^{\mp\mp} \to W^{\pm}jjW^{\mp}jj \geq 7j$ for $M_{H^{\pm\pm}} < 2M_W$ → **Off-shell W decay**

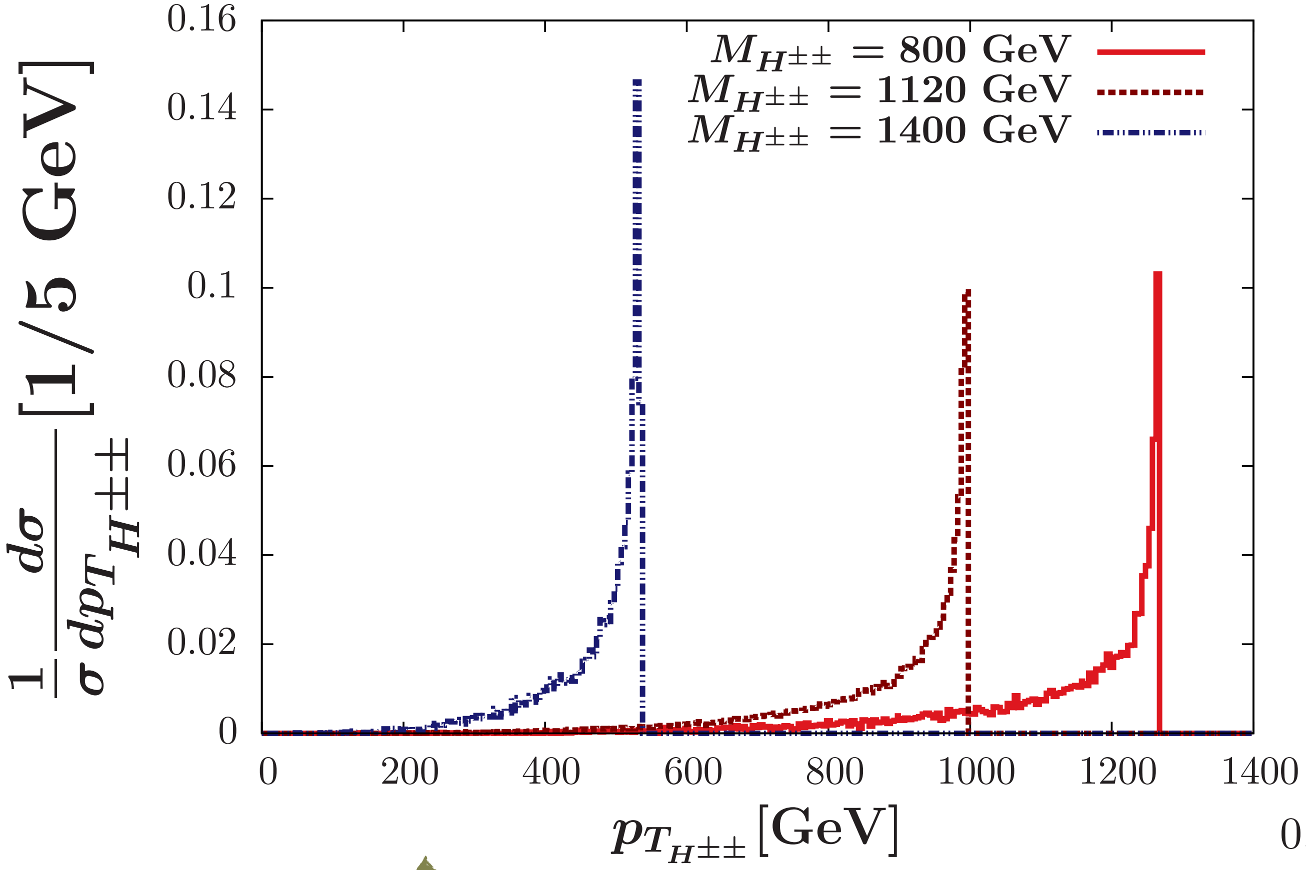


$$M_{H^{\pm\pm}} > 2M_W$$

$$M_{H^{\pm\pm}} < 2M_W$$

$p_T \sim 500\,GeV - 1\,TeV$

Boosted Higgs



Backgrounds for 4 fat-jet

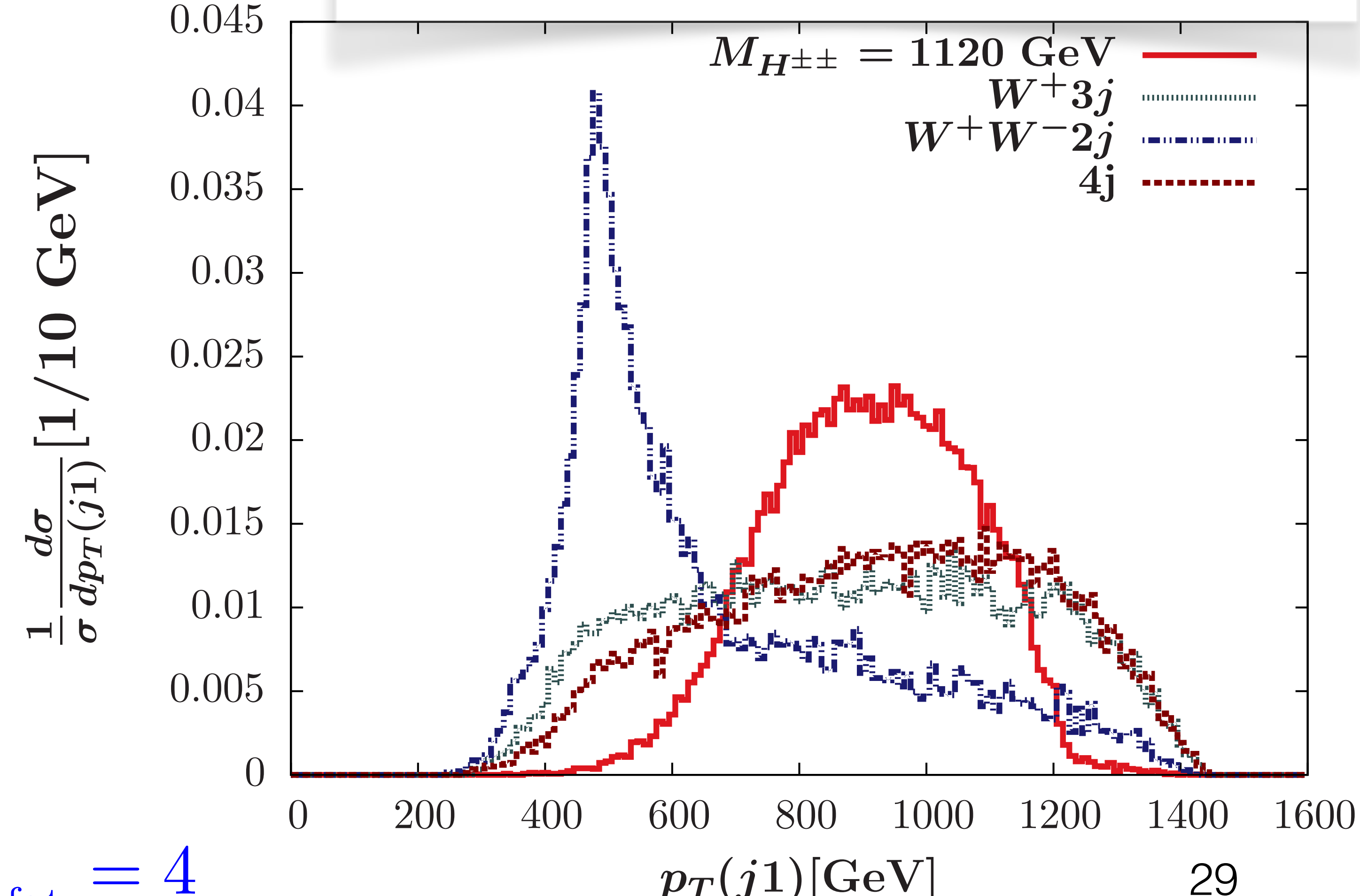
$$4j(\text{QED}, \text{QCD})$$

$$W^{\pm} + 3j, W^{\pm} \to 2j$$

$$W^+W^- + 2j, W^{\pm} \to 2j$$

$$W^+W^-Zjj, V \to 2j$$

$$t\bar{t}$$



$\text{Selection cuts}: \mathrm{p_T(j_i)} > 120\,\mathrm{GeV}, \mathrm{N_{j_{fat}}} = 4$