# Search for heavy neutral leptons from $D_s$ decays in CMS

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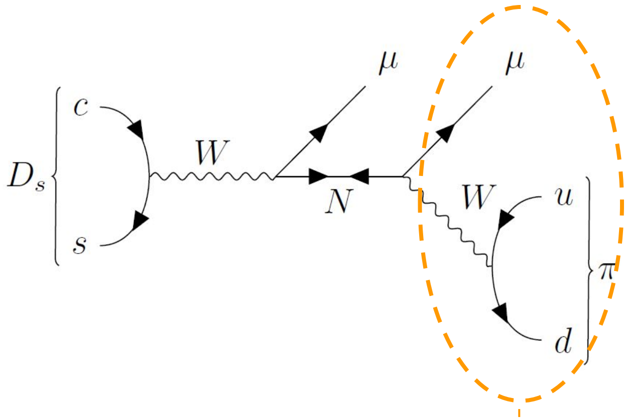
# Outline

Overview of the HNL search from Ds decays

- Data set: 2018 CMS B-Parking data set
- Analysis workflow
- MC: $D_S \to N(\to \mu\pi)\mu$ generation using pythia+evtgen
- Expected limits on the active-sterile neutrino mixing $|V_\mu|^2$

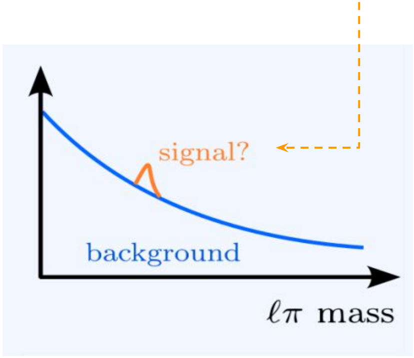
# In a nutshell

- **Search for right-handed neutrinos within νMSM** [1], called heavy neutral leptons (HNL) or simply heavy neutrinos (N)
- assuming **HNL mixing only with $\nu_\mu$** ($|V_e|^2 = |V_\tau|^2 = 0$)
- **production from $D_S$**
  - leptonic decays of $D_S$ ($D_S \rightarrow N$ + lepton) dominate in the HNL production from charmed mesons [2] ➨ using **$D_S \rightarrow N\mu$**
  - sensitive to N mass below $D_S$ mass ($\lesssim$ 2 GeV)
- **decay of N to a fully visible final state** ➨ using **N→μπ**




Fully visible final state allows to :

- reconstruct the secondary vertex formed by the N decay products (**μ and π**)
  - search N decaying within the tracker volume (<1m)
- reconstruct the invariant mass of the N with optimal resolution
  - narrow peak for background rejection and bump hunting
- μμπ must be compatible with the $D_S$ meson mass



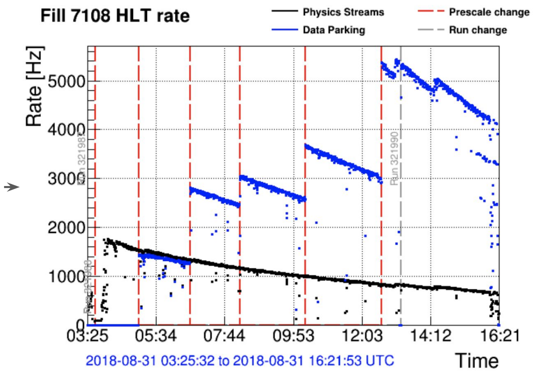

Profiting from **B-parking data collected by the CMS** experiment during 2018 at √s = 13 TeV

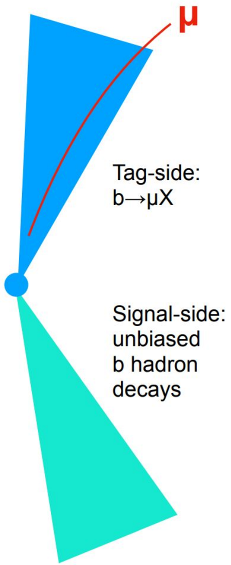

[1] "The νMSM, dark matter and neutrino masses" T. Asaka, S. Blanchet, and M. Shaposhnikov 10.1016/j.physletb.2005.09.070
[2] "Phenomenology of GeV-scale Heavy Neutral Leptons": K.Bondarenko, A.Boyarsky, D.Gorbunov, O.Ruchayskiy 10.1007/JHEP11(2018)032

# 2018 B-Parking data set

**B-Parking data stream**: events were recorded with higher trigger rate, written (parked) to tape and reconstructed at a later stage (DP Note 2019-043)

- HLT rate for the B-Parking stream (blue curve) increases in steps at changes in the prescale column (red dashed) during a CMS run, reaching as high as ~5 kHz



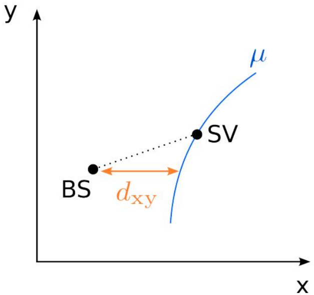

**Trigger logic requires** the presence of at least a **single, non-prompt muon**

- low thresholds on the muon $p_T$ , mainly restricted in $|\eta|<1.5$
- thresholds on impact parameter significance (IP)
- the thresholds evolve during a fill, as the instantaneous luminosity falls

**Large BB(bar) dataset collected**

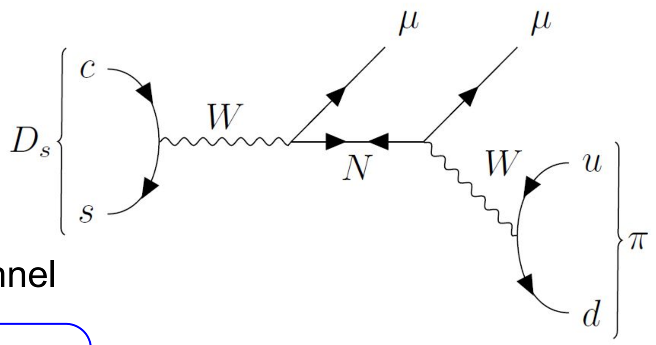
- ~ 10 billion events containing unbiased decays of B hadrons
- Total luminosity of 41.7 /fb at √s = 13 TeV

| B-parking HLT paths |
|---|
| HLT_Mu7_IP4 |
| HLT_Mu8_IP3 |
| HLT_Mu8_IP5 |
| HLT_Mu8_IP6 |
| HLT_Mu8p5_IP3p5 |
| HLT_Mu9_IP4 |
| HLT_Mu9_IP5 |
| HLT_Mu9_IP6 |
| HLT_Mu10p5_IP3p5 |
| HLT_Mu12_IP6 |



# HNL from $D_s$ decays: strategy

- **Exploiting the exclusive $D_s \to N(\to \mu\pi)\mu$ decay**
  - The $D_s$ can be fully reconstructed
  - Inclusive $D_s$ production
  - Sensible to HNL masses below $D_s$ mass
  - exploring $|V_\mu|^2$ down to ~$10^{-5}$
- Signal yield estimated using the **$D_s \to \varphi(\to \mu\mu)\pi$ normalization** channel

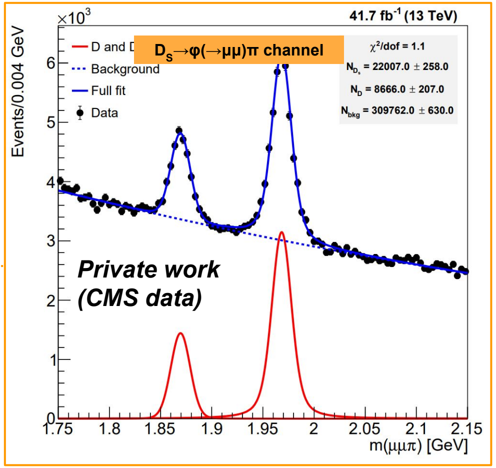



$$N_{D_s^+ \to N\mu^+} = N_{D_s^+ \to \phi\pi^+} \frac{\mathcal{B}(D_s^+ \to N\mu^+)\mathcal{B}(N \to \mu^+\pi^-)}{\mathcal{B}(D_s^+ \to \phi\pi^+)\mathcal{B}(\phi \to \mu^+\mu^-)} \frac{\varepsilon_{D_s^+ \to N\mu^+}}{\varepsilon_{D_s^+ \to \phi\pi^+}}$$

Reconstructed $D_s \to \varphi(\to \mu\mu)\pi$ from data

PDG+theory

Selection efficiency from MC




- $D_s \to N(\to \mu\pi)\mu$ MC samples generated for 1.0 GeV and 1.5 GeV mass points and cτ = 10,100,1000 mm points
  - reweighting signal using HNL proper lifetime for a fine cτ scan
- Background yield estimation from data using HNL mass sidebands

# $D_s \to N(\to \mu\pi)\mu$ simulation

The choice of the event generation setup was driven by what is currently available and fully integrated in the CMS production workflow, which is based on CMS software (CMSSW)

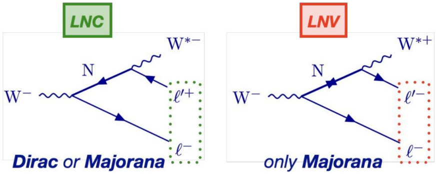
- A first test was done using SHERPA: fully integrated in CMSSW and allowed an easy integration of the heavy neutrino model, however it was not possible to generate the heavy neutrino from $D_s$ meson decays
- HNLs were also integrated in PYTHIA, but the integration is not available in the central PYTHIA software → it was very complicated to integrate it in the full CMSSW-based production workflow
- A final compromise has been found using PYTHIA for the generation of the hard event and EVTGEN as decayer:
  - **PROS**
    - easy to use and fully integrated in the CMSSW software;
    - largely used in the CMS B-Physics community;
    - already in use in a similar analysis searching for HNL from B decays;
  - **CONS**
    - no model for HNLs is available: the HNL is added "by hand" and the $BR(Ds \to N(\to \mu\pi)\mu)=1$
    - no model for spin correlation is available in evtgen for massive neutrinos: a simple phase space model is used to simulate the $Ds \to N(\to \mu\pi)\mu$ decay

# HNL from $D_s$ decays: workflow

MiniAOD —preselection→ Flat nTuples —categorization + optimized cut-based selection→ Selected events —stat. analysis→ Limits

- Signal/background discrimination using QCD MC to model combinatorial background shape

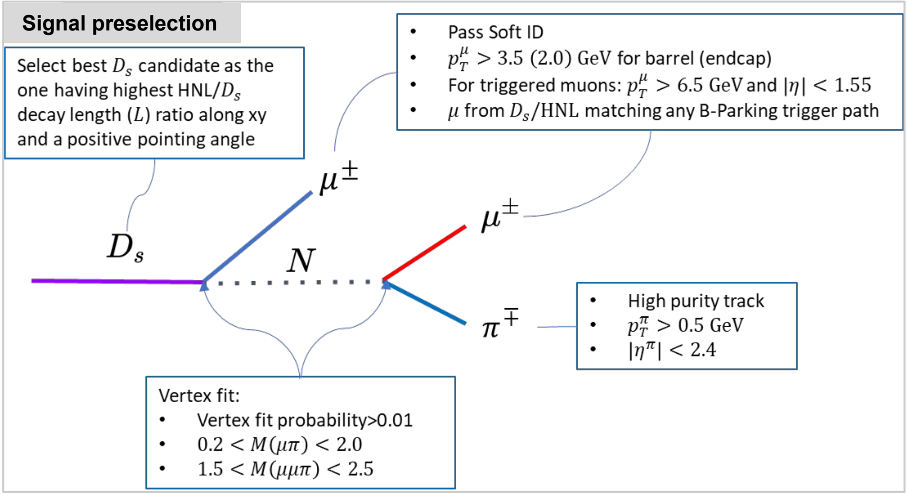
- Event categorization based on:
  - Opposite/Same muon sign

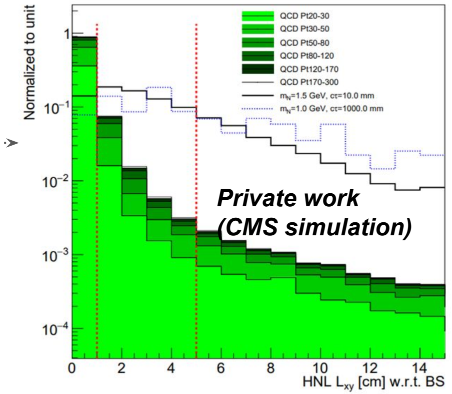



  - HNL displacement $L_{xy}$ in cm: (0,1), (1,5) and (5,∞)

- HNL vertex significance, μ and π IP/IPS used for selection optimization
- Selection cuts optimized maximizing the discovery significance

$$Z_0 = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right)-s\right]}$$

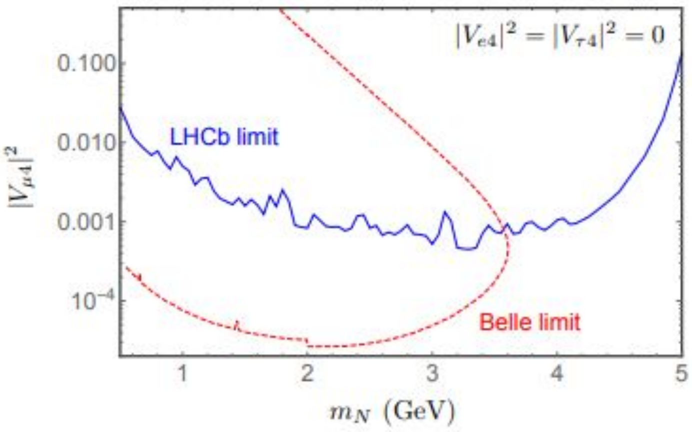


# HNL from $D_s$ decays: results

- The analysis is still blinded!
  - It has till to go through the CMS results approval process

- Expected limit at 95% confidence level on $|V_\mu|^2$
  - for $m_N$=1.0 GeV ~ $10^{-4}$
  - for $m_N$=1.5 GeV ~ $7 \times 10^{-5}$

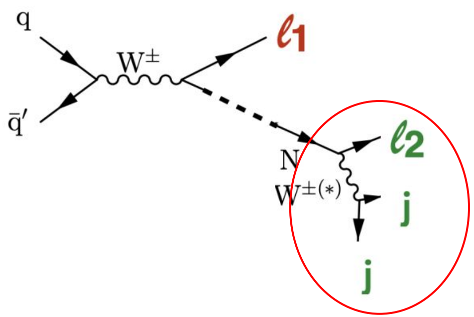



- BELLE “Search for heavy neutrinos at Belle” (2013) 10.1103/PhysRevD.87.071102
- LHCb (2014) 10.1103/PhysRevLett.112.131802 + “Revision of the LHCb limit on Majorana neutrinos” B.Shuve, M. E. Peskin 10.1103/PhysRevD.94.113007

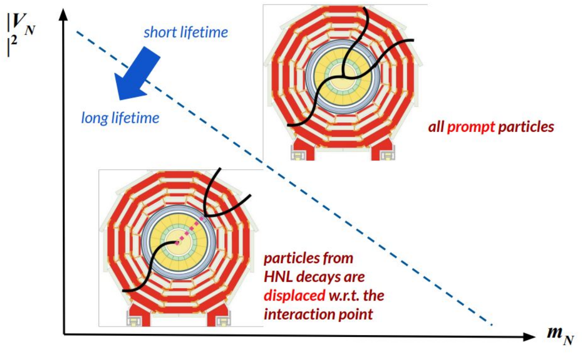
# BACKUP

# Possible involvement in future analyses

- production of N via the decay of W bosons




The HNL lifetime only depends on **mass** and **ν–N coupling**: $\tau \propto \sum_i |V_{iN}|^{-2} m_N^{-5}$




- search for N decaying in the muon detector
  - producing particle showers detected as high multiplicity cluster of muon detector hits
- N with $c\tau$ between 0.5 and 10 m ⇒ probing $m_N$ below 5 GeV
- trigger on high multiplicity hits in muon detector to be developed

# Production from Ds

“Phenomenology of GeV-scale Heavy Neutral Leptons”**:** K.Bondarenko, A.Boyarsky, D.Gorbunov, O.Ruchayskiy 10.1007/JHEP11(2018)032

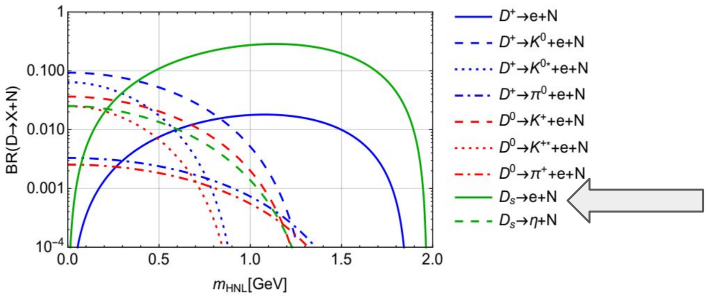



**Figure 4**. Dominant branching ratios of HNL production from different charmed and beauty mesons. For charged mesons two-body leptonic decays are shown, while for the neutral mesons decays are necessarily semi-leptonic. For these plots we take $U_e = 1$, $U_\mu = U_\tau = 0$.

“Probing the Majorana neutrinos and their CP violation in decays of charged scalar mesons π, K, D, Ds, B, Bc ∗ “ G.Cvetic, C.Dib, C. S. Kim, J. Zamora-Saa (2015) https://doi.org/10.48550/arXiv.1503.01358

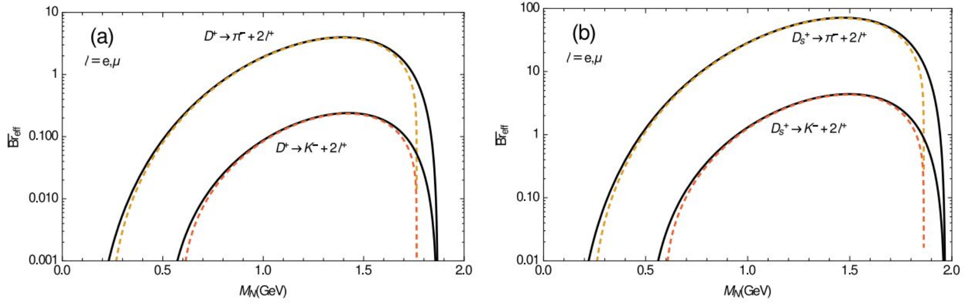



FIG. 5: The same as in Figure 4, but now for the decay of (**a**) $D^\pm$ mesons; (**b**) $D_s^\pm$ mesons. The solid lines are for $\ell = e$, and the dashed lines for $\ell = \mu$.

canonical (i.e., without any mixing dependence) effective BR

detector length L

TABLE III: Values of the factor $\overline{\mathrm{Br}}_{\mathrm{eff}}$, Equation (32), with $L = 1$ m and $\gamma_N = 2$, for some of the LNV decays $M^\pm \to \ell^\pm \ell^\pm \pi^\mp$. The value of $M_N$ is chosen such that the maximal value of $\overline{\mathrm{Br}}_{\mathrm{eff}}$ is obtained (the value of $M_N$ is given in parentheses, in GeV). For $M^\pm = K^\pm$, two different values are given, for $\ell = e$ and $\ell = \mu$. For all other cases, $\ell = \mu$ is taken (when $\ell = e$ the values are similar).

| $M^\pm$: | $K^\pm$ $(\ell = e)$ | $K^\pm$ $(\ell = \mu)$ | $D^\pm$ | $D_s^\pm$ | $B^\pm$ | $B_c^\pm$ |
|---|---|---|---|---|---|---|
| $\overline{\mathrm{Br}}_{\mathrm{eff}}$ | 6.8 (0.38) | 3.8 (0.35) | 3.9 (1.39) | 70. (1.47) | 0.96 (3.9) | 199. (4.7) |

Multiplying this expression by the probability $P_N$ of the decay in the detector, Equation (26), we obtain the effective branching ratio $\mathrm{Br}_{\mathrm{eff}}$

$$\mathrm{Br}_{\mathrm{eff}}(M^\pm \to \ell^\pm \ell^\pm M'^\mp) = P_N \mathrm{Br}(M^\pm \to \ell^\pm \ell^\pm M'^\mp) = \left[\overline{P}_N \left(\frac{L}{1\mathrm{m}}\right) \widetilde{\mathcal{K}}\right] \times \left[4 \frac{|B_{\ell N}|^4}{\widetilde{\mathcal{K}}} \overline{\mathrm{Br}}\right] \quad (31a)$$

$$= \left(\frac{L}{1\mathrm{m}}\right) 4 |B_{\ell N}|^4 \overline{P}_N \overline{\mathrm{Br}} \equiv |B_{\ell N}|^4 \left(\frac{L}{1\mathrm{m}}\right) \overline{\mathrm{Br}}_{\mathrm{eff}} \quad (31b)$$