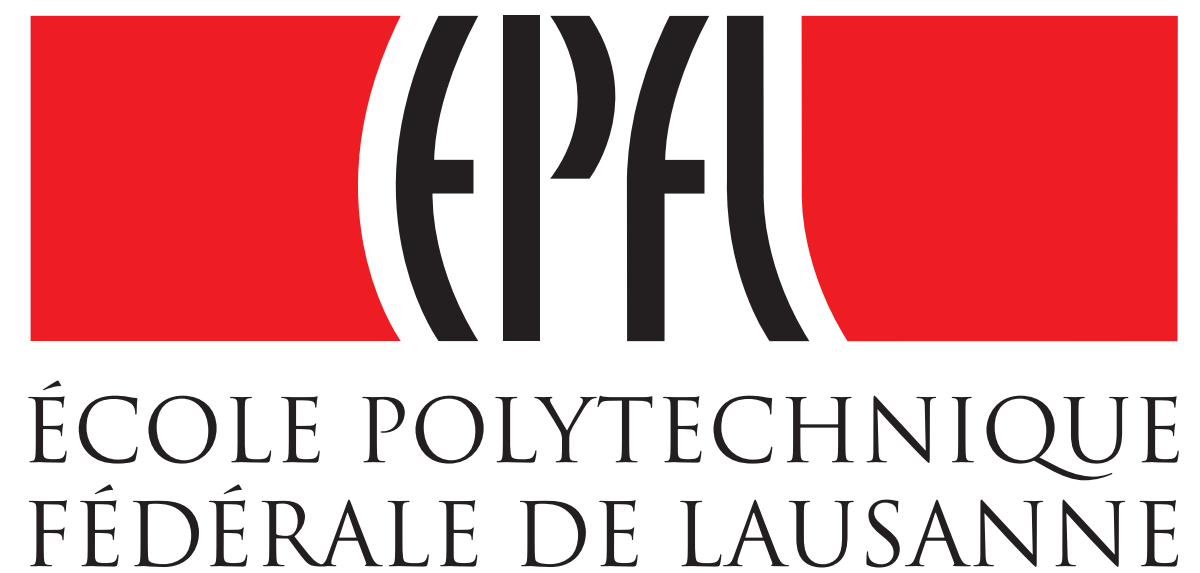
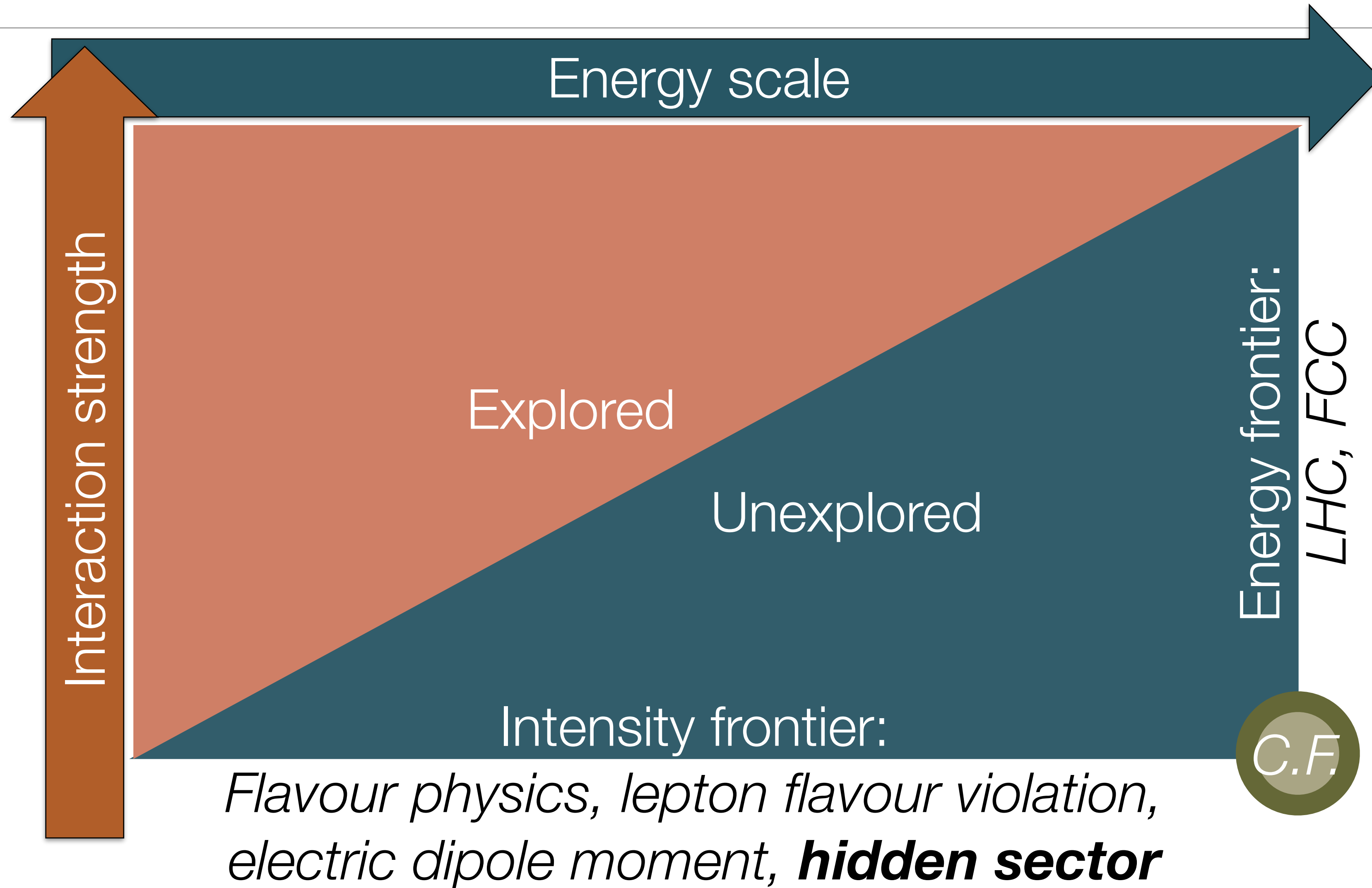


HNL in LLP searches at LHC

WG summary





Landscape today / 1

- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **dark sectors** and **lepton flavour violation** in τ .
- **Landscape**: LHC results in brief:
 - Direct searches for **NP** by **ATLAS** and **CMS** have not been successful so far
 - Parameter space for popular **BSM** models is **decreasing rapidly**, but only $< 5\%$ of the complete HL-LHC data set has been delivered so far
 - NP discovery **still may happen!**
 - **LHCb** reported intriguing hints for the violation of lepton flavour universality
 - In $b \rightarrow c\mu\nu$ / $b \rightarrow c\tau\nu$, and in $b \rightarrow se+e-$ / $b \rightarrow s\mu+\mu-$ decays
 - **Clear evidence of BSM** physics if substantiated with further studies (possibly by **BELLE II**)

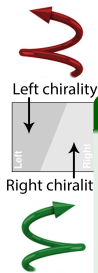
What happened

- 0) Monday 13:30: Plenary introductory by **Oliver**
- 1) Monday 16:00: Plenary introductory talks from Kyrilo **Bondarenko** and Martina **Vit**
- 2) Tuesday morning: Zhen **Liu**, Jan **Hajer**, Philippe **Mermod**, Haifa **Sfar**, and Sonia **Bouchiba**
- Thanks to all the speakers! And to all the people that participated!

Why heavy neutral leptons

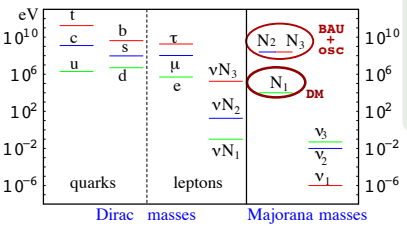
Heavy neutral lepton = HNL = sterile neutrino = heavy Majorana neutrino

2.4 MeV $\frac{2}{3}$ Left u up Right	1.27 GeV $\frac{2}{3}$ Left c charm Right	171.2 GeV $\frac{2}{3}$ Left t top Right
4.8 MeV $-\frac{1}{3}$ Left d down Right	104 MeV $-\frac{1}{3}$ Left s strange Right	4.2 GeV $-\frac{1}{3}$ Left b bottom Right
<0.0001 eV Left ν_e electron neutrino Right	\sim keV Left N_1 sterile neutrino Right	\sim GeV Left N_2 sterile neutrino Right
<0.0001 eV Left ν_μ muon neutrino Right	\sim keV Left N_2 sterile neutrino Right	\sim GeV Left N_3 sterile neutrino Right
<0.0001 eV Left ν_τ tau neutrino Right	\sim keV Left N_2 sterile neutrino Right	\sim GeV Left N_3 sterile neutrino Right
0.511 MeV Left e electron Right	105.7 MeV Left μ muon Right	1.777 GeV Left τ tau Right



HNL can explain ...

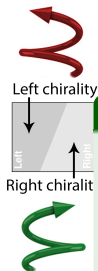
- ... neutrino oscillations
Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79;
Mohapatra & Senjanovic'80; Schechter & Valle'80
- ... Baryon asymmetry
Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05-
- ... Dark matter
Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+;
Asaka, Shaposhnikov, Laine'06 -



Why heavy neutral leptons

Heavy neutral lepton = HNL = sterile neutrino = heavy Majorana neutrino

	2.4 MeV $\frac{2}{3}$ Left u Right up	1.27 GeV $\frac{2}{3}$ Left c Right charm	171.2 GeV $\frac{2}{3}$ Left t Right top
Quarks	4.8 MeV $-\frac{1}{3}$ Left d Right down	104 MeV $-\frac{1}{3}$ Left s Right strange	4.2 GeV $-\frac{1}{3}$ Left b Right bottom
	<0.0001 eV 0 Left e Right electron	~ 0.01 eV 0 Left ν_μ Right muon neutrino	~ 0.04 eV 0 Left ν_τ Right tau neutrino
	$\sim \text{keV}$ sterile neutrino N ₁	$\sim \text{GeV}$ sterile neutrino N ₂	$\sim \text{GeV}$ sterile neutrino N ₃
Leptons	0.511 MeV -1 Left e Right electron	105.7 MeV -1 Left μ Right muon	1.777 GeV -1 Left τ Right tau



HNL can explain ...

- ... neutrino oscillations

Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79;

Mohapatra & Senjanovic'80; Schechter & Valle'80

- ... Baryon asymmetry

Fukuzita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis &

HNL can explain all of it

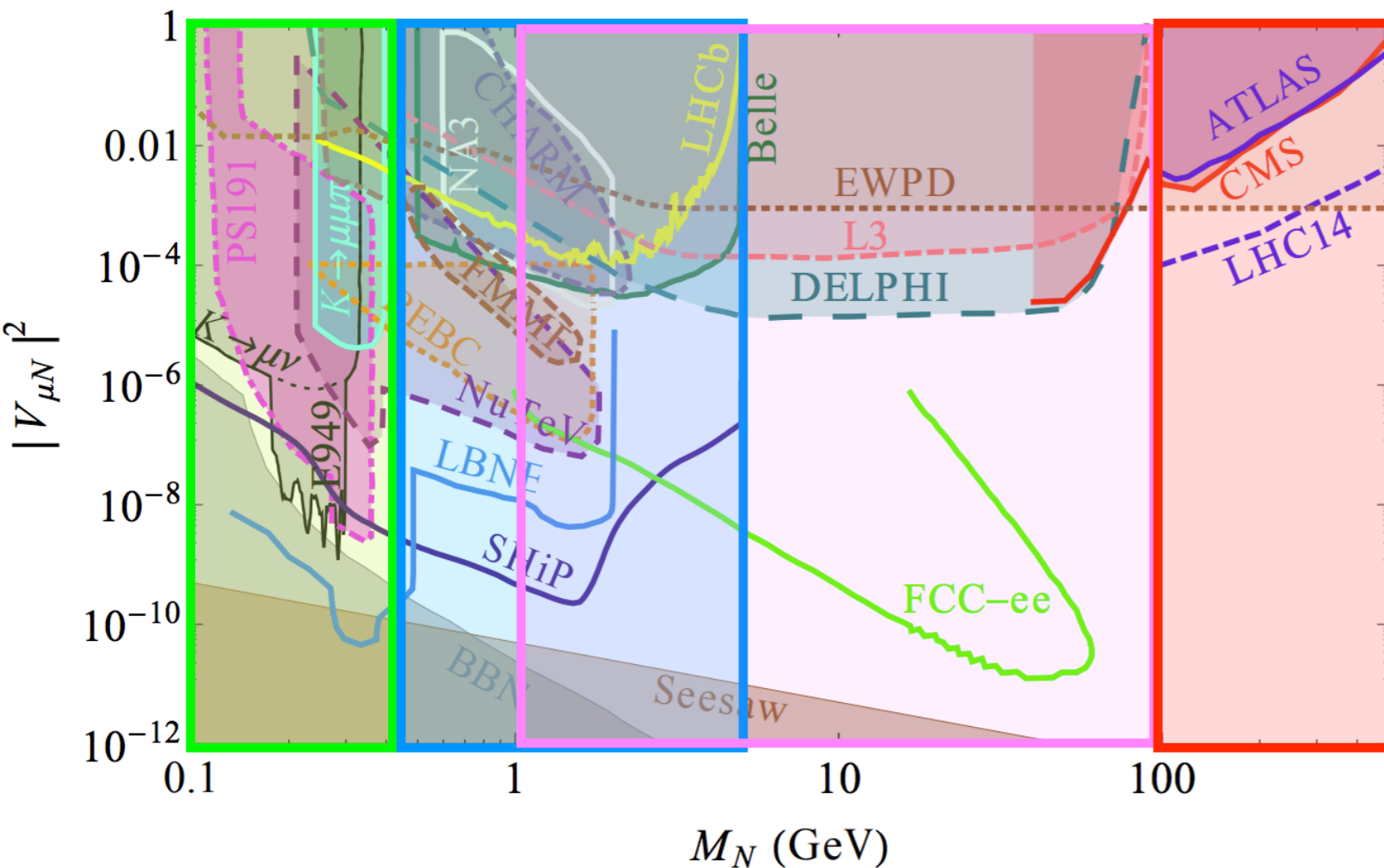
- Neutrino Minimal Standard Model (ν MSM)

Asaka & Shaposhnikov'05 + ... hundreds of subsequent works

- Masses of HNL are of the order of masses of other leptons

- Reviews: Boyarsky, Ruchayskiy, Shaposhnikov *Ann. Rev. Nucl. Part. Sci.* (2009), [0901.0011]

Direct searches: state and projections



- $m_N > m_Z$
- LHC can exceed the limits from electroweak precision data

- $m_N < m_Z$
- Results from LEP ($Z \rightarrow \nu N$)
- Currently explored at the LHC (ATLAS, CMS)

- $m_N < m_K$
- Using K decays, such as $K^\pm \rightarrow \ell N$, $K^\pm \rightarrow \mu\mu\pi$
- E.g. NA62

- $m_N < m_{D,B}$
- Explored at colliders (e.g. Belle, LHCb) or beam-dump experiments (e.g. SHiP)

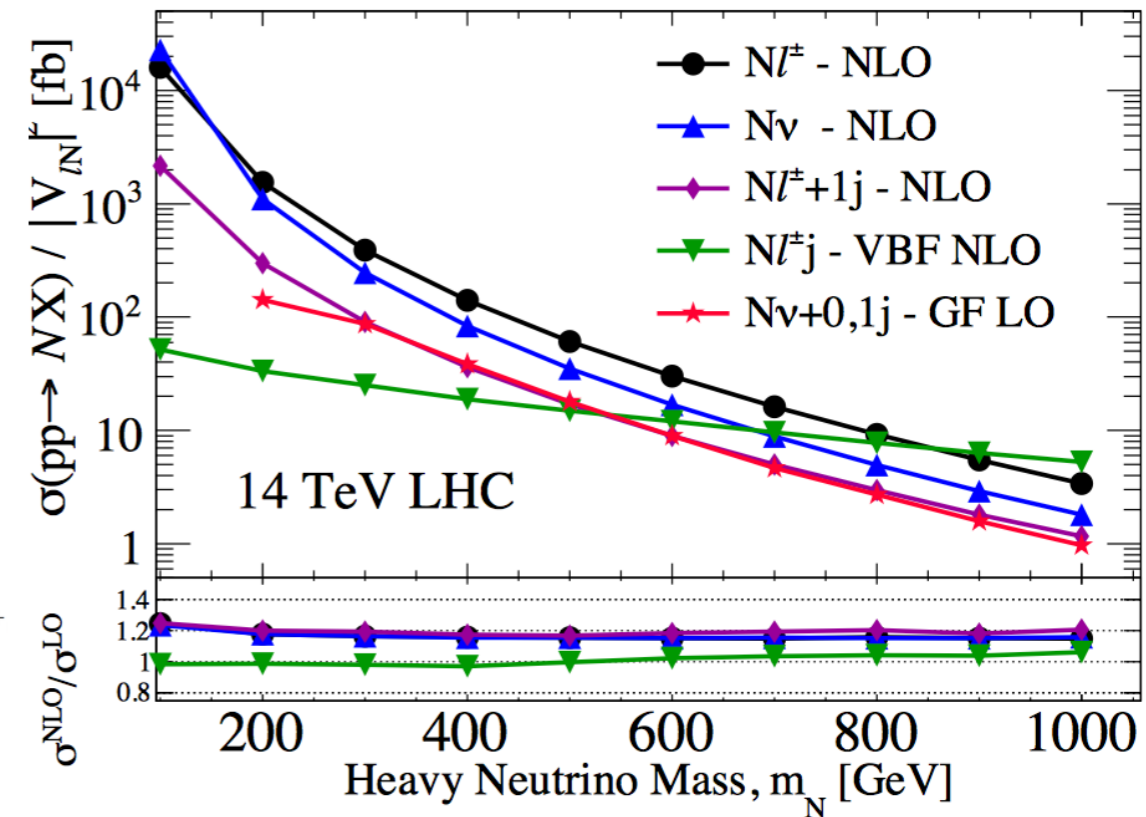
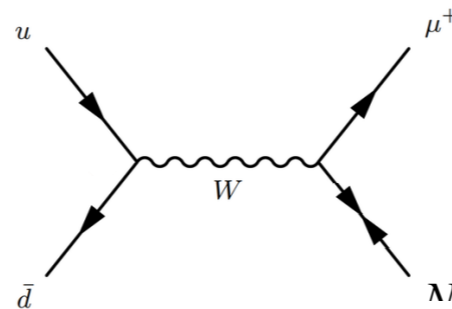
[arXiv:1502.06541 \[hep-ph\]](https://arxiv.org/abs/1502.06541)

HNL production at LHC

● $W^{\pm(*)} \rightarrow l+N$ (or $Z/H \rightarrow \nu N$)

- High momentum lepton \rightarrow easy to trigger
- Relatively large cross section
- for high N masses **VBF channel** ($W\gamma$ fusion) becomes important

- Final states with multiple charged-leptons (Nl^{\pm}) are experimentally more accessible
- charged DY current
VBF ($W\gamma$ fusion)



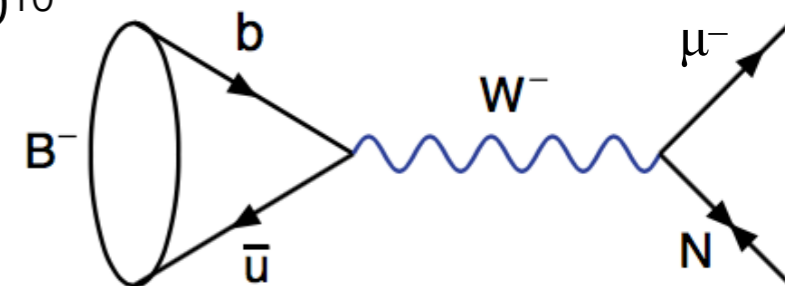
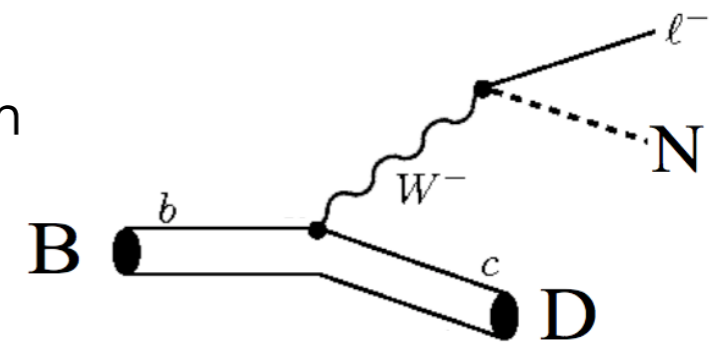
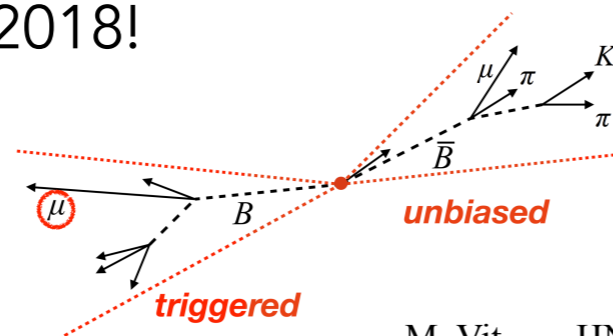
[arXiv:1602.06957](https://arxiv.org/abs/1602.06957)

● B-hadron decays

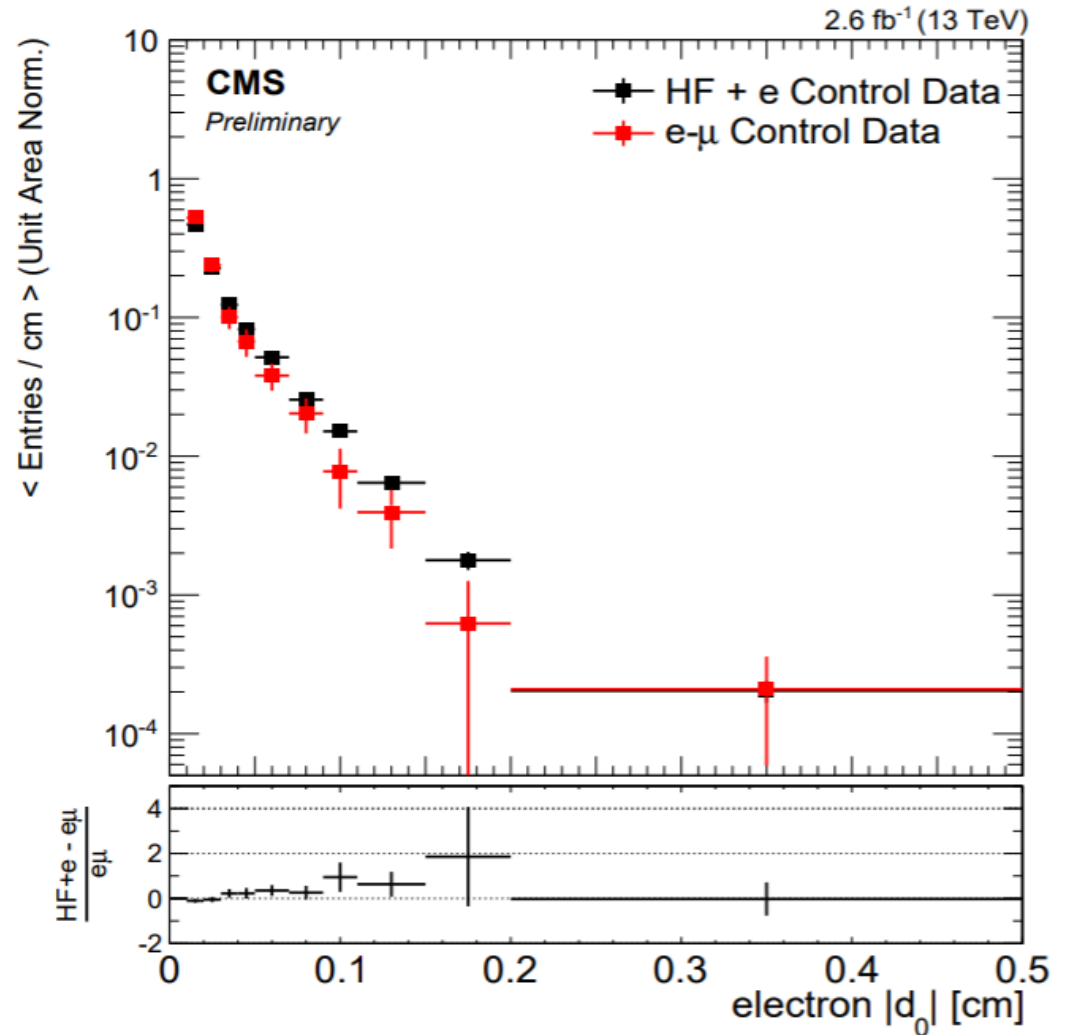
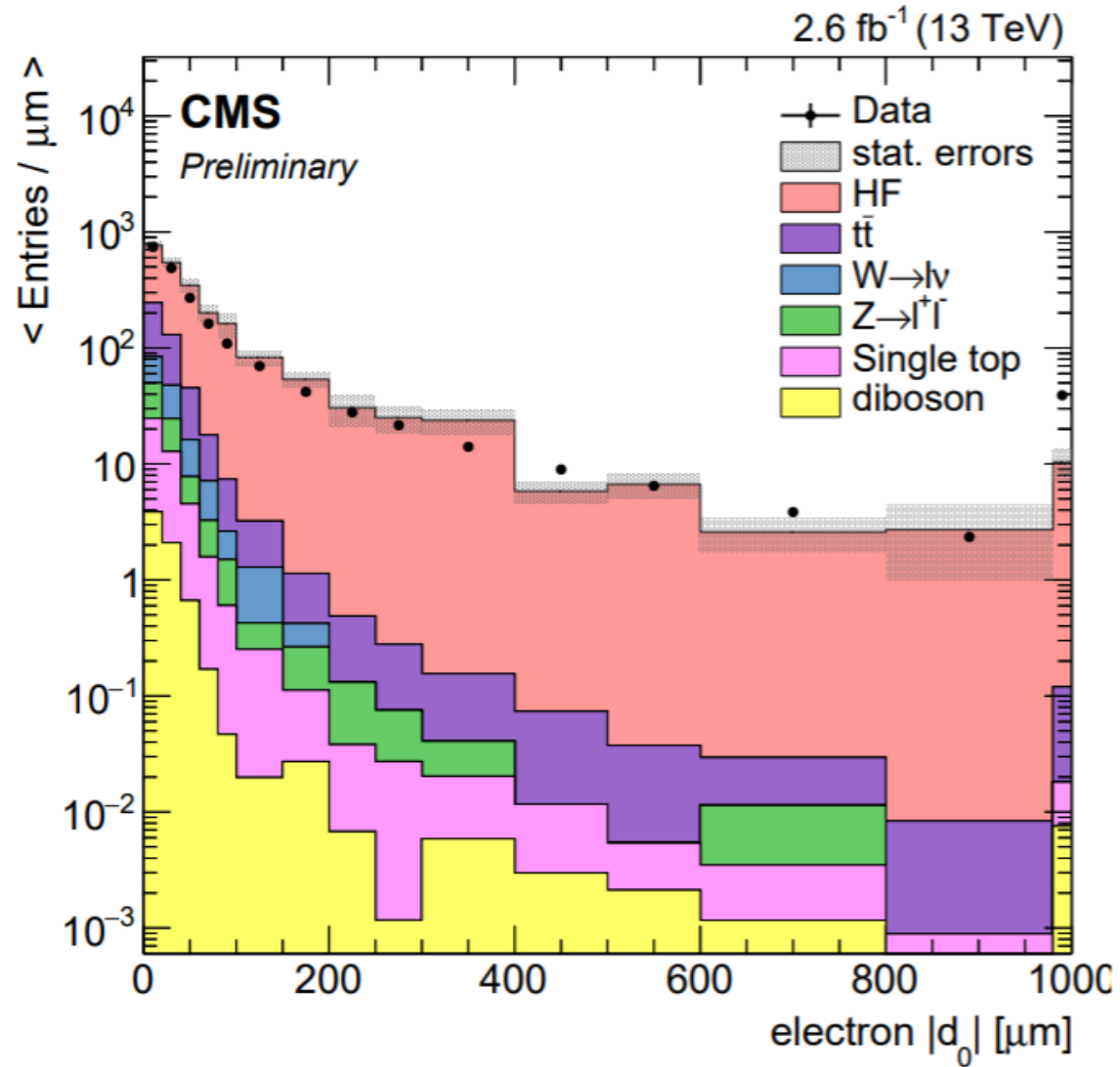
- **large cross section**, but large background and low-momentum \Rightarrow hard to trigger

- feasible at **LHCb**, tricky at ATLAS/CMS

- but the **CMS "data parking"** allowed us to record $\sim 10^{10}$ unbiased B in 2018!

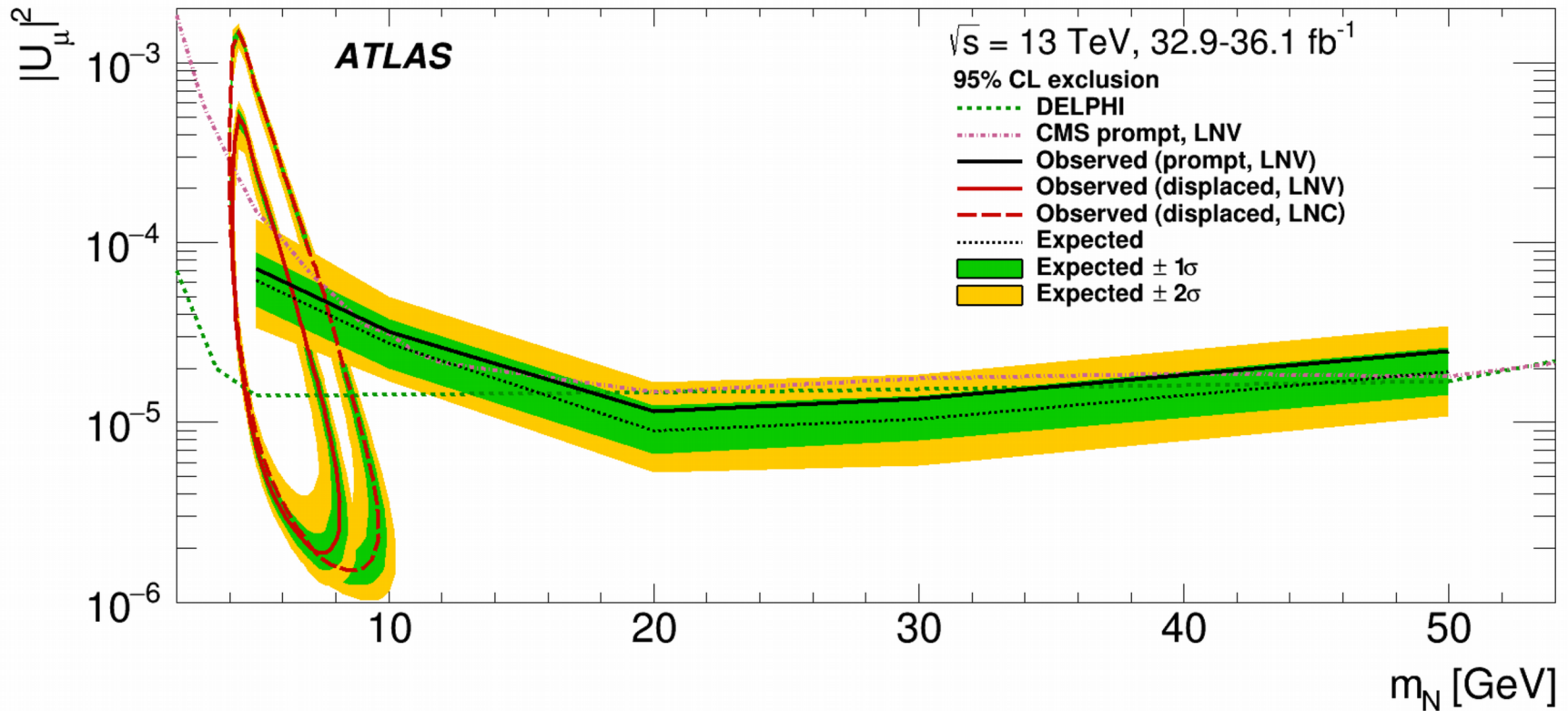


Valuable knowledge from a SUSY search



Pioneering signature : lepton + DV (low pT) for the first time at the LHC

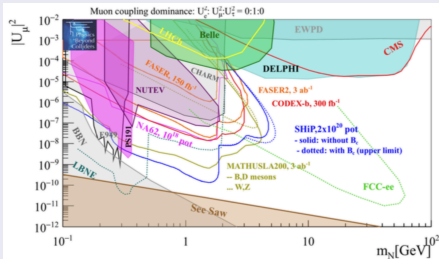
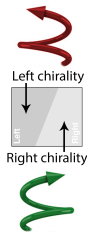
arXiv:1905.09787



Probe coupling 1 order of magnitude below Delphi
for $5 < m_N < 10 \text{ GeV}$

Conclusions

	2.4 MeV Left $\frac{2}{3}$ u Right up	1.27 GeV Left $\frac{2}{3}$ c Right charm	171.2 GeV Left $\frac{2}{3}$ t Right top
	4.8 MeV Left $-\frac{1}{3}$ d Right down	104 MeV Left $-\frac{1}{3}$ s Right strange	4.2 GeV Left $-\frac{1}{3}$ b Right bottom
Quarks	≤ 0.0001 eV Left 0 ν_e Right electron neutrino	$\sim -\text{keV}$ Left 0 N_1 Right sterile neutrino	~ -0.01 eV Left 0 ν_μ Right muon neutrino
	$\sim -\text{keV}$ Left 0 N_2 Right sterile neutrino	$\sim -\text{GeV}$ Left 0 ν_τ Right tau neutrino	~ -0.04 eV Left 0 N_3 Right sterile neutrino
Leptons	0.511 MeV Left -1 e Right electron	105.7 MeV Left -1 μ Right muon	1.777 GeV Left -1 τ Right tau



- HNLs naturally come as mechanism of neutrino oscillations
- Turns out that the same HNLs can resolve major BSM problems
- Searches at LHC and Intensity Frontier experiments (SHiP, FASER, ...) are complimentary to each other
- ν MSM shares all the success of the SM while at the same time is a successful cosmological model
... and small parameters become new slightly broken symmetries [Boyarsky \[0901.0011\]](#)

What will happen?

- Need some sort of platform to work together different from mailing list
- Shared knowledge will save lot of time to both experimentalists and theorists
- Information of background is a good example
- Need of shared benchmarks between experiments

Conclusions

- The days of “guaranteed” discoveries or of no-lose theorems in particle physics are over, at least for the time being
- but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU,)
- This simply implies that, more than for the past 30 years, future HEP’s progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Michelangelo Mangano



Thanks

Federico Leo Redi