LNV and LFV at colliders: a theory perspective in the post-ESU era

BLV circa 2020, Case Western Reserve University

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post-European Strategy Update era

Snowmass in Context

Like the **Snowmass process**

- The **European Strategy Update** is a (roughly) decadal community-review process
- From 2018 to 2020, pan-European effort (with crucial input from Asia and Americas) to realign priorities and trajectory in global context
- Built on experiences from **Snowmass 2013 exercises** + new data

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The **European Strategy Update** officially concluded in June 2020

(indico.cern.ch/event/808335/timetable/)

- Encouraging projections on collider sensitivity to LNV and cLFV

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Today's aim: LNV@Colliders (TH)

- Selective summary of results since last Snowmass / ESU

see E. Thomson's talk for LNV@colliders (EX)

- Potential opportunities and directions for **current Snowmass process**

Acknowledgements, Apologies, and Disclaimers

apologies:

- finite time constraints $\implies$ many omissions
- Focus largely on now-operating colliders and upgrades, e.g., HL-LHC
- Focus largely on ph developments see P-F Perez's (TH) and E. Thomson's (EX) talks

source material:

1. Review on Nu Mass Models at Colliders

   Y. Cai, T. Han, T. Li, RR, [1711.02180]
2. European Strategy Update Chapter on Nu Mass Models,

   T. Han, T. Li, X. Marcano, S. Pascoli, RR, C. Weiland [1812.07831]
3. Other community documents and some newer results

humble reminder: right-handed neutrinos are **not** the only explanation for tiny ν masses nor are they necessary (e.g., Type II Seesaw)

- Lack of guidance from data and theory $\implies$ broad approach needed (careful about putting all eggs in one basket!)

motivation for new physics from ν physics

Nu Masses and New Particles

Nonzero neutrino masses  $\Longrightarrow$ new degrees of freedom exist: [Ma'98]

$$m_\nu \neq 0 + \text{left}-\text{handed (LH) Weak currents}$$

$(renormalizability)$

LH Majorana Mass : $m_\nu^L \overline{\nu_L} \nu_L^c$

Dirac Mass : $m_\nu^D \overline{\nu_L} \nu_R$

$(gauge\ invariance)$

$m_\nu^L = y\langle \Delta \rangle$ or new dynamics

$m_\nu^D = y\langle \Phi_{\rm SM} \rangle$

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- New particles might be charged under new or old gauge symmetries
- Typically manifests as processes that do not conserve lepton number (LNV) and/or lepton flavor (LFV) quantum numbers

Theory Developments:

Clarity on Lepton Number Violation at Colliders

Subtle assumptions in ν mass models have led to **overstatements** in literature and confusion on feasibility of LNV at colliders

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Pascoli, et al, [1712.07611], but see also Pilaftsis [hep-ph/9901206], Kersten and Smirnov [0705.3221]

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1. **High-scale seesaw**: $\mu_M \gg \langle \Phi_{SM} \rangle \implies m_\nu \sim m_D \left(\frac{m_D}{\mu_M}\right), \quad m_N \sim \mu_M$
2. **Low-scale seesaw**: $\mu_M \ll \langle \Phi_{SM} \rangle \implies m_\nu \sim \mu_M \left(\frac{m_D}{m_R}\right)^2, \quad m_N \sim m_R$

Known also in literature as Inverse Seesaw, Linear Seesaw, Protective Symmetries, etc.

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Corollaries: Low-scale Type I + $m_\nu \approx 0$ on experimental scale,
$\implies$ approximate L conservation w/ Pascoli, RR, et al, [1812.08750]
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$\implies$ EW/TeV-scale Dirac-like N_i do not decouple in Type I scenarios
$\implies$ collider LNV via $N_i \implies$ *more new particles!*

For ***discovery purposes***, no need to complicate life. Take agnostic/pheno. approach with generic $V_{\ell N}$ parametrization and one N mass eigenstate

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis}}$$

The SM W chiral coupling to **leptons** in **flavor basis** is

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left[\overline{\nu_{\ell L}} \gamma^\mu P_L \ell^-\right] \quad + \quad H.c.$$

$\implies$ SM W coupling to N and charged **leptons** in the **mass basis is**

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left[\sum_{m=1}^{3} \overline{\nu_m} U_{m\ell}^* + \overline{N^c} V_{N\ell}^*\right] \gamma^\mu P_L \ell^- \quad + \quad H.c.$$

$\implies$ N is **accessible through** SM currents

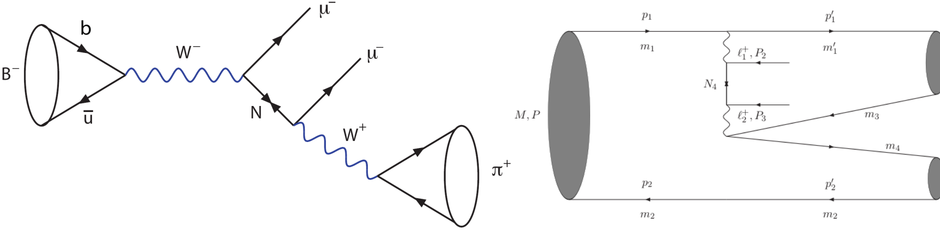
colliders searches for N

searches for low mass N

Searches for Low Mass *N*

For $m_N \ll M_W$, *N* can appear in decays of baryons, mesons, and τs!

Atre, Han, Pascoli, & Zhang [0901.3589]; Castro & Quintero [1302.1504]; Yuan, Wang ×2 , Ju, & Zhang [1304.3810]; + others



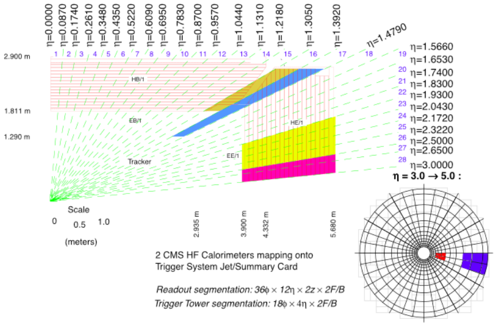
Production rate of mesons ($\pi^{\pm}, \mathcal{D}, \mathcal{B}$) at colliders is ***big*** ($\sigma_{bX}^{\mathrm{LHC}} \sim 0.1$ *mb*)

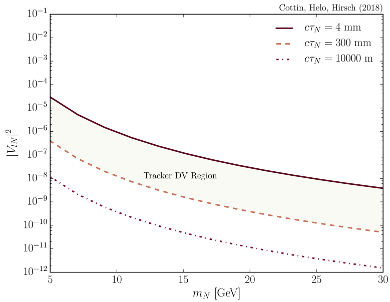
- Sufficient[1] to overcome ***tiny*** mixing for MeV-scale, Majorana *N*
- Sufficient to probe *L*-conserving, charged lepton flavor violation

[1] Specifically, Kersten-Smirnov [0705.3221] and Pascoli, et al [1712.07611]

N with intermediate masses:

non-prompt decays / displaced vertices





Decays of light N through SM weak currents can be very long-lived:

$$\Gamma_{\text{Tot.}} \sim G_F^2 m_N^5 \sum |V|^2 \text{ (small } |V| \implies \text{ long lifetime!)}$$

$$\implies d_0 = \beta c \tau = \frac{\beta c \hbar}{\Gamma_{\text{Tot.}}} \sim \frac{1.45 \ m}{\sum |V|^2} \left(\frac{1 \text{ GeV}}{m_N}\right)$$

Detectors have *finite* detector volume, with radius $< \mathcal{O}(10)$ m

- N may decay in ECAL (1-2m), HCAL (2-3m), μChamber ($>$5m)

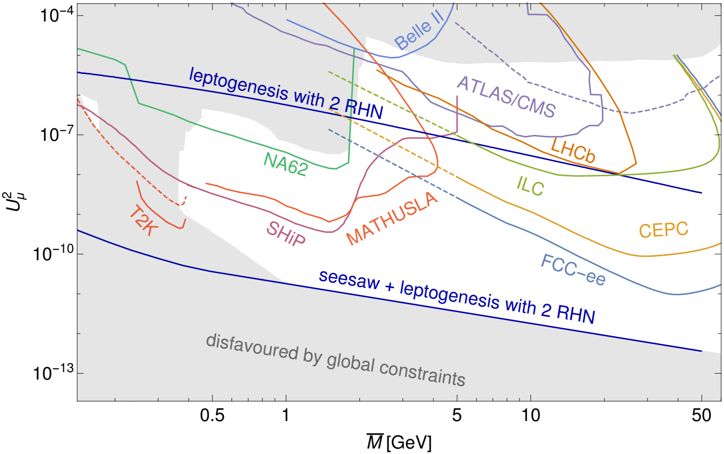
Light/Intermediate N at Current and Future Machines

List of current and proposed experiments sensitive to displaced N decays

- **Ongoing:** ATLAS, CMS, LHCb, Belle2: sensitivity to μ, τ flavors
  ATLAS[1905.09787], CMS[1802.02965]
- **Ongoing:** T2K: $N \to \pi\ell, 2\ell\nu$ at ND280 [Lamoureux, Neutrino2018]
- **Proposed:** FCC-ee, CepC(5YP-2021): $ee \to N\nu$
- **Future:** SHiP [1805.08567] and MATHUSLA [1803.02212]

Many, many studies past few years with a coherent message forming.

Community Message: Next-gen. facilities will be able to directly test *simplest* resonant leptogenesis scenarios with high-scale Type I Seesaw



Update of Drewes, et al [1609.09069]

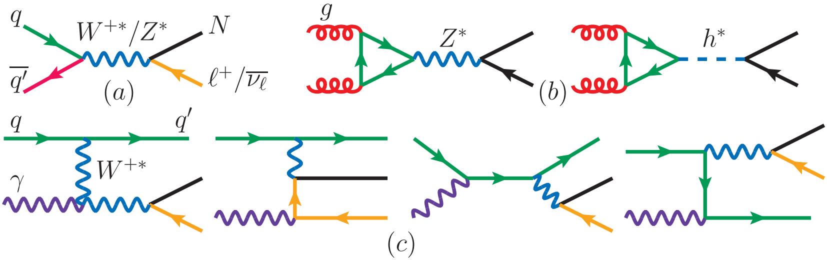
Warning: LHC picture evolving with better strategies and add'l channels

Cottin, Helo, Hirsch [1806.05191]; Abada, Bernal, Losada, Marcano [1812.01720]; K. Cheung, H. Ishida, et al [2004.11537]

Searching for High Mass N

Heavy Neutrinos (N) at Hadron Colliders

... can be produced via mixing through a number of mechanisms



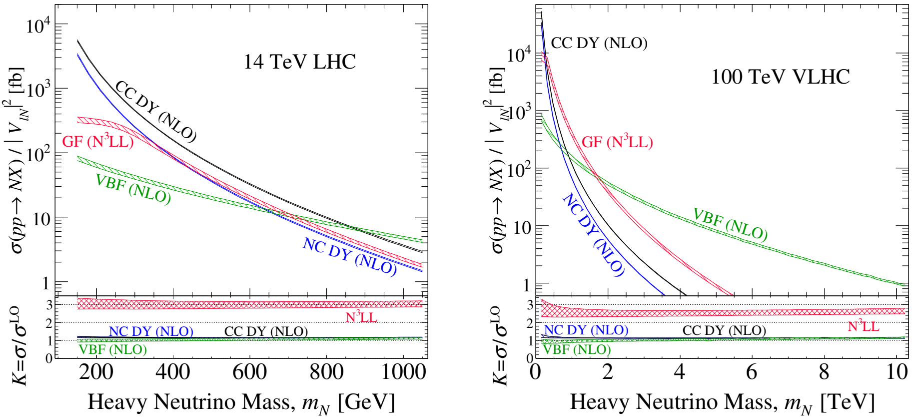
Since 2014, active research program to systematically compare channels

For overview, see review: [1711.02180]

- Clarity needed on $m_N, \sqrt{s}$ **dependence** and **fill gaps in lit.**
- Explore **how new techniques can improve** analyses from 90's-00's

$\Longrightarrow$ better sensitivity, more robust analyses, new public tools

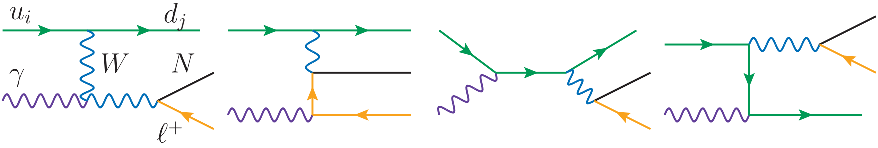
Across $\sqrt{s}$, wild interplay of PDF and matrix elements Pascoli, RR, et al [1812.08750]



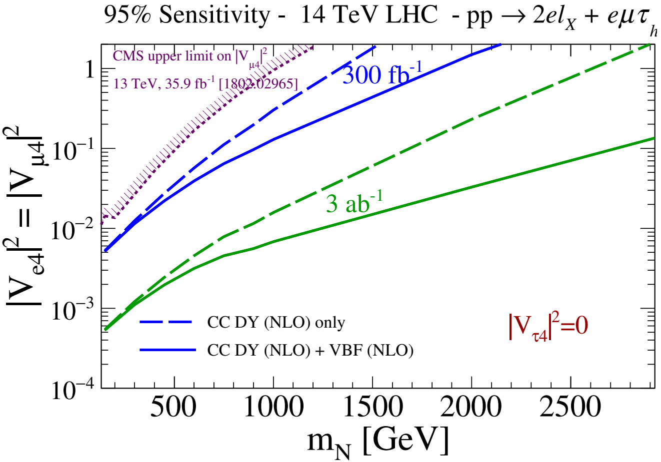
Plotted: Flavor-independent heavy N production rate $(\sigma/|V|^2)$ vs mass

- **GF** and **VBF** dominate at larger $\sqrt{s}$, m_N
- At $\sqrt{s} = 100$ TeV and $|V_{\ell N}|^2 \sim 10^{-3}$, about one $N(10\text{ TeV})/\text{ab}^{-1}$
  If roughly BR$\times\varepsilon \times \mathcal{A} \times \mathcal{L} \sim \frac{1}{3} \times 30$ ab^{-1}, then $\sqrt{N_{Obs.}} > 3\sigma$

How important are new channels, e.g., $W\gamma$ fusion?

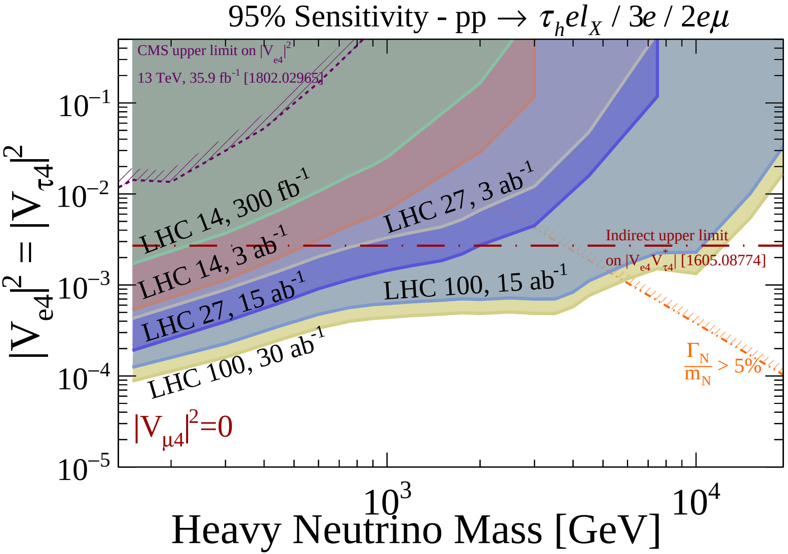


Plotted: LHC 14 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass (m_N) in search for $pp \to \mu^{\pm} e^{\mp} \ell_X \quad (\ell_X = e, \mu, \tau_h)$



[1411.7305, 1812.08750]

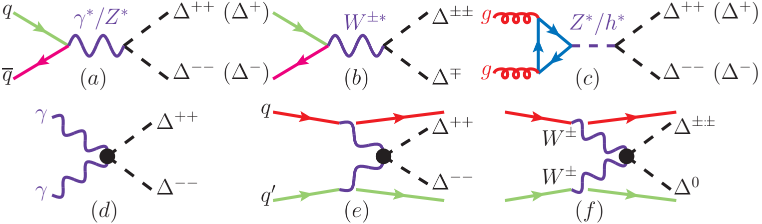
- Dash = trilepton analysis without $W\gamma$ fusion
- Solid = $+W\gamma$ fusion $\implies$ $W\gamma$ drives high-mass sensitivity!



After 3 yrs, *total* rewrite of *pp* → $3\ell X$ search for **Dirac** *N*!

10 − 11× improved sensitivity to cLFV at LHC Pascoli, RR, et al, [1805.09335, 1812.08750]

Type II Seesaw[2]



[2] Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

The Type II Seesaw Mechanism is special: generates neutrino masses ***without*** hypothesizing right-handed neutrinos

- Important example that $m_\nu \neq 0 \not\Rightarrow$ that ν_R exist

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Hypothesize a **scalar** $SU(2)_L$ triplet with **lepton number** $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^{+} & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^{0} & -\Delta^{+} \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi^\dagger \hat{\Delta} \cdot \Phi^\dagger + \text{H.c.}\right)$$

The mass scale $\mu_{h\Delta}$ breaks lepton number, and induces $\langle \Delta \rangle \neq 0$:

$$\sqrt{s}\langle \hat{\Delta} \rangle = v_\Delta \approx \frac{\mu_{h\Delta} v_{\rm EW}^2}{\sqrt{2} m_\Delta^2}$$

which leads to **left-handed Majorana masses** for neutrinos

$$\Delta\mathcal{L} = -\frac{y_\Delta^{ij}}{\sqrt{2}} \overline{L^c} \hat{\Delta} L = -\frac{y_\Delta^{ij}}{\sqrt{2}} \begin{pmatrix} \overline{\nu^{jc}} & \overline{\ell^{jc}} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix} \begin{pmatrix} \nu^i \\ \ell^i \end{pmatrix}$$

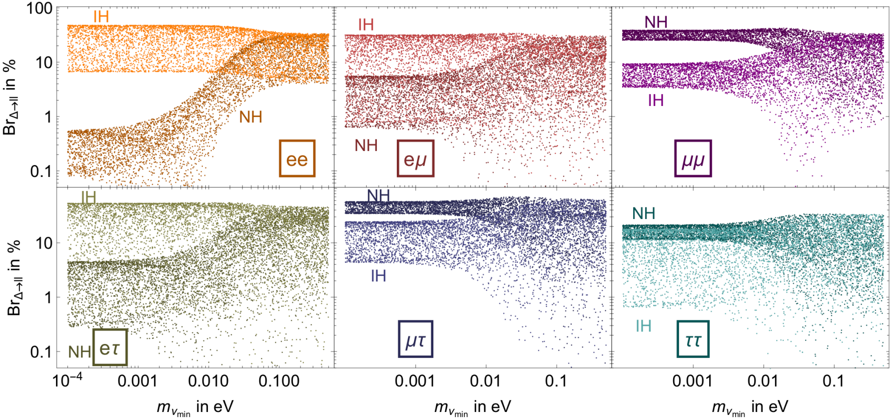
$$\ni -\frac{1}{2} \underbrace{\left(\sqrt{2} y_\Delta^{ij} v_\Delta\right)}_{= m_\nu^{ij}} \overline{\nu^{jc}} \nu^i$$

Fewer free parameters $\Longrightarrow$ richer experimental predictions

Fileviez Perez, Han, Li, et al, [0805.3536], Crivellin, et al [1807.10224], Fuks, Nemevšek, RR [1912.08975] + others

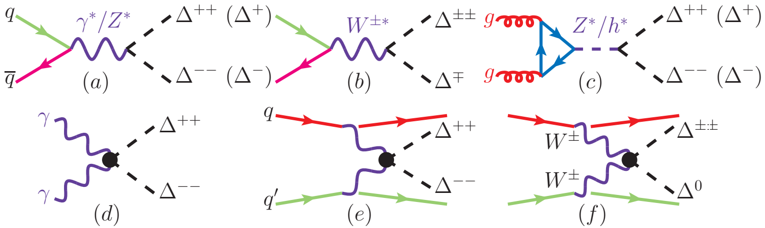
- E.g., Δ branching rates encode inverse (IH) vs normal (NH) ordering of light neutrino masses

$$\text{BR}(\Delta^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim y_\Delta^{ij} \sim (U^*_{\text{PMNS}}\tilde{m}_\nu^{\text{diag}}U^\dagger_{\text{PMNS}})_{ij}$$



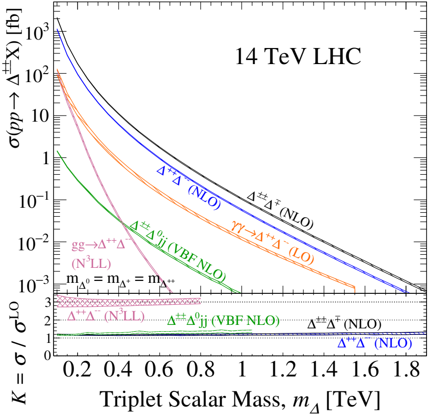
What is new? Two things.

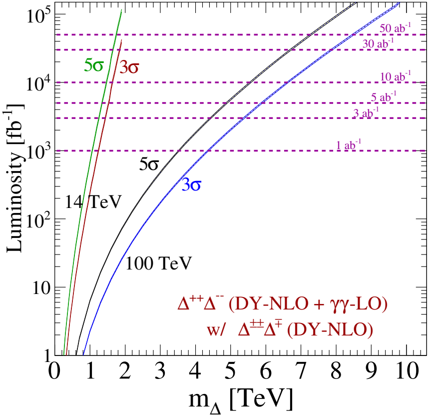
1. Modernization of MC tools and reassessing uncertatines



NEW: a revised outlook for both $\sqrt{s} = 14$ TeV and 100 TeV!

w / Fuks and Nemevšek [1912.08975]

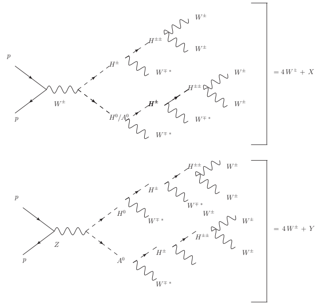


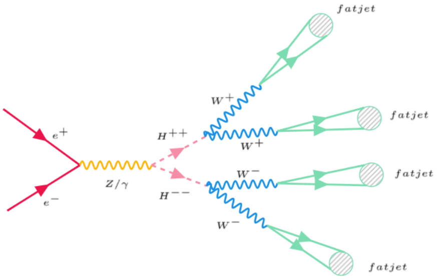


- At LHC with $\mathcal{L} = 5$ ab^{-1}, 3σ sensitivity up to $m_\Delta \sim 1.5$ TeV
- At $\sqrt{s} = 100$ TeV with $\mathcal{L} = 30 - 50$ ab^{-1} $\implies$ $m_\Delta \approx 8 - 9$ TeV
- **Warning**: can be improve for specialized final state / parameter space

2. Non-standard searches and new colliders[3]

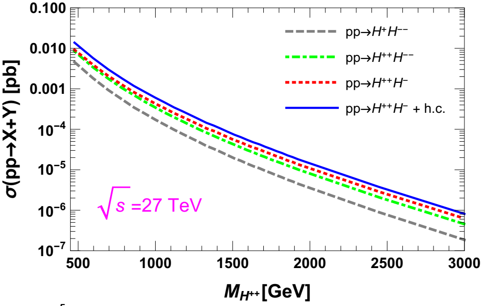
see also J. C. Vazquez's talk!

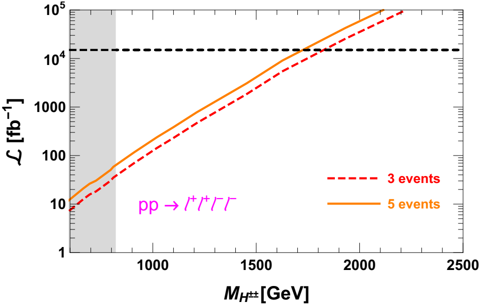




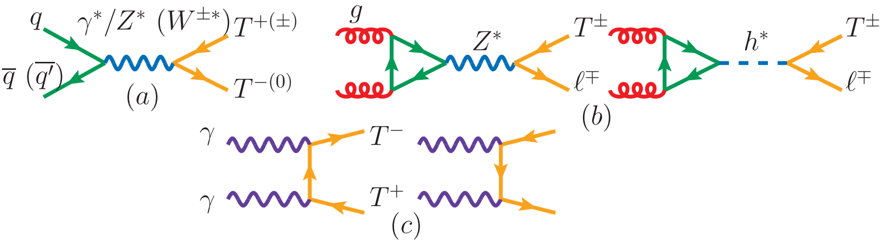
[3] Dev, M. Mitra, et al [1903.01431]; R. Padhan, M. Mitra, et al [1909.10495]; E.J. Chun, M. Mitra, et al [1911.00971]; + others

A peak at options beyond standard search modes and parameter regions





Type III Seesaw



Type III Seesaw combines main features of Types I and II Seesaws:

- **Idea:** add $SU(2)_L$ fermion triplet ($Y = 0$) with mass m_Σ
- Key to reconciling GUTs with proton decay E.g., Bajc, Senjanovic [hep-ph/0612029], ...

$$\mathcal{L}_{\nu \text{ Yuk.}} = -y_\Sigma \overline{L}\Sigma\Phi_{\rm SM} = -y_\Sigma \begin{pmatrix} \overline{\nu_L} & \overline{\ell_L} \end{pmatrix} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix} \begin{pmatrix} \langle \Phi_{\rm SM} \rangle + h \\ 0 \end{pmatrix}$$

$$= \underbrace{-y_\Sigma \langle \Phi_{\rm SM} \rangle}_{=m_D} \overline{\nu_L \Sigma^0} + \ldots$$

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Assuming that m_Σ (Majorana mass) $\gg y_\Sigma\langle\Phi\rangle$ (Dirac mass)

$$m_{\mathrm{light}} \approx y_\Sigma^2 v^2/2m_\Sigma, \quad m_{\mathrm{heavy}} \approx -m_\Sigma$$

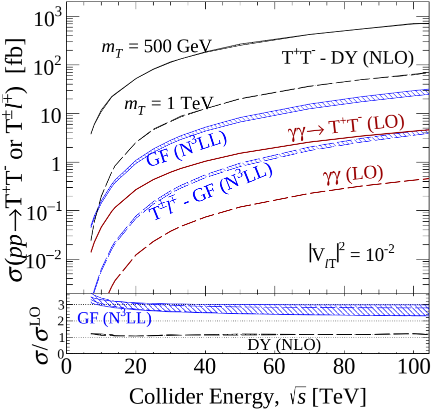
For $m_{\mathrm{light}} = 0.1$ eV, if $y_\Sigma \sim \mathcal{O}(y_e) \sim 1 \cdot 10^{-6}$, $m_{\mathrm{heavy}} \approx 300$ GeV!

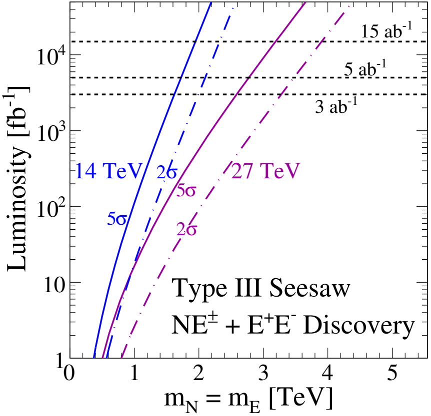
After rotating into the mass basis, mixing-induced cLFV:

$$|T^0\rangle = \cos\theta\ |\Sigma^0\rangle + \sin\theta\ |\nu_\ell\rangle \approx (1-\varepsilon^2/2)\ |\Sigma^0\rangle + \epsilon\ |\nu_\ell\rangle$$
$$|T^\pm\rangle = \cos\phi\ |\Sigma^\pm\rangle + \sin\phi\ |\ell^\pm\rangle \approx (1-\varepsilon^2/2)\ |\Sigma^\pm\rangle + \epsilon\ |\ell^\pm\rangle$$

Collider prediction: heavy charged ($T^{\pm}$) and neutral (T^0) leptons:

- Production through gauge couplings to W, Z, γ
- Decays to SM leptons through mixing, e.g., $T^{\pm} \to \ell^{\pm}\nu$





TeV-scale heavy charged and neutral leptons discoverable at LHC

Grand Unified Theories and

Theories with Gauged Lepton Number[4]

Arise when UV completing simplified Seesaw Models. No time! See backup and PFP's talk.

[4] Many, many omissions: e.g., SO(10), $U(1)_{B-L}$, etc

ν non-standard interactions / EFT

see T. Han's talk

Lots of improvement since last Snowmass. What has changed?

Improved outlook for collider tests of LNV and cLFV stems from:

- New channels, e.g., VBF, GF, $W/Z/h/\gamma$ associated production
- New kinematic limits, e.g., off-shell portals, boosted topologies
- Predictions for **both** Dirac and Majorana particles w/ LNV and cLFV
- Quantitatively reliable descriptions of jets, kinematics, and rates

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Part of this stems from improved MC support!

Now available: robust input libraries (FeynRules UFOs) for powerful, mainstream event generators, e.g., MadGraph5aMC@NLO, that saves time and standardizes results

- `HeavyN`: Dirac and Majorana N_k feynrules.irmp.ucl.ac.be/wiki/HeavyN
- Simplified LRSM: $W_R,\ Z_R,\ N_k$ feynrules.irmp.ucl.ac.be/wiki/EffLRSM
- $W'/Z'/\gamma_D/Z_D$ with arbitrary coup: feynrules.irmp.ucl.ac.be/wiki/WZPrimeAtNLO
- `TypeIISeesaw`: $\Delta^{\pm\pm},\ \Delta^{\pm},\ \Delta^0,\ \xi^0$ feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw
- ... with more in development (collaborators and friends are welcome!)

Open topics for the Snowmass process[5]

[5] Biased but professional opinions. Other topics exist, too!

Building on the ESU

Much was learned from the latest European Strategy Update

(indico.cern.ch/event/808335/timetable/)

- clarity lepton number violation; sensitivity to low- and high-mass, Dirac and Majorana N; viability of displaced vertex searches; importance of new production modes; new MC tools and recs.

How to build on the ESU?

Directions for the Snowmass process - RF4

Much was learned from the European Strategy Update

(indico.cern.ch/event/808335/timetable/)

How to build on the ESU?

- Displaced Vertices (I): Most (not all) work done in context of (Phenomenological) Type I Seesaw or LRSM. How about Type III? Type II? Loop models? Other gauge models? Hybrid models?
- Displaced Vertices (II): Most work done with non-standard cuts, PID, geometry. Results "optimistic" or hard to compare. How about community recommendations with PID, geometry, etc.?
- τ leptons: Most studies ignore τ leptons ☹ (complicated but not impossible to model) and sensitivity projections are needed

remember: τ-mixing least constrained, e.g., Parke and Ross-Lonergan [1508.05095]

Directions for the Snowmass process - RF4 (con't)

How to build on the ESU?

- ν NSI/EFTs: Growing in popularity and interest. Studies on comparative sensitivity as done for Higgs and top in SMEFT helpful.

see T. Han's talk

- LNV vs cLFV: Comparative studies often treat LNV and cLFV constraints on same footing, e.g, exclusions from $\ell^\pm\ell^\pm$ vs $3\ell\nu$. Some global comparisons need updates to resolve inconsistencies

- New colliders (I): FCC-ee and FCC-hh are officially priorities (TDR due by next ESU in 2030s). Projections now steer discussions later

- New colliders (II): ILC (complement to FCC) and muon collider (competitor) remain serious options. More projections needed.

- New colliders (III): Projections needed for BNL's Electron Ion Collider

Summary

Summary

Lack of clear guidance from data and theory means we must take a broad, open approach to uncovering the origin of tiny ν masses.

- Colliders are *incredibly complementary* to oscillation facilities:
  - Direct production of Seesaw particles
  - Test UV realizations of low-scale neutrino EFTs / NSIs

- e^+e^- and DIS machines explore new depths for light N
  - Searches for $\mathcal{B}, \tau \to N + X$, $Z \to N\nu$, $h \to NN$
  - Baseline luminosities at $\sqrt{s} = 240$ GeV sufficient to go beyond LHC

- pp machines explore both energy and intensity frontiers:
  - New analysis techniques $\implies$ new territory for cLFV and LNV at LHC
  - N, $H^{\pm\pm}$, Z_{B-L}, $T^{0,\pm}$ masses up to 10-15 TeV scale at $\sqrt{s} = 100$ TeV

- Studies aided by publication of user friendly simulation tools
  - Saves time and standardizes results across hep-th/-ph/-ex communities

Summary (con't)

Lack of clear guidance from data and theory means we must take a broad, open approach to uncovering the origin of tiny ν masses.

- The **European Strategy Update** has officially concluded
  - Lots of encouraging projections on collider sensitivity to LNV and cLFV
  - Lots not covered todays, but plenty of review documents, e.g., [1711.02180]
- The **Snowmass Process** has officially started
  - Community studies are iterative processes and pleanty to do for Snowmass - Rare Processes Frontier 4
- Be encouraged! More data soon.
  - Let's get to work and prepare for a discovery!

Thank you.

Backup

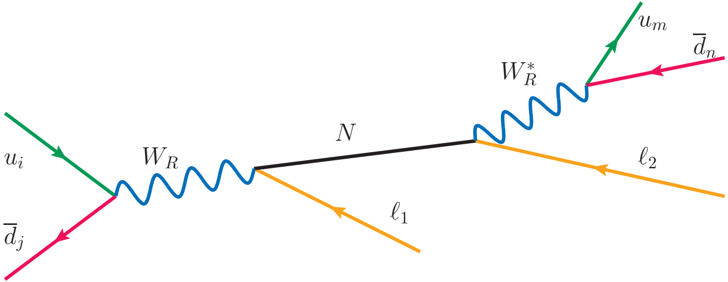
Grand Unified Theories and

Theories with Gauged Lepton Number[6]

[6] Many, many omissions: e.g., SO(10), $U(1)_{B-L}$, etc

Gauged Left-Right Parity

[Pati, Salam, Mohapatra, Senjanovic, etc., ('74-'79)]



Left-Right Symmetric Model

LRSM asks what is the origin of $(V - A)$ structure in the SM?

- Why is nature weird and differentiates between LH and RH particles?

Idea: suppose nature was once parity symmetric:

$$\mathcal{G} = \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \otimes \mathcal{P}_{LR}$$

- Ask about parity and automatically learn about $B - L$!
- Larger Higgs sector needed to breakdown "right-handed" sector to SM
- Light neutrino masses are complicated

$$m^{\nu}_{\text{light}} = \underbrace{y_L \langle \Delta_L \rangle}_{\text{Type II}} - \underbrace{\left(y_D y_R^{-1} y_D^T \right) \langle \Phi \rangle^2 \langle \Delta_R \rangle^{-1}}_{\text{Type I a la Type II}}$$

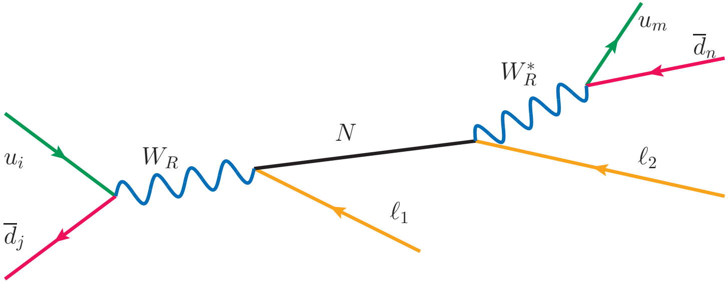
Collider predictions: Majorana N, Z_R, W_R guage bosons, Type II Scalars

- All enable collider-scale LNV and cLFV

Hallmark Collider Test: Searching for $pp \to W_R^{\pm} \to N\ell^{\pm} \to \ell^{\pm}\ell^{\pm}jj$

Keung, Senjanovic PRL('83)

- **Signature**: same-sign $\ell_1^{\pm}\ell_2^{\pm}$+2j+ no MET, with $p_T^{\ell,j} \gtrsim \mathcal{O}(M_{W_R})$



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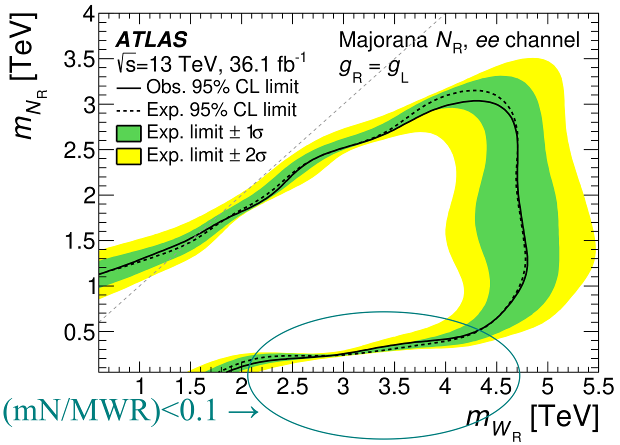


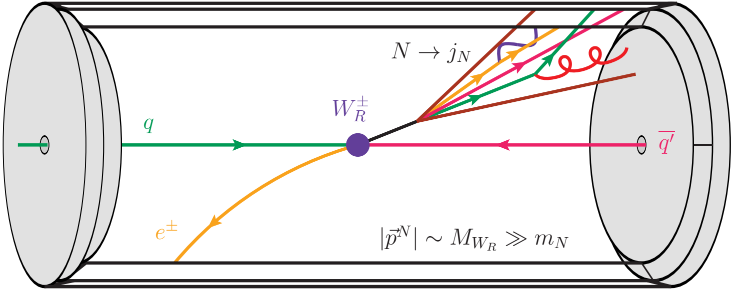
For $(m_N/M_{W_R}) \ll 1$, i.e., boosted N, searches are losing sensitivity!

For a $1 \to 2$ decay, $m_{ij}^2 = (p_i + p_j)^2 \approx 2E_iE_j(1-\cos\theta_{ij}) \approx E_iE_j\theta_{ij}^2$

$$\Rightarrow \text{Angle between } e \text{ and } (q\overline{q'})\text{-system} = \theta_{e(q\overline{q'})} \sim \frac{m_N}{\sqrt{E_iE_j}} \sim \frac{4m_N}{M_{W_R}}$$

As (m_N/M_{W_R}) shrinks, N is more boosted, and its decay *more collimated:*

For $\left(\frac{m_N}{M_{W_R}}\right) < 0.1, \theta_{e(q\overline{q'})}$ falls below det. isolation threshold, $\theta_{\ell X}^{\min} = 0.4$

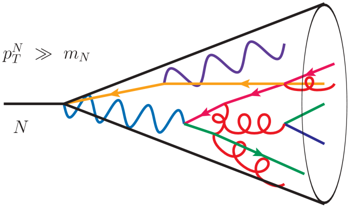


Fun Idea: Why not treat second $e^{\pm}$ like any other poorly isolated particle bathed in QCD radiation and label it as constituent of a jet?

w/ Mitra, Scott, Spannowsky, PRD ('17) [1607.03504], w/ Mitra, Mattelaer [1607.03504]

Left-Right Symmetric Model and $SM \otimes U(1)_{B-L}$

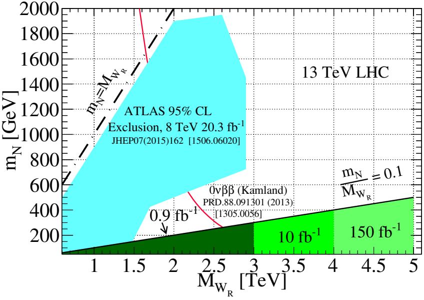
Like boosted t, treat decays of boosted N as a single ***neutrino jet*** (j_N)

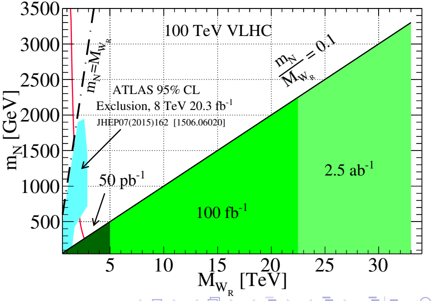


j_N sensitivity (green) is precisely where current $\ell\ell jj$ searches exclusion (blue) stop

Mitra, RR, Scott, Spannowsky + w/ Mattelaer [1607.03504; 1610.08985]

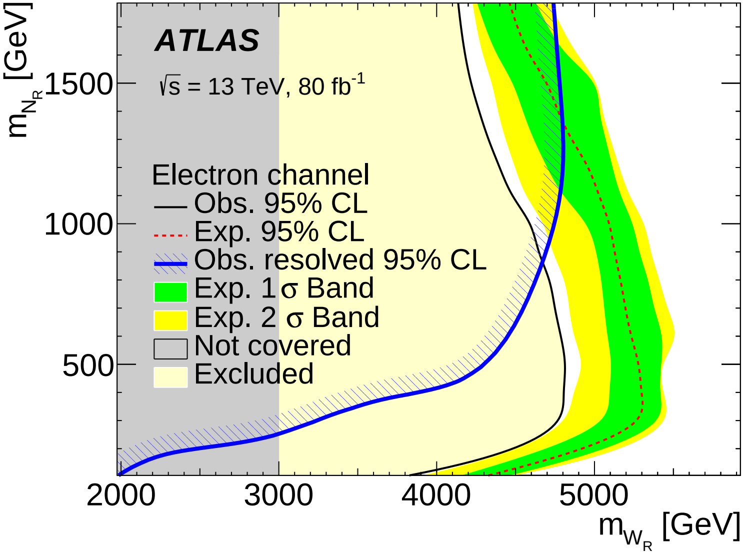
W_R sensitivity recovered and can reach $5 - 6$ $(35 - 45)$ TeV at $\sqrt{s} = 14$ (100) TeV





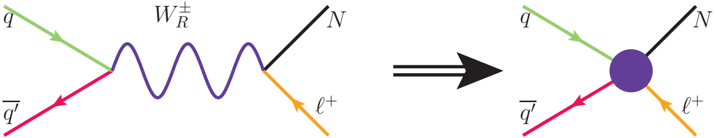
Neutrino Jets at ATLAS

New: search for $pp \to \ell^{\pm} j_N + X$ at ATLAS [1904.12679]



Can a gauge boson be too heavy for the LHC?

If new gauge mediators are too heavy, light N are still accessible



When $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N\ell + X$ production in the LRSM and minimal Type I Seesaw are not discernible

Han, Lewis, RR, Si, [1211.6447]; RR, [1703.04669]

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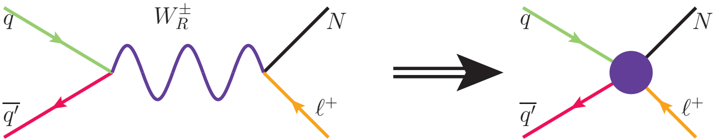
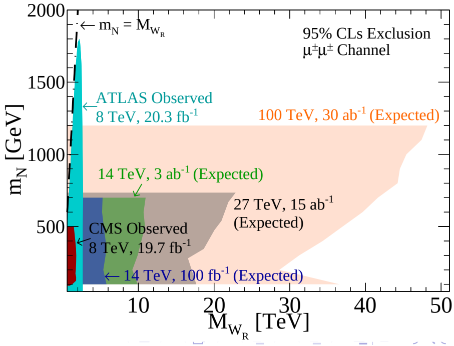


When $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N\ell + X$ production in the LRSM and minimal Type I Seesaw are not discernible

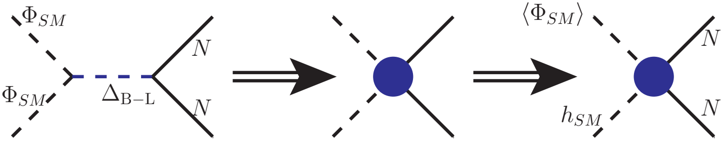
- **Signature:** $pp \to \ell^\pm \ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N) +$ no MET
- At 14 (100) TeV with $\mathcal{L} = 1$ (10) ab^{-1}, $M_{W_R} \lesssim 9$ (40) TeV probed
- **DO NOT STOP SEARCHING FOR HEAVY MAJORANA N**

Han, Lewis, RR, Si, [1211.6447]; RR, [1703.04669]



LNV at Higgs Factories

If Higgs that breaks $U(1)_{B-L}$ is too heavy, light N are still accessible



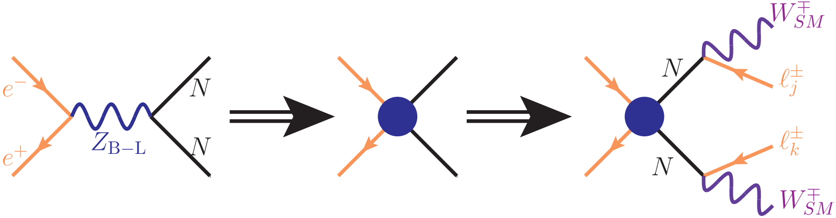
SM-invariant effective field theories with sterile neutrinos exist!

- Heavy Neutrinos EFT (NEFT) — Aparici, et al [0904.3244]

$$\mathcal{L}_{\rm NEFT} = \mathcal{L}_{\rm Type\ I} + \sum_5 \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)}, \qquad \mathcal{O}_S^{(5)} = \left(\Phi^\dagger_{\rm SM}\Phi_{\rm SM}\right)\left(\overline{N_R^c} N_R\right)$$

One subtlety: N_R here is *chiral/interaction* state — RR [1703.04669]

- Must decompose into mass basis: $N_R = \sum X_{\ell m}\nu_m + \sum Y_{\ell m'} N_{m'}$
- After EWSB, NEFT operators map onto light neutrino NSI operators!
- Can mediate $h_{\rm SM} \to NN$ decays! — See, e.g., Caputo, et al [1704.08721]



- If ν are Majorana, is (B-L) broken spontaneously?
- If Z_{BL} gauge boson of $U(1)_{B-L}$ is too heavy, LNV is still accessible
- For $g_{BL} = g_W \approx 0.65$, LNV territory beyond LHC reach accessible at Higgs factory!