Indirect HNL searches at ATLAS

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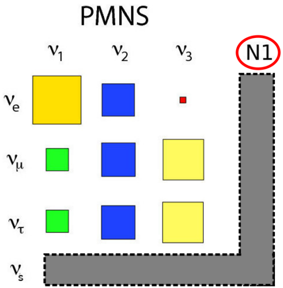
"New-ν Physics:
From Colliders to Cosmology"

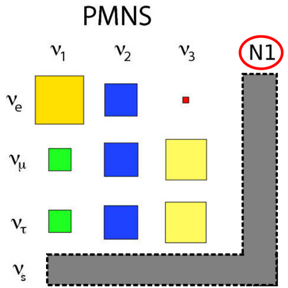
Durham (UK) – April 10, 2025

HNL production at the LHC



- **Heavy Neutral Lepton (HNL) = heavy, sterile, Majorana neutrino**
  - seesaw mechanism $\rightarrow$ neutrino mass
  - zero coupling $\rightarrow$ dark matter
  - CP violation $\rightarrow$ baryon asymmetry

HNL production at the LHC



The LHC is an **everything** factory

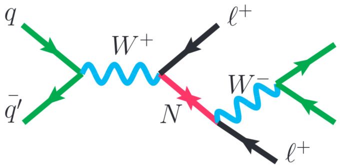
Particle	Produced in 140 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.8 million	
Top quark	275 million	
Z boson	8 billion	($\rightarrow \ell\ell$, 270 million per flavour)
W boson	26 billion	($\rightarrow \ell\nu$, 2.8 billion per flavour)
Bottom quark	~160 trillion	(significantly reduced by acceptance)

source

- **Heavy Neutral Lepton (HNL) = heavy, sterile, Majorana neutrino**
  - seesaw mechanism $\rightarrow$ neutrino mass
  - zero coupling $\rightarrow$ dark matter
  - CP violation $\rightarrow$ baryon asymmetry
- **At LHC, can be singly produced in the numerous W decays**
  - but also in: Z, Higgs, mesons and τ decays

Signal models

HNL predicted in many models $\rightarrow$ benchmarks defined



- **'Minimal',** ex: phenomenological type-I seesaw, $\rightarrow$ **used for direct + indirect searches**
  - HNLs + mass mixing parameters
  - relevant new particles: 1 HNL (typically others set to large mass)
  - relevant parameters: m_N, $V_{\ell N}$ (typically one flavor considered)

Signal models

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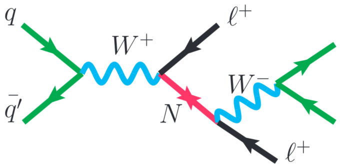

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  - HNLs + mass mixing parameters
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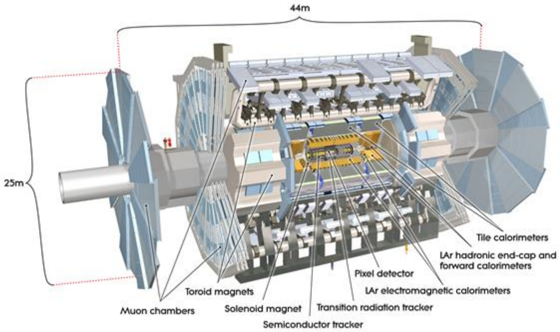
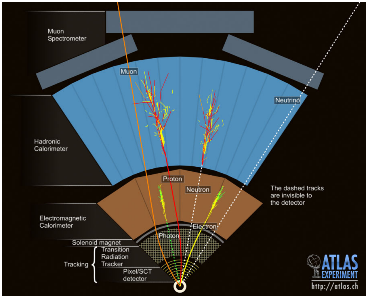
- ‘UV complete’, ex: left-right symmetric models, $\rightarrow$ **this afternoon (‘Direct Searches’ talk)**

The ATLAS detector at the LHC



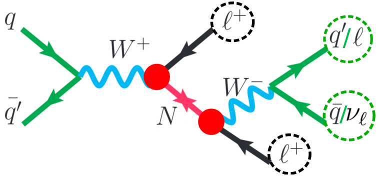
Particle identification



- Recording of LHC proton-proton collisions at $\sqrt{s}$ = 13 TeV
- Very large dataset collected during **Run 2 (2015-2018)**
  - 139 fb^{-1} available $\rightarrow$ 7.8M Higgs, 275M top quarks, 8000M Z bosons, ...
- Multi-purpose, **high efficiency/acceptance detector**

Experimental signatures at ATLAS and CMS (1/2)

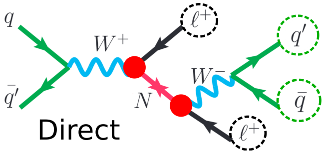
‘Direct’ search at the LHC

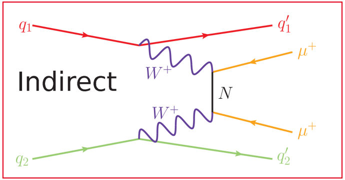


- **Final state:** ‘2 same-sign leptons + 2 jets’ **or** ‘3 leptons’ (if $W \to \ell\nu$)
- ! More about this this afternoon (‘direct searches’ talk)

Experimental signatures at ATLAS and CMS (2/2)

'Indirect' search at the LHC (**high m_N**)





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  - but different topology: forward jets (closer to beam axis) well separated in η

Experimental signatures at ATLAS and CMS (2/2)

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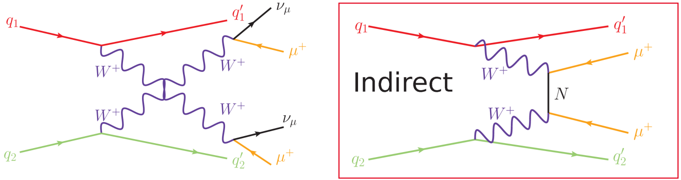
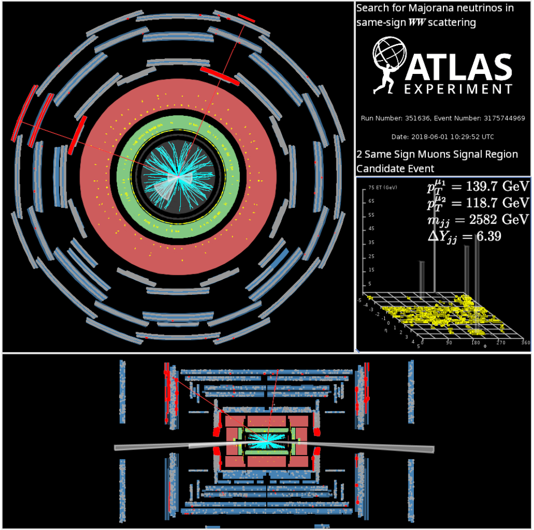


- **Final state is similar:** '2 same-sign leptons + 2 jets'
  - but different topology: forward jets (closer to beam axis) well separated in η
- **Realization of the $0\nu\beta\beta$ process in high-energy proton collisions**
  - irreducible background: same-sign *WW* scattering
- **Topic of this talk!**

Event display

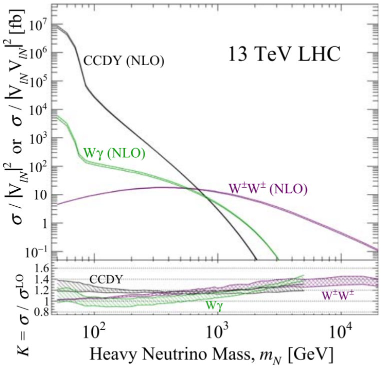


- Candidate signal event in 2018 data
- 2 same-sign muon + 2 jets
- 2 jets well-separated in η (vector boson fusion topology)

Eur. Phys. J. C 83 (2023) 824

HNL production at the LHC vs m_N for $V_{\ell N}^2$=1

Phys. Rev. D103, 055005 (2021)



- **'Direct' production diagram** dominates for $m_N < 800$ GeV or so
- **'Indirect' production diagram** dominates at higher mass
- But scales as $V_{\ell N}^4$ (vs $V_{\ell N}^2$ for direct!)

$$\sigma(pp \to \mu^\pm\mu^\pm + X) \equiv |V_{\mu N}|^4 \times \sigma_0(pp \to \mu^\pm\mu^\pm + X)$$

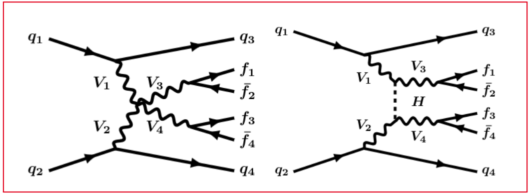
- Direct production diagram eventually larger at smaller $V_{\ell N}^2$

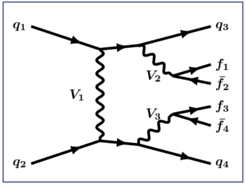
Related ATLAS results

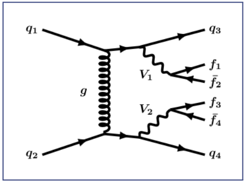
- **Measurement of same-sign W boson pair production in association with two jets**
  - full Run 2, JHEP 04 (2024) 026
- **Search for heavy Majorana neutrinos in same-sign WW scattering events ($\mu\mu$)**
  - full Run 2, Eur. Phys. J. C 83 (2023) 824
- **Search for heavy Majorana neutrinos in same-sign WW scattering events ($e\mu$, ee)**
  - full Run 2, Phys. Lett. B 856 (2024) 138865

ATLAS same-sign WW analysis

JHEP 04 (2024) 026



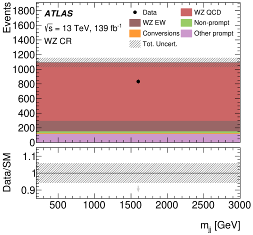




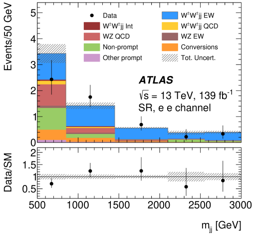
- **Rare, irreducible background** of the HNL search
- Complex interplay of EW production (VBF and non-VBF) and QCD production
- Selection of **2 same-sign leptons, 2 jets** with $m_{jj} > 500$ GeV and $|\Delta y_{jj} > 2|$
- **Requires $E_T^{miss} > 30$ GeV** (neutrinos) $\rightarrow$ large suppression of any possible HNL signal

WZ background

WZ CR pre-fit



ssWW SR post-fit (ee)



- **Dominant background:** *WZ* with 1ℓ out of acceptance
- WZ modeling constrained in 3ℓ control region
  - rest of selection essentially same as SR
- $\boldsymbol{\mu^{\mathrm{QCD}}_{\mathrm{WZjj}}}$ **= 0.67 ± 0.07**, consistent w/ other ATLAS measurements (1,2)

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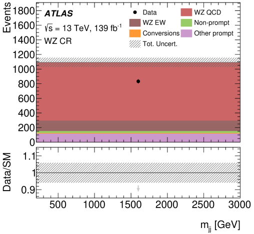

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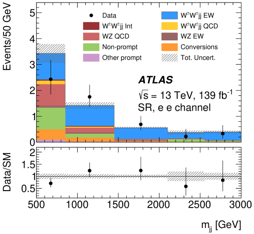
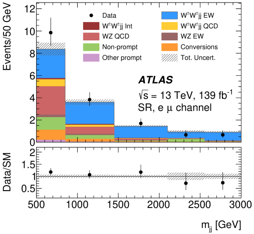
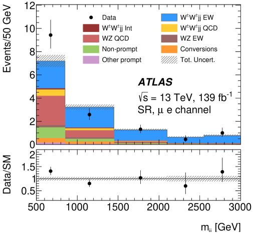
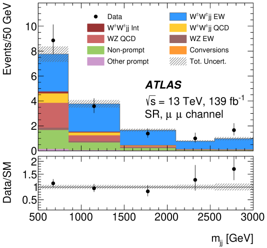


SRs post-fit for other lepton channels: $\mu\mu$, $e\mu$, μe







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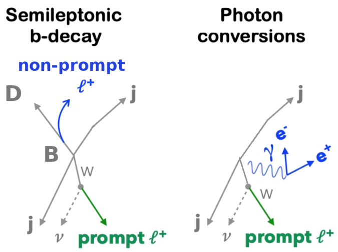
Background from non-prompt leptons



- **2nd largest background,** mostly from $t\bar{t}$ and W+jets
- 1 lepton not originating from W, Z or (prompt) HNL decays
  - dominated by heavy flavor hadron decays
  - fake electrons also include
    - hadronic jets
    - photon conversions

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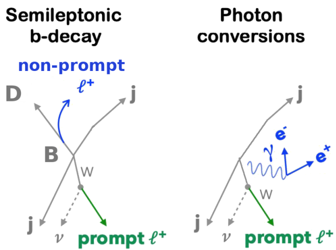

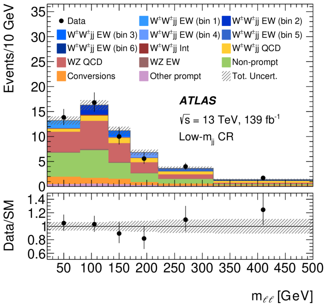

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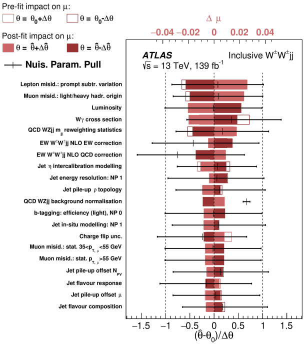
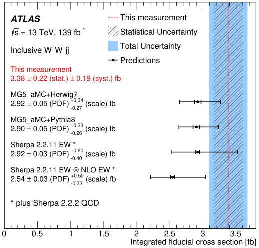
- Data-driven evaluation (normalisation + shape)
- Based on transfer factors derived in bkg-dominated 1ℓ regions
- Validated in low m_{jj} control region

ATLAS same-sign WW measurements



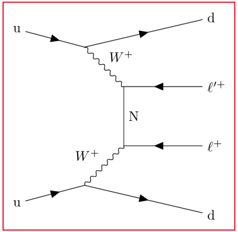


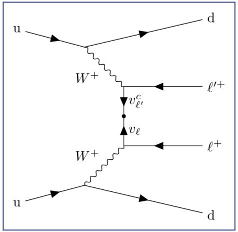
Variable	EW $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	EW $W^{\pm}W^{\pm}jj$ p-value	Inclusive $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	Inclusive $W^{\pm}W^{\pm}jj$ p-value	Max. value in data
$m_{\ell\ell}$	4.5/6	0.605	7.34/6	0.291	1081 GeV
m_{T}	13.0/6	0.043	16.33/6	0.012	1270 GeV
m_{jj}	7.6/6	0.266	8.67/6	0.193	6328 GeV
$N_{\text{gap jets}}$	2.5/2	0.282	2.53/2	0.282	5
ξ_{j3}	4.2/5	0.517	4.93/5	0.424	1.74

- **Overall good agreement with SM**
- $\mu_{\mathrm{sig}}^{\text{EW+Int+QCD}} = 1.16 \pm 0.08$ (stat) ± 0.04 (mod. syst.) ± 0.05 (exp. syst.) ± 0.02 (lumi.)
- Results also available for $\mu_{\mathrm{sig}}^{\mathrm{EW}}$, differential cross sections measured, EFT fits, H++ search, ...

ATLAS searches for heavy Majorana ν in ssWW

$\mu\mu$: Eur. Phys. J. C 83 (2023) 824   *ee*, $e\mu$: Phys. Lett. B 856 (2024) 138865

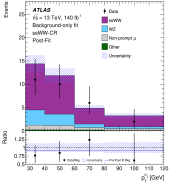




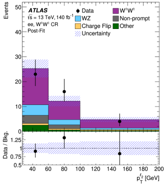
- Essentially the ssWW measurement w/ reoptimised cuts for HNL search
  - optimised for Type-I seesaw, but interpreted also using the d=5 Weinberg operator
- Selection of **2 same-sign leptons, 2 jets** with $m_{jj} > 500$ GeV and $|\Delta y_{jj} > 2|$
  - $m_{jj} > 300$ GeV and $|\Delta y_{jj} > 4|$ for $\mu\mu$
- **Requires low E_T^{miss} significance** (no neutrino) in $\mu\mu$ and *ee* channels
  - large $\Delta\phi_{e\mu}$ used instead in $e\mu$

ssWW searches: analysis strategy

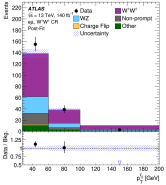
ssWW CR post-fit ($\mu\mu$)



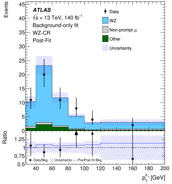
(ee)



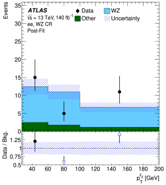
($e\mu$)



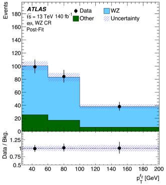
WZ CR post-fit ($\mu\mu$)



(ee)



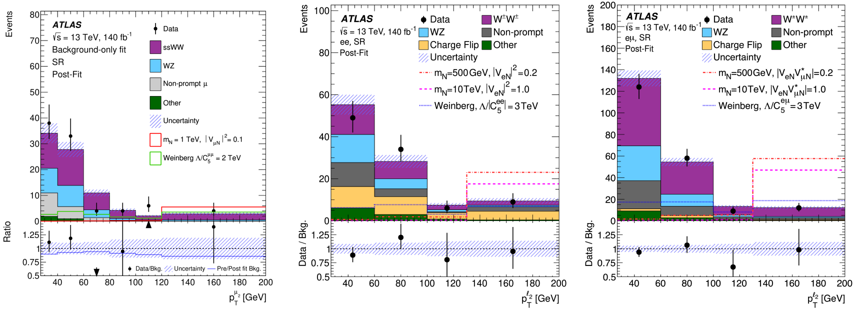
($e\mu$)



- **Final discriminating variable:** subleading lepton p_T
- **Main backgrounds:** ssWW (EW) and WZ (QCD), constrained in control regions
  - ssWW: requiring large E_T^{miss} ($\Delta\phi_{e\mu}$ in $e\mu$) $\rightarrow$ $\mu_{ssWW} \sim 1.15 - 1.25$
  - WZ: requiring 3ℓ $\rightarrow$ $\mu_{WZ} \sim 0.65 - 0.9$ all compatible w/ ssWW ATLAS measurement
- **Other background:** charge flipped electrons (ee) and non-prompt (ee, $e\mu$)
  - estimation similar to ssWW

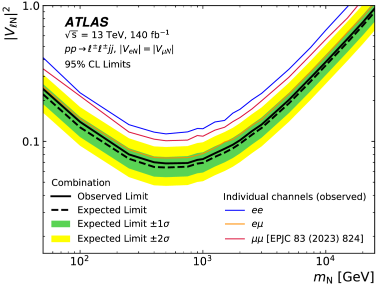
ssWW searches: results

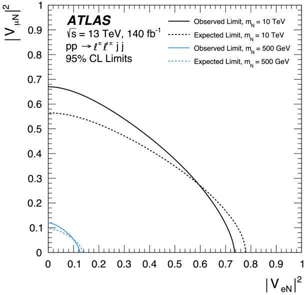
SR post-fit ($\mu\mu$) (ee) ($e\mu$)



- **No excess,** very good agreement with the post-fit SM predictions
- Final results formulated as exclusion limits in (m_N, $V_{\ell N}$) for Type-I seesaw and on the Wilson coefficient matrix of the Weinberg operator

ssWW searches: exclusion

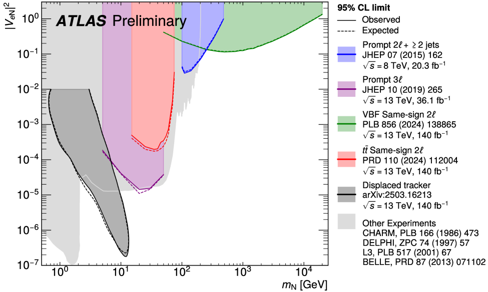


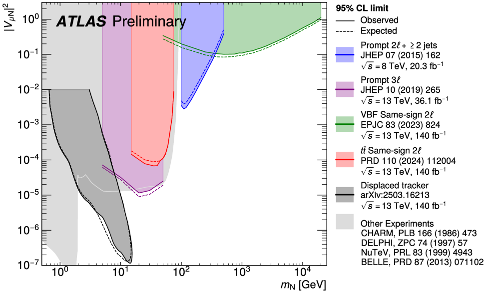


- **Limits set up to m_N = 20 TeV** but only down to $V^2_{\ell N} = \mathcal{O}(0.1)$
  - *ee* and $\mu\mu$ set limits on single flavour, whereas $e\mu$ sets limits on $|V_{eN}V^*_{\mu N}|$
- **Limits on Weinberg operator:** $\Lambda/C_5 > 4.9$ TeV ($e\mu$), 3.6 TeV ($\mu\mu$) and 2.5 TeV (ee)
  - which translate to $|m_{e\mu}| < 12$ GeV, $|m_{\mu\mu}| < 17$ GeV and $|m_{ee}| < 24$ GeV
- **Limits stat-dominated,** selection efficiency dominated by:
  - muon reconstruction at high p_T AND central electron requirement (to reduce the charge flip background)

ATLAS summary plots (electrons & muons)

ATL-PHYS-PUB-2025-008 electron mixing muon mixing





- **Colliders** currently provide strongest direct constraints for $m_N > m_K$
- **Unique sensitivity of ATLAS and CMS for $m_N > m_Z$**
  - some analyses still in progress
- LEP sensitivity is / will be exceeded by LHC by the end of Run 3 (electrons and muons)

Summary & Outlook

- **HNL searched in ATLAS at very high m_N in a new channel** (same-sign WW scattering)
  - realization of the $0\nu\beta\beta$ process in high-energy proton collisions
- **No excess observed, limits set up to m_N = 20 TeV** but only down to $V_{\ell N}^2 = \mathcal{O}(0.1)$
  - sensitivity limited by data statistics
  - other limiting factors: muon reconstruction efficiency at high p_T and the fact that only central electrons are considered
- **These searches will benefit from the additional Run 3 data**
- **Some interests to explore tau channels**

Thank you for your attention

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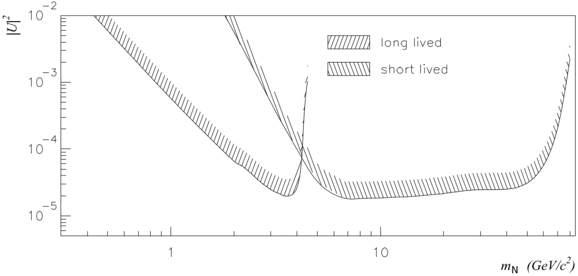
Current sensitivity: the LEP1 legacy (Type-I seesaw)

Z. Phys. C 74, 57–71 (1997)



$$N \to \nu\, Z^* \hookrightarrow \nu\bar{\nu}, \ell\bar{\ell}, q\bar{q}$$

$$N \to \ell'\, W^* \hookrightarrow \nu\bar{\ell}, q\bar{q}'$$

- **Search for HNL in $Z \to N\nu$ decays at LEP1** (stat $\sim$ 3.3M hadronic decays!)
  - 👎 limits only for $m_N < m_Z$ 👍 but apply for mixing to all 3 flavours
- **Four decay topologies studied, no excess observed**
  - $\nu\nu\bar{\nu}$, $\nu\ell\bar{\ell}$, $\nu q\bar{q}$, $\ell q\bar{q}'$,
  - short-lived and long-lived signatures (up to 10m!)

Indirect constraints above the electroweak scale

JHEP08 (2016) 033

$$\sqrt{2|\eta_{ee}|} < 0.050, \quad \sqrt{2|\eta_{e\mu}|} < 0.026,$$
$$\sqrt{2|\eta_{\mu\mu}|} < 0.021, \quad \sqrt{2|\eta_{e\tau}|} < 0.052,$$
$$\sqrt{2|\eta_{\tau\tau}|} < 0.075, \quad \sqrt{2|\eta_{\mu\tau}|} < 0.035,$$

$$\sqrt{2|\eta_{\alpha\beta}|} = \sum_i \sqrt{\Theta_{\alpha i}\Theta^*_{\beta i}}$$

- **Example of global fit with 28 observables** (μ and Z decays, CKM unitarity, ...)
- **Strong limits above the electroweak scale: mixing $<$ few 10^{-2} for all flavors at 95% CL**
  - e.g. for 1 HNL mixing only with muons: $|U|^2 < 4 \cdot 10^{-4}$
- **However, results are model-dependent**
  - limits can be relaxed in more complicated scenarios