HNL experimental overview

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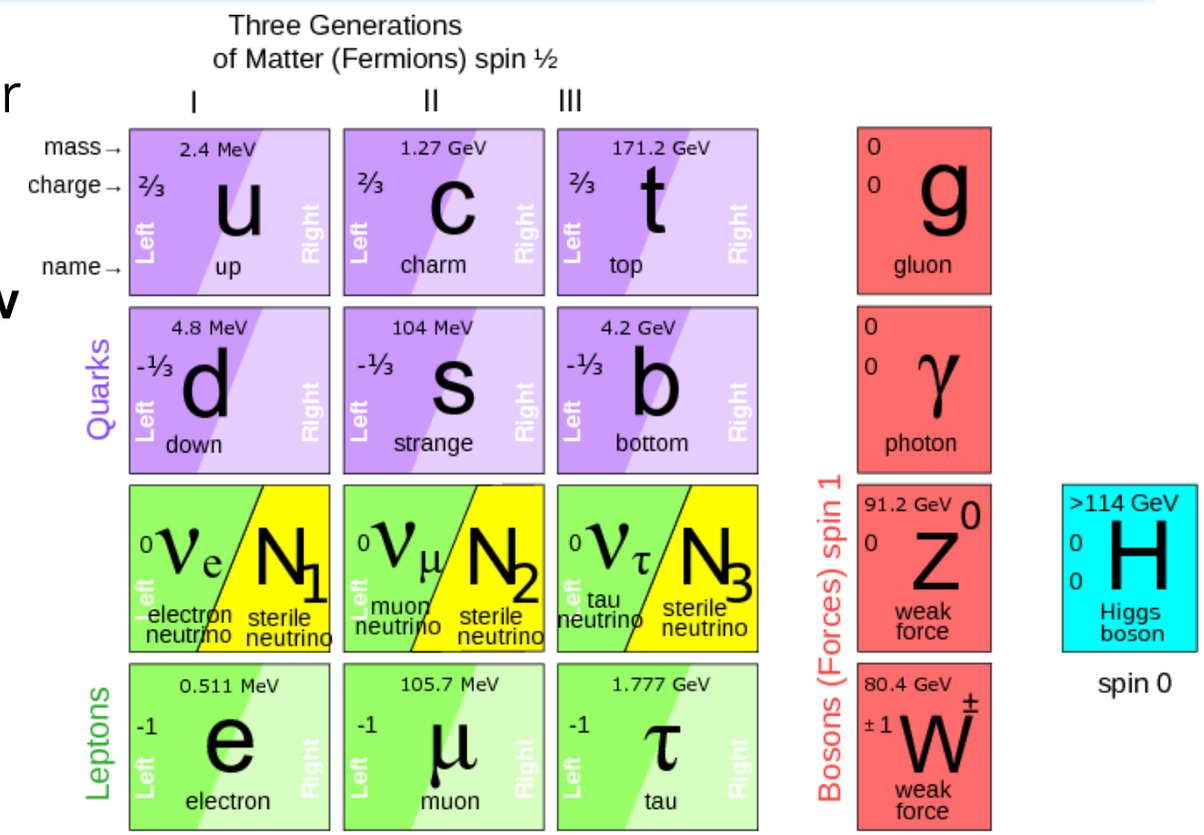
ULB, Salle Solvay

Heavy neutral leptons (HNL)

Right-handed **HNL** as potential solution for some of the outstanding problems of the SM.

- Origin of the **SM neutrino masses (seesaw mechanism)**;
- **dark matter candidate**;
- **matter-antimatter asymmetry.**

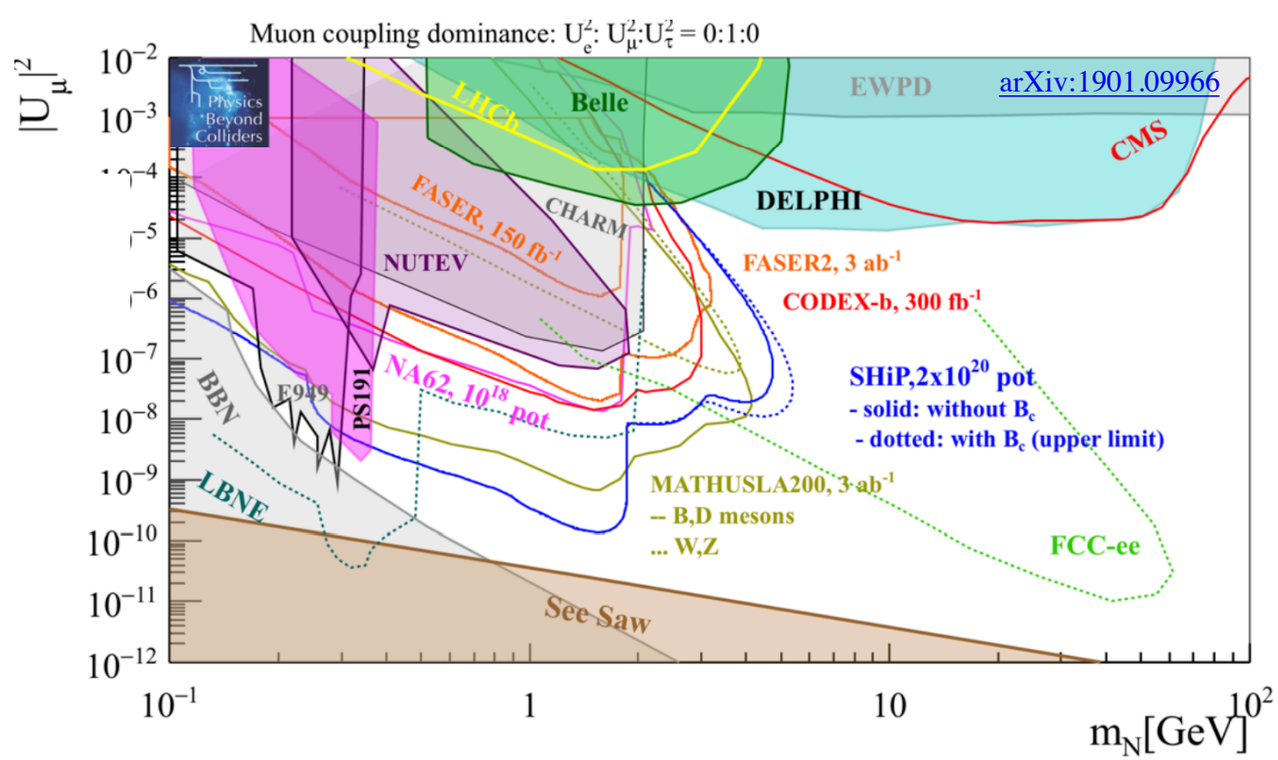
arXiv:hep-ph/0503065



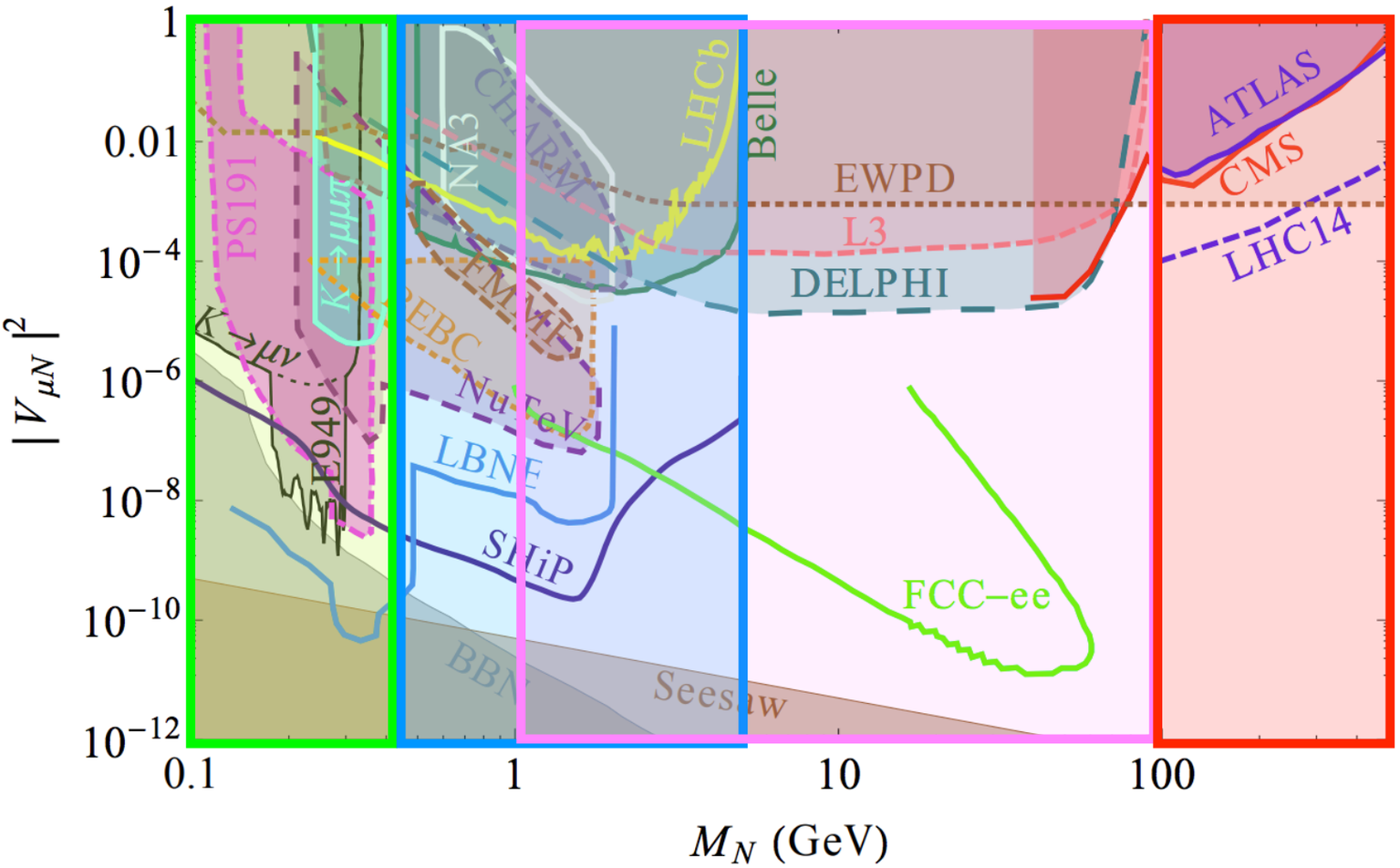
- N are sterile:
  - only interact with ν_{SM} through mixing: $\nu_{SM} \longrightarrow N$
- very low rate of $\nu \rightarrow$N: due to small mixing parameter $|V_{\ell N}|^2$ between ν_ℓ and N

Direct searches provide existing constraints and future projections on the mass and couplings with ν_{SM}

(filled areas - excluded; contours - projected experiments)



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 ($Z \to \nu N$)
- Currently explored at the LHC (ATLAS, CMS)

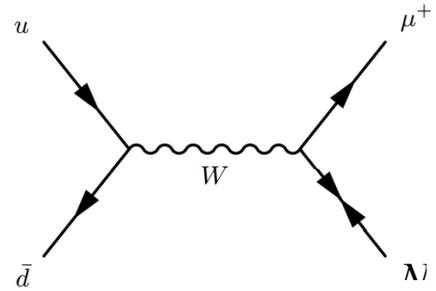
- $m_N < m_K$
- Using K decays, such as $K^\pm \to \ell N$, $K^\pm \to \mu\mu\pi$
- E.g. NA62

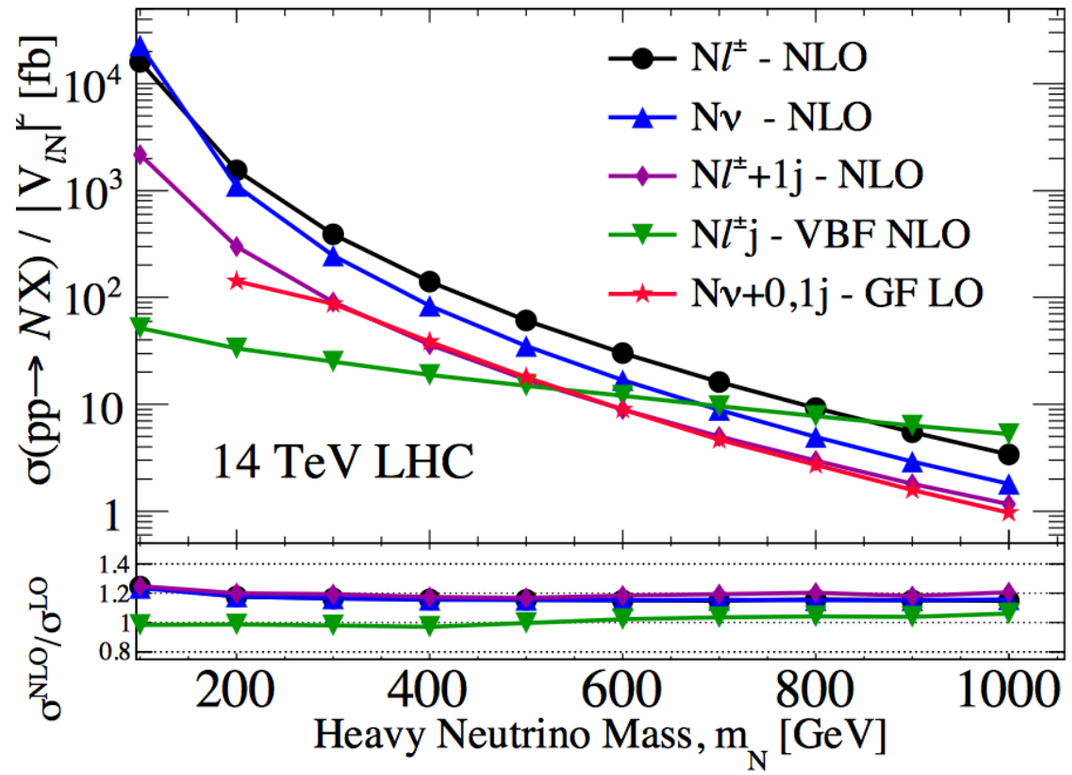
- $m_N < m_{D,B}$
- Explored at colliders (e.g. Belle, LHC*b*) or beam-dump experiments (e.g. SHiP)

arXiv:1502.06541 [hep-ph]

HNL production at LHC

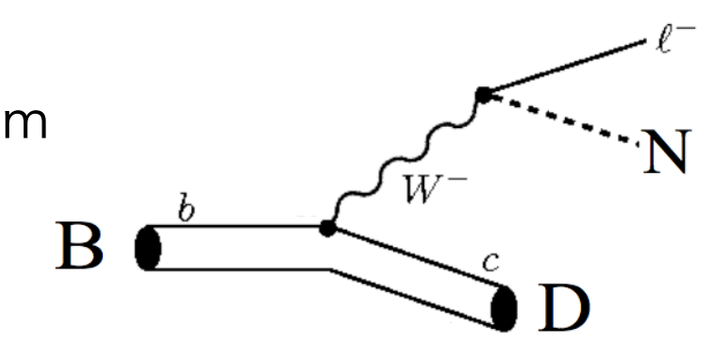
- **$W^{\pm(*)}$ –> l+N (or Z/H –> νN)**
  - Hight momentum lepton -> easy to trigger
  - Relatively large cross section
  - for high N masses VBF channel (Wγ fusion) becomes important
  - Final states with multiple charged-leptons ($Nl^{\pm}$) are experimentally more accessible
    - charged DY current
    - VBF (Wγ fusion)

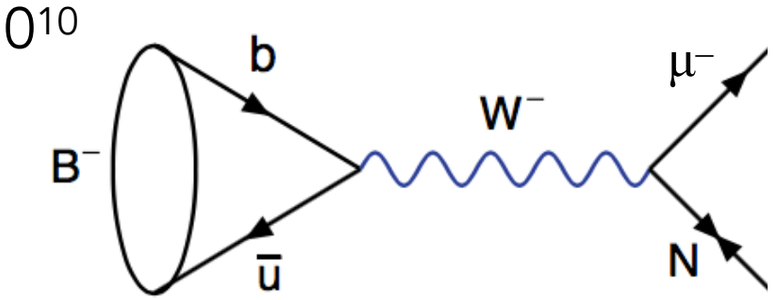


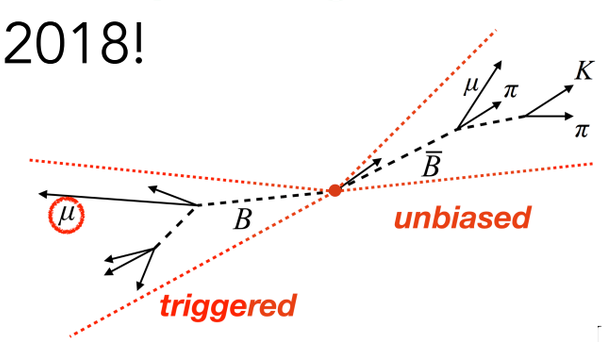


arXiv:1602.06957

- **B-hadron decays**
  - **large cross section**, but large background and low-momentum
  ⇒ hard to trigger
  - feasible at **LHC*b***, tricky at ATLAS/CMS
    - but the **CMS "data parking"** allowed us to record ~10^{10} unbiased *B* in 2018!

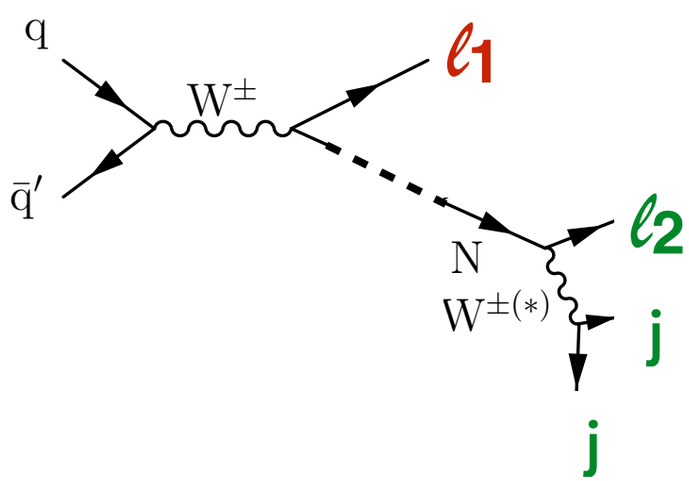




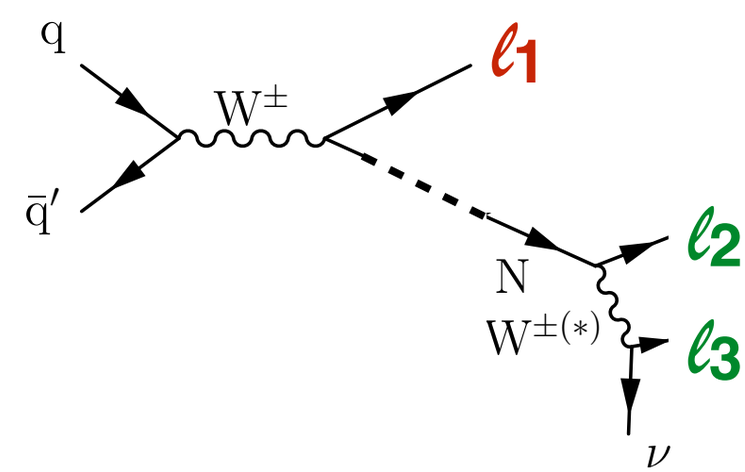


HNL from W decays: signatures

- Dilepton + 2 jets
  - fully reconstruct m_N peak
  - mostly sensitive to
    - high m_N (jet $p_T \gtrsim 30$ GeV)



- Trilepton + missing energy (ν)
  - no clear m_N peak
  - can identify e and μ down to few GeV
    → low m_N

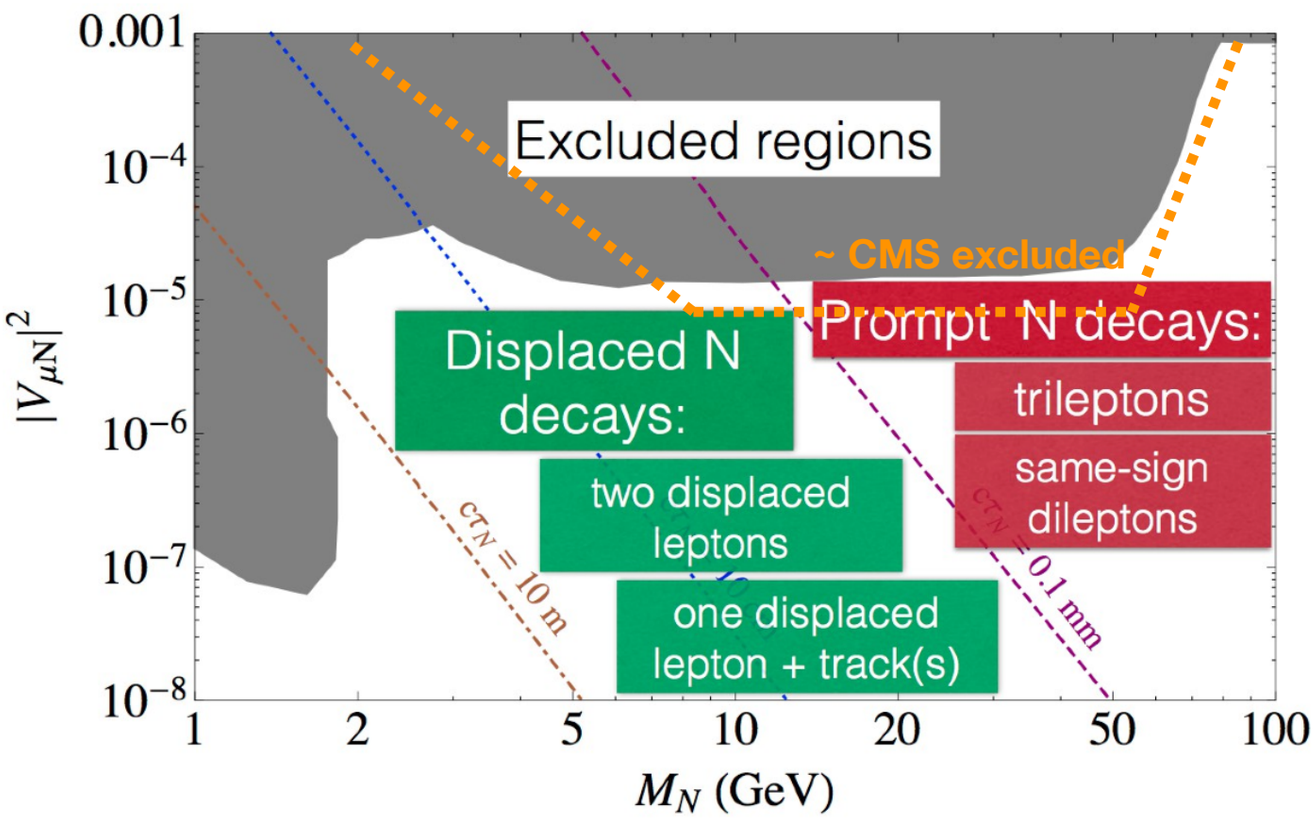


Depending on the nature of these *heavy neutral leptons* (HNL), decays can **conserve** or **violate** the lepton number

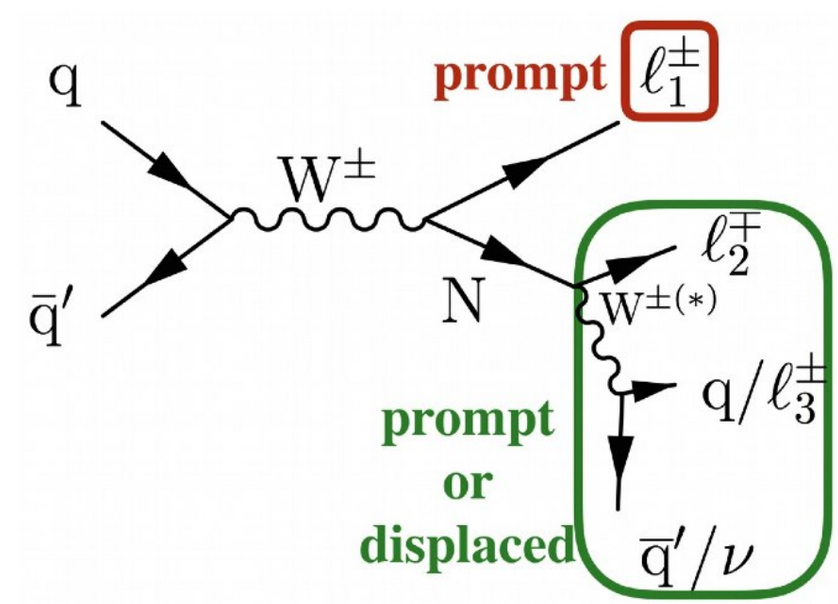
- **Dirac:** lepton number conserved (**LNC**) —> ℓ_1 and ℓ_2 OS
- **Majorana:** lepton number conserved (**LNC**) or violated (**LNV**) (LNV/LNC ratio is model dependent)
  - **LNC**: ℓ_1 and ℓ_2 **OS**
  - **LNV**: ℓ_1 and ℓ_2 **SS**

Change of perspective at LHC

- HNL **production**: in decays of W bosons or b quarks
- HNL **decays**: $N \to W\ell$ $N \to Z\nu$ or $N \to H\nu$
- HNL **lifetime**: smaller is the mass or the N- mixing — longer N lives $\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$



⇨ from very small (prompt decays) to macroscopic distances from production vertex (displaced decays) at very low mass and couplings.



We should consider new searches with pioneering signature: displaced objects

New physics, unconventional searches?

While the SM is in excellent agreement with the LHC measurements, many problems should be still resolved ⇒ BSM (SM) scenarios exist to cover the limitations of it.

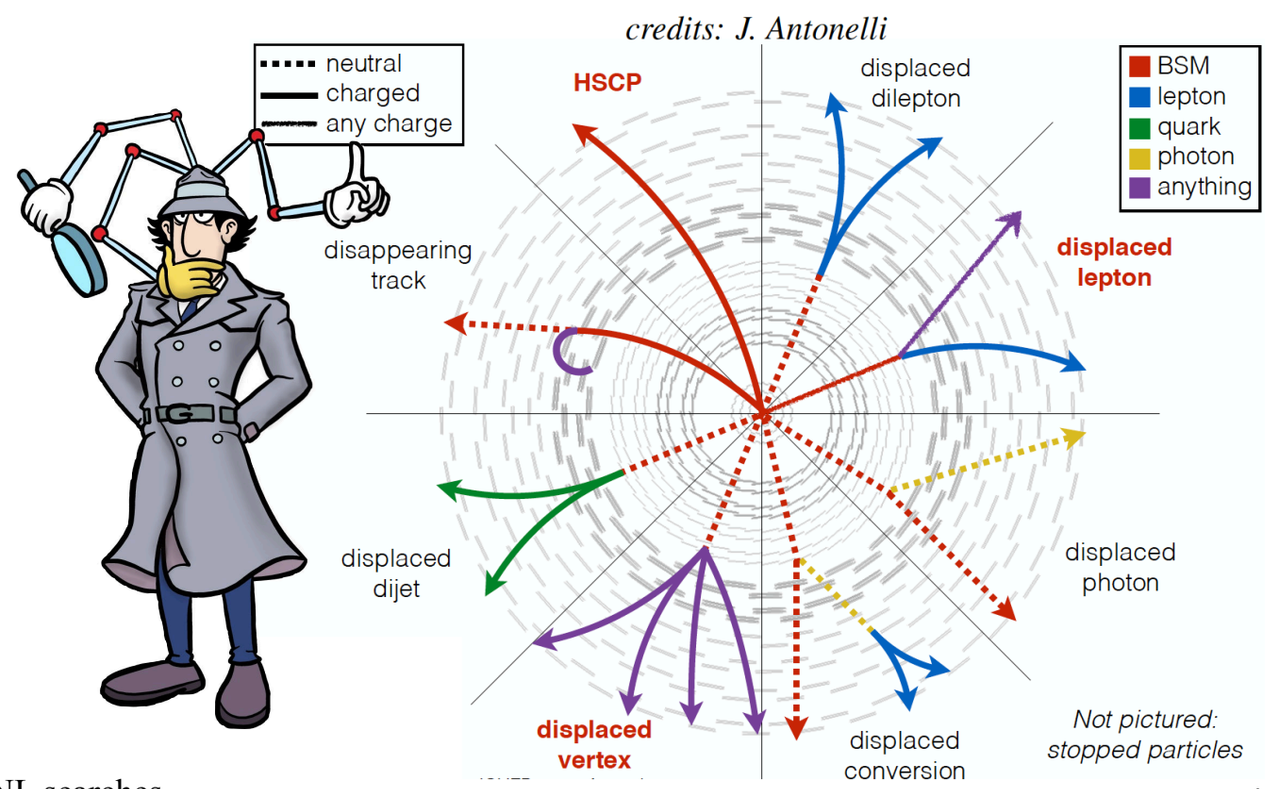
The new particles can either be:

- Prompt decaying —> standard SUSY-EXOTICA searches
- **Long-Lived Particles (LLPs), decay in the detector**
- Detector-stable (decay outside the detector) and stable

So we should be ready for **unconventional signature** searches even though ATLAS and CMS were initially designed to optimize object identification for prompt particles

Challenges:

- Trigger:
  - Suboptimal triggers
  - Timing information not always available
- Reconstruction
  - Secondary vertex finding algorithms
  - interaction point constraint in triggering/ reconstruction
- Backgrounds:
  - instrumental background
  - Cosmic rays
  - In-time out-of-time pileup
  - Long-lived standard model hadrons

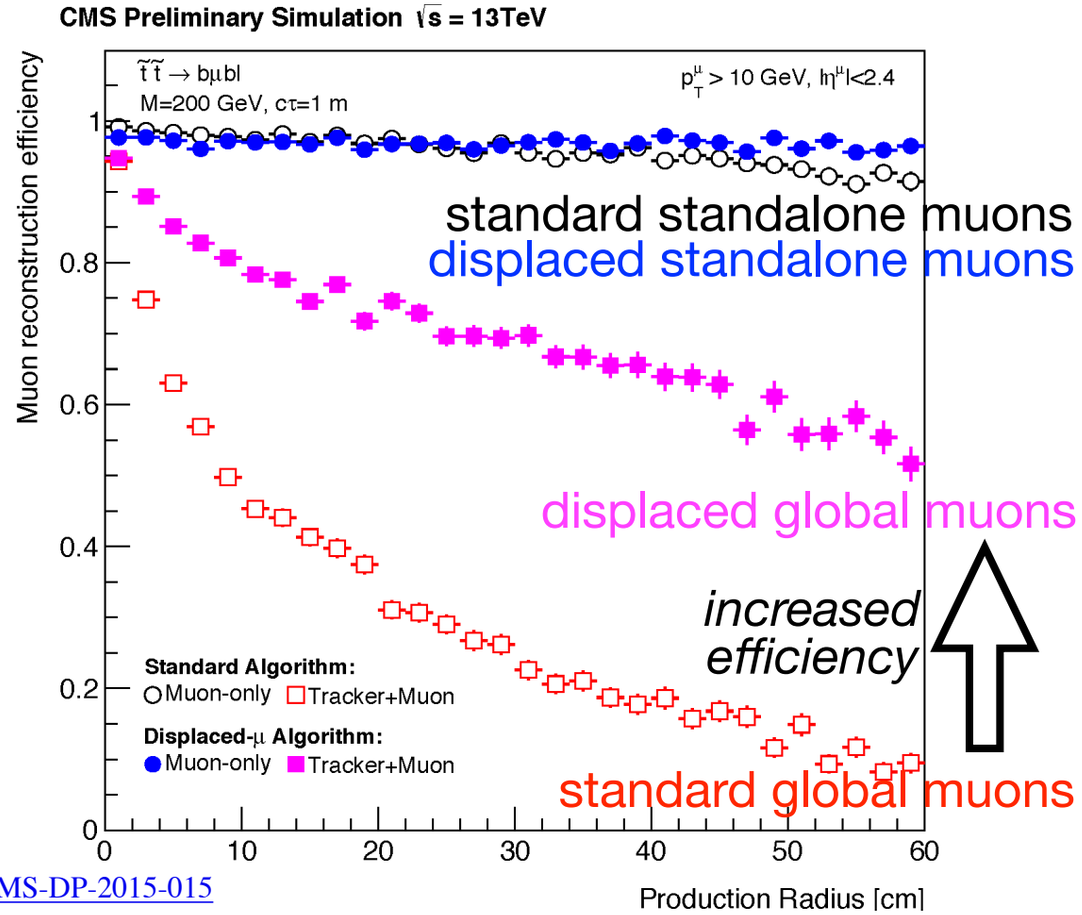


Track reconstruction efficiency

- CMS and ATLAS have different reconstruction algorithms -> different approaches when it comes to overcome low eff-cy for displaced tracks.

Dedicated tracking and identification **algorithm in the PF** using:

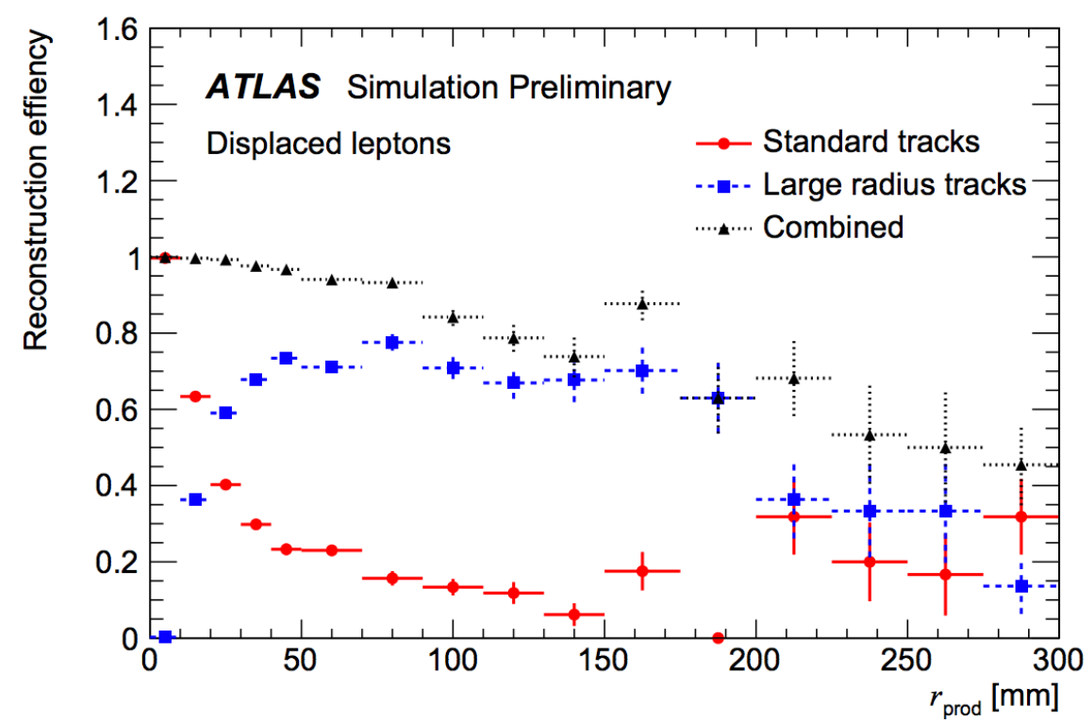
- muon system alone: decays very far from the p-p interaction point, also out of time
- muon system+inner tracker: in-time μ produced within the inner-tracker volume. Any constraints to the interaction point



CMS-DP-2015-015

Large-radius tracking (**LRT**) algorithm.

- Larger d_0 ~300 mm (wrt standard reconstruction)
- computer-intensive, can be run only on a limited fraction of the RAW data → "filter" selection



ATL-PHYS-PUB-2017-014

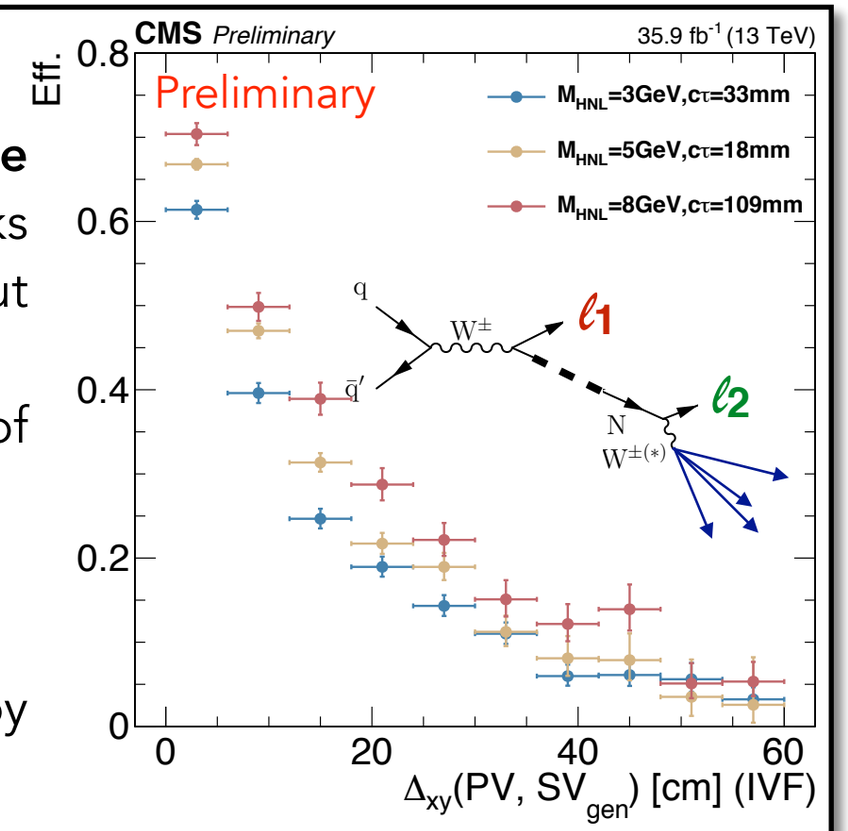
Displaced vertex reconstruction

- CMS is using 2 different ways to find the HNL decay vertices according to the final state under study

- HNL + **hadronic W decay**

The Inclusive Vertex Finder algorithm is used. IVF is an **iterative procedure** which selects, clusters,fits tracks in vertices, then discard tracks from vertices that don't really match, fit one vertex again without discarded tracks, repeat.

The efficiency is higher than the Kalman-filter approach in case of **unknown numbers of tracks in the vertex.**



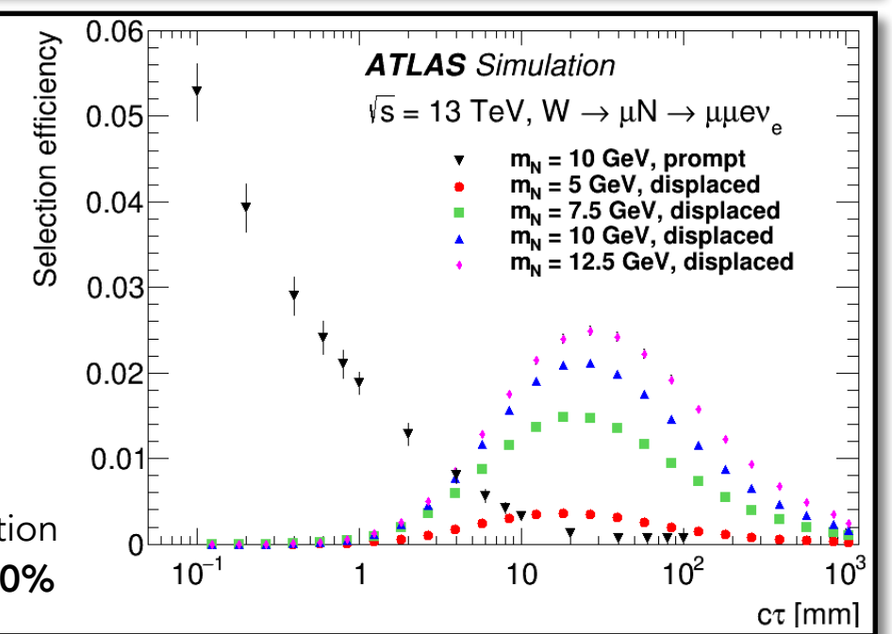
- HNL + **leptonic W decay**

For displaced leptons pair a common vertex of origin is reconstructed by fitting the two tracks to a common point with a Kalman-filter approach.

DV reconstruction algorithm.

It finds two-track seed vertices from pairs of selected tracks excluding seed vertex positions inside or within several millimeters of a tracker layer ('material veto').

Multitrack DVs are then formed iteratively using the collection of seed vertices



For an HNL decay length of the order of a cm, the DV reconstruction efficiency (including the track reconstruction efficiency) is about **20%**

Background understanding

The main challenge of this search is the understanding of the background.

Expected and "easy" backgrounds for 3L analysis:

- non-prompt *leptons*
  - *Z/γ** + jets
  - *tt*
- Photon conversions *with the material*

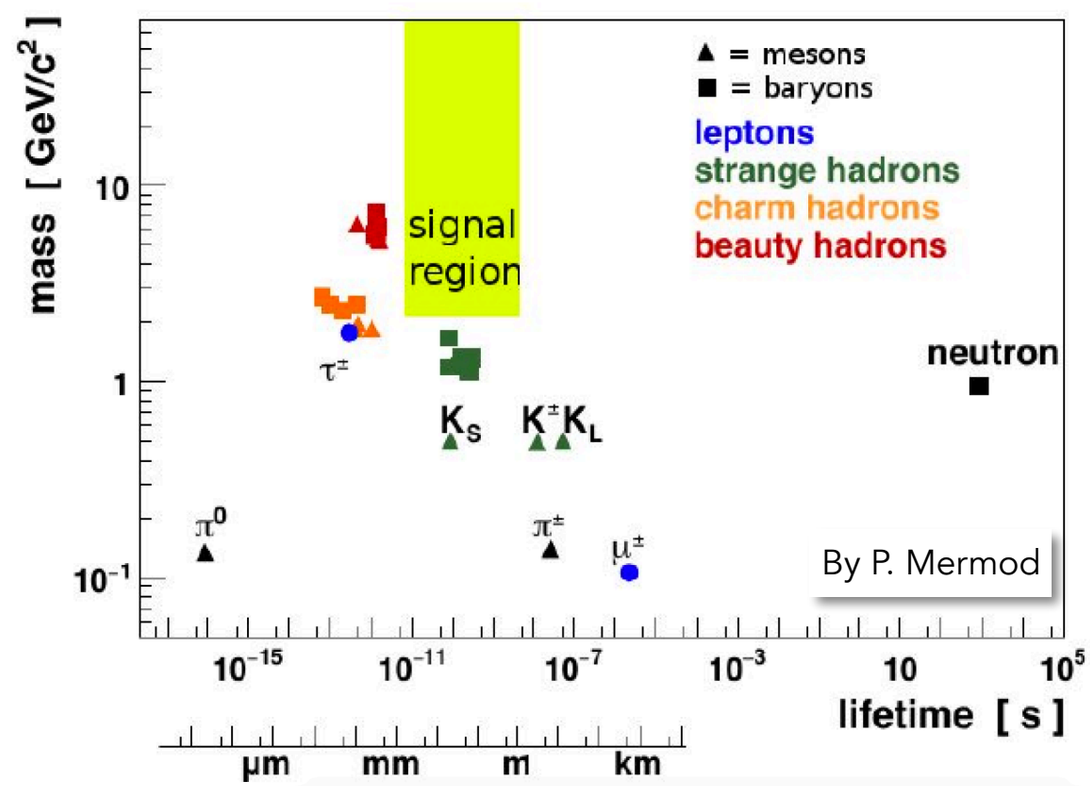
Backgrounds for dilepton + jet analysis:

- non-prompt *leptons*
  - *W+jets,*
  - *DY,*
  - *tt*

Other backgrounds:

- **Decay in flight of hadrons**
- **Light resonances decays** – Example: boosted B decay into J/Psi or Psi(2S) → dimuon SV with mSV ~ 3 GeV
- **Random crossings of pile-up tracks**
- **Cosmics producing back-to-back displaced muons**

  ATLAS: cosmic-ray veto is applied to eliminate high-mass vertices from a single cosmic-ray muon which is reconstructed as two back-to-back muons



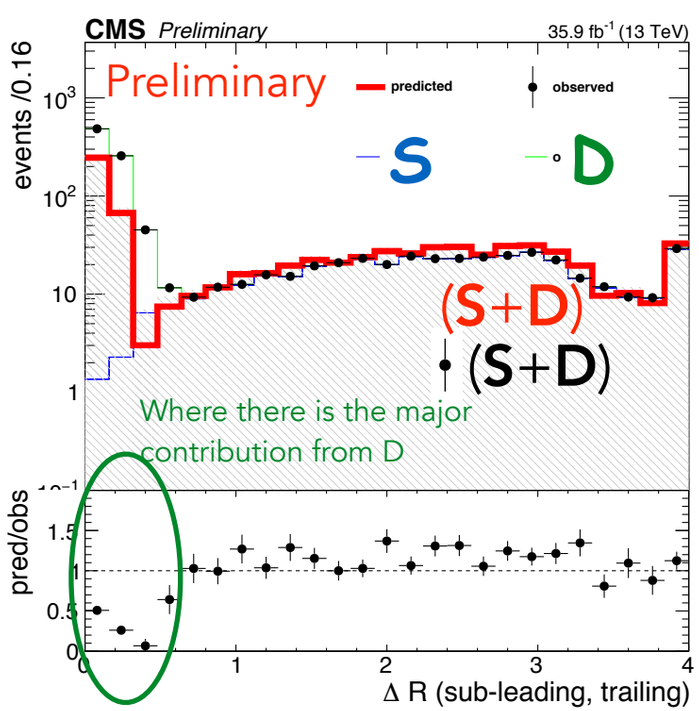
Background estimation

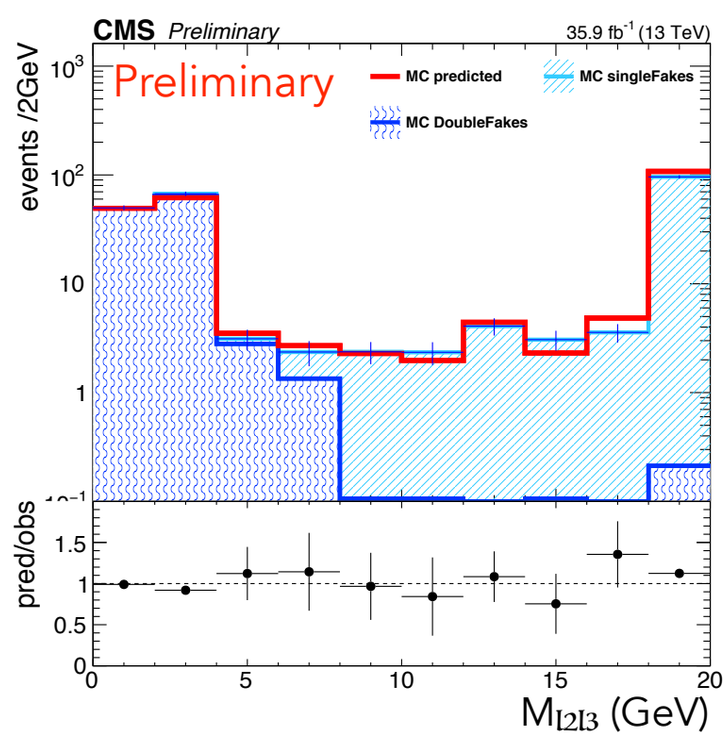
The way to study the contribution of the background would be to design specific control regions enriched with the background under investigation.

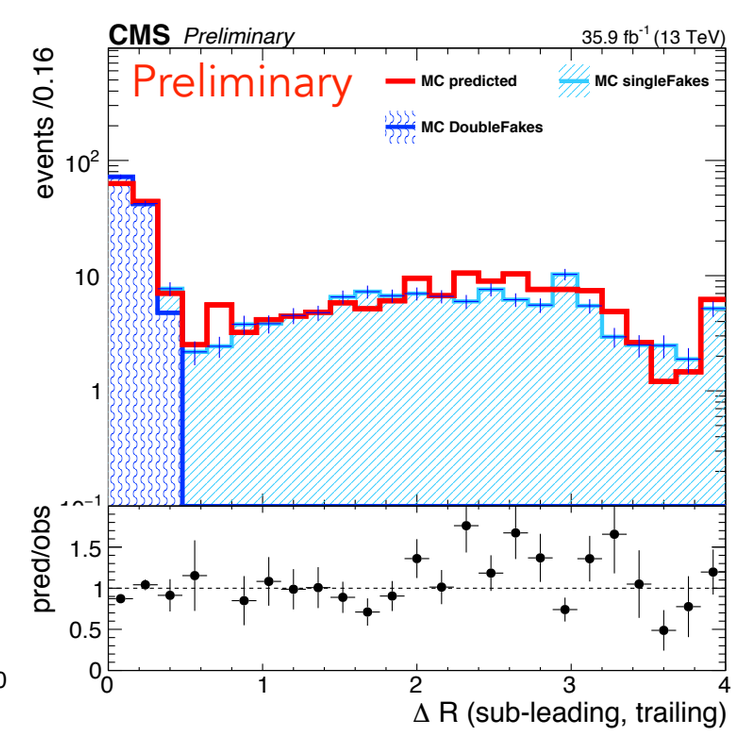
- **non-prompt *leptons*** can have different origin and they have to be predicted in separated ways

- **double fake nonprompt leptons**:
  - ✦ produced in the decay chain of the same hadron (a B meson, e.g. b $\to \ell^- \bar{\nu}_\ell c \to \ell^- \bar{\nu}_\ell \ell'^+ \nu_{\ell'} s$ or a quarkonium state (J/ψ —> $\ell^+\ell^-$);
  - ✦ they contribute at **low masses** ($M_{l_2 l_3}$ < 5GeV) and they are quite **collimated** (close in $\Delta R(l_2, l_3) < 1$);
  - ✦ the two leptons are manifestly not independent and their selection probabilities are correlated
- **Single fake nonprompt leptons** like muons from light-flavor mesons that decay in flight, or electrons from unidentified conversions of photons

→ Standard method is not feasible, new approach to be able to take into account the 2 contributions





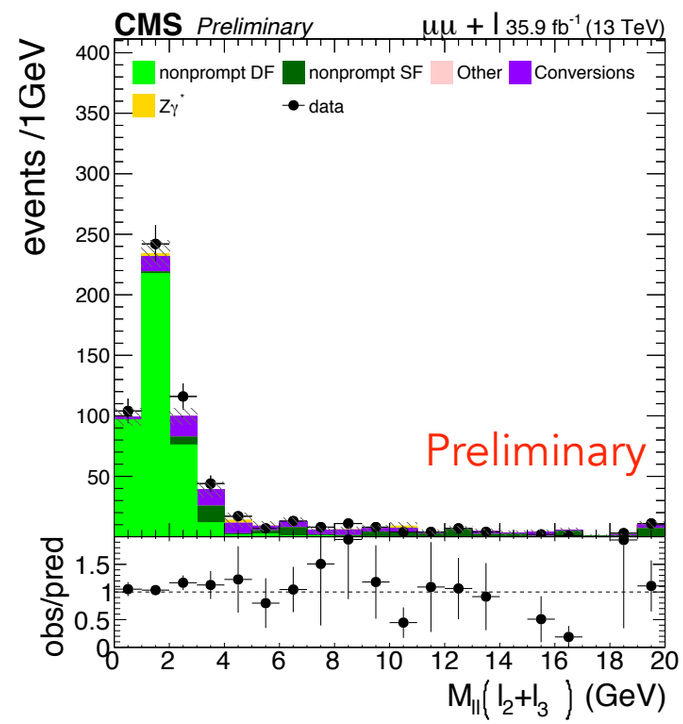


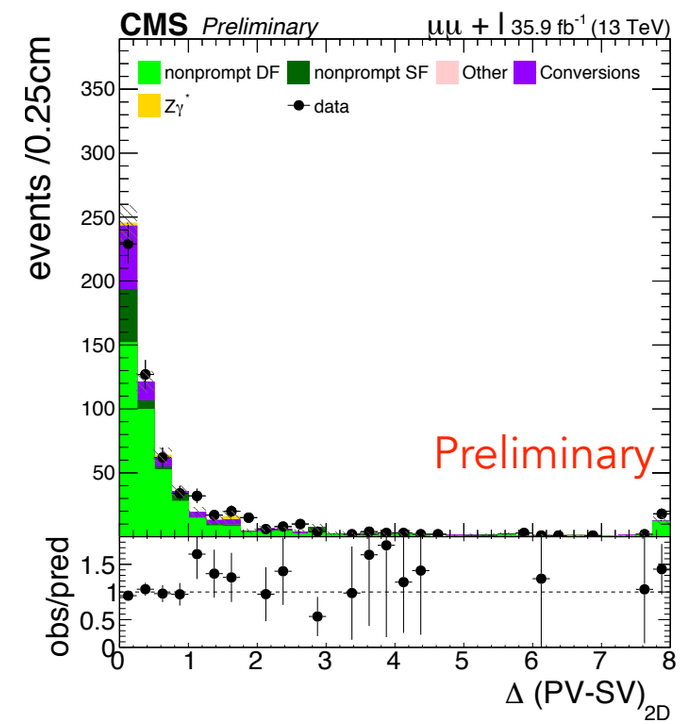
Validation of background prediction

- Validate the data-driven method to predict non-prompt background
- Checks performed in control regions orthogonal to search regions

Sideband CR

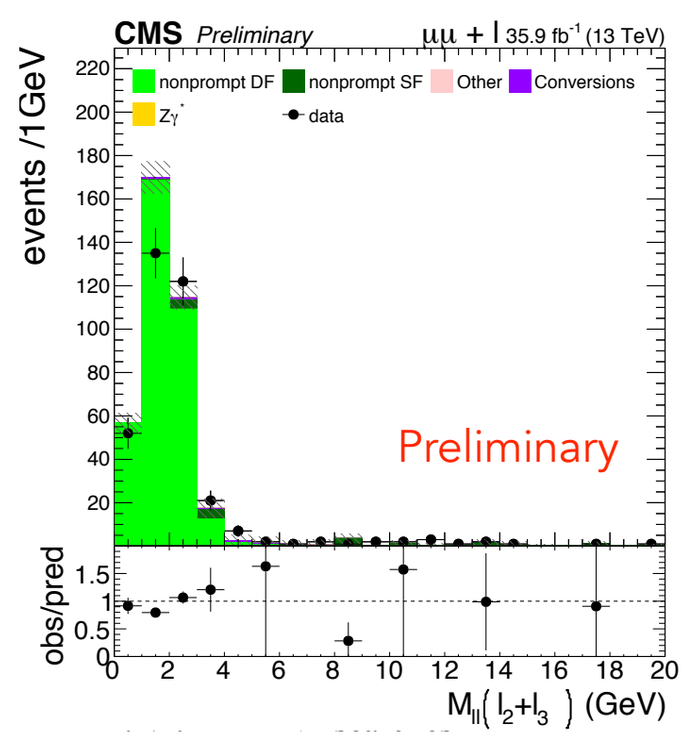
- Collimated displaced leptons: $\Delta R(l_2 l_3) < 1$
- Orthogonal invariant mass cut: $M(3\ell) < 45$ || $M(3\ell) > 85$ GeV

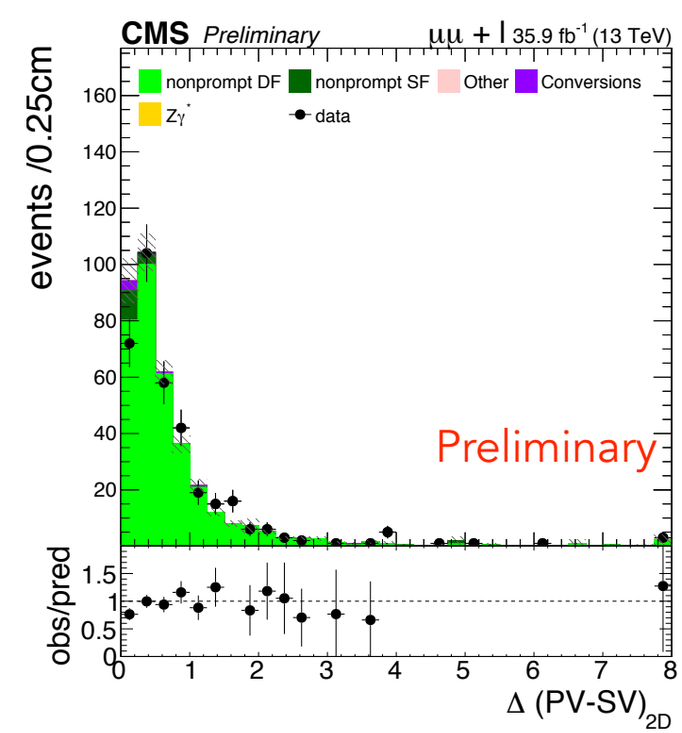




Top-antitop CR

- Collimated displaced leptons: $\Delta R(l_2 l_3) < 1$
- Orthogonal cut: presence bjet



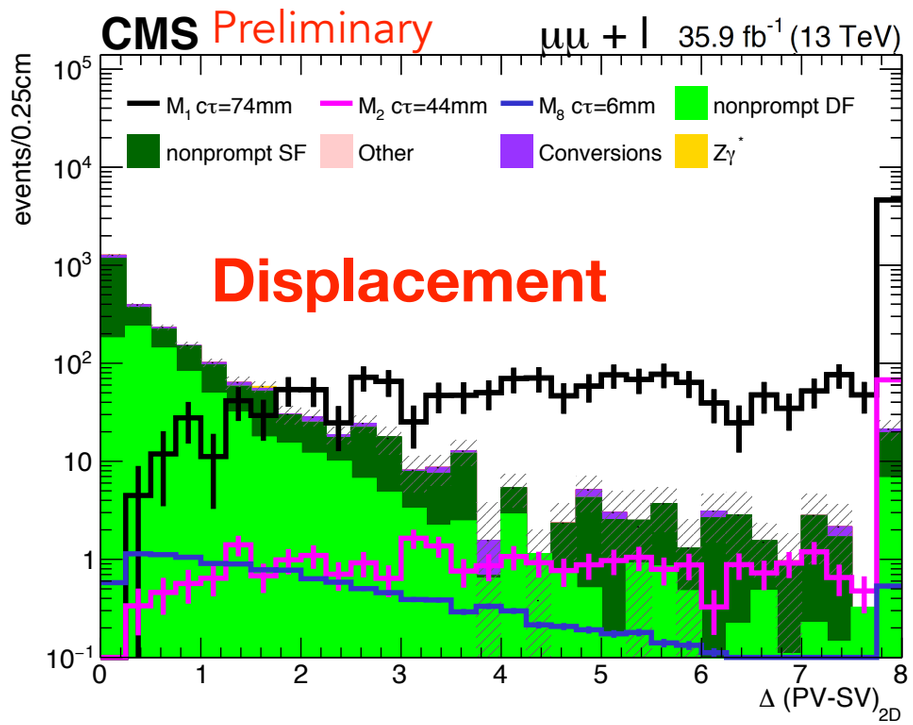


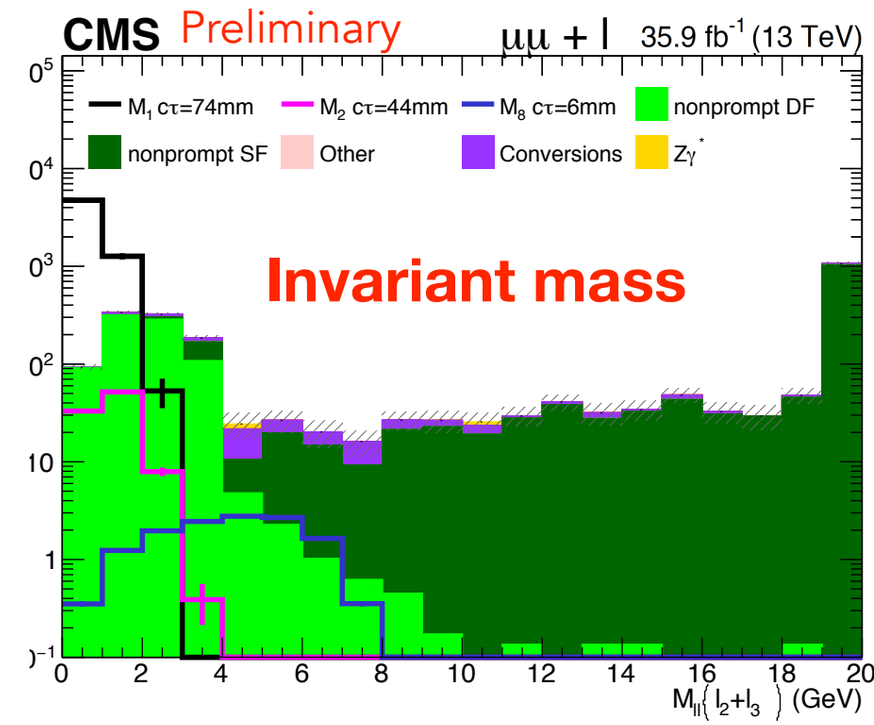
Background is understood and under control within 30% uncertainty

Search strategy

Data set: **Full Run2**

- Signal MC samples: Madgraph aMC@NLO version 2.4.2. mixing parameters $|V_{lN}|$ ON for **electrons and μ and τ**.
- HNL mass **<20 GeV**
- **Single lepton trigger, l_1**





We design the analysis using different discriminating variables:

- **Displacement**: at large values more sensitivity for low masses and "background free regime"
- **Invariant mass of the two displaced leptons**: avoid resonances region

In addition, the events are split into 3 different final states.

- In case of $V_{\mu N}$ the 3 final states are **μμμ, $\mu^\pm\mu^\mp e^\pm$ and $\mu^\pm\mu^\pm e^\mp$**;
- in case of V_{eN}, the 3 final states are: **eee, $e^\pm e^\mp \mu^\pm$ and $e^\pm e^\pm \mu^\mp$**.

This categorization is necessary to provide separated limits for the case of **LNC** (**$\mu^\pm\mu^\mp e^\pm$** and **$e^\pm e^\mp \mu^\pm$**) and for the case **LNV** (**$\mu^\pm\mu^\pm e^\mp$** and **$e^\pm e^\pm \mu^\mp$**).

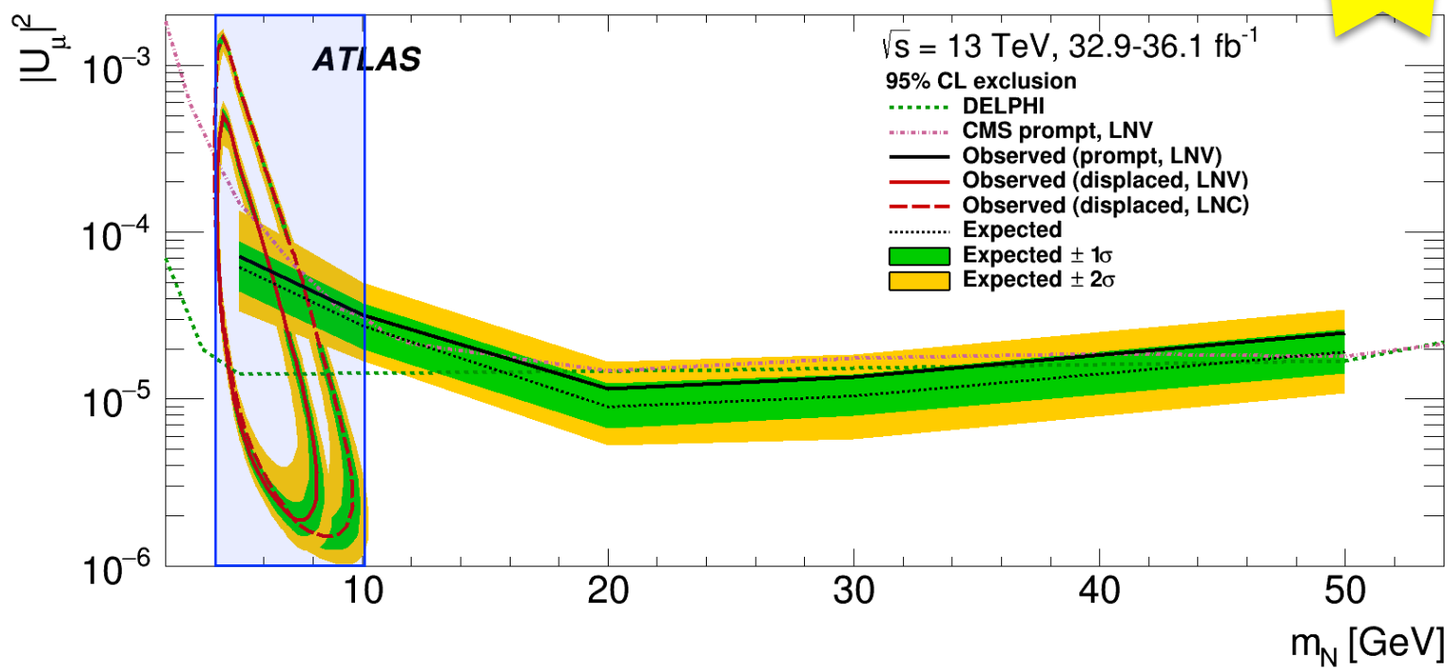
The different categories → background levels and composition → different sensitivities.

Results ATLAS

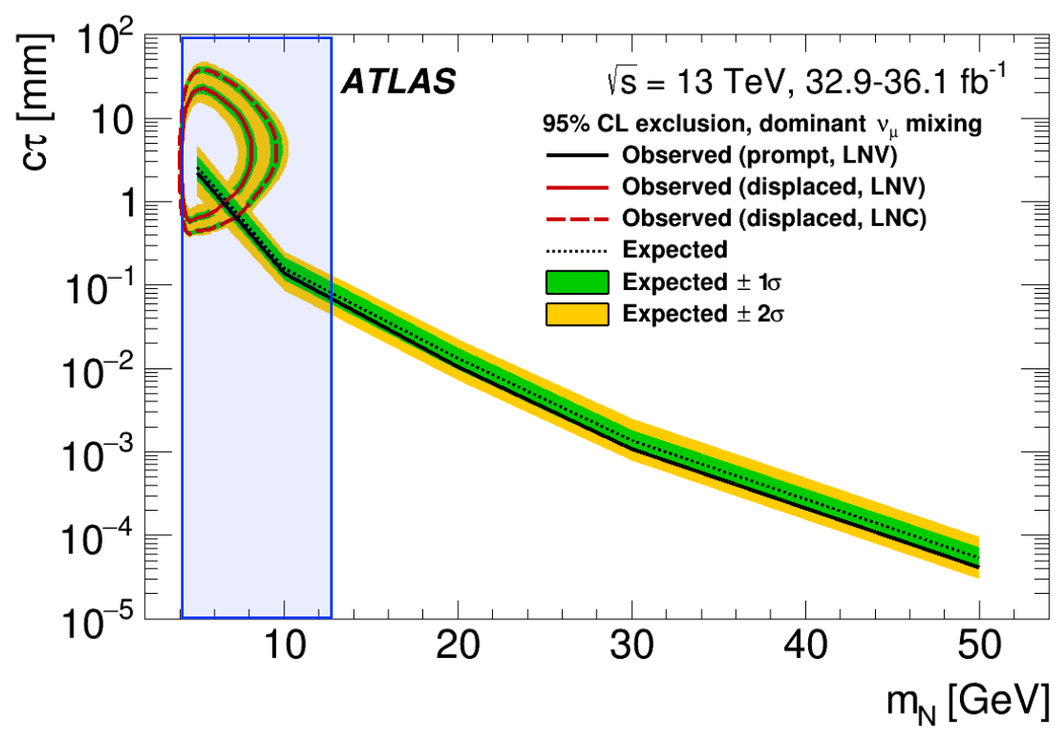
New results presented at LHCP on 23rd May!!!!!!

NEW

- Data set: **2016, 32.9 fb^{-1}**
- Results on **$|V_{\mu N}|$;**
- HNL mass range: **[4.5,10] GeV;**
- Results presented with **LNC and LNV separately;**
- Search regions in **bins of m_{DV}**

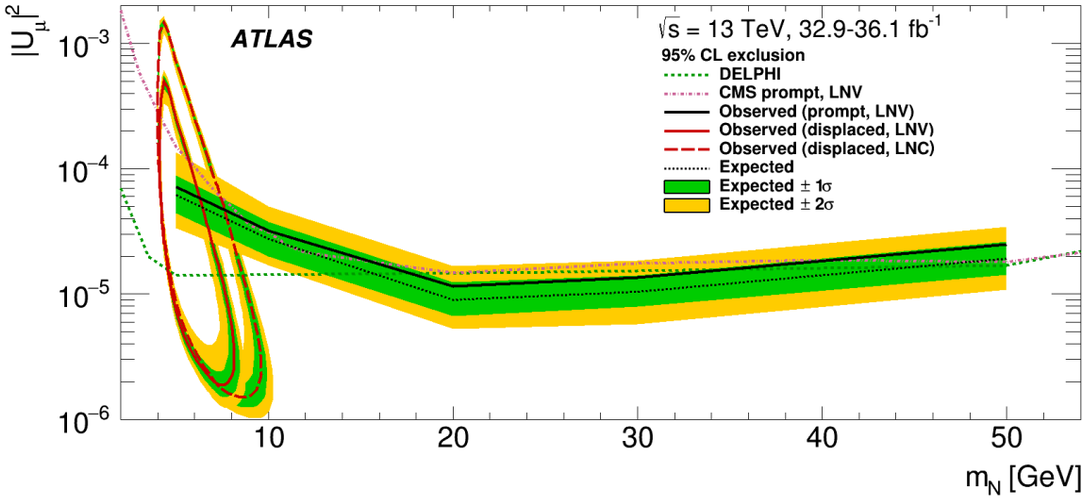


- Excluded coupling strength down to **$|V_{\mu N}|^2$ ~ $2*10^{-6}$ ($1.5*10^{-6}$)** assuming LNV (LNC);
- The shape of an oblique ellipse approximately corresponds to HNL proper decay lengths in the range 1–30 mm. It is also limited from below by the product of integrated luminosity and efficiency.



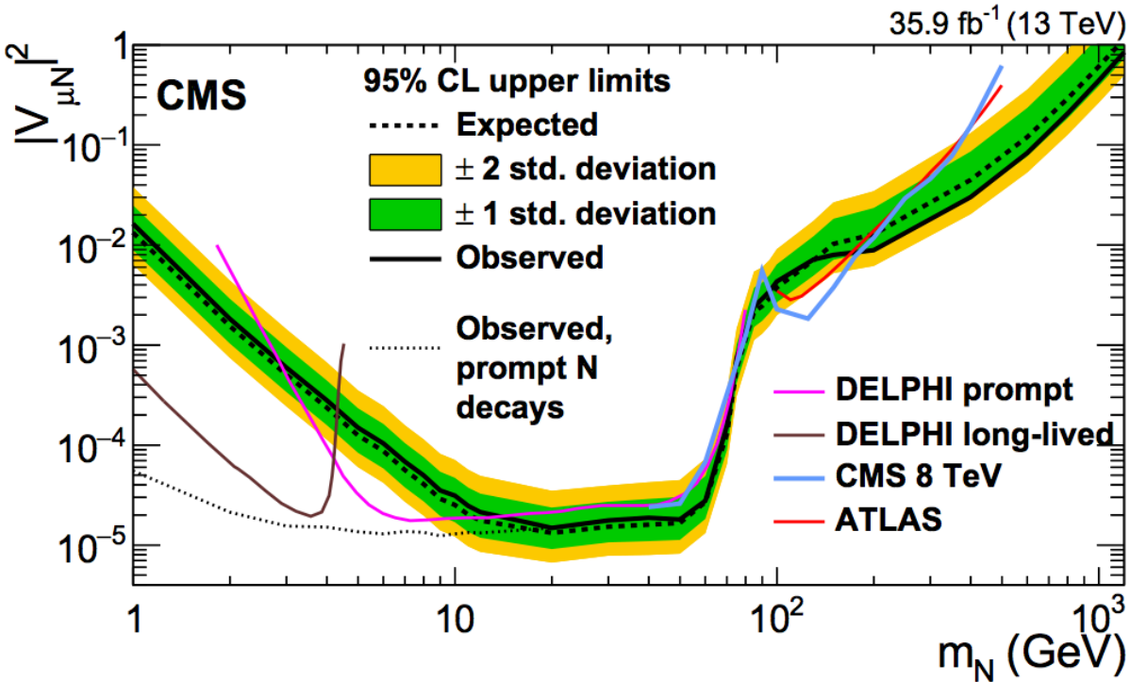
Conclusions

HNL with displaced signature has become a hot and interesting topic for all the 3 experiments at LHC, giving a taste for a future discovery.



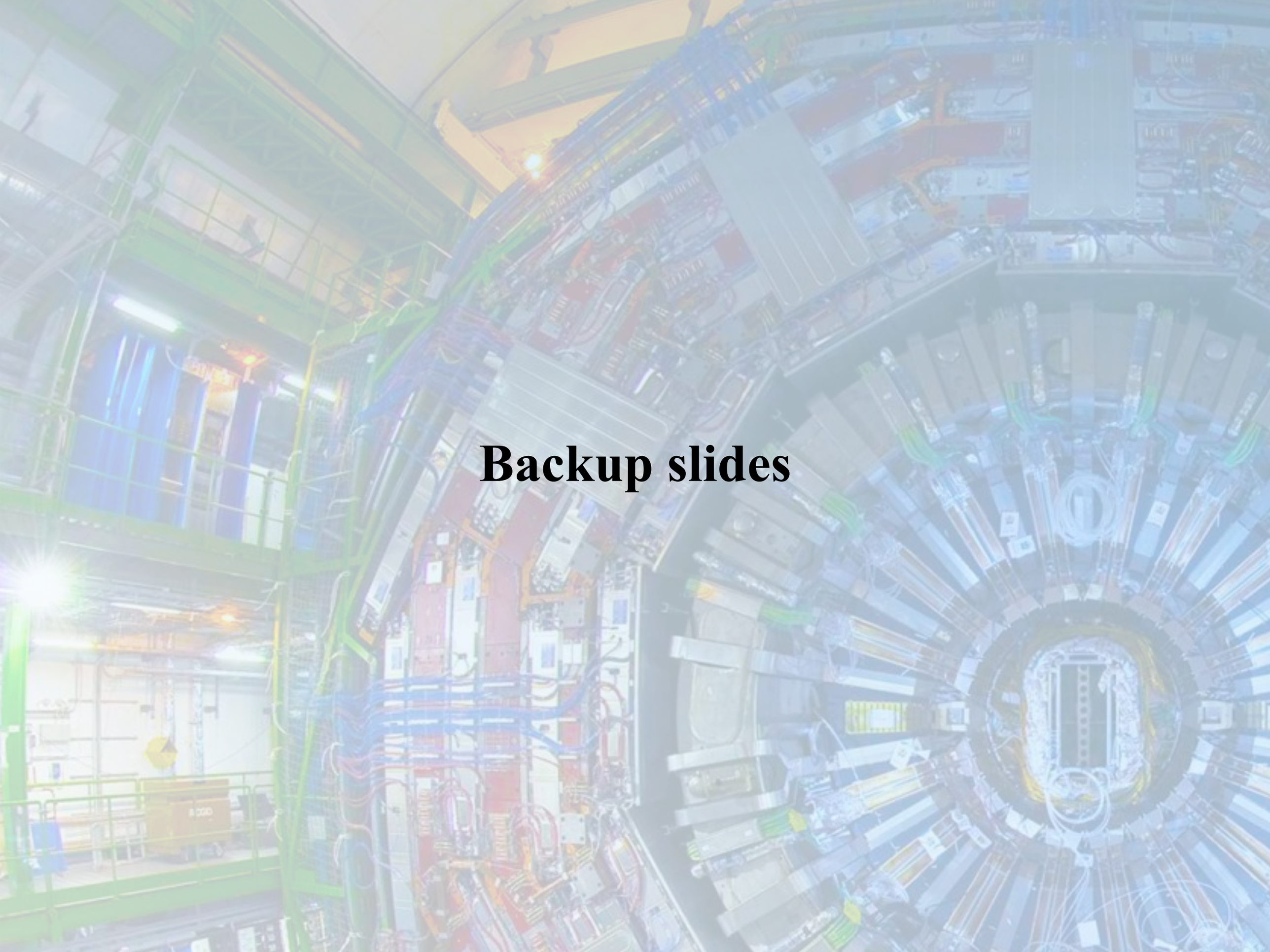
A lot of progress has been made both in the fully leptonic and semi-leptonic final states:

- new techniques to estimate the background
- Introduction of neural network to perform more optimal selection on displaced objects (jet, leptons)
- Separate interpretations for LNC and LNV
- Separate limits for each of the 3 mixing coupling, $|V|_N|$



First results at the hadron collider for the search of HNL with displaced signature published by ATLAS in May at LHCP!
Soon CMS…

HNL hunting is open!



Backup slides

Background estimation - II

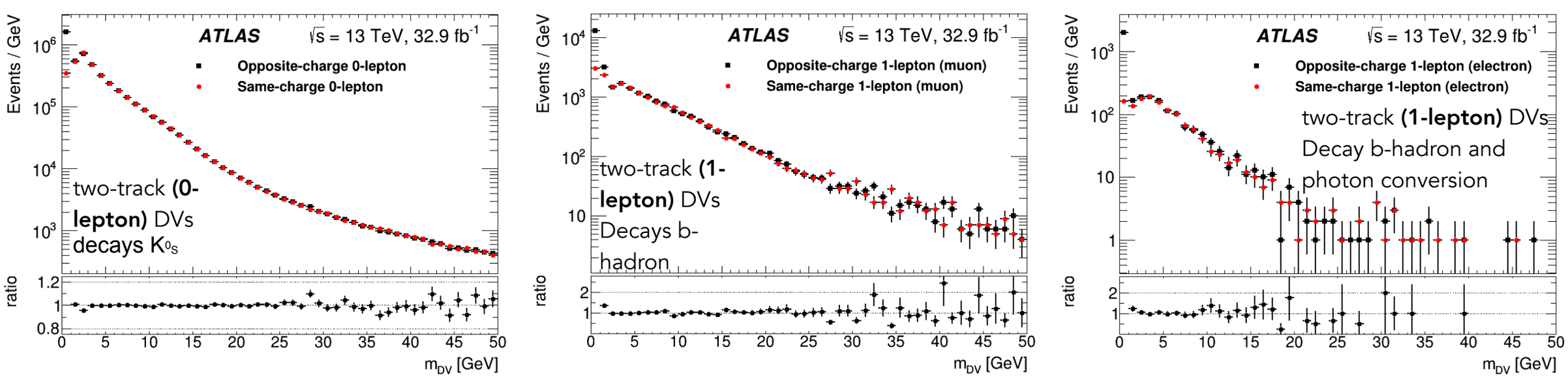
arXiv:1905.09787v1

NEW

New results presented at LHCP on 23rd May!!!!!!

- **Cosmics producing back-to-back displaced muons:** cosmic-ray veto $\sqrt{(\sum \eta)^2 + (\pi - \Delta\phi)^2} > 0.04$ is applied to eliminate high-mass vertices from a single cosmic-ray muon which is reconstructed as two back-to-back muons

- **Hadronic interaction with the material,** decays of metastable particle (**M_{DV} > 4 GeV** is applied in the SR)
  Studies of these bgks are done in control samples of events where the prompt μ (l_1) fails the tight ID (12*stat)
  1. DVs containing either no reconstructed lepton (0-lepton) or only one reconstructed lepton (1-lepton) with **m_{DV} < 2.5 GeV** ==> this region is used to estimate, the contribution of hadronic interaction with the material and the contribution of metastable particle decays —> excess in high density material region wrt low density material and OS wrt SS.
     It is **found to be 5% in the SR with m_{DV} > 4 GeV.**



Background estimation - III

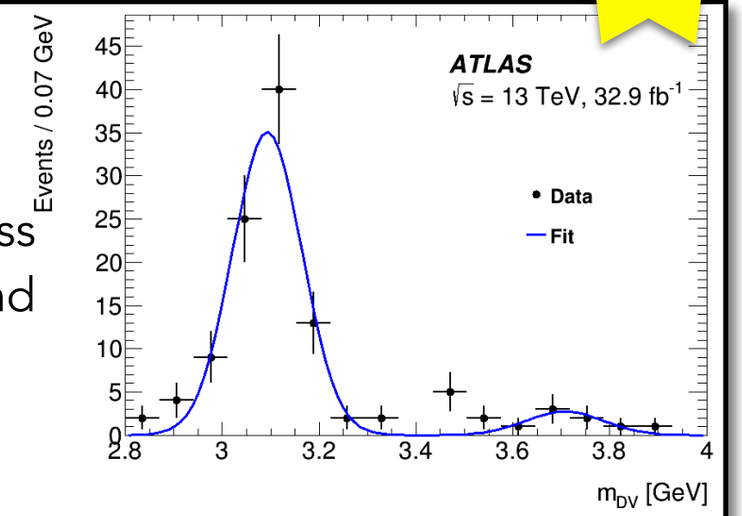
arXiv:1905.09787v1

NEW

New results presented at LHCP on 23rd May!!!!!!

- Hadronic interaction with the material, **decays of metastable particle** (**M_{DV} > 4 GeV** is applied in the SR)

2. DVs containing 2 μ, peaks in the m_{DV} distribution are observed at the mass value of the J/ψ and ψ(2S) mesons. A contribution of less than 0.005 background events from J/ψ and ψ(2S) decays is estimated in the signal region.



- **Background from accidental crossing, including cosmic ray μ**

To estimate the number of background events in the SR, with OS DVs, **the control region with SS DVs, is used**.

—> transfer factor from 0-lepton DVs to 2-lepton DVs measured in SS control region. Unbiased estimate of all backgrounds remaining after the selection for which the ratio of 2-lepton background DVs to 0-lepton background DVs does not depend on the DV charge configuration.

N.B.: not single cosmic-ray muons reconstructed as back-to-back muons nor decays of neutral hadrons

Validation done in sample of 1-lepton DVs.

Leptons in DV	Same-charge DV	Opposite-charge DV	Opposite-charge DV estimated
2	0	0 (signal region)	< 2.3 at 90% CL
1 (μ)	83	89	82.4±9.0
1 (e)	28	35	27.8±5.3
0	169254	168037	

Systematics

The uncertainties on the final yields are calculated by varying the MC event weights according to the data-MC efficiency difference for each nonprompt lepton (i.e. two per event), as a function of:

- the number of missing inner hits (for electrons)
- the SV transverse displacement (for muons).

NEW

- Reconstruction efficiency of displaced tracks, **15%**
  - Dominant systematics in ATLAS search
  - Use sample of K^0_s (select two-pion in invariant mass window 488-508 MeV) (no high-mass DVs)
  - Parameterized
  - From data/MC comparison, extract DV-level weights in bins of r_{DV} and ΣpT
  - Apply those weights to signal MC and check difference in efficiency
- Displaced lepton ID efficiency, **5%**
- uncertainties in the modelling of lepton kinematic distributions and individual decay branching ratios, **10%**
- Prompt-lepton reconstruction and identification, **1%**

Total systematic uncertainty is 24%

Re-weighting procedure

The values of M_N and $|V_{\ell N}|^2$ do not only determine the HNL production cross section, but also its mean lifetime and, consequently, its kinematics, acceptance, and reconstruction efficiency. For a fixed value of M_N, therefore, a simple cross section rescaling is not sufficient to correctly reproduce the behavior of other HNLs with same mass and different $|V_{\ell N}|^2$. To this purpose, a per-event re-weighting technique based on the HNL lifetime is used. This properly accounts for all the variations in kinematics and acceptance.

First, we notice that the average kinematics of a HNL decay is entirely defined by the HNL mass M_N, its momentum $p_N = \beta\gamma M_N$, and its decay length, independently of its mean lifetime τ_N. Therefore, given a simulated HNL sample of mass MN and mean lifetime τ_0, we can reproduce the kinematic distributions of any other HNL with same mass and different mean lifetime τ_1 by simply re-weighting each event—with proper decay time t—by the ratio of probabilities to obtain a lifetime of t for mean lifetimes τ_0 and τ_1:

$$W(t) = \frac{dN_1(t)/dt}{dN_0(t)/dt} = \frac{\tau_0}{\tau_1} \exp\left[-t\left(\frac{1}{\tau_1} - \frac{1}{\tau_0}\right)\right].$$

Note that $\tau_0/\tau_1 = |V_{N\ell,1}|^2/|V_{N\ell,0}|^2$, therefore this method allows us to move along the $|V_{N\ell}|^2$ axis of the $(M_N, |V_{N\ell}|^2)$ plane.