Neutrinos That Are NOT Gone Missing

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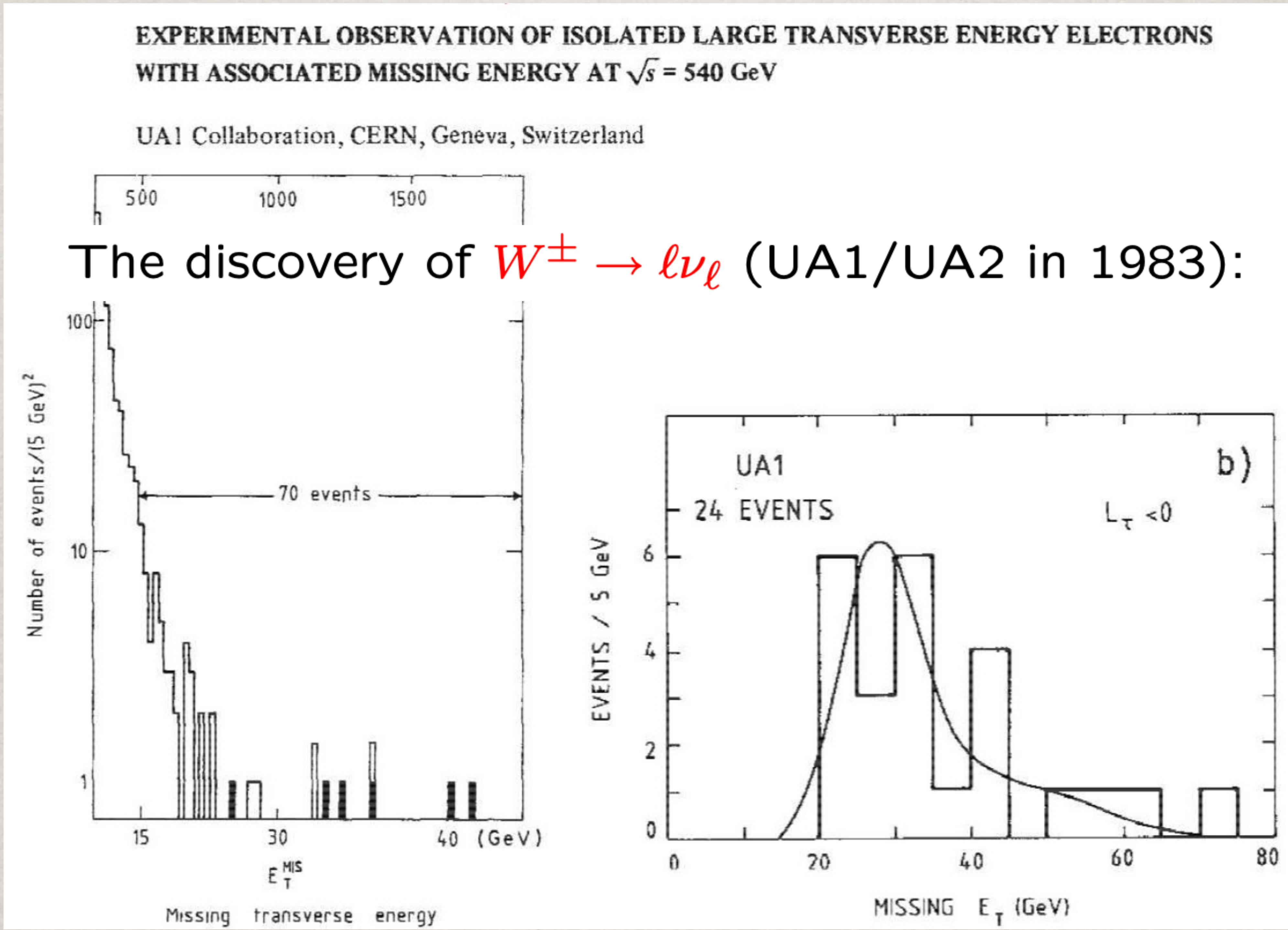
Rabi-Fest 2022

October 21, 2022

“Neutrino physics at colliders”

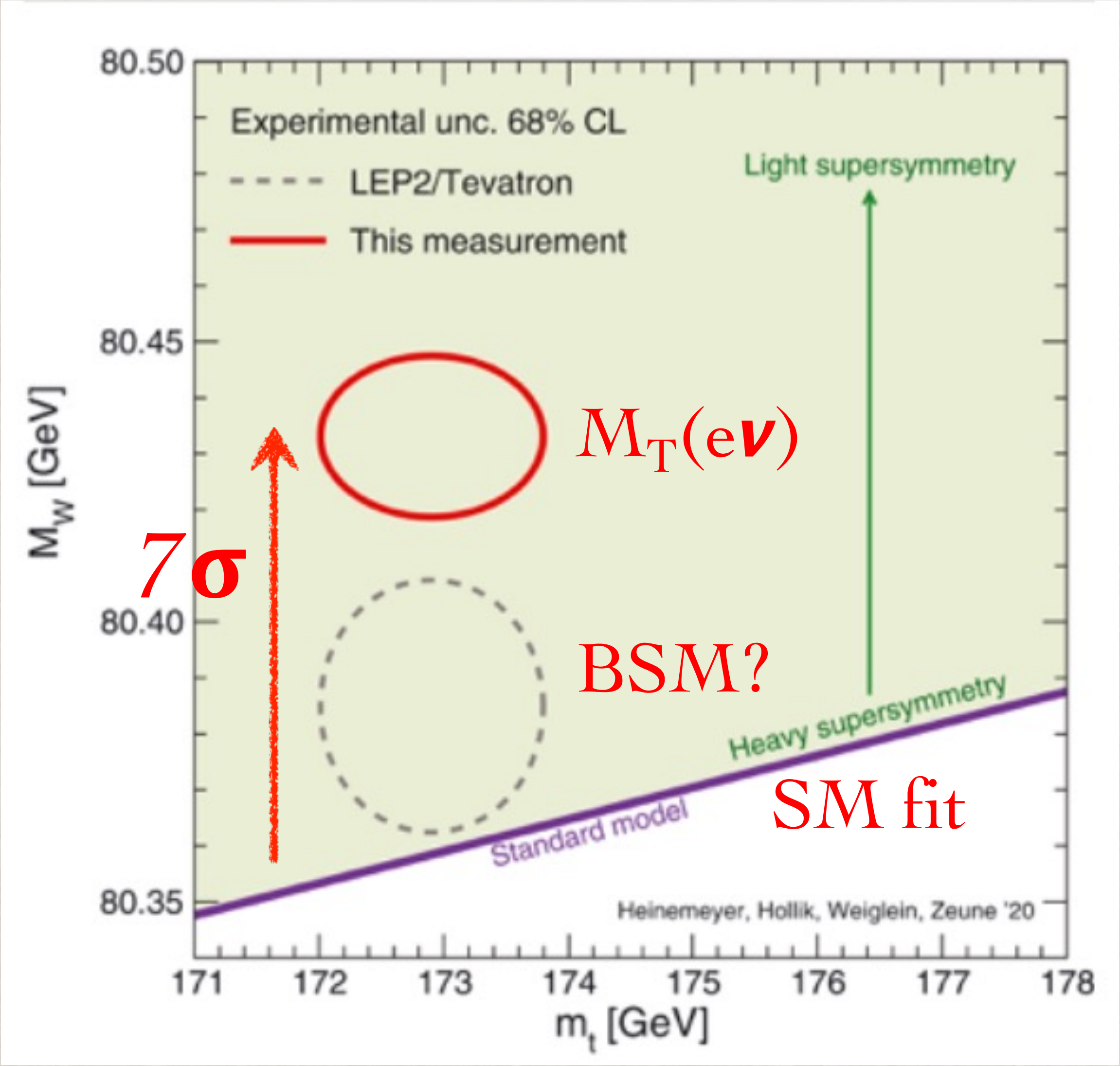
They are all gone!

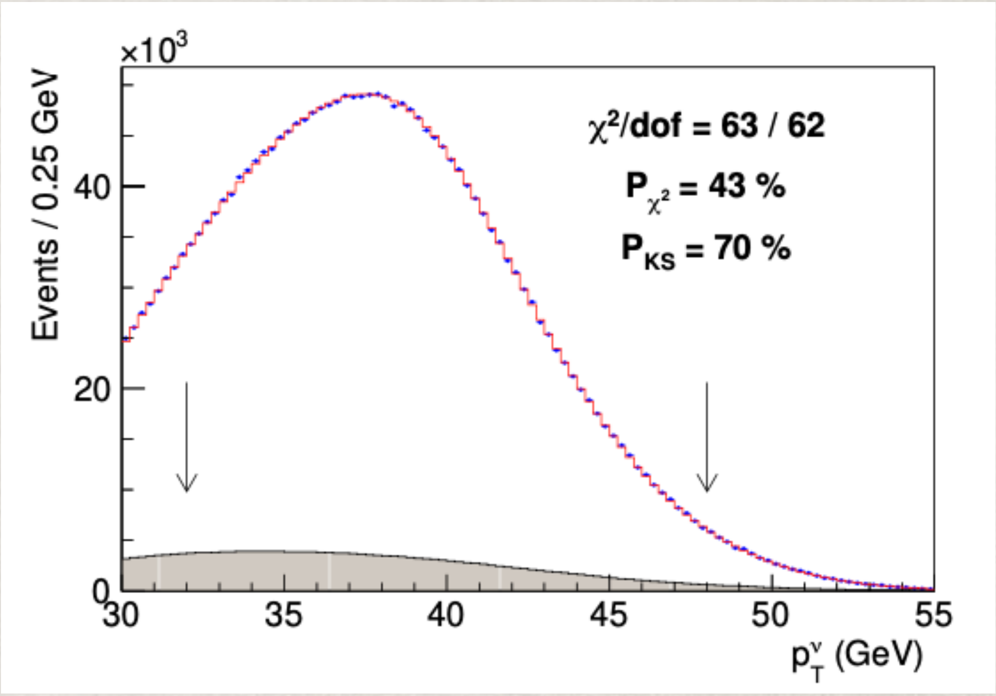
but leaving an important trace behind …

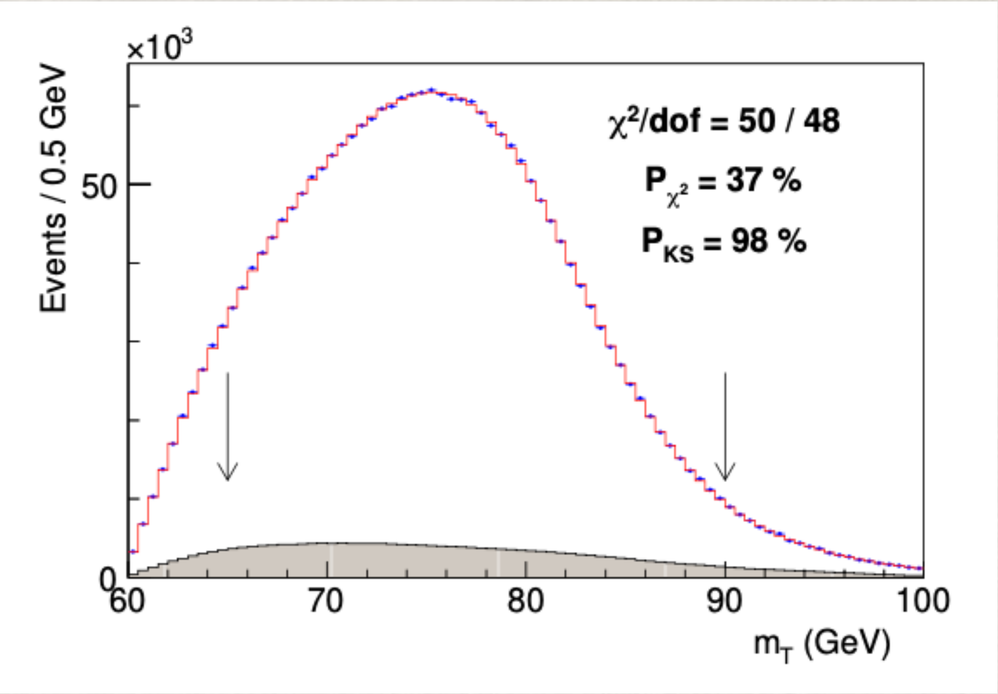


CDF new Measurement

CDF: Science , April 8, 2022







M_W is a fit from a kinematic edge, due to missing ν's

“Neutrino physics at colliders”

Missing neutrinos is NOT the whole story!

Oscillations experiments & theoretical considerations → Much richer physics!

Historically, Rabi led the way

Exact Left-Right Symmetry and Spontaneous Violation of Parity

G. Senjanovic (City Coll., N.Y.), Rabindra N. Mohapatra (City Coll., N.Y.) (May, 1975)

Published in: *Phys.Rev.D* 12 (1975) 1502

Neutrino Mass and Spontaneous Parity Nonconservation

Rabindra N. Mohapatra (City Coll., N.Y.), Goran Senjanovic (Maryland U.) (Nov, 1979)

Published in: *Phys.Rev.Lett.* 44 (1980) 912

Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation

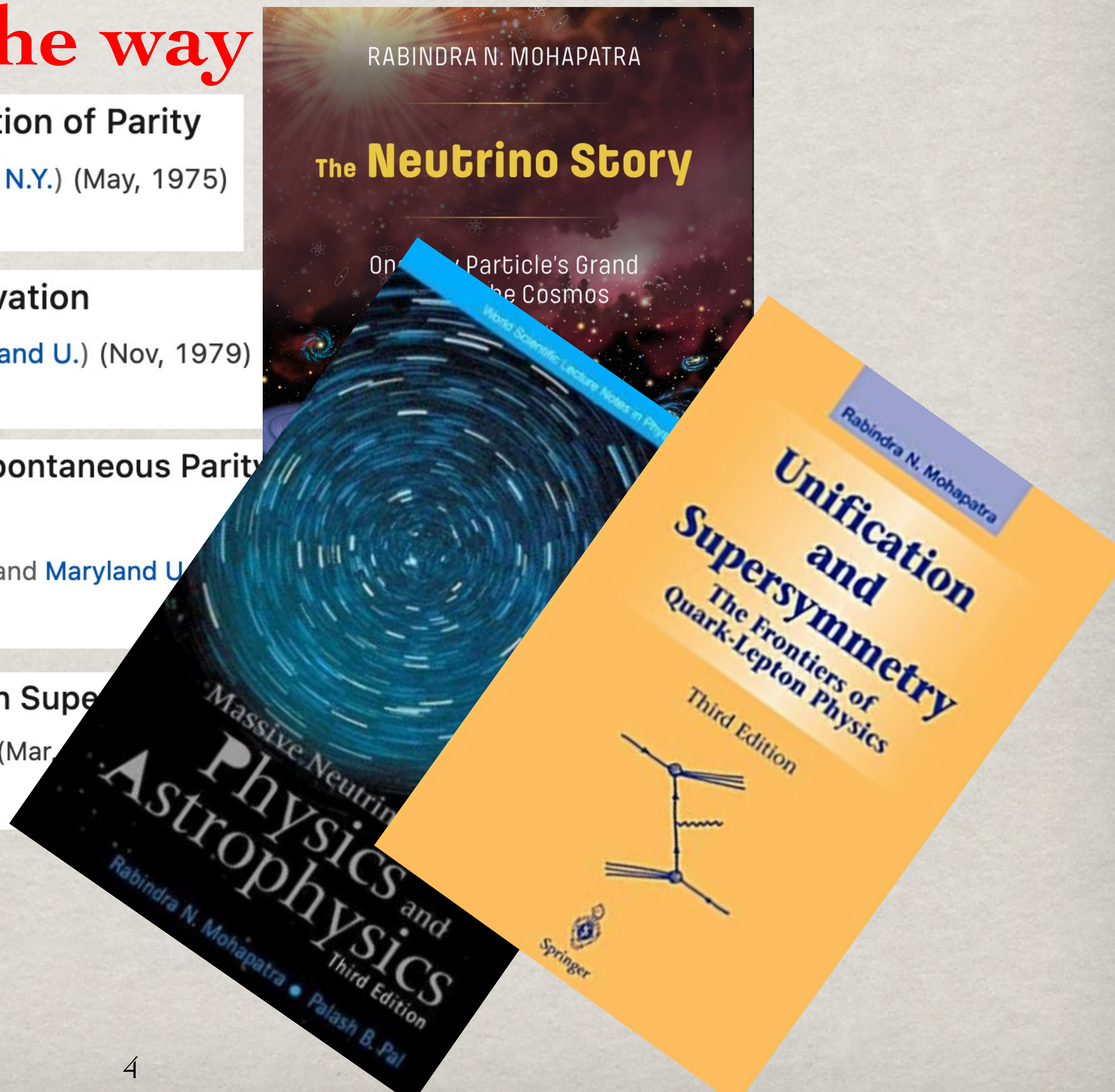
Rabindra N. Mohapatra (City Coll., N.Y.), Goran Senjanovic (Fermilab and Maryland U

Published in: *Phys.Rev.D* 23 (1981) 165

Neutrino Mass and Baryon Number Nonconservation in Supe

R.N. Mohapatra (Maryland U.), J.W.F. Valle (Barcelona, Autonoma U.) (Mar

Published in: *Phys.Rev.D* 34 (1986) 1642 • Contribution to: ICHEP 86



\+ many many more ……

The Seesaw Mechanism:

The leading SM gauge invariant operator is at dim-5:*

$$\frac{1}{\Lambda}(y_\nu LH)(y_\nu LH) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\, \overline{\nu_L}\, \nu_R^c.$$

*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

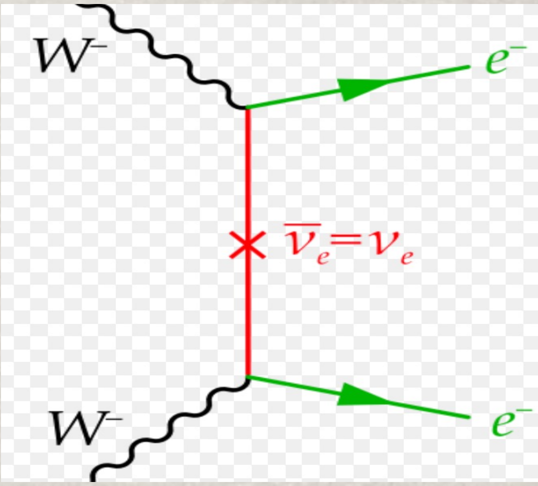
Implications:

- Λ → new scale / particles,
  implies an underlying (UV) theory!

The See-saw spirit: †

If $m_\nu \sim 1$ eV, then $\Lambda \sim y_\nu^2$ (10^{14} GeV).

$$\Lambda \Rightarrow \begin{cases} 10^{14} \text{ GeV for } y_\nu \sim 1; \\ 100 \text{ GeV for } y_\nu \sim 10^{-6}. \end{cases}$$



- ΔL=2 → Majorana mass (Majorana neutrinos)

Minkowski; Yanagita; Gell-Mann+Ramond+Slansky;
Glashow; Mohapatra+Senjanovic

UV completion of the Weinberg operator

The Weinberg operator non-renormalizable
→ Need Ultra-Violet completion at/above Λ .

Group representations based on SM $SU_L(2)$ doublets:

$$2 \otimes 2 = 1(\text{singlet}) + 3(\text{triplet})$$

→ There are three possibilities:

- Type I: Fermion singlets $\otimes (L\ H)_S$
- Type II: Scalar triplet $\otimes (L\ L)_T$
- Type III: Fermion triplets $\otimes (L\ H)_T$

Type I Seesaw features:

😀 Existence of N_R (possibly low mass*)

$$U^2_{\ell m} \sim V^2_{PMNS} \approx \mathcal{O}(1); \;\; V^2_{\ell m} \approx m_\nu / m_N.$$

$U_{\ell m}, \;\; \Delta m_\nu$ are from oscillation experiments

m_N a free parameter: could be accessible!

🙁 But difficult to see N_R:

The mixing is typically small, mass wide open:

$$V^2_{\ell m} \approx (m_\nu/eV)/(m_N/GeV) \times 10^{-9}$$
$$< 6 \times 10^{-3} (low\ energy\ bound)$$

(Fine-tune or hybrid could make it sizeable.)

* Casas and Ibarra (2001);
A. Y. Smirnov and R. Zukanovich Funchal (2006);
A. de Gouvea, J. Jenkins and N. Vasudevan (2007);
W. Chao, Z. G. Si, Z. Z. Xing and S. Zhou (2008).

Type II Seesaw: No need for N_R, with Φ-triplet*

With a scalar triplet Φ $(Y = 2)$: $\phi^{\pm\pm}, \phi^{\pm}, \phi^0$ (many representative models).
Add a gauge invariant/renormalizable term:

$$Y_{ij} L_i^T C (i\sigma_2) \Phi L_j + h.c.$$

That leads to the Majorana mass:

$$M_{ij} \nu_i^T C \nu_j + h.c.$$

where

$$M_{ij} = Y_{ij} \langle \Phi \rangle = Y_{ij} v' \lesssim 1 \text{ eV},$$

Very same gauge invariant/renormalizable term:

$$\mu H^T (i\sigma_2) \Phi^\dagger H + h.c.$$

predicts

$$v' = \mu \, \frac{v^2}{M_\phi^2},$$

leading to the Type II Seesaw. †

*Magg, Wetterich (1980); Lazarides, Shafi (1981); Mohapatra, Senjanovic (1981). ...

†In Little Higgs model: T.Han, H.Logan, B.Mukhopadhyaya, R.Srikanth (2005).

Type II Seesaw features*

- Triplet vev → Majorana mass → neutrino mixing pattern!

$H^{\pm\pm} \to \ell_i^{\pm} \ell_i^{\pm}$ → neutrino mixing pattern!

$H^{\pm\pm} \to W^{\pm} W^{\pm}$. Competing channel

Variations

Naturally embedded in L-R symmetric model:[#]

$W^{\pm}{}_R \rightarrow N_R\, e^{\pm}$

(* Large Type I signals via W_R-N_R)

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

[#] Mohapatra, Senjanovic (1981). ...

Type III Seesaw: with a fermionic triplet*

With a lepton triplet T $(Y=0)$: $T^+ \; T^0 \; T^-$, add the terms:

$$-M_T(T^+T^- + T^0T^0/2) + y_T^i H^T i\sigma_2 T L_i + h.c.$$

These lead to the Majorana mass:

$$M_{ij} \approx y_i y_j \frac{v^2}{2M_T}.$$

Again, the seesaw spirit: $m_\nu \sim v^2/M_T$.

Features:

Demand that $M_T \lesssim 1$ TeV, $M_{ij} \lesssim 1$ eV,

Thus the Yukawa couplings:†

$$y_j \lesssim 10^{-6},$$

making the mixing $T^{\pm,0} - \ell^{\pm}$ very weak.

T^0 a Majorana neutrino;
Decay via mixing (Yukawa couplings);
$T\overline{T}$ Pair production via EW gauge interactions.

*Foot, Lew, He, Joshi (1989); G. Senjanovic et al. ...

Beyond 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
- … …

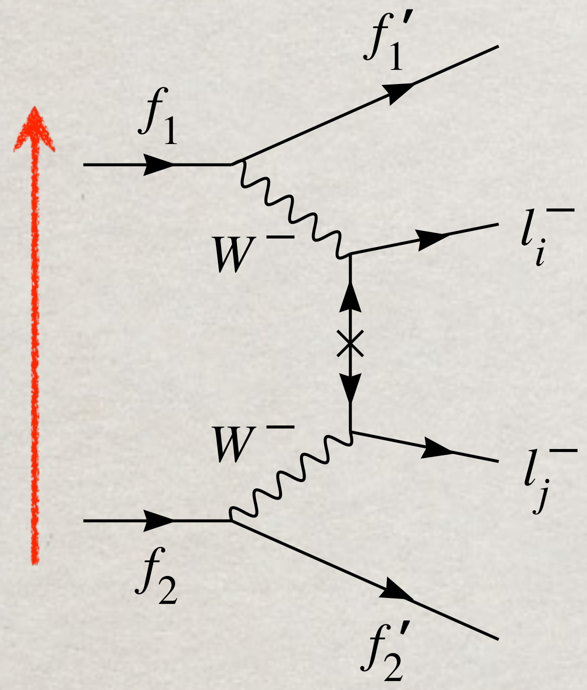
Typically, they introduce additional Higgs states and thus new (model-dependent) experimental signatures.

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

Observational Aspects: ν's Not Gone Missing

Will focus on 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^{++}

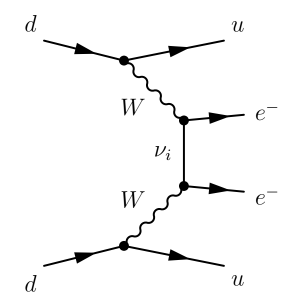
The transition rates are proportional to

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

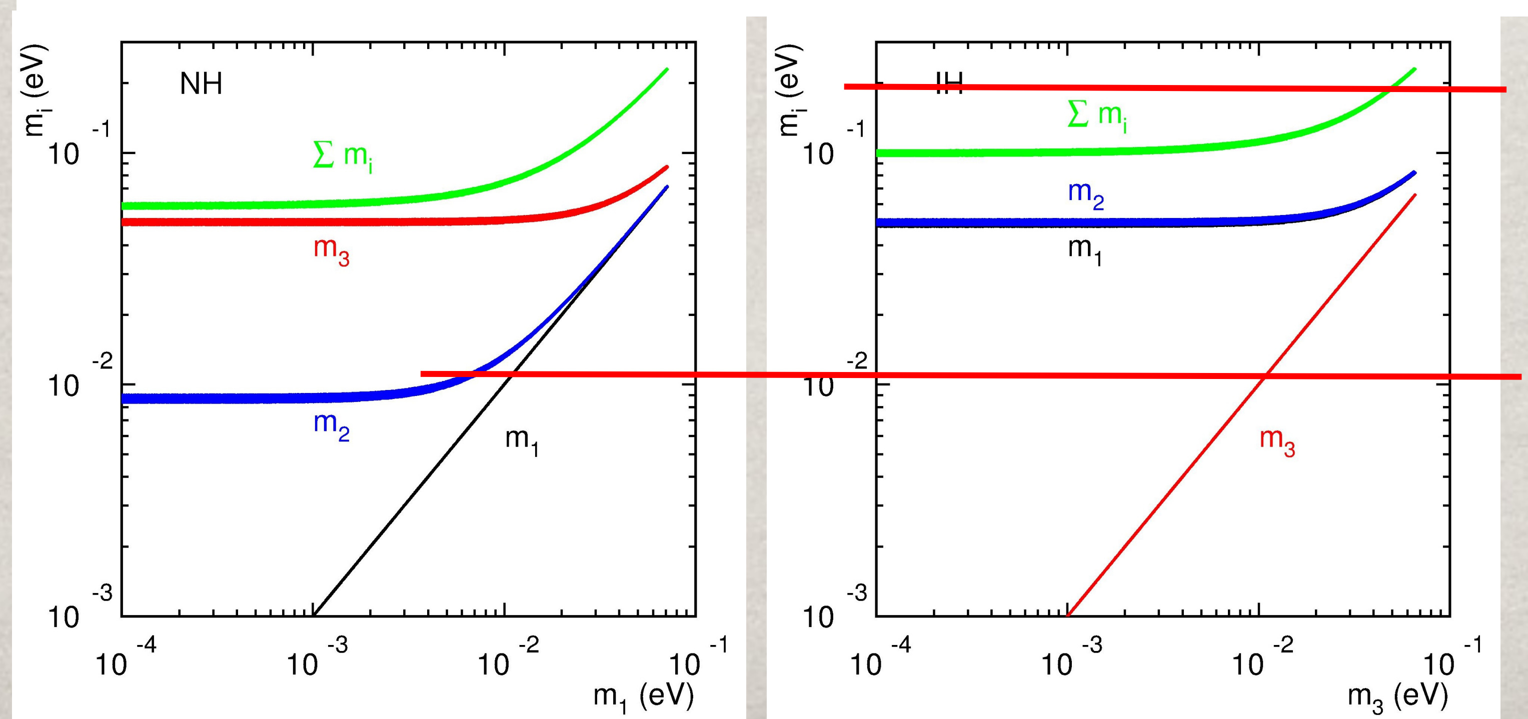
1. Neutrino-less double-beta decay

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



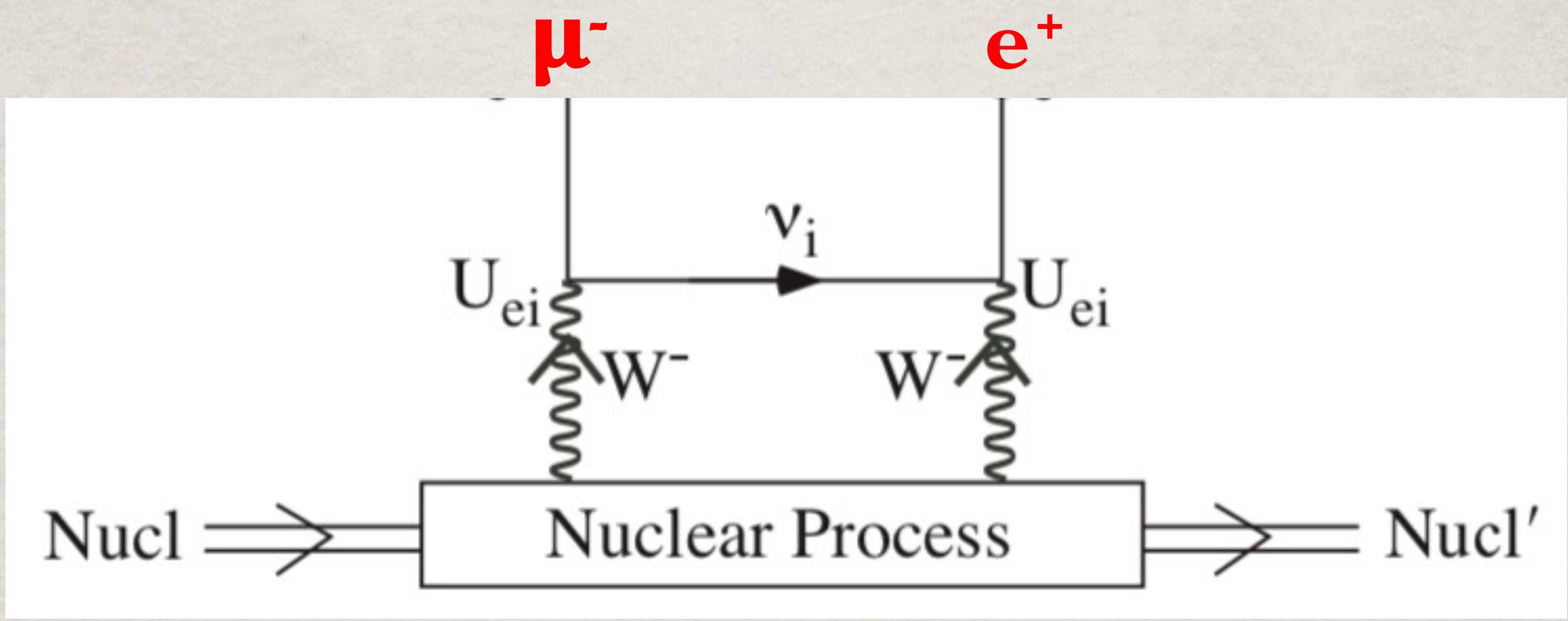
(a) (b)

Future expts:

- SNO+
- SuperNEMO
- nEXO
- CUPID
- LEGEND100

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

2. μ^- - e^+ conversion



PDG expt bound:

$$B = \frac{\Gamma(Ti + \mu^- \to e^+ + Ca_{gs})}{\Gamma(Ti + \mu^- \to \nu_\mu + Sc)} < 1.7 \times 10^{-12} \sim \left(\frac{\langle m \rangle_{e\mu}}{m_e}\right)^2$$

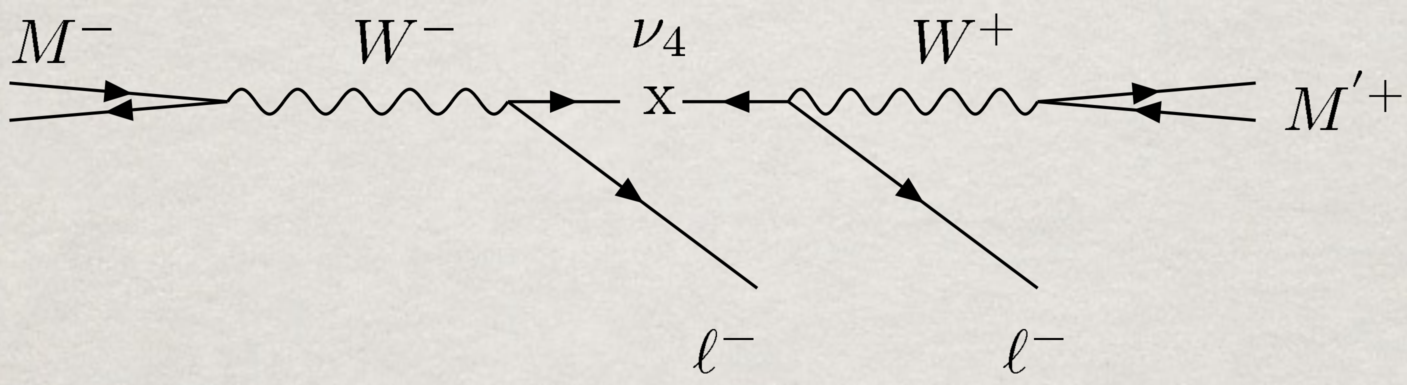
→ $\langle m \rangle_{e\mu} \leq 17\ (82)$ MeV, for nuclear singlet (triplet)

Near future experiments:

Mu2e (FNAL), COMET (J-PARC)

3. 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

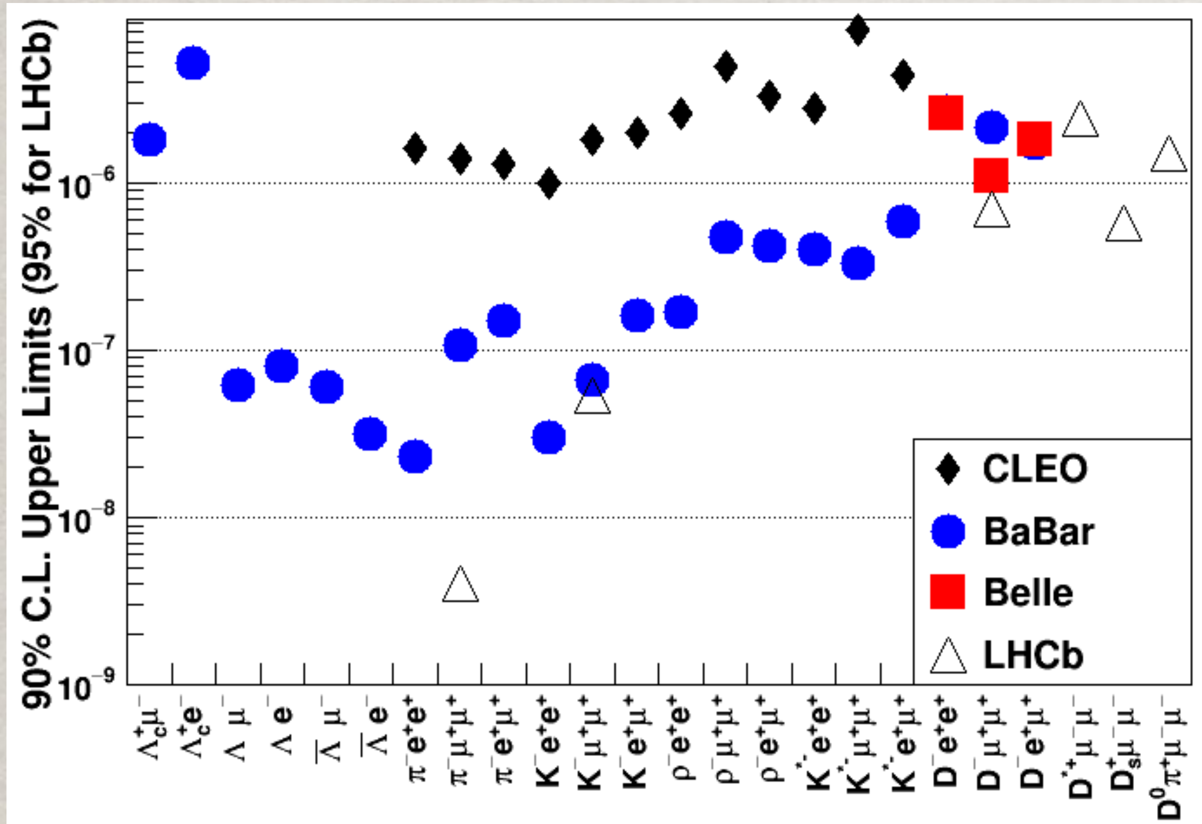
- Other processes to look for:

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

Atre, TH, Pascoli, Zhang, arXiv:0901.3589

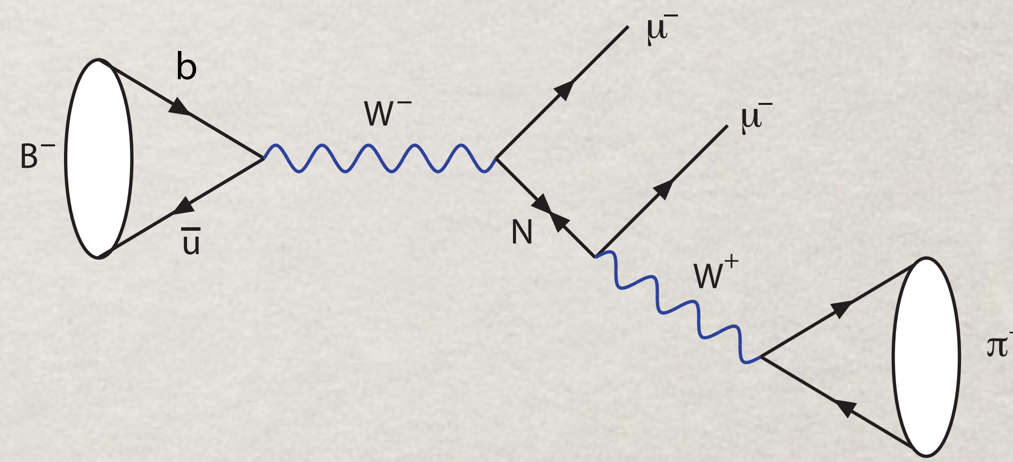
τ, K, D, B decays: $M^+ \to \ell_i^+ \ell_j^+ M^-$ via N

BaBar collaboration: arXiv:1503.08267v1.

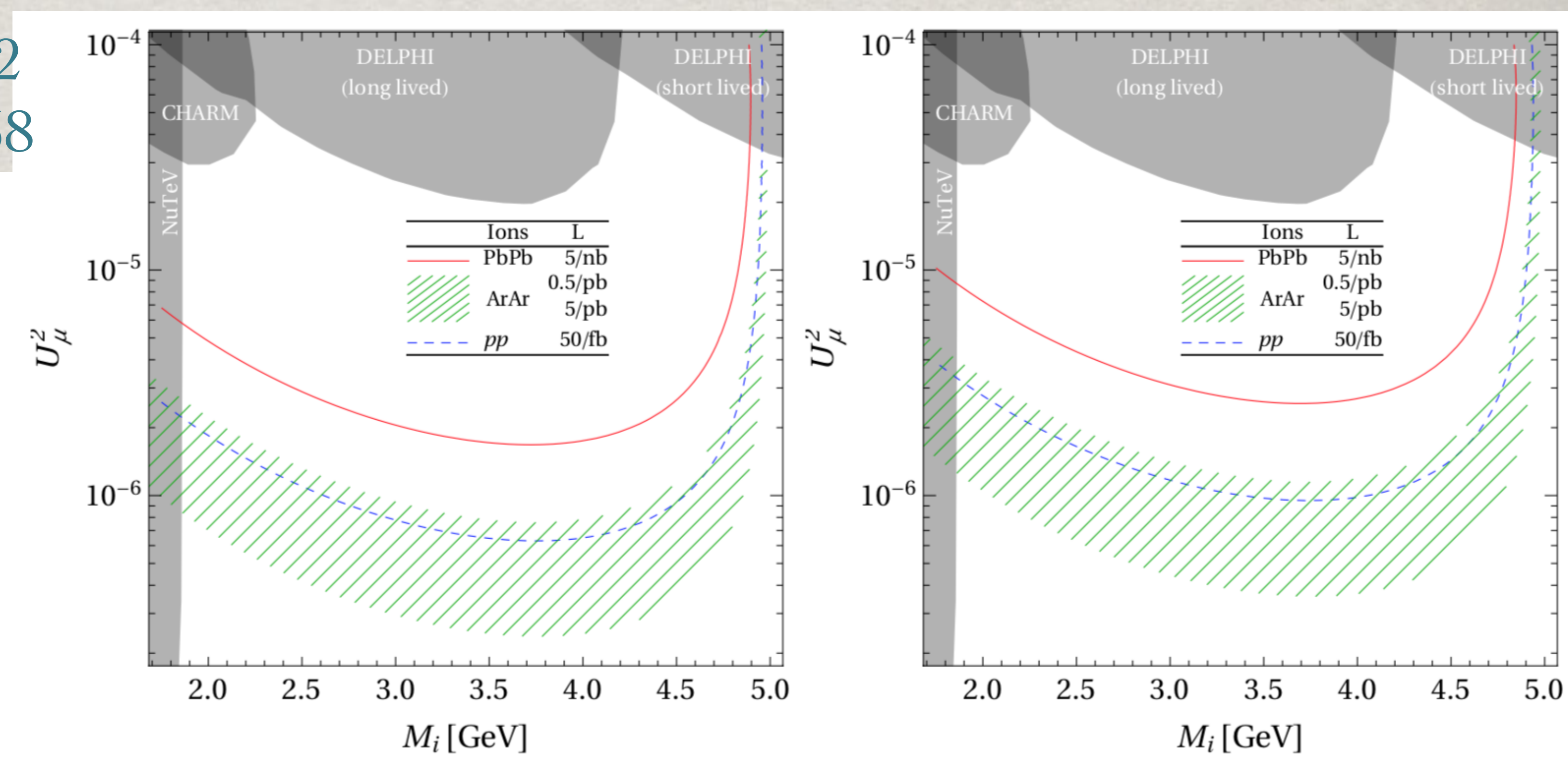


CERN NA62, arXiv:1905.07770

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

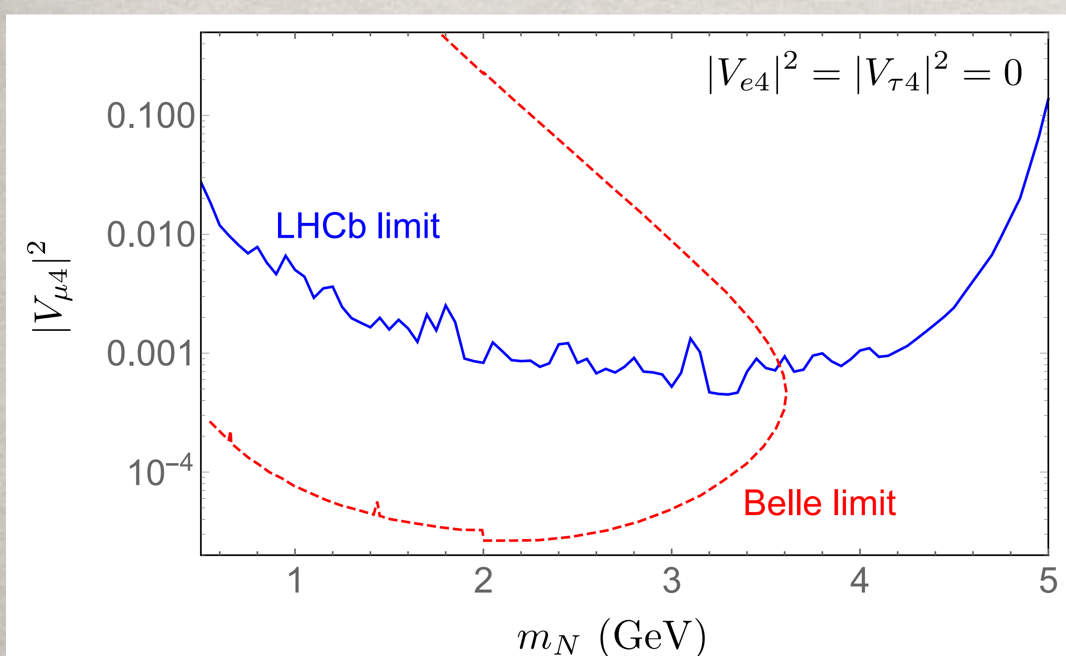


M. Drewes, J. Hajer et al., arXiv:1905.19828
Heavy ion with low trigger threshold

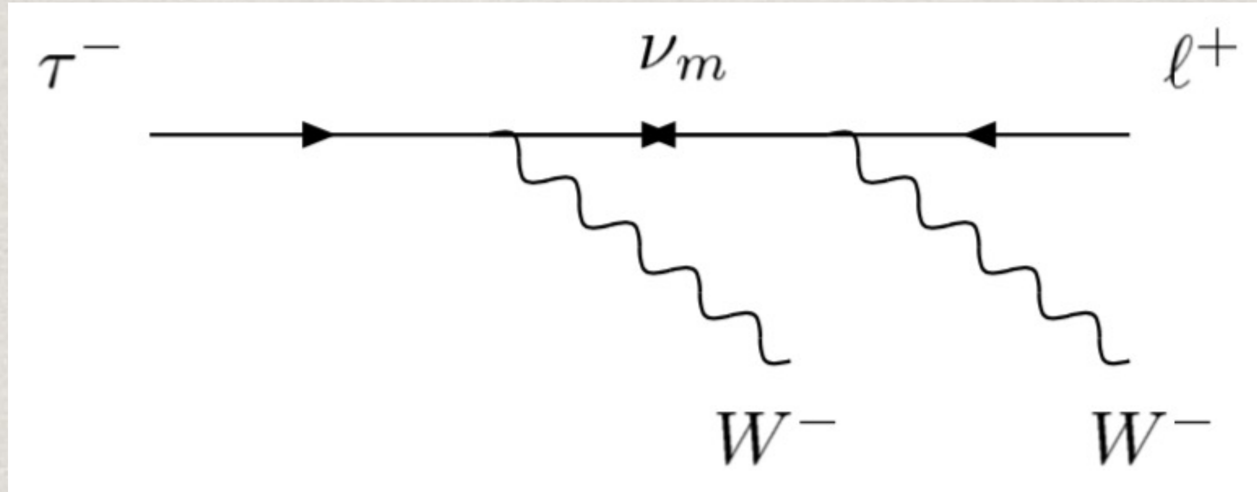


(a) Exclusion with $2\,\sigma$. (b) Discovery with $5\,\sigma$.

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



4. τ± lepton decays



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

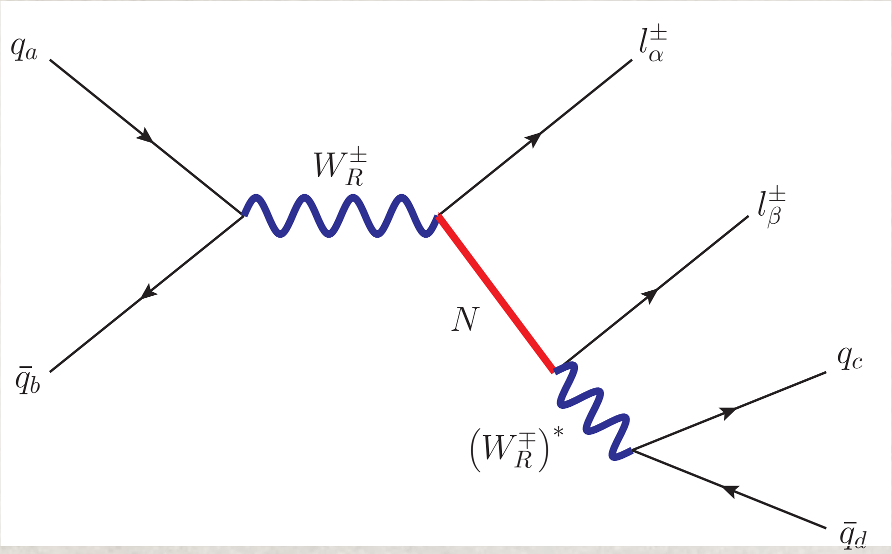
Mixing element	Range of m_4(MeV)	Decay mode	B_{exp}
$\|V_{e4}V_{\tau 4}\|$	140 - 1637	$\tau^- \to e^+\pi^-\pi^-$	2.7×10^{-7}
	140 - 1637	$\tau^- \to e^+\pi^-K^-$	1.8×10^{-7}
	494 - 1283	$\tau^- \to e^+K^-K^-$	1.5×10^{-7}
$\|V_{\mu 4}V_{\tau 4}\|$	245 - 1637	$\tau^- \to \mu^+\pi^-\pi^-$	0.7×10^{-7}
	245 - 1637	$\tau^- \to \mu^+\pi^-K^-$	2.2×10^{-7}
	599 - 1283	$\tau^- \to \mu^+K^-K^-$	4.8×10^{-7}

For non-resonance, weaker bound:

$\langle m \rangle_{e\tau}$ and $\langle m \rangle_{\mu\tau}$ < O(1 TeV)

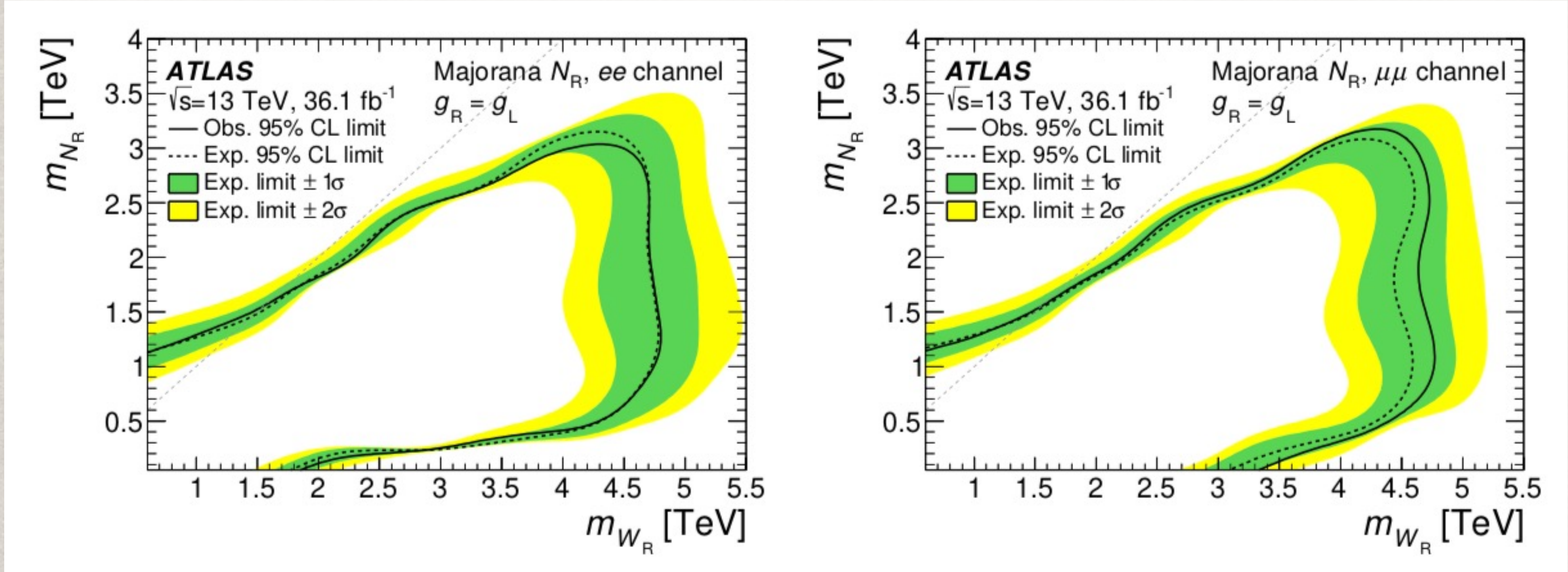
Atre, TH, Pascoli, Zhang, arXiv:0901.3589

5. N_R & W_R @ Hadron Colliders



W. Keung & G. Senjanovic
PRL 50 (1983) 1427
The K-S process!

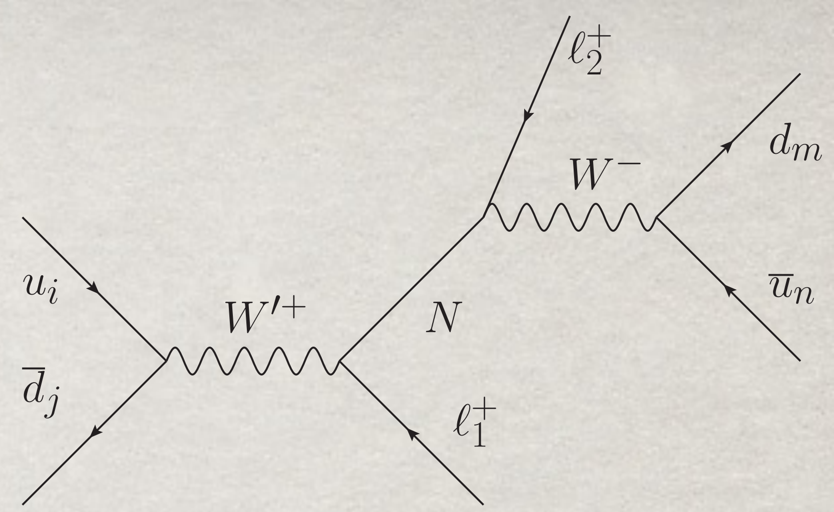
- No mixing suppression
- New unknown mass scale M_R



ATLAS collaboration: arXiv:1809.11105.

W_R & N_R Properties:

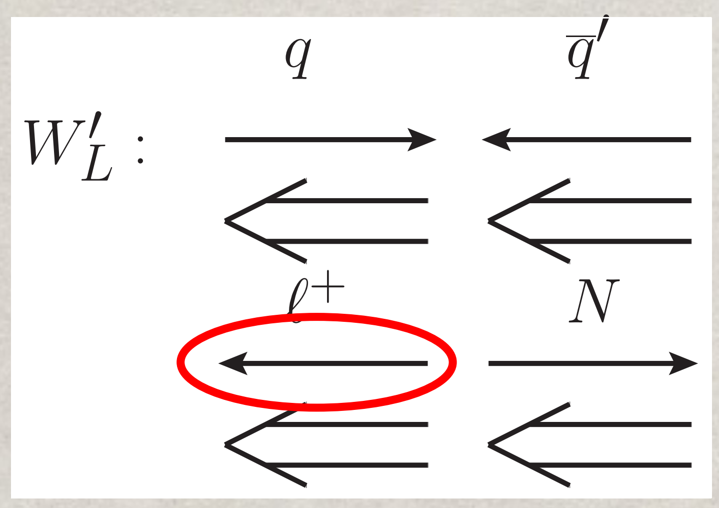
$SU(2)_L \otimes SU(2)_R$ symmetric model:

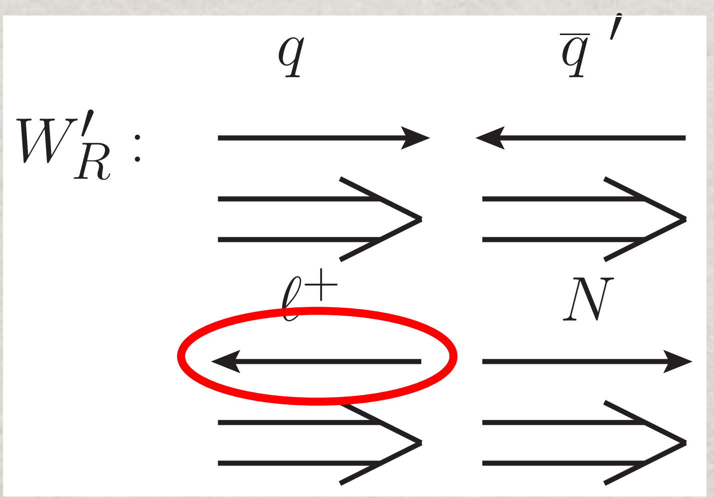


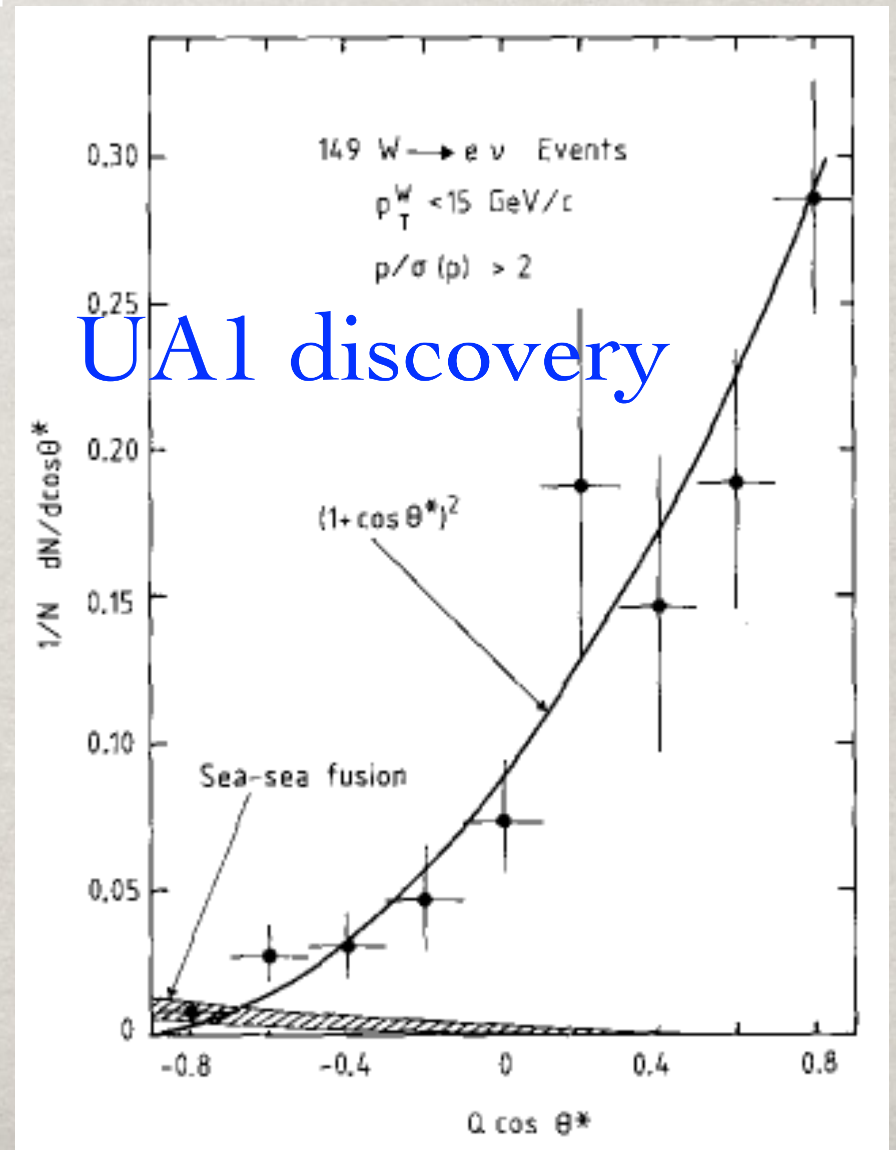
A clean channel with rich physics:[†]

- 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:



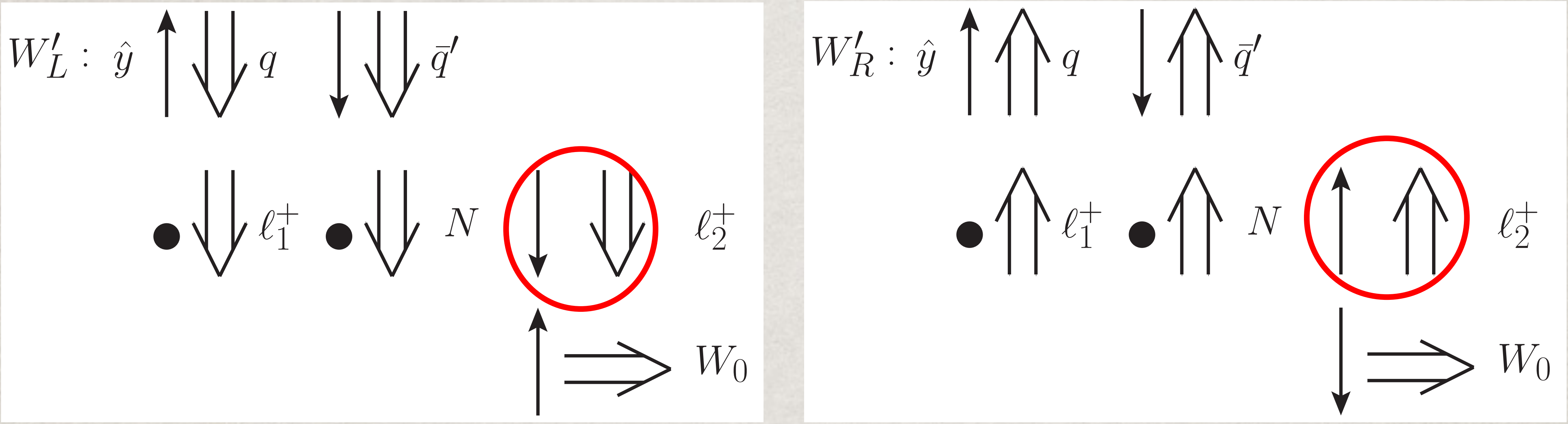




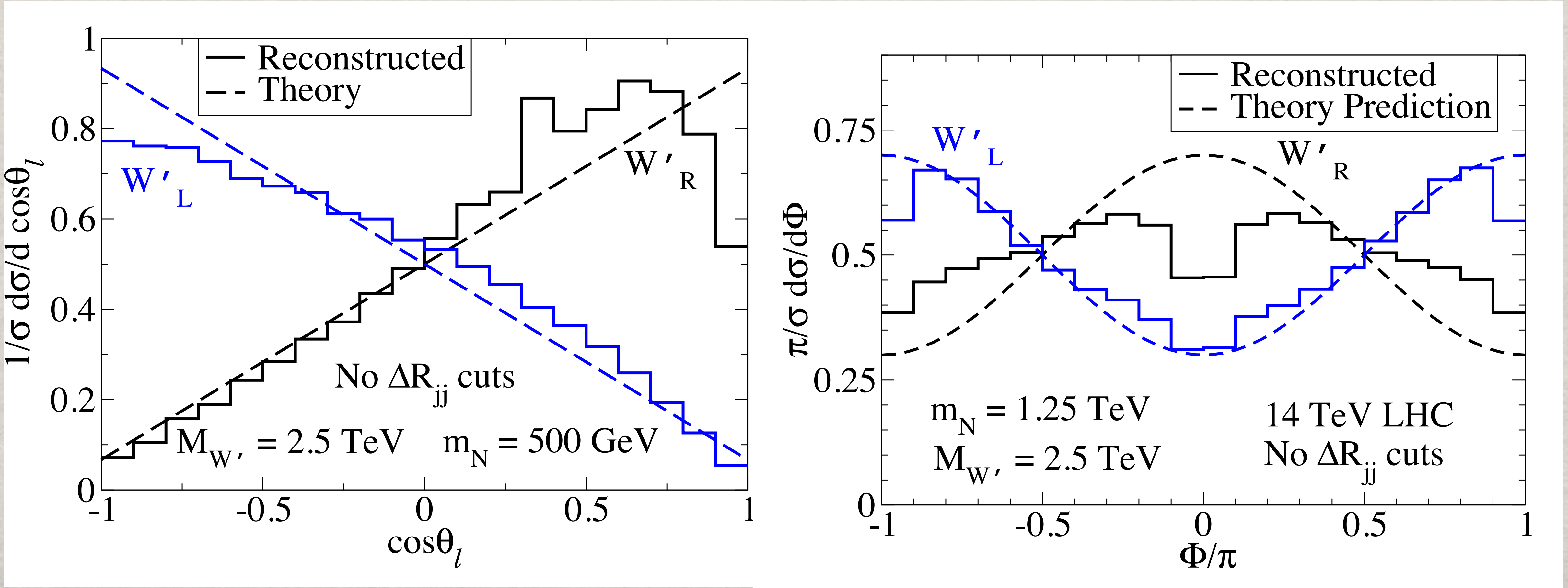
Keung & Senjanovic, PRL (1983).

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

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

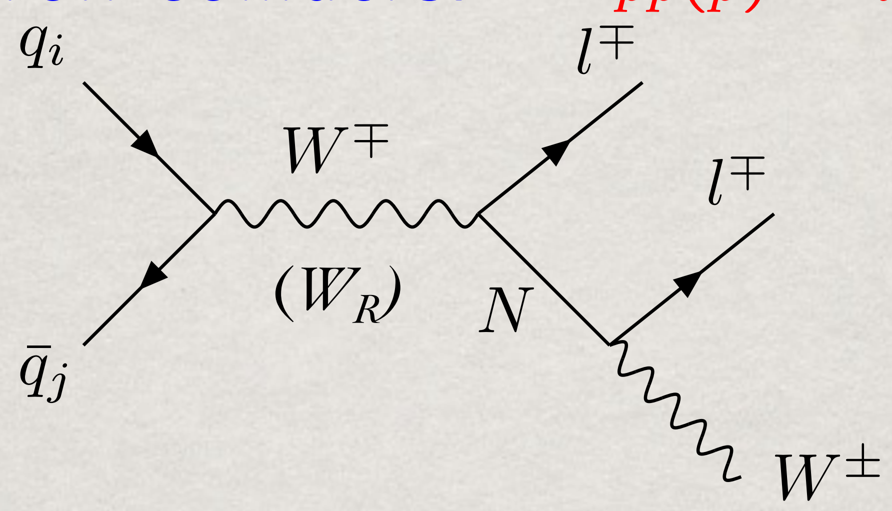


$$N_{L,R} \to \ell^+ W^- \to \ell^+ q\bar{q}'$$



6. N_R at Hadron Colliders

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

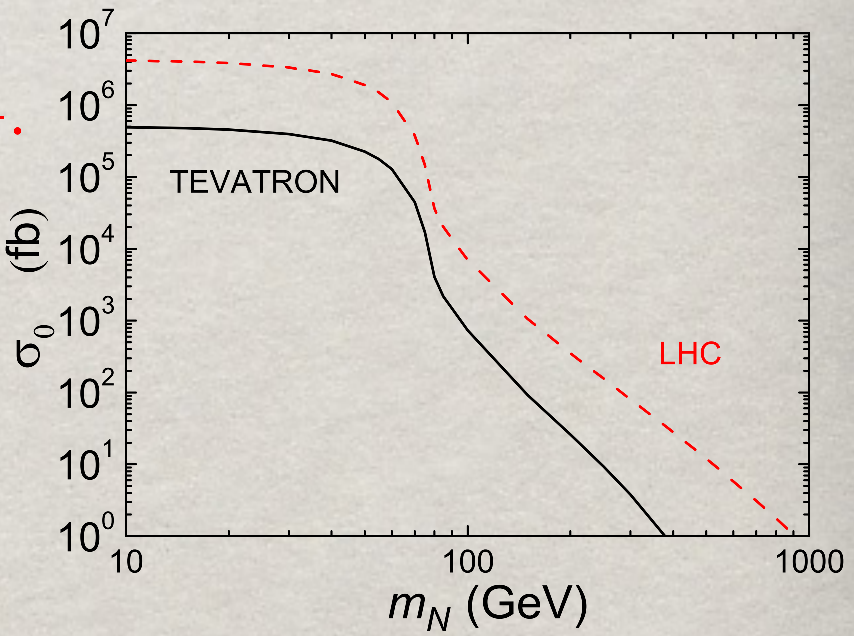


$$\sigma(pp \to \mu^\pm \mu^\pm W^\mp) \approx \sigma(pp \to \mu^\pm N) Br(N \to \mu^\pm W^\mp) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V^{\ell N}\right|^2} V_{\mu N}^2 \, \sigma_0.$$

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:

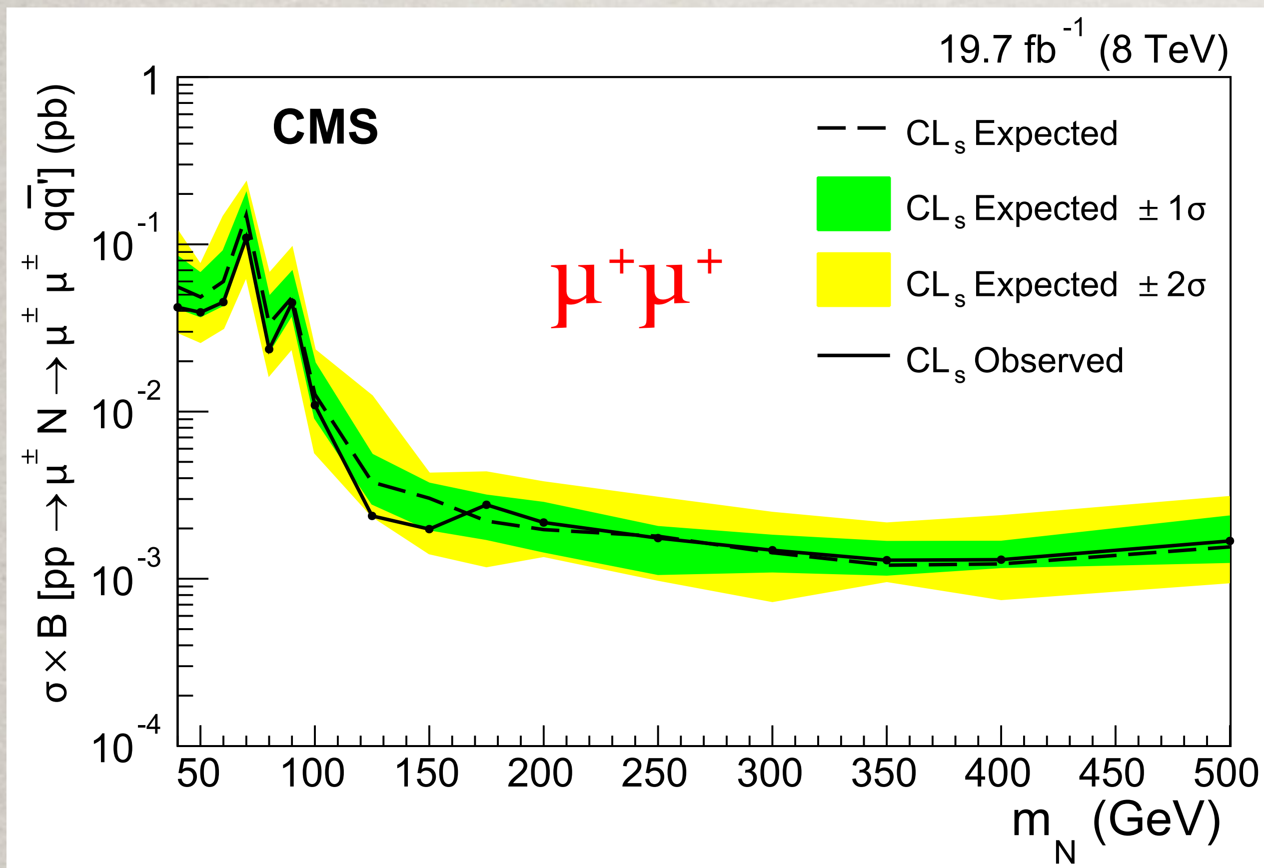
- like-sign di-muons plus two jets;
- no missing energies;
- $m(jj) = M_W, \; m(jj\mu) = m_N$.

[§] 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).

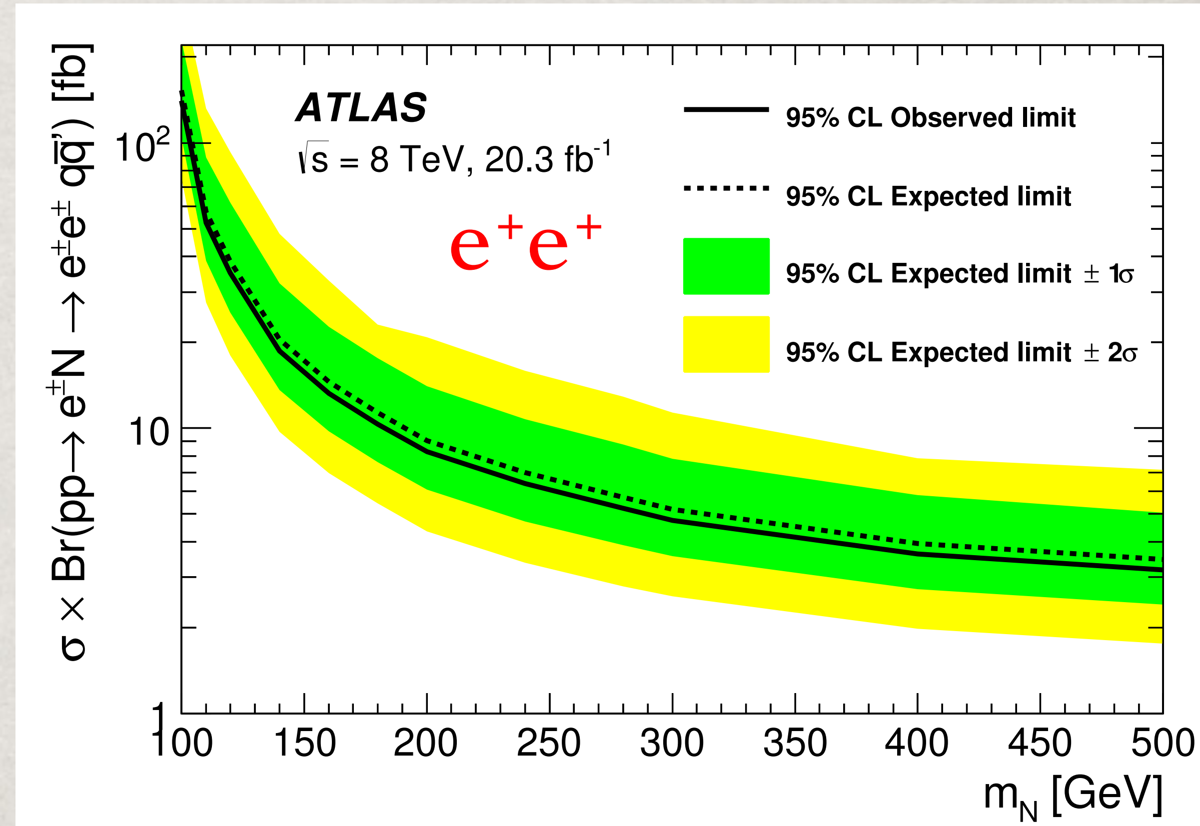
CMS:

CMS collaboration: arXiv:1501.05566v1.

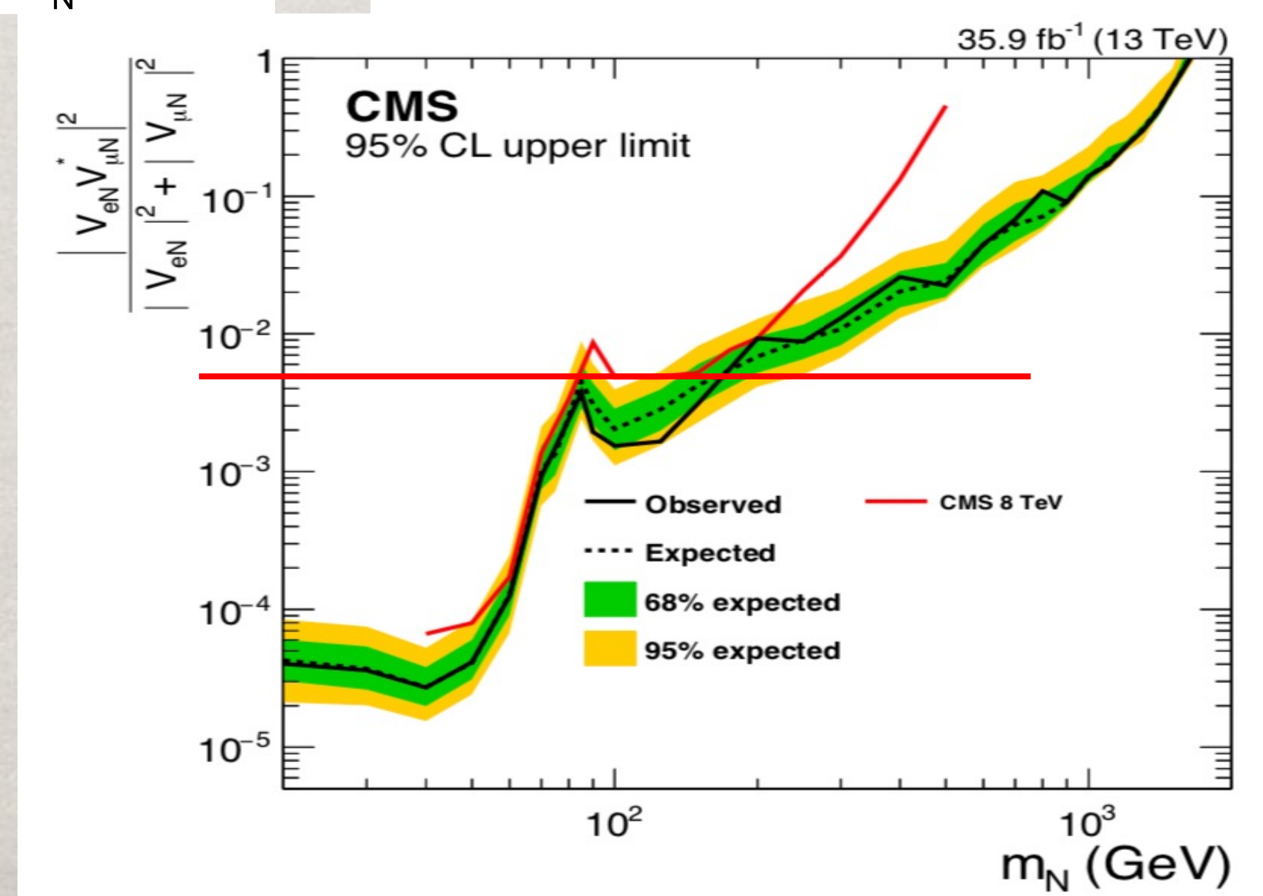


ATLAS:

ATLAS collaboration: arXiv:1506.06020v2.

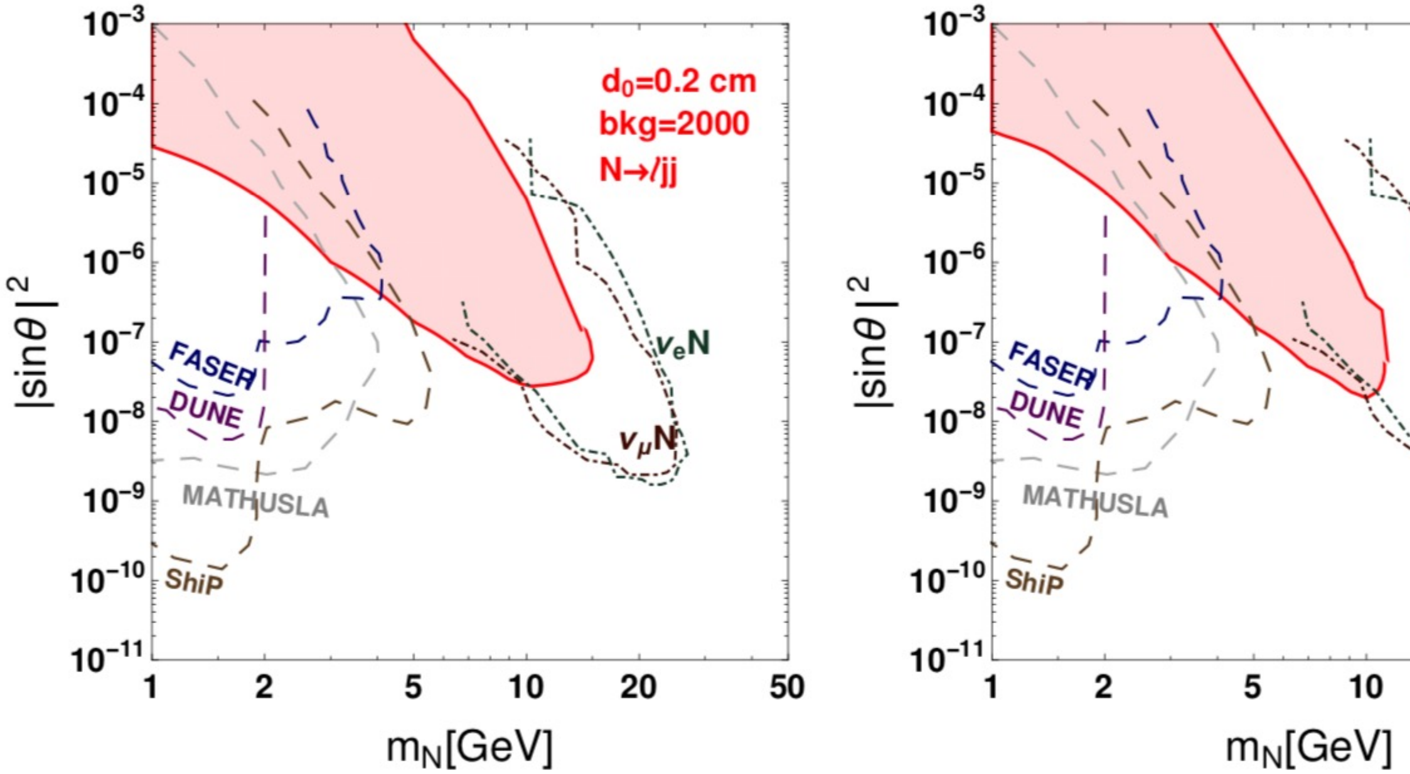


CMS collaboration update: arXiv:1806.10905.



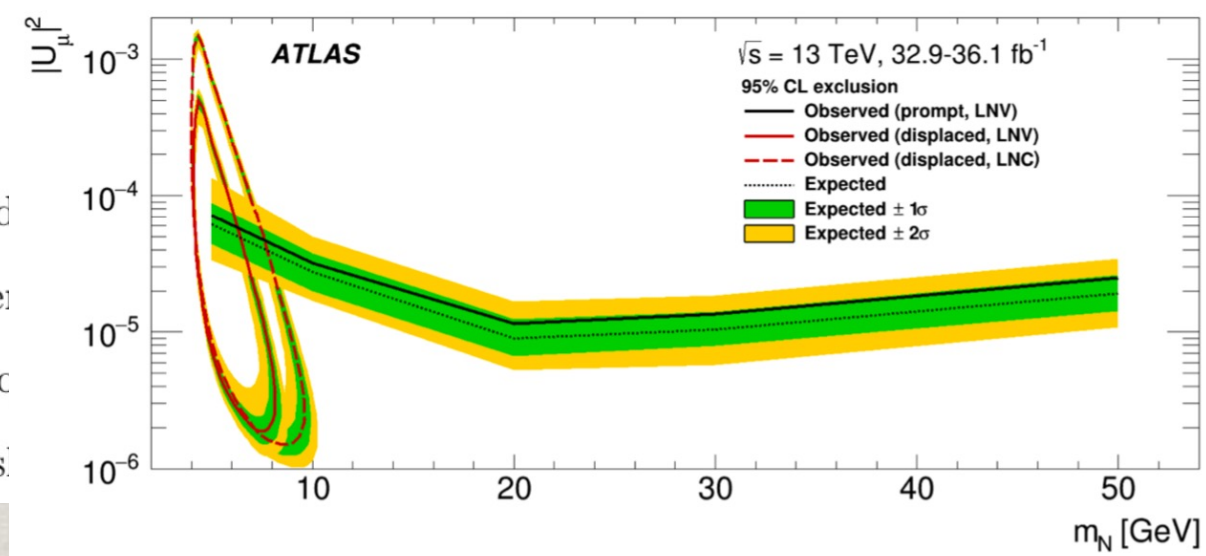
Insensitive to low mass:
There is a trigger threshold
~ 20 GeV!

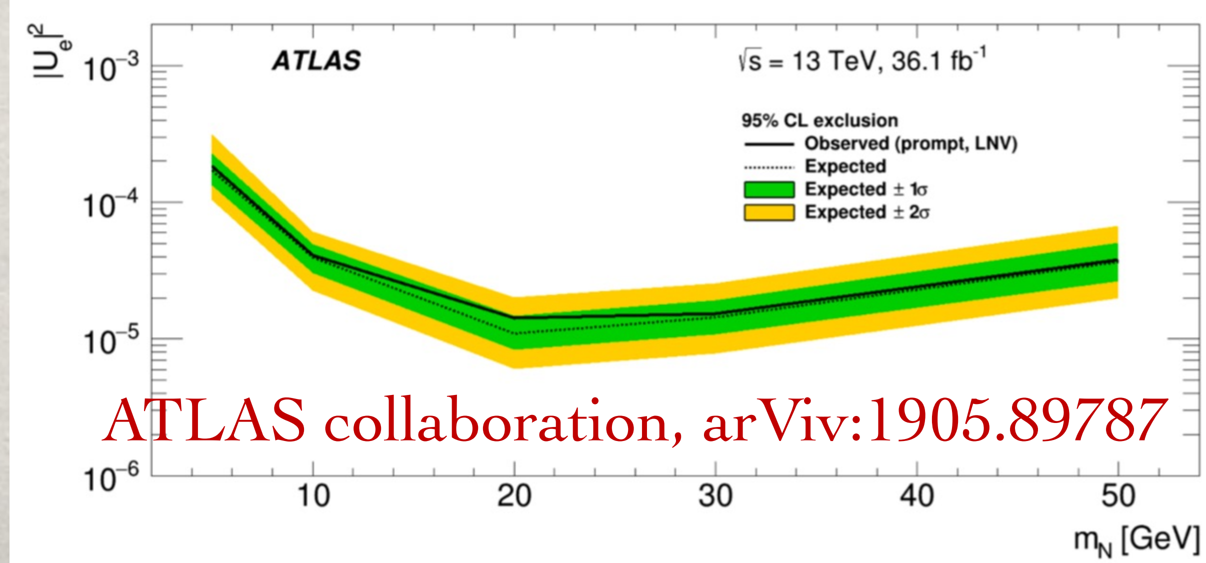
New Strategy: Long Lived Particles @ Low mass



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

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





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

ATLAS collaboration, arViv:1905.89787

Heavy Neutral Leptons at the Electron-Ion Collider

10.09287v1 [hep-ph] 17 Oct 2022

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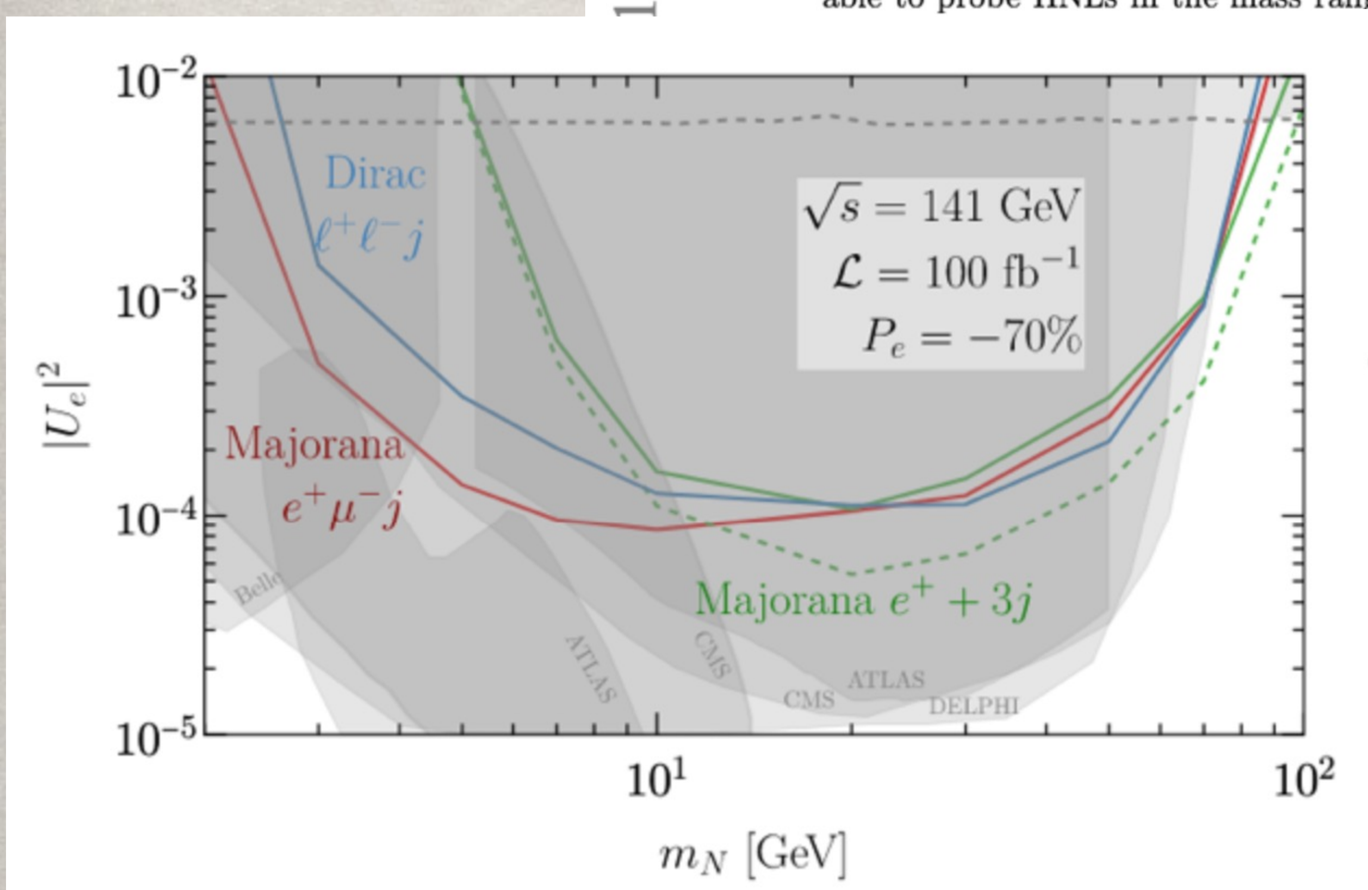
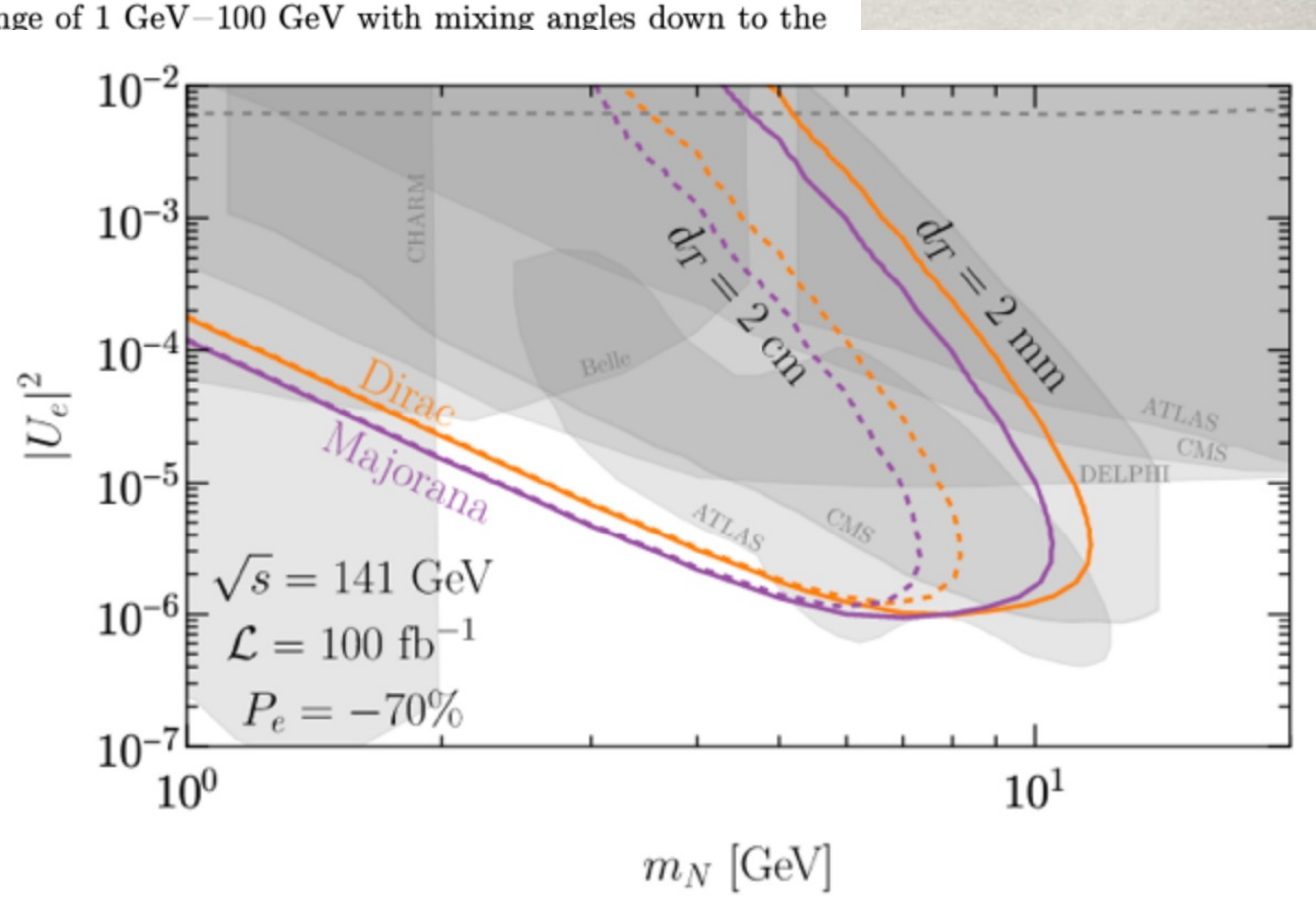
ABSTRACT: The future Electron-Ion Collider (EIC) at Brookhaven National Laboratory, along with its primary capacity to elucidate the nuclear structure, will offer new opportunities to probe physics beyond the Standard Model coupled to the electroweak sector. Among the best motivated examples of such new physics are new heavy neutral leptons (HNLs), which are likely to play a key role in neutrino mass generation and lepton number violation. We study the capability of the EIC to search for HNLs, which can be produced in electron-proton collisions through charged current interactions as a consequence of their mixing with light neutrinos. We find that, with the EIC design energy and integrated luminosity, one is able to probe HNLs in the mass range of 1 GeV – 100 GeV with mixing angles down to the

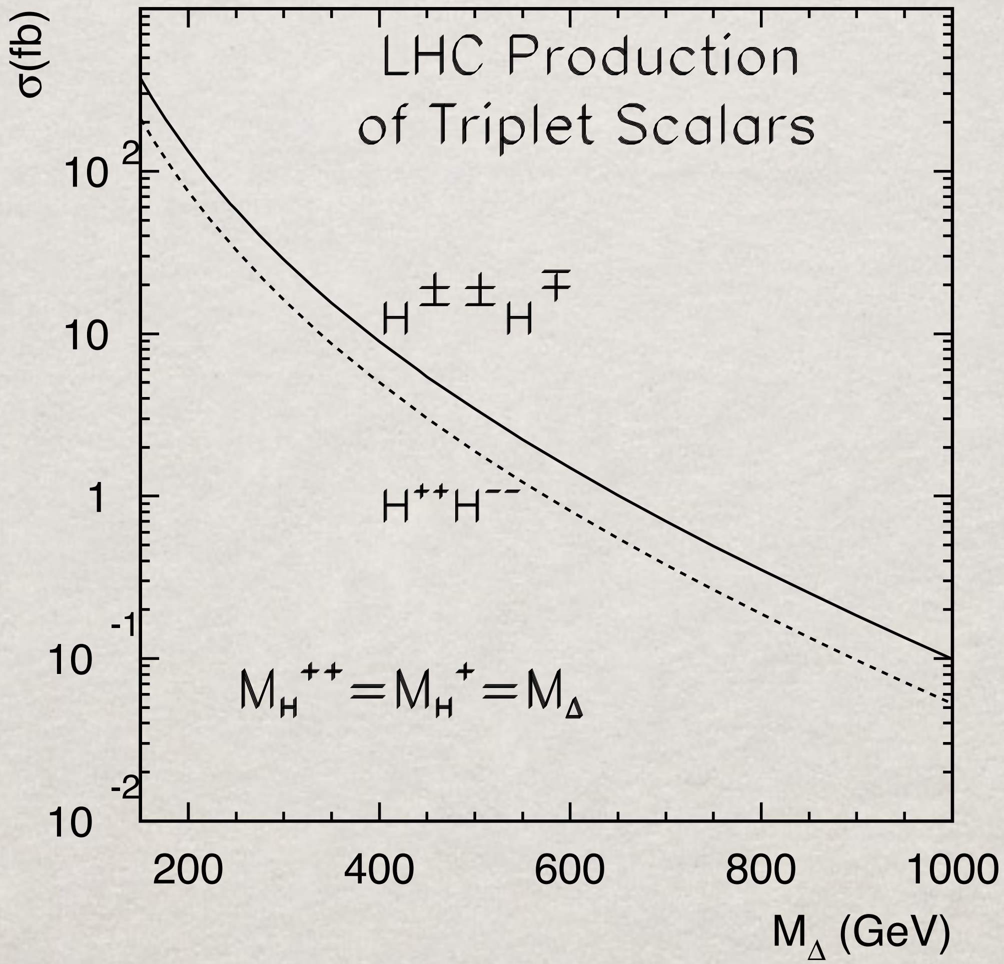




8. Type II Seesaw: $H^{\pm\pm}$ & $H^{\pm}$

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

Pure electroweak gauge interactions



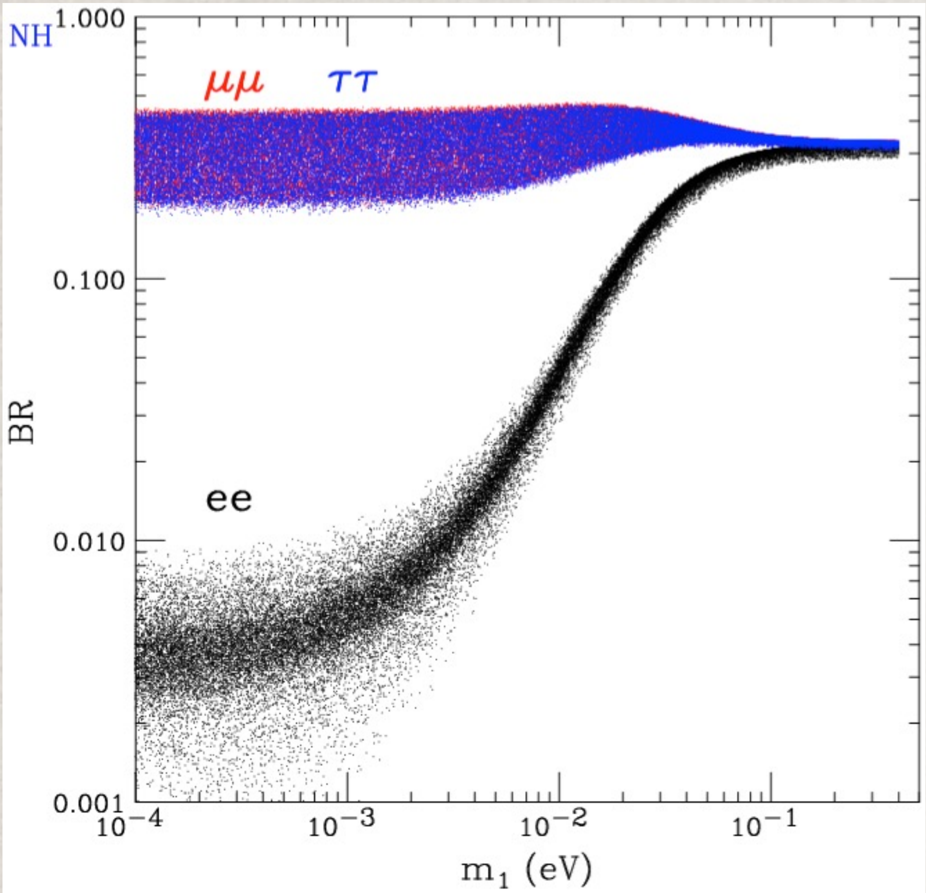
Akeroyd, Aoki, Sugiyama, 2005, 2007.

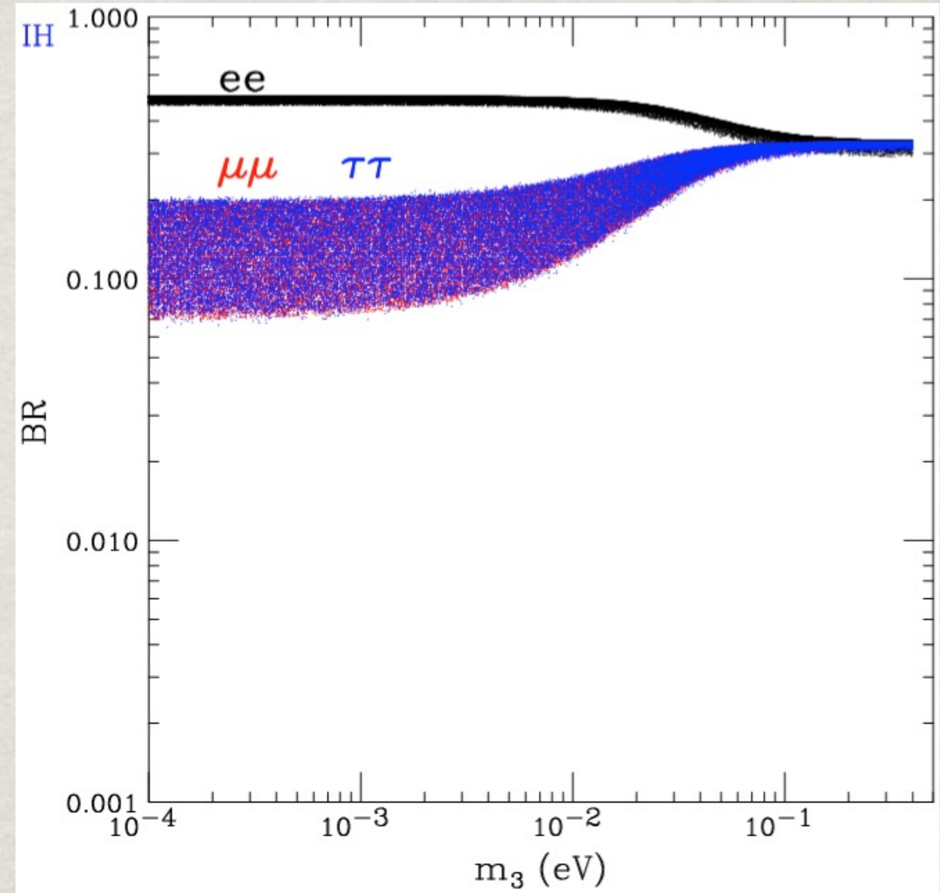
$\gamma\gamma \to H^{++}H^{--}$ 10% of the DY.

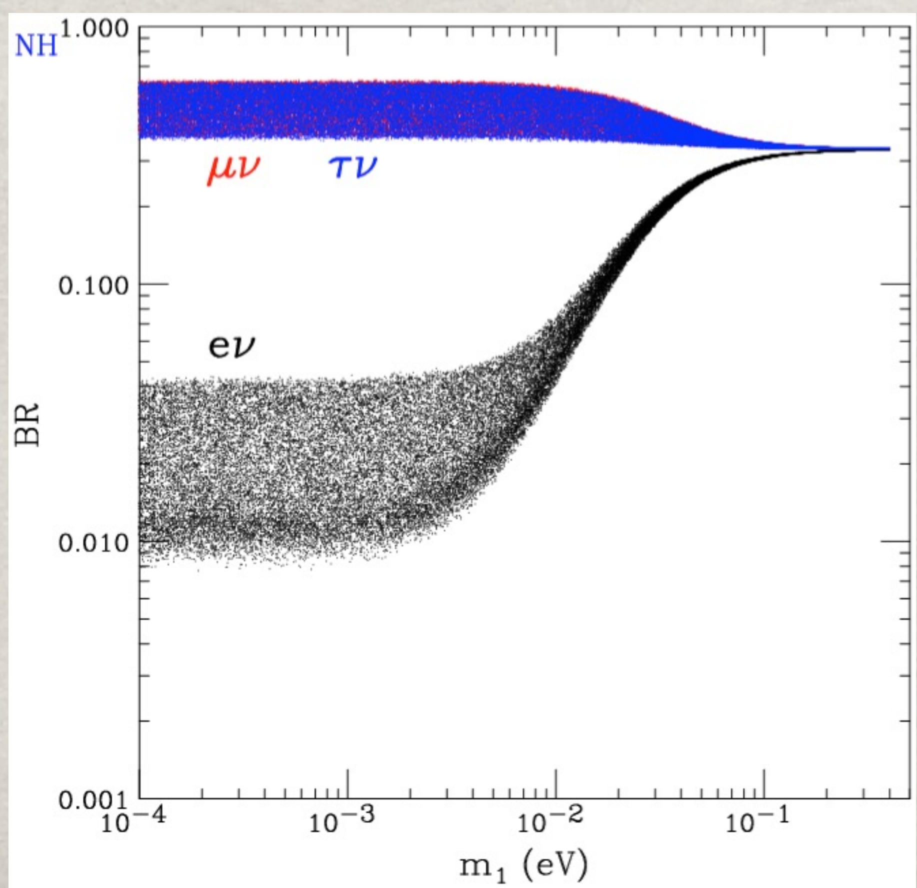
†Revisit, T.Han, B.Mukhopadhyaya, Z.Si, K.Wang, arXiv:0706.0441.

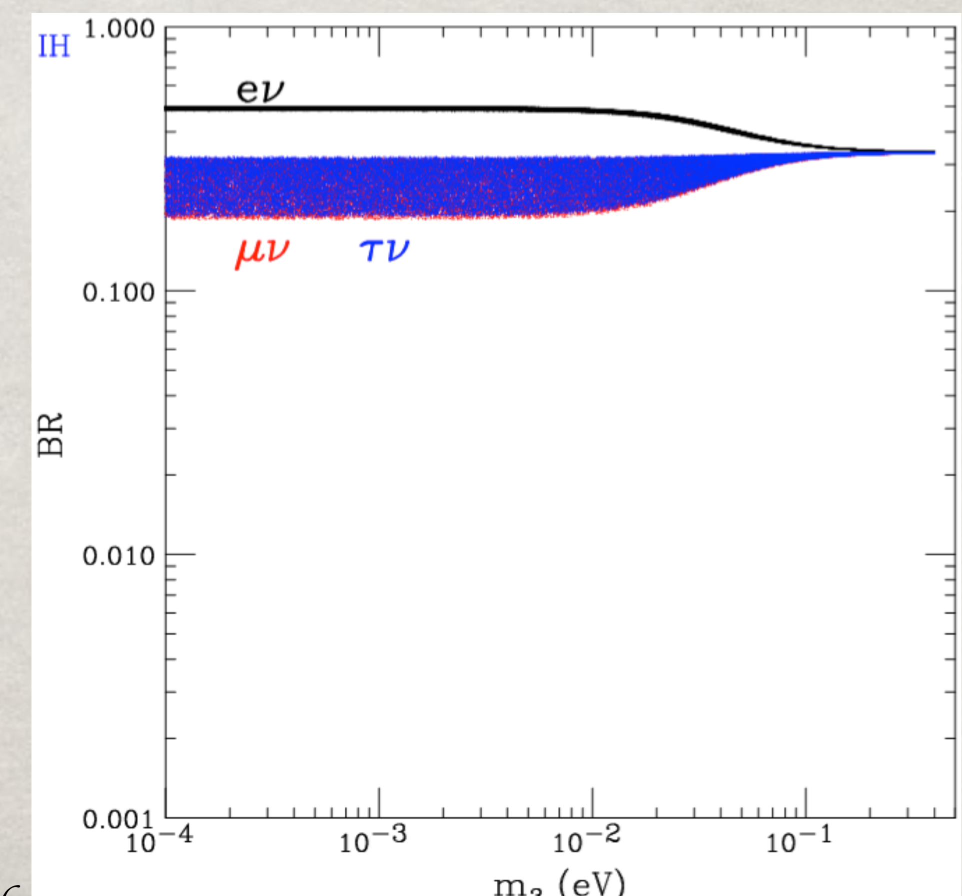
Z.L. Han, R. Ding, Y. Liao, arXiv:1502.05242; 1506.08996;
J. Gehrlein, D. Goncalves, P. Machado, Y. Perez-Gonzalez: arXiv:1804.09184.

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



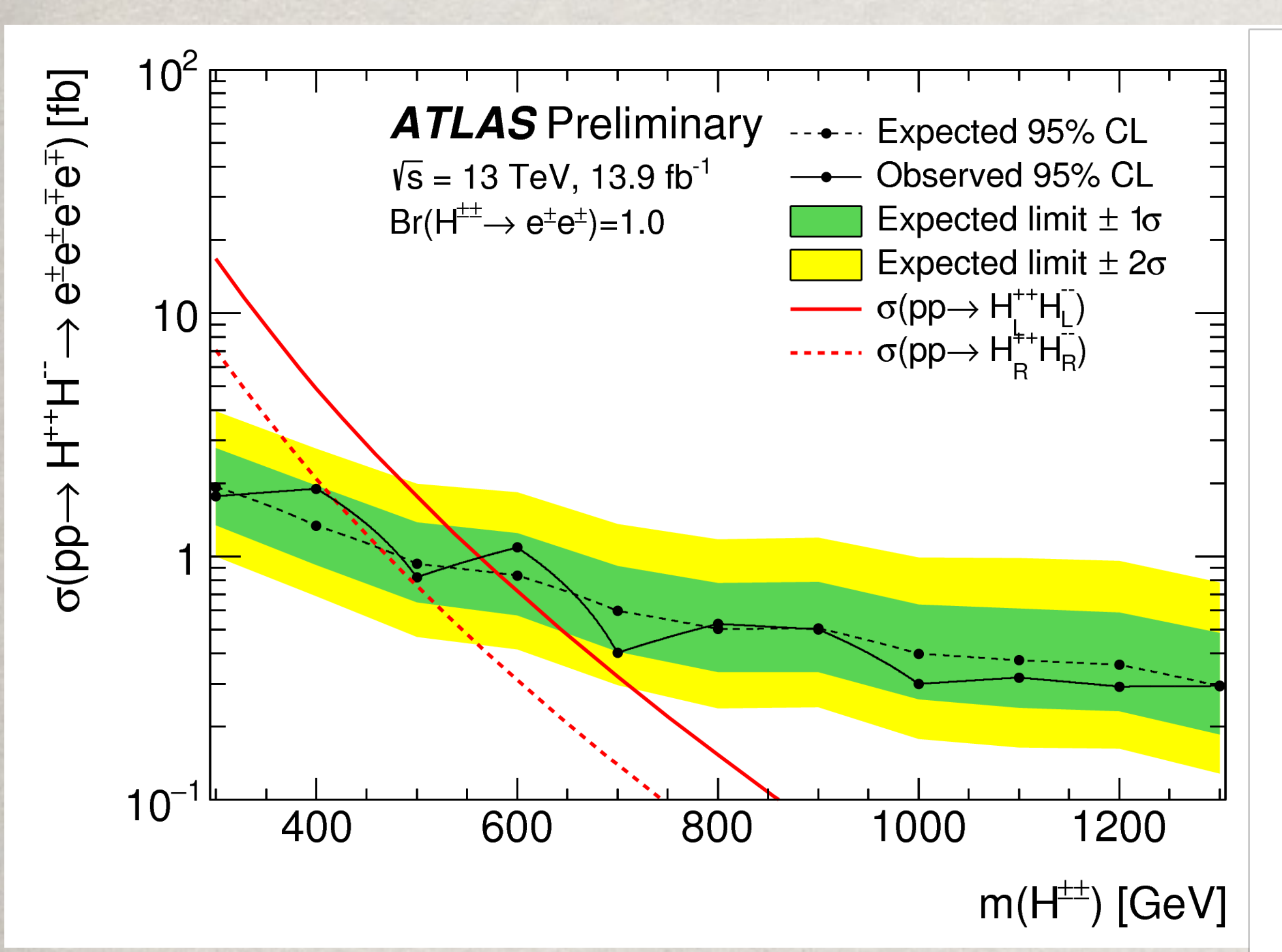






Sensitivity to $H^{++}H^{--} \to \ell^+\ell^+,\ \ell^-\ell^-$ Mode:

ATLAS Bounds:



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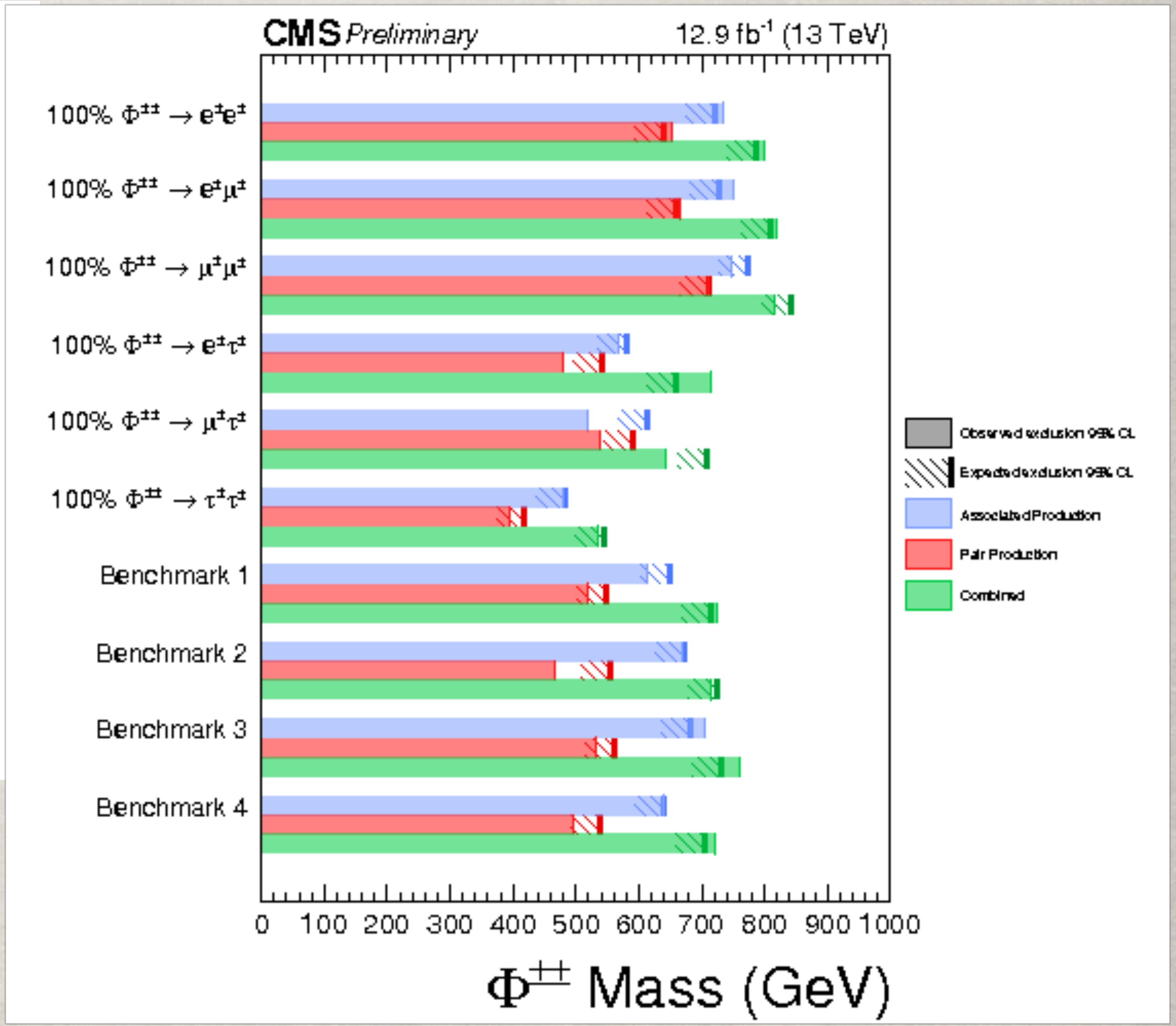


With 300 fb^{-1} integrated luminosity,

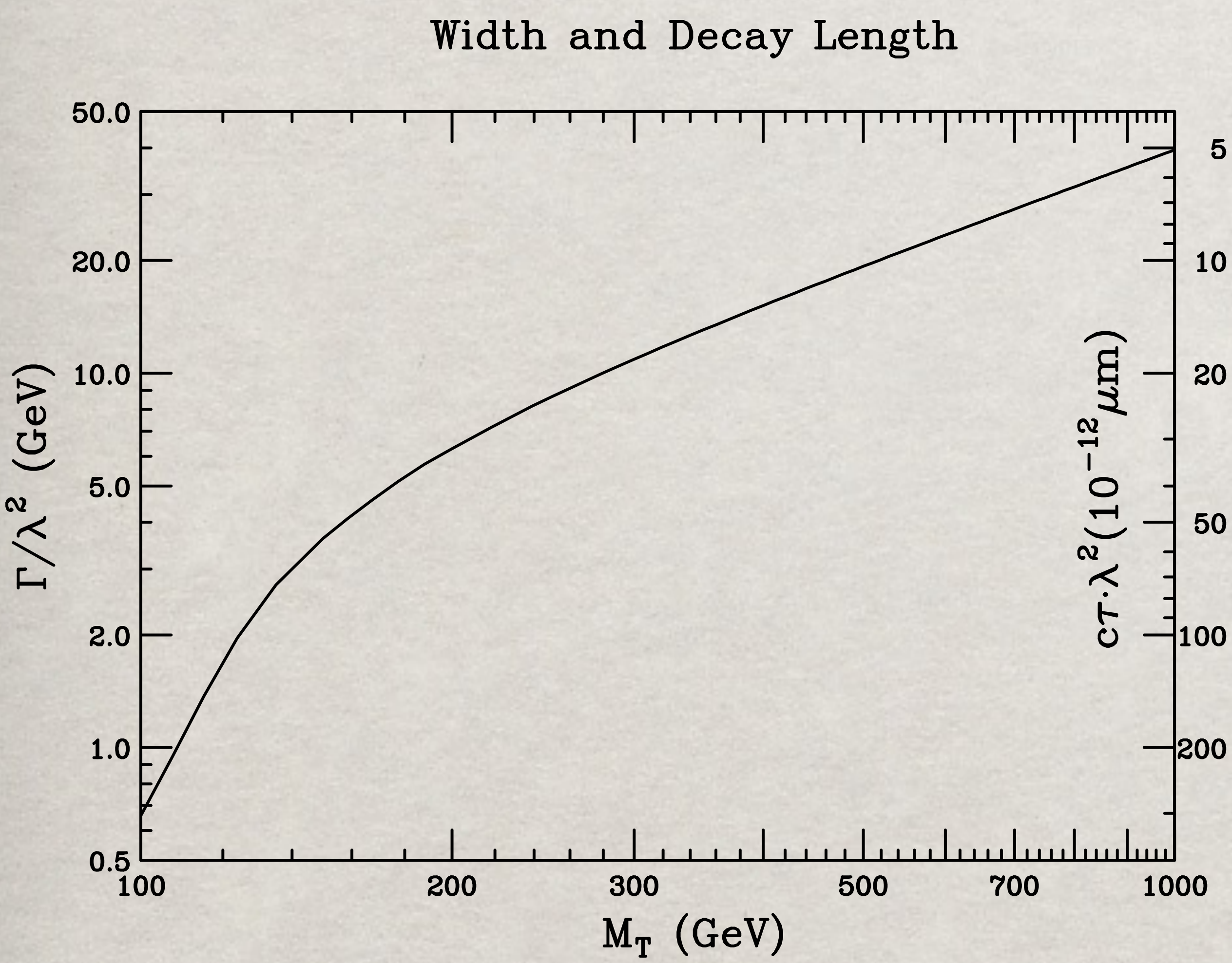
a coverage upto $M_{H^{++}} \sim 1$ TeV even with $BR \sim 40-50\%$.

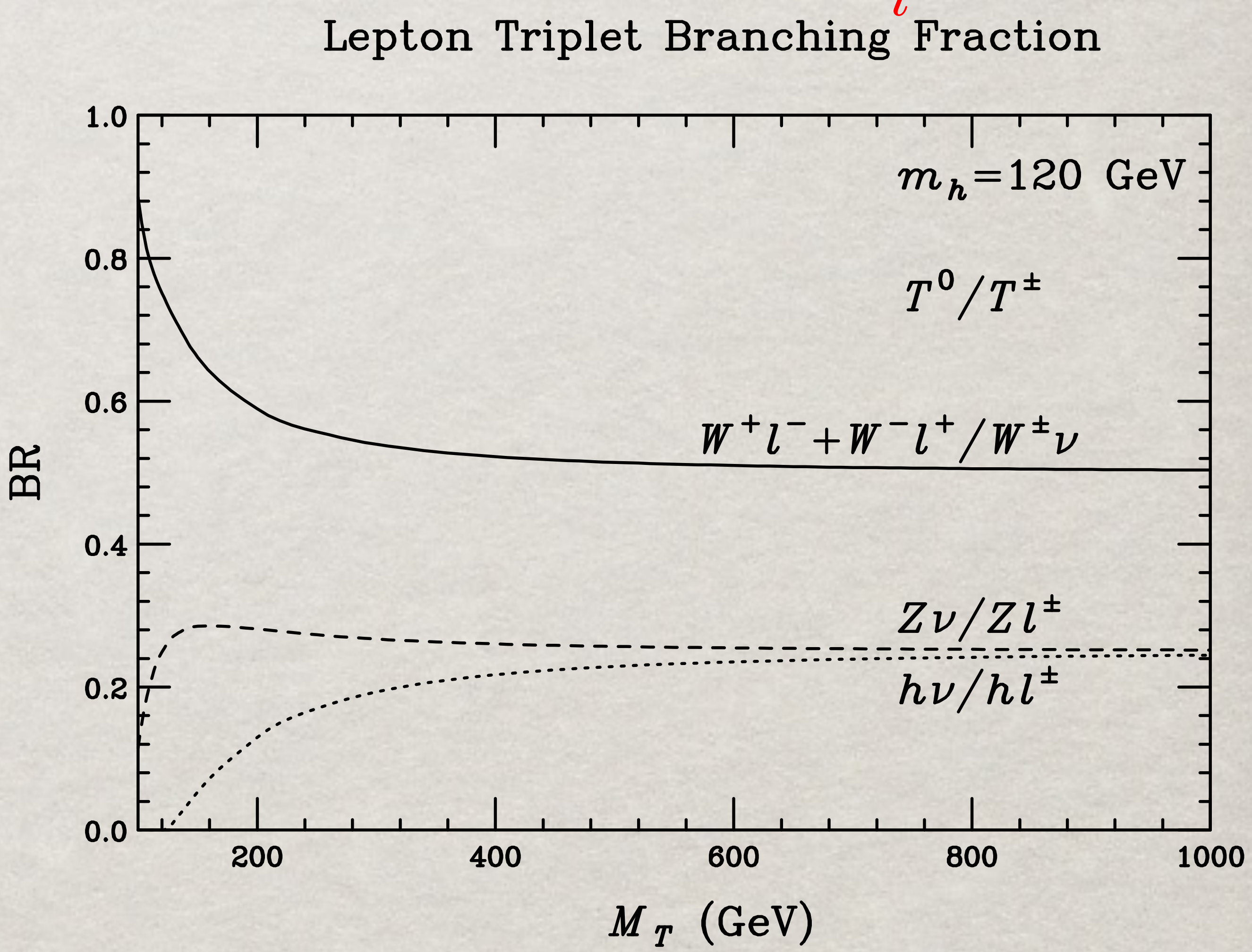
Possible measurements on BR's.

9. Type III Seesaw: $T^{\pm}$ & T^{0}

Consider their decay length:

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





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

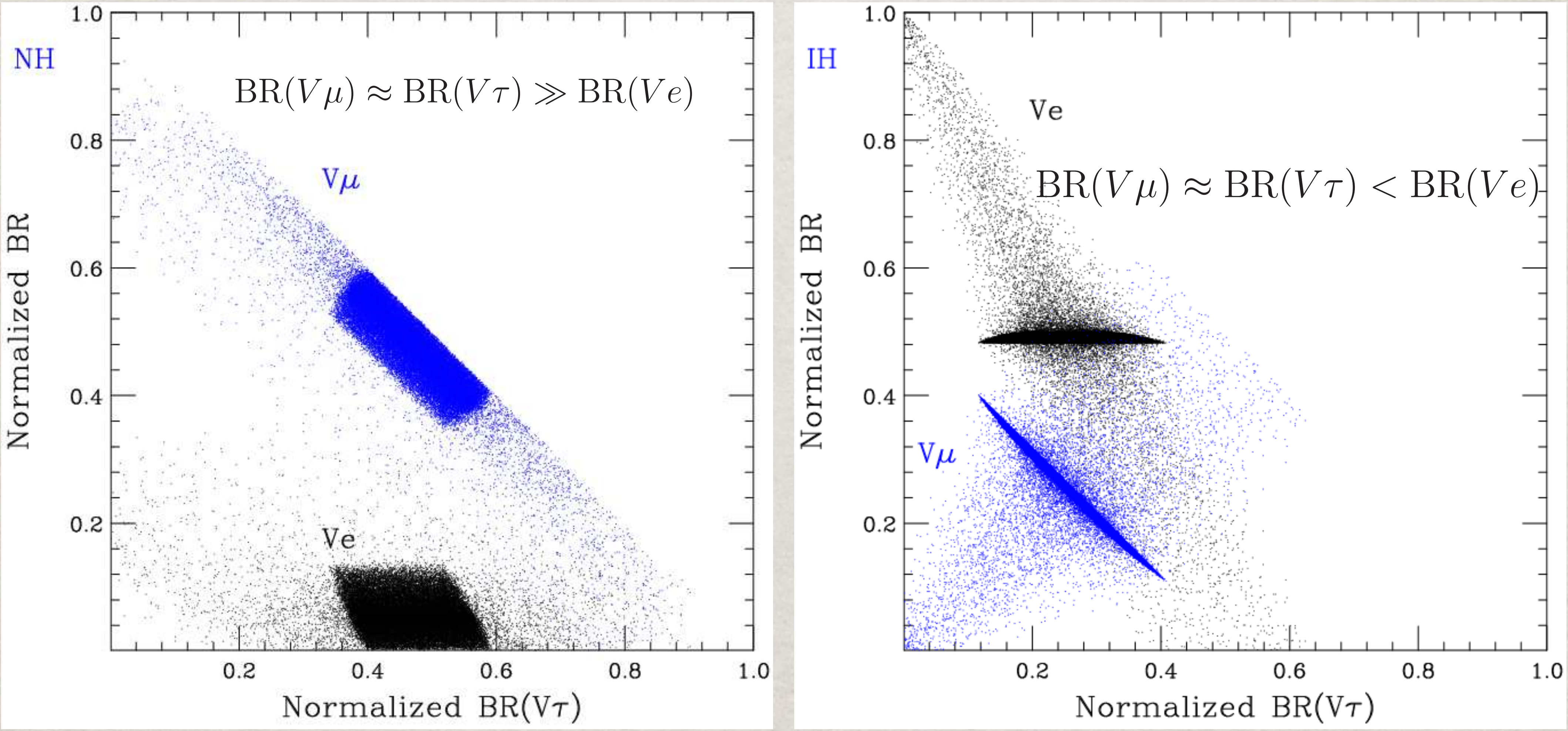
Still not too long-lived, but possibly large displaced vertices.

Tong Li & X.G. He, hep-ph/0907.4193.

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

Lepton flavor combination determines the ν mass pattern: †

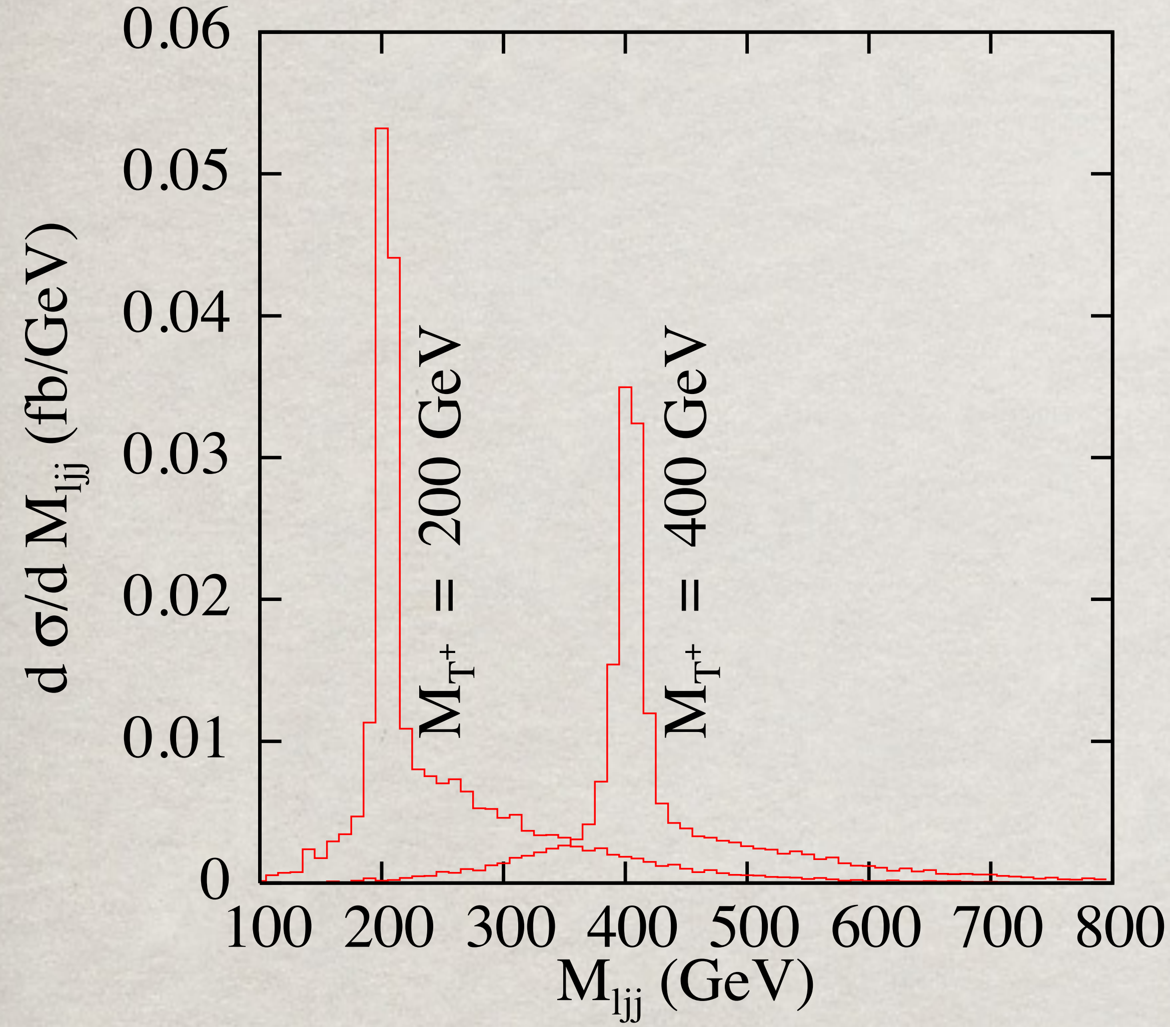
$$m_\nu^{ij} \sim -v^2 \frac{y_T^i y_T^j}{M_T}, \quad BR(T^{\pm,0} \to W^{\pm}\ell,\ Z\ell) \sim y_T^2 \sim V_{PMNS}^2 \, \frac{M_T m_\nu}{v^2}.$$



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.

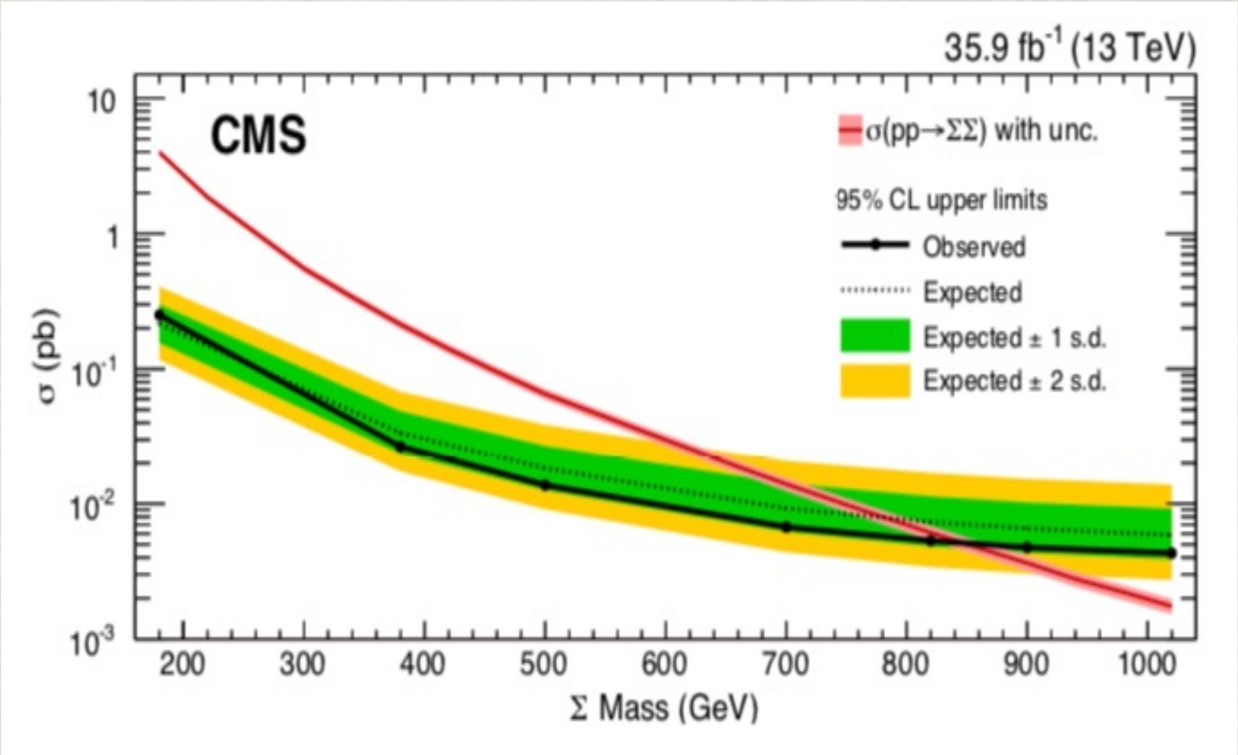
ΔL=2 & mass reconstruction for $T^{\pm}$ & T^0



Current LHC bounds:

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

CMS: arXiv:1708.07962



In conclusion

As part of Rabi's legacy:
Neutrinos are NOT "all gone missing".
Neutrino physics is flourishing,
and likely to lead to the next breakthrough in HEP.

Rabi:
Look forward to your new ideas/papers.
And enjoy your new endeavor!