



# Search for heavy neutral leptons, RH neutrinos and long-lived particles in CMS

*Moriond EW 2018, 10-17 March, La Thuile*

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On behalf of the CMS Collaboration

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*March 16th, 2018*



# Searches in this talk

- Focus on a selection of recent results :
  - Heavy neutral leptons :
    - Trilepton channel (CMS-EXO-17-012) arXiv:1802.02965
    - Same-sign dilepton channel (CMS-PAS-EXO-17-028)
  - Right-handed neutrinos :
    - WR  $\rightarrow \ell\ell jj$  (CMS-PAS-EXO-17-011)
  - Long-lived particles :
    - Stopped long-lived particles (CSM-EXO-16-004) arXiv:1801.00359
    - Disappearing tracks (CMS-PAS-EXO-16-044)

Other related CMS talks @Moriond :

- Willem Verbeke on HNL
- Claudia Seitz on prompt RPV SUSY scenarios

These results are just a fraction of the CMS searches.. to read more :  
<http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html>

# Heavy neutrinos

- SM very successful but neutrino sector not completely accommodated (e.g. neutrino oscillations)
- Right-handed neutrinos missing in SM → added with **neutrino Minimal Standard Model ( $\nu$ MSM)**

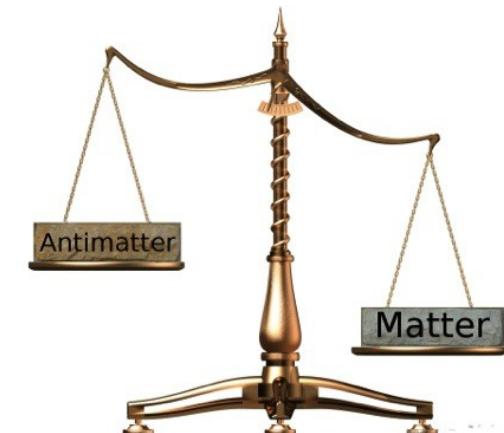
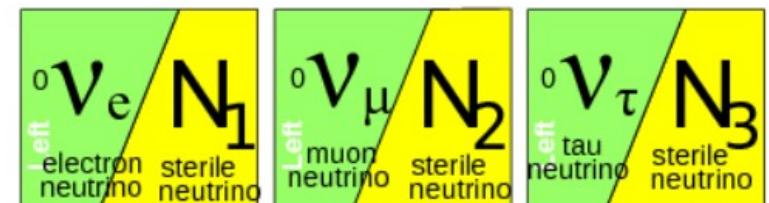
- **sterile** heavy neutrinos

- interact only with the light active ones through mixing  $\theta^2 \sim m_\nu/m_N$

- possible solution for long-standing puzzles :

- origin of **SM neutrino masses** via **seesaw mechanism**
    - $N_1$  ( $m \sim \text{keV}$ ) = **dark matter candidate**
    - degenerate  $N_2$  and  $N_3$  ( $1 < m < 100 \text{ GeV}$ ) = possible explanation for **matter-antimatter asymmetry** of the Universe

- can be searched for at LHC



# Heavy neutrinos

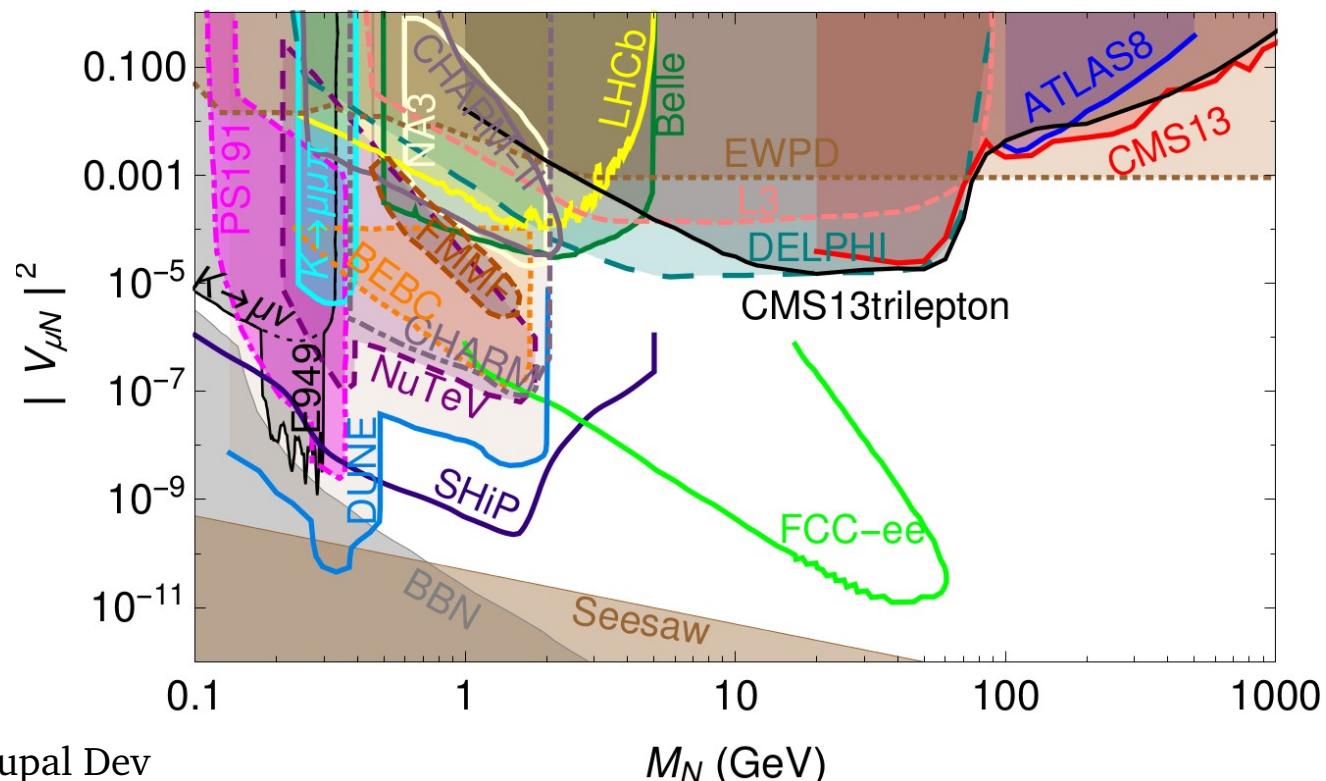
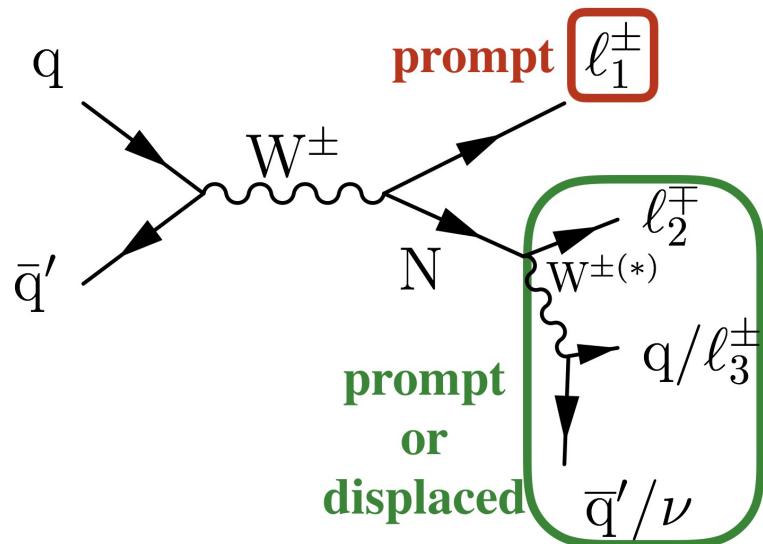
- SM very successful but neutrino sector not completely accommodated (e.g. neutrino oscillations)
- Right-handed neutrinos missing in SM → added with **Left-Right symmetric model** :

$$SU(3)_C \times SU(2)_L \times \textcolor{green}{SU(2)_R} \times U(1)$$

- 3 additional gauge bosons :  $W_R^{+/-}$ ,  $Z'$
- 3 heavy RH neutrinos  $N_l$  ( $l = e, \mu, \tau$ )
- possible explanation for :
  - parity violation in weak interactions
  - origin of SM neutrino masses via seesaw mechanism

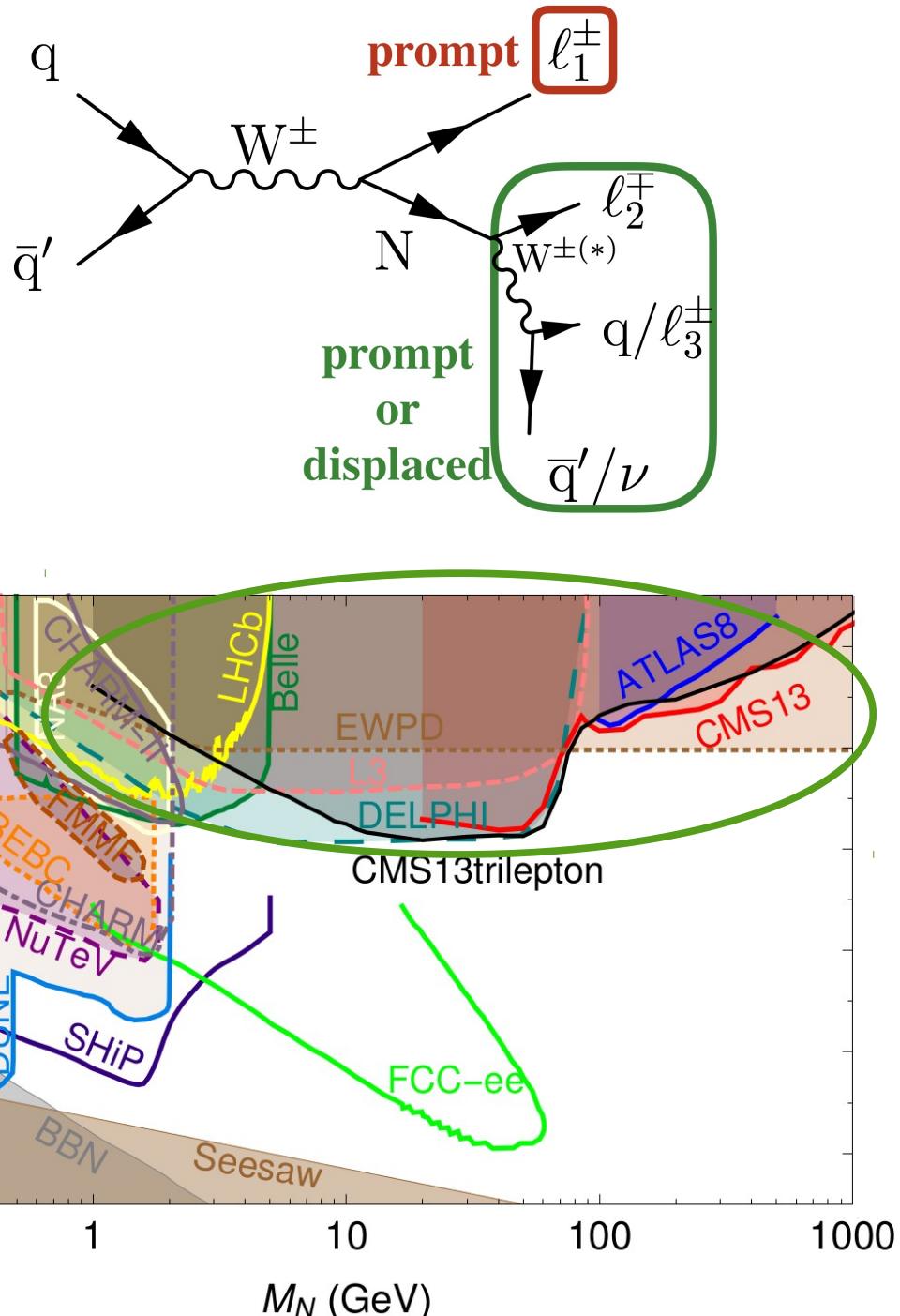
# Heavy neutrinos

- Production :  $W \rightarrow \ell N$ ,  $Z \rightarrow \nu N$ ,  $H \rightarrow \nu N$ , ...
- Decay :  $N \rightarrow W^{(*)} \ell$  (experimentally more accessible),  $N \rightarrow Z^{(*)} \nu$ ,  $N \rightarrow H \nu$ , ...
- Lifetime :
  - very small  $\rightarrow$  prompt decays
  - macroscopic distances from production vertex  
 $\rightarrow$  displaced decays for lower couplings at low masses
- Existing constraints (filled area) and future projections (contours) on mixing angle and mass:



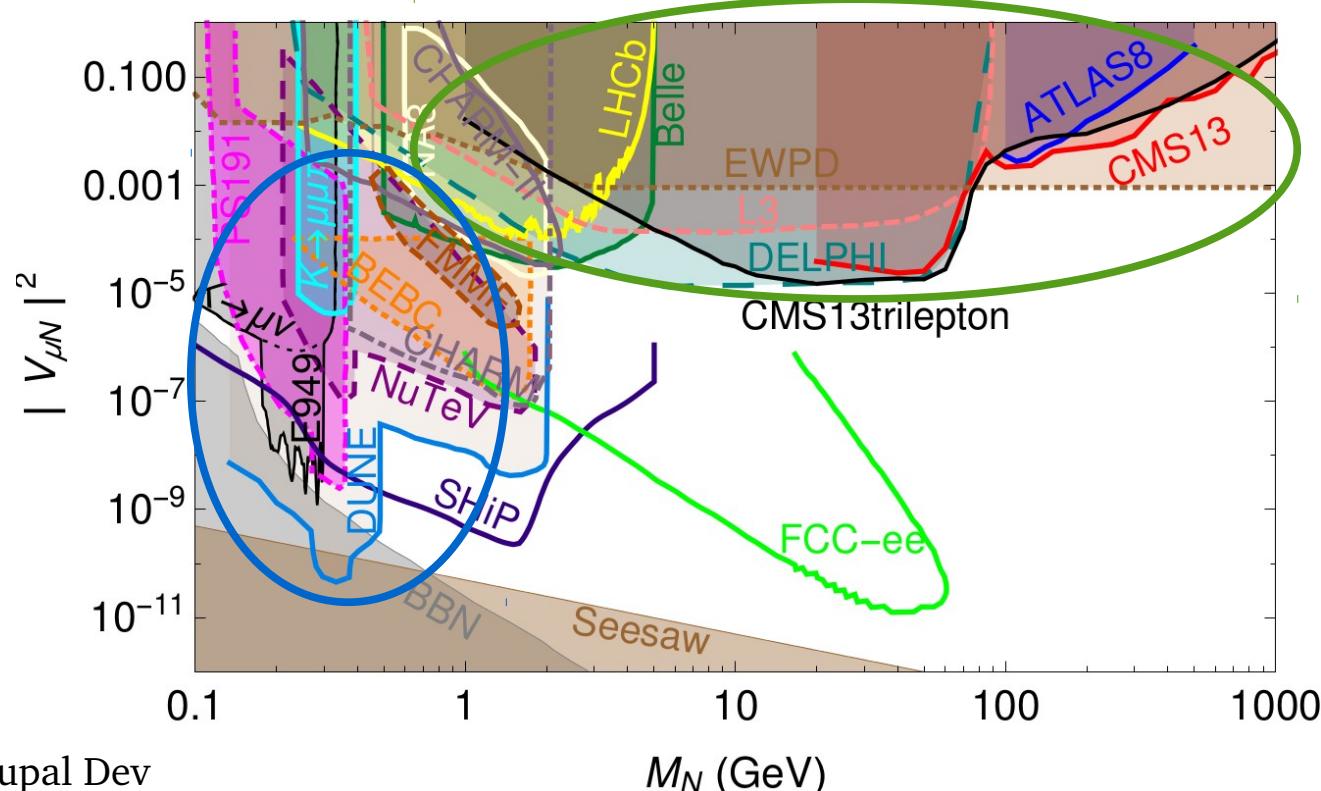
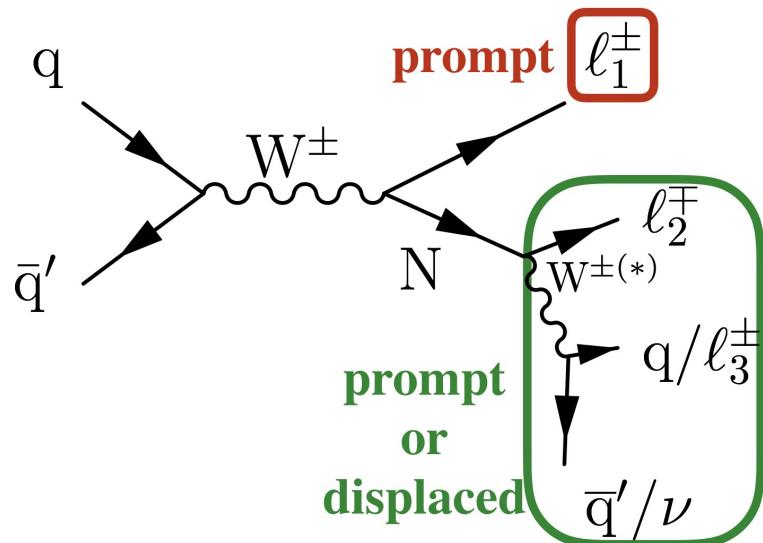
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# Heavy neutrinos

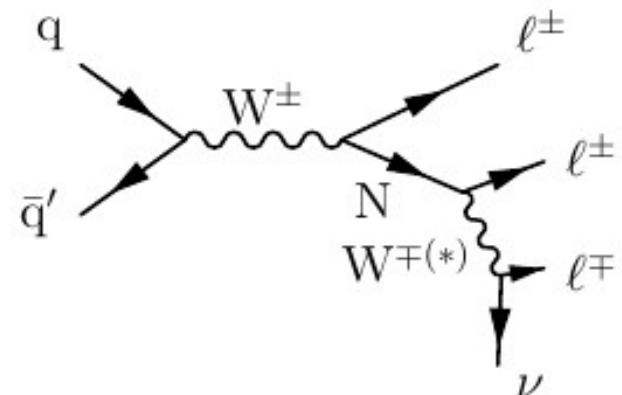
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# HNL: trileptons final state

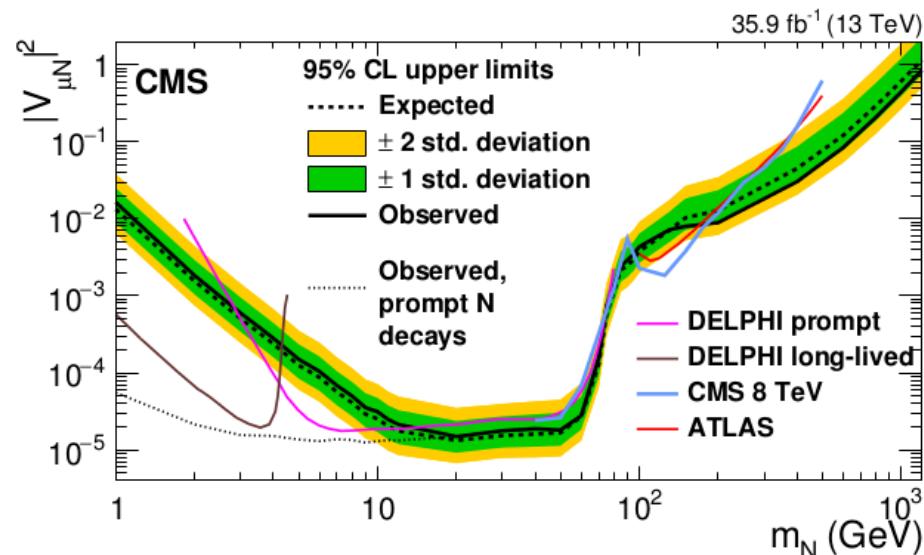
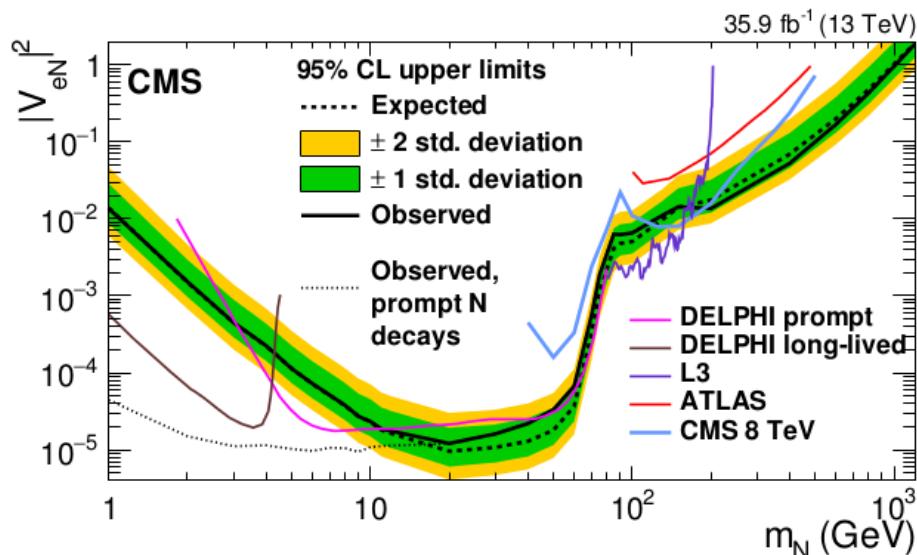
- Signature: 3 leptons ( $p_T > 5$  GeV) + missing  $E_T$
- Main backgrounds :
  - non-prompt leptons (DY+jets,  $t\bar{t}$ )
  - prompt trileptons ( $WZ \rightarrow 3\ell\nu$ ,  $ZZ \rightarrow 4\ell..$ )
  - conversions ( $Z\gamma^*$  with  $\gamma^* \rightarrow \ell\ell$ )

CMS-EXO-17-012



- Limits set on mixing parameters  $|V_{eN}|^2$  and  $|V_{\mu N}|^2$
- $\rightarrow 1.5 \times 10^{-5} - 1.8$  for  $1 \text{ GeV} < m_N < 1.2 \text{ TeV}$

2016 data @ 13 TeV  
(lumi =  $35.9 \text{ fb}^{-1}$ )



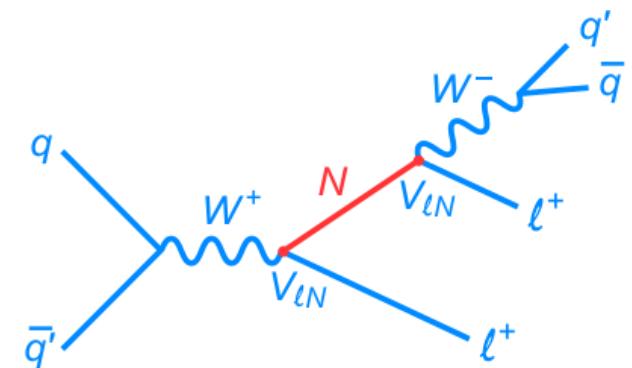
- For details: see W. Verbeke's talk

# HNL: SS dileptons final state

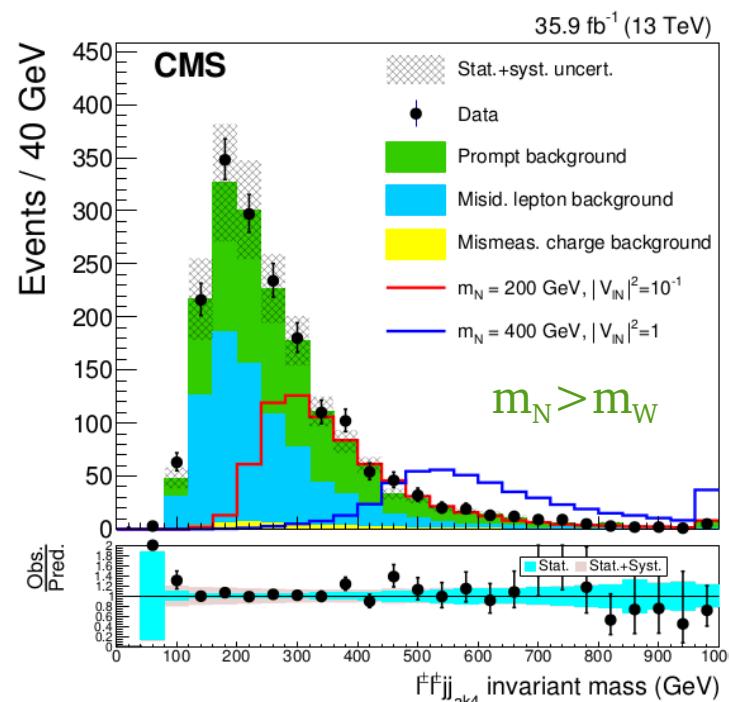
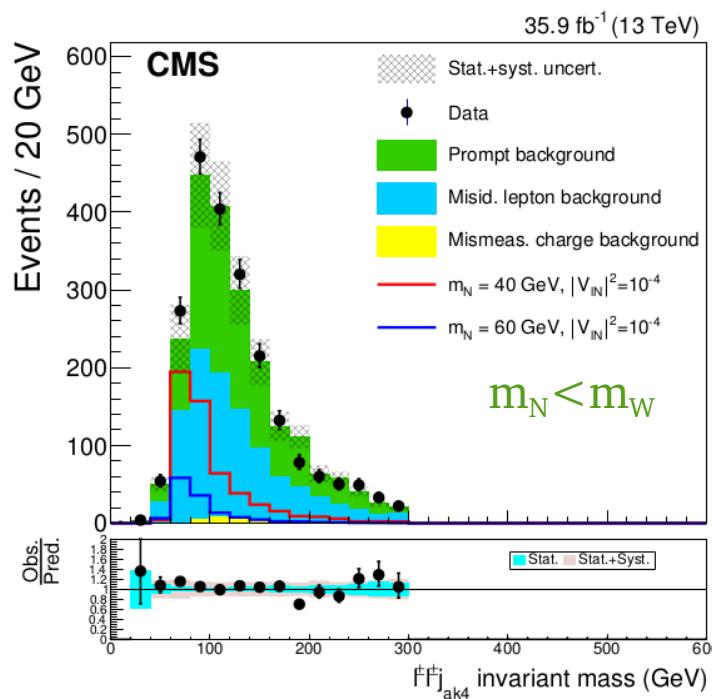
- Signature: 2 SS leptons ( $p_T > 8$  GeV) + 2 jets

CMS-PAS-EXO-17-028

- same-sign lepton pair possible if Majorana neutrino
- Main backgrounds :
  - prompt leptons ( $WZ$ ,  $ZZ$ ) → from simulation
  - misidentified leptons ( $DY+jets$ ,  $t\bar{t}$ ,  $W+jets$ ) → data-driven estimation
  - mismeasured charge ( $DY$ ) → from simulation
- Cut & count method** → no significant excess observed



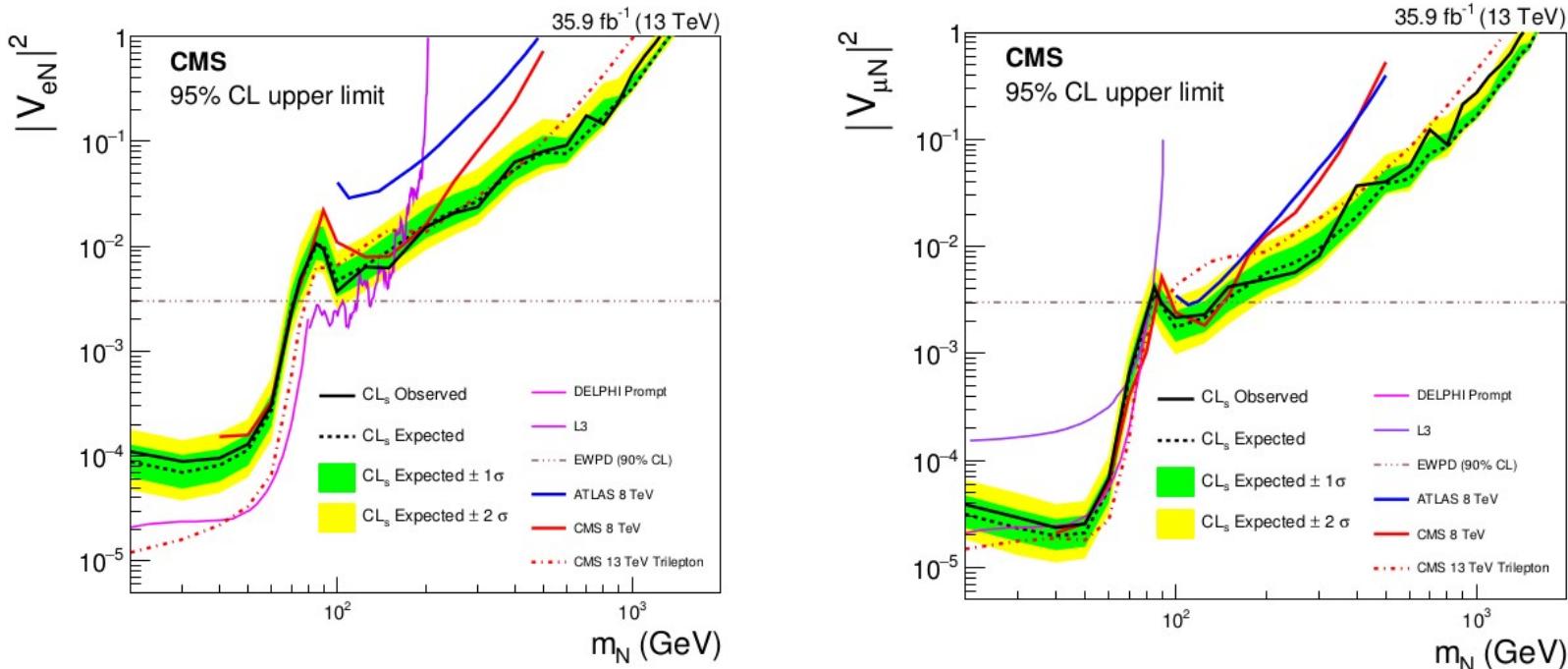
2016 data @ 13 TeV  
(lumi = 35.9  $\text{fb}^{-1}$ )



# HNL: SS dileptons final state

- Limits set on mixing parameters  $|V_{eN}|^2$  and  $|V_{\mu N}|^2$

$\rightarrow 2.3 \times 10^{-5} - 1$  for  $20 < m_N < 1600$  GeV

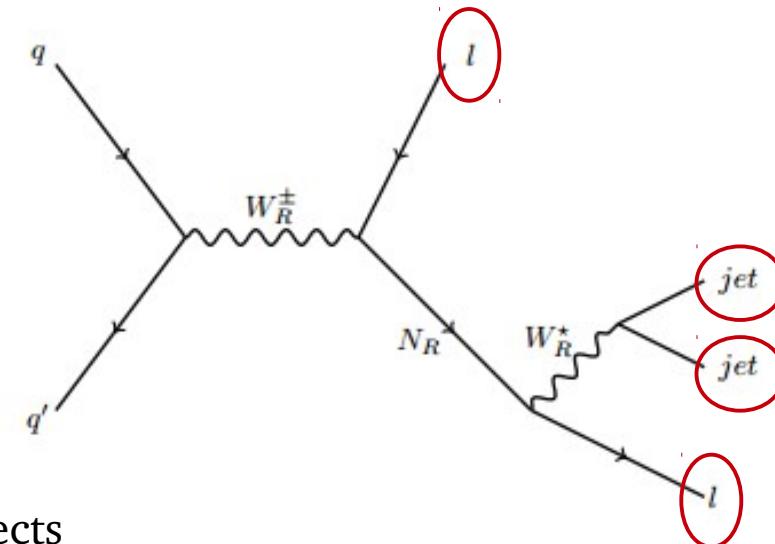


- Comparison with trilepton channel :
  - trileptons have stringent limits for low  $m_N$
  - SS-dilepton have higher sensitivity at high masses
    - $\rightarrow$  most restrictive direct limits for  $m_N > 100$  GeV
    - $\rightarrow$  first limits on mixing parameters for  $m_N > 1.2$  TeV

# RH neutrinos: WR in $\ell\ell jj$ final state

CMS-PAS-EXO-17-011

- LR symmetric model, no flavor changing
- Signatures : 2 electrons + 2 jets, 2 muons + 2 jets
- Selections :
  - 2 high- $p_T$  leptons ( $p_T^{\text{leading}} > 60 \text{ GeV}$ ,  
 $p_T^{\text{subleading}} > 53 \text{ GeV}$ ) and  $|\eta| < 2.4$
  - 2 high- $p_T$  jets ( $> 40 \text{ GeV}$ ) and  $|\eta| < 2.4$
  - $\Delta R > 0.4$  to ensure separation between final state objects
- Signal region requirements :  $m_{\ell\ell} > 200 \text{ GeV}$ ,  $m_{\ell\ell jj} > 600 \text{ GeV}$
- Background estimation :
  - $t\bar{t}$  ( $\sim 75\%$ )  $\rightarrow$  data-driven estimate from e- $\mu$  CR
  - Drell-Yan+jets ( $\sim 20\%$ )  $\rightarrow$  from simulation, normalized to data in Z peak region
  - W+jets, diboson, single top ( $\sim 5\%$ )  $\rightarrow$  from simulation

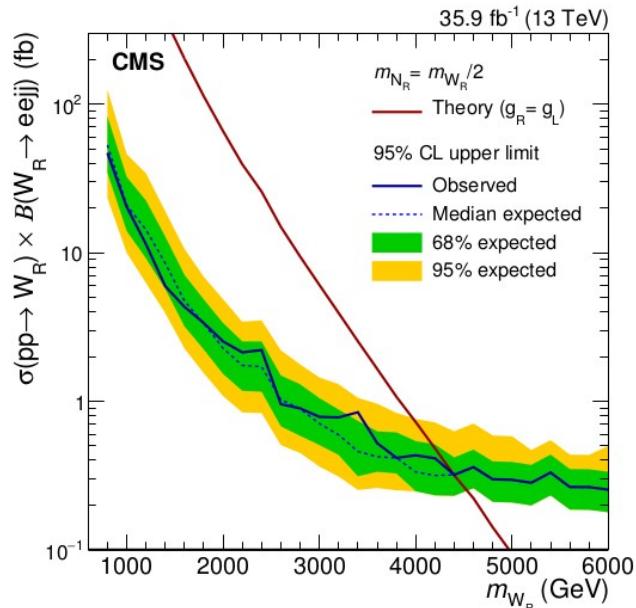


2016 data @ 13 TeV  
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# RH neutrinos: WR in $\ell\ell jj$ final state

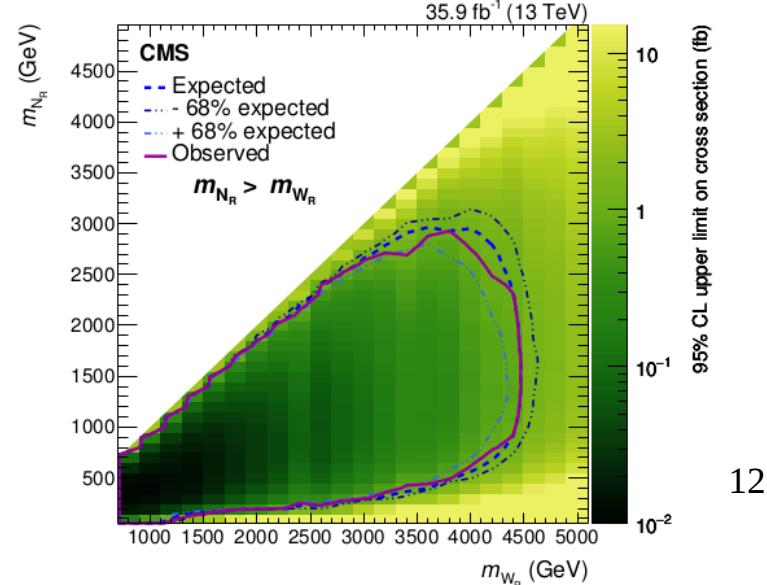
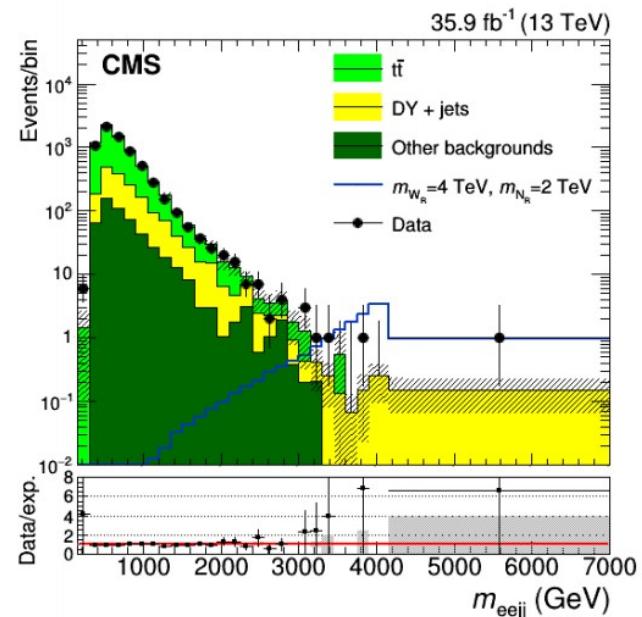
- *Cut & count* limit extraction in different  $m_{\ell\ell jj}$  search regions → no new significant excess observed
- Limits sets on  $m_{W_R}$ , assuming  $m_{N_R} = \frac{1}{2} m_{W_R}$

electron channel  
(similar results for  
muon channel)



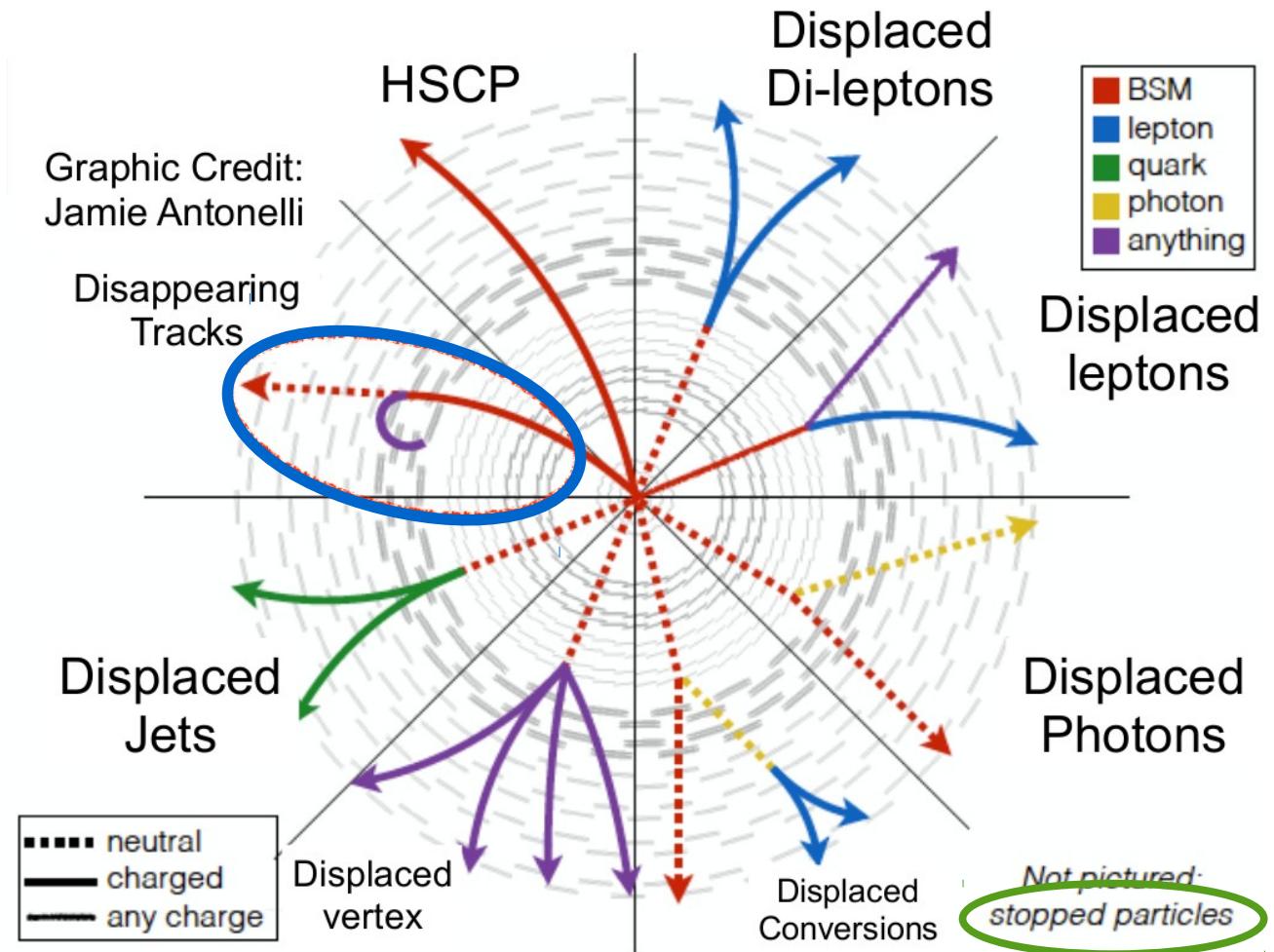
- Limits estimated in 2D plane ( $m_{N_R}$  vs  $m_{W_R}$ ) :

exclude  $m_{W_R} < 4.4 \text{ TeV}$  in both channels → improvement of  $\sim 1 \text{ TeV}$  w.r.t. last public results (2015)



# Long-lived particles

- Long-lived particles (LLPs) are resonances that live long enough to:
  - decay in the detector with a displaced vertex (outside the tracker)  
→ loosing energy via ionization (if charged) or strong interactions (R-hadrons)
  - escape the detector
- Many models predicting LLPs : small couplings (RPV decays), decay through heavy particle ( $Z'$ , split SUSY), small mass splitting (almost degenerate NLSP), ...
- Many different unusual signatures visible in different parts of the detector → many dedicated searches with specialized triggers
- Backgrounds :  
detector noise (material interactions), beam halo particles, cosmic rays



# Stopped long-lived particles

- 2 decays of heavy exotic LLPs coming to rest in the detector (lifetimes  $\sim 100$  ns –  $10^6$  s) :

- hadronic decay detected in the HCAL calorimeter
  - muon decay detected in the muon system →

first search  
at the LHC!

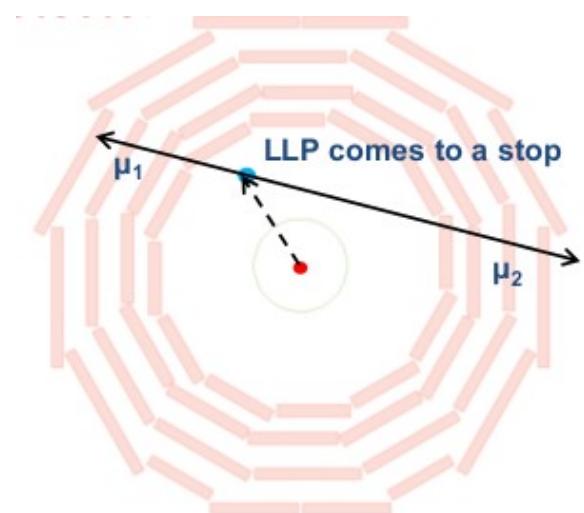
- Signature :

- out-of-time jets = large energy deposits ( $E_{\text{jet}} > 50$  GeV) in barrel calorimeter
  - 2 out-of-time muons = displaced tracks ( $p_T \mu > 40$  GeV)
  - at least 2BX (50ns) away from any proton bunch  
→ decay when no colliding beams present

- Benchmark signal models :

- 2/3-body decay of gluino :  $g \rightarrow g X^0$ ,  $g \rightarrow q \bar{q} X^0$  (“split SUSY”)
  - decay of top squark :  $t \rightarrow t X^0$
  - 3-body decay of gluino :  $g \rightarrow q \bar{q} X^0_2$ ,  $X^0_2 \rightarrow \mu \mu X^0$  (“T3lh” SUSY model)
  - multiply charged massive particles (MCHAMPS) with  $|Q| = 2e$  decaying into 2 back-to-back same-sign muons

CMS-EXO-16-004

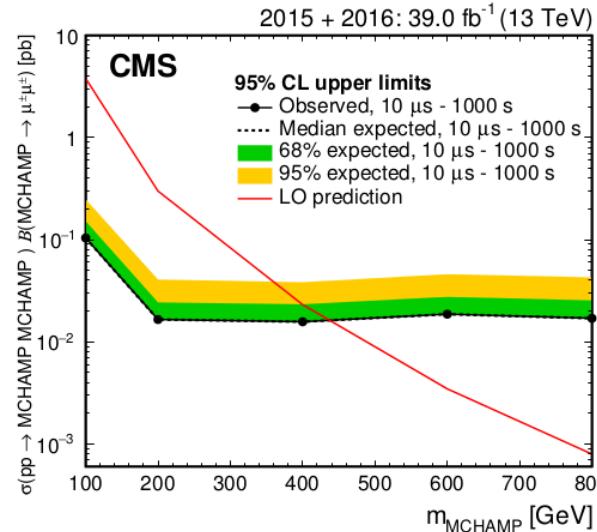
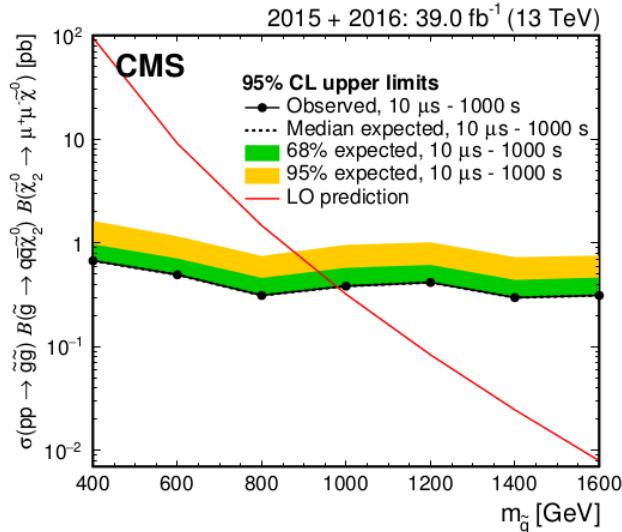
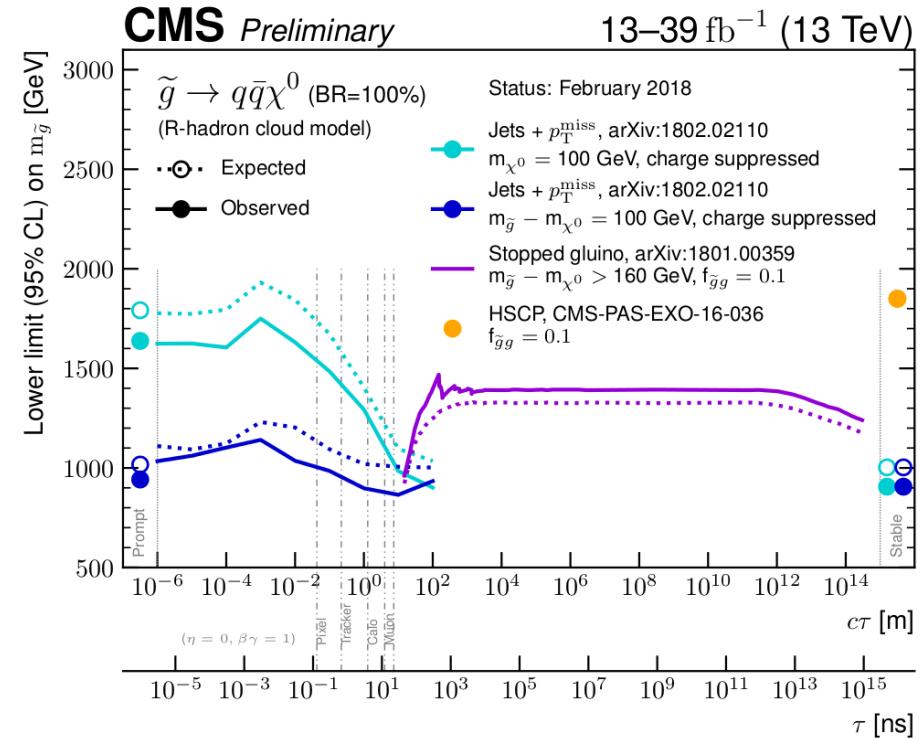


2015 and 2016 data  
@ 13 TeV  
(lumi = 38.6/39.0  $\text{fb}^{-1}$ ,  
search interval = 721/744 h)

# Stopped long-lived particles

- Main backgrounds: cosmic rays, beam halo, detector noise → estimated from control samples in data
- Data events (4 in 2015, 13 in 2016) show no excess over background
- Combining results from 2015 and 2016, for  $10 \mu\text{s} < \tau < 1000 \text{ s}$ , exclusion of :

- gluinos decaying via  $g \rightarrow g X^0$  ( $g \rightarrow q\bar{q}X^0$ ) with  $m_g < 1385(1393) \text{ GeV}$
- top squarks with  $m_t < 744 \text{ GeV}$



- gluinos with  $400 < m_g < 980 \text{ GeV}$
- MCHAMPs with  $|Q| = 2e$  and  $100 < m_{\text{MCHAMP}} < 440 \text{ GeV}$

# Disappearing tracks

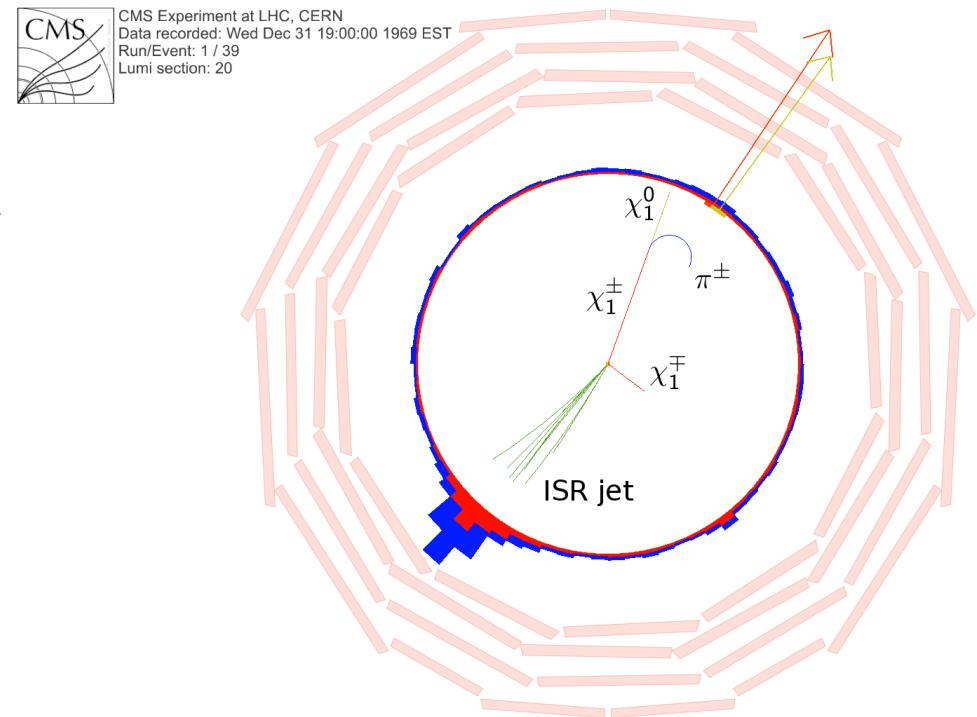
CMS-PAS-EXO-16-044

- LLPs decaying in the inner tracker with very weakly interacting decay products
- Benchmark signal model = anomaly-mediated SUSY breaking (AMSB) :

$$X^\pm \rightarrow \pi^\pm + (\text{LSP/stable}) X^0$$

- small chargino/neutralino mass splitting  
→ long-lived chargino ( $\tau \sim 1$  ns)
- very soft pion ( $p_T \sim 100$  MeV)  
too low to be reconstructed

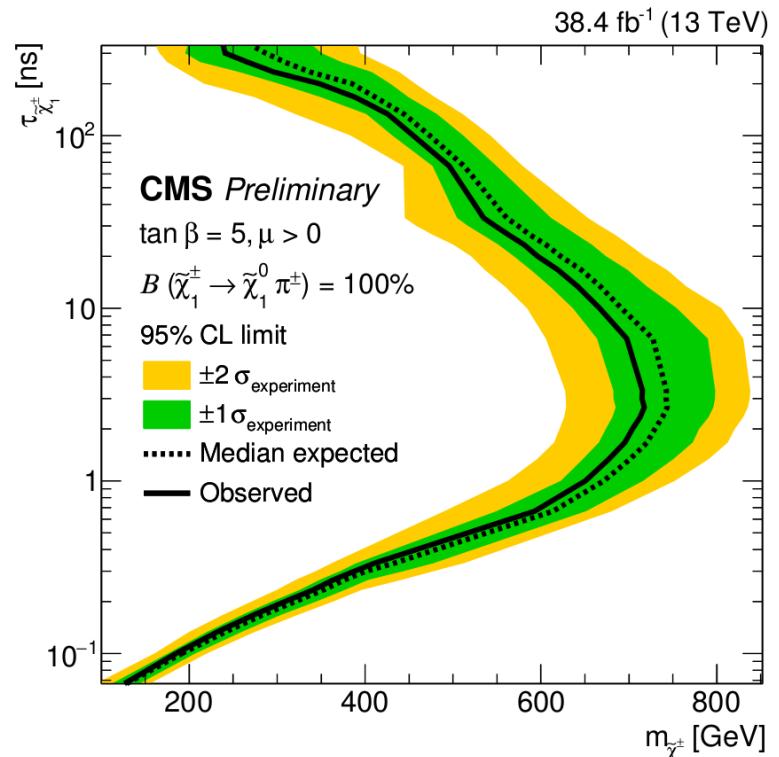
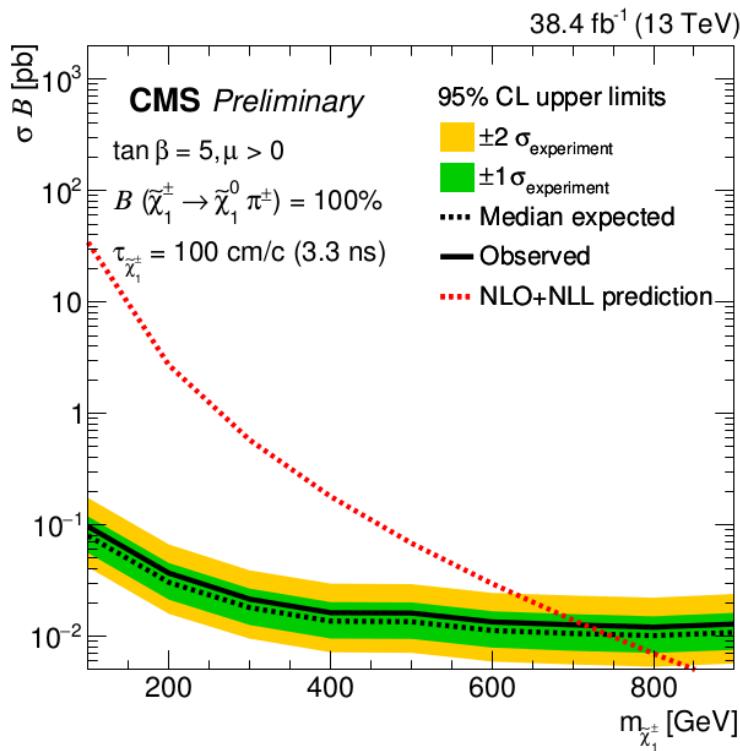
- Disappearing track signature:
  - chargino pair produced with ISR jet
  - missing hits in outer silicon tracker
  - little associated calorimeter energy
  - no hits in muon chambers
- Trigger on  $\text{MET} > 100$  GeV,  $p_T \text{jet} > 110$  GeV,  $p_T \text{track} > 55$  GeV



2015 and 2016 data  
@ 13 TeV  
(lumi = 38.4 fb⁻¹)

# Disappearing tracks

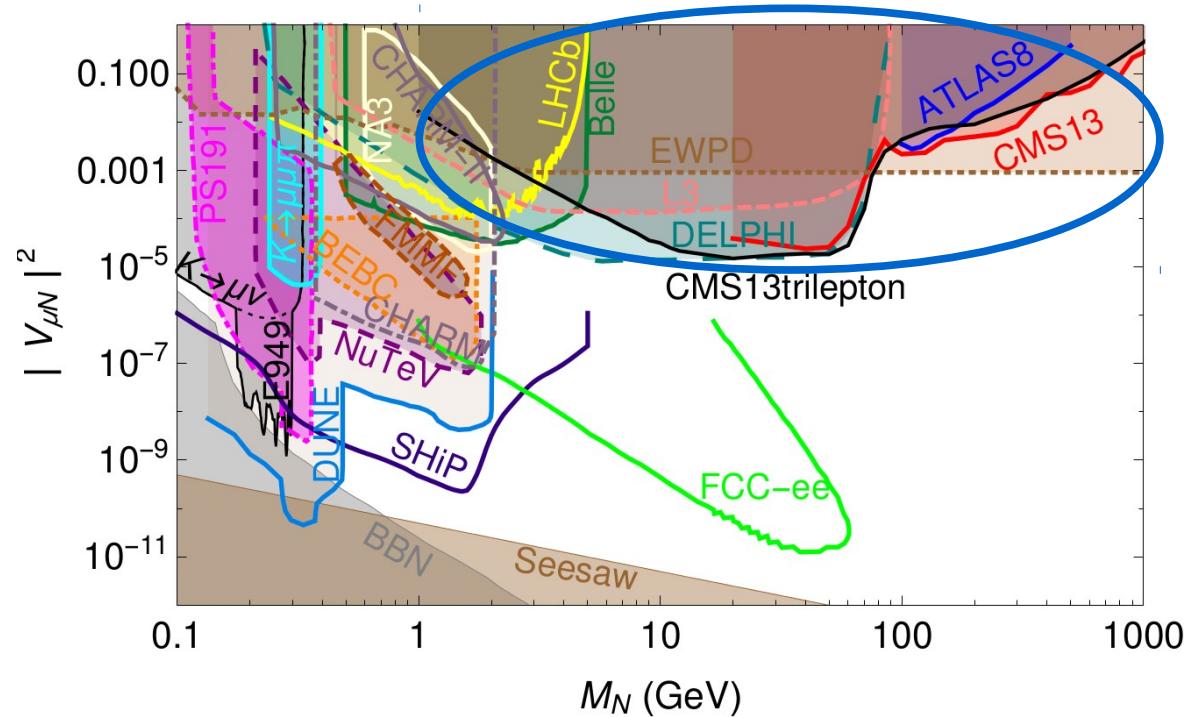
- Main backgrounds (data-driven estimation) :
  - charged leptons ( $W \rightarrow \ell\nu$ ,  $Z \rightarrow \ell\ell$ , ..)
  - spurious tracks
- Observed data (7 events) shows **no excess over expected background**
- 95% CL limits set on chargino mass versus chargino lifetime



charginos excluded up to 715 GeV  
for  $\tau=3$  ns → improvement of  
~200 GeV w.r.t. Run1 results

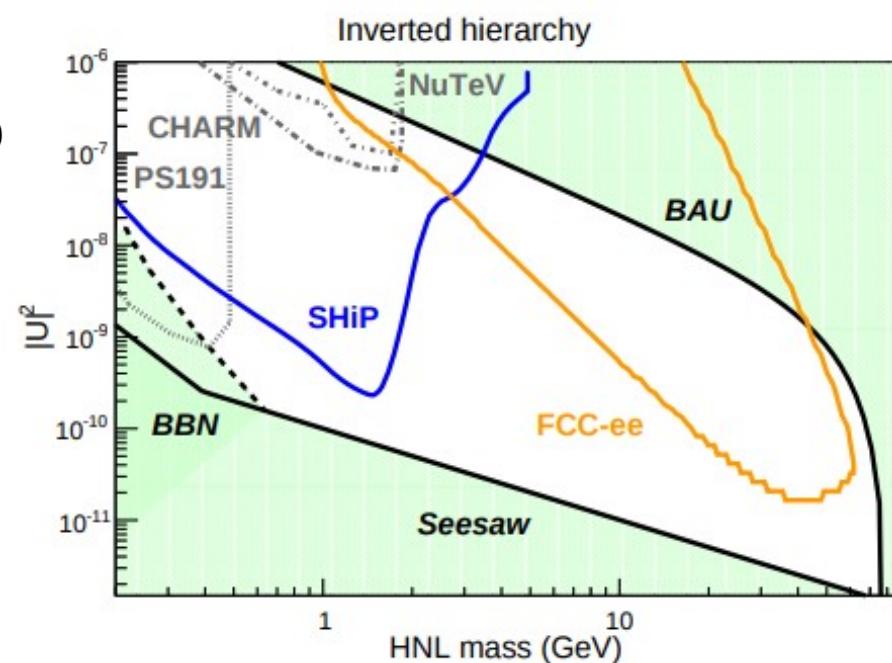
# Heavy neutrinos @ future experiments

- LHC just started to probe region not excluded by EW precision data



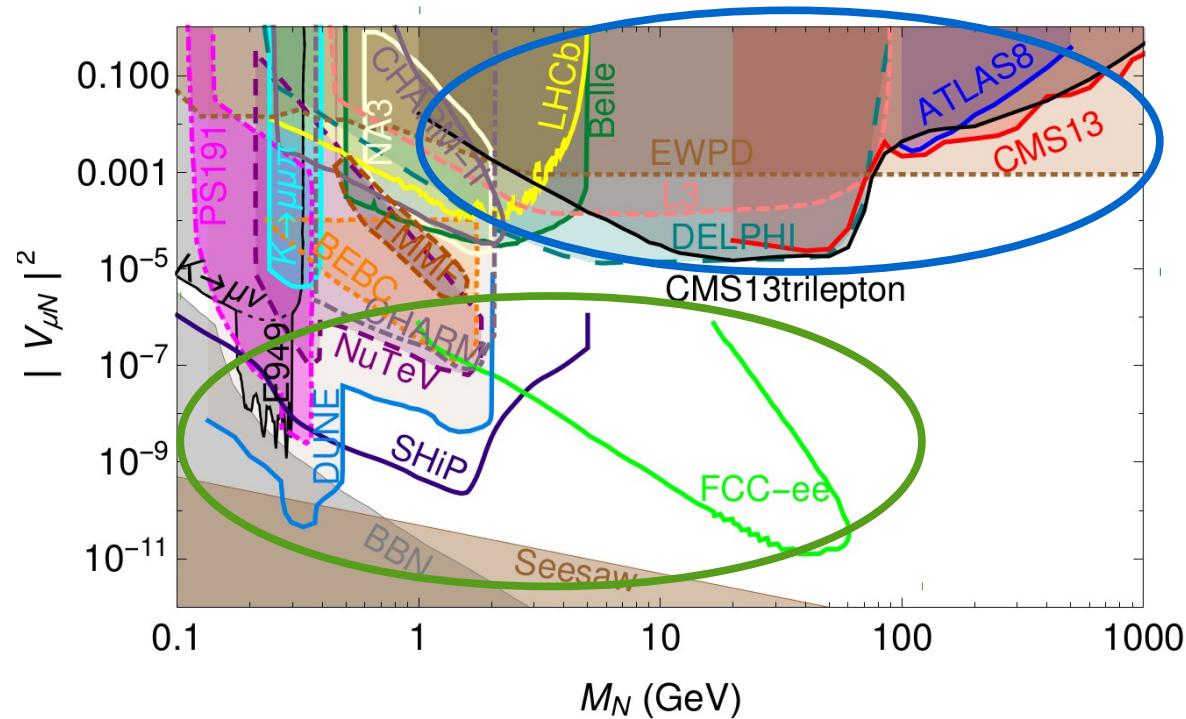
- Direct searches @ future experiments :
  - SHiP** (fixed target experiment)  
→ can **improve sensitivity** to HNL below 2 GeV by several orders of magnitude
  - FCC-ee** (circular collider)  
→ can **improve sensitivity** to RH neutrinos above 2 GeV

- Available parameter space limited theoretically by :
  - observations of baryon asymmetry of the Universe (**BAU**)
  - big bang nucleosynthesis (**BBN**)
  - see-saw** model



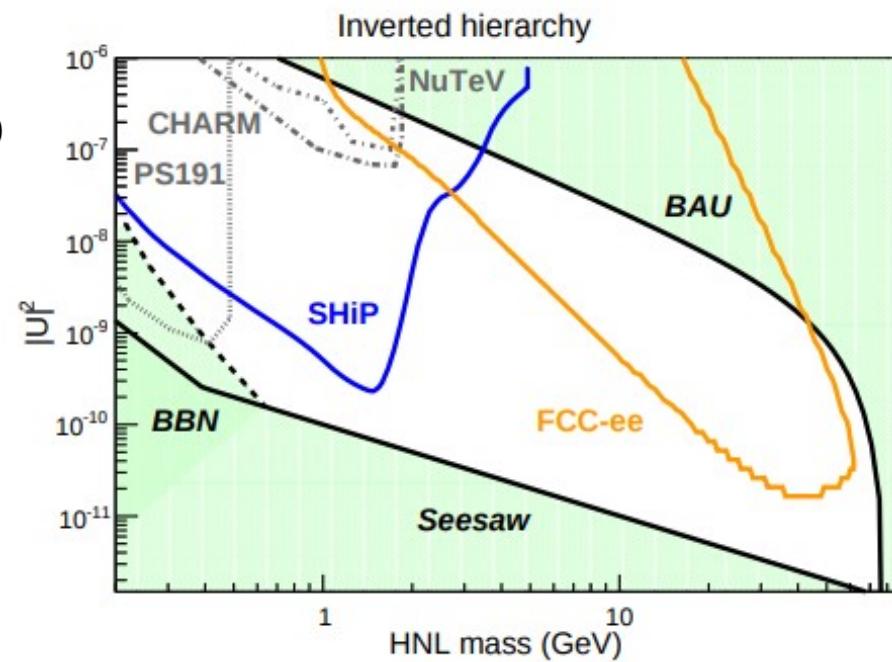
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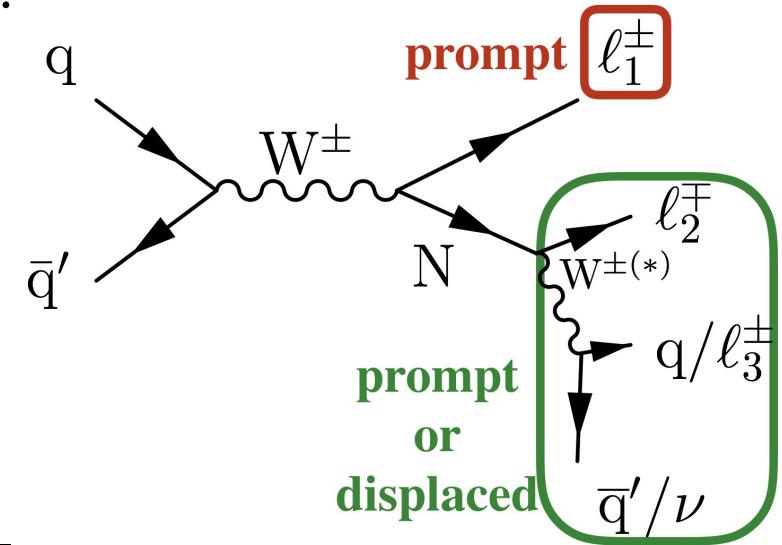
# Summary

- CMS covers a wide program of HNL, RH neutrinos and LLPs searches
- First limits on stopped particles decaying to highly delayed and displaced muons at LHC!
- Stringent limits are set on different benchmark models
- No significant excesses are observed above SM predictions.. yet!
- LHC is still a developing area of research : more data, new techniques, specific triggers...
  - .. and still a lot of channels to explore :
    - other production modes
    - displaced decays → will increase sensitivity to HNL with low mass and low couplings
  - future searches @ LHC will allow to significantly extend the probed parameter space!
- SHiP and FCC-ee would allow the exploration of a large parameter space
  - great prospects for RH neutrino searches also @ future experiments!

# **BACKUP**

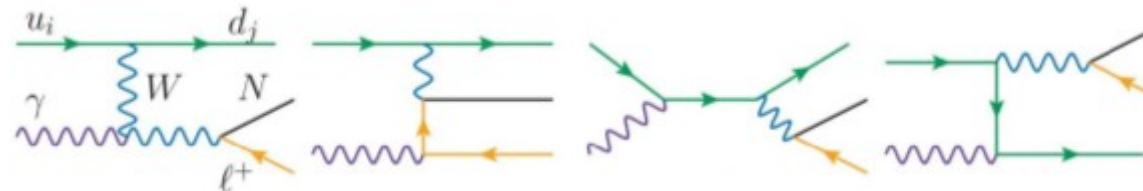
# Heavy neutrinos

- So far explored **prompt decays** :
  - **same-sign dileptons + 2 jets** for high masses :
    - fully reconstruction of N mass peak
    - sensitive only to lepton-number-violating (LNV) decays
  - **trileptons (+ missing  $E_T$ )** for low masses :
    - no clear N mass peak (escaping  $\nu$ )
    - sensitive to both LNV and lepton-number-conserving (LNC) decays
- **Displaced decays** searches started → will allow to reach lower couplings at low masses

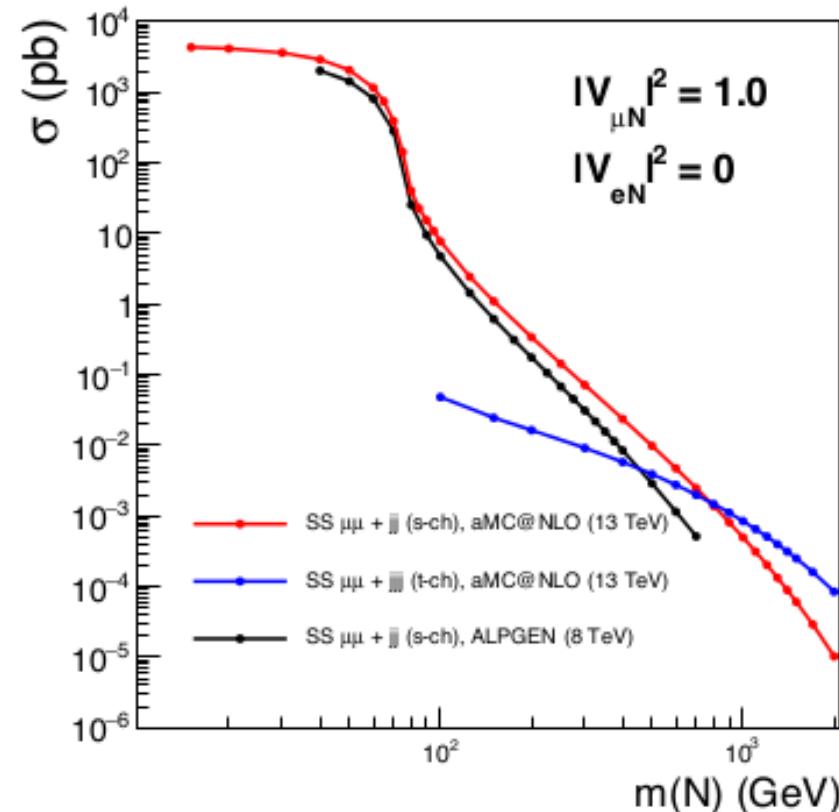


# HNL: SS dileptons final state

- Added also t-channel cross section =  $W\gamma$  production



- Cross sections :
  - for  $m_N < 80$  GeV  $\rightarrow \sim 1.5$  times of 8 TeV
  - for  $m_N > 800$  GeV  $\rightarrow$  t-channel is larger  
(@2 TeV  $\sim 8$  times of s-channel)



# HNL: SS dileptons final state

- Selection requirements for the low- and high-mass search regions :
  - SR1 → AK4 jets  $\geq 2$
  - added SR2 to improve signal efficiency  
→ AK4 jets = 1 for low-mass region, AK8 jets  $\geq 1$  for high-mass region

| Region           | $p_T^{\text{miss}}$<br>(GeV) | $(p_T^{\text{miss}})^2 / S_T$<br>(GeV) | $m(\ell^\pm \ell^\pm W_{\text{jet}})$<br>(GeV) | $m(\ell^\pm \ell^\pm)$<br>(GeV) | $m(W_{\text{jet}})$<br>(GeV) | $p_T^j$<br>(GeV) |
|------------------|------------------------------|--|--|---------------------------------|------------------------------|------------------|
| Low-mass SR1+SR2 | < 80                         | —                                      | < 300  | > 10                            | —                            | > 20             |
| High-mass SR1    | —                            | < 15                                   | —  | > 10                            | 30-150                       | > 25             |
| High-mass SR2    | —                            | < 15                                   | —  | > 10                            | 40-130                       | > 200            |

# HNL: SS dileptons final state

- Background estimation :
  - prompt leptons normalized in CR → SF for WZ, Zgamma, ZZ samples
  - misidentified leptons = most important background source for low-mass signals
    - misidentification probability of a jet that passes minimal lepton selection requirements (“loose leptons”) to also pass the more stringent requirements used to define leptons after the full selection (“tight leptons”) calculated in independent data sample enriched in multijet events
    - misidentification probability applied to the application sample by counting the number of events in which 1lepton passes the tight selection, while the other lepton fails the tight selection but passes the loose selection, and the number of events in which both leptons fail the tight selection, but pass the loose criteria
    - total contribution to the signal sample (i.e., the number of events when both leptons pass the tight selection) obtained by weighting events of the 2 different types by the appropriate misidentification probability factors
  - mismeasured charge :
    - consider probability of mismeasuring the lepton charge
      - background due to mismeasurement of the muon charge determined from simulation and studies with cosmic ray data and found to be negligible → only mismeasurement of the electron charge is considered
    - estimated only in the ee and eμ channels using DY→ee sample
    - extract SF from data by selecting Z→ee events
    - validate SFs by selecting data events in data and checking data CR

# HNL: SS dileptons final state

- Backgrounds estimates validated in several data CR :

CR1: (SS2 $\ell$ ), at least one b-tagged AK4 jet,

CR2: (SS2 $\ell$ ),  $\Delta R(\ell_1, \ell_2) > 2.5$  and no b-tagged AK4 jet,

CR3: (SS2 $\ell$ ), low-mass SR1 and either  $\geq 1$  b-tagged jet or  $p_T^{\text{miss}} > 100$  GeV,

CR4: (SS2 $\ell$ ), low-mass SR2 and either  $\geq 1$  b-tagged jet or  $p_T^{\text{miss}} > 100$  GeV,

CR5: (SS2 $\ell$ ), high-mass SR1 and either  $\geq 1$  b-tagged jet or  $(p_T^{\text{miss}})^2 / S_T > 20$  GeV,

CR6: (SS2 $\ell$ ), high-mass SR2 and either  $\geq 1$  b-tagged jet or  $(p_T^{\text{miss}})^2 / S_T > 20$  GeV.

| Channel  | Control region | Estimated background | Observed |
|----------|----------------|----------------------|----------|
| ee       | 1              | $365.9 \pm 72.8$     | 378      |
|          | 2              | $694.0 \pm 101.8$    | 671      |
|          | 3              | $221.7 \pm 41.9$     | 242      |
|          | 4              | $48.4 \pm 10.7$      | 38       |
|          | 5              | $334.3 \pm 55.9$     | 347      |
|          | 6              | $25.7 \pm 4.3$       | 28       |
| $\mu\mu$ | 1              | $883.8 \pm 230.0$    | 925      |
|          | 2              | $885.5 \pm 201.7$    | 1013     |
|          | 3              | $422.5 \pm 100.2$    | 439      |
|          | 4              | $156.2 \pm 41.9$     | 174      |
|          | 5              | $556.9 \pm 122.1$    | 568      |
|          | 6              | $35.1 \pm 7.0$       | 38       |
| $e\mu$   | 1              | $1014.2 \pm 235.1$   | 1106     |
|          | 2              | $1354.3 \pm 232.1$   | 1403     |
|          | 3              | $650.5 \pm 140.2$    | 706      |
|          | 4              | $142.8 \pm 32.4$     | 150      |
|          | 5              | $918.1 \pm 175.7$    | 988      |
|          | 6              | $62.2 \pm 11.1$      | 64       |

# HNL: SS dileptons final state

- **Systematics** in signal yields and background for low-mass (high-mass) region :
  - input value of each parameter is changed by  $\pm 1$  st. dev. from its central value
  - main sources of bkg syst. unc. associated with SM cross section, JES and background estimates
  - main sources of signal syst. unc. from PDF and JES

→ predictions in agreement with observations within the syst. unc.

| Channel / Source            | ee signal (%)  | ee bkgd. (%)  | $\mu\mu$ signal (%) | $\mu\mu$ bkgd. (%) | e $\mu$ signal (%) | e $\mu$ bkgd. (%) |
|-----------------------------|----------------|---------------|---------------------|--------------------|--------------------|-------------------|
| <u>Simulation:</u>          |                |               |                     |                    |                    |                   |
| SM cross section            | –              | 12–14 (15–27) | –                   | 13–18 (22–41)      | –                  | 12–14 (16–30)     |
| Jet energy scale            | 2–5 (0–1)      | 2–6 (5–6)     | 2–8 (0–1)           | 3–5 (4–7)          | 1–6 (0–1)          | 1–4 (3)           |
| Jet energy resolution       | 1–2 (0–0.3)    | 1–2 (2–6)     | 1–2 (0–0.3)         | 0–0.8 (1–3)        | 0.8 (0–0.3)        | 0–0.8 (0–3)       |
| Jet mass scale              | 0–0.3 (0–0.1)  | 0–1 (1–3)     | 0–0.2 (0–0.1)       | 0–0.3 (0.7)        | 0–0.1 (0–0.1)      | 0–0.2 (0–5)       |
| Jet mass resolution         | 0–0.4 (0–0.3)  | 0–1 (0–2)     | 0–0.1 (0–0.2)       | 0–0.1 (0–0.5)      | 0–0.4 (0–0.3)      | 0–0.4 (0–3)       |
| Subjettiness                | 0–1 (0–8)      | 0–1.0 (1–7)   | 0–0.3 (0–8)         | 0–0.1 (0–8)        | 0–0.2 (0–8)        | 0–0.4 (0–8)       |
| Event pileup                | 2–3 (1)        | 2 (0–2)       | 0–1 (0–1)           | 0–1 (0–3)          | 0.7 (0.8)          | 2 (2–4)           |
| Unclustered energy          | 0–0.7 (0–0.1)  | 1 (2–5)       | 0–1 (0–0.1)         | 0–1 (3–4)          | 0–0.5 (0–0.1)      | 0.9 (1–2)         |
| Integrated luminosity       | 2.5 (2.5)      | 2.5 (2.5)     | 2.5 (2.5)           | 2.5 (2.5)          | 2.5 (2.5)          | 2.5 (2.5)         |
| Lepton selection            | 2–4 (4)        | 2–4 (2–6)     | 3 (3–4)             | 3 (3–5)            | 2 (3)              | 2 (2–6)           |
| Trigger selection           | 3–4 (1)        | 3 (3–5)       | 0–0.9 (0–0.4)       | 0–1 (0–0.8)        | 3 (0–0.2)          | 3 (2)             |
| b tagging                   | 0–0.8 (0–1)    | 0.7 (1)       | 0–0.5 (0–0.6)       | 0–1 (1–3)          | 0–0.7 (0–0.7)      | 0–1 (1–4)         |
| PDF                         | 0–1.0 (1)      |               | 1.0 (1)             |                    | 0.9 (1)            |                   |
| $\alpha_S$                  | 0–0.9 (0–0.03) | <15 (<20)     | 0–0.9 (0–0.05)      | <15 (<20)          | 0–0.9 (0–0.06)     | <15 (<20)         |
| PDF Scale                   | 5–8 (1–2)      |               | 5–7 (1–2)           |                    | 4–8 (1–2)          |                   |
| <u>Estimated from data:</u> |                |               |                     |                    |                    |                   |
| Misidentified leptons       | –              | 30 (30)       | –                   | 30 (30)            | –                  | 30 (30)           |
| Mismeasured charge          | –              | 29–41 (53–88) | –                   | –                  | –                  | –                 |

# HNL: SS dileptons final state

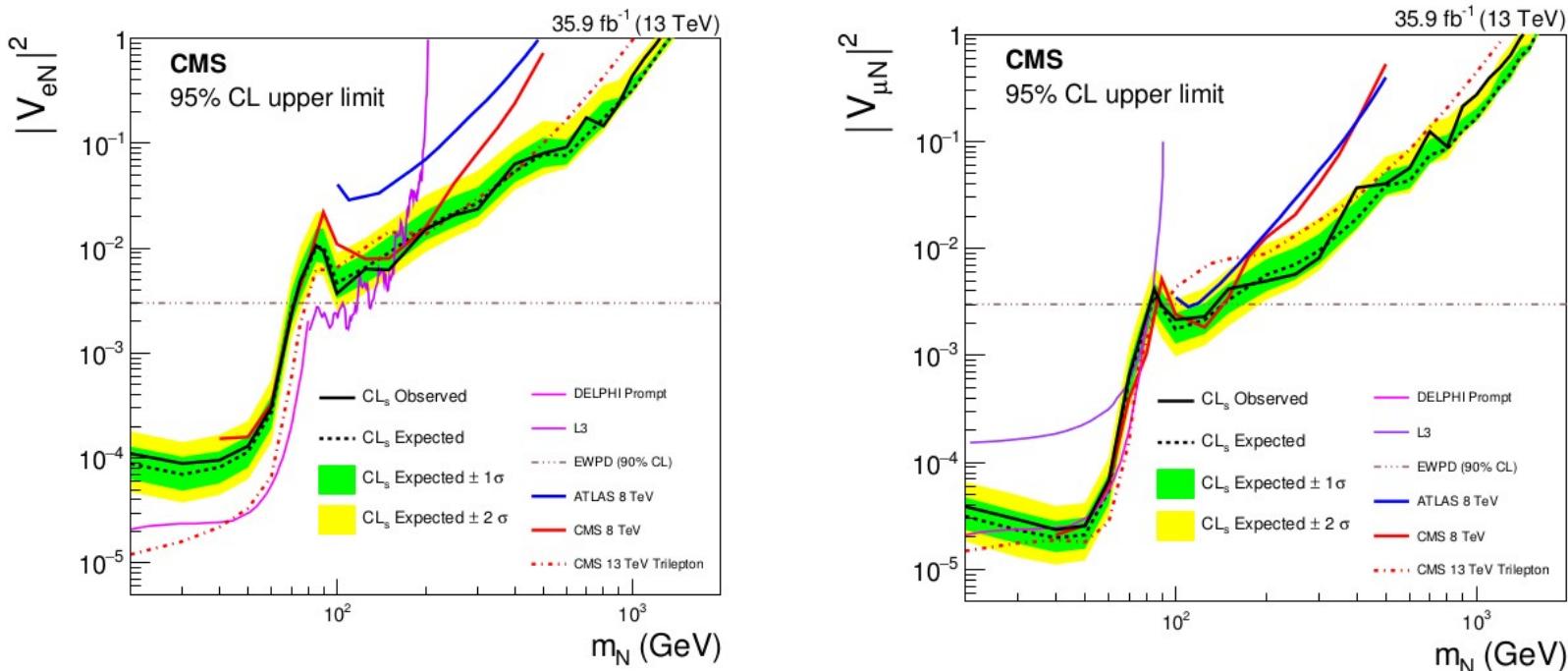
- Observed event yields and estimated backgrounds

| SR                                  | Prompt bkgd.              | Misid. bkgd.               | Charge mismeas. bkgd.   | Total bkgd.                 | $N_{obs}$ |
|-------------------------------------|---------------------------|----------------------------|-------------------------|-----------------------------|-----------|
| <u>ee channel:</u>                  |                           |                            |                         |                             |           |
| Low-mass SR1                        | $206.4 \pm 9.8 \pm 21.0$  | $127.9 \pm 5.5 \pm 38.4$   | $29.8 \pm 0.2 \pm 12.3$ | $364.1 \pm 11.3 \pm 45.5$   | 324       |
| Low-mass SR2                        | $281.4 \pm 12.2 \pm 28.3$ | $143.5 \pm 6.7 \pm 43.0$   | $36.4 \pm 0.1 \pm 10.7$ | $461.2 \pm 13.9 \pm 52.6$   | 460       |
| High-mass SR1                       | $236.0 \pm 10.2 \pm 24.6$ | $141.2 \pm 5.7 \pm 42.4$   | $45.2 \pm 0.3 \pm 24.0$ | $422.4 \pm 11.7 \pm 54.5$   | 382       |
| High-mass SR2                       | $8.0 \pm 1.3 \pm 1.6$     | $2.0 \pm 0.6 \pm 0.6$      | $0.9 \pm 0.1 \pm 0.8$   | $10.9 \pm 1.4 \pm 1.9$      | 10        |
| <u><math>\mu\mu</math> channel:</u> |                           |                            |                         |                             |           |
| Low-mass SR1                        | $150.5 \pm 6.5 \pm 15.8$  | $275.8 \pm 7.0 \pm 82.7$   | —                       | $426.3 \pm 9.5 \pm 84.2$    | 487       |
| Low-mass SR2                        | $208.7 \pm 8.4 \pm 19.4$  | $393.3 \pm 8.7 \pm 118.0$  | —                       | $602.0 \pm 12.1 \pm 119.6$  | 663       |
| High-mass SR1                       | $166.1 \pm 6.3 \pm 20.0$  | $244.1 \pm 6.5 \pm 73.2$   | —                       | $410.3 \pm 9.0 \pm 75.9$    | 502       |
| High-mass SR2                       | $7.1 \pm 0.8 \pm 1.9$     | $4.4 \pm 0.8 \pm 1.3$      | —                       | $11.5 \pm 1.1 \pm 2.3$      | 13        |
| <u><math>e\mu</math> channel:</u>   |                           |                            |                         |                             |           |
| Low-mass SR1                        | $418.4 \pm 13.3 \pm 37.1$ | $431.7 \pm 10.4 \pm 129.5$ | —                       | $850.2 \pm 16.9 \pm 134.7$  | 907       |
| Low-mass SR2                        | $566.2 \pm 16.7 \pm 47.2$ | $464.5 \pm 12.1 \pm 139.3$ | —                       | $1030.7 \pm 20.6 \pm 147.1$ | 1042      |
| High-mass SR1                       | $462.6 \pm 13.6 \pm 41.7$ | $408.6 \pm 9.9 \pm 122.6$  | —                       | $871.2 \pm 16.8 \pm 129.5$  | 901       |
| High-mass SR2                       | $16.8 \pm 1.9 \pm 3.5$    | $7.4 \pm 1.3 \pm 2.2$      | —                       | $24.2 \pm 2.3 \pm 4.2$      | 31        |

# HNL: SS dileptons final state

- Limits set on mixing parameters  $|V_{eN}|^2$  and  $|V_{\mu N}|^2$

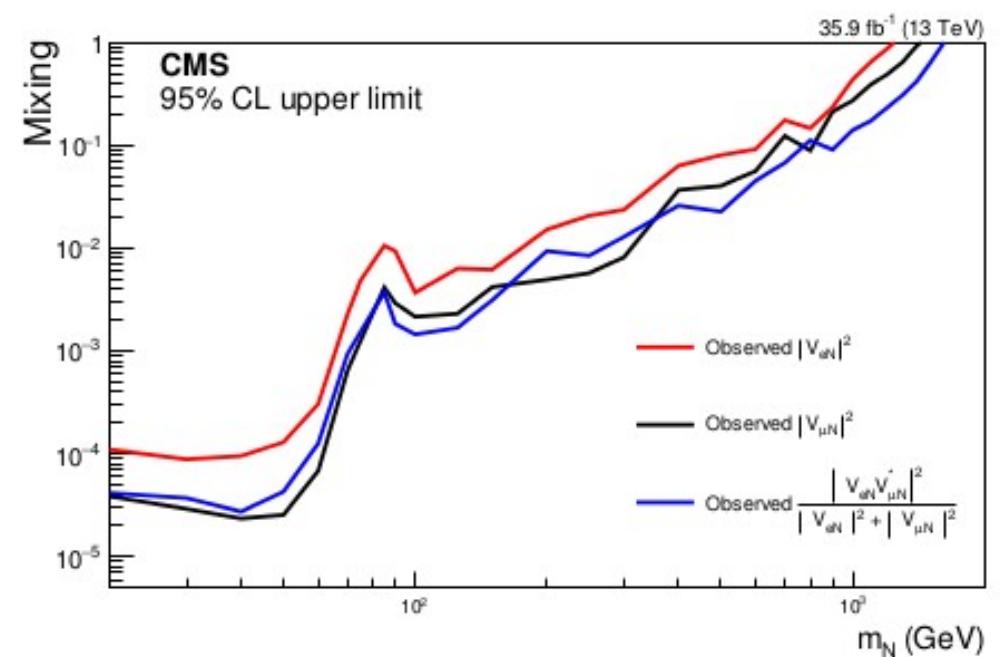
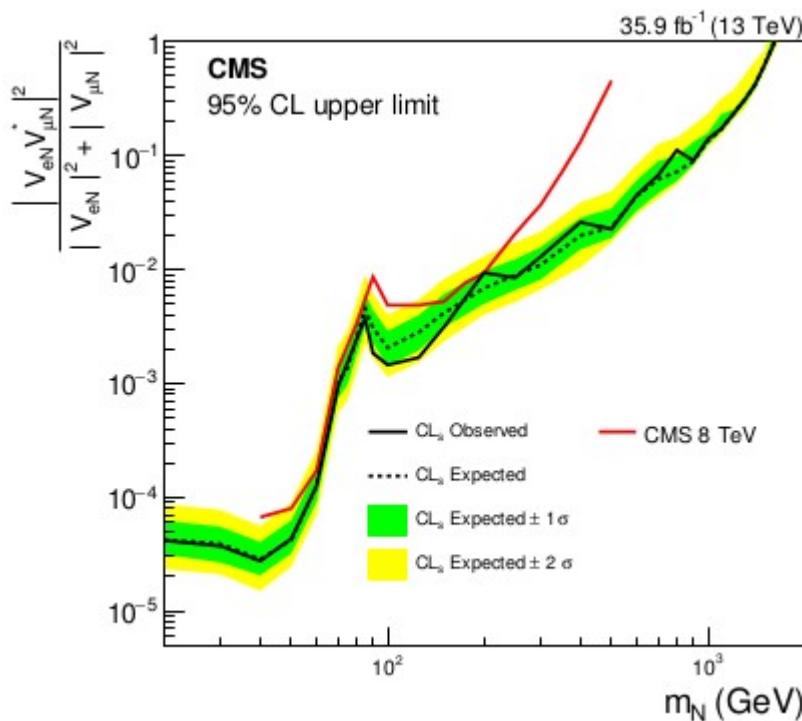
$$\rightarrow 2.3 \times 10^{-5} - 1 \text{ for } 20 < m_N < 1600 \text{ GeV}$$



- mass range below  $m_N = 20$  GeV not considered because of very low selection efficiency and because finite lifetime of N in this mass range become significant and results in displaced decays with neutrino no longer considered prompt
- behavior of limits around  $m_N = 80$  GeV caused by the fact that as the mass of N approaches the W boson mass, the lepton produced together with N or the lepton from N decay have very low pT
- SR2 improves masses  $m_N < 70$  GeV and  $m_N > 300$  GeV
- t-channel increase sensitivity: @500 GeV ( $\mu\mu$ ) limits improved by factor 13

# HNL: SS dileptons final state

- Limits set also on mixing parameters  $|V_{eN}V_{\mu N}^*|^2/(|V_{eN}|^2 + |V_{\mu N}|^2)$   
 $\rightarrow$  first direct limits in  $e\mu$  for  $m_N > 500$  GeV



# RH neutrinos: event selections & sidebands

|            | <b>Signal</b>       | <b>Flavor</b>       | <b>Low <math>m_{ll}</math></b> | <b>Low <math>m_{lljj}</math></b> |
|------------|---------------------|---------------------|--------------------------------|----------------------------------|
| ll         | 2ele/2muons         | 1ele+1muon          | 2ele/2muons                    | 2ele/2muons                      |
| $m_{ll}$   | $> 200 \text{ GeV}$ | $> 200 \text{ GeV}$ | $< 200 \text{ GeV}$            | $> 200 \text{ GeV}$              |
| $m_{lljj}$ | $> 600 \text{ GeV}$ | $> 600 \text{ GeV}$ | NA                             | $< 600 \text{ GeV}$              |

to suppress the DY

to define the search region

## Flavor Control Region:

- for ttbar background estimate
- signal free CR (under assumption of lepton flavor conservation in decay chain)

## Low di-lepton mass CR:

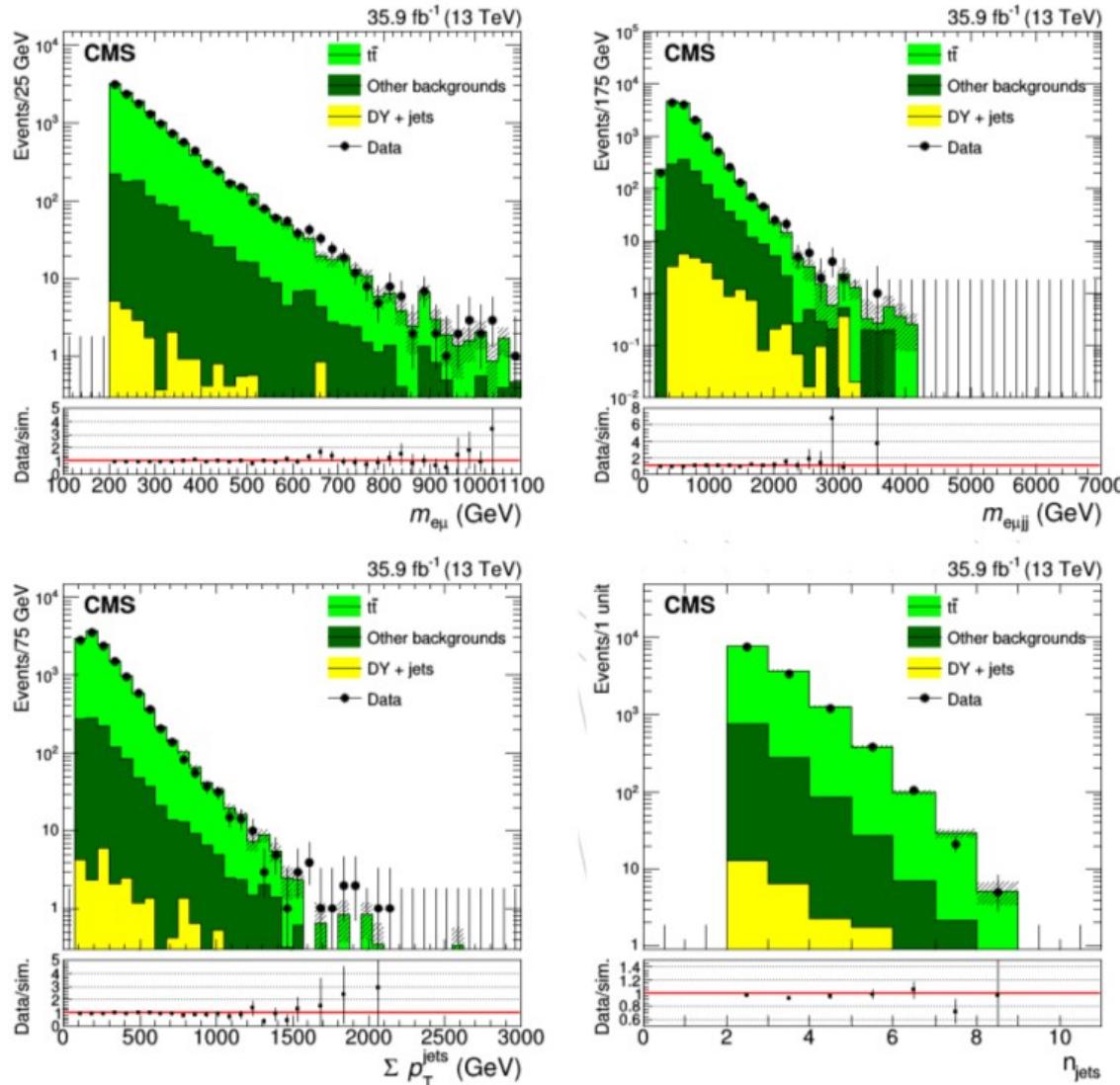
- check scales, smearings
- measure SF for DY+jets in  $80 \text{ GeV} < m_{ll} < 100 \text{ GeV}$  region

## Low 4-object mass CR:

- data/MC agreement used to verify that SF measured for DY+jets around the Z peak is valid also at higher masses

# RH neutrinos: ttbar background

- Data-driven estimate from flavor sideband
- Overall good data/MC agreement



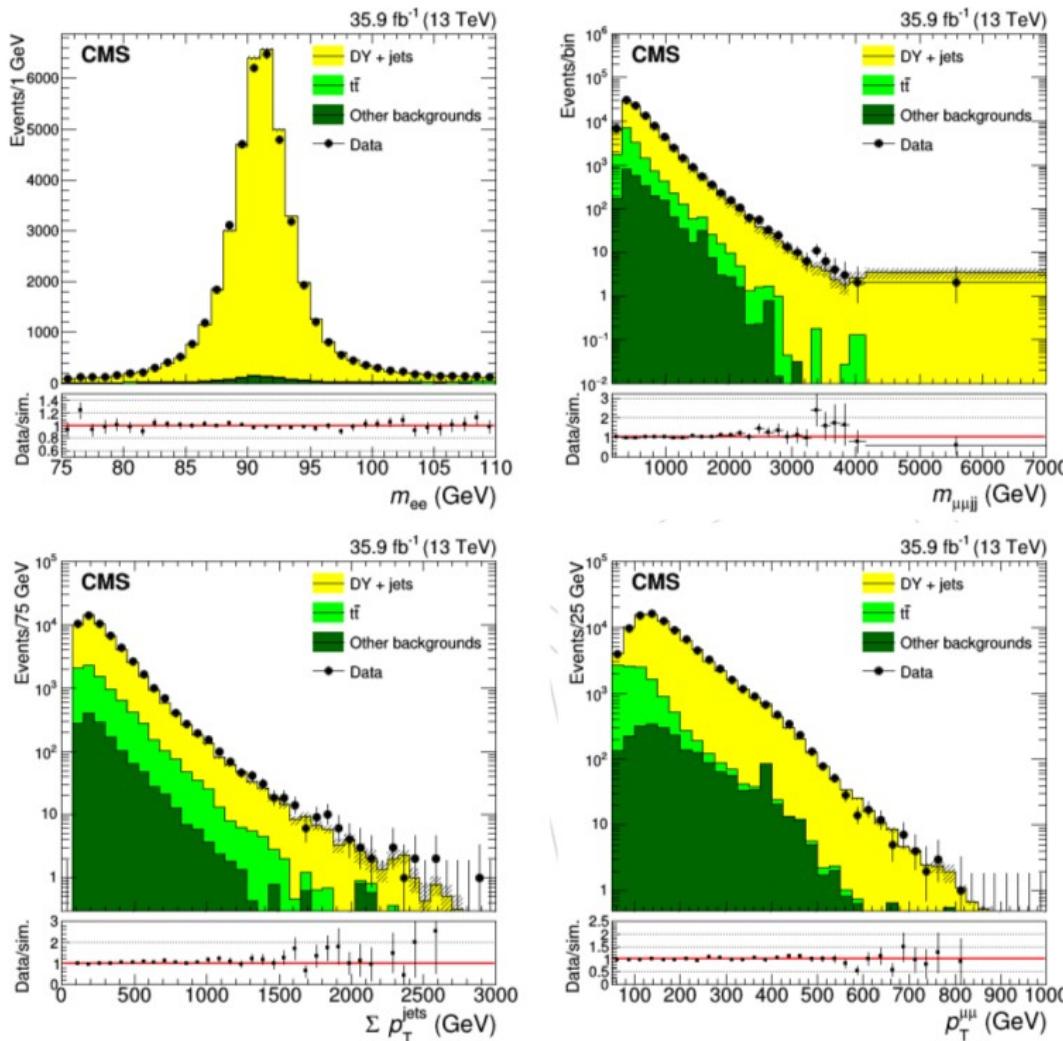
# RH neutrinos: ttbar background

- Data events are scaled from flavor CR to signal region, accounting for different lepton ( $e, \mu$ ) efficiencies estimated on simulation  
 $\rightarrow N_{\text{ttbar}}(\text{signal region}) = N_{\text{ttbar}}(\text{flavor CR}) * R_{e\mu/\text{ll}}$
- The transfer factor  $R_{e\mu/\text{ll}}$  ( $\text{ll} = ee$  or  $\mu\mu$ ) is calculated with MC simulated events (ttbar dilepton aMC@NLO):  
 $\rightarrow R_{e\mu/\text{ll}} = N_{\text{lljj}}(\text{signal region}) / N_{e\mu jj}(\text{flavor CR})$
- The dependency of the ttbar extrapolation SF vs  $m_{\text{lljj}}$  is checked with a bin-by-bin ratio  $\rightarrow$  no dependency found
- Ratio fit to a linear polynomial
- Systematic uncertainty on ttbar extrapolation SF = difference between the values of the polynomial at high (4 TeV) and low (200 GeV) four-object mass

| Channel                         | Transfer factor | Stat. uncertainty | Syst. uncertainty |
|---------------------------------|-----------------|-------------------|-------------------|
| $e\mu jj \rightarrow ee jj$     | 0.423           | 0.010             | 0.071             |
| $e\mu jj \rightarrow \mu\mu jj$ | 0.720           | 0.015             | 0.144             |

# RH neutrinos: DY+jets background

- DY+jets estimated from simulation
- DY MC normalized to data in the **low dilepton sideband** near the Z peak ( $80 < m_{ll} < 100$  GeV)



SF = data/MC ratio in the  
dilepton invariant mass  
distribution

| channel                               | SF    | stat. unc. |
|---------------------------------------|-------|------------|
| $Z \rightarrow e^+ e^-$ (aMC@NLO)     | 1.069 | 0.008      |
| $Z \rightarrow \mu^+ \mu^-$ (aMC@NLO) | 1.071 | 0.006      |

# RH neutrinos: statistical uncertainties

- To incorporate statistical uncertainties, [Gamma distributions](#) with 2 parameters  $N(\geq 0)$  and  $\alpha (> 0)$  [included in the datacards](#) for each background :
  - for [ttbar background](#) (estimated with **data**):
    - $N$  = number of events in CR
    - $\alpha$  = SF from CR to signal region
  - for [DY and Other backgrounds](#) (estimated with **MC simulation**):
    - $N$  = number of events passing selections in signal region
    - $\alpha$  = overall scaling factor ( $= \text{lumi} * \text{xs} / \text{Ntot}$ )
- [Number of expected events in signal region](#) :
  - most probable value (rate) =  $N * \alpha$
- In cases where  $N < 0$  (due to [negative aMC@NLO weights](#) for DY events at high  $m_{lljj}$ ) :
  - $N = 0$
  - rate = 0.0001

# RH neutrinos: systematics uncertainties

- To evaluate systematic effect of object reconstruction uncertainties (energy scale/resolution, ID/iso/trigger..) :
  - thrown 5000 toys for each background varying all the systematics at the same time in an uncorrelated way
  - Gaussian distribution sampled for each toy :
    - mean = expected uncertainty
    - width = error on uncertainty
  - variations before selections → full analysis chain
- For each search window, from integral of WR mass distribution :
  - number of expected events  $\mu$  = mean of integral the distribution
  - systematic uncertainty *syst.* = std. dev. of the integral distribution
- To incorporate the systematics effects into the datacards we use logNormal distributions :  $\ln N = 1 + \text{syst.}/\mu$

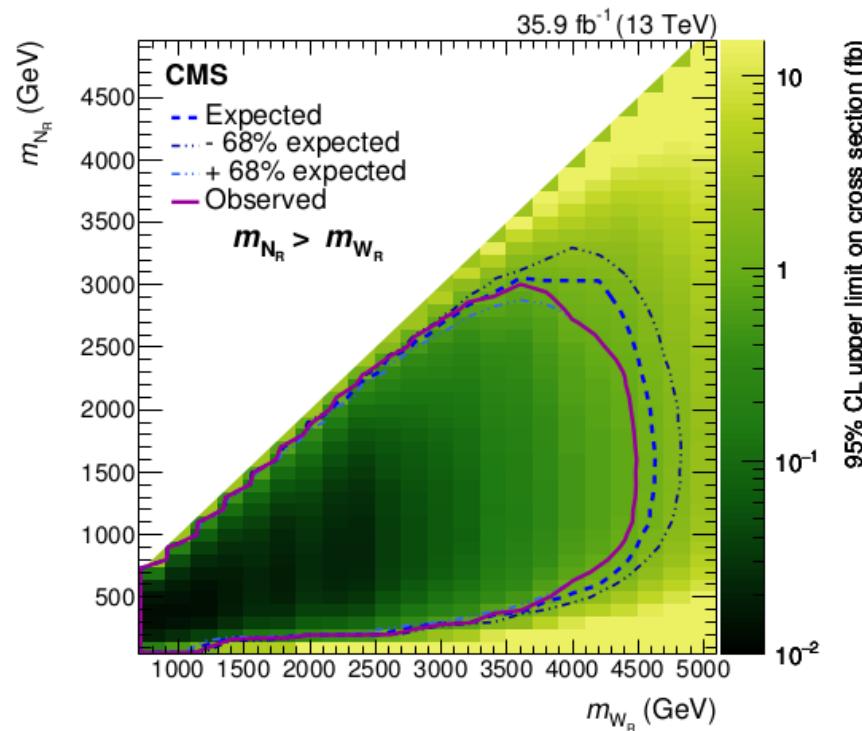
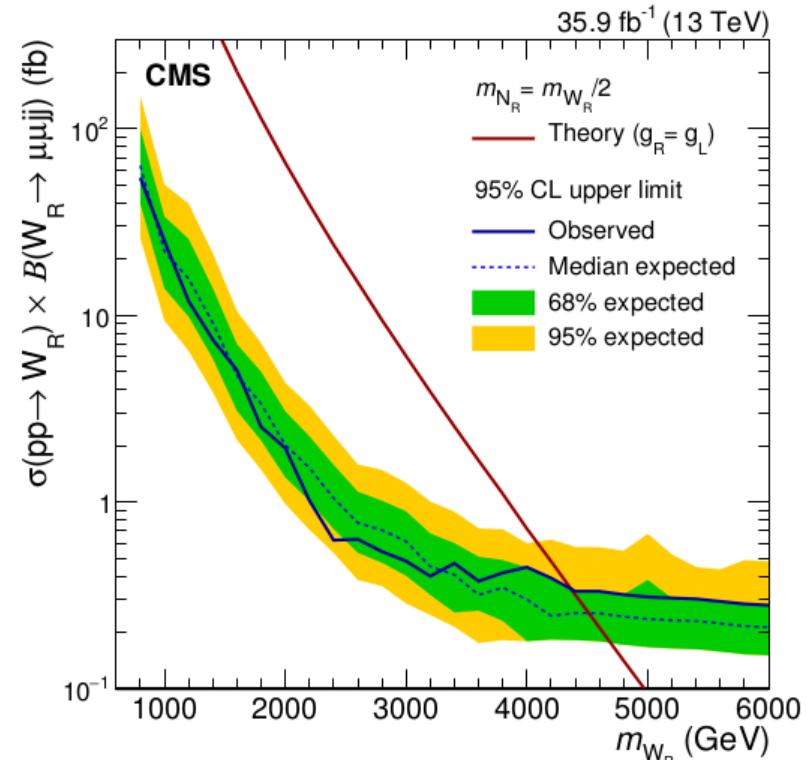
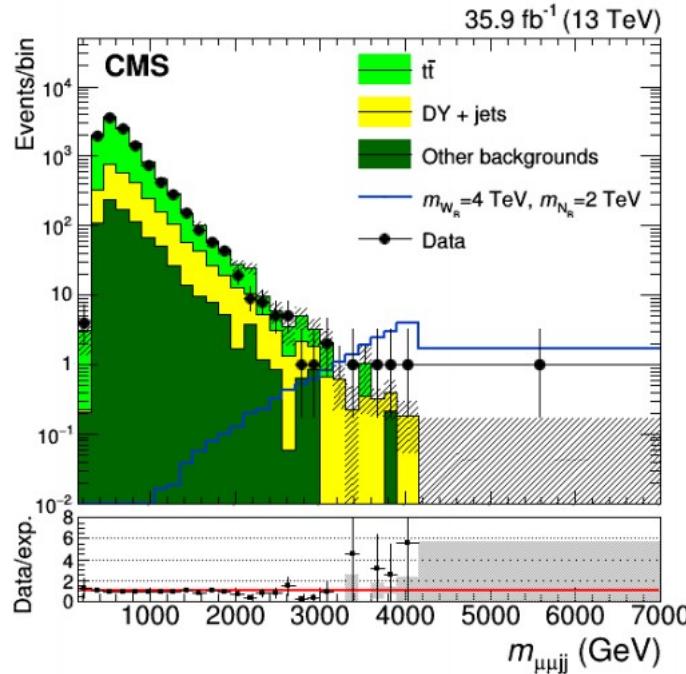
# RH neutrinos: systematics uncertainties

Effect of systematic uncertainties on event yields

| Uncertainty                | Signal (%) | Background (%) |
|----------------------------|------------|----------------|
| Jet energy resolution      | 3.2 – 25.8 | 0.9 – 25.2     |
| Jet energy scale           | 0.2 – 28.9 | 4.8 – 26.8     |
| Electron energy resolution | 3.7 – 4.8  | 2.7 – 4.5      |
| Electron energy scale      | 3.7 – 6.4  | 4.9 – 5.9      |
| Electron reco/trigger/ID   | 8.7 – 10.9 | 6.1 – 10.4     |
| Muon energy resolution     | 4.7 – 10.1 | 6.9 – 12.2     |
| Muon energy scale          | 4.7 – 10.2 | 6.2 – 11.9     |
| Muon trigger/ID/iso        | 2.3 – 4.7  | 1.9 – 5.2      |

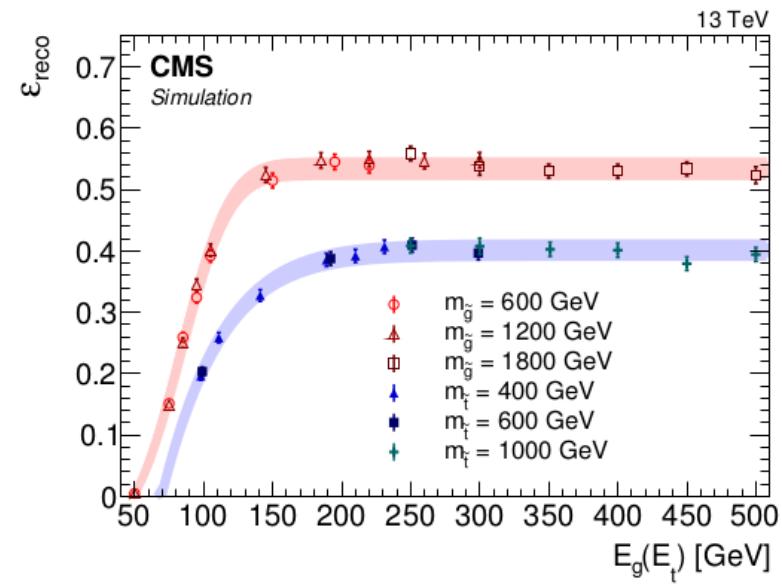
| Uncertainty                                   | Magnitude (%)    |
|---|------------------|
| $t\bar{t}$ extrapolation ee/e $\mu$ SF        | 16.9 (stat+syst) |
| $t\bar{t}$ extrapolation $\mu\mu$ /e $\mu$ SF | 20.1 (stat+syst) |
| DY ee PDF                                     | 15 – 70 (syst)   |
| DY ee renormalization/factorization           | 5 – 40 (syst)    |
| DY $\mu\mu$ PDF                               | 10 – 70 (syst)   |
| DY $\mu\mu$ renormalization/factorization     | 10 – 50 (syst)   |
| Integrated luminosity                         | 2.5 (stat+syst)  |

# RH neutrinos: muon channel



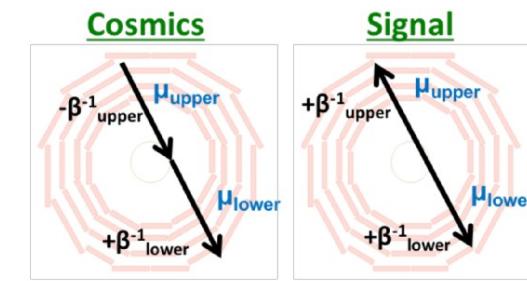
# Stopped LLPs : efficiencies

- Stopping efficiency :
  - $\epsilon_{\text{stopping}}$  = probability that R-hadron stops in barrel calorimeters ( $\sim 5\%$  for gluino @1000 GeV,  $\sim 4\%$  for stop @600 GeV)
  - $\epsilon_{\text{stopping}}$  = probability of each LLP to stop in any region of the detector ( $\sim 20\%$  for gluino,  $\sim 30\%$  for MCHAMP)
- Reconstruction efficiency :  $\epsilon_{\text{reco}}$  = fraction of events passing all offline selection criteria ( $\sim 53\%$  for gluino with  $E > 130$  GeV,  $\sim 39\%$  for stop with  $E > 170$  GeV,  $\sim 0.3\%$  for gluino,  $\sim 4\%$  for MCHAMP)
- Signal events rejected if coincide with CSC/DT segments induced from thermal neutron effects →  $\epsilon_{\text{CSCveto/DTveto}}$  = fraction of noise events surviving the beam halo/cosmic ray muon vetoes ( $\sim 94\% / 88\%$ )
- Signal efficiency :
  - $\epsilon_{\text{signal}} = \epsilon_{\text{stopping}} * \epsilon_{\text{reco}} * \epsilon_{\text{CSCveto}} * \epsilon_{\text{DTveto}}$
  - $\epsilon_{\text{signal}} = \epsilon_{\text{stopping}} * \epsilon_{\text{reco}}$



# Stopped LLPs : backgrounds

- Dominant backgrounds to rejects:



## BEAM HALO

- signal-like jet from calorimeter shower of photon emitted by halo muon
- reject events with CSC segments having at least 5 reconstructed hits

- muons produced from beam halo interactions and giving endcap CSC hits
- reject events by vetoing muons with CSC hits and requiring lower hemisphere muon track to be outgoing (? non upper?)

negligible after  
selection criteria

## COSMIC RAYS

- signal-like jet from calorimeter shower of photon emitted by energetic cosmic muon
- reject cosmic events based on topology of DT segments, barrel RPC hits, and jets

- muon track going straight through the detector
- reject events with RPC and DT time-of-flight cuts, and muon momentum cuts

## DETECTOR NOISE

- signal-like jet from interaction in HCAL readout box
- reject events failing the noise filter and other offline selection criteria based on the spatial distribution of reconstructed tower

- low number of hits, randomly distributed, inefficient tracking
- reject events by requiring good quality muons with good time measurement

# Stopped LLPs : backgrounds

Hadronic decay

- All dominant backgrounds :
  - drop exponentially as a function of the jet energy →  $E_{\text{leadingJet}} > 70 \text{ GeV}$
- Secondary background sources :
  - out-of-time collisions from remnant protons between bunches
  - beam-gas interactions in the detector
  - they all become negligible after requirement on no reconstructed collision vertices in the events

# Stopped LLPs : backgrounds

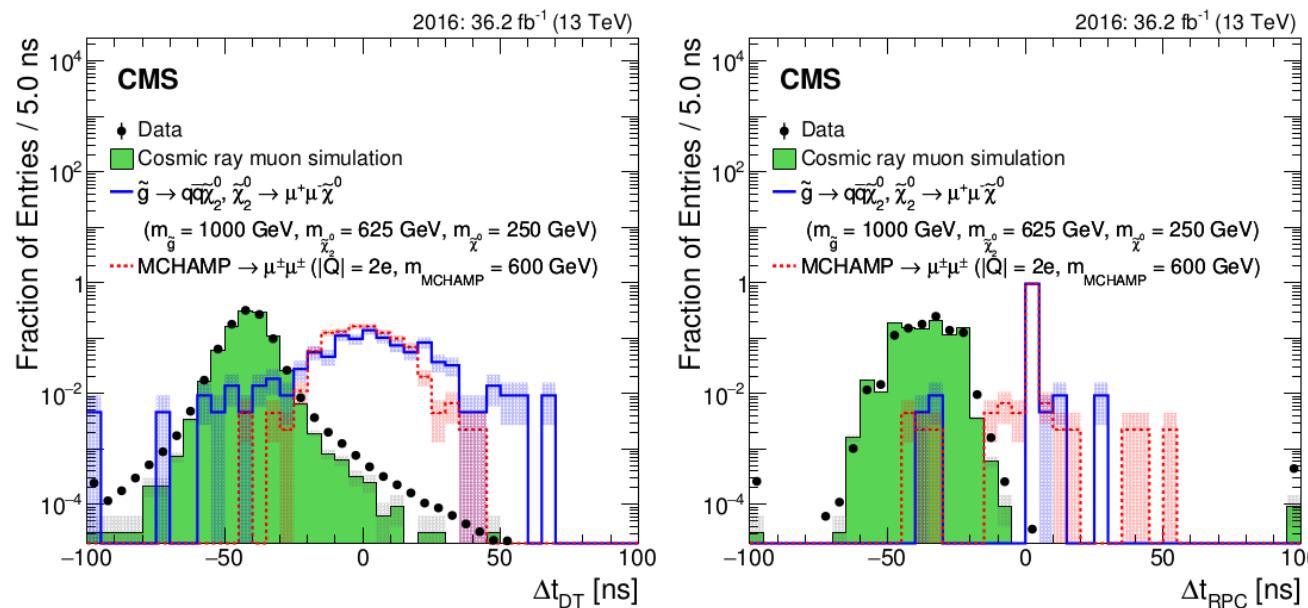
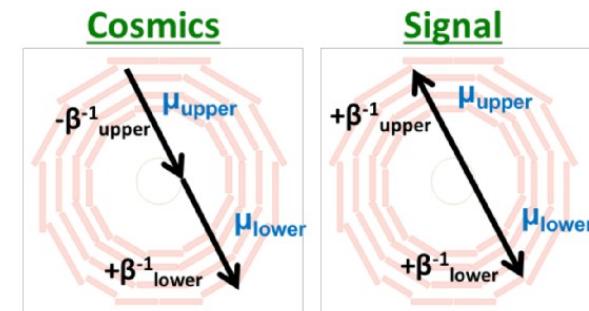
- **Background inefficiency** = probability of bkg events escaping the background veto and thus being observed
- **Cosmic ray muon background :**
  - veto inefficiency = fraction of preselected simulated cosmic ray muon events passing the cosmic ray muon rejection criteria  $\sim 1 \times 10^{-3}$
  - syst. unc. = difference between cosmic ray muon data and simulation (32%)
  - estimate =  $2.6 \pm 0.9$  in 2015,  $8.8 \pm 3.1$  in 2016
- **Halo background :**
  - veto inefficiency using data driven method = (# of incoming-only events x # of outgoing-only events) / (# of both-track events x # of all events)  $\sim 1 \times 10^{-4}$
  - estimate =  $1.1 \pm 0.1$  in 2015,  $2.6 \pm 0.2$  in 2016 data
- **Noise background :**
  - extrapolated from cosmic ray data sample (signal free and halo free) from cosmic runs taken without LHC beams, then scaled to search data
  - veto inefficiency  $\leq 1 \times 10^{-4}$
  - estimate =  $0.4^{+2.9}_{-0.4}$  in 2015,  $0.0^{+9.8}_{-0.0}$  in 2016
- **Total background** estimate:  $4.1^{+3.0}_{-1.0}$  in 2015,  $11.4^{+10.3}_{-3.1}$  in 2016

Hadronic decay

# Stopped LLPs : backgrounds

Muon decay

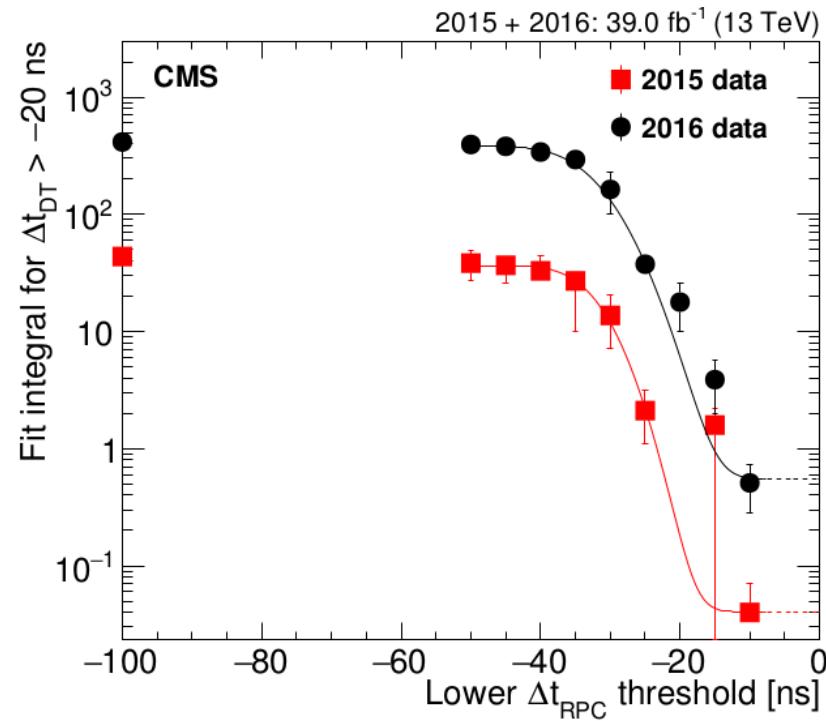
- No reconstructed collision vertices in events
- Developed new muon reconstruction algorithm :
  - reconstruct displaced muon tracks using only hits in the muon system without constraints to the IP
- To rejects cosmic rays RPC and DT time-of-flight cuts are used :
  - $\Delta t_{DT/RPC} = t_{DT/RPC}(\text{upper}) - t_{DT/RPC}(\text{lower})$
  - $\Delta t_{DT} > -20 \text{ ns}, \Delta t_{RPC} > -7.5 \text{ ns}$



# Stopped LLPs : backgrounds

- Cosmic ray muon background :
  - extrapolated from data from background-dominated region into signal region:
    - fit  $\Delta t_{DT}$  distribution with sum of 2 Gaussians + CB function
    - integral for  $\Delta t_{DT} > -20$  ns and different  $\Delta t_{RPC}$  ranges
    - fit integral vs  $\Delta t_{RPC}$  with error function
  - syst. unc. = difference between nominal case and case with 2 Gaussians + Landau fit
  - 2015 estimate =  $0.04 \pm 0.00(\text{stat.}) \pm 0.03(\text{syst.})$
  - 2016 estimate =  $0.50 \pm 0.02 (\text{stat.}) \pm 0.40 (\text{syst.})$
- 2 coincident cosmic ray muons background estimate found to be negligible

Muon decay



statistical error in background prediction comes from error in fit parameters

# Stopped LLPs : systematic uncertainties

- Syst. unc. on trigger efficiency is negligible
- Syst. unc. on reconstruction efficiency is :
  - $\sim 7\%$  for gluino
  - $\sim 5\%$  for stop

Hadronic decay

| Systematic uncertainty    | 2015 | 2016 |
|---------------------------|------|------|
| Reconstruction efficiency | 7.7% | 7.5% |
| Integrated luminosity     | 2.3% | 2.5% |
| Jet energy scale          | 2.0% | 2.0% |

- Syst. unc. on MC simulation modeling :
  - $q/p_T$  resolution compared in cosmic data and MC

$$R(Q/p_T) = \frac{(Q/p_T)^{\text{upper}} - (Q/p_T)^{\text{lower}}}{\sqrt{2}(Q/p_T)^{\text{lower}}}$$

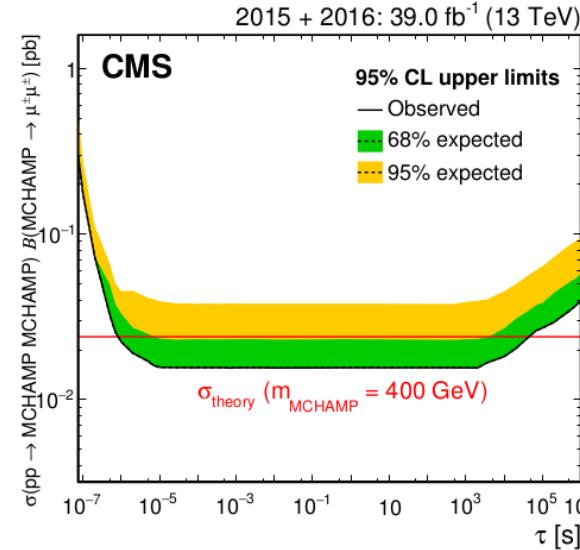
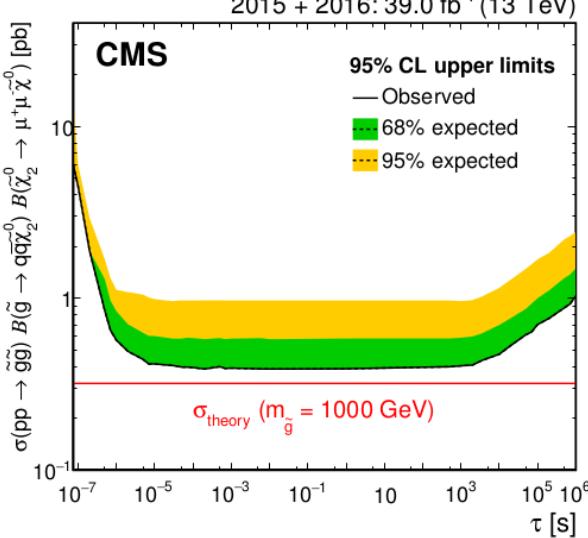
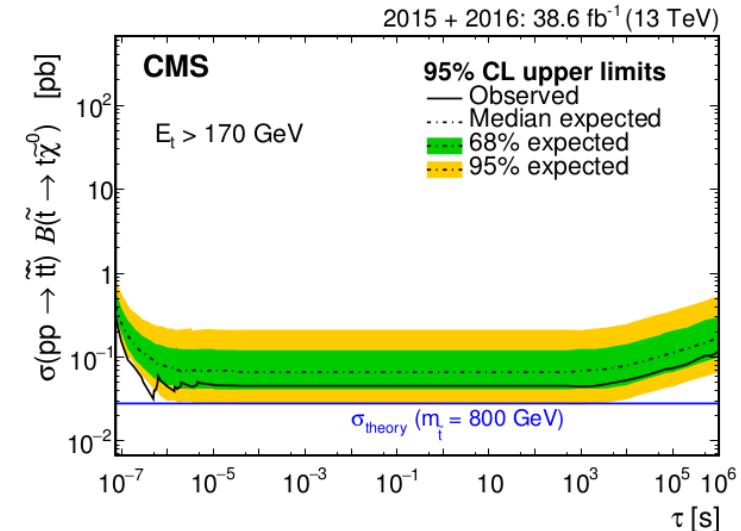
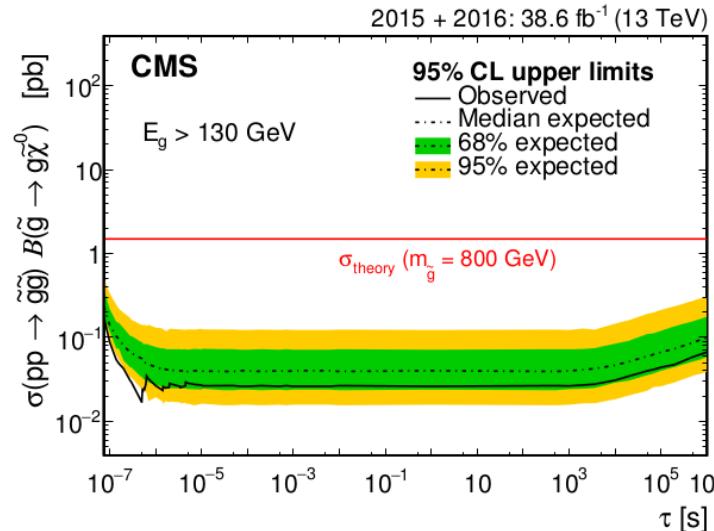
Muon decay

| Systematic Uncertainty          | 2015 | 2016 |
|---------------------------------|------|------|
| Luminosity                      | 2.3% | 2.5% |
| $Q/p_T$ Resolution Mis-modeling | 13%  | 7%   |
| Trigger Acceptance              | 13%  | 2.8% |

# Stopped long-lived particles

- Upper limits on the signal production cross section set using a hybrid method with the CLs criterion to incorporate syst. unc. :

Hadronic decay



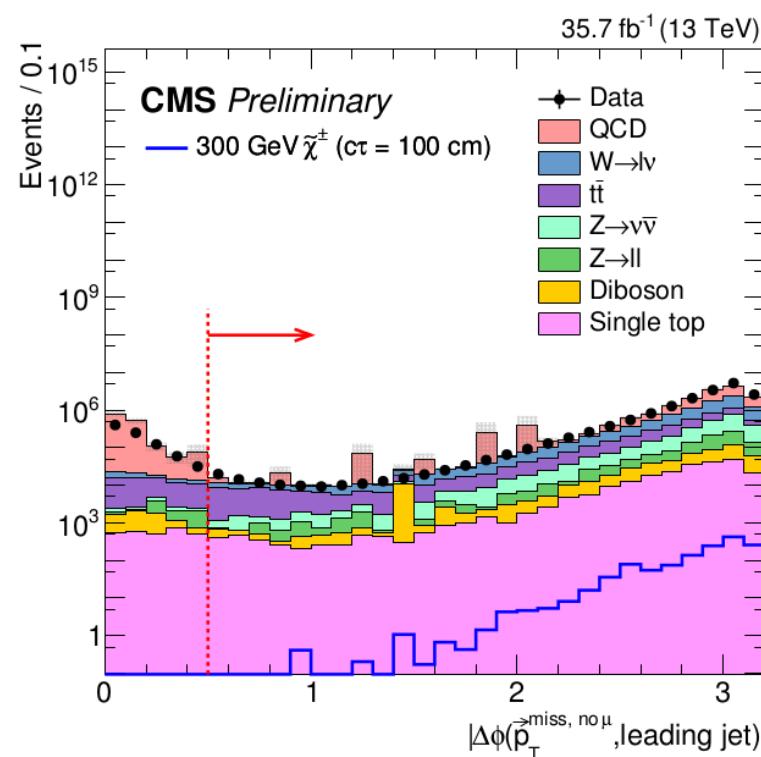
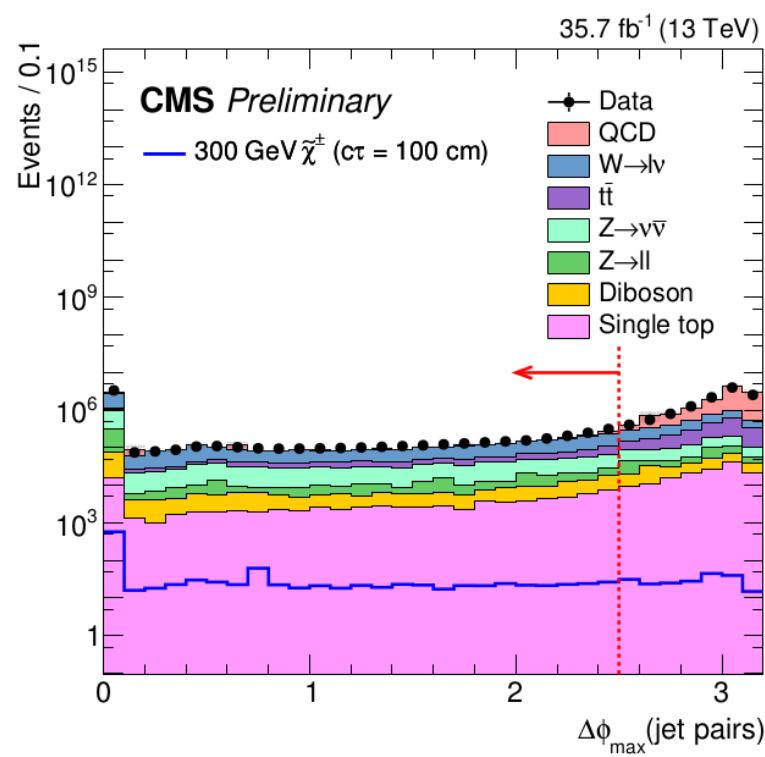
Muon decay

# Disappearing tracks : selections

- Basic selections:

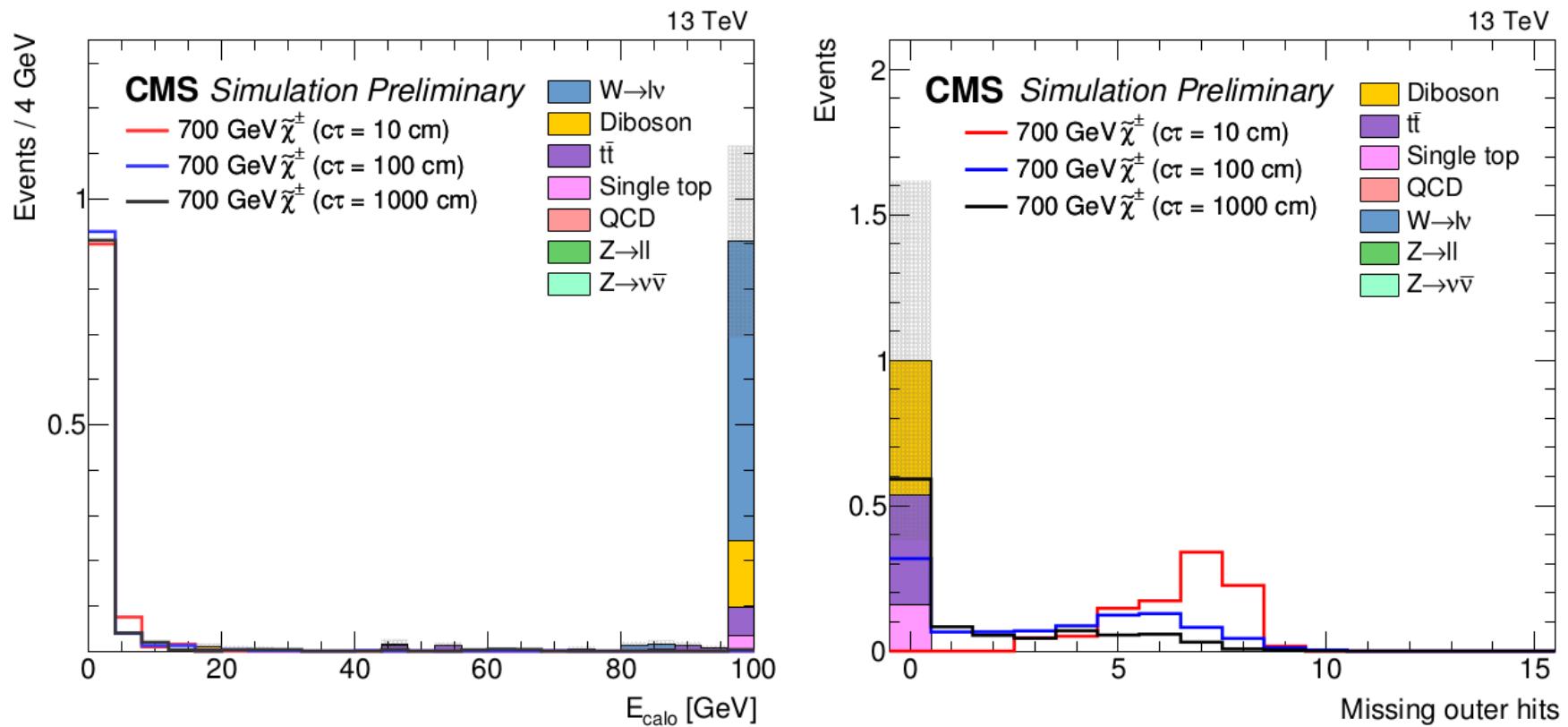
| quantity | object                       | selection  |
|----------|------------------------------|--|
| $\geq 1$ | primary vertices             | event passes MET triggers  |
| $\geq 1$ | $p_T^{\text{miss, no } \mu}$ | passing good primary vertex requirements                             |
| $\geq 1$ | jets                         | $p_T > 100 \text{ GeV}$  |
| $\geq 1$ | jets                         | $p_T > 110 \text{ GeV}$  |
| $\geq 1$ | jets                         | $ \eta  < 2.4$   |
|          | jet pairs                    | passing tight ID with lepton veto requirements                       |
|          | $p_T^{\text{miss, no } \mu}$ | $\max  \Delta\phi_{\text{jet,jet}}  < 2.5$                           |
|          |                              | $ \Delta\Phi(\text{leading jet}, p_T^{\text{miss, no } \mu})  > 0.5$ |

remove reducible  
QCD background



# Disappearing tracks : selections

- Candidate signal tracks:
  - $\geq 3$  missing outer hits (missing hits in the tracker outside of the last hit on the track)
  - associated calorimeter energy within  $\Delta R < 0.5$  of the track momentum  $< 10$  GeV



missing outer hits and  $E_{\text{calo}}$  are very effective at isolating the signal, as tracks from background events typically have no missing outer hits and significant  $E_{\text{calo}}$

# Disappearing tracks : backgrounds

- Samples of simulated SM processes for validation of data-driven methods used to estimate backgrounds and for calculation of systematic uncertainties
- Isolated charged leptons = not correctly reconstructed by the PF algorithm
  - enter search region if:
    - lepton failed to be reconstructed, but still leaving a track in the silicon tracker
    - resulting  $p_T^{\text{miss,no } \mu}$  large enough for the event to pass the offline  $p_T^{\text{miss,no } \mu}$  requirements
    - resulting  $p_T^{\text{miss}}$  and  $p_T^{\text{miss,no } \mu}$  must be large enough for the event to pass the triggers
  - background estimate based on calculating probability of these 3 conditions in data
  - background from each lepton flavor treated independently

# Disappearing tracks : backgrounds

- To mitigate isolated charged leptons :
  - events where candidate tracks are close to reconstructed leptons ( $\Delta R$  (track, lepton)  $< 0.15$ ) are vetoed
  - $P_{\text{veto}} = P(\text{pass lepton veto})$  estimated using T&P studies
    - same-sign T&P selections used to remove background from spurious tracks in the calculation
  - $P_{\text{offline}} = P(\text{pass offline MET cuts} \mid \text{pass lepton veto})$ 
    - single lepton CR used to “simulate” what the MET would look like if the selected lepton were not reconstructed
    - estimated calculating how many events would pass modified-MET cuts
  - $P_{\text{trigger}} = P(\text{pass MET triggers} \mid \text{pass lepton veto \& pass MET cuts})$ 
    - single lepton CR used to match the selected offline lepton to a trigger object of the appropriate type and add its  $p_T$  to the nominal online MET
    - estimated with fraction of events passing MET cuts that also pass the MET triggers given these modifications

$$\rightarrow P(\text{enter search region}) = P_{\text{veto}} * P_{\text{offline}} * P_{\text{trigger}}$$

$$\rightarrow N_{\text{est}} = N_{\text{CR}} * P_{\text{veto}} * P_{\text{offline}} * P_{\text{trigger}}$$

# Disappearing tracks : backgrounds

- Spurious tracks = pattern recognition errors that do not correspond to an actual charged particle :
  - can be missing hits in the outer layers of the silicon tracker and muon detectors, not generally associated to large energy deposits in the calorimeters → mimick a disappearing track
  - suppressed by requiring that candidate tracks have at least 3 hits in the pixel detector and at least 7 hits overall in the tracker
  - estimated using a  $Z \rightarrow \mu\mu$  CR
  - a track, separate from the muons coming from the Z candidate, is required to pass the track requirements of the search region except for the transverse impact parameter criterion, replaced with a sideband selection,  $0.02 < |d_0| < 0.1$  cm, designed to enhance the likelihood that the tracks selected are spurious
  - Pspurious = probability of spurious tracks passing the nominal impact parameter requirement = probability of spurious tracks that satisfy the above requirements multiplied by a transfer factor obtained from a sample of 3-hit tracks to ensure that the  $d_0$  distribution of spurious tracks is being sampled without significant risk of contamination from tracks originating from actual charged particles

$$\rightarrow N_{\text{est}} = N_{\text{CR}} * \text{Pspurious}$$

# Disappearing tracks : backgrounds

| Run period | Estimated number of background events |                       |                       | Observed events |
|------------|---------------------------------------|-----------------------|-----------------------|-----------------|
|            | Leptons                               | Spurious tracks       | Total                 |                 |
| 2015       | $0.1 \pm 0.1$                         | $0^{+0.1}_{-0}$       | $0.1 \pm 0.1$         | 1               |
| 2016A      | $2.0 \pm 0.4 \pm 0.1$                 | $0.4 \pm 0.2 \pm 0.4$ | $2.4 \pm 0.5 \pm 0.4$ | 2               |
| 2016B      | $3.1 \pm 0.6 \pm 0.2$                 | $0.9 \pm 0.4 \pm 0.9$ | $4.0 \pm 0.7 \pm 0.9$ | 4               |
| Total      | $5.2 \pm 0.8 \pm 0.3$                 | $1.3 \pm 0.4 \pm 1.0$ | $6.5 \pm 0.9 \pm 1.0$ | 7               |

| run period | $p_{fake}$                        | estimate                        |                                |
|------------|-----------------------------------|---------------------------------|--------------------------------|
|            |                                   | $N_{ctrl}^{\text{basic}}$       | $N_{\text{est}}^{\text{fake}}$ |
| 2015       | $(0^{+5.05}_{-0}) \times 10^{-8}$ | $(1.566 \pm 0.001) \times 10^6$ | $0^{+0.0791}_{-0}$             |
| 2016B+C    | $(6.50 \pm 3.25) \times 10^{-8}$  | $(5.890 \pm 0.002) \times 10^6$ | $0.383 \pm 0.193$              |
| 2016D-H    | $(4.30 \pm 1.63) \times 10^{-8}$  | $(2.1230 \pm 0.0005)^7$         | $0.913 \pm 0.346$              |
| total      |                                   |                                 | $1.30 \pm 0.40$                |

| run period | $N_{ctrl}^l$     | electron background              |                     |                     | estimate          |
|------------|------------------|----------------------------------|---------------------|---------------------|-------------------|
|            |                  | $p_{veto}$                       | $p_{offline}$       | $p_{trigger}$       |                   |
| 2015       | $58820 \pm 240$  | $(6.1 \pm 4.3) \times 10^{-6}$   | $0.9024 \pm 0.0054$ | $0.369 \pm 0.0043$  | $0.119 \pm 0.084$ |
| 2016B+C    | $156120 \pm 400$ | $(1.95 \pm 0.61) \times 10^{-5}$ | $0.8987 \pm 0.0033$ | $0.3475 \pm 0.0034$ | $0.95 \pm 0.30$   |
| 2016D-H    | $470140 \pm 690$ | $(1.59 \pm 0.42) \times 10^{-5}$ | $0.9004 \pm 0.0019$ | $0.2841 \pm 0.0020$ | $1.91 \pm 0.50$   |

| run period | $N_{ctrl}^l$     | muon background                  |                     |                     | estimate          |
|------------|------------------|----------------------------------|---------------------|---------------------|-------------------|
|            |                  | $p_{veto}$                       | $p_{offline}$       | $p_{trigger}$       |                   |
| 2015       | $64200 \pm 250$  | $(0^{+1.3}_{-0}) \times 10^{-6}$ | $0.9057 \pm 0.0052$ | $0.9257 \pm 0.0078$ | $0^{+0.072}_{-0}$ |
| 2016B+C    | $145930 \pm 380$ | $(8.8 \pm 2.6) \times 10^{-6}$   | $0.8969 \pm 0.0034$ | $0.8736 \pm 0.0063$ | $1.01 \pm 0.30$   |
| 2016D-H    | $555420 \pm 750$ | $(2.89 \pm 0.98) \times 10^{-6}$ | $0.8932 \pm 0.0017$ | $0.7588 \pm 0.0032$ | $1.09 \pm 0.37$   |

| run period | $N_{ctrl}^l$   | tau background                   |                   |                 | estimate                     |
|------------|----------------|----------------------------------|-------------------|-----------------|------------------------------|
|            |                | $p_{veto}$                       | $p_{offline}$     | $p_{trigger}$   |                              |
| 2015       | $1280 \pm 120$ | $(8^{+12}_{-8}) \times 10^{-5}$  | $0.12 \pm 0.035$  | $0.31 \pm 0.28$ | $0.0037^{+0.0066}_{-0.0037}$ |
| 2016B+C    | $3230 \pm 180$ | $(1.41 \pm 0.70) \times 10^{-4}$ | $0.26 \pm 0.033$  | $0.27 \pm 0.12$ | $0.032 \pm 0.022$            |
| 2016D-H    | $8910 \pm 670$ | $(1.04 \pm 0.35) \times 10^{-4}$ | $0.318 \pm 0.048$ | $0.21 \pm 0.13$ | $0.063 \pm 0.045$            |

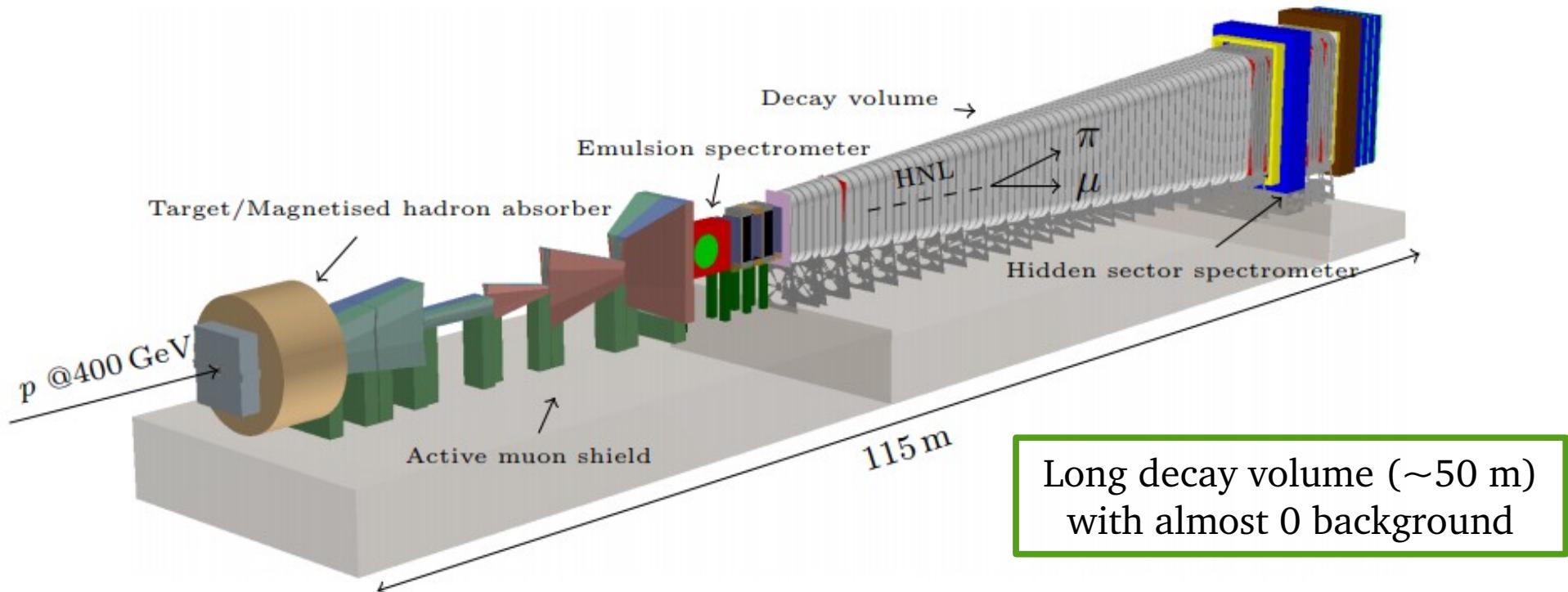
# Disappearing tracks : systematics

- Systematics on signal yields

| Source of uncertainty                 | Typical value |
|---------------------------------------|---------------|
| Integrated luminosity                 | 2.3–2.5%      |
| Pileup                                | 2–3%          |
| ISR                                   | 8–9%          |
| Jet energy scale/resolution           | 2–6%          |
| $p_T^{\text{miss, no } \mu}$ modeling | 0.4%          |
| Missing inner hits                    | 1–3%          |
| Missing middle hits                   | 0.3–3%        |
| Missing outer hits                    | 0.03–3%       |
| $E_{\text{calo}}$ selection           | 0.6–1%        |
| Trigger efficiency                    | 4–6%          |
| Track reconstruction efficiency       | 1.5–4.5%      |
| Total                                 | 10–16%        |

# SHiP

- Heavy target to maximize heavy flavour production (large A) and minimize production of neutrinos in  $\pi/K \rightarrow \mu\nu$  decays (source of bkg)
- Hadron absorber after the target stop most SM particles, except  $\mu$  and  $\nu$
- Active muons shield (magnetic deflection away from the detectors)
- Decay volume under vacuum to prevent neutrino interactions within the fiducial volume



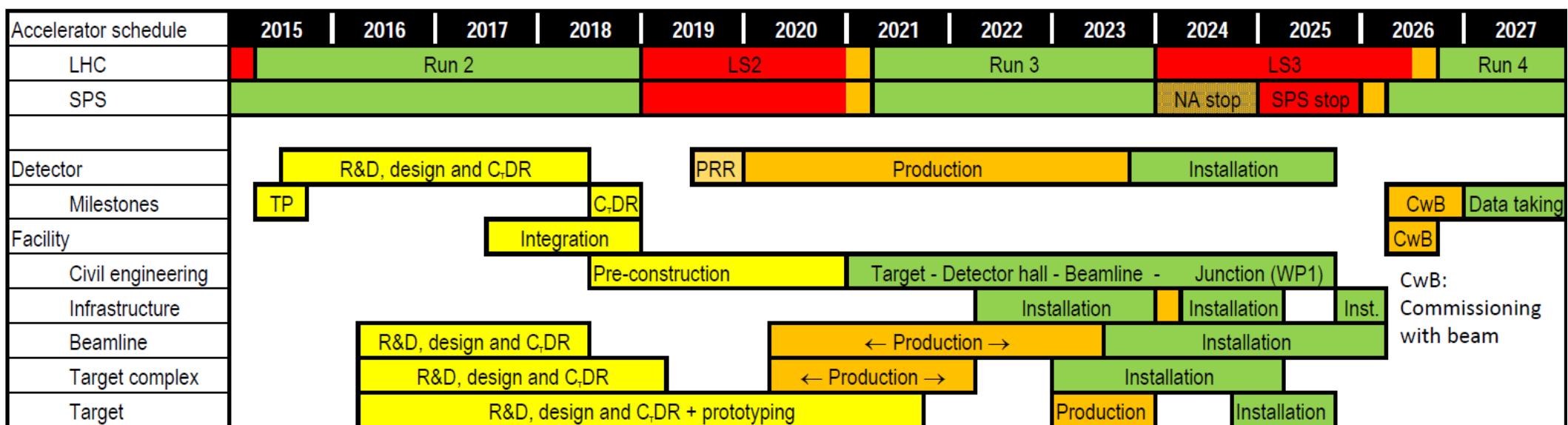
- Spectrometer with usual detectors (tracking system, magnet, timing detector, calorimeters, muon system)
- Slow and uniform beam extraction ( $\sim 1\text{s}$ ) to reduce occupancy in the detector

# SHiP

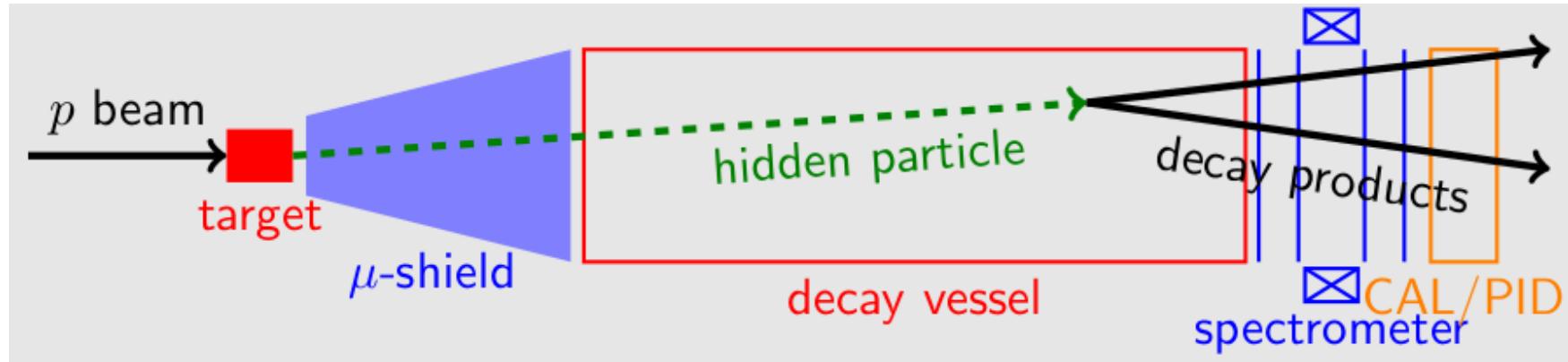
- SHiP timeline :

- currently in R&D and detector design optimization
- aim for CDR this year and TDR next year
- data-taking not earlier than 2026:

LHC should deliver 300/fb to CMS and ATLAS by then → complementary sensitivity and window for discovery



# SHiP



- Detection of hidden particles through their decay in SM particles
- Detector must be sensitive to as many decay modes as possible → full reconstruction and PID essential to minimize model dependence
- Branching ratios suppressed compared to SM couplings  $\mathcal{O}(10^{-10})$  → challenging background suppression → estimated  $\mathcal{O}(0.01)$  needed
- Hidden sector models share a number of unique and common physics phenomenologies

| Particle                                 | Final states  |
|--|---|
| HNL, neutralino                          | $\ell^\pm \pi^\mp, \ell^\pm K^\mp, \ell^\pm \rho^\mp$ |
| Vector, scalar, axion portals; goldstino | $\ell^\pm \ell^\mp$                                   |
| HNL, neutralino, axino                   | $\ell^\pm \ell^\mp v_\ell$                            |
| Axion portal, sgoldstino                 | $\gamma\gamma$  |
| Sgoldstino                               | $\pi^0 \pi^0$   |

# Heavy neutrinos @ SHiP

- HNLs:
  - production through :
    - meson decays ( $\pi$ , K, D, B) if mass small enough
    - W and Z if higher masses
  - production and decay rate are strongly suppressed w.r.t. SM
    - production BR  $O(10^{-10})$
    - long-lived objects  $O(\mu\text{s})$
  - very weakly interaction with matter (travel unperturbed through matter)
  - typical lifetimes  $>10 \mu\text{s}$  for  $m_{\text{N}_{2/3}} \sim 1 \text{ GeV}$
  - decay distance  $O(\text{km})$

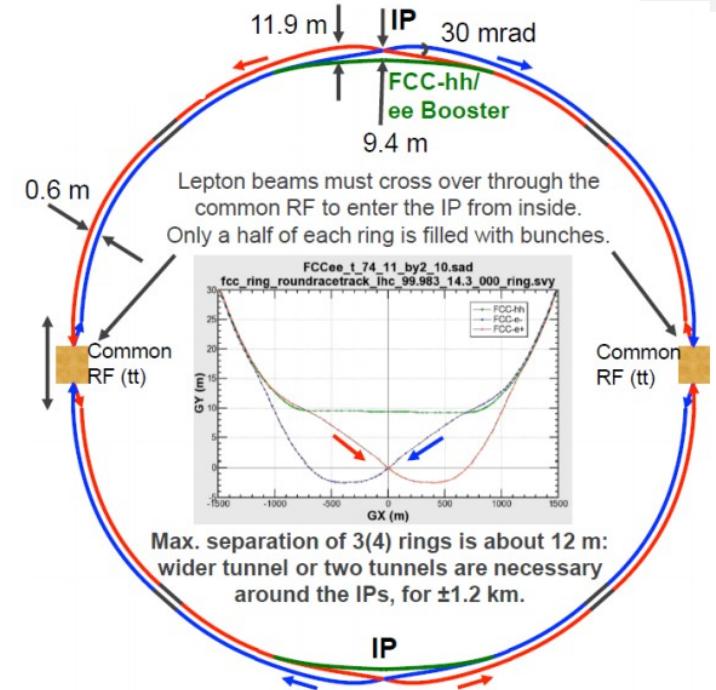
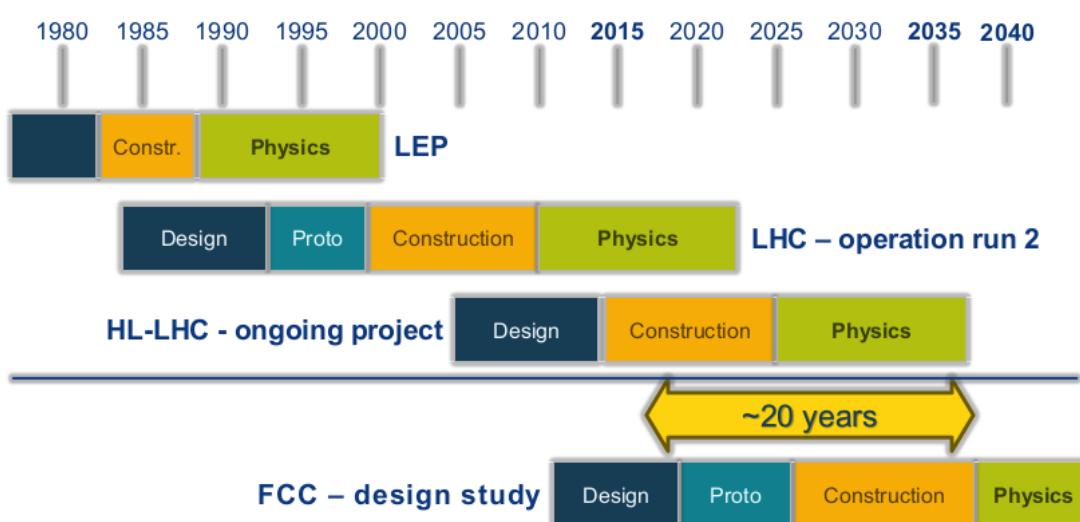
# SHiP

- Rejection strategies of background sources :
  - $\nu$ - and  $\mu$ -induced backgrounds (e.g. inelastic  $\nu$ -interactions in the surroundings of the HP detector)
    - reconstructed momentum must point back to proton target
    - veto upstream the decay volume
    - reconstructed vertex must be in decay volume
  - random combination of tracks (rate at spectrometer = 7 kHz/spill) :
    - timing veto with a precision of  $O(100 \text{ ps})$
    - surround background tagger and upstream veto detector
  - cosmic muons (scattering/DIS on cavern and vessel walls) :
    - surround background tagger and upstream veto detector
    - event topology, pointing of momentum
- Backgrounds investigated  
extensive MC studies  
**expected less than  
events in 5 years!**

| Background source  | Statistical factor | Expected background |
|--|--------------------|---------------------|
| $\nu (p > 10.0 \text{ GeV}/c)$                                   | 35.                | < 0.07              |
| $\nu (4.0 \text{ GeV}/c < p < 10.0 \text{ GeV}/c)$               | $\sim 1$           | 0 (MC)              |
| $\nu (2.0 \text{ GeV}/c < p < 4.0 \text{ GeV}/c)$                | 0.07               | 0 (MC)              |
| $\mu$ DIS HS   | $\sim 1$           | 0 (MC)              |
| $\mu$ DIS wall   | 0.001              | 0 (MC)              |
| $\mu$ Combinatorial  | $10^4$             | < 0.1               |
| $\mu$ Cosmics ( $p < 100 \text{ GeV}/c$ )                        | 0.2                | 0 (MC)              |
| $\mu$ Cosmics ( $p > 100 \text{ GeV}/c$ )                        | 800.               | < 0.1               |
| $\mu$ Cosmics DIS ( $p > 100 \text{ GeV}/c$ )                    | $10^3$             | < 0.1               |
| $\mu$ Cosmics DIS ( $10 \text{ GeV}/c < p < 100 \text{ GeV}/c$ ) | $\sim 1$           | 0 (MC)              |

# FCC

- New proposed 100 km circular collider at CERN :
  - can explore the 10-100 TeV energy scale with **precision measurements of W, Z, H, top** properties
  - **can discover very weakly coupled particles** in the 5-100 GeV mass range
  - there is a strong scientific case for an electron positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded
  - **large potential beyond the HL-LHC :**
    - experimental errors at FCC-ee will be 20-100 times smaller than the present errors but only 10-30 times smaller than present level of theory errors
  - full proposal for the end of next year :
    - give **priority to pp collider**, timeline constrained by magnet technology evolution and by HL-LHC timeline



# FCC-hh parameters

| parameter  | FCC-hh    |          | HE-LHC     | HL-LHC | LHC  |
|--|-----------|----------|------------|--------|------|
| collision energy cms [TeV]                                 | 100       |          | 27         | 14     | 14   |
| dipole field [T]   | 16        |          | 16         | 8.33   | 8.33 |
| circumference [km]   | 97.75     |          | 26.7       | 26.7   | 26.7 |
| beam current [A]   | 0.5       |          | 1.12       | 1.12   | 0.58 |
| bunch intensity [ $10^{11}$ ]                              | 1         | 1 (0.2)  | 2.2 (0.44) | 2.2    | 1.15 |
| bunch spacing [ns]   | 25        | 25 (5)   | 25 (5)     | 25     | 25   |
| synchr. rad. power / ring [kW]                             | 2400      |          | 101        | 7.3    | 3.6  |
| SR power / length [W/m/ap.]                                | 28.4      |          | 4.6        | 0.33   | 0.17 |
| long. emit. damping time [h]                               | 0.54      |          | 1.8        | 12.9   | 12.9 |
| beta* [m]  | 1.1       | 0.3      | 0.25       | 0.20   | 0.55 |
| normalized emittance [ $\mu\text{m}$ ]                     | 2.2 (0.4) |          | 2.5 (0.5)  | 2.5    | 3.75 |
| peak luminosity [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ] | 5         | 30       | 25         | 5      | 1    |
| events/bunch crossing                                      | 170       | 1k (200) | ~800 (160) | 135    | 27   |
| stored energy/beam [GJ]                                    | 8.4       |          | 1.3        | 0.7    | 0.36 |

# FCC-ee parameters

| parameter   | Z         | W    | H (ZH) | ttbar |
|---|-----------|------|--------|-------|
| cm collision energy [GeV]                             | 91        | 160  | 240    | 350   |
| beam current [mA]                                     | 1400      | 147  | 29     | 6.4   |
| no. bunches   | 71000     | 7500 | 740    | 62    |
| bunch intensity [ $10^{11}$ ]                         | 0.4       | 0.4  | 0.8    | 2.1   |
| bunch spacing [ns]                                    | 2.5 / 5.0 | 40   | 400    | 5000  |
| SR energy loss / turn [GeV]                           | 0.036     | 0.34 | 1.71   | 7.72  |
| total RF voltage [GV]                                 | 0.25      | 0.8  | 3.0    | 9.5   |
| long. damping time [turns]                            | 1280      | 235  | 70     | 23    |
| horizontal beta* [m]                                  | 0.15      | 1    | 1      | 1     |
| vertical beta* [mm]                                   | 1         | 2    | 2      | 2     |
| horiz. geometric emittance [nm]                       | 0.27      | 0.26 | 0.61   | 1.33  |
| vert. geom. emittance [pm]                            | 1.0       | 1.0  | 1.2    | 2.66  |
| bunch length with SR & BS [mm]                        | 4.1       | 2.3  | 2.2    | 2.9   |
| luminosity [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ] | 130       | 16   | 5      | 1.4   |

# FCC

- So far null results for BSM searches @ LHC :
  - only few events could be needed for discovery, but missed by standard searches → need a search program at “lifetime frontier”
- Lessons from LHC:
  - focus on displaced decay signature
  - signature space for LLPs is quite complex
  - complicated mix of mostly irreducible backgrounds difficult to simulate
- Challenges:
  - for short lifetimes ( $\leq mm$ ) and soft decay products : large background and high PU → solution = ee / ep colliders
  - for long lifetimes ( $\geq 100 m$ ) LLPs almost always escape main detector : signal possible if large production rate, but large backgrounds → solution = external LLP detector
    - need of displaced vertex + X signature  
(X = high energy jets, leptons, another displaced vertex, ...)

# FCCs

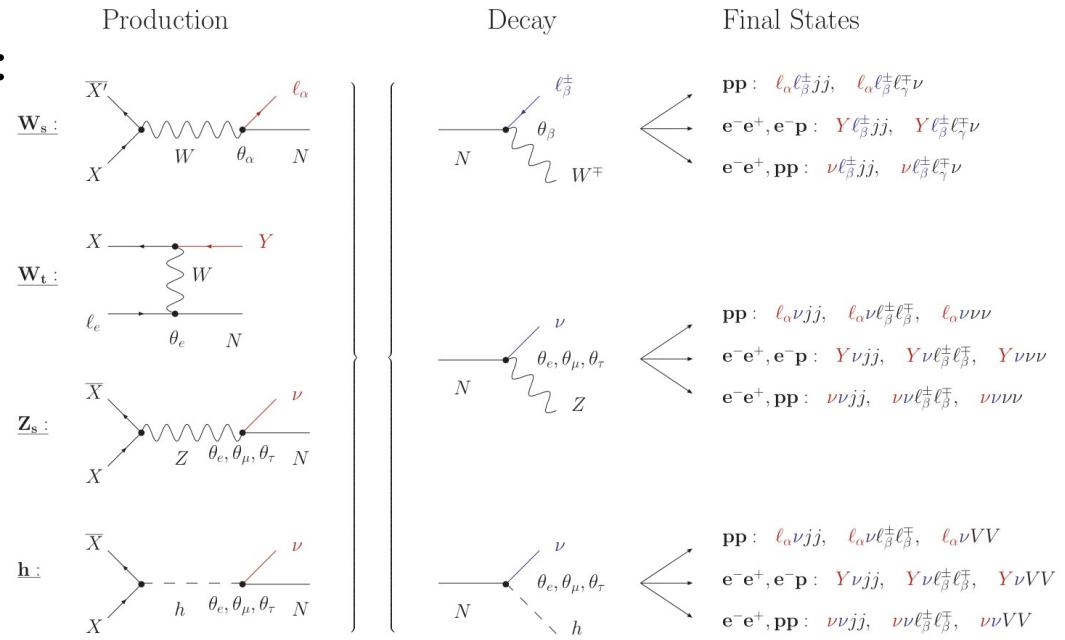
- FCC-ee :
  - clean experimental environment (track segments recoiling vs a photon) → can probe:
    - complicated signatures (displaced vertex signatures, disappearing tracks..)
    - small mass/lifetime/coupling scenarios
  - foreseen luminosity will allow to cover almost all the parameter space at any energy
  - highest sensitivity for  $m_N < m_W$  (**low mass regime**) → test model predictions
  - high sensitivity of SM precision tests (**mass independent**) → test heavy  $\nu$  up to  $\sim 60$  TeV, not sensitive to number of  $\nu$
- FCC-hh and -eh :
  - sensitive to **high mass regime**
  - direct test of lepton-flavor (and -number) violation → number of heavy neutrino generations and their masses
  - indirect test via measurement of Higgs potential
- FCC-eh :
  - good sensitivity for softly decaying, short-lived ( $\sim \mu\text{m}$ ) LLPs (very low PU, good tracking resolution, boosted final state with larger  $E_{\text{CM}}$  than most lepton colliders)
  - **w.r.t. FCC-hh :**
    - pros: clean environment (smaller bkg), forward objects, detection of BSM signal which looks like hadronic noise at pp colliders
    - cons: small production due to smaller  $\sqrt{s}$
    - specialized scenarios with large signal rate (LQ, heavy neutrinos, WR from LR symmetry).. but corresponding pp program has greater richness

# Heavy neutrinos @ FCC

- Sterile neutrino direct searches at FCC:

## FCC-ee

| Name                   | Final State                       | $ \theta , Z$ pole  | $ \theta , \sqrt{s} > m_Z$                    |
|------------------------|-----------------------------------|---------------------|---|
| lepton-dijet           | $\ell_\alpha \nu jj$              | $ \theta_\alpha ^2$ | $\frac{ \theta_e \theta_\alpha ^2}{\theta^2}$ |
| mixed flavour dilepton | $\ell_\alpha \ell_\beta \nu \nu$  | $ \theta_\alpha ^2$ | $\frac{ \theta_e \theta_\alpha ^2}{\theta^2}$ |
| same flavour dilepton  | $\ell_\alpha \ell_\alpha \nu \nu$ | $ \theta ^2$        | $ \theta_e ^2$                                |
| dijet                  | $\nu \nu jj$                      | $ \theta ^2$        | $ \theta_e ^2$                                |
| invisible              | $\nu \nu \nu \nu$                 | $ \theta ^2$        | $ \theta_e ^2$                                |



## FCC-eh

| Name          | Final State                        | $ \theta_\alpha $ Dependency                  | LFV |
|---------------|------------------------------------|---|-----|
| lepton-trijet | $jjj \ell_\alpha^-$                | $\frac{ \theta_e \theta_\alpha ^2}{\theta^2}$ | ✓   |
| jet-dilepton  | $j \ell_\alpha^- \ell_\beta^+ \nu$ | $\frac{ \theta_e \theta_\alpha ^2}{\theta^2}$ | ✓   |
| trijet        | $jjj \nu$                          | $ \theta_e ^2$                                | ✗   |
| monojet       | $j \nu \nu \nu$                    | $ \theta_e ^2$                                | ✗   |

| Name           | Final State                              | Channel [production,decay]    | $ \theta_\alpha $ dependency  | LNV/LFV |
|----------------|--|-------------------------------|---|---------|
| dilepton-dijet | $\ell_\alpha \ell_\beta jj$              | [ $W_s, W$ ]                  | $\frac{ \theta_\alpha \theta_\beta ^2}{\theta^2}$                                     | ✓/✓     |
| trilepton      | $\ell_\alpha \ell_\beta \ell_\gamma \nu$ | [ $W_s, \{W, Z(h)\}$ ]        | $\left\{ \frac{ \theta_\alpha \theta_\beta ^2}{\theta^2},  \theta_\alpha ^2 \right\}$ | ✗/✓     |
| lepton-dijet   | $\ell_\alpha \nu jj$                     | [ $W_s, Z(h)$ ], [ $Z_s, W$ ] | $ \theta_\alpha ^2$   | ✗       |
| dilepton       | $\ell_\alpha \ell_\beta \nu \nu$         | [ $Z_s, \{W, Z(h)\}$ ]        | $\{ \theta_\alpha ^{2(*)},  \theta ^2\}$  | ✗       |
| mono-lepton    | $\ell_\alpha \nu \nu \nu$                | [ $W_s, Z$ ]                  | $ \theta_\alpha ^2$   | ✗       |
| dijet          | $\nu \nu jj$                             | [ $Z_s, Z(h)$ ]               | $ \theta ^2$  | ✗       |

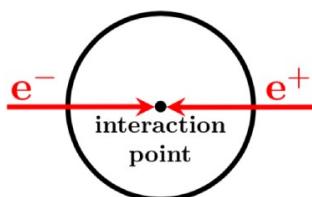
# Heavy neutrinos @ FCC

- Most promising search strategies for sterile neutrinos:
  - FCC-ee :
    - displaced vertices (Z-pole)
    - EW precision measurements (mostly Z-pole)
    - H production and decay modes
  - FCC-hh :
    - displaced vertices
    - LFV di-leptons + jets
    - LNV di-leptons
  - FCC-eh :
    - LFV lepton-trijet
    - LNV antilepton-trijets
- Synergy of FCCs : the combination of direct and indirect signatures at all FCCs will pin down the parameters and test model specific predictions, testing origin of neutrino masses

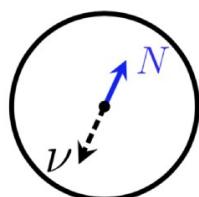
# Heavy neutrinos @ FCC

- Very high luminosity of the FCC-ee at the Z pole, allowing a total of  $10^{12}$  Z bosons to be produced in a few years
- The direct search appears very promising due to the long lifetime of heavy neutrinos for small mixing angles:
  - a sensitivity down to a heavy-light mixing of  $|\theta| \sim 10^{-12}$  is obtained, covering a large phase space for heavy neutrino masses between 10 and 80 GeV
- Heavy neutrinos with  $m \lesssim m_W$  can be long-lived  
→ very sensitive searches possible via displaced vertices

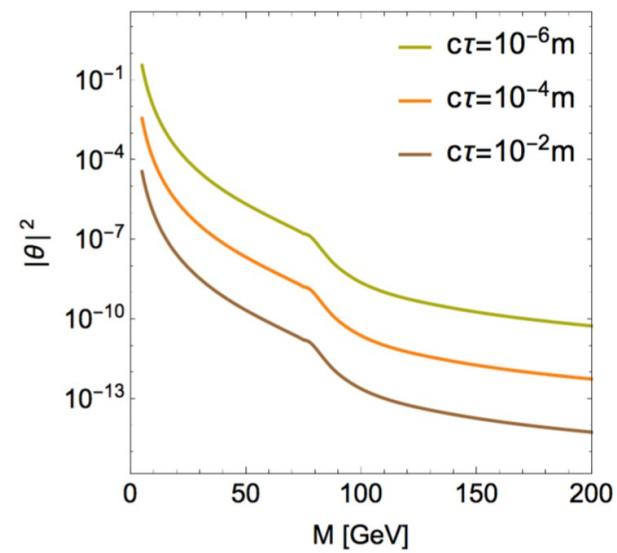
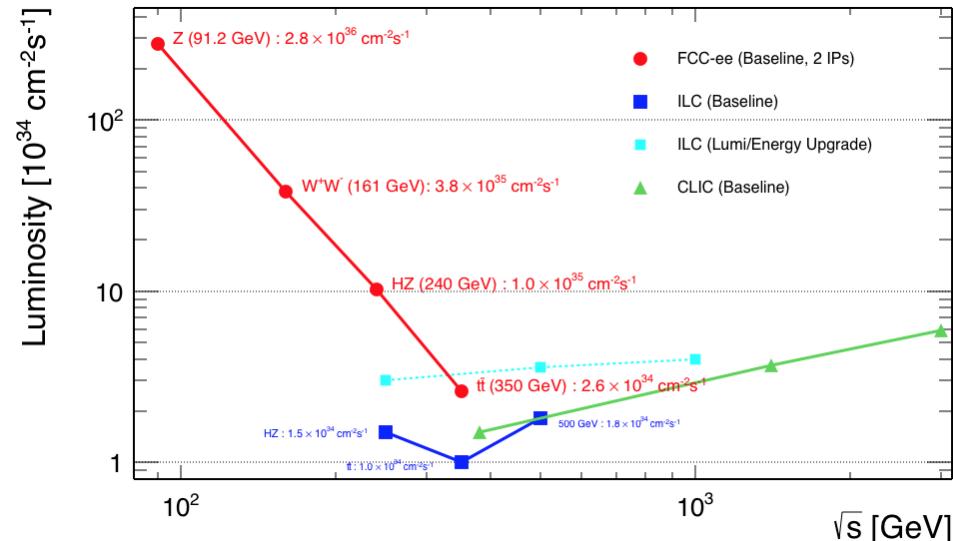
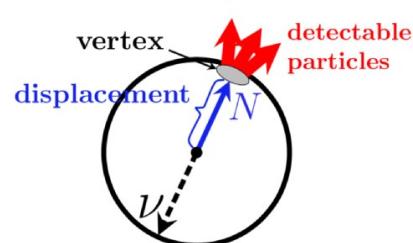
$t = 0$   
electron-positron collision



$0 < t <$ lifetime of  $N$   
production of  $N$  and propagation

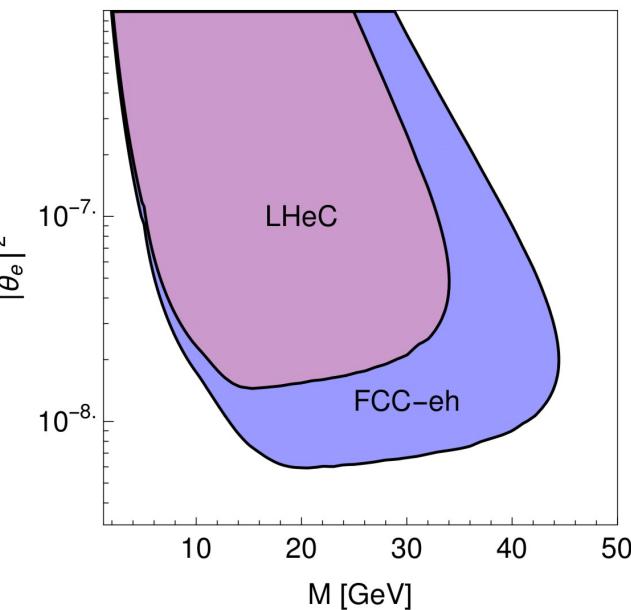


lifetime of  $N < t$   
decay of  $N$  into detectable particles

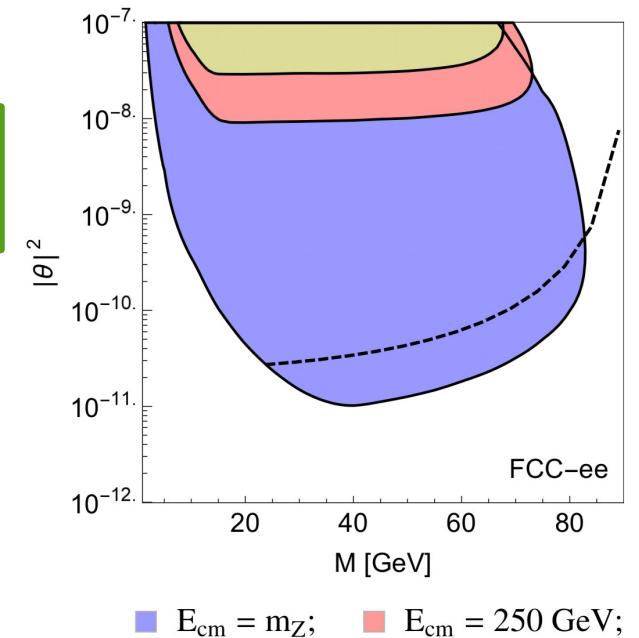


# Heavy neutrinos @ FCC

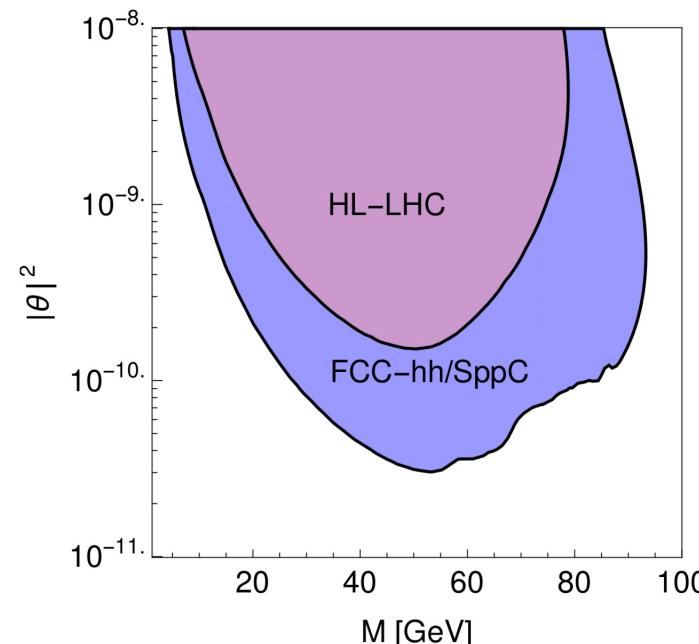
- Sensitivity forecasts for FCCs:



estimate for FCC-hh,  
 $L=20 \text{ ab}^{-1}$



estimate for FCC-ee,  
 $L=110 \text{ ab}^{-1}$  at Z pole



estimate for FCC-eh,  
 $L=1 \text{ ab}^{-1}$