ATLAS displaced HNL analysis

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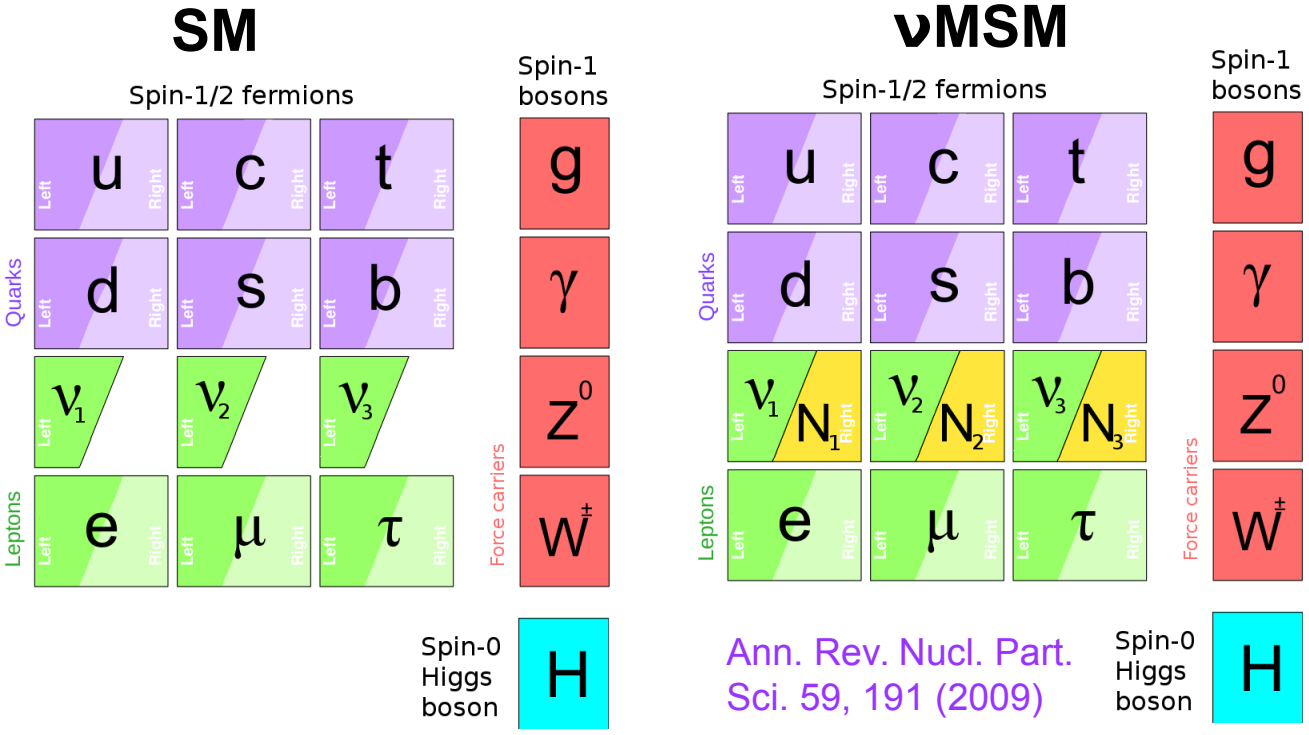
LHCLLP workshop, 29 May 2019



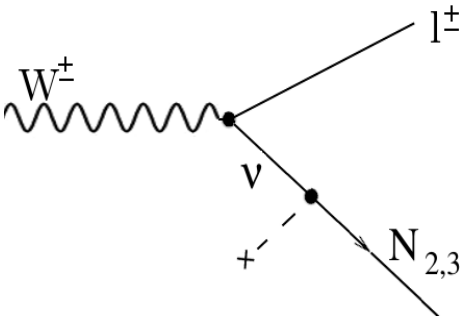
Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

N_1 mass ~keV
→ **dark matter**

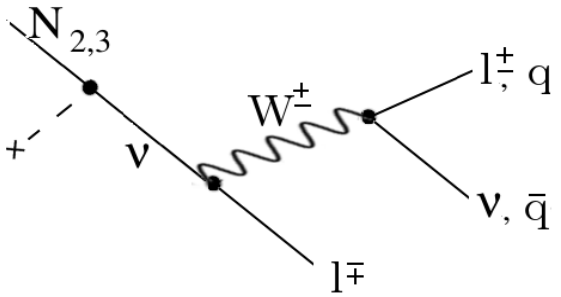
$N_{2,3}$ mass ~GeV
→ **seesaw**
→ **leptogenesis**

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

production

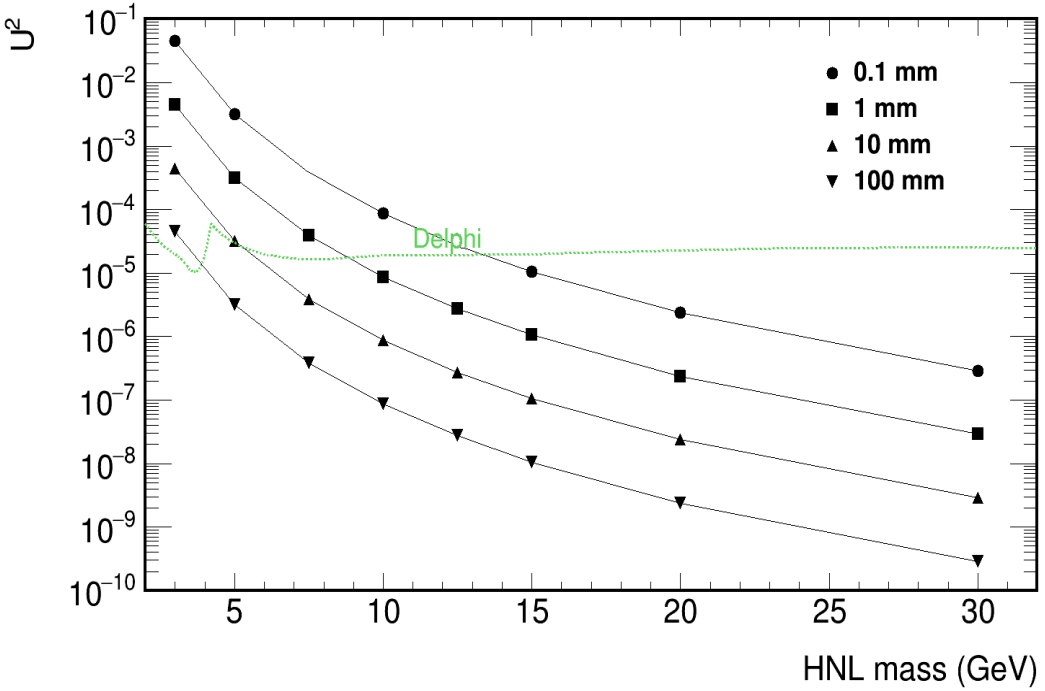


decay



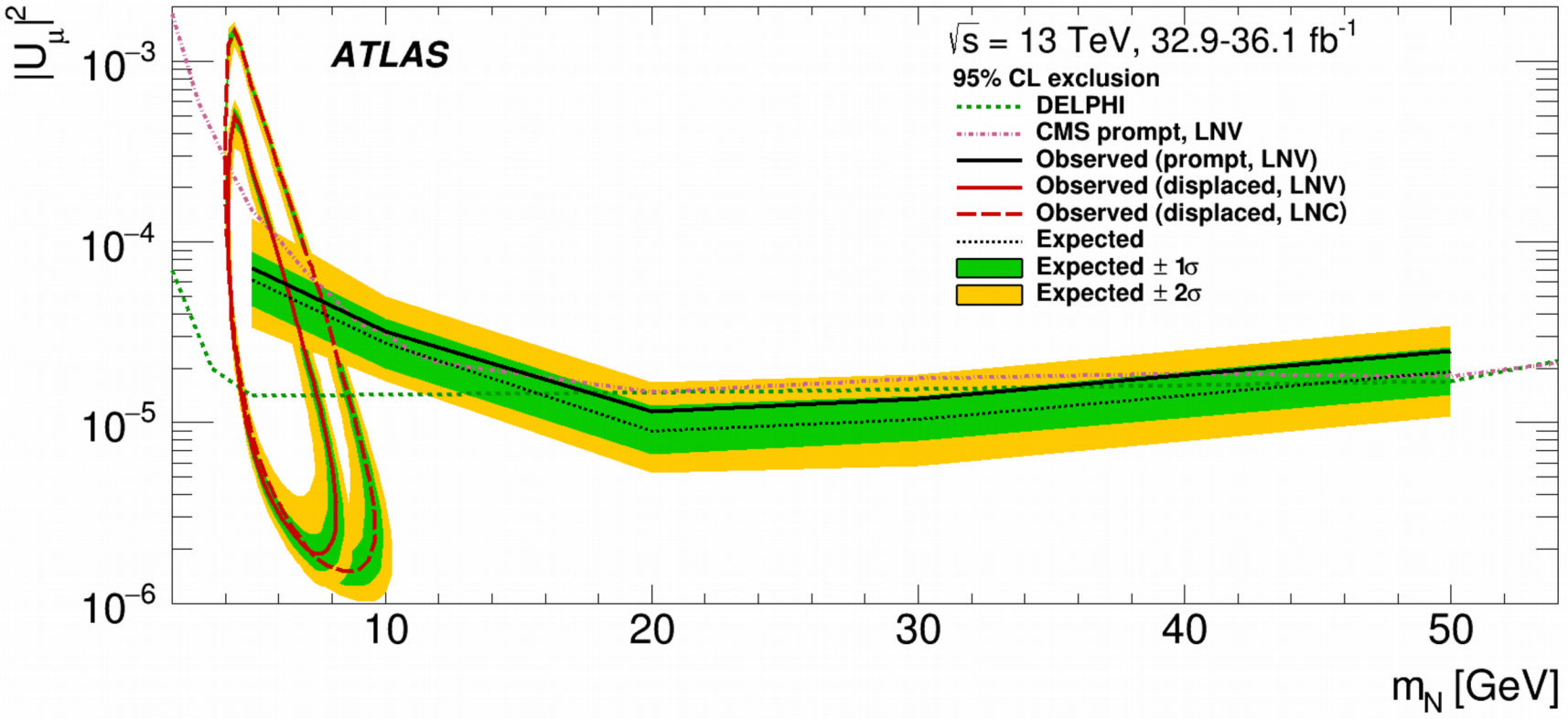
Few cm displacement

- 2016 data suffice to probe HNLs in mass range 5-10 GeV beyond LEP constraints
- High-impact search



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

arXiv:1905.09787



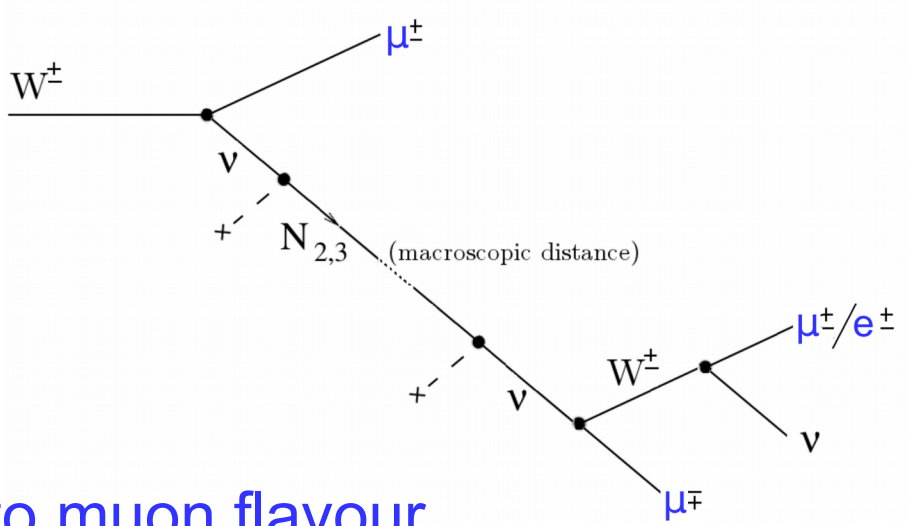
Probe coupling 1 order of magnitude below Delphi

for $5 < m_N < 10$ GeV

Signal MC samples

$$W^{\pm} \to \mu^{\pm} + N \to \mu^{\pm} + \mu^{\mp}\mu^{\pm}\nu_{\mu}$$

$$W^{\pm} \to \mu^{\pm} + N \to \mu^{\pm} + \mu^{\mp}e^{\pm}\nu_{e}$$

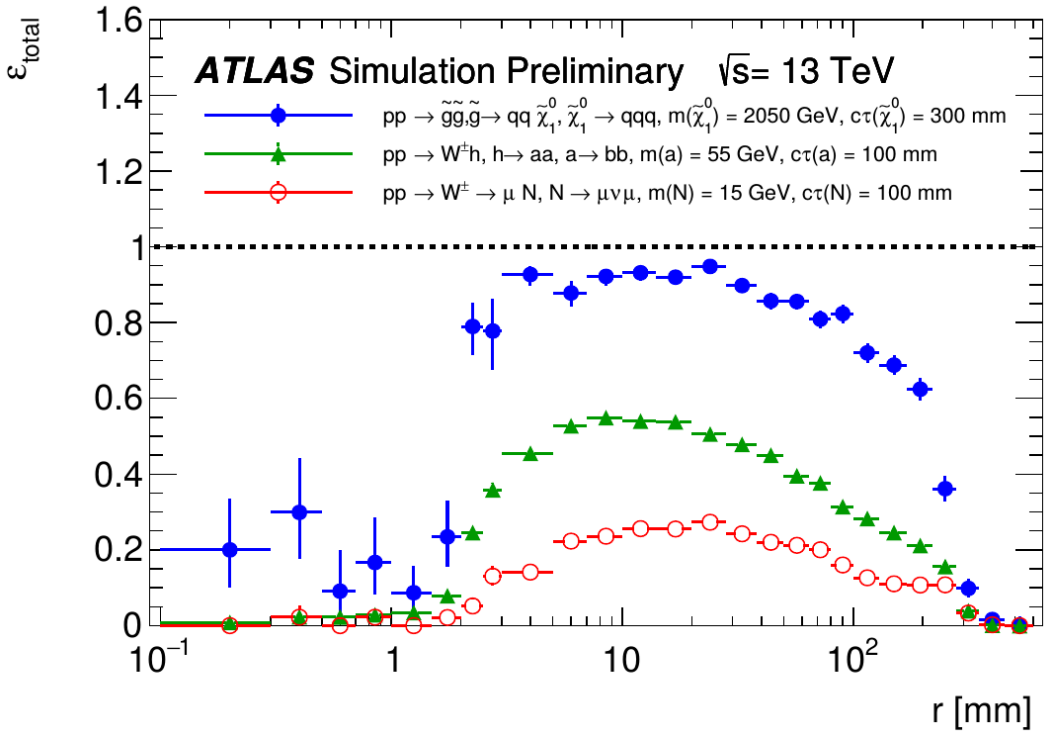


- Pythia generator
- Consider dominant mixing to muon flavour
- Consider only leptonic *N* decays
  - branching ratio = 0.17 ± 0.01
- Neglect contribution of *N* decay to $\mu+\tau+\nu_{\tau}$
- No lepton number violation
  - does not matter in this analysis
- Full simulations with *N* lifetimes of 1, 10, 100 mm

Large-radius tracking

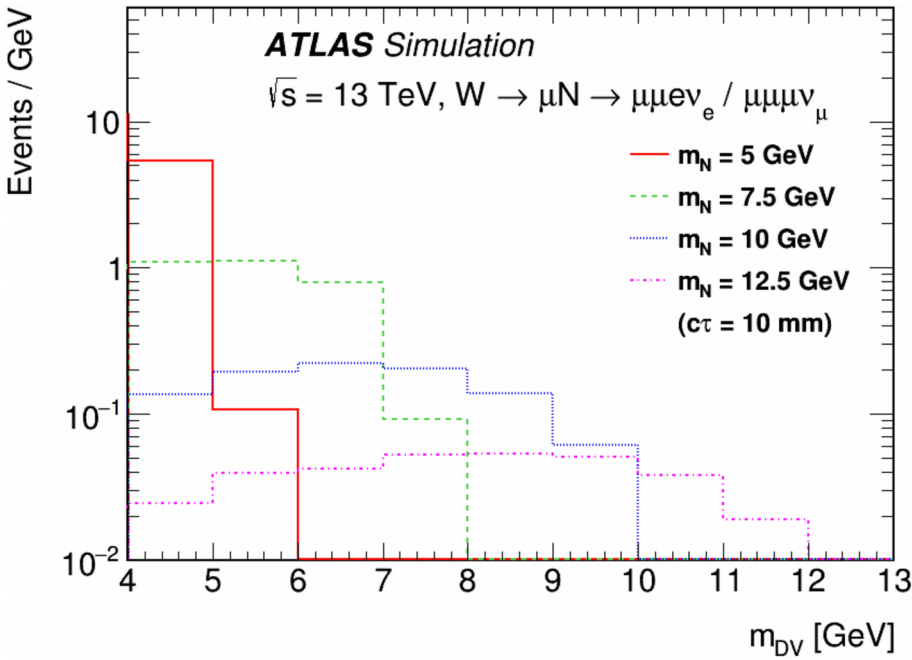
- Special tracking needed to access large-d0 tracks from DV
- Computer-intensive, can be run only on a limited fraction of the RAW data → "filter" selection

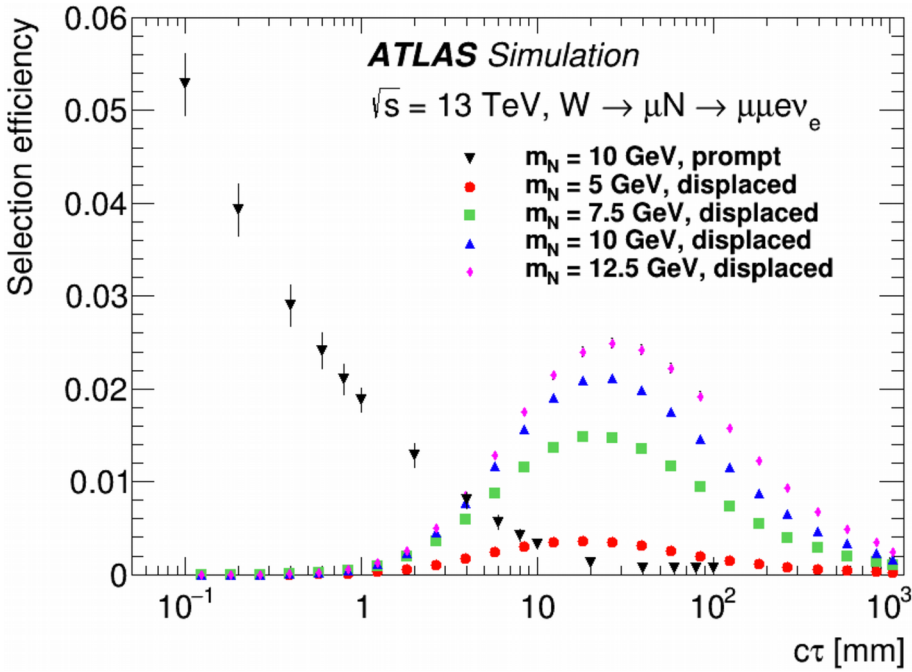
  - Mu26 trigger
  - Combined muon with $p_T > 28$ GeV
  - Second muon with $p_T > 5$ GeV either standalone, or, if combined, either large d0 or large Chi² for ID-MS matching



Offline event selection

- Tight prompt muon
- The DV should satisfy :
  - Within ID fiducial volume
  - Two tracks of opposite charge
  - Two tight leptons (either μμ or μe)
  - Tracks are not back-to-back (cosmic veto)
  - Reconstructed vertex mass m_{DV} > 4 GeV

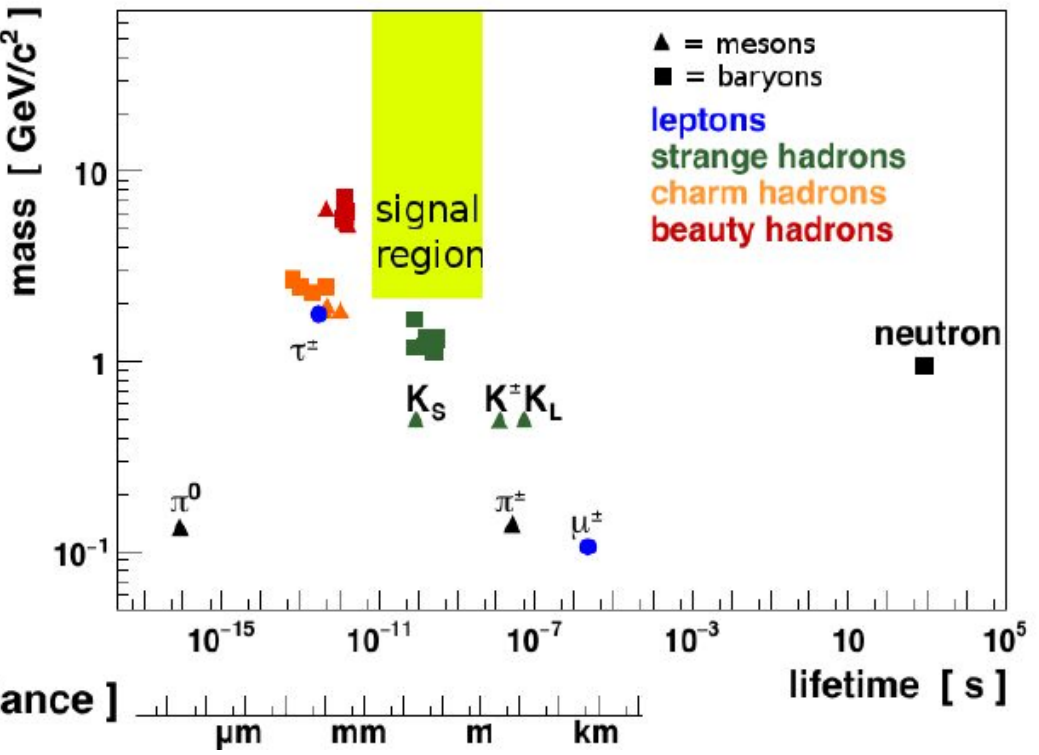




Backgrounds which can produce DVs

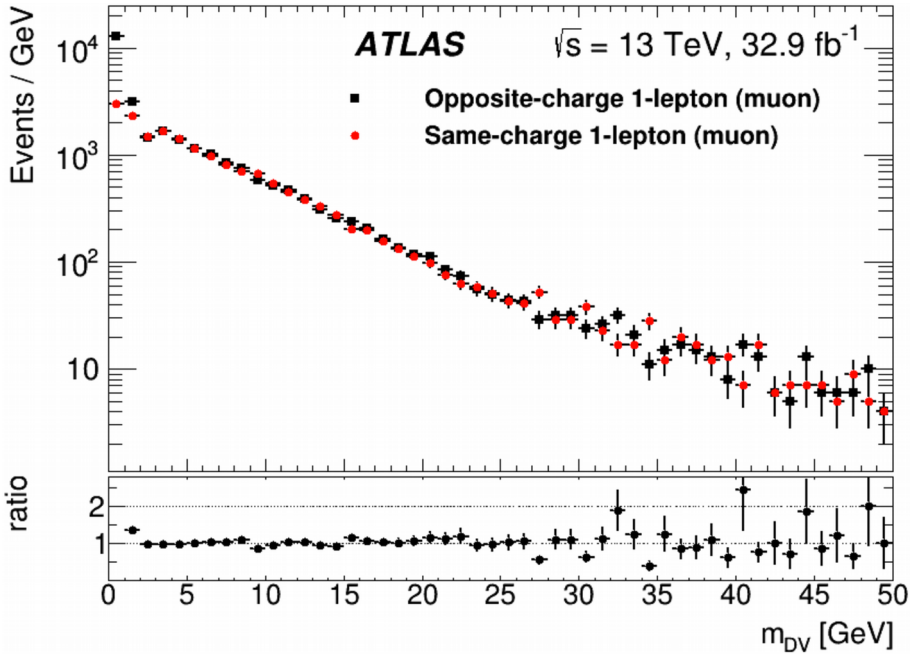
- Hadronic interactions with detector material
- Cosmics producing back-to-back displaced muons
- Metastable particle decays – low mass
- Random crossings of pile-up tracks – largely dominant at high mass (> 3 GeV)

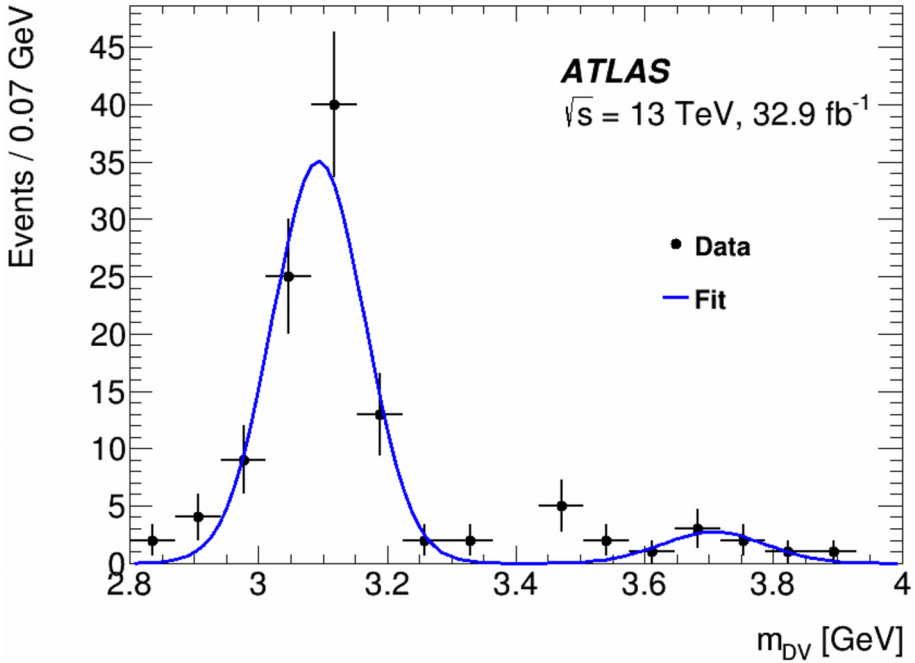
Most of these give hadrons, hence the "tight" lepton ID requirements to reduce fakes



Qualitative background studies

- Statistically enhanced sample (whole DRAW, no material veto: x25 enhancement)
- Fit to J/Psi and Psi(2S) gives 0.04 events at $m_{DV} > 4$ GeV
- No Upsilon candidate found in $m_{DV} \sim 10$ GeV region





Background estimate: same-charge DV control region

- Assumption: presence of high-mass DV does not depend on sign configuration
- 0 events observed in C → A < 2.3 at 90% c.l.
- 1-lepton DV validation (A',C')

	Same-charge DV	Opposite-charge DV
2-lepton DV	C 2μ: 0 μe: 0	A 0
1-lepton DV	C' μ: 83 e: 28	A' μ: 89 e: 35
0-lepton DV	D 169254	B 168037

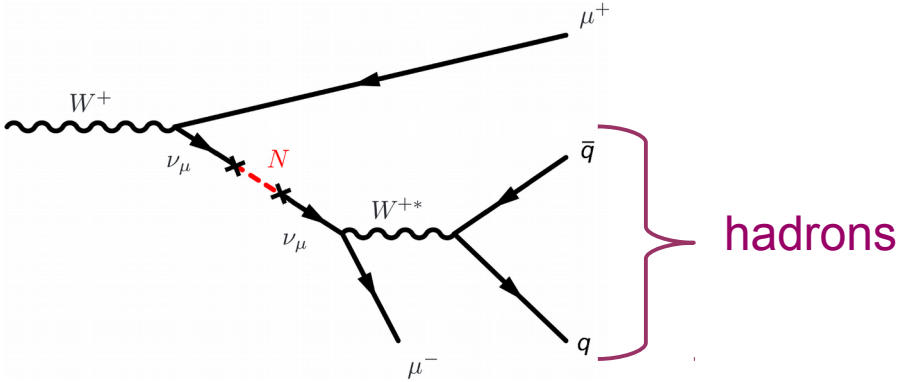
Displaced track reconstruction systematics

- Dominant systematics – dedicated study using K0s
- Comparison between data and MC to extract weight factors in bins of p_T and r_{DV}
- Applying weights → max 15% effect in signal efficiency, used as systematic uncertainty

What next in ATLAS?

- Full run-2 dataset – repeat search in leptonic (muonic) channel, aim at publication this winter
  - Lepton-seeded vertexing algorithm (no d0 cut) → ~30% efficiency increase, but also more backgrounds
- Leptonic electron channel – not started yet (lack of manpower)
- Exploring options for probing lower masses (lack of manpower)
- Semi-leptonic channel – started

Pythia model for HNL semi-leptonic decays



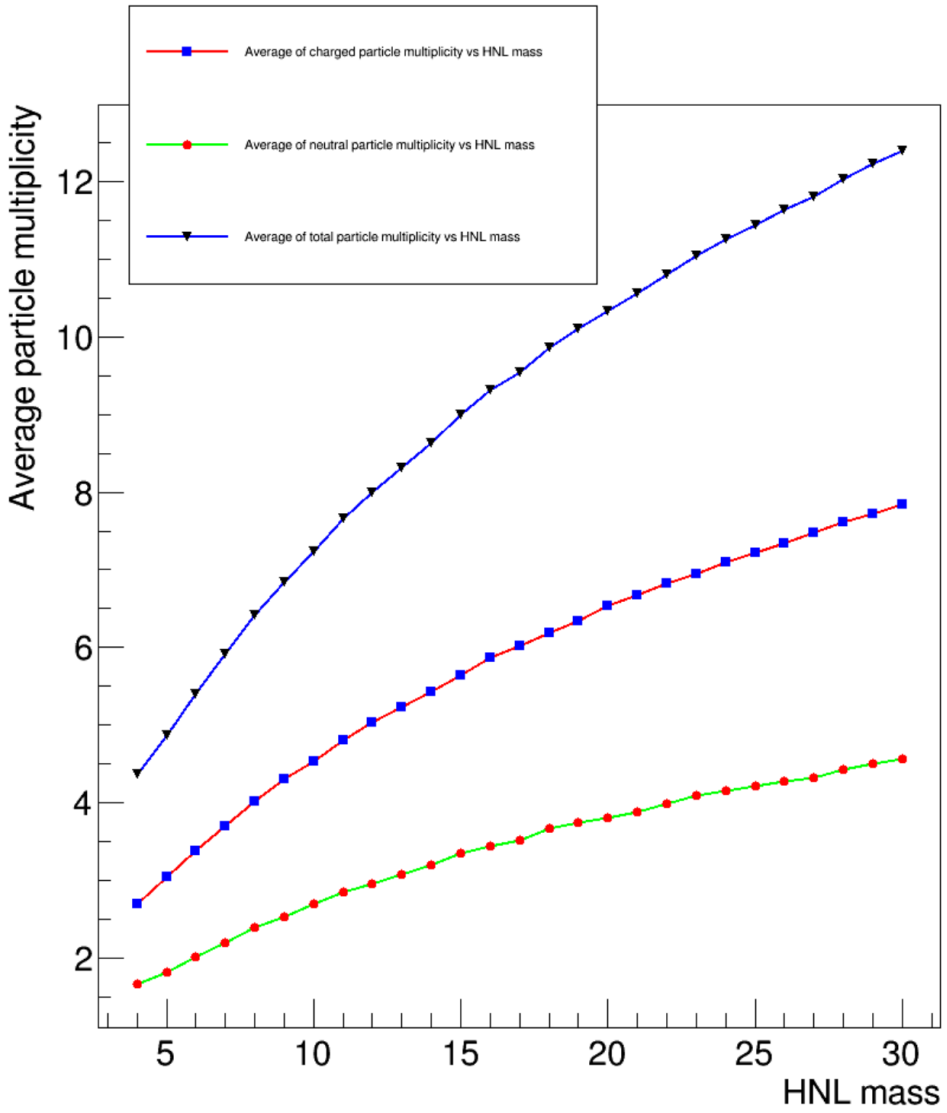
- Current Pythia version does not provide a way to decay virtual W to hadrons, as most decay codes will turn partons into hadrons before doing phase space
- Communicated with Pythia author Torbjörn Sjöstrand, who proposed small fix in Pythia code (ParticleDecays.cc), introducing decay modes 93 and 94 (94 to be used as it takes virtual W into account in the kinematics)
- Change is implemented in the trunk version, and will appear with the next Pythia release
- In the meantime, produced samples privately

Pythia event generation joboptions

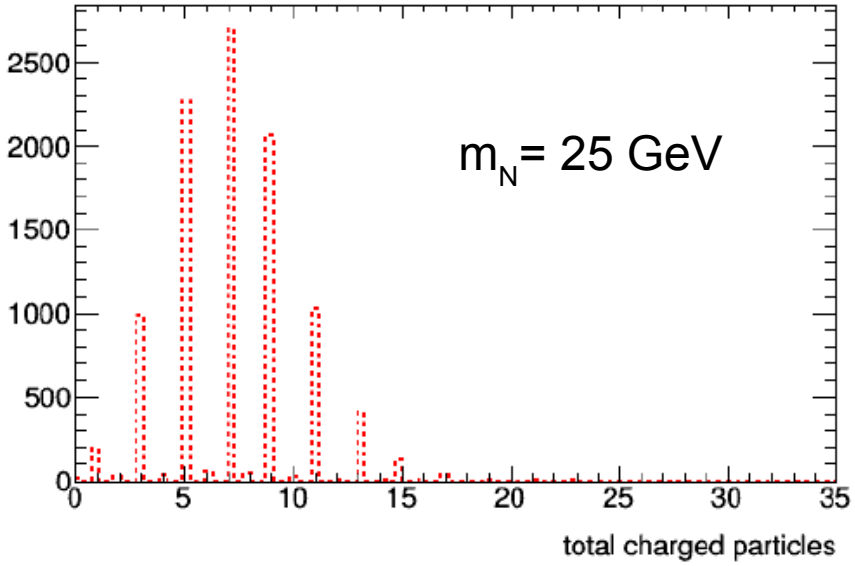
```
## Pythia8 W->mu+HNL

evgenConfig.description = "W->mu+HNL production with the A14 NNPDF23LO tune"
evgenConfig.keywords = ["electroweak", "W"]
evgenConfig.contact = ["Jyoti Prakash Biswal, jyoti.prakash.biswal@cern.ch"]

include("MC15JobOptions/Pythia8_A14_NNPDF23LO_EvtGen_Common.py")

from EvgenProdTools.EvgenProdToolsConf import TestHepMC
genSeq += TestHepMC()
TestHepMC.MaxTransVtxDisp = 200000 #in mm
TestHepMC.MaxTransVtxDispLoose = 300000 #in mm
TestHepMC.MaxVtxDisp = 500000 #in mm

genSeq.Pythia8.Commands += ["50:new = N2 N2 2 0 0 10.0 0.0 0.0 0.0 10.0 0 1 0 1 0",
                            "50:isResonance = false",
                            "50:addChannel = 1 0.1994 94 1 -2 -13",# HNL decay in d ubar mu+
                            "50:addChannel = 1 0.1994 94 -1 2 13", # HNL decay in dbar u mu-
                            "50:addChannel = 1 0.0461 94 3 -2 -13",# HNL decay in s ubar mu+
                            "50:addChannel = 1 0.0461 94 -3 2 13", # HNL decay in sbar u mu-
                            "50:addChannel = 1 0.0007 94 5 -2 -13",# HNL decay in b ubar mu+
                            "50:addChannel = 1 0.0007 94 -5 2 13", # HNL decay in bbar u mu-
                            "50:addChannel = 1 0.0461 94 1 -4 -13",# HNL decay in d cbar mu+
                            "50:addChannel = 1 0.0461 94 -1 4 13", # HNL decay in dbar c mu-
                            "50:addChannel = 1 0.19925 94 3 -4 -13",# HNL decay in s cbar mu+
                            "50:addChannel = 1 0.19925 94 -3 4 13", # HNL decay in sbar c mu-
                            "50:addChannel = 1 0.00845 94 5 -4 -13",# HNL decay in b cbar mu+
                            "50:addChannel = 1 0.00845 94 -5 4 13", # HNL decay in bbar c mu-
                            "50:mayDecay = on",
                            "WeakSingleBoson:ffbar2W = on", # create W bosons
                            "24:onMode = off", # switch off all W decays
          "24:addchannel = 1 1. 103 -13 50",# W decay in mu+ N
          "ParticleDecays:limitTau0 = off", # switch off decaying lifetime limits
          "ParticleDecays:tau0Max = 600.0"]
```

- Added decays to all possible quark species, following CKM matrix elements

Semi-leptonic decays – (truth) hadron multiplicities



- Number of hadrons of order 5-10, among which ~60% charged
- Increases with HNL mass as expected



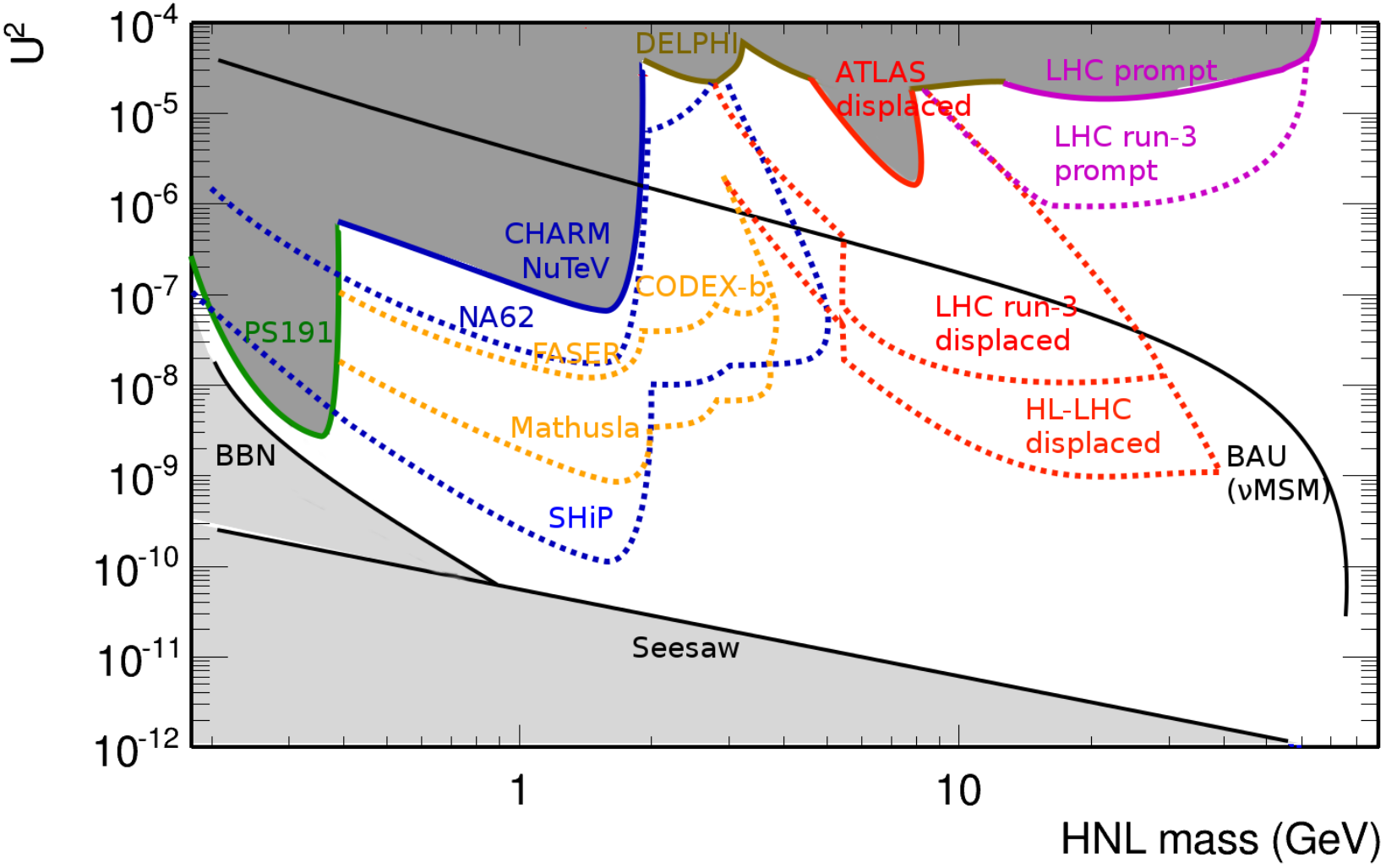
Validation of hadron multiplicities

- Near the non-perturbative regime
- Generate HNL decays via virtual Z, with HNL mass of 15 GeV
- Select window in invariant mass of all hadrons around 10 GeV
- Compare with existing data of e^+e^- annihilation at the same invariant mass
- Need to be careful to include decay products for $c\tau < 10$ cm

Average multiplicities	e^+e^- data (PDG)	our Pythia model
$\pi^\pm$	6.52 ± 0.11	6.04 ± 0.04
π^0	3.2 ± 0.3	3.43 ± 0.03
$K^\pm$	0.95 ± 0.02	1.09 ± 0.02
K^0	0.91 ± 0.05	1.01 ± 0.06

- Reasonable agreement

Outlook


U²
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
1
10
HNL mass (GeV)
DELPHI
ATLAS displaced
LHC prompt
LHC run-3 prompt
CHARM
NuTeV
CODEX-b
NA62
PS191
FASER
LHC run-3 displaced
HL-LHC displaced
Mathusla
BBN
BAU (νMSM)
SHiP
Seesaw