Neutrino Models at Colliders

Bhupal Dev

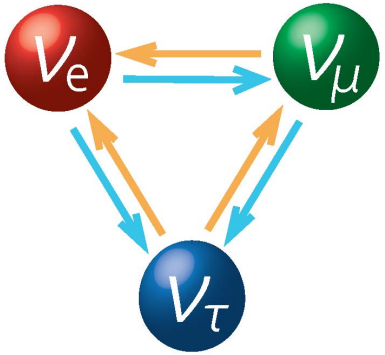
Washington University in St. Louis

SUSY2019

Corpus Christi

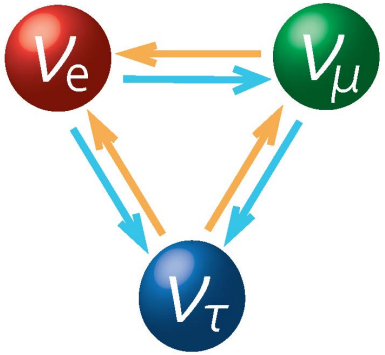
May 22, 2019

Harbinger of New Physics



Non-zero neutrino mass $\Longrightarrow$ physics beyond the Standard Model

Harbinger of New Physics



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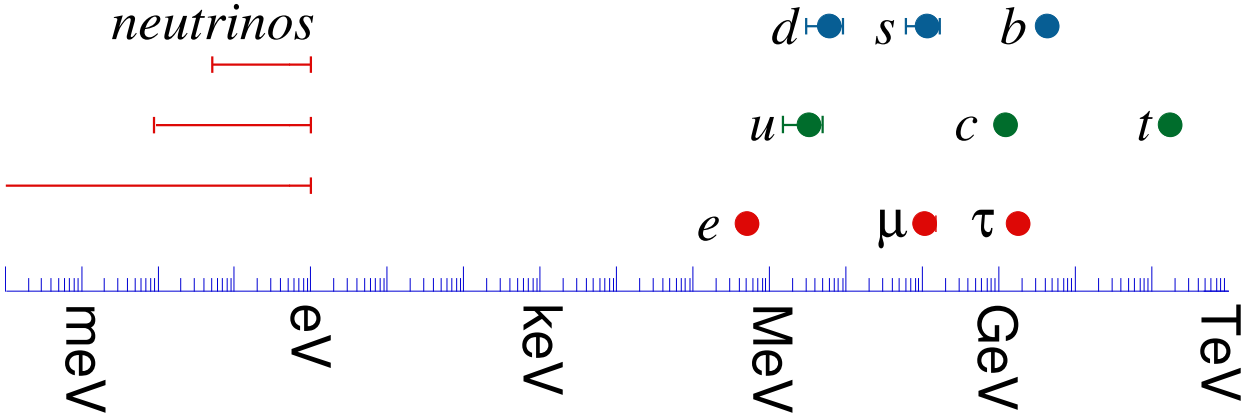

Perhaps something beyond the standard Higgs mechanism...

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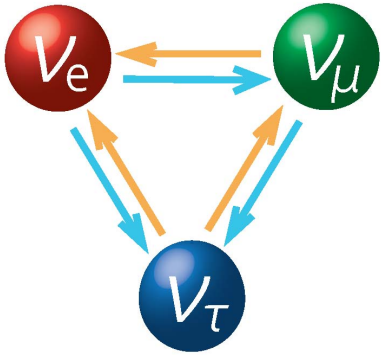

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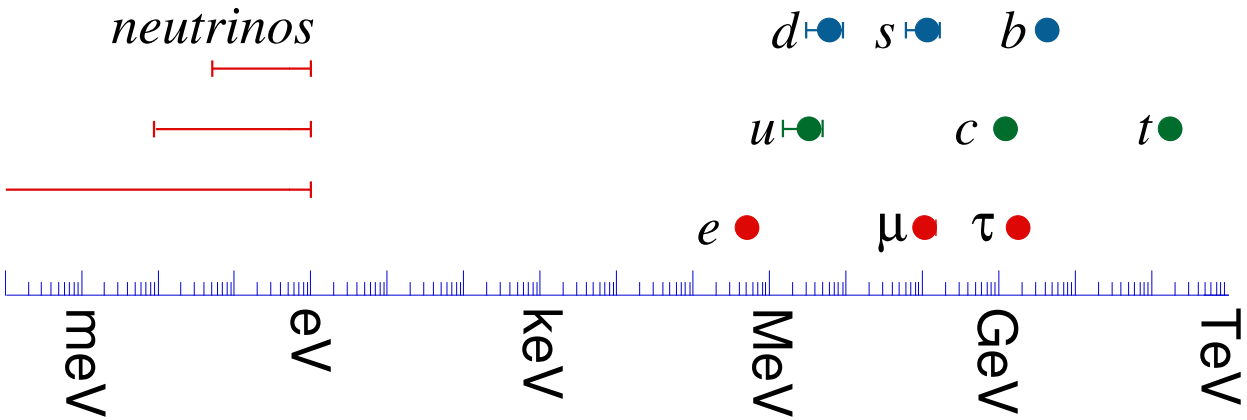

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Can we probe the origin of neutrino mass at colliders?

Neutrino Mass Models

[see Tuesday plenary talk by S. King]

- From pheno point of view, can broadly categorize into
  - Tree-level (seesaw) vs loop-level (radiative)
  - Minimal (SM gauge group) vs gauge-extended [e.g. $U(1)_{B-L}$, Left-Right]
  - Non-supersymmetric vs Supersymmetric

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- New fermions, gauge bosons, and/or scalars – **messengers of neutrino mass physics**.
- Rich phenomenology.
- For messenger scale $\lesssim \mathcal{O}(\text{few TeV})$, accessible at the LHC and/or future colliders.
- Connection to other puzzles (e.g. baryogenesis, dark matter).

New Fermions

(aka sterile neutrinos/heavy neutrinos/heavy neutral leptons)

Type-I Seesaw

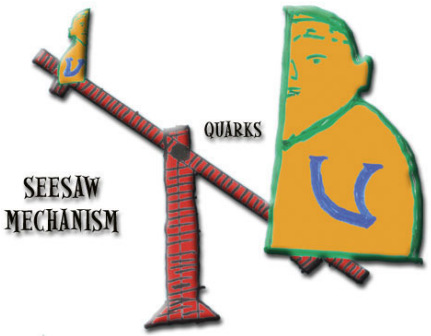
[Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]

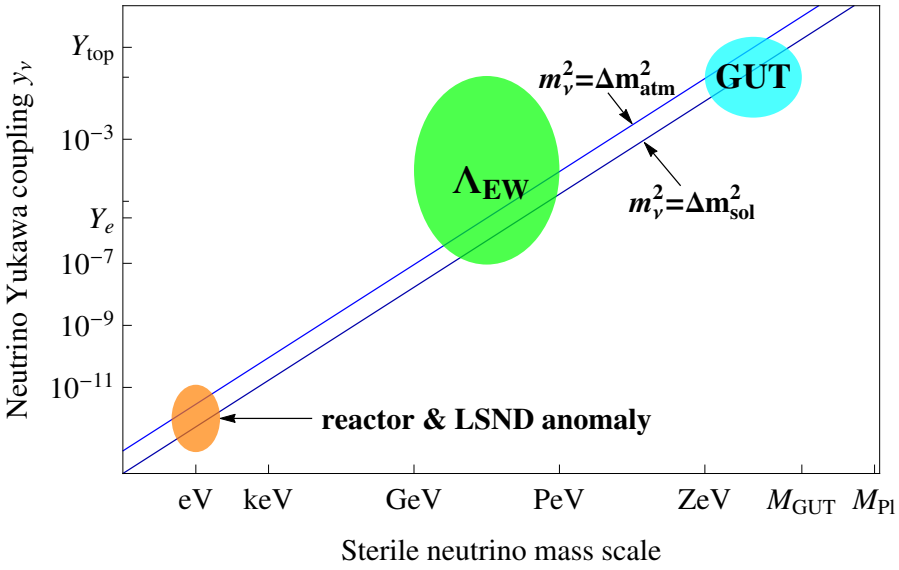
- Introduce SM-singlet **Majorana** fermions (N).

$$-\mathcal{L} \supset Y_\nu \overline{L}\phi^c N + \frac{1}{2} M_N \overline{N}^c N + \text{H.c.}$$

- After EWSB, $m_\nu \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}$, where $M_D = v Y_\nu$.

[Figure from Antusch, Cazzato, Fischer (IJMPA '17)]





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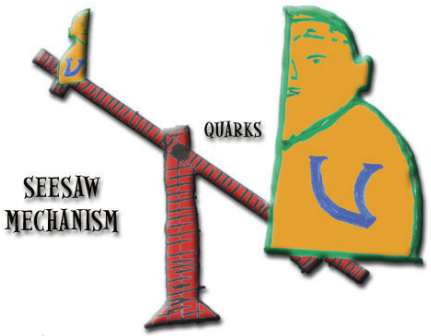
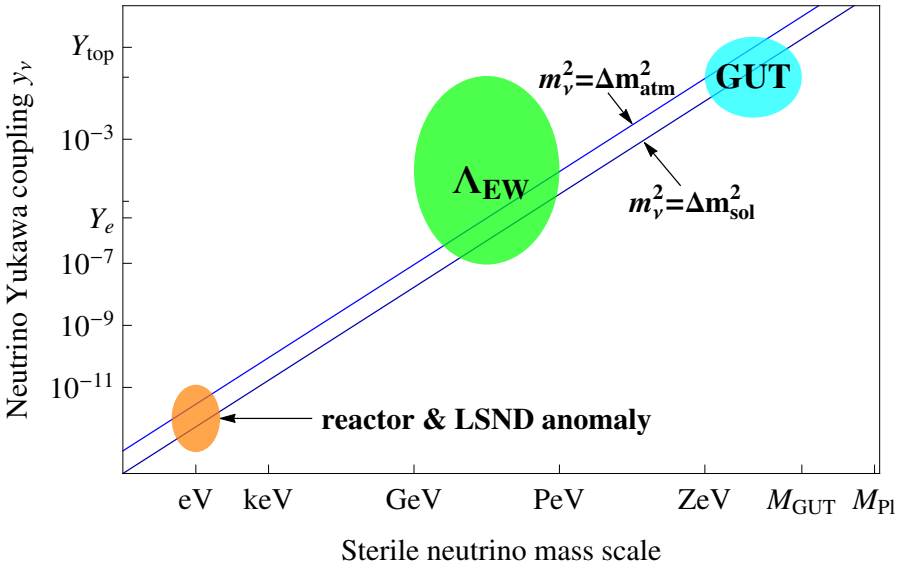




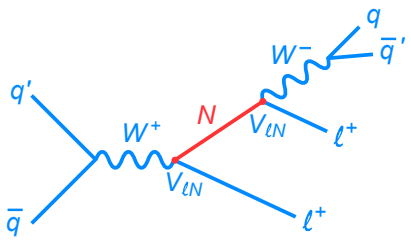
- Naturalness of Higgs mass suggests $M_N \lesssim 10^7$ GeV.

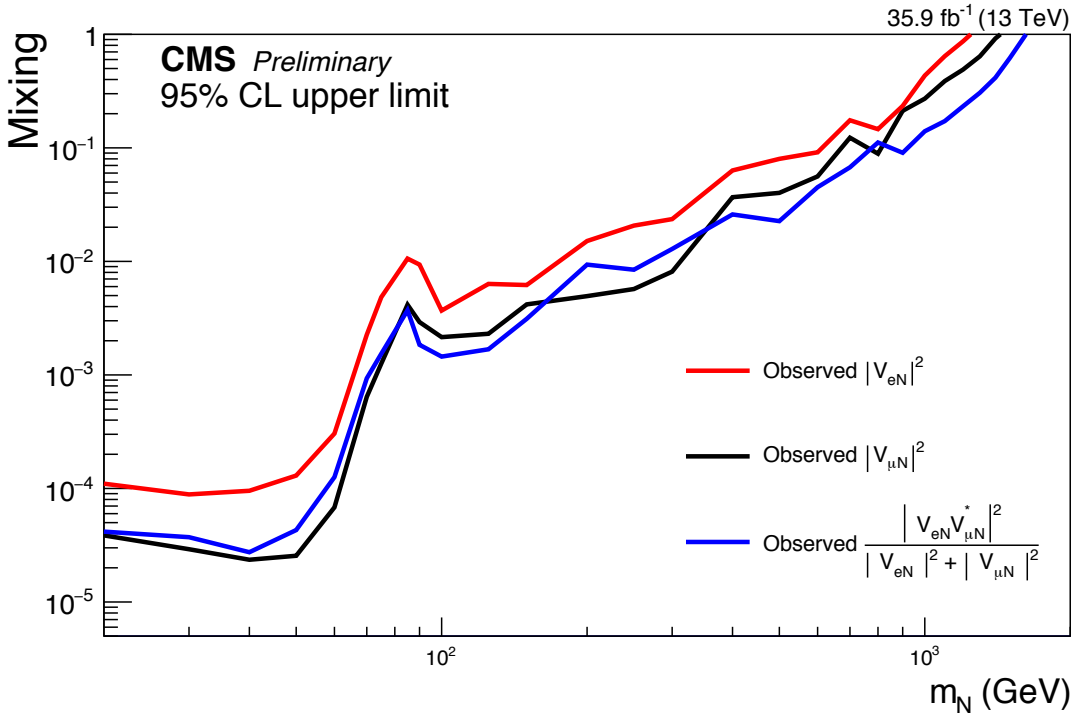
[Vissani (PRD '98); Clarke, Foot, Volkas (PRD '15); Bambhaniya, BD, Goswami, Khan, Rodejohann (PRD '17)]

Heavy Majorana Neutrinos at the LHC

[Keung, Senjanović (PRL '83); Datta, Guchait, Pilaftsis (PRD '94); Panella, Cannoni, Carimalo, Srivastava (PRD '02); Han, Zhang (PRL '06); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07); Atre, Han, Pascoli, Zhang (JHEP '09)]

Same-sign dilepton plus jets (without $\not{E}_T$)





[CMS PAS EXO-17-028]

Probes (sub) TeV-scale heavy **Majorana** neutrinos with 'large' active-sterile mixing.

Low-scale Seesaw with Large Mixing

- Naively, active-sterile neutrino mixing is small for EW-scale seesaw:

$$V_{\ell N} \simeq M_D M_N^{-1} \simeq \sqrt{\frac{m_\nu}{M_N}} \lesssim 10^{-6} \sqrt{\frac{100\ \mathrm{GeV}}{M_N}}$$

- 'Large' mixing effects possible with special structures of M_D and M_N.

  [Pilaftsis (ZPC '92); Gluza (APPB '02); de Gouvea '07; Kersten, Smirnov (PRD '07); Gavela, Hambye, Hernandez, Hernandez (JHEP '09); Ibarra, Molinaro, Petcov (JHEP '10); Adhikari, Raychaudhuri (PRD '11); Mitra, Senjanović, Vissani (NPB '12); BD, Lee, Mohapatra (PRD '13);...]

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- One example: [Kersten, Smirnov (PRD '07)]

$$M_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \quad \text{and} \quad M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix} \quad \text{with } \epsilon_i, \delta_i \ll m_i.$$

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- But the steriles with large mixing are 'quasi-Dirac' with suppressed LNV.
- Generic requirement in order to satisfy neutrino oscillation data and $0\nu\beta\beta$ constraints. [Abada, Biggio, Bonnet, Gavela, Hambye (JHEP '07); Ibarra, Molinaro, Petcov (JHEP '10); Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, Lucente (JHEP '15); Drewes, Garbrecht, Gueter, Klaric (JHEP '16)]
- Should also look for lepton number conserving channels at the LHC.

Inverse Seesaw

- Provides a (technically) natural low-scale seesaw framework.
- Two sets of SM-singlet fermions with opposite lepton numbers. [Mohapatra, Valle (PRD '86)]

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\begin{aligned}
-\mathcal{L}_Y &\supset Y_\nu \overline{L}\phi^c N + M_N \overline{S} N + \frac{1}{2}\mu_S \overline{S} S^c + \text{H.c.} \\
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V_{\ell N} \simeq \sqrt{\frac{m_\nu}{\mu_S}} \approx 10^{-2} \sqrt{\frac{1\ \text{keV}}{\mu_S}}
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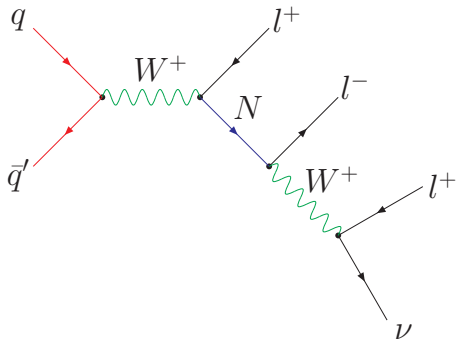
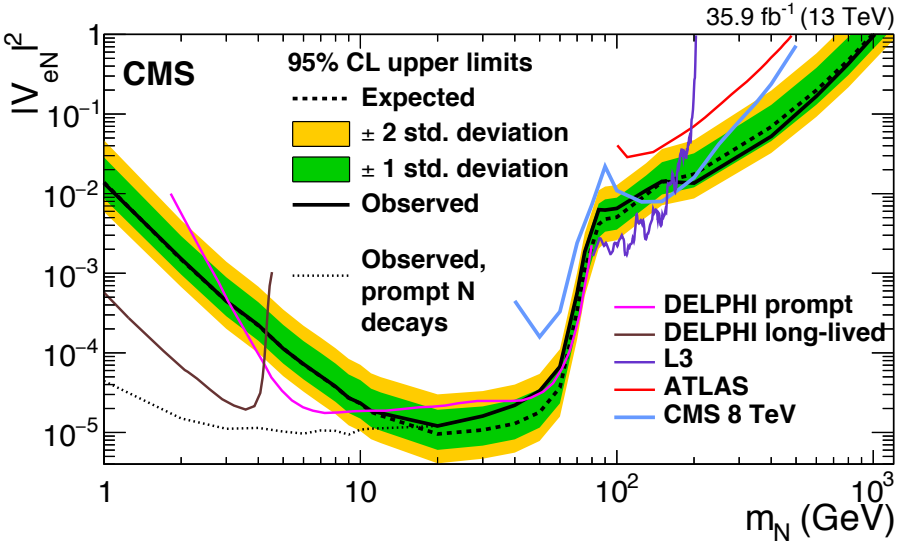
- But again quasi-Dirac heavy neutrinos.
- Should look for **both** lepton number conserving and violating channels at the LHC.
- Ratio of same-sign to opposite-sign dilepton signal could test the Majorana vs. Dirac nature. [Gluza, Jelinski (PLB '15); BD, Mohapatra (PRL '15); Gluza, Jelinski, Szafron (PRD '16); Anamiati, Hirsch, Nardi (JHEP '16); Das, BD, Mohapatra (PRD '17)]

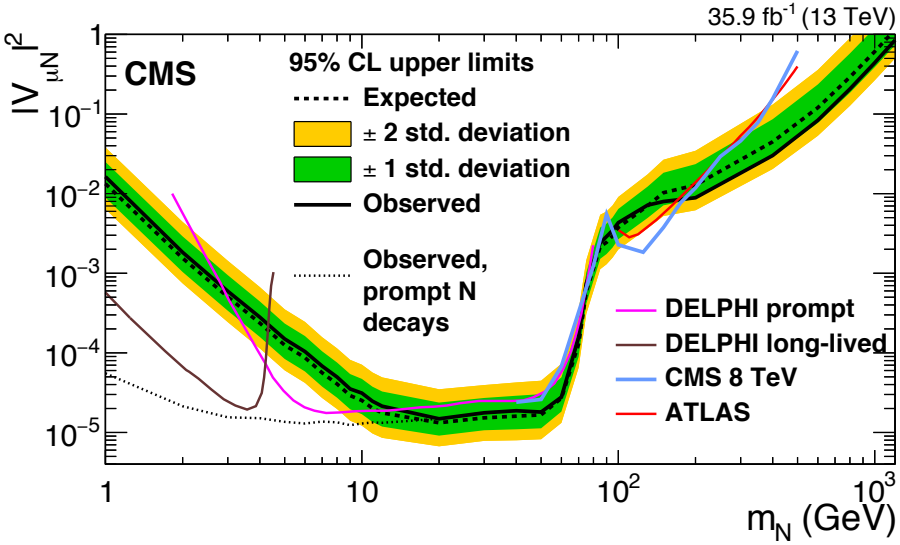
Heavy (Pseudo) Dirac Neutrinos at the LHC

[del Aguila, Aguilar-Saavedra (PLB '09; NPB '09); Chen, BD (PRD '12); Das, Okada (PRD '13); Das, BD, Okada (PLB '14); Izaguirre, Shuve (PRD '15); Dib, Kim (PRD '15); Dib, Kim, Wang (PRD '17; CPC '17); Dube, Gadkari, Thalapillil (PRD '17)]

Trilepton plus $\not{E}_T$



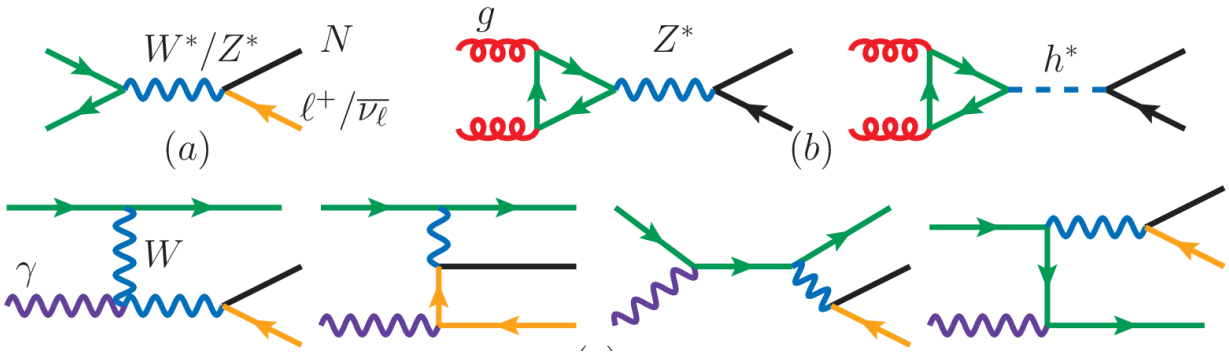


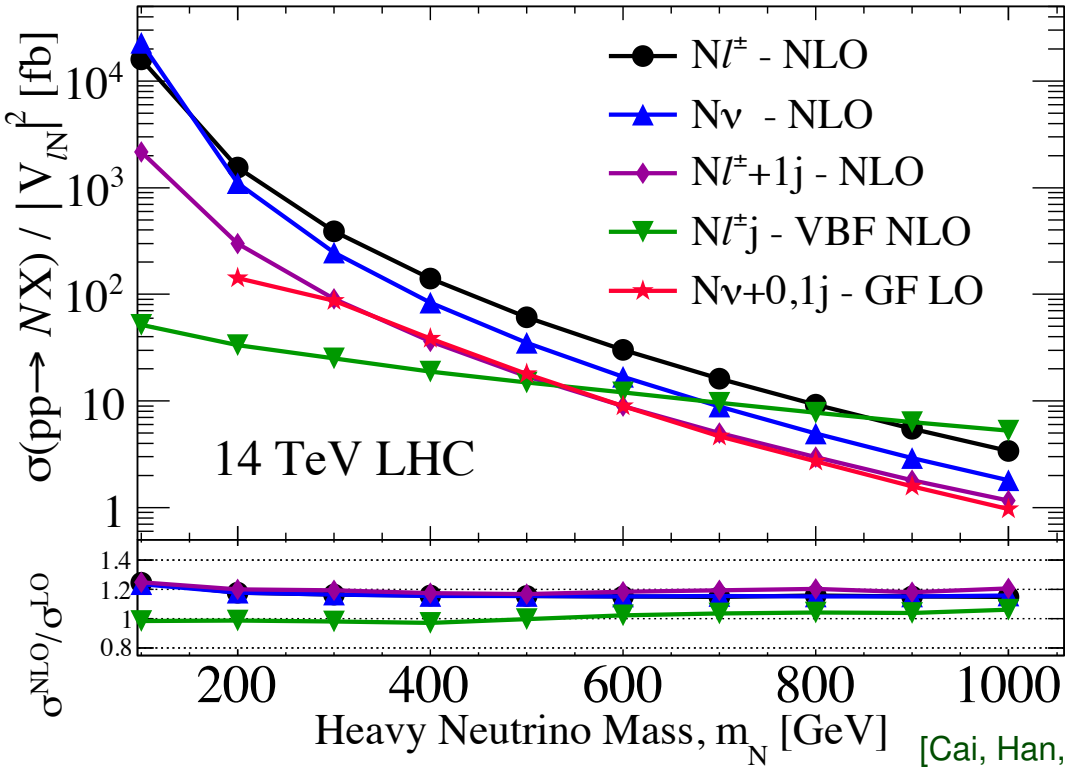


[CMS Collaboration, Phys. Rev. Lett. **120**, 221801 (2018)]

Importance of VBF for Heavy Neutrino Production

[BD, Pilaftsis, Yang (PRL '14); Alva, Han, Ruiz (JHEP '15); Degrande, Mattelaer, Ruiz, Turner (PRD '16); Das, Okada (PRD '16)]

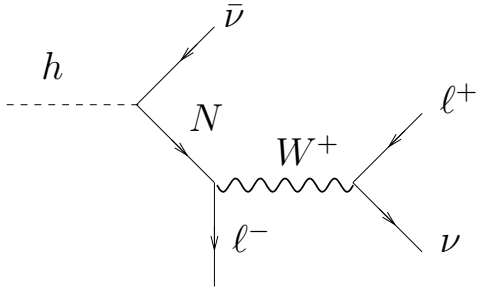


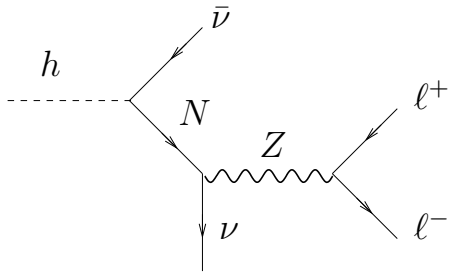


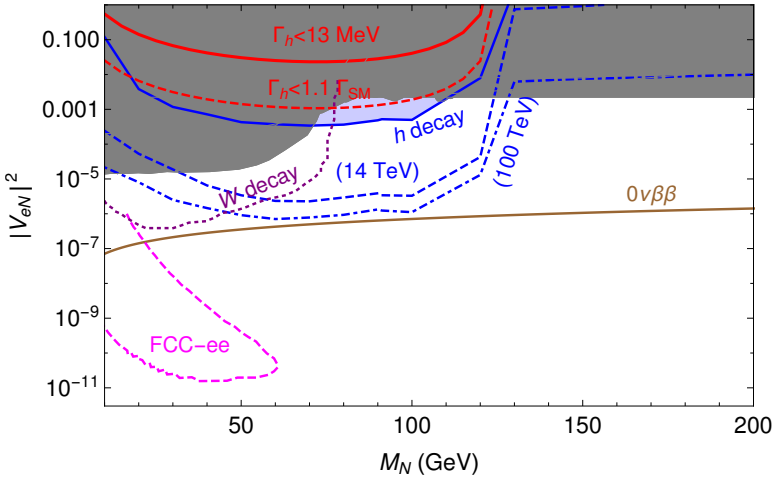
[Cai, Han, Li, Ruiz (Front. in Phys. '18)]

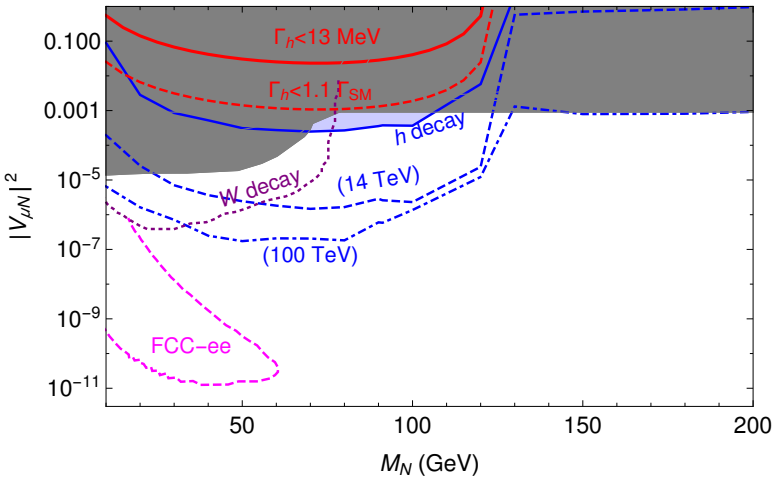
Higgs Decay

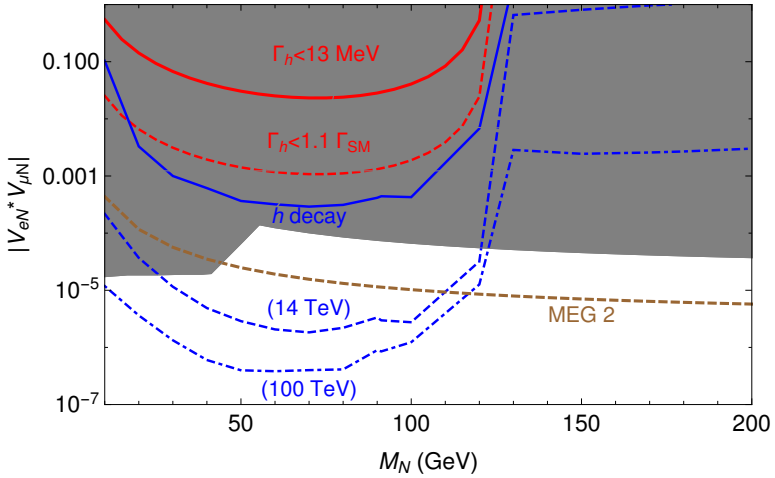
[BD, Franceschini, Mohapatra (PRD '12); Cely, Ibarra, Molinaro, Petcov (PLB '13)]





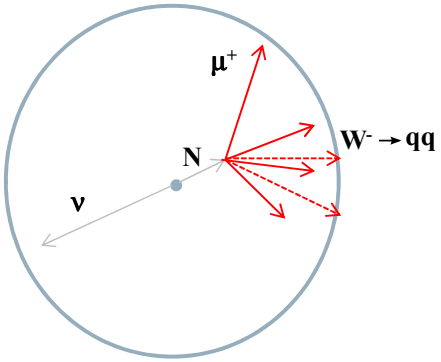


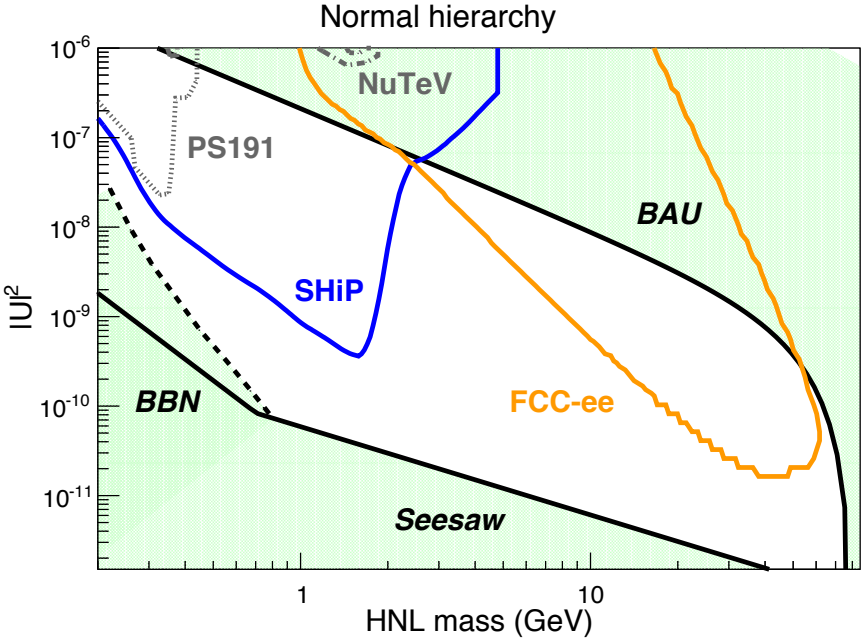




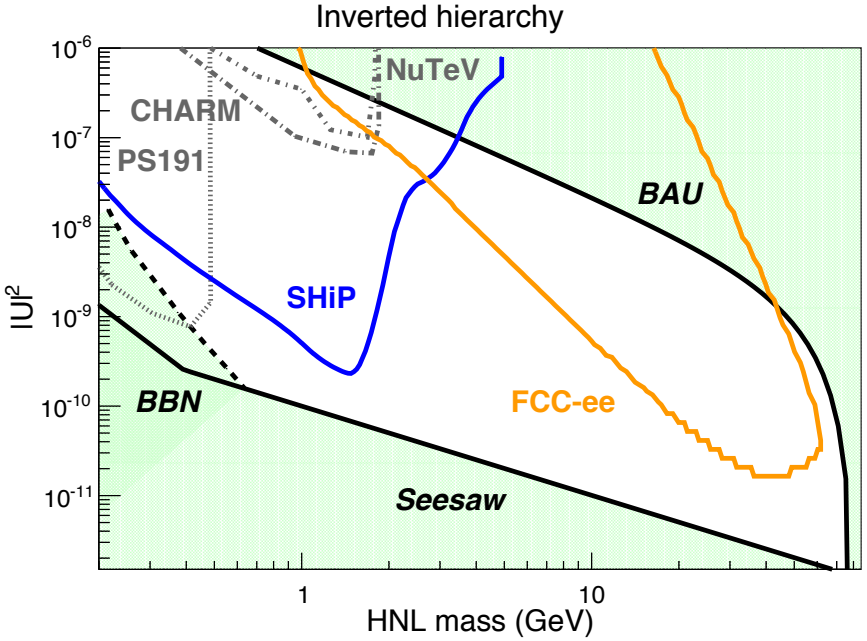
[Das, BD, Kim (PRD '17)]

Z Decay





(a) Decay length 10-100 cm, 10^{12} Z^0

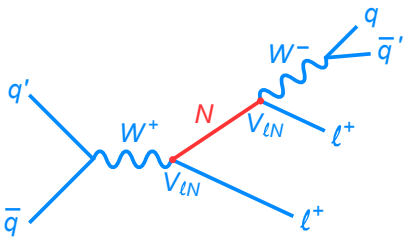


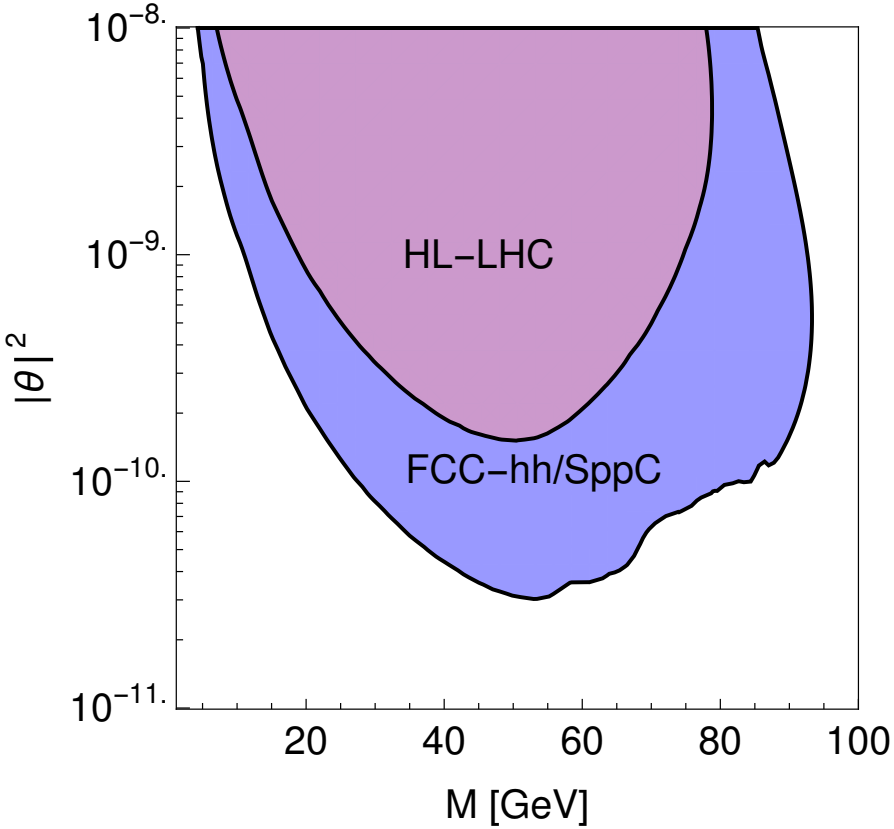
(a) Decay length 10-100 cm, 10^{12} Z^0

[Blondel, Graverini, Serra, Shaposhnikov, 1411.5230]

Can access the region for successful **leptogenesis** via heavy neutrino oscillations.

Displaced Vertex Search





[Antusch, Cazzato, Fischer (IJMPA '17)]

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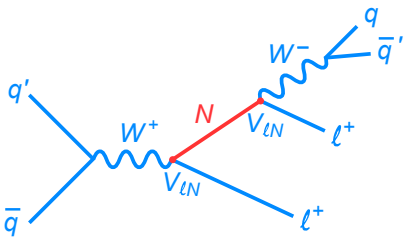
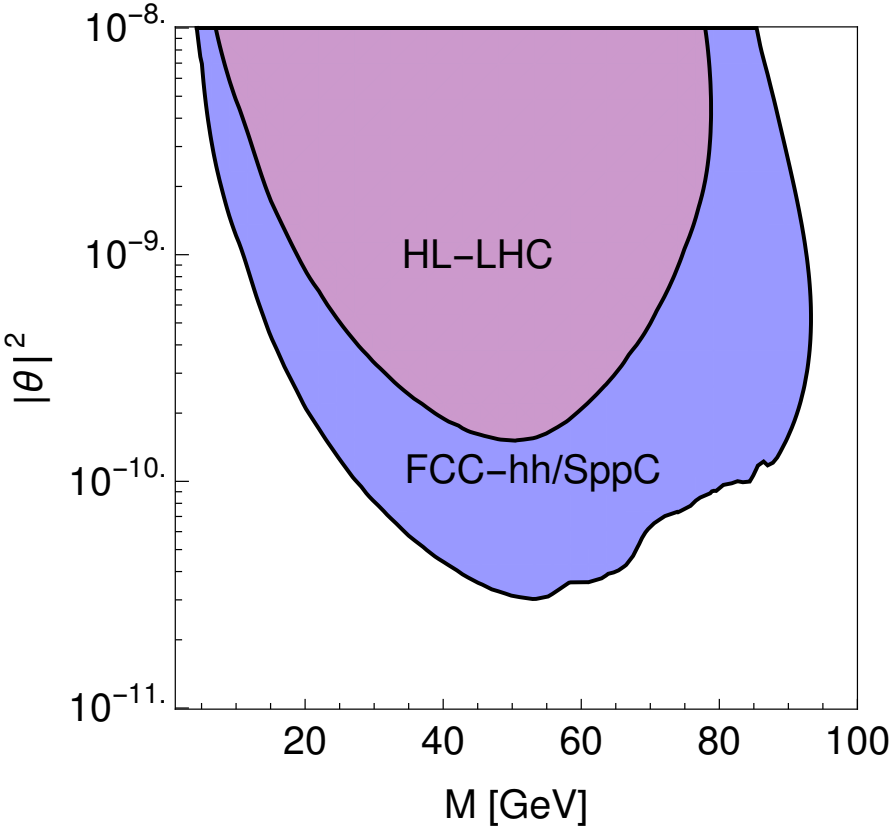
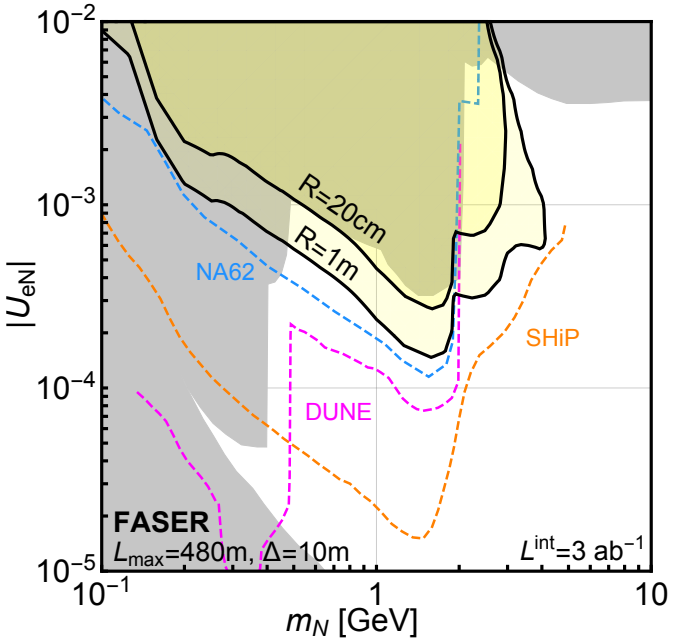




[Antusch, Cazzato, Fischer (IJMPA '17)]

[Kling, Trojanowski (PRD '18)]



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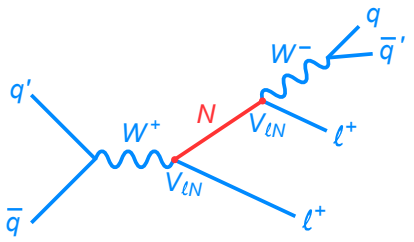
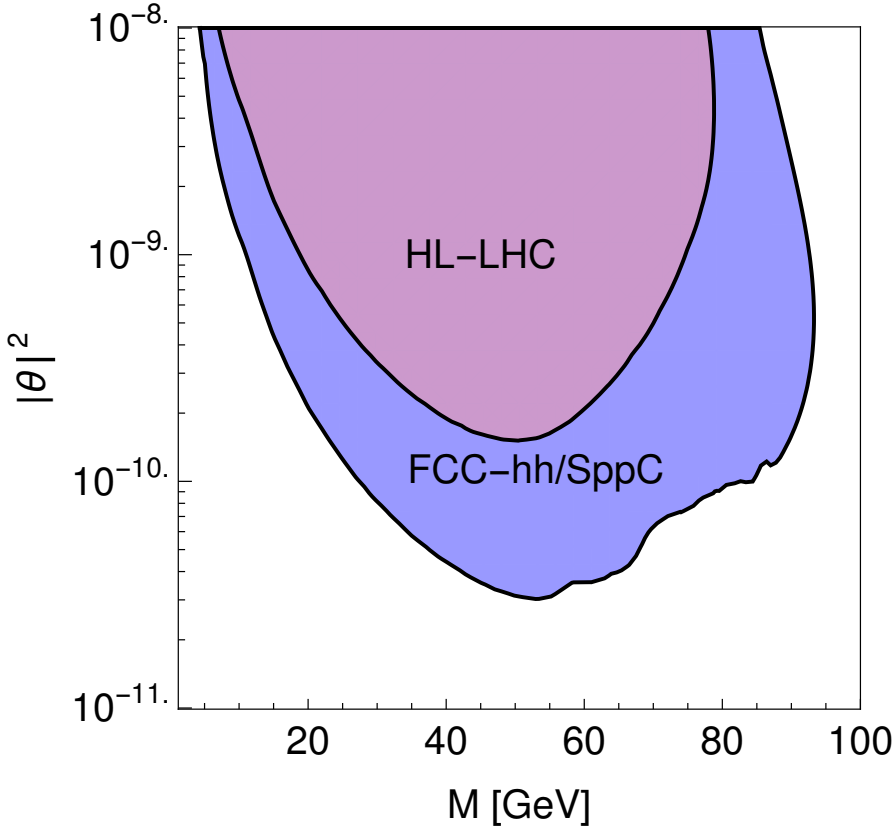
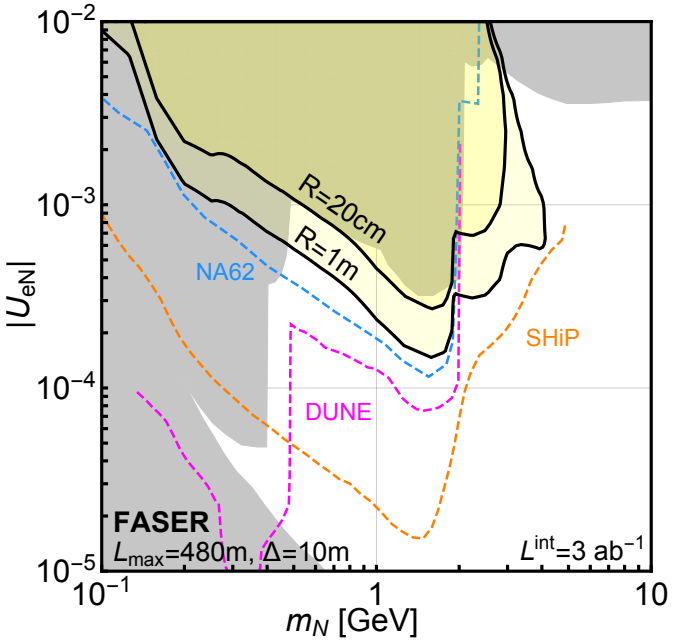
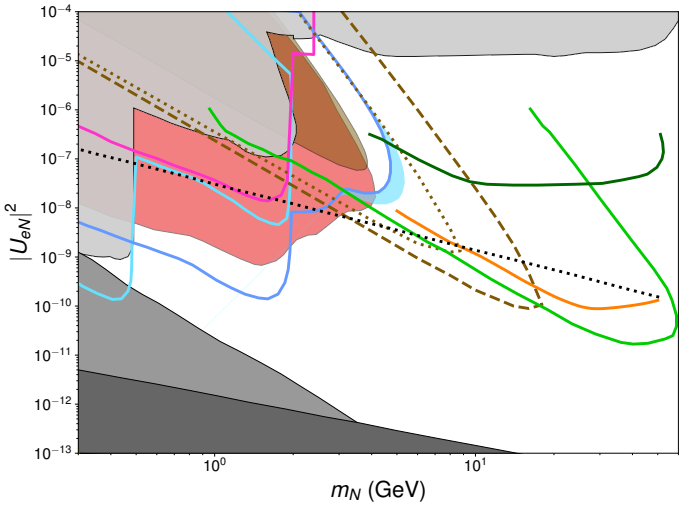




[Antusch, Cazzato, Fischer (IJMPA '17)]

[Kling, Trojanowski (PRD '18)]

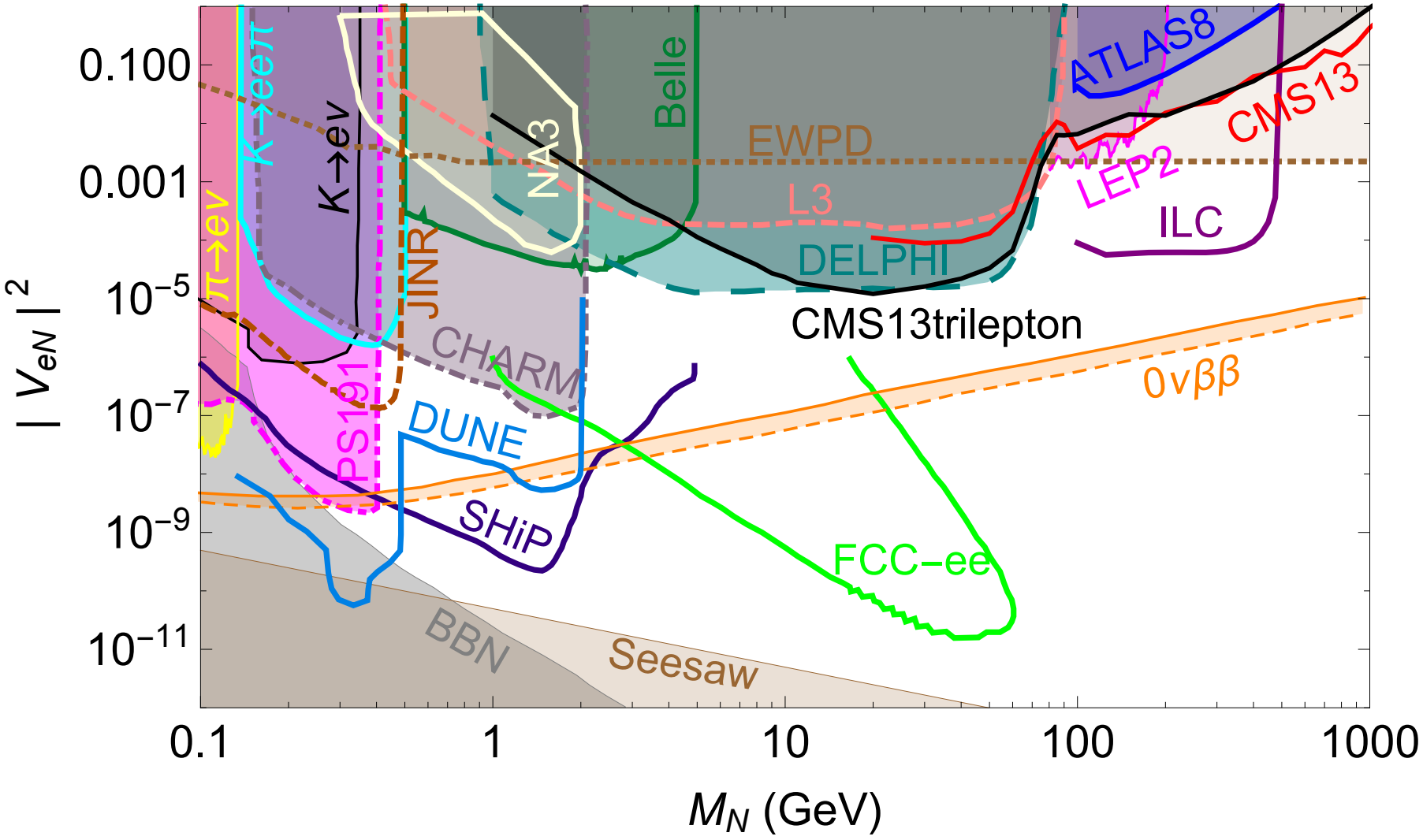




[MATHUSLA Collaboration '18]

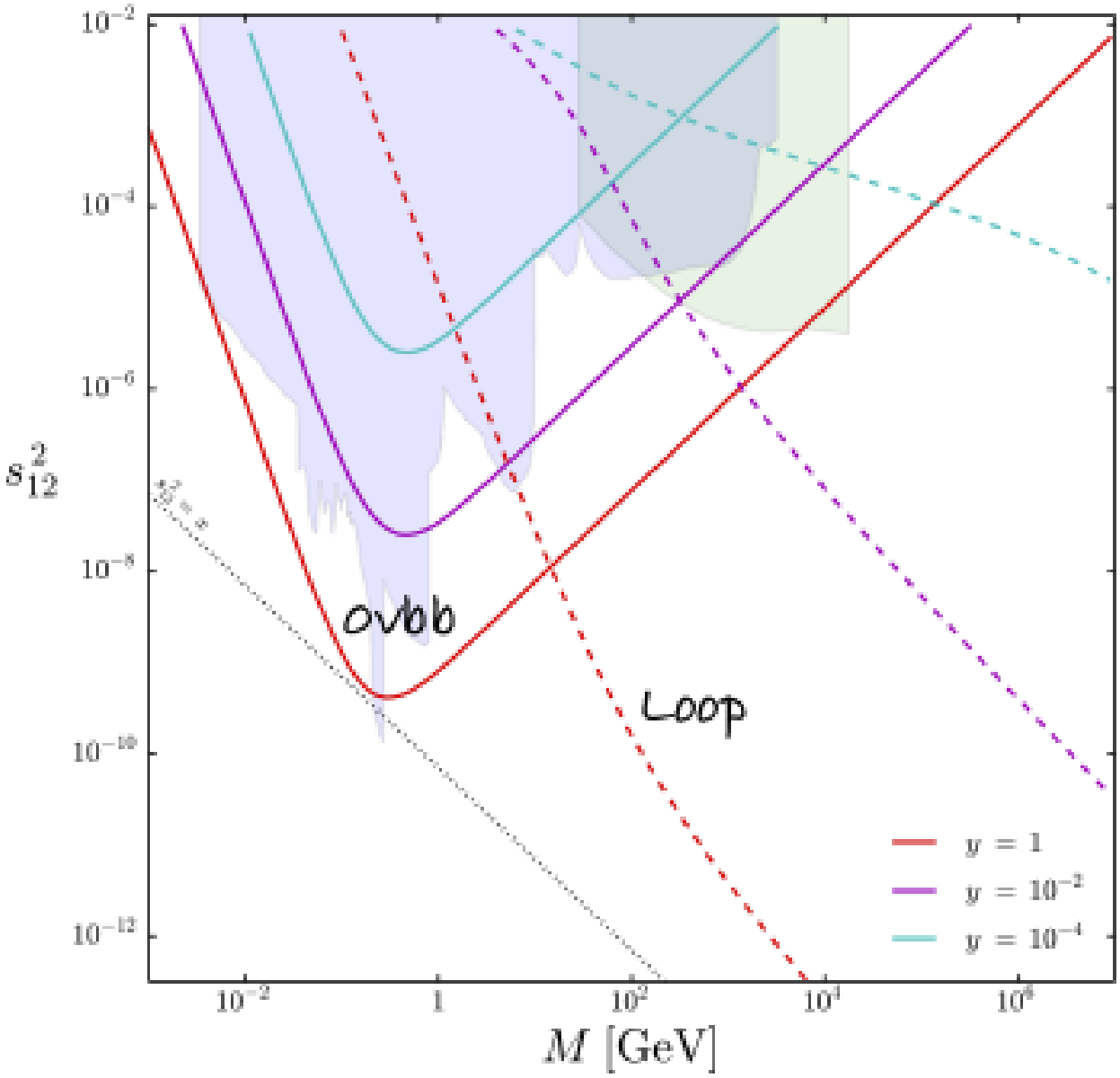
[see Wednesday plenary talks by D. Curtin and J. Feng]

Summary of Constraints and Prospects



[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15)]

Interference Effect



[Hernandez, Jones-Perez, Suarez-Navarro (EPJC '19); Bolton, Deppisch, BD (to appear)]

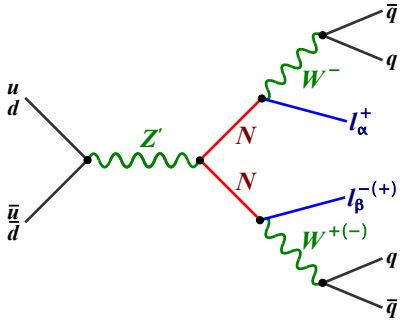
New Gauge Bosons

(W', Z')

$U(1)_X$ Extension

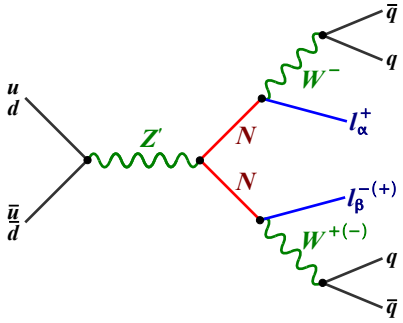
[Buchmuller, Greub (NPB '91); Fileviez Perez, Han, Li (PRD '09); Kang, Ko, Li (PRD '15); Heeck, Teresi (PRD '16);

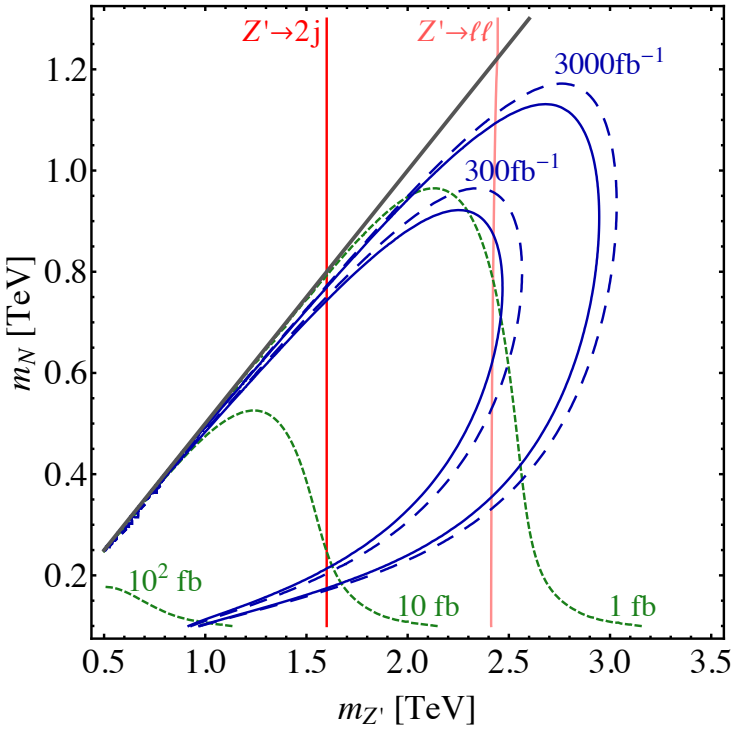
BD, Mohapatra, Zhang (JHEP '17); Das, Okada, Raut (EPJC '18); Cox, Han, Yanagida (JHEP '18); ...]



$U(1)_X$ Extension

[Buchmuller, Greub (NPB '91); Fileviez Perez, Han, Li (PRD '09); Kang, Ko, Li (PRD '15); Heeck, Teresi (PRD '16); BD, Mohapatra, Zhang (JHEP '17); Das, Okada, Raut (EPJC '18); Cox, Han, Yanagida (JHEP '18); ...]

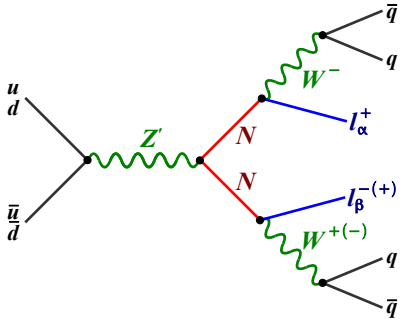


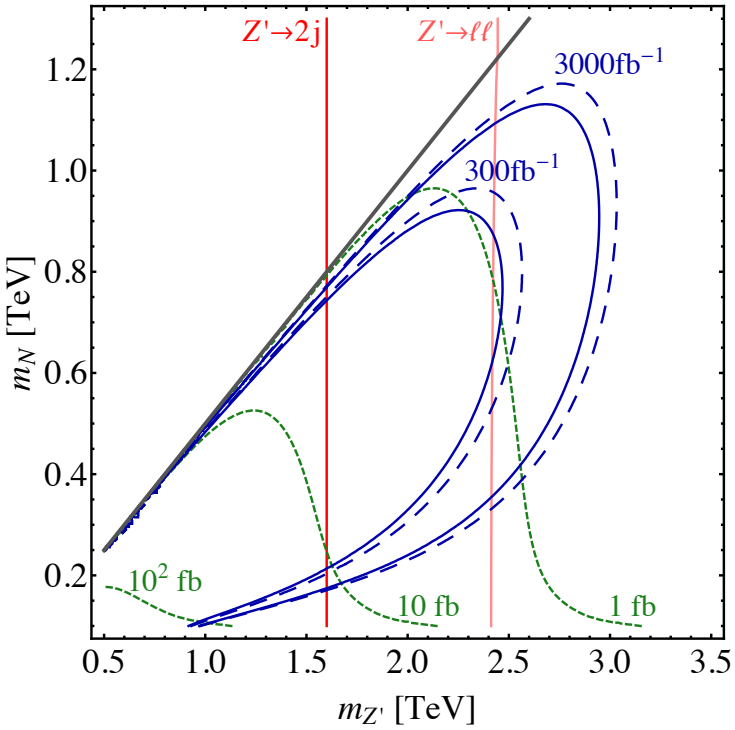


[Deppisch, Desai, Valle (PRD '14)]

$U(1)_X$ Extension

[Buchmuller, Greub (NPB '91); Fileviez Perez, Han, Li (PRD '09); Kang, Ko, Li (PRD '15); Heeck, Teresi (PRD '16); BD, Mohapatra, Zhang (JHEP '17); Das, Okada, Raut (EPJC '18); Cox, Han, Yanagida (JHEP '18); ...]





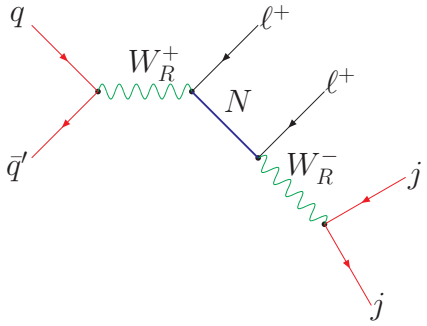
[Deppisch, Desai, Valle (PRD '14)]

One of the RHNs can be made a **dark matter** candidate. [see parallel talk by S. Okada]

Left-Right Symmetric Extension

[Keung, Senjanović (PRL '83); Ferrari *et al* (PRD '00); Nemevsek, Nesti, Senjanović, Zhang (PRD '11); Das, Deppisch, Kittel, Valle (PRD '12); Mitra, Ruiz, Scott, Spannowsky (PRD '16);...]; see Tuesday plenary talk by G. Senjanović

New contribution to same-sign dilepton signal (independent of mixing)



Left-Right Symmetric Extension

[Keung, Senjanović (PRL '83); Ferrari *et al* (PRD '00); Nemevsek, Nesti, Senjanović, Zhang (PRD '11); Das, Deppisch, Kittel, Valle (PRD '12); Mitra, Ruiz, Scott, Spannowsky (PRD '16);...]; see Tuesday plenary talk by G. Senjanović

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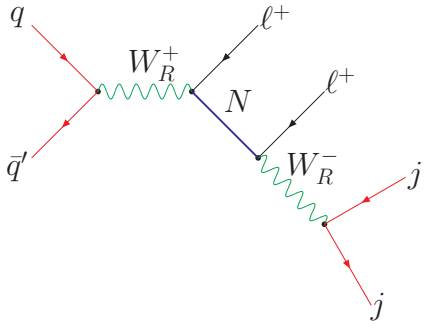
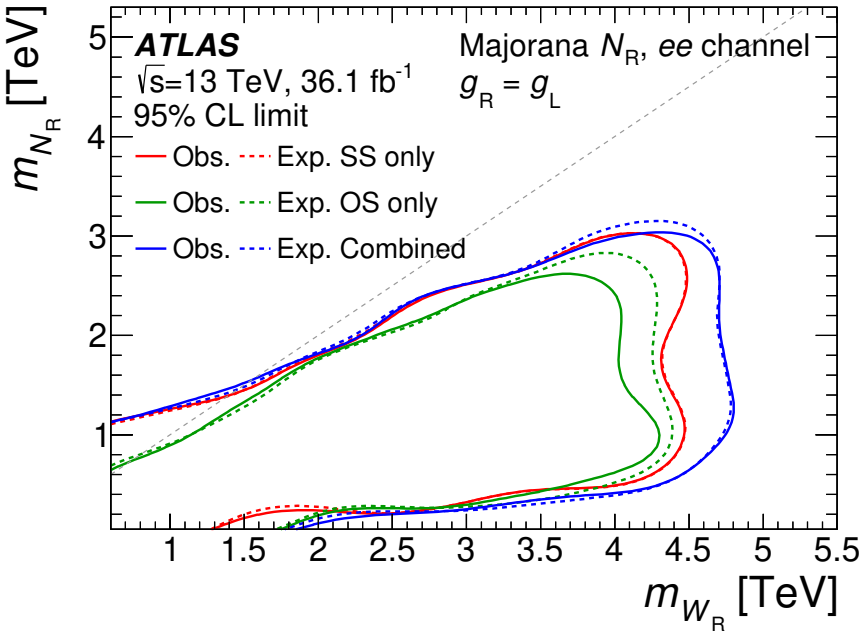
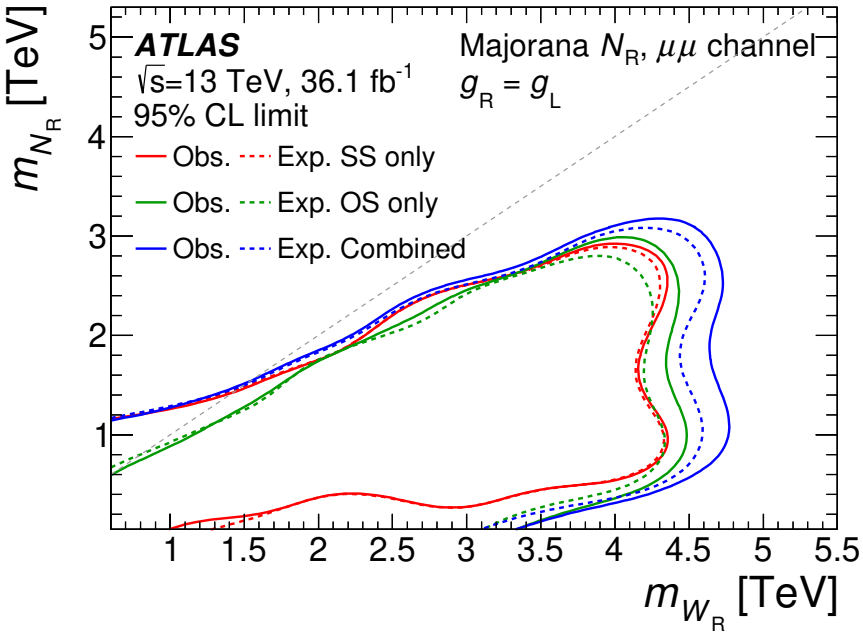




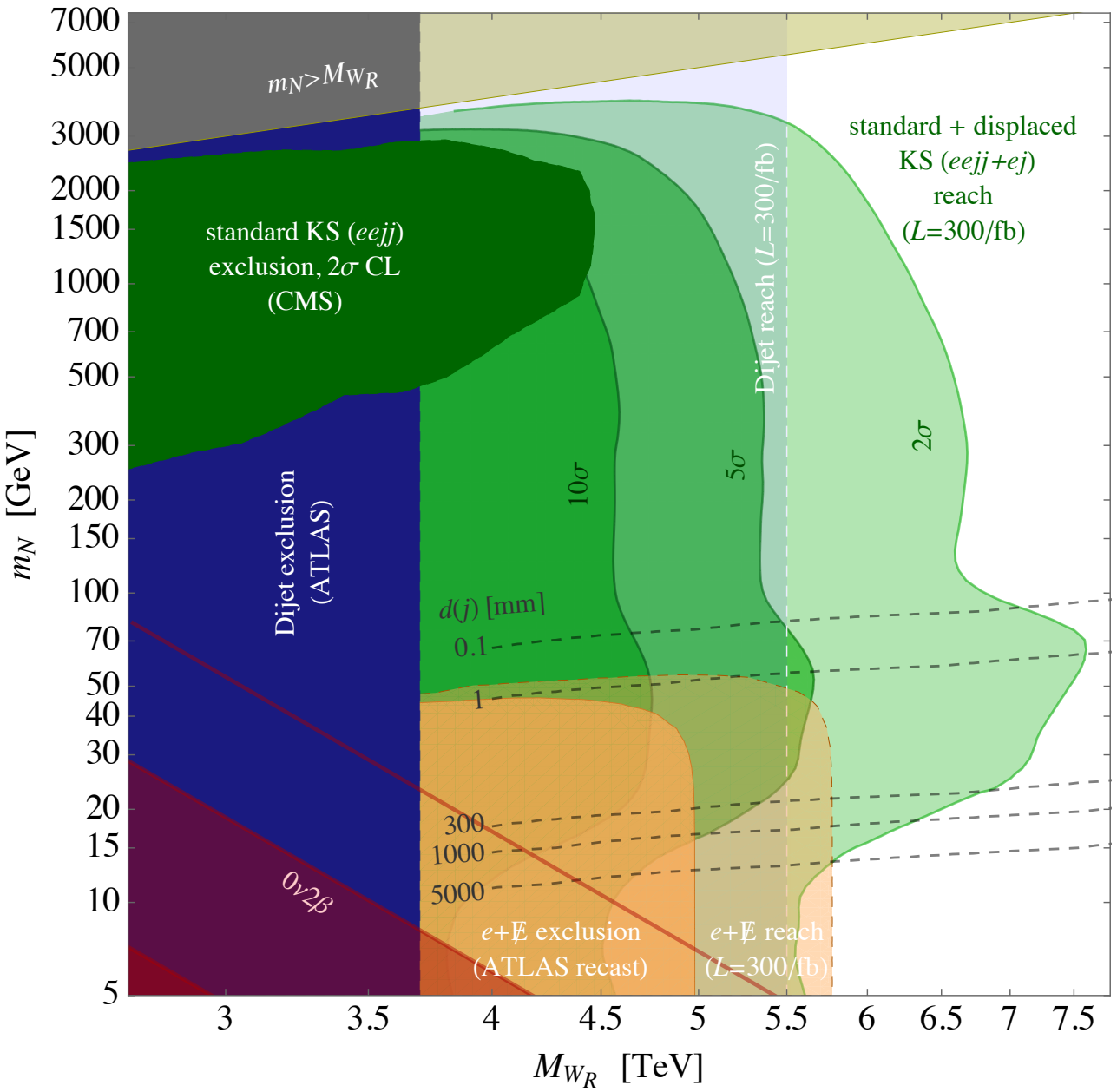
(a)



(b)

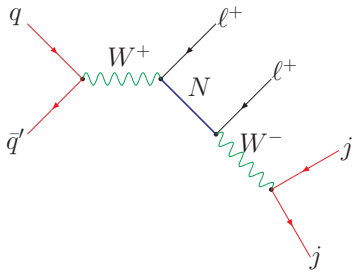
[ATLAS Collaboration, JHEP 1901, 016 (2019)]

Future Prospects

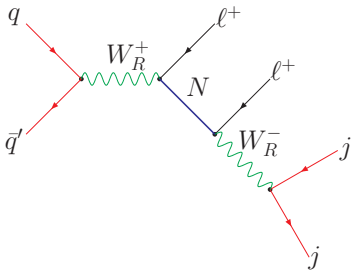


[Nemevsek, Nesti, Popara (PRD '18)]

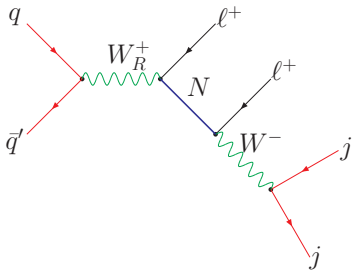
L-R Seesaw Phase Diagram



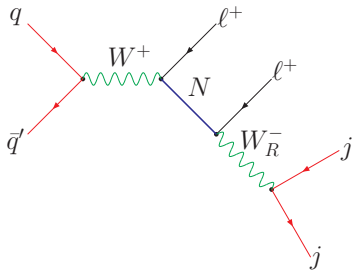
(a) LL



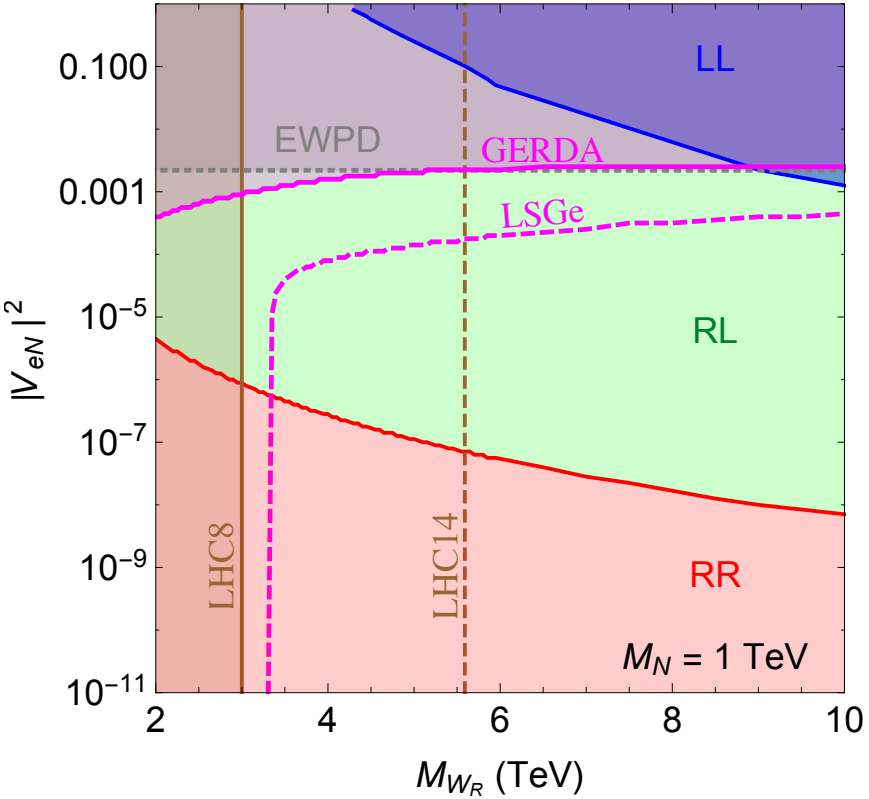
(b) RR



(c) RL



(d) LR



[Chen, BD, Mohapatra (PRD '13); BD, Kim, Mohapatra (JHEP '16)]

CPV in the RHN Sector

$$\begin{pmatrix} N_e \\ N_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_R & \sin\theta_R e^{-i\delta_R} \\ -\sin\theta_R e^{i\delta_R} & \cos\theta_R \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} .$$

Same sign charge asymmetry : $\mathcal{A}_{\alpha\beta} \equiv \dfrac{\mathcal{N}(\ell_\alpha^+ \ell_\beta^+) - \mathcal{N}(\ell_\alpha^- \ell_\beta^-)}{\mathcal{N}(\ell_\alpha^+ \ell_\beta^+) + \mathcal{N}(\ell_\alpha^- \ell_\beta^-)} .$

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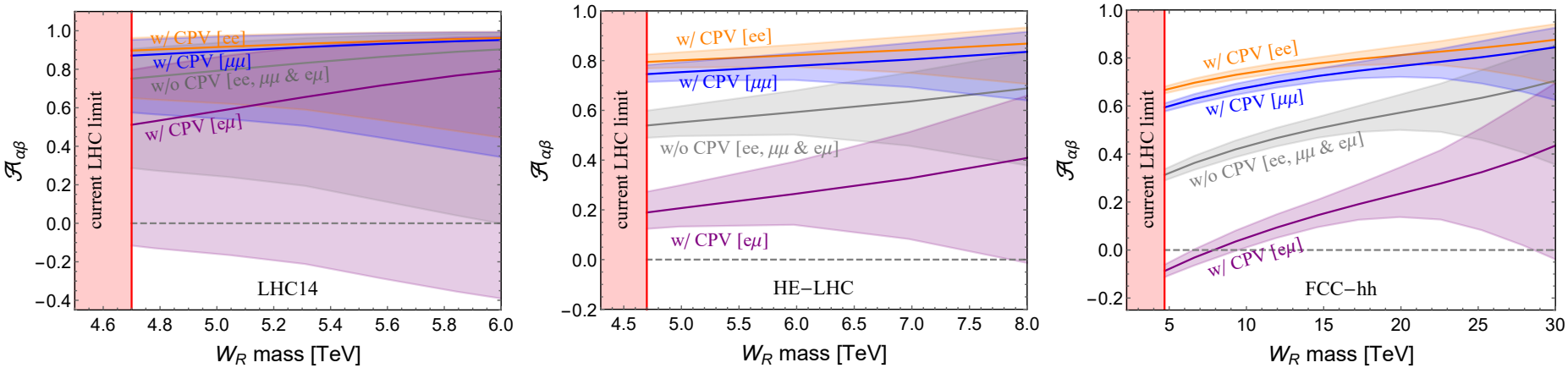

CPV in the RHN Sector

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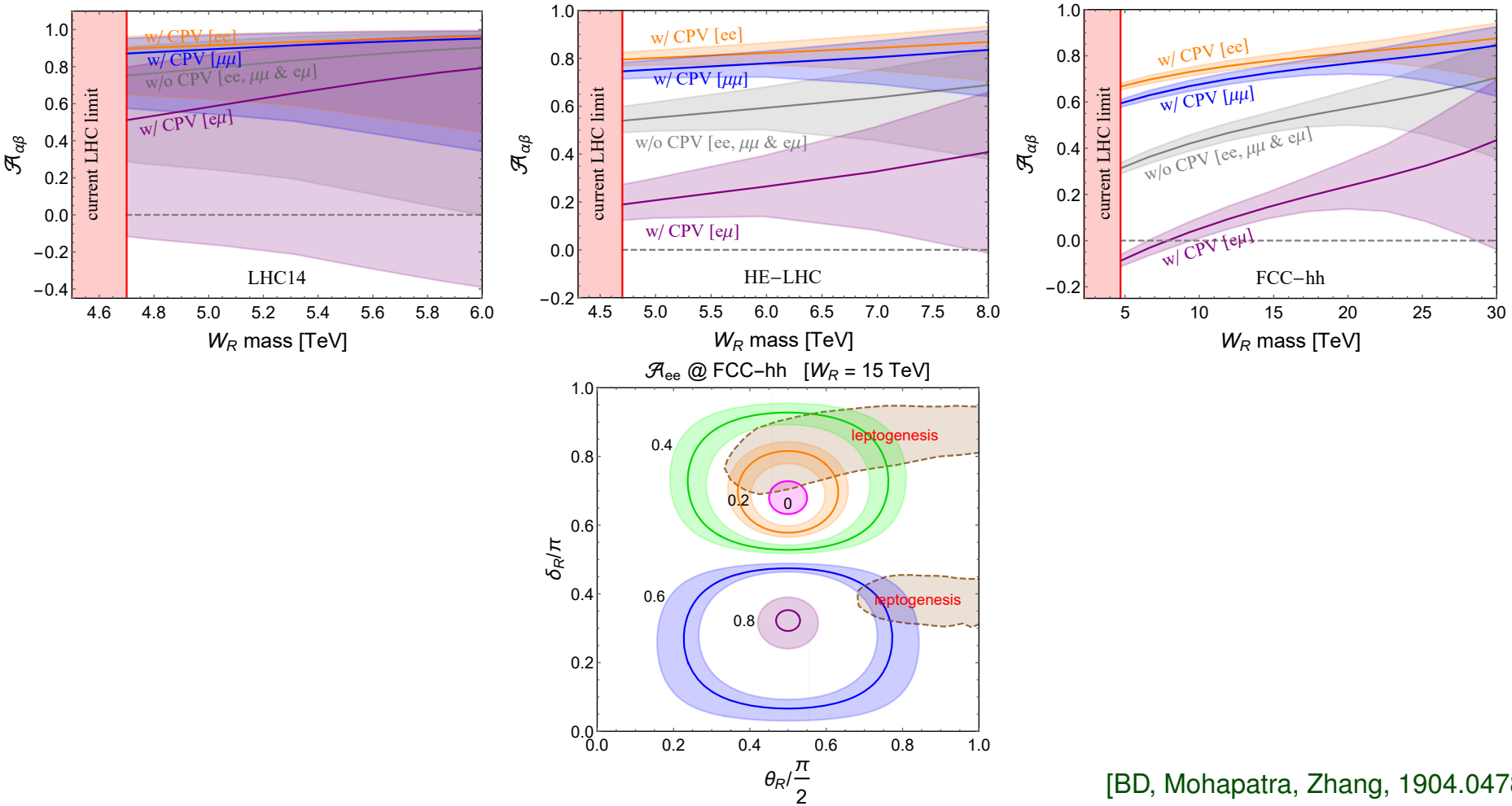


[BD, Mohapatra, Zhang, 1904.04787]

New Scalars

L-R Seesaw Higgs Sector

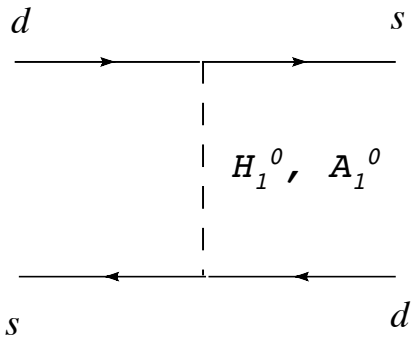
$$\blacksquare = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \quad \blacksquare_R = \begin{pmatrix} \frac{\blacksquare_R^+}{\sqrt{2}} & \blacksquare_R^{++} \\ \blacksquare_R^0 & -\frac{\blacksquare_R^+}{\sqrt{2}} \end{pmatrix}, \quad \blacksquare_L = \begin{pmatrix} \frac{\blacksquare_L^+}{\sqrt{2}} & \blacksquare_L^{++} \\ \blacksquare_L^0 & -\frac{\blacksquare_L^+}{\sqrt{2}} \end{pmatrix}$$

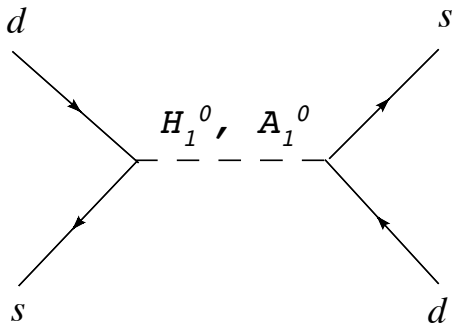
- $\langle \blacksquare_R^0 \rangle \equiv v_R$ gives rise to RH Majorana neutrino masses, and hence, type-I seesaw.
- $\langle \blacksquare_L^0 \rangle \equiv v_L$ gives rise to a type-II seesaw contribution.
- 14 physical scalar fields (compared to just 1 in the SM).
- Very rich phenomenology.

  [Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); Polak, Zralek (PLB '92); Akeroyd, Aoki (PRD '05); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); Bambhaniya, Chakrabortty, Gluza, Kordiaczyńska, Szafron (JHEP '14); Dutta, Eusebi, Gao, Ghosh, Kamon (PRD '14); Maiezza, Nemevsek, Nesti (PRL '15); BD, Mohapatra, Zhang (JHEP '16);...]

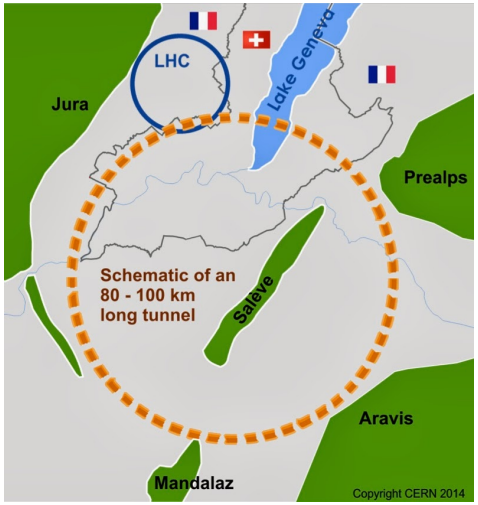
Bidoublet Sector

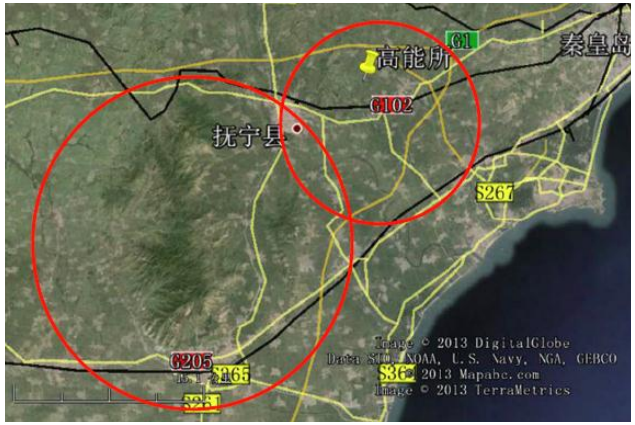
- FCNC constraints require the bidoublet scalars (H_1^0, A_1^0, $H_1^\pm$) to be very heavy $\gtrsim$ 15 TeV. [An, Ji, Mohapatra, Zhang (NPB '08); Bertolini, Maiezza, Nesti (PRD '14)]





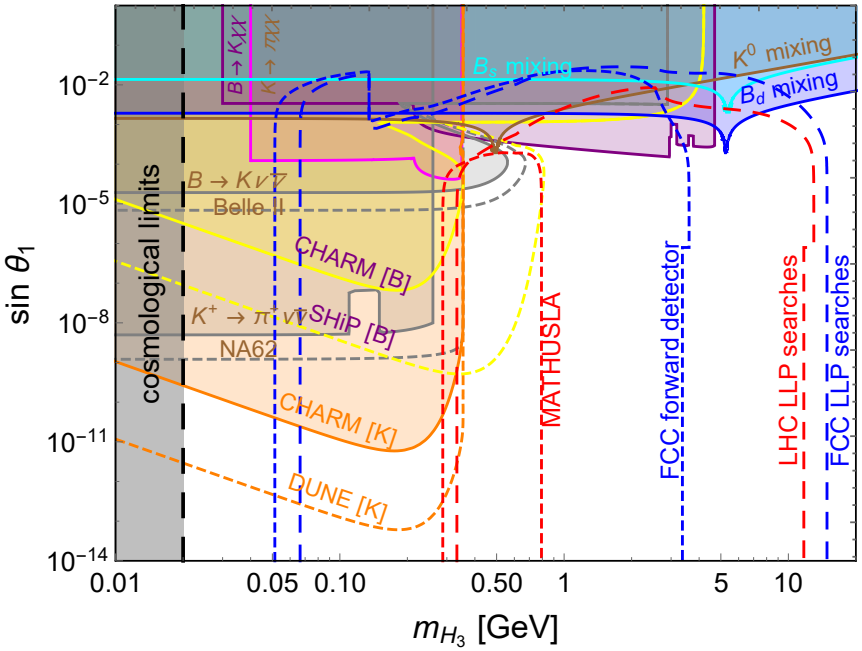
- No hope for them at the LHC. **Need a 100 TeV collider!** [see Monday plenary talk by T. Han]



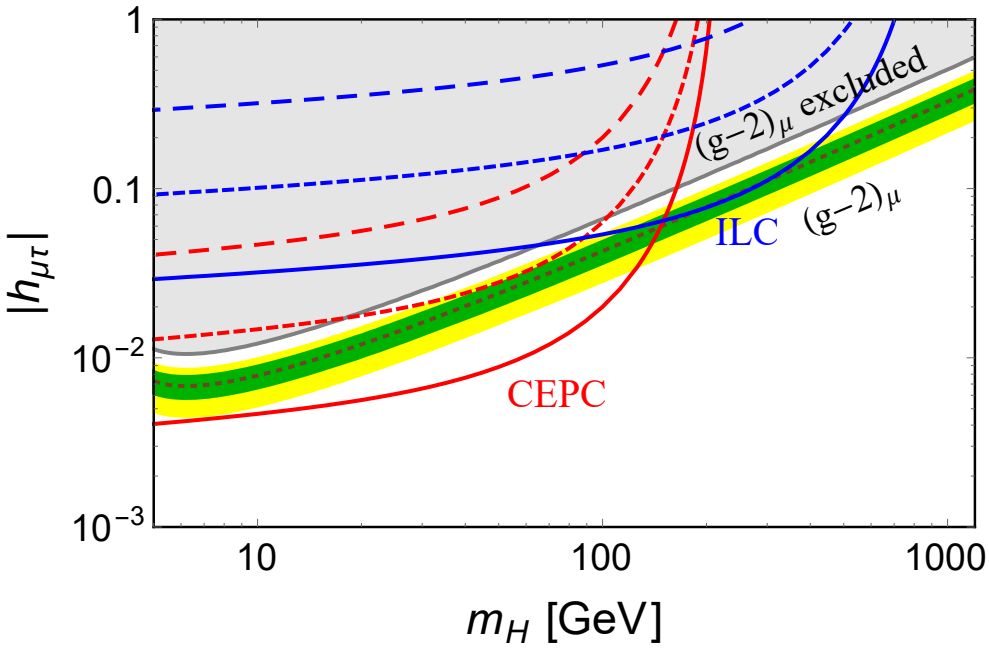


Neutral Triplet Sector

- Hadrophobic and allowed to be light (down to sub-GeV scale) by current constraints.
- Suppressed coupling to SM particles (either loop-level or small mixing).
- Necessarily long-lived at the LHC, with displaced vertex signals.
- Clean LFV signals at future lepton colliders.

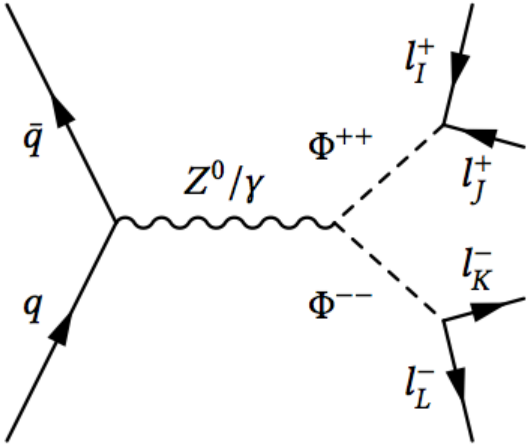


[BD, Mohapatra, Zhang (PRD '17; NPB '17)]

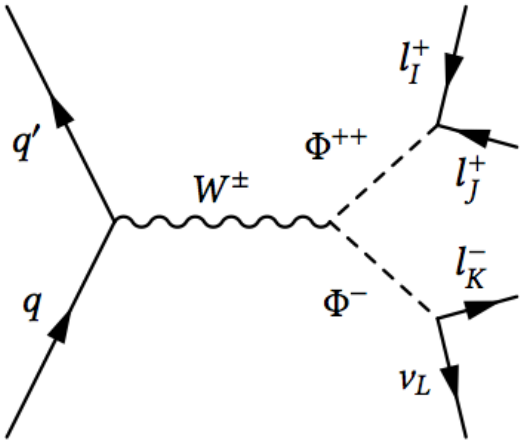


[BD, Mohapatra, Zhang (PRL '18; PRD '18)]

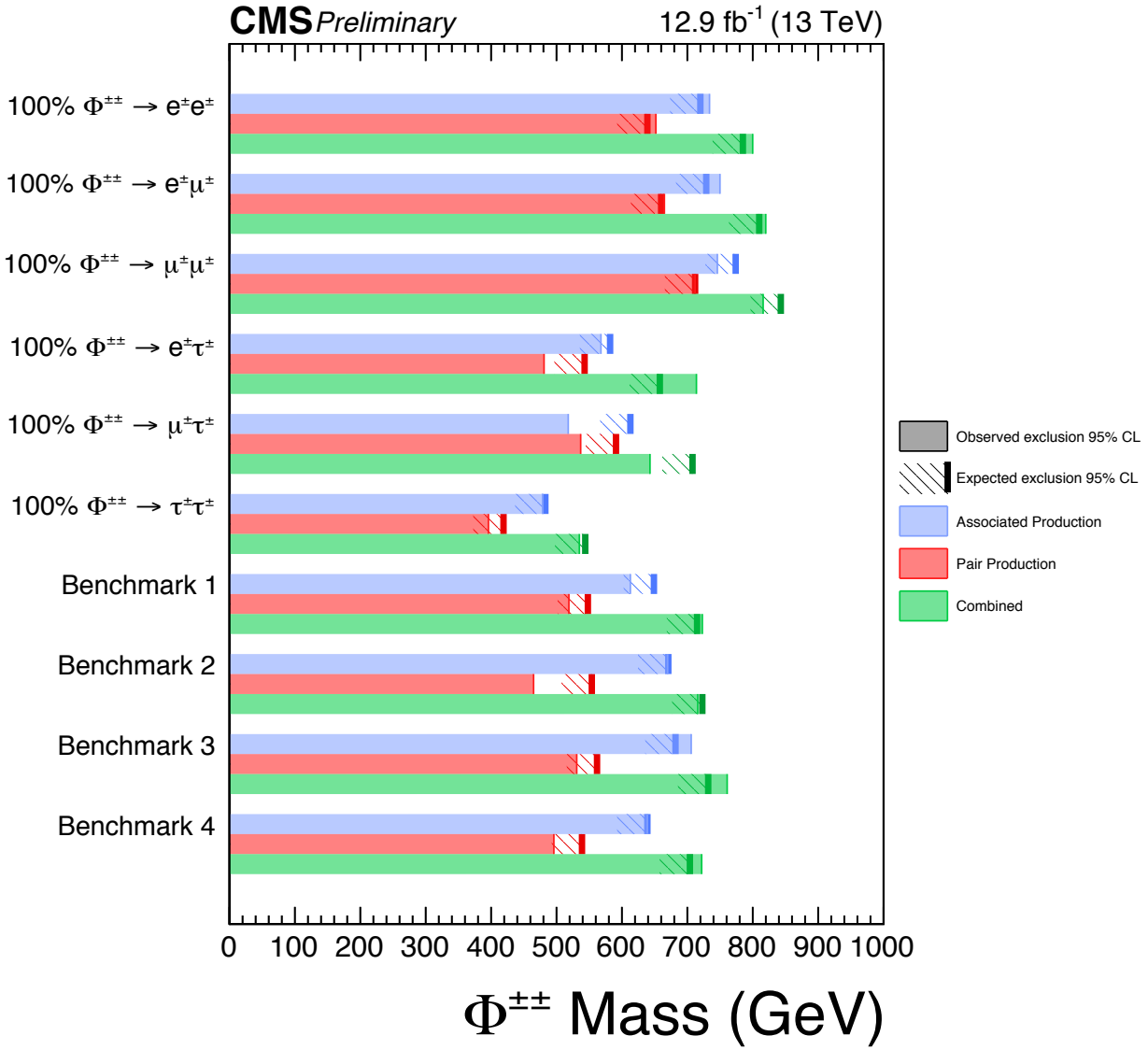
Charged Triplet Sector



(a) 4ℓ

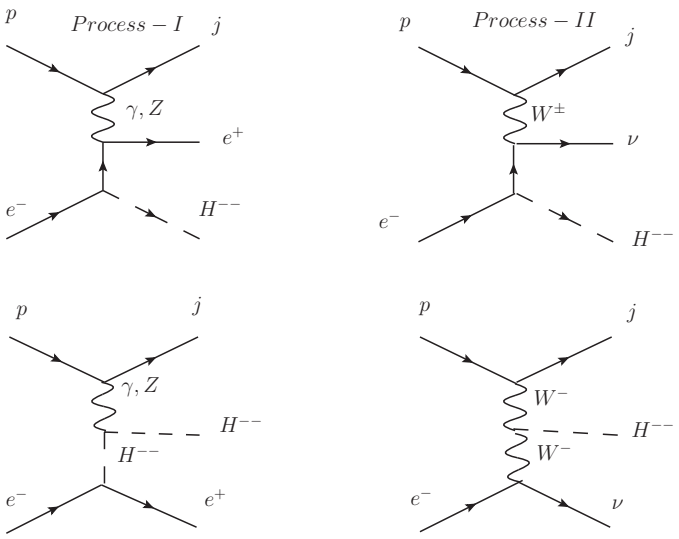


(b) 3ℓ

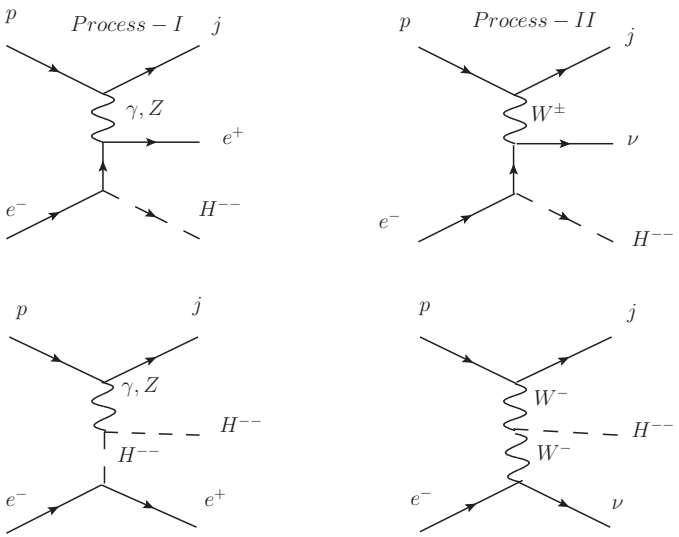


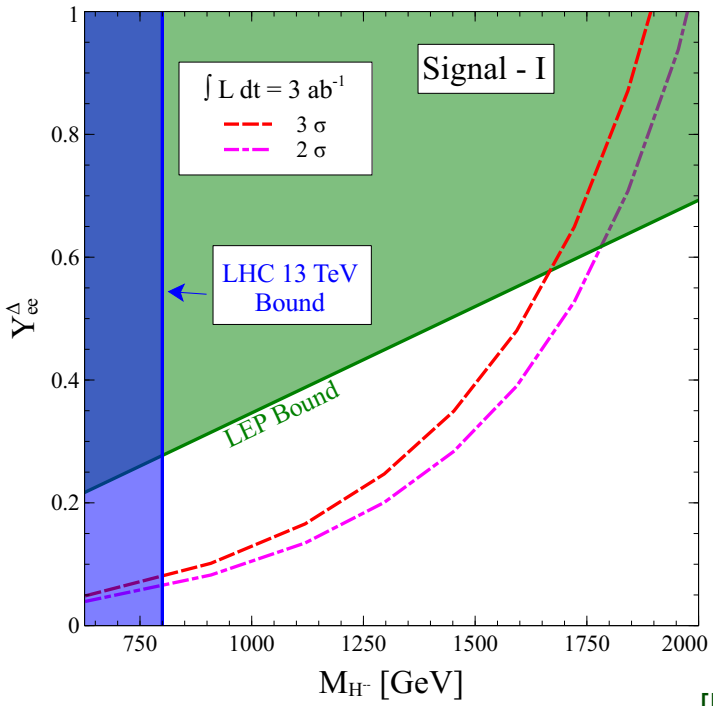
[CMS-PAS-HIG-16-036]

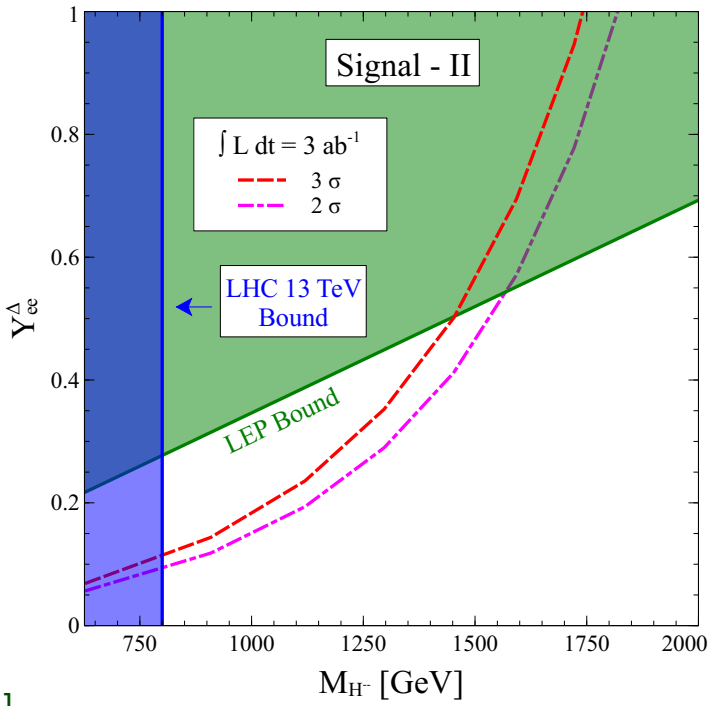
Prospects at $e^- p$ Collider



Prospects at $e^- p$ Collider

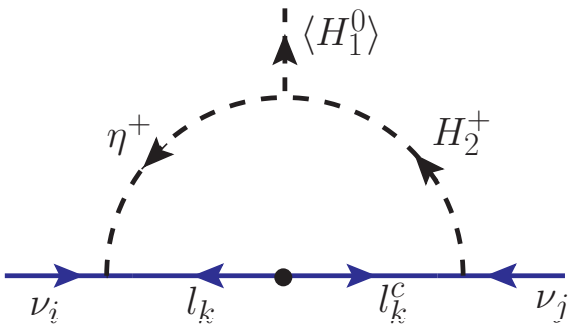




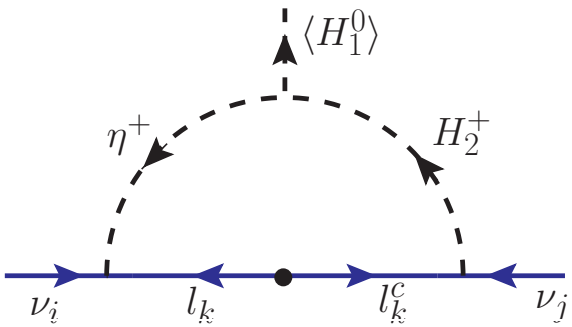


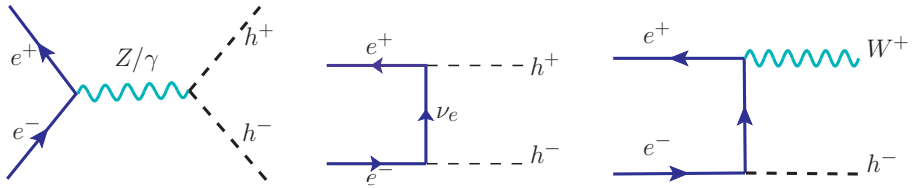
[BD, Khan, Mitra, Rai, 1903.01431]

Zee Model

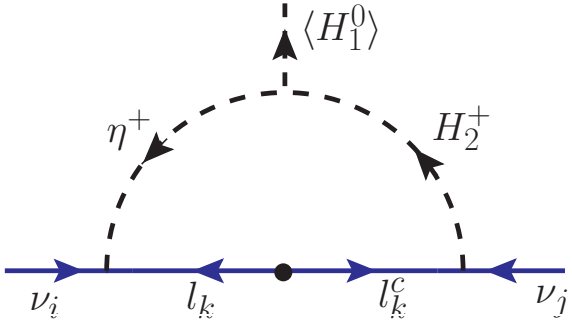


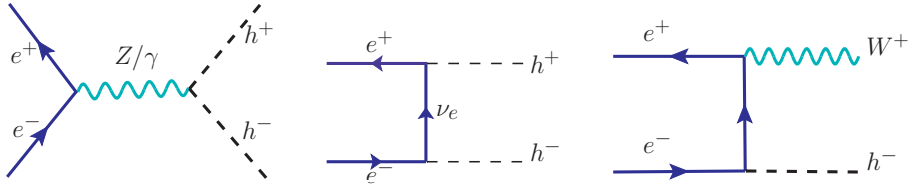
Zee Model

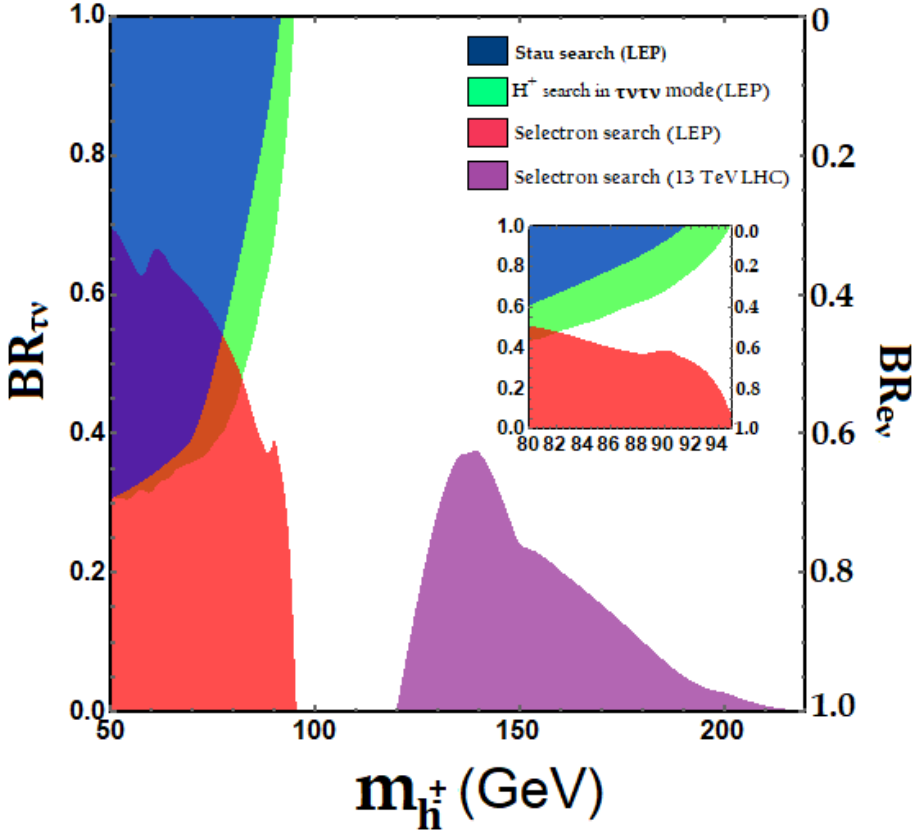

$\langle H_1^0 \rangle$
η^+
H_2^+
ν_i
l_k
l_k^c
ν_j


e^+
e^-
Z/γ
h^+
h^-
e^+
e^-
ν_e
h^+
h^-
e^+
e^-
W^+
h^-

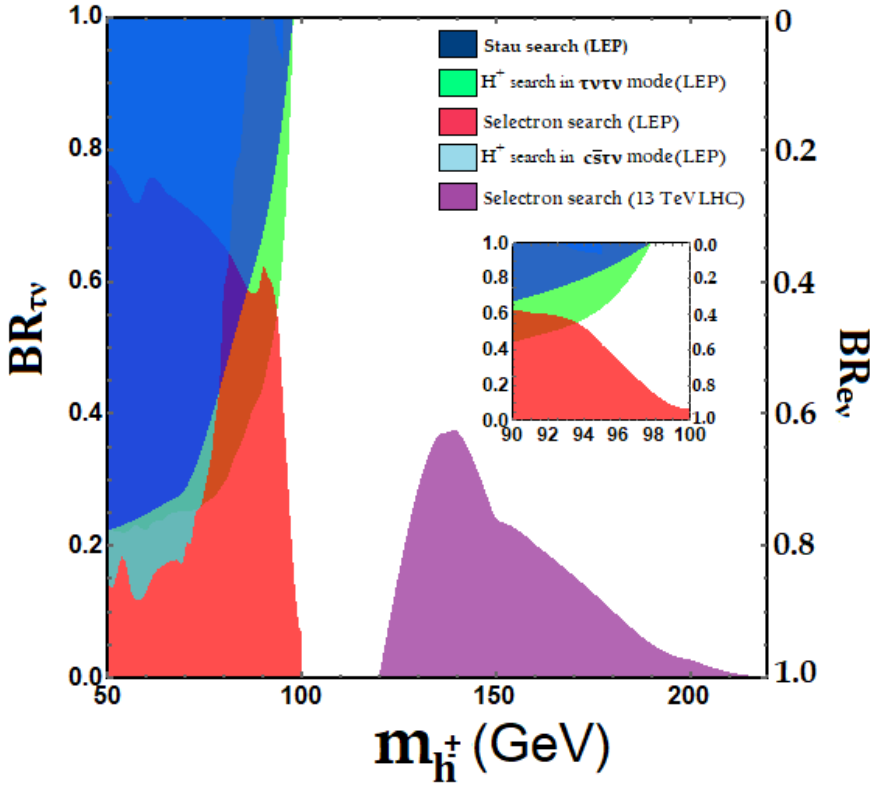
Zee Model







($y_{\alpha e} = 0$)

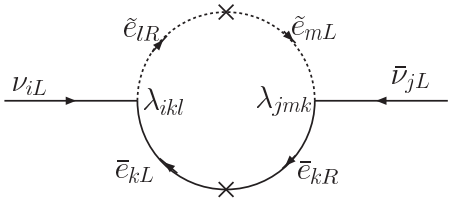


($y_{\alpha e} = 1$)

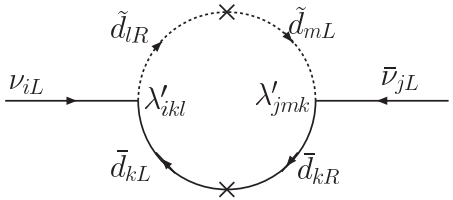
[Babu, BD, Jana, Thapa (to appear); see Tuesday parallel talk by K. S. Babu]

RPV SUSY

$$W_{\mathrm{RPV}} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$



(a)

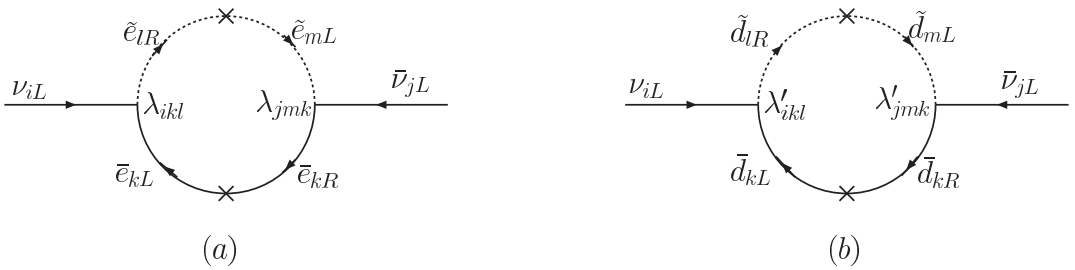


(b)

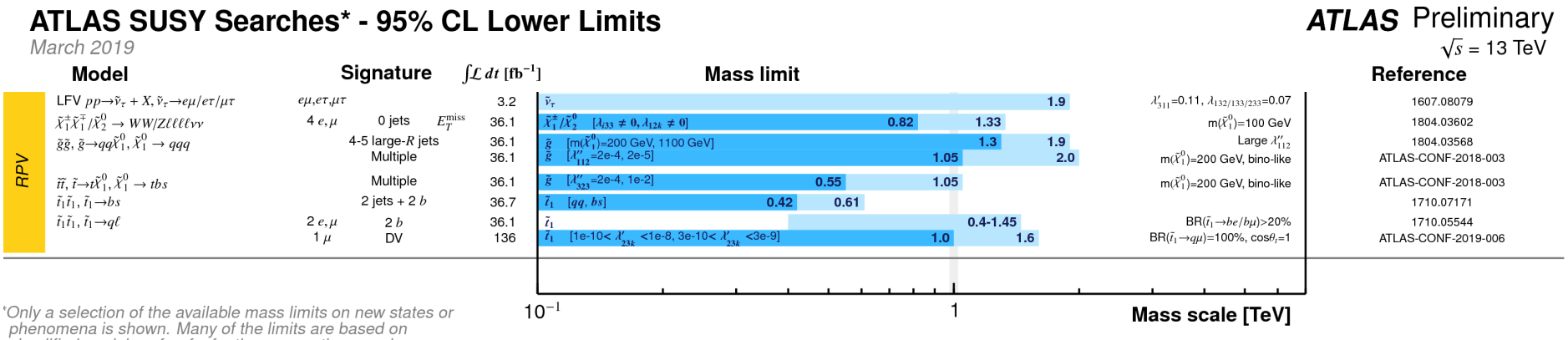
[Hall, Suzuki (NPB '84); Babu, Mohapatra (PRL '90)]

RPV SUSY

$$W_{\rm RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$

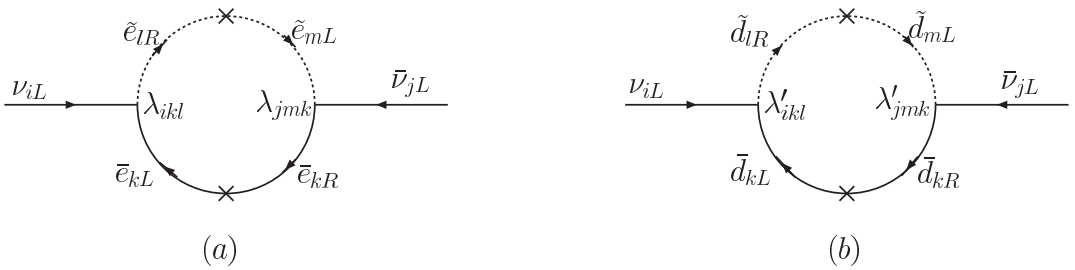


[Hall, Suzuki (NPB '84); Babu, Mohapatra (PRL '90)]

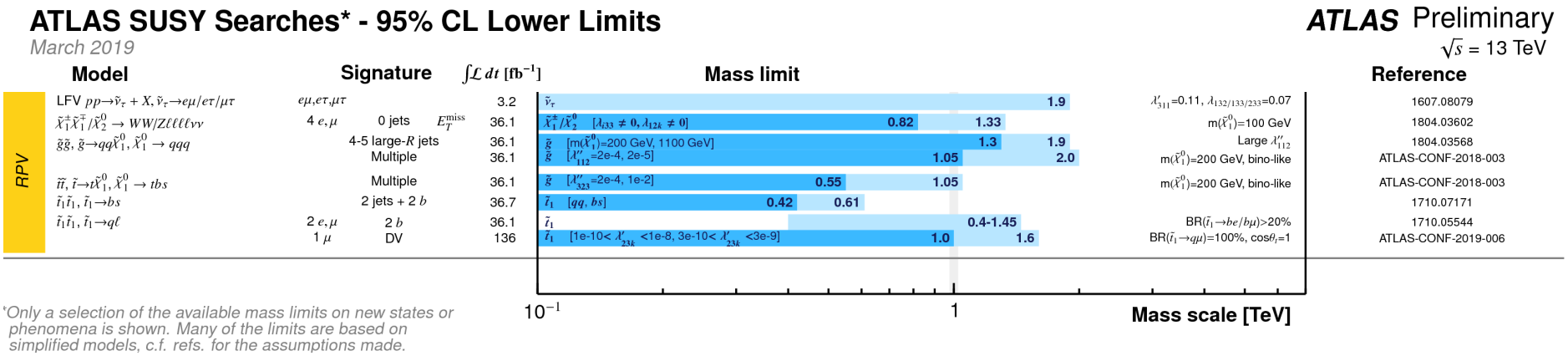


RPV SUSY

$$W_{\rm RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$



[Hall, Suzuki (NPB '84); Babu, Mohapatra (PRL '90)]



- Recent interest in light of the ***B*-anomalies**. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); Das, Hati, Kumar, Mahajan (PRD '17); Earl, Gregoire (JHEP '18); Trifinopoulos (EPJC '18)] – see Friday plenary talk by X.-G. He
- Can also address the ANITA anomalous events. [Collins, BD, Sui (PRD '19); see Tuesday parallel talk by Y. Sui]

Conclusion

- Understanding the neutrino mass mechanism will provide important insights into the BSM world.
- Current and future colliders provide a ripe testing ground for low-scale neutrino mass models.
- Can probe the messenger particles (new fermions/gauge bosons/scalars) in a wide range of parameter space.
- Healthy complementarity at the intensity frontier.
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Conclusion

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Thank You!