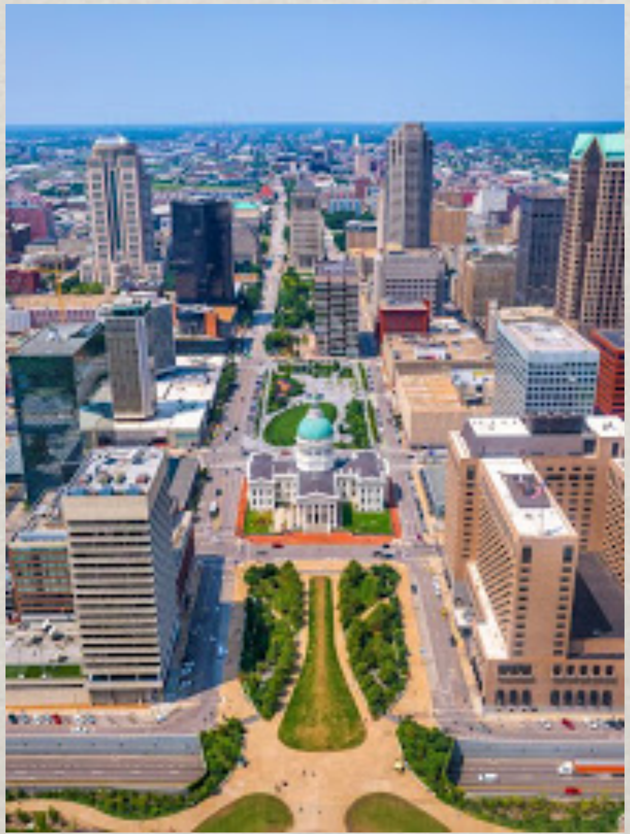
Overview of neutrino Physics at colliders
or
Testing Seesaw

Tao Han, University of Pittsburgh

NTN Workshop on Neutrino NSI

Washington Univ., St. Louis, May 29, 2019

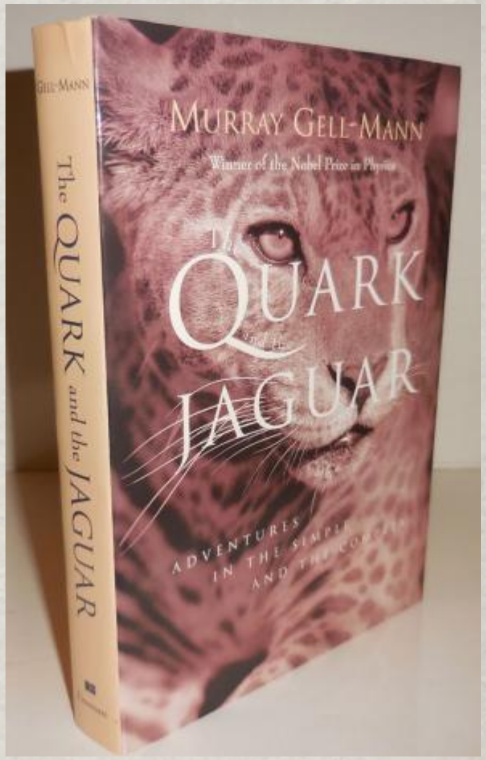


On May 24, 2019:

Murray Gell-Mann, Nobel Prize-winning physicist who named quarks, dies at 89

- 1969 Nobel laureate helped discover subatomic particles
- Death confirmed by Santa Fe Institute he co-founded

▲ Murray Gell-Mann, seen Santa Fe Institute in 2003. Photograph: Jane Bernard/AP



2010 in Aspen

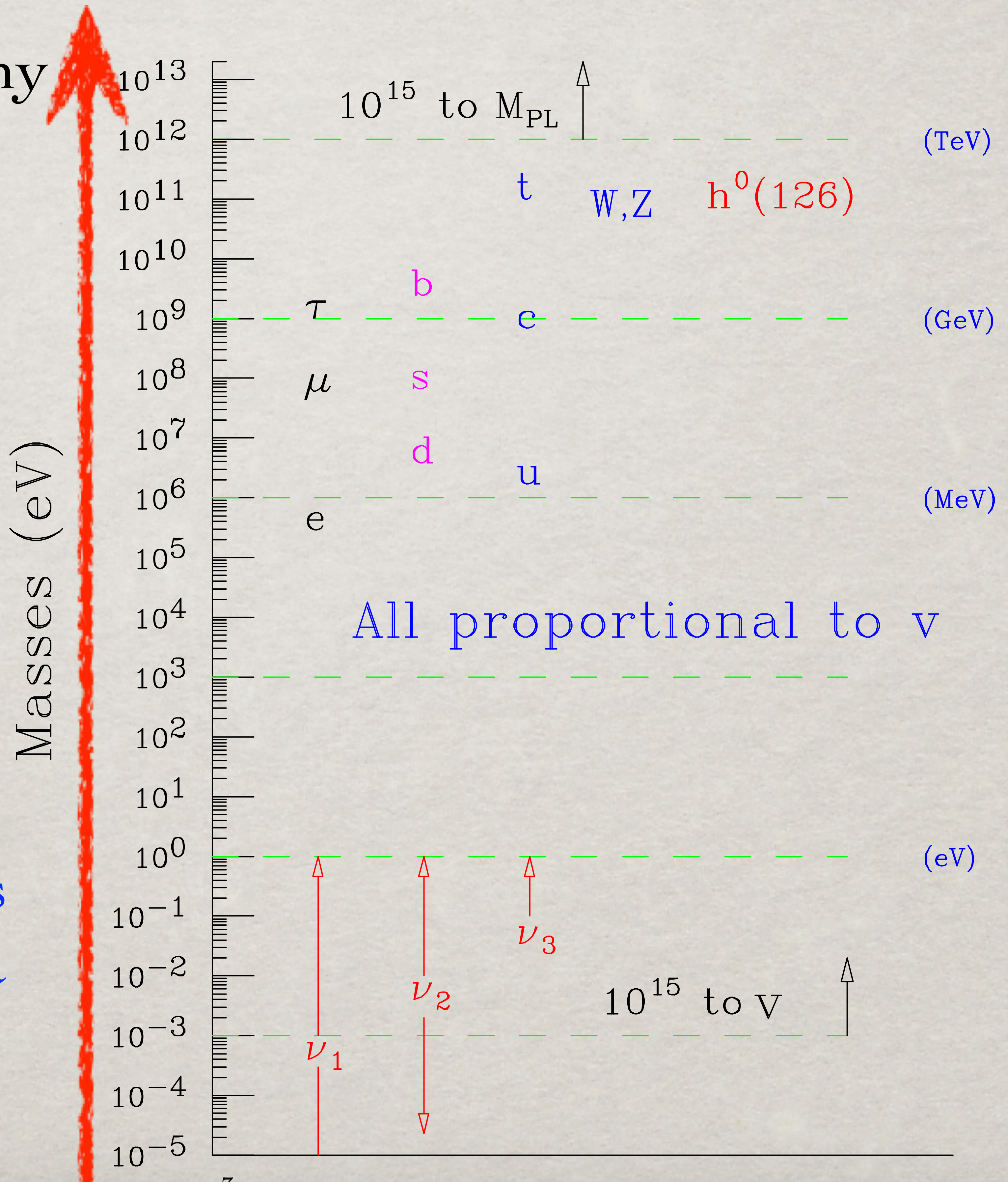
His "Totalitarian Principle" argument made a Majorana mass term "compulsory" (almost)

1. Flavor Puzzle is a much^n harder problem

- Particle mass hierarchy
- Patterns of quark-neutrino-mixings
- Neutrino mass: Dirac (Higgs) vs. Majorana (seesaw)
- New CP-violation sources

Nu-physics:

One of the best chances for Nature to teach us a lesson!



On the theory side:

- "Technically natural" in t'Hooft sense:
  small values are protected by symmetry.
  At a "new physics" (cut-off) scale Λ :
  "natural": $\boldsymbol{\delta} m_f \sim g^2/(16\boldsymbol{\pi}^2)\ m_f \ln(\Lambda^2/m_f^2)$
  in contrast to "unnatural": $\boldsymbol{\delta} m_H^2 \sim -\, y_t^2/(8\boldsymbol{\pi}^2)\ \Lambda^2$

Two ways to generate small values naturally:

- Suppression by integrating out heavy states:

  $$\sim g^2\, E^2/M^2$$

  the higher dimension $1/\Lambda^n$, the lower Λ can be.

- Suppression by loop radiative generation:
  the higher loops $1/(16\boldsymbol{\pi}^2)^n$, the lower m_ν can be.

→ Scale and couplings wide open in theory space.

On the phenomenology side:

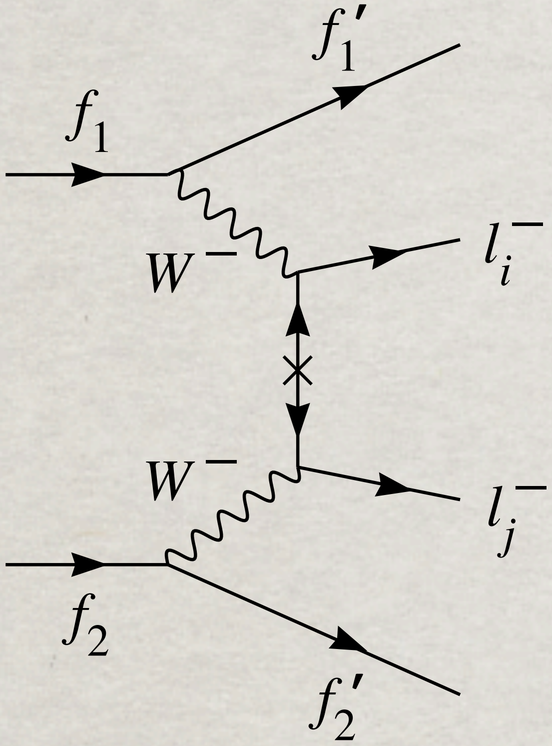
- Will search for ANYTHING
  new states of mass M, new couplings/mixings k, V_{ij} …
- Will search EVERY WHERE
  low-energy & high-energy regimes.
  - Today, primarily,

    target on Majorana nature: **Δ**L=2
  - Equally important,

    charged lepton flavor transition: **Δ**L= 0
  - Observables ←→ Theory connections

2. The most-wanted process: ΔL=2

The fundamental diagram:



$$U_{iN}\ \frac{\not p+m_N}{p^2-m_N^2+i\epsilon}\ U_{jN}.$$

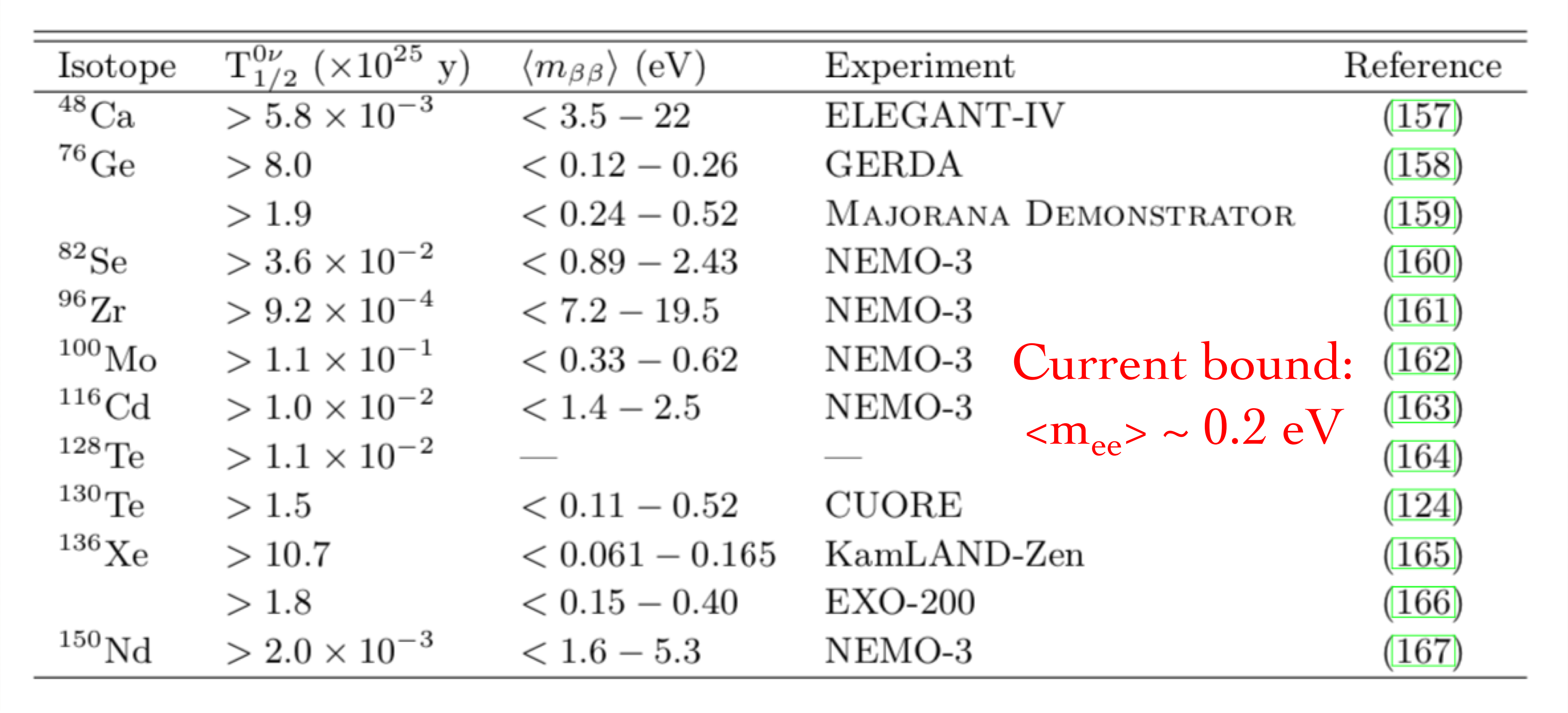
The crossing diagrams can probe different processes and new physics of N/T^0, W^+_R, H^{++}

The transition rates are proportional to

$$|\mathcal{M}|^2 \propto \begin{cases} \langle m\rangle^2_{\ell_1\ell_2} = \left|\sum_{i=1}^{3} U_{\ell_1 i}U_{\ell_2 i}m_i\right|^2 & \text{for light } \nu; \\ \frac{\left|\sum_i^n V_{\ell_1 i}V_{\ell_2 i}\right|^2}{m_N^2} & \text{for heavy } N; \\ \frac{\Gamma(N\to i)\ \Gamma(N\to f)}{m_N\Gamma_N} & \text{for resonant N production.} \end{cases}$$

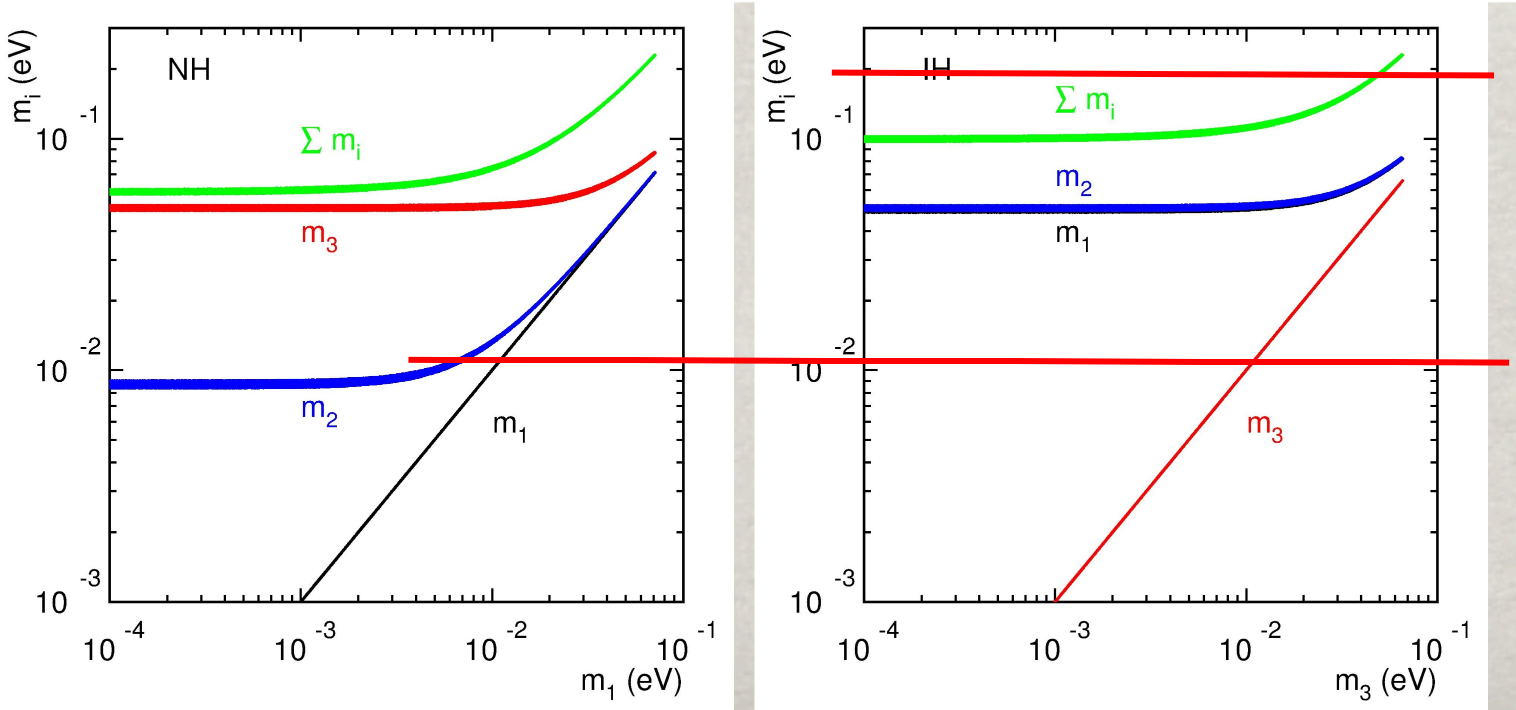
3. Neutrino-less double-beta decay

arXiv:1902.04097, M. Dolinski, A. Poon, W. Rodejohann



Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta}\rangle$ (eV)	Experiment	Reference
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV	(157)
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA	(158)
	> 1.9	$< 0.24 - 0.52$	Majorana Demonstrator	(159)
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	NEMO-3	(160)
^{96}Zr	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3	(161)
^{100}Mo	$> 1.1 \times 10^{-1}$	$< 0.33 - 0.62$	NEMO-3	(162)
^{116}Cd	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3	(163)
^{128}Te	$> 1.1 \times 10^{-2}$	—	—	(164)
^{130}Te	> 1.5	$< 0.11 - 0.52$	CUORE	(124)
^{136}Xe	> 10.7	$< 0.061 - 0.165$	KamLAND-Zen	(165)
	> 1.8	$< 0.15 - 0.40$	EXO-200	(166)
^{150}Nd	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3	(167)

Current bound:
$\langle m_{ee}\rangle \sim 0.2$ eV



(a) (b)

Future expts:

- SNO+
- SuperNEMO
- nEXO
- CUPID
- LEGEND100

Future:
$\langle m_{ee}\rangle \sim 0.01$ eV

Already severe bounds:

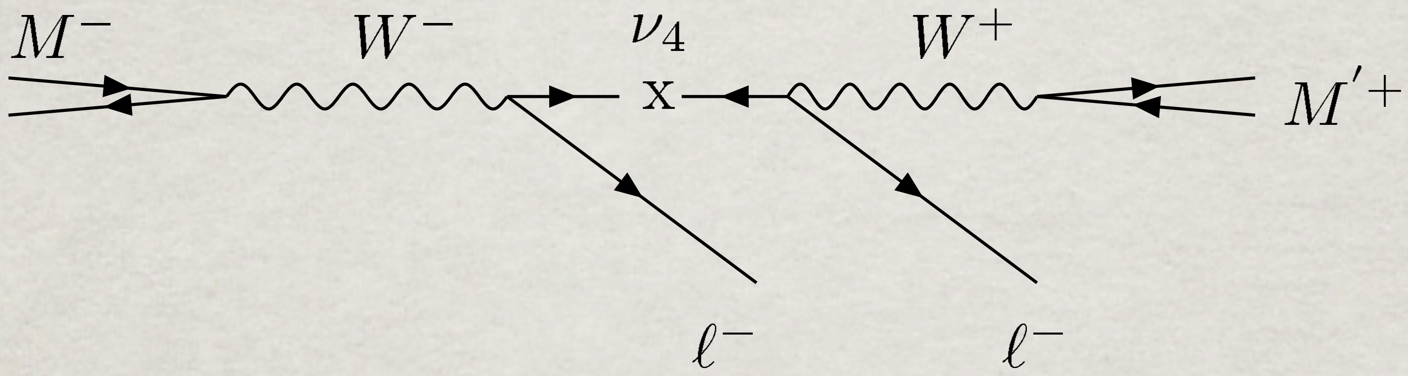
$$|\mathcal{M}| \propto \begin{cases} G_F^2 \dfrac{\langle m \rangle_{ee}}{q^2} & \text{for light } \nu \quad \Rightarrow \langle m \rangle_{ee} \sim \mathcal{O}(0.2\ \text{eV})\ \text{(current)} \\[2ex] G_F^2 \dfrac{|\sum_i^n V_{ei} V_{ei}|}{m_N} & \text{for heavy } N \quad \Rightarrow m_N > |V_{eN}/\,10^{-2}|^2\ \text{TeV} \\[2ex] G_F^2 \dfrac{M_W^4}{M_R^4} \dfrac{1}{m_N} & \text{for } W_R,\ M_R \sim m_N \quad \Rightarrow M_R > 1\ \text{TeV} \\[2ex] G_F^2 \dfrac{v'}{M_{H^{++}}^2} & \text{for doubly charged Higgs} \quad \Rightarrow M_{H^{++}} > \sqrt{v'/10\ \text{MeV}}\ \text{TeV} \end{cases}$$

Remain to be most sensitive:

- but for ee final state only!
- What about other models?

4. Meson decays

N Resonance Production and Decay



$$|\mathcal{M}|^2 \propto \frac{\Gamma(N \to i)\ \Gamma(N \to f)}{m_N \Gamma_N}$$

On resonance at m_N, only V_{4l}^2 suppressed!

- Active searches:*

  $\tau,\ K,\ D,\ B$ decays: $M^+ \to \ell_i^+ \ell_j^+ M^-$ via N

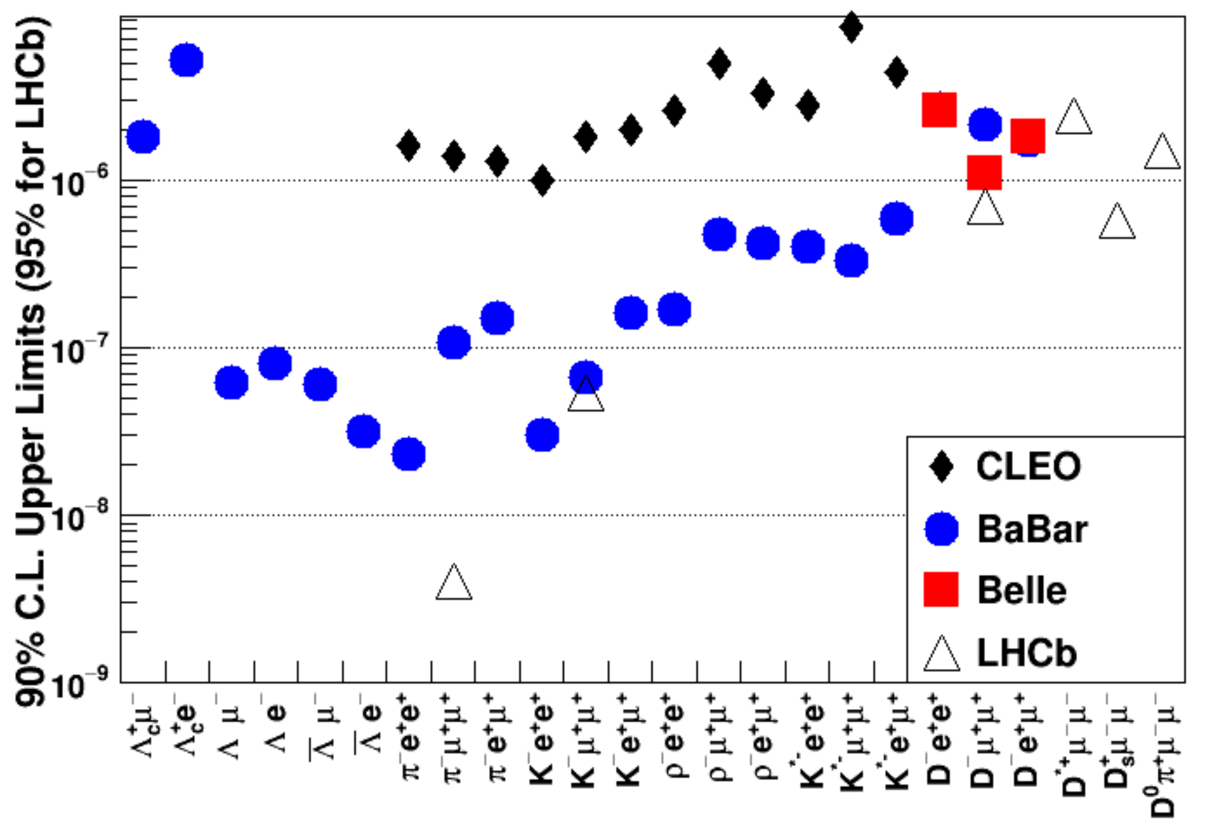
- Other processes to look for:

$$D^+,\ B^+ \to \ell^+\ell^+K^*,$$
$$B^+ \to \tau^+e^+M^-,\ \tau^+\mu^+M^-,\ \tau^+\tau^+M^-.$$

Atre, TH, Pascoli, Zhang, arXiv:0901.3589

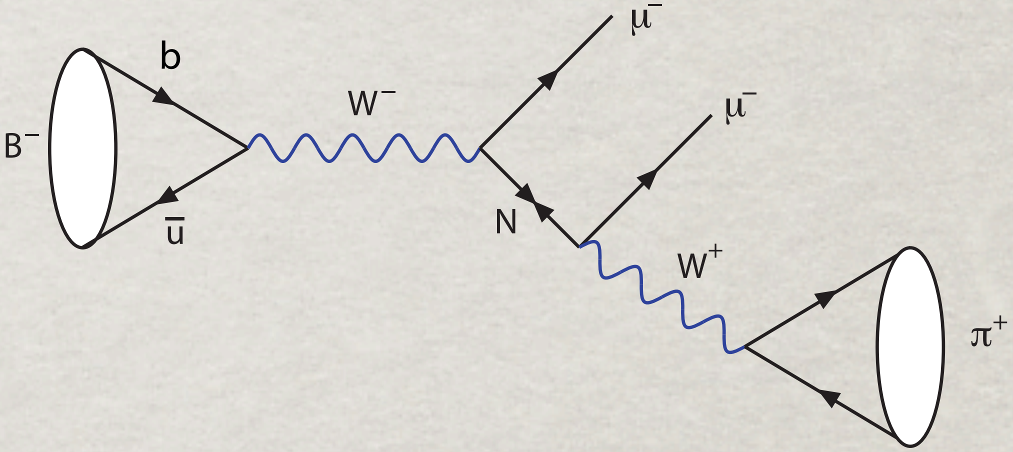
τ, K, D, B decays: $M^+ \to \ell_i^+\ell_j^+ M^-$ via N

BaBar collaboration: arXiv:1503.08267v1.



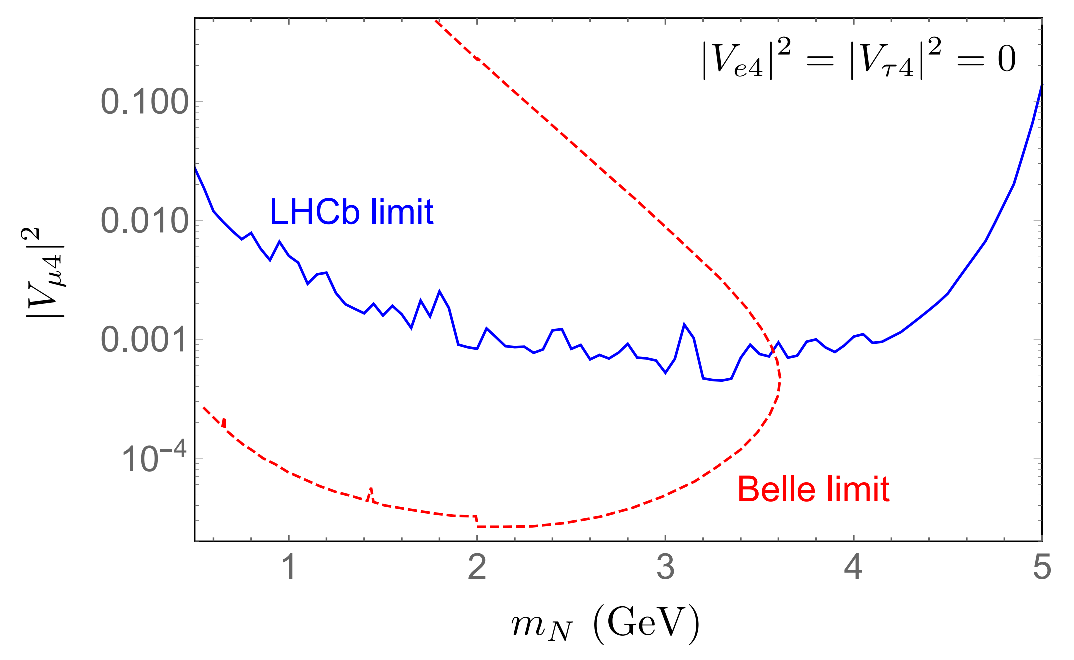
CERN NA62, arXiv:1905.07770

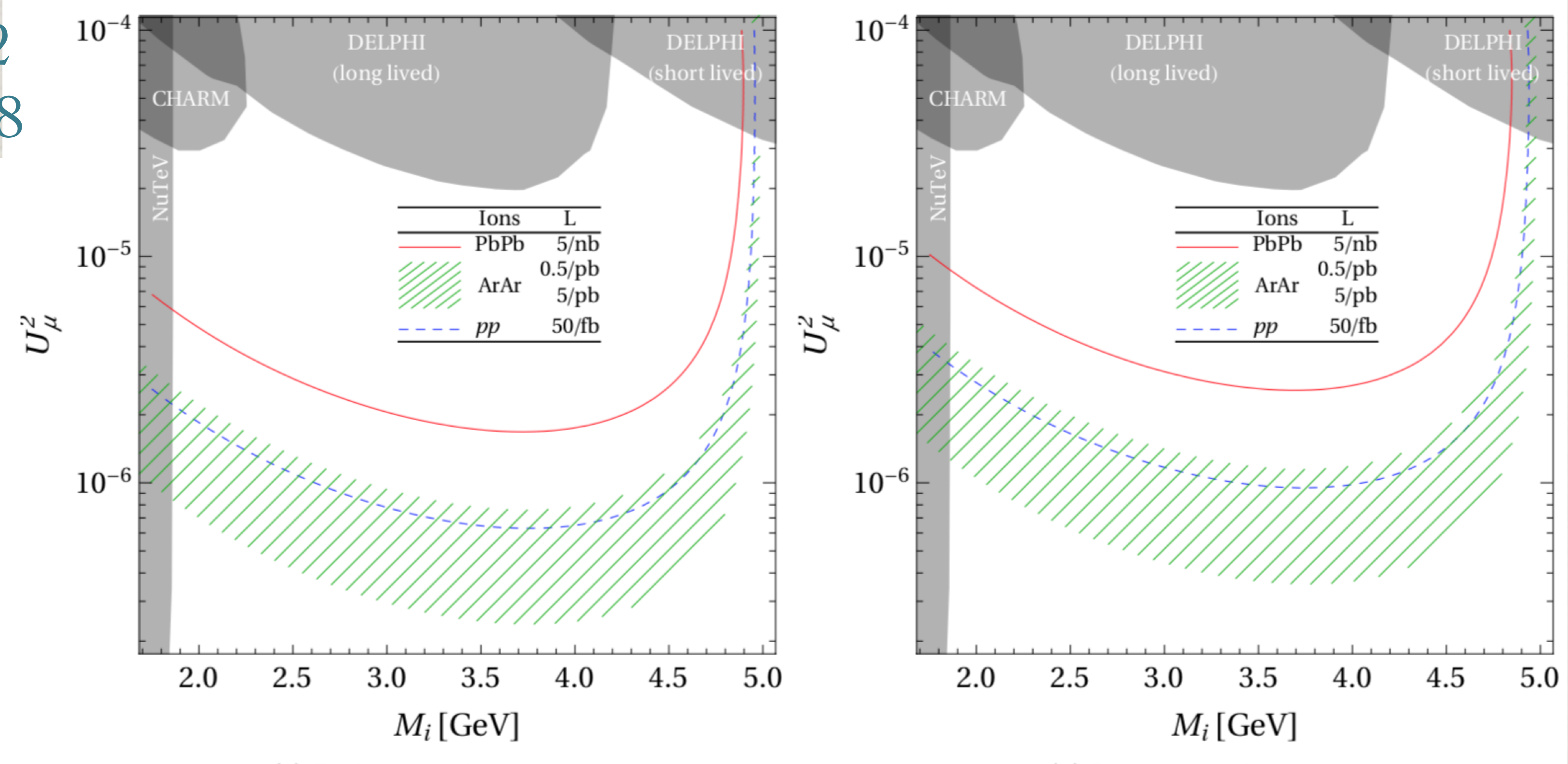
$$\begin{aligned}\mathcal{B}(K^+ \to \pi^-e^+e^+) &< 2.2\times 10^{-10},\\ \mathcal{B}(K^+ \to \pi^-\mu^+\mu^+) &< 4.2\times 10^{-11}.\end{aligned}$$



M. Drewes, J. Hajer et al., arXiv:1905.19828
Heavy ion with low trigger threshold

LHCb collaboration: arXiv:1401.5361v2
B. Shuve & M. Peskin, arXiv:1607.04258



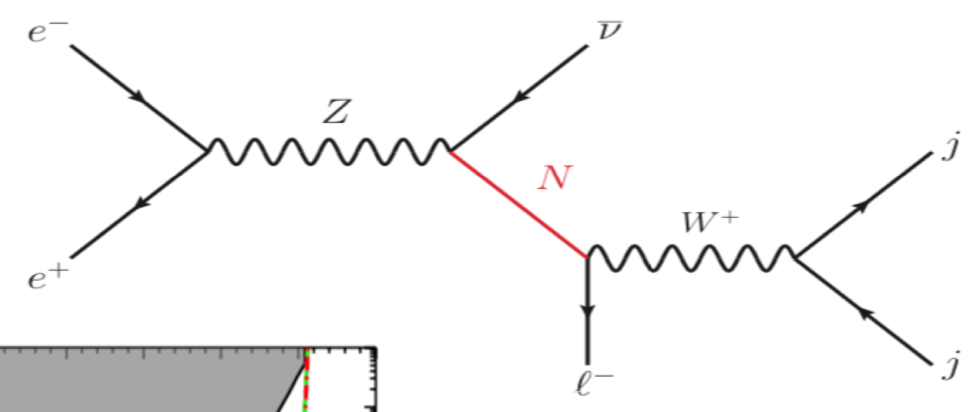


(a) Exclusion with $2\,\sigma$.

(b) Discovery with $5\,\sigma$.

5. “Type I” at Lepton Colliders

Jian-Nan Ding, Qin Qin, Fu-Sheng Yu:
arXiv:1903.02570



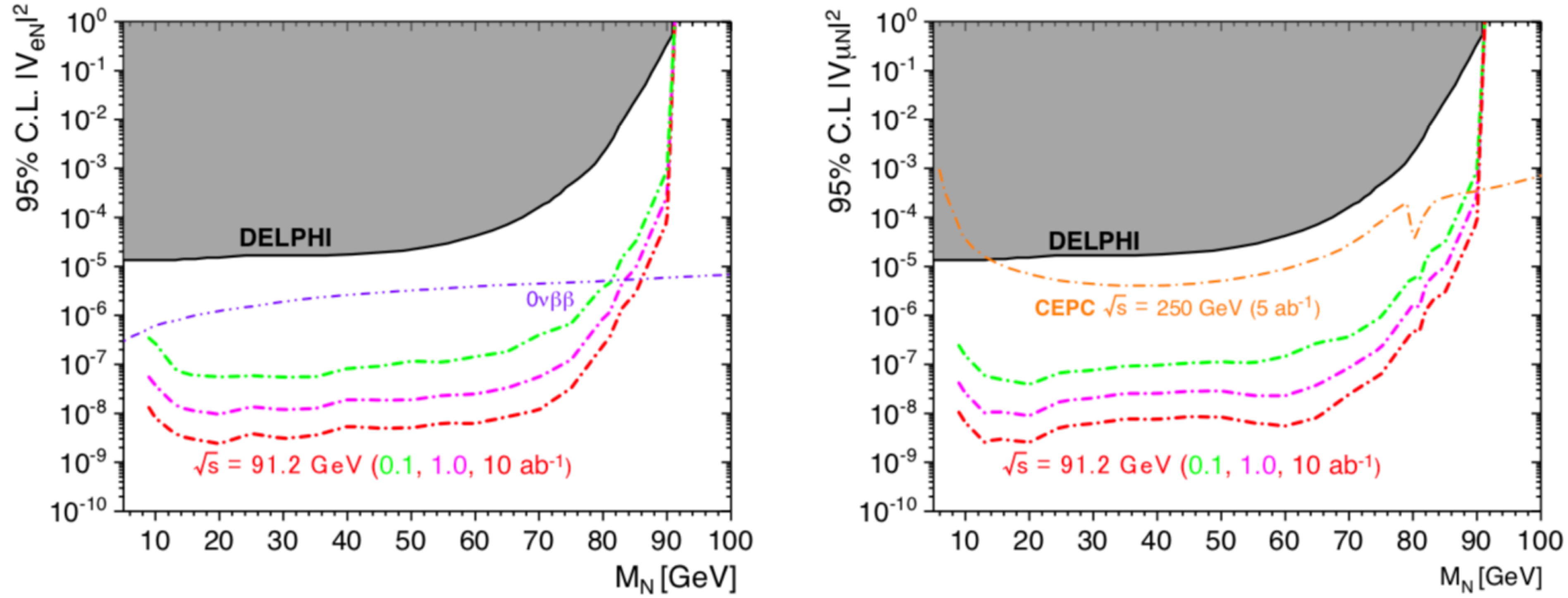
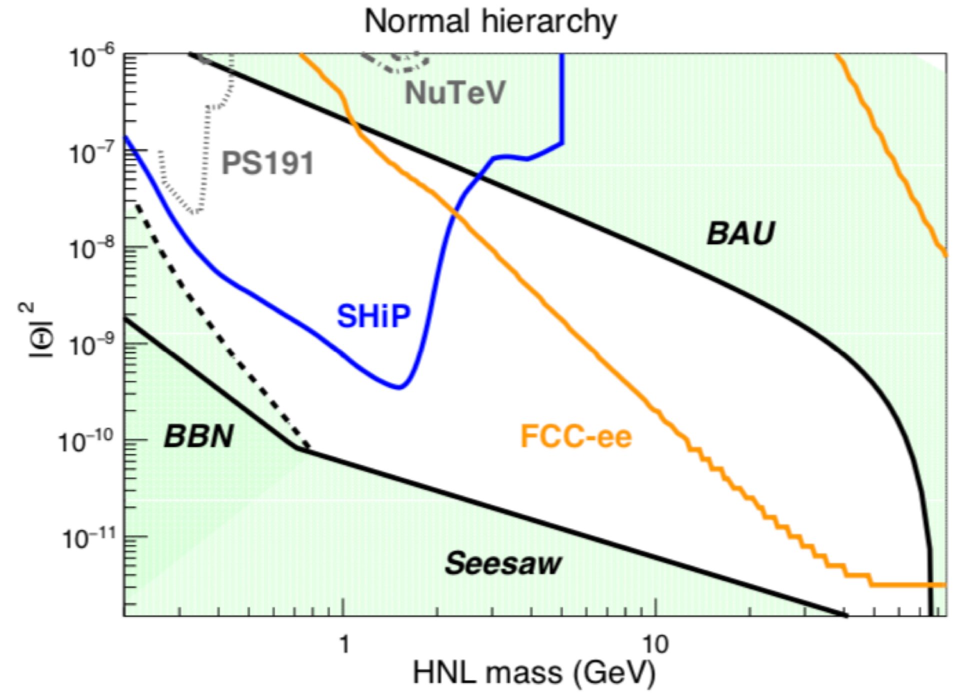


FIG. 6: The upper bounds on the mixing parameters $|V_{eN}|^2$ (left) and $|V_{\mu N}|^2$ (r
Z-factories at 95% CL, compared to the upper bounds given by DELPHI [18], t
experiments [19–21] and the CEPC as a Higgs factory [32]. The green, pink a
correspond to integrated luminosities of 0.1 ab^{-1}, 1.0 ab^{-1} and 10 ab^{-1}, respectivel
details.

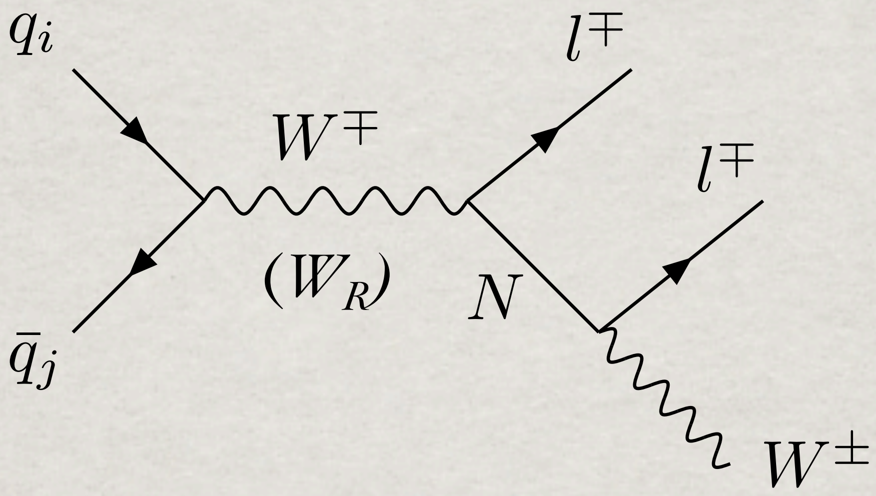
FCCee CDR Vol.2



Decay length 100 μm to 2 m

6. "Type I" at Hadron Colliders

At hadron colliders: § $pp(\bar{p}) \to \ell^{\pm}\ell^{\pm}jjX$

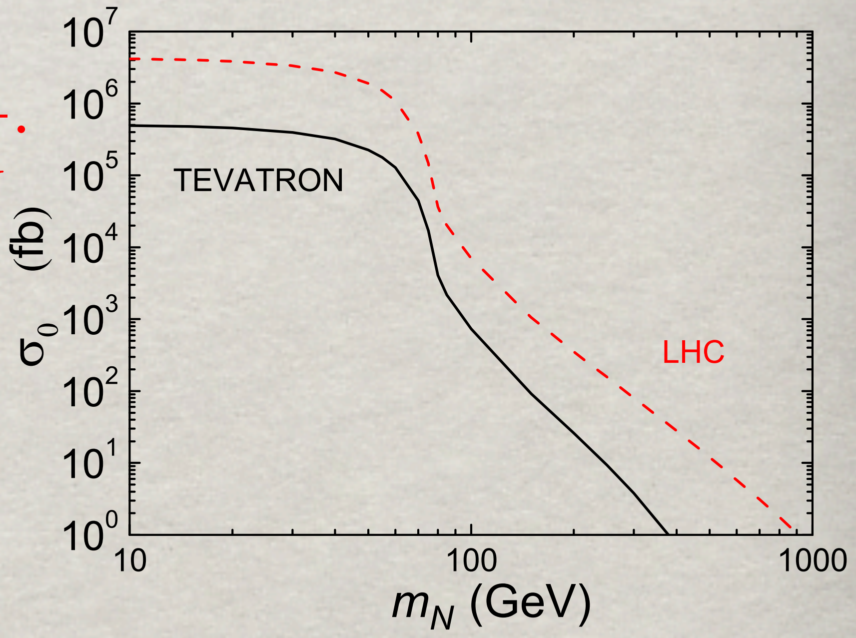


$$\sigma(pp \to \mu^{\pm}\mu^{\pm}W^{\mp}) \approx \sigma(pp \to \mu^{\pm}N)Br(N \to \mu^{\pm}W^{\mp}) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V^{\ell N}\right|^2} V_{\mu N}^2 \; \sigma_0.$$

Factorize out the mixing couplings: †

$$\sigma(pp \to \mu^{\pm}\mu^{\pm}W^{\mp}) \equiv S_{\mu\mu} \; \sigma_0,$$

$$S_{\mu\mu} = \frac{V_{\mu N}^4}{\sum_l |V_{\ell N}|^2} \approx \frac{V_{\mu N}^2}{1 + V_{\tau N}^2/V_{\mu N}^2}.$$



A very clean channel:

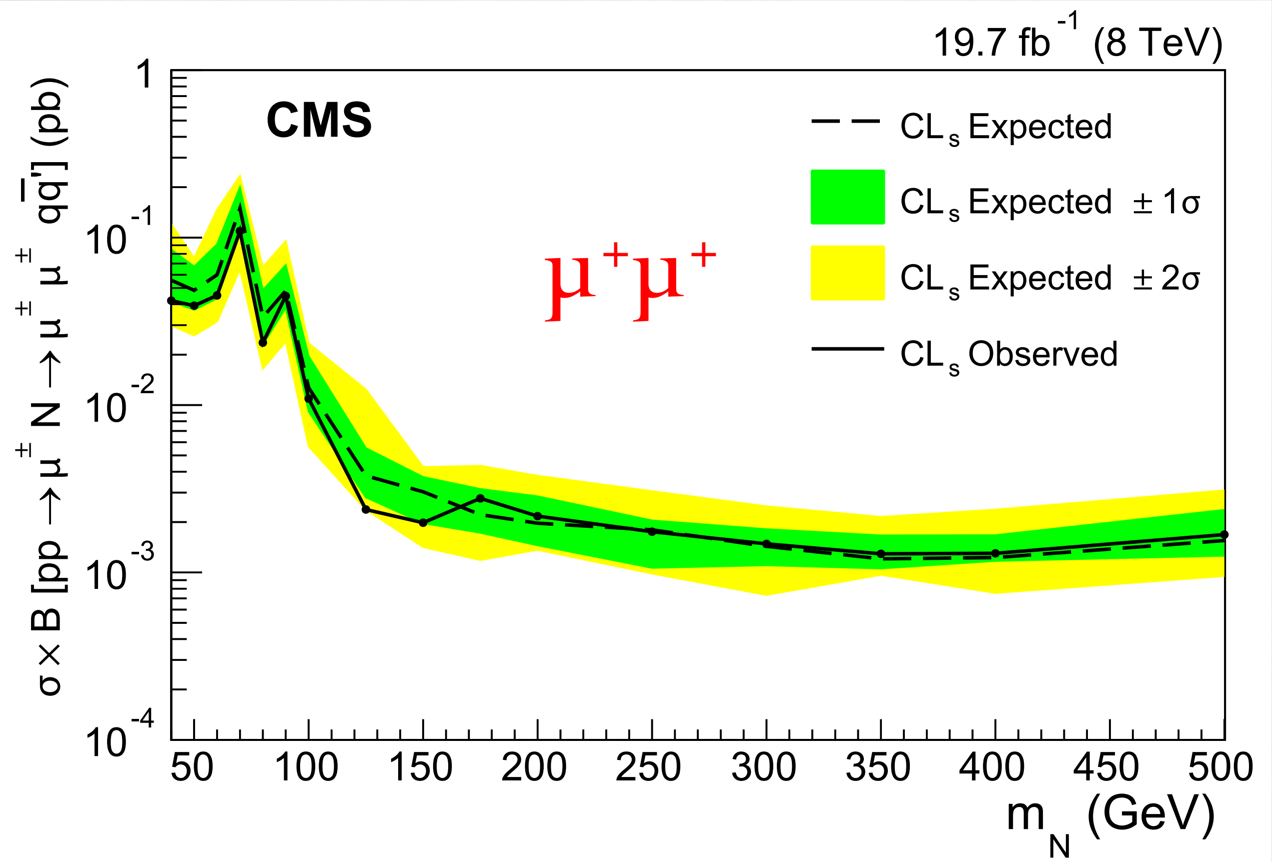
- like-sign di-muons plus two jets;
- no missing energies;
- $m(jj) = M_W, \; m(jj\mu) = m_N$.

[§] Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); ATLAS TDR (1999); F. Almeida et al. (2000); F. del Aguila et al. (2007).

[†] T. Han and B. Zhang, hep-ph/0604064, PRL (2006).

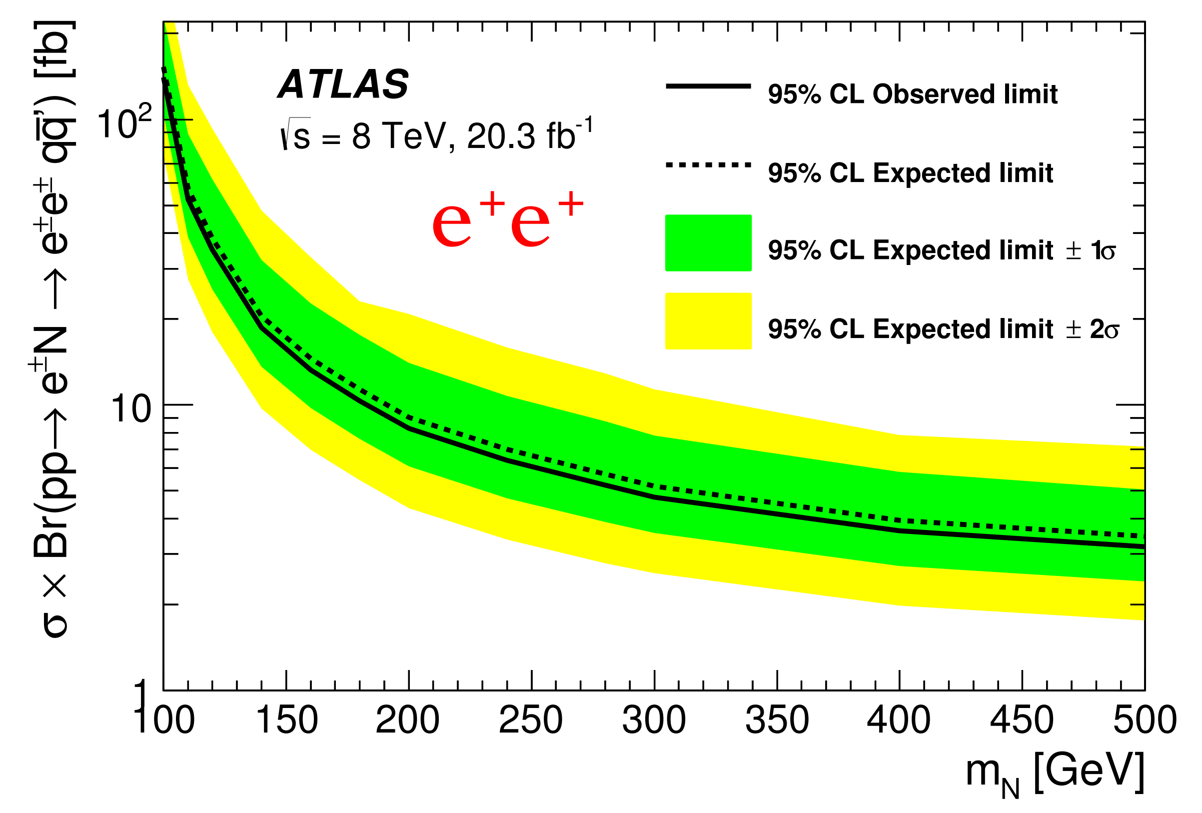
CMS:

CMS collaboration: arXiv:1501.05566v1.

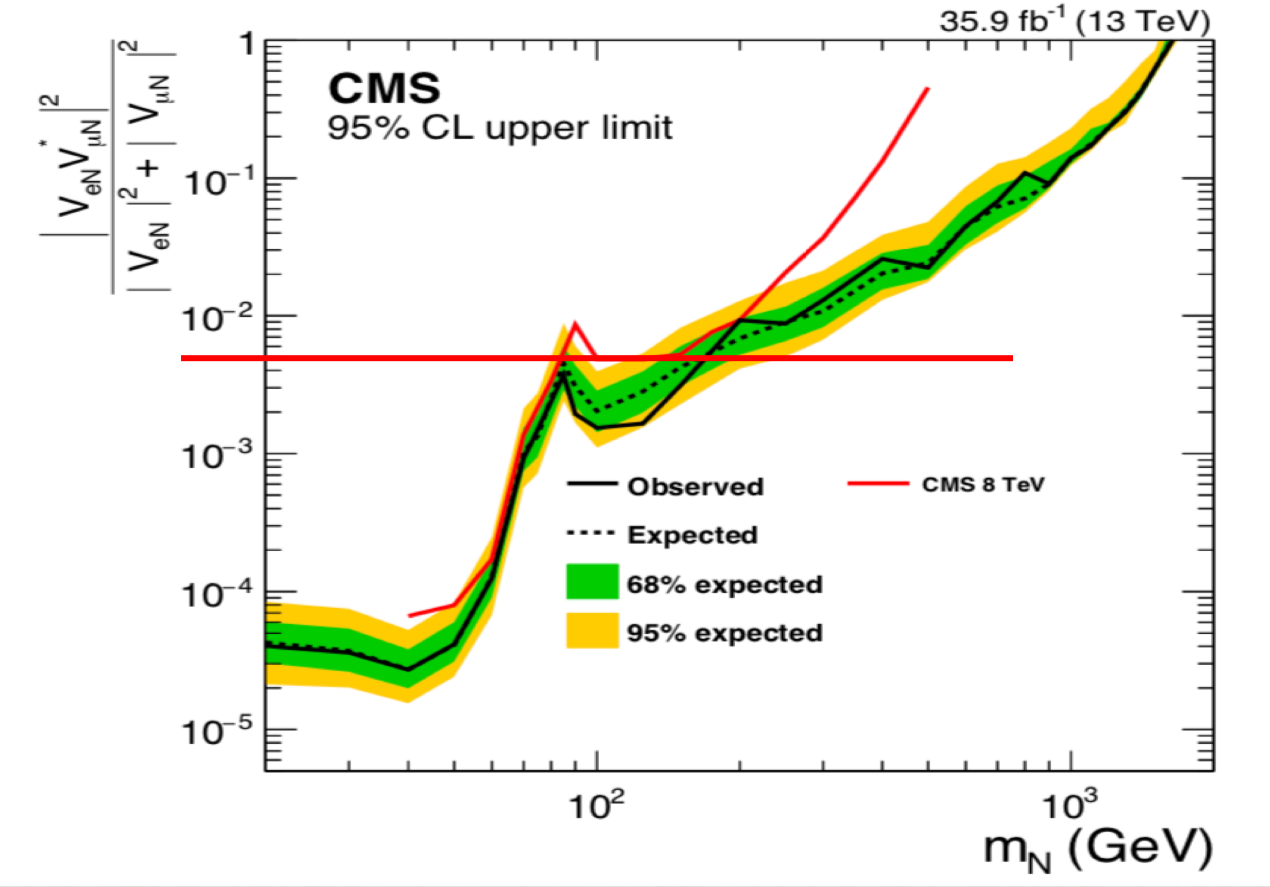


ATLAS:

ATLAS collaboration: arXiv:1506.06020v2.



CMS collaboration update:
arXiv:1806.10905.

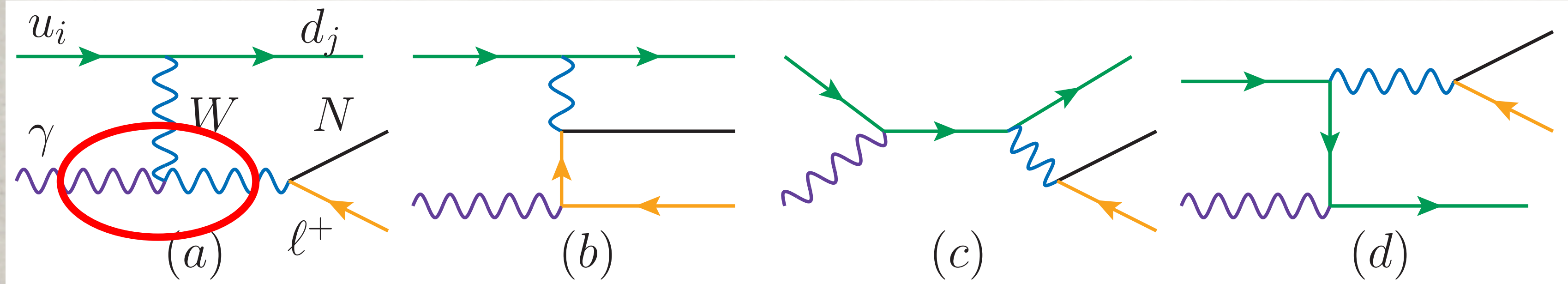


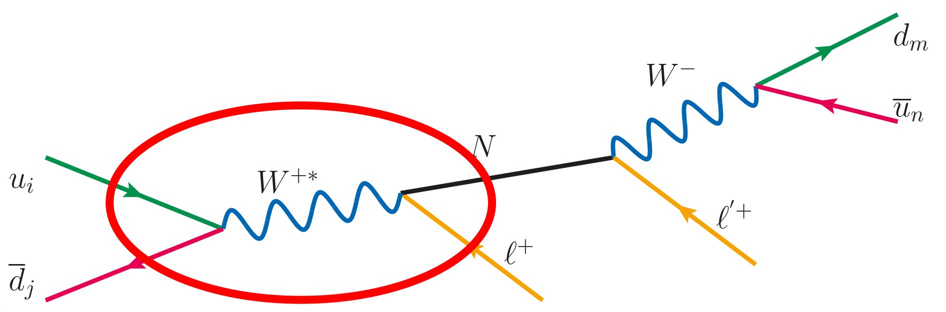
Insensitive to low mass:
There is a trigger threshold
~ 20 GeV!

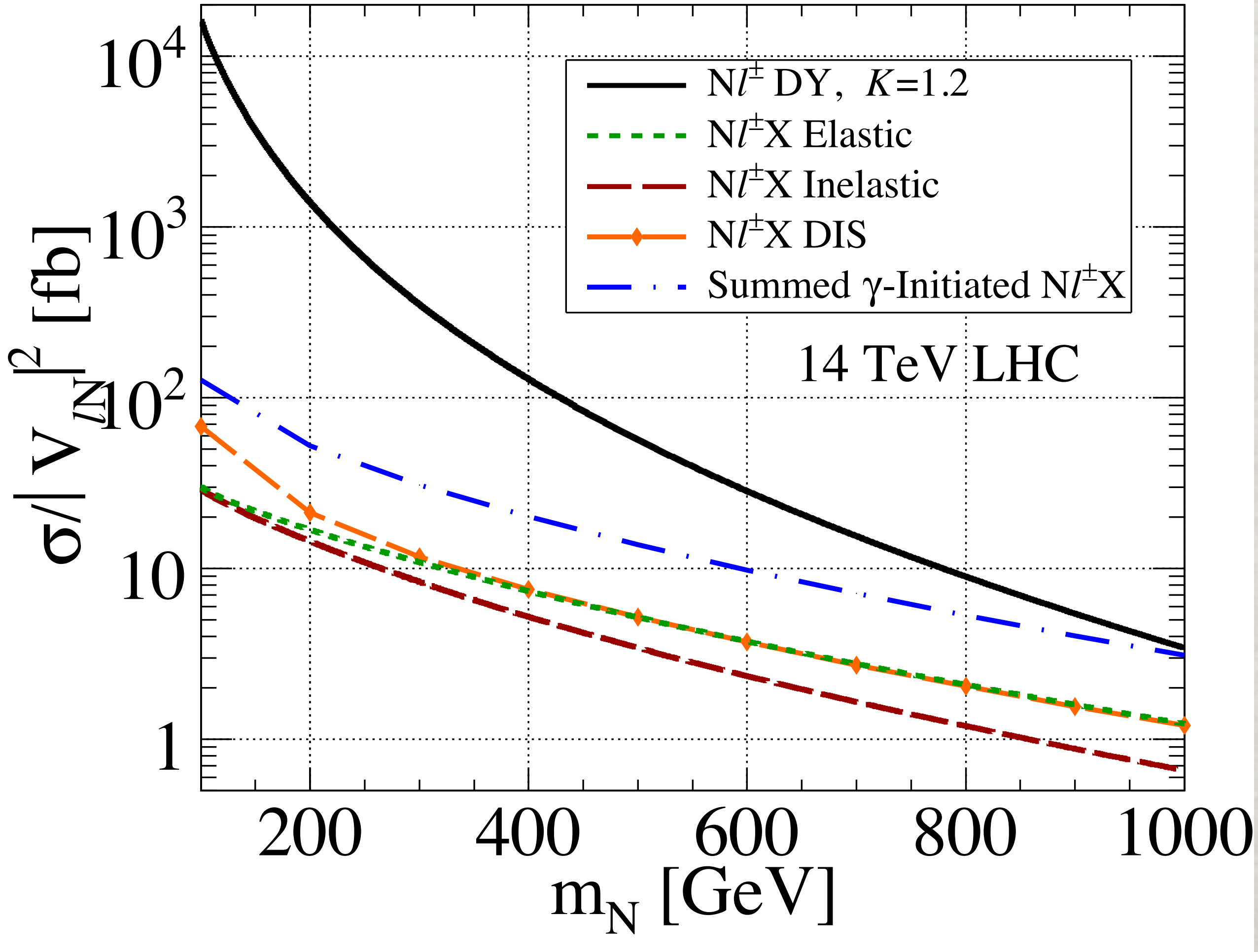
A recent update:

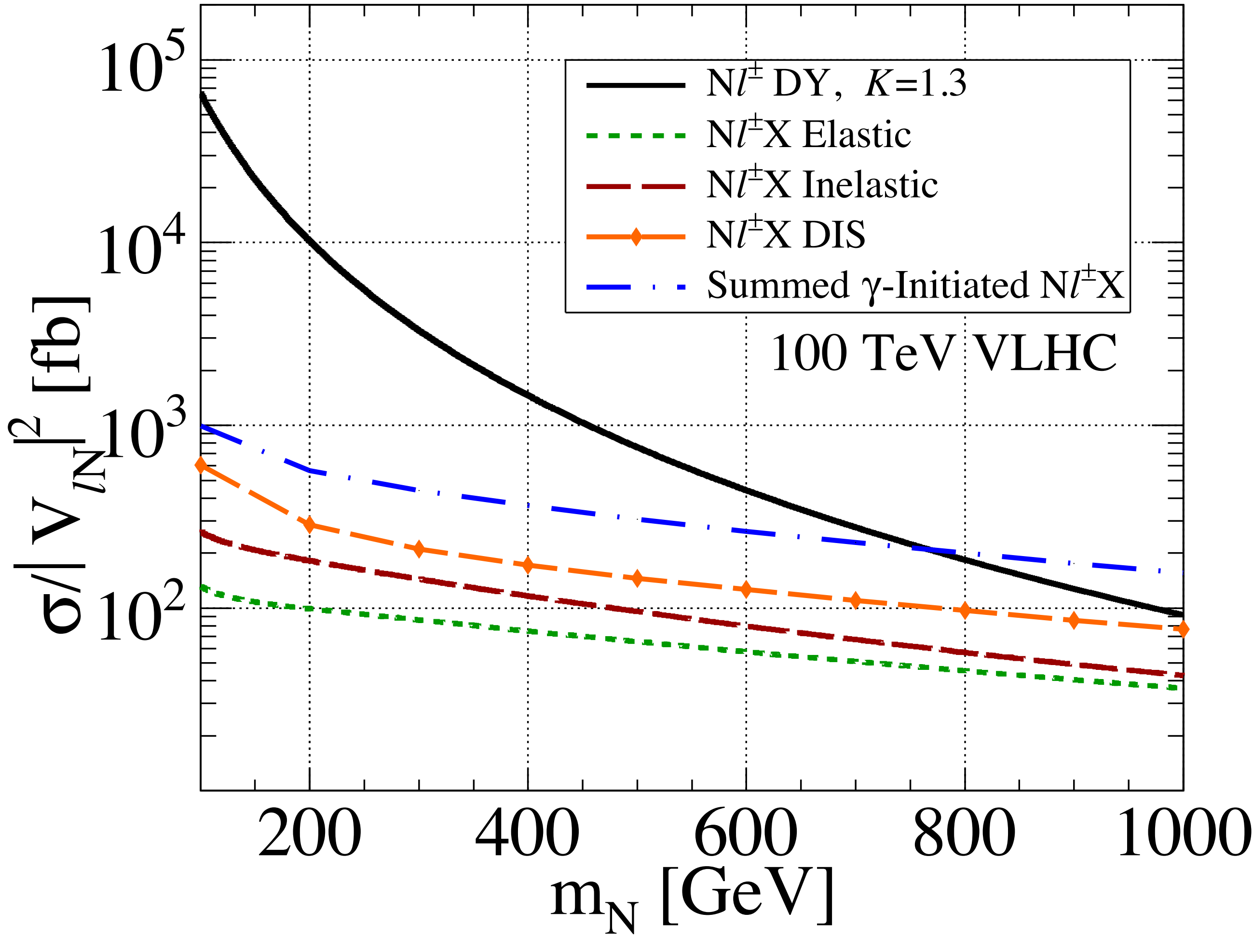
VBF (Wγ) contributions and NNLO QCD effects

P. S. B. Dev, A. Pilaftsis and U.-k. Yang,
Phys. Rev. Lett. 112 (2014) 081801;
Alva, TH, Ruiz: arXiv:1411.7305









New Strategy: Long Lived Particles @ Low mass

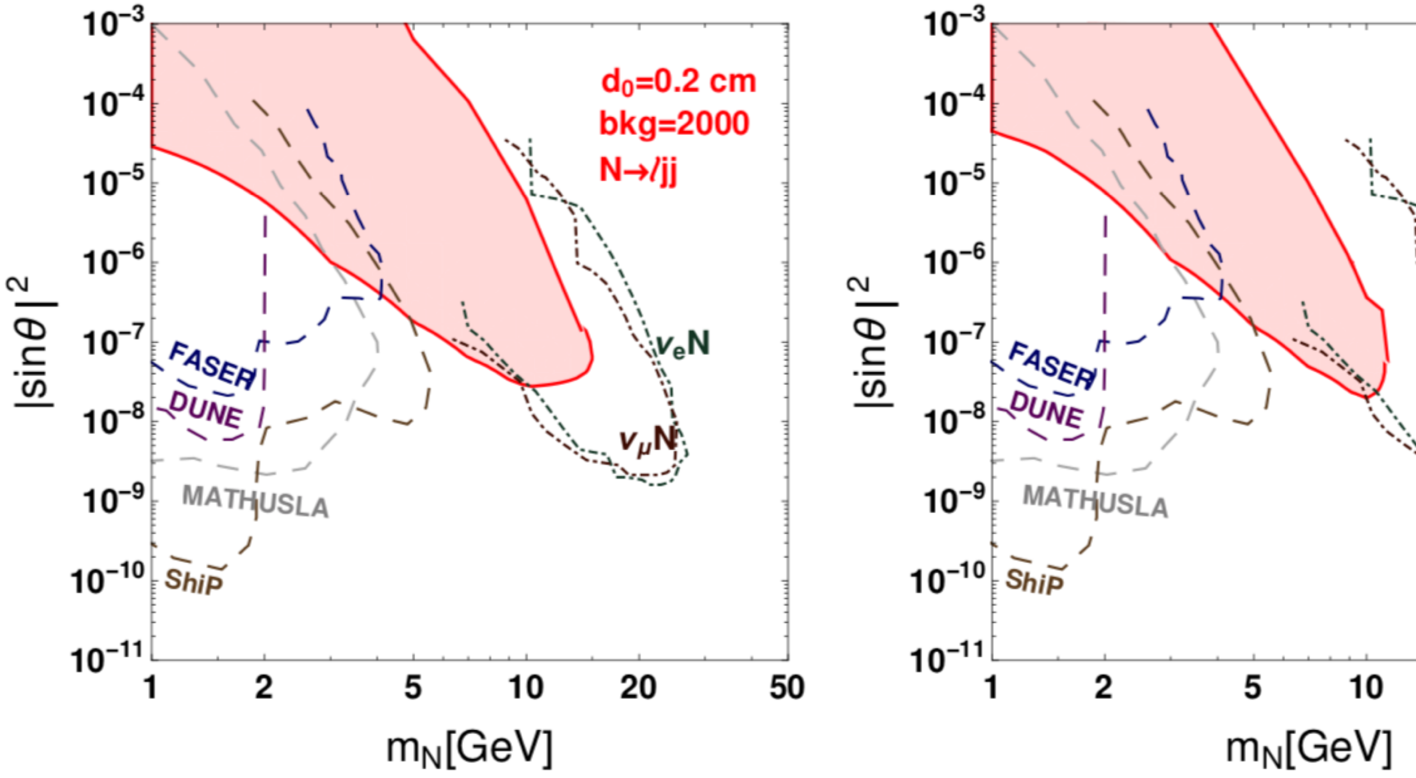


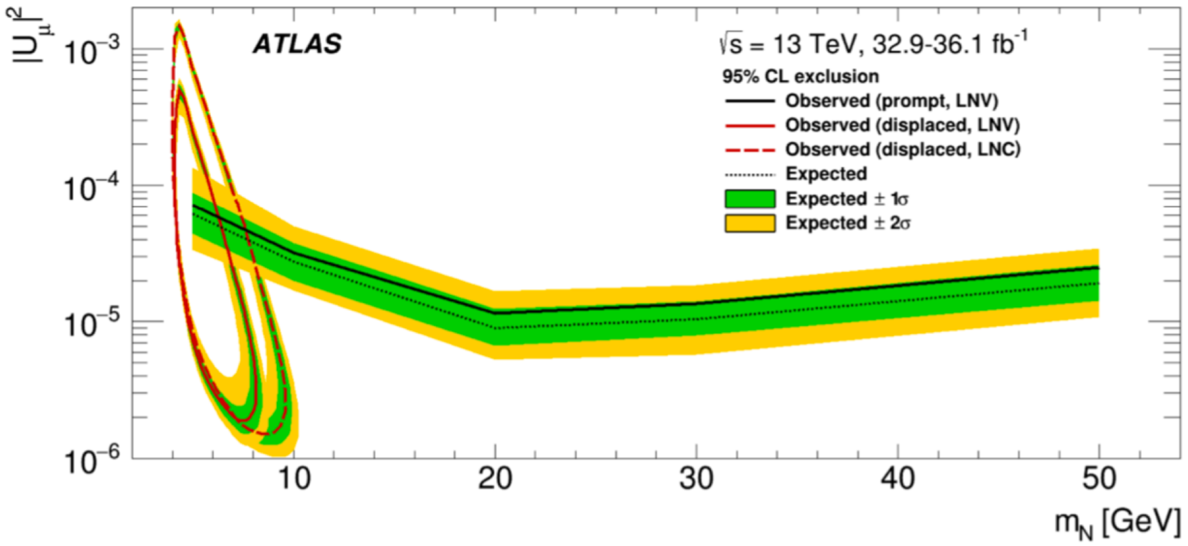
FIG. 6. The 95% C.L. reach for sterile neutrino from W gauge boson decay, plotted

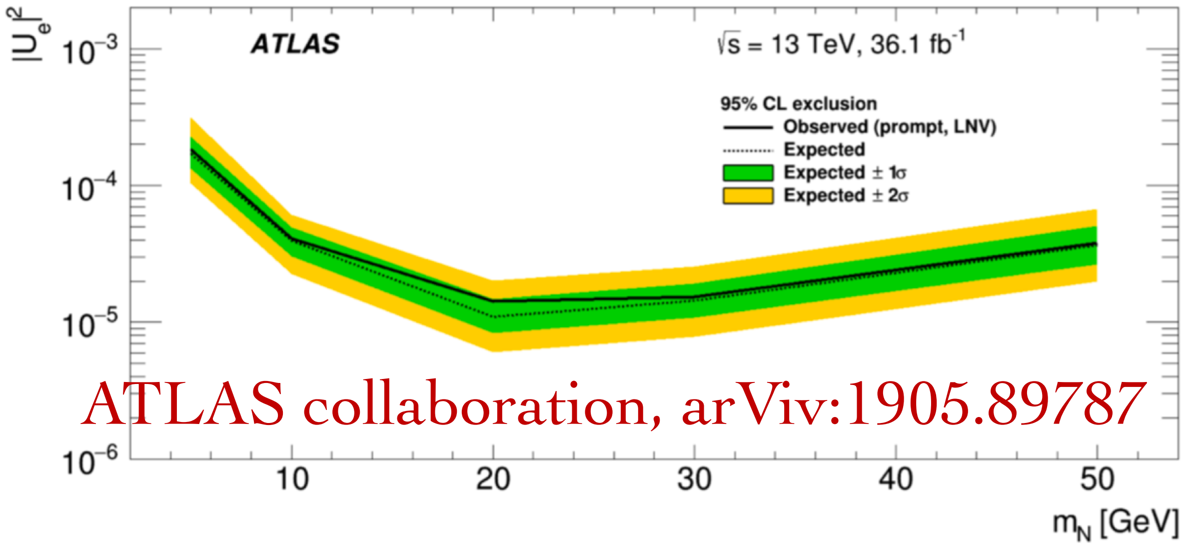
plane . The sensitivities for “$\nu_e N$” and “$\nu_\mu N$” come from prompt lepton trigge

displaced vertex projection at HL-LHC [70] assuming zero background. The pr

reach for MATHUSLA [45], FASER [44], DUNE [29] and SHiP [30, 71] are also s

$$c\tau \simeq 12\ \mathrm{km} \times \left(\frac{10^{-12}}{\sin^2\theta}\right)\left(\frac{10\ \mathrm{GeV}}{m_N}\right)^5$$

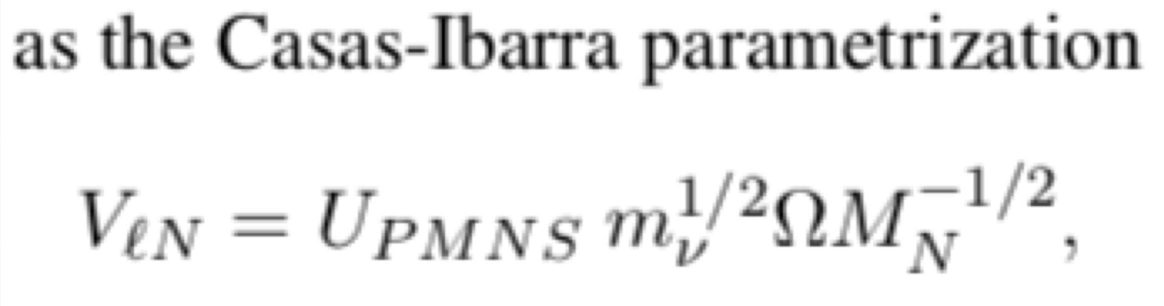




ATLAS collaboration, arViv:1905.89787

M. Drewes and J. Hajer, arXiv:1903.06100;
J. Liu, Z. Liu, L.-T. Wang, X. Wang, arXiv:1904.01020.

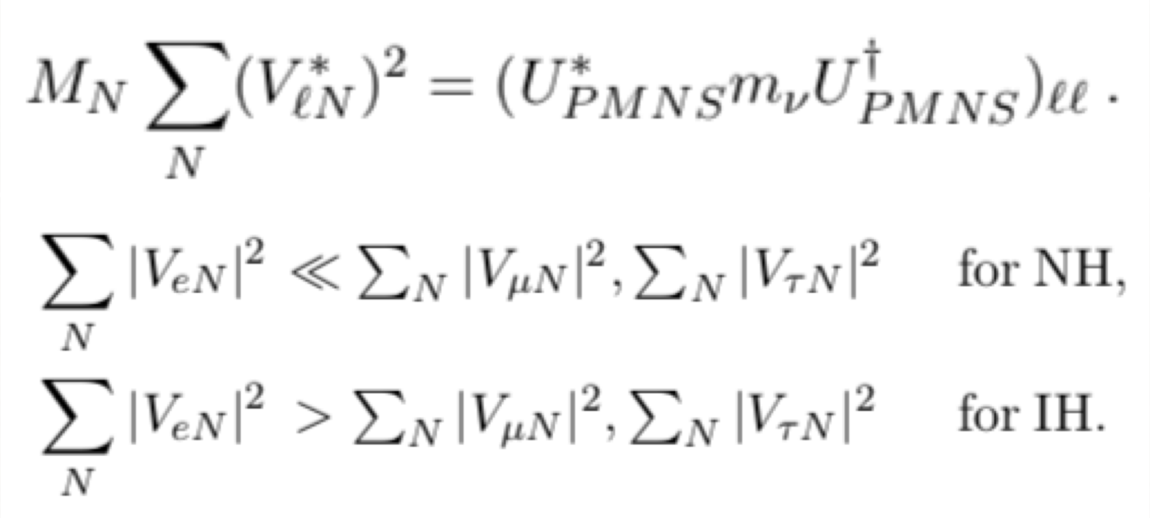
Type I, in general, too many theory parameters,



as the Casas-Ibarra parametrization

$$V_{\ell N} = U_{PMNS}\, m_\nu^{1/2} \Omega M_N^{-1/2},$$

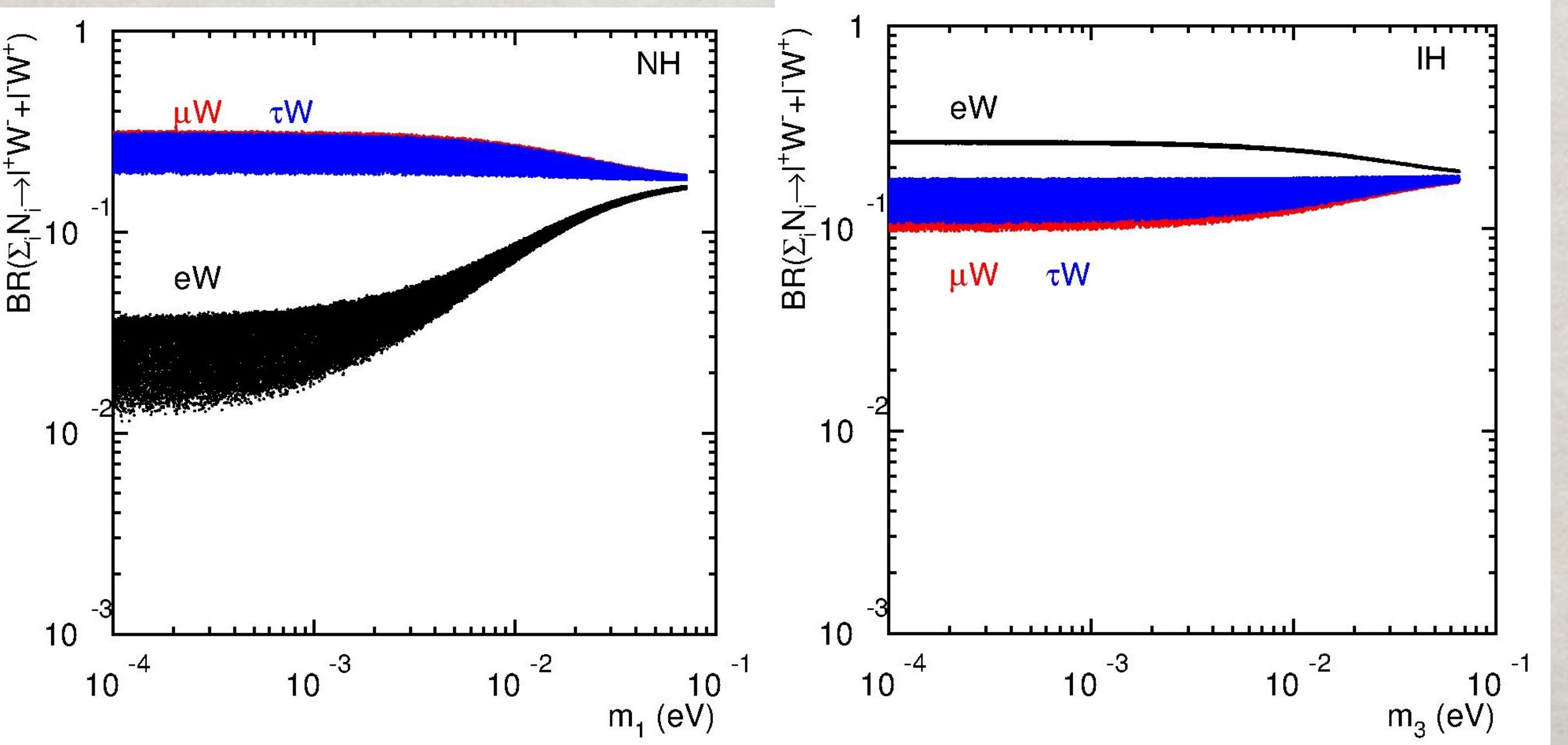
If assuming degenerate N_i



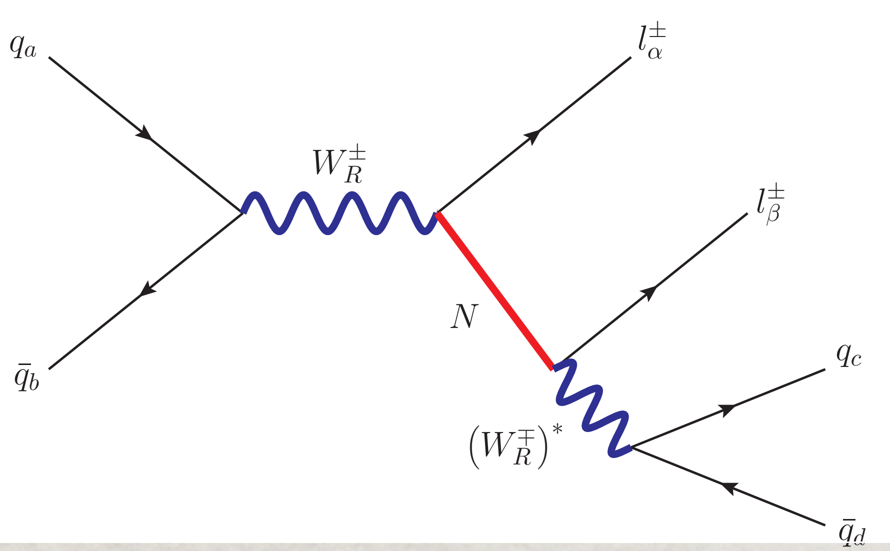
$$M_N \sum_N (V^*_{\ell N})^2 = (U^*_{PMNS} m_\nu U^\dagger_{PMNS})_{\ell\ell}\,.$$

$$\sum_N |V_{eN}|^2 \ll \textstyle\sum_N |V_{\mu N}|^2, \sum_N |V_{\tau N}|^2 \quad \text{for NH,}$$

$$\sum_N |V_{eN}|^2 > \textstyle\sum_N |V_{\mu N}|^2, \sum_N |V_{\tau N}|^2 \quad \text{for IH.}$$

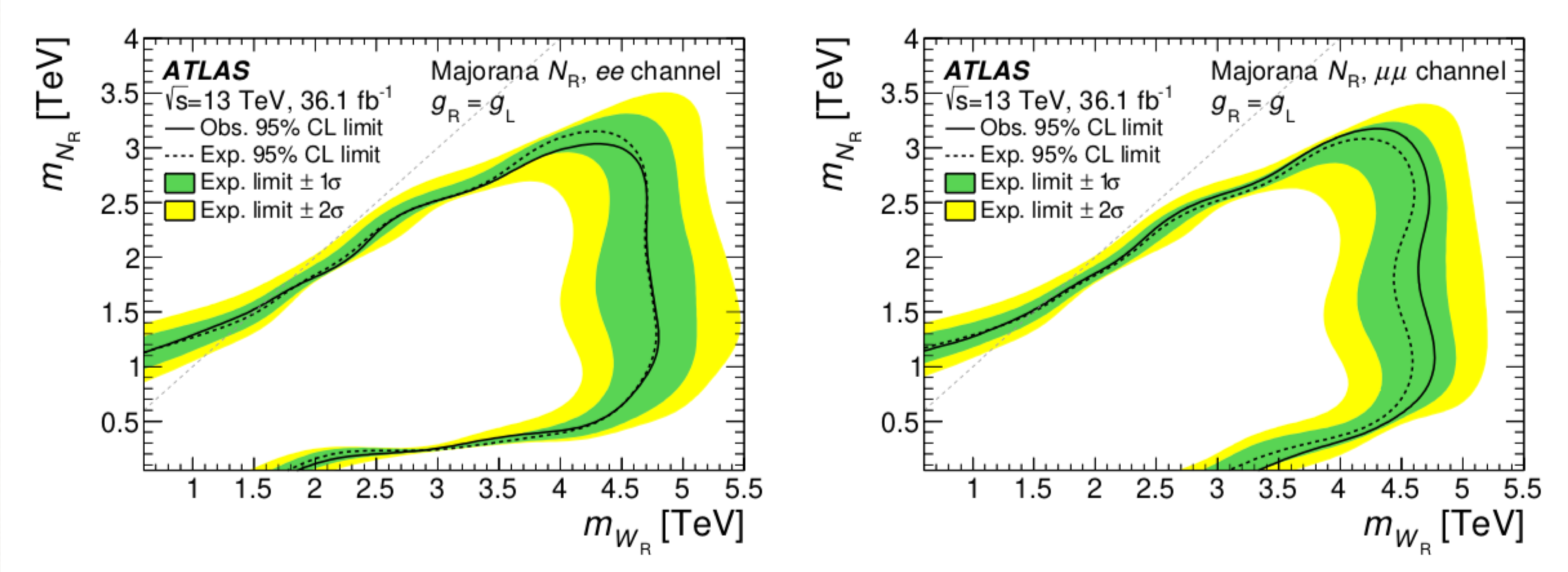


7. W_R & N @ Hadron Colliders



G. Senjanovic & W. Keung,
PRL 50 (1983) 1427

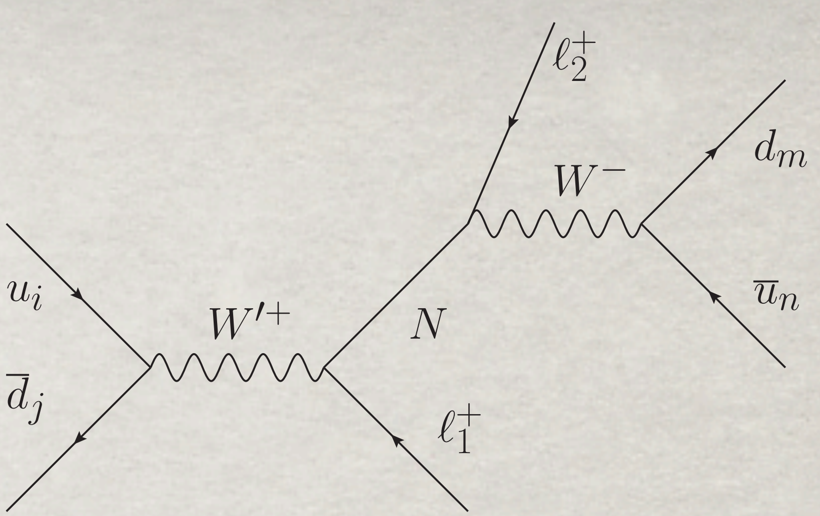
- No mixing suppression
- New unknown mass scale MR



ATLAS collaboration: arXiv:1809.11105.

W_R & N_R Properties:

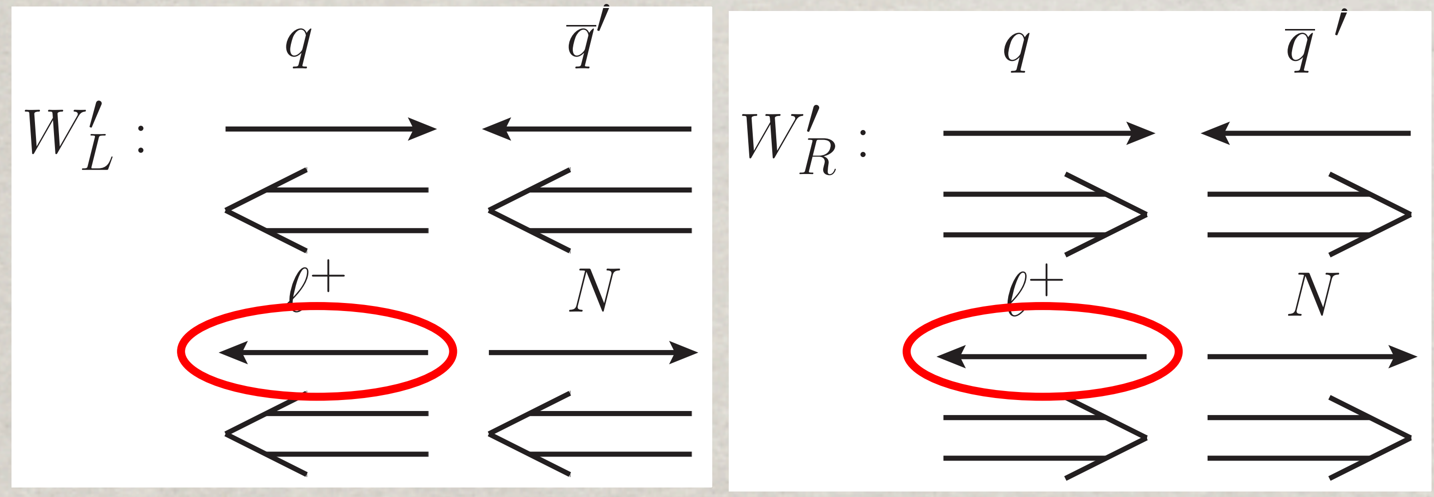
$SU(2)_L \otimes SU(2)_R$ symmetric model:

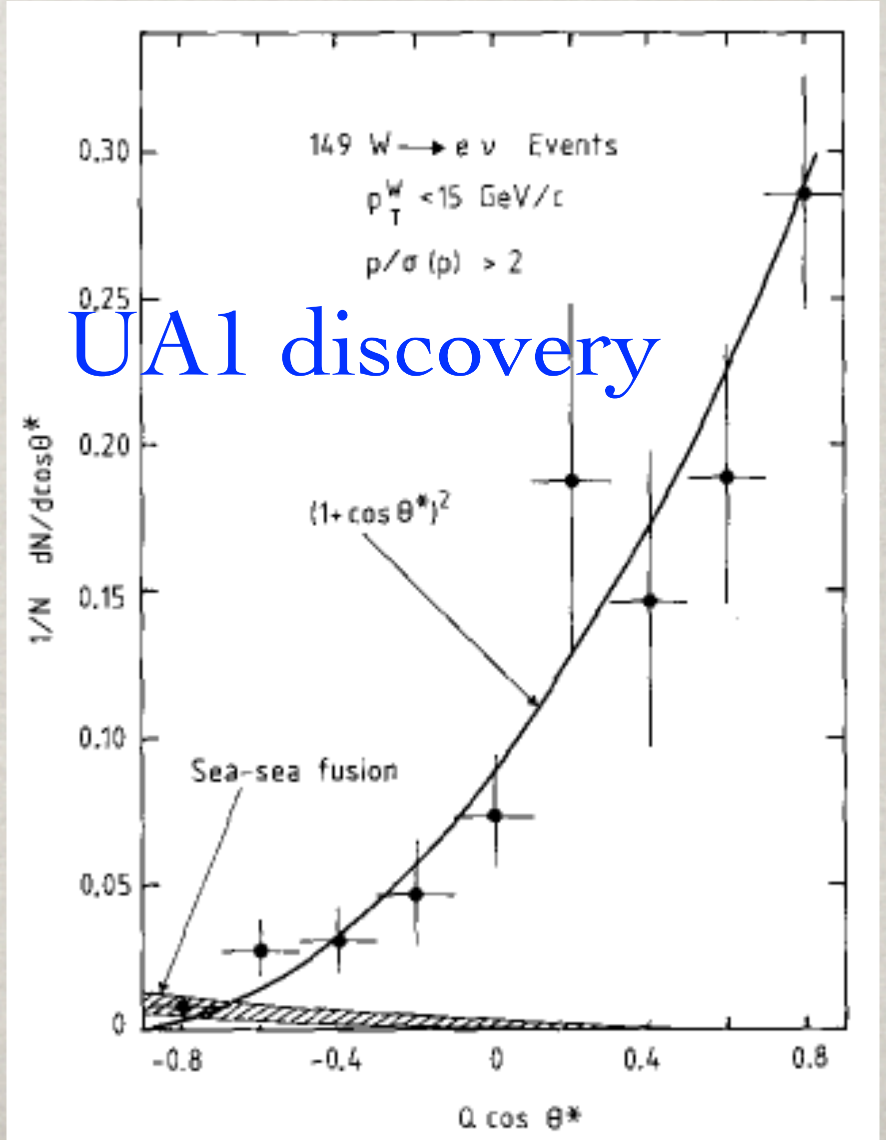


A clean channel with rich physics:[†]

- Significantly enhanced rate at W_R resonance; [¶]
- If observed, determine N's nature: $\Delta L = 2$, azimuthal angle …
- and determine W' chiral coupling to $\ell - N_{R,L}$ and $q - \bar{q}$.

The primary lepton does not provide L-R discrimination:



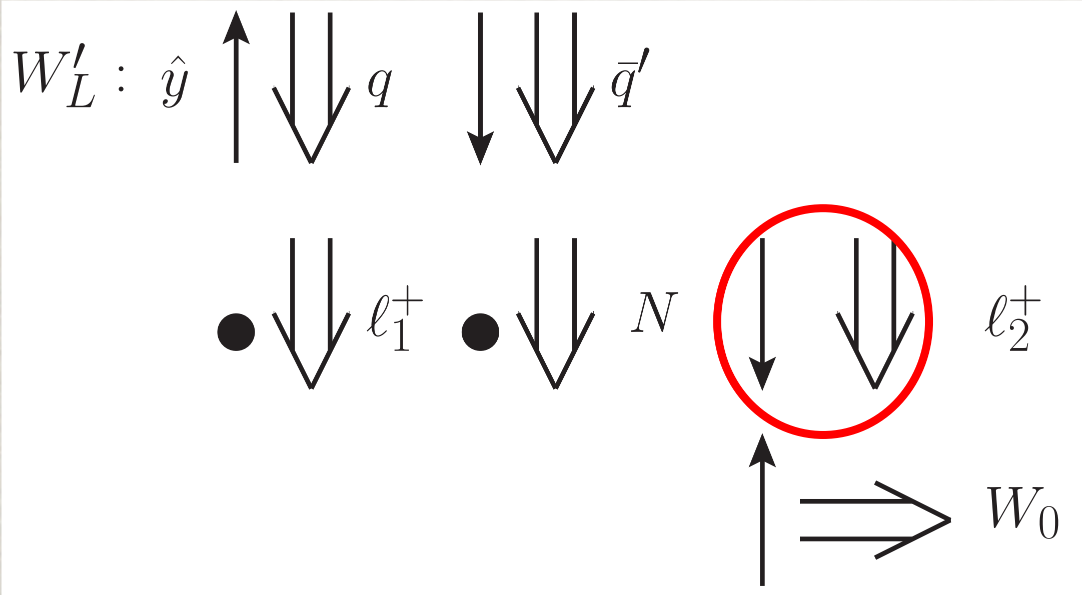


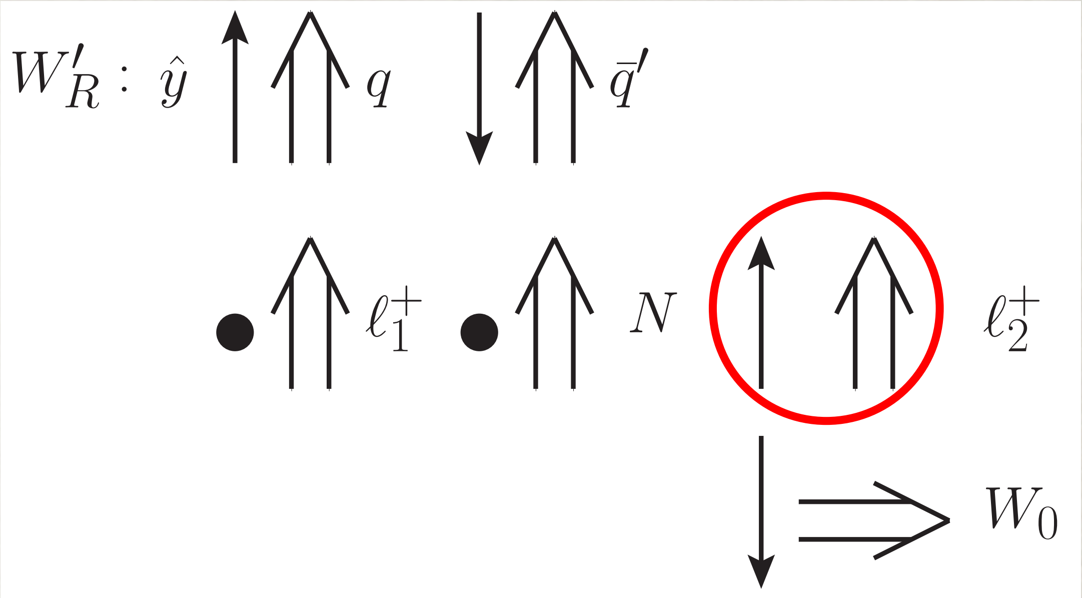
UA1 discovery

Keung & Senjanovic, PRL (1983).

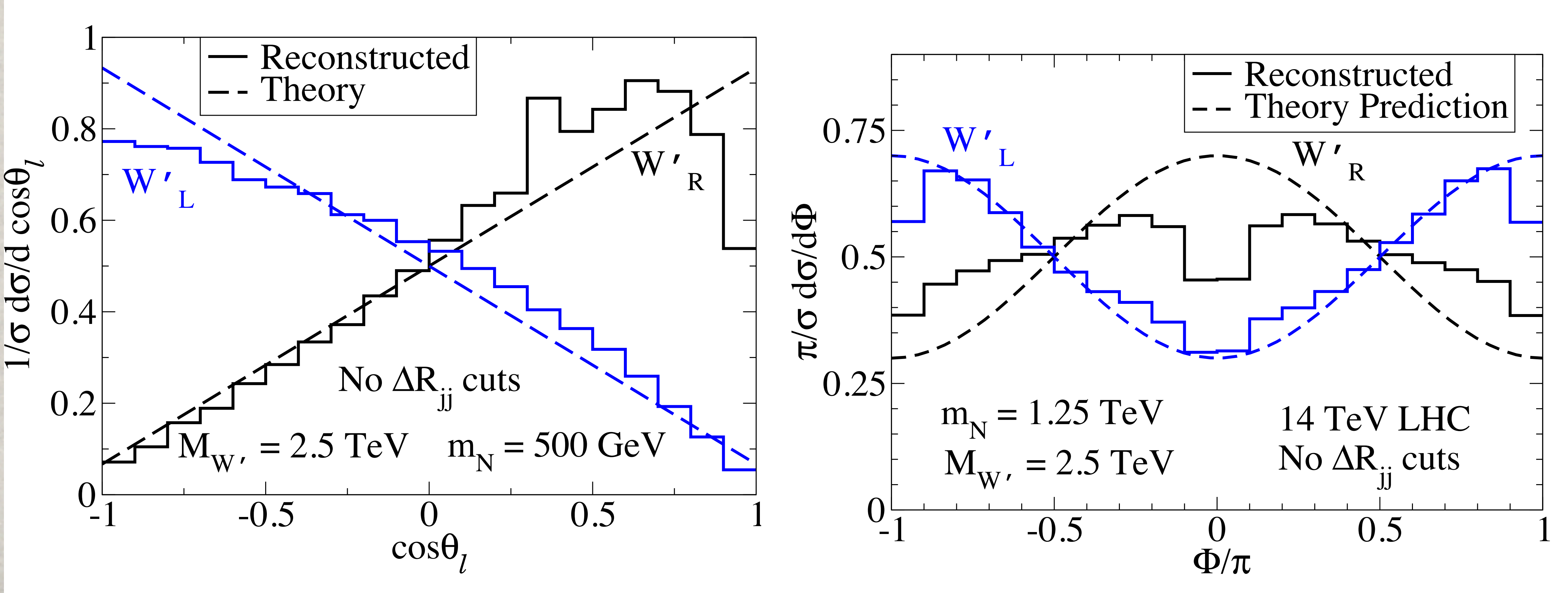
T. Han, I. Lewis, R. Ruiz, Z. Si, arXiv:1211.6447v2

$W_{L,R}$ Discrimination via $N_{L,R}$ Decay:





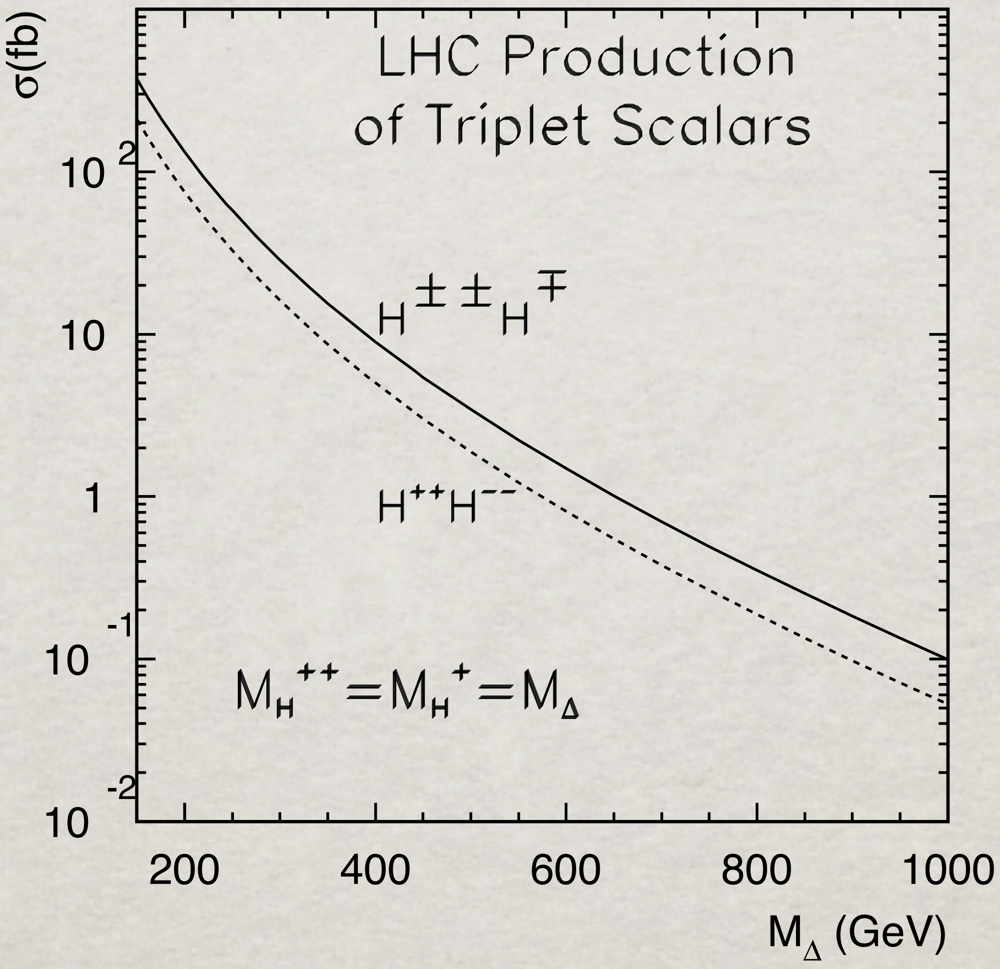
$$N_{L,R} \to \ell^+ W^- \to \ell^+ q\bar{q}'$$



8. Type II Seesaw: $H^{\pm\pm}$ & $H^{\pm}$

$H^{++}H^{--}$ production at hadron colliders: †

Pure electroweak gauge interactions



Akeroyd, Aoki, Sugiyama, 2005, 2007.

$\gamma\gamma \rightarrow H^{++}H^{--}$ 10% of the DY.

†Revisit, T.Han, B.Mukhopadhyaya, Z.Si, K.Wang, arXiv:0706.0441.

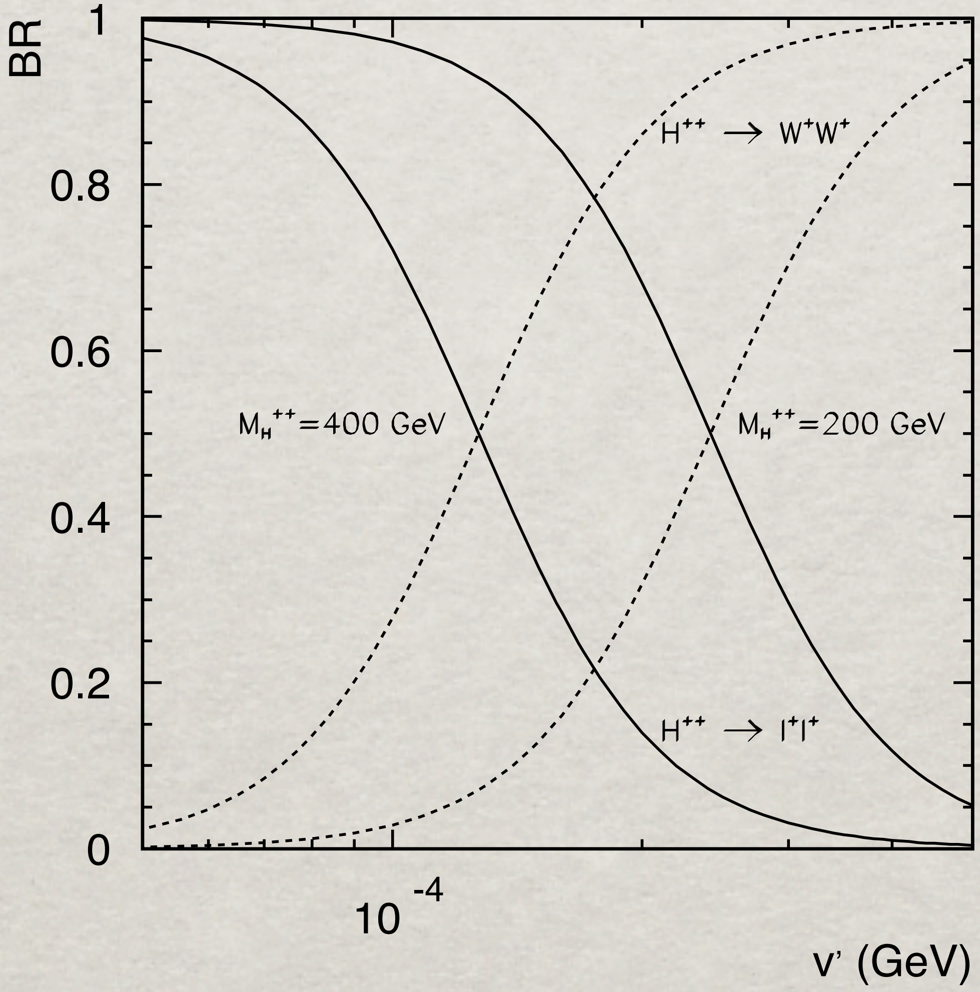
Recently, a new model: J. Gehrlein, D. Goncalves, P. Machado, Y. Perez-Gonzalez: arXiv:1804.09184.

Type II Seesaw: Complimentary Decays

$$\Gamma(\phi^{++} \to \ell^+\ell^+) \propto Y_{ij}^2 M_\phi$$

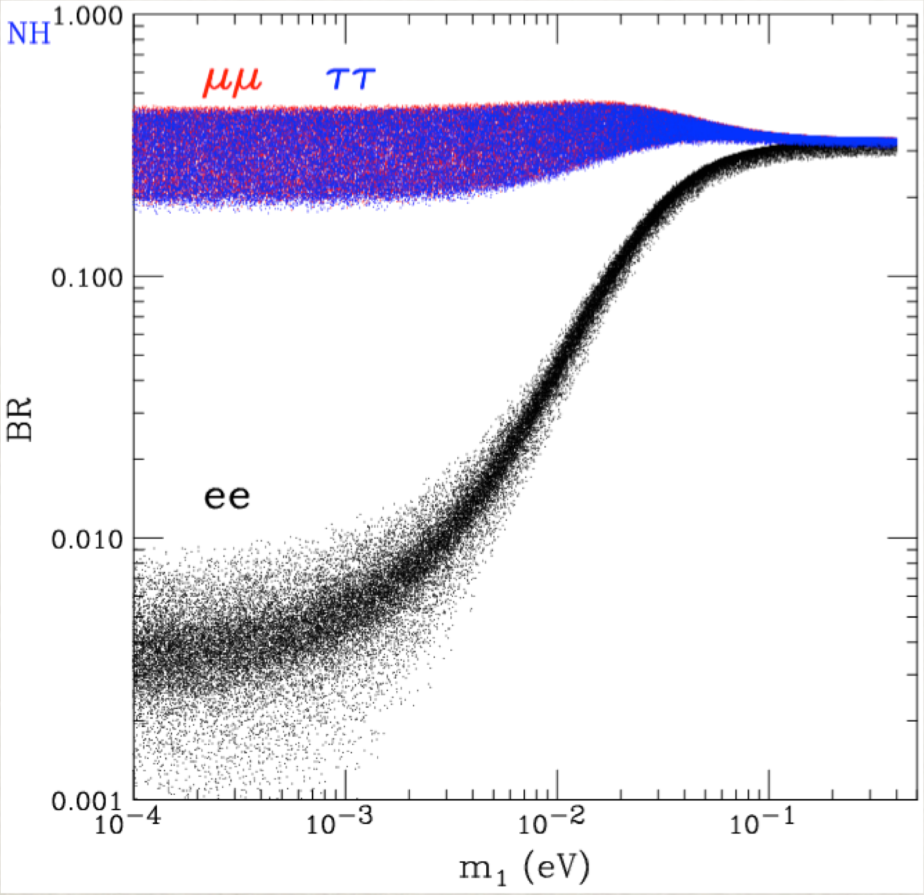
$$\Gamma(\phi^{++} \to W^+W^+) \propto \frac{v'^2 M_\phi^3}{v^4},$$

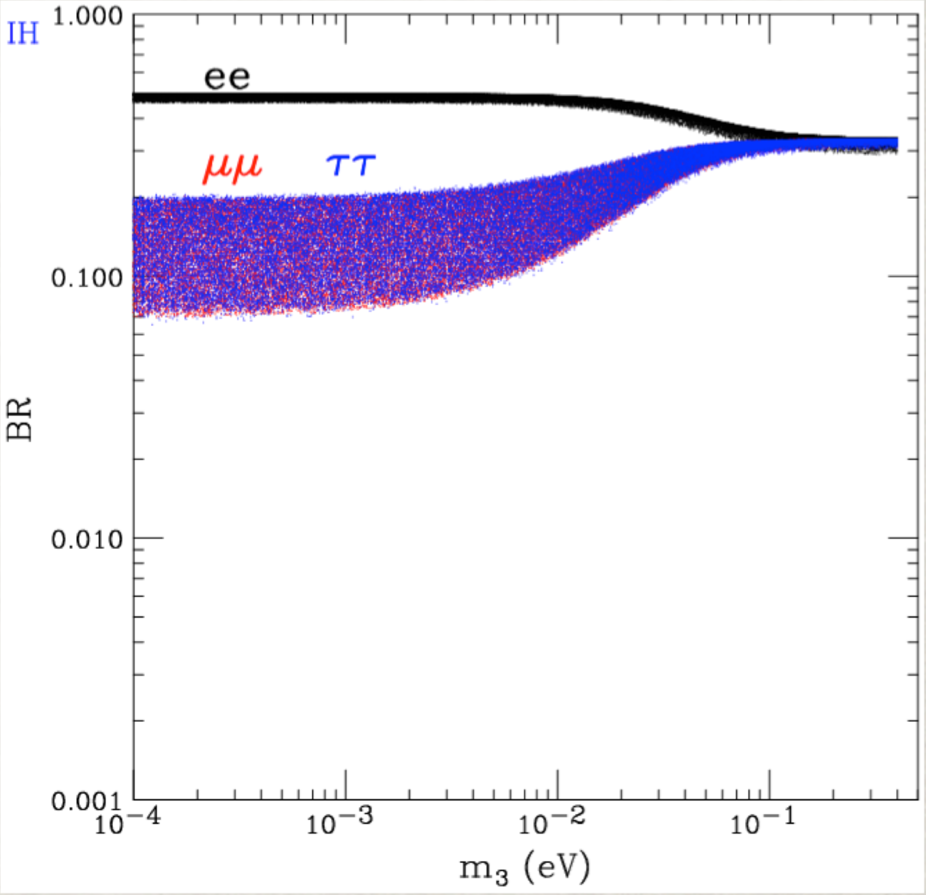
with $Y_{ll}v' \approx m_\nu\ (eV) \Rightarrow v' \approx 2 \times 10^{-4}$ GeV the division.

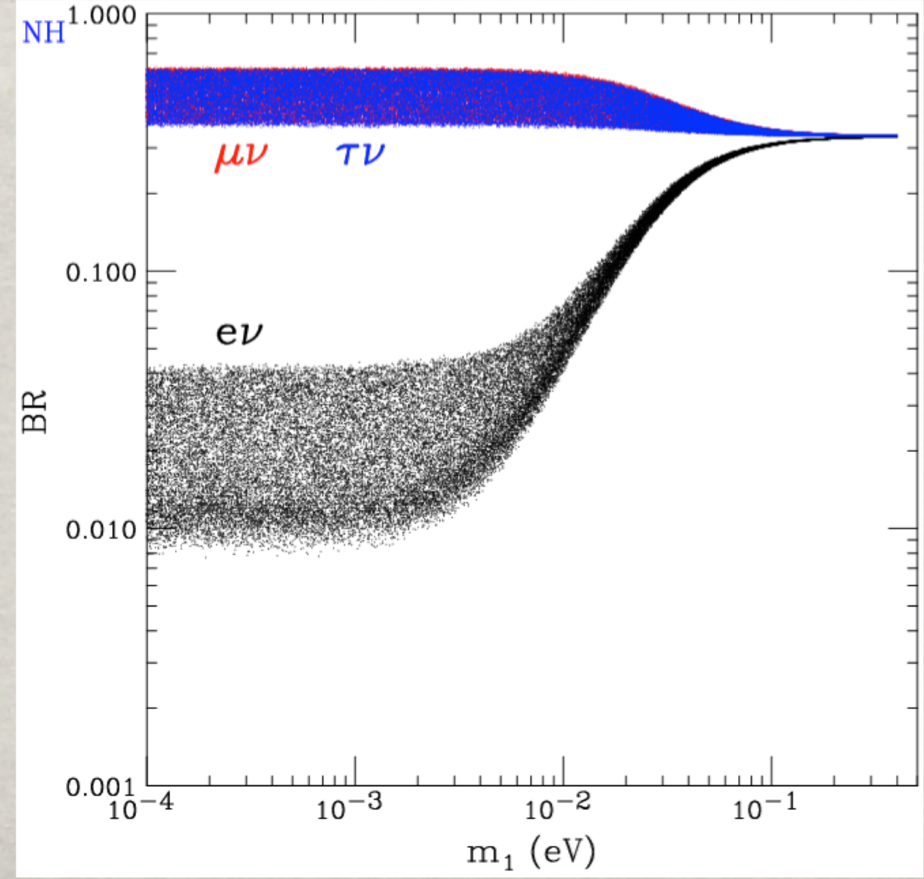


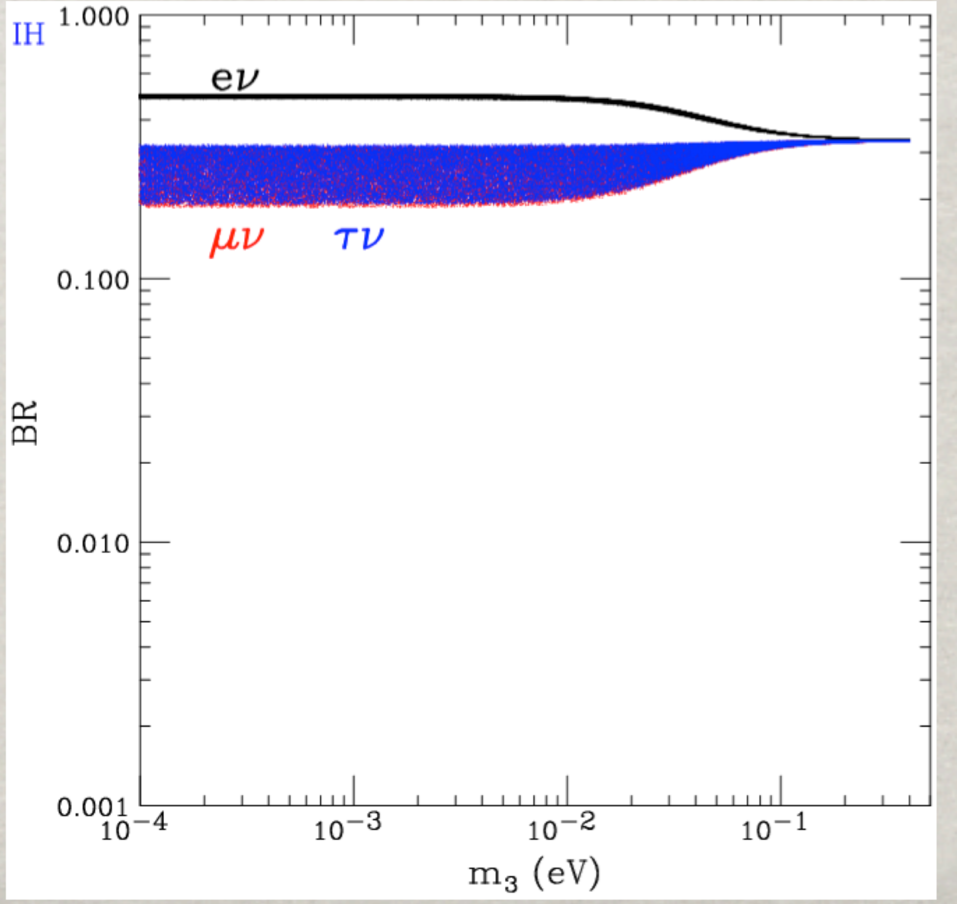
We will focus on the leptonic decays, with a small v'.

$H^{++,\,--}$, $H^{+,\,-}$ Decays: Revealing the flavor pattern









Neutrino – charged lepton correlations

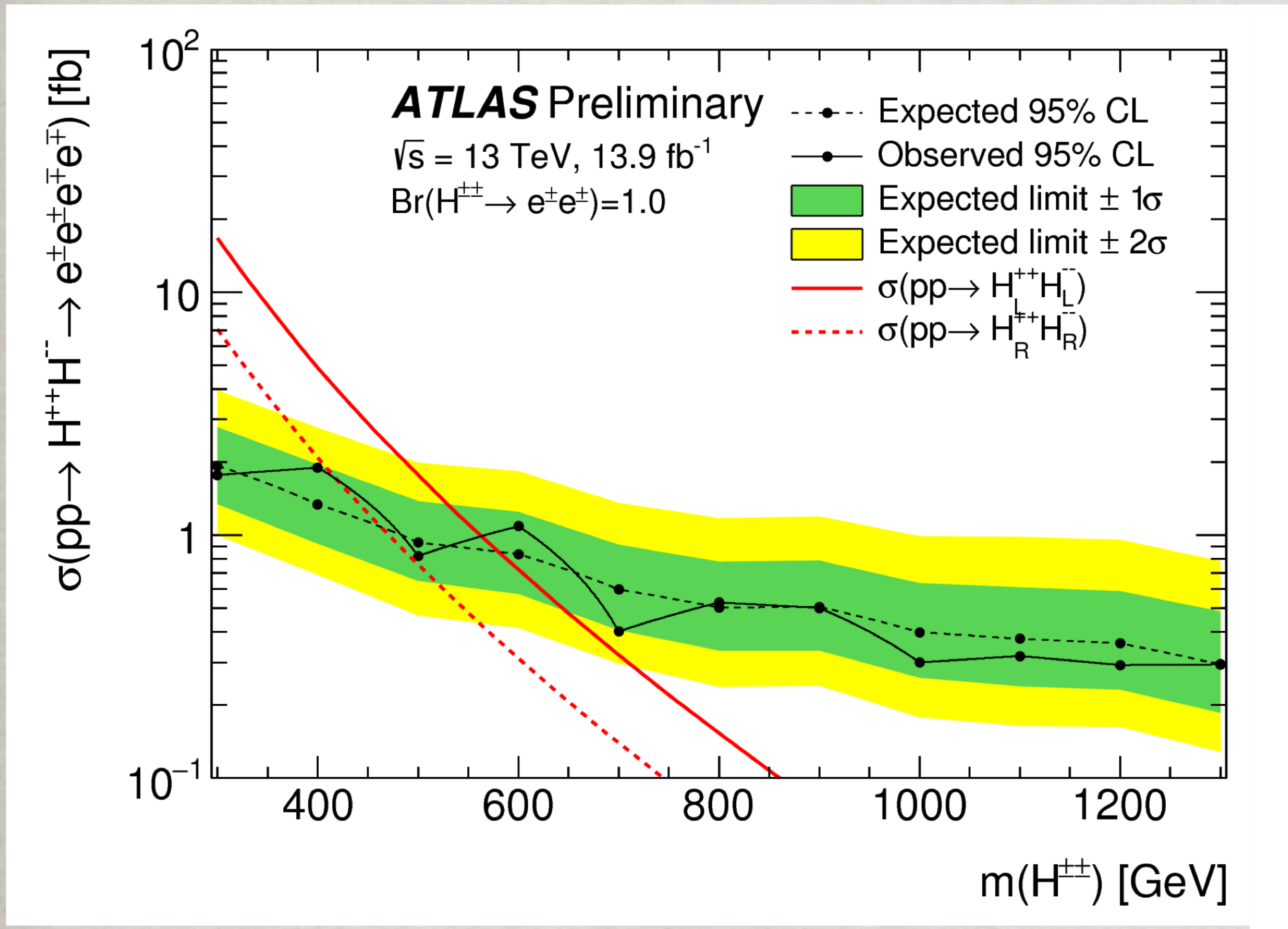
Summarize the discovery modes:

Spectrum	Relations
Normal Hierarchy ($\Delta m^2_{31} > 0$)	BR($H^{++} \to \tau^+\tau^+$), BR($H^{++} \to \mu^+\mu^+$) $\gg$ BR($H^{++} \to e^+e^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\mu^+$), BR($H^{++} \to e^+\tau^+$) BR($H^+ \to \tau^+\bar{\nu}$), BR($H^+ \to \mu^+\bar{\nu}$) $\gg$ BR($H^+ \to e^+\bar{\nu}$)
Inverted Hierarchy ($\Delta m^2_{31} < 0$)	BR($H^{++} \to e^+e^+$) $>$ BR($H^{++} \to \mu^+\mu^+$), BR($H^{++} \to \tau^+\tau^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\tau^+$), BR($H^{++} \to e^+\mu^+$) BR($H^+ \to e^+\bar{\nu}$) $>$ BR($H^+ \to \mu^+\bar{\nu}$), BR($H^+ \to \tau^+\bar{\nu}$)
Quasi-Degenerate ($m_1, m_2, m_3 > \|\Delta m_{31}\|$)	BR($H^{++} \to e^+e^+$) $\sim$ BR($H^{++} \to \mu^+\mu^+$) $\sim$ BR($H^{++} \to \tau^+\tau^+$) $\approx 1/3$ BR($H^+ \to e^+\bar{\nu}$) $\sim$BR($H^+ \to \mu^+\bar{\nu}$) $\sim$BR($H^+ \to \tau^+\bar{\nu}$) $\approx 1/3$

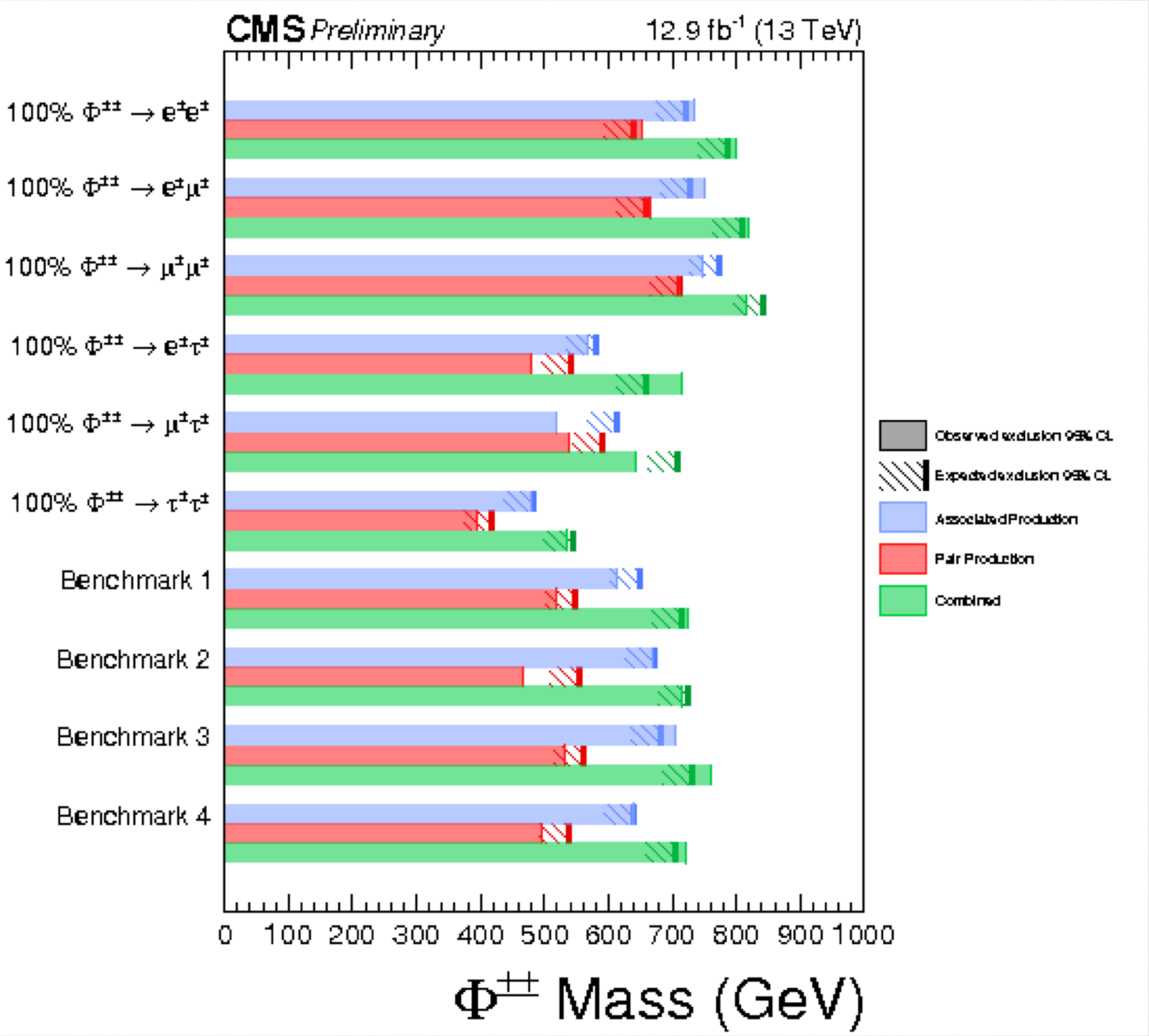
†Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

Sensitivity to $H^{++}H^{--} \to \ell^+\ell^+,\ \ell^-\ell^-$ Mode:

ATLAS Bounds:



CMS-PAS-HIG-16-036



With 300 fb^{-1} integrated luminosity,
a coverage upto $M_{H++} \sim$ 1 TeV even with $BR \sim 40 - 50\%$.

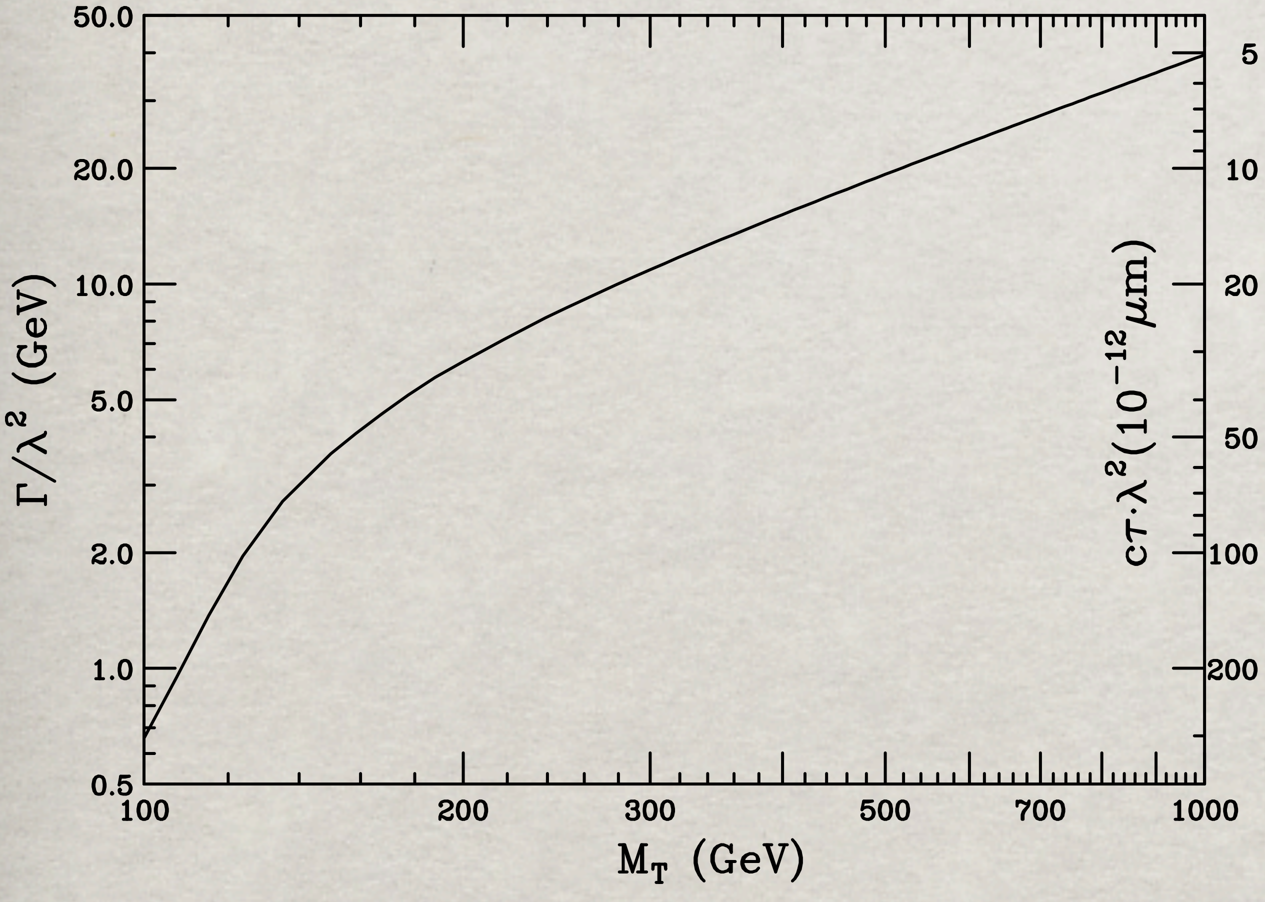
Possible measurements on BR's.

9. Type III Seesaw: T± & T^0

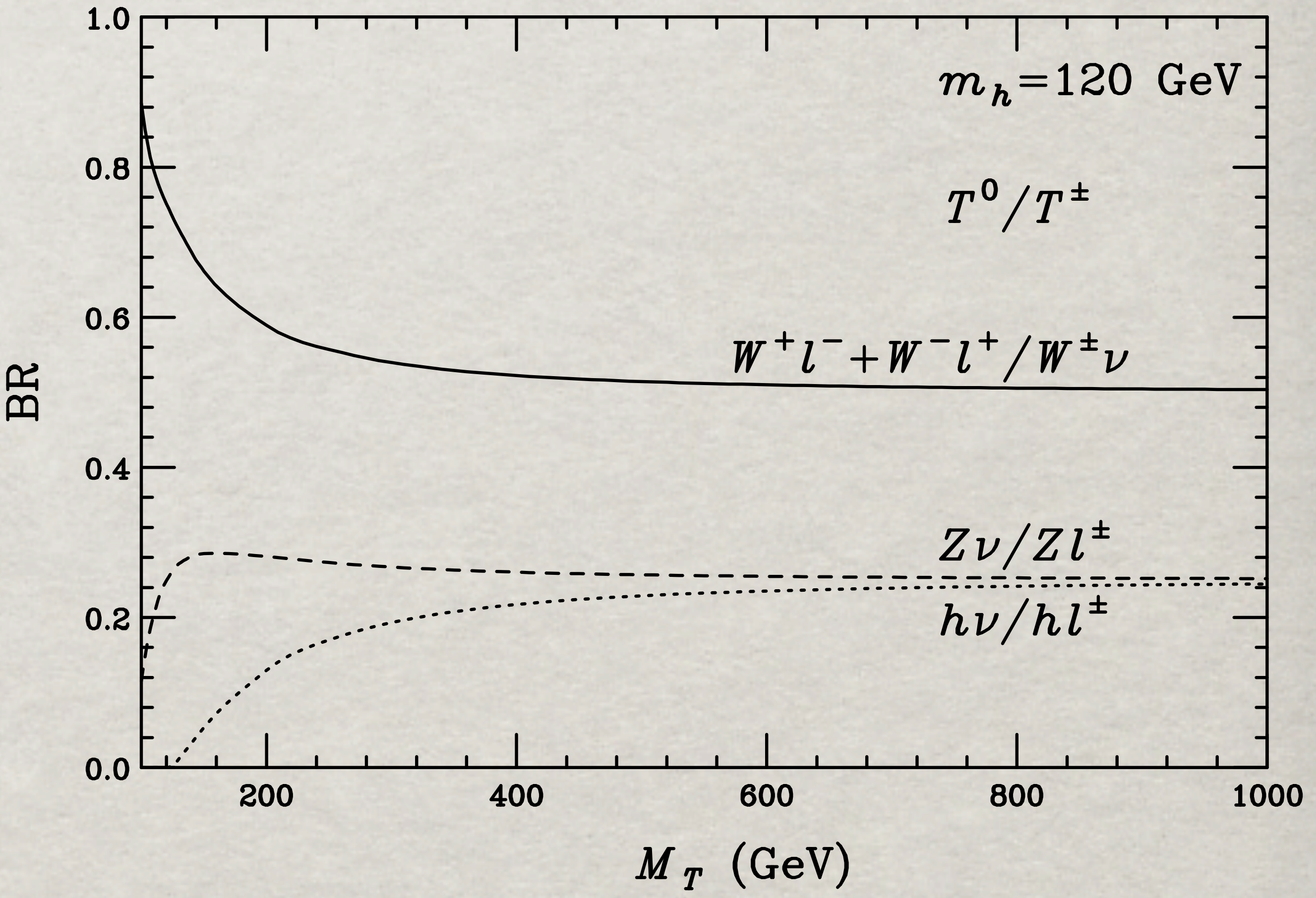
Consider their decay length:

$$\begin{aligned}\Gamma(T^+ \to W^+\nu) &\approx 2\Gamma(T^+ \to Z\ell^+) \approx 2\Gamma(T^+ \to h\ell^+)\\ &\approx \Gamma(T^0 \to W^+\ell^- + W^-\ell^+) \approx \frac{M_T}{16\pi}\sum_i |y_i|^2.\end{aligned}$$

Width and Decay Length



Lepton Triplet Branching Fraction



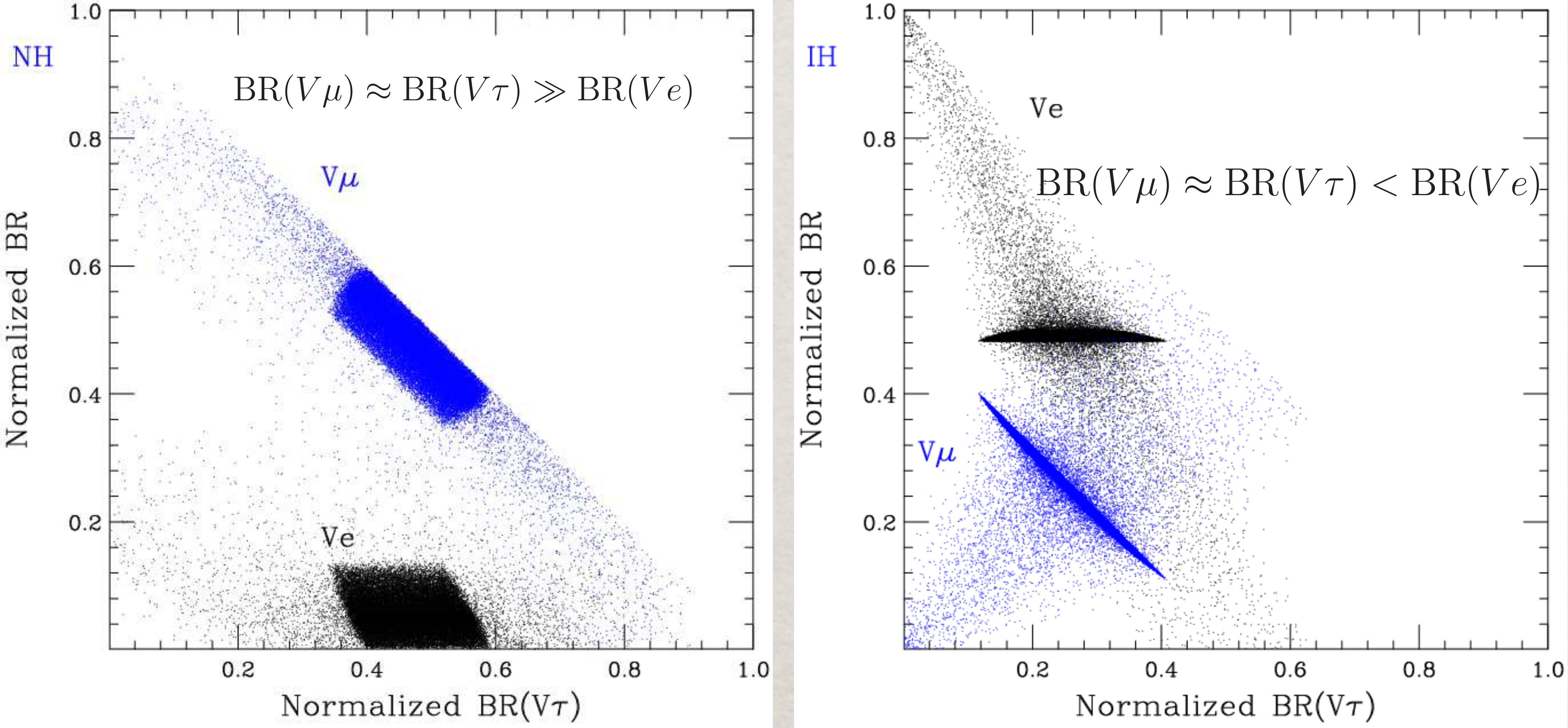
With $\lambda^2 = y_j^2 \sim 10^{-16} - 10^{-12}$, then $c\tau \sim 10^{-2} - 10^{-4}$ m

Still not too long-lived, but possibly large displaced vertices.

Type III Seesaw: $T^\pm$ & T^0

Lepton flavor combination determines the ν mass pattern: [†]

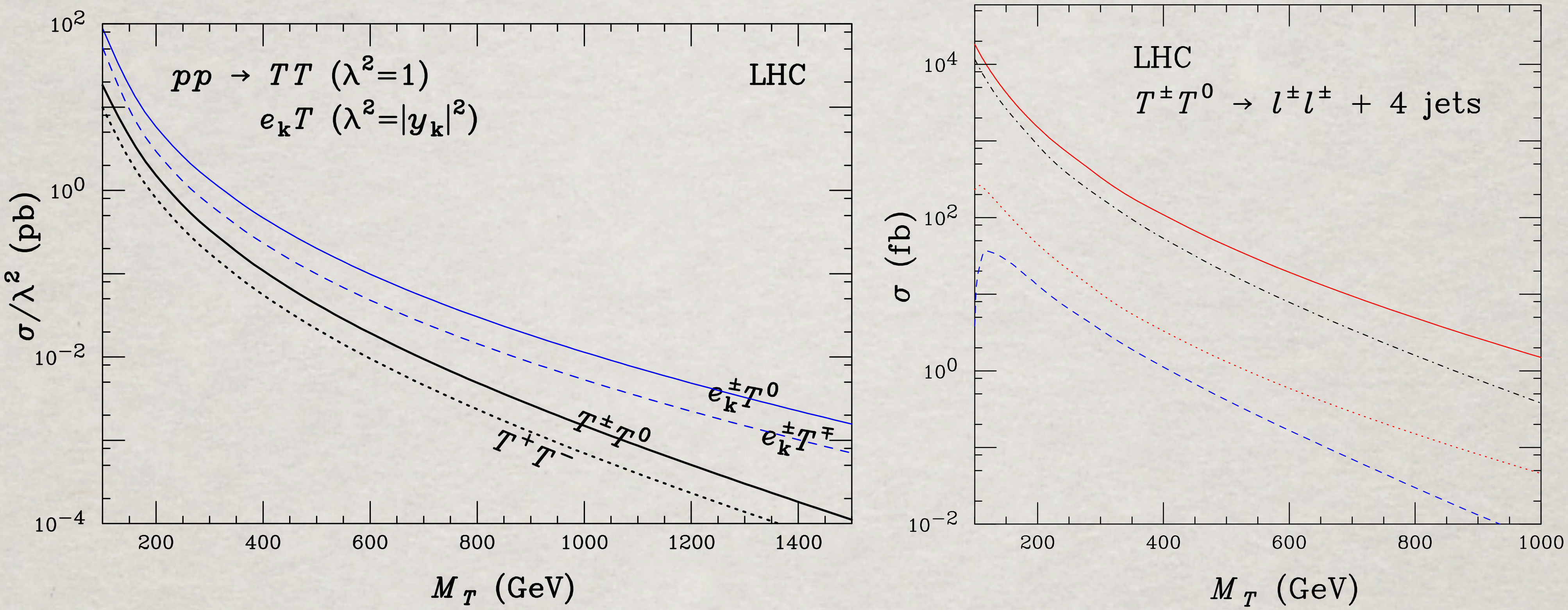
$$m_\nu^{ij} \sim -v^2 \frac{y_T^i y_T^j}{M_T}, \qquad BR(T^{\pm,0} \to W^\pm \ell,\ Z\ell) \sim y_T^2 \sim V_{PMNS}^2 \frac{M_T m_\nu}{v^2}.$$



Lepton flavors correlate with the ν mass pattern.

[†] Abdesslam Arhrib, Borut Bajc, Dilip Kumar Ghosh, Tao Han, Gui-Yu Huang, Ivica Puljak, Goran Sejanovic, arXiv:0904.2390.

Type III Seesaw: $T^\pm$ & T^0



- Single production $T^{\pm}\ell^{\mp}$, $T^{0}\ell^{\pm}$:

Kinematically favored, but highly suppressed by mixing.

- Pair production with gauge couplings.

Example: $T^{\pm} + T^{0} \to \ell^{+}Z(h) + \ell^{+}W^{-} \to \ell^{+}jj(b\bar{b}) + \ell^{+}jj.$

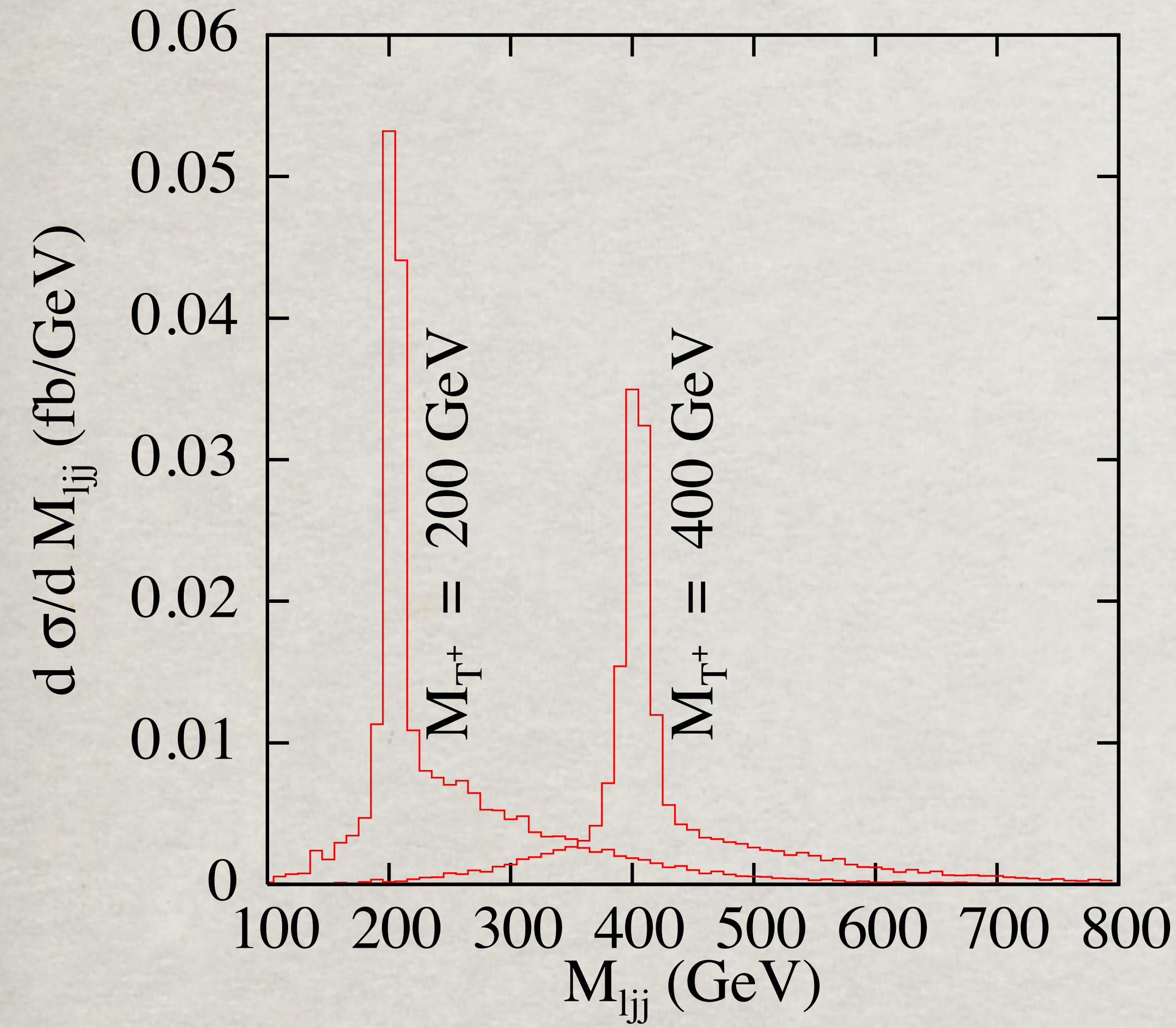
Low backgrounds.

- LHC studies with Minimal Flavor Violation implemented. [‡]

[†] Similar earlier work: Franceschini, Hambye, Strumia, arXiv:0805.1613.

[‡] O. Eboli, J. Gonzalez-Fraile, M.C. Gonzalez-Garcia, arXiv:1108.0661 [hep-ph].

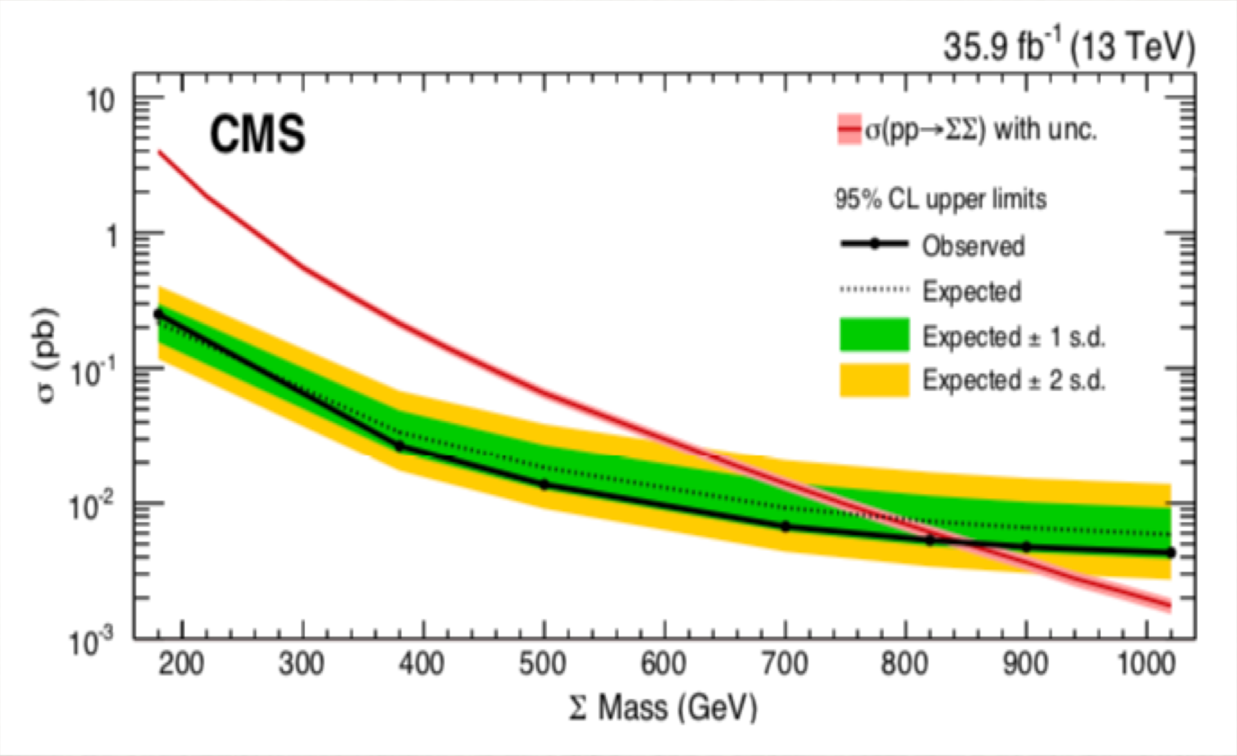
ΔL=2 & mass reconstruction for $T^{\pm}$ & T^0



Current LHC bounds:

$M_{T_{+-}}$ > 840 GeV @ 95% CL

CMS: arXiv:1708.07962



Summary

- It is of fundamental importance to test the Majorana nature of ν's.

- Type I See-saw:
  - $\tau,\ K,\ D,\ B$ rare decays sensitive to

    $$140 \text{ MeV} < m_4 < 5 \text{ GeV},\ 10^{-9} < |V_{\ell 4}|^2 < 10^{-2};$$
  - LHC sensitive: $10 \text{ GeV} < m_4 < 400 \text{ GeV},\ 10^{-6} < |V_{\mu 4}|^2 < 10^{-2}$.
  - Difficulty! May be helped with the "inverse seesaw" mechanism.

- Type II See-saw: for a scalar triplet $\Phi^{\pm\pm}$
  - LHC sensitive: $M_\phi \sim 600 - 1000$ GeV ($\ell^\pm \ell^\pm$ *or* $W^\pm W^\pm$).
  - Distinguish Normal/Inverted Hierarchy; Probe Majorana phases.
  - With $W'^\pm \to N\ell^\pm$, reach $M_N < M_{W'} \sim 4 - 5$ TeV.

- Type III See-saw: for a lepton triplet $T^\pm,\ T^0$
  - LHC sensitive: $M_T \sim 800$ GeV.
  - Also distinguish Normal/Inverted Hierarchy.

Radiative seesaw → rich physics in extended Higgs sector.

IF lucky, hadron colliders may serve
as the discovery machine for Majorana nature of ν's.

OTHER MODELS & PHENOMENOLOGY

Thus far, we only considered Type I, II, III seesaw models

Many models to account for the neutrino mass.*
Another class of well-motivated models:
Radiative generation of neutrino masses.

- Zee (1986)-Babu (1988) Model:
  add singlet scalar fields m_ν generate at 2-loop
  → change Higgs physics
- Ma Models (2006):
  add singlet scalars + Z_2 symmetry
  → Dark matter
- … …

Typically, they introduce additional Higgs states and thus new (model-dependent) collider signatures.

* For a review, see, M.C. Chen & J.R. Huang, arXiv:1105.3188v2.

Summary: Fill up a Matrix:

	$0\nu2\beta$	μ-e conversion $\mu \to e\gamma$ etc.	rare decays τ, K, D, B	colliders e^+e^-, pp	features
Type-I	$\surd$	$\surd$	$\surd$	$\surd$	N
Type-II	$\surd$	$\surd$	$\surd$	$\surd$	$H^{\pm\pm},\ W_R^\pm$
Type-III	$\surd$	$\surd$	?	$\surd$	$T^\pm$
Zee-Babu	?	$\surd$	?	$\surd$	$k^{\pm\pm},\ h^\pm$
Ma models	?	$\surd$	?	$\surd$	scalars, DM
RPV/leptoquarks	?	$\surd$	$\surd$	$\surd$	ℓ_q
extra-dim	?	?	$\surd$	$\surd$	KK states
Inverse/linear	?	?	$\surd$	$\surd$	
Pseudo Dirac	?	?	$\surd$	$\surd$	
NSI	?	?	?	$\surd$	mediators
… …					

Please help to

- Fill the entries
- Expand on both sides

More work to do !