Sterile neutrino searches at the LHC

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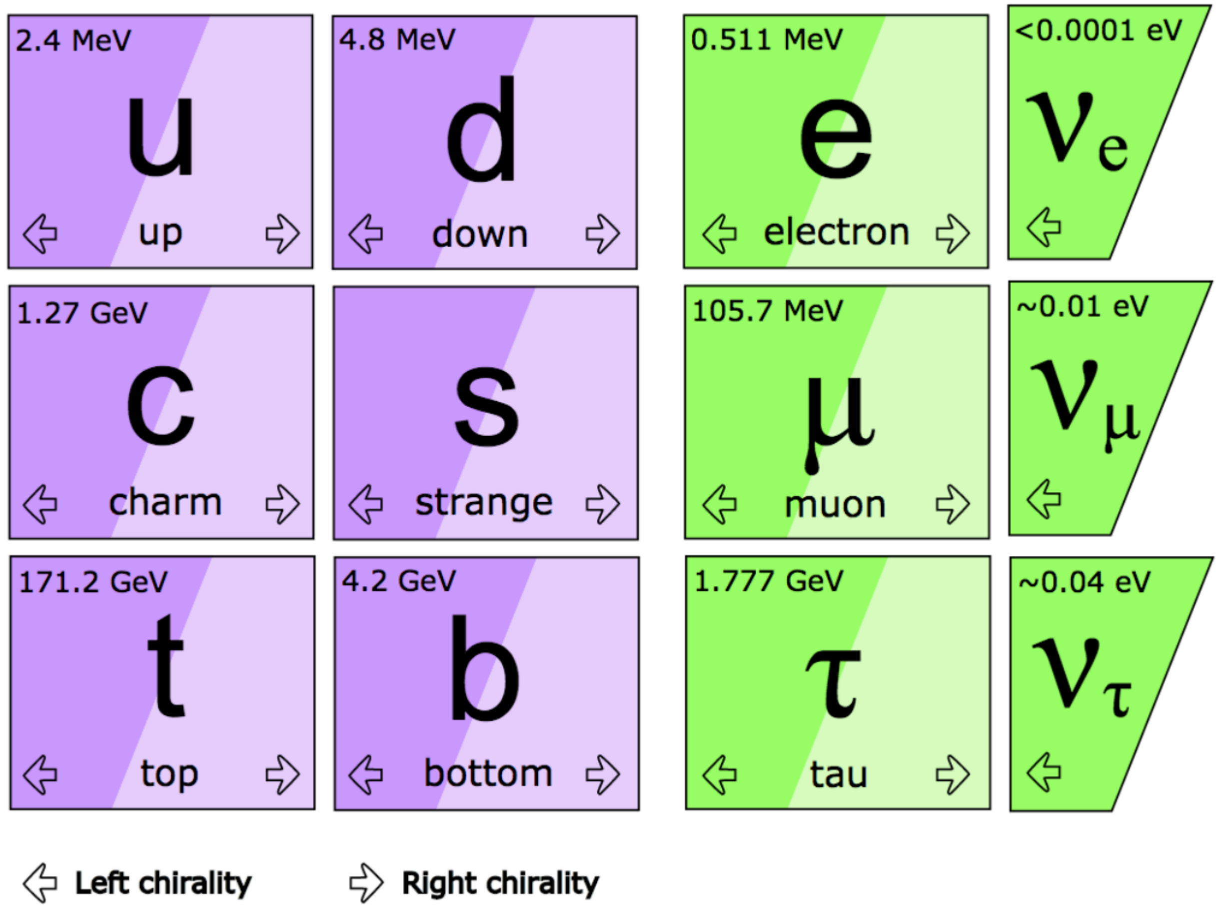
Sterile neutrinos

- Neutrino oscillations suggest that ν_ℓ have nonzero mass
  - not naturally included in the SM



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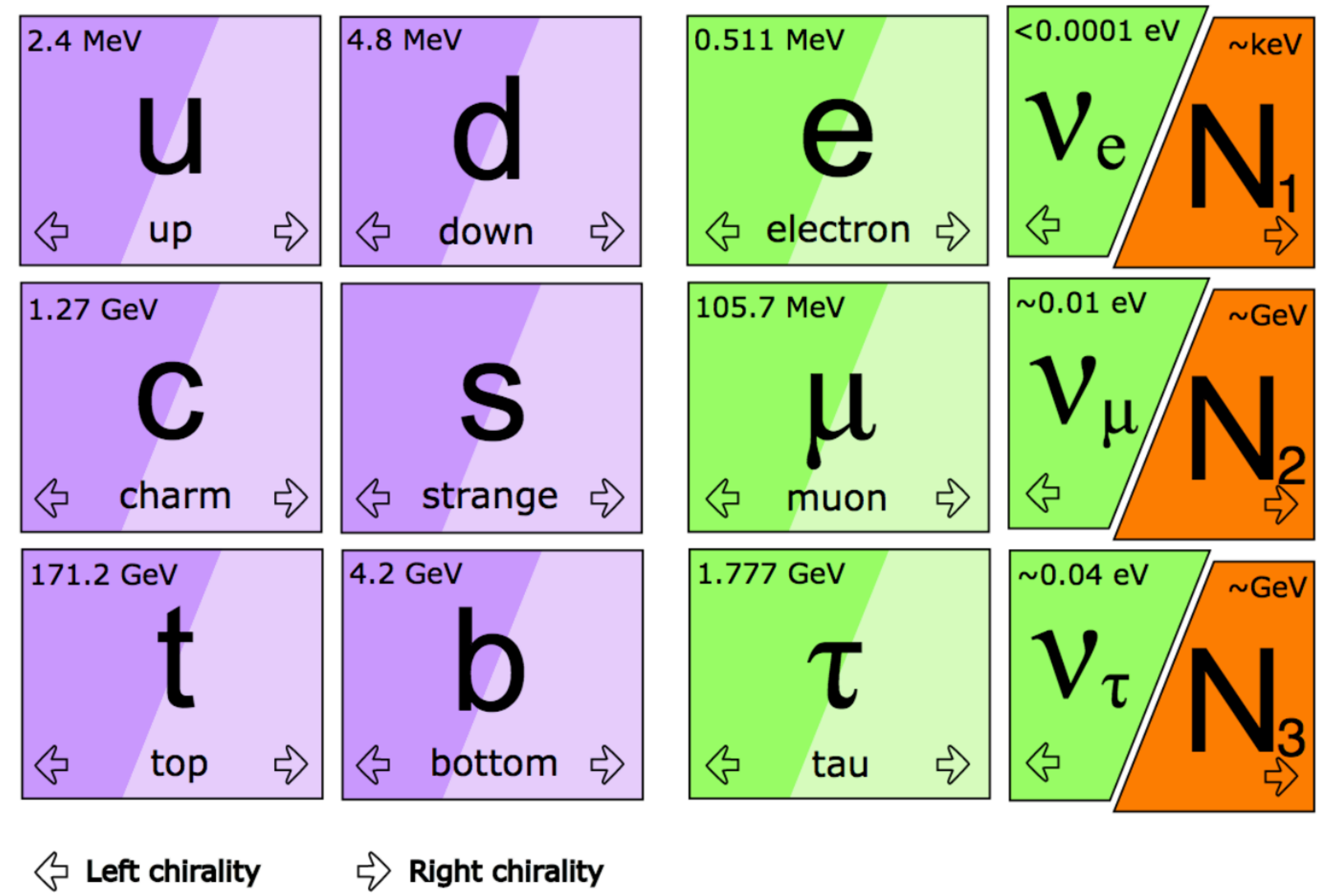


- They can be explained by minimal extensions to the SM (νMSM)
  - additional right-handed sterile neutrinos (N_i)
  - ν_ℓ masses generated via (low-scale) type-I seesaw mechanism
  - N_i singlets under all SM gauge groups $\Rightarrow$ *sterile*, only produced via mixing with active neutrinos ν_ℓ

Sterile neutrinos: mass and lifetime

- Can add both Dirac (M_D) and Majorana (M_R) mass terms

$$\Delta\mathcal{L}_\mathrm{HNL} \approx i\overline{N}_i \partial\!\!\!/ N_i - Y_{i\ell}\overline{N}_i L_\ell H - \frac{1}{2}\overline{N}_i^C M_{ij} N_j + h.c.$$

- If $M_\mathrm{D} \ll M_\mathrm{R}$, neutrino masses are given by

$$m_{\nu_\ell} \sim \frac{M_\mathrm{D}^2}{M_\mathrm{R}} \qquad \left(m_{\nu_\ell} \sim \mu \frac{M_\mathrm{D}^2}{M_\mathrm{R}^2} \text{ in low-scale seesaw} \right)$$

$$m_{N_i} \sim M_\mathrm{R}$$

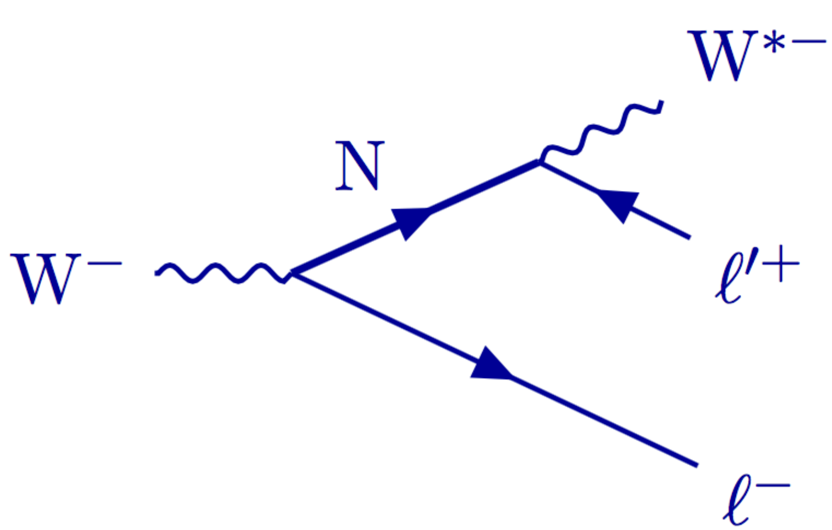
- Mixing ν_ℓ-N_i is governed by a parameter $V_{i\ell} \sim M_\mathrm{D}/M_\mathrm{R} \ll 1$
    - $\nu_\ell \leftrightarrow N_i$ rate $\sim |V_{i\ell}|^2$

- N_i lifetime depends on $V_{i\ell}$ and m_{N_i}: $\tau_i \sim \left|V_{i\ell}\right|^{-2} m_{N_i}^{-5}$

HNL decays: LNC *vs* LNV

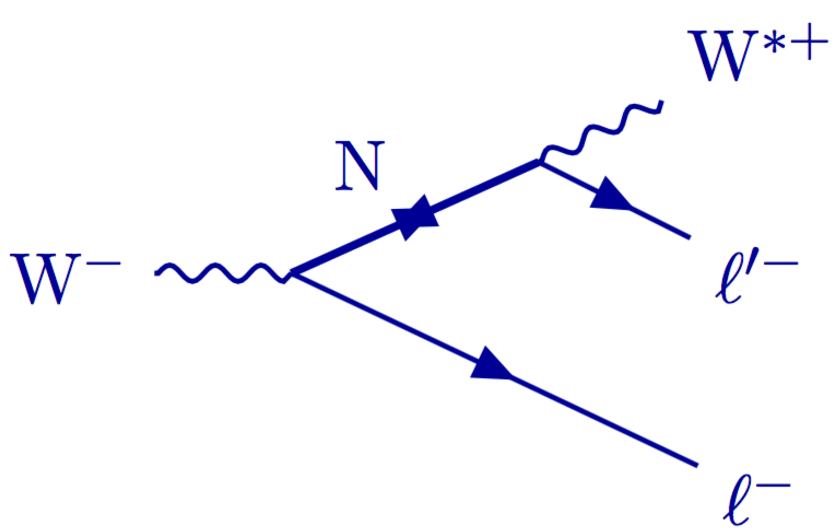
- Depending on the nature of these *heavy neutral leptons* (HNL), decays can conserve or violate the lepton number
  - **Dirac:** lepton number conserved (**LNC**)
  - **Majorana:** lepton number conserved (**LNC**) or violated (**LNV**)
    - LNV/LNC ratio is model dependent

LNC



(***Dirac*** *or* ***Majorana***)

LNV

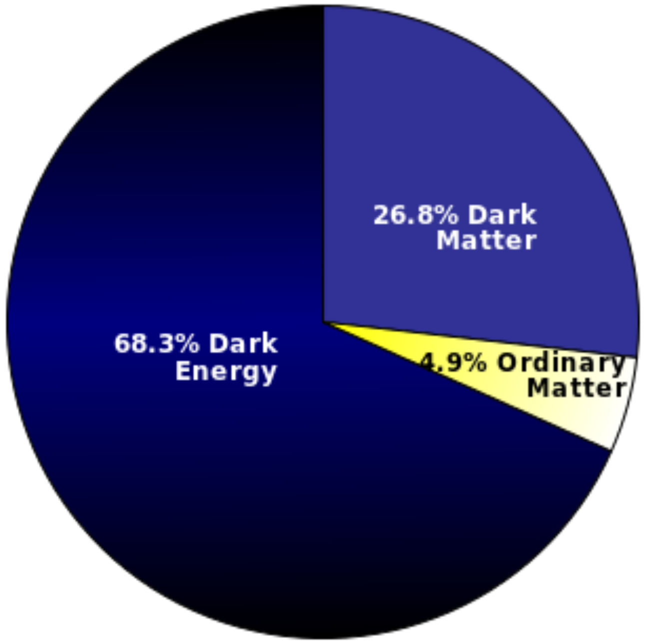


(*only* ***Majorana***)

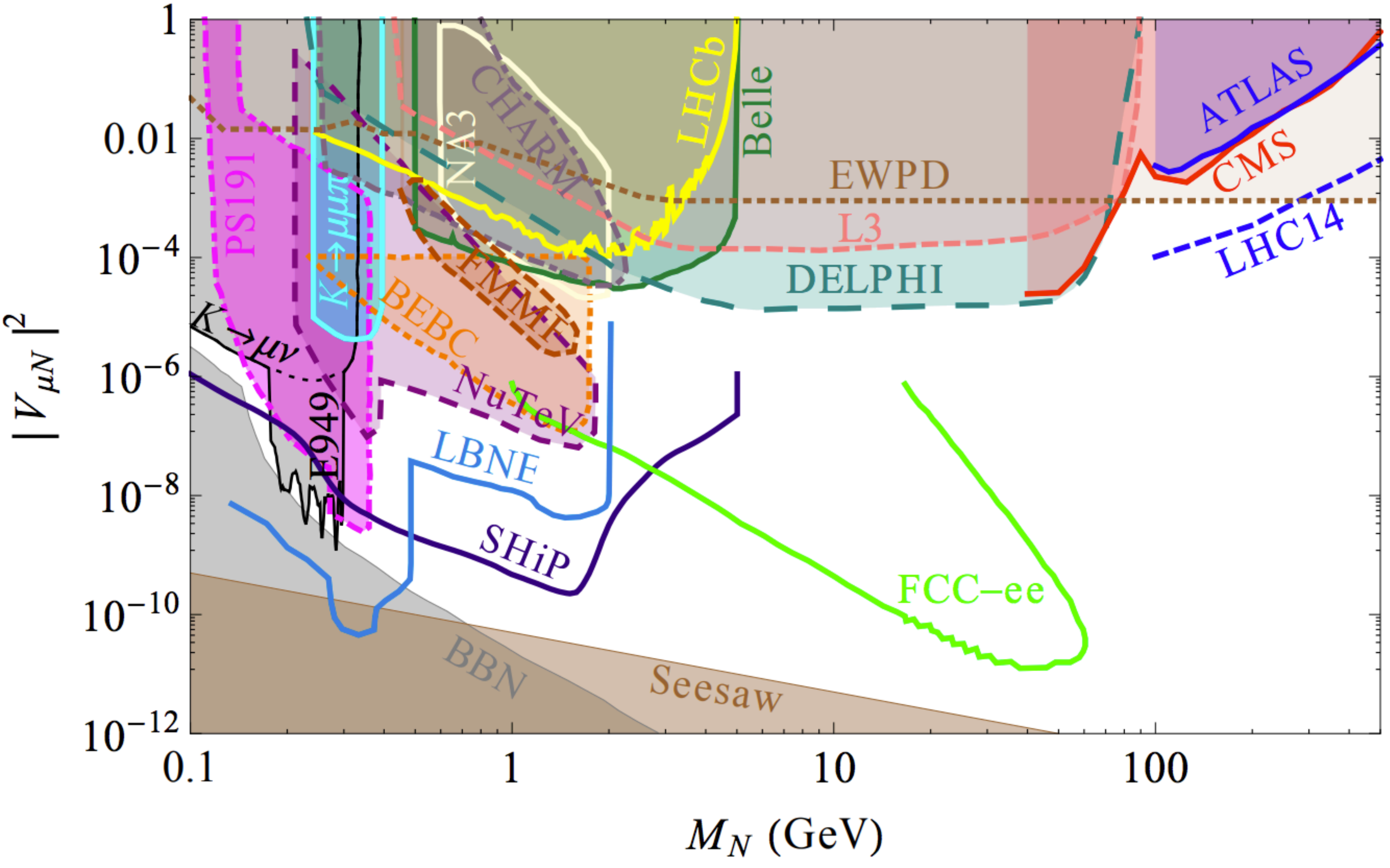
More motivations for sterile neutrinos

- Other than the origin of SM neutrino masses, models with sterile heavy neutral leptons (HNL) can explain
  - matter-antimatter asymmetry of the universe (BAU)
    - degenerate N_2 and N_3 with small mass splitting can lead to a dramatic increase of CP violation

  - dark matter
    - if the lightest HNL N_1 has a mass $\sim \mathrm{keV}$, its lifetime may be long enough to make a suitable dark matter candidate



Direct searches: state and projections



arXiv:1502.06541 [hep-ph]

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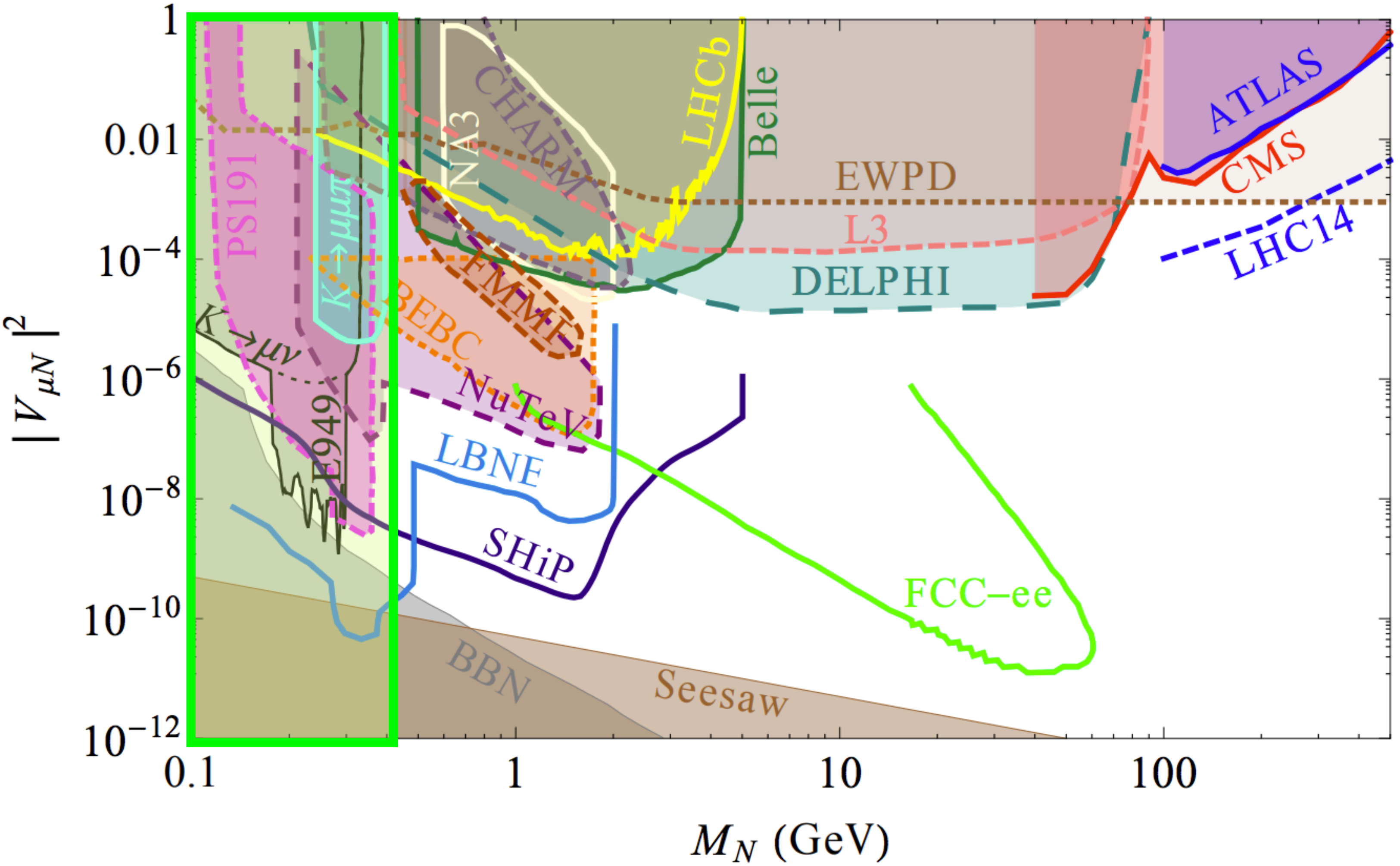

- $m_N < m_K$
- Using K decays, such as $K^{\pm} \longrightarrow \ell N, \;\; K^{\pm} \longrightarrow \mu\mu\pi$
- E.g. NA62 (see talk by R. Volpe)

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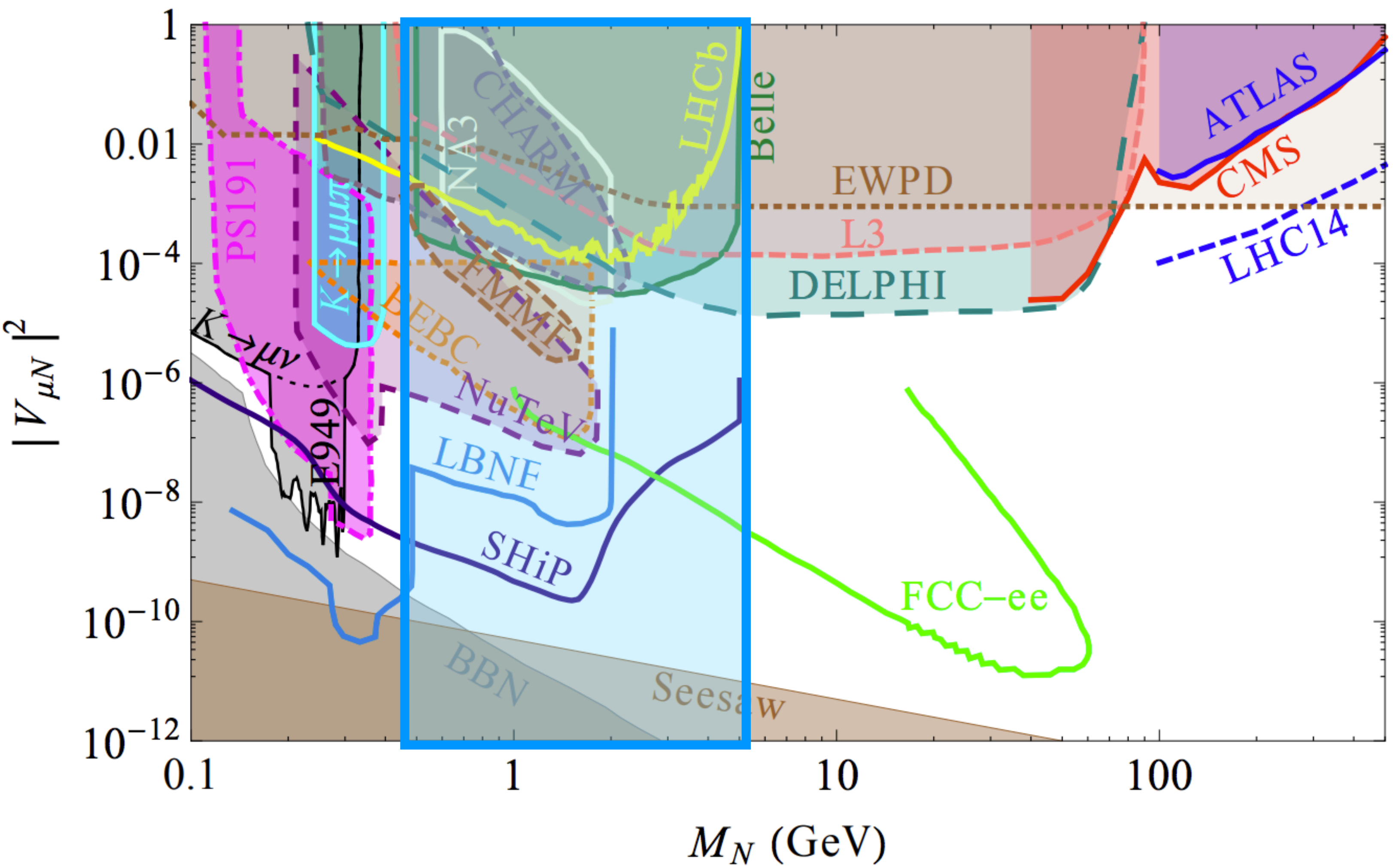

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- $m_N < m_{D,B}$
- Explored at colliders (e.g. Belle, LHC*b*) or beam-dump experiments (e.g. SHiP)

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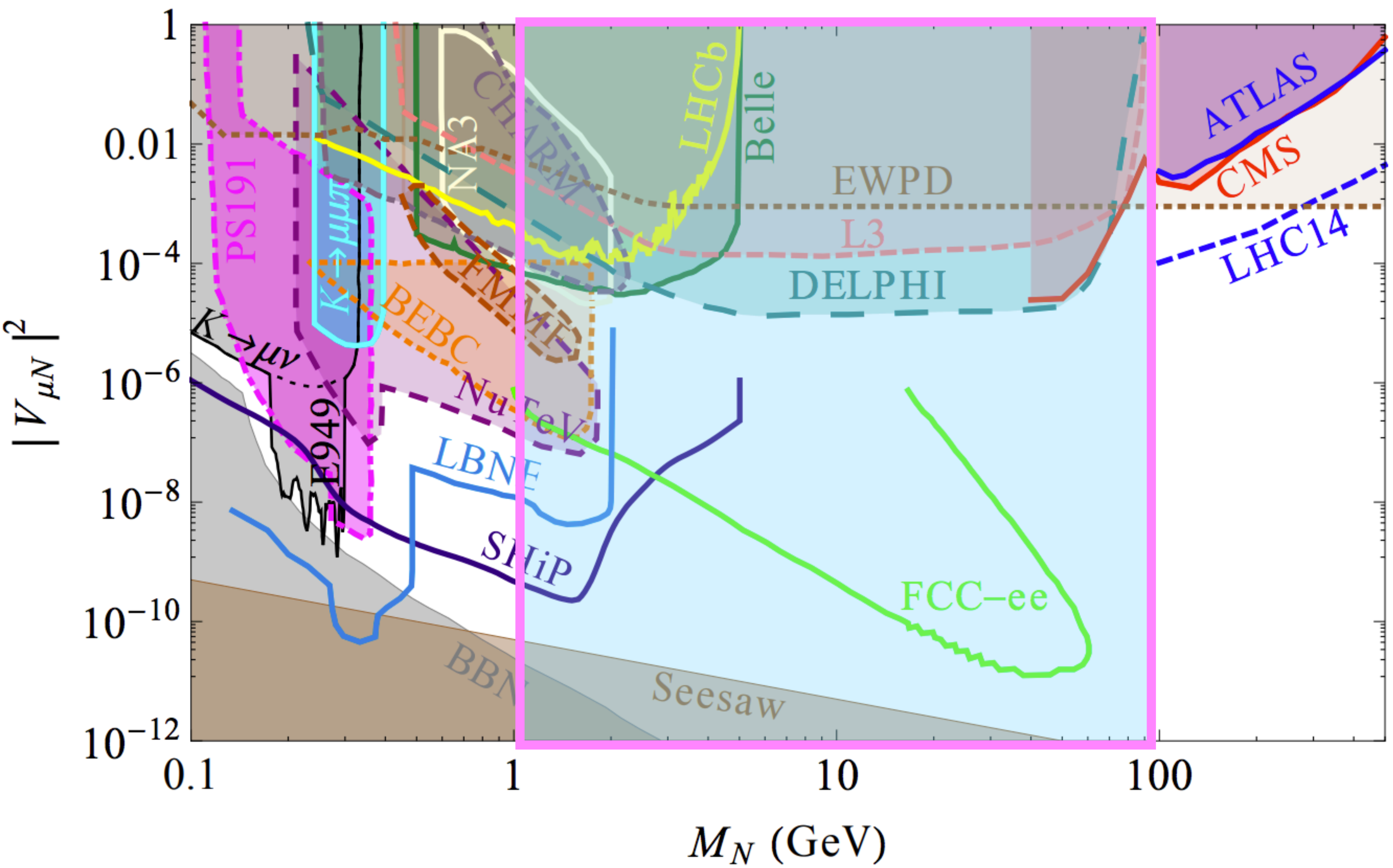
Direct searches: state and projections



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

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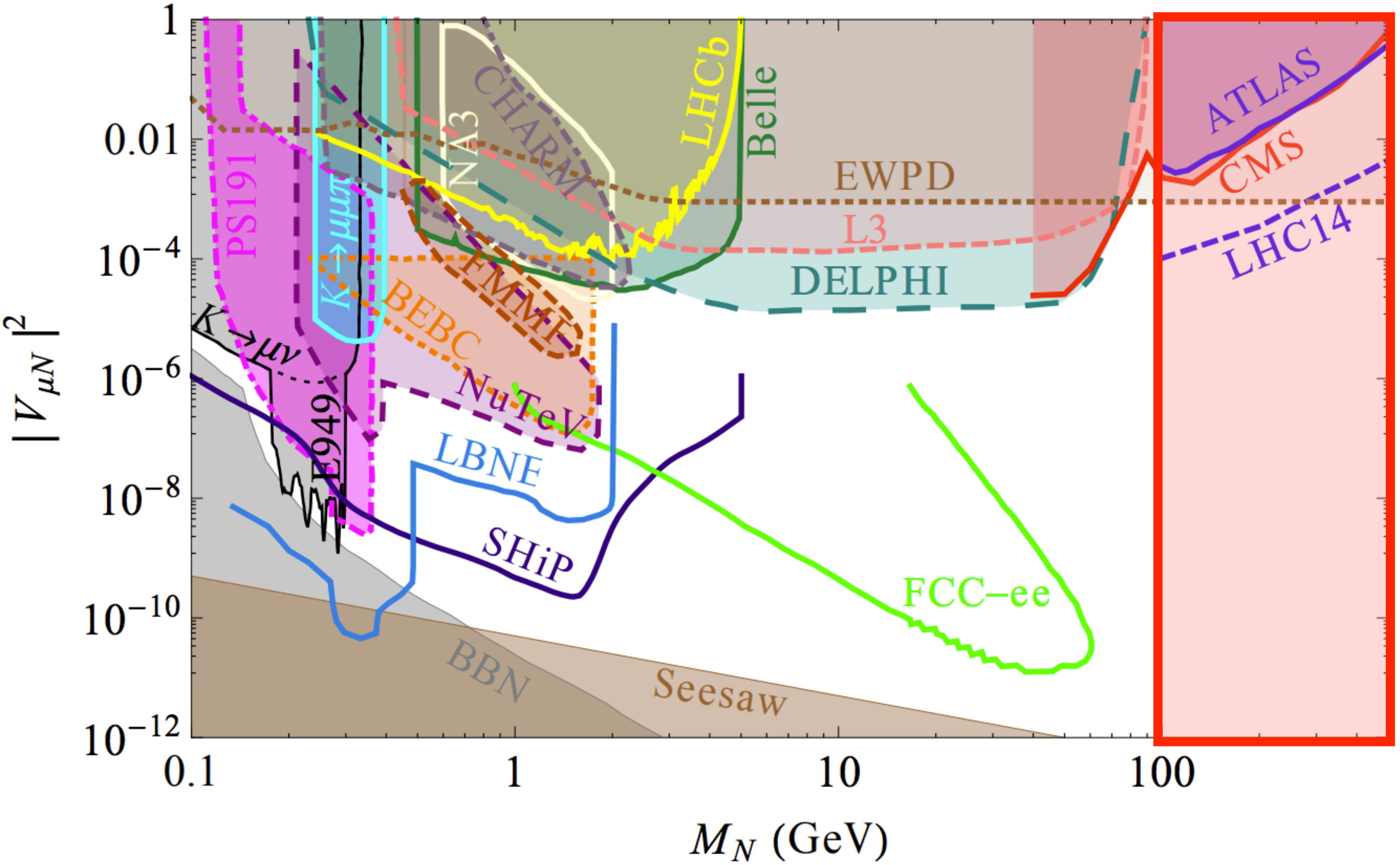

- $m_N > m_Z$
- LHC can exceed the limits from electroweak precision data

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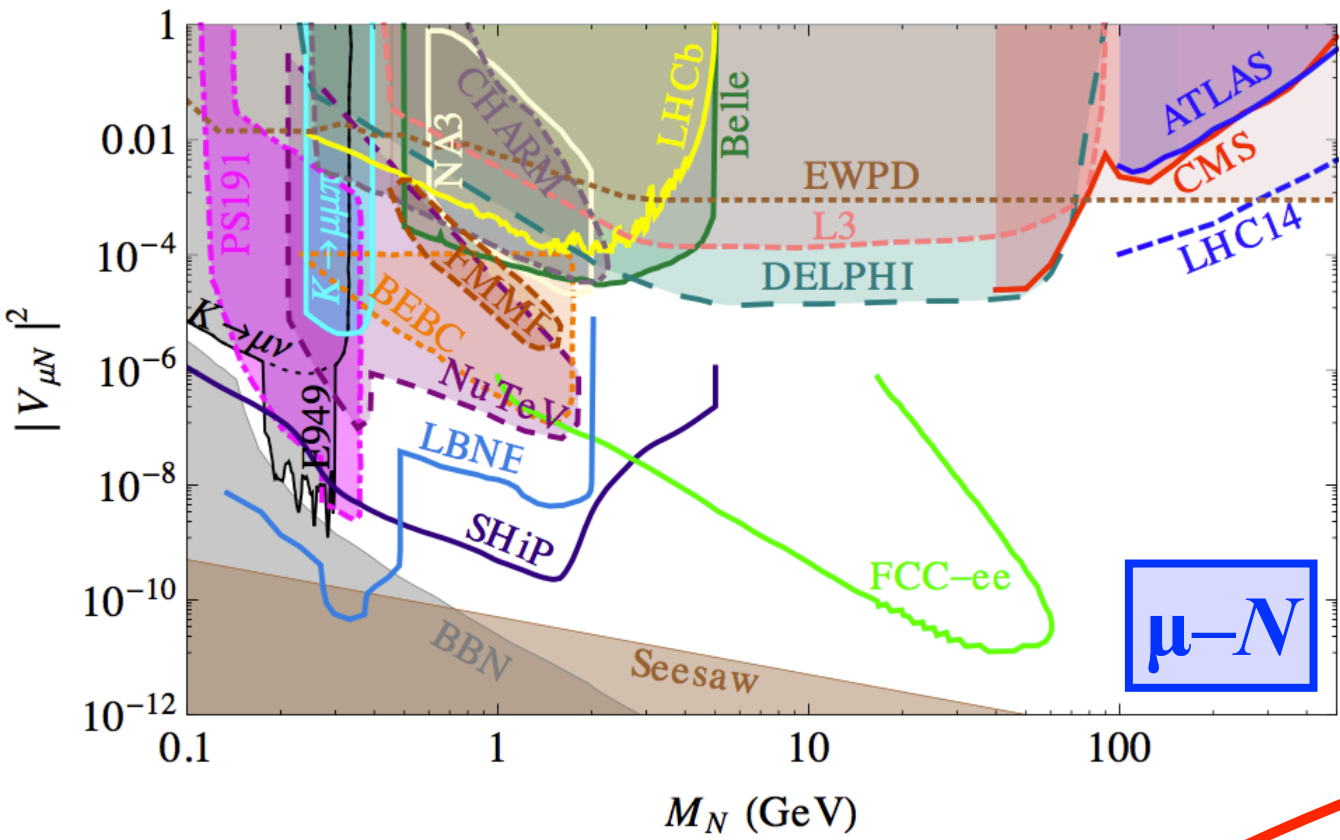
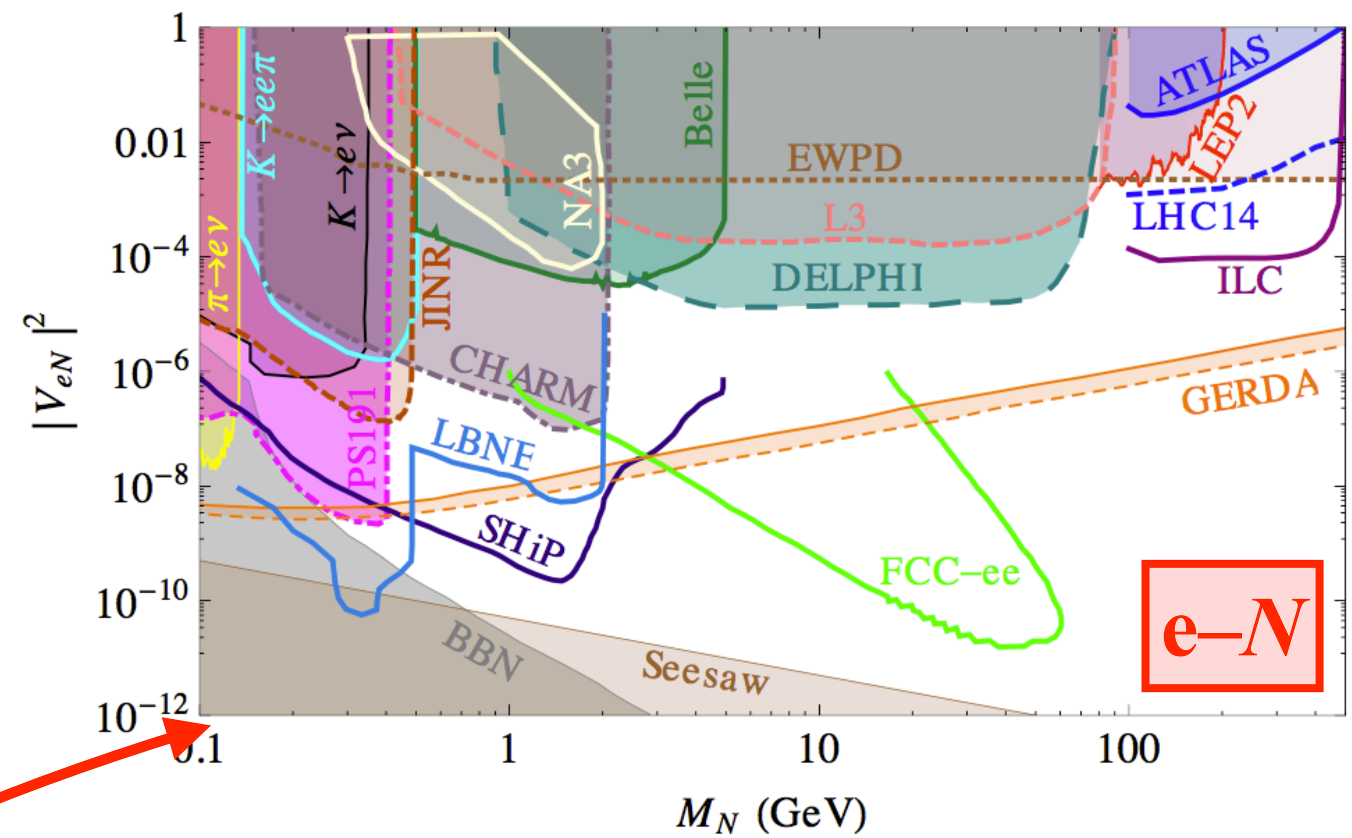
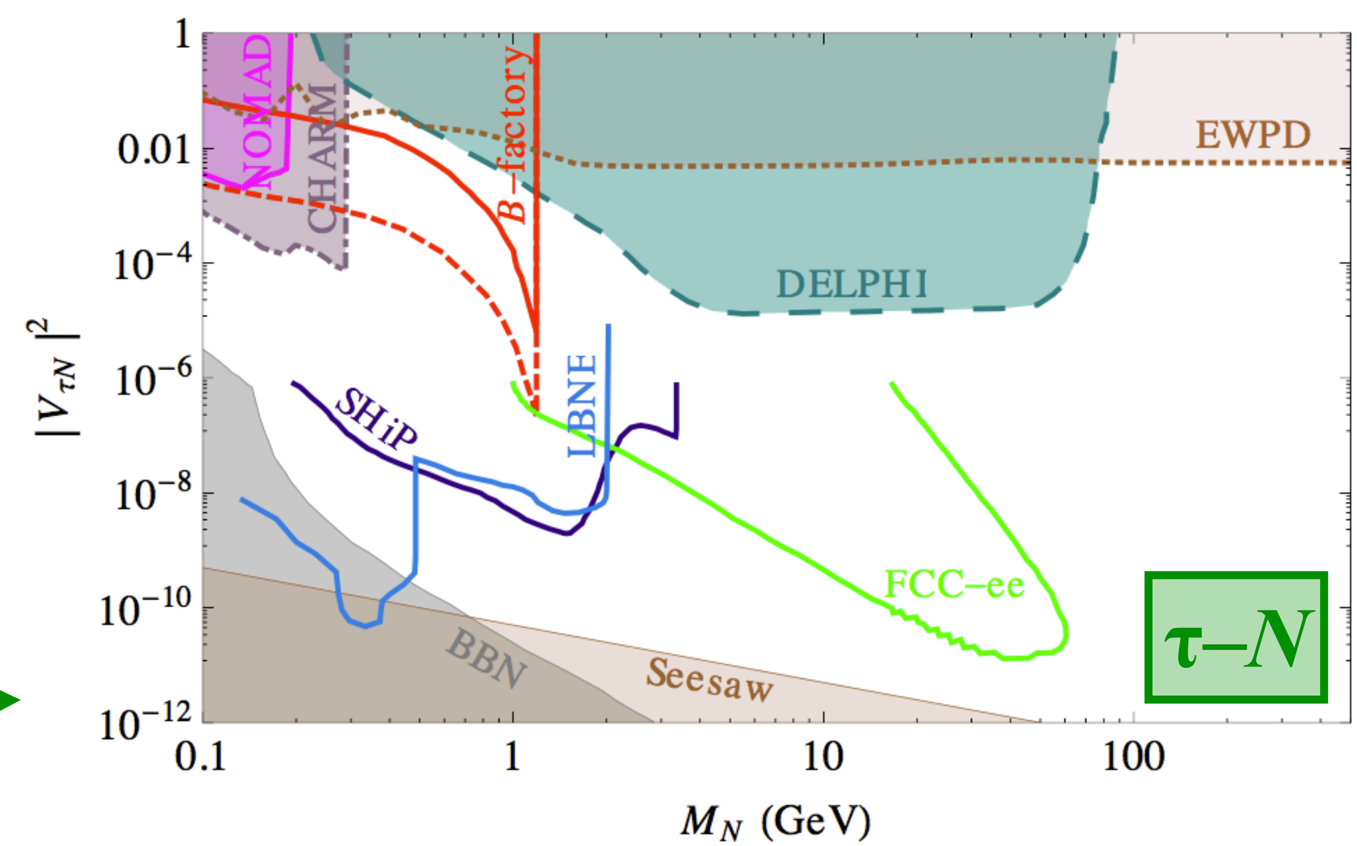
HNL couplings to ν_e, ν_μ, ν_τ





- **e–*N* :** limits from 0νββ experiments (GERDA)

- **τ–*N* :** mostly unexplored



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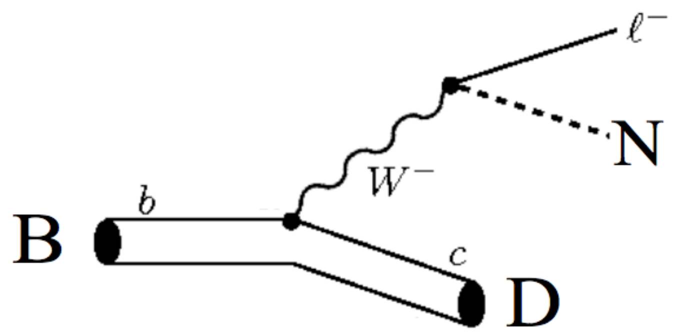
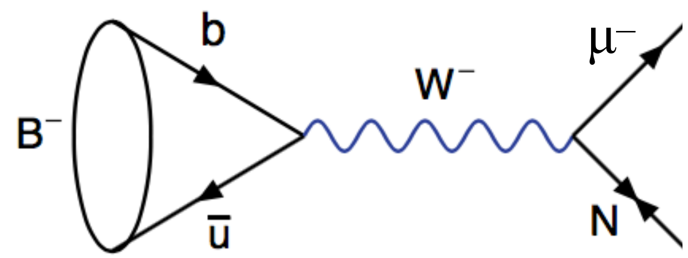
HNL production at the LHC

HNL production at the LHC

- b-hadron decays (low-mass W*)
  e.g. $B \to D\ell N$, $B^\pm \to \ell^\pm N$
  - large cross section, but large background and low-momentum ⇒ hard to trigger
  - feasible at LHC*b*, tricky at ATLAS/CMS
    - but the CMS "data parking" will allow us to record ~10^{10} B in 2018!





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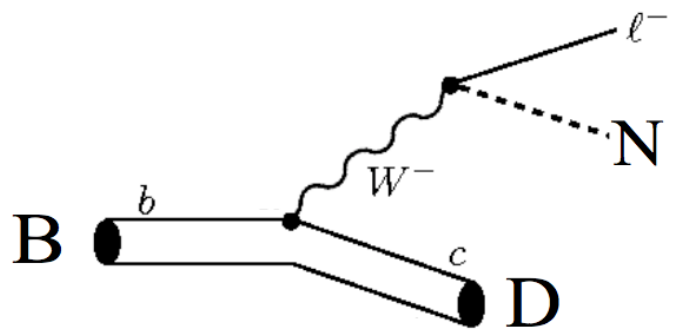
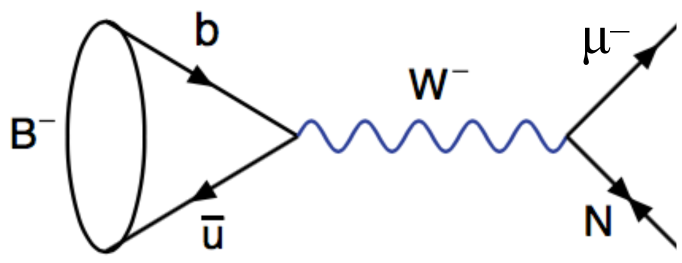
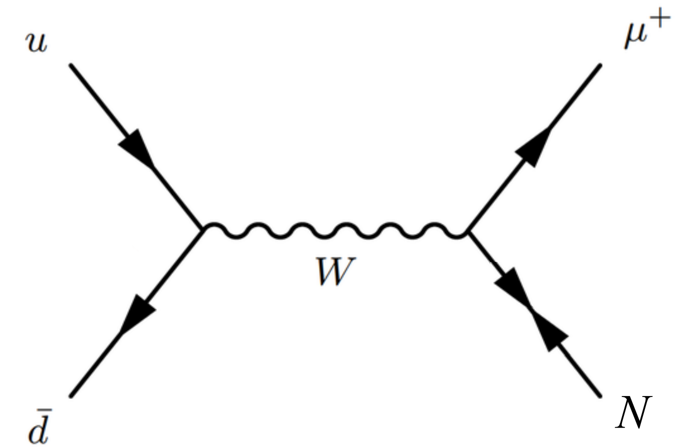
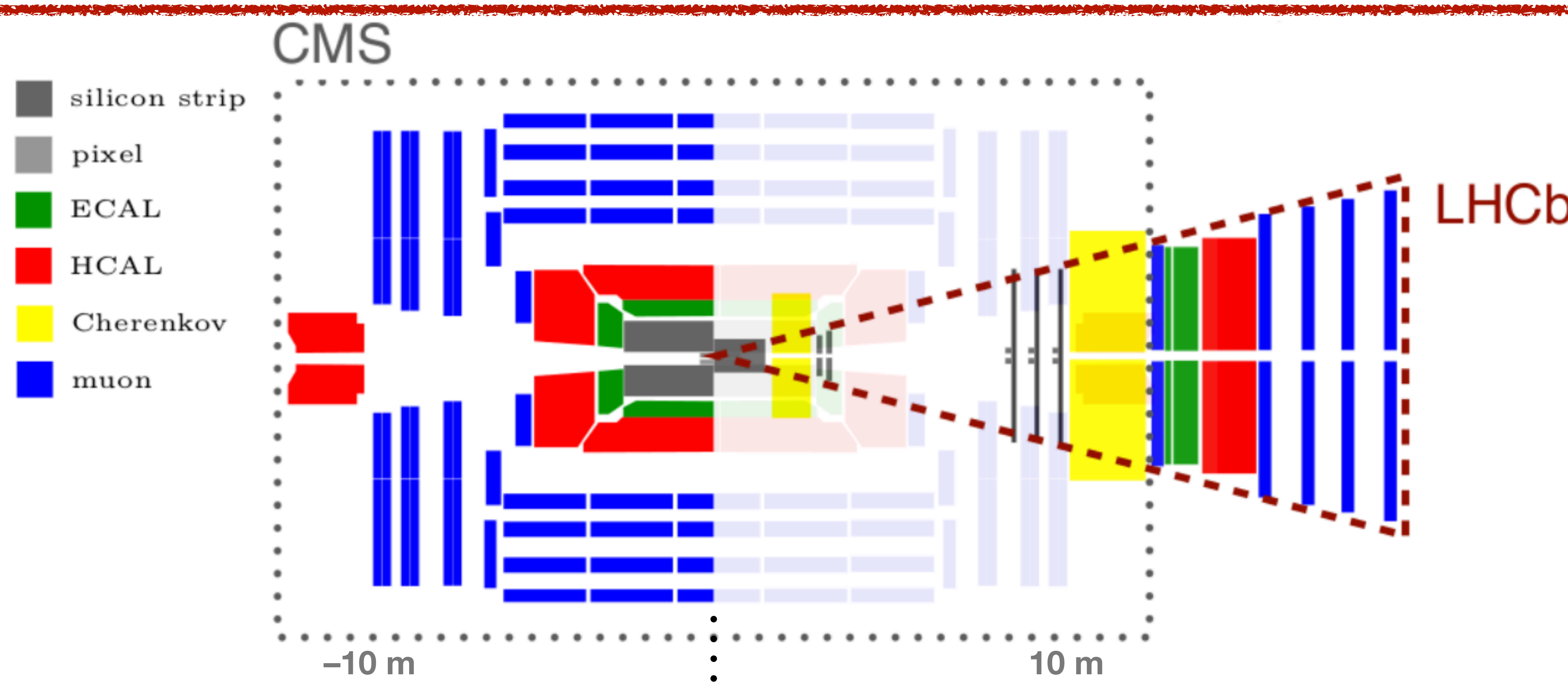




- $W^{(*)}$, $Z^{(*)}$ decays
  - 10^4–10^5 lower cross sections, but cleaner experimental signature
  - high-momentum lepton, easy to trigger



LHC Detectors: CMS *vs* LHC*b*



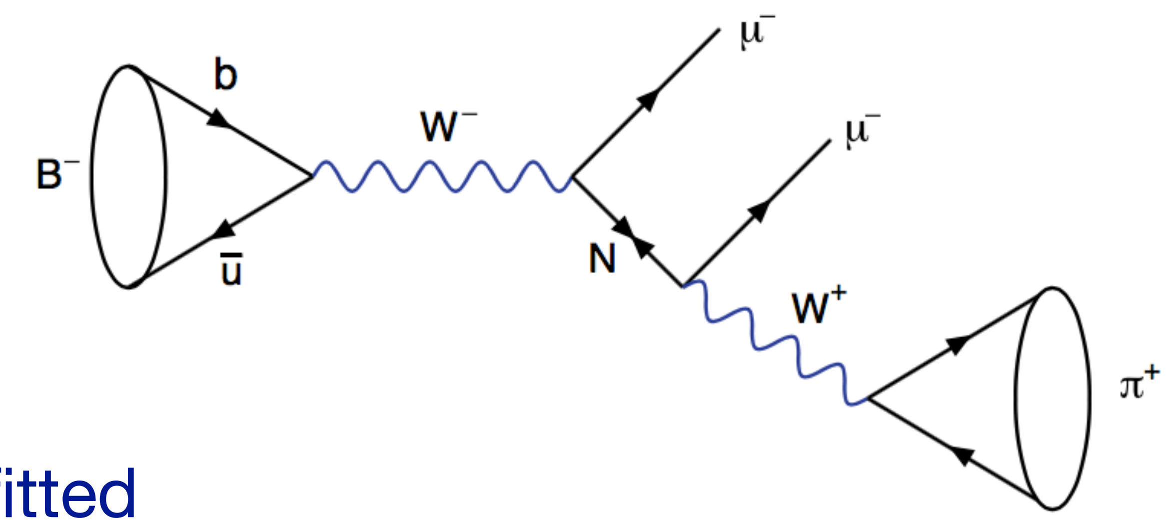
- Quasi-hermetic coverage: $|\eta| < 5$
- Tracking up to $|\eta| < 2.5$
- Main components [Radius]
  - Silicon tracker: 4 mm – 1 m
  - ECAL: 1.3 – 1.8 m
  - HCAL: 1.8 – 2.9 m
  - Muon spectrometer: 4 – 7 m

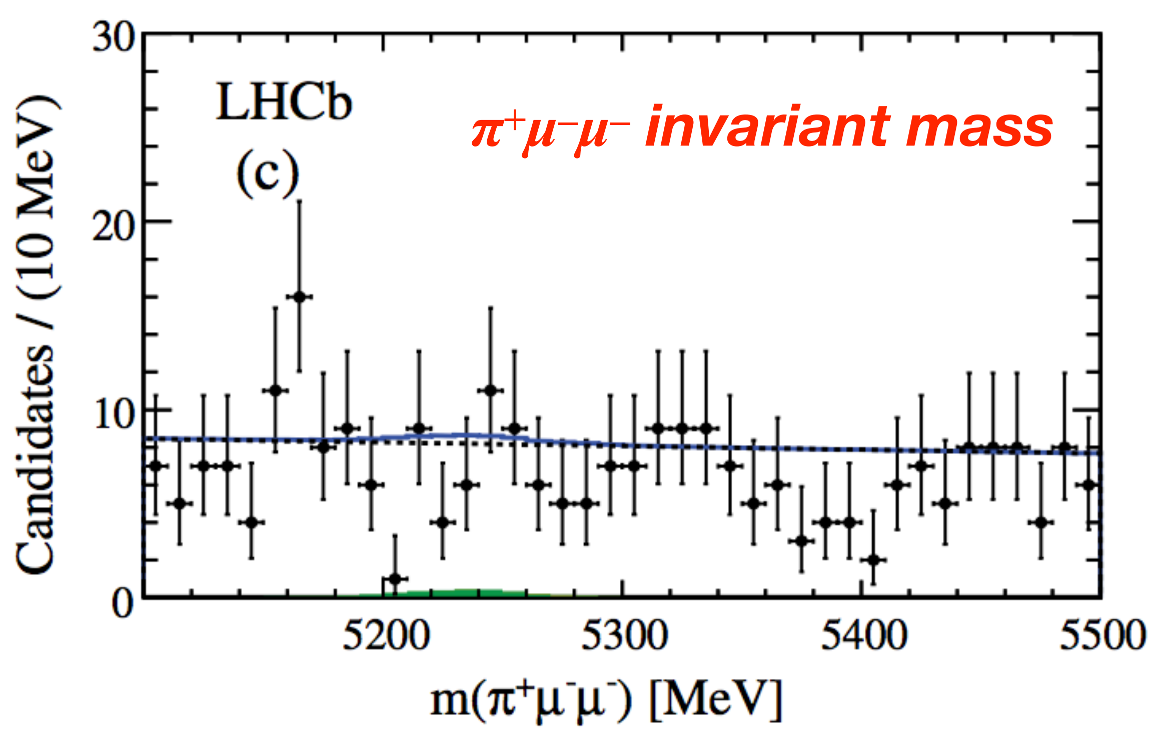
- Forward detector: $2 < \eta < 5$
- 1-2 interactions per bunch crossing
- Main components [Dist. from IP]
  - Vertex locator (VELO): 4 mm – 50 cm
  - Silicon tracker layers: ~ 2 m + 8-10 m
  - Muon spectrometer: 15 – 19 m
  - Particle identification (RICH)

HNL from B hadron decays

[Phys. Rev. Lett. 112, 131802 (2014)](#)

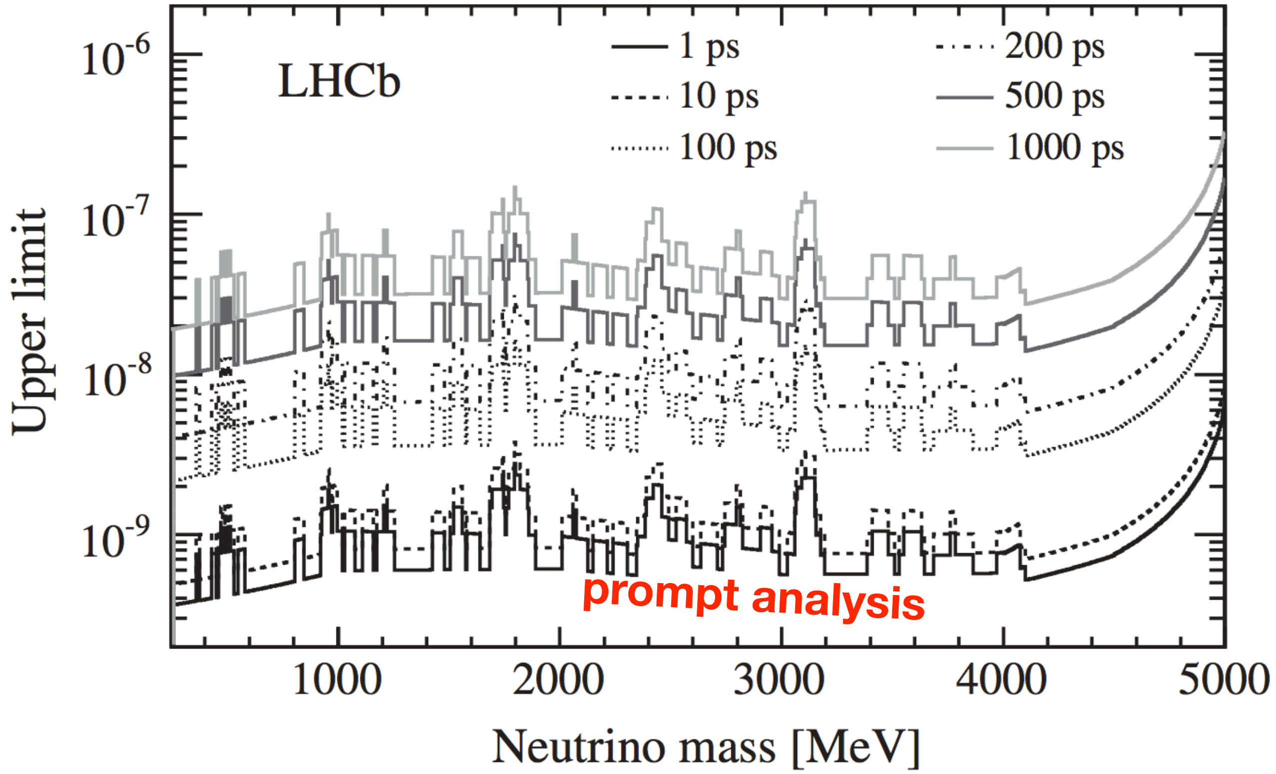
- LHC*b* search for LNV decay $B^- \to \pi^+\mu^-\mu^-$
  - 3 fb^{-1} pp data at 7–8 TeV
  - HNL mass 250 MeV – 5 GeV
  - HNL lifetime 0–1000 ps ($c\tau \approx$ 30 cm)
    - for $\tau \leq 1$ ps, a single $\pi\mu\mu$ vertex is fitted
    - for $\tau > 1$ ps, a separate $\pi^+\mu^-$ vertex is required





- Main backgrounds
  - combinatorics
  - B decays to charmonium

HNL from B hadron decays



Phys. Rev. Lett. 112, 131802 (2014)

- Scanning the N mass, upper limits on the branching fraction $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-)$
- Constraints on $\mathcal{B}$ reinterpreted as limits on the μN mixing

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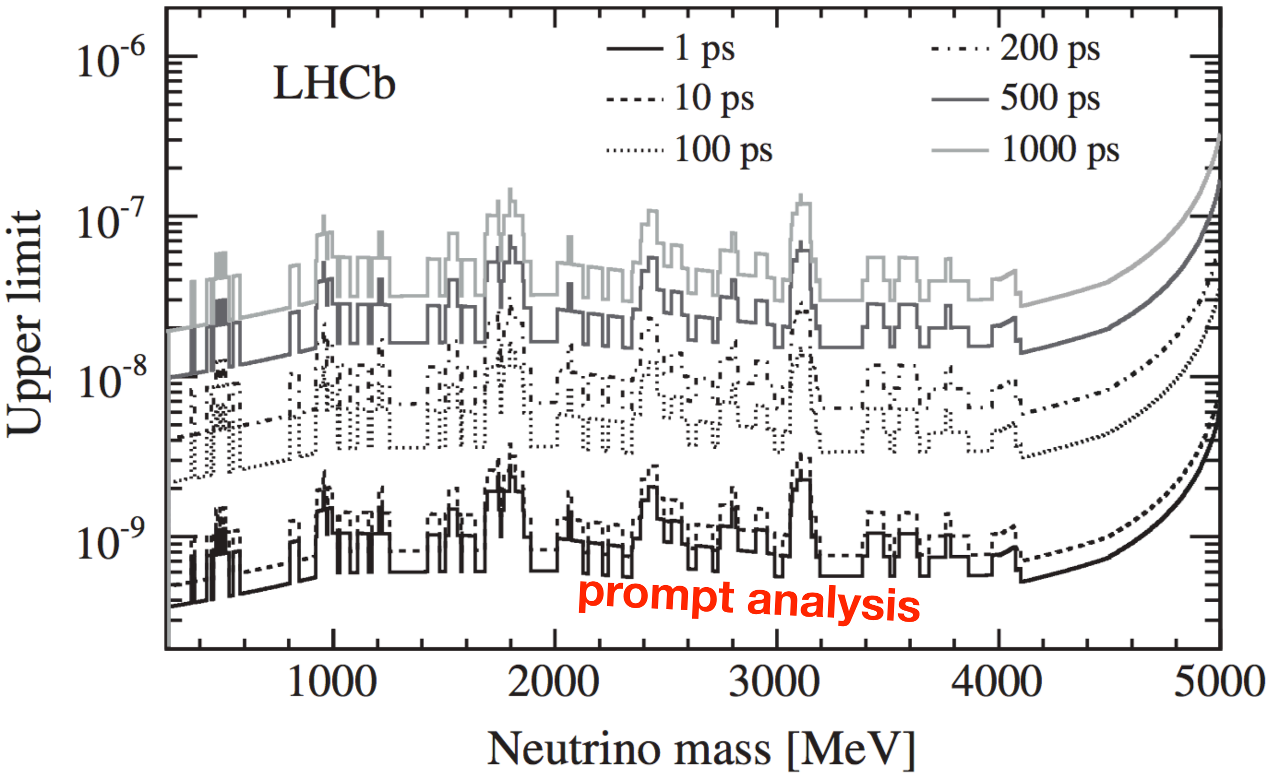

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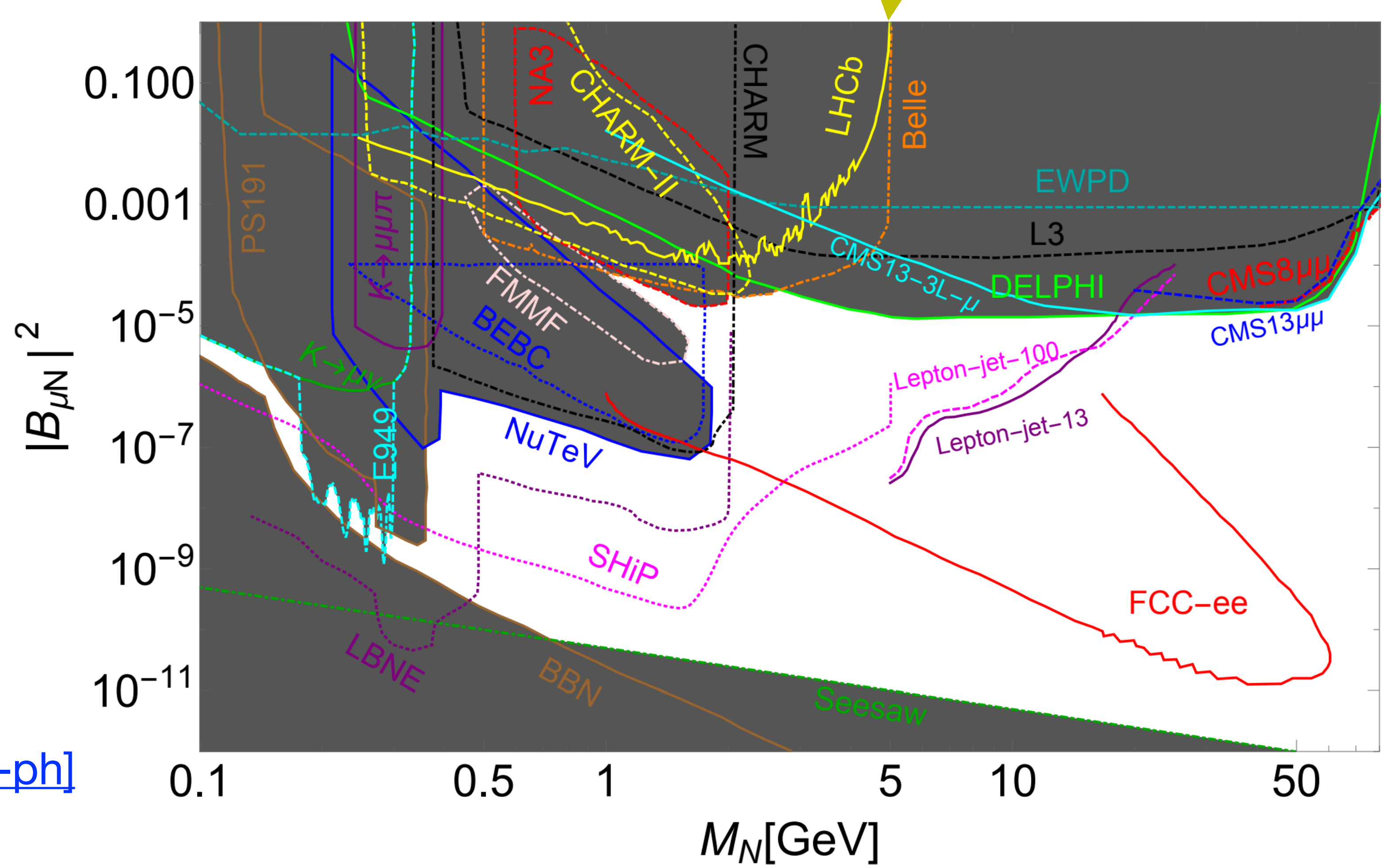
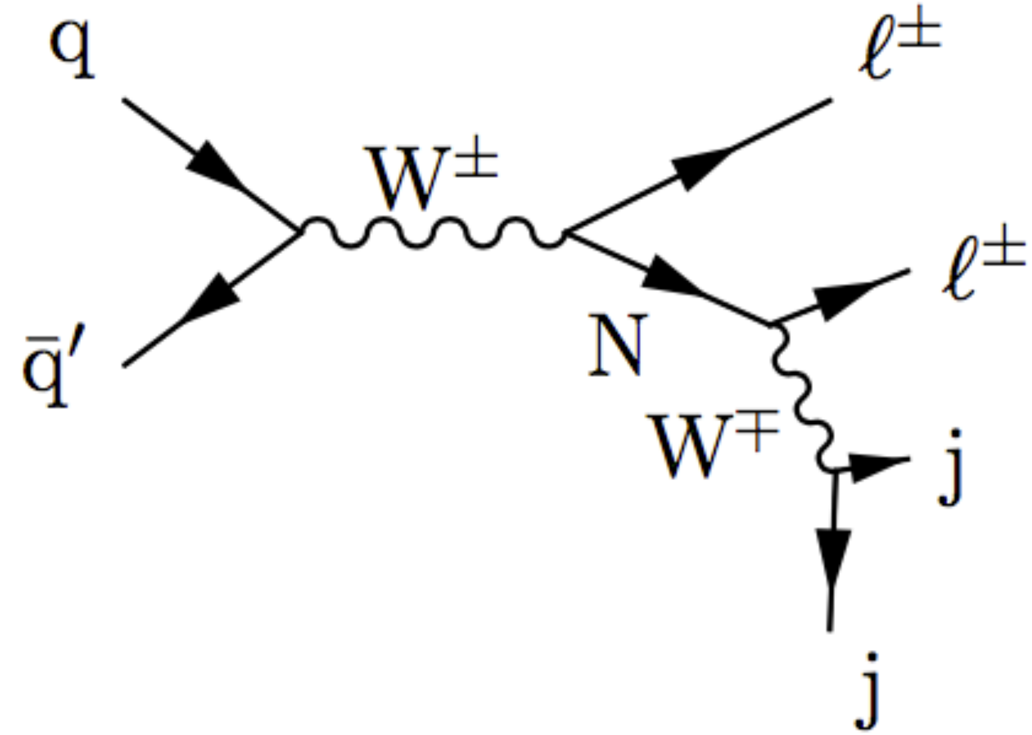


- Now analyzing 13 TeV data

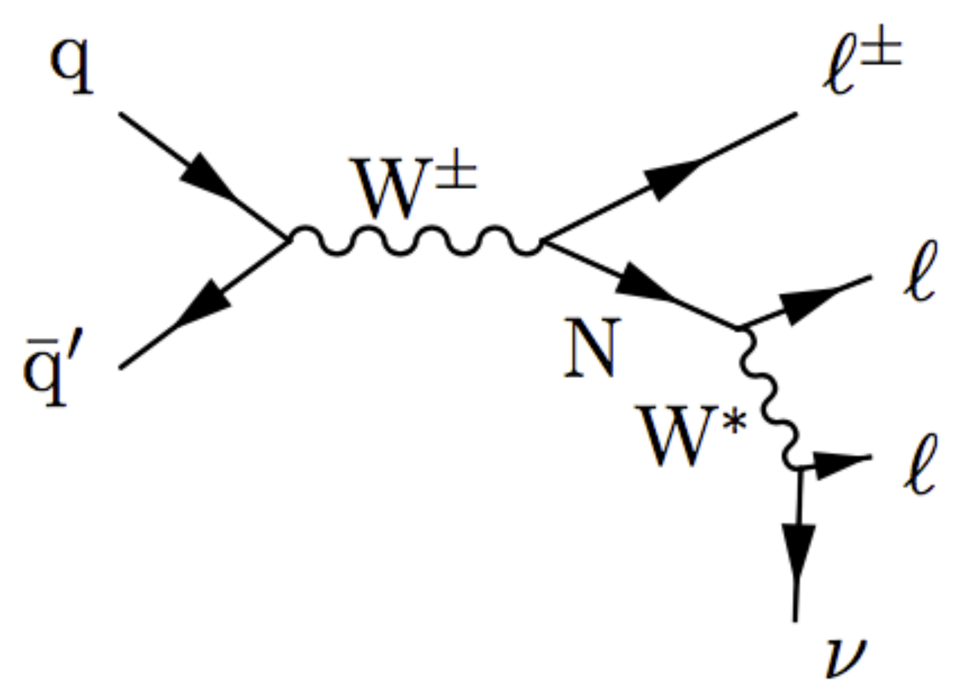
[arXiv:1805.00070 [hep-ph]]

HNL from W decays: signatures

- Same-sign dilepton + 2 jets
  - fully reconstruct m_N peak
  - mostly sensitive to
    - high m_N (jet $p_T \gtrsim 30$ GeV)
    - LNV decays (lower background)



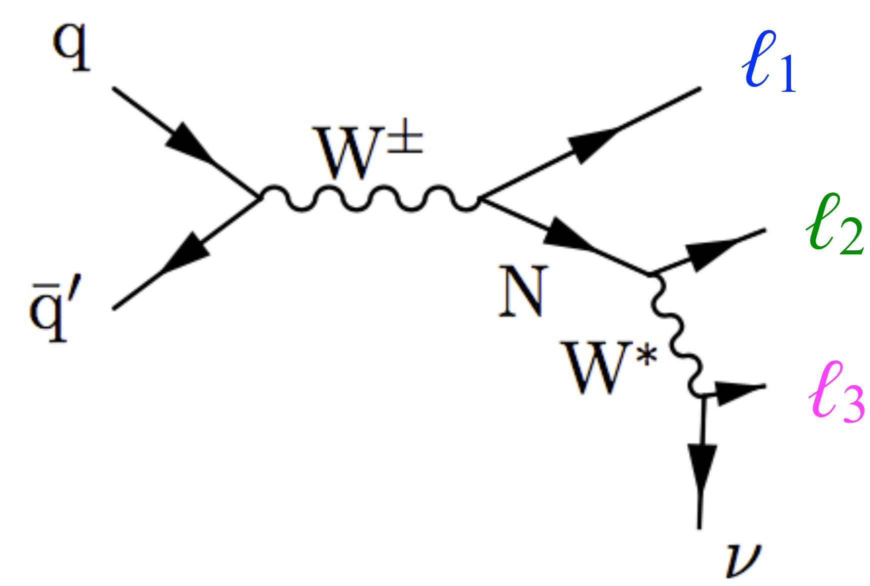
- Trilepton + missing energy (ν)
  - no clear m_N peak
  - can identify e and μ down to few GeV → low m_N
  - both LNC and LNV decays



3ℓ search: outline

Phys. Rev. Lett. 112, 131802 (2014)

- HNL with mass 1 GeV–1.2 TeV in trilepton events (e, μ)
- Lepton tracking and identification optimized for leptons emerging near the interaction point (*prompt*)
  - drastic efficiency loss for $m_N \lesssim$ 20 GeV when τ_N becomes important



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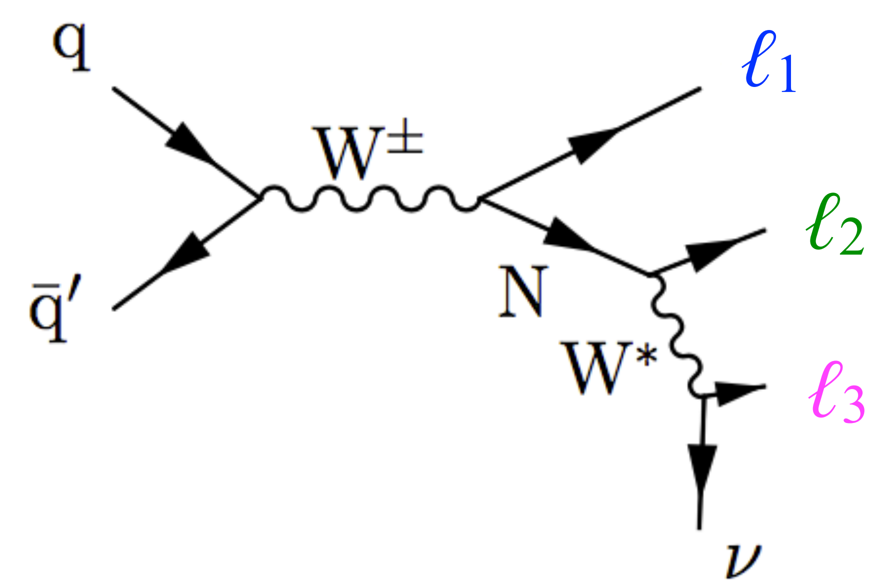
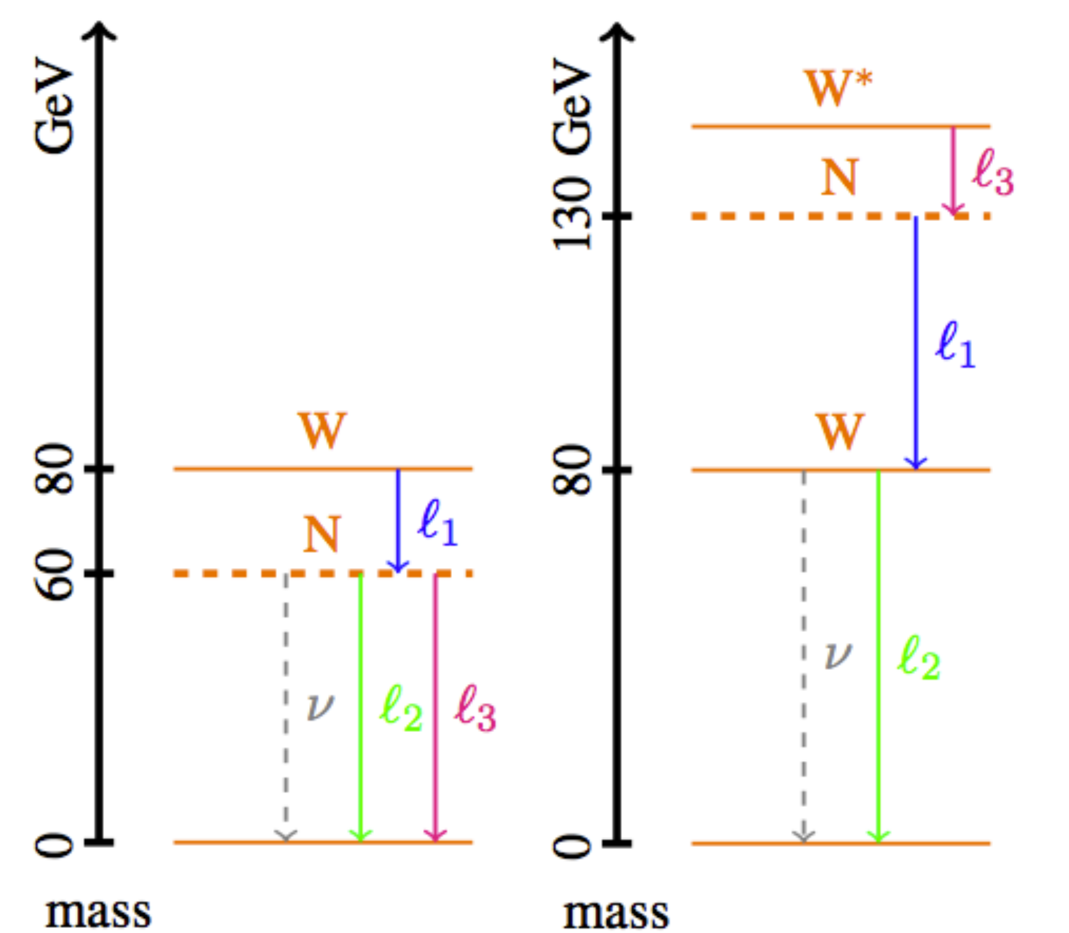


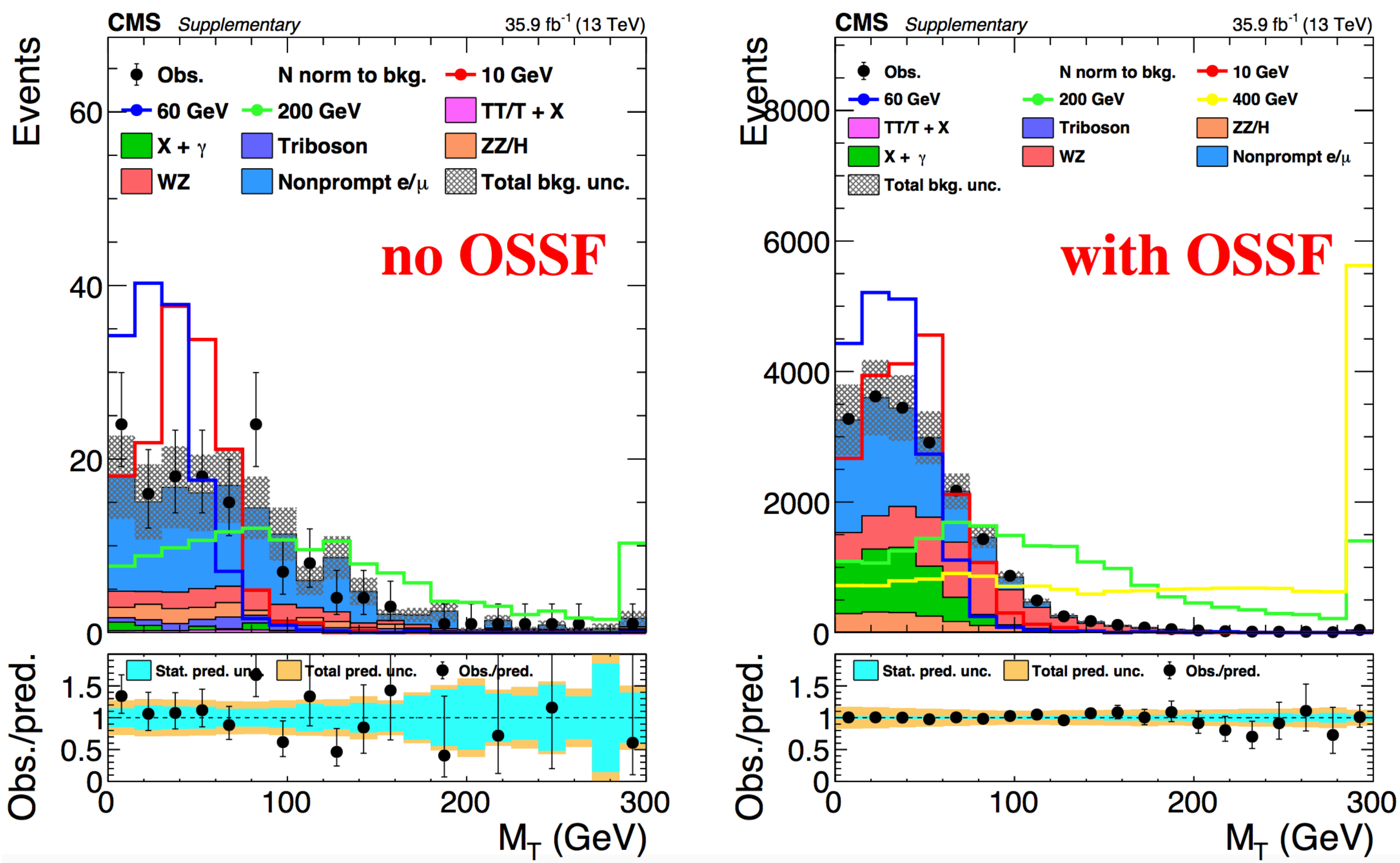
- Kinematics and background level vary significantly with m_N
  - e.g. different lepton energy spectra for $m_N > m_W$ or $m_N < m_W$

➡ data split according to the transverse momentum p_T of the leading lepton (*low-mass* and *high-mass* categories)



3ℓ search: OSSF *vs* no-OSSF

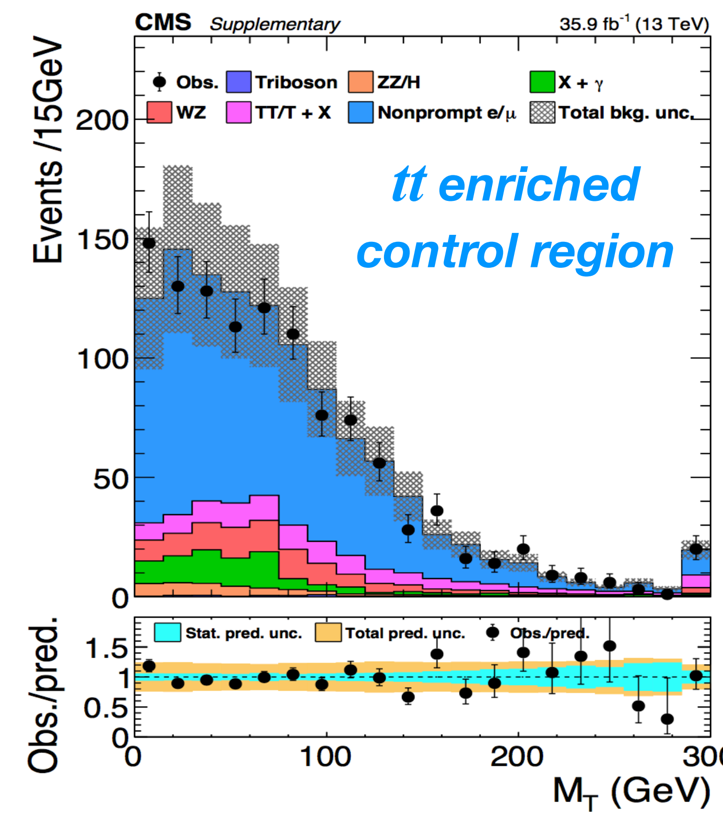
- In case of LNV decay, we can have trilepton events with no opposite-sign, same-flavor pairs (no-OSSF)
    - SM background drastically reduced (e.g. $Z/\gamma^* \rightarrow \ell^+\ell^-$)

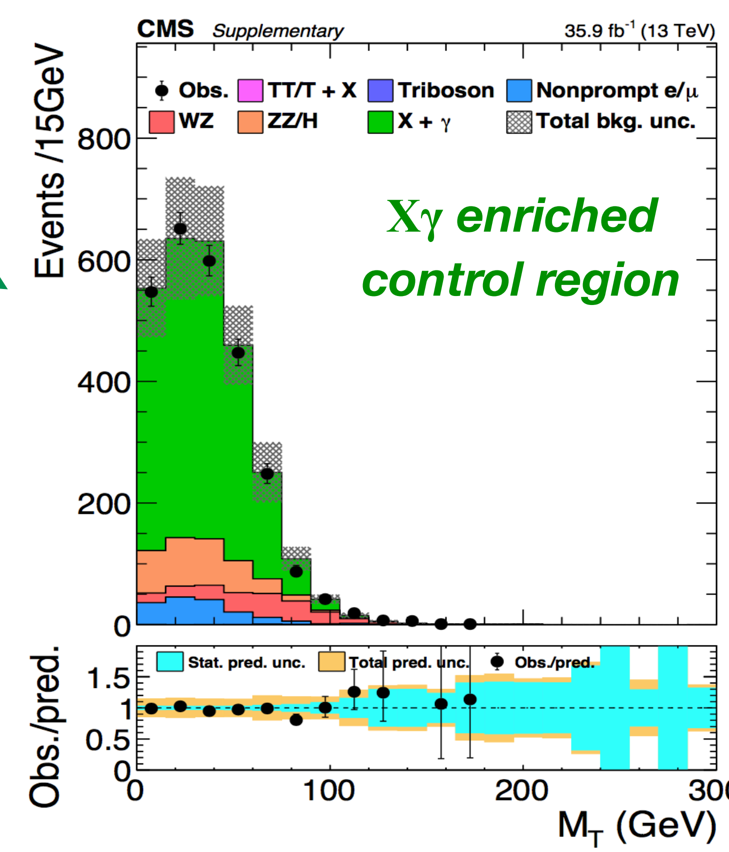


[Phys. Rev. Lett. 112, 131802 (2014)]

3ℓ search: main backgrounds

- Nonprompt leptons
  - $t\bar{t} \rightarrow 2\ell + X$ and $Z/\gamma^* \rightarrow 2\ell$
  - one mis-identified ℓ
- $W\gamma^{(*)}$ and $Z\gamma^{(*)}$
  - Prompt $\gamma^* \rightarrow 2\ell$ decay or $\gamma \rightarrow 2e$ conversion in the detector material
- $WZ \rightarrow 3\ell\nu$ and $ZZ \rightarrow 4\ell$
- Tribosons and other rare processes

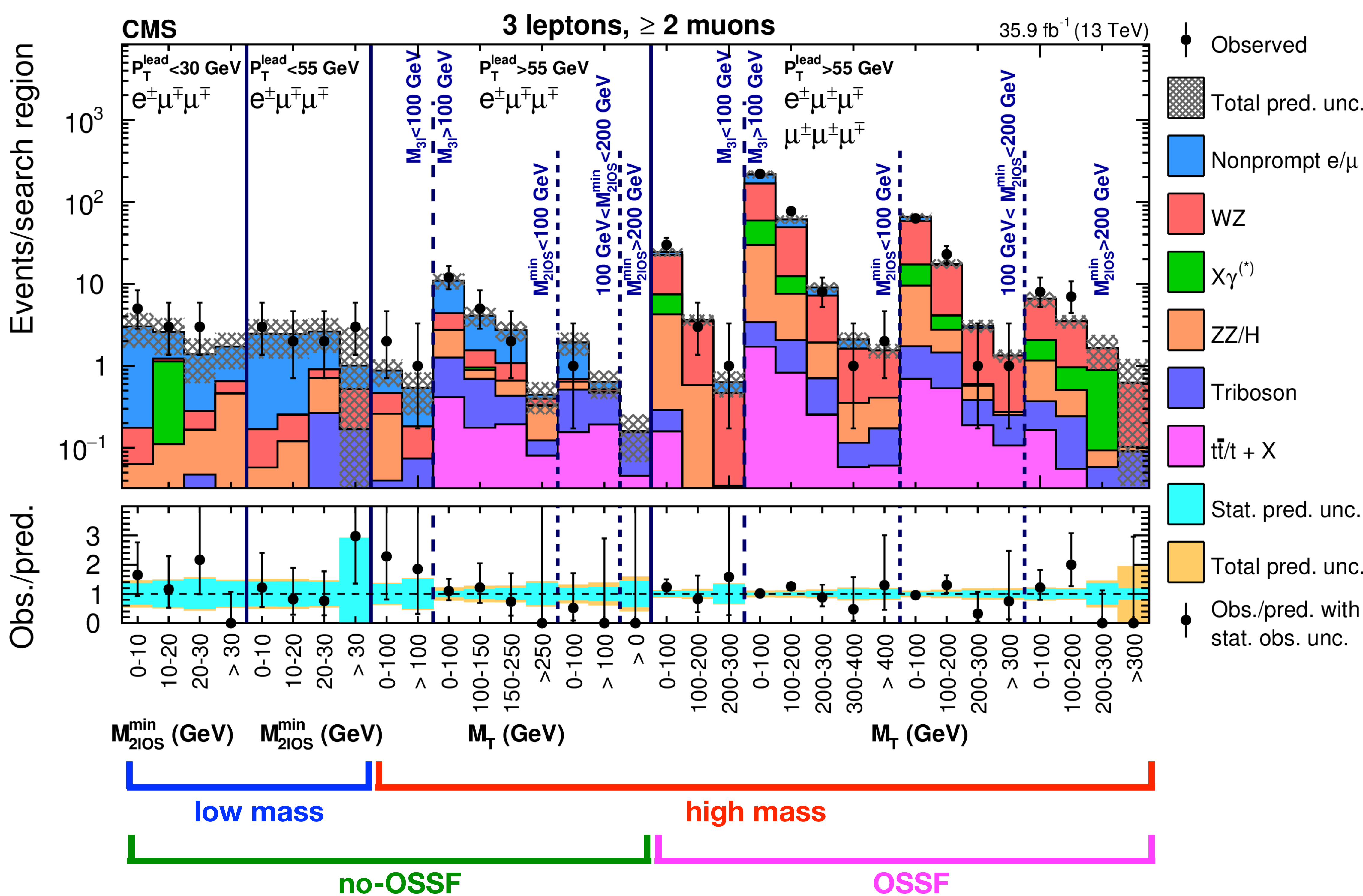




Phys. Rev. Lett. 112, 131802 (2014)

3ℓ channel: results

- Data split into several categories, based on various variables



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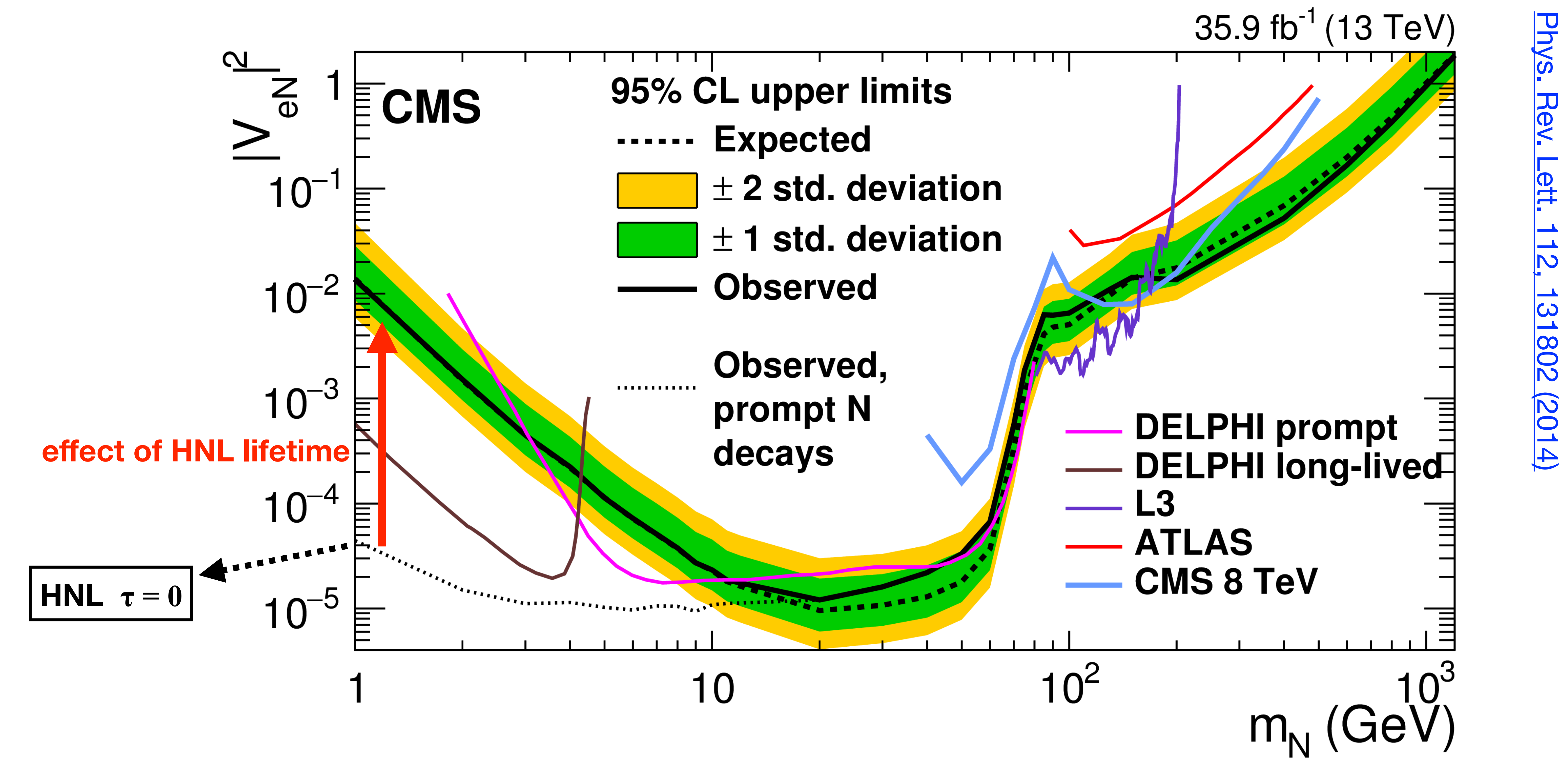
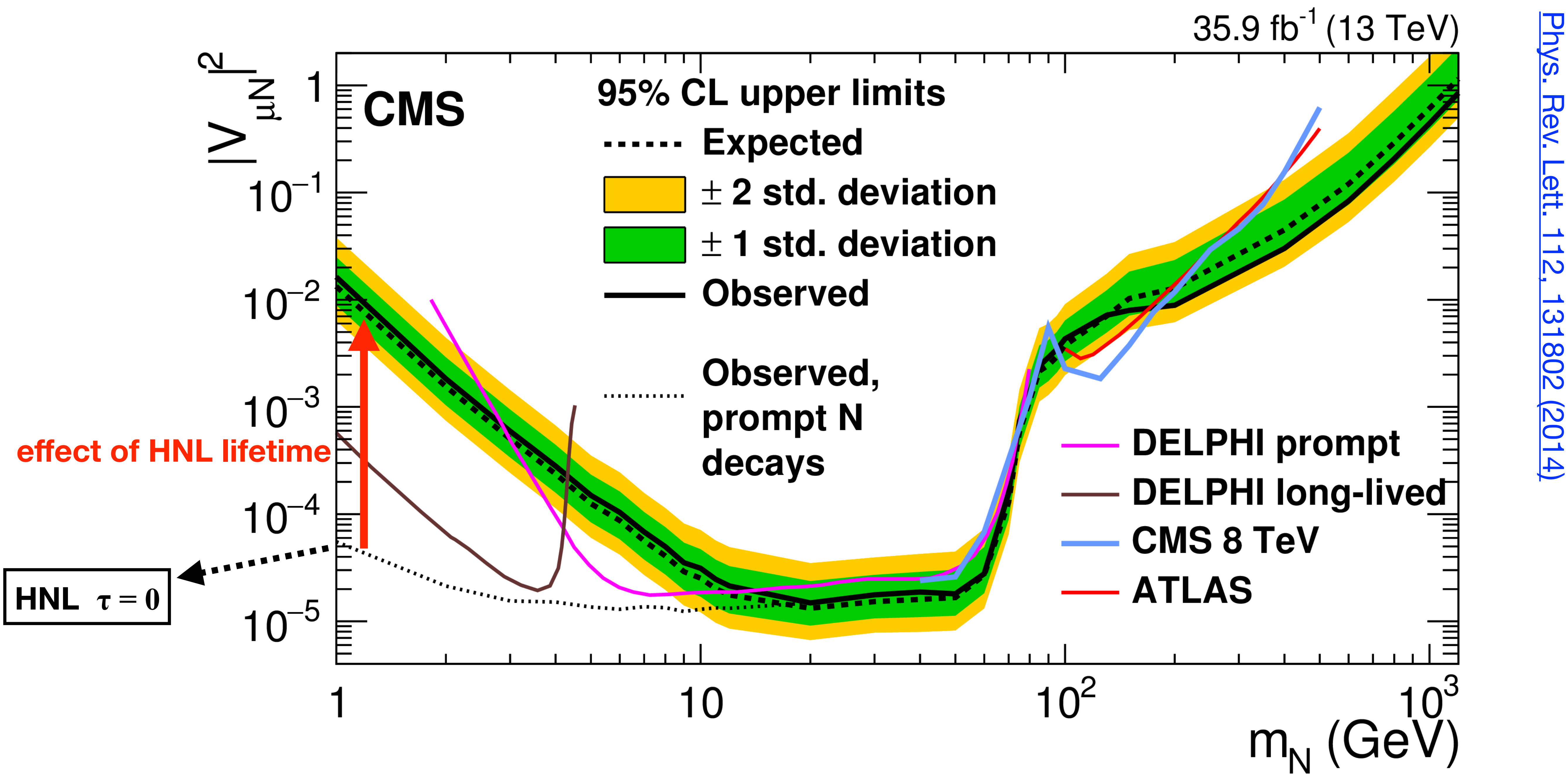
3ℓ channel: $|V_{eN}|^2$ coupling



- First time a single experiment probes such a large m_N range!
- Very first results for $m_N > 500$ GeV

3ℓ channel: $|V_{\mu N}|^2$ coupling

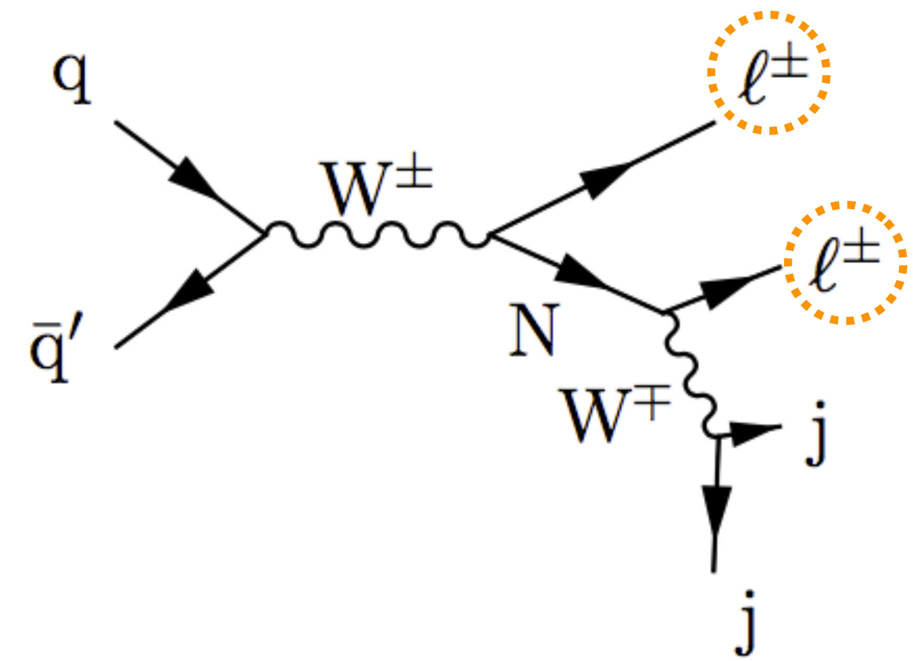


- First time a single experiment probes such a large m_N range!
- Very first results for $m_N > 500$ GeV

2ℓ2q search: outline

CMS-PAS-EXO-17-028

- HNL with mass 20 GeV–1.7 TeV in events with
  - 2 same-sign leptons
  - 2 jets or 1 (large-cone) jet



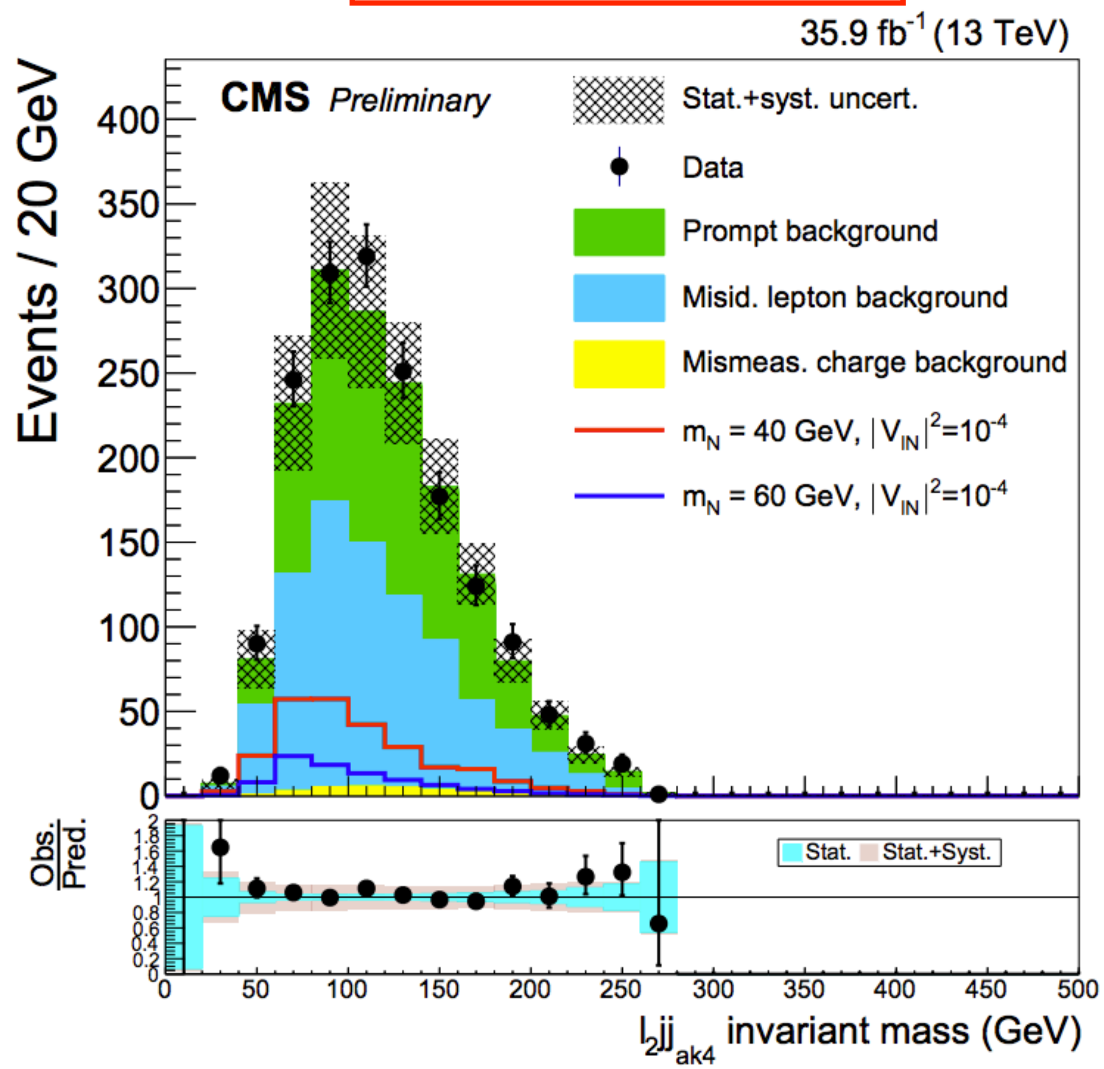
- Only LNV decays considered
- All flavor combinations considered: $e^\pm e^\pm$, $\mu^\pm\mu^\pm$ and $e^\pm\mu^\pm$
  - set limits separately on:

$$\left|V_{eN}\right|^2, \quad \left|V_{\mu N}\right|^2, \quad \frac{\left|V_{eN}V^*_{\mu N}\right|^2}{\left|V_{eN}\right|^2 + \left|V_{\mu N}\right|^2}.$$

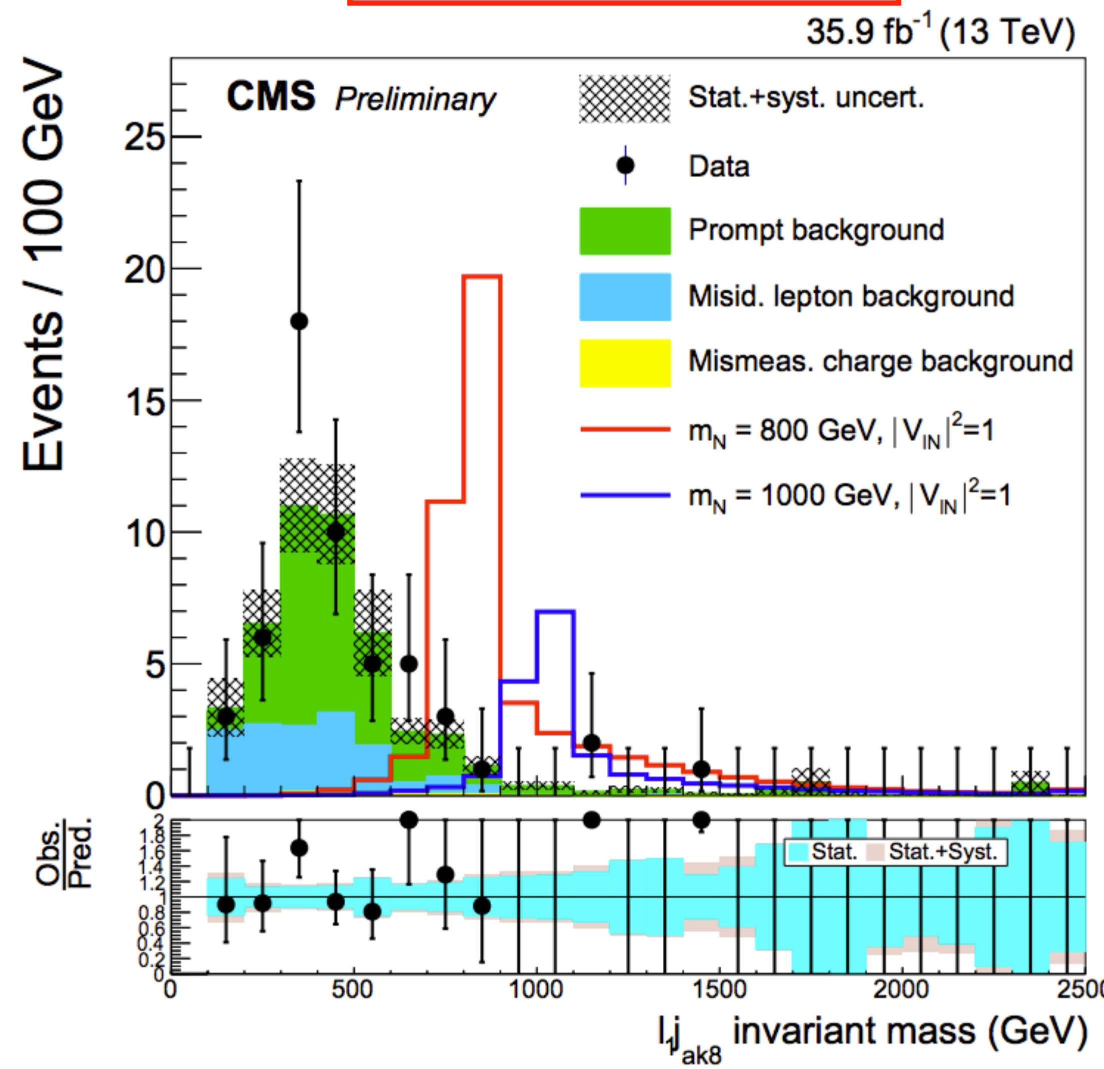
2ℓ2q channel: results

CMS-PAS-EXO-17-028

low mass, $m(\ell, 2j)$



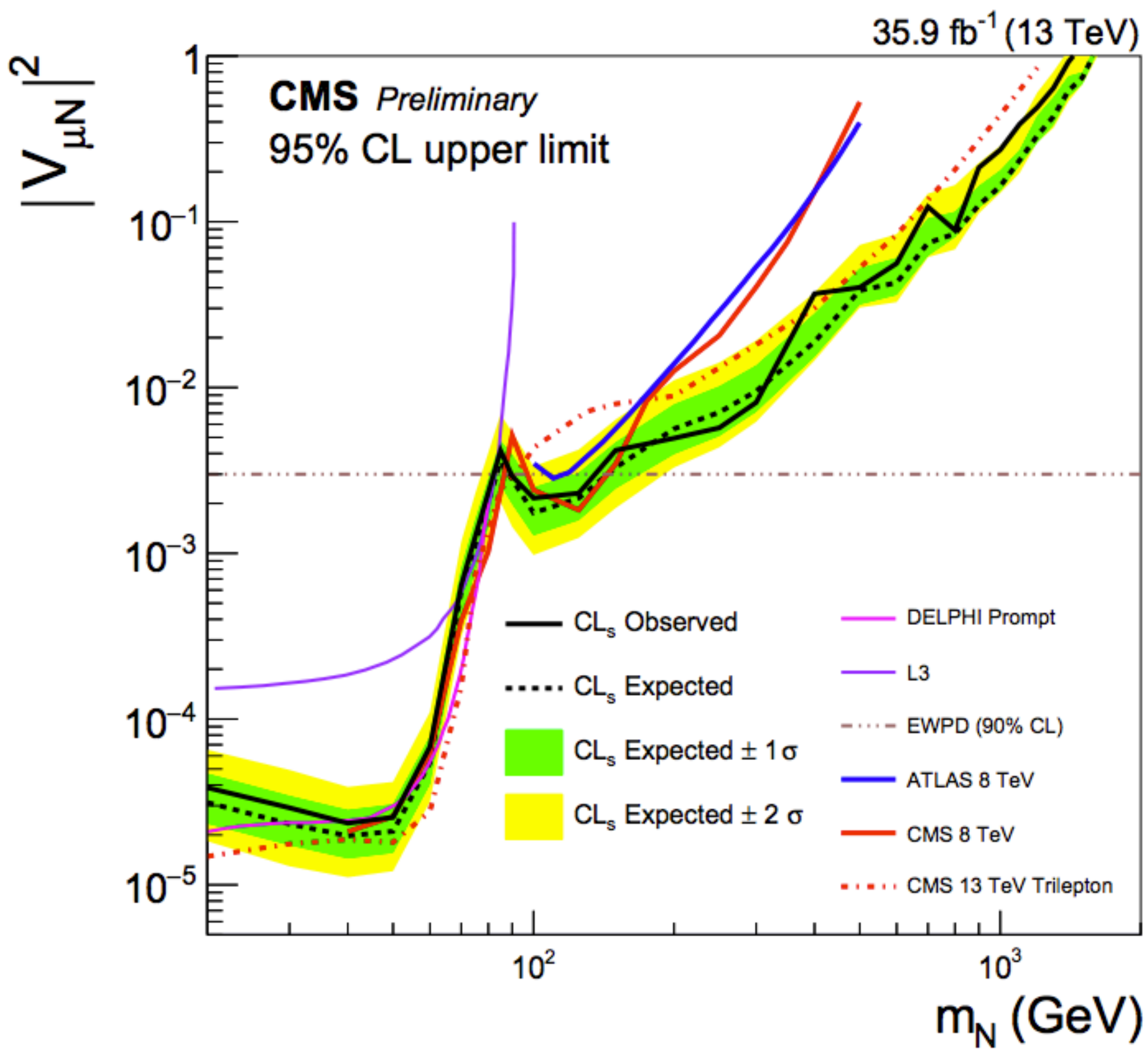
high mass, $m(\ell, J)$

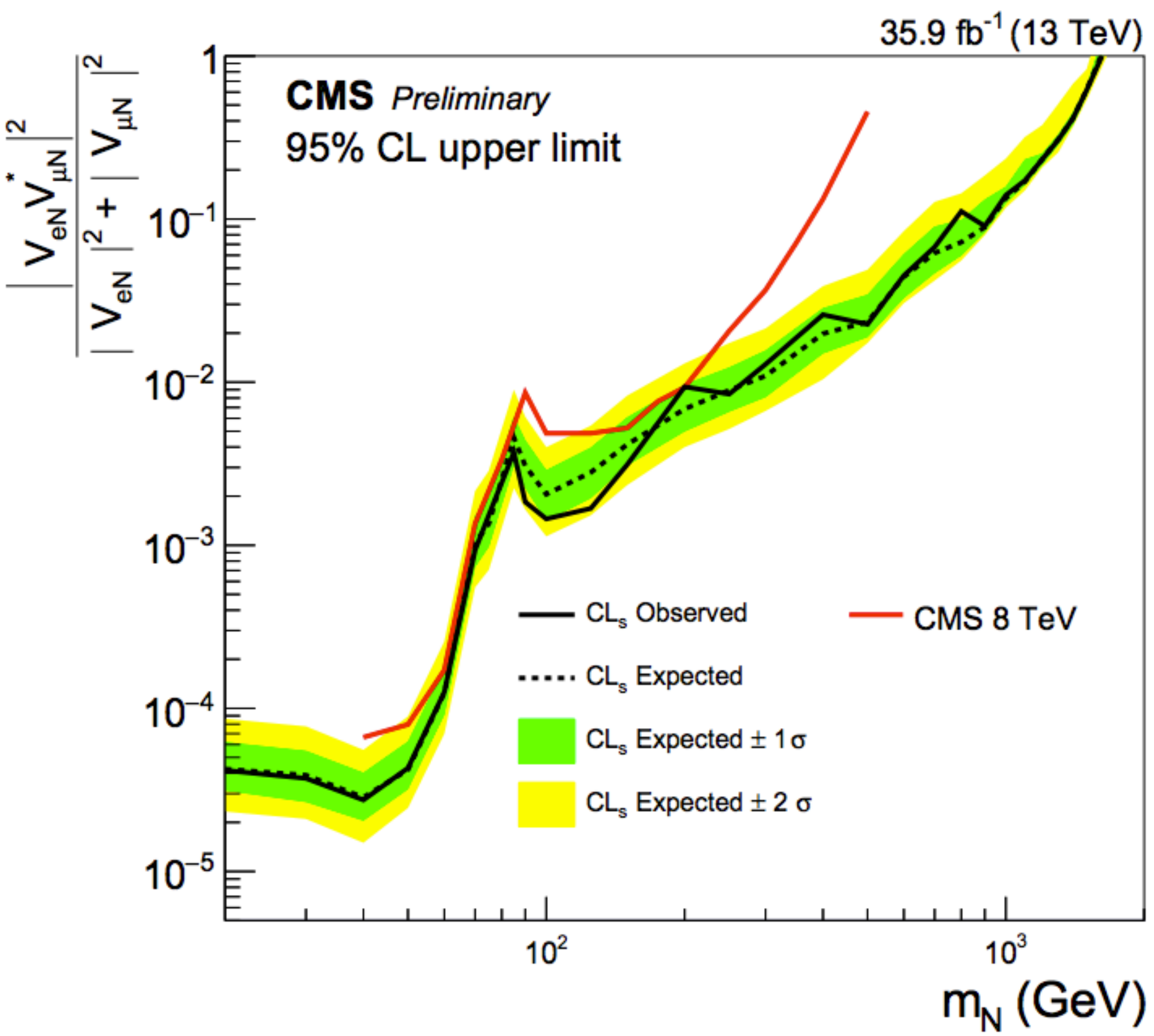


- The final selection is optimized separately for each N mass hypothesis

2ℓ2q channel: limits

CMS-PAS-EXO-17-028

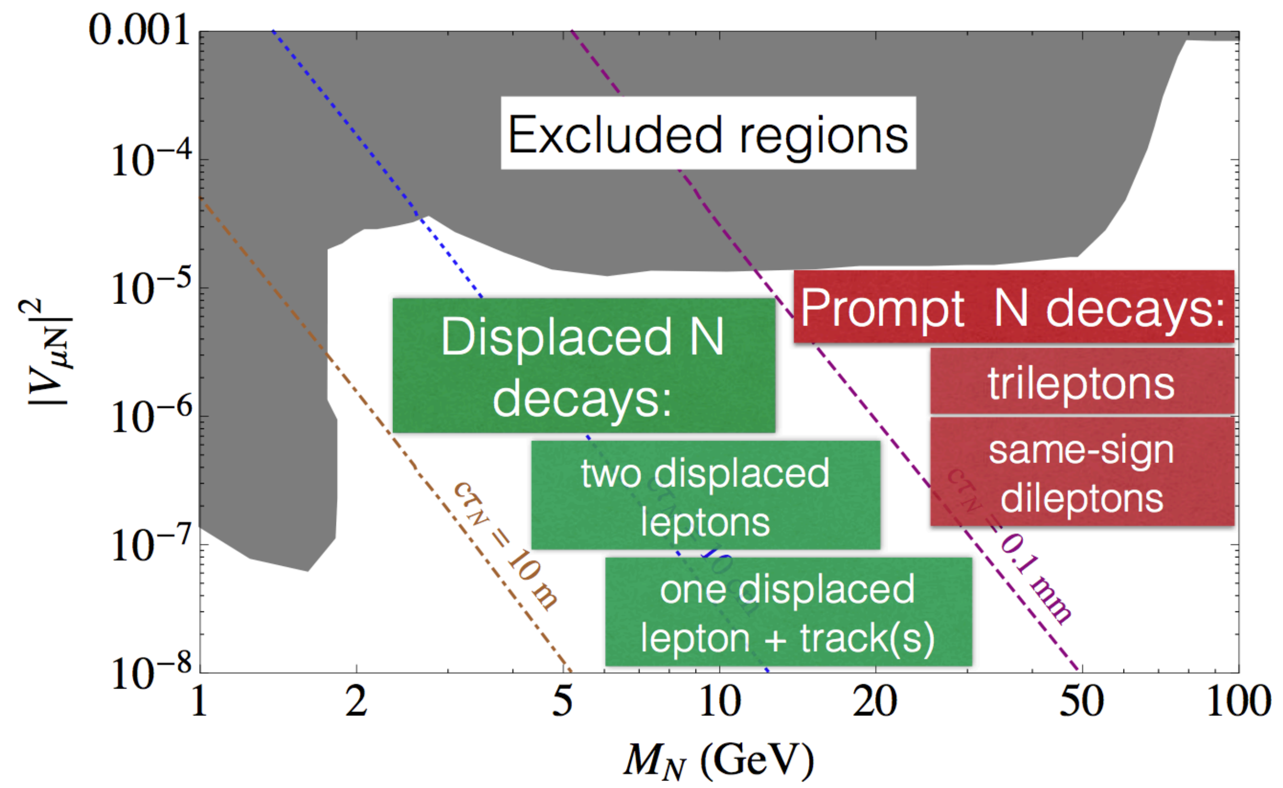


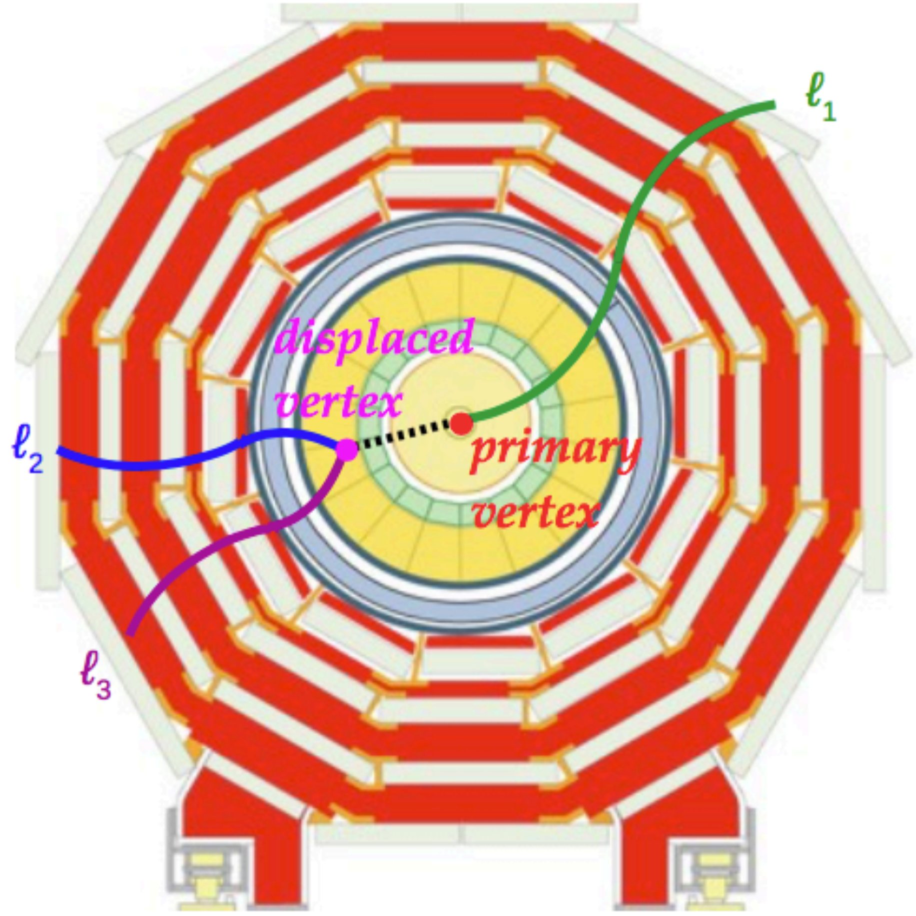


Next step: long-lived HNL

- The HNL lifetime increases drastically for small values of mass and mixing parameter

$$\tau_i \sim \left|V_{i\ell}\right|^{-2} m_i^{-5}$$





- Developing specific strategies for such nonprompt particles
  - dedicated tracking and identification
  - particle reconstruction without inner tracker (esp. for muons → muon system alone)
  - fit of a secondary (displaced) vertex

Conclusions

- The LHC participates actively in the HNL hunting
  - extend the search to ~TeV masses
- Several searches already carried out with 8 TeV data, new results with 13 TeV data are starting to come out
  - HNL from decay of B hadrons and W bosons
  - only couplings to ν_e and ν_μ explored so far
- New developments are underway
  - already tackling long-lived HNLs
  - searches with τ leptons for ν_μ coupling

Bonus slides

3ℓ search: OSSF *vs* no-OSSF

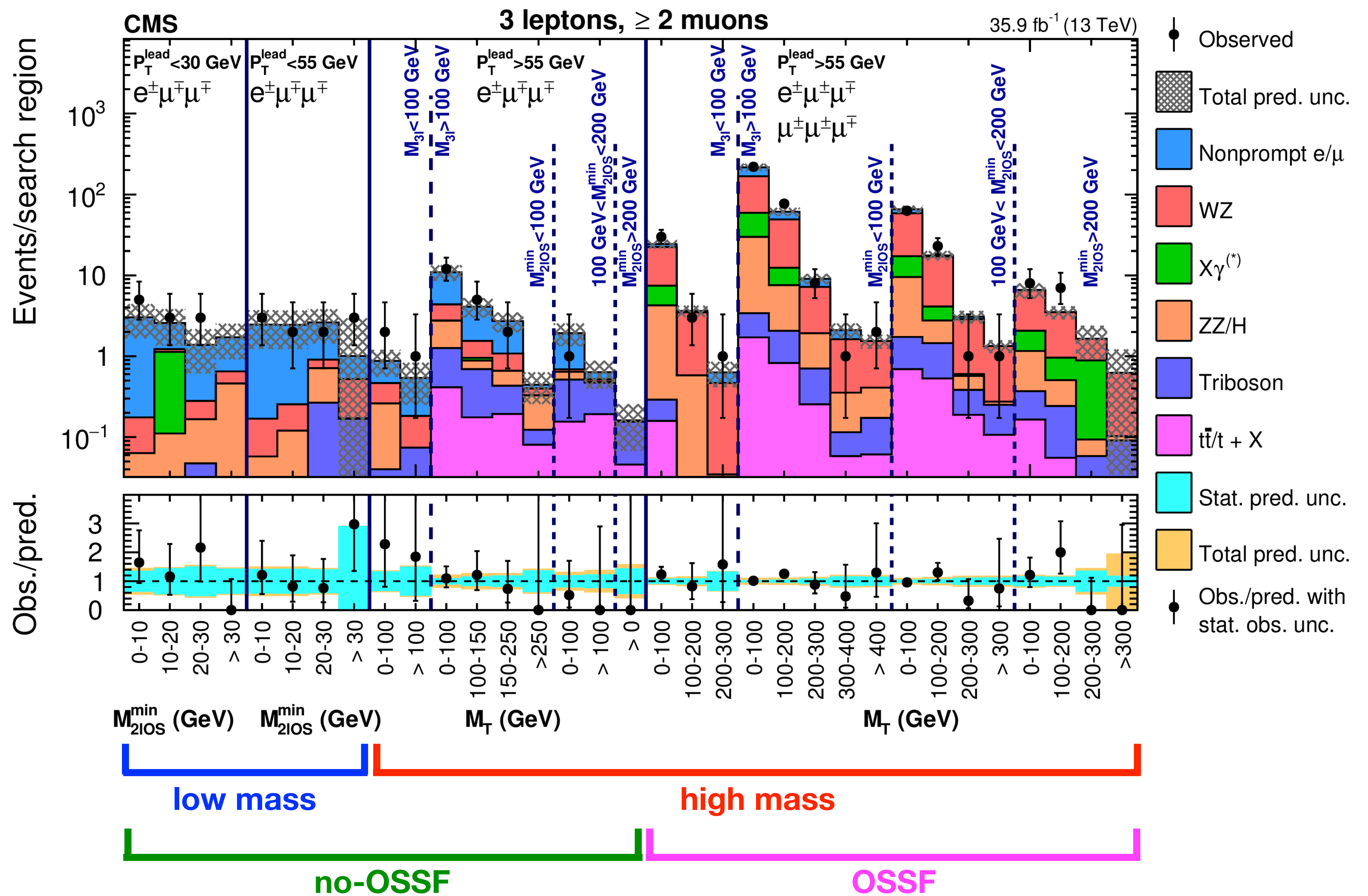
Phys. Rev. Lett. 112, 131802 (2014)

- N can couple to e or μ or both: $|V_{eN}|^2$, $|V_{\mu N}|^2$, $|V_{eN} V^*_{\mu N}|$
- We consider each coupling separately, setting the other to 0
  - resulting limits less model-dependent and more conservative
- In case of LNV decay, we can have trilepton events with no opposite-sign, same-flavor pairs (no-OSSF)
  - SM background drastically reduced (e.g. $Z/\gamma^* \to \ell^+\ell^-$)

	OSSF		no-OSSF		OSSF	
	eee	$e^\pm e^\mp \mu$	$e^\pm e^\pm \mu$	$e^\pm \mu^\pm \mu$	$e^\pm \mu^\mp \mu$	μμμ
$\|V_{eN}\|^2 \neq 0,\ \|V_{\mu N}\|^2 = 0$	✓	✓	✓			
$\|V_{eN}\|^2 = 0,\ \|V_{\mu N}\|^2 \neq 0$				✓	✓	✓
Background level	*high*		*low*		*high*	

3ℓ channel: results

- Data split into several categories, based on various variables
  - lepton p_T, di-/tri-lepton mass, transverse mass, (no-)OSSF



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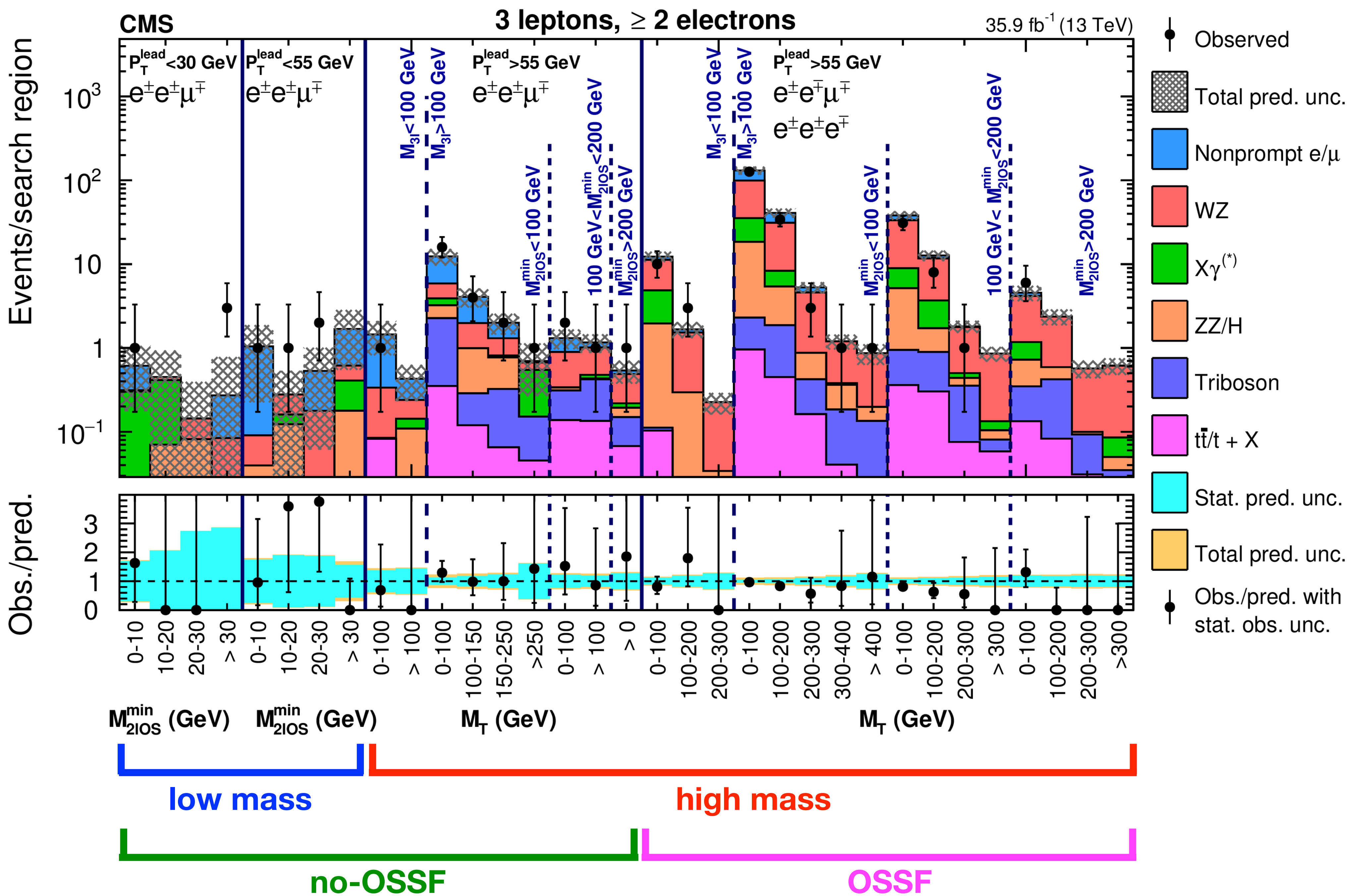
3ℓ channel: results

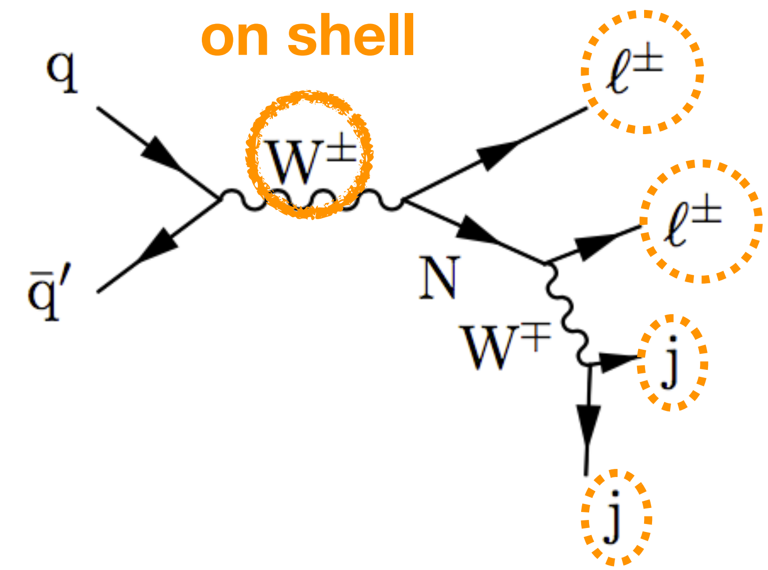
- Data split into several categories, based on various variables
  - lepton p_T, di-/tri-lepton mass, transverse mass, (no-)OSSF



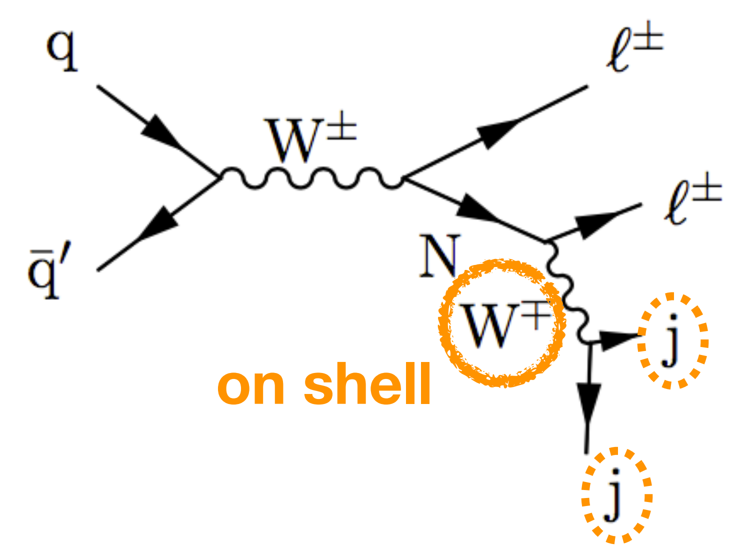
2ℓ2q search: search regions

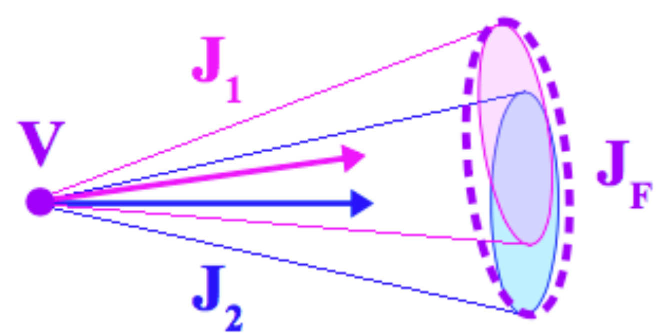
CMS-PAS-EXO-17-028

- Four search regions identified
  - **Low mass:** m_N = 20–80 GeV $< m_W$
    - ≥ 2 jets, select jet pair such that $m(2\text{jet}, 2\ell)$ is closest to m_W
    - Retain also events with 1 jet only to recover possible inefficiencies



  - **High mass:** m_N = 80 GeV–1.7 TeV $> m_W$
    - ≥ 2 jets, select jet pair such that $m(2\text{jet})$ is closest to m_W
    - ≥ 1 large-cone jet, select the one with invariant mass closest to m_W

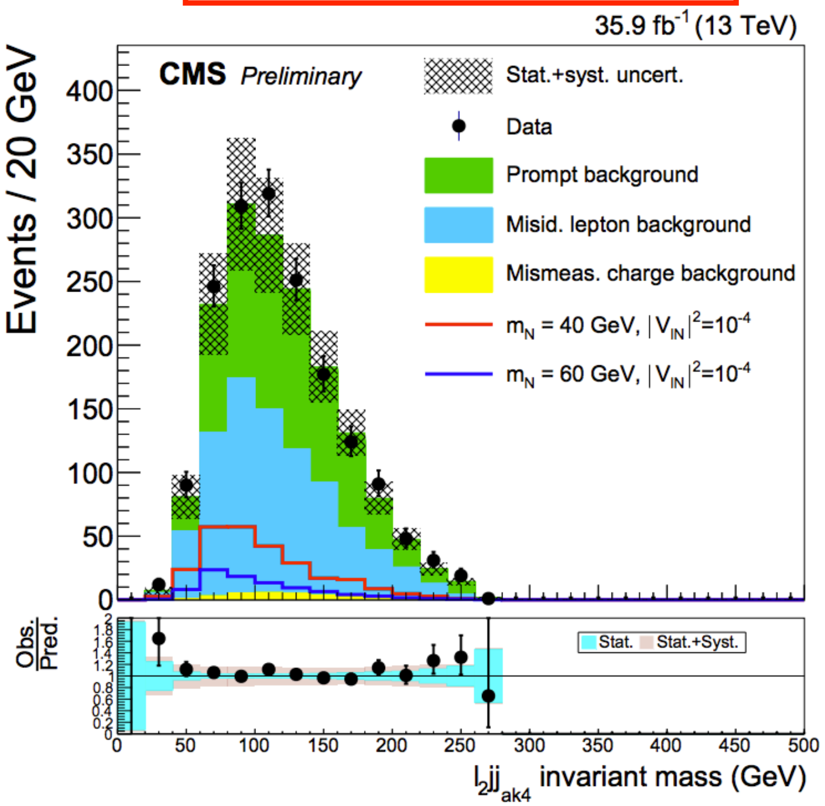




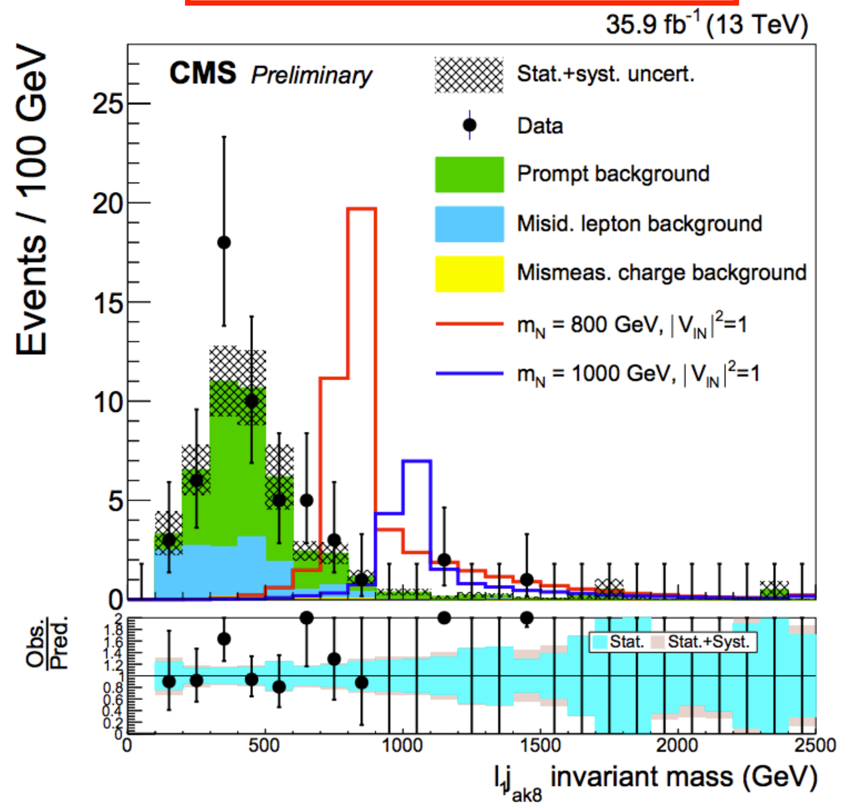
2ℓ2q channel: results

CMS-PAS-EXO-17-028

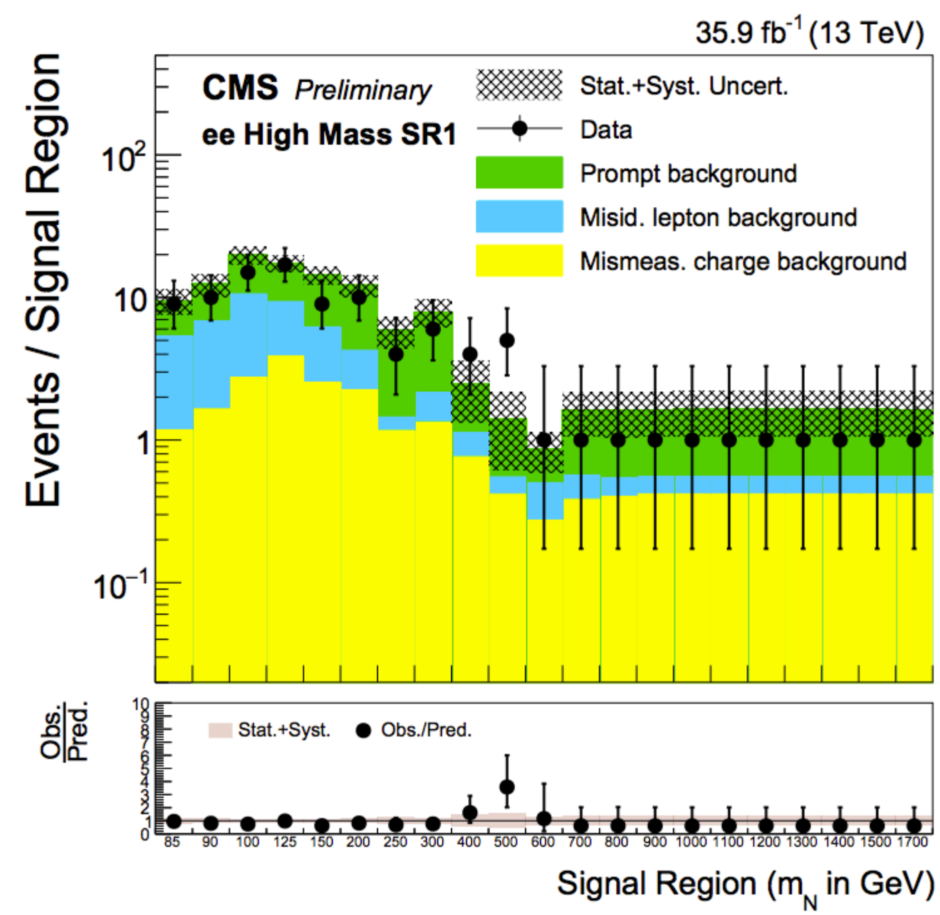
low mass, $m(\ell, 2j)$



high mass, $m(\ell, J)$



ee signal regions vs m_N
high mass, 2 jets



- In each search region, the final selection is optimized separately for each N mass hypothesis

2ℓ2q channel: limits

CMS-PAS-EXO-17-028